Hindawi
Advances in High Energy Physics
Volume 2018, Article ID 7302797, 12 pages
https://doi.org/10.1155/2018/7302797

Research Article

Effects of a Single Universal Extra Dimension in $B_c \to (D_s, D)\ell^+\ell^-$ Decays

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Received 20 December 2017; Revised 6 May 2018; Accepted 14 May 2018; Published 14 June 2018

Academic Editor: Filipe R. Joaquim

The rare semileptonic $B_c \to D_{s,d}\ell^+\ell^-$ decays are studied in the universal extra dimension with a single extra dimension scenario. The sensitivity of differential and total branching ratios and polarization asymmetries of final state leptons to the compactification parameter are presented, for both muon and tau decay channels. Considering the ability of available experiments, it would be useful to study these effects.

1. Introduction

The decays induced by flavor changing neutral current (FCNC) $b \to s, d$ transitions play an important role in testing the standard model (SM) and also they are very sensitive to the new physics. The decays of $B_{u,d,s}$ mesons have been intensively studied since the observation of the rare radiative $b \to s\gamma$ decay [1], and it will make the B physics more complete if similar decays of B_c meson are included.

The B_c meson is the ground state of a family of mesons containing two different heavy flavor quarks, b and c. Compared with the $c\bar{c}$ and $b\bar{b}$ bound states which have implicit flavors, the B_c meson has explicit flavor and decays weakly. $B_{u,d,s}$ decays are described well in the framework of the heavy quark limit. The flavor and the spin symmetries must be reconsidered while discussing B_c. B_c was first observed by CDF Collaboration [2] and, due to those outstanding properties, B_c decays have received great attraction since then (for more about the Bc physics, see for example [3]).

Considering the experimental facilities, the high centre of mass energies at the Large Hadron Collider (LHC) enables the experiments, such as LHCb, to study the production, properties, and decays of the B_c meson. At the LHC in pp collisions, B_c is mainly produced through the gluon-gluon fusion process $gg \to B_c + b + \bar{c}$ and the production cross-sections of the B_c mesons have been calculated in the fragmentation approach and complete order α_s^4 approach. At $\sqrt{s} = 8$ TeV approximately $10^3 B_c^+$ is obtained [4, 5]. In addition, at $\sqrt{s} = 14$ TeV and the design luminosity $10^{10} B_c$ events per year are estimated [6, 7]. The available experimental facilities and their future improvements encourage studying the B_c meson phenomenology including the rare decays.

In the rare B meson decays, new physics contributions appear through the modification of the Wilson coefficients existing in the SM or by adding new structures in the SM effective Hamiltonian. Among the various extensions of the SM, extra dimensions are especially attractive because of including gravity and other interactions, giving hints on the hierarchy problem and a connection with string theory.

The models with universal extra dimensions (UED) allow the SM fields to propagate in all available dimensions [8–11]. The extra dimensions are compactified and the compactification scale allows Kaluza-Klein (KK) partners of the SM fields in the four-dimensional theory and also KK excitations without corresponding SM partners. Throughout the UED, a model including only a single universal extra dimension is the Appelquist-Cheng-Dobrescu (ACD) model [12]. The only additional free parameter with respect to the SM is the inverse of the compactification radius, $1/R$. In particle spectrum of the ACD model, there are infinite towers of KK modes and the ordinary SM particles are presented in the zero mode.

The experimental and theoretical discussions on the free parameter have been taken a significant part in the literature and the lower bound was commonly taken as $1/R \geq 250\,GeV$ or $1/R \geq 350\,GeV$ [13–17]. An analysis of the electroweak precision tests with inclusive [18] and exclusive [19] rare radiative B decays is conducted, where the later one also includes the experimental results of $B \to K^{(*)}\ell^+\ell^-$ and the lower bound is estimated as $1/R > 600\,GeV$. Later analysis using the ATLAS and CMS data leads to $1/R > (700 - 715)\,GeV$ [20, 21] and another discussion on the UEDs including the $126\,GeV$ Higgs puts this limit as $1/R > 500\,GeV$ [22]. Under above discussion on the compactification factor, we will take the $1/R > 500\,GeV$ in this paper.

The effective Hamiltonian of several FCNC processes [23, 24], semileptonic and radiative decays of B mesons [25–33], and FCNC baryonic decays [34–36] have been investigated in the ACD model. Polarization properties of final state particles in semileptonic decays, which is an powerful tool in searching new physics beyond the SM, have also been studied widely besides the other observables in these works, e.g., [17, 25, 29, 33].

The main aim of this paper is to find the possible effects of the ACD model on some physical observables related to the $B_c \to (D_s, D)\ell^+\ell^-$ decays. We study differential decay rate, branching ratio, and polarization of final state leptons, including resonance contributions in as many as possible cases. We analyze these observables in terms of the compactification factor and the form factors. The form factors for $B_c \to (D_s, D)\ell^+\ell^-$ processes have been calculated using different quark models [37–40] and three-point QCD sum rules [41]. In this work, we will use the form factors calculated in the constituent quark model [37].

This paper is organized as follows. In Section 2, we give the effective Hamiltonian for the quark level processes $b \to (s, d)\ell^+\ell^-$ with a brief discussion on the Wilson coefficients in the ACD model. We derive matrix element using the form factors and calculate the decay rate in Section 3. In Section 4, lepton polarizations are evaluated and the last two sections are dedicated to our numerical analysis, discussion on the obtained results, and conclusion.

2. Theoretical Framework

The effective Hamiltonian describing the quark level $b \to (s, d)\ell^+\ell^-$ processes in the SM is given by the following [42]:

$$\begin{aligned}\mathcal{H}_{eff} = \frac{G_F\alpha}{\sqrt{2}\pi}V_{tq'}V_{tb}^{*}\Big[&C_9^{eff}\left(\bar{q}'\gamma_\mu Lb\right)\bar{\ell}\gamma^\mu\ell \\ &+ C_{10}\left(\bar{q}'\gamma_\mu Lb\right)\bar{\ell}\gamma^\mu\gamma_5\ell \\ &- 2C_7^{eff}m_b\left(\bar{q}' i\sigma_{\mu\nu}\frac{q^\nu}{q^2}Rb\right)\bar{\ell}\gamma^\mu\ell\Big],\end{aligned} \tag{1}$$

where $q = p_{B_c} - p_{D_{q'}}$ is the momentum transfer and $q' = s, d$.

New physics effects in the ACD model come out by the modification of the SM Wilson coefficients appearing in the above Hamiltonian. This process can be done by writing the Wilson coefficients in terms of $1/R$-dependent periodic functions, the details of which can be found in [23, 24]. That is $F_0(x_t)$ in the SM is generalized by $F(x_t, 1/R)$ accordingly:

$$F\left(x_t, \frac{1}{R}\right) = F_0\left(x_t\right) + \sum_{n=1}^{\infty}F_n\left(x_t, x_n\right) \tag{2}$$

where $x_t = m_t^2/m_W^2$, $x_n = m_n^2/m_W^2$ and $m_n = n/R$. Here, m_n is the mass of KK particles with $n = 0$ for the ordinary SM particles. These modified Wilson coefficients can widely be found in the literature and the details are discussed in Appendix.

