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Phys. Rev. D **93**, 014024 — Published 22 January 2016

DOI: [10.1103/PhysRevD.93.014024](https://doi.org/10.1103/PhysRevD.93.014024)

# Resolving the $B \rightarrow K\pi$ puzzle by Glauber-gluon effects

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We extend the perturbative QCD (PQCD) formalism including the Glauber gluons, which has been shown to accommodate the measured  $B \rightarrow \pi\pi$  and  $B^0 \rightarrow \rho^0\rho^0$  branching ratios simultaneously, to the analysis of the  $B \rightarrow K\pi$  and  $K\bar{K}$  decays. It is observed that the convolution of the universal Glauber phase factors with the transverse-momentum-dependent kaon wave function reveals weaker (stronger) Glauber effects than in the pion ( $\rho$  meson) case as expected. Our predictions for the branching ratios and the direct CP asymmetries of the  $B \rightarrow K\pi$  and  $K\bar{K}$  modes at next-to-leading-order accuracy agree well with data. In particular, the predicted difference of the  $B^\pm \rightarrow K^\pm\pi^0$  and  $B^0 \rightarrow K^\pm\pi^\mp$  direct CP asymmetries,  $\Delta A_{K\pi} \equiv A_{\text{CP}}^{\text{dir}}(K^\pm\pi^0)[0.021 \pm 0.016] - A_{\text{CP}}^{\text{dir}}(K^\pm\pi^\mp)[-0.081 \pm 0.017] = 0.102 \pm 0.023$ , is consistent with the measured  $\Delta A_{K\pi} = 0.119 \pm 0.022$  within uncertainties, and the known  $B \rightarrow K\pi$  puzzle is resolved. The above  $B \rightarrow \pi\pi$ ,  $K\pi$  and  $K\bar{K}$  studies confirm that the Glauber gluons associated with pseudo Nambu-Goldstone bosons enhance the color-suppressed tree amplitude significantly, but have a small impact on other topological amplitudes.

PACS numbers: 13.25.Hw, 12.38.Bx, 11.10.Hi

Several long-standing puzzles in two-body charmless hadronic  $B$  meson decays, which might reveal new physics signals, have motivated thorough investigations of heavy-quark decay dynamics. Among them, we have carefully examined the  $B \rightarrow \pi\pi$  puzzle [1–3], that originates from the contradiction between the theoretically small and experimentally large  $B^0 \rightarrow \pi^0\pi^0$  branching ratios. It is generally believed that the enhancement of the color-suppressed tree amplitude  $C$  resolves the  $B \rightarrow \pi\pi$  puzzle [4–7]. We then observed in [1, 2] that the Glauber gluons, resulting in a nonperturbative strong phase in the  $k_T$  factorization theorem, could provide such enhancement mechanism: the additional Glauber phase turns the destructive interference between the spectator diagrams in the  $B \rightarrow \pi\pi$  decays into constructive one, and further increases the amplitude  $C$  on top of the contribution from next-to-leading-order (NLO) vertex corrections [8]. The remaining challenge resides in understanding why the Glauber-gluon effect is significant in the  $B \rightarrow \pi\pi$ , but not  $B \rightarrow \rho\rho$  decays, for which theoretical predictions agree well with the data [9]. We have speculated [1, 2] that the dual role of a pion as a pseudo Nambu-Goldstone (NG) boson and as a  $q\bar{q}$  bound state [10] may account for its difference from a  $\rho$  meson.

