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Research Article

Investigation of the Rare Exclusive $B_c^* \to D_s \nu\bar{\nu}$ Decays in the Framework of the QCD Sum Rules

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Exclusive $B_c^* \to D_s \nu\bar{\nu}$ decay is studied in the framework of the three-point QCD sum rules approach. The two gluon condensate contributions to the correlation function are calculated and the form factors of this transition are found. The decay width and total branching ratio for this decay are also calculated.

1. Introduction

The standard model (SM) Higgs boson which is one of the most important components of the SM has been discovered by the ATLAS [1] and CMS [2] collaborations. Nowadays, we aim to find out the new physics beyond the SM. Heavy mesons with the different flavors like B_c and B_c^* mesons can provide a good testing benchmark not only for the predictions of the SM but also for searching the new physics beyond SM. The LHCb experiment has aimed to test the SM predictions and discover the possible new physics signals. In this regard, a lot of the experimental data are released by the LHCb experiment [3].

The dominant decay mode of B_c^* is $B_c^* \to B_c\gamma$ [4]. Rare $B_c^* \to D_s \nu\bar{\nu}$ proceeds FCNC transitions. This decay is roughly of the same order as that of the $B_c^* \to \eta_c \ell\bar{\nu}_\ell$ [5]. In the SM framework, the rare $B_c^* \to D_s \nu\bar{\nu}$ decay is dominated by the Z-penguin and box diagrams involving top quark exchanges. The theoretical uncertainties related to the renormalization scale dependence of running quark mass can be essentially neglected after the inclusion of next-to-leading order corrections [6]. This decay is theoretically very clean process in comparison with the semileptonic decays like the $B_c^* \to D_s \ell^+\ell^-$ decay and is also sensitive to the new physics beyond the SM [7]. Moreover, this decay is complementary to the $B_c^* \to D_s \ell^+\ell^-$ decay. Note that the direct calculation of physical observables such as form factors suffers from sizable uncertainties. These can be greatly reduced through a combined analysis of the rare $B_c^* \to D_s \nu\bar{\nu}$ and $B_c^* \to D_s \ell^+\ell^-$ [8] decays.

These decays have not yet been measured by the LHCb. There are no theoretical studies relevant to the form factors and branching ratios of $B_c^* \to D_s \nu\bar{\nu}$ decay. The form factors of these decays can be evaluated with the different approaches. Some of them are the light front, the constituent quark models [9], and the QCD sum rules. In this study the three-point QCD sum rules approach is used in the calculation of form factors. It is worth mentioning that the QCD sum rules have widely been utilized in calculation of the form factors (some of them can be found in [10–17]).

The paper has 3 sections. In Section 2, the effective Hamiltonian and the three-point QCD sum rules approach are presented for completeness. In Section 3, the numerical values of form factors are given and the sensitivity of the branching ratio is studied and conclusion is presented.

2. Sum Rules for the $B_c^* \to D_s \nu\bar{\nu}$ Transition Form Factors

The FCNC $b \to s\nu\bar{\nu}$ decay is described within the framework of the SM at the quark level by the effective Hamiltonian [18, 19]:

$$\mathcal{H}_{\text{eff}} = \frac{G_F\alpha}{2\sqrt{2}\pi\sin^2\theta_W} V_{tb}V_{ts}^* X(x)\,\bar{b}\gamma^\mu(1-\gamma_5)\,s\bar{\nu}\gamma_\mu(1-\gamma_5)\,\nu, \tag{1}$$

where G_F is the Fermi constant, θ_W is the Weinberg angle, α is the fine structure coupling constant, and

$$X(x) = X_0(x) + \frac{\alpha_s}{4\pi}X_1(x). \tag{2}$$

The $X_0(x)$ is

$$X_0 = \frac{x}{8}\left[\frac{x+2}{x-1} + \frac{3(x-2)}{(x-1)^2}\ln x\right], \tag{3}$$

where $x = m_t^2/m_W^2$. The explicit form of $X_1(x)$ is given in [18–20]. Note that $X_1(x)$ gives about 3% contribution to the $X_0(x)$ term [21].

The Wilson coefficients (in our case $X_0(x)$ and $X_1(x)$) can be calculated in any gauge and they are gauge independent and the results should be gauge invariant. The Wilson coefficients are calculated in R_ξ gauge. It is worth mentioning that local operators in the considered problem have anomalous dimensions. We have checked that taking into account anomalous dimensions can change numerical results at most 10%.

The matrix element of the exclusive $B_c^* \to D_s\nu\bar{\nu}$ decays is found by inserting initial meson state B_c^* and final meson state D_s in (1):

$$M = \frac{G_F\alpha}{2\sqrt{2}\pi\sin^2\theta_W} V_{tb}V_{ts}^* X(x) \times \left\langle D_s(p_D)\left|\bar{s}\gamma_\mu(1-\gamma_5)\,b\right|B_c^*(p_B,\varepsilon)\right\rangle \bar{\nu}\gamma_\mu(1-\gamma_5)\,\nu, \tag{4}$$

where ε is the polarization vector of B_c^* meson, p_B is the momentum of the B_c^*, and p_D is the momentum of D_s meson. The matrix element of (4) is written in terms of the form factors as follows:

$$\begin{aligned}&\left\langle D_s(p_D)\left|\bar{s}\gamma_\mu(1-\gamma_5)\,b\right|B_c^*(p_B,\varepsilon)\right\rangle \\ &= \frac{A_V(q^2)}{m_{B_c^*}}\varepsilon_{\mu\nu\alpha\beta}\varepsilon^{*\nu}p_B^\alpha p_D^\beta - iA_0(q^2)\,m_{B_c^*}\varepsilon_\mu^* \\ &\quad - i\frac{A_+(q^2)}{m_{B_c^*}}(\varepsilon^* p_D)P_\mu - i\frac{A_-(q^2)}{m_{B_c^*}}(\varepsilon^* p_D)q_\mu.\end{aligned} \tag{5}$$

Here, Lorentz invariant and parity conservation are considered. Also, $A_i(q^2)$, where $i = V, 0, +, -$ are the dimensionless transition form factors. $P_\mu = (p_B + p_D)_\mu$ and $q_\mu = (p_B - p_D)_\mu$ is the transfer momentum or the momentum of the Z boson.

