CERN-TH Institute
Workshop on high-energy implications of flavor anomalies

Leptoquarks in $b \to sll$

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Leptons and quarks

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

SM interactions cannot mix colorless leptons into colored quarks

$$D = \partial + i g_s T \cdot G + \cdots$$

GUT gauge bosons and scalars do convert between leptons/quarks

$$\bar{5} = \begin{pmatrix} \nu \\ e \\ d^c \end{pmatrix} \qquad 10 = \begin{pmatrix} e^c \\ u^c \\ u_L \\ d_L \end{pmatrix}$$

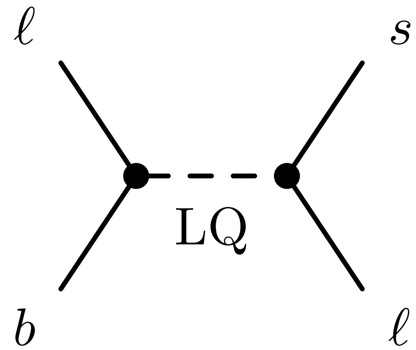
Leptoquarks (LQs) are colored triplet bosons, originating from GUT scalar representations or from GUT gauge bosons

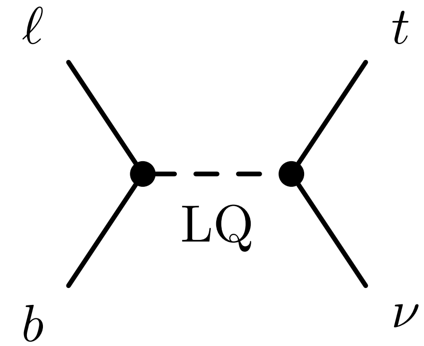
$$5_S = H(1,2,1/3) \oplus S_1^*(3,1,-1/3)$$

$$\bar{5}\, 10\ 5_H \quad \rightarrow \quad Y_{ul} u_L e_L S_1 + \cdots$$

Semileptonic processes, natural arena for LQs

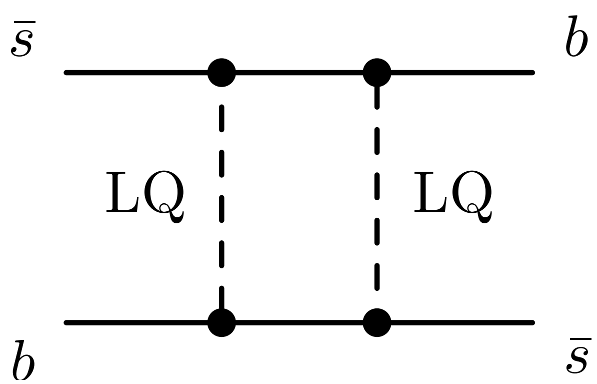
Leading order LQ effects expected in neutral and charged semileptonic processes

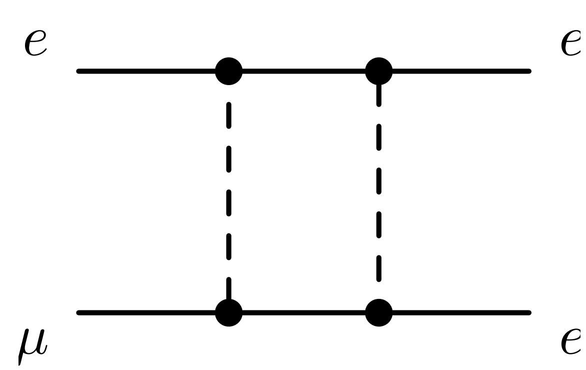




$$\sim \frac{y^2}{m_{\mathrm{LQ}}^2}$$

Loop suppression of meson mixing and leptonic LFV

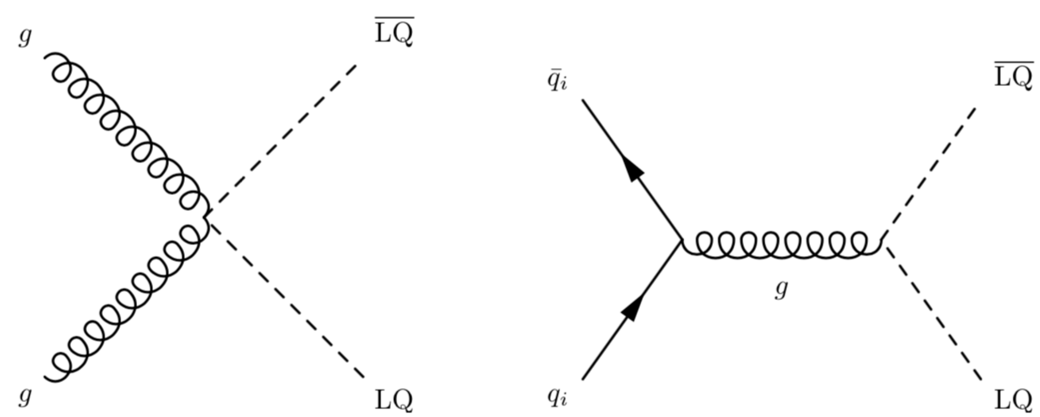




$$\sim \frac{y^4}{(4\pi)^2 m_{\mathrm{LQ}}^2}$$

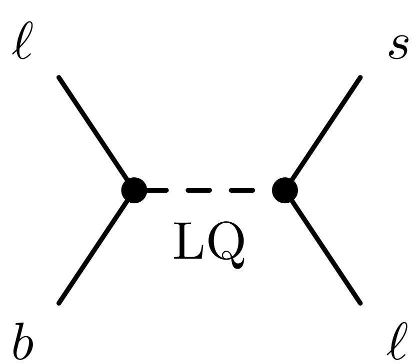
Scalar LQs in b→sll

LQs are colored and are directly produced→ their mass must be above ~TeV



Matching onto SM_{eff}, resulting in low-energy effective interactions

$$\mathcal{H}_{\text{eff}}^{b\to sll} = -\frac{4G_F\lambda_t}{\sqrt{2}}\Big(\sum_{i=S,P,7,9,10} + \sum_{i'}\Big)C_i(\mu)\mathcal{O}_i(\mu)$$

