New physics in $b \to s\ell\ell$ transitions at one loop

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Outline

The $b \to s$ anomalies

- Theoretically clean test of LFUV in $b \to s$ transitions

$$R_{K^{(*)}}^{[q_1^2,q_2^2]} = \frac{\int_{q_1^2}^{q_2^2} dq^2 d\Gamma(B \to K^{(*)}\mu^+\mu^-)/dq^2}{\int_{q_1^2}^{q_2^2} dq^2 d\Gamma(B \to K^{(*)}e^+e^-)/dq^2} \quad (1)$$

- Several anomalies at LHCb:

$$R_K^{[1,6](SM)} = 1.00 \pm 0.01 \qquad R_K^{[1,6](exp)} = 0.846^{+0.062}_{-0.056} \qquad (2.5\sigma)$$

$$R_{K^*}^{[1.1,6](SM)} = 1.00 \pm 0.01 \qquad R_{K^*}^{[1.1,6](exp)} = 0.660^{+0.113}_{-0.074} \qquad (3.0\sigma)$$

$$R_{K^*}^{[0.045,1.1](SM)} \simeq 0.92 \pm 0.03 \qquad R_{K^*}^{[0.045,1.1](exp)} = 0.685^{+0.122}_{-0.083} \qquad (1.9\sigma)$$

- Additional deviation from SM in $b \to s$ at LHC:

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

$$BR(B_s \to \mu^+\mu^-)^{(exp)} = (2.93 \pm 0.42) \times 10^{-9} \qquad (1.5\sigma)$$

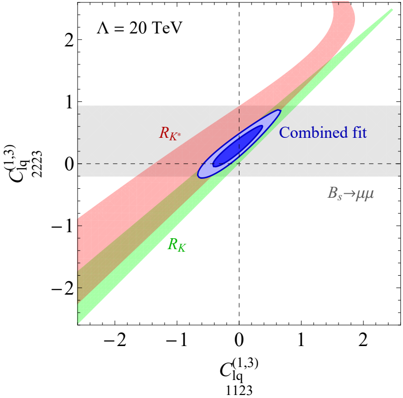
Tree-level explanations in EFT

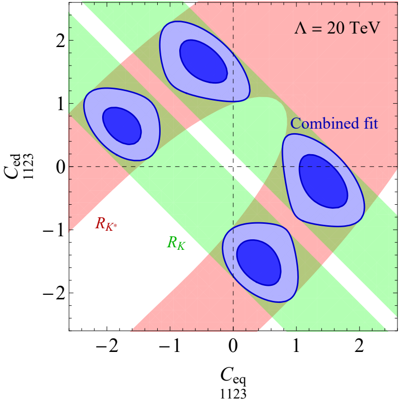
- Data indicative of new physics which induces vector-current semi-leptonic operator(s)
- Considering physics about EW scale, should respect full SM gauge-invariance (SMEFT)
- Working cases involve:

$$Q^{(1)}_{\substack{lq\\ \alpha\alpha 23}} = (\overline{l_{L\alpha}}\gamma_\mu l_{L\alpha})(\overline{q_{L2}}\gamma^\mu q_{L3}) \qquad Q^{(3)}_{\substack{lq\\ \alpha\alpha 23}} = (\overline{l_{L\alpha}}\gamma_\mu \sigma^A l_{L\alpha})(\overline{q_{L2}}\gamma^\mu \sigma^A q_{L3})$$

$$Q_{\substack{eq\\ \alpha\alpha 23}} = (\overline{e_{R\alpha}}\gamma_\mu e_{R\alpha})(\overline{q_{L2}}\gamma^\mu q_{L3}) \qquad Q_{\substack{ed\\ \alpha\alpha 23}} = (\overline{e_{R\alpha}}\gamma_\mu e_{R\alpha})(\overline{d_{R2}}\gamma^\mu d_{R3})$$

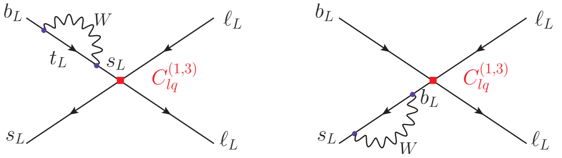
Tree-level explanations of the anomalies





Now at one-loop

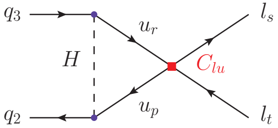
- New physics with $C/\Lambda^2 \sim 1/(20\ \text{TeV})^2$ difficult to observe, but one-loop solutions involve much lower scales
- Searched for single WCs which could viably explain the anomalies at loop level

