PROCEEDINGS OF SCIENCE

A Roadmap to Controlling Penguin Effects in ϕ_d and ϕ_s

Kristof De Bruyn*
CPPM/CNRS/Aix-Marseille Université
E-mail: debruyn@cppm.in2p3.fr

Measurements of CP violation in $B^0 \to J/\psi K_S^0$, $B_s^0 \to J/\psi \phi$ and $B_s^0 \to D_s^- D_s^+$ decays play key roles in testing the quark-flavour sector of the Standard Model. The theoretical interpretation of these observables is, however, limited by uncertainties from doubly Cabibbo-suppressed penguin topologies. With continuously increasing experimental precision, it is mandatory to get a handle on these contributions, which cannot be calculated reliably in QCD. In this summary, we discuss a data driven method based on the $SU(3)$ flavour symmetry of QCD to relate the penguin contributions in $B^0 \to J/\psi K_S^0$, $B_s^0 \to J/\psi \phi$ and $B_s^0 \to D_s^- D_s^+$ to unsuppressed counterparts in decay modes with similar dynamics. The fit results obtained with the currently available data are presented for all three modes. In addition, we discuss prospects for the LHCb upgrade and Belle II era, and illustrate the possibilities for the determination of hadronic parameters.

16th International Conference on B-Physics at Frontier Machines
2-6 May 2016
Marseille, France

*Speaker.

PoS(BEAUTY2016)004

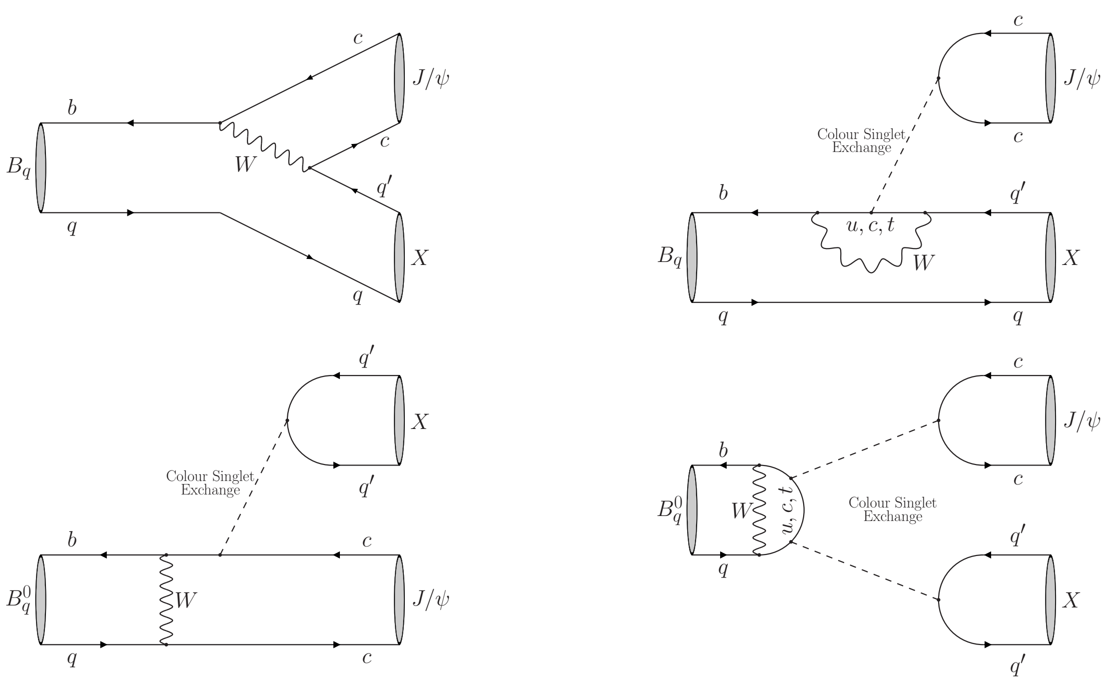

Figure 1: Illustration of the colour-suppressed tree [Top Left], penguin [Top Right], exchange [Bottom Left], and penguin-annihilation [Bottom Right] topologies contributing to the $B_q \to J/\psi X$ channels. Similar diagrams exist for the $B \to D\bar{D}$ decays.

1. Introduction

We have yet to see an unambiguous signal from physics beyond the Standard Model. The picture emerging from the first years of data taking at the Large Hadron Collider (LHC) is, within the current level of precision, globally consistent with the Standard Model (SM). This is in particular true for the determination of the "B_q^0–$\bar{B}_q^0$ mixing phases" ϕ_d and ϕ_s from *CP* violation measurements in $B^0 \to J/\psi K_S^0$, $B_s^0 \to J/\psi\,\phi$ and $B_s^0 \to D_s^- D_s^+$. If these CP phases are at all affected by new physics (NP) contributions, the impact is small and thus more challenging to differentiate from the suppressed, and so far ignored, higher order SM corrections. In view of the forthcoming physics runs at the LHC and KEK e^+e^- super B factory, which promise to reduce the experimental uncertainties on the CP measurements in these decays, we thus need to have a critical look at the theoretical assumptions underlying the experimental analyses. Only by doing so can we match the (future) experimental results with equally accurate theoretical predictions.

