SEARCH FOR NEW PHYSICS IN ELECTROWEAK PENGUINS VIA B_s DECAYS*

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The discrepancies found in the $\bar{B} \to \pi\bar{K}$ decays between theory and experiment suggest the presence of new physics in the electroweak penguin sector of the theory. We show that this hypothesis can be tested more efficiently including in the analysis the non-leptonic decays $\bar{B}_\mathrm{s} \to \phi\pi, \phi\rho$.

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1. Introduction

In recent years tensions at the $\sim 2\,\sigma$ level have been found between theoretical predictions and experimental results in the $\bar{B} \to \pi\bar{K}$ decays. These differences point in the direction of new physics (NP) in the electroweak (EW) penguin sector of the theory [1]. The issue is still open because the discrepancies decreased since the first time they were found and it is not yet possible to claim for NP. On the one hand, this is due to the still insufficient experimental statistics, which however will improve at LHCb and the future super-B factories; on the other hand, non-leptonic B decays are still a challenge to theory. Due to the dominant low-energy QCD effects, it is difficult to single out the high-energy weak transition which is responsible for the decays and which could contain NP effects. Methods developed so far rely on flavour symmetries of QCD or on the factorization properties of low-energy QCD dynamics (QCDF) [2, 3]. Alas, none of the two is able to predict the

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decay amplitudes with the required precision. The former is applicable only to a handful of decays while the latter, which implies an expansion of the amplitudes in $\Lambda_{\rm QCD}/m_b$, receives important contributions from a number of subleading terms which can only be estimated. Given this situation, in order to decide whether the tensions in the $\bar{B} \to \pi\bar{K}$ data are indeed due to NP, it is important to inspect also other non-leptonic decays, where effects of a new EW penguin amplitude are expected to be large. Among these there are the $\bar{B} \to \rho\bar{K}, \pi\bar{K}^*, \rho\bar{K}^*$ and $\bar{B}_{\rm s} \to \phi\pi, \phi\rho$ decays. We focus in particular on the latter two because they are pure isospin-violating decays whose branching ratio in the Standard Model (SM) is predicted to be small. We consider various extensions of the SM where new-physics effects arise in the EW penguin sector and show that the branching ratios of the $\bar{B}_{\rm s} \to \phi\pi, \phi\rho$ decays can easily be enhanced by a factor 2 to 4 and in this way be in reach of LHCb and the planned super-B factories.

2. Analysis of the $\bar{B} \to \pi\bar{K}$ modes

We start reviewing the current status of the $\bar{B} \to \pi\bar{K}$ decays. We compare the most recent experimental results with the theoretical predictions obtained within QCDF [3]. Usually, one considers ratios of different branching fractions which exploit the isospin symmetries of the decays and present smaller uncertainties. In particular, the ratios

$$\begin{aligned}
R_c &\equiv 2\frac{{\rm Br}(B^- \to \pi^0 K^-) + {\rm Br}(B^+ \to \pi^0 K^+)}{{\rm Br}(B^- \to \pi^- K^0) + {\rm Br}(B^+ \to \pi^+ K^0)} \\
&= 1.23^{+0.24}_{-0.20}|_{\rm THEO}\,, \qquad 1.12^{+0.07}_{-0.07}|_{\rm EXP}\,, \\
R_n &\equiv \frac{1}{2}\frac{{\rm Br}(\bar{B}^0 \to \pi^+ K^-) + {\rm Br}(B^0 \to \pi^- K^+)}{{\rm Br}(\bar{B}^0 \to \pi^0 \bar{K}^0) + {\rm Br}(B^0 \to \pi^0 K^0)} \\
&= 1.22^{+0.28}_{-0.22}|_{\rm THEO}\,, \qquad 0.99^{+0.07}_{-0.07}|_{\rm EXP}\,, \\
R &\equiv 2\frac{\Gamma(\bar{B}^0 \to \pi^0 \bar{K}^0) + \Gamma(B^- \to \pi^0 K^-)}{\Gamma(B^- \to \pi^- \bar{K}^0) + \Gamma(\bar{B}^0 \to \pi^+ K^-)} \\
&= 1.03^{+0.03}_{-0.02}|_{\rm THEO}\,, \qquad 1.07^{+0.05}_{-0.05}|_{\rm EXP}\,,
\end{aligned} \tag{1}$$