The matrix element in terms of the form factors is as

$$\begin{aligned}M = {}&\frac{G_F\alpha}{2\sqrt{2}\pi\sin^2\theta_W} V_{tb}V_{ts}^* X(x) \\ &\times\left[i\frac{A_1(q^2)}{m_{B_c^*}}\varepsilon_{\mu\nu\alpha\beta}\varepsilon^{*\nu}p_B^\alpha p_D^\beta - iA_0(q^2)\,m_{B_c^*}\varepsilon_\mu^*\right. \\ &\left. -i\frac{A_+(q^2)}{m_{B_c^*}}(\varepsilon^* p_D)P_\mu - i\frac{A_-(q^2)}{m_{B_c^*}}(\varepsilon^* p_D)q_\mu\right] \\ &\times\bar{\nu}\gamma_\mu(1-\gamma_5)\,\nu,\end{aligned} \tag{6}$$

where $A_1 = -iA_V$.

We try to calculate the aforementioned form factors by means of the QCD sum rules. The QCD sum rules begin with the following correlation functions:

$$\Pi_{\mu\nu}^{V-AV}(p_B^2, p_D^2, q^2) = i^2\int d^4x d^4y e^{-ip_B x}e^{ip_D y} \times\left\langle 0\left|T\left[J_{D_s}(y)\,J_\mu^{V-AV}(0)\,J_{\nu B_c^*}(x)\right]\right|0\right\rangle, \tag{7}$$

where the interpolating currents are $J_{D_s}(y) = \bar{c}\gamma_5 s$ and $J_{\nu B_c^*}(x) = \bar{b}\gamma_\nu c$ the D_s and the B_c^* meson states, respectively. $J_\mu^{V-AV} = \bar{s}\gamma_\mu(1-\gamma_5)b$ consists of the vector (V) and axial vector (AV) transition currents. After inserting the two complete sets of the B_c^* and D_s meson, the correlation functions in (7) are written as follows:

$$\begin{aligned}&\Pi_{\mu\nu}^{V-AV}(p_B^2, p_D^2, q^2) \\ &= -\left(\left\langle 0\left|J_{D_s}\right|D_s(p_D)\right\rangle\left\langle D_s(p_D)\left|J_\mu^{V-AV}\right|B_c^*(p_B,\varepsilon)\right\rangle \right. \\ &\quad\left.\times\left\langle B_c^*(p_B,\varepsilon)\left|J_{\nu B_c^*}\right|0\right\rangle\right) \\ &\quad\times\left(\left(p_D^2 - m_{D_s}^2\right)\left(p_B^2 - m_{B_c^*}^2\right)\right)^{-1} + \cdots,\end{aligned} \tag{8}$$

where "$\cdots$" shows the contributions come from higher states and continuum of the currents with the same quantum numbers.

The $\langle 0|J_{D_s}|D_s(p_D)\rangle$ and $\langle B_c^*(p_B,\varepsilon)|J_{\nu B_c^*}|0\rangle$ matrix elements are defined as follows:

$$\begin{aligned}\left\langle 0\left|J_{D_s}\right|D_s(p_D)\right\rangle &= -i\frac{f_{D_s}m_{D_s}^2}{m_s + m_c}, \\ \left\langle B_c^*(p_B,\varepsilon)\left|J_{\nu B_c^*}\right|0\right\rangle &= f_{B_c^*}m_{B_c^*}\varepsilon_\nu,\end{aligned} \tag{9}$$

where f_{B_c} and f_{D_s} are the leptonic decay constants of B_c^* and D_s mesons, respectively. Using these equations and

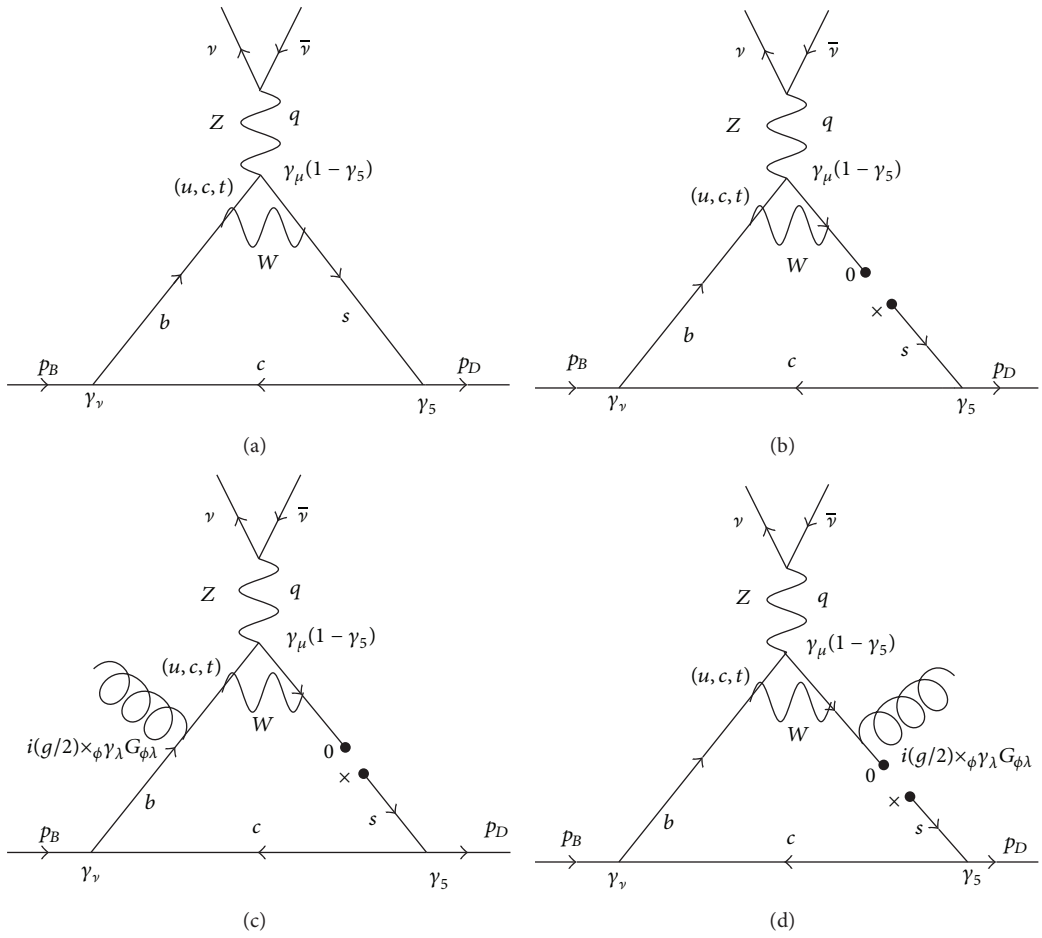

FIGURE 1: The bare-loop and light quarks condensates contributions to $B_c^* \to D_s l^+ l^-$ transitions.