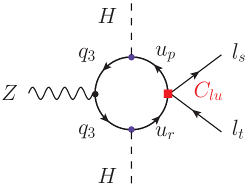


- Worked in Warsaw basis, with Y_d diagonal at Λ, and computed at leading-log order

Constraints on the EFT

- Lower new physics scale ⇒ more stringent constraints
- Include shift in Z-boson couplings to leptons, LEP contact interaction bounds on operators of the form $\mathcal{O}_{ij}^{XY} = (\overline{e}\gamma_\mu P_X e)(\overline{q_i}\gamma^\mu P_Y q_j)$, and meson decay ratios
- LEP bounds mean operators with electrons generally more constrained than those with muons





Meson decays

- Bounds from meson decays: define

$$r_K^{e/\mu} = \frac{BR(K^- \to e\overline{\nu})}{BR(K^- \to \mu\overline{\nu})}, \quad r_D^{\mu/e} = \frac{BR(B \to D\mu\overline{\nu})}{BR(B \to De\overline{\nu})} \tag{2}$$

- $C_{lq}^{(3)}$ is very constrained by the measurements

$$r_K^{e/\mu(exp)} = (2.488 \pm 0.010) \cdot 10^{-5} \quad r_K^{e/\mu(\mathrm{SM})} = (2.477 \pm 0.001) \cdot 10^{-5} \tag{3}$$

$$r_D^{\mu/e(exp)} = 0.995 \pm 0.045 \qquad r_D^{\mu/e(\mathrm{SM})} = 0.9957 \pm 0.0004 \tag{4}$$

- These give us

$$\underset{1122}{C_{lq}^{(3)}} - \underset{2222}{C_{lq}^{(3)}} \in (-0.10, 0.03) \times (\Lambda/1\ \mathrm{TeV})^2 \tag{5}$$

$$\underset{1133}{C_{lq}^{(3)}} - \underset{2233}{C_{lq}^{(3)}} \in (-0.80, 0.70) \times (\Lambda/1\ \mathrm{TeV})^2 \tag{6}$$

Results

- Set $\Lambda = 1$ TeV; enforced $|C| \leq 10$, which corresponds to $|\delta C_{9,10}| \lesssim |C_{9,10}^{(\text{SM})}|$

Wilson Coeff.	Indices	2σ range	R_K
$C_{lq}^{(1)}$	(1133)	$(-0.41, 0.02)$	$(0.91, 1.01)$
	(2222)	$(-5.4, 0.90)$	$(0.48, 1.1)$
	(2233)	$(-0.31, 0.72)$	$(0.85, 1.07)$
$C_{lq}^{(1)} = C_{lq}^{(3)}$	(1133)	$(-0.41, 0.18)$	$(0.84, 1.09)$
	(2233)	$(-0.56, 0.42)$	$(0.83, 1.25)$
C_{lu}	(2223)	$(-10, 10)$	$(0.88, 1.07)$

- In the last column: $R_K^{[1,6]} \simeq R_{K^*}^{[1.1,6]}$

Single mediator solutions

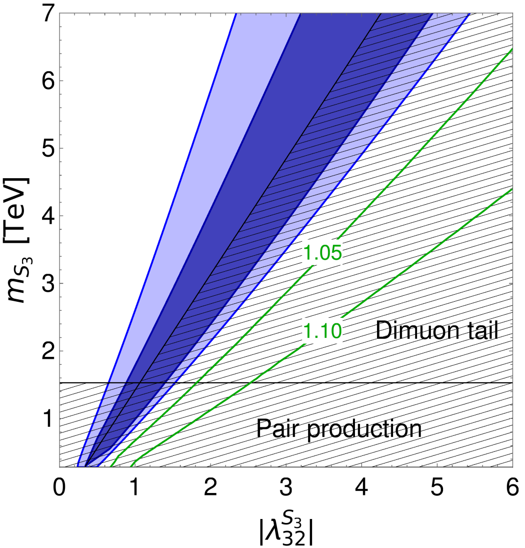
- Used EFT results to find single-mediator models: either LQ with one coupling or Z' with two couplings

- Four solutions:

1. $S_3 \sim (\overline{3}, 3)_{1/3}$ coupled to $l_{L2} q_{L3}$
2. $S_1 \sim (\overline{3}, 1)_{1/3}$ coupled to $l_{L1} q_{L3}$
3. $U_1^\mu \sim (3, 1)_{2/3}$ coupled to $l_{L1} q_{L3}$
4. $Z'^\mu \sim (1, 1)_0$ coupled to $l_{L2} l_{L2}$ and $u_{R2} u_{R3}$

