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$B \to \pi \ell^+ \ell^-$ form factors reexamined in the whole kinematically accessible region

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Abstract

We reexamine the $B \to \pi \ell^+ \ell^- (\ell = e, \mu, \tau)$ form factors, $f_+^{B\to\pi}(q^2)$, $f_0^{B\to\pi}(q^2)$ and $f_T^{B\to\pi}(q^2)$, in the entire region of the momentum transfer squared q^2, by taking advantage of the complementarity between lattice QCD (LQCD) simulation and light cone sum rule approach (LCSR), and analyticity of the form factors. A LCSR calculation with a chiral current correlator, which could avoid pollution by twist-3 components, is performed at twist-2 next-to-leading order (NLO) accuracy, to determinate the form factor shapes in the small and intermediate q^2 region. Further, fitting simultaneously the LCSR results for these form factors and the related LQCD ones (available or based on a $SU_F(3)$ symmetry breaking ansatz) to a Bourrely–Caprini–Lellouch (BCL) parametrization, we get a global understanding of their q^2 behaviors. Our findings turn out to be consistent with the recent study by Ali, Parkhomenko and Rusov, and the resulting observation for the vector form factor provides support for the existing LQCD as well as LCSR predictions extrapolated to the entire kinematically accessible region.

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1. Introduction

As is known to all, dileptonic rare B decays induced by flavor-changing neutral current (FCNC) serve as an important avenue to test the standard model (SM) and search for physics beyond it. Recently, a discovery of the $B^+ \to \pi^+\mu^+\mu^-$ decay has been reported using a pp collision data sample, corresponding to integrated luminosity of $1.0 fb^{-1}$, collected with the LHCb experiment at the Large Hadron Collider [1]. The branching ratio is measured at $\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) = (2.3 \pm 0.6(stat.) \pm 0.1(syst.)) \times 10^{-8}$ with 5.2σ significance. It is the first time FCNC $b \to d\ell^+\ell^-$ transition has been observed. As data accumulates, more and more attention will be paid to this aspect.

Much theoretical effort has been devoted to the exclusive decays $B \to \pi\ell^+\ell^-$ ($\ell = e, \mu, \tau$) within [3–7,2] and beyond [8–10] the SM. The naive factorization approach is extensively applied to estimate their branching ratios, the resulting SM predictions for the dimuonic modes [4–7] being consistent with the experimental data. Very recently, a detailed discussion appeared [2] on CP asymmetry in the $B \to \pi\mu^+\mu^-$ decays within the framework of QCD factorization (QCDF) [11–17], which modifies naive factorization by including the factorizable hard-gluon corrections to weak vertex and non-factorizable hard spectator scattering contributions in the limits of the heavy quark mass and large recoil energy, identifying W-weak annihilation as an additional potential source of CP-asymmetry. A partial understanding is also achievable of the nonlocal corrections due to soft-gluon emission and hadronic resonances which could not be covered by QCDF, using the QCD light cone sum rule (LCSR) approach applied for the $B \to K$ dileptonic modes [18]. Obviously, the largest uncertainty in calculating the decay widths originates from the $B \to \pi$ transition form factors $f_+^{B\to\pi}(q^2)$, $f_0^{B\to\pi}(q^2)$ and $f_T^{B\to\pi}(q^2)$ (conventionally called vector, scalar and tensor form factors, respectively), of which, the first two and $f_T^{B\to\pi}(q^2)$ parameterize, respectively, the matrix elements of the vector and the tensor currents as

$$
\begin{aligned}
\langle\pi(p)|\bar{d}\gamma_\mu b|B(p+q)\rangle &= (2p+q)_\mu f_+^{B\to\pi}(q^2) \\
&\quad + \frac{m_B^2 - m_\pi^2}{q^2} q_\mu \left(f_0^{B\to\pi}(q^2) - f_+^{B\to\pi}(q^2) \right), \\
\langle\pi(p)|\bar{d}\sigma_{\mu\nu}q^\nu b|B(p+q)\rangle &= i\left((2p+q)_\mu q^2 - \left(m_B^2 - m_\pi^2 \right) q_\mu \right) \frac{f_T^{B\to\pi}(q^2)}{m_B + m_\pi},
\end{aligned}
\tag{1}
$$

where the 4-momentum assignment is specified in brackets, and m_B (m_π) denotes the B (π) meson mass. Among the existing QCD approaches to the form factors are lattice QCD (LQCD) simulation, LCSR and perturbative QCD (pQCD) methods. However, none of them is available in the entire q^2 region. Whereas the former, as a rigorous approach, provides predictions at large q^2, LCSR [19,20] and pQCD [21] approaches are applicable for low and intermediate q^2. Here it should be added that as compared with the pQCD calculation, in which hard-exchange dominates, the LCSR one involves soft-overlap as well as hard-exchange components, and the former plays a predominant role. Let us go back to the subject we are discussing. To have an all-around understanding of q^2 behaviors of the form factors, one extrapolates usually theoretical predictions of an approach to the whole kinematical region in a certain form factor parameterization. LQCD- and LCSR-based investigations into the form factors in question have already been undertaken many times, and some new progresses have been made [22–27]. Concerning the application of LCSR approach, at QCD next-to-leading order (NLO) for twist-2 and -3 and with the pole mass for the underlying b quark, a complete and detailed computation is given