Dealing with $\mathcal{O}(\Lambda_{QCD}/m_b)$ corrections in charmless hadronic B decays

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Abstract. Using the determination of the CKM matrix by UTfit and the most recent experimental measurements of decay rates and CP asymmetries for non-leptonic two-body $B$ decays into charmless pseudoscalar-pseudoscalar and pseudoscalar-vector final states, we evaluate the impact of non factorizable terms in the decay amplitudes. Taking into account these contributions, we predict the values of new-physics sensitive quantities in the Standard Model. Removing the information on the CKM matrix, we also obtain a determination of the value of the CKM phase $\gamma$ from these decay modes.

The study of $B$ decay allows to perform several tests of the Standard Model (SM) and to indirectly probe the TeV scale before the start of LHC running. Among the New Physics (NP) sensitive decay modes that one can annoverate, penguin-dominated charmless two-body $B$ decays have been considered for a long time as a rich source of information. In practise, problems arise from the fact that the most reliable calculations [1, 2, 3] of the decay amplitudes are done in the infinite-mass limit ($m_b \rightarrow \infty$), which takes into account $\mathcal{O}(\alpha_s)$ corrections, while ignoring $\mathcal{O}(\Lambda_{QCD}/m_b)$ terms from non-perturbative QCD effects. Indeed, current data confirm that non-perturbative $\mathcal{O}(\Lambda_{QCD}/m_b)$ $c$-penguins (charming penguins) are important in $B \rightarrow K\pi$ and $B \rightarrow \pi\pi$ decays [4]: large CP violation in $B \rightarrow K\pi$ [5] and the enhancement of $\mathcal{B}(B^0 \rightarrow \pi^0\pi^0)$ [6] have been both established by experimental measurements, as previously predicted in the context of the charming penguins model.

Anyhow, a data-driven strategy allows to calculate the SM expectation value of the $S_{CP}$ parameters for several interesting decay channels, as a function of the upper value (UV) of the $\mathcal{O}(\Lambda_{QCD}/m_b)$ contributions. We calculate decay amplitudes for charmless two-body $B$ decays starting from the effective Hamiltonian, obtained using the Operator Product Expansion. We compute the decay amplitudes contracting the Hamiltonian on the considered initial and final states. We then simplify the result, grouping the contractions of the effective operators into Renormalization Group Invariant (RGI) quantities [7]. The perturbative parts of the RGI quantities, are calculated in QCD factorization [1], assuming SU(2) flavor symmetry for the form factors and the decay constants. Ignoring OZI suppressed sub-leading terms, we allow the presence of $\mathcal{O}(\Lambda_{QCD}/m_b)$ corrections to the perturbative calculation of all the RGI quantities (except for the tree-level disconnected emission $E_1$), adding a complex number to the factorized expression. We assume these complex unknowns to be the same for processes related by SU(2) flavor symmetry.

For example, the decay amplitudes of $B^+ \rightarrow K^+\pi^0$ decays can be written as:

$$\sqrt{2}A(B^+ \rightarrow K^+\pi^0) = V_{tb}^*V_{ts}P_1 - V_{ub}^*V_{us}(E_1 + E_2 + A_1 - P_1^{GIM})$$ (1)
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input the two decay rates, the two direct CP asymmetries and the value of $S$ of the same order of magnitude. This implies that the sensitivity to $O(P)$ value of all the numerical results we quote for the sizes of the SM prediction on $S_{B\rightarrow\pi\pi}$ suppression due to the CKM factor. Nevertheless, it is possible to perform a fit to the decay providing useful information for other charmless factorization, and we allow for

can write:

$$E$$

where

$O$ contributions in the range $[0, UV]$, with the upper value $UV$ scanned between zero and one (in units of $E_1$). For comparison, the experimental 68% (95%) probability range is given by the dark (light) band.

where $E_1$ and $E_2$ correspond to the color allowed and color suppressed combinations of tree-level contractions and all the other terms represent subleading terms: $P_1$ and $P_1^{GIM}$ are the charming and GIM (i.e. $c-u$) penguin RGI quantities (including the penguin contractions of the tree-operators $O^{hc}_1$ and $O^{hc}_2$), while $A_1$ is the disconnected annihilation, contributing to charged $B$ decay. We calculate $E_1$ and the perturbative parts of the other parameters in QCD factorization, and we allow for $O(A_{QCD}/m_b)$ corrections to $P_1^{GIM}$, $A_1$, and $E_2$. In the following, all the numerical results we quote for the sizes of $O(A_{QCD}/m_b)$ corrections are normalized to the value of $E_1$ for $B\rightarrow\pi\pi$ decays. Even if in principle there is enough experimental information to fit for all these quantities, it is not possible to determine precisely all of them, because of the suppression due to the CKM factor. Nevertheless, it is possible to perform a fit to the decay rate and the CP asymmetries, limiting the $O(A_{QCD}/m_b)$ corrections in the range $[0,UV]$ and obtaining a prediction on $S_{CP}$. The error on the prediction will be a function of the chosen UV.