LQ with single coupling

$$\mathcal{L} \supset \lambda^{S_3}_{i\alpha} \overline{q^c_{Li}} i\sigma^2 \sigma^A S^A_3 l_{L\alpha} + h.c.$$

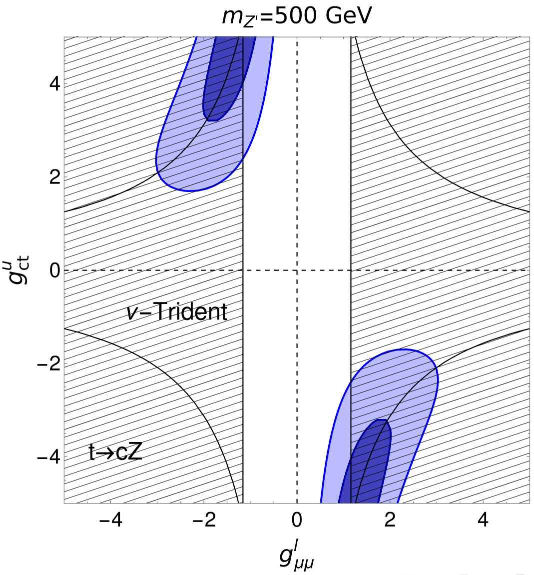


Green lines denote

$$R^{\nu}_{K^{(*)}} = \frac{BR(B \to K^{(*)} \nu\bar{\nu})}{BR(B \to K^{(*)} \nu\bar{\nu})^{SM}}$$

Z' with two couplings

$$\mathcal{L} \supset -g^l_{ii} Z'_\mu \overline{l_{Li}} \gamma^\mu l_{Li} - g^u_{jk} Z'_\mu \overline{u_{Rj}} \gamma^\mu u_{Rk} + h.c.$$



Concluions

- Interesting pattern of deviations from the SM in $b \to s\ell\ell$ transitions
- We comprehensively classified new physics explanations in the language of the SMEFT, including viable contributions at one-loop leading-log order
- The C_{lu} case previously known, $C_{lq}^{(1)}$ and $C_{lq}^{(1)} + C_{lq}^{(3)}$ options pointed out for first time
- Demonstrated minimal single-mediator solutions to the anomalies

Back-up slides

Effect of Yukawa running I

- Neglecting gauge couplings, the SM Yukawas run as

$$16\pi^2 \frac{dY_d}{d\log\mu} \simeq \frac{3}{2}\left(Y_d Y_d^\dagger Y_d - Y_d Y_u^\dagger Y_d\right) + 3\mathrm{tr}\left[Y_u^\dagger Y_u + Y_d^\dagger Y_d\right] - 8g_3^2 Y_d \tag{7}$$

- If Y_d is diagonal at scale Λ, this running induces an off-diagonal entry at $\mu = m_t$, namely

$$(Y_d)_{32}\Big|_{\mu=m_t} \simeq \frac{3V_{tb}^* V_{ts} y_b' y_t'^2}{32\pi^2} \log\frac{\Lambda}{m_t} \ , \tag{8}$$

where $y_i' \equiv y_i(\mu = \Lambda)$

Effect of Yukawa running II

- Shift in C_9, C_{10} is given by

$$C_9^\alpha = -C_{10}^\alpha \simeq -\frac{m_t^2}{16\pi\alpha_{em}\Lambda^2}\log\frac{\Lambda}{m_t}\left(\Delta_{\rm mix}^\alpha + \Delta_{\rm diag}^\alpha\right) , \qquad (9)$$

where the RGEs give

$$\Delta_{\rm mix}^\alpha = C^{(1)}_{\substack{lq\\ \alpha\alpha22}} + C^{(1)}_{\substack{lq\\ \alpha\alpha33}} + C^{(3)}_{\substack{lq\\ \alpha\alpha22}} + C^{(3)}_{\substack{lq\\ \alpha\alpha33}} , \qquad (10)$$

and the contribution induced by the SM Yukawa running and quark doublet redefinition at m_t is

$$\Delta_{\rm diag}^\alpha = 3\left(-C^{(1)}_{\substack{lq\\ \alpha\alpha22}} + C^{(1)}_{\substack{lq\\ \alpha\alpha33}} - C^{(3)}_{\substack{lq\\ \alpha\alpha22}} + C^{(3)}_{\substack{lq\\ \alpha\alpha33}}\right) . \qquad (11)$$