The higher order hadronic corrections to the *CP* observables of $B^0 \to J/\psi K_S^0$, $B_s^0 \to J/\psi\,\phi$ and $B_s^0 \to D_s^- D_s^+$ originate from so-called penguin, exchange and penguin-annihilation topologies, illustrated in Fig. 1. Contributions from the latter two diagrams, which only affect the $B_s^0 \to J/\psi\,\phi$ and $B_s^0 \to D_s^- D_s^+$ decays, are suppressed compared to the effects from the penguin diagrams, and are ignored in this summary. The presence of these loop diagrams affects the relation

$$\frac{\mathscr{A}_{CP}^{\text{mix}}(B_q^0 \to f)}{\sqrt{1-\left(\mathscr{A}_{CP}^{\text{dir}}(B_q^0 \to f)\right)^2}} = \sin\left(\phi_q^{\text{eff}}\right) = \sin\left(\phi_q^{\text{SM}} + \phi_q^{\text{NP}} + \Delta\phi_q\right) \tag{1.1}$$

between the measured *CP* asymmetries of the decay $B_q^0 \to f$ and the CP phase ϕ_q, itself decomposed in terms of its SM contribution ϕ_q^{SM} and a possible NP contribution ϕ_q^{NP}, by introducing an additional shift $\Delta\phi_q$ [1]. Initial studies, like those presented below, put the size of this shift at the degree level. The LHCb upgrade [2] and Belle II [3] programmes, on the other hand, foresee to achieve a precision on ϕ_d and ϕ_s below the degree level. Controlling the size of these penguin shifts is therefore mandatory in order to differentiate them from possible NP effects.

Although rough theoretical estimates for these shifts are available [4, 5], it is, in view of the non-perturbative long-distance QCD contributions to these corrections, difficult to accurately calculate them directly within the quantum field theory framework. An alternative approach is therefore pursued in this summary. It relies on the $SU(3)$ flavour symmetry of QCD to relate the doubly Cabibbo-suppressed penguin contributions in the decay amplitudes of $B^0 \to J/\psi K_S^0$, $B_s^0 \to J/\psi\phi$ and $B_s^0 \to D_s^- D_s^+$ to those of similar decay modes in which they are no longer suppressed. In this way, the sizes of the penguin shifts can be estimated directly from the experimental data, as discussed in more detail in Ref. [6, 7, 8, 9, 1, 10, 11, 12, 13], and in particular Refs. [14, 15] on which this summary is based.

2. Framework

Assuming only contributions from tree and penguin topologies, the transition amplitudes of the $B^0 \to J/\psi K_S^0$, $B_s^0 \to J/\psi\phi$ and $B_s^0 \to D_s^- D_s^+$ decay channels can be written in the general form [6]

$$A\left(B_q^0 \to f\right) = \left(1 - \frac{\lambda^2}{2}\right)\mathscr{A}'\left[1 + \epsilon a_f' e^{\theta_f'} e^{+i\gamma}\right], \tag{2.1}$$

where $\lambda = |V_{us}|$ is an element of the Cabibbo–Kobayashi–Maskawa (CKM) matrix, $\mathscr{A}'$ is a *CP*-conserving hadronic amplitude that represents the tree topology of the decay, and a_f parametrises the relative contribution from the penguin topologies. The *CP*-conserving strong phase difference between both terms is parametrised as θ_f, whereas the relative weak phase difference is given by the CKM angle γ. A key feature of the decay amplitude in Eq. (2.1) is the double Cabibbo-suppression of the penguin contribution $a' e^{i\theta'} e^{i\gamma}$ by the tiny factor [16]

$$\epsilon \equiv \frac{\lambda^2}{1-\lambda^2} = 0.0536 \pm 0.0003\,, \tag{2.2}$$

which allowed us to ignore this term up to now. Using the above parametrisation, both the penguin shift $\Delta\phi_q$ and the CP observables can be expressed as functions of the penguin parameters a' and θ' [6, 1].

In order to determine a_f' and θ_f', which in principle are different for the three decay modes, the $B^0 \to J/\psi K_S^0$, $B_s^0 \to J/\psi\phi$ and $B_s^0 \to D_s^- D_s^+$ decays are related via $SU(3)$ symmetry to partner modes in which the penguin contributions are not suppressed. For $B^0 \to J/\psi K_S^0$ the most promising candidate in the long run is its U-spin partner $B_s^0 \to J/\psi K_S^0$. These two decay modes are related to each other by interchanging all d and s quarks, leading to a one-to-one correspondence between all decay topologies, which in turn minimises the associated theoretical uncertainty. The $B_s^0 \to J/\psi K_S^0$ CP asymmetries have recently been measured by LHCb [17], but the obtained precision is not yet sufficient to derive constraints on a' and θ'. Instead, the results discussed below use input from the $SU(3)$-related modes $B^+ \to J/\psi\,\pi^+$ and $B^0 \to J/\psi\,\pi^0$ (as well as $B^+ \to J/\psi\,K^+$). This requires additional assumptions to be made, and thus leads to a larger associated theoretical uncertainty, which disfavours the strategy once high precision CP measurement of $B_s^0 \to J/\psi\,K_S^0$ become available. For the $B_s^0 \to J/\psi\,\phi$ mode, which decays into two vector mesons, the transition amplitudes, and hence also the penguin parameters, are polarisation dependent. They thus need to be determined for each of the three polarisation states (0, $\parallel$, $\perp$) individually. This can be done using the decays $B^0 \to J/\psi\,\rho^0$ and $B_s^0 \to J/\psi\,\bar{K}^{*0}$, which also contain two vector mesons in the final state. For $B_s^0 \to D_s^- D_s^+$, which differs from the $B \to J/\psi\,X$ modes by having only pseudo-scalars in the final state, the $SU(3)$ partner is the $B^0 \to D_d^- D_d^+$ decay, related by interchanging all d and s quarks with one another.

