Charmless Two-body $B \to PP, VP$ decays In Soft-Collinear-Effective-Theory

Cai-Dian Lü
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, P.R. China
E-mail: lucd@ihep.ac.cn

Wei Wang
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, P.R. China
E-mail: wwang@ihep.ac.cn

Yu-Ming Wang
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, P.R. China
E-mail: wangym@ihep.ac.cn

De-Shan Yang
Graduate University of Chinese Academy of Sciences, Beijing 100049, P.R. China
E-mail: yangds@gucas.ac.cn

We provide the analysis of charmless two-body $B \to VP$ decays under the framework of the soft-collinear-effective-theory, where $V(P)$ denotes a light vector (pseudoscalar) meson. Using the available data, we fit 16 non-perturbative inputs responsible for the $B \to PP$ and $B \to VP$ decay channels in the $\chi^2$ fit method. We find that chirally enhanced penguins can change several charming penguins sizably, but most of the other non-perturbative inputs and predictions on branching ratios and CP asymmetries are not changed too much. We predict the branching fractions and CP asymmetries of other modes especially $B_s \to VP$ decays. The agreements and disagreements with results in QCD factorization and perturbative QCD approach are analyzed.

International Workshop on Effective Field Theories: from the pion to the upsilon
February 2-6 2009
Valencia, Spain

*Speaker.
1. Introduction

Charmless hadronic $B$ decays are helpful for the precise test of the standard model and the search for possible new physics scenarios. In recent years, great progresses have been made in the studies of charmless two-body $B$ decays. These decays were dynamically investigated in three popular theoretical approaches: the QCD factorization (QCDF) [1 2 3], the perturbative QCD (PQCD) [4 5 6], and the soft-collinear effective theory (SCET) [7 8]. Despite many differences, all of them are based on power expansions in $\Lambda_{QCD}/m_b$, where $m_b$ is the $b$-quark mass and $\Lambda_{QCD}$ is the typical hadronic scale. Factorization of the hadronic matrix elements is proved to hold to the leading power in $\Lambda_{QCD}/m_b$ in a number of decays.

SCET provides an elegant theoretical tool to separate the physics at different scales. The matching from QCD onto SCET is always performed in two stages. The fluctuations with off-shellness $O(m_b^2)$ is firstly integrated out and one results in the intermediate effective theory SCET$_I$. In SCET$_I$, the generic factorization formula for $B \rightarrow M_1 M_2$ is written by:

$$
\langle M_1 M_2 | O | B \rangle = T(u) \otimes \phi_{M_1}(u) e^{B-M_1} + T_J(u, z) \otimes \phi_{M_1}(u) e^{B-M_2}(z),
$$

(1.1)

where $T$ and $T_J$ are perturbatively calculable Wilson coefficients. In the second step, the fluctuations with typical off-shellness $m_b \Lambda_{QCD}$ are integrated out and one reaches SCET$_{II}$. In SCET$_{II}$, end-point singularities prohibit the factorization of $\zeta$, while the function $\zeta_J$ can be further factorized into the convolution of a hard kernel (jet function) with light-cone distribution amplitudes. In the phenomenological framework proposed in Ref. [9], the expansion at the intermediate scale $\mu_{bc} = \sqrt{m_b \Lambda_{QCD}}$ is not used. Instead the experimental data are used to fit the non-perturbative inputs. This method is firstly applied to $B \rightarrow K \pi, B \rightarrow K \bar{K}$ and $B \rightarrow \pi \pi$ decays [9]. Subsequently, it is applied to charmless two-body $B \rightarrow PP$ decays involving the iso-singlet mesons $\eta$ and $\eta' [10].$

In our work [11], we extend this method to the $B \rightarrow VP$ decays and use a wealth of the experimental data to fit the non-perturbative inputs (in our analysis, we also take the $B \rightarrow PP$ decays into account). Besides leading power contributions, we also take into account a part of chirally enhanced penguin whose operator basis and the factorization formulae are derived in Ref. [12 13].

