New Probes of New Physics with Leptonic Rare B Decays

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Abstract

Decays of the kind $B_{s,d}^0 \to \ell^+\ell^-$ belong to the most favourable processes for probing the flavour structure of the Standard Model, with outstanding sensitivity to new (pseudo)-scalar contributions. While the branching ratio of $B_s^0 \to \mu^+\mu^-$ has already been measured at the LHC in the ballpark of the Standard Model expectation, there is still significant room for New-Physics effects. We discuss how these may be revealed in the future super-high precision era of $B$-decay studies by utilising new theoretically clean observables, including CP-violating asymmetries. Another promising decay is $B_s^0 \to e^+e^-$, which has received little attention in view of its enormously helicity suppressed Standard Model branching ratio, with the most recent experimental upper bound dating back to 2009. Using the current constraints on New Physics from $B_s^0 \to \mu^+\mu^-$ as a guideline, we show that the $B_s^0 \to e^+e^-$ branching ratio may be hugely enhanced through new (pseudo)-scalar contributions up to the regime of $B_s^0 \to \mu^+\mu^-$. 

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1 Setting the Stage

Within the Standard Model (SM), the leptonic decays $B_{q}^0 \rightarrow \ell^+\ell^- (q = s, d)$ receive only loop contributions from penguin and box topologies, and show a helicity suppression which results in branching ratios proportional to $m_{\ell}^2$, where $m_{\ell}$ denotes the masses of the final state leptons. Another key feature is the simple situation concerning strong interactions, which are described by a single hadronic parameter, the $B_{q}$ decay constant $f_{B_q}$. These modes belong to the cleanest rare $B$ decays and offer an outstanding setting to explore the flavour sector of the SM, with high sensitivity to New Physics (NP) contributions. Particularly interesting are new (pseudo)-scalars, which may lift the helicity suppression. In Fig. 1, we show a compilation of experimental information in comparison with the SM picture. So far, only $B_s^0 \rightarrow \mu^+\mu^-$ has been observed, which was a highlight of LHC run 1. In the case of $B_{s,d}^0 \rightarrow \tau^+\tau^-$, the helicity suppression is not very effective due to the large $\tau$ mass but the $\tau$ reconstruction makes experimental analyses challenging. Interestingly, the $B_{s,d}^0 \rightarrow e^+e^-$ modes, which are extremely helicity suppressed in the SM, have not yet received attention at the LHC.

New observables of the decay $B_s \rightarrow \mu^+\mu^-$ were pointed out, which offer interesting probes at the high-precision frontier. In the following, we focus on the constraints for NP effects following from the current $B_s \rightarrow \mu^+\mu^-$ data2 their implications for the branching ratios of $B_{s,d}^0 \rightarrow \tau^+\tau^-$, $B_{s,d}^0 \rightarrow e^+e^-$; and address the impact of new sources of CP violation. 

2 In Pursuit of New Physics

The theoretical framework is given by effective quantum field theory, where the decays at hand are described by a low-energy effective Hamiltonian. In the SM, only the operator $O_{10} = (\bar{q} \gamma_{\mu} P_L b)(\bar{\ell} \gamma_{\mu} \gamma_5 \ell)$ contributes with a real Wilson coefficient. In the presence of NP, new four-
fermion operators involving (pseudo)-scalar lepton densities may enter. Their effect is described by short-distance coefficients $P^q_{\ell\ell}$ and $S^q_{\ell\ell}$, where the former includes the SM and pseudo-scalar NP effects while the latter originates from new scalars. In the SM, we have $P^q_{\ell\ell} = 1$ and $S^q_{\ell\ell} = 0$.

Due to the presence of $B^0_s - \bar{B}^0_s$ mixing and the sizeable $B_s$ decay width difference $\Delta\Gamma_s/\Gamma_s \sim 0.1$, a subtle difference arises between the untagged, time-integrated branching ratio

$$B(B_s \to \mu^+\mu^-) \equiv \frac{1}{2} \int_0^\infty \langle \Gamma(B_s(t) \to \mu^+\mu^-) \rangle dt \stackrel{\text{LHC}}{=} (3.0 \pm 0.5) \times 10^{-9},$$

measured at the LHC, and theoretical predictions $B(B_s \to \mu^+\mu^-)$ which usually refer to a setting without the oscillations. The conversion involves an observable $A_{\mu\mu}^{\Delta\Gamma_s}$, which depends on $P_{\mu\mu}$ and $S_{\mu\mu}$ and takes the SM value $+1$, yielding

$$B(B_s \to \mu^+\mu^-)_{\text{SM}} = (3.57 \pm 0.16) \times 10^{-9}.$$

Electromagnetic corrections were recently calculated in Ref. 6 and were found to be tiny. The observable $A_{\mu\mu}^{\Delta\Gamma_s}$ contains information equivalent to the effective lifetime

$$\tau_{\mu\mu} \equiv \left[ \int_0^\infty \frac{\langle \Gamma(B_s(t) \to \mu^+\mu^-) \rangle dt}{\langle \Gamma(B_s(t) \to \mu^+\mu^-) \rangle dt} \right] = [2.04 \pm 0.44(\text{stat}) \pm 0.05(\text{syst})] \text{ ps}$$

which was measured by the LHCb collaboration for the first time with the value given above.