have been widely considered in the literature. Nowadays the discrepancy between theory and experiment has decreased and (1) shows that the results are compatible within the errors. More interesting are the direct CP-asymmetry difference

$$\begin{aligned}
\Delta A_{\rm CP} &= A_{\rm CP}(B^- \to \pi^0 K^-) - A_{\rm CP}(\bar{B}^0 \to \pi^+ K^-) \\
&= 0.026^{+0.053}_{-0.049}|_{\rm THEO}\,, \quad 0.148^{+0.027}_{-0.028}|_{\rm EXP}
\end{aligned} \tag{2}$$

and the time-dependent CP asymmetry

$$S_{\rm CP}(\bar{B}^0 \to \pi^0 \bar{K}^0) = 0.80^{+0.06}_{-0.08}|_{\rm THEO}\,, \quad 0.57^{+0.17}_{-0.17}|_{\rm EXP}\,, \tag{3}$$

which show a $\sim 1.5\,\sigma$ and $\sim 1\,\sigma$ discrepancy between the theoretical and experimental result, respectively. The large experimental value for $\Delta A_{\rm CP}$ is difficult to explain within the SM using QCDF, which in general predicts direct CP asymmetries to be small. The observed data can be accommodated better introducing a new EW amplitude in such a way that the $\bar{B} \to \pi \bar{K}$ amplitudes read

$$\begin{aligned}
\mathcal{A}_{B^- \to \pi^- \bar{K}^0} &= P\left(1 + r_{\rm P}\, e^{-i\gamma}\right)\,, \\
\sqrt{2}\,\mathcal{A}_{B^- \to \pi^0 K^-} &= P\left(1 + r_{\rm EW} - (r_{\rm T} + r_{\rm C} - r_{\rm P})\, e^{-i\gamma} + r'_{\rm EW} e^{-i\delta_z}\right)\,, \\
\mathcal{A}_{\bar{B}^0 \to \pi^+ K^-} &= P\left(1 - (r_{\rm T} - r_{\rm P})\, e^{-i\gamma}\right)\,, \\
\sqrt{2}\,\mathcal{A}_{\bar{B}^0 \to \pi^0 \bar{K}^0} &= -P\left(1 - r_{\rm EW} + (r_{\rm C} + r_{\rm P})\, e^{-i\gamma} - r'_{\rm EW} e^{-i\delta_z}\right)\,.
\end{aligned} \tag{4}$$

Here $r_{\rm T,\,C,\,P,\,EW}$ denote the ratios of the colour-allowed tree-level, the colour-suppressed tree-level, the doubly Cabbibbo suppressed part of the QCD penguin and the colour-allowed electroweak penguin amplitudes to the dominant QCD penguin contribution P. The factor $r'_{\rm EW}$ represents the corresponding ratio of the new EW amplitude, δ_z being a new weak phase. Introducing this new term and expanding in the small ratios $r_{\rm T,C,P,\,EW^{(\prime)}}$, $\Delta A_{\rm CP}$ and $S_{\rm CP}(\bar{B}^0 \to \pi^0 \bar{K}^0)$ read:

$$\begin{aligned}
\Delta A_{\rm CP} &\simeq -2\,[{\rm Im}\,(r_{\rm C}) - {\rm Im}\,(r_{\rm T} r_{\rm EW})] \sin\gamma + 2{\rm Im}(r'_{\rm EW}) \sin\delta_z\,, \\
S_{\rm CP}(\bar{B}^0 \to \pi^0 \bar{K}^0) &\simeq \sin 2\beta + 2{\rm Re}\,(r_{\rm C}) \cos 2\beta \sin\gamma - 2{\rm Re}(r'_{\rm EW}) \cos 2\beta \sin\delta_z\,.
\end{aligned} \tag{5}$$

The new term can give a large contribution in particular to $\Delta A_{\rm CP}$ since it is not suppressed by $r_{\rm T}$ as it happens for the SM EW amplitude $r_{\rm EW}$. On the other hand, from (5) one notes that a similar effect could be obtained due to an enhanced colour-suppressed tree contribution $r_{\rm C}$, which in QCD factorization has the largest uncertainties and is also suggested to be larger in comparison to *e.g.* the $\bar{B} \to \pi^0 \pi^0$ decays. Because of these uncertainties the problem stays open.