calculating the summation over the polarization of the vector meson B_c^*, (8) is as follows:

$$\begin{aligned}\Pi_{\mu\nu}^{V-AV}&\left(p_B^2, p_D^2, q^2\right)\\ &= -\frac{f_{D_s} m_{D_s}^2}{(m_c + m_s)} \frac{f_{B_c^*} m_{B_c^*}}{\left(p_D^2 - m_{D_s}^2\right)\left(p_B^2 - m_{B_c^*}^2\right)}\\ &\quad\times \left[A_0\left(q^2\right) m_{B_c^*} g_{\mu\nu} + \frac{A_+\left(q^2\right)}{m_{B_c^*}} P_\mu p_{B\nu}\right.\\ &\quad\left. + \frac{A_-\left(q^2\right)}{m_{B_c^*}} q_\mu p_{B\nu} + i\frac{A_1\left(q^2\right)}{m_{B_c^*}} \varepsilon_{\mu\nu\alpha\beta} p_B^\alpha p_D^\beta\right]\\ &\quad + \text{excited states}.\end{aligned} \tag{10}$$

This correlation function is calculated in terms of the quarks and gluons parameters by means of the operator product expansion (OPE) as

$$\begin{aligned}\Pi_{\mu\nu}^{V-AV}\left(p_B^2, p_D^2, q^2\right) &= \Pi_0^{V-AV} m_{B_c^*} g_{\mu\nu} + \frac{\Pi_+^{V-AV}}{m_{B_c^*}} P_\mu p_{B\nu}\\ &\quad + \frac{\Pi_-^{V-AV}}{m_{B_c^*}} q_\mu p_{B\nu} + i\frac{\Pi_1^{V-AV}}{m_{B_c^*}} \varepsilon_{\mu\nu\alpha\beta} p_B^\alpha p_D^\beta.\end{aligned} \tag{11}$$

Each Π_i with $i = 0, +, -$ and 1 contains the perturbative and nonperturbative parts as in the following:

$$\Pi_i = \Pi_i^{\text{pert}} + \Pi_i^{\text{nonpert}}. \tag{12}$$

The bare-loop diagram given in Figure 1(a) is the contribution of the perturbative part. The nonperturbative part consists of the two gluon condensates diagrams {see Figures 2(a)–2(f)}. Hence, contributions of the light quark condensates {diagrams shown in Figures 1(b), 1(c), and 1(d)} vanish by applying the double Borel transformations [16].

The following double dispersion integrals are the contributions of the bare-loop diagrams in the correlation function:

$$\begin{aligned}\Pi_i^{\text{per}} &= -\frac{1}{(2\pi)^2}\int du \int ds \frac{\rho_i\left(s, u, q^2\right)}{\left(s - p_B^2\right)\left(u - p_D^2\right)}\\ &\quad + \text{subtraction terms}.\end{aligned} \tag{13}$$

One of the basic methods to solve the Feynman Integrals in order to calculate the spectral densities $\rho_i(s, u, q^2)$ is Cutkosky rules where the quark propagators are replaced by Dirac Delta Functions: $1/(p^2 - m^2) \to -2\pi i\delta(p^2 - m^2)$, which indicates that all quarks are on-shell.

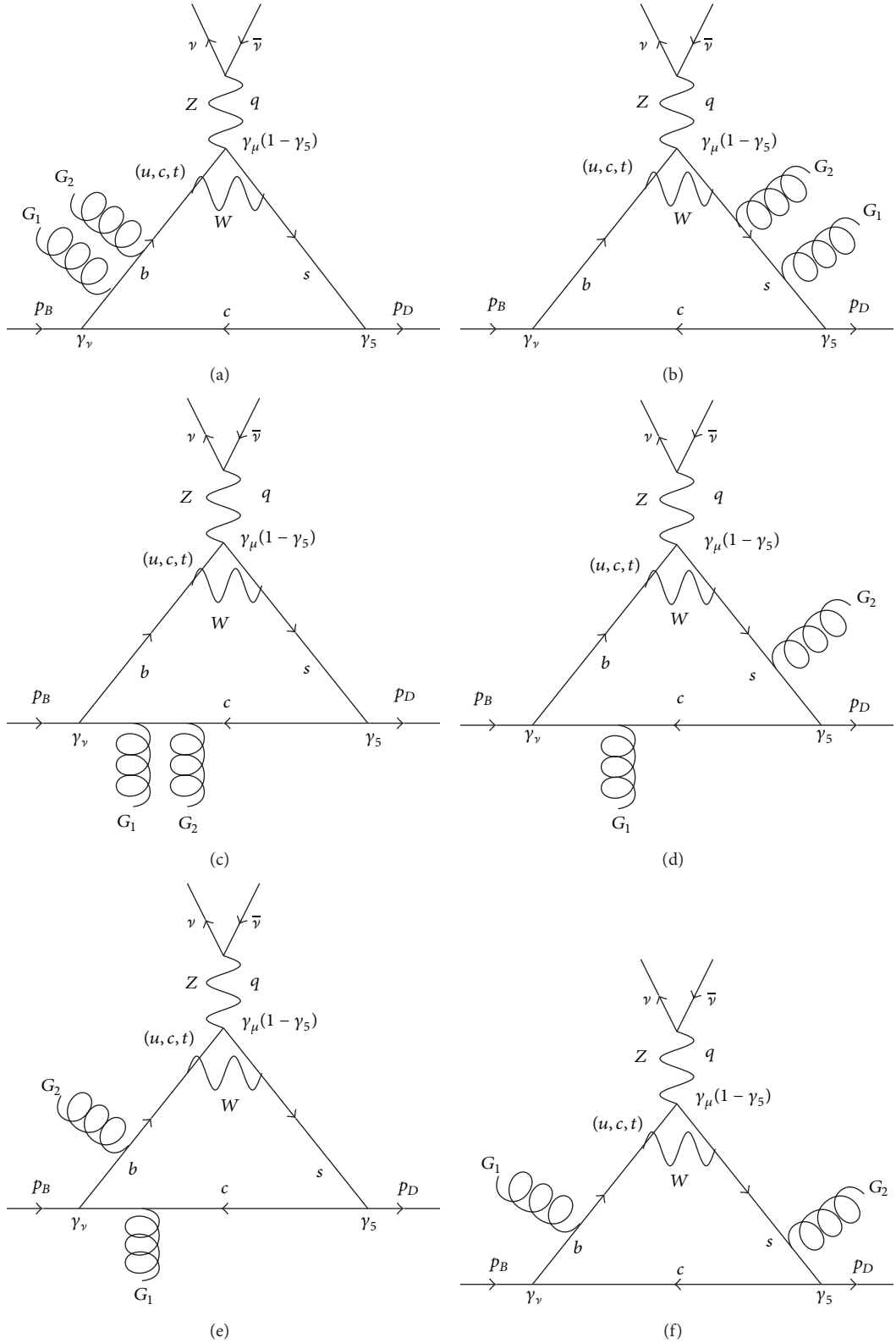

Figure 2: Gluon condensate contributions to $B_c^* \to D_s \nu^+ \nu^-$ transitions.