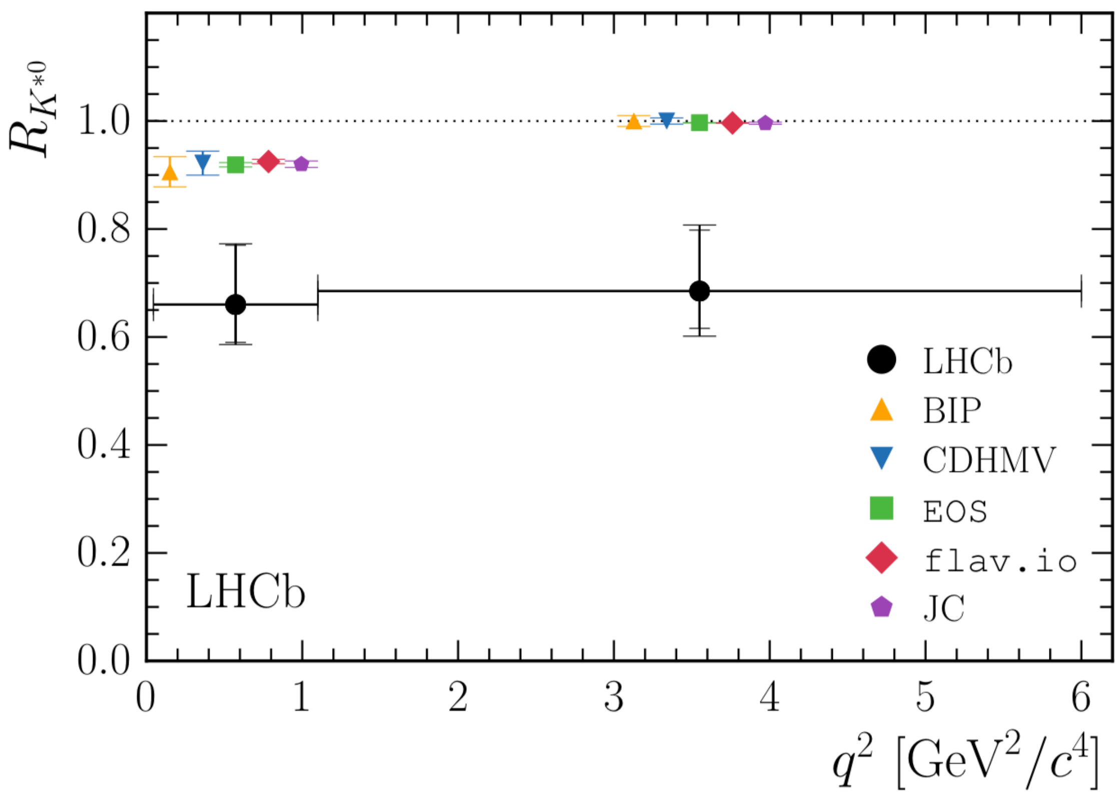


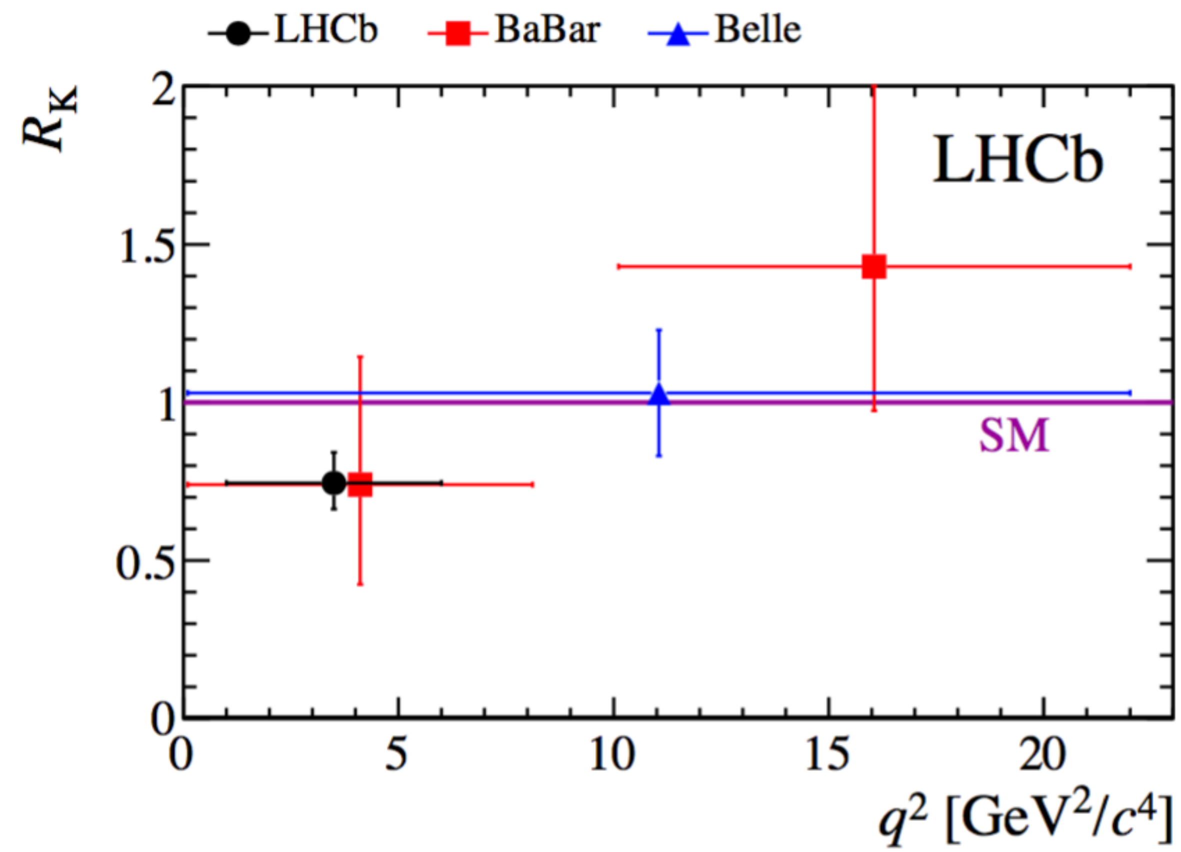
$$\mathcal{O}_{S(P)} = \frac{e^2}{(4\pi)^2}\left(\bar{s}_L b_R\right)\left(\bar{l}(\gamma^5)l\right)$$ (pseudo)scalar

$$\mathcal{O}_{9(10)} = \frac{e^2}{(4\pi)^2}\left(\bar{s}_L\gamma_\mu b_L\right)\left(\bar{l}\gamma^\mu(\gamma^5)l\right)$$ vector(axial)

$$\mathcal{O}_7 = \frac{em_b}{(4\pi)^2}\left(\bar{s}_L\sigma_{\mu\nu}F^{\mu\nu}b_R\right)$$ dipole

LFU in B→K$^{(*)}\ell^+\ell^-$





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

	LHCb	SM	dev.
R_K	0.745(97)	1.00(1)[2]	2.6σ
$R_{K^*\text{low}}$	0.660(113)	0.906(28)	2.1σ
R_{K^*}	0.685(122)	1.00(1)[2]	2.6σ
			$\sim 4\sigma$

