Theoretical Review of $\gamma/\phi_s$ Measurements with $B_s$ Decays to Charm

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We give an overview of various determinations of $\gamma/\phi_s$ with the help of $B_s$ decays into charmed final states, distinguishing between transitions with tree and penguin contributions and pure tree decays. In the corresponding strategies, the $U$-spin flavour symmetry of strong interactions provides a very useful tool, and offers interesting “by-products” for the $B$-physics programme at the LHC, including the control of the $B_s$ uncertainties in the determinations of the $B^0_s-B^0\bar{s}$ and $B^0_s-B^0\bar{d}$ mixing phases $\phi_\delta$ and $\phi_s$ from $B_d \to J/\psi K_S$ and $B_s \to J/\psi \phi$, respectively, and an alternative extraction of the latter phase through $B_s \to D^+_s D^-$. Finally, we point out that the cleanest determinations of the mixing phases $\phi_\delta$ and $\phi_s$ are offered by the pure tree decays $B_s \to D_s K_{S(L)}$ and $B_s \to D^\pm \pi^0$, $D^\pm \rho^0$, ..., respectively, which are very interesting for the searches of new physics.

I. SETTING THE STAGE

During the recent years, we have seen a tremendous progress in $B$ physics [1]. The data agree globally with the Kobayashi–Maskawa (KM) mechanism of CP violation, i.e. with the Standard Model (SM). However, we have also hints for discrepancies, which could be first signals of new physics (NP). Unfortunately, the uncertainties are still too large to draw firm conclusions.

Thanks to the start of the LHC, exciting new perspectives will arise in the autumn of 2007, also for $B$-decay studies [2]. The LHCb experiment will allow us to fully exploit the physics potential of the $B_s$-meson system, and precision determinations of the angle $\gamma$ of the unitarity triangle will become possible, which are a key ingredient of the search for NP in the flavour sector.

Let us therefore have a closer look at $B_s$ decays into final states with charm, which is the topic of WG5 of the CKM2006 workshop, where this talk was given. The notation and formulae for the CP asymmetries in decays of neutral $B_q$ mesons ($q \in \{d, s\}$) are given as follows [3]:

\[
\begin{align*}
\Gamma(B^0_q(t) \to f) &= \Gamma(B^0_q(t) \to \bar{f}) \quad \text{(direct CP asymmetry)} \\
\Gamma(B^0_q(t) \to f) &= \Gamma(B^0_q(t) \to \bar{f}) - 2\Gamma(B^0_q(t) \to f) \quad \text{(mixing CP asymmetry)}
\end{align*}
\]

where

\[
A_{\text{dir}}^{CP} = \frac{1 - |\xi_f|^2}{1 + |\xi_f|^2} \quad \text{and} \quad A_{\text{mix}}^{CP} = \frac{2 \text{Im} \xi_f}{1 + |\xi_f|^2},
\]

denote the “direct” and “mixing-induced” CP-violating observables, respectively. The quantity $A_{\Delta t}$, which should be accessible in the $B_s$-meson system because of the expected sizeable width difference $\Delta \Gamma_s$, satisfies

\[
(A_{\Delta t})^2 = 1 - (A_{\text{dir}}^{CP})^2 - (A_{\text{mix}}^{CP})^2.
\]

These observables are governed by

\[
\xi_f^{(s)} \sim e^{-i\phi_f} \left[ A(B^0_q \to f) \over A(B^0_\bar{q} \to \bar{f}) \right],
\]

where the $B^0_q-B^0_\bar{q}$ mixing phases

\[
\phi_q = 2 \text{arg}(V_{tq} V_{tb}) = \begin{cases} +2\beta \quad (q = d) \\
-2\lambda_\gamma \eta \quad (q = s)
\end{cases}
\]

are an important input for the following discussion. The data for the CP violation in $B^0 \to J/\psi K_S$ and similar decays imply $\phi_\delta = (42.4 \pm 2) \circ [4]$. Performing a measurement of the untagged, time-dependent three-angle distribution of the $B^0 \to J/\psi \to \ell^+\ell^- \to s \to K^+K^- \to J/\psi K_S$ decay products [3], the D0 collaboration has recently reported the following result [6]:

\[
\phi_s = -0.79 \pm 0.56 \text{ (stat.)} \pm 0.01 \text{ (syst.)}.
\]

