Extracting the $B_s - \bar{B}_s$ mixing angle from $B \to VV$ decays and comments on the puzzling $B \to K^*l^+l^-$ decay

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Three different strategies to extract the weak mixing phase $\phi_s$ of the $B_s$ system using $B \to VV$ decays ($B_s \to K^{*0}K^{*0}$, $B_s \to \phi\bar{K}^{*0}$ and $B_s \to \phi\phi$) are discussed. Those penguin-mediated decays are computed in the framework of a new combined QCD-Factorisation/Flavour Symmetry Method. Also some comments on the recent interesting results found by Babar concerning the decay $B \to K^*l^+l^-$ are included.

1. Introduction

The present era of Precision Flavour Physics may turn soon due to the excellent performance of the $B$-factories and Tevatron (and hopefully LHC) into an era of Precision Flavour New Physics. Rare $b \to s$ transitions in several inclusive and exclusive modes start exhibiting some tension with the SM predictions$^1$. Indeed, there is certain theoretical prejudice$^2$ to expect deviations in $b \to s$ transitions and SM-like results in the corresponding $b \to d$ ones.

In order to reach the accuracy needed in some $B$ decay processes to get to the discovery level it is of an utmost importance to refine the methods used to predict those decays. There are two main approaches in the literature: $1/m_b$-expansion based methods, namely, QCD Factorization (QCDF)$^3$$^4$. Soft collinear effective theories$^5$ or PQCD$^6$ and Flavour Symmetry methods like U-spin$^7$. Here I will discuss a new method$^8$ that combines the predictive power of QCD techniques with the model-independence of Flavour symmetries. Moreover, a main advantage of this method is that it reduces substantially the sensitivity to the dangerous chirally enhanced IR divergences in QCDF and the arbitrariness in the choice of the size of SU(3) breaking in Flavour Symmetries.

Before briefly discussing the method and its application to decays of $B$ mesons into vectors$^9$ to extract the weak mixing angle $\phi_s$, I will open a parenthesis to comment on the results of the measurement of the $B \to K^*l^+l^-$ decay. Here I will focus on certain observables that were proposed in$^{10}$,$^{11}$.$^{12}$

2. Comments on $B \to K^*l^+l^-$

Recently, Babar has found a set of very interesting results$^{13}$,$^{14}$ while measuring observables based on the $B \to K^*l^+l^-$ channel, namely: i) longitudinal polarization fraction of the $K^*$: $F_L$, ii) Forward-Backward asymmetry: $A_{FB}$, iii) isospin asymmetry $A_I$ of $B^0 \to K^{*0}l^+l^-$ and $B^{\pm} \to K^{*\pm}l^+l^-$ channels and soon iv) the transverse asymmetry: $A_T^{(2)}$. I will discuss them in turn and comment on the impact of two scenarios (flipped sign solution for $C_7^{(f)}$) and Right Handed currents (RH) scenario ($C_7^{(f)} \neq 0$). Even if, at a first sight, the flipped sign scenario (not my favorite one) may appear as a possible solution for all these deviations, indeed it is not a completely satisfactory solution. Moreover, this scenario is somehow disfavoured (under certain assumptions) by the inclusive mode, but not ruled out. Of course, this should be taken only as an exercise, since data should still give the final answer and, other scenarios may lead to a better explanation if data changes substantially.

- $F_L(s) = \frac{|A_0|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}$

where $A_0, \perp, \parallel$ are, respectively, the longitudinal, perpendicular and parallel spin amplitude.
of the $K^*$. The theoretical prediction for this observable was computed in QCDF at NLO in [11] and including possible $\Lambda/m_b$ corrections of order 10% in each amplitude in [12]. From [12] (see Fig.1) one gets an average value (weighted by the distribution $d\Gamma/dq^2$) in the region $1 \leq q^2 \leq 6.25$GeV$^2$ of $0.83 \pm 0.08$ ($\xi_\perp (0)$ was taken 0.35). An update of this calculation has been done in [15] with an average value $0.86 \pm 0.05$ slightly higher due to the different choice in [15] for $\xi_\perp (0) = 0.26$. Recently an experimental averaged value of $0.35 \pm 0.16$ [13] was measured on a larger region $4m_\mu^2 \leq q^2 \leq 6.25$GeV$^2$. Even if these two numbers cannot be yet compared, it is presumable that the averaged experimental value once taken in the $1 \leq q^2 \leq 6.25$GeV$^2$ region will certainly increase but still probably will remain a low value. (One can do the opposite exercise and compute the theory average from $4m_\mu^2$ to $6.25$GeV$^2$, not taken into account possible low resonances effects obtaining $0.67 \pm 0.08$. Of course, this number should be taken only as an indication). Let me now discuss the impact of the two scenarios: first, it was found in [12] that supersymmetry with non-minimal flavour violation in the down sector, as an example of RH current contribution ($C_7^{eff} \neq 0$) do not deviate much from the SM region (Fig.1). Indeed, beyond the supersymmetric case, picking up some extreme but allowed values of $C_7^{eff}$ one finds that it is hard to go down more than a 10% with respect to the SM band. The other scenario, the flipped sign solution for $C_7^{eff}$ deviate more substantially[11] (see Fig.1) from the SM region and in the direction of the measured value.

