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QCD Factorization in charmless $B \to PV$ decays

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Performing a global fit of the experimental branching ratios and CP asymmetries of the charmless $B \to PV$ decays according to QCD factorization, we find it impossible to reach a satisfactory agreement, the confidence level (CL) of the best fit being smaller than 0.1%. The main reason for this failure is the difficulty to accomodate several large experimental branching ratios of the strange channels. Furthermore, experiment was not able to exclude a large direct CP asymmetry in $\overline{B^0} \to \rho^+\pi^-$, which is predicted very small by QCD factorisation. Then, trying a fit with QCD factorisation complemented by a charming-penguin inspired model, we reach a best fit which is not excluded by experiment (CL of about 8%) but is not fully convincing. These negative results must be tempered by the remark that some of the experimental data used are recent and might still evolve significantly.

1 Introduction

It is an important theoretical challenge to master the non-leptonic decay amplitudes and particularly the B non-leptonic decays. Understanding these transitions will allow us to estimate the CKM matrix elements and the CP violating parameters. Moreover, we have at our diposal many experimental mesaurements (see [1] and references therein) which provide constraints to the models. Among those models, there is the "QCD factorisation model" [2,3] (noted QCDF) which improves the naïve factorization hypothesis by taking into account some QCD corrections.

In this brief paper, we present the results of [1] where a systematic analysis of the charmless $B \to PV$ decays was performed in order to confront QCDF with the experimental data available.

2 Theoretical framework

When dealing with matrix elements of 4-quark operators, it was usually assumed that these matrix elements could be written as the product of a semi-leptonic matrix element and a non-leptonic one (naïve factorization hypothesis). That gives reasonable results but we know there are problems like wrong renormalization scale dependence because the gluon exchanges between the mesons are neglected. But recently [2,3], it was noted that, in $B \to M_1 M_2$ decays, the soft gluon exchanges are power suppressed in the heavy quark limit, so that the $B \to PV$ transitions can be expanded into two parameters : α_s (QCD corrections, i.e. hard gluon exchange, calculable perturbatively) and Λ_{QCD}/m_b (heavy mass corrections but not much is known about them). The QCDF approach keeps the order O in Λ_{QCD}/m_b and the order 1 in α_s and the decay amplitudes for $B \to P\ V$ can be written as

$$\mathcal{A}(B \to PV) \propto \sum_{p=u,c} \sum_{i=1}^{10} \lambda_p\ a_i^p\ \langle P\ V|O_i|B\rangle_{\rm nf}. \qquad (1)$$

where the index nf represents the factorized hadronic matrix elements, in the "naïve factorization" sense, the λ_p are products of CKM matrix elements, the O_i's are the operators of the effective hamiltonian which describes the transition and the a_i^p's are the non-factorized part of the amplitude which can be perturbatively calculated (expansion in α_S). All the explicit expressions can be found in [1].

Furthermore, though the contributions of the weak annihilation terms to the decay amplitudes are power suppressed [2] and do not appear in the preceding formula, they have to be added [9–11] because they could give rise to large strong phases with the QCD corrections :

$$\mathcal{A}^{ann}(B \to PV) \propto f_B\ f_P\ f_V \sum \lambda_p\ b_i\ , \qquad (2)$$

where the f_i are decay constants and b_i annihilation parameters which are collected in [1].

However, some of the topologies involved in the evaluation of (1) and (2) present endpoint singularities which must be smoothed out by some non-perturbative effects. But QCDF does not know how to calculate them, so we followed [3] and parametrized the corresponding integrals by :

$$X_A = \ln \frac{m_B}{\Lambda_h}(1 + \rho_A\, e^{i\phi_A}).$$

We used the *same* parameter X_A for the annihilation and the factorized terms.