Consequently, this phase is still not stringently constrained. However, it is very accessible at the LHC [2]. The determinations of the $\phi_q$ work also in the presence of CP-violating NP contributions to $B^0_q-B^0_\bar{q}$ mixing, provided we have negligible contributions of this kind to the corresponding decay amplitudes, which is a very plausible (and testable, see below) assumption for the $B^0 \to J/\psi K_S$ and $B^0_s \to J/\psi \phi$ decays. For the following discussion, we hence assume that the $\phi_q$ are known.

II. DECAYS WITH TREE AND PENGUIN CONTRIBUTIONS

In this section, we have a fresh look at the strategies proposed in [7]. Here the $U$-spin flavour symmetry of strong interactions, which relates down and strange quarks in the same way as the isospin symmetry relates down and up quarks, is used to extract $\gamma$ from $B_{d,s}$ decays with tree and penguin contributions. The conceptual advantage of these $U$-spin strategies is – in contrast to the “conventional” $SU(3)$ flavour-symmetry strategies – that no additional dynamical assumptions, such as the neglect of annihilation topologies, have to be made.

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[2] In the following, I shall use the $\gamma(\equiv \phi_3), \beta(\equiv \phi_1)$ notation.
A. The $B_{s(d)} \to J/\psi K_S$ System

In the SM, the decay amplitudes of $B^0 \to J/\psi K_S$ and $B^0_d \to J/\psi K_S$ channels can be written as follows:

$$A(B^0 \to J/\psi K_S) = \lambda A \left[1 - a e^{i\theta} e^{i\gamma}\right]$$  \hspace{1cm} (7)

$$A(B^0_d \to J/\psi K_S) = \left(1 - \frac{\lambda^2}{2}\right) A' \left[1 + e a' e^{i\theta'} e^{i\gamma}\right]$$  \hspace{1cm} (8)

where $\epsilon \equiv \lambda^2/(1 - \lambda^2) = 0.05$, and

$$A = \text{tree+pen}$$

$$ae^{i\theta} = \text{pen}/(\text{tree+pen})$$

are CP-conserving strong quantities. The untagged rates

$$\langle \Gamma(B \to f) \rangle \equiv \Gamma(B(t) \to f) + \Gamma(B(\bar{t}) \to f)$$

allow us to introduce

$$H \equiv \text{PhSp} \times \frac{1}{\epsilon} \left| \frac{A'}{A} \right|^2 \frac{(\Gamma(B_s \to J/\psi K_S))}{(\Gamma(B_d \to J/\psi K_S))}$$

$$= \frac{1 - 2a e \cos \theta \cos \gamma + a^2}{1 + 2a' e \cos \theta' \cos \gamma + e^2 a'^2},$$

(11)

where PhSp denotes a straightforward phase-space factor. On the other hand, tagged, time-dependent rate measurements allow us to extract

$$A_{\text{dir}}^{\text{CP}}(B_s \to J/\psi K_S) = F_1(a, \theta, \gamma)$$

$$A_{\text{mix}}^{\text{CP}}(B_s \to J/\psi K_S) = F_2(a, \theta, \gamma, \phi_d),$$

as well as

$$A_{\text{dir}}^{\text{CP}}(B_d \to J/\psi K_S) = F_1'(a', \theta', \gamma) = 0 + \mathcal{O}(a')$$

$$A_{\text{mix}}^{\text{CP}}(B_d \to J/\psi K_S) = F_2'(a', \theta', \gamma, \phi_d)$$

$$= -\sin \phi_d + \mathcal{O}(e a').$$

(15)

It is an important feature of the $B_{s(d)} \to J/\psi K_S$ system that the corresponding decays are related through the interchange of all down and strange quarks. The U-spin flavour symmetry of strong interactions hence implies:

$$|A'| = |A|;$$

$$a' = a, \hspace{1cm} \theta' = \theta.$$  \hspace{1cm} (16)

(17)

Consequently, (16) and (17) allow us to determine the quantity $H$ introduced in (11). Here U-spin-breaking corrections to (16) have the most important impact:

$$\left| \frac{A'}{A_{\text{fact}}} \right| = \frac{F_{B^0 K^0}(M^2_{J/\psi,1^-})}{F_{B^0 K^0}(M^2_{J/\psi,1^-})},$$

(18)

whereas corrections to (17) play a minor rôle because of the $\epsilon$ suppression in (16). Finally, $\gamma, \alpha, \theta$ can be determined from $H, A_{\text{dir}}^{\text{CP}}(B_s \to J/\psi K_S)$ and $A_{\text{mix}}^{\text{CP}}(B_s \to J/\psi K_S)$.

