$R_{K^{(*)}}$ with leptoquarks at tree level

based on arXiv: 1704.05444 with G. Hiller

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Introduction

- Gauge interactions of leptons universal within Standard Model - Lepton Universality (LU) broken by the masses
- Chance to look for potential new sources of LU violation provided by rare $|\Delta B| = |\Delta S| = 1$ semileptonic transitions that are suppressed in SM

The observables: [Hiller, Krüger, PRD (2004)]

$$R_H = \frac{\mathcal{B}(B \to H\mu^+\mu^-)}{B(B \to He^+e^-)}\,, \qquad H = K, K^*, X_s, \ldots, \tag{1}$$

very close to $R = 1$ in SM; free of lepton-universal hadronic uncertainties.

- LHCb Collaboration measured R_K and R_{K^*}

[LHCb, Phys. Rev. Lett. **113** (2014) 151601; S. Bifani (LHCb), public seminar (2017); LHCb, arXiv:1705.05802v1]

$$R^{\rm LHCb}_{K\,[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036, \tag{2}$$

$$R^{\rm LHCb}_{K^*\,[0.045,1.1]} = 0.66^{+0.11}_{-0.07} \pm 0.03, \quad R^{\rm LHCb}_{K^*\,[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05. \tag{3}$$

- Low q^2-bin somewhat more complicated in SM, muon mass more important, e-m effects more involved, $R^{\rm SM}_{K^*\,[0.045,1]} = 0.906 \pm 0.028$ [Bordone, Isidori, Pattori], EPJC (2016)

Model Independent Interpretations

- Usual Hamiltonian, now with lepton specific Wilson coefficients (ignoring LFV processes in this talk)

$$\mathcal{H}_{\rm eff} = -\frac{4G_F\lambda_t}{\sqrt{2}}\frac{\alpha}{4\pi}\sum_i C_i^\ell \mathcal{O}_i^\ell + \text{h.c.}, \tag{4}$$

with semileptonic operators:

$$\begin{aligned} \mathcal{O}_9^\ell &= (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \ell), \quad \mathcal{O}_9'^\ell = (\bar{s}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu \ell), \\ \mathcal{O}_{10}^\ell &= (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu\gamma_5 \ell), \quad \mathcal{O}_{10}'^\ell = (\bar{s}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu\gamma_5 \ell). \end{aligned} \tag{5}$$

- Instructive to work with chiral bais of semileptonic operators:

$$\mathcal{O}_{AB}^\ell = (\bar{s}\gamma^\mu P_A b)(\bar{\ell}\gamma_\mu P_B \ell)\,, \qquad A, B = L, R \tag{6}$$

Relations:

$$\begin{aligned} C_{LL}^\ell &= C_9^\ell - C_{10}^\ell, \quad C_{LR}^\ell = C_9^\ell + C_{10}^\ell, \\ C_{RL}^\ell &= C_9'^\ell - C_{10}'^\ell, \quad C_{RR}^\ell = C_9'^\ell + C_{10}'^\ell. \end{aligned} \tag{7}$$

- In SM $C_9^{SM} \simeq -C_{10}^{SM}$, $C_{LL}^{SM} = C_9^{SM} - C_{10}^{SM} \simeq 8.4$. Effects from photon exchange (dipole operators, charm effects) small at current level of precision - when neglected, lead to simple formulas:

$$R_K = 1 + \Delta_+ + \Sigma_+, \quad R_{K^*} = 1 + \Delta_+ + \Sigma_+ + p(\Sigma_- - \Sigma_+ + \Delta_- - \Delta_+), \tag{8}$$

with

$$\Delta_\pm = 2\,\mathrm{Re}\left(\frac{C_{LL}^{\mathrm{NP}\,\mu} \pm C_{RL}^{\mu}}{C_{LL}^{\mathrm{SM}}} - (\mu \to e)\right), \quad \Sigma_\pm = \frac{|C_{LL}^{\mathrm{NP}\,\mu} \pm C_{RL}^{\mu}|^2 + |C_{LR}^{\mu} \pm C_{RR}^{\mu}|^2}{|C_{LL}^{\mathrm{SM}}|^2} - (\mu \to e) \tag{9}$$

- dominant effect from linear terms $\Delta_\pm$. Coefficient $p = (f_0^2 + f_\parallel^2)/(f_0^2 + f_\parallel^2 + f_\perp^2) \sim 1$ in $q^2 \in [1.1, 6]\,\mathrm{GeV}^2$
- Approximately: $R_K \simeq 1 + \Delta_+, R_{K^*} \simeq 1 + \Delta_-$, so that $R_K \simeq R_{K^*} \neq 1$ requires NP via LUV left-left current C_{LL}.

