

Phenomenological discussion of $B \rightarrow PV$ decays in QCD improved factorization approach¹

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Abstract

Trying a global fit of the experimental branching ratios and CP-asymmetries of the charmless $B \rightarrow PV$ decays according to QCD factorization, we find it impossible to reach a satisfactory agreement, the confidence level (CL) of the best fit is smaller than .1 %. This failure reflects the difficulty to accommodate several large experimental branching ratios of the strange channels. Furthermore, experiment was not able to exclude a large direct CP asymmetry in $\overline{B}^0 \rightarrow \rho^+ \pi^-$, which is predicted very small by QCD factorization. Proposing a fit with QCD factorization 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 well known that the non-leptonic decay and particularly the non-leptonic B decay is one of the most exciting and challenging sector in the Standard Model, especially due to its non-perturbative regime. A good understanding of these transitions will not only provide a good estimate of the CKM parameters and the CP violating parameters (particularly the so-called angle α of the unitarity triangle²), but also of the hadronic dynamics, such as form factors and long distances contributions.

Experimentally, many branching ratios and CP asymmetries of two body non-leptonic B-decays, especially charmless $B \rightarrow PV$ decays, have been reported recently with increasing accuracy by BaBar,

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²It is well known that extracting α from measured indirect CP asymmetries needs a sufficient control of the relative size of the so-called tree (T) and penguins (P) amplitudes.

Belle and CLEO (see [1] and references therein), providing a crucial challenge to the theory, which is a difficult issue in this sector.

Since long, one has used what is now called “naive factorization” which replaces the matrix element of a four-fermion operator in a heavy-quark decay by the product of the matrix elements of two currents, one semi-leptonic matrix element and one purely leptonic. For long it was noticed that naive factorization did provide reasonable results although it was impossible to derive it rigorously from QCD except in the $N_c \rightarrow \infty$ limit. It was also well-known that the matrix elements computed via naive factorization have a wrong anomalous dimension. Recently an important theoretical progress has been performed [2,3] which is commonly called “QCD factorization”. It is based on the fact that the b quark is heavy compared to the intrinsic scale of strong interactions. This allows to deduce that non-leptonic decay amplitudes in the heavy-quark limit have a simple structure. It implies that corrections termed “non-factorizable”, which were thought to be intractable, can be calculated rigorously. The anomalous dimension of the matrix elements is now correct to the order at which the calculation is performed. Unluckily the subleading $\mathcal{O}(\Lambda/m_b)$ contributions cannot in general be computed rigorously because of infrared singularities, and some competitive chirally enhanced terms, which could justify a significantly larger bound with the risk of seeing these unpredictable terms become dominant [2,3]. It is then of utmost importance to check experimentally QCD factorization.

Since a few years it has been applied to $B \rightarrow PP$ (two charmless pseudoscalar mesons) decays. The general feature is that the decay to non-strange final states is predicted slightly larger than experiment while the decay to strange final states is significantly underestimated. In [3] it is claimed that this can be cured by a value of the unitarity-triangle angle γ larger than generally expected, larger maybe than 90 degrees. Taking also into account various uncertainties the authors conclude positively as for the agreement of QCD factorization with the data. In [4,5] it was objected that the large branching ratios for strange channels argued in favor of the presence of a specific non perturbative contribution called “charming penguins” [5,6,7,8,9]. We will return to this approach later.

The $B \rightarrow PV$ (charmless pseudoscalar + vector mesons) channels are more numerous and allow a more extensive check. In ref. [10] it was shown that naive factorization implied a rather small $|P|/|T|$ ratio, for $\overline{B}^0 \rightarrow \rho^\pm \pi^\mp$ decay channel, to be compared to the larger one for the $B \rightarrow \pi^+ \pi^-$. This prediction is still valid in QCD factorization where the $|P|/|T|$ ratio is of about 3 % (8 %) for the $\overline{B}^0 \rightarrow \rho^+ \pi^-$ ($\overline{B}^0 \rightarrow \rho^- \pi^+$) channel against about 20 % for the $\overline{B}^0 \rightarrow \pi^+ \pi^-$ one. If this prediction was reliable it would put the $\overline{B}^0 \rightarrow \rho^+ \pi^-$ channel in a good position to measure the CKM angle α via indirect CP violation. This remark triggered the present work: we wanted to check QCD factorization in the $B \rightarrow PV$ sector to estimate the chances for a relatively easy determination of the angle α .