In Fig. 1 we illustrate this determination: using $\gamma = 65^\circ$, $\phi_s = -2^\circ$, $a = a' = 0.2$ and $\theta = \theta' = 30^\circ$ as input parameters, we obtain $A_{\text{dir}}^{\text{CP}}(B_s \to J/\psi K_S) = 0.20$,

$$A_{\text{mix}}^{\text{CP}}(B_s \to J/\psi K_S) = 0.35 \text{ and } H = 0.89.$$  \hspace{1cm} (19)

These observables can be converted into the contours shown in the figure, where the one following from the CP asymmetries $A_{\text{dir}}^{\text{CP}}$ and $A_{\text{mix}}^{\text{CP}}$ is theoretically clean. The intersection of the two contours allows a transparent extraction of $\gamma$ and $a$ (we have excluded additional solutions arising for unphysically large values of $a > 1$).

Another interesting aspect of this strategy is that we have so far not used the $B^0_d, B^0_s$ mixing phase $\phi_d$. The $U$-spin relation (17) allows us – in combination with the extracted values of $\gamma, \alpha$ and $\theta$ – to control the penguin uncertainties affecting the determination of $\phi_d$ from (15). These corrections received quite some attention \cite{15}, and can actually be controlled at the LHC through the data for the $B_s \to J/\psi K_S$ channel. For the practical implementation, also the $U$-spin relation

$$A_{\text{dir}}^{\text{CP}}(B_d \to J/\psi K_S) = -\epsilon H A_{\text{dir}}^{\text{CP}}(B_s \to J/\psi K_S)$$

is very useful.

The strategy discussed above has also a counterpart in the $B_s$-meson system. As we noted above, $\phi_s$ can be extracted from $B_s \to J/\psi \phi$ \cite{16}. Since we have two vector mesons in the final state, the CP eigenstates have to be disentangled through the $J/\psi \to \ell^- \ell^+$, $\phi \to K^+ K^-$ angular distribution. Here it is convenient to introduce linear polarization states $f \in \{0, \parallel (\text{CP even}); \perp (\text{CP odd})\}$, which allow us to write

$$\xi^{(s)}(\psi) \propto e^{-i\phi_s}\left[1 - 2i\lambda^2 a' e^{i\theta'} \sin \gamma + \mathcal{O}(\lambda^4)\right].$$

(20)

As $\phi_s \approx -2^\circ$ in the SM, the penguin effects have a significant impact in this case, at least at the 20% level (which may be enhanced through final-state interaction effects). Therefore, the question of how to control these effects arises, which is particularly relevant for LHCb upgrade plans. These uncertainties can actually be controlled through an analysis of the $B_d \to J/\psi \phi$, $B_s \to J/\psi$ system \cite{17}: using $\phi_s$ and the $U$-spin symmetry, $\gamma$ and the hadronic parameters $(a', \theta')$ can be extracted, allowing us to include the penguins in the extraction of $\phi_s$.\textsuperscript{15}
B. The $B_{d(s)} \to D_{d(s)}^+ D_{d(s)}^- \to J/\psi \phi$ System