The transition amplitude of the control modes can be written in the form

$$A\left(B_q^0 \to f\right) = -\lambda \mathscr{A}\left[1 - a e^{i\theta} e^{i\gamma}\right] . \tag{2.3}$$

In contrast to Eq. (2.1), there is no ε factor present in front of the second term, thereby enhancing the penguin effects. On the other hand, the λ factor in front of the overall amplitude suppresses the branching ratio with respect to its partner mode and makes the decay more challenging to study experimentally. Using the above parametrisation, the CP observables can be expressed as functions of the penguin parameters a and θ. Complementing the experimental measurements of the CP asymmetries with external input on the CKM angle γ allows us to determine a and θ, either numerically by using a χ^2 fit to the inputs, or graphically by plotting the measurements of the CP observables as contours in the θ–a plane and looking at the intersection of these contours.

The obtained solution for a and θ can be related via $SU(3)$ symmetry to the penguin parameters a' and θ' in $B^0 \to J/\psi\,K_S^0$, $B_s^0 \to J/\psi\,\phi$ and $B_s^0 \to D_s^- D_s^+$ as

$$a' = \xi a\,, \qquad \theta' = \theta + \delta\,, \tag{2.4}$$

where ξ and δ parametrise the non-factorisable $SU(3)$-breaking effects between the control mode and its partner decay. Under perfect $SU(3)$ symmetry, $\xi = 1$ and $\delta = 0$. However, to account for possible $SU(3)$-breaking effects, it is assumed throughout this summary that $\xi = 1.00 \pm 0.20$ and $\delta = (0 \pm 20)^\circ$. It should be noted that factorisable $SU(3)$-breaking effects, which enter the hadronic amplitudes $\mathscr{A}^{(\prime)}$, cancel out in the ratio $a^{(\prime)} e^{i\theta^{(\prime)}} e^{i\gamma}$.

Besides the CP asymmetries, also the branching fractions contain information on the penguin parameters $a^{(\prime)}$ and $\theta^{(\prime)}$. But in order to access this information, the prefactors linking the branching fractions to their transition amplitudes in Eqs. (2.1) and (2.3) need to be cancelled. This can be accomplished by making ratios of branching fractions through the construction of the so-called H observable [6]. For the $B^0 \to J/\psi\,K_S^0$ decay it takes the form

$$H \equiv \frac{1}{\varepsilon}\left|\frac{\mathscr{A}'}{\mathscr{A}}\right|^2 \frac{\mathrm{PhSp}\left(B_d \to J/\psi\,K_S^0\right)}{\mathrm{PhSp}\left(B_s \to J/\psi\,K_S^0\right)} \frac{\tau_{B^0}}{\tau_{B_s^0}} \frac{\mathscr{B}\left(B_s \to J/\psi\,K_S^0\right)}{\mathscr{B}\left(B_d \to J/\psi\,K_S^0\right)}\,, \tag{2.5}$$

where PhSp is the relevant phase-space factor and $\tau_{B_q^0}$ is the B_q^0 lifetime. Similar observables can be defined for the $B_s^0 \to J/\psi\,\phi$ and $B_s^0 \to D_s^- D_s^+$ decays. Because of the ratio of hadronic amplitudes $\mathscr{A}'/\mathscr{A}$, the H observable is affected by factorisable $SU(3)$-breaking effects, and thus associated with a large theoretical uncertainty. Its use as an input to constrain the penguin parameters is

PoS(BEAUTY2016)004

therefore disfavoured when alternatives are available. For the fits set up to determine $\Delta\phi_d$, $\Delta\phi_s$ from $B^0 \to D_d^- D_d^+$, as well as for the analysis of the decay $B_s^0 \to J/\psi \bar{K}^{*0}$, this is not (yet) the case.

In case the use of the H observables is not necessary for the determination of the penguin parameters a and θ, it can instead provide experimental information on the ratio of hadronic amplitudes $\mathscr{A}'/\mathscr{A}$ by inverting the above relation, i.e.

$$\left|\frac{\mathscr{A}'}{\mathscr{A}}\right| = \sqrt{\varepsilon H_{(a,\theta)} \frac{\text{PhSp}\left(B_s \to J/\psi K_S^0\right)}{\text{PhSp}\left(B_d \to J/\psi K_S^0\right)} \frac{\tau_{B_s}}{\tau_{B_d}} \frac{\mathscr{B}\left(B_d \to J/\psi K_S^0\right)}{\mathscr{B}\left(B_s \to J/\psi K_S^0\right)}} \,. \tag{2.6}$$

Here $H_{(a,\theta)}$ is the value of the H observable calculated from the solution for a and θ, obtained from the χ^2 fit to the CP asymmetries only. Experimental information on $\mathscr{A}'/\mathscr{A}$ would form an interesting test of the U-spin symmetry.