2. Decay amplitudes of $B \rightarrow M_1 M_2$ in SCET

In SCET, the factorization formula for $B \rightarrow M_1 M_2$ is easily proved to hold to all order in $\alpha_s$: the amplitudes have the form of a convolution of the universal light-cone distribution amplitudes and the perturbative hard kernels. Using the perturbative expansion in $\alpha_s(\sqrt{m_b \Lambda})$ for the jet functions and in $\alpha_s(m_b)$ for the Wilson coefficients, one can predict the branching ratios, CP asymmetries and other observables for $B \rightarrow M_1 M_2$ decays. One can also use another parallel method: the non-perturbative parameters can be fitted by experimental measurements on the $B \rightarrow M_1 M_2$ decays. This approach is especially useful at leading order in $\alpha_s$, since then the hard kernels $T_1(u)$ are constants, while $T_J(u, z)$ are functions of $u$ only. Furthermore at this order, terms with hard kernels $T_{1J}^r(u, z), T_{1J}^q(u, z), T_{2J}^r(u, z), T_{2J}^q(u)$ do not contribute at all. Thus the decay amplitudes of $B \rightarrow M_1 M_2$ decays at LO in $\alpha_s(m_b)$ are written by:

$$
A(B \rightarrow M_1 M_2) = \frac{G_F}{\sqrt{2}} m_B \left\{ f_{M_1} \left[ e^{BM_1} \int du \phi_{M_1}(u) T_{1J}^r(u) + e^{BM_2} \int du \phi_{M_1}(u) T_{1J}^q(u) \right] \right\}
$$

$$
+ f_{M_2} \left[ e^{BM_1} \int du \phi_{M_2}(u) T_{1J}^r(u) + e^{BM_2} \int du \phi_{M_2}(u) T_{1J}^q(u) \right].
$$
where $A_{cc}^{M_1,M_2}$ denotes the non-perturbative charming penguins. $T_i$ are hard kernels which can be calculated using perturbation theory. Based on the flavor structure of the four-body operators and five-body operators, it is possible to construct master equations for hard kernels $T_i$ [11]. The four functions $\zeta^{BM_1}$, $\zeta_g$ and $\xi^{BM_2}$, $\xi_g$ are treated as non-perturbative parameters to be fitted from experiment measurements.

Power corrections are expected to be suppressed at least by the factor $\Lambda_{QCD}/m_b$, but chirally enhanced penguins are large enough to compete with the leading power QCD penguins as the sup-

ting penguin terms, the 16 real inputs responsible for $B \to PP$ decays, when emitting a pseudoscalar meson, the amplitude take a minus sign; when a vector meson emitted, there is no contribution from chirally enhanced penguin since $\mu_V = 0$.

For $B \to PP$ decays, the chirally enhanced penguin takes a plus sign; while in $B \to VP$ decays, when emitting a pseudoscalar meson, the amplitude take a minus sign; when a vector meson emitted, there is no contribution from chirally enhanced penguin since $\mu_V = 0$.

3. Numerical analysis of $B \to VP$ decays

With these data for branching fractions and CP asymmetries, $\chi^2$ fit method can be used to determine the non-perturbative inputs: form factors and charming penguins. Straightforwardly, we obtain the two solutions for numerical results of the 16 non-perturbative inputs [11] at the leading power. After the inclusion of chirally enhanced penguins, several parameters in there two solutions are changed. As shown in Fig.[11] chirally enhanced penguins have the same topology with the charming penguins. The former two diagrams do not only contribute to decays without iso-
singlet mesons $\eta$ or $\eta'$ but also decays with these mesons. The two diagrams in the lower line only contribute to decays involving $\eta$ or $\eta'$, where $q = q'$. The inclusion of chirally enhanced penguin will mainly change the size of three charming penguins $A^{PP}_{cc}, A^{PP}_{ccg}, A^{PV}_{ccg}$. Predictions for branching fractions and CP asymmetries are not changed sizably.