Systematically lower than SM prediction

[Kruger, Hiller '03]
[LHCb '14, '16]
[Bordone, Isidori, Pattori '16]

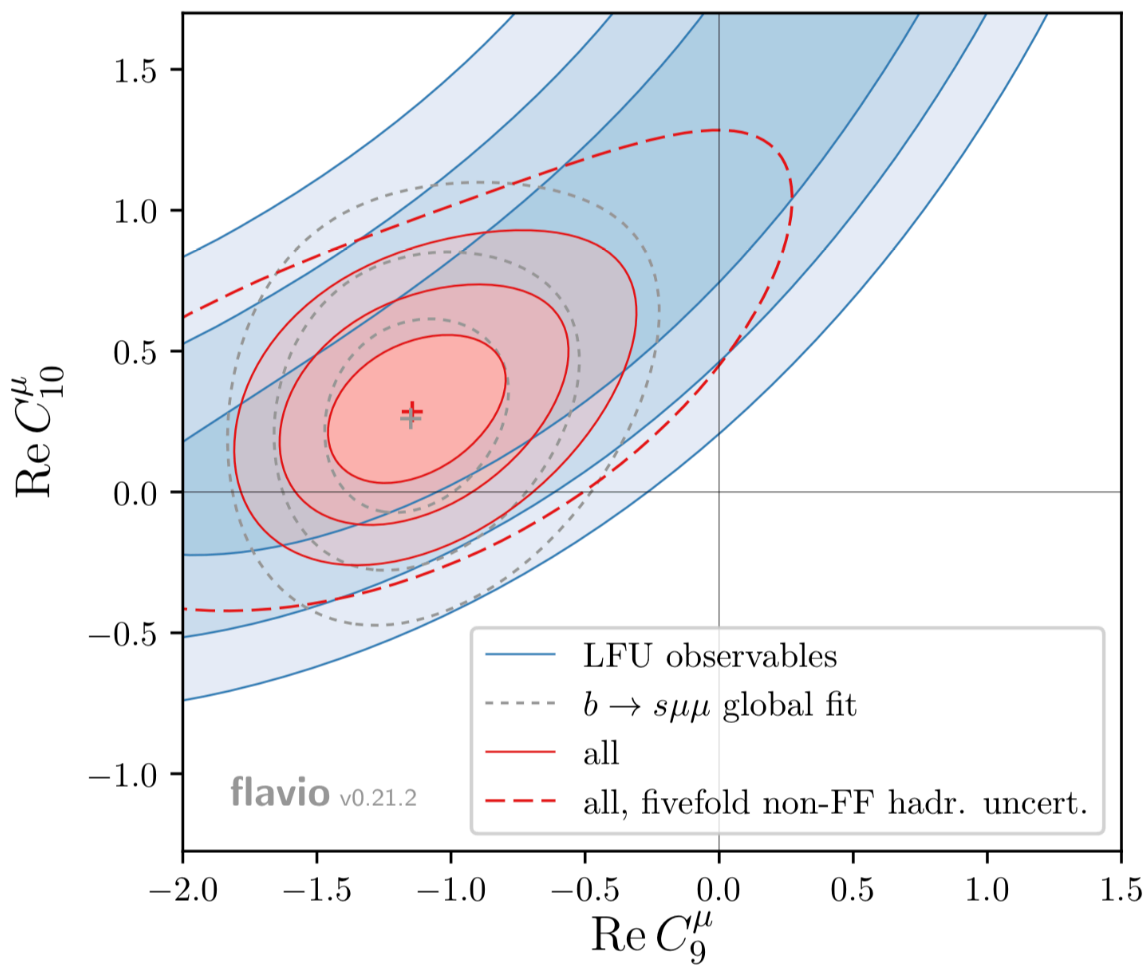
b → sll global picture

Global fit of all observables does not dilute the significance observed in LFU

$B \to K^{(*)} \mu^+ \mu^-$ $\qquad S_i, P_i^{(\prime)}$

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

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



[Altmannshofer et al ’17]

Strong indications of destructive NP * SM interference in C_9

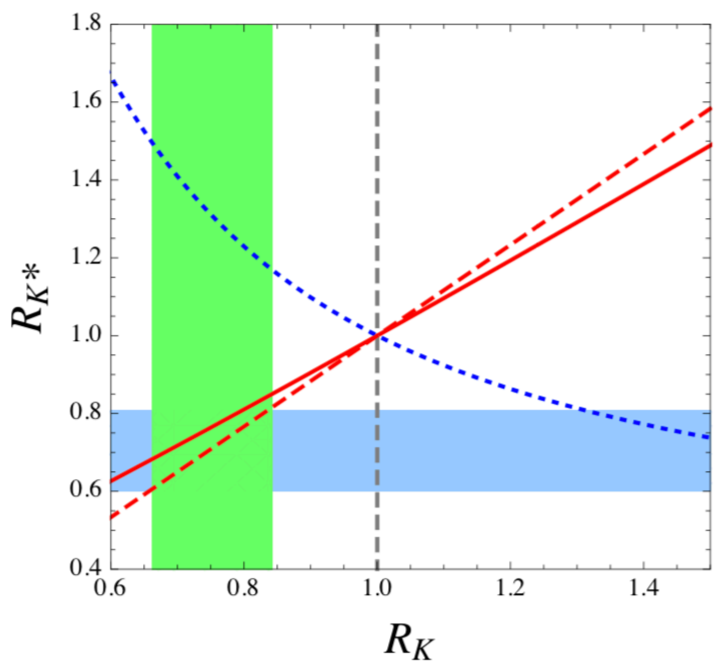
Possible C_{10}, $C_{10} = -C_9$ is theoretically attractive

(S)calar and (P)seudoscalar operators enhance $Br(B_s \to \mu\mu)$ by $\sim(m_B/m_\mu)^2$

See also [Capdevilla et al ’17, Geng et al ’17]

LQs in b→sll

SCALARS	tree	loop	
S_3	$C_9 = -C_{10}$		
R_2	$C_9 = C_{10}$	$C_9 = -C_{10}$	[Becirevic, Sumensari '17]
$\sim R_2$	$C'_9 = -C'_{10}$		
$\sim S_1$	$C'_9 = C'_{10}$		
S_1		C_9 , C_{10}	[Neubert, Bauer '15]



