New Physics in $b \to s\mu^+\mu^-$ after the Measurement of R_{K^*}

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Talk based on work done in collaboration with A.K. Alok, B. Bhattacharya, A. Datta, D. Kumar and J. Kumar (arXiv: 1704.07397)

Experimental Results

1. $B \to K^* \mu^+ \mu^-$ [LHCb (2013, 2016), Belle (2016), ATLAS (2017), CMS (2017)]: angular distribution, especially angular observable P_5', deviates from SM predictions. $\exists$ theoretical uncertainties (form factors, higher-order contributions). Taking them into account, discrepancy could still reach the 4σ level.

2. $B_s^0 \to \phi \mu^+ \mu^-$ [LHCb (2013, 2015)]: branching fraction, angular distribution disagree with SM predictions (based on lattice QCD, QCD sum rules) at the level of 3.5σ.

3. $R_K \equiv \mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)/\mathcal{B}(B^+ \to K^+ e^+ e^-)$ [LHCb (2014)]:

$$R_K^{\rm expt} = 0.745^{+0.090}_{-0.074}\,({\rm stat}) \pm 0.036\,({\rm syst})~, \quad 1 \le q^2 \le 6.0~{\rm GeV}^2~.$$

Differs from the SM prediction of $R_K^{\rm SM} = 1 \pm 0.01$ by 2.6σ.

4. $R_{K^*} \equiv \mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)/\mathcal{B}(B^0 \to K^{*0}e^+e^-)$ [LHCb (2017)]:

$$R_{K^*}^{\rm expt} = \begin{cases} 0.660^{+0.110}_{-0.070}\,({\rm stat}) \pm 0.024\,({\rm syst})\ , & 0.045 \le q^2 \le 1.1~{\rm GeV}^2\ , \\ 0.685^{+0.113}_{-0.069}\,({\rm stat}) \pm 0.047\,({\rm syst})\ , & 1.1 \le q^2 \le 6.0~{\rm GeV}^2\ . \end{cases}$$

SM: $R_{K^*}^{\rm SM} \simeq 0.93$ at low q^2 (due to e-μ mass difference), $R_{K^*}^{\rm SM} \simeq 1$ elsewhere $\Longrightarrow$ discrepancy is 2.2-2.4σ (low q^2), 2.4-2.5σ (medium q^2).

We have several hints of NP. #1 and #2 have theoretical input, but #3 and #4 are "clean." Simplest explanation: $\exists$ NP in $b \to s\mu^+\mu^-$. (For R_K and R_{K^*}, some studies also consider NP in $b \to se^+e^-$.)

Assuming NP is present in $b \to s\mu^+\mu^-$, what can we learn about it?

Model-Independent Analysis

$b \to s\mu^+\mu^-$ transitions:

$$
\begin{aligned}
H_{\rm eff} &= -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb} V_{ts}^* \sum_{a=9,10} (C_a O_a + C'_a O'_a) \ , \\
O_{9(10)} &= [\bar{s}\gamma_\mu P_L b][\bar{\mu}\gamma^\mu(\gamma_5)\mu] \ .
\end{aligned}
$$

Primed operators: replace L with R. WCs $C_a^{(\prime)}$ include both SM and NP contributions.

Idea: assume only one WC (or combination of WCs) is affected. Do a fit to all $b \to s\mu^+\mu^-$ data (both with and without discrepancies with the SM) to see which possibilities give a good fit.

Following announcement of the R_{K^*} result, 7 papers did this:
B. Capdevila et al. (1704.05340), W. Altmannshofer et al. (1704.05435),
G. D'Amico et al. (1704.05438), G. Hiller et al. (1704.05444),
L. S. Geng et al. (1704.05446), M. Ciuchini et al. (1704.05447),
A. Celis et al. (1704.05672).
Results found varied, depending on way analysis done.

Three scenarios were suggested as explanations:

$$\begin{array}{lll} \text{(I)} & C_9^{\mu\mu}(\text{NP}) < 0 \ , & \text{NP operator} : [\bar{s}\gamma_\mu P_L b][\bar{\mu}\gamma^\mu \mu] \ , \\ \text{(II)} & C_9^{\mu\mu}(\text{NP}) = -C_{10}^{\mu\mu}(\text{NP}) < 0 \ , & \text{NP operator} : [\bar{s}\gamma_\mu P_L b][\bar{\mu}\gamma^\mu P_L \mu] \ , \\ \text{(III)} & C_9^{\mu\mu}(\text{NP}) = -C_9^{\prime\mu\mu}(\text{NP}) < 0 \ , & \text{NP operator} : [\bar{s}\gamma_\mu \gamma_5 b][\bar{\mu}\gamma^\mu \mu] \ . \end{array}$$

Scenarios (I), (II) and (III) were mentioned in 3, all and 1 of the 7 papers, respectively. General consensus: $\exists$ significant disagreement with the SM, somewhere in the range of 4-6σ, even taking into account the theoretical hadronic uncertainties.