3. $\bar{B}_s \to \phi\pi$ $\bar{B}_s \to \phi\rho$ and other relevant decays

In presence of a new EW amplitude, large modifications are expected in other decays, too. The amplitude of the $\bar{B}_s \to \phi\pi, \phi\rho$ modes reads [3]

$$\begin{aligned}
\mathcal{A}_{\bar{B}_s \to \phi M_2} = \frac{A_{\phi M_2}}{\sqrt{2}} \Big(& \lambda_u^{(s)} \alpha_2(\phi M_2) + \tfrac{3}{2} \lambda_c^{(s)} \alpha_{3,\rm EW}(\phi M_2) \\
& + \tfrac{3}{2} \lambda_c^{(s)} \left(\delta\alpha_{3,\rm EW}(\phi M_2) + \tilde{\alpha}_{3,\rm EW}(\phi M_2)\right) e^{-i\delta_z}\Big)\,,
\end{aligned} \tag{6}$$

with $M_2 = \pi, \rho$. We consider explicitly the possibility of having a new left-handed ($\delta\alpha_{3,\mathrm{EW}}$) and a new right-handed ($\tilde{\alpha}_{3,\mathrm{EW}}$) EW penguin contribution. In the SM the two contributing terms are the colour-suppressed tree and the EW penguin amplitude. In QCDF the latter is predicted to be dominating since the ratio of the two reads *e.g.*

$$r^h_{\phi\pi} \equiv \left|\frac{\lambda_u^{(s)}}{\lambda_c^{(s)}}\right| \frac{2}{3}\frac{\alpha_2}{\alpha^c_{3,\mathrm{EW}}} = -0.41^{+0.41}_{-0.37} + 0.13^{+0.30}_{-0.30}\, i\,. \tag{7}$$

The SM branching ratios are quite small [3],

$$\mathrm{Br}(\bar{B}_\mathrm{s}\to\pi^0\phi)=0.15^{+0.11}_{-0.04}\times10^{-6}\,, \qquad \mathrm{Br}(\bar{B}_\mathrm{s}\to\rho^0\phi)=0.43^{+0.28}_{-0.11}\times10^{-6}\,, \tag{8}$$

and a new EW amplitude of the same order as the SM one can easily enhance the branching fractions up to a factor 4.

$\alpha^p_{3,\mathrm{EW}} + \delta\alpha^p_{3,\mathrm{EW}}$	$\tilde{\alpha}^p_{3,\mathrm{EW}}$	
$a^p_9 + \delta a^p_9 - a^p_7 - \delta a^p_7$	$-\tilde{a}^p_9 + \tilde{a}^p_7$	if $M_1M_2 = PP$
$a^p_9 + \delta a^p_9 + a^p_7 + \delta a^p_7$	$\tilde{a}^p_9 + \tilde{a}^p_7$	if $M_1M_2 = PV$
$a^p_9 + \delta a^p_9 - a^p_7 - \delta a^p_7$	$\tilde{a}^p_9 - \tilde{a}^p_7$	if $M_1M_2 = VP$
$a^p_9 + \delta a^p_9 + a^p_7 + \delta a^p_7$	$-\tilde{a}^p_9 - \tilde{a}^p_7$	if $M_1M_2 = V^0V^0$
$a^p_9 + \delta a^p_9 + a^p_7 + \delta a^p_7$	$-f^{M_1}_\pm\,(\tilde{a}^p_9 + \tilde{a}^p_7)$	if $M_1M_2 = V^\pm V^\pm$

A more quantitative prediction can be made only considering some specific model. This can be understood looking at the table above, where the EW amplitudes are given in terms of the QCDF building blocks a_i for decays into PP, PV, VP and VV final states. The left column contains the SM and a possible left-handed NP contribution, while the right column contains a new right-handed amplitude. Because of the different interference patterns among the various terms a_i, δa_i, different NP models can give very different results, *e.g.* effects can be larger in PP or PV or VP or VV final states, depending on the handedness of NP, on its contribution to δa_7 ($\tilde{a}_7$) *versus* δa_9 ($\tilde{a}_9$) *etc.* Because of these patterns, one expects the new contributions to be relevant in the $\bar{B} \to \rho\bar{K}, \pi\bar{K}^*, \rho\bar{K}^*$ decays, too, which have the same flavour content as the $\bar{B} \to \pi\bar{K}$ modes. For this reason, we consider them as constraints in our analysis.