In addition, a data-driven determination of UV can be derived from $B\rightarrow K\pi$, for which we can write:

$$A(B^+ \rightarrow K^+\bar{K}^0) = -V^*_{tb}V_{td}P_1 - V^*_{ub}V_{ud}(P^{GIM}_1 - A_1)$$

$$A(B^0 \rightarrow K^0\bar{K}^0) = -V^*_{tb}V_{td}P_1 - V^*_{ub}V_{ud}P^{GIM}_1.$$ (2)

For these decays no $O(1)$ contributions are present and the two combinations of CKM terms have the same order of magnitude. This implies that the sensitivity to $O(A_{QCD}/m_b)$ contributions is maximal. We use the experimental information to determine the hadronic quantities, using as input the two decay rates, the two direct CP asymmetries and the value of $S_{CP}$ for $B^0\rightarrow K^0\bar{K}^0$. The result of the fit indicates a value for UV around 0.5. The 95% probability ranges for the $O(A_{QCD}/m_b)$ contributions are $|P_1^{KK}| < 0.28$, $|P^{GIM}_{KK}| < 0.37$, and $|A^{KK}| < 0.55$. It is remarkable to notice that, even if the experimental errors are still large, non factorizable terms of $O(1)$ are already excluded, as expected from the power counting of the $O(A_{QCD}/m_b)$ expansion. Improving the precision on $B\rightarrow K\pi$ inputs will allow to reduce the upper bounds, providing useful information for other charmless $B$ decays.

In a similar way we can use the four decay rates and the four direct CP asymmetries of $B\rightarrow K\pi$ decays, together with the determination of the CKM matrix in the SM, to determine the SM prediction on $S_{CP}(B^0 \rightarrow K^0\pi^0)$, allowing the size of the four $O(A_{QCD}/m_b)$ corrections $(P_1^{(GIM)}$, $A_1$, and $E_2)$ to be in the range $[0,UV]$ and the strong phases to be in $[0,2\pi]$. In Fig. 1 we plot the output values on BR’s and CP asymmetries for $B\rightarrow K\pi$, as a function of UV. It is interesting to note that the so-called puzzle of $A_{CP}(B^0 \rightarrow K^+\pi^-)$ vs. $A_{CP}(B^+ \rightarrow K^+\pi^0)$ is induced by requiring that non-factorizable contributions are small. When corrections to
the factorized amplitudes as large as 0.3 are allowed, all the experimental values are consistently reproduced. A similar consistency is found for $B \to K^\ast \pi$ and $B \to K\rho$, where significative contributions from non-factorizable terms are also found. In particular, in all the three cases the fit provides a determination of the charming penguin parameter $P_1$, which barely depends on the chosen UV. For a reference value UV=0.5 we obtain $P_{K\pi}^1 = (0.066 \pm 0.017)e^{i(134 \pm 20)^\circ}$, $P_{K\rho}^1 = (0.034 \pm 0.012)e^{i(-61 \pm 27)^\circ}$, and $P_{K^\ast\pi}^1 = (0.033 \pm 0.008)e^{i(177 \pm 26)^\circ}$. In addition, removing the information on $\bar{\rho}$ and $\bar{\eta}$ from the fit, it is possible to combine the information from $B \to K\pi$, $B \to K^\ast\pi$ and $B \to K\rho$ decays to obtain $\gamma = (60 \pm 10)^\circ$ ($\gamma = (63 \pm 9)^\circ$) for UV=0.5 (UV=1.0). An additional negative solution is present for UV=1.0. reducing the value of UV reduces the relative probability of this second solution with respect to the SM one.

Because of the lack of independent information from SU(2)-related channels, this strategy cannot be used for $B \to \phi K$ decays, since no handle is available to suppress large values for non-factorizable contributions in the CKM suppressed part of the amplitude. Using additional information (such as SU(3) bounds [9]) or reducing by-hand the value of UV to be small, on the basis of what we have learned from the other channels, represent possible solutions to the problem. On the other hand, these further assumptions introduce a source of theoretical error which is hard to quantify. This is why we believe that the golden mode for NP search in $b \to s$ channel should $B_s \to K^{(*)0}\bar{K}^{(*)0}$, for which the effect of CKM-suppressed amplitudes can be taken into account using a data-driven approach [10]. It is also true that, as we showed here, an important information can also come from channels like $B \to K\pi$, $B \to K^\ast\pi$, and $B \to K\rho$, for which the hadronic uncertainties introduced on $S_{CP}$ by the presence of two combinations of CKM factors can be controlled with a simultaneous fit that takes into account all the $O(\Lambda_{QCD}/m_b)$ correction to the perturbative calculations.

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