Three delta functions appear as a result of the applying Cutkosky rules. These delta functions have to vanish at the same time. Therefore, we get the following inequality from the arguments of the delta functions:

$$-1 \leq \frac{2su + \left(s+u-q^2\right)\left(m_b^2 - s - m_c^2\right) + \left(m_c^2 - m_s^2\right)2s}{\lambda^{1/2}\left(m_b^2, s, m_c^2\right)\lambda^{1/2}\left(s,u,q^2\right)} \leq +1, \tag{14}$$

where $\lambda(a,b,c) = a^2 + b^2 + c^2 - 2ac - 2bc - 2ab$.

Following the standard calculations, the spectral densities are evaluated as

$$\rho_1^{V-AV} = N_c I_0\left(s,u,q^2\right)\left\{C_1\left(m_b - m_c\right) - \left(C_2+1\right)m_c + C_2 m_s\right\},$$

$$\begin{aligned}\rho_0^{V-AV} &= \frac{N_c}{2} I_0\left(s,u,q^2\right)\\ &\times \left\{-2m_c^3 + 2m_s m_c^2 - \left[\left(C_1+C_2+1\right)\left(-q^2+s+u\right) + 2C_1 s + 2C_2 u\right]m_c \right.\\ &+ m_b\left[2m_c^2 - 2m_s m_c + 2C_2 u + C_1\left(-q^2+s+u\right)\right]\\ &\left. + m_s\left[2C_1 s + C_2\left(-q^2+s+u\right)\right]\right\},\end{aligned}$$

$$\begin{aligned}\rho_+^{V-AV} &= \frac{N_c}{2} I_0\left(s,u,q^2\right)\\ &\times \left\{C_1\left(m_b - 2C_2 m_c - m_c + 2C_2 m_s\right)\right.\\ &\left. - \left(2C_2+1\right)\left(C_2 m_c + m_c - C_2 m_s\right)\right\},\end{aligned}$$

$$\begin{aligned}\rho_-^{V-AV} &= \frac{N_c}{2} I_0\left(s,u,q^2\right)\\ &\times \left\{\left(2C_2-1\right)\left(C_2 m_c + m_c - C_2 m_s\right)\right.\\ &\left. + C_1\left(m_b - 2C_2 m_c - m_c + 2C_2 m_s\right)\right\},\end{aligned} \tag{15}$$

where

$$I_0\left(s,u,q^2\right) = \frac{1}{4\lambda^{1/2}\left(s,u,q^2\right)},$$

$$C_1 = \frac{m_c^2\left(s-u-q^2\right) + u\left(2m_b^2 - s + u - q^2\right) - m_s^2\left(s+u-q^2\right)}{\lambda\left(s,u,q^2\right)}$$

$$C_2 = \frac{s\left(2m_s^2 + s - u - q^2\right) - m_b^2\left(s+u-q^2\right) - m_c^2\left(s-u+q^2\right)}{\lambda\left(s,u,q^2\right)}$$

$$N_c = 3. \tag{16}$$

Now, it is aimed to calculate the nonperturbative part of (12) which consists of the gluon condensates diagrams shown in Figure 2. The gluon condensate contributions are calculated in Fock-Schwinger gauge because in this gauge the gluon field is expressed in terms of gluon field strength tensor directly. The following type of the integrals has to be calculated in order to get the results of the gluon condensate diagrams [15, 22]:

$$I_0[a,b,c] = \int \frac{d^4k}{(2\pi)^4}\frac{1}{\left[k^2 - m_b^2\right]^a\left[\left(p_B+k\right)^2 - m_c^2\right]^b\left[\left(p_D+k\right)^2 - m_s^2\right]^c},$$

$$I_\mu[a,b,c] = \int \frac{d^4k}{(2\pi)^4}\frac{k_\mu}{\left[k^2 - m_b^2\right]^a\left[\left(p_B+k\right)^2 - m_c^2\right]^b\left[\left(p_D+k\right)^2 - m_s^2\right]^c},$$

$$I_{\mu\nu}[a,b,c] = \int \frac{d^4k}{(2\pi)^4}\frac{k_\mu k_\nu}{\left[k^2 - m_b^2\right]^a\left[\left(p_B+k\right)^2 - m_c^2\right]^b\left[\left(p_D+k\right)^2 - m_s^2\right]^c}, \tag{17}$$

where k is the momentum of the spectator quark c. The generic solutions for these integrals can be seen in [22, 23]. A part of our results for the contributions of the gluon condensate diagrams following similar methods shown in [22, 23] is given in the Appendix.

The Borel transformations are applied for both phenomenological and QCD side {see (11)} in order to suppress the contributions of higher states and continuum. The QCD sum rules for the form factors (A_V, A_0, A_+, and A_-) are obtained by equalizing the Borel transformed forms of the physical side. The result is in the following formula:

$$\begin{aligned}A_i\left(q^2\right) &= \frac{\left(m_s+m_c\right)e^{m_{B_c^*}^2/M_1^2}e^{m_{D_s}^2/M_2^2}}{f_{B_c^*}m_{B_c^*}f_{D_s}m_{D_s}^2}\\ &\times\left[\frac{1}{(2\pi)^2}\int_{u_{\min}}^{u_0}du\int_{s_{\min}}^{s_0}ds\rho_i^{V-AV}\left(s,u,q^2\right)e^{-s/M_1^2 - u/M_2^2}\right.\\ &\left. + i\frac{1}{24\pi^2}C^{A_i}\left\langle\frac{\alpha_s}{\pi}G^2\right\rangle\right].\end{aligned} \tag{18}$$

Note that the contributions of the gluon condensates (C^{A_i}) are already considered in the numerical analysis. However, each of these explicit expressions is extremely long; it is found unnecessary to show all of them in this study. Therefore, one of these expressions (C^{A_V}) is shown as a sample in Appendix. The s_0 and u_0 are the continuum thresholds in s and u channels, respectively. Also $s_{\min} = (m_b + m_c)^2$ and $u_{\min} = (m_s + m_c)^2$.

