Model-Independent Implications of LHCb's Measurement of R_K

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Including results from 1408.4097, with Diptimoy Ghosh and Marco Nardecchia

Outline

- The recent LHCb measurement of R_K, which is the ratio of $\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)$ to $\mathcal{B}(B^+ \to K^+ e^+ e^-)$, shows a 2.6σ discrepancy with Standard Model prediction
- Points to NP that doesn't behave lepton universally?
- Operators that could explain the effect
- Fit to vector and axial vector operators in muon and electron sector
- Connection to $B \to K^* \mu\mu$ fits

R_K: definition, measurement and SM prediction

Recent measurement by the LHCb collaboration [LHCb, 1406.6482] of R_K,

$$R_K = \frac{\mathcal{B}\left(B^+ \to K^+\mu^+\mu^-\right)_{[1,6]}}{\mathcal{B}\left(B^+ \to K^+e^+e^-\right)_{[1,6]}}$$

In the Standard Model, predicted to be $R_K^{\mathrm{SM}} = 1$ (1.0003 ± 0.0001, including lepton mass effects [Bobeth, Hiller, Piranishvili 0709.4174]).
LHCb found

$$R_K = 0.745^{+0.090}_{-0.074}(\mathrm{stat}) \pm 0.036(\mathrm{syst}) \tag{1}$$

Represents a 2.6σ deviation from the SM prediction. Suggestive of NP which treats muons and electrons differently?

Effective field theory framework

$|\Delta B| = |\Delta S| = 1$ effective Hamiltonian,

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} \left(V_{ts}^* V_{tb}\right) \sum_i \hat{C}_i^\ell(\mu)\, \mathcal{O}_i^\ell(\mu) \; ,$$

where $\hat{C}_i^\ell = C_i^{SM} + C_i^\ell$, $((\ell = e, \mu))$, $\mathcal{O}_i^\ell$ are:

$$\mathcal{O}_7^{(\prime)} = \tfrac{e}{16\pi^2} m_b \left(\bar{s}\sigma_{\alpha\beta} P_{R(L)} b\right) F^{\alpha\beta} \qquad \text{DIPOLE}$$

$$\mathcal{O}_9^{\ell(\prime)} = \tfrac{\alpha_{\rm em}}{4\pi} \left(\bar{s}\gamma_\alpha P_{L(R)} b\right) \left(\bar{\ell}\gamma^\alpha \ell\right) \qquad \text{VECTOR}$$

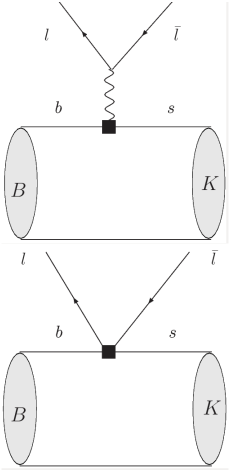
$$\mathcal{O}_{10}^{\ell(\prime)} = \tfrac{\alpha_{\rm em}}{4\pi} \left(\bar{s}\gamma_\alpha P_{L(R)} b\right) \left(\bar{\ell}\gamma^\alpha \gamma_5 \ell\right) \qquad \text{AXIAL VECTOR}$$

$$\mathcal{O}_S^{\ell(\prime)} = \tfrac{\alpha_{\rm em}}{4\pi} \left(\bar{s} P_{R(L)} b\right) \left(\bar{\ell}\ell\right) \qquad \text{SCALAR}$$

$$\mathcal{O}_P^{\ell(\prime)} = \tfrac{\alpha_{\rm em}}{4\pi} \left(\bar{s} P_{R(L)} b\right) \left(\bar{\ell}\gamma_5 \ell\right) \qquad \text{PSEUDOSCALAR}$$

$$\mathcal{O}_T^{\ell} = \tfrac{\alpha_{\rm em}}{4\pi} \left(\bar{s}\sigma_{\mu\nu} b\right) \left(\bar{\ell}\sigma^{\mu\nu} \ell\right) \qquad \text{TENSOR}$$

$$\mathcal{O}_{T5}^{\ell} = \tfrac{\alpha_{\rm em}}{4\pi} \left(\bar{s}\sigma_{\mu\nu} b\right) \left(\bar{\ell}\sigma^{\mu\nu} \gamma_5 \ell\right) \qquad \text{PSEUDOTENSOR}$$



In the SM:

- Coefficients of (pseudo)scalar, (pseudo)tensor and dashed operators are negligible
- Coefficients are lepton universal

Figures from Khodjamirian, Mannel, Wang 1211.0234

Types of NP operators that could be involved in R_K

What it can't be...