In the ACD model, a normalization scheme independent effective coefficient C_7^{eff} can be written as follows:

$$\begin{aligned}C_7^{eff}\left(\mu_b, \frac{1}{R}\right) = \eta^{16/23}C_7\left(\mu_W, \frac{1}{R}\right) &+ \frac{8}{3}\left(\eta^{14/23} - \eta^{16/23}\right)C_8\left(\mu_W, \frac{1}{R}\right) \\ &+ C_2\left(\mu_W, \frac{1}{R}\right)\sum_{i=1}^{8}h_i\eta^{a_i}.\end{aligned} \tag{3}$$

The coefficient C_9^{eff} has perturbative part and we will also consider the resonance contributions coming from the conversion of the real $c\bar{c}$ into lepton pair. So, C_9^{eff} is given by

$$\begin{aligned}C_9^{eff}\left(s', \frac{1}{R}\right) = C_9\left(\mu, \frac{1}{R}\right)\left(1 + \frac{\alpha_s\left(\mu\right)}{\pi}w\left(s'\right)\right) \\ + Y\left(\mu, s'\right) + C_9^{res}\left(\mu, s'\right),\end{aligned} \tag{4}$$

where $s' = q^2/m_b^2$. For C_9, in the ACD model and in the naive dimensional regularization (NDR) scheme, we have

$$\begin{aligned}C_9\left(\mu, \frac{1}{R}\right) = P_0^{NDR} + \frac{Y\left(x_t, 1/R\right)}{\sin^2\theta_W} - 4Z\left(x_t, \frac{1}{R}\right) \\ + P_E E\left(x_t, \frac{1}{R}\right)\end{aligned} \tag{5}$$

where $P_0^{NDR} = 2.60 \pm 0.25$ and the last term, $P_E E(x_t, 1/R)$, is numerically negligible.

The perturbative part, coming from one-loop matrix elements of the four quark operators, is

$$\begin{aligned}Y\left(\mu\right) = h\left(y, s'\right)&\left[3C_1\left(\mu\right) + C_2\left(\mu\right) + 3C_3\left(\mu\right) + C_4\left(\mu\right) \right.\\ &\left.+ 3C_5\left(\mu\right) + C_6\left(\mu\right)\right] - \frac{1}{2}h\left(1, s'\right)\left(4C_3\left(\mu\right) + 4C_4\left(\mu\right)\right. \\ &\left.+ 3C_5\left(\mu\right) + C_6\left(\mu\right)\right) - \frac{1}{2}h\left(0, s'\right)\left[C_3\left(\mu\right) + 3C_4\left(\mu\right)\right] \\ &+ \frac{2}{9}\left(3C_3\left(\mu\right) + C_4\left(\mu\right) + 3C_5\left(\mu\right) + C_6\left(\mu\right)\right),\end{aligned} \tag{6}$$

with $y = m_c/m_b$. The explicit forms of the functions appear above equations can be found in [43, 44]. The resonance contribution can be done by using a Breit-Wigner formula [45]:

$$C_9^{res} = -\frac{3}{\alpha_{em}^2}\kappa \sum_{V_i=\psi_i} \frac{\pi \Gamma(V_i \to \ell^+\ell^-) m_{V_i}}{s m_b^2 - m_{V_i}^2 + i m_{V_i}\Gamma_{V_i}} \times [3C_1(\mu) + C_2(\mu) + 3C_3(\mu) + C_4(\mu) + 3C_5(\mu) + C_6(\mu)]. \quad (7)$$

The normalization is fixed by the data in [46] and κ is taken 2.3.

The Wilson coefficient C_{10} is independent of scale μ and given by

$$C_{10} = -\frac{Y(x_t, 1/R)}{\sin^2\theta_W}. \quad (8)$$

3. Matrix Elements and Decay Rate

The matrix elements for $B_c \to D_{q'}\ell^+\ell^-$ can be written in terms of the invariant form factors over B_c and $D_{q'}$. The parts of transition currents containing γ_5 do not contribute, so the nonvanishing matrix elements are as follows [47]:

$$\begin{aligned} &\left\langle D_{q'}(p_{D_{q'}}) \left| \overline{q'} i\sigma_{\mu\nu} q^\nu b \right| B_c(p_{B_c}) \right\rangle \\ &= -\frac{f_T(q^2)}{m_{B_c} + m_{D_{q'}}} \left[(P_{B_c} + P_{Dq'})_\mu q^2 - q_\mu \left(m_{B_c}^2 - m_{D_{q'}}^2 \right) \right], \\ &\left\langle D_{q'}(p_{D_{q'}}) \left| \overline{q'} \gamma_\mu b \right| B_c(p_{B_c}) \right\rangle = f_+(q^2) \left(P_{B_c} + P_{D_{q'}} \right)_\mu + f_-(q^2) q_\mu. \end{aligned} \quad (9)$$

The transition amplitude of the $B_c \to D_{q'}\ell^+\ell^-$ decays can be written using the effective Hamiltonian and (9) as follows:

$$\begin{aligned} \mathcal{M}(B_c \longrightarrow D_{q'}\ell^+\ell^-) &= \frac{G\alpha}{2\sqrt{2}\pi} \cdot V_{tb}V_{tq'}^* \left\{ \bar{\ell}\gamma^\mu \ell \left[A \left(P_{B_c} + P_{D_{q'}} \right)_\mu + B q_\mu \right] \right. \\ &\left. + \bar{\ell}\gamma^\mu\gamma_5 \ell \left[C \left(P_{B_c} + P_{D_{q'}} \right)_\mu + D q_\mu \right] \right\}, \end{aligned} \quad (10)$$

with

$$\begin{aligned} A &= C_9^{eff} f_+ + \frac{2m_b f_T}{m_{B_c} + m_{D_{q'}}} C_7^{eff}, \\ B &= C_9^{eff} f_- - \frac{2m_b \left(m_{B_c}^2 - m_{D_{q'}}^2 \right) f_T}{q^2 \left(m_{B_c} + m_{D_{q'}} \right)} C_7^{eff}, \\ C &= C_{10} f_+, \\ D &= C_{10} f_-. \end{aligned} \quad (11)$$

Finally, the following dilepton mass spectrum is obtained by eliminating angular dependence in the double differential decay rate:

$$\frac{d\Gamma}{ds} = \frac{G^2\alpha^2 m_{B_c}}{2^{12}\pi^5} \left| V_{tb}V_{tq'}^* \right|^2 \sqrt{\lambda} v \Delta_{D_{q'}} \quad (12)$$

where $s = q^2/m_{B_c}^2$, $\lambda = 1 + r^2 + s^2 - 2r - 2s - 2rs$, $r = m_{D_s^*}^2/m_{B_c}^2$, $v = \sqrt{1 - 4m_\ell^2/sm_{B_c}^2}$ and

$$\begin{aligned} \Delta_{D_{q'}} &= \frac{4}{3} m_{B_c}^4 \left(3 - v^2 \right) \lambda \left(|A|^2 + |C|^2 \right) \\ &+ 4m_{B_c}^4 s (2 + r - s) \left(1 - v^2 \right) |C|^2 \\ &+ 16 m_{B_c}^2 m_\ell^2 s |D|^2 \\ &+ 32 m_{B_c}^2 m_\ell^2 (1 - r) \operatorname{Re}(CD^*). \end{aligned} \quad (13)$$

4. Lepton Polarization Asymmetries

Studying polarization asymmetries of final state leptons is an useful way of searching new physics. Therefore, we will discuss the possible effects of the ACD model in the lepton polarization. Using the convention in [48, 49], we define the orthogonal unit vectors S_i^- $(i = L, T, N)$ for the longitudinal, transverse, and normal polarizations in the rest frame of ℓ^- as follows:

$$\begin{aligned} S_L^- &\equiv \left(0, \vec{e}_L \right) = \left(0, \frac{\vec{p}_\ell}{\left| \vec{p}_\ell \right|} \right), \\ S_T^- &\equiv \left(0, \vec{e}_T \right) = \left(0, \vec{e}_N \times \vec{e}_L \right), \\ S_N^- &\equiv \left(0, \vec{e}_N \right) = \left(0, \frac{\vec{p}_{D_{q'}} \times \vec{p}_\ell}{\left| \vec{p}_{D_{q'}} \times \vec{p}_\ell \right|} \right), \end{aligned} \quad (14)$$

where $\vec{p}_\ell$ and $\vec{p}_{D_{q'}}$ are the three momenta of ℓ^- and $D_{q'}$ meson in the centre of mass (CM) frame of final state leptons, respectively. The longitudinal unit vector S_L^- is boosted by Lorentz transformation:

$$S_{L,CM}^{-\mu} = \left(\frac{\left| \vec{p}_\ell \right|}{m_\ell}, \frac{E_\ell \vec{p}_\ell}{m_\ell \left| \vec{p}_\ell \right|} \right), \quad (15)$$

while vectors of perpendicular directions remain unchanged under the Lorentz boost.

