PROCEEDINGS OF SCIENCE

New Probes of Electron–Muon Universality in $B \to K\ell^+\ell^-$ Decays

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In the pursuit of physics beyond the Standard Model, a promising path is the study of B-meson decays caused by the transition $b \to s\ell^+\ell^-$. A key observable in such decays is the ratio R_K, which measures electron–muon universality in $B \to K\mu^+\mu^-/e^+e^-$. At first sight, the recent LHCb measurement of $R_K \sim 1$ may seem to largely constrain deviations from universality in these decays. However, we show that this is actually not the case: new sources of CP violation allow for significant universality violation consistent with $R_K \sim 1$. This provides an exciting new opportunity to search for New Physics by measuring differences between CP asymmetries in $B \to K\mu^+\mu^-$ and $B \to Ke^+e^-$.

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1. Introduction

Do New Physics (NP) effects beyond the Standard Model (SM) discriminate between different lepton flavours? This question has been explored through the measurement of lepton–flavour universality ratios, most prominently through [1]

$$R_K \equiv \frac{\Gamma(B^- \to K^-\mu^+\mu^-) + \Gamma(B^+ \to K^+\mu^+\mu^-)}{\Gamma(B^- \to K^-e^+e^-) + \Gamma(B^+ \to K^+e^+e^-)} . \tag{1}$$

For several years measurements of this observable deviated from the SM value of 1 [2–5]. Recently, however, R_K was measured by the LHCb collaboration to be consistent with the SM within one standard deviation [6, 7]. At first sight, this new result seems to strongly limit violations of electron–muon universality in $B \to K\ell^+\ell^-$ decays. However, puzzling tensions still exist in data on $B^+ \to K^+\mu^+\mu^-$ and other, related $b \to s\mu^+\mu^-$ decays (see e.g. [8] for a recent review). Given this situation, is there still space left for electron–muon universality violation?

2. Charting the parameter space for electron–muon universality violation

The low-energy effective Hamiltonian for $b \to s\ell^+\ell^-$ decays is

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} \left[\lambda_u \Big\{ C_1(O_1^c - O_1^u) + C_2(O_2^c - O_2^u) \Big\} + \lambda_t \sum_{i \in I} C_i O_i \right] , \tag{2}$$

where $\lambda_q = V_{qb}V_{qs}^*$ and $I = \{1c, 2c, 3, 4, 5, 6, 8, 7^{(\prime)}, 9^{(\prime)}\ell, 10^{(\prime)}\ell, S^{(\prime)}\ell, P^{(\prime)}\ell, T^{(\prime)}\ell\}$. For simplicity we consider only NP in the coefficient $C_{9\ell}$ $(\ell = \mu, e)$, whose operator is defined as

$$O_{9\ell} = \frac{e^2}{(4\pi)^2} [\bar{s}\gamma^\mu P_L b](\bar{\ell}\gamma_\mu \ell) . \tag{3}$$

For a broader discussion including $C_{10\ell}$ see [9], where we also discuss our treatment of the relevant form factors and hadronic long-distance effects.

We first constrain the muonic coefficient $C_{9\mu}$ using experimental data. We then use the new R_K measurement to study by how much C_{9e} can differ from $C_{9\mu}$. We perform this procedure twice, first assuming the Wilson coefficients to be real numbers and then allowing them to be complex, thereby opening the door to new sources of CP violation.

2.1 Real Wilson coefficients

To constrain a real $C_{9\mu}$, we use the most recent data on the branching ratio $\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$ [10]. To accommodate these data within 1σ, we find that $C_{9\mu}$ needs to take a value within

$$C_{9\mu}^{\text{NP}} = [-1.32, -0.40] C_9^{\text{SM}} . \tag{4}$$

Fixing $C_{9\mu}$ within this range, we use the recent R_K measurement to calculate the allowed values for C_{9e}. Fig. 1 shows the result. The curve indicates R_K as a function of C_{9e}, the horizontal band the recent R_K measurement, and the dashed vertical line the value that $C_{9\mu}$ is fixed to. Within the band C_{9e} is constrained to one of two values: it can either take the same value as $C_{9\mu}$, respecting universality, or assume a different, more negative value. Consequently, with real Wilson coefficients, the recent R_K measurement leaves little space for violations of electron–muon universality.

