Study on branching ratios and direct CP asymmetries of $D \rightarrow PV$ decays

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Published 16 April 2014

We study the non-leptonic two-body decays of D mesons decaying into one pseudoscalar meson (P) and one vector meson (V) in the factorization-assisted topological-amplitude approach. In this approach, the decay amplitudes are factorized into two parts, the short-distance contribution (Wilson coefficients) and the long-distance contribution (hadronic matrix elements). We predict the branching ratios of $D \rightarrow PV$ decays using a global fit with the non-perturbative parameters. Our results agree well with the experimental data. We also predict the direct CP asymmetries by combining short-distance dynamics associated with penguin operators and long-distance hadronic matrix elements determined by branching ratios. The large asymmetries in $D^+ \rightarrow \pi^+ \rho^0$ and $D_s^+ \rightarrow K^+ \phi$ may be measurable in the LHCb and future Belle II experiments.

Keywords: CP asymmetry; D decay; factorization.

PACS Numbers: 13.85.Ni, 13.25.Ft, 12.39.St

1. Introduction

In 2011, the LHCb experiment measured the difference between the time integrated CP asymmetries in $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ \pi^-$ decays, $\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})]\%$.¹ The measured values are much larger than the naive estimation in the Standard Model (SM), $\Delta A_{CP} \sim 10^{-4}$, which receives dual

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suppression from the CKM matrix elements and the Wilson coefficients.² Many theoretical efforts have been made to explain this discrepancy, both within and beyond the SM.^{3–9} However, their predictions range from $\mathcal{O}(10^{-5})$ to $\mathcal{O}(10^{-2})$.

To estimate the penguin amplitudes precisely, a theoretical framework named the factorization-assisted topological-amplitude (FAT) approach was proposed in Ref. 10. It parameterizes the tree amplitudes based on the factorization of short-distance and long-distance dynamics into Wilson coefficients and hadronic matrix elements. The introduced parameters are obtained after the fit of parameterized branching ratios to data. The penguin amplitudes can either be related to the tree amplitudes or be factorized except the negligible ones. Therefore, direct CP asymmetries can be predicted.

In Ref. 10, the $D \rightarrow PP$ decays have been studied in the FAT approach, which improved the global fit to measured $D \rightarrow PP$ branching ratios. The direct CP asymmetries were also calculated, specifically, the prediction for ΔA_{CP} being -1.0×10^{-3} . After the publication of this work, the LHCb collaboration has updated the data for ΔA_{CP} . From two sources of D meson production, the measured results are $[-0.34 \pm 0.15(\text{stat}) \pm 0.10(\text{syst})]\%$ ¹¹ and $[+0.49 \pm 0.30(\text{stat}) \pm 0.14(\text{syst})]\%$,¹² respectively. The sign flip of the central value may indicate a small ΔA_{CP} .

In this article, we shall extend the FAT approach to study the $D \rightarrow PV$ decays, which also have abundant data of branching ratios to determine the nonperturbative parameters. The $\rho^0 - \omega$ mixing effect is considered. We also predict the direct CP asymmetries in the $D \rightarrow PV$ decays, among which those in $D^+ \rightarrow \pi^+ \rho^0$ and $D_s^+ \rightarrow K^+ \phi$ decay modes are hopeful to be observed in future experiments.

In Sec. 2, the tree contributions to the $D \rightarrow PV$ branching ratios are parameterized in the FAT approach, and the free parameters are obtained through the global fit. In Sec. 3, we formulate the penguin contributions from the penguin operators O_{3-6} , the quark loops and the magnetic penguin operator O_{8g} , and then predict the direct CP asymmetries in the $D \rightarrow PV$ decays. Section 4 is the summary.

2. Branching Ratios

In the FAT approach, we only take into account the tree amplitudes to parameterize the $D \rightarrow PV$ branching ratios, because the penguin contributions are suppressed by both the Wilson coefficients and the CKM matrix elements.