The non-charmed $B \rightarrow PV$ amplitudes have been computed in naive factorization [11], in some extension of naive factorization including strong phases [12], in QCD factorization [13,14,15] and some of them in the so-called perturbative QCD [16]. In [17], a global fit to $B \rightarrow PP, PV, VV$ was investigated using QCDF in the heavy quark limit and it has been found a plausible set of soft QCD parameters that apart from three pseudoscalar vector channels, fit well the experimental branching ratios. Recently in [15] it was claimed from a global fit to $B \rightarrow PP, PV$ that the predictions of QCD factorization are in good agreement with experiment when one excludes the channels containing a K^* in the final states, from the global fit.

In this talk, we present the result of [1], where a systematic analysis of the charmless $B \rightarrow PV$ decays was performed in order to understand and try to settle the present status of the comparison of QCD factorization with experiment.

2 Theoretical framework

When the QCD factorization (QCDF) method is applied to the decays $B \rightarrow PV$, the hadronic matrix elements of the local effective operators can be written as

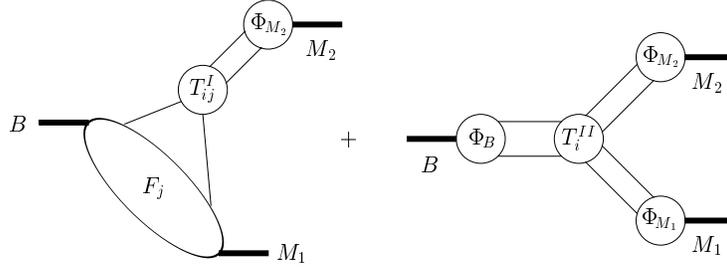


Figure 1: Graphical representation of the factorization formula (1), with only one of the two form-factor shown.

$$\begin{aligned}
\langle PV|\mathcal{O}_i|B\rangle &= F_1^{B\rightarrow P}(0) T_{V,i}^I \star f_V \Phi_V + A_0^{B\rightarrow V}(0) T_{P,i}^I \star f_P \Phi_P \\
&\quad + T_i^{II} \star f_B \Phi_B \star f_V \Phi_V \star f_P \Phi_P,
\end{aligned} \tag{1}$$

where Φ_M are leading-twist light-cone distribution amplitudes, and the \star -products imply an integration over the light-cone momentum fractions of the constituent quarks inside the mesons. A graphical representation of this result is shown in figure 1.

Here $F_1^{B\rightarrow P}$ and $A_0^{B\rightarrow V}$ denote the form factors for $B\rightarrow P$ and $B\rightarrow V$ transitions, respectively. $\Phi_B(\xi)$, $\Phi_V(x)$, and $\Phi_P(y)$ are the light-cone distribution amplitudes (LCDA) of valence quark Fock states for B , vector, and pseudoscalar mesons, respectively. $T_i^{I,II}$ denote the hard-scattering kernels, which are dominated by hard gluon exchange when the power suppressed $\mathcal{O}(\Lambda_{QCD}/m_b)$ terms are neglected. So they are calculable order by order in perturbation theory. One of the most interesting results of the QCDF approach is that, in the heavy quark limit, the strong phases arise naturally from the hard-scattering kernels at the order of α_s . As for the nonperturbative part, they are, as already mentioned, taken into account by the form factors and the LCDA of mesons up to corrections which are power suppressed in $1/m_b$.

In QCDF, the decay amplitudes for $B\rightarrow P V$ in the heavy quark limit can be written as

$$\mathcal{A}(B\rightarrow PV) \propto \sum_{p=u,c} \sum_{i=1}^{10} \lambda_p a_i^p \langle P V|\mathcal{O}_i|B\rangle_{nf}. \tag{2}$$

The above $\langle PV|\mathcal{O}_i|B\rangle_{nf}$ are the factorized hadronic matrix elements, which have the same definitions as those in the NF approach. The “nonfactorizable” effects are included in the coefficients a_i which are process dependent. The coefficients a_i and the explicit expressions for the decay amplitudes of $B\rightarrow P V$ can be found in ref. [1].

