Semileptonic $B(B_s, B_c)$ decays in the light-cone QCD sum rules

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Semileptonic $B(B_s, B_c)$ decays are investigated systematically in the light-cone QCD sum rules. Special emphasis is put on the LCSR calculation on weak form factors with an adequate chiral current correlator, which turns out to be particularly effective to control the pollution by higher twist components of spectator mesons. The result for each channel depends on the distribution amplitude of the producing meson. The leading twist distribution amplitudes of the related heavy mesons and charmonium are worked out by a model approach in the reasonable way. A practical scenario is suggested to understand the behavior of weak form factors in the whole kinematically accessible ranges. The decay widths and branching ratios are estimated for several $B(B_c)$ decay modes of current interest.

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1. Introduction

Semileptonic $B(B_s, B_c)$ decays provide an important ground to understand and test the standard model (SM), and perhaps, a window into new physics beyond the SM. To test the SM with the experimental data demands that we have the ability to precisely compute the physical amplitudes in QCD theory. In this talk we focus on a

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discussion about how to compute the related hadronic matrix elements in the QCD light cone sum rules (LCSR’s), which have proved to be a powerful tool to derive the desired form factors with a minimal number of phenomenological assumptions. Instead of the procedure followed by conventional sum rule calculations, a LCSR computation starts with a vacuum-meson correlator, with the related light meson being on its mass shell, and operator product expansion (OPE) of the correlator is performed in term of the vacuum-meson matrix elements of certain nonlocal operators near light cone \( x^2 = 0 \). Then one parameterizes these nonlocal matrix elements in terms of light-cone wavefunctions of the light meson with increasing twist. In contrast to the case of the 3-point sum rules (3PSR’s), the effective region of the momentum transfer \( q^2 \) can be fixed without any extrapolation. However, it is our concern how to effectively control the nonperturbative dynamics embedded in the light-cone wavefunctions for enhancing the predictive power of the LCSR method. As shown in Ref. 2, the contributions would, in general, be important from some of the higher twist distribution amplitudes, especially twist-3 ones, in many situations. A pragmatic prescription has been put forward by us to reduce the contamination by the higher-twists. In the improved LCSR approach, we choose to use a certain proper chiral current operator as interpolating fields in the related correlators, which make twist-3 wavefunctions disappear in the sum rule results. Accordingly, this can enhance considerably one’s confidence in applying LCSR’s to calculate the nonperturbative quantities.

In this paper, we would like to give the complete discussion of the semileptonic form factors for \( B, B_s \rightarrow P(V) \) transitions with the chiral current correlators. A model for leading twist distribution amplitudes is formulated in the reasonable way, for the related heavy mesons and charmonium. Also, a practical scenario is suggested to have an all-around understanding of the form factors in the whole kinematical ranges.

2. \( B, B_s \rightarrow P(V) \) transition form factors

The hadronic matrix elements for \( B, B_s \rightarrow P(V) \) transitions can be parameterized in term of the form factors in the following way:

\[
<P(p)|\bar{q}\gamma_\mu b|B_{(s)}(p+q)> = f_+(q^2)(2p+q)_\mu + f_-(q^2)q_\mu, \tag{1}
\]

\[
<V(p, \eta)|\bar{q}\gamma_\mu(1 - \gamma_5)b|B_{(s)}(p+q)> = -i\eta_\mu^*(m_B+m_V)A_1(q^2) + i(\eta^*q^2)
\]

\[
A_+(q^2)(2p+q)_\mu + i\eta_\mu(q^2)\frac{A_-(q^2)}{m_B+m_V} + \epsilon_{\mu\alpha\beta\gamma}\eta^{*\alpha}q^\beta p_\gamma \frac{2V(q^2)}{m_B+m_V}, \tag{2}
\]

where \( q \) and \( \eta_\mu \) are the momentum transfer and polarization vector of the vector meson, respectively.