The differential decay rate of $B_c \to D_{q'}\ell^+\ell^-$ for any spin direction $\vec{n}^-$ of the ℓ^- can be written in the following form:

$$\frac{d\Gamma(\vec{n}^-)}{ds} = \frac{1}{2} \left(\frac{d\Gamma}{ds} \right)_0 \left[1 + \left(P_L \vec{e}_L^- + P_N^- \vec{e}_N^- + P_T^- \vec{e}_T^- \right) \cdot \vec{n}^- \right], \quad (16)$$

TABLE 1: $B_c \to D_{s,d}$ decays form factors calculated in the constitute quark model.

$B_c \to D_s \ell^+ \ell^-$	$F(0)$	a	b
f_+	0.165	−3.40	3.21
f_-	−0.186	−3.51	3.38
f_T	−0.258	−3.41	3.30
$B_c \to D \ell^+ \ell^-$	$F(0)$	a	b
f_+	0.126	−3.35	3.03
f_-	−0.141	−3.63	3.55
f_T	−0.199	−3.52	3.38

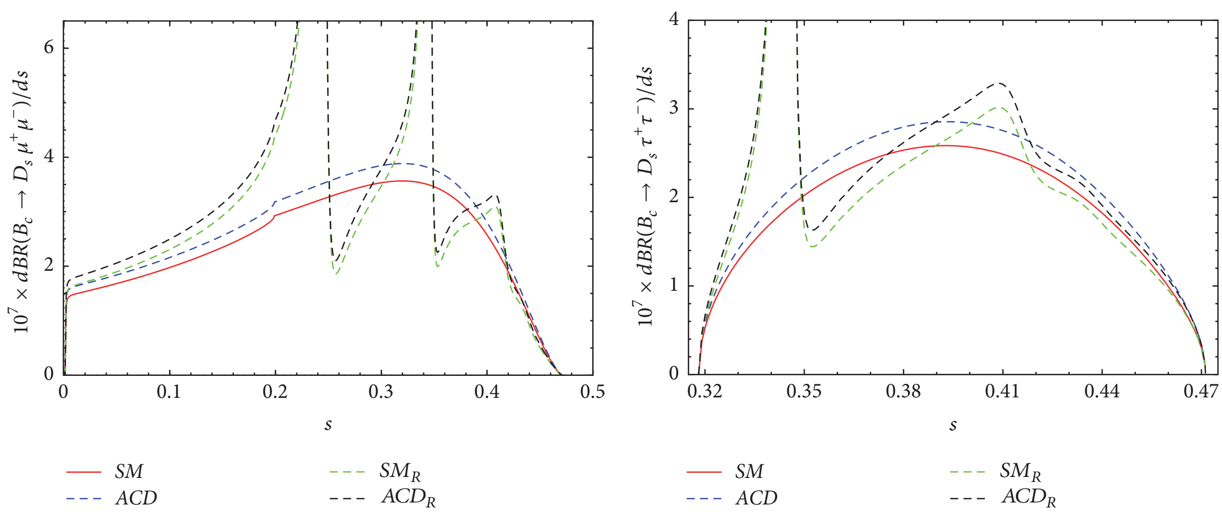

FIGURE 1: The dependence of differential branching ratio on s with and without resonance contributions for $B_c \to D_s \ell^+ \ell^-$ in the SM and the ACD Model for $1/R = 500\,GeV$. (The subscript R represents resonance contribution.)

where $(d\Gamma/ds)_0$ corresponds to the unpolarized decay rate, the explicit form of which is given in (13).

The polarizations P_L^-, P_T^-, and P_N^- in (7) are defined by the following:

$$P_i^-(s) = \frac{d\Gamma(\mathbf{n}^- = \mathbf{e}_i^-)/ds - d\Gamma(\mathbf{n}^- = -\mathbf{e}_i^-)/ds}{d\Gamma(\mathbf{n}^- = \mathbf{e}_i^-)/ds + d\Gamma(\mathbf{n}^- = -\mathbf{e}_i^-)/ds}. \quad (17)$$

Here, P_L^- and P_T^- represent the longitudinal and transversal asymmetries, respectively, of the charged lepton ℓ^- in the decay plane, and P_N^- is the normal component to both of them.

The straightforward calculations yield the explicit form of the longitudinal polarization for $B_c \to D_{s,d} \ell^+ \ell^-$ as follows:

$$P_L^- = \frac{16}{3\Delta} m_{B_c}^4 v \lambda Re\left[AC^*\right], \quad (18)$$

and the transversal polarization is given by the following:

$$P_T^- = \frac{4 m_{B_c}^3 m_\ell \pi \sqrt{s\lambda}}{\Delta}\left[\frac{(r-1)}{s} Re\left[AC^*\right] + Re\left[AD^*\right]\right]. \quad (19)$$

The normal component of polarization is zero so we have not stated its explicit form here.

5. Numerical Analysis

In this section, we will introduce numerical analysis of physical observables. Some of the input parameters used in this work are $m_{B_c} = 6.28\,GeV$, $m_{D_s} = 1.968\,GeV$, $m_D = 1.870\,GeV$, $m_b = 4.8\,GeV$, $m_\mu = 0.105\,GeV$, $m_\tau = 1.77\,GeV$, $|V_{tb}V_{ts}^*| = 0.041$, $|V_{tb}V_{td}^*| = 0.008$, $G_F = 1.17 \times 10^{-5}\,GeV^{-2}$ and $\tau_{B_c} = 0.46 \times 10^{-12}\,s$ [46].

To make numerical predictions, we also need the explicit forms of the form factors f_+, f_-, and f_T. In our analysis, we used the results of [37], calculated in the constituent quark model, and q^2 parametrization is given by

$$F(q^2) = \frac{F(0)}{1 - a\left(q^2/m_{B_c}^2\right) + b\left(q^2/m_{B_c}^2\right)^2}, \quad (20)$$

where the values of parameters $F(0)$, a and b for the $B_c \to (D_s, D)$ decays, are listed in Table 1.

In this work, we also took the long-distance contributions into account. While doing this, to minimize the hadronic uncertainties, we introduce some cuts around J/ψ and $\psi(2s)$ resonances as discussed in [17].

In the analysis, first the differential branching ratios are calculated with and without resonance contributions and s dependence for the SM and $1/R = 500\,GeV$ are presented in Figures 1 and 2 for $B_c \to (D_s, D)\ell^+\ell^-$. One can notice the

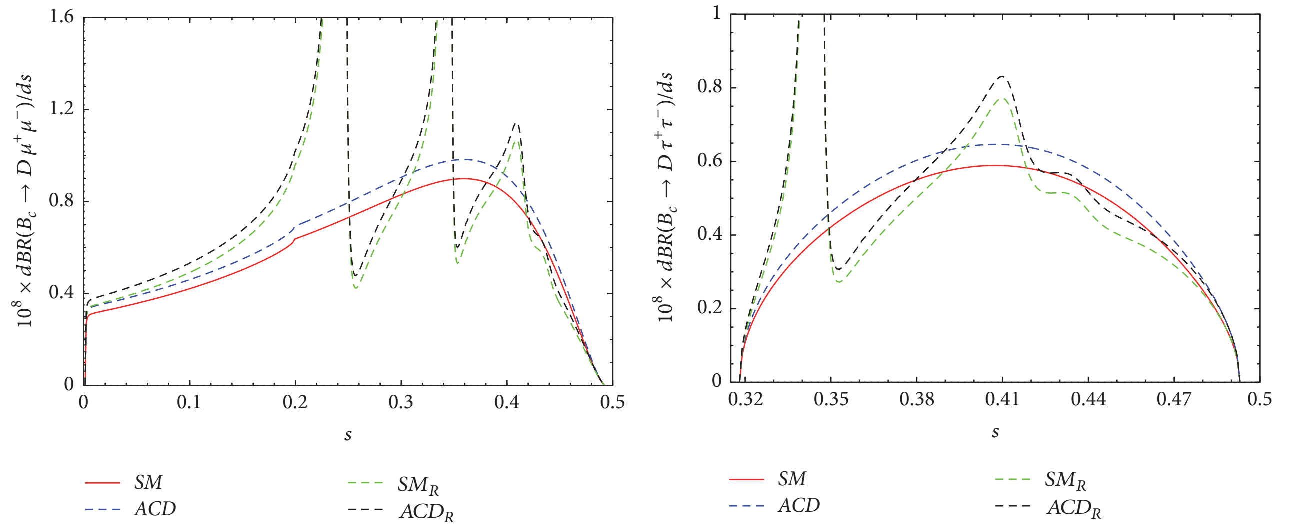

FIGURE 2: The dependence of differential branching ratio on s with and without resonance contributions for $B_c \to D\ell^+\ell^-$ in the SM and the ACD Model for $1/R = 500\,GeV$.