3. The Penguin Shift $\Delta\phi_d$

Fit to Current Data To determine the penguin shift $\Delta\phi_d$ from the currently available experimental data, a χ^2 fit is performed to the CP asymmetries and/or branching fractions of the modes $B^0 \to J/\psi K_S^0$, $B_s^0 \to J/\psi K_S^0$, $B^+ \to J/\psi K^+$, $B^+ \to J/\psi \pi^+$ and $B^0 \to J/\psi \pi^0$. The modes $B^+ \to J/\psi \pi^+$ and $B^0 \to J/\psi \pi^0$ have Cabibbo-allowed penguin contributions, and their transition amplitudes can be written as in Eq. (2.3). They are related to $B_s^0 \to J/\psi K_S^0$ by replacing the strange spectator quark with an up or down quark, respectively. The mode $B^+ \to J/\psi K^+$ has doubly Cabibbo-suppressed penguin contributions, and its transition amplitude can be written as in Eq. (2.1). It is related to $B^0 \to J/\psi K_S^0$ by replacing the down spectator quark with an up quark. These three modes have additional decay topologies which have no counterpart in $B^0 \to J/\psi K_S^0$ and $B_s^0 \to J/\psi K_S^0$, and are ignored in this analysis. In addition, the fit assumes that all five modes can be parametrised by a single set of penguin parameters a and θ, i.e. non-factorisable $SU(3)$-breaking effects between the decays are ignored. External input on the CKM angle γ, whose value is taken to be [16]

$$\gamma = \left(73.2^{+6.3}_{-7.0}\right)^\circ \,, \tag{3.1}$$

is included as a Gaussian constraint. The values of a and θ obtained from the χ^2 fit are [18]

$$a = 0.17^{+0.14}_{-0.12} \,, \qquad \theta = (179.3 \pm 4.2)^\circ \,, \tag{3.2}$$

which result in a penguin phase shift

$$\Delta\phi_d^{J/\psi K_S^0} = -\left(1.03^{+0.69}_{-0.85}\right)^\circ \,, \tag{3.3}$$

and a solution for the CP phase

$$\phi_d = (43.9 \pm 1.7)^\circ \,. \tag{3.4}$$

The constraints on the penguin parameters derived from the individual observables entering the χ^2 fit are illustrated as different light-coloured bands in Fig. 2. This highlights the importance of the H observables in the current fit, which are necessary to constrain the parameter a.

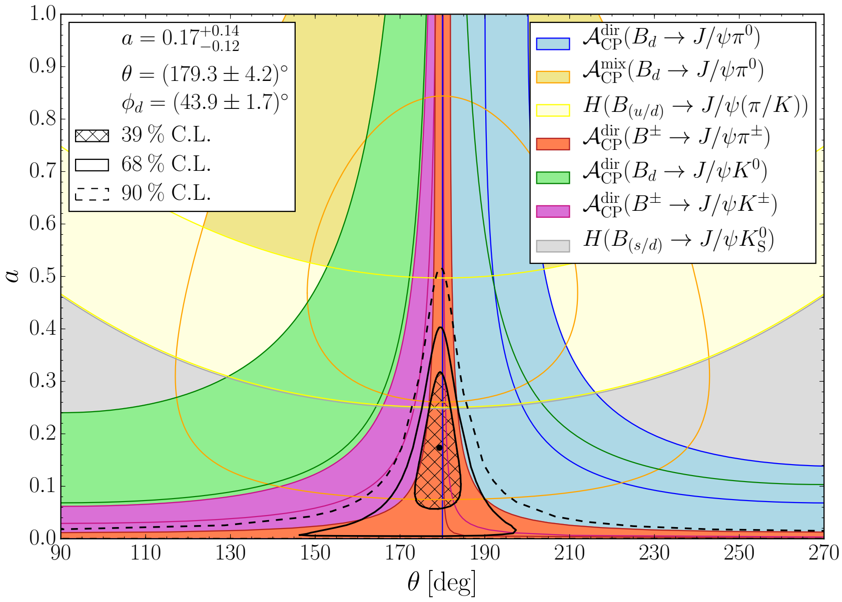

Figure 2: Determination of the penguin parameters a and θ through intersecting contours derived from CP asymmetries and branching ratios of $B_q \to J/\psi P$ decays, where P is a pseudo-scalar meson. Superimposed are the confidence level contours obtained from a χ^2 fit to the current data. Taken from Ref. [18].