According to the arguments in [2], the contributions of weak annihilation to the decay amplitudes are power suppressed, and they do not appear in the QCDF formula (1). But, as emphasized in [18,19,20], the contributions from weak annihilation could give large strong phases with QCD corrections, and hence large CP violation could be expected, so their effects cannot simply be neglected. However, in the QCDF method, the annihilation topologies violate factorization because of the endpoint divergence, which could be unfortunately controlled just as a phenomenological parameters [3]. In this work, we will follow the treatment of ref. [3] and express the weak annihilation topological decay amplitudes as

$$\mathcal{A}^a(B\rightarrow PV) \propto f_B f_P f_V \sum \lambda_p b_i, \tag{3}$$

where the parameters b_i are collected in [1].

3 QCD factorisation versus experiment

In order to propose a test of QCD factorization with respect to experiment, a compilation of various charmless branching fractions and direct CP asymmetries was performed. This compilation

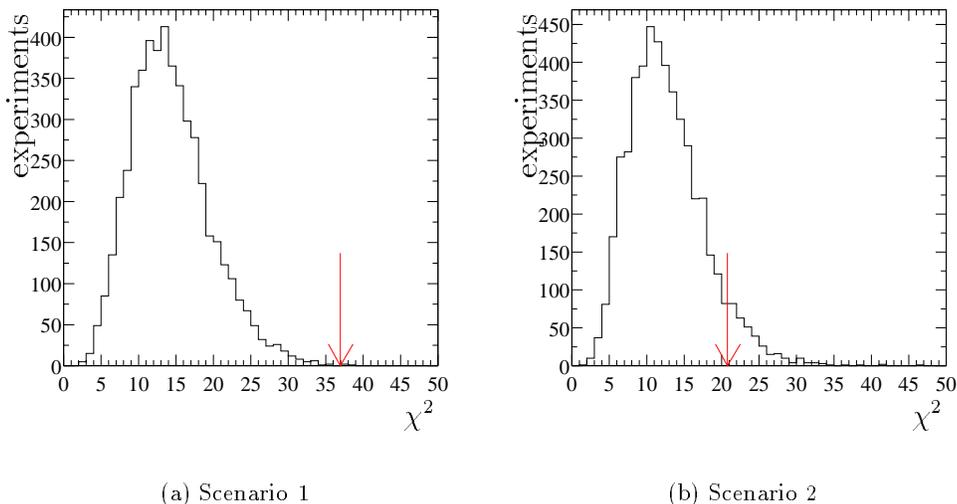


Figure 2: *Goodness of fit test of the two proposed scenarios: the arrow points at the value χ^2_{data} found from the measurements, and the histogram shows the corresponding χ^2 in the case that the models predictions are correct.*

includes the latest results from BaBar, Belle and CLEO.

In order to compare the theoretical predictions with the experimental measurements, we have computed the χ^2 and then minimized it using MINUIT [21], letting free all theoretical parameters in their allowed range. The theoretical predictions, with the theoretical parameters yielding the best fits, are compared to experiment in table 2 for two scenarios to be explained below. The asymmetries of the $\rho^\pm\pi^\mp$ channels can be expressed (see ref. [9] in [1]) in terms of the quantities reported in table 4 of [1]. The comparison between their theoretical predictions and experiment is reported in table 3.

Scenario 1 refers to a fit according to QCD factorization, varying all theoretical parameters in the range presented in table 1. Even the unitarity triangle angle γ is varied freely and ends up not far from 90 degrees. To label our ignorance of the non perturbatively calculable subdominant contribution to the annihilation and hard scattering, we have taken for simplicity $X_A = X_H$ in the range proposed in ref. [3]:

$$X_{A,H} = \int_0^1 \frac{dx}{x} = \ln \frac{m_B}{\Lambda_h} (1 + \rho_{A,H} e^{i\phi_{A,H}}). \quad (4)$$

Scenario 2 in table 2 refers to a fit adding a charming penguin inspired long distance contribution which will be presented and discussed in section 4. In this fit γ is constrained within the range $[34^\circ, 82^\circ]$.

The values of the theoretical parameters found for the two best fits is given in table 1: many parameters are found to be at the edge of their allowed range³. In order to estimate the quality of the agreement between measurements and predictions, the standard Monte Carlo based “goodness of fit” test was performed (see ref. [1] for further details). The results of the “goodness of fit” tests are given in figure 2, where, one obtains an upper limit for the confidence level in scenario 1, $CL \leq 0.1\%$ and $CL \leq 7.7\%$ for the scenario 2.