- $A_{FB}(s) = \frac{3}{2} \frac{\text{Re}(A_{R,b}A_{R,B}^*) - \text{Re}(A_{R,b}A_{L,B}^*)}{|A_{R,b}|^2 + |A_{R,b}|^2 + |A_{L,b}|^2}$ [10][16].

The forward-backward asymmetry, is par-
particularly interesting on its zero, where form factors drop at leading order giving a precise relation between $C_7^{eff}$ and $C_9$, but also due to its sensitivity to the sign of $C_7^{eff}$. Experimentally, it was found (Fig.2) again a deviation that tend to prefer the reversed sign of $C_7^{eff}$. An scenario compatible with this situation was discussed in [10] in the case of MSSM with large $\tan\beta$ (see Fig.2). Again for this observable, like in the case of $F_L$, RH currents originating from a supersymmetric model do not seem to deviate substantially from the SM prediction. Experimentally, it was found (Fig.2) again a deviation from the SM predictive, pointing towards the experimental result, although still far from the measured value.

- $A_T = \frac{d\Gamma(B^0 \rightarrow K^{*0}t^+t^-)/ds - d\Gamma(B^0 \rightarrow K^{*0}t^+t^-)/ds}{d\Gamma(B^0 \rightarrow K^{*0}t^+t^-)/ds + d\Gamma(B^0 \rightarrow K^{*0}t^+t^-)/ds}$ [10]. This asymmetry in the SM arises from graphs where a photon is radiated from the spectator quark in annihilation or spectator-scattering diagrams. The sensitivity to the different charge of the spectator quark for a $B^0$ or a $B^+$ induces a non-zero value. The computation of this isospin asymmetry for $B \rightarrow K^{*0}l^+l^-$ in the framework of QCDF was done in [10]. It was found that for values of $q^2 > 0$ no sizeable isospin asymmetry is expected in the SM (see Fig.3). The case of $q^2 = 0$ was computed in [17]. In the limit $q^2 \rightarrow 0$, where the photon pole dominates, our isospin asymmetry reduces to $A_T(B \rightarrow K^{*0}) = \text{Re}(b_{\gamma}^0(0) - b_{\gamma}^0(0))$ (in agreement with [17]). It is remarkable the good agreement with the SM prediction and the experiment at this point and this is puzzling. The $q^2 = 0$ solution is also sensitive to the sign of $C_7$, although relatively to the sign of $C_5 - C_6$. On the contrary, for larger values of $q^2$ the isospin asymmetry is dominated by the longitudinal polarization amplitude and the dominant operators are $O_3 - O_4$. So even if one may devise a solution to accommodate SM at $q^2 = 0$ and beyond SM at $q^2 > 0$ any solution looks a bit unnatural. Remarkably again it is where the longitudinal polarization dominates where it was found experimentally (Fig.3) a deviation from the SM prediction. Barring the $q^2 = 0$ problem, in [10] it was found that for the scenario of MSSM with large $\tan\beta$ the flipped sign solution of $C_7^{eff}$ induces negative values for the isospin asymmetry (Fig.3), pointing towards the experimental result, although still far from the measured value.

- $A_T^{(2)}(s) = \frac{|A_4|^2 - |A_1|^2}{|A_4|^2 + |A_1|^2}$ [11][12]. This last observable, still not measured could provide an important piece of the puzzle. This is an observable constructed to minimize theoretical uncertainties and show a maximal sensitivity to the presence of RH currents. If all the impact of New Physics consist on flipping the sign of $C_7^{eff}$ one should not see any deviation from the SM prediction in $A_T^{(2)}$. On the contrary, if it deviates, the presence of RH currents would be favored (with or without flipped $C_7^{eff}$).