3. Numerical Analysis

Having known the matrix element, that is, (6), the decay rate for $B_c^* \to D_s \nu\bar{\nu}$ decay is evaluated as follows:

$$\begin{aligned}
&\frac{d\Gamma}{dq^2} \\
&= \frac{\alpha^2 G_f^2 \lambda^{1/2}\left(m_{B_c^*}^2, m_{D_s}^2, q^2\right)\left|V_{tb}V_{ts}^*\right|^2 \nu X^2(x)}{3072\pi^5 m_{B_c^*}^3 \sin^4\theta_W} \\
&\times \left\{ \left|A_0\right|^2 \left(m_{B_c^*}^4 - 2m_{B_c^*}^2\left(m_{D_s}^2 - 5q^2\right) + \left(m_{D_s}^2 - q^2\right)^2\right) \right. \\
&\quad - 2\mathrm{Re}\left[A_+ A_0^*\right] \\
&\quad \times \left(\left(m_{B_c^*}^6 - \left(m_{D_s}^2 - q^2\right)^3 - m_{B_c^*}^4\left(3m_{D_s}^2 + q^2\right)\right.\right. \\
&\qquad \left.\left. + m_{B_c^*}^2\left(3m_{D_s}^4 - 2m_{D_s}^2 q^2 - q^4\right)\right) \times \left(m_{B_c^*}^2\right)^{-1}\right) \\
&\quad + 2\left|A_1\right|^2 q^2 \frac{\lambda\left(m_{B_c^*}^2, m_{D_s}^2, q^2\right)}{m_{B_c^*}^2} \\
&\quad \left. + \left|A_+\right|^2 \frac{\lambda^2\left(m_{B_c^*}^2, m_{D_s}^2, q^2\right)}{m_{B_c^*}^4} \right\}.
\end{aligned} \tag{19}$$

The expression for the decay rate shows that we need to know the input parameters shown in Table 1, taken from [24].

Moreover, the values of the leptonic decay constants $f_{B_C^*} = 0.415 \pm 0.031\,\mathrm{GeV}$ [25] and the gluon condensate $\langle(\alpha_s/\pi)G^2\rangle = 0.012\,\mathrm{GeV}^4$ [26] are necessary for the evaluation of the form factors. In addition, the form factors contain four auxiliary parameters: the Borel mass squares M_1^2 and M_2^2 and the continuum threshold s_0 and u_0. The form factors are assumed to be independent of or weakly dependent on these auxiliary parameters in the suitable chosen regions named as "working regions."

The contributions proportional to the highest power of $1/M_{1,2}^2$ are supposed to be less than about 30% of the contributions proportional to the highest power of $M_{1,2}^2$. The lower bound of the M_1^2 and M_2^2 can be determined by the above condition. In addition, the contributions of continuum must be less than that of the first resonance. This helps us to fix the upper bound of the M_1^2 and M_2^2. Therefore, we find the suitable region for the Borel mass parameters in the following intervals; $10\,\mathrm{GeV}^2 \le M_1^2 \le 25\,\mathrm{GeV}^2$ and $4\,\mathrm{GeV}^2 \le M_2^2 \le 10\,\mathrm{GeV}^2$.

The numerical value of the s_0 and u_0 is supposed to be less than the mass squared of the first excited state meson with the same quantum numbers. In other words, the s_0 and u_0 are between mass squared of the ground sate meson and excited state meson with the same quantum numbers. The following regions for the s_0 and u_0 are chosen: $(m_{B_c^*} + 0.3)^2 \le s_0 \le (m_{B_c^*} + 0.7)^2$ and $(m_{D_s} + 0.3)^2 \le u_0 \le (m_{D_s} + 0.7)^2$.

Table 1: The values of the input parameters [24].

$\lvert V_{tb}\rvert$	$0.77^{+0.18}_{-0.24}$
$\lvert V_{ts}\rvert$	$(40.6 \pm 2.7) \times 10^{-3}$
$\tau_{B_c^*}$	$(0.452 \pm 0.033) \times 10^{-12}$ s
$\alpha(m_w^2)$	1/128
$\sin^2\theta_W$	0.2315
m_t	$173.07 \pm 0.52 \pm 0.72$ GeV
m_W	80.385 ± 0.015 GeV
$m_{B_c^*}$	6.2745 ± 0.0018 GeV
m_{D_s}	1968.30 ± 0.11 MeV
f_{D_s}	$(206.7 \pm 8.5 \pm 2.5)$ MeV
m_b	(4.18 ± 0.03) GeV
$m_c(\mu = m_c)$	1.275 ± 0.015 GeV

Table 2: Parameters appearing in the form factors of the $B_c^* \to D_s \nu\bar{\nu}$ decay in a four-parameter fit, for $M_1^2 = 15\,\mathrm{GeV}^2$, $M_2^2 = 6\,\mathrm{GeV}^2$, $s_0 = 46\,\mathrm{GeV}^2$, and $u_0 = 6\,\mathrm{GeV}^2$.

	m_{fit}	a	b
$A_1(q^2)$	5.01 ± 1.1	-0.14 ± 0.04	0.26 ± 0.08
$A_0(q^2)$	6.44 ± 1.4	-0.11 ± 0.03	0.17 ± 0.06
$A_+(q^2)$	5.00 ± 1.08	-0.14 ± 0.04	0.28 ± 0.08
$A_-(q^2)$	4.98 ± 1.07	-0.14 ± 0.04	0.28 ± 0.08

The form factors depend on the q^2. The detail of the dependence is complicated. We fit them to the following function:

$$F\left(q^2\right) = \frac{a}{1 - q^2/m_{\mathrm{fit}}^2} + \frac{b}{\left(1 - q^2/m_{\mathrm{fit}}^2\right)^2}. \tag{20}$$

The a, b, and m_{fit} are given in Table 2.

The origin of the errors in Table 2 is the variation of s_0, u_0, and $M_{1,2}$ in the chosen intervals and the uncertainties of the input parameters.