Alonso, Grinstein and Martin Camalich [1407.7044] consider NP effects in terms of a $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariant EFT.
In this context

- Tensor and pseudotensor: $C_T = C_{T5} = 0$
- (Pseudo)scalar operators: $C_S = -C_P$ and $C'_S = C'_P$.
- They find that (pseudo)scalar operators too constrained by $\mathcal{B}(B_{s,d} \to l^+ l^-)$ to explain R_K.

Hiller and Schmaltz [1408.1627] found

- (Pseudo)scalar contributions too strongly constrained by $\mathcal{B}(B_s \to l^+ l^-)$
- Tensor operators too strongly constrained by flat term F_H in angular distribution of $B \to K^+ \mu^+ \mu^-$.

Types of NP operators that could be involved in R_K

<u>What it could be...</u>

- Only operators that can receive large enough contributions are (axial) vector operators $\mathcal{O}_9^{(\prime)}$ and $\mathcal{O}_{10}^{(\prime)}$

$$\mathcal{O}_9^{\ell(\prime)} = \frac{\alpha_{\rm em}}{4\pi}\left(\bar{s}\gamma_\alpha P_{L(R)} b\right)\left(\bar{\ell}\gamma^\alpha \ell\right), \quad \mathcal{O}_{10}^{\ell(\prime)} = \frac{\alpha_{\rm em}}{4\pi}\left(\bar{s}\gamma_\alpha P_{L(R)} b\right)\left(\bar{\ell}\gamma^\alpha \gamma_5 \ell\right)$$

- A negative contribution in C_9^μ could fit R_K
- If NP couples to a particular lepton chirality, will generate combinations $C_9^{\ell(\prime)} = \pm C_{10}^{\ell(\prime)}$
- H& S find $C_9^\mu = -C_{10}^\mu \approx -0.5$ fits data well
- They provide leptoquark explanations: one generating $C_9^\mu = -C_{10}^\mu$ and another generating $C_9^{\prime e} = -C_{10}^{\prime e}$

Expression for R_K in terms of Wilson Coefficients

Since NP contributions to C_7 constrained to be small, and also $|C_7^{SM}| \ll C_9^{SM}$ and C_{10}^{SM}, R_K is approximately

$$R_K \approx \frac{\left|C_{10}^{SM} + C_{10}^{\mu} + C_{10}^{\mu'}\right|^2 + \left|C_9^{SM} + C_9^{\mu} + C_9^{\mu'}\right|^2}{\left|C_{10}^{SM} + C_{10}^{e} + C_{10}^{e'}\right|^2 + \left|C_9^{SM} + C_9^{e} + C_9^{e'}\right|^2}$$

$\implies$ data ($R_K < 1$) favours an increase in magnitude of electron WCs and/or a decrease in magnitude of muon WCs. (But NB that in the SM $C_9^{SM} > 0$ and $C_{10}^{SM} < 0$)

Details of the fit

- Fit NP Wilson coefficients $C_9^\ell, C_{10}^\ell, C_9'^\ell, C_{10}'^\ell$ to R_K and some other $b \to s\ell\ell$ observables to find favoured regions.
- Also computed the Bayesian Evidence (BE) of each scenario.
- If hypothesis "New Physics in C_i^ℓ, no New Physics in other WCs" is called $\mathcal{H}\left(C_i^\ell\right)$,

$$\mathrm{BE}(\mathcal{H}\left(C_i^\ell\right)) \propto \int \mathcal{L}\left(C_i^\ell|\mathrm{data}\right) \times P_0(C_i^\ell) dC_i^\ell \tag{2}$$

where $\mathcal{L}$ is the likelihood function and P_0 is our choice of prior for the WC C_i^ℓ, which we assume to be a flat distribution in the range [-10, 10].