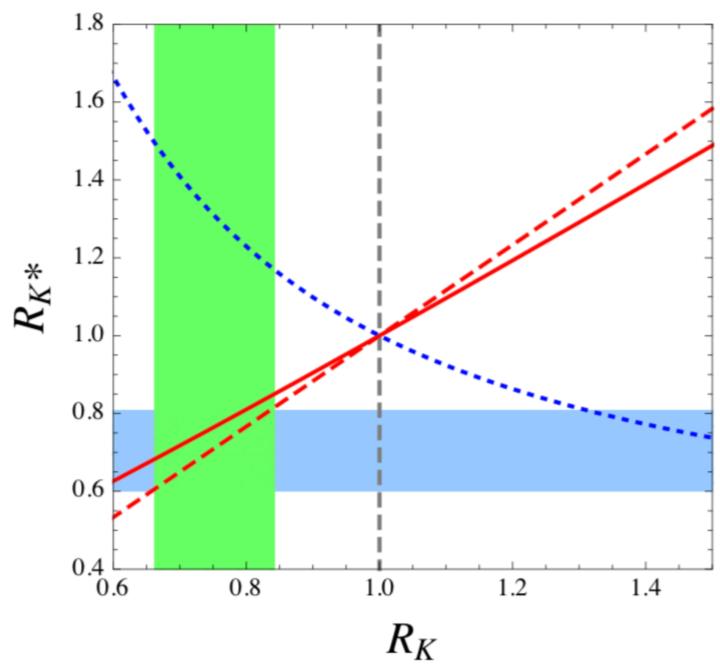
$C_9 = -C_{10}$

[Hiller, Schmaltz '14]
[Hiller, Nisandzic '17]

LQs in b→sll

VECTORS	tree	loop
U_3	$C_9 = -C_{10}$	
V_2	$C_9 = C_{10}$,...	
$\sim U_1$		C_9
U_1	$C_9 = -C_{10}$,...	

[Talk by D. A. Faroughy]



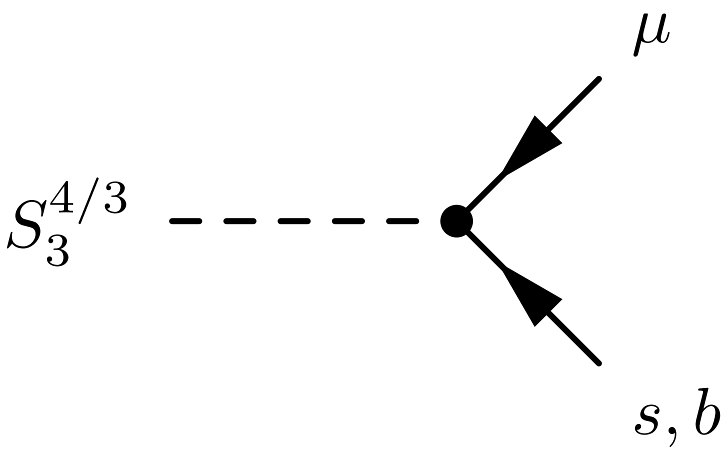
$C_9 = -C_{10}$

[Hiller, Schmaltz ’14]
[Hiller, Nisandzic ’17]

S_3 scalar LQ

Quantum numbers ($\bar{3}$,3,1/3) allow for a single LQ Yukawa

$$y\,\vec{S}_3 \cdot \bar{Q}^c i\tau^2 \vec{\tau} L$$



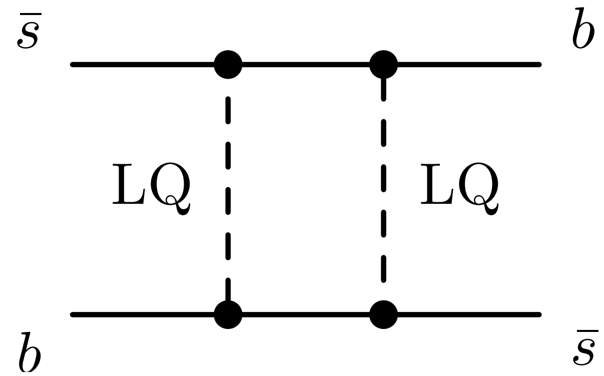
$$C_9 = -C_{10} = \frac{\pi}{V_{tb}V_{ts}^*\alpha}\, y_{b\mu} y_{s\mu}^* \frac{v^2}{m_{S_3}^2}$$