The Glauber phases associated with a pion were treated as free parameters, and those associated with a  $\rho$  meson were assumed to vanish in the earlier studies of two-body charmless hadronic  $B$  meson decays [1, 2]. Recently, we derived a perturbative QCD (PQCD) factorization formalism, which contains convolution of transverse-momentum-dependent (TMD) hadron wave functions with universal Glauber phase factors [3]. The fitting to the relevant  $B$  meson transition form factors indicated that the TMD pion ( $\rho$  meson) wave function exhibits a weak (strong) falloff in parton transverse momentum  $k_T$ , a feature in accordance with the special role of a pion, which requires a tighter spatial distribution of its leading Fock state relative to higher Fock states [10] in the conjugate  $b$  space. Simply parameterizing the Glauber phase as an sinusoidal function in the  $b$  space, we showed quantitatively that the leading Fock state of a pion may be tight enough to explore the Glauber effect from the oscillatory phase factor on the enhancement of the amplitude  $C$ , while the leading Fock state of a  $\rho$  meson is not. Our detailed analysis in [3] confirmed that the convolution of the universal Glauber phase factors with the TMD pion ( $\rho$  meson) wave function leads to large (moderate) modification of the  $B^0 \rightarrow \pi^0\pi^0$  ( $B^0 \rightarrow \rho^0\rho^0$ ) branching ratio. Namely, the  $B \rightarrow \pi\pi$  puzzle could be resolved under the stringent constraint from the  $B^0 \rightarrow \rho^0\rho^0$  data.

Encouraged by the success of the PQCD approach with the Glauber effects on accommodating the measured  $B \rightarrow \pi\pi$  and  $B^0 \rightarrow \rho^0\rho^0$  branching ratios simultaneously, we extend it to the investigation of the known  $B \rightarrow K\pi$

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puzzle [11]: the direct CP asymmetries of the  $B^0 \rightarrow K^\pm \pi^\mp$  and  $B^\pm \rightarrow K^\pm \pi^0$  modes are expected to be roughly equal, but the data <sup>1</sup>[13, 14],

$$A_{\text{CP}}^{\text{dir}}(B^0 \rightarrow K^\pm \pi^\mp) = -0.082 \pm 0.006, \quad (1)$$

$$A_{\text{CP}}^{\text{dir}}(B^\pm \rightarrow K^\pm \pi^0) = +0.037 \pm 0.021, \quad (2)$$

imply the deviation of their difference  $\Delta A_{K\pi} \equiv A_{\text{CP}}^{\text{dir}}(K^\pm \pi^0) - A_{\text{CP}}^{\text{dir}}(K^\pm \pi^\mp) = 0.119 \pm 0.022$  from zero at  $5\sigma$  level. The  $B \rightarrow K\pi$  decays have been discussed in the NLO PQCD approach in Refs. [2, 8, 15], whose predictions for the branching ratios match the data within theoretical errors in general, but those for  $\Delta A_{K\pi}$  still do not. It is then worthwhile to examine whether the  $B \rightarrow K\pi$  puzzle can be resolved in the same formalism with the universal Glauber phase factors.

It will be demonstrated that the TMD kaon wave function, extracted from the  $B \rightarrow K$  transition form factor, exhibits a stronger (weaker) falloff in the parton transverse momentum  $k_T$  than the TMD pion ( $\rho$  meson) wave function does. That is, the leading  $q\bar{q}$  Fock state of a kaon, which is also a pseudo NG boson, is not as tight as of a pion in the spatial distribution. This difference can be understood as a consequence of SU(3) symmetry breaking. The convolution of the universal Glauber phase factors with the TMD kaon wave function then reveals weaker (stronger) Glauber effects than in the pion ( $\rho$  meson) case. For a complete analysis of the Glauber effects associated with the kaon, we also consider the  $B \rightarrow K\bar{K}$  modes, for which NLO PQCD predictions have not yet been available. It will be seen at NLO accuracy that our predictions for the branching ratios and the direct CP asymmetries of the  $B \rightarrow K\pi$  and  $K\bar{K}$  decays all agree well with data. In particular, the predicted difference  $\Delta A_{K\pi} \equiv A_{\text{CP}}^{\text{dir}}(K^\pm \pi^0)[0.021 \pm 0.016] - A_{\text{CP}}^{\text{dir}}(K^\pm \pi^\mp)[-0.081 \pm 0.017] = 0.102 \pm 0.023$  is consistent with the measured  $\Delta A_{K\pi} = 0.119 \pm 0.022$  within uncertainties, and the  $B \rightarrow K\pi$  puzzle is resolved. Overall speaking, the impact of the Glauber effects on the  $B \rightarrow K\pi$  modes is more significant than on the  $B \rightarrow K\bar{K}$  ones as expected, since the latter do not involve the amplitude  $C$ .

