Complementarity of $B_s \rightarrow \mu^+\mu^-$ and $B \rightarrow K\ell^+\ell^-$ in New Physics searches

Damir Bećirević$^a$, Nejc Košnik$^b$, Federico Mescia$^{c *,}$, Elia Schneider$^d$

$^a$ Laboratoire de Physique Théorique (Bât. 210) and Université Paris Sud, Centre d’Orsay, F-91405 Orsay Cedex, France.
$^b$LAL (Bât. 200), Université Paris-Sud B.P. 34, 91898 Orsay, France, and J. Stefan Institute, Jamova 39, P. O. Box 3000, 1001 Ljubljana, Slovenia
$^{c *}$ECM & ICCUB, Facultat de Fisica Universitat de Barcelona, Diagonal 647, E-08028 Barcelona, Spain.
$^d$Dipartimento di Fisica, Università degli Studi di Trento, and INFN Gruppo collegato di Trento, Via Sommarive 14, Povo (Trento), I-38123 Italy.

Abstract

This year, LHC provided a very stringent bound on $\text{Br}(B_s \rightarrow \mu^+\mu^-)$, bringing it closer to the value predicted by the Standard Model (SM). $B_s \rightarrow \mu^+\mu^-$ was believed to be the golden mode at LHCb to find SUSY because a large enhancement was expected in the regime of moderate and large values of $\tan \beta$. Other scenarios are still possible and a correlation with other decay channels is needed. We show that a complementary information on New Physics (NP) can be obtained model-independently from the $B \rightarrow K\ell^+\ell^-$ decay mode. We provide a prediction $\text{Br}(B \rightarrow K\ell^+\ell^-)$ based on the first lattice QCD results for all three relevant form factors, $f_0(q^2)$ and $f_2(q^2)$. We were then able to provide the model-independent bounds on the complex couplings to scalar and pseudoscalar operators in the $b \rightarrow s$ sector.

Keywords: PACS: 13.25.Hw, 11.30.Er, 11.30.Hv.

1. Introduction

At Moriond 2012, LHCb lowered the upper limit $^1$ on $\text{Br}(B_s \rightarrow \mu^+\mu^-)$, pushing it very close to the Standard Model (SM) value $^2$,$^3$

$$\text{Br}(B_s \rightarrow \mu^+\mu^-)_{\text{exp}} < 4.1 \times 10^{-9}. \quad (1)$$

The current upper bound is now only about 1.3 times larger than the SM one, namely

$$\text{Br}(B_s \rightarrow \mu^+\mu^-)_{\text{SM}} = (3.3 \pm 0.3) \times 10^{-9}. \quad (2)$$

In 2011, before the LHC results appeared, the best bound was from CDF $^4$ and it was about 10 times the SM value.

The fact that the current bound on $\text{Br}(B_s \rightarrow \mu^+\mu^-)$ is closer to the SM forces us to scrutinize this process and disentangle the possible NP effects. To that end, other processes such as $B \rightarrow K\ell^+\ell^-$ become particularly helpful $^7$.

Despite its closeness to the SM prediction, $B_s \rightarrow \mu^+\mu^-$ remains interesting. The SM contribution to this decay is helicity suppressed whereas the contribution of the (pseudo)scalar operators are not. In SUSY the extended Higgs sector provides a natural scalar contributions and enhances significantly the $\text{Br}(B_s \rightarrow \mu^+\mu^-)$.

In a model-independent scenario the (pseudo) scalar couplings are free complex parameters and can enhance or suppress $\text{Br}(B_s \rightarrow \mu^+\mu^-)$. Importantly, however, the same (pseudo) scalar couplings affect the $B \rightarrow K\mu^+\mu^-$ decay in a complementary way, namely

$$\text{Br}(B_s \rightarrow \mu^+\mu^-) \propto f \left[ m_{\mu}^2 \left( C_{10} - C'_{10} \right) \right]$$

$$\text{Br}(B \rightarrow K\ell^+\ell^-) \propto g \left[ \left( C_{7,9,10} + C'_{7,9,10} \right) \right]$$