Benchmark Fit for $B_s^0 \to J/\psi K_S^0$ Let us also illustrate the potential of the $B_s^0 \to J/\psi K_S^0$ mode in providing high precision constraints on the shift $\Delta\phi_d^{J/\psi K_S^0}$, using a benchmark scenario for the LHCb upgrade era. This hypothetical scenario assumes the CP asymmetries have been measured as

$$\mathscr{A}_{CP}^{\rm dir}(B_s \to J/\psi K_S^0) = 0.004 \pm 0.065\,, \qquad \mathscr{A}_{CP}^{\rm mix}(B_s \to J/\psi K_S^0) = -0.274 \pm 0.065\,, \tag{3.5}$$

and that the precision on the external inputs improves to

$$\gamma = (73.2 \pm 1.0)^\circ\,, \qquad \phi_s = -\left(2.1 \pm 0.5|_{\rm exp} \pm 0.3|_{\rm theo}\right)^\circ\,. \tag{3.6}$$

The values of a and θ obtained from a χ^2 fit to these inputs are [18]

$$a = 0.174 \pm 0.040\,, \qquad \theta = (179.3 \pm 12.7)^\circ\,, \tag{3.7}$$

and lead to a precision on the penguin shift of

$$\Delta\phi_d^{J/\psi K_S^0} = -\left(1.02^{+0.23}_{-0.25}\,({\rm stat})^{+0.17}_{-0.24}\,(U\text{-spin})\right)^\circ\,, \tag{3.8}$$

matching the expected experimental precision on ϕ_d. As this fit does not rely on branching ratio information, the results in Eq. (3.7) can instead be used to predict the value of the H observable as

$$H_{(a,\theta)} = 1.136 \pm 0.039\,(a,\theta) \pm 0.0012\,(\xi,\delta)\,. \tag{3.9}$$

Because the dependence of H on the a' parameter enters in combination with the tiny ε factor, the U-spin breaking corrections, parametrised through ξ and δ have a negligible impact. Using

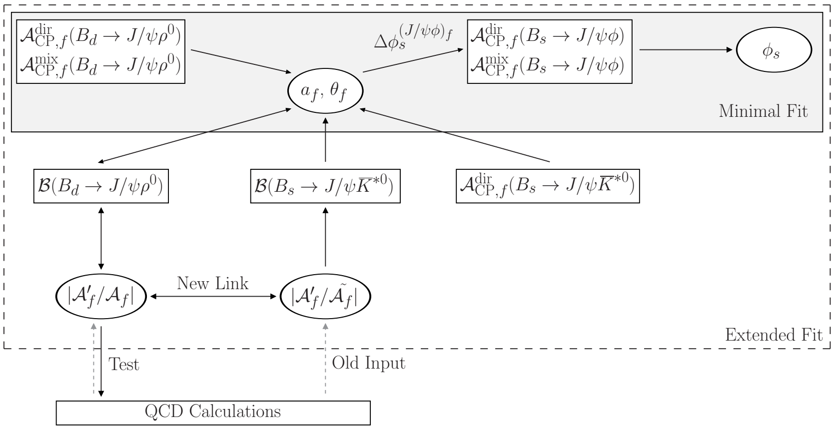

Figure 3: Graphical illustration of the combined analysis of the $B^0 \to J/\psi\,\rho^0$, $B_s^0 \to J/\psi\,\bar{K}^{*0}$ and $B_s^0 \to J/\psi\,\phi$ modes to simultaneously determine the penguin parameters, the ratio of $SU(3)$-breaking strong amplitudes, and the CP phase ϕ_s. Taken from Ref. [14].

Eq. (2.6) and conservative assumptions for the measured ratio of branching fractions would then lead to an experimental determination of the ratio of hadronic amplitudes of

$$\left|\frac{\mathscr{A}'}{\mathscr{A}}\right|_{\mathrm{exp}} = 1.160 \pm 0.034\,. \tag{3.10}$$

The obtained precision is about five times smaller that the current theoretical uncertainties from factorisation and Light Cone QCD Sum Rules (LCSR), which gives

$$\left|\frac{\mathscr{A}'}{\mathscr{A}}\right|_{\mathrm{fact}} = 1.16 \pm 0.18\,. \tag{3.11}$$

4. The Penguin Shift $\Delta\phi_s$

To determine the penguin shift $\Delta\phi_s$ from the currently available experimental data and for each of the three polarisation states individually, the strategy proposed in Ref. [14] and illustrated in Fig. 3 has been implemented by the LHCb collaboration [19]. A χ^2 fit is performed to the CP asymmetries and branching fractions of the modes $B_s^0 \to J/\psi\,\bar{K}^{*0}$ and $B^0 \to J/\psi\,\rho^0$ [19]. The fit ignores contributions from exchange and penguin-annihilation topologies, which affect $B^0 \to J/\psi\,\rho^0$ and $B_s^0 \to J/\psi\,\phi$ but are not present in $B_s^0 \to J/\psi\,\bar{K}^{*0}$, and assumes the relation

$$\left|\frac{\mathscr{A}_i'(B_s^0 \to J/\psi\,\phi)}{\mathscr{A}_i(B^0 \to J/\psi\,\rho^0)}\right| = \left|\frac{\mathscr{A}_i'(B_s^0 \to J/\psi\,\phi)}{\mathscr{A}_i(B_s^0 \to J/\psi\,\bar{K}^{*0})}\right| \tag{4.1}$$

between the hadronic amplitudes of both modes. This equality allows us to determine the ratio of hadronic amplitudes directly from the experimental data and avoids the need for theoretical input from LCSR. External inputs on γ and ϕ_d, i.e. Eqs. (3.1) and (3.4), are included as Gaussian constraints in the fit. The values of a and θ obtained from the χ^2 fit are [19]

