Search for new physics in $B_s \rightarrow \mu^+ \mu^-$ and $B \rightarrow K^{(*)} \mu^+ \mu^-$

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Transitions of the type $b \rightarrow s l^+l^−$ are flavour changing neutral current processes where new physics can enter in competing loop diagrams with respect to the Standard Model contributions. In these decays several observables sensitive to new physics, and where theoretical uncertainties are under control, can be constructed. Particularly interesting are the angular asymmetries in the decay $B_d \rightarrow K^+ \mu^+ \mu^−$ and the measurement of the branching fraction of the decays $B_{s,d} \rightarrow \mu^+ \mu^−$. Recent measurements of these observables and the measurement of the isospin asymmetry in the decays $B \rightarrow K^{(*)} \mu^+ \mu^−$ are presented.

I. INTRODUCTION

Rare decays which proceed via Flavour Changing Neutral Currents (FCNC) are induced by one-loop diagrams in the Standard Model (SM) and are excellent probes for New Physics (NP). New particles can enter in competing loop-order diagrams, resulting in large deviations from SM predictions. In general, an effective Hamiltonian formalism is used to describe the amplitudes of FCNC processes, according to the formula:

$$H_{eff} = \frac{G_F}{\sqrt{2}} \sum_i V^*_{CKM_i} C_i(\mu) Q_i ,$$

where $V^*_{CKM}$ are the relevant factors of the CKM matrix; $Q_i$ are local operators; $C_i$ are the corresponding couplings (Wilson coefficients); and $\mu$ is the QCD renormalization scale. The information on heavy degrees of freedom is embedded in the Wilson coefficients, which are, in general, different for the SM and NP models. Moreover, the correlation of different channels, where different combinations of Wilson coefficients contribute, is a powerful tool for searching and understanding the structure of NP. This approach is complementary to the direct search for NP at general purpose detectors. At current experiments, precision measurements of flavour physics allow energy scales as high as 200 TeV [1] to be tested, which exceed the reach for direct production by about two orders of magnitude [3]. In this paper recent measurements of the decays $B_{s,d} \rightarrow \mu^+ \mu^-$ and $B \rightarrow K^{(*)} \mu^+ \mu^−$ and the implication for the search for physics beyond the SM will be discussed.

II. THE $B_s \rightarrow \mu^+ \mu^-$ DECAY

The decays $B_{d,s} \rightarrow \mu^+ \mu^−$ are suppressed in the SM, being FCNC and helicity suppressed. Their branching fractions are predicted to be: $B(B_s \rightarrow \mu^+ \mu^-) = (3.2 \pm 0.2) \times 10^{-9}$ and $B(B_d \rightarrow \mu^+ \mu^-) = (1.0 \pm 0.1) \times 10^{-10}$ in the SM [2][3]. It is worth emphasising that while the theory predictions refer to branching fractions at $t = 0$, experiments measure time integrated branching fractions. This implies that the effective measured branching fraction for $B_s \rightarrow \mu^+ \mu^-$ is about 10% larger than predictions [4][5]. The correction due to soft photons, which are not detected experimentally, is discussed in Ref. [6].

In general these branching fractions are given by the following formula:

$$BR(B_q \rightarrow \mu^+ \mu^-) \propto \left( \sqrt{1 - \frac{4m_q^2}{m_{B_q}^2}} \left| \frac{m_{B_q}^2}{2} (C_S - C'_S) \right|^2 + \left| \frac{m_{B_q}^2}{2} (C_P - C'_P) + m_{\mu} (C_{10} - C'_{10}) \right|^2 \right) ,$$

where $C_{10}^{(i)}$ is an electroweak axial-vector Wilson coefficient and $C_S^{(i)}$ and $C_P^{(i)}$ are scalar and pseudo-scalar coefficients. In the SM the (pseudo-)scalar operators are negligibly small, but this is not generally the case in NP models. For instance in models with an extended Higgs sector [7]. In particular, in the Minimal Supersymmetric extension of the SM these branching fractions are proportional to $\tan^6 \beta$, where $\tan \beta$ is the ratio of the vacuum expectation value of
the two Higgs doublets. Constraints on these branching fractions have been set by the experiments D0 \cite{8}, CDF \cite{9}, ATLAS \cite{10}, CMS \cite{11} and LHCb \cite{12}. The strongest upper limit was set by LHCb: $BR(B_s \to \mu^+\mu^-) < 4.5 \times 10^{-9}$ and $BR(B_d \to \mu^+\mu^-) < 1.0 \times 10^{-9}$ at 95\%CL. Present constraints for the decay $B_s \to \mu^+\mu^-$ are shown in Fig. 1.