To conclude, we observe that the solution with the flipped sign of $C_7^{eff}$ seems to go in the right direction (but it is still not sufficient) to explain the preliminary observed deviations. However, it has two important caveats: it is disfavoured by the inclusive mode and, moreover, it may require a weird solution to avoid conflicts with $A_T$ at $q^2 = 0$. RH current solution ($C_7^{eff} \neq 0$) seems not to deviate enough from SM prediction for $F_L$ and $A_{FB}$ ($A_T^{(2)}$ may help to favour or rule out this solution). Second, observables containing the longitudinal polarization ($F_L$, $A_{FB}$, $A_T$) seems to systematically exhibit deviations (consistently with this remark one would expect that $A_T^{(2)}$, like $A_T$ at $q^2 = 0$ will not deviate). In this sense, the new longitudinal observables proposed in [15] may play an important role. Finally, it will be very interesting to see the comparison between theory and experiment strictly inside the theoretically well controlled region $1 < q^2 < 6.25\text{GeV}^2$. This closes the parenthesis.

3. Description of the Method

One of the main source of uncertainties in QCDF comes from IR divergences originating from:

- Hard spectator-scattering: Hard gluons exchange between spectator quark and the outgoing energetic meson gives rise to integrals of the
following type (see [1] for definitions):

\[ H_i(M_1M_2) = C \int_0^1 dx \int_0^1 dy \left[ \frac{\Phi_{M_2}(x)\Phi_{M_1}(y)}{x y} \right. \]
\[ + \left. r_{M_1} \Phi_{M_2}(x)\Phi_{m_1}(y) + \frac{1}{x^2 y} \right] + r_{M_1} r_{M_2} \Phi_{m_1}(x)\Phi_{m_1}(y) \frac{2}{x y} \]

where the second term (formally of order \( \Lambda/m_b \)) diverges when \( y \to 1 \).

- Weak annihilation: These type of diagrams also exhibit endpoint IR divergences as it is explicit in the corresponding integrals:

\[ A_i^I = \pi \alpha_s \int_0^1 dx dy \left\{ \Phi_{M_2}(x)\Phi_{M_1}(y) \left[ \frac{1}{y(1 - x y)} \right. \right. \]
\[ + \left. \left. \frac{1}{x^2 y} \right] + r_{M_1} r_{M_2} \Phi_{m_1}(x)\Phi_{m_1}(y) \frac{2}{x y} \right\} \]

Both divergences are modeled in the same way in QCDF: \( \int_0^1\frac{dy}{y}\Phi_{m_1}(y) = \Phi_{m_1}(1) X_{H,A} + r \), with \( r \) a finite piece and \( X_{H,A} = (1 + \rho_{H,A}) \ln(m_b/\Lambda) \).

These divergences are the main source of error in QCDF. If one splits the SM amplitude for a

\[ B \text{-decay into two mesons in two pieces:} \]
\[ \tilde{A} = A(B_q \rightarrow M \bar{M}) = \lambda_q^{(q)} T^{qC}_M + \lambda_q^{(q)} P^{qC}_M, \]

with \( C \) denoting the charge of the decay products, and \( \lambda \)'s the products of CKM factors \( \lambda_p^{(q)} = V_{pb}V_{pq}^* \), one observes that for certain processes the structure of the IR divergences at NLO in QCDF is the same for both pieces. This allows to identify an IR safe quantity at this order, defined by \( \Delta = T - P \) that can be evaluated safely in QCDF and that will be taken as the main input from QCDF.

Another important remark is that this quantity can be directly related to observables leading to
a set of sum rules that can be translated into predictions for the UT angles \([9,18,19]\) (see Strategy 2 in Sec.3.1). In \([9]\) this idea was extended to vector-vector final states. In this case, there is a \(\Delta\) associated to each helicity amplitude. But we focus on the leading (in a naive power counting in \(1/m_b\)) longitudinal one. We obtain for the longitudinal \(\Delta\) of the \(B_d \rightarrow K^{*0}K^{*0}\) (\(B_s \rightarrow K^{*0}K^{*0}\)) decay denoted by \(\Delta^{K,K^*}_{K^*K^*}\) \([9]\):

\[
|\Delta^{K,K^*}_{K^*K^*}| = \left| A_{K^*K^*}^{d,0} \cdot \frac{C_{F}\alpha_s}{4\pi N_c} C_1 [\hat{G}_{K^*}(s_c) - \hat{G}_{K^*}(0)] \right|
\]

\[
= (1.85 \pm 0.79) \times 10^{-7} \text{ GeV}
\]

\[
|\Delta^{K,K^*}_{K^*K^*}| = \left| A_{K^*K^*}^{d,0} \cdot \frac{C_{F}\alpha_s}{4\pi N_c} C_1 [\hat{G}_{K^*}(s_c) - \hat{G}_{K^*}(0)] \right|
\]

\[
= (1.62 \pm 0.69) \times 10^{-7} \text{ GeV}
\]

where \(\hat{G}_V \equiv G_V - r^V G_V\) are the usual penguin factors and \(A_{V_1V_2}^{d,0}\) are the naive factorization factors. The corresponding \(\Delta\)’s for the other modes can be found in \([9]\).