For performing a LCSR computation of the form factors for \( B(B_s) \rightarrow P \), we choose the following correlator \( \Pi_\mu(p, q) \) with the chiral current:

\[
\Pi_\mu(p, q) = i \int d^4xe^{iqx} <P(p)|T\{\bar{q}_1(x)\gamma_\mu(1 + \gamma_5)b(x), \bar{b}(0)i(1 + \gamma_5)q_2(0)\}|0> \tag{3}
\]
By contracting the $b$-quark operators to a free propagator, we get leading twist contribution to the correlator,

$$\Pi_{\mu}(\bar{q}q) = -2m_b i \int \frac{d^4xd^4k}{(2\pi)^8} e^{i(q-k)\cdot x} \frac{1}{k^2 - m_b^2} \langle P(p)|T\bar{q}_1(x)\gamma_\mu\gamma_5q_2(0)|0\rangle >$$

$$= 2f_P m_b p_\mu \int_0^1 du \frac{\varphi_P(u)}{m_b^2 - (up + q)^2} + \text{higher twist terms} \quad (4)$$

where we have substituted the definition of the leading twist distribution amplitude $\varphi_P(u)$:

$$\langle P(p)|T\bar{q}_1(x)\gamma_\mu\gamma_5q_2(0)|0\rangle = -ip_\mu f_P \int_0^1 du e^{iuP\cdot x} \varphi_P(u) + \text{higher twist terms}. \quad (5)$$

Because of the chiral nature of the selected correlator (3), only the leading non-local matrix element $\langle P(p)|\bar{q}_1(x)\gamma_\mu\gamma_5q_2(0)|0\rangle$ contributes to the correlator, while those with leading twist-3 $\langle P(p)|\bar{q}_1(x)i\gamma_5q_2(0)|0\rangle$ and $\langle P(p)|\bar{q}_1(x)\sigma_{\mu\nu}\gamma_5q_2(0)|0\rangle$ disappear from the sum rule. Including the effect of the background gluon field by writing down a full $b$-quark propagator, it is shown that all the twist-3 terms actually vanish in the OPE of this special correlator. Twist-4 and yet higher twist terms are found to be numerically small, and the resulting uncertainties can always be neglected comparing with those of the approach itself. Matching Eq. (4) to the hadronic representation of the correlator and omitting QCD radiative corrections, we get the following simple LCSR result for $f_+(q^2)$

$$f_+(q^2) = \frac{m_b^2 f_P}{m_b^2 M^2} e^{m_b^2/M^2} \int_{\Delta_P}^1 du \frac{\varphi(u)}{u} \exp\left[-\frac{m_b^2 - \bar{u}(q^2 - um_b^2)}{uM^2}\right] + \text{twist-4 terms} \quad (6)$$

with $\bar{u} = 1 - u$ and

$$\Delta_P = \frac{\sqrt{(s_0^P - q^2 - m_0^2)^2 + 4m_0^2(m_0^2 - q^2) - (s_0^P - q^2 - m_0^2)^2}}{2s_0^P}. \quad (7)$$

where $M^2$ denotes the corresponding Borel variable, and $s_0$ the threshold parameter. When setting $M_P = 0$, we get a simpler $\Delta_P = \frac{m_b^2 - q^2}{s_0 - q^2}$. As a byproduct, we also find the relation $f_-(q^2) = -f_+(q^2)$, which holds up to twist-4 terms. We would like to stress that the resulting form factors are just valid for $0 < q^2 < m_b^2 - 2m_b\Lambda_{\text{QCD}}$.

Form factor $f_+(q^2)$, as an illustrative example, has been calculated in terms of the above expression in the cases of $B \rightarrow \pi$ and $B_s \rightarrow K$. QCD radiative corrections have been added to the twist-2 part in the $B \rightarrow \pi$ case, with a negligibly small numerical impact. By applying LCSR’s to do such calculations, what is meant is that one is assuming soft exchanges to predominate in this transition. Thus, the semileptonic form factors in the whole kinematical range can be determined by combing the LCSR results with those of lattice QCD, which turn out to be available near the smallest recoil. While an alternative choice is made, which assumes hard exchanges to dominate at larger recoil for which the PQCD approach is applicable, a combined use should be in order of the three different approaches.
to fully understand the behavior of the form factor in the whole kinematic regions. A similar discussion on the case of $B \to K$ form factor is presented in Ref.\textsuperscript{6}.