Input	Range	Scenario 1	Scenario 2
γ (deg)		99.955	81.933
m_s (GeV)	$[0.085, 0.135]$	0.085	0.085
μ (GeV)	$[2.1, 8.4]$	3.355	5.971
ρ_A	$[0, 1]$	1.000	1.000
ϕ_A(deg)	$[-180, 180]$	-22.928	-87.907
λ_B (GeV)	$[0.2, 0.5]$	0.500	0.500
f_B (GeV)	$[0.14, 0.22]$	0.220	0.203
R_u	$[0.35, 0.49]$	0.350	0.350
R_c	$[0.018, 0.025]$	0.018	0.018
$A_0^{B\to\rho}$	$[0.3162, 0.4278]$	0.373	0.377
$F_1^{B\to\pi}$	$[0.23, 0.33]$	0.330	0.301
$A_0^{B\to\omega}$	$[0.25, 0.35]$	0.350	0.326
$A_0^{B\to K^*}$	$[0.3995, 0.5405]$	0.400	0.469
$F_1^{B\to K}$	$[0.28, 0.4]$	0.333	0.280
$\mathrm{Re}[\mathcal{A}^P]$	$[-0.01, 0.01]$		0.00253
$\mathrm{Im}[\mathcal{A}^P]$	$[-0.01, 0.01]$		-0.00181
$\mathrm{Re}[\mathcal{A}^V]$	$[-0.01, 0.01]$		-0.00187
$\mathrm{Im}[\mathcal{A}^V]$	$[-0.01, 0.01]$		0.00049

Table 1. *Various theoretical inputs used in our global analysis of $B \to PV$ decays in QCDF. The parameter ranges have been taken from literature [3,12–14]. The two last columns give the best fits of both scenarios.*

3 QCD factorization and experiment

Before confronting QCDF with experiment, a compilation of various charmless branching ratios and direct CP asymmetries was performed which includes the latest results from BaBar, Belle and CLEO. Then in a first stage, in order to compare our theoretical predictions with the data, we computed the χ^2 and minimized it, letting free all the theoretical parameters in their allowed range : we ended up with the theoretical parameters giving the best fit. Using those best-fitted parameters, we were then able to make theoretical predictions (branching ratios[1], CP asymmetries). In a second stage, we tested the quality of the agreement between measurements and predictions by a Monte-Carlo based "goodness-of-fit" test (see [1] for further details).

In table 1 are collected the values found for two best fits : in scenario 1, we consider QCDF alone where all the theoretical parameters are allowed to vary in specified ranges, except for γ totally free. The second scenario, to be explained in the next section, refers to a fit performed by adding to the model a charming penguin inspired term and where γ is constrained in the range $[34°, 82°]$. We can see that many parameters are dragged to their limit values.

The theoretical predictions, obtained from the theoretical parameters yielding the best fits, are compared to experiment in table 3.

[1]We excluded the channels containing η' mesons which are more special.

	Experiment	Scenario 1	Scenario 2
$\mathcal{A}_{CP}^{\rho^+\pi^-}$	$-0.82 \pm 0.31 \pm 0.16$	-0.04	-0.23
$\mathcal{A}_{CP}^{\rho^-\pi^+}$	$-0.11 \pm 0.16 \pm 0.09$	-0.0002	0.04

Table 2. *Values of the CP asymmetries for $B \to \pi\rho$ decays in QCDF (scenario 1) and QCDF+Charming Penguins (scenario 2). The notations are explained in ref. [9] of [1].*

4 The charming penguin modification

As seen in table 3 the failure of our overall fit with QCDF can be traced to two main facts. First, the strange branching ratios are underestimated by QCDF. Second the direct CP asymmetries in the non-strange channels might also be underestimated. A priori this could be cured if some non-perturbative mechanism was contributing to $|P|$. Indeed, in the strange channels, $|P|$ is Cabibbo enhanced and such a non-perturbative contribution could increase the branching ratios, and, increasing $|P|/|T|$ in the non-strange channels with non-small strong phases could increase significantly the direct CP asymmetries. We have therefore tried adding a long-distance interaction term, inspired from the charming-penguin model [4–8], which depends only on two fitted complex numbers[2].

Let us start by describing our charming-penguin inspired model for strange final states. In the "charming penguin" picture the weak decay of a $\overline{B}^0$ (B^-) meson through the action of the operator $Q_1^c = (\bar{c}b)_{V-A}(\bar{s}c)_{V-A}$ creates an hadronic system containing the quarks $s, d(\bar{u}), c, \bar{c}$, for example $\overline{D}_s^{(*)} + D^{(*)}$ systems. This system goes to long distances, the $c\,\bar{c}$ eventually annihilates, a pair of light quarks is created by non-perturbative strong interaction and one is left with two light mesons.

