PROCEEDINGS OF SCIENCE

The rare $B \to \pi\ell^+\ell^-$ decay

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The very rare decay $B^+ \to \pi^+\mu^+\mu^-$ has been observed for the first time in 2012 with an integrated luminosity of 1.0 fb^{-1} by the LHCb experiment. A more precise measurement may appear before or during the 13 TeV run in 2015. Driven by the new data and the lack of updated SM prediction, we provide a new estimation of this rare decay process based on the QCD factorization (QCDF) approach. Explicitly, We give branching ratios of all four modes of $B \to \pi\mu^+\mu^-$ at large recoil energy region, as well as the associated CP asymmetry and isospin asymmetry among these modes, which should be testable in the future by LHCb and Bell II.

PACS numbers 12.15.Hh 11.30.Er 13.20.He

The European Physical Society Conference on High Energy Physics -EPS-HEP2013
18-24 July 2013
Stockholm, Sweden

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[†]I thank my collaborators Wei-Shu Hou and Masaya Kohda.

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1. INTRODUCTION AND BASIC FORMULAE

The decay $B^+ \to \pi^+ \mu^+ \mu^-$, discovered by LHCb [1] with 5.2 σ significance, claims that we have entered the era of $b \to d\ell^+\ell^-$ precise measurement. However, the current theoretical study of this decay mode still requires update due to the naive QCD factorization based estimation. To fill the gap between experimental and theoretical studies, we provide SM predictions to the decays in QCDF approach as well as the associated asymmetries in this work.

We start from effective Hamiltonian and adopt the same convention and operator basis as Ref. [2]. Based on QCDF, the differential decay rate is

$$\frac{d\Gamma}{dq^2} = S_P \frac{G_F^2 M_B^3}{96\pi^3} \left(\frac{\alpha}{4\pi}\right)^2 \lambda(q^2, m_\pi^2)^3 \xi_P(q^2)^2 \left(|\lambda_t \mathscr{C}_{9,P}^{(t)}(q^2) + \lambda_u \mathscr{C}_{9,P}^{(u)}(q^2)|^2 + |\lambda_t C_{10}|^2 \right), \quad (1.1)$$

where $S_P = 1$ $(1/2)$ for $P = \pi^-$ (π^0) and $\lambda_q = V_{qd}^* V_{qb}$ for $q = u,c,t$. The CKM factor λ_u is comparable to λ_t in magnitude with a sizable phase difference in $b \to d$ case, which is the main difference from $b \to s$ transition. And other important quantities are given as

$$\mathscr{C}_{9,P}^{(i)}(q^2) = \delta_{it} C_9 + \frac{2m_b}{M_B} \frac{\mathscr{T}_P^{(i)}(q^2)}{\xi_P(q^2)} \quad (1.2)$$

$$\mathscr{T}_P^{(i)} = \xi_P C_P^{(i)} + \frac{\pi^2}{N_c} \frac{f_B f_P}{M_B} \sum_{\pm} \int_0^\infty \frac{d\omega}{\omega} \Phi_{B,\pm}(\omega) \int_0^1 du\, \phi_P(u) T_{P,\pm}^{(i)}(u,\omega) \quad (1.3)$$

for $i = t,u$. $C_P^{(i)}$ and $T_{P,\pm}^{(i)}$ are described by short-distance physics with NNLO Wilson coefficients and their perturbative expressions can be referred to [4]. The information of long-distance physics are encoded in the form factor ξ_P and the light-cone distribution amplitude for the B (P) meson, $\Phi_{B,\pm}$ (ϕ_P). The less hadronic uncertainty sensitive observables, CP asymmetry $A_{\rm CP}$ and CP-averaged isospin asymmetry A_I, are defined as follows,

$$\frac{dA_{\rm CP}^{N(C)}(q^2)}{dq^2} \equiv \frac{d\Gamma(\overline{B^0}(B^-) \to \pi^0(\pi^-)\ell^+\ell^-)/dq^2 - d\Gamma(B^0(B^+) \to \pi^0(\pi^+)\ell^+\ell^-)/dq^2}{d\Gamma(\overline{B^0}(B^-) \to \pi^0(\pi^-)\ell^+\ell^-)/dq^2 + d\Gamma(B^0(B^+) \to \pi^0(\pi^+)\ell^+\ell^-)/dq^2} \quad (1.4)$$

$$\frac{dA_I(q^2)}{dq^2} \equiv \frac{2d\Gamma(B^0 \to \pi^0\ell^+\ell^-)/dq^2 - d\Gamma(B^+ \to \pi^+\ell^+\ell^-)/dq^2}{2d\Gamma(B^0 \to \pi^0\ell^+\ell^-)/dq^2 + d\Gamma(B^+ \to \pi^+\ell^+\ell^-)/dq^2} \quad (1.5)$$

Though not been measured yet, they could be analyzed when more data accumulated due to their importance.