$$\approx -0.6$$

$$\frac{y_{b\mu} y_{s\mu}}{m_{S_3}^2} \approx \frac{10^{-3}}{\text{TeV}^2}$$

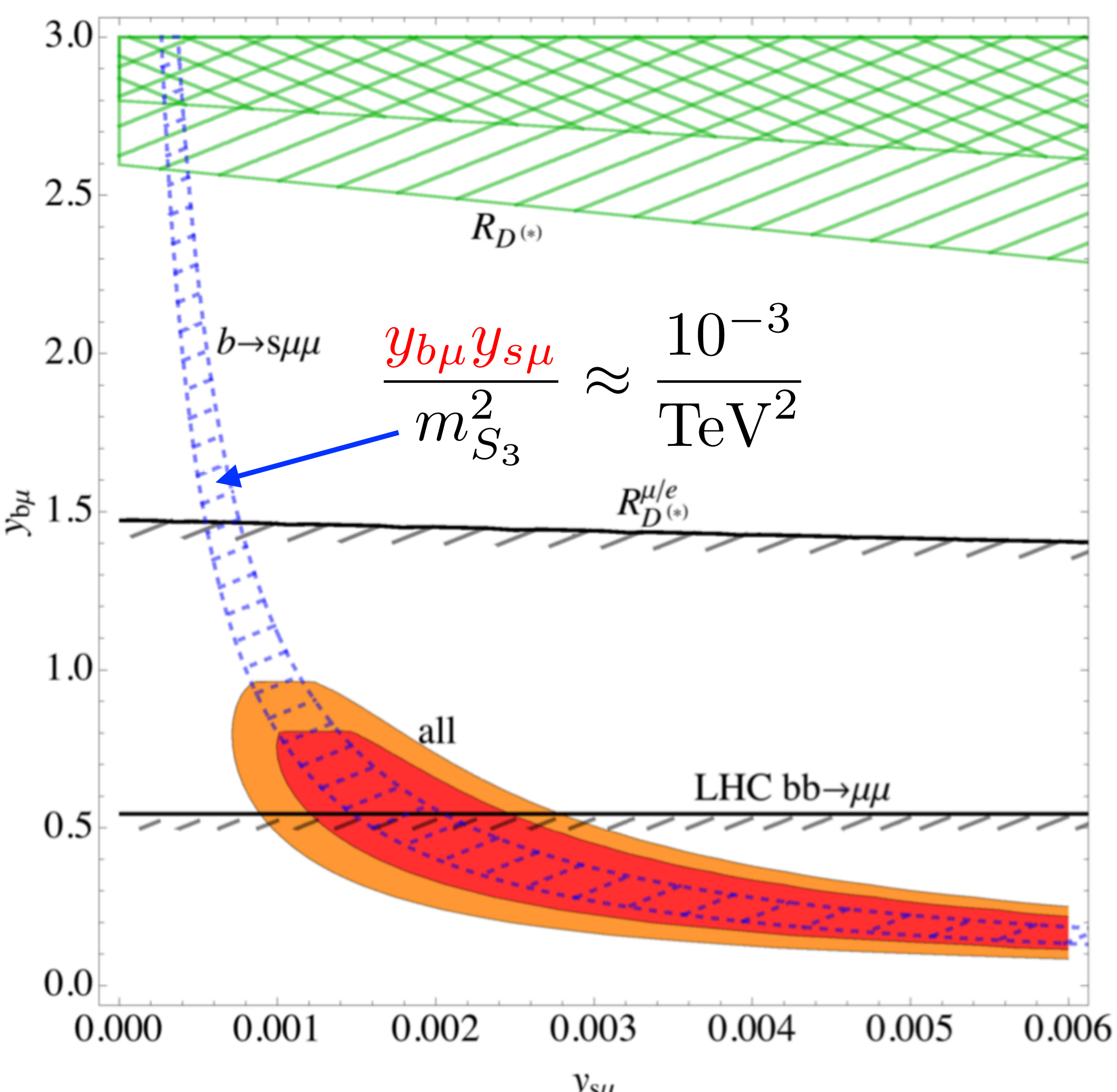
S_3 scalar LQ

Small effect, effectively hidden from other FCNC



$$\sim \quad \frac{(y_{b\mu} y_{s\mu})^2}{m_{S_3}^2} \approx \left(\frac{10^{-3}}{\mathrm{TeV}^2}\right)^2 m_{S_3}^2$$

mass enhanced!



[Dorsner et al '17]

NB. Even with couplings to tau, $R_{D(*)}$ does not work ($B \to K\nu\nu$)

$$\mathrm{Re}\left[V_{cb}\left(|y_{b\tau}|^2 - |y_{b\mu}|^2\right) + V_{cs}\left(y_{b\tau} y_{s\tau}^* - y_{b\mu} y_{s\mu}^*\right)\right] =$$

$$= -2 C_{V_L} \left(m_{S_3}/\mathrm{TeV}\right)^2, \quad C_{V_L} = 0.18 \pm 0.04$$

[Freytsis et al '15]

S_3 scalar LQ

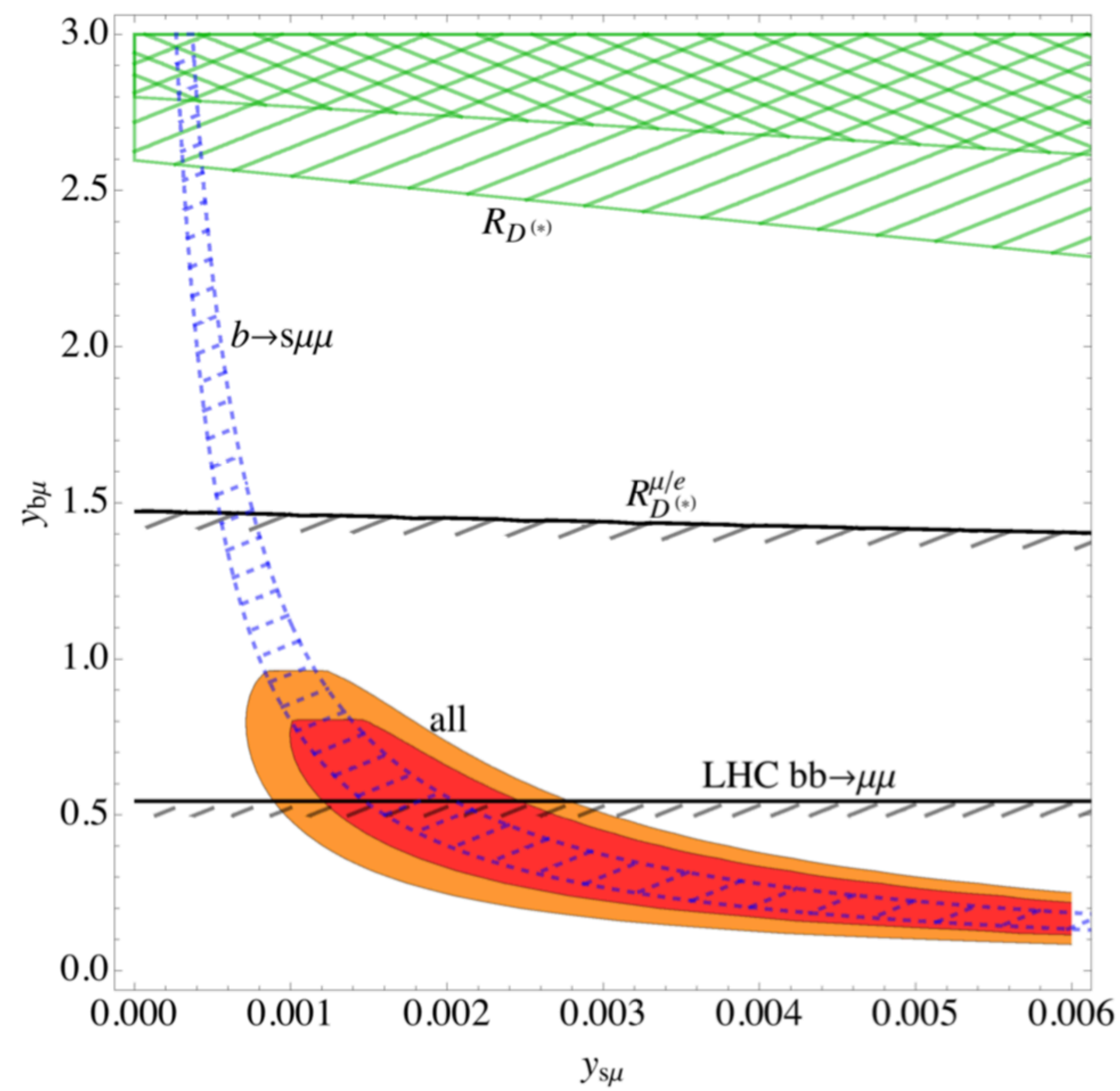
Focussing only on b→sll explanation, expect signals in

- direct searches bb, sb, ss → μμ

["Anomalies tails at high pT", talk by A. Greljo]

- $(g-2)_\mu$

$$\delta a_\mu^{S_3} = -\frac{3m_\mu^2}{(32\pi^2 m_{S_3}^2} \left(|y_{s\mu}|^2 + |y_{b\mu}|^2\right)$$



- If LQ is very heavy ~100 TeV, deviations in B_s mixing

- To address R_{D^*} have to add another LQ

→ S_3 and R_2 [talk by O. Sumensari]
→ S_3 and S_1 [talk by D. Marzzocca]