Assuming the flavor-$SU(3)$ symmetry and the OZI rule in the decay amplitude, one can express the long distance term by two universal complex amplitudes respectively as $\mathcal{A}^{\mathcal{P}}$ ($\mathcal{A}^{\mathcal{V}}$) when the active quark ends up in the Pseudoscalar (Vector) meson, weighted by a Clebsch-Gordan coefficient computed simply by the overlap factor (see [1]). In practice, to the QCDF's decay amplitudes, we add the long distance amplitudes, given by:

$$\mathcal{A}^{\mathrm{LD}}(B \to PV) = \frac{G_F}{\sqrt{2}} m_B^2 \lambda_p (Cl^P\,\mathcal{A}^P + Cl^V\,\mathcal{A}^V). \qquad (3)$$

The fit with long distance penguin contributions is presented in table 3 under the label "Scenario 2". The agreement with experiment is improved, as expected, but not in such a fully convincing manner. The goodness of the fit is about 8 % which implies that this model is not excluded

[2]In order to avoid to add too many new parameters which would make the fit void of signification.

by experiment. However a look at table 1 shows that several fitted parameters are still stuck at the end of the allowed range of variation. In particular $\rho_A = 1$ means that the uncalculable subleading contribution to QCDF is again stretched to its extreme.

5 Conclusion

We have made a global fit according to QCD factorization of published experimental data concerning charmless $B \to PV$ decays including CP asymmetries and excluding the channels containing the η' meson. Our conclusion is that it is impossible to reach a good fit. As can be seen in the scenario 1 of table 3, the reasons of this failure is that the branching ratios for the strange channels are predicted significantly smaller than experiment except for the $B \to \phi K$ channels, and in table 2 it can be seen that the direct CP asymmetry of $\overline{B}^0 \to \rho^+\pi^-$ is predicted very small while experiment gives it very large but only two sigmas from zero. Not only is the "goodness of the fit" smaller than .1 %, but the fitted parameters show a tendency to evade the allowed domain of QCD factorization.

Both the small predicted branching ratios of the strange channels and the small predicted direct CP asymmetries in the non strange channels could be blamed on too small P amplitudes with too small "strong phases" relatively to the T amplitudes. We have therefore tried the addition of two "charming penguin" inspired long distance complex amplitudes combined, in order to make the model predictive enough, with exact flavor-$SU(3)$ and OZI rule. This fit is better than the pure QCDF one: with a goodness of the fit of about 8 %, the model is not excluded by experiment. But the parameters show again a tendency to reach the limits of the allowed domain and the best fit gives rather small value to the long distance contribution.

Altogether, the present situation is unpleasant. QCDF seems to be unable to comply with experiment. QCDF implemented by an ad-hoc long distance model is not fully convincing either. No clear hint for the origin of this problem is provided by the total set of experimental data. If this means that the subdominant unpredictable contributions are larger than expected, the situation will remain stuck until some new theoretical ideas are found.

Maybe however, the coming experimental data will move enough to resolve, at least partly, this discrepancy. We would like to insist on the crucial importance of direct CP asymmetries in non-strange channels. If they confirm the tendency to be large, this would make the case for QCDF really difficult.

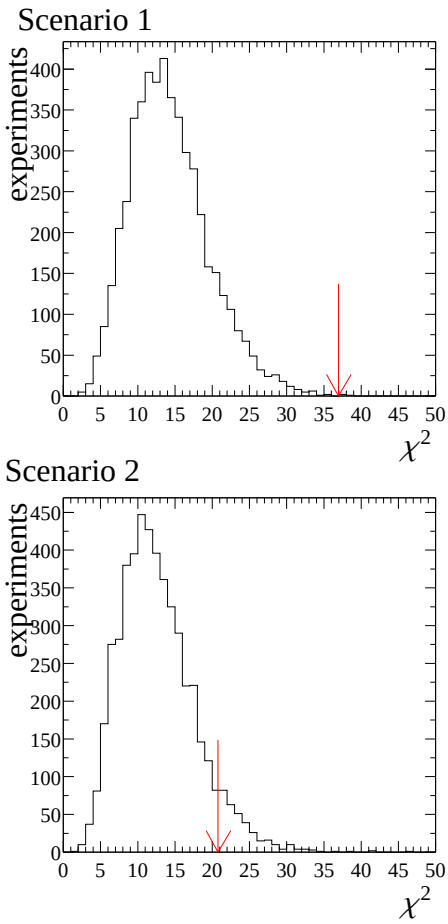

Figure 1. *Goodness of fit test of the two proposed scenarios: the arrow points at the value $\chi^2_{\rm data}$ found from the measurements, and the histogram shows the corresponding χ^2 in the case that the models predictions are correct.*