It is straightforward to extend our discussion to the $B \to D$ case. In Ref.\textsuperscript{7}, the $B \to D$ form factor is calculated using three different models for the $D$ meson distribution amplitude. In order to compare with the results of heavy quark effective theory (HQET), the form factor has been redefined according to

$$f_+(q^2) = \frac{m_B + m_D}{2\sqrt{m_B m_D}} F_{B \to D}(v \cdot v' = \frac{m_B^2 + m_D^2 - q^2}{2m_B m_D}).$$

The numerical results, which correspond to the region $0 \leq q^2 \leq (m_B - m_D)^2$, are shown in Fig.\textsuperscript{1}. At zero recoil $F_{B \to D}^{LC}(1) = 1.02$ (using model III in Ref.\textsuperscript{7}), which is in good agreement with the evaluation obtained using the heavy quark symmetry: $F_{B \to D}(1) = 0.98 \pm 0.07$.\textsuperscript{5} In the larger recoil region $1.35 < v \cdot v' < 1.59$, the yielded results are consistent with those of pQCD.\textsuperscript{9} Therefore, a full understanding of the dynamics involved in $B \to D$ transition may be obtained by combining the three different approaches — HQET, LCSR’s and pQCD, which are complementary to each other.

For $B(B_s) \to V$ modes, we choose the following correlator as our starting point:

$$\Pi_\mu(p, q) = -i \int d^4xe^{iq \cdot x} V(p, \eta) \langle T \{ \bar{q}_1(x)\gamma_\mu(1 - \gamma_5)b(x), \bar{b}_1(0)(1 + \gamma_5)q_2(0) \} \rangle |0\rangle$$

$$= \Gamma^n \eta_\mu^\prime - \Gamma^+(\eta^* q)(2p + q) \mu - \Gamma^- (\eta^* q)q_\mu + i\Gamma^V \epsilon_{\mu \alpha \beta \gamma} \eta^{\alpha \gamma} q^\beta p^\gamma.$$  

(9)

Fig. 1. $F_{B \to D}$ as a function of the velocity transfer. The thin lines expresses the experiment fits with the HQET result at zero momentum transfer as input, where the solid line represents the central values, the dashed(dash-dotted) lines give the bounds from the linear(quadratic) fits. The thick lines correspond to our results, with the solid, dashed and dash-dotted lines for model III, II and I respectively.
Also we take the standard definition of the twist-2 and twist-3 distribution amplitudes of the vector meson:

\[
<V(p)|\bar{q}_1\gamma(x)q_2\alpha(0)|0> = \frac{1}{4} \int_0^1 du e^{iupx} \left[ f_V m_V [\eta\gamma_v g_{\perp}^\alpha(u) + \frac{\eta}{p_x} (\phi(u) - g_{\perp}^\alpha(u))] - i f_V \sigma_{\mu\nu} \eta^\nu p^\mu \phi_{\perp}(u) + \frac{m_V}{4} (f_V - f_V^T \frac{m_1 + m_2}{m_V}) \epsilon^{\mu\nu\rho\sigma} \gamma_\mu \gamma_5 \eta^\nu \rho \sigma g_{\perp}^\alpha(u) \right] \epsilon_{\alpha\beta},
\]