$$a_0 = 0.01^{+0.10}_{-0.01}\,, \qquad \theta_0 = -\left(83^{+97}_{-263}\right)^\circ\,, \qquad \left|\frac{\mathscr{A}_0'}{\mathscr{A}_0}\right| = 1.195^{+0.074}_{-0.056}\,, \tag{4.2}$$

$$a_\parallel = 0.07^{+0.11}_{-0.05}\,, \qquad \theta_\parallel = -\left(85^{+72}_{-63}\right)^\circ\,, \qquad \left|\frac{\mathscr{A}_\parallel'}{\mathscr{A}_\parallel}\right| = 1.238^{+0.104}_{-0.080}\,, \tag{4.3}$$

$$a_\perp = 0.04^{+0.12}_{-0.04}\,, \qquad \theta_\perp = \left(38^{+142}_{-218}\right)^\circ\,, \qquad \left|\frac{\mathscr{A}_\perp'}{\mathscr{A}_\perp}\right| = 1.042^{+0.081}_{-0.063}\,, \tag{4.4}$$

with the two-dimensional confidence level contours given in Fig. 4. This also shows the constraints on the penguin parameters derived from the individual observables entering the χ^2 fit as different light-coloured bands. The penguin shifts derived from the above results on a_i and θ_i are

$$\Delta\phi_{s,0}^{J/\psi\phi} = 0.000^{+0.009}_{-0.011}\,(\text{stat})\ {}^{+0.004}_{-0.009}\,(\text{syst})\ \text{rad}\,, \tag{4.5}$$

$$\Delta\phi_{s,\parallel}^{J/\psi\phi} = 0.001^{+0.010}_{-0.014}\,(\text{stat}) \pm 0.008\,(\text{syst})\ \text{rad}\,, \tag{4.6}$$

$$\Delta\phi_{s,\perp}^{J/\psi\phi} = 0.003^{+0.010}_{-0.014}\,(\text{stat}) \pm 0.008\,(\text{syst})\ \text{rad}\,. \tag{4.7}$$

These results are dominated by the input from the *CP* asymmetries in $B^0 \to J/\psi\rho^0$, and show that the penguin pollution in the determination of ϕ_s from $B_s^0 \to J/\psi\phi$ is small.

5. The $B \to D\bar{D}$ Decays

Fit to Current Data To determine the penguin shift $\Delta\phi_s$ affecting the decay $B_s^0 \to D_s^- D_s^+$ from the currently available experimental data, a χ^2 fit is performed to the H observable and CP asymmetries of the $B^0 \to D_d^- D_d^+$ mode. Contrary to the $B \to J/\psi X$ decays discussed above, the data suggests non-negligible contributions from the exchange and penguin-annihilation modes, which complicates the calculation of the H observable. Omitting further details on this calculation, which relies on branching ratio information of $B^0 \to D^-\ell^+\nu$ and $B \to D\bar{D}$ decays and can be found in Ref. [15], the values of a and θ obtained from the χ^2 fit are

$$a = 0.35^{+0.19}_{-0.20}\,, \qquad \theta = \left(215^{+51}_{-17}\right)^\circ\,. \tag{5.1}$$

This results in a penguin phase shift

$$\Delta\phi_s^{D_s^- D_s^+} = -\left(1.7^{+1.6}_{-1.2}\,(\text{stat})^{+0.3}_{-0.7}\,(U\text{-spin})\right)^\circ\,, \tag{5.2}$$

and a solution for the CP phase

$$\phi_s = -\left(0.6^{+9.8}_{-9.9}\,(\text{stat})^{+0.3}_{-0.7}\,(U\text{-spin})\right)^\circ\,. \tag{5.3}$$

Despite the suppression through the parameter ε, penguin topologies may have a sizeable impact on the extraction of ϕ_s from $B_s^0 \to D_s^- D_s^+$, although the uncertainties are still too large to draw strong conclusions.