The full table—electron operators

Wilson Coeff.	Indices	2σ range	R_K
$C_{lq}^{(3)}$	(1122)	$(-0.10, 0.02)$	≈ 1
	(1133)	$(-0.05, 0.48)$	$(0.98, 1.11)$
$C_{lq}^{(1)}$	(1122)	$(-0.19, 0.14)$	≈ 1
	(1133)	$(-0.41, 0.02)$	$(0.91, 1.01)$
$C_{lq}^{(1)} = C_{lq}^{(3)}$	(1122)	$(-0.10, 0.03)$	≈ 1
	(1133)	$(-0.41, 0.18)$	$(0.84, 1.09)$
C_{eq}	(1122)	$(-0.35, 0.83)$	≈ 1
	(1133)	$(-0.21, 0.28)$	≈ 1
C_{lu}	(1123)	$(-1.5, 1.5)$	$(0.97, 1.02)$
	(1133)	$(-0.02, 0.43)$	$(0.95, 1.01)$
C_{eu}	(1123)	$(-1.5, 1.5)$	≈ 1
	(1133)	$(-0.29, 0.21)$	≈ 1
C_{He}, $C_{Hl}^{(1)}$ or $C_{Hl}^{(3)}$	(11)	$(-0.02, 0.03)$	≈ 1
$C_{Hl}^{(1)} = -C_{Hl}^{(3)}$	(11)	$(-0.03, 0.02)$	≈ 1

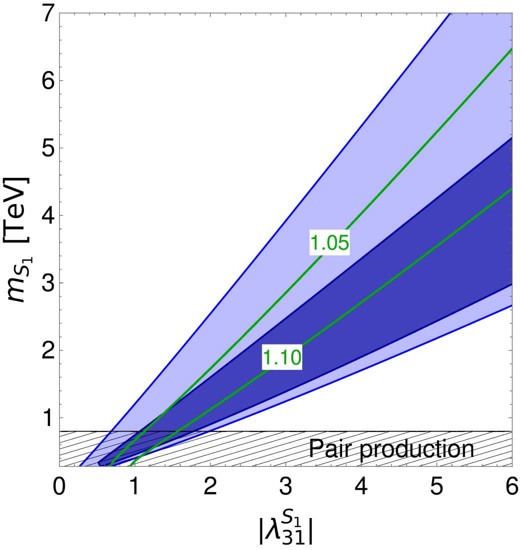
The full table—muon operators

Wilson Coeff.	Indices	2σ range	R_K
$C_{lq}^{(3)}$	(2222)	$(-0.03, 0.10)$	≈ 1
	(2233)	$(-0.60, 0.24)$	$(0.95, 1.13)$
$C_{lq}^{(1)}$	(2222)	$(-5.4, 0.90)$	$(0.48, 1.1)$
	(2233)	$(-0.31, 0.72)$	$(0.85, 1.07)$
$C_{lq}^{(1)} = C_{lq}^{(3)}$	(2222)	$(-0.03, 0.10)$	$(0.99, 1.03)$
	(2233)	$(-0.56, 0.42)$	$(0.83, 1.25)$
C_{eq}	(2222)	$(-1.92, 10)$	≈ 1
	(2233)	$(-0.90, 0.24)$	≈ 1
C_{lu}	(2223)	$(-10, 10)$	$(0.88, 1.07)$
	(2233)	$(-0.76, 0.36)$	$(0.92, 1.04)$
C_{eu}	(2223)	$(-10, 2.4)$	$(1, 1.07)$
	(2233)	$(-0.28, 0.96)$	≈ 1
C_{He}, $C_{Hl}^{(1)}$ or $C_{Hl}^{(3)}$	(22)	$(-0.04, 0.05)$	≈ 1
$C_{Hl}^{(1)} = -C_{Hl}^{(3)}$	(22)	$(0.0, 0.13)$	≈ 1

LQ with single coupling

$$\mathcal{L} \supset \lambda^{S_1}_{i\alpha} \overline{q^c_{Li}} i\sigma^2 S_1 l_{L\alpha} + h.c.$$

Green lines denote $R^\nu_{K^{(*)}}$



LQ with single coupling

$$\mathcal{L} \supset \lambda^U_{i\alpha} \overline{q_{Li}} \gamma_\mu U_1^\mu l_{L\alpha} + h.c.$$