At hadron colliders relative measurements of branching fractions are preferred to absolute ones, in order to minimize systematic uncertainties. At the LHCb experiment the three decays $B^+ \to J/\psi K^+$, $B^0 \to K^+\pi^-$ and $B_s \to J/\psi\phi$ are used for the normalization in the measurement of $BR(B_s \to \mu^+\mu^-)$ \cite{34}. The CDF, ATLAS and CMS experiments use the decay $B^+ \to J/\psi K^+$ for normalization and CMS also uses the decay $B_s \to J/\psi\phi$ as a control channel. For all the experiments, the knowledge of the fraction of $B_s$ and $B_{d,u}$ mesons produced in the primary $pp$ interaction $f_s/f_d$ is needed \cite{35}. This quantity was measured at LHCb by combining measurements with semi-leptonic and hadronic decays \cite{13} to be $f_s/f_d = 0.267^{+0.021}_{-0.020}$ \cite{13,15}. The uncertainty on this parameter is, in the long run, one of the dominant systematic uncertainties in the measurement of the branching fraction of the decay $B_s \to \mu^+\mu^-$, thereby limiting the discriminating power between SM and NP contributions in this decay. Knowledge of $f_s/f_d$ is also necessary for the measurement of the ratio $B(B_s \to \mu^+\mu^-)/B(B_d \to \mu^+\mu^-)$, which is affected by small theoretical uncertainties and is a test of Minimal Flavour Violation \cite{16}. The correlation between the branching fractions of the decay $B_d \to \mu^+\mu^-$ and $B_s \to \mu^+\mu^-$ is shown in Fig. 2 for several scenarios of physics beyond the SM. The recent limits set by LHCb on these decays exclude large fraction of the parameter space in a whole range of new models. Large scalar effective couplings are no longer considered a probable scenario for NP. However, it is also possible that NP and SM contributions interfere destructively, decreasing the $B_{s,d} \to \mu^+\mu^-$ branching fractions. Therefore, precise measurements of $B(B_{s,d} \to \mu^+\mu^-)$ remain key observables for the search for physics beyond the SM.

III. ANGULAR ASYMMETRIES IN THE DECAY $B^0 \to K^*\mu^+\mu^-$

In the decay $B_d \to K^*\mu^+\mu^-$ several angular observables, which are sensitive to physics beyond the SM, can be constructed. For some of these observables theoretical uncertainties are under control or cancel out (see \cite{19,21} and references therein). These observables include the forward-backward asymmetry of the dimuon system, $A_{FB}^\ell$, the fraction of $K^*$ longitudinal polarization, $F_L$, the transverse asymmetry, $S_3$ \cite{20} (often referred to as $\frac{1}{2}(1 - F_L)A_T^\ell$ in the literature \cite{22}), and the CP averaged quantity $S_0$ \cite{20}, proportional to the imaginary component of the product of the transverse and longitudinal amplitude of the $K^{*0}$.

These observables can be extracted by performing an angular analysis as a function of the dimuon invariant mass squared, $q^2$, with respect to the following angles: the angle $\theta_1$ between the $\mu^+$ ($\mu^-$) and the $B^0$ ($\bar{B}^0$) in the dimuon rest frame; the angle $\theta_K$ between the kaon and $B^0$ in the $K^*$ rest frame; and the angle $\phi$ between the planes of the

\begin{center}
\begin{tabular}{|c|}
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\textbf{Intervals at 95\% CL for $BR(B_s \to \mu^+\mu^\prime)$} \\
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D0 (PLB 693 2010 539) \\
CDF (H. Miyake, La Thuile 2012) \\
ATLAS (arXiv:1204.0735) \\
CMS (JHEP 1204 (2012) 033) \\
LHCb (Phys. Rev. Lett. 108 (2012) 231801) \\
SM \\
\hline
\end{tabular}
\end{center}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{Figure1}
\caption{Present limits on $B(B_s \to \mu^+\mu^-)$ at 95\% CL set by the experiments D0 \cite{8}, CDF \cite{9}, ATLAS \cite{10}, CMS \cite{11} and LHCb \cite{12}. The SM prediction is indicated by the blue-dashed line.}
\end{figure}
FIG. 2: Correlation for the branching fractions of the decays $B_s \rightarrow \mu^+\mu^-$ and $B_d \rightarrow \mu^+\mu^-$ for several models of NP. Details on the models can be found in Ref. [17]. The recent upper limits by LHCb are shown by the shaded region. Reproduced from Ref. [18].