For the sake of definiteness let us remind that the branching ratios for any charmless B decays,

³In Table 1, the fit value of ρ_A appears at the edge of the input range, $\rho_A = 1$. However enlarging its range, such as $|\rho_A| \leq 10$, brings a large annihilation contributions $\{\rho_A, \phi_A\} = \{2.3(4.4), -41(-108)^\circ\}$ for scenario 1 (2).

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	[-1, 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
$A_0^{B \rightarrow \rho}$	[0.3162, 0.4278]	0.373	0.377
$F_1^{B \rightarrow \pi}$	[0.23, 0.33]	0.330	0.301
$A_0^{B \rightarrow \omega}$	[0.25, 0.35]	0.350	0.326
$A_0^{B \rightarrow K^*}$	[0.3995, 0.5405]	0.400	0.469
$F_1^{B \rightarrow K}$	[0.28, 0.4]	0.333	0.280
$\text{Re}[\mathcal{A}^P]$	[-0.01, 0.01]		0.00253
$\text{Im}[\mathcal{A}^P]$	[-0.01, 0.01]		-0.00181
$\text{Re}[\mathcal{A}^V]$	[-0.01, 0.01]		-0.00187
$\text{Im}[\mathcal{A}^V]$	[-0.01, 0.01]		0.00049

Table 1: *Various theoretical inputs used in our global analysis of $B \rightarrow PV$ decays in QCDF. The parameter ranges have been taken from literature [3, 13, 14, 22]. The two last columns give the best fits of both scenarios.*

$B \rightarrow PV$ channel, in the rest frame of the B -meson, is given by

$$BR(B \rightarrow PV) \propto |\mathcal{A}(B \rightarrow PV) + \mathcal{A}^a(B \rightarrow PV) + \mathcal{A}^{\text{LD}}(B \rightarrow PV)|^2. \quad (5)$$

The amplitudes \mathcal{A} , \mathcal{A}^a and \mathcal{A}^{LD} are defined in appendix A, B of ref. [1] and in eq. (6) respectively. In the case of pure QCD factorization (scenario 1) we take of course $\mathcal{A}^{\text{LD}} = 0$.

Our negative conclusion about the QCD factorization fit of the $B \rightarrow PV$ channels is at odds with the conclusion of the authors of ref. [15], who have performed a successful fit of both $B \rightarrow PP$ and $B \rightarrow PV$ channels using the same theoretical starting point, and excluding from their fits the K^* final state channels⁴.

We have thus made a fit without the channels containing the K^* , and indeed we find as ref. [15] that the global agreement between QCD factorization and experiment was satisfactory. Notice that this fit was done without discarding the channels $B^+ \rightarrow \omega\pi^+(K^+)$ as done by Du *et al.*

Notice also that the parameters $C_{\rho\pi}$ and the $A_{CP}^{\rho\pi}$ have been kept in this fit. The disagreement between QCDF and experiment for these quantities was not enough to spoil the satisfactory agreement of the global fit because the experimental errors are still large on these quantities.

⁴These channels seemed questionable to them.