Observable	SM prediction	Measurement
$\mathcal{B}\left(B^+ \to K^+\mu^+\mu^-\right)_{[1,6]}$	$\left(1.75^{+0.60}_{-0.29}\right) \times 10^{-7}$ [1]	$(1.21 \pm 0.09 \pm 0.07) \times 10^{-7}$ [2]
$\mathcal{B}\left(B^+ \to X_s\mu^+\mu^-\right)_{[1,6]}$	$(1.59 \pm 0.11) \times 10^{-6}$ [3]	$\left(0.66^{+0.82+0.30}_{-0.72-0.24} \pm 0.07\right) \times 10^{-6}$ [4]
$\mathcal{B}\left(B_s \to \mu^+\mu^-\right)$	$(3.65 \pm 0.23) \times 10^{-9}$ [5]	$(2.9 \pm 0.7) \times 10^{-9}$ [6]
$\mathcal{B}\left(B^+ \to X_s e^+e^-\right)_{[1,6]}$	$(1.64 \pm 0.11) \times 10^{-6}$ [7]	$\left(1.93^{+0.47+0.21}_{-0.45-0.16} \pm 0.18\right) \times 10^{-6}$ [8]
$\mathcal{B}\left(B_s \to e^+e^-\right)$	$(8.54 \pm 0.55) \times 10^{-14}$ [9]	$< 2.8 \times 10^{-7}$ [10]
$R_{K\,[1,6]}$	1.0003 ± 0.0001 [11]	$0.745^{+0.090}_{-0.074} \pm 0.036$ [12]

Sensitivity of observables to different Wilson coefficients:

- $\mathcal{B}(B^+ \to K^+\ell^+\ell^-)$: $C_9^\ell + C_9^{\ell'}$, $C_{10}^\ell + C_{10}^{\ell'}$
- $\mathcal{B}(B_s \to \ell^+\ell^-)$: $C_{10}^\ell - C_{10}^{\ell'}$
- $\mathcal{B}(B^+ \to X_s\ell^+\ell^-)$: depends on a sum of C_9^ℓ, $C_9^{\ell 2}$, C_{10}^ℓ, $C_{10}^{\ell 2}$, $C_9^{\ell\prime}$, $C_9^{\ell\prime 2}$, $C_{10}^{\ell'}$, $C_{10}^{\ell' 2}$ with various coefficients

[1]:Bobeth et al. 1212.2321; [2]:LHCb 1209.4284; [3],[7]:Huber et al. 0712.3009; [4],[8]:Babar 1312.5364; [5],[9]:Bobeth et al. 1311.0903; [6]:CMS and LHCb CERN-LHCb-CONF-2013-012; [10] PDG 2012; [11]:Bobeth et al. 0709.4174; [9]:LHCb 1406.6482