4. A particular new physics scenario

As a first example we considered a modified Z^0 scenario, a well motivated model [4] which gives rise to new contributions mainly to the Wilson coefficients of the EW penguin operators. One has a $(\bar{s}b)_{V\pm A}$ current mediated at tree level by the Z^0 boson. We write the weak Hamiltonian as

$$\mathcal{H}^{\rm eff} = \frac{G_{\rm F}}{\sqrt{2}} \sum_{p=u,c} \lambda_p^{(s)} \left(C_1 Q_1^p + C_2 Q_2^p + \sum_{i=3}^{10} (C_i Q_i + \tilde{C}_i \tilde{Q}_i) \right) , \qquad (9)$$

with $\lambda_p^{(s)} = V_{pb} V_{ps}^*$. The operators Q_i are defined as in [2] and the $\tilde{Q}_i$ are obtained from them replacing $P_{\rm L} \leftrightarrow P_{\rm R}$. Parameterizing the flavour changing Z^0-couplings as $\kappa_{\rm L,R}^{sb} \equiv z e^{-i\delta_z}$ as in the first reference of [4], the new contributions to the Wilson coefficients at the high scale M_Z read

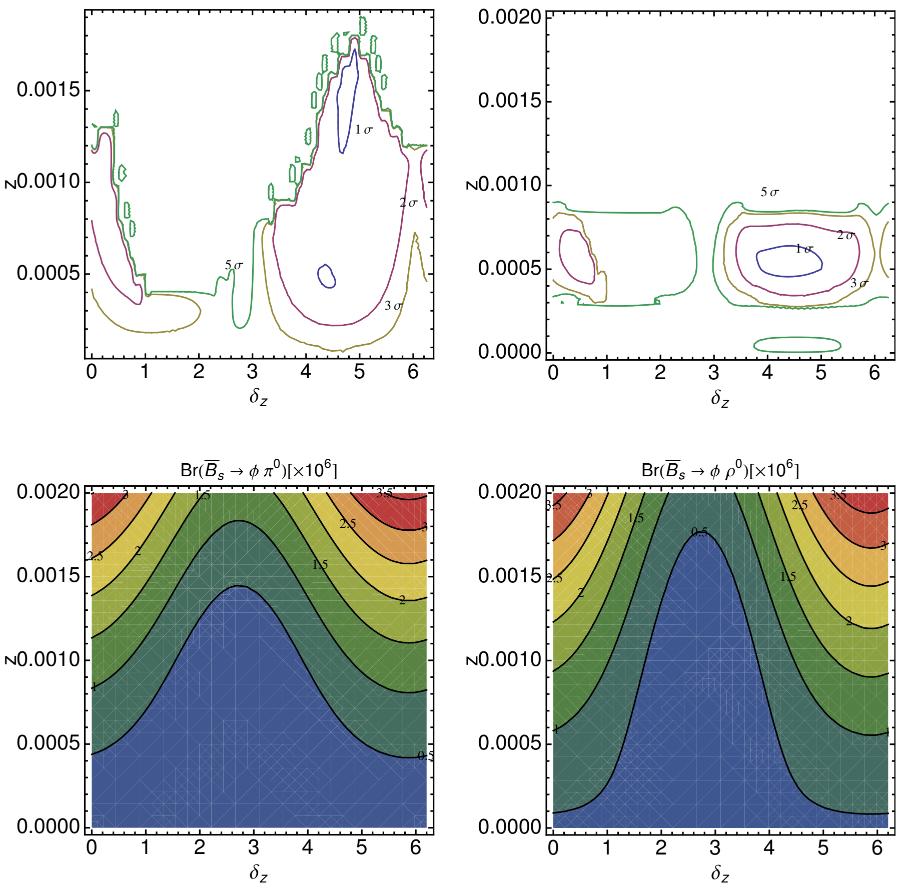
$$\begin{aligned} \delta C_3 &= \frac{\kappa_L^{sb}}{6\lambda_t^{(s)}} , \qquad \delta C_7 = \frac{2}{3} \frac{\kappa_{\rm L}^{sb} \sin^2 \theta_W}{\lambda_t^{(s)}} , \qquad \delta C_9 = -\frac{2}{3} \frac{\kappa_{\rm L}^{sb} \cos^2 \theta_W}{\lambda_t^{(s)}} , \\ \tilde{C}_5 &= \frac{\kappa_R^{sb}}{6\lambda_t^{(s)}} , \qquad \tilde{C}_7 = -\frac{2}{3} \frac{\kappa_{\rm R}^{sb} \cos^2 \theta_W}{\lambda_t^{(s)}} , \qquad \tilde{C}_9 = \frac{2}{3} \frac{\kappa_{\rm R}^{sb} \sin^2 \theta_W}{\lambda_t^{(s)}} . \end{aligned} \qquad (10)$$