2.1. Parametrization of tree amplitudes

In this subsection, the tree amplitudes are formulated. We give here the corresponding effective weak Hamiltonian as

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{CKM} [C_1(\mu) O_1(\mu) + C_2(\mu) O_2(\mu)], \quad (1)$$

with G_F the Fermi coupling constant, V_{CKM} the product of the corresponding CKM matrix elements, $O_{1,2}$ the tree operators¹³ and $C_{1,2}$ the Wilson coefficients.

Fig. 1. $D \rightarrow PV$ topological tree diagrams: (a) the color-favored tree amplitude $T_{P(V)}$, (b) the color-suppressed tree amplitude $C_{P(V)}$, (c) the W -exchange amplitude $E_{P(V)}$, and (d) the W -annihilation amplitude $A_{P(V)}$.

In Fig. 1, we show the topological diagrams of $D \rightarrow PV$ decays, including the the color-favored tree amplitude $T_{P(V)}$ and the color-suppressed tree amplitude $C_{P(V)}$ with the $D \rightarrow P(V)$ transition, and the W -exchange amplitude $E_{P(V)}$ and the W -annihilation amplitude $A_{P(V)}$ with the $P(V)$ meson containing the anti-quark from the weak vertex.

We give the amplitudes T_P and C_P as

$$T_P(C_P) = \frac{G_F}{\sqrt{2}} V_{CKM} a_1(\mu) (a_2^P(\mu)) f_V m_V F_1^{DP}(m_V^2) 2(\varepsilon_V \cdot p_D), \quad (2)$$

with f_V (m_V , ε_V) the decay constant (mass, polarization vector) of the V meson, F_1^{DP} the $D \rightarrow P$ transition form factor, and p_D the D meson momentum. Similarly, T_V and C_V are expressed as

$$T_V(C_V) = \frac{G_F}{\sqrt{2}} V_{CKM} a_1(\mu) (a_2^V(\mu)) f_P m_P A_0^{DV}(m_P^2) 2(\varepsilon_V \cdot p_D), \quad (3)$$

with f_P the decay constant of the P meson, and A_0^{DV} the $D \rightarrow V$ transition form factor. The explicit forms of the Wilson coefficients a_1 and $a_2^{P,V}$ are $a_1(\mu) = C_2(\mu) + C_1(\mu)/N_C$ and $a_2^{P(V)}(\mu) = C_1(\mu) + C_2(\mu)[1/N_C + \chi_{P(V)}^C e^{i\phi_{P(V)}^C}]$, where N_C is the number of colors. The nonfactorizable contributions in $T_{P,V}$ have been neglected for suppression from the Wilson coefficient C_1 ; while those in $C_{P,V}$ are characterized by $\chi_{P,V}^C e^{i\phi_{P,V}^C}$. Suggested by the perturbative QCD (PQCD) approach,¹⁴ we follow [10] to set the scale as $\mu = \sqrt{\Lambda m_D(1 - r_{V(P)}^2)}$, with the mass ratio of the emitted V (P) meson $r_{V(P)} = m_{V(P)}/m_D$, and the soft degree of freedom in D meson Λ .

The factorizable contributions in annihilation-type amplitudes are negligible due to helicity suppression, so the amplitudes $E_{P,V}$ and $A_{P,V}$ are formulated as

$$E_{P,V} = \frac{G_F}{\sqrt{2}} V_{CKM} C_2(\mu) \chi_{q(s)}^E e^{i\phi_{q(s)}^E} f_D m_D \frac{f_P}{f_\pi} \frac{f_V}{f_\rho} (\varepsilon_V \cdot p_D), \quad (4)$$

$$A_{P,V} = \frac{G_F}{\sqrt{2}} V_{CKM} C_1(\mu) \chi_{q(s)}^A e^{i\phi_{q(s)}^A} f_D m_D \frac{f_P}{f_\pi} \frac{f_V}{f_\rho} (\varepsilon_V \cdot p_D), \quad (5)$$

with $f_{D(\pi,\rho)}$ the decay constant of the $D(\pi,\rho)$ meson. $\chi_{q(s)}^{E,A} e^{i\phi_{q(s)}^{E,A}}$ characterize the nonfactorizable contributions in corresponding amplitudes. We differentiate here the strongly produced light-quark (u or d) and strange-quark pair to introduce the SU(3) breaking effect. The scale in the annihilation-type amplitudes is $\mu = \sqrt{\Lambda m_D (1 - r_\rho^2)(1 - r_V^2)}$.