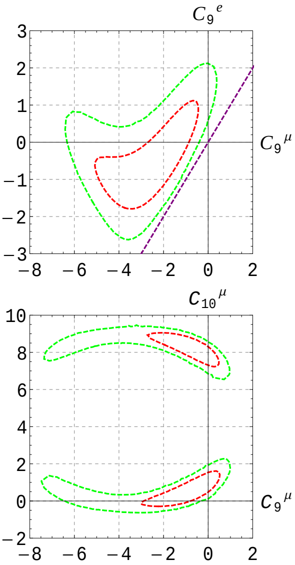
Fitting with one Wilson Coefficient

Hypothesis	Fit	BE
C_9^μ	[-3.1,-0.7]	1 : 1
$C_9^{\mu'}$	[-1.9,-0.8]	0.20 : 1
C_{10}^μ	[0.7,1.3], [7.5,8.1]	0.82 : 1
$C_{10}^{\mu'}$	[0.2,0.7]	4.8×10^{-3} : 1
$C_9^\mu = +C_{10}^\mu$	[0.1,0.8]	2.7×10^{-3} : 1
$C_9^\mu = -C_{10}^\mu$	[-0.8,-0.4]	0.42 : 1
$C_9^{\mu'} = +C_{10}^{\mu'}$	[-0.4,0.3]	9.3×10^{-4} : 1
$C_9^{\mu'} = -C_{10}^{\mu'}$	[-0.2,-0.6]	1.3×10^{-2} : 1
C_9^e	[-8.4,-8.4], [0.6,2.1]	0.13 : 1
$C_9^{e'}$	[0.8,1.9]	0.10 : 1
C_{10}^e	[-1.6,-0.7], [9.5,10.0]	0.14 : 1
$C_{10}^{e'}$	[-1.7,-0.7]	9.7×10^{-2} : 1
$C_9^e = +C_{10}^e$	[-2.4,-1.4], [2.2,3.4]	0.20 : 1
$C_9^e = -C_{10}^e$	[0.3,1.1]	6.7×10^{-2} : 1
$C_9^{e'} = +C_{10}^{e'}$	[-2.6,-1.5], [2.2,3.2]	0.20 : 1
$C_9^{e'} = -C_{10}^{e'}$	[0.4,0.9]	5.2×10^{-2} : 1
$C_9^\mu = C_9^e$	[-4.3,-1.1]	2.9×10^{-2} : 1
$C_{10}^\mu = C_{10}^e$	[0.3,1.2], [7.6,8.4]	1.7×10^{-2} : 1

- Slight preference for NP in muon sector
- Best Bayes factor for C_9^μ
- Best chiral combination is $C_9^\mu = -C_{10}^\mu$ - this was the benchmark point highlighted by Hiller and Schmaltz, and their suggested value of $C_9^\mu = -C_{10}^\mu \approx -0.5$ is within our 68% region.

Fitting with two Wilson Coefficients

Hypothesis	Fit	BE
C_9^μ C_{10}^μ	[-1.9,0.3] [-0.1,0.9], [8.0,8.8]	0.15 : 1
C_9^μ $C_9^{\mu\prime}$	[-4.2,-1.2] [-1.7,1.2]	0.20 : 1
C_9^μ C_9^e	[-4.2,-1.4] [-7.4,-5.9], [-1.3,0.2]	0.28 : 1
$C_9^\mu = -C_{10}^\mu$ $C_9^e = -C_{10}^e$	[-1.0,0.4] [-0.5,0.4], [-8.2,-7.4]	4.5×10^{-2} : 1
$C_9^\mu = -C_{10}^\mu$ $C_9^e = C_{10}^e$	[-0.7,-0.4] [-1.2,1.6]	8.3×10^{-2} : 1
$C_9^\mu = C_{10}^\mu$ $C_9^e = -C_{10}^e$	[0.1,0.9] [0.3,1.1]	8.0×10^{-3} : 1
$C_9^\mu = C_{10}^\mu$ $C_9^e = C_{10}^e$	[0.1,0.9] [-2.4,-1.5], [2.2,3.4]	2.4×10^{-2} : 1

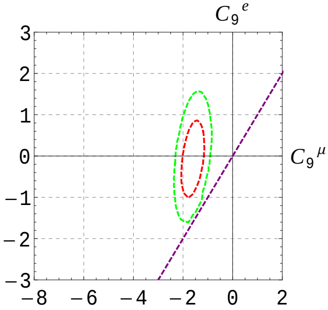


NB. BEs updated since 1408.4097!

What about $B \to K^* \mu\mu$?

- LHCb measurement saw deviations in several observables from their SM predictions (LHCb, 1308.1707)
- In particular in observables P_5' and P_2' .
- Several model-independent fits to the data (eg. Descotes-Genon, Matias, Virto 1307.5683, Altmannshofer and Straub 1308.1501, Beaujean, Bobeth, van Dyk 1310.2487, Horgan, Liu, Meinel, Wingate 1310.3887, Hurth and Mahmoudi 1312.5267,see also Hambrock, Hiller, Schacht, Zwicky 1308.4379, Lyon and Zwicky 1406.0566)
- General trend of a negative contribution $C_9^\mu \approx -1$
- We followed an approximate procedure to use the fit of C_9^μ from Descotes-Genon, Matias, Virto as a prior $C_9^\mu \in [-1.9, -1.3]$

Hypothesis	Fit	BE
C_9^μ	[-1.9,-1.3]	1 : 1
C_9^μ C_9^e	[-1.9,-1.3] [-7.7,-6.6], [-0.7,0.6]	0.14 : 1
C_9^μ C_{10}^e	[-1.8,-1.4] [-0.4,0.5], [8.3,9.3]	0.13 : 1
C_9^μ $C_9^e = C_{10}^e$	[-1.8,-1.3] [-0.9,1.5]	0.16 : 1
C_9^μ $C_9^e = -C_{10}^e$	[-1.9,-1.3] [-8.2,-7.8], [-0.3,0.3]	6.0×10^{-2} : 1



Summary

LHCb's recent measurement of R_K could be a hint of NP that does not behave lepton universally...