The considered model is quite general and simple since we parameterize it with at most two independent free parameters. Our intention is to consider the experimental results for the $\bar{B} \to \pi \bar{K}$ modes as influenced by this new contributions, so that we fit the free model parameters to this experimental data. Subsequently we use these results to make predictions for the $\bar{B}_s \to \phi\pi, \phi\rho$ decays. However, since the new FCNC coupling $\kappa_{\rm L,R}^{sb}$ contributes also to other low-energy processes, like *e.g.* the semileptonic decays $\bar{B} \to X_s ll, X_s \nu\nu$, these have to be taken into account and they give strong constraints. Once these constraints are considered, the new coefficients can be at most of the same size as the SM EW short-distance coefficients, however with a potentially large weak phase.

5. Results

- The fit of the current $\bar{B} \to \pi \bar{K}$ data gives a new EW contribution which is of the same order as the SM one in case of left-handed NP, while in case of right-handed NP larger contributions of order 2 to 3 times the SM EW amplitude are preferred. For comparison, one gets a new contribution of the same size as the SM EW one for $|\kappa_{\rm L/R}^{sb}| = z = 6.9 \times 10^{-4}$.
- The VP and VV modes are more sensitive to right-handed new physics, which, combined with the previous item, gives in some cases up to an order of magnitude enhancement for the $\bar{B}_s \to \phi\pi, \phi\rho$ decays.
- In case of the modified Z^0 penguin scenario the constraints from semileptonic decays limit the possible enhancement to a factor of 2, which would be difficult to be distinguished from the SM result, due to the theoretical error.

- In case of left-right symmetric NP with $\kappa_{\rm L}^{sb} = \kappa_{\rm R}^{sb}$, the two contributions cancel exactly in the $\bar{B}_s \to \phi\pi, \phi\rho$ decays and no modifications arise. However, modifications can still arise in $\bar{B} \to \pi\bar{K}, \pi\bar{K}^*$ decays.
- The $\bar{B} \to \rho\bar{K}, \pi\bar{K}^*, \rho\bar{K}^*, \bar{K}\phi, \bar{K}^*\phi$ modes gives (at present) only weak constraints, mostly in case of right-handed NP. They are always weaker than the constraints from semileptonic decays. Their inclusion is however important in other models, where the latter do not apply.



In the figure above we support these analyses, providing as an example the result of the fit (upper graphs) for a right-handed $b \to s$ current, with (left) and without (right) the constraint from the semileptonic decay $\bar{B} \to X_s ll$. The lower graphs show, for the same scenario, the branching ratios of the $\bar{B}_s \to \phi\pi, \phi\rho$ decays. Inside the $2\,\sigma$ region individuated in the fit, the BRs can be up to one order of magnitude larger than in the SM.

6. Conclusion

Our analysis shows that the decays $\bar{B}_s \to \phi\pi, \phi\rho$ can be used to improve our current understanding of the $\bar{B} \to \pi\bar{K}$ "puzzle". The presence of a new EW contribution would enhance the branching ratio of the $\bar{B}_s \to \phi\pi, \phi\rho$ modes. We considered a modified Z penguin scenario, where the enhancement is limited to a factor 2 by constraints from semileptonic B decays; such an enhancement would be difficult to be distinguished from the SM result. However, in other extensions of the SM the semileptonic bounds do not apply and one finds enhancement up to one order of magnitude [5], making them very interesting decays. A correlated analysis of these decays, together with the $\bar{B} \to \rho\bar{K}, \pi\bar{K}^*, \rho\bar{K}^*$ modes is useful to overcome the theoretical uncertainties. We underline therefore that these decays should be investigated at LHCb and future super-B factories.

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