Following Refs. [16–18], we write the intrinsic  $k_T$ -dependent kaon wave function as

$$\phi_K(x, \mathbf{k}_T) = \frac{\pi}{2\beta_K^2} \exp\left(-\frac{\mathcal{M}^2}{8\beta_K^2}\right) \frac{\phi_K(x)}{x(1-x)}, \quad (3)$$

where  $x$  is the parton momentum fraction of the light quark,  $\beta_K$  is a shape parameter, and  $\phi_K(x)$  represents the standard twist-2 and twist-3 light-cone distribution amplitudes. The first (second) argument  $k_T$  in the factor

$$\mathcal{M}^2 = \frac{k_T^2 + m_q^2}{x} + \frac{k_T^2 + m_s^2}{1-x}, \quad (4)$$

denotes the transverse momentum carried by the light (strange) quark, with  $m_{q(s)}$  standing for the light (strange) quark mass. The two-argument kaon wave function [19] to be convoluted with the Glauber phase factors in the PQCD framework [3] is then given by

$$\begin{aligned} \bar{\phi}_K(x, \mathbf{b}', \mathbf{b}) &\equiv \int \frac{d^2 \mathbf{k}'_T}{(2\pi)^2} \frac{d^2 \mathbf{k}_T}{(2\pi)^2} \exp(-i\mathbf{k}'_T \cdot \mathbf{b}') \exp(-i\mathbf{k}_T \cdot \mathbf{b}) \phi_K(x, \mathbf{k}'_T, \mathbf{k}_T), \\ &= \frac{2\beta_K^2}{\pi} \exp\left[-\frac{1}{8\beta_K^2}\left(\frac{m_q^2}{x} + \frac{m_s^2}{1-x}\right)\right] \exp\left[-2\beta_K^2 x b'^2 - 2\beta_K^2 (1-x)b^2\right] \phi_K(x). \end{aligned} \quad (5)$$

In the above expression  $b'$  ( $b$ ) labels the transverse coordinate of the light (strange) quark of a kaon.

The shape parameter  $\beta_K$  is constrained neither theoretically nor experimentally. Therefore, we determine it in the way the same as determining the  $\rho$ -meson shape parameter [3], namely, by fitting to the  $B \rightarrow K$  transition form factor  $F_0^{B \rightarrow K}(0) \sim 0.34$ , which is better known in the literature. The value  $\beta_K \sim 0.25$  GeV is obtained, implying a stronger (weaker) falloff in  $k_T$  compared to the pion ( $\rho$ -meson) wave function with  $\beta_\pi \sim 0.40$  ( $\beta_\rho \sim 0.13$ ) GeV [3]. That is, a kaon demands a broader (tighter) spatial distribution in the  $b$  space for the leading  $q\bar{q}$  Fock state than the pion ( $\rho$  meson) does. It is then expected that the TMD kaon wave function can partially probe the oscillatory phase of the universal Glauber factor, and reveal the Glauber effect in between the pion and  $\rho$  meson cases. The underlying reason is that a kaon, despite of being also a NG boson, has less tension to its another role as a  $q\bar{q}$  bound state due to the larger mass, i.e., due to SU(3) symmetry breaking. We will verify this observation by explicitly evaluating the Glauber effects on the color-suppressed tree amplitude later.

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<sup>1</sup> The most precise measurement of  $A_{\text{CP}}^{\text{dir}}(B^0 \rightarrow K^\pm \pi^\mp)$  to date was performed by the Large Hadron Collider-beauty (LHCb) Collaboration, giving  $-0.080 \pm 0.007(\text{stat}) \pm 0.003(\text{syst})$  [12].

TABLE I. Branching ratios of the  $B \rightarrow K\pi$  decays from the NLO PQCD formalism in units of  $10^{-5}$ , in which NLO (NLOG) denotes the results without (with) the Glauber effects.