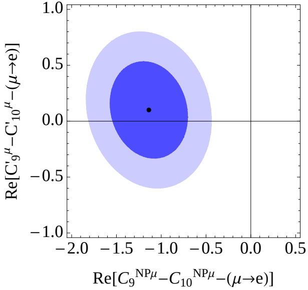
- Experimental values (3) result in

$$X_{K^*} = R_{K^*}/R_K = 0.94 \pm 0.18\,, \quad R_{K^*} + R_K - 2 = -0.54 \pm 0.14, \tag{10}$$

leading to

$$\begin{aligned} \mathrm{Re}[C_9^{NP\mu} - C_{10}^{NP\mu} - (\mu \to e)] &\sim -1.1 \pm 0.3 \\ \mathrm{Re}[C_9'^{NP\mu} - C_{10}'^{NP\mu} - (\mu \to e)] &\sim 0.1 \pm 0.4. \end{aligned} \tag{11}$$

- Solution $C_9^{NP\mu} \simeq -C_{10}^{NP\mu} \sim -0.5$ compatible with the global fits of $b \to s\mu\mu$ observables [Descotes-Genon, Hofer, Matias, Virto, JHEP (2016); Beaujean, Bobeth, van Dyk, EPJC (2014); Altmannshofer, Straub EPJC (2014); Hurth, Mahmoudi, Neshatpour JHEP(2016)]



Leptoquark (LQ) explanations at tree level

$$Q = T_3 + Y$$

a) Spin-0 LQs [Košnik, PRD (2012); Hiller, Loose, Schönwald, JHEP (2016); Hiller, Schmaltz PRD(2014); Bečirević, Fajfer, Košnik, PRD(2015); Gripaios, Nardechia, Renner JHEP (2015); Doršner, Fajfer, Greljo, Kamenik, Košnik, Phys.Rept. (2016)]

label	representation	Wilson coefficient	Relation	$R_{K^{(*)}}$
$\tilde{S}_2$	$(3, 2, 1/6)$	C_{RL}	$C_9' = -C_{10}'$	$R_K < 1$, $R_{K^*} > 1$
S_3	$(\bar{3}, 3, 1/3)$	C_{LL}^{NP}	$C_9 = -C_{10}$	$R_K \simeq R_{K^*} < 1.$
S_2	$(3, 2, 7/6)$	C_{LR}	$C_9 = C_{10}$	$R_K \simeq R_{K^*} \simeq 1$
$\tilde{S}_1$	$(\bar{3}, 1, 4/3)$	C_{RR}	$\mathcal{C}_9' = \mathcal{C}_{10}'$	$R_K \simeq R_{K^*} \simeq 1$

Relations between Wilson coefficients, assuming a single leptoquark at the time. The last column: implications for R_{K^*} assuming $R_K < 1$.

- $(3, 1, 1/3)$ - LQ at one loop in $b \to s\ell\ell$ [Bauer, Neubert, PRL (2016)]; see also [Bečirević, Košnik, Sumensari, Zukanovich Funchal, JHEP (2016)]; [Das, Hati, Kumar, Mahajan, PRD2016].

b) Spin-1 LQs [Košnik, Fajfer, PLB (2015); Hiller, Loose, Schönwald, JHEP (2016); Alonso, Grinstein, Martin Camalich, JHEP (2015)]

label	representation	Wilson coefficient	Relation	$R_{K^{(*)}}$
V_1	$(3,1,2/3)$	C_{LL}^{NP}	$C_9 = -C_{10}$	$R_K \simeq R_{K^*} < 1$
		C_{RR}	$C_9' = +C_{10}'$	$R_K \simeq R_{K^*} \simeq 1$
V_2	$(3,2,-5/6)$	C_{RL}	$C_9' = -C_{10}'$	$R_K < 1$, $R_{K^*} > 1$
		C_{LR}	$C_9 = +C_{10}$	$R_K \simeq R_{K^*} \simeq 1$
V_3	$(3,3,-2/3)$	C_{LL}^{NP}	$C_9 = -C_{10}$	$R_K \simeq R_{K^*} < 1$