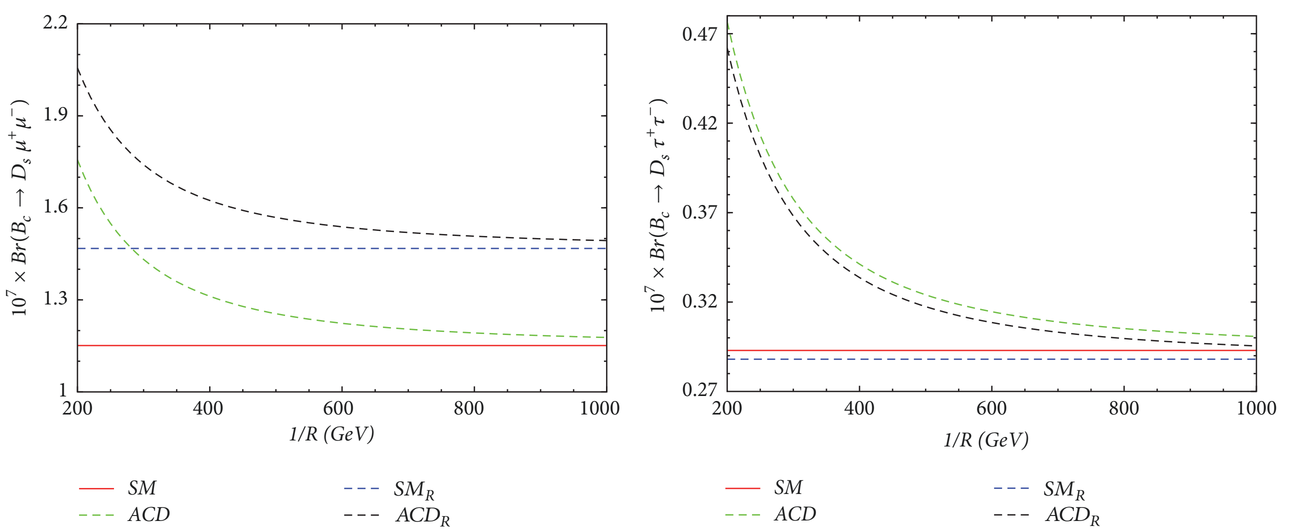

FIGURE 3: The dependence of branching ratio on 1/R with and without resonance contributions for $B_c \to D_s\ell^+\ell^-$. (The subscript R represents resonance contribution.)

change in the differential decay rate and difference between the SM results and new effects in the figures. The maximum deviation is around $s = 0.32(0.39)$ in Figure 1 and $s = 0.36(0.40)$ in Figure 2 for $\mu(\tau)$. The deviation is ~10% and less for $1/R > 500\,GeV$. Considering the resonance effects, the differential decay rates also differ from their SM values.

To introduce the contributions of the ACD model on the branching ratio, we present $1/R$-dependent ratios with and without resonance cases in Figures 3 and 4. The common feature is that as $1/R$ increases, the branching ratios approach to their SM values and vary in the following ranges for $1/R \geq 500\,GeV$:

$$Br\left(B_c \longrightarrow D_s\mu^+\mu^-\right) = (1.151 - 1.255) \times 10^{-7}$$
$$Br\left(B_c \longrightarrow D_s\tau^+\tau^-\right) = (0.293 - 0.324) \times 10^{-7}$$
$$Br\left(B_c \longrightarrow D\mu^+\mu^-\right) = (0.290 - 0.317) \times 10^{-8}$$
$$Br\left(B_c \longrightarrow D\tau^+\tau^-\right) = (0.077 - 0.078) \times 10^{-8}. \tag{21}$$

Here, the first value in any branching ratios above is corresponding to the SM, while the second one is for $1/R = 500\,GeV$, without resonance contributions. A similar behavior is valid for resonance case which can be followed by the figures.

Adding the uncertainty on the form factors may influence the contribution range of the ACD model. However, the variation of the branching ratios, calculated with the central values of form factors, in the ACD model with the SM values, can be considered as a signal of new physics.

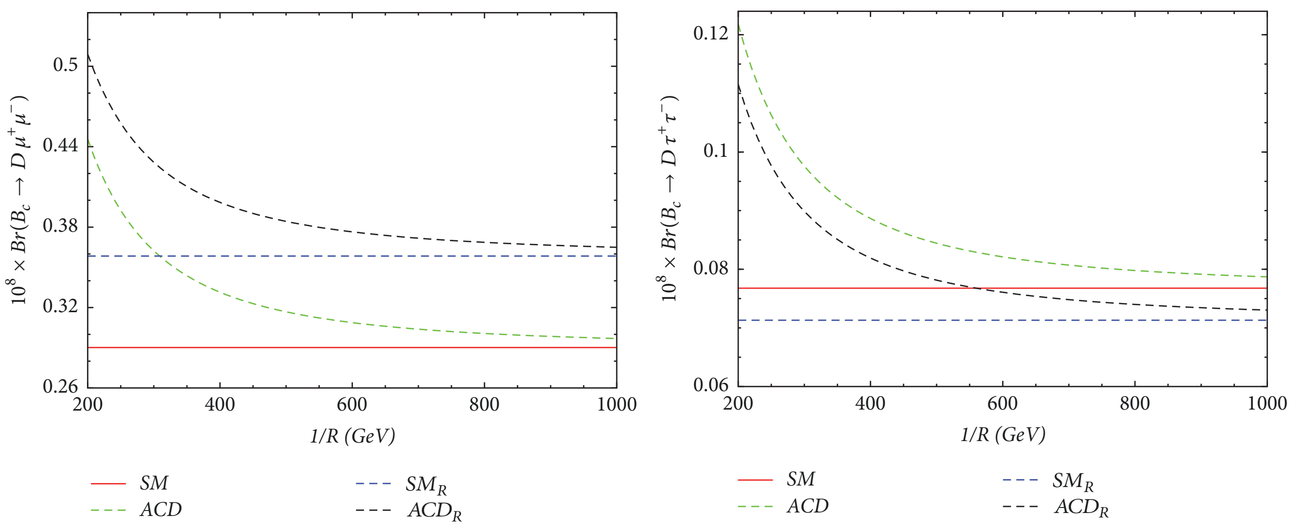

FIGURE 4: The dependence of branching ratio on 1/R with and without resonance contributions for $B_c \to D\ell^+\ell^-$.