In heavy meson hadronic decays, there exist a type of infra-red gluons named Glauber gluons.¹⁵ Because pion is simultaneously a $\bar{q}q$ bound state and a Nambu-Goldstone boson,¹⁶ we assume that the Glauber gluons have significant effect in decays containing pions. For such decays, an additional phase factor $\exp(iS_\pi)$ is multiplied to the annihilation amplitudes, as has been done in [10]. In summary, we have formulated the $D \rightarrow PV$ branching ratios with 14 free parameters: the soft scale Λ , six strong magnitudes (phases) $\chi's$ ($\phi's$) and the Glauber phase S_π .

2.2. Numerical results

The partial decay width of a $D \rightarrow PV$ decay mode is given by

$$\Gamma(D \rightarrow PV) = \frac{|\vec{p}_V|}{8\pi m_D^2} \sum_{pol} |\mathcal{A}|^2, \quad (6)$$

where the summation is taken over the polarization states of the V meson. Using this formula, we do the global fit of the branching ratios to 33 experimental data, and obtain the values for the 14 free parameters

$$\begin{aligned} \Lambda &= 0.44 \text{ GeV}, \quad S_\pi = -0.96, \\ \chi_P^C &= -0.40, \chi_V^C = -0.53, \chi_q^E = 0.25, \chi_q^A = 0.11, \chi_s^E = 0.29, \chi_s^A = 0.10, \\ \phi_P^C &= -0.53, \phi_V^C = -0.25, \phi_q^E = 1.73, \phi_q^A = -0.35, \phi_s^E = 3.11, \quad \phi_s^A = 1.60, \end{aligned} \quad (7)$$

with the $\chi^2 = 2.8$ per degree of freedom.

We displayed some Cabibbo-favored and Cabibbo-suppressed $D \rightarrow PV$ branching ratios corresponding to the parameters in Eq. (7) in the column Br(FAT) of Tables 1 and 2, respectively. Our results are compared to the experimental data¹⁸ and other theoretical predictions, including the calculations containing the final state interaction (FSI) effects,¹⁹ the diagrammatic approach,²⁰ and the pole model.²¹ Our results are more consistent with the experimental measurements.

Table 1. Branching ratios for some Cabibbo-favored $D \rightarrow PV$ decays in units of percentage(%). Our results excluding (FAT) and including (FAT[mix]) the ρ - ω mixing are compared to the experimental data and other theoretical calculations: Br(FSI), Br(diagrammatic) and Br(pole). The amplitudes of the decays are also displayed.