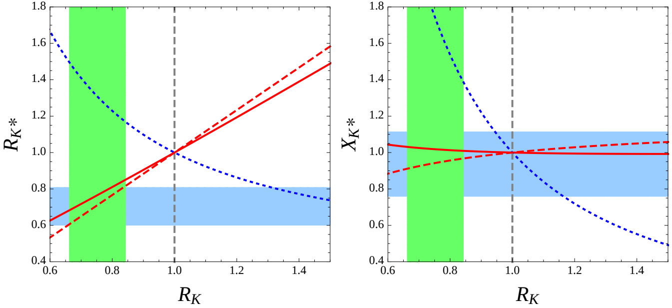
Same as above, but for spin-1 (vector) LQs.

- Before R_{K^*} measurement $\tilde{S}_2$ (RPV SUSY) and V_2 could explain LUV in $R_K < 1$; with $R_{K^*} < 1$ these are no more viable as dominant sources but can appear as admixtures.

- Integrating out a LQ component at tree level and Fierz-rearranging gives: [Košnik, PRD (2012); Hiller, Loose, Schönwald, JHEP (2016); Doršner, Fajfer, Greljo, Kamenik, Košnik, Phys.Rept. (2016)]

$$C_{LL}^{\mathrm{NP}\ell} = k_{LQ} \frac{\pi\sqrt{2}}{G_F \lambda_t \alpha} \frac{YY^*}{M^2}, \qquad k_{LQ} = +1, -1, -1 \quad \text{for} \quad S_3, V_1, V_3\,, \tag{12}$$

$$C_{RL}^{\ell} = k_{LQ} \frac{\pi\sqrt{2}}{G_F \lambda_t \alpha} \frac{YY^*}{M^2}, \qquad k_{LQ} = -1/2, +1 \quad \text{for} \quad \tilde{S}_2, V_2. \tag{13}$$



Solid red: C_{LL}^{NP} ($C_9^{\mathrm{NP}} = -C_{10}^{\mathrm{NP}}$) corresponding to leptoquarks S_3, V_1 or V_3, red dashed: C_{LL}^{NP} and $C_{RL} = -1/10\, C_{LL}^{\mathrm{NP}}$ (S_3 plus 10% of $\tilde{S}_2$), blue dotted curve C_{RL} (leptoquark $\tilde{S}_2$ or V_2), gray dashed curve: $C_{RL} = -C_{LL}^{\mathrm{NP}}$ (no single leptoquark).

$S_3 \equiv (\bar{3}, 3, 1/3)$

Lagrangian involving electric charge eigenstates of $SU(2)_L$ triplet:

$$\mathcal{L}_{\rm QL} = -\sqrt{2}\lambda\, \bar{d}_L^C \ell_L\, S_3^{4/3} - \bar{d}_L^C\, \nu_L\, S_3^{1/3} + \sqrt{2}\lambda\, \bar{u}_L^C\, \nu_L\, S_3^{-2/3} - \bar{u}_L^C\, \ell_L\, S_3^{1/3} + \text{h.c.} \qquad (14)$$

Contribution to C_{LL} from the exchange of $S_3^{4/3}$:

$$\frac{Y_{b\mu}Y_{s\mu}^* - Y_{be}Y_{se}^*}{M^2} \simeq \frac{1.1}{(35\,\text{TeV})^2}\,, \qquad (S_3) \qquad (15)$$

analogously for V_3, for V_1 (after setting $C_{LR} \to 0$).
Admixture of right handed currents could come from $\tilde{S}_2$,
$(Y_{b\mu}Y_{s\mu}^* - (\mu \to e)/M^2 \simeq -0.1/(24\,\text{TeV})^2$.