In short the method consist in relating the hadronic complex parameters \(P_s^C, T_s^C\) that describes the dynamics of a \(b \rightarrow s\) governed transition with the corresponding parameters of an U-spin \(b \rightarrow d\) related process. This requires to include SU(3) breaking factorizable \((f = A_{V_1V_2}^{d,0}/A_{V_1V_2}^{d,0})\) and non-factorizable U-spin breaking \(1/m_b\) suppressed corrections. Those non-factorizable corrections are sensitive to the different distribution amplitude of a \(B_d\) and \(B_s\) and spectator quark dependent contributions coming from gluons emitted from a \(d\) or \(s\) quark. The next step is to determine the complex hadronic parameters of the \(b \rightarrow d\) related decay \(P_d^C, T_d^C\).

This is done using the data on BR and direct CP asymmetry of the \(b \rightarrow d\) decay and its associated \(\Delta = T_d^C - P_d^C\) computed in QCDF.

The method was first applied to \(B_s \rightarrow KK\) decays in the SM \([8]\) and supersymmetry \([20]\), leading to the most precise predictions for \(B_s \rightarrow K^+K^-\) and \(B_s \rightarrow K^0\bar{K}^0\) decay modes.

### 3.1. \(B_s \rightarrow VV\): A way to extract \(\phi_s\).

Recent controversial claims on evidence of New Physics in the weak mixing phase \(\phi_s\) \([21]\) has focused the attention into this mixing phase. Here I will describe three possible strategies to measure this phase using \(B\) mesons decaying into vectors that were discussed in \([9]\). We will focus on the golden mode \(B_s \rightarrow K^{0*}\bar{K}^{0*}\) which can be easily reconstructed from the decays of the \(K^*\) into kaons and pions.

**First Strategy:** It applies to \(B_s \rightarrow K^{0*}\bar{K}^{0*}\), \(B_s \rightarrow \phi\bar{K}^{0*}\), and \(B_s \rightarrow \phi\phi\) decays. This strategy requires to measure the longitudinal BR and mixing-induced CP asymmetry of those modes and compute its corresponding \(\Delta = T - P\) (see Eq.1 from QCDF).

Expanding the longitudinal mixing-induced CP asymmetry in power of \(\lambda_s^a/\lambda_s^a\) one obtains:

\[
A_{\text{mix}}^\text{long}(B_s \rightarrow K^{0*}\bar{K}^{0*}) \approx \sin \phi_s + \Delta S
\]

(2)

with \(\Delta S = 2 \left| \frac{\lambda_s^a}{\lambda_s^a} \right| \Re \left( \frac{r^{\phi\bar{K}^{0*}}}{r^{K^{0*}\bar{K}^{0*}}} \right) \sin \gamma \cos \phi_s + \cdots\)

In order to evaluate the size of the \(\Delta S\) pollution, one must constrain the size of \(\Re(T/P)\) and translate these constrains into bounds on \(\Delta S\). These bounds can be found in \([9]\). The steps to follow are: first, one measures the longitudinal \(BR(B_s \rightarrow K^{0*}\bar{K}^{0*})\), second, for each value of this BR and using the bounds on \(\Re(T/P)\) one obtains a possible range for \(\Delta S\) \([9]\). Finally, once measured \(A_{\text{mix}}^\text{long}\) of this decay mode one can then determine a range for \(\sin \phi_s\) from:

\[
\left( A_{\text{mix}}^\text{long} - \Delta S_{\text{max}} \right) < \sin \phi_s < \left( A_{\text{mix}}^\text{long} - \Delta S_{\text{min}} \right)
\]

If this range is inconsistent with the predicted SM value for \(\phi_s\) that would signal the presence of New Physics.
Second Strategy: It is quite general, it applies to any $B$ decay into two pseudoscalars or vectors. For what concerns the measurement of $\phi_s$ we will focus here on two cases:

1. $B_s$ decay through a $b \to s$ process, e.g. $B_s \to K^{*0}\bar{K}^{*0}$

2. $B_s$ decay through a $b \to d$ process, e.g. $B_s \to \phi \bar{K}^{*0}$ (with a subsequent decay into a CP eigenstate)