	Experiment	Scenario 1		Scenario 2	
		Prediction	χ^2	Prediction	χ^2
$BR(\overline{B}^0 \rightarrow \rho^0 \pi^0)$	2.07 ± 1.88	0.132	1.1	0.177	1.0
$BR(\overline{B}^0 \rightarrow \rho^+ \pi^-)$		11.023		10.962	
$BR(\overline{B}^0 \rightarrow \rho^- \pi^+)$		18.374		17.429	
$BR(\overline{B}^0 \rightarrow \rho^\pm \pi^\mp)$	25.53 ± 4.32	29.397	0.8	28.391	0.4
$BR(B^- \rightarrow \rho^0 \pi^-)$	9.49 ± 2.57	9.889	0.0	7.879	0.4
$BR(B^- \rightarrow \omega \pi^-)$	6.22 ± 1.7	6.002	0.0	5.186	0.4
$BR(B^- \rightarrow K^{*-} K^0)$		0.457		0.788	
$BR(B^- \rightarrow K^{*0} K^-)$		0.490		0.494	
$BR(B^- \rightarrow \Phi \pi^-)$		0.004		0.003	
$BR(B^- \rightarrow \rho^- \pi^0)$		9.646		11.404	
$BR(\overline{B}^0 \rightarrow \rho^0 \overline{K}^0)$		5.865		8.893	
$BR(\overline{B}^0 \rightarrow \omega \overline{K}^0)$	6.34 ± 1.82	2.318	4.9	5.606	0.2
$BR(\overline{B}^0 \rightarrow \rho^+ K^-)$	15.88 ± 4.65	6.531	4.0	14.304	0.1
$BR(\overline{B}^0 \rightarrow K^{*-} \pi^+)$	19.3 ± 5.2	9.760	3.4	10.787	2.7
$BR(B^- \rightarrow K^{*-} \pi^0)$	7.1 ± 11.4	7.303	0.0	8.292	0.0
$BR(\overline{B}^0 \rightarrow \Phi \overline{K}^0)$	8.72 ± 1.37	8.360	0.1	8.898	0.0
$BR(B^- \rightarrow \overline{K}^{*0} \pi^-)$	12.12 ± 3.13	7.889	1.8	11.080	0.1
$BR(B^- \rightarrow \rho^0 K^-)$	8.92 ± 3.6	1.882	3.8	5.655	0.8
$BR(B^- \rightarrow \rho^- \overline{K}^0)$		7.140		14.006	
$BR(B^- \rightarrow \omega K^-)$	2.92 ± 1.94	2.398	0.1	6.320	3.1
$BR(B^- \rightarrow \Phi K^-)$	8.88 ± 1.24	8.941	0.0	9.479	0.2
$BR(\overline{B}^0 \rightarrow \overline{K}^{*0} \eta)$	16.41 ± 3.21	22.807	4.0	18.968	0.6
$BR(B^- \rightarrow K^{*-} \eta)$	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			
$\mathcal{A}_{CP}^{\rho\pi}$	-0.22 ± 0.11	-0.015			
$\mathcal{A}_{CP}^{\rho K}$	0.19 ± 0.18	0.060	} 0.5	0.197	} 0.0
$\mathcal{A}_{CP}^{\omega\pi^-}$	-0.21 ± 0.19	-0.072			
$\mathcal{A}_{CP}^{\omega K^-}$	-0.21 ± 0.28	0.029		0.7	
$\mathcal{A}_{CP}^{\eta K^{*-}}$	-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 2: Best fit values using the global analysis of $B \rightarrow PV$ decays in QCDF with free γ (scenario 1) and QCDF+Charming Penguins (scenario 2) with constrained γ .

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

4 A simple model for long distance interactions

As seen in table 2 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, first, in the strange channels, $|P|$ is Cabibbo enhanced and such a non-perturbative contribution could increase the branching ratios, and second, increasing $|P|/|T|$ in the non-strange channels with non-small strong phases could increase significantly the direct CP asymmetries as already discussed. We have therefore tried a model for long distance penguin contributions, namely the charming-penguin inspired model, which depends only on two fitted complex numbers⁵.

Let us start by describing our charming-penguin inspired model for strange final states. In the “charming penguin” picture the weak decay of a \bar{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 $s, \bar{d}(\bar{u}), c, \bar{c}$, for example $\bar{D}_s^{(*)} + D^{(*)}$ systems. This system goes to long distances, the c, \bar{c} eventually annihilate, a pair of light quarks are created by non-perturbative strong interaction and one is left with two light meson⁶.

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}^P (\mathcal{A}^V) when the active quark ends up in the Pseudoscalar (Vector) meson, weighted by a CG coefficient computed simply by the overlap factor (see [1] for further details). In practice, to the QCDF’s decay amplitudes, we add the long distance amplitudes, given by:

$$\mathcal{A}^{\text{LD}}(B \rightarrow PV) = \frac{G_F}{\sqrt{2}} m_B^2 \lambda_p (C I^P \mathcal{A}^P + C I^V \mathcal{A}^V). \quad (6)$$

The fit with long distance penguin contributions is presented in table 2 under the label “Scenario 2”. The agreement with experiment is improved, it should be so, but not in such a fully convincing manner. The goodness of the fit is about 8 % which implies that this model is not excluded 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 $B \rightarrow PV$ 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 2, the reasons of this failure is that the branching ratios for the strange channels are predicted significantly smaller than experiment except for the $B \rightarrow \phi K$ channels, and in table 3 it can be seen that the direct CP asymmetry of $\bar{B}^0 \rightarrow \rho^+ \pi^-$ is predicted very small while experiment gives it very

⁵In order to avoid to add too many new parameters which would make the fit void of signification.

⁶We leave aside from now on the η' which is presumably quite special.

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 to experiment. QCDF implemented by an ad-hoc long distance model is not fully convincing. 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.

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