and the two can be used to unravel the couplings $C_i$ which encode the short-distance physics information that, at $m_b$ scale, enter the $b \rightarrow s$ Hamiltonian as (see $^7$ for details),

$$H_{\text{eff}} = \sum_{i=7,8,9,10} (C_i O_i + C'_i O'_i) \quad (3)$$

The operator basis in which the Wilson coefficients $C_i$
have been computed in the SM is:

\[ \mathcal{O}_7^{(c)} = \frac{e}{g^2} m_b (3 \sigma_{\mu \nu} P_{R,L} b) F^{\mu \nu}, \]

\[ \mathcal{O}_9^{(c)} = \frac{e^2}{g^2} (\bar{\gamma}_\mu P_{L,R} b) (\bar{\gamma}^\nu \ell), \]

\[ \mathcal{O}_{10}^{(c)} = \frac{e^2}{g^2} (\bar{\gamma}_\mu P_{L,R} b) (\bar{\gamma}^\nu \gamma_5 \ell), \]

\[ \mathcal{O}_S^{(c)} = \frac{e^2}{16\pi^2} (3 P_{L,R} b) (\bar{\ell} \ell), \]

\[ \mathcal{O}_T^{(c)} = \frac{e^2}{16\pi^2} (\sigma_{\mu \nu} b) (\bar{\ell} \sigma^{\mu \nu} \ell), \]

\[ \mathcal{O}_{TS}^{(c)} = \frac{e^2}{16\pi^2} (3 \sigma_{\mu \nu} b) (\bar{\ell} \sigma^{\mu \nu} \gamma_5 \ell), \]

(4)

$C_{7,9,10}$ receive contributions in SM from the $W$- and $Z$-boxes and penguin diagrams, while $C_{T,FS}$, $C_{7,9,10}$ and $C_{T,FS}$ are totally negligibly in the SM.

At Moriond 2012, the results of the first accurate measurement of Br($B \to K \ell^+ \ell^-$) were presented by BaBar \cite{5}. \[ \text{Br}(B \to K \ell^+ \ell^-) = (4.7 \pm 0.6) \times 10^{-7}. \] (5)

Within their statistics BaBar observe no isospin asymmetries between $B^+ \to K^+ \ell^+ \ell^-$ and $B^0 \to K^0 \ell^+ \ell^-$ and make the average of the two modes assuming the lepton flavor universality. LHCb, very recently, presented their results and quoted \cite{6}

\[ \text{Br}(B^0 \to K^0 \mu^+ \mu^-) = (3.1^{+0.7}_{-1.0}) \times 10^{-7}. \] (6)

LHCb and BaBar results agree within one standard deviation. A surprising feature of the LHCb result is that, contrary to BaBar, they observe a large isospin asymmetry, a puzzling phenomenon that could partly be described by the effect of (structure dependent) soft photons. That issue is beyond the scope of this paper and will be addressed elsewhere. After comparing the above experimental results with our theory estimate (see next section)

\[ \text{Br}(B \to K \ell^+ \ell^-)_{SM} = (7.0 \pm 1.8) \times 10^{-7}, \] (7)

we see that the BaBar result agrees well with theory, whereas the LHCb is by more than one-sigma lower. In the following we first discuss the theoretical (hadronic) uncertainties entering the Br($B \to \mu^+ \mu^-$) and Br($B \to K \ell^+ \ell^-$), and then discuss the model independent information about NP that can be deduced from a simultaneous study of these two decay modes.

\[ \langle K|\bar{b} \gamma^\mu |B^0 \rangle \propto f_{s,\ell}(q^2), \]

\[ \langle K|\bar{b} \sigma^{\mu \nu} |B^0 \rangle \propto f_{T}(q^2), \] (10)

parameterized by the three form factors $f_{s,\ell,TT}(q^2)$, which are either computed in the numerical simulations of quenched QCD on the lattice (LQCD), or by the

\[ \langle 0|\bar{b} \gamma^\mu \gamma_5 |B^0 \rangle \rangle = i p^\mu f_{B^0}, \]

that has been computed by means of lattice QCD (with $N_f = 2$ and $2 + 1$ light flavors) by many groups. Recent results obtained in full QCD are shown in fig. 1 from which we estimate $f_{B^0} = (234 \pm 10) \text{ MeV}$. Note that the resulting $\sim 4\%$ uncertainty used to be $20\%$ and its reduction is a net result of recent progress in lattice QCD \cite{9}. The uncertainty in $f_{B^0}$ implies an overall $\sim 7\%$ theory error on Br($B \to \mu^+ \mu^-$).