In order to probe NP effects through the measured $B^0_s \to \mu^+\mu^-$ branching ratio, the quantity

$$R_{\mu\mu}^s \equiv \frac{B(B_s \to \mu^+\mu^-)/B(B_s \to \mu^+\mu^-)_{\text{SM}} = 0.84 \pm 0.16$$

plays a central role. Assuming real coefficients $P_{\mu\mu}$ and $S_{\mu\mu}$, we obtain the constraints shown in Fig. 2. Interestingly, $R_{\mu\mu}^s$ alone does not allow a separation of these contributions and sizeable NP effects could still be present. They could be revealed through a future measurement of $A_{\mu\mu}^{\Delta\Gamma_s}$. Unfortunately, the current value of $A_{\mu\mu}^{\Delta\Gamma_s} = 8.24 \pm 10.72$ does not yet have an impact.

Let us now explore implications of these NP constraints for other $B_q \to \ell^+\ell^-$ processes. To this end, we employ a scenario with flavour-universal NP (FUNP) contributions, which is
characterised by the feature that $C_{10}^{\ell\ell}$, $C_{F}^{\ell\ell}$, $C_{S}^{\ell\ell}$ do not depend on flavour labels. In Fig. 3, the corresponding strategy is illustrated in a flowchart.

In the case of $B_{d}^{0} \rightarrow \mu^{+}\mu^{-}$, the ratio

$$\frac{\mathcal{B}(B_{d} \rightarrow \mu^{+}\mu^{-})}{\mathcal{B}(B_{s} \rightarrow \mu^{+}\mu^{-})} \propto \left[ \frac{|P_{d\mu\mu}|^{2} + |S_{d\mu\mu}|^{2}}{|P_{s\mu\mu}|^{2} + |S_{s\mu\mu}|^{2}} \right] \left( \frac{f_{B_{d}}}{f_{B_{s}}} \right)^{2} \frac{V_{td}}{V_{ts}}^{2}$$

is a particularly interesting quantity, where the ratio of CKM matrix elements can be determined from an analysis of the unitarity triangle. In the FUNP scenario, an essentially linear correlation between the branching ratios arises, with a moderate suppression of $\mathcal{B}(B_{d} \rightarrow \mu^{+}\mu^{-})$ with respect to the SM expectation, in analogy to the current LHC data for $B_{s} \rightarrow \mu^{+}\mu^{-}$.

Concerning $B_{d}^{0} \rightarrow \tau^{+}\tau^{-}$ decays, the NP effects are strongly suppressed by the mass ratio $m_{\mu}/m_{\tau} \sim 0.06$ in the FUNP scenario, resulting in

$$0.8 \leq \mathcal{R}_{\tau\tau} \equiv \frac{\mathcal{B}(B_{d} \rightarrow \tau^{+}\tau^{-})}{\mathcal{B}(B_{s} \rightarrow \tau^{+}\tau^{-})}_{SM} \leq 1.0, \quad 0.995 \leq A_{\Delta\tau_{\tau}} \leq 1.000,$$

with a similar picture for $B_{d}^{0} \rightarrow \tau^{+}\tau^{-}$. First experimental bounds were obtained by LHCb.\(^8\)

In the case of $B_{d}^{0} \rightarrow e^{+}e^{-}$, we have a situation complementary to $B_{d}^{0} \rightarrow \tau^{+}\tau^{-}$ within the FUNP framework, where the NP effects are hugely amplified by the mass ratio $m_{\mu}/m_{e} \sim 207$. In this scenario, the (pseudo)-scalar New Physics contributions lift the helicity suppression of the extremely small SM branching ratio, as illustrated in Fig. 4, where the red and green bands describe $P_{s\mu\mu} < 0$ and $P_{s\mu\mu} > 0$, respectively. These results correspond to

$$0 \leq \mathcal{R}_{ee} \leq 1.7 \times 10^{5}, \quad 0 \leq \mathcal{B}(B_{s} \rightarrow e^{+}e^{-}) \leq 1.4 \times 10^{-8};$$