Modes	Amplitudes	Br(FSI)	Br(diagrammatic)	Br(pole)	Br(FAT)	Br(FAT[mix])	Br(exp)
$D^0 \rightarrow \pi^+ K^{*-}$	$T_V, (E_P)$	4.69	5.91 ± 0.70	3.1 ± 1.0	6.21	6.09	$5.44^{+0.70}_{-0.53}$
$D^0 \rightarrow \pi^0 \bar{K}^{*0}$	$C_P, (E_P)$	3.49	2.82 ± 0.34	2.9 ± 1.0	3.42	3.25	3.44 ± 0.35
$D^0 \rightarrow \bar{K}^0 \rho^0$	$C_V, (E_V)$	0.88	1.54 ± 1.15	1.7 ± 0.7	1.31	1.17	$1.26^{+0.14}_{-0.16}$
$D^0 \rightarrow \bar{K}^0 \omega$	$C_V, (E_V)$	2.16	2.26 ± 1.38	2.5 ± 0.7	2.26	2.22	2.22 ± 0.12
$D^0 \rightarrow \bar{K}^0 \phi$	E_P	0.90	0.868 ± 0.139	0.8 ± 0.2	0.800	0.800	0.834 ± 0.074
$D^0 \rightarrow K^- \rho^+$	$T_P, (E_V)$	11.19	10.8 ± 2.2	8.8 ± 2.2	9.6	9.6	10.8 ± 0.7
$D^0 \rightarrow \eta \bar{K}^{*0}$	$C_P, (E_P, E_V)$	0.51	0.96 ± 0.32	0.7 ± 0.2	0.55	0.57	0.96 ± 0.30
$D^0 \rightarrow \eta' \bar{K}^{*0}$	$C_P, (E_P, E_V)$	0.005	0.012 ± 0.003	0.016 ± 0.005	0.018	0.018	< 0.11
$D^+ \rightarrow \pi^+ \bar{K}^{*0}$	T_V, C_P	0.64	1.83 ± 0.49	1.4 ± 1.3	1.70	1.70	1.51 ± 0.16
$D^+ \rightarrow \bar{K}^0 \rho^+$	T_P, C_V	11.77	9.2 ± 6.7	15.1 ± 3.8	6.4	6.0	9.6 ± 2.0
$D_s^+ \rightarrow \pi^+ \rho^0$	A_P, A_V	0.080		0.4 ± 0.4	0	0.004	0.020 ± 0.012
$D_s^+ \rightarrow \pi^+ \omega$	A_P, A_V	0.0		0	0.30	0.26	0.25 ± 0.07
$D_s^+ \rightarrow \pi^+ \phi$	T_V	2.89	4.38 ± 0.35	4.3 ± 0.6	3.4	3.4	4.5 ± 0.4
$D_s^+ \rightarrow K^+ \bar{K}^{*0}$	$C_P, (A_V)$	3.86		4.2 ± 1.7	4.08	4.07	3.95 ± 0.2
$D_s^+ \rightarrow \bar{K}^0 K^{*+}$	$C_V, (A_P)$	3.37		1.0 ± 0.6	2.5	3.1	5.4 ± 1.2
$D_s^+ \rightarrow \eta \rho^+$	$T_P, (A_P, A_V)$	9.49		8.3 ± 1.3	8.2	8.8	8.9 ± 0.8
$D_s^+ \rightarrow \eta' \rho^+$	$T_P, (A_P, A_V)$	2.61		3.0 ± 0.5	1.7	1.6	5.6 ± 1.1^a

Note: ^a data from Ref. 17.

Table 2. Same as Table 1 for the singly Cabibbo-suppressed $D \rightarrow PV$ decays in units of 10^{-3} .