Modes	Data [13, 14]	NLO	NLOG
$B^0 \rightarrow K^\pm \pi^\mp$	$1.96 \pm 0.05$	$2.33^{+0.74}_{-0.52}(\omega_B)^{+0.12}_{-0.11}(a^K)^{+0.21}_{-0.20}(a^\pi)$	$2.17^{+0.71}_{-0.49}(\omega_B)^{+0.11}_{-0.10}(a^K)^{+0.17}_{-0.16}(a^\pi)$
$B^\pm \rightarrow K^\pm \pi^0$	$1.29 \pm 0.05$	$1.53^{+0.50}_{-0.35}(\omega_B)^{+0.08}_{-0.07}(a^K)^{+0.12}_{-0.12}(a^\pi)$	$1.40^{+0.46}_{-0.33}(\omega_B)^{+0.06}_{-0.06}(a^K)^{+0.10}_{-0.10}(a^\pi)$
$B^\pm \rightarrow \pi^\pm K^0$	$2.37 \pm 0.08$	$2.72^{+0.88}_{-0.61}(\omega_B)^{+0.15}_{-0.13}(a^K)^{+0.25}_{-0.24}(a^\pi)$	$2.41^{+0.80}_{-0.56}(\omega_B)^{+0.11}_{-0.11}(a^K)^{+0.17}_{-0.17}(a^\pi)$
$B^0 \rightarrow K^0 \pi^0$	$0.99 \pm 0.05$	$1.02^{+0.32}_{-0.22}(\omega_B)^{+0.05}_{-0.05}(a^K)^{+0.11}_{-0.10}(a^\pi)$	$0.93^{+0.30}_{-0.21}(\omega_B)^{+0.06}_{-0.05}(a^K)^{+0.08}_{-0.07}(a^\pi)$

TABLE II. Direct CP asymmetries of the  $B \rightarrow K\pi$  decays from the NLO PQCD formalism, in which NLO (NLOG) denotes the results without (with) the Glauber effects.

Modes	Data [13, 14]	NLO	NLOG
$B^0 \rightarrow K^\pm \pi^\mp$	$-0.082 \pm 0.006$	$-0.076^{+0.008}_{-0.009}(\omega_B)^{+0.013}_{-0.013}(a^K)^{+0.007}_{-0.007}(a^\pi)$	$-0.081^{+0.009}_{-0.009}(\omega_B)^{+0.011}_{-0.011}(a^K)^{+0.010}_{-0.009}(a^\pi)$
$B^\pm \rightarrow K^\pm \pi^0$	$+0.037 \pm 0.021$	$-0.008^{+0.008}_{-0.009}(\omega_B)^{+0.009}_{-0.009}(a^K)^{+0.006}_{-0.006}(a^\pi)$	$+0.021^{+0.008}_{-0.008}(\omega_B)^{+0.003}_{-0.004}(a^K)^{+0.014}_{-0.013}(a^\pi)$
$B^\pm \rightarrow \pi^\pm K_S^0$	$-0.017 \pm 0.016$	$+0.003^{+0.001}_{-0.000}(\omega_B)^{+0.001}_{-0.001}(a^K)^{+0.000}_{-0.000}(a^\pi)$	$+0.004^{+0.000}_{-0.001}(\omega_B)^{+0.001}_{-0.002}(a^K)^{+0.000}_{-0.000}(a^\pi)$
$B^0 \rightarrow K_S^0 \pi^0$	$0.00 \pm 0.13$	$-0.056^{+0.001}_{-0.001}(\omega_B)^{+0.004}_{-0.004}(a^K)^{+0.000}_{-0.001}(a^\pi)$	$-0.089^{+0.001}_{-0.000}(\omega_B)^{+0.013}_{-0.009}(a^K)^{+0.005}_{-0.005}(a^\pi)$