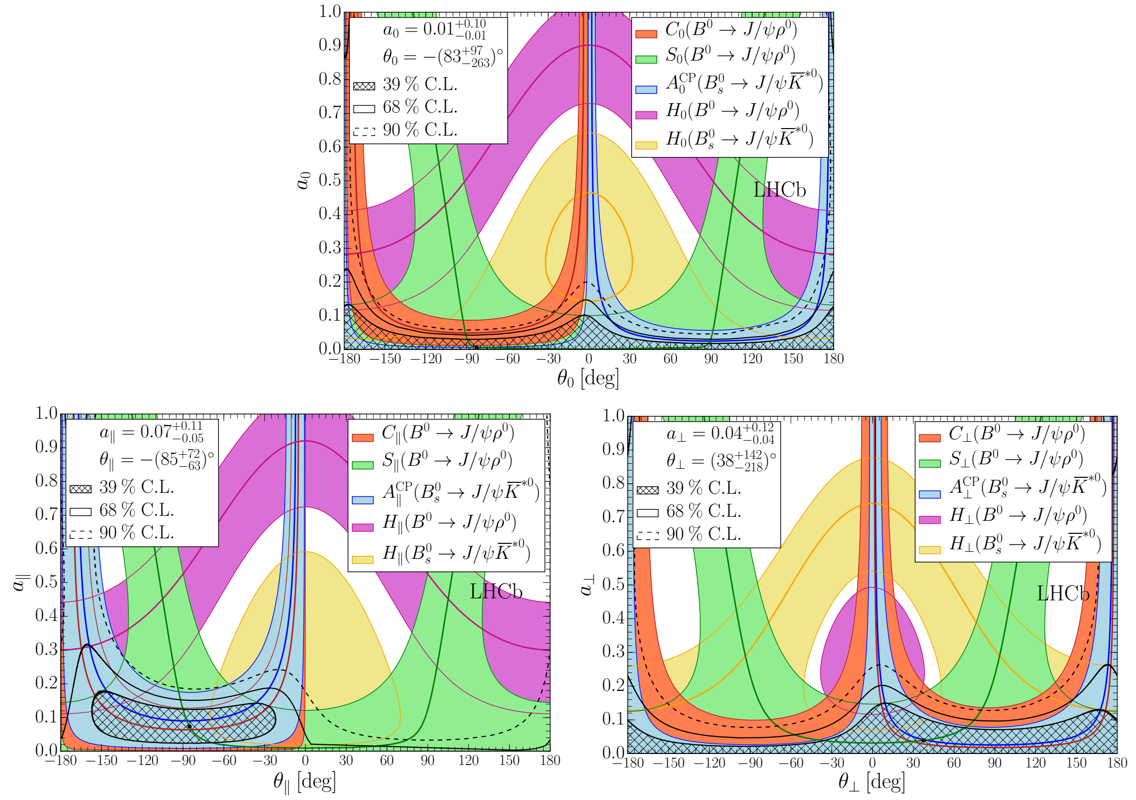

Figure 4: Determination of the penguin parameters a and θ through intersecting contours derived from CP asymmetries and branching ratios of $B_q \to J/\psi V$ decays, where V is a vector meson. Superimposed are the confidence level contours obtained from a χ^2 fit to the current data. Shown are the longitudinal [Top], parallel [Bottom Left] and perpendicular [Bottom Right] polarisation states. Taken from Ref. [19].

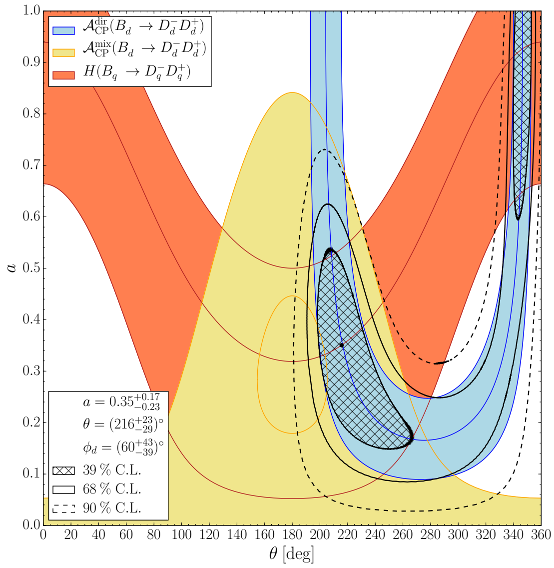

Figure 5: Determination of the penguin parameters a and θ through intersecting contours derived from CP asymmetries and branching ratios of $B \to D\overline{D}$ decays. Superimposed are the confidence level contours obtained from a χ^2 fit to the current data. Taken from Ref. [15].

Future Prospects Looking at how the picture derived from the current data can evolve for the LHCb upgrade and Belle II era, two main strategies can be identified. In a favourable scenario the input from the CP asymmetries in $B^0 \to D_d^- D_d^+$ is sufficient to determine a and θ, i.e. the use of the H observable is not necessary. This situation has the smallest associated theoretical uncertainty, and in addition allows us to get experimental access to the ratio of hadronic amplitudes, similar to Eq. (2.6).

In a less favourable scenario, the overlap between the contours derived from the direct and mixing-induced CP asymmetry is too large to obtain a high precision determination of a and θ. The CP asymmetries therefore need to be complemented with branching ratio information. If we end up in this scenario, a high precision calculation of the H observable will be crucial to constrain the penguin parameters and thus also the penguin shift $\Delta\phi_s$. In order to avoid the dominant uncertainties due to factorisable $SU(3)$ symmetry breaking, arising from the ratio of hadronic amplitudes, the H observable could be calculated using the differential decay rate information from the semileptonic $B^0 \to D^- \ell^+ \nu$ and $B_s^0 \to D_s^- \ell^+ \nu$ decays.

Further details as well as explicit examples for both scenarios are discussed in Ref. [15].

6. Conclusion

Controlling higher order hadronic corrections due to the presence of penguin topologies becomes mandatory to further improve the precision on the "B_q^0–$\bar{B}_q^0$ mixing phases" ϕ_d and ϕ_s, obtained from CP asymmetry measurements in $B^0 \to J/\psi K_S^0$, $B_s^0 \to J/\psi \phi$ and $B_s^0 \to D_s^- D_s^+$. This summary, based on more detailed work in Refs. [14] and [15], illustrates strategies to determine these corrections directly from experimentally accessible observables, based on the $SU(3)$ flavour symmetry of QCD. This method has already been adopted by the LHCb collaboration in their analyses of the $B^0 \to J/\psi \rho^0$ and $B_s^0 \to J/\psi \bar{K}^{*0}$ decays, and other modes will follow. Using these strategies, it can be demonstrated that the penguin effects can be controlled to below the degree level, matching the prospects for the LHCb upgrade and Belle II era. In addition, the summary highlights new possibilities to get experimental insights into hadronic physics and the $SU(3)$ symmetry through the ratio of hadronic amplitudes $|\mathscr{A}'/\mathscr{A}|$, which arises as a by-product of the proposed strategy.