The great advantage of this strategy is that by measuring the longitudinal branching ratio, and the direct and mixing induced CP asymmetry of a $B_s$ meson decaying through a $b \to d$ or $b \to s$ process one gets a direct determination of the weak mixing angle $\phi_s$ with only one single theoretical input: the corresponding $\Delta$ of the process. Even more, the precise way the asymmetries enter into this expression tells you that a measurement of the branching ratio and the 'untagged rate' is enough to determine $\beta_s$ but also $\gamma$. This can be seen explicitly in the expressions [9,18]:

$$\sin^2\beta_s = \frac{BR}{2|\lambda_u^{(D)}|^2|\Delta|^2} (1 - A_{\Delta}^\gamma)$$

$$\sin^2(\beta_s + \gamma) = \frac{BR}{2|\lambda_u^{(D)}|^2|\Delta|^2} (1 - A_{\Delta}^\gamma)$$

where $A_{\Delta}^\gamma$ verifies $|A_{\text{dir}}|^2 + |A_{\text{mix}}|^2 + |A_{\Delta}^\gamma|^2 = 1$. This extraction of $\beta_s$ is done in this strategy under the assumption that there is no significant New Physics affecting the $b \to s$ decay. This strategy has the advantage of minimizing the theoretical input, but it requires to measure several of the $B_s$ observables.

Third Strategy: This last strategy is the most theoretically driven. It focus only on the golden mode $B_s \to K^{0*}\bar{K}^{0*}$ and assumes no sizeable New Physics in the $B_d \to K^{0*}\bar{K}^{0*}$ U-spin related decay. The steps to follow here are the same that were done for $B \to K K$ decays. First, one has to relate the hadronic parameters of both processes:

$$P_{K^*K^*}^s = f P_{K^*K^*}^d (1 + \delta_{K^*K^*}^P)$$

$$T_{K^*K^*}^s = f T_{K^*K^*}^d (1 + \delta_{K^*K^*}^T)$$

computing factorizable

$$f = \frac{m_{B_s}^2 A_0^{B_s \to K^* \bar{K}^{*0}}}{m_B^2 A_0^{B \to K^* \bar{K}^{*0}}} = 0.88 \pm 0.19$$

and non-factorizable SU(3) breaking parameters:

$$|\delta_{K^*K^*}^P| \leq 0.12, \quad |\delta_{K^*K^*}^T| \leq 0.15$$

Then using as main inputs the $BR^{long}(B_d \to K^{0*}\bar{K}^{0*})$, $\Delta_{K^*K^*}$ together with the longitudinal direct CP asymmetry of $B_d \to K^{0*}\bar{K}^{0*}$ one obtains a prediction in the SM for the corresponding $B_s$ observables:

$$\frac{BR^{long}(B_s \to K^{0*}\bar{K}^{0*})}{BR^{long}(B_d \to K^{0*}\bar{K}^{0*})} = 17 \pm 6$$

$$A_{\text{dir}}^{long}(B_s \to K^{0*}\bar{K}^{0*}) = 0.000 \pm 0.014$$

$$A_{\text{mix}}^{long}(B_s \to K^{0*}\bar{K}^{0*}) = 0.004 \pm 0.018$$

Finally a measurement of the longitudinal mixing induced CP asymmetry of $B_s \to K^{0*}\bar{K}^{0*}$ allow to extract the weak mixing angle $\phi_s$ including all penguin pollution. Figure 5 shows the correlation between $A_{\text{mix}}^{long}$ and $\phi_s$. The extraction of $\phi_s$ from this plot is possible even in the presence of New Physics under the condition that there are only New Physics contributions in $\Delta B = 2$ but not large New Physics effects in $\Delta B = 1$ FCNC amplitudes. This requirement can be easily accomplished for generic type of New Physics.
models if two conditions are fulfilled (see [22]): i) \( \Lambda_{NP} \ll \Lambda_{ew} \) and ii) the effective coupling in \( \Delta B = 2 \) can be expressed as the square of the effective coupling in \( \Delta B = 1 \) amplitudes. These conditions can be easily understood using an effective lagrangian language[22].

Summary: Three different strategies to extract the weak mixing phase \( \phi_s \) from \( B \to VV \) were presented. Also the recent results on the \( B \to K^{*+}l^+l^- \) decay are discussed.

Acknowledgements: I would like to thank Giulia for such a nice and pleasant conference. I acknowledge financial support from FPA2005-02211, 2005-SGR-00994 and RyC program.

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