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

Wei Wang$^{a,b}$, Yu-Ming Wang$^{a,b}$, De-Shan Yang$^b$ and Cai-Dian L"u$^a$

$^a$ Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, P.R. China
$^b$ Graduate University of Chinese Academy of Sciences, Beijing 100049, P.R. China

We analyze the charmless two-body $B \to VP$ decays in the soft-collinear-effective-theory (SCET), where $V(P)$ denotes a light vector (pseudoscalar) meson. Using the current experimental data, we find two solutions in $\chi^2$ fit for the 16 non-perturbative inputs responsible for the 87 $B \to PP$ and $B \to VP$ decay channels in SU(3) symmetry. Chirally enhanced penguins can only change several charming penguins sizably, since they share the same topology. The $(S-P)(S+P)$ annihilation penguins in the perturbative QCD approach have the same topology with charming penguins in SCET, which play an important role in direct CP asymmetries.

1 Introduction

The charmless two-body non-leptonic $B$ decays are important for the precise test of the standard model and the search for possible new physics signals. To predict branching ratios and CP asymmetries, one has to compute the hadronic decay amplitudes. In recent years, great progresses have been made in studies of charmless two-body $B$ decays, such as the generalized factorization approach, the QCD factorization (QCDF), the perturbative QCD (pQCD) and the soft-collinear effective theory (SCET). Despite of many differences, all of them are based on power expansions in $\Lambda_{\text{QCD}}/m_b$. Factorization of the hadronic matrix elements is proved to hold in the leading power in $\Lambda_{\text{QCD}}/m_b$ in a number of decays.

It is almost an impossible task to include all power corrections, but we can include the relatively important one. Importance of chirally enhanced penguins has been noted long time ago, and numerics show that chiraly enhanced penguins are comparable with the penguin contributions at leading power, in both of QCDF and pQCD approaches. In SCET, the complete operator basis and the corresponding factorization formulae for this term are recently derived. A new factorization formula for chiraly enhanced penguin was proved to hold to all orders in $\alpha_s$, and more importantly the factorization formula does not suffer from the endpoint divergence.

One phenomenological framework is introduced not using the expansion at the intermediate scale $\mu_{hc} = \sqrt{m_b \Lambda_{\text{QCD}}}$ Instead the experimental data are used to fit the non-perturbative inputs. This method is very useful especially at tree level, where only a few inputs are required in decay amplitudes. In this framework, an additional term from the intermediate charm quark loops, which is called charming penguin is also taken into account. Charming penguins are not factorized into the LCDAs and form factors, since the heavy charm quark pair can not be viewed as collinear quarks. They are also treated as non-perturbative inputs. This method is first applied to $B \to K\pi$, $B \to KK$ and $B \to \pi\pi$ decays, and later to charmless two-body $B \to PP$ decays involving the iso-singlet mesons $\eta$ and $\eta'$. 

In the present work, we extend this method to the $B \to VP$ decays, including the chirally enhanced penguins. We will use the wealth of the experimental data to fit the non-perturbative inputs (in our analysis, we also take the $B \to PP$ decays into account).\footnote{11}

2 $B \to VP$ decay amplitudes at leading power in SCET

The weak effective Hamiltonian which describes $b \to D$ ($D = d, s$) transitions is:\footnote{12}

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \left\{ \sum_{q=u,c} V_{qb} V_{qD}^* \left[ C_1 O_1^q + C_2 O_2^q \right] - V_{tb} V_{tD}^* \left[ \sum_{i=3}^{10, 7, 8} C_i O_i \right] \right\} + \text{H.c.},$$

where $V_{qb(D)}$ are the CKM matrix elements.

In $B \to M_1 M_2$ decays, both of the final state mesons move very fast and are generated back-to-back in the rest frame of $B$ meson. Correspondingly, there exist three typical scales: the $b$ quark mass $m_b$, the soft scale $\Lambda_{\text{QCD}}$ set by the typical momentum of the light degrees of freedom in the heavy $B$ meson, the intermediate scale $\sqrt{m_b \Lambda_{\text{QCD}}}$ which arise from the interaction between collinear particles and soft modes. SCET provides an elegant theoretical tool to separate the physics at different scales and factorization for $B \to M_1 M_2$ was proved to hold to all orders in $\alpha_s$ at leading power of $1/m_b$.\footnote{8, 13} After integrating out the fluctuations with off-shellness $m_b^2$, one reaches the intermediate effective theory SCET$_I$, where the generic factorization formula for $B \to M_1 M_2$ is written by:

$$\langle M_1 M_2 | O_i | B \rangle = T(u) \otimes \phi_{M_1}(u) \zeta^{B \to M_1} + T_J(u, z) \otimes \phi_{M_1}(u) \otimes \zeta_J^{B \to M_2}(z),$$

with $T$ and $T_J$ the perturbatively calculable Wilson coefficients. In the second step, the fluctuations with typical off-shellness $m_b \Lambda_{\text{QCD}}$ 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:

$$\zeta_J(z) = \phi_{M_2}(x) \otimes J(z, x, k_+) \otimes \phi_B(k_+).$$

In order to reduce the independent inputs, one can utilize the SU(3) symmetry for $B$ to light form factors and charming penguins. In the exact SU(3) limit, only two form factors are needed for $B \to PP$ decays without iso-singlet mesons $\zeta_{B,P}(J) \equiv \zeta_{B,P}^{J,0}(J) = \zeta_{B,P}^{J,0}$. There are two additional non-perturbative functions $\zeta_{J,\eta}(J)$ in decays involving iso-singlet mesons $\eta_q$ and $\eta_s$.\footnote{11}
from the intrinsic gluon contributions. Since there is no gluonic contribution in vector meson, there are only two $B \to V$ form factors $\zeta^{BV}_{(J)} \equiv \zeta^{B_P}_{(J)} = \zeta^{B_K^+}_{(J)} = \zeta^{B_{\omega}}_{(J)} = \zeta^{B_{\phi}}_{(J)}$ in the SU(3) symmetry and five complex charming penguins. With the assumption of flavor SU(3) symmetry for $B$ to light form factors and charming penguin terms, the non-perturbative, totally 16 real inputs responsible for $B \to PP$ and $B \to VP$ decays are $\zeta^{BP}, \zeta^{BP}, \zeta^{BP}, \zeta^{BP}, \zeta^{BP}, \zeta^{BP}, \zeta^{BP}, \zeta^{BP}, A^{PP}, A^{PP}, A^{PP}, A^{PP}, A^{PV}, A^{PV}, A^{PV}$. Power corrections are expected to be suppressed by at least the factor $\Lambda_{QCD}/m_b$, but chirally enhanced penguins are large enough to compete with the leading power QCD penguins as the suppression factor becomes $2\mu_P/m_b$, where $\mu_P \sim 2$ GeV is the chiral scale parameter. The complete operator basis and the corresponding factorization formulae for the chiraly enhanced penguin are recently derived. The factorization formula will introduce a new form factor $\zeta_\chi$ and a new light-cone distribution amplitude $\phi_{PP}$.

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

With experimental data for branching fractions and CP asymmetries, $\chi^2$ fit method is used to determine the non-perturbative inputs: form factors and charming penguins. Straightforwardly, we obtain two solutions for numerical results of the 16 non-perturbative inputs. As shown in Fig. 1 chiraly enhanced penguins have the same topology with the charming penguins. 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 $A^{PP}_cc$, $A^{PP}_cc$, $A^{PV}_cc$. Predictions for branching fractions and CP asymmetries will not be changed sizably.

Our predictions for branching ratios of $\bar{B}^0 \to \pi^0 \rho^0$ are larger than that in QCDF. The tree contribution proportional to the soft form factor $\zeta$ is color-suppressed, thus the branching fractions of $\bar{B}^0 \to \pi^0 \rho^0$ in QCDF approach and pQCD approach are much smaller than $BR(\bar{B}^0 \to \rho^+ \rho^-)$. One important feature of the SCET framework is that the hard-scattering form factor $\zeta_j$ is relatively large and comparable with the soft form factor $\zeta$. Besides, this term has a large Wilson coefficient $b_f^j \sim 1.23$, it can give larger production rates which are consistent with the present experimental data. The agreement is very encouraging. We also predict larger branching ratios for color-suppressed $B_s$ decays than QCDF and pQCD which can be tested on the future experiments.

For the decays with sizable branching fractions, our predictions on direct CP asymmetries are typically small and most of them have the correct sign with experimental data. Predictions in QCDF approach on these channels are also small in magnitude, but most of them have different signs with our results and experimental data. In pQCD approach, the strong phases mainly come from the $(S-P)(S+P)$ annihilation operators. These operators are chiraly enhanced and the imaginary part are dominant. Thus the direct CP asymmetries in pQCD approach are typically large in magnitude.

In pQCD approach, annihilation diagrams can be directly calculated. The large $(S-P)(S+P)$ annihilation penguin operators can explain the correct branching ratios and direct CP asymmetries of $B^0 \to \pi^+ \pi^-$ and $\bar{B}^0 \to K^- \pi^+ \pi^+ \pi^-$, the polarization problem of $B \to \phi K^+$ etc. In Fig. 1 we draw the Feynman diagrams for this term. Comparing with charming penguins, we can see they have the same topologies in flavor space. Charming penguins in SCET as shown in Fig. 1 play the similar role with $(S-P)(S+P)$ annihilation penguin operators in pQCD. But, the CKM matrix elements associated with charming penguins and $(S-P)(S+P)$ annihilation penguin operators are proportional to $V_{cb} V_{cD}^*$ and $V_{cb} V_{cD}^*$, respectively. The differences in the CKM matrix elements will affect direct CP asymmetries and mixing-induced CP asymmetries sizably, which can be tested at the future experiments.
4 Conclusions

In the soft-collinear-effective theory, we analyze the charmless two-body $B \to PP$, $B \to VP$ 
decays by taking some power corrections (chiraly enhanced penguins) into account. Using the 
experimental data on branching fractions and CP asymmetry variables, we find two solutions in 
$\chi^2$ fit for the 16 non-perturbative inputs. Chiraly enhanced penguin could change some 
charming penguins sizably, since they have the same topology with each other. However, most 
of other non-perturbative inputs and predictions on 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. For example, we predict larger branching ratios for $B^0 \to \pi^0, \rho^0$ 
than QCDF and pQCD approach, but our results are consistent with the experimental data.

The $(S-P)(S+P)$ operators annihilation penguins provide the main strong phase in pQCD 
approach. In the SCET framework, charming penguins play similar role especially the strong 
phase in $b \to s$ transitions. The $(S-P)(S+P)$ annihilations have the same topology with 
charming penguin. There are also differences in these two objects including weak phases, strong 
phases, SU(3) symmetry property and factorization property. These differences will be tested 
in the future experiments.

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