We take the distribution amplitudes

$$\begin{aligned} \phi_K^A(x) &= \frac{6f_K}{2\sqrt{2}N_c}x(1-x) \left[ 1 + 3a_1^K(2x-1) + \frac{3}{2}a_2^K \left( 5(2x-1)^2 - 1 \right) + \frac{15}{8}a_4^K \left( 1 - 14(2x-1)^2 + 4(2x-1)^4 \right) \right], \\ \phi_K^P(x) &= \frac{f_K}{2\sqrt{2}N_c} \left[ 1 + \frac{1}{2} \left( 30\eta_3 - \frac{5}{2}\rho_K^2 \right) \left( 3(2x-1)^2 - 1 \right) \right. \\ &\quad \left. - \frac{3}{8} \left\{ \eta_3\omega_3 + \frac{9}{20}\rho_K^2(1+6a_2^K) \right\} \left( 3 - 30(2x-1)^2 + 35(2x-1)^4 \right) \right], \end{aligned} \quad (6)$$

$$\phi_K^T(x) = \frac{f_K}{2\sqrt{2}N_c} (1-2x) \left[ 1 + 6 \left( 5\eta_3 - \frac{1}{2}\eta_3\omega_3 - \frac{7}{20}\rho_K^2 - \frac{3}{5}\rho_K^2 a_2^K \right) (1-10x+10x^2) \right], \quad (7)$$

for a kaon [20], whose parametrization is the same as for a pion in Ref. [3] but with different hadronic parameters. Here we adopt the light  $u, d$  quark mass  $m_q = 7.5$  MeV, the strange quark mass  $m_s = 130$  MeV [13], the kaon decay constant  $f_K = 0.16$  GeV, the Gegenbauer moments  $a_1^K = 0.17$  and  $a_2^K = 0.115$  [8], the coefficients  $a_4^K = -0.015$ ,  $\eta_3 = 0.015$ ,  $\omega_3 = -3$ , and the factor  $\rho_K = m_K/m_0^K$  with the kaon mass  $m_K = 0.496$  GeV and the chiral mass  $m_0^K = 1.7$  GeV [8]. The choice of the quark masses is not crucial, whose variation can be compensated by that of the Gegenbauer moments. The hadronic parameters associated with a pion are the same as in Ref. [3]. We have checked that the NLO results for the  $B \rightarrow K\pi$  decays [8] in the PQCD approach without the Glauber effects are reproduced with the above TMD wave functions and parameters. It is noticed that the  $B \rightarrow \pi$  and  $B \rightarrow K$  transition form factors  $F_0^{B \rightarrow \pi}(0)$  and  $F_0^{B \rightarrow K}(0)$  in Ref. [15], which include the NLO contributions, are smaller than those in Refs. [2, 8].

The parameterized Glauber phase factor  $S(\mathbf{b}) = r\pi \sin(pb)$ , in which the parameters  $r = 0.60$  and  $p = 0.544$  GeV govern the magnitude and the frequency of the oscillation, also remain the same as in the analysis of the  $B \rightarrow \pi\pi$  and  $\rho\rho$  decays [3] because of their universality for two-body charmless hadronic  $B$  meson decays. The oscillatory behavior can be understood via the Fourier transformation of the nonperturbative Glauber gluon propagator,  $\int_0^\Lambda d^2l_T \exp(-il_T \cdot \mathbf{b})/(l_T^2 + m_g^2)$ , with  $m_g$  being a gluon mass. Choosing the cutoff for the loop momentum,  $\Lambda \sim 0.5$  GeV, which is reasonable for collecting soft contribution, roughly yields the period  $p$  obtained in [3]. The gluon mass  $m_g$ , together with the coefficient in the associated loop correction, such as the strong coupling in the nonperturbative region, control the magnitude of the oscillation. The  $b \rightarrow 0$  limit corresponds to the integration over the transverse momentum, namely, to the collinear factorization theorem. It has been known that the color-suppressed tree amplitude is dominated by the contribution from an energetic spectator quark in the collinear factorization for two-body charmless hadronic  $B$  meson decays [21]. According to the discussion in [1, 2], the Glauber region is not pinched as a spectator quark becomes energetic, implying the vanishing of the Glauber phase in the  $b \rightarrow 0$  limit. The above reasoning explains the parametrization  $S(\mathbf{b}) = r\pi \sin(pb)$  in Ref. [3].