Our predictions on branching fractions of $B^0 \to \pi^+ \rho^−$ decays are smaller than those in QCDF [3]. The main reason is the smaller $B \to P$ and $B \to V$ form factors predicted by the SCET, while
QCDF uses much larger form factors. In the SCET, $\mathcal{BR}(B^0 \to \rho^+ \pi^-)$ is a bit smaller than $\mathcal{BR}(B^0 \to \rho^- \pi^+)$ in the first solution, the fitted $B \to V$ form factor $A_0 = 0.233$ is almost equal with the $B \to P$ form factor $F = 0.206$. Since the decay constant of $\rho$ meson is much larger than that of $\pi$: $0.209/0.131 \sim 1.5$, we expect $\mathcal{BR}(B^0 \to \rho^+ \pi^-)$ is only one half of $\mathcal{BR}(B^0 \to \rho^- \pi^+)$. Charming penguins $A_{cc}^{VP}$ and $A_{cc}^{PV}$ can slightly change the ratio: the charming penguin $A_{cc}^{PV}$ in $B^0 \to \rho^+ \pi^-$ gives a constructive contribution, while $A_{cc}^{VP}$ in $B^0 \to \rho^- \pi^+$ gives a destructive contribution. In the second solution, contributions proportional to form factors are almost equal with each other, as the $B \to V$ form factor $A_0^{B \to V} = 0.291$ is much larger than $F^{B \to P} = 0.198$ which can compensate differences caused by decay constants. But unlike in the first solution, the role of charming penguin totally changes: the charming penguin in $B^0 \to \rho^- \pi^+$ can give a constructive contribution. It is reasonable, since the charming penguins $A_{cc}^{VP}$ and $A_{cc}^{PV}$ almost interchanges the phases.

Our predictions for branching ratios of $B^0 \to \pi^0 \rho^0$ are larger than that in QCDF. In this channel, two kinds of charming penguin almost cancel with each other, since they have similar magnitudes but different signs. The tree contribution proportional to the soft form factor $\zeta$ is color-suppressed (the Wilson coefficient $C_2 + \frac{C_1}{N_c} \sim 0.12$ is small compared with that of $B^0 \to \rho^\pm \pi^\mp$: $C_1 + \frac{C_2}{N_c} \sim 1.03$), thus the branching fractions of $B^0 \to \pi^0 \rho^0$ in QCDF approach and PQCD approach are much smaller than $\mathcal{BR}(B^0 \to \rho^\pm \pi^\mp)$. One important feature of the SCET framework is: the hard-scattering form factor $\zeta_\rho$ is relatively large and comparable with the soft form factor $\zeta$. Besides, since this term has a large Wilson coefficient $b_1^f = C_2 + \frac{1}{N_c}(1 - \frac{m_b}{m_0})C_1 \sim 1.23$, it can give larger production rates which are consistent with the present experimental data.

In $b \to s$ decay amplitudes, tree operators are highly CKM-suppressed, but the CKM matrix elements for the rest two kinds of contributions (penguin operators and charming penguins) are in similar size. Together with the hierarchy in Wilson coefficients: $C_{1,2} \gg C_{3-10}$, charming penguins will provide a dominant contribution. For example, the penguin operators in $B^- \to \pi^- \bar{K}^0$ decay
process is proportional to $a_4 + r_\chi a_6$, $B^- \rightarrow \pi^- K^{*0}$ is proportional to $a_4$ while $B^- \rightarrow \rho^- K^0$ is proportional to $a_4 - r_\chi a_6$, where $a_{4,6} = C_{4,6} + C_{3,5}/N_c$ and $r_\chi = 2\mu_\rho/m_b$. If we only consider the emission diagrams, $\mathcal{BR}(B^- \rightarrow \pi^- K^{*0}) > \mathcal{BR}(B^- \rightarrow \pi^- K^0) > \mathcal{BR}(B^- \rightarrow \rho^- K^0)$ holds, since $a_4 \sim a_6$ and $r_\chi \sim 1$. But in the present framework, contributions from penguin operators proportional to $V_{tb}V_{ts}^*$ do not play the most important role. Compared with charming penguins in two solutions, we find penguin operators are smaller than charming penguins. According to the size of charming penguins, we expect the relation $\mathcal{BR}(B^- \rightarrow \rho^- K^0) \sim \mathcal{BR}(B^- \rightarrow \pi^- K^{*0})$. This is well consistent with the experimental data.

4. Comparisons with the PQCD approach

\[ d(s) \]
\[ b \]
\[ q' \]
\[ \bar{q} \]
\[ q \]
\[ \bar{q}' \]
\[ (a) \]

\[ d(s) \]
\[ b \]
\[ q' \]
\[ q \]
\[ \bar{q}' \]
\[ (b) \]

Figure 2: Feynman diagrams for the $(S-P)(S+P)$ annihilation operators in PQCD approach and charming penguins in SCET.