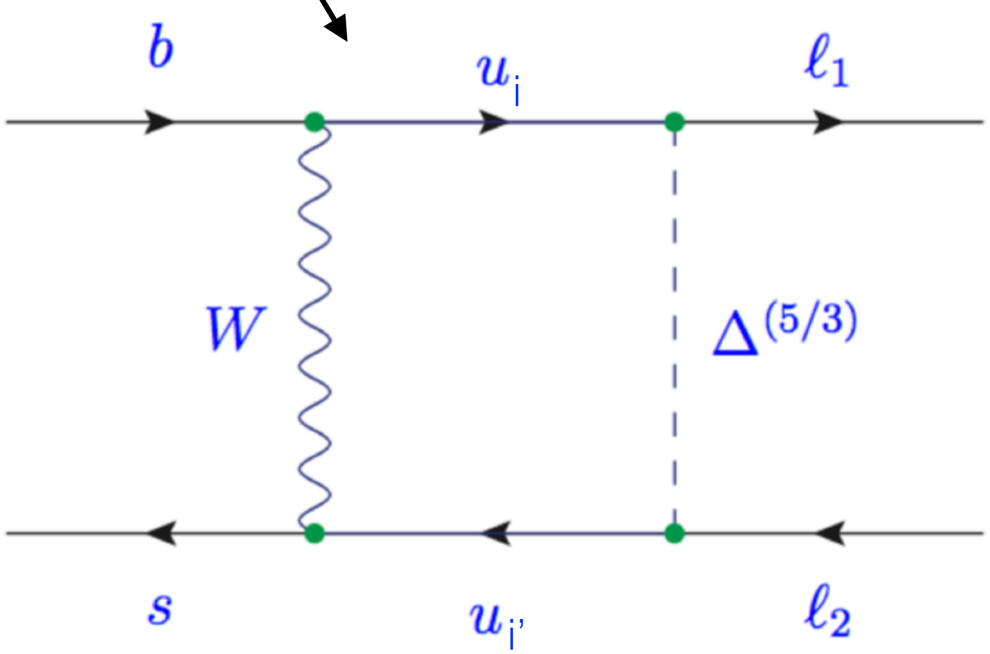
Loop LQs for b → sll

R_2 (3,2,7/6)

$$Y_R \bar{Q} \ell_R R_2 + Y_L \bar{u}_R L \widetilde{R}_2^\dagger$$

tree ✖ $C_9 = C_{10} \sim Y_{R,b\mu} Y_{R,s\mu}$

loop ✔



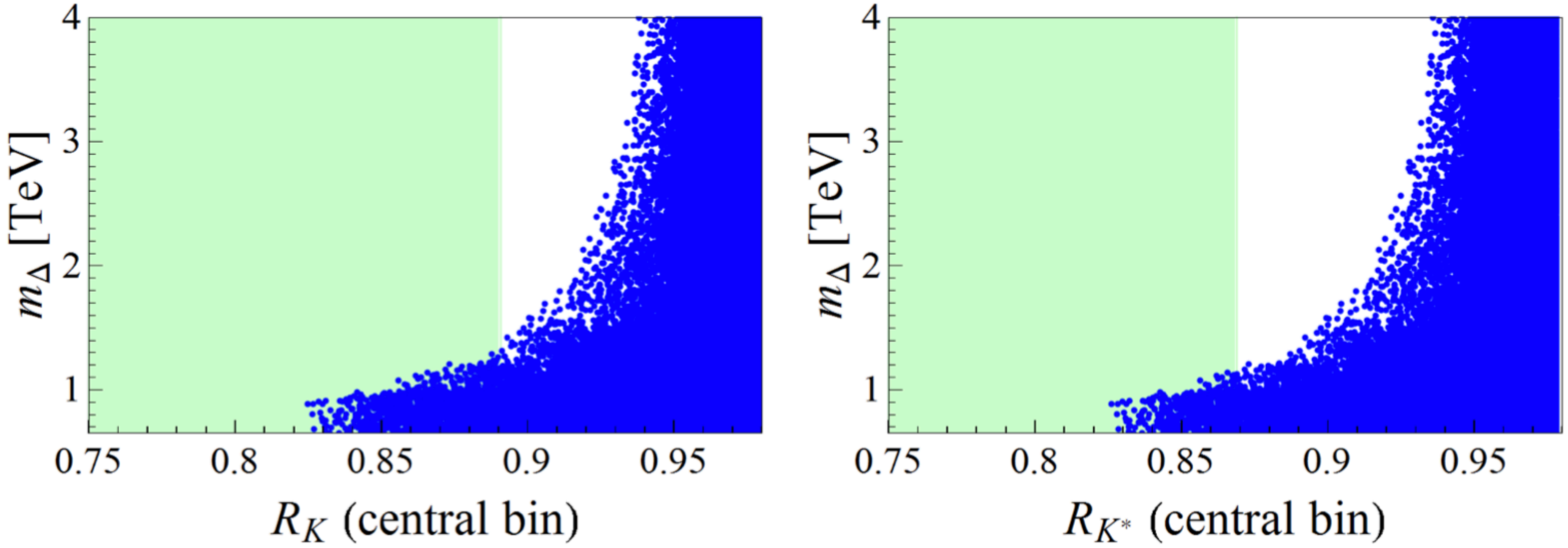
$$C_9 = -C_{10} = \sum_{i,i'} \frac{V_{ib} V_{i's}^*}{V_{tb} V_{ts}^*} y_{L,i'\mu} y_{L,i\mu}^* F(m_i, m_{i'})$$

[Becirevic, Sumensari '17]

Loop LQs for b → sll

R₂ (3,2,7/6)

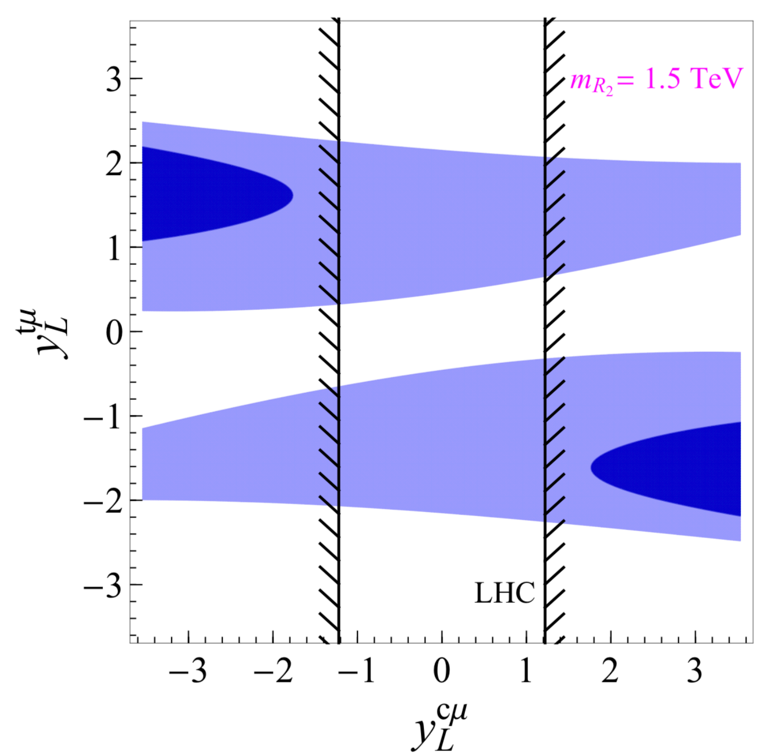
Contrary to tree-level solutions, the couplings are larger