dimuon system and the plane of the $K^*$. A formal definition of these angles can be found in Ref. [23]. It should be noticed that the definition of the angles varies in the literature. In particular, the sign of the $\phi$ angle in LHCb is opposite to that of CDF for the $B^0$ decay, while it is the same for the $B^0$ decay. Consequently, in place of $A_{lm}$ [27] the angular distribution measured at LHCb is sensitive to the CP-average $S_9$, whereas CDF is sensitive to the CP asymmetry $A_9$ [20, 24]. Recent measurements of these observables are shown in Fig. 4. These measurements are dominated by the LHCb results [31]. Measurements of the differential branching fraction as function of $q^2$ are shown in Fig. 3. All these measurements are consistent with each other and with SM predictions.

FIG. 3: $dBF/dq^2$ measured by the experiments BaBar [28], Belle [29], CDF [30] and LHCb [31]. The comparison with the SM prediction, taken from Ref. [25, 26], is also shown. Reproduced from Ref. [31].

The point in $q^2$ where $A_{FB}$ changes sign is a sensitive probe for NP and it is theoretically clean, since form factor uncertainties cancel out at first order. The LHCb collaboration reported the world’s first measurement of this observable, shown in Fig. 4. The measurement of the zero-crossing point is $q^2_0 = 4.9^{+1.1}_{-1.3}$ GeV$^2$/c$^4$, which is in agreement with the SM prediction. This measurement strongly disfavours scenarios with flipped $C_7$ sign with respect to the SM, which early measurements of $A_{FB}$ seemed to be hinting at.
IV. ISOSPIN ASYMMETRY IN THE DECAYS $B \to K^{(*)}l^+l^-$

The isospin asymmetry of the decays $B \to K^0 l^+l^-$ and $B \to K^{(*)} l^+l^-$ are defined as:

$$A_I = \frac{B(B^0 \to K^{(*)} l^+l^-) - \frac{\tau_0}{\tau_{K^0}} B(B^\pm \to K^{(*)} l^+l^-)}{B(B^0 \to K^{(*)} l^+l^-) + \frac{\tau_0}{\tau_{K^0}} B(B^\pm \to K^{(*)} l^+l^-)},$$

where $\tau_{0,\pm}$ is the $B^{0,±}$ lifetime. In the SM, this quantity is expected to be at the percent level. Measurements of this quantity have been made by the BaBar [28] and Belle [29] experiments, using electrons and muons and by CDF [30] and LHCb [31], using muons. These results are shown in Fig. 4. All the measurements are consistent with each other and they are consistent with SM predictions for the $B \to K^0 l^+l^-$ decays. For the $B \to K^0 l^+l^-$ decays the measurements are in agreement with each other but they show a tension with respect to naive expectations. In particular, LHCb data show a deviation from zero at the level of about four standard deviations [32]. At present there is no theoretical explanation for this large isospin asymmetry.

V. CONCLUSIONS

Measurements in flavour physics have a great track record in paving the way to significant discoveries in particle physics. Most NP scenarios predict deviations from SM expectations in rare B-meson decays. Sensitive probes for NP are the leptonic decays $B_{s,d} \to \mu^+\mu^-$ and the rare semi-leptonic decays $B \to K^{(*)} l^+l^-$. The most recent measurements of the decays $B_{s,d} \to \mu^+\mu^-$ and the decay $B_d \to K^{(*)} l^+l^-$ are in good agreement with SM predictions and set strong constraints on a number of NP models. The isospin asymmetry in the decays $B \to K^{(*)} l^+l^-$ has been measured by several experiments. These measurements agree with each other and with SM predictions for the decays with a $K^*$, while there is a significant tension with respect to expectations for the decays with a kaon.

While no convincing sign of NP has been found yet in rare decays, these measurements are at the moment statistically limited and the room for physics beyond the SM is still large. Future and more precise measurements will be important to test SM predictions and understand the flavour structure of NP.
FIG. 5: Isospin asymmetry for the decays $B \rightarrow K\ell^+\ell^-$, measured by the experiments BaBar [28], Belle [29] (with electrons and muons), CDF [30] and LHCb [32] (with muons).

Acknowledgments

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[33] The exact value of the NP scale that can be tested with flavour physics observables is model dependent.

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[35] Isospin symmetry, i.e. $f_u = f_d$, has been assumed.