Modes	Amplitudes	Br(FSI)	Br(diagrammatic)	Br(pole)	Br(FAT)	Br(FAT[mix])	Br(exp)
$D^0 \rightarrow \pi^+ \rho^-$	$T_V, (EP)$	6.5	3.92 ± 0.46	3.5 ± 0.6	4.74	4.66	4.96 ± 0.24
$D^0 \rightarrow \pi^0 \rho^0$	$C_P, C_V, (EP, EV)$	1.7	2.96 ± 0.98	1.4 ± 0.6	3.55	3.83	3.72 ± 0.22
$D^0 \rightarrow \pi^0 \omega$	$C_P, C_V, (EP, EV)$	0.08	0.10 ± 0.18	0.08 ± 0.02	0.85	0.18	< 0.26
$D^0 \rightarrow \pi^0 \phi$	C_P	1.1	1.22 ± 0.08	1.0 ± 0.3	1.11	1.11	1.31 ± 0.10
$D^0 \rightarrow \pi^- \rho^+$	$T_P, (EV)$	8.2	8.34 ± 1.69	10.2 ± 1.5	10.2	10.0	9.8 ± 0.4
$D^0 \rightarrow K^+ K^{*-}$	$T_V, (EP)$	2.8	1.99 ± 0.24	1.6 ± 0.3	1.72	1.73	1.56 ± 0.12
$D^0 \rightarrow K^0 \bar{K}^{*0}$	E_P, EV	0.99	0.29 ± 0.22	0.16 ± 0.05	1.1	1.1	< 1
$D^0 \rightarrow \bar{K}^0 K^{*0}$	E_P, EV	0.99	0.29 ± 0.22	0.16 ± 0.05	1.1	1.1	< 0.56
$D^0 \rightarrow K^- K^{*+}$	$T_P, (EV)$	4.5	4.25 ± 0.86	4.7 ± 0.8	4.37	4.37	4.38 ± 0.21
$D^0 \rightarrow \eta \phi$	$C_P, (EP, EV)$	0.57	0.31 ± 0.10	0.23 ± 0.06	0.19	0.18	0.14 ± 0.05
$D^+ \rightarrow \pi^+ \rho^0$	$T_V, C_P, (AP, AV)$	1.7		0.8 ± 0.7	0.42	0.58	0.81 ± 0.15
$D^+ \rightarrow \pi^+ \omega$	$T_V, C_P, (AP, AV)$	0.35		0.3 ± 0.3	0.95	0.80	< 0.34
$D^+ \rightarrow \pi^+ \phi$	C_P	5.9	6.21 ± 0.43	5.1 ± 1.4	5.65	5.65	$5.42^{+0.22}_{-0.24}$
$D^+ \rightarrow K^+ \bar{K}^{*0}$	$T_V, (AV)$	2.5		4.1 ± 1.0	3.61	3.60	$3.675^{+0.14}_{-0.21}$
$D^+ \rightarrow \bar{K}^0 K^{*+}$	$T_P, (AP)$	1.70		12.4 ± 2.4	11	11	32 ± 14
$D^+ \rightarrow \eta \rho^+$	$T_P, C_V, (AP, AV)$	0.002		0.4 ± 0.4	0.7	2.2	< 15
$D_s^+ \rightarrow \pi^+ K^{*0}$	$T_V, (AV)$	3.3		1.5 ± 0.7	2.52	2.35	2.25 ± 0.39
$D_s^+ \rightarrow K^+ \rho^0$	$C_P, (AP)$	2.4		1.0 ± 0.6	1.9	2.5	2.7 ± 0.5
$D_s^+ \rightarrow K^+ \omega$	$C_P, (AP)$	0.72		1.8 ± 0.7	0.6	0.07	< 2.4
$D_s^+ \rightarrow K^+ \phi$	$T_V, C_P, (AV)$	0.15		0.3 ± 0.3	0.166	0.166	0.184 ± 0.045
$D^0 \rightarrow \pi^- K^{*+}$	$T_P, (EV)$		0.359 ± 0.072	0.27 ± 0.06	0.482	0.472	0.339 ± 0.141
$D^+ \rightarrow \pi^+ K^{*0}$	$C_P, (AV)$			0.22 ± 0.09	0.333	0.333	0.375 ± 0.060
$D^+ \rightarrow K^+ \rho^0$	$T_V, (AP)$			0.05 ± 0.04	0.19	0.24	0.20 ± 0.05
$D_s^+ \rightarrow K^+ K^{*0}$	T_V, C_P		0.020 ± 0.005	0.02 ± 0.02	0.023	0.023	0.090 ± 0.053

In Refs. 19 and 21, the prediction for $D_s^+ \rightarrow \pi^+ \omega$ branching ratio is zero which is considerable in experiments, while that for the $D_s^+ \rightarrow \pi^+ \rho^0$ branching ratio is much larger than the datum. The inconsistency can be explained by the topological amplitudes, $\mathcal{A}(D_s^+ \rightarrow \pi^+ \rho^0) \propto (A_P - A_V)$ and $\mathcal{A}(D_s^+ \rightarrow \pi^+ \omega) \propto (A_P + A_V)$. The pole model²¹ and the PQCD approach²² suggests that $A_P^f = -A_V^f$, $A_{P,V}^f$ being the factorizable W -annihilation contributions. Therefore the two contributions enhance (cancel) each other in the $\pi^+ \rho^0(\omega)$ mode. In our approach, the relation $A_P = A_V$ after the factorizable contributions are neglected leads to the consistence between our predictions and the experimental data, as is shown in Table 1.

In the diagrammatic approach,²⁰ it is impossible to find a reasonable solution to the $D_s^+ \rightarrow \pi^+ \rho^0$, $\pi^+ \omega$, $K^+ \bar{K}^{*0}$ and $\bar{K}^0 K^{*+}$ data simultaneously, because the global fit was performed in the flavor SU(3) symmetry limit. For the four decay modes, we have included significant SU(3) breaking effects by differentiating the strongly produced quark pairs in the annihilation-type amplitudes, so our predictions are in better agreement with the data in our global fit.