The explicit factorization formulas for a general  $B \rightarrow M_1 M_2$  decay containing the convolution with the universal Glauber phase factors can be found in Ref. [3]. The results for all the considered quantities are listed in Tables I and II. Generally speaking, the NLO PQCD predictions for the  $B \rightarrow K\pi$  branching ratios without the Glauber effects match the data within theoretical errors. Taking into account the Glauber effects, one sees that the predicted branching ratios, labelled by NLOG, are reduced by around 10% as indicated in Table I. The moderate dependence of these branching ratios on the Glauber effects is attributed to the fact that they are dominated by the penguin contributions, and not sensitive to the color-suppressed tree amplitude  $C$ . However, the direct CP asymmetry of the  $B^\pm \rightarrow K^\pm \pi^0$  mode is sensitive to  $C$ , which may be modified significantly by the Glauber effects. Table II shows that  $A_{\text{CP}}^{\text{dir}}(K^\pm \pi^0)$  flips sign, changing from the central value  $-0.008$  to  $+0.021$ . The NLOG results in Tables I and II, agreeing well with the data within errors, represent the NLO PQCD predictions, which best accommodate the data to date.

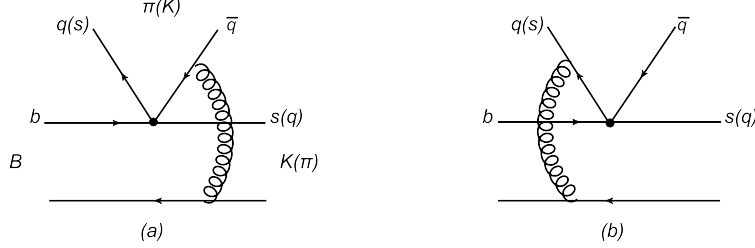


FIG. 1. LO spectator diagrams for the  $B \rightarrow K\pi$  decays corresponding to the pion or kaon emission from the weak vertex.

To have a clear idea of the Glauber effects on the  $B \rightarrow K\pi$  decays, we present the amplitudes (in units of  $10^{-2} \text{ GeV}^3$ ) from the two leading-order (LO) spectator diagrams in Figs. 1(a) and 1(b) associated with the four-fermion operator  $O_2$ ,

$$\mathcal{A}_{a,b}(B^\pm \rightarrow \pi^0 K^\pm) = \begin{cases} -16.71 + i13.71, & 10.85 - i9.96, & (\text{NLO}), \\ -12.57 + i10.80, & -9.96 + i5.85, & (\text{NLOG}), \end{cases} \quad (8)$$

for the pion emission from the weak vertex, and the amplitudes associated with the four-fermion operator  $O_1$ ,

$$\mathcal{A}_{a,b}(B^\pm \rightarrow K^\pm \pi^0) = \begin{cases} 4.55 - i3.98, & -3.37 + i2.25, & (\text{NLO}), \\ 3.59 - i3.23, & 3.14 - i0.90, & (\text{NLOG}), \end{cases} \quad (9)$$

for the kaon emission. Here  $\mathcal{A}_a$  and  $\mathcal{A}_b$  denote the amplitudes corresponding to the spectator diagrams with the hard gluons attaching to the valence antiquark and the valence quark, respectively. As exhibited in Eqs. (8) and (9), the destructive interferences between the two spectator diagrams have become constructive ones under the Glauber effects, due to the significant modification of the amplitudes  $\mathcal{A}_b$  with a sign flip. The summation of the amplitudes changes from  $6.96e^{i2.57} (2.09e^{-i0.97}) \times 10^{-2} \text{ GeV}^3$  to  $28.01e^{i2.51} (7.90e^{-i0.55}) \times 10^{-2} \text{ GeV}^3$  after including the Glauber effects associated with the TMD pion (kaon) wave functions in the NLO PQCD approach. Especially, the modification in Eq. (8), which contributes to the color-suppressed tree amplitude, results in the rotation of the total tree amplitude by a strong phase, and turns the previous negative direct CP asymmetry of the  $B^\pm \rightarrow K^\pm \pi^0$  modes into a positive value.