Acknowledgements I would like to thank Robert Fleischer and my other colleagues for the pleasant collaboration on the topics presented in this talk.

References

[1] S. Faller, M. Jung, R. Fleischer and T. Mannel, *The golden modes $B^0 \to J/\psi K_{S,L}$ in the era of precision flavour physics*, *Phys. Rev. D* **79** (2009) 014030 [arXiv:0809.0842 [hep-ph]].

[2] R. Aaij *et al.* [LHCb Collaboration], *Implications of LHCb measurements and future prospects*, *Eur. Phys. J. C* **73** (2013) no.4, 2373 [arXiv:1208.3355 [hep-ex]].

[3] T. Abe *et al.* [Belle II Collaboration], *Belle II technical design report*, arXiv:1011.0352 [physics.ins-det].

[4] X. Liu, W. Wang and Y. Xie, *Penguin pollution in $B \to J/\psi V$ decays and impact on the extraction of the B_s^0–$\bar{B}_s^0$ mixing phase*, *Phys. Rev. D* **89** (2014) no.9, 094010 [arXiv:1309.0313 [hep-ph]].

[5] P. Frings, U. Nierste and M. Wiebusch, *Penguin contributions to CP phases in $B_{d,s}$ decays to charmonium*, *Phys. Rev. Lett.* **115** (2015) no.6, 061802 [arXiv:1503.00859 [hep-ph]].

[6] R. Fleischer, *Extracting γ from $B_{(s/d)} \to J/\psi K_S^0$ and $B_{(d/s)} \to D^+_{(d/s)} D^-_{(d/s)}$*, *Eur. Phys. J. C* **10** (1999) 299 [arXiv:hep-ph/9903455].

[7] R. Fleischer, *Extracting CKM phases from angular distributions of $B_{(d,s)}$ decays into admixtures of CP eigenstates*, *Phys. Rev. D* **60** (1999) 073008 [arXiv:hep-ph/9903540].

[8] R. Fleischer, *Recent theoretical developments in CP violation in the B system*, *Nucl. Instrum. Meth. A* **446** (2000) 1 [arXiv:hep-ph/9908340].

[9] M. Ciuchini, M. Pierini and L. Silvestrini, *The effect of penguins in the $B^0 \to J/\psi K_S^0$ CP asymmetry*, *Phys. Rev. Lett.* **95** (2005) 221804 [arXiv:hep-ph/0507290].

[10] S. Faller, R. Fleischer and T. Mannel, *Precision physics with $B_s^0 \to J/\psi \phi$ at the LHC: The quest for new physics*, *Phys. Rev. D* **79** (2009) 014005 [arXiv:0810.4248 [hep-ph]].

[11] K. De Bruyn, R. Fleischer and P. Koppenburg, *Extracting gamma and penguin topologies through CP violation in $B_s^0 \to J/\psi K_S^0$*, *Eur. Phys. J. C* **70** (2010) 1025 [arXiv:1010.0089 [hep-ph]].

[12] M. Ciuchini, M. Pierini and L. Silvestrini, *Theoretical uncertainty in sin 2β: An update*, arXiv:1102.0392 [hep-ph].

[13] M. Jung, *Determining weak phases from $B \to J/\psi P$ decays*, *Phys. Rev. D* **86** (2012) 053008 [arXiv:1206.2050 [hep-ph]].

[14] K. De Bruyn and R. Fleischer, *A roadmap to control penguin effects in $B^0 \to J/\psi K_S^0$ and $B_s^0 \to J/\psi \phi$*, *JHEP* **1503** (2015) 145 [arXiv:1412.6834 [hep-ph]].

[15] L. Bel, K. De Bruyn, R. Fleischer, M. Mulder and N. Tuning, *Anatomy of $B \to D\bar{D}$ decays*, *JHEP* **1507** (2015) 108 [arXiv:1505.01361 [hep-ph]].

[16] J. Charles *et al.*, *Current status of the Standard Model CKM fit and constraints on $\Delta F = 2$ new physics*, *Phys. Rev. D* **91** (2015) no.7, 073007 [arXiv:1501.05013 [hep-ph]].

[17] R. Aaij *et al.* [LHCb Collaboration], *Measurement of the time-dependent CP asymmetries in $B_s^0 \to J/\psi K_S^0$*, *JHEP* **1506** (2015) 131 [arXiv:1503.07055 [hep-ex]].

[18] K. De Bruyn, *Searching for penguin footprints: Towards high precision CP violation measurements in the B meson systems*, CERN-THESIS-2015-126.

[19] R. Aaij *et al.* [LHCb Collaboration], *Measurement of CP violation parameters and polarisation fractions in $B_s^0 \to J/\psi \bar{K}^{*0}$ decays*, *JHEP* **1511** (2015) 082 [arXiv:1509.00400 [hep-ex]].