In the PDG2012,¹⁸ the branching ratio of $D_s^+ \rightarrow \eta' \rho^+$ is $(12.5 \pm 2.2)\%$, which is larger than our result by one order. However, it is questioned for exceeding the inclusive $D_s^+ \rightarrow \eta' X$ fraction $(11.7 \pm 1.8)\%$.¹⁸ The CLEOc collaboration has recently updated the branching ratio of this mode, which turns out to be $(5.6 \pm 1.1)\%$.¹⁷ It is getting closer to our prediction.

In our results, some ω -involved branching ratios are high, while those of the corresponding ρ^0 -involved ones are low, compared to data. Specifically, the predicted branching ratio of $D^0 \rightarrow \pi^0 \omega$ in the column Br(FAT) of Table 2 exceeds the experimental upper bound 0.26×10^{-3} , while that of $D^0 \rightarrow \pi^0 \rho^0$ is slightly lower than the experimental data. Besides, we may have also overestimate the $D^+ \rightarrow \pi^+ \omega$ and $D_s^+ \rightarrow K^+ \omega$ branching ratios and underestimated the $D^+ \rightarrow \pi^+ \rho^0$ and $D_s^+ \rightarrow K^+ \rho^0$ ones. It indicates that better consistency shall be obtained after the $\rho^0 - \omega$ mixing effect is included.

We introduce the ρ^0 - ω mixing following

$$|\rho^0\rangle = |\rho_I^0\rangle - \epsilon|\omega_I\rangle, \quad |\omega\rangle = \epsilon|\rho_I^0\rangle + |\omega_I\rangle, \quad (8)$$

with $|\rho_I^0\rangle$ and $|\omega_I\rangle$ denoting the isospin eigenstates. After the mixing angle ϵ is set as 0.12, another group of values for the nonperturbative parameters

$$\begin{aligned} \Lambda &= 0.44 \text{ GeV}, \quad S_\pi = -0.85, \\ \chi_P^C &= -0.40, \quad \chi_V^C = -0.63, \quad \chi_q^E = 0.26, \quad \chi_q^A = 0.17, \quad \chi_s^E = 0.29, \quad \chi_s^A = 0.10, \\ \phi_P^C &= -0.53, \quad \phi_V^C = -0.42, \quad \phi_q^E = 1.74, \quad \phi_q^A = -0.77, \quad \phi_s^E = 3.10, \quad \phi_s^A = 1.61, \end{aligned} \quad (9)$$

are obtained with the $\chi^2 = 2.3$ per degree of freedom. We list in the column Br(FAT[mix]) of Tables 1 and 2 the corresponding branching ratios, which agree with the data better. Specifically, we get a lower prediction for the $D^0 \rightarrow \pi^0 \omega$ branching ratio, 0.18×10^{-3} , now below the experimental upper bound.

3. Direct CP Asymmetries

Direct CP asymmetry of a $D \rightarrow PV$ decay mode is defined by

$$A_{CP} = \frac{\Gamma(D \rightarrow PV) - \Gamma(\bar{D} \rightarrow \bar{P}\bar{V})}{\Gamma(D \rightarrow PV) + \Gamma(\bar{D} \rightarrow \bar{P}\bar{V})}, \quad (10)$$

In this section, we predict $D \rightarrow PV$ direct CP asymmetries by estimating the penguin contributions in the FAT approach.

3.1. Formulation of penguin amplitudes

The effective weak Hamiltonian corresponding to the penguin amplitudes is

$$\Delta H_{eff} = -\frac{G_F}{\sqrt{2}} V_{cb}^* V_{ub} \left[\sum_{i=3}^6 C_i(\mu) O_i(\mu) + C_{8g}(\mu) O_{8g}(\mu) \right], \quad (11)$$

where O_{3-6} and O_{8g} are the QCD- and chromomagnetic penguin operators.¹³ The topological penguin diagrams include the color-favored and — suppressed penguin amplitude $PT_{P(V)}$ and $PC_{P(V)}$, the gluon-annihilation and — exchange penguin amplitude $PE_{P(V)}$ and $PA_{P(V)}$, which correspond to the tree ones $T_{P(V)}$, $C_{P(V)}$, $E_{P(V)}$ and $A_{P(V)}$, respectively.