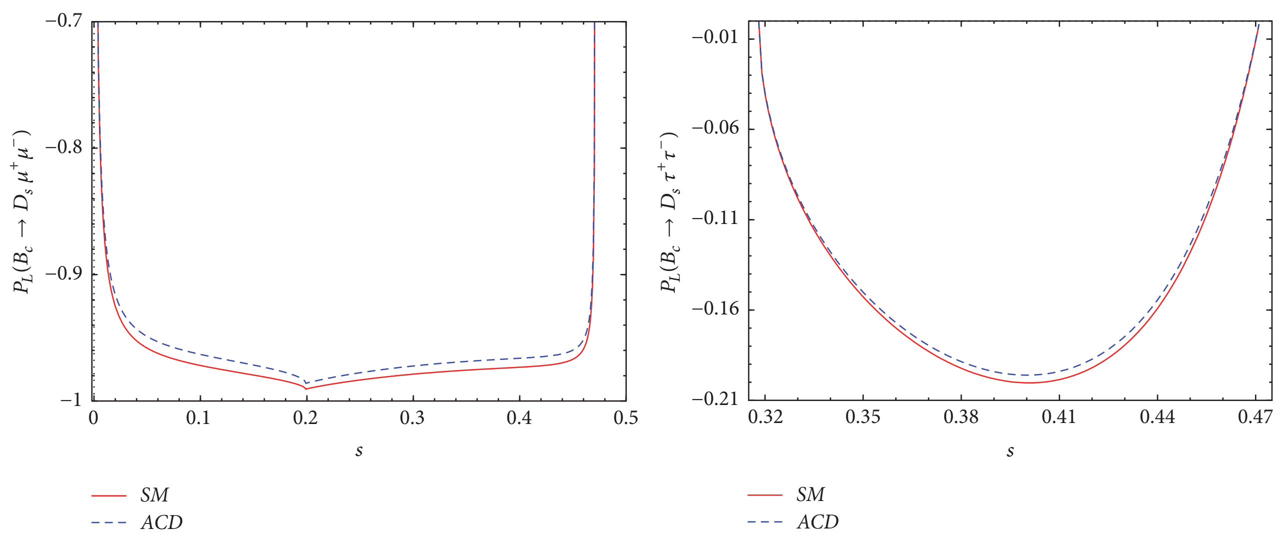

FIGURE 5: The dependence of longitudinal polarization on s without resonance contributions for $B_c \to D_s\ell^+\ell^-$.

The polarization properties of final state leptons give useful clues for new physics. Hence, the dependence of longitudinal polarization on s without resonance contributions is given by Figures 5 and 6. The longitudinal polarization differ from the SM values slightly. The maximum deviation can be found to be less than 5%.

In order to clarify the dependence on $1/R$, we eliminate the dependence of the lepton polarizations on s, by considering the averaged forms over the allowed kinematical region as

$$\langle P_i \rangle = \frac{\int_{(2m_\ell/m_{B_c})^2}^{(1-m_{D_{q'}}/m_{B_c})^2} P_i\,(d\mathscr{B}/ds)\,ds}{\int_{(2m_\ell/m_{B_c})^2}^{(1-m_{D_{q'}}/m_{B_c})^2} (d\mathscr{B}/ds)\,ds}. \qquad (22)$$

The $1/R$-dependent average longitudinal polarizations are given in Figures 7 and 8. As it can be seen from the figures, the maximum deviation is 2% for μ channels and 3% for $B_c \to (D_s, D)\tau^+\tau^-$, respectively, at $1/R = 500\,GeV$.

The variation of transversal polarization with respect to s is given by Figures 9 and 10. In μ channels the difference is negligible. In τ channels up to $s \sim 0.46(0.48)$ for $B_c \to D_s(D)\ell^+\ell^-$ decays, respectively, the effects of the UED can be followed. Although the deviation with the SM values is very small, finally, the average transversal polarization can be observed by Figures 11 and 12.

6. Conclusion

In this work, we have studied $B_c \to D_s(D)\ell^+\ell^-$ in the framework of a single universal extra dimension and calculated the contributions to some physical observables.

As an overall conclusion, considering the lower bound on the compactification factor which is $1/R > 500\,GeV$,

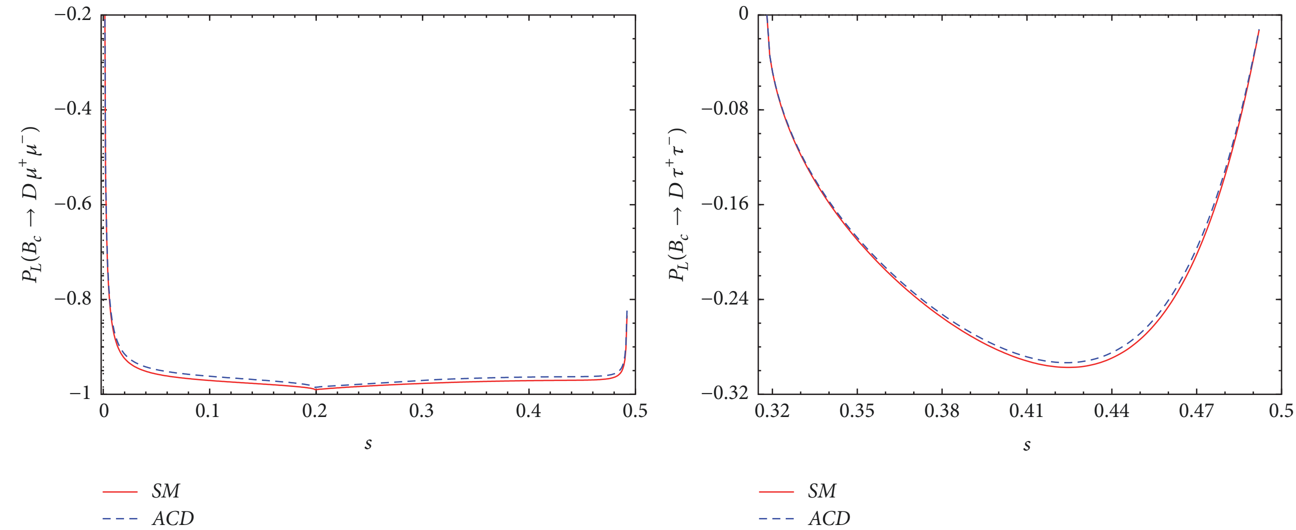

FIGURE 6: The dependence of longitudinal polarization on s without resonance contributions for $B_c \to D\ell^+\ell^-$.

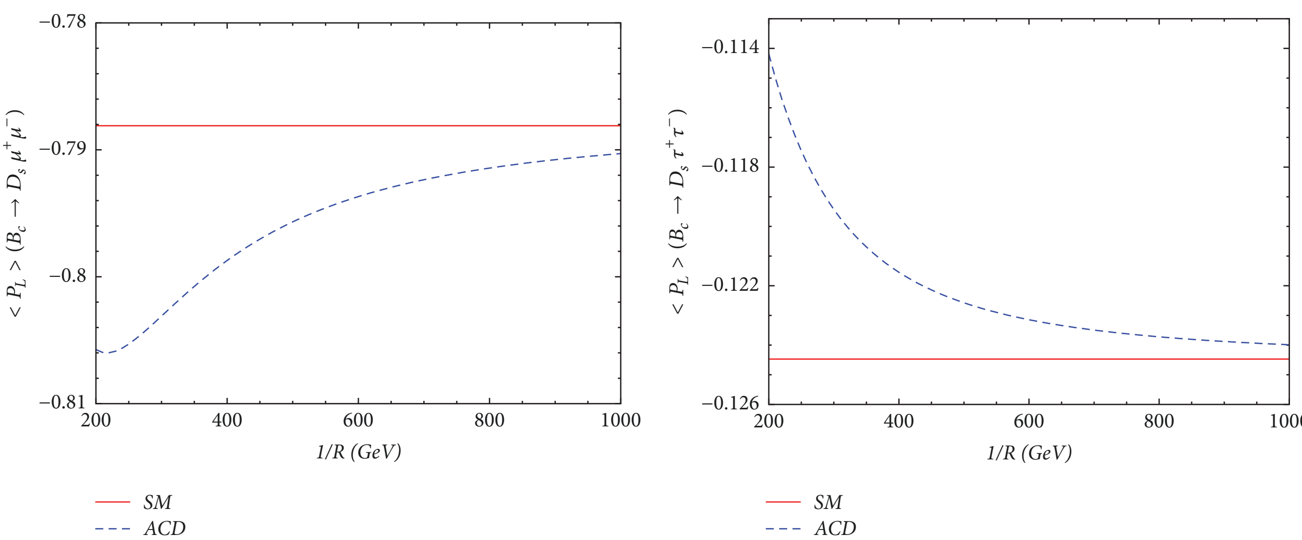

FIGURE 7: The dependence of longitudinal polarization on $1/R$ with resonance contributions for $B_c \to D_s\ell^+\ell^-$.