Interesting phenomenology

$$Z \to \ell\ell$$

$$\Delta a_\mu = -\frac{3m_\mu^2}{32\pi^2 m_{R_2}^2}\left(|y_L^{c\mu}|^2 + |y_L^{t\mu}|^2\right)$$



[Angelescu et al, '18]

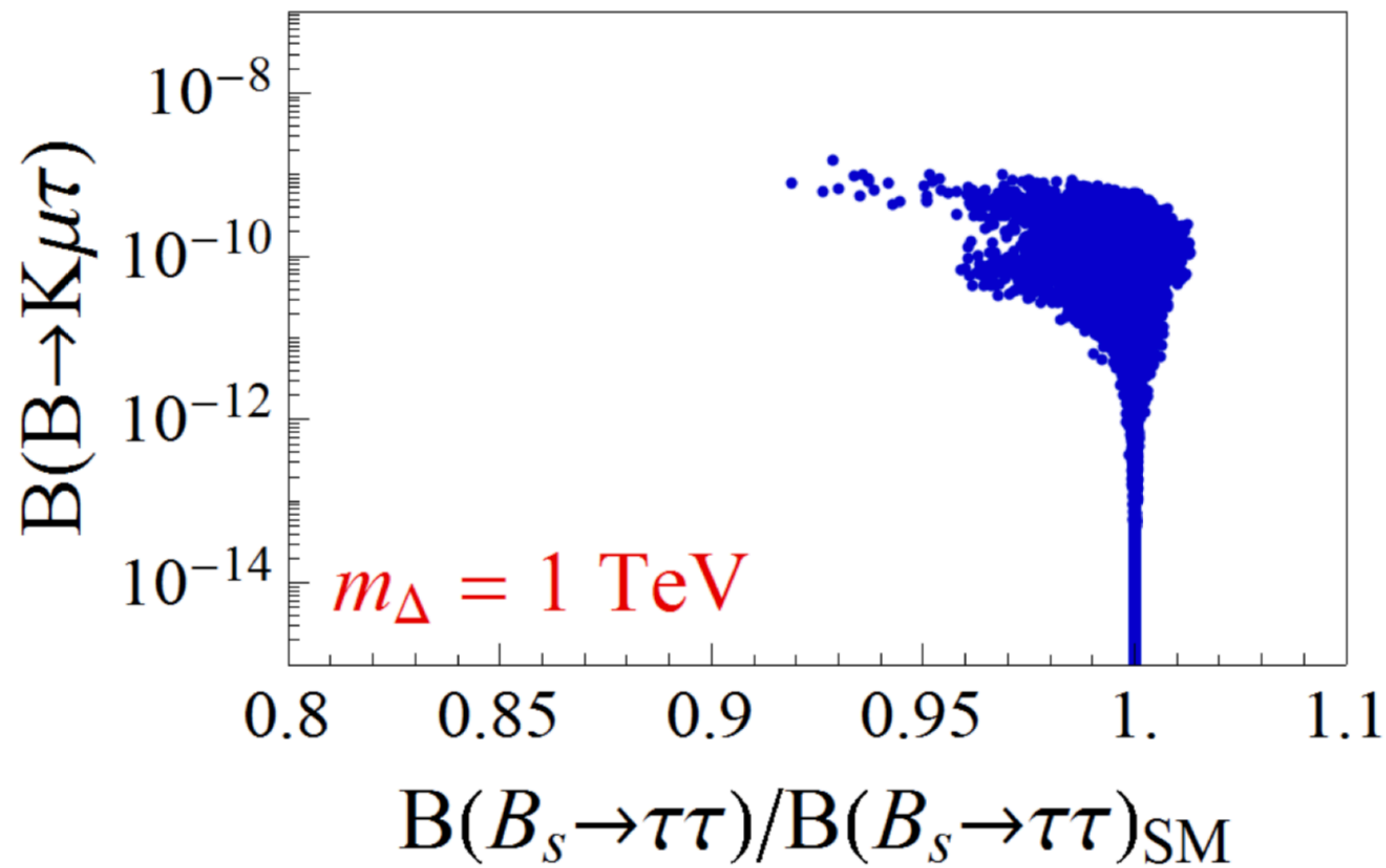
Loop LQs for b → sll

R_2 (3,2,7/6)

Allowing for perturbative τ couplings → LFV

$$\mathcal{B}(Z \to \tau\mu) \lesssim \text{few} \times 10^{-7}$$

$$\mathcal{B}(B \to K\nu\nu) \approx \mathcal{B}(B \to K\nu\nu)_{\rm SM}$$



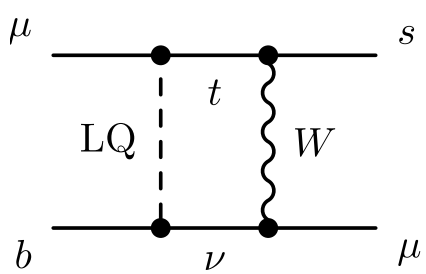
[Becirevic, Sumensari '17]

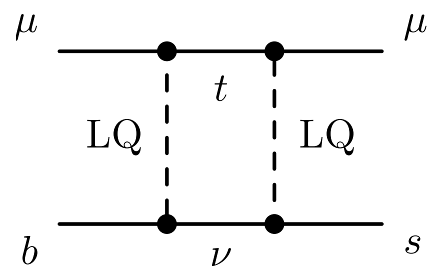
Loop LQs for b → sll

S_1 ($\bar{3}$,1,1/3)