We can immediately obtain the contributions from $O_{3,4}$ by substituting the Wilson Coefficients and CKM matrix elements in the tree amplitudes. PT_P doesn't receive contribution from $O_{5,6}$ since a V meson can't be generated from a scalar or pseudoscalar operator, and the nonfactorizable contributions are ignored as has been done in T_P . PT_V is written as

$$PT_V = -\frac{G_F}{\sqrt{2}} V_{cb}^* V_{ub} [a_4(\mu) - r_X a_6(\mu)] f_P m_V A_0^{DV}(m_P^2) 2(\varepsilon_V \cdot p_D), \quad (12)$$

where the chiral factor $r_X = 2m_0^P/m_c$, $a_4 = C_4 + C_3/N_c$ and $a_6 = C_6 + C_5/N_c$.

Accepting the relation between the contributions from $O_{5,6}$ and those from $O_{3,4}$ in $PC_{P,V}$ calculated in the PQCD approach,²³ we formulate $PC_{P,V}$ to be

$$\begin{aligned} PC_P &= -\frac{G_F}{\sqrt{2}} V_{cb}^* V_{ub} [a_3^P(\mu) + a_5^P(\mu)] f_V m_V F_1^{DP}(m_V^2) 2(\varepsilon_V \cdot p_D), \\ PC_V &= -\frac{G_F}{\sqrt{2}} V_{cb}^* V_{ub} [a_3^V(\mu) - a_5^V(\mu)] f_P m_V A_0^{DV}(m_P^2) 2(\varepsilon_V \cdot p_D). \end{aligned} \quad (13)$$

The explicit forms of the Wilson coefficients are $a_3^{P(V)}(\mu) = C_3(\mu) + C_4(\mu)[1/N_c + \chi_{P(V)} e^{i\phi_{P(V)}}]$ and $a_5^{P(V)}(\mu) = C_5(\mu) + C_6(\mu)[1/N_c - \chi_{P(V)} e^{i\phi_{P(V)}}]$.

In $PE_{P,V}$ amplitudes, the factorizable contributions are suppressed by helicity conservation, so we only take into account the nonfactorizable contributions. The PQCD approach²³ suggests that they can be presented as

$$PE_{P,V} \propto [C_4(\mu) - C_6(\mu)] \chi_{q(s)}^E e^{i\phi_{q(s)}^E}. \quad (14)$$

Similarly, we have the nonfactorizable contributions from penguin operators in $PA_{P,V}$ amplitudes,

$$PA_{P,V}^{nf} \propto C_3(\mu) \chi_{q(s)}^A e^{i\phi_{q(s)}^A}. \quad (15)$$

Additionally, the factorizable contributions from $O_{5,6}$ are considerable in $PA_{P,V}$ amplitudes, which can be written as

$$\begin{aligned} PA_P^f &= 2 \frac{G_F}{\sqrt{2}} V_{cb}^* V_{ub} a_6(\mu) (2g_{PPV} p_D \cdot \epsilon_V) \frac{1}{m_D^2 - m_{P^*}^2} (f_{P^*} m_{P^*}^0) \left(f_D \frac{m_D^2}{m_c} \right), \\ PA_V^f &= 2 \frac{G_F}{\sqrt{2}} V_{cb}^* V_{ub} a_6(\mu) (-2g_{PPV} p_D \cdot \epsilon_V) \frac{1}{m_D^2 - m_{P^*}^2} (f_{P^*} m_{P^*}^0) \left(f_D \frac{m_D^2}{m_c} \right), \end{aligned} \quad (16)$$

where factorization hypothesis and the pole resonance model have been applied. P^* is the pole resonant P meson, and H_s is the corresponding strong Hamiltonian. We follow [21] to set the values for the effective coupling constants g_{PPV} 's.