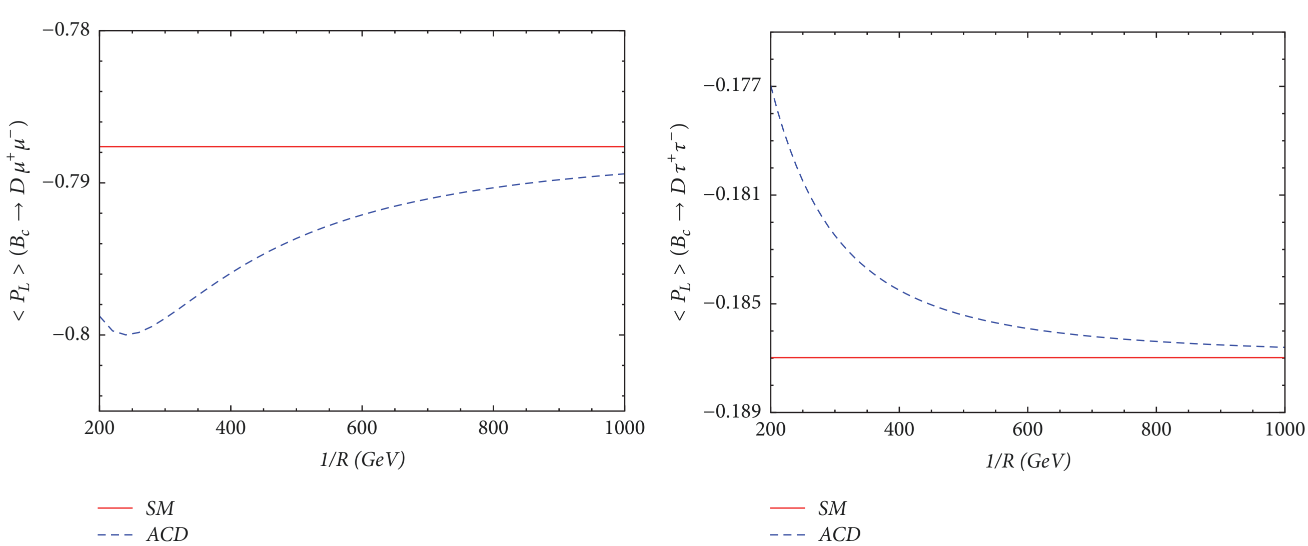

FIGURE 8: The dependence of longitudinal polarization on $1/R$ with resonance contributions for $B_c \to D\ell^+\ell^-$.

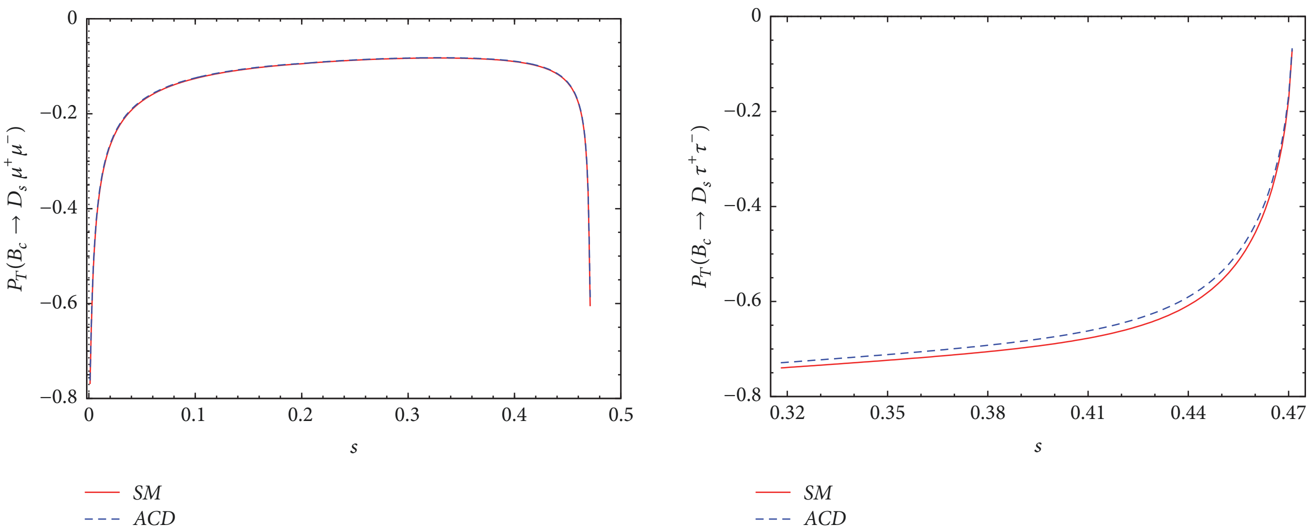

FIGURE 9: The dependence of transversal polarization on s without resonance contributions for $B_c \to D_s \ell^+ \ell^-$.

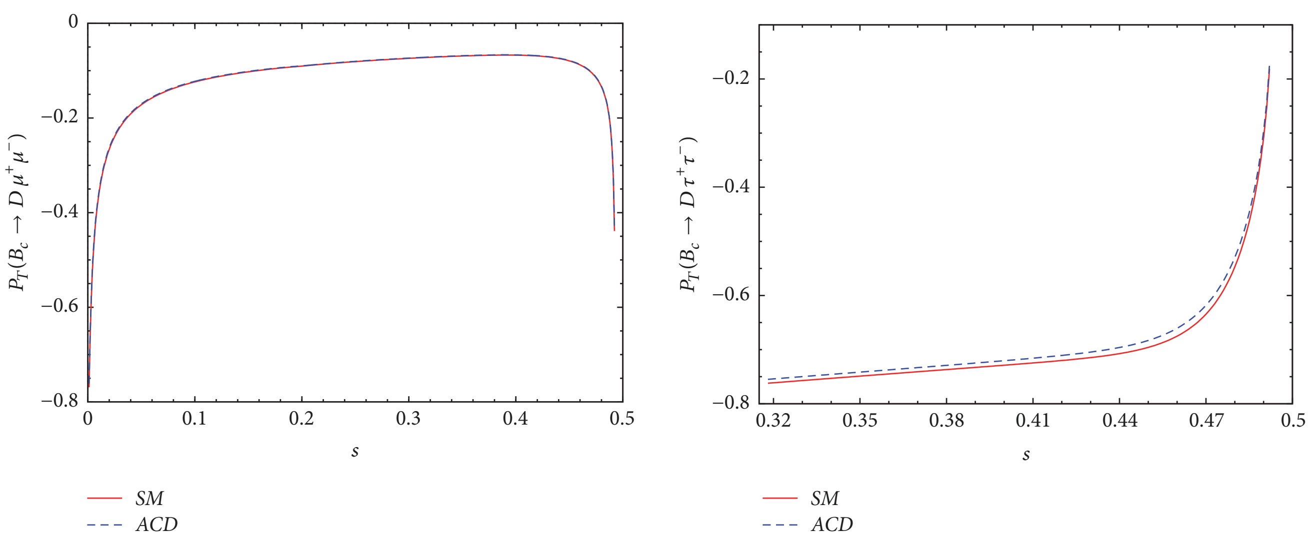

FIGURE 10: The dependence of transversal polarization on s without resonance contributions for $B_c \to D \ell^+ \ell^-$.