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	Experiment	Scenario 1		Scenario 2	
		Prediction	χ^2	Prediction	χ^2
$\mathcal{BR}(\overline{B}^0 \to \rho^0 \pi^0)$	2.07 ± 1.88	0.132	1.1	0.177	1.0
$\mathcal{BR}(\overline{B}^0 \to \rho^+ \pi^-)$		11.023		10.962	
$\mathcal{BR}(\overline{B}^0 \to \rho^- \pi^+)$		18.374		17.429	
$\mathcal{BR}(\overline{B}^0 \to \rho^\pm \pi^\mp)$	25.53 ± 4.32	29.397	0.8	28.391	0.4
$\mathcal{BR}(B^- \to \rho^0 \pi^-)$	9.49 ± 2.57	9.889	0.0	7.879	0.4
$\mathcal{BR}(B^- \to \omega \pi^-)$	6.22 ± 1.7	6.002	0.0	5.186	0.4
$\mathcal{BR}(B^- \to \Phi \pi^-)$		0.004		0.003	
$\mathcal{BR}(B^- \to \rho^- \pi^0)$		9.646		11.404	
$\mathcal{BR}(B^- \to K^{*-} K^0)$		0.457		0.788	
$\mathcal{BR}(B^- \to K^{*0} K^-)$		0.490		0.494	
$\mathcal{BR}(\overline{B}^0 \to \rho^0 \overline{K}^0)$		5.865		8.893	
$\mathcal{BR}(\overline{B}^0 \to \omega \overline{K}^0)$	6.34 ± 1.82	2.318	4.9	5.606	0.2
$\mathcal{BR}(\overline{B}^0 \to \rho^+ K^-)$	15.88 ± 4.65	6.531	4.0	14.304	0.1
$\mathcal{BR}(\overline{B}^0 \to K^{*-} \pi^+)$	19.3 ± 5.2	9.760	3.4	10.787	2.7
$\mathcal{BR}(B^- \to K^{*-} \pi^0)$	7.1 ± 11.4	7.303	0.0	8.292	0.0
$\mathcal{BR}(\overline{B}^0 \to \Phi \overline{K}^0)$	8.72 ± 1.37	8.360	0.1	8.898	0.0
$\mathcal{BR}(B^- \to \overline{K}^{*0} \pi^-)$	12.12 ± 3.13	7.889	1.8	11.080	0.1
$\mathcal{BR}(B^- \to \rho^0 K^-)$	8.92 ± 3.6	1.882	3.8	5.655	0.8
$\mathcal{BR}(B^- \to \rho^- \overline{K}^0)$		7.140		14.006	
$\mathcal{BR}(B^- \to \omega K^-)$	2.92 ± 1.94	2.398	0.1	6.320	3.1
$\mathcal{BR}(B^- \to \Phi K^-)$	8.88 ± 1.24	8.941	0.0	9.479	0.2
$\mathcal{BR}(\overline{B}^0 \to \overline{K}^{*0} \eta)$	16.41 ± 3.21	22.807	4.0	18.968	0.6
$\mathcal{BR}(B^- \to K^{*-} \eta)$	25.4 ± 5.6	17.855	1.8	15.543	3.1
$\Delta C_{\rho\pi}$	0.38 ± 0.23	0.250	8.1/4	0.228	3.9/4
$C_{\rho\pi}$	0.45 ± 0.21	0.019		0.092	
$\mathcal{A}_{CP}^{\rho\pi}$	-0.22 ± 0.11	-0.015		-0.115	
$\mathcal{A}_{CP}^{\rho K}$	0.19 ± 0.18	0.060		0.197	
$\mathcal{A}_{CP}^{\omega\pi^-}$	-0.21 ± 0.19	-0.072	0.5	-0.198	0.0
$\mathcal{A}_{CP}^{\omega K^-}$	-0.21 ± 0.28	0.029	0.7	0.189	2.0
$\mathcal{A}_{CP}^{\eta K^{*-}}$	-0.05 ± 0.3	-0.138	0.1	-0.217	0.3
$\mathcal{A}_{CP}^{\eta \overline{K}^{*0}}$	0.17 ± 0.28	-0.186	1.6	-0.158	1.4
$\mathcal{A}_{CP}^{\phi K^-}$	-0.05 ± 0.2	0.006	0.1	0.005	0.1
			36.9		20.8

Table 3. *Best fit values using the global analysis of $B \to PV$ decays in QCDF with free γ (scenario 1) and QCDF+Charming Penguins (scenario 2) with constrained γ.*