2.2 Complex Wilson coefficients

We constrain a complex $C_{9\mu}$ in Fig. 2a by using the branching ratio and direct CP asymmetry of $B^+ \to K^+\mu^+\mu^-$. Fixing $C_{9\mu}$ to the blue star (see [11] for a determination of $C_{9\mu}$), we use the

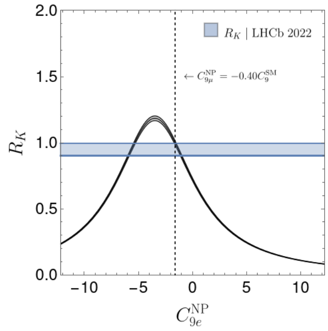

Figure 1: The ratio R_K as a function of a real $C^{\rm NP}_{9e}$, corresponding to no new sources of CP violation.

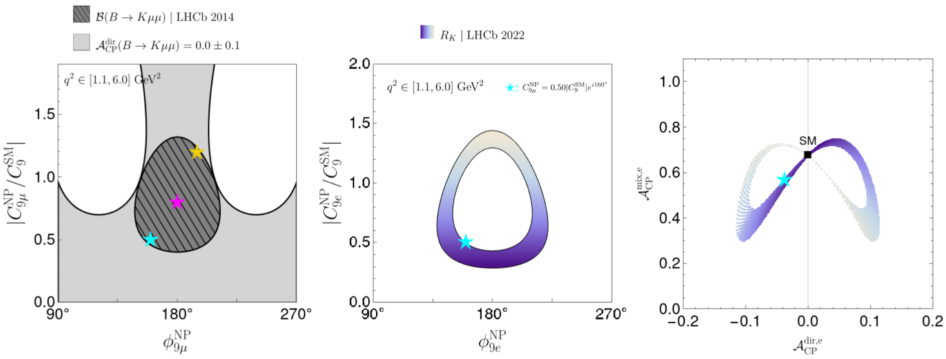

Figure 2: Constraints on a complex $C^{\rm NP}_{9\mu}$ (left), $C^{\rm NP}_{9e}$ (middle), and CP asymmetries in $B \to Ke^+e^-$ (right).

new R_K measurement to constrain C_{9e}. The resulting bound is shown in Fig. 2b. If NP respects electron–muon universality, then C_{9e} will take the same value as $C_{9\mu}$, i.e. the blue star. However, Fig. 2b shows that this is not necessarily the case. Instead, C_{9e} can take any value within the egg-shaped region, thereby leaving a surprising amount of space for universality violation.

To obtain the full picture, measuring R_K is not sufficient. We also need measurements of CP asymmetries in $B \to K\mu^+\mu^-$ and $B \to Ke^+e^-$. Complex, non-universal Wilson coefficients can cause these CP asymmetries to differ significantly from each other. Fig. 2c shows the parameter space allowed within the bounds of Fig. 2b for a direct and a mixing-induced CP asymmetry of $B^0_d \to K_S e^+e^-$, a decay related to $B^+ \to K^+e^+e^-$ through isospin symmetry. We could access much of this space given data on $\mathcal{A}^{\rm dir}_{\rm CP}(B^0_d \to K_S e^+e^-)$ (or the related $\mathcal{A}^{\rm dir}_{\rm CP}(B^+ \to K^+e^+e^-)$), which would draw a vertical band in the figure. And we could reach the remaining space with data on $\mathcal{A}^{\rm mix}_{\rm CP}(B^0_d \to K_S e^+e^-)$, which would draw a horizontal band. If either band were to exclude a known $C_{9\mu}$ point (blue star), we would have a clear signal of electron–muon universality violation.

3. Conclusions

In light of the recent R_K measurement, we have charted the remaining parameter space for violations of electron–muon universality in $B \to K\ell^+\ell^-$ decays. We have found that there remains a significant amount of unexplored space linked to new sources of CP violation. This space can be explored by searching for differences between CP asymmetries in $B \to K\mu^+\mu^-$ and $B \to Ke^+e^-$ decays, providing an exciting new opportunity to reveal NP effects in the coming high-precision era.

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