To examine the similarity between the kaon and the pion from the viewpoints of Glauber gluons, we calculate the spectator amplitudes, which contain only the Glauber phase factor  $S_{e2}$  associated with the emitted meson  $M_2$  in the  $B \rightarrow M_1 M_2$  decays. The ratios of the NLOG  $-S_{e2}$  amplitudes over the NLO amplitudes in magnitude,

$$R_\pi \equiv \frac{|\mathcal{A}_a(\pi^0 K^\pm) + \mathcal{A}_b(\pi^0 K^\pm)|_{\text{NLOG}-S_{e2}}}{|\mathcal{A}_a(\pi^0 K^\pm) + \mathcal{A}_b(\pi^0 K^\pm)|_{\text{NLO}}} \approx 4.69, \quad (10)$$

$$R_K \equiv \frac{|\mathcal{A}_a(K^\pm \pi^0) + \mathcal{A}_b(K^\pm \pi^0)|_{\text{NLOG}-S_{e2}}}{|\mathcal{A}_a(K^\pm \pi^0) + \mathcal{A}_b(K^\pm \pi^0)|_{\text{NLO}}} \approx 3.90, \quad (11)$$

indicate that a kaon reveals weaker Glauber enhancement than a pion does. Besides, both the pion and the kaon reveal the Glauber effects more dramatic than that given in Eq. (35) of Ref. [3] for a  $\rho$  meson. As stated before, a kaon is also a pseudo NG boson like a pion, but with non-negligible SU(3) symmetry breaking. It should be stressed that the direct CP asymmetry of the  $B^\pm \rightarrow K^\pm \pi^0$  modes predicted by the NLO PQCD formalism will not flip sign, if only the Glauber phase factor  $S_{e2}$  is considered. This fact confirms the effect of the Glauber phase factor  $S_{e1}$

TABLE III. Same as Table I but for the  $B \rightarrow K\bar{K}$  decays (in units of  $10^{-6}$ ).

Modes	Data [13, 14, 22]	NLO	NLOG
$B^\pm \rightarrow K^\pm \bar{K}^0$	$1.52 \pm 0.22$ <sup>a</sup>	$2.45^{+0.83}_{-0.58}(\omega_B)^{+0.17}_{-0.17}(a^K)$	$2.27^{+0.79}_{-0.54}(\omega_B)^{+0.17}_{-0.14}(a^K)$
$B^0 \rightarrow K^0 \bar{K}^0$	$1.21 \pm 0.16$	$2.19^{+0.77}_{-0.54}(\omega_B)^{+0.09}_{-0.09}(a^K)$	$2.02^{+0.72}_{-0.50}(\omega_B)^{+0.08}_{-0.08}(a^K)$

<sup>a</sup> This is the very recent measurement reported by the LHCb Collaboration [22], which is comparable with  $1.64 \pm 0.45$  by the BABAR Collaboration [23] and a bit larger than  $1.11 \pm 0.20$  by the Belle Collaboration [24].

TABLE IV. Same as Table II but for the  $B \rightarrow K\bar{K}$  decays.

Modes	Data [13, 14, 22]	NLO	NLOG
$B^\pm \rightarrow K^\pm \bar{K}_S^0$	$-0.21 \pm 0.14$	$-0.03^{+0.01}_{-0.01}(\omega_B)^{+0.02}_{-0.02}(a^K)$	$-0.03^{+0.01}_{-0.01}(\omega_B)^{+0.02}_{-0.02}(a^K)$
$B^0 \rightarrow K_S^0 \bar{K}_S^0$	$0.0 \pm 0.4$	$-0.09^{+0.00}_{-0.00}(\omega_B)^{+0.01}_{-0.01}(a^K)$	$-0.09^{+0.00}_{-0.00}(\omega_B)^{+0.00}_{-0.00}(a^K)$

associated with the meson  $M_1$ , which gives an additional strong phase to the color-suppressed tree amplitude having been enhanced by  $S_{e2}$  [2]. That is, both Glauber phase factors are crucial for resolving the  $B \rightarrow K\pi$  puzzle.