In the SM, the decay amplitudes take the form

$$A(B_d^0 \to D_d^+ D_d^-) = -\lambda \bar{\mathcal{A}} \left[ 1 - \bar{a} e^{i\bar{\theta}} e^{i\gamma} \right] \quad (21)$$

$$A(B_s^0 \to D_s^+ D_s^-) = \left( 1 - \frac{\lambda^2}{2} \right) \mathcal{A} \left[ 1 + \bar{\alpha} e^{i\bar{\theta}} e^{i\gamma} \right] \quad (22)$$

where $\bar{\mathcal{A}}$ and $\bar{a} e^{i\bar{\theta}}$ are defined in analogy to $\mathcal{A}$ and $a e^{i\theta}$. We may then, as in (11), introduce a quantity

$$\tilde{H} = \text{PhSp} \left\{ -\frac{1}{\epsilon} \frac{\bar{\mathcal{A}}^2}{\mathcal{A}} \right\}^{2} \left( \frac{\Gamma(B_d \to D_d^+ \bar{D}_d^-)}{\Gamma(B_s \to D_s^+ \bar{D}_s^-)} \right)$$

$$= \frac{1 - 2\bar{a} \cos \bar{\theta} \cos \gamma + \bar{a}^2}{1 + 2\bar{\alpha} \cos \bar{\theta} \cos \gamma + \epsilon^2 \bar{a}^2}. \quad (23)$$

Furthermore, we may write

$$\mathcal{A}_{\text{CP}}^{\text{dir}}(B_d \to D_d^+ \bar{D}_d^-) = F_1(\bar{a}, \bar{\theta}, \gamma) \quad (24)$$

$$\mathcal{A}_{\text{CP}}^{\text{mix}}(B_d \to D_d^+ \bar{D}_d^-) = F_2(\bar{a}, \bar{\theta}, \gamma, \phi_d) \quad (25)$$

as well as

$$\mathcal{A}_{\text{CP}}^{\text{mix}}(B_s \to D_s^+ \bar{D}_s^-) = F_1'(\bar{a}', \bar{\theta}', \gamma) = 0 + O(\epsilon \bar{a}') \quad (26)$$

$$\mathcal{A}_{\text{CP}}^{\text{dir}}(B_s \to D_s^+ \bar{D}_s^-) = F_2'(\bar{a}', \bar{\theta}', \gamma, \phi_s) \quad (27)$$

Since the $B_{d(s)} \to D_{d(s)}^+ \bar{D}_{d(s)}^-$ decays are again related through the interchange of all $d$ and $s$ quarks, the $U$-spin flavour symmetry of strong interactions implies

$$|\bar{\mathcal{A}}| = |\mathcal{A}| \quad (28)$$

$$\bar{a}' = \bar{a}, \quad \bar{\theta}' = \bar{\theta} \quad (29)$$

Consequently, (28) and (29) allow us to determine $\tilde{H}$, where the $U$-spin-breaking corrections to (28) have the most important impact:

$$\left\{ \frac{\bar{\mathcal{A}}}{\mathcal{A}} \right\}^{2} \approx \frac{(M_{B_d} - M_{D_s}) \sqrt{M_{B_d} M_{D_s} (w_s + 1) f_{D_s} \xi_s(w_s)}}{(M_{B_s} - M_{D_s}) \sqrt{M_{B_s} M_{D_s} (w_d + 1) f_{D_d} \xi_d(w_d)}} \quad (30)$$

Because of the $\epsilon$ suppression in (23), corrections to (29) play a minor rôle. Finally, we may extract $\gamma, \bar{a}$ and $\bar{\theta}$ from the measured values of $\tilde{H}, \mathcal{A}_{\text{CP}}^{\text{dir}}(B_d \to D_d^+ \bar{D}_d^-)$ and $\mathcal{A}_{\text{CP}}^{\text{mix}}(B_d \to D_d^+ \bar{D}_d^-)$, as illustrated in Fig. 2. In this example, we have used the input parameters $\gamma = 65^\circ, \phi_d = 42.4^\circ, \bar{a}' = 0.1$ and $\bar{\theta}' = 210^\circ$, which allow the observables $\mathcal{A}_{\text{CP}}^{\text{dir}}(B_d \to D_d^+ \bar{D}_d^-) = -0.08$, $\mathcal{A}_{\text{CP}}^{\text{mix}}(B_d \to D_d^+ \bar{D}_d^-) = 0.78$ and $\tilde{H} = 1.1$. It should be noted that the contour following from $\tilde{H}, \mathcal{A}_{\text{CP}}^{\text{mix}}$ is theoretically clean.