As far as Br($B \to K \ell^+ \ell^-$) is concerned, the dominant uncertainties are those associated with the following two hadronic matrix elements,

\[ \text{Br}(B \to K \ell^+ \ell^-)_{SM} = (7.0 \pm 1.8) \times 10^{-7}, \] (7)

\[ \text{Br}(B \to K \ell^+ \ell^-)_{SM} = (7.0 \pm 1.8) \times 10^{-7}, \] (7)
QCD sum rule analysis near the light cone (LCSR) \[\text{{LCSR}}\] \[\text{\cite{10}}\]. Since we present the first lattice QCD determination of the \( f_T(q^2) \) form factor, we plot its shape and values in fig. 2 along with the estimates made by using LCSR. LQCD results appear to be consistent with those obtained from LCSR within 30% of error in results obtained by both methods. This leaves room for improvement by the new generation of unquenched LQCD simulations. Several such studies are underway \[\text{\cite{11}}\]. Notice that the improvement of \( f_T(q^2) \) is much more realistic to expect than those parameterizing the \( B \to K^* \) transition matrix elements, because the latter decay involves many more form factors, with at least three of them being subject to very large uncertainties (see e.g. ref. \[\text{\cite{12}}\]). With the currently available estimates of the form factors we obtain \[\text{\cite{13}}\]

\[
\text{Br}(B \to \ell^+ \ell^-)_{\text{SM}} = \begin{cases} 
(7.5 \pm 1.4) \times 10^{-7} & \text{LQCD} \\
(6.8 \pm 1.6) \times 10^{-7} & \text{LCSR}
\end{cases}
\]

The result quoted in eq. \[\text{\cite{7}}\] covers both of the above values. For our purpose it is crucial to note that contrary to eq. \[\text{\cite{8}}\], the expression for \( \text{Br}(B \to K\ell^+ \ell^-) \) involves the sums of the Wilson coefficients \( C_{10.5,p} + C_{10.5,p} \), and therefore the two decays provide the complementary information about NP. A detailed analysis of various such scenarios is presented in ref. \[\text{\cite{7}}\]. Here we focus on one example.

3. A New Physics Scenario

As an example of the complementarity of constraints we add to the SM a scalar and a pseudoscalar operators,

\[
H^{\text{NP}} = C_5 O_S + C_P O_P \,.
\]

derive the expressions for \( \text{Br}(B_s \to \mu^+ \mu^-)^{\text{NP}} \) and \( \text{Br}(B \to K\ell^+ \ell^-)^{\text{NP}} \), and then plot the allowed values for \( |C_{S,P}| \) consistent with eqs. \[\text{\cite{1}}\] and \[\text{\cite{5}}\], respectively. The largest range of \( |C_{S,P}| \neq 0 \) is obtained when the pseudoscalar coupling is real, \( \phi_P = 0 \). Considering the case \( \phi_P 
eq 0 \) is essential because \( C_P \) interferes with \( C_{10} \). Note that the negative interference could lead to \( \text{Br}(B_s \to \mu^+ \mu^-) \) even smaller than the one predicted in the SM \[\text{\cite{c.f. eq. \cite{5}}}. \] \( C_S \), instead, only enters via its moduli.