After contributions from the quark-loops and the chromomagnetic penguin operator are included, the Wilson coefficients are corrected following Eqs. (31) and (36) in [10].

3.2. Numerical results

Predictions of some $D \rightarrow PV$ direct CP asymmetries without and with kinds of corrections are displayed in Table 3. The $\rho^0 - \omega$ mixing effect has considerable influence on direct CP asymmetries in ω -involved decay modes.

Table 3. Direct CP asymmetries for some $D \rightarrow PV$ decays in units of 10^{-3} . The results excluding and including various corrections (QCD-penguins, chromomagnetic penguin, quark loops, pole resonances, and $\rho - \omega$ mixing) are listed. The amplitudes are also listed, those out of parentheses being dominant.

Modes	Amplitudes	A_{CP} (tree)	A_{CP} (+penguin)	A_{CP} (+cm,ql)	A_{CP} (+pole)	A_{CP} (mixing)
$D^0 \rightarrow K^0 \bar{K}^{*0}$	PE	-0.7	-0.7	-0.7	-0.7	-0.7
$D^0 \rightarrow \bar{K}^0 K^{*0}$	PE	-0.7	-0.7	-0.7	-0.7	-0.7
$D^0 \rightarrow \eta \rho^0$	$PT, PC, (PE, PA)$	0.8	0.8	0.8	0.8	1.0
$D^0 \rightarrow \eta' \omega$	$PT, PC, (PE, PA)$	1.8	1.2	1.2	1.2	2.2
$D^+ \rightarrow \pi^+ \rho^0$	PT, PC, PA	0	-0.5	-0.5	0.7	0.5
$D^+ \rightarrow \pi^+ \phi$	PC	0	-0.0001	-0.0001	-0.0001	-0.0001
$D^+ \rightarrow \eta \rho^+$	$PT, PC, (PA)$	-0.7	-0.7	-0.7	-0.7	-0.6
$D^+ \rightarrow \eta' \rho^+$	$PT, PC, (PA)$	0.2	0.1	0.3	0.3	0.5
$D_s^+ \rightarrow K^+ \omega$	PT, PC, PA	0.03	0.09	0.2	-0.6	-2.3
$D_s^+ \rightarrow K^+ \phi$	PT, PC, PA	0	0.4	0.3	-0.8	-0.8
$D_s^+ \rightarrow \eta K^{*+}$	PT, PC, PA	0.5	0.4	0.8	-0.3	1.1

The decay modes whose direct CP asymmetries reach $\mathcal{O}(10^{-3})$ can be found in Table 3. Specially, the experimental detecting efficiency of the final states in $D^+ \rightarrow \pi^+ \rho^0$ and $D_s^+ \rightarrow K^+ \phi$ is high, in which we expect the LHCb and Belle II experiments can observe CP violation in future. Actually, LHCb has measured the direct CP asymmetry in $D^+ \rightarrow \pi^+ \phi$ to be $(-0.04 \pm 0.14 \pm 0.13)\%$.²⁴

4. Summary

We have studied the branching ratios and direct CP asymmetries in the $D \rightarrow PV$ decays in the factorization-assisted topological-amplitude approach. We have formulated tree amplitudes to predict the branching ratios, where the topological parametrization associated with the factorization hypothesis has been used. The Glauber gluon effects have been considered. After the global fit to experimental data of $D \rightarrow PV$ branching ratios, our results agrees well with the experimental data, rather than the other theoretical methods. The inclusion of $\rho^0 - \omega$ mixing improves the consistency between the prediction and experimental results in the ρ^0 - and ω -involved modes. By relating penguin amplitudes to tree amplitudes and introducing the pole resonance model, we predict the direct CP asymmetries in the $D \rightarrow PV$ decays, in which the $D^+ \rightarrow \pi^+ \rho^0$ and $D_s^+ \rightarrow K^+ \phi$ decays are hopeful to be measured in the LHCb and future Bell II experiments.

Acknowledgments

The work is partly supported by the National Science Council of R.O.C. under the Grant No. NSC-101-2112-M-001-006-MY3 and National Science Foundation of China under the Grant Nos. 11075168, 11228512 and 11235005.

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