Actually there are also two other twist-3 distribution amplitudes, \(h_{\parallel}^{(s)}(u), h_{\parallel}^{(t)}(u)\), which are related to the square of light meson mass, and therefore can be neglected in comparison with those written above. We also neglected twist-4 and higher terms, and the whole three-particle contributions. Following the standard procedure, one obtains:

\[
A_1(q^2) = \frac{f_V^T m_b}{f_B m_B^2} e^{m_B^2/M_B^2} \times \int_0^1 \frac{du}{u} \exp \left[ - \frac{m_2^2 - u(q^2 - um_V^2)}{um_V^2} \right] \phi_{\perp}(u),
\]

\[
A_+(q^2) = \frac{f_V^T m_b (m_B + m_V)}{f_B m_B^2} e^{m_B^2/M_B^2} \times \int_0^1 \frac{du}{u} \exp \left[ - \frac{m_2^2 - u(q^2 - um_V^2)}{um_V^2} \right] \phi_{\perp}(u),
\]

\[
A_-(q^2) = -A_+(q^2),
\]

\[
V(q^2) = A_+(q^2)
\]

with

\[
\Delta_V = \left[ \sqrt{s_0^V - q^2 - m_B^2}^2 + 4m_B^2 (m_V^2 - q^2) - (s_0^V - q^2 - m_B^2) \right] / (2m_B^2),
\]

The same technique can be used to discuss the rare decay \(B \to V\gamma\). The electromagnetic penguin operator dominates in this transition, and relevant decay amplitude reads

\[
A(B \to V\gamma) = C m_b \epsilon_\mu <V(p, \eta)|\bar{q}\sigma_{\mu\nu}(1 + \gamma_5)q^\nu|B(p + q)>,
\]

where \(\epsilon_\mu\) and \(q\) are the emitted photon polarization vector and momentum, respectively. The constant \(C\) depends on the product of CKM matrix elements \(V_{ub} V_{ud}^*\) and the corresponding Wilson coefficient \(C_7\). The hadronic matrix element may be parameterized in terms of the form factor \(T(q^2 = 0)\),

\[
<V(p, \eta)|\bar{q}\sigma_{\mu\nu}(1 + \gamma_5)q^\nu|B(p + q) > = 2(i \epsilon_{\mu\nu\alpha\beta} \eta^{\nu\rho} q^{\rho} p^\beta + p \cdot q n_\mu - q \cdot \eta^* p_\mu) T(0).
\]

A correlator, which is suitable for our purpose, is

\[
F_\mu(p, q) = i \int d^4xe^{ipx} <V(p, \eta)|T\bar{q}(x)\sigma_{\mu\nu}(1 + \gamma_5)q^\nu b(x), \bar{b}(0)i(1 + \gamma_5)q_2(0)|0> = [2i \epsilon_{\mu\nu\alpha\beta} \eta^{\nu\rho} q^{\rho} p^\beta + 2p \cdot q n_\mu - 2q \cdot \eta^* p_\mu] F \left[ (p + q)^2 \right].
\]
According to the definition in Eq. (11) we can parameterize the nonlocal matrix element \( < V(\eta, \eta) | q_1(x) \sigma_{\mu\nu} q''(1 + \gamma_5) q_2(0) | 0 > \) using the the leading twist-2 wavefunction \( \phi_\perp(u) \) as the following,

\[
< V(\eta, \eta) | q_1(x) \sigma_{\mu\nu} q''(1 + \gamma_5) q_2(0) | 0 > = i \left[ (q \cdot \eta^*) p_\mu - p \cdot q \eta_\mu^* - i \epsilon_{\mu\nu\alpha\beta} \eta^\alpha q^\beta \right] f'_\perp \times \int_0^1 du e^{iup} \phi_\perp(u). \tag{19}
\]

Then we get the final LCSR for the form factor \( T(0) \)

\[
T(q^2 = 0) = \frac{m_b f_V m_\perp^2}{m_B J_B} \int_{\Delta_V^\perp}^{1} du \frac{\phi_\perp(u)}{u} \exp \left[ - \frac{m_b^2 + u\eta^2}{uM_V^2} \right], \tag{20}
\]

where \( \Delta_V^\perp = \Delta_V |_{q^2 = 0} \). Notice that

\[
T(q^2 = 0) = \frac{m_b}{(m_B + m_V)} A_+(q^2 = 0). \tag{21}
\]