- Cannot be fully explained by (pseudo) scalar or tensor operators (or the dipole operator $\mathcal{O}_7$)
- Slight preference for NP in muon sector
- Data fits to a negative NP contribution in C_9^μ, in agreement with some $B \to K^* \mu\mu$ fits

For the future...

- Scope for more sophisticated fits, incorporating $B \to K^* \mu\mu$ more fully
- Theoretical prediction for R_K is very clean, so further measurements with more data will be very interesting

Gaussian vs Flat Priors

Hypothesis	Fit	BE
C_9^μ	[-3.1,-0.7]	1 : 1
$C_9^{\mu\prime}$	[-1.9,-0.8]	0.20 : 1
C_{10}^μ	[0.7,1.3], [7.5,8.1]	0.82 : 1
$C_{10}^{\mu\prime}$	[0.2,0.7]	4.8×10^{-3} : 1
$C_9^\mu = +C_{10}^\mu$	[0.1,0.8]	2.7×10^{-3} : 1
$C_9^\mu = -C_{10}^\mu$	[-0.8,-0.4]	0.42 : 1
$C_9^{\mu\prime} = +C_{10}^{\mu\prime}$	[-0.4,0.3]	9.3×10^{-4} : 1
$C_9^{\mu\prime} = -C_{10}^{\mu\prime}$	[-0.2,-0.6]	1.3×10^{-2} : 1
C_9^e	[-8.4,-8.4], [0.6,2.1]	0.13 : 1
$C_9^{e\prime}$	[0.8,1.9]	0.10 : 1
C_{10}^e	[-1.6,-0.7], [9.5,10.0]	0.14 : 1
$C_{10}^{e\prime}$	[-1.7,-0.7]	9.7×10^{-2} : 1
$C_9^e = +C_{10}^e$	[-2.4,-1.4], [2.2,3.4]	0.20 : 1
$C_9^e = -C_{10}^e$	[0.3,1.1]	6.7×10^{-2} : 1
$C_9^{e\prime} = +C_{10}^{e\prime}$	[-2.6,-1.5], [2.2,3.2]	0.20 : 1
$C_9^{e\prime} = -C_{10}^{e\prime}$	[0.4,0.9]	5.2×10^{-2} : 1
$C_9^\mu = C_9^e$	[-4.3,-1.1]	2.9×10^{-2} : 1
$C_{10}^\mu = C_{10}^e$	[0.3,1.2], [7.6,8.4]	1.7×10^{-2} : 1

Flat priors in the range [-10,10] for all WCs

Hypothesis	Fit	BE
C_9^μ	[-2.7,-0.8]	1 : 1
$C_9^{\mu\prime}$	[-1.9,-0.8]	0.22 : 1
C_{10}^μ	[0.5,1.5]	0.64 : 1
$C_{10}^{\mu\prime}$	[0.2,0.8]	5.7×10^{-3} : 1
$C_9^\mu = +C_{10}^\mu$	[0.1,0.8]	3.1×10^{-3} : 1
$C_9^\mu = -C_{10}^\mu$	[-0.8,-0.4]	0.49 : 1
$C_9^{\mu\prime} = +C_{10}^{\mu\prime}$	[-0.3,0.2]	1.1×10^{-3} : 1
$C_9^{\mu\prime} = -C_{10}^{\mu\prime}$	[-0.2,-0.6]	1.5×10^{-2} : 1
C_9^e	[0.7,1.9]	0.12 : 1
$C_9^{e\prime}$	[0.8,1.9]	0.11 : 1
C_{10}^e	[-1.7,-0.6]	0.11 : 1
$C_{10}^{e\prime}$	[-1.7,-0.7]	0.10 : 1
$C_9^e = +C_{10}^e$	[-2.4,-1.4], [2.2,3.3]	0.21 : 1
$C_9^e = -C_{10}^e$	[0.4,0.9]	6.6×10^{-2} : 1
$C_9^{e\prime} = +C_{10}^{e\prime}$	[-2.6,-1.4], [2.2,3.1]	0.21 : 1
$C_9^{e\prime} = -C_{10}^{e\prime}$	[0.4,1.0]	6.1×10^{-2} : 1
$C_9^\mu = C_9^e$	[-3.9,-0.8]	2.9×10^{-2} : 1
$C_{10}^\mu = C_{10}^e$	[0.2,1.4]	1.3×10^{-2} : 1