An interesting by-product of this strategy is that we can now also control the penguin effects in the extraction of $\phi_s$ from (27). This avenue provides an attractive alternative to the conventional determination of the $B_d^0, B_s^0$ mixing phase through the $B_s \to J/\psi \phi$ angular analysis.

![FIG. 2: Illustration of the extraction of $\gamma$ and $\bar{a}$ from the $B_d(s) \to D_{d(s)}^+ D_{d(s)}^-$ system through contours in the $\gamma - \bar{a}$ plane.](image)

III. PURE TREE DECAYS

The determination of $\gamma$ from $B \to D^{(*)} K^{(*)}$ tree decays suffers currently from large uncertainties:

$$\gamma|_{D^{(*)} K^{(*)}} = \begin{cases} (62^{+38}_{-24}) \circ \text{(CKMfit)} \\ (82 \pm 20) \circ \text{(UTfit)} \end{cases} \quad (31)$$

This unfavourable situation can be significantly improved at LHCb, where also $B_s$ decays into final states with charm play an important rôle.

A. The $B_s \to D_s^+ K^+, B_d \to D^+ \pi^-$ System

The key feature of these decays is that both a $B_q^0$ and a $B_q^0$ meson may decay into the same final state $D_q \bar{q}$, thereby leading to interference between mixing and decay processes. This phenomenon brings $\phi_q$ and $\gamma$ into the game, which enter actually in the combination $\phi_q + \gamma$. In the case of $q = s$, corresponding to the final states $D_s \in \{D_s^+, D_s^{*+}, \ldots\}$ and $u_s \in \{K^+, K^{*+}, \ldots\}$, the interference effects are governed by a hadronic parameter $X_s e^{i\delta_s} \propto R_b$, where $R_b$ is the usual side of the unitarity triangle, and are hence large. On the other hand, for $q = d$ with $D_d \in \{D_d^+, D_d^{*+}, \ldots\}$ and $u_d \in \{\pi^+, \rho^+, \ldots\}$, a doubly Cabibbo-suppressed hadronic parameter $X_{d} e^{i\delta_d} \propto -\lambda^2 R_b$ enters, which leads to tiny interference effects.

If the $\cos(\Delta M_d t)$ and $\sin(\Delta M_d t)$ terms of the time-dependent decay rates are measured, $\phi_q + \gamma$ can be extracted in a theoretically clean way [11]. Since the mixing phases $\phi_q$ are known, this determination can be converted into a measurement of $\gamma$. However, the practical implementation is affected by problems: we encounter an eightfold discrete ambiguity for $\phi_q + \gamma$, which has to be resolved for the search of NP. Moreover, in the $q = d$ case, an additional input is required to extract $\Delta_{3}$, since $O(X_s^2)$ interference effects would have to be resolved, which is impossible.

As was pointed out in [11], a combined analysis of $B^0 \to D_s^{(*)+} K^-$ and $B^0 \to D^{(*)+} \pi^-$ allows us to resolve these problems with the help of the $U$-spin symmetry. In this strategy, where $X_d$ has not to be fixed and $X_s$
enters only through a $1 + X^2$ correction, which can be determined through untagged $B_s$ rates, an unambiguous value of $\gamma$ can be extracted. The first studies for LHCb are very promising \cite{12}, and are currently further refined.

**B. $B_s \to D\eta(\bar{\psi})$, $B_s \to D\phi$, ... and $B_d \to D\bar{K}_{S(L)}$**

These transitions are the colour-suppressed counterparts of the $B_s \to D^{\pm}\bar{K}^{\mp}$ channels. If we consider the CP eigenstates $D_{\pm}$ of the neutral $D$ mesons, we may introduce the following untagged rate asymmetry \cite{13}:

$$\Gamma_{\mp}^{f_{\pm}} = \langle \Gamma(B_{\mp} \to D_{\pm} f_{\pm}) \rangle - \langle \Gamma(B_{\pm} \to D_{\pm} f_{\mp}) \rangle,$$

which allows us to constrain $\gamma$ through $|\cos \gamma| \geq |\Gamma_{-\pm}^{f_{-\pm}}|$. Additional observables are provided by the coefficients $C_{\mp}^{f_{\pm}}$ and $S_{\mp}^{f_{\pm}}$ of the $\cos(\Delta M_{f_{\pm}} t)$ and $\sin(\Delta M_{f_{\pm}} t)$ terms of the CP asymmetries, respectively. It is convenient to define the following combinations:

$$(C_{f_{\pm}})_{\pm} \equiv \frac{1}{2} \left[ C_{\mp}^{f_{\pm}} \pm C_{\pm}^{f_{\mp}} \right], \quad (S_{f_{\pm}})_{\pm} \equiv \frac{1}{2} \left[ S_{\mp}^{f_{\pm}} \pm S_{\pm}^{f_{\mp}} \right].$$

An unambiguous determination of $\gamma$ is then possible with the help of the following expression \cite{13}:

$$\tan \cos \phi_q = \frac{\eta_{f_{\pm}}(S_{f_{\pm}})_{\pm}}{\Gamma_{f_{\pm}}^{\mp}} + \eta_{f_{\mp}}(S_{f_{\mp}})_{-\pm} - \sin \phi_q,$$

where $\eta_{f_{\pm}} = (-1)^{L} \eta_{\mp}$ depends on the angular momentum $L$ of the $D_{\mp} f_{\pm}$ final state.

**C. $B_s \to D_{\pm}\bar{K}_{S(L)}$ and $B_d \to D_{\pm}\rho^0$, $D_{\pm}\bar{D}^0$, ...**

Let us finally have a look at the $b \to d$ counterparts of the $B_s \to D\eta(\bar{\psi})$, $B_s \to D\phi$, ... and $B_d \to D\bar{K}_{S(L)}$ modes. The relevant interference effects are governed by hadronic parameters $x_{f_d} e^{i \theta_{f_d}} \propto \lambda^2 R_0 \approx 0.02$. Consequently, these decays are not promising for the extraction of $\gamma$. However, since their observable combinations $(S_{f_{\pm}})_{-\pm}$, which are defined in analogy to \cite{33}, satisfy the simple relation

$$\eta_{f_{\pm}}(S_{f_{\pm}})_{-\pm} = \sin \phi_q + O(x_{f_d}^2) = \sin \phi_q + O(4 \times 10^{-4}),$$

they offer extremely clean extractions of $\sin \phi_q$ \cite{12}. In comparison with the $B_s \to J/\psi \phi$ and $B_d \to J/\psi K_S$ determinations, the theoretical accuracy is one order of magnitude higher. Moreover, as no penguin contributions are present, these determinations are very robust with respect to NP effects at the decay amplitude level, which is an interesting topic in view of the low value of $(\sin 2\beta)_{\psi K_S}$ and the “tension” in the fits of the unitarity triangle. In particular, NP effects entering through $B^0_d - \bar{B}^0_d$ mixing or through tiny effects at the $B \to J/\psi K$ amplitude level (for instance, through penguin-like topologies) could be distinguished this way.

**IV. CONCLUDING REMARKS**

Decays of $B_s$ mesons into final states with charm offer various determinations of $\gamma$. In these strategies, the $U$-spin flavour symmetry of strong interactions provides a powerful tool, allowing us to fully exploit the physics potential of the $B_s$ mesons through a simultaneous analysis of the $U$-spin related $B_d$ decays.

We also encountered interesting “by-products” for the $B$-physics programme at the LHC, including ways to control the penguin uncertainties in the extractions of $\phi_d$ and $\phi_s$ from $B^0_d \to J/\psi K_S$ and $B^0_d \to J/\psi \phi$, respectively, which seem to be particularly relevant for LHCb upgrade plans, and an alternative determination of $\phi_s$ with the help of $B^0_d \to D^+_s D^-_s$.

The cleanest determinations of the mixing phases $\phi_s$ and $\phi_d$ are offered by the pure tree decays $B_s \to D_{\pm}\bar{K}_{S(L)}$ and $B_d \to D_{\pm}\pi^0, D_{\pm}\rho^0, \ldots$, respectively. These channels would be very interesting for the search of NP, but are unfortunately extremely challenging for LHCb. On the other hand, they may be accessible at an $e^+e^-$ super-$B$ factory. Detailed experimental feasibility studies in this direction are strongly encouraged.

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