Constraints on LQs

- $\bar{B}_s$-B_s mixing effective Hamiltonian:

$$\mathcal{H}_{\text{eff}}^{\Delta B=2} = (C_1^{SM} + C_1^{LQ})(\bar{b}\gamma_\mu(1-\gamma_5)s)(\bar{b}\gamma_\mu(1-\gamma_5)s) + \text{h.c.} \qquad (16)$$

where

$$C_1^{LQ} = p_{LQ}\frac{(YY^*)^2}{128\pi^2 M^2}, \qquad p_{LQ} = 5, 4, 20 \quad \text{for} \quad S_3, V_1, V_3. \qquad (17)$$

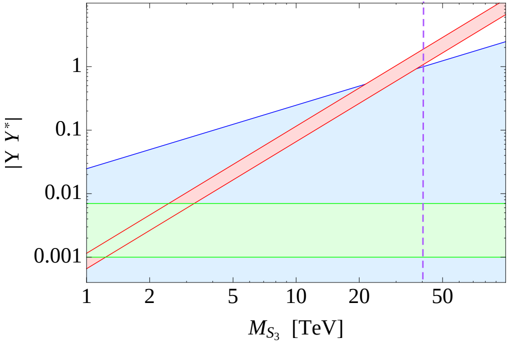
In general, $(YY^*)^2 \to \sum_{\ell_i,\ell_j}(Y_{b\ell_i}Y^*_{s\ell_i})(Y_{b\ell_j}Y^*_{s\ell_j})$.
Assuming the degeneracy of the S_3 components we obtain B_s-mixing upper limits:

Upper limits:

$$M \lesssim 40\,\text{TeV}\,, 45\,\text{TeV}\,, 20\,\text{TeV} \qquad \text{for } S_3, V_1, V_3\,. \qquad (18)$$

- Collider limits: a) scalars decaying 100% into a muon and jet ($M > 1050\,\text{GeV}$)[ATLAS, New J. Phys 18, 093016 (2016)] and into an electron and a jet are are ($M > 1755\,\text{GeV}$) [CMS, PRD (2016)]; b) vectors: 100% into $\mu+$ jet ($M > 1200 - 1720\,\text{GeV}$), e+jet ($M > 1150 - 1660\,\text{GeV}$)[CMS, PRD 032004 (2016)]. Bounds weaken with ν in final state

Summary of constraints on S_3:



a) the allowed region by Δm_{B_s} (light blue), b) the allowed range for $R_{K^{(*)}}$ (light red), c) flavor models expectations (green)

Some implications

- E.g. for S_3 (weak triplet), assuming coupling to muons only, $B \to K^* \bar{\nu}\nu$ receives contributions:

$$C_{LL}^{NP\,\nu_\mu} = \frac{1}{2} C_{LL}^{NP\,\mu}, \tag{19}$$

leading to enhancement of $B \to K^{(*)}\nu\bar{\nu}$ of $\sim 5\%$.

- The ratio of inclusive rates:

$$R_{X_s} \simeq 1 + (\Delta_+ + \Delta_-)/2. \tag{20}$$

Current data on $R_{K^{(*)}}$ suggests:

$$R_{X_s} \sim 0.73 \pm 0.07. \tag{21}$$

Flavor

- LQs couple to both leptons and quarks - if present with low enough masses one could learn something about the flavor, assuming that the fermion mass and mixing structure is governed by symmetries
- E.g. quark masses/mixings accommodated with $U(1)_{FN}$ (Froggatt-Nielsen) together with a discrete non-abelian group for neutrinos, one can obtain lepton isolation pattern (couplings only to muons, or electrons) by placing a LQ in a non-trivial representation under A_4: [de Medeiros Varzielas, Hiller, JHEP (2015); Loose, Schönward, JHEP (2016)]

$$Y_{q_3\ell} \sim c_\ell \,, \quad Y_{q_2\ell} \sim c_\ell \lambda^2, \tag{22}$$

and $c_\ell \sim \lambda \sim 0.2$ from spurion insertion for a lepton - green range in the above plot.