We repeated this analysis. (A) we fit to only the $b \to s\mu^+\mu^-$ observables (no R_K or R_{K^*}). WCs are real, pull $\equiv \sqrt{\chi^2_{SM} - \chi^2_{min}}$:

Scenario	WC	pull
(I) $C_9^{\mu\mu}(\mathrm{NP})$	-1.20 ± 0.20	5.0
(II) $C_9^{\mu\mu}(\mathrm{NP}) = -C_{10}^{\mu\mu}(\mathrm{NP})$	-0.62 ± 0.14	4.6
(III) $C_9^{\mu\mu}(\mathrm{NP}) = -C_9^{\prime\mu\mu}(\mathrm{NP})$	-1.10 ± 0.18	5.2

(B) We then added the R_{K^*} and R_K data to the fit:

Scenario	WC	pull
(I) $C_9^{\mu\mu}(\mathrm{NP})$	-1.25 ± 0.19	5.9
(II) $C_9^{\mu\mu}(\mathrm{NP}) = -C_{10}^{\mu\mu}(\mathrm{NP})$	-0.68 ± 0.12	5.9
(III) $C_9^{\mu\mu}(\mathrm{NP}) = -C_9^{\prime\mu\mu}(\mathrm{NP})$	-1.11 ± 0.17	5.6

Comparison: average pull $= 4.9$ (fit A), $= 5.8$ (fit B) $\Longrightarrow$ addition of R_{K^*} and R_K substantially increases disagreement with SM. In fit B, scenario (III) has pull $= 5.6 \Longrightarrow$ it is a viable candidate for explaining the $b \to s\mu^+\mu^-$ anomalies.

Alternative way to include R_{K^*} and R_K: take preferred WCs from fit A and *predict* R_{K^*} and R_K. Find: scenario (III) predicts $R_K = 1$, as in the SM, and in clear disagreement with the measurement. How can it be a viable candidate?

What's going on: global fit dominated by the > 100 $b \to s\mu^+\mu^-$ observables. The effect of the single R_K observable is diminished.

Two options: (i) R_K is clean observable $\Longrightarrow$ more important than $b \to s\mu^+\mu^-$ $\Longrightarrow$ scenario (III) is excluded; (ii) R_K only a 2.6σ discrepancy $\Longrightarrow$ don't worry about faulty prediction $\Longrightarrow$ scenario (III) still viable. Which is it?

Model-Dependent Analysis: Leptoquarks

LQs contribute to $b \to s\mu^+\mu^-$ at tree level. $\exists$ three LQ models that can explain the $b \to s\mu^+\mu^-$ data:

- scalar isotriplet with $Y = 1/3$ (S_3),
- vector isosinglet with $Y = -2/3$ (U_1),
- vector isotriplet with $Y = -2/3$ (U_3).

$b \to s\mu^+\mu^-$: S_3, U_1 and U_3 LQ models all have $C_9^{\mu\mu}(\mathrm{NP}) = -C_{10}^{\mu\mu}(\mathrm{NP})$, and so are equivalent. They all contribute differently to $b \to s\nu_\mu\bar{\nu}_\mu$ decays $\Longrightarrow$ distinguishable, in principle. However, present constraints from $B \to K^{(*)}\nu\bar{\nu}$ are far weaker than those from $b \to s\mu^+\mu^-$ (A.K. Alok et al., 1703.09247) $\Longrightarrow$ cannot distinguish the three LQ models.

Bottom line: there is effectively only a single LQ model that can explain the B-decay anomalies, and it is of type scenario (II).

In the LQ model, the $b \to s\mu^+\mu^-$ WC is

$$C_9^{\mu\mu}(\mathrm{NP}) \propto \frac{g_L^{b\mu} g_L^{s\mu}}{M_{\mathrm{LQ}}^2} ,$$

where $g_L^{b\mu}$ and $g_L^{s\mu}$ are the LQ couplings, and $M_{\mathrm{LQ}} > 640$ GeV. To determine the value of the WC required to reproduce the $b \to s\mu^+\mu^-$ data, perform a fit to this data, including all other processes to which the LQ contributes.

Only additional process is $b \to s\nu_\mu\bar{\nu}_\mu$, which does not furnish any additional constraints. In this case, the allowed value of the WC is the same as that found in the model-independent fit (A or B) with scenario (II).

Model-Dependent Analysis: Z' Bosons

LQ models: pure scenario (II) $\Longrightarrow$ scenarios (I) and (III) can only arise in Z' models. Is this possible?

Four-fermion $b \to s\mu^+\mu^-$ operators are

$$\begin{aligned}
&(\mathrm{I}) \quad [\bar{s}\gamma_\mu P_L b][\bar{\mu}\gamma^\mu \mu] \ , \\
&(\mathrm{II}) \quad [\bar{s}\gamma_\mu P_L b][\bar{\mu}\gamma^\mu P_L \mu] \ , \\
&(\mathrm{III}) \quad [\bar{s}\gamma_\mu \gamma_5 b][\bar{\mu}\gamma^\mu \mu] \ .
\end{aligned}$$

Scenarios (I) and (II): Z' couples vectorially to $\bar{s}b$, clearly allowed. Scenario (III): Z' couples axial-vectorially to $\bar{s}b$. Possible, but requires a rather contrived model. In addition, recall: scenario (III) strongly disfavored by the R_K measurement. Two strikes (experiment and theory) $\Longrightarrow$ scenario (III) excluded.