We observe that at present the current constraint provided by \( B \to K\ell^+ \ell^- \) is redundant for this particular scenario, but that situation could radically change if the errors on \( B \to K \) form factors were significantly reduced. If we keep the central values of the form factors fixed and reduce the errors by 20% the measured and theoretically evaluated \( \text{Br}(B \to K\ell^+ \ell^-)^{\text{SM}} \) would not be compatible and \( B \to K\ell^+ \ell^- \) would become the essential constraint on the possible values of \( |C_{S,P}| \). In fig. 4 we show the cases for which the overlapping region (satisfied by both constraints) exists. E.g. for \( \phi_P \gtrsim 40^\circ \) such a solution would not exist, which would be a valuable information about NP. This further exacerbates the necessity for a better control of errors on the \( B \to K \) form factors, \( f_{+0,T}(q^2) \). Furthermore, the experiment effort to measure the partial decay width of \( B \to K\ell^+ \ell^- \) at large values of \( q^2 \) (see ref. \[\text{\cite{5}}\]) would be highly welcomed because that range of \( q^2 \)'s is more convenient for the precision computations in LQCD.

4. Conclusions

\( \text{Br}(B_s \to K\mu^+ \mu^-) \) is sensitive to (pseudo)scalar operators, \( O^{(0)}_S \) and \( O^{(0)}_P \), which are to large extent absent in the SM. Importantly, only one hadronic parameter needs to be controlled, \( f_{B_s} \), which nowadays has only small theoretical uncertainties.

\( \text{Br}(B \to K\ell^+ \ell^-) \) is very sensitive to (pseudo)scalar operators too, and the theoretical predictions involve 3 form factors, which have been computed both in LQCD and by using the LCSR, but still suffer from large errors that can be substantially reduced if computed in the new generation of full LQCD simulations. Importantly, this decay mode offers a complementary information to the coupling to NP particles, with respect to the one that can be deduced from \( \text{Br}(B_s \to \mu^+ \mu^-) \).
These modes constitute the essential probe to NP couplings that could be combined with the other theoretically clean observables, such as the transverse asymmetries in $B \to K^*\ell^+\ell^-$ \cite{14}.

Acknowledgements

F.M. thanks the LPTA-Montpellier for hospitality and acknowledges financial support from FPA2010-20807 and the Consolider CPAN project.

References

[1] R. Aaij et al. [LHCb Collaboration], arXiv:1203.4493
[2] K. De Bruyn et al., Phys. Rev. Lett. 109 (2012) 041801; S. Descotes-Genon et al., Phys. Rev. D 85, 034010 (2012)
[3] R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. 108 (2012) 101803, ibid 241801.
[4] T. Aaltonen et al. [CDF Collaboration], Phys. Rev. Lett. 107, 239903 (2011)
[5] J.P. Lees et al. [BABAR Collaboration], arXiv:1204.3933
[6] R. Aaij et al. [LHCb Collaboration], JHEP 1207 (2012) 133.
[7] D. Becirevic, et al., arXiv:1205.5811 [hep-ph].
[8] A. J. Buras et al., arXiv:1208.0934 [hep-ph].
[9] V. Lubicz and C. Tarantino, Nuovo Cim. B 123, 674 (2008).
[10] P. Ball and R. Zwicky, Phys. Rev. D 71 (2005) 014029; A. Khodjamirian et al., Phys. Rev. D 75 (2007) 054013.
[11] R. Zhou et al. [Fermilab Lattice and MILC Collaborations], arXiv:1111.0981 [hep-lat]; D. Becirevic et al., in preparation.
[12] A. Abada, et al. [SPQcdR collaboration], Nucl. Phys. Proc. Suppl. 119 (2003) 625; K. C. Bowler, et al. [UKQCD Collaboration], JHEP 0408 (2004) 035; D. Becirevic, et al. Nucl. Phys. B 769, 31 (2007).
[13] C. Bobeth, et al., JHEP 0712 (2007) 040.
[14] F. Kruger and J. Matias, Phys. Rev. D 71 (2005) 094009; U. Egede, et al., JHEP 0811, 032 (2008); D. Becirevic and E. Schneider, Nucl. Phys. B 854 (2012) 321; JHEP 1204, 104 (2012); S. Descotes-Genon, et al., arXiv:1207.2753 [hep-ph]. C. Bobeth et al., JHEP 1007, 098 (2010).