a similar picture arises for the $B_{d} \rightarrow e^{+}e^{-}$ decay, with $0 \leq \mathcal{B}(B_{d} \rightarrow e^{+}e^{-}) \leq 4.0 \times 10^{-10}$. The most recent experimental constraints on these modes were obtained by the CDF collaboration: $\mathcal{B}(B_{s} \rightarrow e^{+}e^{-}) < 2.8 \times 10^{-7}$ and $\mathcal{B}(B_{d} \rightarrow e^{+}e^{-}) < 8.3 \times 10^{-8}$, and date back to 2009.\(^9\) It would be most interesting to search for these modes at the LHC, where an observation would give an unambiguous signal for physics beyond the SM.

Figure 3 – Flowchart to explore the impact of $B_{s} \rightarrow \mu^{+}\mu^{-}$ NP constraints for other $B_{s,d} \rightarrow \ell^{+}\ell^{-}$ decays.

Figure 4 – Correlation between the $B_{s} \rightarrow e^{+}e^{-}$ and $B_{s} \rightarrow \mu^{+}\mu^{-}$ branching ratios in the FUNP scenario.
3 Impact of CP Violation

New sources of CP violation may enter through phases of the short-distance coefficients. In the case of $B_s \to \mu^+\mu^-$ decays, we have the following time-dependent CP asymmetry:

$$\frac{\Gamma(B_s^0(t) \to \mu^+\mu^-) - \Gamma(B_s^0(t) \to \mu^-\mu^+)}{\Gamma(B_s^0(t) \to \mu^+\mu^-) + \Gamma(B_s^0(t) \to \mu^-\mu^+)} = \frac{C^\lambda_{\mu\mu} \cos(\Delta M_s t) + S_{\mu\mu} \sin(\Delta M_s t) + A^{\mu\mu}_{\Delta \Gamma_s} \sin(y_s t/\tau_{B_s})}{\cosh(y_s t/\tau_{B_s}) + A^{\mu\mu}_{\Delta \Gamma_s} \sin(y_s t/\tau_{B_s})},$$

(7)

where $\lambda$ is the muon helicity and $y_s \equiv \Delta\Gamma_s \tau_{B_s}/2$. The $C^\lambda_{\mu\mu}$ term cancels in the helicity-averaged rates, and $(C^\lambda_{\mu\mu})^2 + (S_{\mu\mu})^2 + (A^{\mu\mu}_{\Delta \Gamma_s})^2 = 1$. These CP asymmetries were analysed within specific NP models\cite{13072}, and a detailed study to probe possible CP-violating phases of $P_{\mu\mu}^s \equiv |P_{\mu\mu}| e^{i\phi_{\mu\mu}}$ and $S_{\mu\mu}^s \equiv |S_{\mu\mu}| e^{i\phi_{\mu\mu}}$ has recently been performed\cite{156}, showing that the CP asymmetries do not offer sufficient information to determine all parameters from the data. However, assuming specific scenarios, much sharper pictures can be obtained. Explorations of CP violation offer valuable insights and are an essential part for revealing the full dynamics of the $B_s^0 \to \mu^+\mu^-$ decays.

4 Conclusions

We are moving towards new frontiers with $B_s \to \ell^+\ell^-$ decays. The $B_s^0 \to \mu^+\mu^-$ mode has been observed, and $\Delta \Gamma_s$ provides access to a new – theoretically clean – observable $A^{\mu\mu}_{\Delta \Gamma_s}$, which should be fully exploited in the future. What are the implications of the $B_s^0 \to \mu^+\mu^-$ measurement for the other $B_{s,d} \to \ell^+\ell^-$ decays? Assuming flavour-universal NP effects, $B_d \to \mu^+\mu^-$ is found to be moderately suppressed with respect to the SM and the NP effects strongly suppressed by $m_{\mu}/m_e \sim 0.06$ in $B_{s,d} \to \tau^+\tau^-$ decays. On the other hand, NP effects could be hugely amplified in this scenario by $m_{\mu}/m_e \sim 207$ in $B_{s,d} \to e^+e^-$, thereby lifting $\mathcal{B}(B_s \to e^+e^-)$ up to the regime of $\mathcal{B}(B_s \to \mu^+\mu^-)$, with the exciting possibility that it may be within reach at the LHC. New sources of CP violation may enter $B_q \to \ell^+\ell^-$ decays and offer an interesting playground, both for theorists within specific extensions of the SM and for experimentalists to explore future measurements of the corresponding observables. Decays of the kind $B_q \to \ell^+\ell^-$ offer new degrees of freedom for NP searches at the upcoming LHC upgrade and beyond!

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