Point: by combining both model-independent and model-dependent considerations, we find

- scenario (III) excluded $\Longrightarrow$ only scenarios (I) and (II) are possible as explanations of the B-decay anomalies,
- while scenario (II) can be realized with a LQ or Z' model, scenario (I) can only be due to Z' exchange.

Z': singlet or triplet of $SU(2)_L$. Both options considered in literature. (In the case of a triplet, there is also a W' that can contribute to $\bar{B} \to D^{(*)+}\tau^-\bar{\nu}_\tau$ (B. Bhattacharya, A. Datta, D.L. and S. Shivashankara, PLB **742**, 370 (2015))).

$\exists$ contribution to $b \to s\mu^+\mu^-$ from tree-level exchange of Z'. The WC is

$$C_9^{\mu\mu}(\mathrm{NP}) \propto \frac{g_L^{bs} g_L^{\mu\mu}}{M_{Z'}^2} ,$$

where g_L^{bs} and $g_L^{\mu\mu}$ are the Z' couplings to $\bar{s}b$ and $\mu^+\mu^-$. Most Z' models assume a heavy Z', $M_{Z'} = \mathrm{O(TeV)}$. However, the Z' can be light, e.g., $M_{Z'} = 10$ GeV or 200 MeV.

$\exists$ contribution to B_s^0-$\bar{B}_s^0$ mixing due to tree-level Z' exchange $\Longrightarrow$ puts a constraint on $(g_L^{bs})^2$. And $\exists$ tree-level Z' contribution to $\nu_\mu N \to \nu_\mu N \mu^+\mu^-$ (neutrino trident production) $\Longrightarrow$ puts an upper bound on $(g_L^{\mu\mu})^2$.

We performed global fit using as parameters g_L^{bs} and $g_L^{\mu\mu}$ with $M_{Z'} = 1$ TeV (scenario (I): left, scenario (II): right):

	$M_{Z'} = 1$ TeV	
$g_L^{\mu\mu}$	Z' (I): g_L^{bs} $\times 10^3$	pull
0.01	-3.0 ± 1.6	1.4
0.05	-4.8 ± 1.0	2.8
0.1	-5.2 ± 0.8	4.5
0.2	-4.2 ± 0.6	5.7
0.4	-2.4 ± 0.4	5.9
0.5	-1.9 ± 0.3	5.9

	$M_{Z'} = 1$ TeV	
$g_L^{\mu\mu}$	Z' (II): g_L^{bs} $\times 10^3$	pull
0.01	-3.0 ± 1.6	1.4
0.05	-4.8 ± 1.0	2.8
0.1	-5.2 ± 0.8	4.5
0.2	-4.4 ± 0.7	5.6
0.4	-2.5 ± 0.4	5.9
0.5	-2.1 ± 0.4	5.9

For a given $b \to s\mu^+\mu^-$ WC: if $g_L^{\mu\mu}$ small, g_L^{bs} is big $\Longrightarrow$ problems with B_s^0-$\bar{B}_s^0$ mixing constraints $\Longrightarrow$ poor fit. Good fit has large $g_L^{\mu\mu}$, reproduces model-independent result.

Conclusions

$\exists$ several B-decay measurements in disagreement with predictions of SM. Intriguing: all can be explained if there is NP in $b \to s\mu^+\mu^-$.

Model-independent global fits: $\exists$ significant discrepancy, 4-6σ. Three possible explanations: (I) $C_9^{\mu\mu}(\mathrm{NP}) < 0$, (II) $C_9^{\mu\mu}(\mathrm{NP}) = -C_{10}^{\mu\mu}(\mathrm{NP}) < 0$, (III) $C_9^{\mu\mu}(\mathrm{NP}) = -C_9^{\prime\mu\mu}(\mathrm{NP}) < 0$.

Models: NP in $b \to s\mu^+\mu^-$ is tree-level exchange of a LQ or a Z'. $\exists$ many Z' models, but effectively only a single LQ model. Generally, we have $M_{\mathrm{LQ},Z'} = O(\mathrm{TeV})$, but the Z' can also be light (e.g., $M_{Z'} = 10$ GeV or 200 MeV). Analyses of Z' models must take into account contributions to B_s^0-$\bar{B}_s^0$ mixing and neutrino trident production.

More information by combining model-independent and model-dependent considerations: (i) scenario (III) excluded; only scenarios (I) and (II) are viable explanations, (ii) LQ and Z' models can both give scenario (II), but scenario (I) can only be due to Z' exchange. That is, though supposedly model-independent, scenario (I) is related to Z' models.