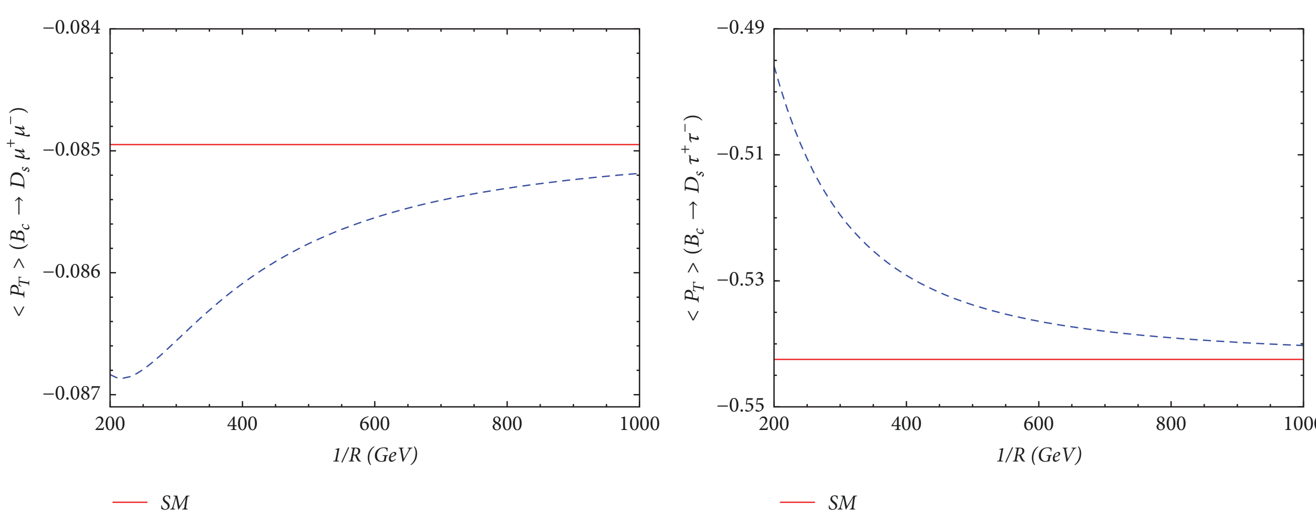

FIGURE 11: The dependence of transversal polarization on $1/R$ with resonance contributions for $B_c \to D_s \ell^+ \ell^-$.

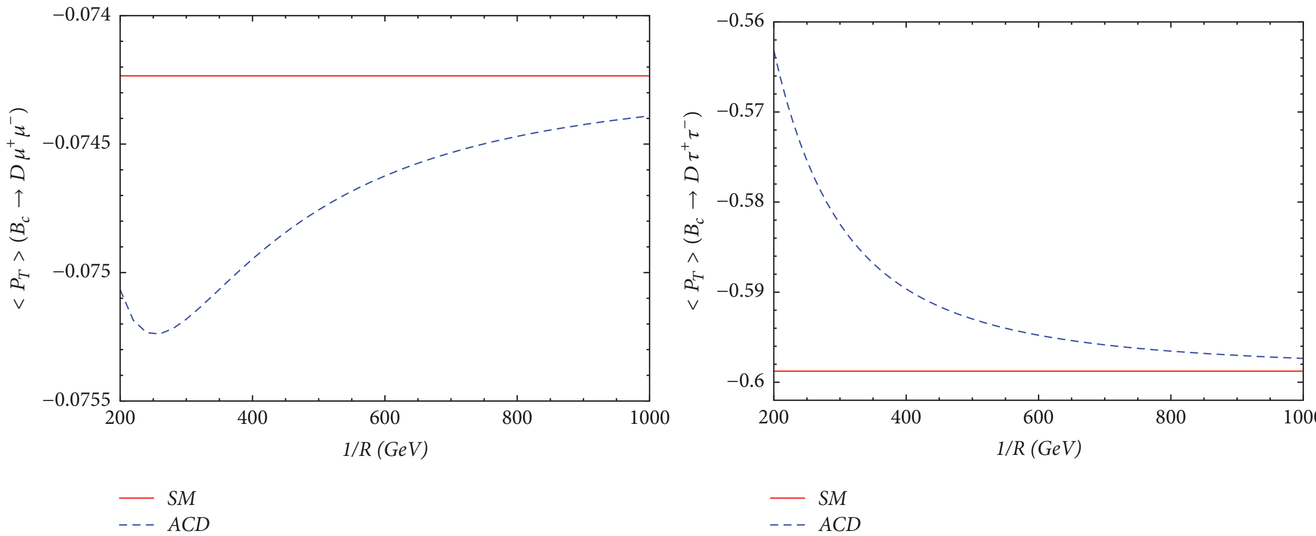

FIGURE 12: The dependence of transversal polarization on $1/R$ with resonance contributions for $B_c \to D\ell^+\ell^-$.

there still appears acceptable difference on the differential and integrated branching ratios compared with the SM results.

The polarization effects in μ channels are either irrelevant nor negligible while in τ channels some small effects are obtained. Under the discussion in this work, studying these decays experimentally can be useful for understanding new physics.

Appendix

Wilson Coefficients in the ACD Model

In the ACD model, new contributions appear by modifying available Wilson coefficients in the SM. The modified Wilson coefficients can be expressed in terms of $F(x_t, 1/R)$ which generalize the corresponding SM functions $F_0(x_t)$ according to

$$F\left(x_t, \frac{1}{R}\right) = F_0(x_t) + \sum_{n=1}^{\infty} F_n(x_t, x_n) \tag{A.1}$$

where $x_t = m_t^2/m_W^2$, $x_n = m_n^2/m_W^2$, and $m_n = n/R$.

The necessary modified Wilson coefficients used in this work have already been calculated in [23, 24] and we will follow them.

Instead of C_7, an effective, normalization scheme independent, coefficient $C_7^{eff}(1/R)$ in the leading logarithmic approximation is defined as

$$C_7^{eff}\left(\mu_b, \frac{1}{R}\right) = \eta^{16/23} C_7\left(\mu_W, \frac{1}{R}\right) + \frac{8}{3}\left(\eta^{14/23} - \eta^{16/23}\right) C_8\left(\mu_W, \frac{1}{R}\right) + C_2\left(\mu_W, \frac{1}{R}\right) \sum_{i=1}^{8} h_i \eta^{a_i} \tag{A.2}$$

with $\eta = \alpha_s(\mu_W)/\alpha_s(\mu_b)$ and

$$\alpha_s(x) = \frac{\alpha_s(m_Z)}{1 - \beta_0(\alpha_s(m_Z)/2\pi)\ln(m_Z/x)} \tag{A.3}$$

where in fifth dimension $\alpha_s(m_Z) = 0.118$ and $\beta_0 = 23/3$.