The  $B \rightarrow K\bar{K}$  decays were investigated in the LO PQCD approach [25] more than a decade ago. The NLO results for these modes in Tables III and IV with and without the Glauber effects are derived for the first time. It has been known that there is no amplitude  $C$  in the  $B \rightarrow K\bar{K}$  decays, but the spectator amplitudes induced by the penguin operators, which do not exhibit strong cancellation at LO. Taking the  $B^+ \rightarrow K^+ \bar{K}^0$  mode as an example, one observes that the predicted branching ratio decreases by few percents, from  $2.45^{+0.81}_{-0.60} \times 10^{-6}$  in the NLO PQCD formalism to the NLOG one  $2.27^{+0.81}_{-0.56} \times 10^{-6}$ , while the direct CP asymmetry remains unchanged, namely,  $-0.03 \pm 0.02$ . The small reduction of the decay rate and the invariance of the direct CP asymmetry under the Glauber effects are expected due to the absence of the amplitude  $C$  here. Within large theoretical errors, the branching ratios and the direct CP asymmetries of the  $B \rightarrow K\bar{K}$  decays predicted in the NLOG PQCD framework match the existent measurements generally.

In summary, we have estimated the Glauber-gluon effects in the  $B \rightarrow K\pi$  and  $K\bar{K}$  decays in the PQCD approach at NLO level by convoluting the universal Glauber phase factors with the TMD meson wave functions. It has been pointed out that the kaon behaves more like the pion but with a broader spatial distribution of the leading Fock state in the  $b$  space conjugate to the parton transverse momentum  $k_T$ , which causes smaller enhancement of the color-suppressed tree amplitude  $C$  with the kaon emission, relative to the pion emission. The  $B \rightarrow K\pi$  branching ratios, being insensitive to  $C$ , are reduced by only around 10%. However, the Glauber phase factors lead to the enhancement and the rotation of the tree amplitude by a strong phase in the  $B^\pm \rightarrow K^\pm \pi^0$  modes, rendering the predicted direct CP asymmetry consistent with the data. All the branching ratios and the direct CP asymmetries in the  $B \rightarrow K\pi$  decays then agree well with the measurements within errors, and the  $B \rightarrow K\pi$  puzzle is resolved in the NLO PQCD formalism with the Glauber effects. The  $B \rightarrow K\bar{K}$  decays, which do not involve the amplitude  $C$ , were also investigated in the same framework. As expected, the Glauber gluons associated with the TMD kaon wave function do not make a sizable impact on these modes, and the NLO PQCD predictions have matched the data of the branching ratios and direct CP asymmetries generally. Our recent analysis of the  $B \rightarrow \pi\pi$ ,  $\rho^0\rho^0$ ,  $K\pi$ , and  $K\bar{K}$  decays seems to indicate that the convolution of the universal Glauber phase factors with different TMD meson wave functions can generate appropriate enhancements and rotations of the amplitude  $C$  for resolving the  $B \rightarrow \pi\pi$  and  $K\pi$  puzzles simultaneously. We have observed a significant impact on the amplitude  $C$  from the Glauber gluons associated with pseudo NG bosons, and might have found a plausible dynamical origin of the additional strong phases required by the data of the above two-body charmless hadronic  $B$  meson decays.

## ACKNOWLEDGMENTS

We thank U. Nierste and Y.M. Wang for useful discussions. This work was supported in part by the Ministry of Science and Technology of R.O.C. under Grant No. NSC-104-2112-M-001-037-MY3, by National Science Foundation of China under Grants Nos. 11205072 and 11235005, and by the Priority Academic Program Development of Jiangsu



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