In order to evaluate the branching ratio of the $B_c^* \to D_s \nu\bar{\nu}$ decay, the mean life time of the B_c^* meson is needed. For the time being there is no experimental data on the mean life time of this meson. We follow the theoretical methods like Bethe-Salpeter model [27] and potential model [28] and estimate that the mean life time of the B_c^* meson is in the order of the mean life time of the B_c meson. We assume that the total life time $\tau_{B_c} \approx \tau_{B_c} = 0.452 \times 10^{-12}$ s [24]. Using the mean life time and the q^2 dependence of the form factors given by (20) in the kinematical allowed region $[0 \le q^2 \le (m_{B_c^*} - m_{D_s})^2]$ we study the branching ratios for $B_c^* \to D_s \nu\bar{\nu}$ decay. Our results for three different values of the $q^2 = (1, 6, 12)\,\mathrm{GeV}^2$ are presented in Table 3. In addition, Figure 3 depicts the dependence of the branching ratio on q^2 for full kinematical allowed region.

Finally, we calculate the integrated branching ratio for $B_c^* \to D_s \nu\bar{\nu}$ decay as follows:

$$\mathcal{B}_r = \int_0^{(m_{B_c^*} - m_{D_s})^2} \mathcal{B}_r\left(q^2\right) dq^2 = (5.47 \pm 1.30) \times 10^{-8}. \tag{21}$$

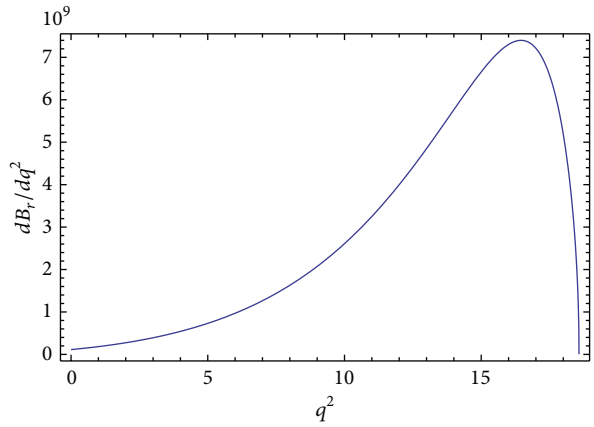

FIGURE 3: The dependence of the branching ratio on q^2 for $B_c^* \to D_s\mu^+\mu^-$ transitions.

TABLE 3: Values for the branching ratio of the $B_c^* \to D_s\nu\bar{\nu}$ decay at three different values of the dileptonic invariant mass.

q^2 (GeV^2)	$\mathcal{B}_r(q^2)(B_c^* \to D_s\nu\bar{\nu})$
1	1.83×10^{-10}
6	9.68×10^{-10}
12	3.99×10^{-9}

To sum up, we investigated the branching ratio and decay rate of the $B_c^* \to D_s\nu\bar{\nu}$ decay. The form factors of this decay were found in the framework of the QCD sum rules. In addition, the contributions of the two gluon condensates diagrams to the correlations function were obtained.

Appendix

In this section, we present the explicit expression for the coefficients C^{A_V} corresponding to the gluon condensates contributions of $g_{\mu\nu}$ structure entering to the expression for the form factors in (18):

$$
\begin{aligned}
C^{A_V} &= \left(8m_b + 16m_c\right) I\left(1,1,2\right) \\
&- \left(32m_c^3 + 16m_b m_c^2 + 8m_c q^2\right) I\left(1,1,3\right) \\
&- \left(16m_c^3 + 8m_b m_c^2 + +8m_c q^2\right) I\left(1,2,2\right) \\
&+ \left(8m_c^5 - 16m_b m_c^4 - 8m_c^3 q^2\right) I\left(1,2,3\right) \\
&+ \left(-24m_b m_c^2 - 24m_b^2 m_c\right) I\left(1,3,1\right) \\
&- 24m_b m_c^4 I\left(1,3,2\right) - 8m_b m_c^6 I\left(1,3,3\right) \\
&+ 8m_c I\left(2,1,1\right) \\
&+ \left(-16m_b^3 - 8m_c m_b^2 - 8q^2 m_b\right) I\left(2,2,1\right) \\
&- 24m_b^4 m_c I\left(2,3,1\right) \\
&+ \left(32m_b^3 - 16m_c m_b^2 - 8q^2 m_b\right) I\left(3,1,1\right) \\
&- \left(8m_b^5 + 16m_c m_b^4 + 8q^2 m_b^3\right) I\left(3,2,1\right) \\
&- 8m_b^6 m_c I\left(3,3,1\right) + \left(8m_b q^2 - 8m_c q^2\right) I_1\left(1,1,3\right) \\
&- 24m_b m_c^2 q^2 I_1\left(1,1,4\right) + 8m_b q^2 I_1\left(1,3,1\right) \\
&+ \left(8m_b q^2 - 8m_c q^2\right) I_1\left(2,1,2\right) \\
&+ \left(-16m_b q^4 + 8m_c q^4 - 24m_c^3 q^2 + 24m_b m_c^2 q^2\right. \\
&\quad \left. + 8m_b^2 m_c q^2\right) I_1\left(2,1,3\right) + 16q^2 m_b^3 I_1\left(2,3,1\right) \\
&- 16m_b q^2 I_1\left(3,1,1\right) \\
&+ \left(-16m_b q^4 + 24m_b^3 q^2 + 16m_b m_c^2 q^2\right) I_1\left(3,1,2\right) \\
&+ \left(8m_b q^6 - 16m_b^3 q^4 - 16m_b m_c^2 q^4\right. \\
&\quad \left. + 8m_b^5 q^2 + 8m_b m_c^4 q^2 - 16m_b^3 m_c^2 q^2\right) I_1\left(3,1,3\right) \\
&+ 16q^2 m_b^3 I_1\left(3,2,1\right) \\
&+ 8q^2 m_b^5 I_1\left(3,3,1\right) + 72m_b^3 q^2 I_1\left(4,1,1\right) \\
&- 16m_c q^2 I_2\left(1,1,3\right) - 24m_c^3 q^2 I_2\left(1,1,4\right) \\
&- 8m_c q^2 I_2\left(1,2,2\right) + 16m_c^3 q^2 I_2\left(1,2,3\right) \\
&+ 8m_c q^2 I_2\left(1,3,1\right) + 16m_c^3 q^2 I_2\left(1,3,2\right) \\
&+ 8m_c^5 q^2 I_2\left(1,3,3\right) + \left(8m_c q^2 - 8m_b q^2\right) I_2\left(2,1,2\right) \\
&+ \left(40m_c^3 q^2 - 16m_c q^4\right) I_2\left(2,1,3\right) \\
&+ \left(-8m_b q^2 - 40m_c q^2\right) I_2\left(3,1,1\right) \\
&+ \left(8m_b q^4 - 16m_c q^4 - 8m_b^3 q^2 + 16m_c^3 q^2\right. \\
&\quad \left. -8m_b m_c^2 q^2 + 8m_b^2 m_c q^2\right) I_2\left(3,1,2\right) \\
&+ \left(8m_c q^6 - 16m_c^3 q^4 - 16m_b^2 m_c q^4 + 8m_c^5 q^2\right. \\
&\quad \left. -16m_b^2 m_c^3 q^2 + 8m_b^4 m_c q^2\right) I_2\left(3,1,3\right) \\
&+ 72m_b^2 m_c q^2 I_2\left(4,1,1\right) \\
&+ D_3^0 \left\{\left(8m_c - 8m_b\right) I_1\left(3,3,1\right)\right\} \\
&+ D_0^3 \left\{8m_b I\left(1,3,3\right) + 8m_c I_2\left(1,3,3\right)\right\} \\
&+ D_0^2 \left\{\left(-24m_b + 8m_c\right) I\left(1,2,3\right)\right. \\
&\quad + \left(8m_c - 24m_b\right) I\left(1,3,2\right) \\
&\quad + \left(8m_c^3 - 24m_b m_c^2 - 8q^2 m_c\right) I\left(1,3,3\right) \\
&\quad - 16m_c I_2\left(1,2,3\right) - 8m_c I_2\left(1,3,2\right) \\
&\quad \left. - \left(16m_c^3 + 8q^2 m_c\right) I_2\left(1,3,3\right)\right\}
\end{aligned}
$$