PQCD approach is based on $k_T$ factorization, where one keeps the intrinsic transverse momentum of quark degrees of freedom. The intrinsic transverse momentum can smear the end-point singularities which often appear in collinear factorization. Resummation of double logarithms results in the Sudakov factor which suppresses contributions from the end-point region to make the PQCD approach more self-consistent. This approach can explain many problems to achieve great successes. In PQCD approach, annihilation diagrams can be directly calculated. Among them, the $(S-P)(S+P)$ annihilation penguin operators (from the Fierz transformation of $(V-A)(V+A)$ operators) are the most important one. According to the power counting in PQCD approach, annihilation diagrams are suppressed by $\Lambda_{QCD}/m_b$ but the suppression for $(S-P)(S+P)$ annihilation penguin operators is $2r_\chi$. This factor is comparable with 1. Thus annihilations play a very important role in PQCD approach. Phenomenologically, the large annihilations can explain the correct branching ratios and direct CP asymmetries of $B^0 \rightarrow \pi^+ \pi^-$ and $\bar{B}^0 \rightarrow K^- \pi^+$ [14], the polarization problem of $B \rightarrow \phi K^*$ [15], etc. In Fig. 2(a), we draw the Feynman diagrams for this term. Comparing with charming penguins, we can see they have the same topologies in flavor space. Generally speaking, charming penguins in SCET as shown in Fig. 2(b) have the same role with $(S-P)(S+P)$ annihilation penguin operators in PQCD. Both of them are essential to explain the branching ratios in these two different approaches. But there are indeed some differences in predictions on other parameters such as direct CP asymmetries and mixing-induced CP asymmetries.

First of all, the CKM matrix elements associated with charming penguins and $(S-P)(S+P)$ annihilation penguin operators are different. If we consider $\bar{B}$ decays in which a $b$ quark annihi-
lates, the \((S - P)(S + P)\) annihilation penguin operators are proportional to \(V_{tb}V_{d*}^{t}\), while charming penguins are proportional to \(V_{cb}V_{c*}^{d}\). The differences in the CKM matrix elements will affect direct CP asymmetries and mixing-induced CP asymmetries sizably in some channels.

In PQCD approach, contributions from the \((S - P)(S + P)\) annihilation penguin operators can be calculated using perturbation theory. These contributions are expressed as the convolution of light-cone distribution amplitudes and a hard kernel. We can also include SU(3) symmetry breaking effects in the calculation in PQCD approach. In SCET, charming penguins are from the charm quark loops. Since the charm quark is heavy, one can not factorize charming penguins. In the present work based on SCET, we have assumed SU(3) symmetries for the contributions from charming penguins. The magnitudes and strong phases of charming penguins can not be calculated using perturbation theory which obtained by fitting the experimental data.

The third difference is the magnitudes of charming penguins in SCET and contributions from the \((S - P)(S + P)\) annihilation penguin operators in PQCD approach. This difference arises from the different power counting in the two approaches. We take \(b \rightarrow s\) transitions to illustrate the difference. In PQCD approach, the \((S - P)(S + P)\) annihilation penguins are enhanced to be of the same order with penguins in emission diagrams. In SCET, charming penguins are more important. Charming penguins in SCET always larger than contributions from emission penguin diagrams.

In PQCD approach, the \((S - P)(S + P)\) annihilation penguin operators are chiraly enhanced and the dominant contribution is from the imaginary part. The main strong phases in PQCD approach which are essential to explain the large CP asymmetries in many channels are also produced through from these operators. But in SCET, strong phases of charming penguins are not too large. Accordingly, our predictions on direct CP asymmetries are smaller compared with predictions in PQCD approach.

5. conclusions

We provide the analysis of charmless two-body \(B \rightarrow VP\) decays under the framework of soft-collinear-effective theory. Besides the leading power contributions, we also take some power corrections (chiraly enhanced penguins) into account. In this framework, decay amplitudes of \(B \rightarrow PP\) and \(B \rightarrow VP\) decay channels are expressed in terms of 16 non-perturbative inputs: 6 form factors and 5 complex (10 real) charming penguins. Using the \(B \rightarrow PP\) and \(B \rightarrow VP\) experimental data on branching fractions and CP asymmetry variables, we find two kinds of solutions in \(\chi^2\) fit method for these 16 non-perturbative inputs. Chiralay enhanced penguin could change some charming penguins sizably, however most of other non-perturbative inputs and results of branching ratios and CP asymmetries are not changed too much. With the two sets of inputs, we predict branching fractions and CP asymmetries. Agreements and differences with results in QCD factorization and perturbative QCD approach are also analyzed.

Acknowledgements

This work is partly supported by National Nature Science Foundation of China under the Grant Numbers 10735080, 10625525 and 10705050.


References