Gaussian priors with $\sigma = 5.0$ for all WCs

Including $\mathcal{B}(B^+ \to K^+ e^+ e^-)$

Hypothesis	Fit	BE
C_9^μ	[-3.1,-0.7]	1 : 1
$C_9^{\mu\prime}$	[-1.9,-0.8]	0.20 : 1
C_{10}^μ	[0.7,1.3], [7.6,8.1]	0.83 : 1
$C_{10}^{\mu\prime}$	[0.2,0.8]	5.0×10^{-3} : 1
$C_9^\mu = +C_{10}^\mu$	[0.1,0.8]	2.9×10^{-3} : 1
$C_9^\mu = -C_{10}^\mu$	[-0.8,-0.4]	0.43 : 1
$C_9^{\mu\prime} = +C_{10}^{\mu\prime}$	[-0.4,0.3]	1.0×10^{-3} : 1
$C_9^{\mu\prime} = -C_{10}^{\mu\prime}$	[-0.6,-0.2]	1.4×10^{-2} : 1
C_9^e	[-8.4,-8.0], [0.5,1.6]	5.3×10^{-2} : 1
$C_9^{e\prime}$	[0.6,1.5]	3.4×10^{-2} : 1
C_{10}^e	[-1.2,-0.5], [9.4,10.0]	5.9×10^{-2} : 1
$C_{10}^{e\prime}$	[-1.3,-0.5]	3.0×10^{-2} : 1
$C_9^e = +C_{10}^e$	[-2.2,-1.1], [1.9,3.0]	8.3×10^{-2} : 1
$C_9^e = -C_{10}^e$	[-8.6,-8.5], [0.2,0.8]	2.6×10^{-2} : 1
$C_9^{e\prime} = +C_{10}^{e\prime}$	[-2.2,-1.2], [1.9,2.9]	8.3×10^{-2} : 1
$C_9^{e\prime} = -C_{10}^{e\prime}$	[0.3,0.7]	1.8×10^{-2} : 1
$C_9^\mu = C_9^e$	[-4.1,0.6]	2.5×10^{-2} : 1
$C_{10}^\mu = C_{10}^e$	[0.3,1.2], [7.6,8,4]	1.7×10^{-2} : 1

Hypothesis	Fit	BE
C_9^μ C_{10}^μ	[-1.9,0.3] [-0.1,0.9], [8.0,8.8]	3.0 : 1
C_9^μ $C_9^{\mu\prime}$	[-4.2,-1.2] [-1.7,1.3]	2.5 : 1
C_9^μ C_9^e	[-4.2,-1.5] [-7.3,-6.0], [-1.2,0.0]	5.5 : 1
$C_9^\mu = -C_{10}^\mu$ $C_9^e = -C_{10}^e$	[-1.0,-0.5] [-8.1,-7.5], [-0.5,0.2]	0.81 : 1
$C_9^\mu = -C_{10}^\mu$ $C_9^e = C_{10}^e$	[-0.7,-0.4] [-0.9,1.4]	1.35 : 1
$C_9^\mu = C_{10}^\mu$ $C_9^e = -C_{10}^e$	[0.1,0.9] [-8.6,-8.5], [0.2,0.8]	0.061 : 1
$C_9^\mu = C_{10}^\mu$ $C_9^e = C_{10}^e$	[0.1,0.9] [-2.1,-1.2], [2.0,3.0]	0.19 : 1