With this sum rule, both \( B \rightarrow K^*\gamma \) and \( B \rightarrow (\rho, \omega)\gamma \) have been discussed in Ref. \[11\][12]. In Ref. \[12\] the form factor and branching ratio for \( B \rightarrow (\rho, \omega)\gamma \) are achieved using two different models for the \( \rho \) meson distribution amplitude:

\[
T^{B \rightarrow \rho^+ \gamma}(0) = 0.335 \pm 0.050, \quad Br(B \rightarrow \rho^+ \gamma) = (2.71 \pm 1.00) \times 10^{-6}
\]

for the model introduced by Ball and Braun in Ref. \[12\] and

\[
T^{B \rightarrow \rho^\pm \gamma}(0) = 0.272 \pm 0.029, \quad Br(B \rightarrow \rho^\pm \gamma) = (1.79 \pm 0.61) \times 10^{-6}
\]

for the model presented by Bakulev and Mikhailo in Ref. \[14\]. Comparing the LCSR predictions with the recent experimental result \[15\]

\[
Br(B \rightarrow \rho^\pm \gamma) = (1.32^{+0.34}_{-0.31}^{(stat)} + 0.10^{(syst)}) \times 10^{-6},
\]

we can determine which model can better describe the \( \rho \) meson.

3. \( B_c \rightarrow P(V) \) transition form factors

\( B_c \rightarrow P(V) \) situations may be discussed in parallel by a corresponding displacement of inputs. We proceed to cope with the semileptonic transitions induced, respectively, by \( b \rightarrow u, c \) and \( c \rightarrow d, s \). However, since the related distribution amplitudes are not available from a QCD calculation, we give a model description for them, which is based on the harmonic oscillator potential \[16\].

Our calculations, as in the \( B \) meson case, are limited to the regions where the OPE goes effectively, namely, \( 0 < q^2 < m_B^2 - 2m_b \Lambda_{QCD} \simeq 15 \text{ GeV}^2 \) for \( b \)-quark decays and \( 0 < q^2 < m_c^2 - 2m_c \Lambda_{QCD} \simeq 0.4 \text{ GeV}^2 \) for \( c \)-quark decays. The numerical results for the form factors at \( q^2 = 0 \) are collected in Tab.1. It turns out that the calculated form factors can be parameterized excellently as

\[
F_i(q^2) = \frac{F_i(0)}{1 - a_i q^2/m_{B_c}^2 + b_i (q^2/m_{B_c}^2)^2}. \tag{22}
\]
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Table 1. The values of the form factors at $q^2 = 0$ in comparison with the estimates in the three points sum rule (3PSR) (with the Coloumb corrections included) and in the quark model (QM).

| Mode          | $f_+(0)$ | $f_-(0)$ | $A_+(0)$ | $A_-(0)$ | $V(0)$ |
|---------------|----------|----------|----------|----------|--------|
| $B_c \rightarrow \bar{c}c[1S]$ | 0.87     | -0.87    | 0.75     | 1.69     | -1.69  | 1.69   |
| This work     |          |          |          |          |        |        |
| 3PSR          | 0.66     | -0.36    | 0.63     | 0.69     | -1.13  | 1.03   |
| QM            | 0.76     | -0.38    | 0.68     | 0.66     | -1.13  | 0.96   |
| $B_c \rightarrow B^{(*)}_s$ | 1.02     | -1.02    | 1.01     | 9.04     | -9.04  | 9.04   |
| This work     |          |          |          |          |        |        |
| 3PSR          | 1.3      | -5.8     | 0.69     | -2.34    | -21.1  | 12.9   |
| QM            | -0.61    | 1.83     | -0.33    | 0.40     | 10.4   | 3.25   |
| $B_c \rightarrow B^{(*)}c$ | 0.90     | -0.90    | 0.90     | 7.9      | -7.9   | 7.9    |
| This work     |          |          |          |          |        |        |
| 3PSR          | 1.27     | -7.3     | 0.84     | -4.06    | -29.0  | 15.7   |
| QM            | -0.58    | 2.14     | -0.27    | 0.60     | 10.8   | 3.27   |
| $B_c \rightarrow D^{(*)}$ | 0.35     | -0.34    | 0.32     | 0.57     | -0.57  | 0.57   |
| This work     |          |          |          |          |        |        |
| 3PSR          | 0.32     | -0.34    | 0.43     | 0.51     | -0.83  | 1.66   |
| QM            | 0.69     | -0.64    | 0.56     | 0.64     | -1.17  | 0.98   |