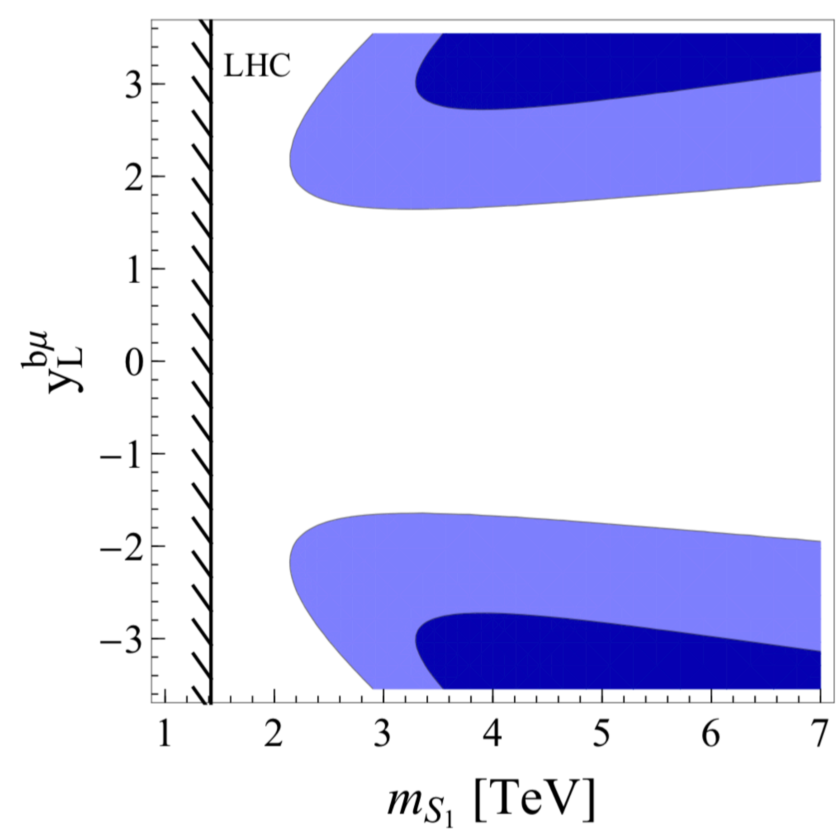
$$y_L S_1 \bar{Q}^c i\tau^2 L + y_R S_1 \bar{u}_R^c e_R$$

[Neubert, Bauer '15]





$$C_9^{kl} - C_{10}^{kl} = \frac{m_t^2}{8\pi\alpha_{\rm em} m_{S_1}^2} (y_R)_{tk} (y_R)^*_{tl} \left[\log \frac{m_{S_1}^2}{m_t^2} - f(x_t) \right]$$
$$- \frac{v^2}{32\pi\alpha_{\rm em} m_{S_1}^2} \frac{(y_L \cdot y_L^\dagger)_{bs}}{V_{tb} V_{ts}^*} (y_L^\dagger \cdot y_L)_{kl}$$



Needs very large masses and couplings

[Becirevic et al, '16]

[Angelescu et al, '18]

[Cai et al, '17]

$\tilde{U}_1$(3,1,5/3) - loop vector LQ model without quark flavor violation

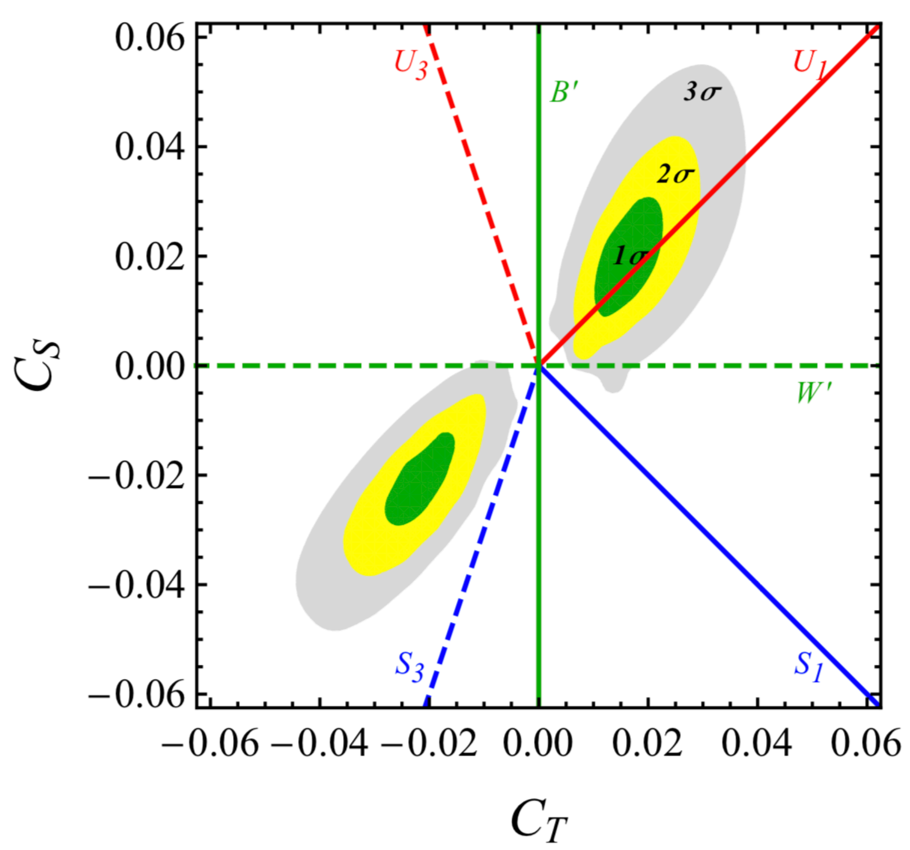
See talk by D. Faroughy

Further vector LQs

$U_3(3,3,2/3)$ $\qquad x_L \vec{U}_3^\mu \cdot \bar{Q}\gamma_\mu \vec{\tau} L$

+ $C_9 = -C_{10}$
— No UV completion - no loops
— $R_{D^{(*)}}$ is in conflict with $B \to K^{(*)}\nu\nu$

$U_1(3,1,2/3)$ $\qquad x_L U_1^\mu \bar{Q}\gamma_\mu L + x_R U_1^\mu \bar{d}_R \gamma_\mu e_R$



+ $C_9 = -C_{10}$
+ Avoids $B \to K^{(*)}\nu\nu$
+ UV frameworks proposed:

[Barbieri et al, ’15]
[Butazzo et al, ’17]
[Di Luzio et al, ’17]
[J. Cline ’17]
…

Pati-Salam, SU(4)xSU(3)xSU(2)xU(1)

Conclusion

Vector and scalar leptoquarks are natural tree-level mediators to address the semileptonic $b \to sll$ (and/or $b \to c\tau\nu$) puzzle

$b \to sll$ allows for small LQ couplings at tree-level

LFV constraints can be avoided (provided $R^{(D*)}$ is ignored)

Only a few LQs accommodate the $b \to sll$ anomalies at tree-level

Loop models require large LQ couplings, in tension with flavor and high-pT constraints