$$
\begin{aligned}
&+ D_2^0 \left\{ D_0^1 \left[8m_c I(3,3,1) + (8m_c - 8m_b) I_1(3,3,1) \right.\right. \\
&\qquad \left.\left. + (16m_c - 16m_b) I_2(3,3,1) \right] \right. \\
&\qquad + 8m_c I(2,3,1) + (-16m_b + 8m_c) I(3,2,1) \\
&\qquad + \left(8m_c^3 - 16m_b m_c^2 + 8m_b^2 m_c - 8q^2 m_c\right) I(3,3,1) \\
&\qquad + (16m_b - 8m_c) I_1(2,3,1) \\
&\qquad + (8m_b - 16m_c) I_1(3,2,1) \\
&\qquad + \left(16m_b^3 - 16m_c m_b^2 + 16m_c^2 m_b + 8q^2 m_b \right. \\
&\qquad \left. \left. -16m_c^3 - 8m_c q^2\right) I_1(3,3,1) \right\} \\
&+ D_0^1 \left\{ D_0^2 \left[8m_c I(1,3,3) + 16m_c I_1(1,3,3) \right.\right. \\
&\qquad \left.\left. +8m_c I_2(1,3,3) \right] \right. \\
&\qquad + D_0^1 \left[-16m_c I(1,2,3) - 16m_c I(1,3,2) \right. \\
&\qquad\quad - 16m_c^3 I(1,3,3) - 16m_c I(2,3,1) \\
&\qquad\quad + (-8m_b - 16m_c) I(3,2,1) \\
&\qquad\quad + \left(-16m_c^3 - 16m_b^2 m_c\right) I(3,3,1) \\
&\qquad\quad -32m_c I_1(1,2,3) - 16m_c I_1(1,3,2) \\
&\qquad\quad - 32m_c^3 I_1(1,3,3) \\
&\qquad\quad + (16m_b - 8m_c) I_1(2,3,1) \\
&\qquad\quad + (8m_b - 16m_c) I_1(3,2,1) \\
&\qquad\quad + \left(16m_b^3 - 16m_c m_b^2 + 16m_c^2 m_b \right. \\
&\qquad\quad \left. -16m_c^3\right) I_1(3,3,1) \\
&\qquad\quad - 16m_c I_2(1,2,3) - 8m_c I_2(1,3,2) \\
&\qquad\quad - 16m_c^3 I_2(1,3,3) \\
&\qquad\quad + (32m_b - 16m_c) I_2(2,3,1) \\
&\qquad\quad + (16m_b - 32m_c) I_2(3,2,1) \\
&\qquad\quad + \left(32m_b^3 - 32m_c m_b^2 + 32m_c^2 m_b \right. \\
&\qquad\quad \left. \left. -32m_c^3\right) I_2(3,3,1) \right] \\
&\qquad + 8m_c I(1,1,3) + 16m_c^3 I(1,2,3) \\
&\qquad - 32m_c I(1,3,1) + 24m_c^3 I(1,3,2) \\
&\qquad + 8m_c^5 I(1,3,3) - 24m_c^3 I(1,4,1) \\
&\qquad + (24m_b - 16m_c) I(2,2,1) \\
&\qquad + \left(-16m_c^3 + 32m_b m_c^2 - 32m_b^2 m_c \right. \\
&\qquad\quad \left. +16q^2 m_c\right) I(2,3,1) \\
&+ (24m_b - 64m_c) I(3,1,1) \\
&+ \left(24m_b^3 - 32m_c m_b^2 + 56m_c^2 m_b \right. \\
&\qquad \left. + 8q^2 m_b - 32m_c^3 + 16m_c q^2\right) I(3,2,1) \\
&+ \left(-16m_c^5 + 32m_b m_c^4 - 32m_b^2 m_c^3 \right. \\
&\qquad + 16q^2 m_c^3 + 32m_b^3 m_c^2 \\
&\qquad \left. -16m_b^4 m_c + 16m_b^2 q^2 m_c\right) I(3,3,1) \\
&+ 72m_b^2 m_c I(4,1,1) \\
&+ (-8m_b + 16m_c) I_1(1,1,3) \\
&- 16m_c I_1(1,2,2) + 32m_c^3 I_1(1,2,3) \\
&+ (-8m_b - 72m_c) I_1(1,3,1) \\
&+ 32m_c^3 I_1(1,3,2) + 16m_c^5 I_1(1,3,3) \\
&+ \left(-72m_c^3 + 24m_b m_c^2\right) I_1(1,4,1) \\
&+ 8m_b I_1(2,1,2) + 16m_b q^2 I_1(2,1,3) \\
&+ \left(-16m_b^3 + 8m_c m_b^2 - 8m_c^2 m_b \right. \\
&\qquad \left. -16q^2 m_b + 16m_c^3 + 8m_c q^2\right) I_1(2,3,1) \\
&+ (32m_b - 136m_c) I_1(3,1,1) \\
&- 8m_b^3 I_1(3,1,2) \\
&+ \left(-8m_b^5 + 16q^2 m_b^3 - 8q^4 m_b\right) I_1(3,1,3) \\
&+ \left(-16m_b^3 + 8m_c m_b^2 - 8m_c^2 m_b \right. \\
&\qquad \left. -8q^2 m_b + 16m_c^3 + 16m_c q^2\right) I_1(3,2,1) \\
&+ \left(-8m_b^5 + 8m_c m_b^4 + 16m_c^2 m_b^3 \right. \\
&\qquad - 16q^2 m_b^3 - 16m_c^3 m_b^2 + 16m_c q^2 m_b^2 \\
&\qquad - 8m_c^4 m_b - 16m_c^2 q^2 m_b \\
&\qquad \left. +8m_c^5 + 16m_c^3 q^2\right) I_1(3,3,1) \\
&+ \left(-72m_b^3 + 216m_c m_b^2\right) I_1(4,1,1) \\
&+ 8m_c I_2(1,1,3) - 8m_c I_2(1,2,2) \\
&+ 16m_c^3 I_2(1,2,3) - 24m_c I_2(1,3,1) \\
&+ 16m_c^3 I_2(1,3,2) + 8m_c^5 I_2(1,3,3) \\
&- 24m_c^3 I_2(1,4,1) + 8m_b I_2(2,1,2)
\end{aligned}
$$