Extrapolating the LCSR results with this parametrization, we can estimate the branching ratios of the semileptonic $B_c$ decays. The results are shown in Table 2 together with those of other approaches, where we have input the following CKM-matrix elements: $V_{cb} = 0.0413$, $V_{ub} = 0.0037$, $V_{cs} = 0.974$, $V_{cd} = 0.224$. For the $b$-quark decay modes, our results for the branching ratios are much larger than the corresponding those of 3PSR’s. In these decays, the kinematical region is rather large and the main contributions to branching ratios should come from QCD dynamics at smaller recoil. The numerical values of the form factors always increase much faster with $q^2$ in the LCSR approach than in the simple pole approximation required in the 3PSR analysis, which accounts for the numerical discrepancy between the two approaches. While in the $c$-quark decays, where the kinematical region is narrow enough, the results of the two approaches are comparable to each other.

Table 2. Branching ratios (in %) of semileptonic $B_c$ decays into ground state charmonium states, and into ground charm and bottom meson states, in comparison with the result of 3PSR, QM, and the approach of the Bethe-Salpeter equation. For the lifetime of the $B_c$ we take $\tau(B_c) = 0.45$ps.

| Mode          | $\eta_c\nu\bar{c}$ | $\eta_c\tau\bar{c}$ | $J/\psi\nu\bar{c}$ | $J/\psi\tau\bar{c}$ | $D\nu\bar{c}$ | $D\tau\bar{c}$ | $D^*\nu\bar{c}$ | $D^*\tau\bar{c}$ | $B\nu\bar{c}$ | $B\tau\bar{c}$ | $B^*\nu\bar{c}$ | $B^*\tau\bar{c}$ |
|---------------|----------------------|-----------------------|---------------------|---------------------|---------------|---------------|----------------|----------------|---------------|---------------|----------------|---------------|
| This work     | 1.64                 | 0.49                  | 2.37                | 0.65                | 0.020         | 0.015         | 0.035          | 0.020          | 0.21          | 0.32          | 3.03          | 4.63          |
| 3PSR          | 0.75                 | 0.23                  | 1.9                 | 0.48                | 0.001         | 0.002         | 0.018          | 0.008          | 0.34          | 0.58          | 4.03          | 5.06          |
| QM            | 0.98                 | 0.27                  | 2.30                | 0.59                | 0.018         | 0.0094        | 0.034          | 0.019          | 0.15          | 0.16          | 2.00          | 2.6           |
| BSE           | 0.97                 | —                     | 2.30                | —                   | 0.006         | —             | 0.018          | —              | 0.16          | 0.23          | 1.82          | 3.01          |

4. summary

In this paper we derive LCSR’s for the form factors for semileptonic $B(B_s,B_c)$ decays of current interest, which depend mainly on the leading twist distribution...
amplitudes of the producing mesons by using suitable chiral currents.

For better understanding the behavior of these form factors in the whole kinematical range, a combined use is necessary of several different approaches which could be complementary to each other, for different kinematical regions. For example, in the $B \to D$ case one can use three different methods (LCSR, pQCD and HQET) for different kinematical regions to understand it in the whole kinematical range.

Based on the models with the harmonic oscillator potential for the light-cone wave functions, we calculate the form factors for several important semileptonic $B_c$ decay modes in the their kinematical regions allowed by LCSR calculation. Extrapolating the LCSR results to the large $q^2$ regions, we derive the decay widths and branching ratios.

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