2. NUMERICAL RESUTLS

For the first time, we calculate branching ratios of rare decay $B \to \pi\ell^+\ell^-$ $(\ell = \mu, e)$ in SM based on QCDF eq.(1.3), and show the numerical results in Table 1. The prediction is not applicable for full q^2 region aiming to future precision measurement bin by bin. To learn the q^2 dependence behavior, we also plot the differential branching ratio for the four separated modes in Fig. (1-a) from 1 to 6 GeV^2. Apparently, the charged B decays are with larger branching ratio than neutral one due to the S_P factor from isospin symmetry. And it is easy to understand the enhancement of

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Table 1: The integrated branching ratio of $B \to \pi \ell^+ \ell^-$ ($\ell = e, \mu$) from 1GeV^2 to 6GeV^2, in the unit of 10^{-8}, the global fit of CKM matrix elements is taken as input.

	QCDF$_{(1,6)}$
$B^+ \to \pi^+ \ell^+ \ell^-$	$0.57 \pm 0.03\vert_{\text{CKM}}{}^{+0.16}_{-0.12}\vert_{\text{had.}}$
$B^- \to \pi^- \ell^+ \ell^-$	$0.41 \pm 0.02\vert_{\text{CKM}}{}^{+0.13}_{-0.10}\vert_{\text{had.}}$
$B^0 \to \pi^0 \ell^+ \ell^-$	$0.23 \pm 0.01\vert_{\text{CKM}}{}^{+0.07}_{-0.05}\vert_{\text{had.}}$
$\overline{B^0} \to \pi^0 \ell^+ \ell^-$	$0.21 \pm 0.01\vert_{\text{CKM}}{}^{+0.07}_{-0.05}\vert_{\text{had.}}$

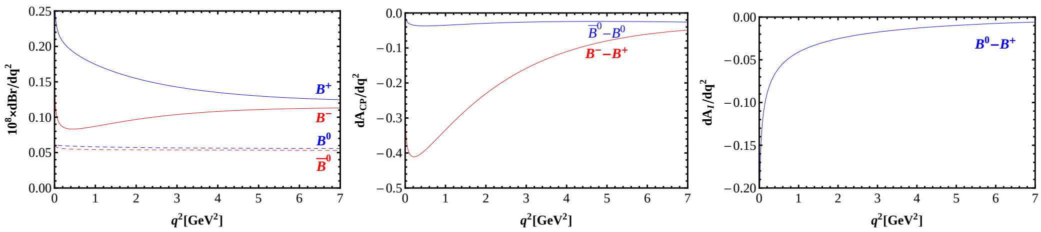

Figure 1: The asymmetries in $B \to \pi \ell^+ \ell^-$, in which (a) the different differential branching ratios in the range of $1-6$ GeV^2; (b) differential CP asymmetries, the blue curve denotes the asymmetry between neutral one while the red one stands for charged B decay ; (c) differential isospin asymmetry.

B^+ to B^- originates from spectator quark interaction (especially in low q^2 region) as well as light quark loop function Y, and this effect cannot be manifested in naive factorization approach [3].

The observables of integrated asymmetries in the region of $(1,6)$GeV^2, ratio of integral of decay rates in Eq. (1.4) and Eq. (1.5), are given as

$$A_{\text{CP}}^{C} = -0.16, \quad A_{\text{CP}}^{N} = -0.03, \quad A_I = -0.02, \tag{2.1}$$

One can easily find in Fig. (1-b) that the charged B decays have a larger CP asymmetry, which originates from Fig. (1-a), for the reason of larger spectator quark contribution (dominated by weak annihilation). We expect A_{CP}^{C} can be observed when more data accumulated. Although the isospin asymmetry might not be measured by LHCb at current stage, possibly it might be observed in Belle II in future. The prediction at low q^2 spectrum is also given in Fig. (1-c).

As a preparation for the advent of more precise measurement, the systematical study of the semileptonic decay $B \to \pi \ell^+ \ell^-$ in QCDF approach [4], containing more phenomenological information, should be useful and timely in the coming $b \to d \ell^+ \ell^-$ precision era.

References

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