The coefficients a_i and h_i are

$$\begin{aligned} a_i &= \left(\frac{14}{23}, \frac{16}{23}, \frac{6}{23}, -\frac{12}{23}, 0.4086, -0.4230, -0.8994, 0.1456\right) \\ h_i &= \left(2.2996, -1.088, -\frac{3}{7}, -\frac{1}{14}, -0.6494, -0.0380, -0.0186, -0.0057\right). \end{aligned} \tag{A.4}$$

The functions in (A.2) are

$$\begin{aligned} C_2(\mu_W) &= 1, \\ C_7\left(\mu_W, \frac{1}{R}\right) &= -\frac{1}{2} D'\left(x_t, \frac{1}{R}\right), \\ C_8\left(\mu_W, \frac{1}{R}\right) &= -\frac{1}{2} E'\left(x_t, \frac{1}{R}\right). \end{aligned} \tag{A.5}$$

Here, $D'(x_t, 1/R)$ and $E'(x_t, 1/R)$ are defined by using (A.1) with the following functions:

$$D_0'(x_t) = -\frac{\left(8x_t^3 + 5x_t^2 - 7x_t\right)}{12(1-x_t)^3} + \frac{x_t^2(2 - 3x_t)}{2(1-x_t)^4} \ln x_t \tag{A.6}$$

$$E_0'(x_t) = -\frac{x_t\left(x_t^2 - 5x_t - 2\right)}{4\left(1 - x_t\right)^3} + \frac{3x_t^2}{2\left(1 - x_t\right)^4}\ln x_t \tag{A.7}$$

$$\begin{aligned} D_n'(x_t, x_n) = {} & \frac{x_t\left(-37 + 44x_t + 17x_t^2 + 6x_n^2\left(10 - 9x_t + 3x_t^2\right) - 3x_n\left(21 - 54x_t + 17x_t^2\right)\right)}{36\left(x_t - 1\right)^3} \\ & - \frac{\left(-2 + x_n + 3x_t\right)\left(x_t + 3x_t^2 + x_n^2\left(3 + x_t\right) - x_n\left(1 + \left(-10 + x_t\right)x_t\right)\right)}{6\left(x_t - 1\right)^2}\ln\frac{x_n + x_t}{1 + x_n} \\ & + \frac{x_n\left(2 - 7x_n + 3x_n^2\right)}{6}\ln\frac{x_n}{1 + x_n} \end{aligned} \tag{A.8}$$

$$\begin{aligned} E_n'(x_t, x_n) = {} & \frac{x_t\left(-17 - 8x_t + x_t^2 - 3x_n\left(21 - 6x_t + x_t^2\right) - 6x_n^2\left(10 - 9x_t + 3x_t^2\right)\right)}{12\left(x_t - 1\right)^3} \\ & + \frac{\left(1 + x_n\right)\left(x_t + 3x_t^2 + x_n^2\left(3 + x_t\right) - x_n\left(1 + \left(-10 + x_t\right)x_t\right)\right)}{2\left(x_t - 1\right)^4}\ln\frac{x_n + x_t}{1 + x_n} \\ & - \frac{1}{2}x_n\left(1 + x_n\right)\left(-1 + 3x_n\right)\ln\frac{x_n}{1 + x_n}. \end{aligned} \tag{A.9}$$

Using [19] or following [23] one gets the expressions for the sum over n as

$$\begin{aligned} \sum_{n=1}^{\infty} D_n'(x_t, x_n) = {} & -\frac{x_t\left(-37 + x_t\left(44 + 17x_t\right)\right)}{72\left(x_t - 1\right)^3} \\ & + \frac{\pi M_W R}{2}\left[\int_0^1 dy \cdot \frac{\left(2y^{1/2} + 7y^{3/2} + 3y^{5/2}\right)}{6}\coth\left(\pi M_W R\sqrt{y}\right)\right. \\ & + \frac{\left(-2 + 3x_t\right)x_t\left(1 + 3x_t\right)}{6\left(x_t - 1\right)^4}J\left(R, -\frac{1}{2}\right) \\ & - \frac{1}{6\left(x_t - 1\right)^4}\left[x_t\left(1 + 3x_t\right) - \left(-2 + 3x_t\right) \cdot \left(1 + \left(-10 + x_t\right)x_t\right)\right]J\left(R, \frac{1}{2}\right) \\ & + \frac{1}{6\left(x_t - 1\right)^4}\left[\left(-2 + 3x_t\right)\left(3 + x_t\right) - \left(1 + \left(-10 + x_t\right)x_t\right)\right]J\left(R, \frac{3}{2}\right) - \frac{\left(3 + x_t\right)}{6\left(x_t - 1\right)^4} \\ & \left.\cdot J\left(R, \frac{5}{2}\right)\right] \end{aligned} \tag{A.10}$$

and

$$\begin{aligned} \sum_{n=1}^{\infty} E_n'(x_t, x_n) = {} & -\frac{x_t\left(-17 + \left(-8 + x_t\right)x_t\right)}{24\left(x_t - 1\right)^3} \\ & + \frac{\pi M_W R}{4}\left[\int_0^1 dy\left(y^{1/2} + 2y^{3/2} - 3y^{5/2}\right)\right. \\ & \cdot \coth\left(\pi M_W R\sqrt{y}\right) - \frac{x_t\left(1 + 3x_t\right)}{\left(x_t - 1\right)^4}J\left(R, -\frac{1}{2}\right) \\ & + \frac{1}{\left(x_t - 1\right)^4}\left[x_t\left(1 + 3x_t\right) - \left(1 + \left(-10 + x_t\right)x_t\right)\right] \\ & \cdot J\left(R, \frac{1}{2}\right) - \frac{1}{\left(x_t - 1\right)^4}\left[\left(3 + x_t\right) - \left(1 + \left(-10 + x_t\right)x_t\right)\right]J\left(R, \frac{3}{2}\right) + \frac{\left(3 + x_t\right)}{\left(x_t - 1\right)^4} \\ & \left.\cdot J\left(R, \frac{5}{2}\right)\right] \end{aligned} \tag{A.11}$$

where

$$\begin{aligned} J(R, \alpha) = {} & \int_0^1 dy\, y^{\alpha}\left[\coth\left(\pi M_W R\sqrt{y}\right)\right. \\ & \left. - x_t^{1+\alpha}\coth\left(\pi m_t R\sqrt{y}\right)\right]. \end{aligned} \tag{A.12}$$

The Wilson coefficient C_9 in the ACD model and NDR scheme is

$$\begin{aligned} C_9(\mu) = {} & P_0^{NDR} + \frac{Y\left(x_t, 1/R\right)}{\sin^2\theta_W} - 4Z\left(x_t, \frac{1}{R}\right) \\ & + P_E E\left(x_t, \frac{1}{R}\right) \end{aligned} \tag{A.13}$$

where $P_0^{NDR} = 2.6 \pm 0.25$ and P_E is numerically negligible. The functions $Y(x_t, 1/R)$ and $Z(x_t, 1/R)$ are defined as

$$Y\left(x_t, \frac{1}{R}\right) = Y_0\left(x_t\right) + \sum_{n=1}^{\infty} C_n\left(x_t, x_n\right) \qquad (A.14)$$

$$Z\left(x_t, \frac{1}{R}\right) = Z_0\left(x_t\right) + \sum_{n=1}^{\infty} C_n\left(x_t, x_n\right) \qquad (A.15)$$

with

$$Y_0\left(x_t\right) = \frac{x_t}{8}\left[\frac{x_t - 4}{x_t - 1} + \frac{3x_t}{\left(x_t - 1\right)^2}\ln x_t\right] \qquad (A.16)$$

$$Z_0\left(x_t\right) = \frac{18x_t^4 - 163x_t^3 + 259x_t^2 - 108x_t}{144\left(x_t - 1\right)^3} + \left[\frac{32x_t^4 - 38x_t^3 - 15x_t^2 + 18x_t}{72\left(x_t - 1\right)^4} - \frac{1}{9}\right]\ln x_t \qquad (A.17)$$

$$C_n\left(x_t, x_n\right) = \frac{x_t}{8\left(x_t - 1\right)^2}\left[x_t^2 - 8x_t + 7 + \left(3 + 3x_t + 7x_n - x_t x_n\right)\ln\frac{x_t + x_n}{1 + x_n}\right] \qquad (A.18)$$

and

$$\sum_{n=1}^{\infty} C_n\left(x_t, x_n\right) = \frac{x_t\left(7 - x_t\right)}{16\left(x_t - 1\right)} - \frac{\pi M_W R x_t}{16\left(x_t - 1\right)^2}\left[3\left(1 + x_t\right) J\left(R, -\frac{1}{2}\right) + \left(x_t - 7\right) J\left(R, \frac{1}{2}\right)\right]. \qquad (A.19)$$

The μ independent C_{10} is given by

$$C_{10} = -\frac{Y\left(x_t, 1/R\right)}{\sin^2\theta_W} \qquad (A.20)$$

where $Y(x_t, 1/R)$ is defined in (A.14).

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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