$$
\begin{aligned}
&+\left(8m_b-48m_c\right)I_2(3,1,1)\\
&+\left(8m_b^3-8q^2m_b\right)I_2(3,1,2)\\
&+72m_b^2m_cI_2(4,1,1)\Big\}\\
&+D_0^1\Big\{-24m_c^3I(1,4,1)+72m_b^2I(4,1,1)m_c\\
&\quad+\left(24m_b-16m_c\right)I(1,1,3)\\
&\quad+\left(16m_b-16m_c\right)I(1,2,2)\\
&\quad+\left(-32m_c^3+48m_bm_c^2+16q^2m_c\right)I(1,2,3)\\
&\quad+\left(24m_b-32m_c\right)I(1,3,1)\\
&\quad+\left(-16m_c^3+40m_bm_c^2\right.\\
&\qquad\left.+16q^2m_c\right)I(1,3,2)\\
&\quad+\left(-16m_c^5+24m_bm_c^4+16q^2m_c^3\right)I(1,3,3)\\
&\quad+\left(8m_b+8m_c\right)I(2,2,1)\\
&\quad+\left(24m_c^3+16m_b^2m_c\right)I(2,3,1)\\
&\quad+\left(8m_b-40m_c\right)I(3,1,1)\\
&\quad+\left(8m_b^3+8m_cm_b^2+8m_c^2m_b+16m_c^3\right)\\
&\quad\times I(3,2,1)\\
&\quad+\left(8m_c^5-16m_b^2m_c^3+8m_b^4m_c\right)I(3,3,1)\\
&\quad-8m_bI_1(1,1,3)\\
&\quad+\left(-8m_b-24m_c\right)I_1(1,3,1)\\
&\quad+\left(24m_bm_c^2-24m_c^3\right)I_1(1,4,1)\\
&\quad-8m_bI_1(2,1,2)+16m_bq^2I_1(2,1,3)\\
&\quad+\left(-16m_b^3+8m_cm_b^2-8m_c^2m_b\right.\\
&\qquad\left.+16m_c^3\right)I_1(2,3,1)\\
&\quad+\left(16m_b-40m_c\right)I_1(3,1,1)\\
&\quad+\left(-24m_b^3+16q^2m_b\right)I_1(3,1,2)\\
&\quad+\left(-8m_b^5+16q^2m_b^3\right.\\
&\qquad\left.-8q^4m_b\right)I_1(3,1,3)\\
&\quad+\left(-16m_b^3+8m_cm_b^2\right.\\
&\qquad\left.-8m_c^2m_b+16m_c^3\right)I_1(3,2,1)\\
&\quad+\left(-8m_b^5+8m_cm_b^4+16m_c^2m_b^3\right.\\
&\qquad\left.-16m_c^3m_b^2-8m_c^4m_b+8m_c^5\right)I_1(3,3,1)\\
&\quad+\left(72m_b^2m_c-72m_b^3\right)I_1(4,1,1)\\
&\quad+\left(-16m_b+8m_c\right)I_2(1,1,3)\\
&\quad-8m_cI_2(1,2,2)\\
&\quad+\left(16m_c^3+16q^2m_c\right)I_2(1,2,3)\\
&\quad+\left(-16m_b-72m_c\right)I_2(1,3,1)\\
&\quad+\left(16m_c^3+8q^2m_c\right)I_2(1,3,2)\\
&\quad+\left(8m_c^5+16q^2m_c^3\right)I_2(1,3,3)\\
&\quad+\left(-72m_c^3+48m_bm_c^2\right)I_2(1,4,1)\\
&\quad-8m_bI_2(2,1,2)\\
&\quad+32m_bq^2I_2(2,1,3)\\
&\quad+\left(-32m_b^3+16m_cm_b^2\right.\\
&\qquad\left.-16m_c^2m_b+32m_c^3\right)I_2(2,3,1)\\
&\quad+\left(40m_b-128m_c\right)I_2(3,1,1)\\
&\quad+\left(-40m_b^3+24q^2m_b\right)I_2(3,1,2)\\
&\quad+\left(-16m_b^5+32q^2m_b^3\right.\\
&\qquad\left.-16q^4m_b\right)I_2(3,1,3)\\
&\quad+\left(-32m_b^3+16m_cm_b^2\right.\\
&\qquad\left.-16m_c^2m_b+32m_c^3\right)I_2(3,2,1)\\
&\quad+\left(-16m_b^5+16m_cm_b^4+32m_c^2m_b^3\right.\\
&\qquad\left.-32m_c^3m_b^2-16m_c^4m_b+16m_c^5\right)\\
&\quad\times I_2(3,3,1)\\
&\quad+\left(-144m_b^3+216m_cm_b^2\right)I_2(4,1,1)\Big\},
\end{aligned}
\tag{A.1}
$$

where

$$
\begin{aligned}
&D_i^j\left[I_n\left(M_1^2,M_2^2\right)\right]\\
&=\left(M_1^2\right)^i\left(M_2^2\right)^j\frac{\partial_i}{\partial\left(M_1^2\right)^i}\frac{\partial^j}{\partial\left(M_2^2\right)^j}\left[\left(M_1^2\right)^i\left(M_2^2\right)^jI_n\left(M_1^2,M_2^2\right)\right].
\end{aligned}
\tag{A.2}
$$

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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