- One can consider more general hierarchical pattern: [de Medeiros Varzielas, Hiller, JHEP (2015)]

$$\lambda^{[\rho\kappa]} \sim \lambda_0 \begin{pmatrix} \rho_d \kappa & \rho_d & \rho_d \\ \rho\kappa & \rho & \rho \\ \kappa & 1 & 1 \end{pmatrix} . \tag{23}$$

Flavor II

Subset of relations: [de Medeiros Varzielas, Hiller, JHEP (2015)]

$$\begin{aligned} Br(B \to K\mu^\pm e^\mp) &\sim 3 \times 10^{-8}\kappa^2 \left(\frac{1-R_K}{0.23}\right)^2, \\ Br(\mu \to e\gamma) &\sim 10^{-12}\kappa^2/\rho^2 \left(\frac{1-R_K}{0.23}\right)^2, \\ Br(\tau \to \mu\eta) &\sim 4 \times 10^{-11}\rho^2 \left(\frac{1-R_K}{0.23}\right)^2, \\ Br(\tau \to \mu\eta) &\sim 4\kappa^2 \left(\frac{1-R_K}{0.23}\right)^2 \ldots \end{aligned} \tag{24}$$

- Phenomenologically viable ranges:

$$\rho_d \lesssim 0.02\,, \quad \kappa \lesssim 0.5\,, \quad 10^{-4} \lesssim \rho \lesssim 1\,, \quad \kappa/\rho \lesssim 0.5\,, \quad \rho_d/\rho \lesssim 1.6\,. \tag{25}$$

- As an example, with $SU(3)_F \times U(1)_F$ symmetry commuting with $SO(10)$ [de Medeiros Varzielas, Ross, Nucl.Phys.B (2006); de Medeiros Varzielas, Hiller, JHEP (2015)] where Yukawas $(\phi^i_A\psi_i)(\phi^j_B\psi_j)h_{u,d}$ - obtained by flavon (ϕ^i_A) vevs and controlled by $U(1)_F$ charges, one can obtain (as a specific example with LQ in singlet of $SU(3)_F$)

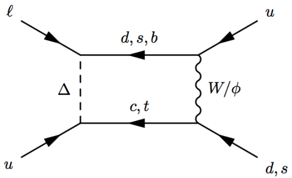
$$|\lambda^{[\rho\kappa]}| \propto \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}. \tag{26}$$

Some UV considerations

- The main challenge with low mass LQs is avoiding (too fast) proton decay
- Invariance under the SM allows the coupling of S_3 to quark bilinears:

$$\mathcal{L}_{QQ} = Y_\kappa \, \bar{Q}_L^{C\,\alpha} (i\,\sigma^2)^{\alpha\beta} (S_3^\dagger)^{\beta\gamma} Q_L^\gamma + \text{h.c.}, \qquad (27)$$

- Even if couplings to first generation quark pairs (uu, ud) are forbidden, loop diagrams need to be considered



An example of a diagram and figure taken from [Doršner, Fajfer, Košnik, PRD (2012)]

- S_3 is contained within the $\overline{126}_H$ scalar multiplet of $SO(10)$ gauge group
- The term $y_{ij}\, 16_i\, 16_j\, \overline{126}_H$ is allowed by $SO(10)$ group and does not embed couplings of S_3 to quark pairs.
- However, one should attempt to build full model to make sure no dangerous couplings arise at some level - low mass scalar would be one more naturalness puzzle

Some UV considerations II

- S_3 as a pion of a new strong dynamics (see next talk by Ben Gripaios)
- Vector leptoquarks appear as super-heavy gauge bosons in a GUT models - V_1 in models for quark-lepton unification, e.g. Pati-Salam or variants thereof
- In this case the coupling-matrices to lepton-quark pairs are unitary - more challenging to suppress both the right-handed couplings and satisfy constraints from first generation.
- Light spin-1 LQs as composite states?
- Embedding of the state V_3 into a (weakly coupled) UV model?

Summary

- Recent measurements by LHCb challenges lepton universality, feature of SM and many of its extensions
- Contribution to LNU in $|\Delta B| = |\Delta S| = 1$ predominantly SM-like chiral
- LQs naturally introduce LNU at tree level, masses up to multi-TeV
- $\tilde{S}_2$ and V_2 could have accounted for $R_K < 1$, $R_K, R_K^* < 1$ suggest S_3, V_1 or V_3 as dominant sources.
- Expectations from flavor models point towards lower masses around few TeV
- LFV generically expected, if the LUV is confirmed, one can probe LFV B, K decays and lepton decays, $\mu \to e$ conversion with more precision to learn more about the flavor structure(s).