New physics in $B^0_s \to J/\psi\phi$ decays?

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Abstract

After a brief review of $B^0_s - \bar{B}^0_s$ oscillations, we discuss the weak decays $B^0_s \to J/\psi\phi$ and $B^0_s \to J/\psi f_0(980)$ and the ratio $\mathcal{R}_{f_0/\phi}$ of their decay rates in the light of recent measurements by the LHCb, D∅ and CDF Collaborations. We point out that the experimental values for $\mathcal{R}_{f_0/\phi}$ impose tight limits on new physics contributions to both decay channels.

1 $B^0_s - \bar{B}^0_s$ oscillations into $J/\psi \phi$

The study of $CP$ violation in $B_s$ mesons is still in its early stages with many contemporary experiments and analyses focussing on the decay $B^0_s \to J/\psi\phi$. The interest in this particular channel owes to the observation that the final state $J/\psi\phi$ is reached by interference of a decay without mixing, $B^0_s \to J/\psi\phi$, and with mixing, $B^0_s \to \bar{B}^0_s \to J/\psi\phi$. In principle, this allows for the observation of the $CP$ violating phase, $-2\beta_s$, where $\beta_s$ is the Standard Model angle in the unitarity triangle for the $B^0_s$ system. Practically, it is predicted to be small, $-2\beta_s = \phi_s = -0.038 \pm 0.002$ [1], about 20 times smaller in magnitude than the corresponding phase in $B^0_d$ mixing.

The mixing occurs in the Standard Model due the nonequivalence of mass and flavor eigenstates and gives rise to particle-antiparticle oscillations. They are described by the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix nowadays established as the leading paradigm for $CP$ violation. The time evolution of $B^0_s$ oscillation follows from the perturbative solution of the time-dependent Schrödinger equation (see, e.g., Ref. [2] for a detailed review of the formalism), written as,

$$i \frac{d}{dt} \begin{pmatrix} |B^0_s(t)\rangle \\ |\bar{B}^0_s(t)\rangle \end{pmatrix} = \left( M^s - \frac{i}{2} \Gamma^s \right) \begin{pmatrix} |B^0_s(t)\rangle \\ |\bar{B}^0_s(t)\rangle \end{pmatrix}.$$  \(1\)

The complex $2 \times 2$ mass and decay rate matrices, $M^s$ and $\Gamma^s$, are hermitian and diagonalization of $M^s - \frac{i}{2} \Gamma^s$ yields the mass eigenstates

$$|\bar{B}^0_{sL}\rangle = p |B^0_s\rangle + q |\bar{B}^0_s\rangle,$$

\(2\)
where the masses, \( M_L^s \) and \( M_H^s \), and decay rates, \( \Gamma_L^s \) and \( \Gamma_H^s \), are distinct. The complex numbers, \( p \) and \( q \), are related to the matrix elements of \( M^s \) and \( \Gamma^s \) by,

\[
\frac{q}{p} = -2(M_{12}^{s*} - \frac{1}{2} \Gamma_{12}^{s*})/(\Delta M^s - \frac{1}{2} \Delta \Gamma^s) \approx -\frac{M_{12}^{s*}}{|M_{12}^s|} \left[ 1 - \frac{1}{2} \text{Im} \left( \frac{\Gamma_{12}^{s*}}{M_{12}^{s*}} \right) \right],
\]

and satisfy \(|p|^2 + |q|^2 = 1\). The \( B_s^0 - \bar{B}_s^0 \) oscillations in Eq. (1) involve the physical quantities \(|M_{12}^s|\), \(|\Gamma_{12}^s|\) and the CP violating phase \( \phi_s = \arg(-M_{12}^s/\Gamma_{12}^s) \). The off-diagonal matrix element \( \Gamma_{12}^s \) is important as it represents the partial width of \( B_s^0 \) and \( \bar{B}_s^0 \) decays to common final states and is related to the decay width difference \( \Delta \Gamma^s \) between the two mass eigenstates by,

\[
\Delta \Gamma^s = \Gamma_{L}^s - \Gamma_{H}^s = 2|\Gamma_{12}^s| \cos \phi_s,
\]

whereas the mass difference in Eq. (4) is proportional to the off-diagonal element \(|M_{12}^s|\),

\[
\Delta M^s = M_H^s - M_L^s = 2|M_{12}^s|,
\]

and equals the frequency of the \( B_s^0 - \bar{B}_s^0 \) oscillations.

The two mass eigenstates of \( B \) mesons are expected to be almost pure CP eigenstates when \( \Delta \Gamma/\Gamma \) is negligible, which is the case for \( |\Gamma_{12}^s| \approx 0 \) and \( \Gamma_{12}^s/M_{12}^s \) is approximately real in the Standard Model (since \( \phi_s \) is very small). By virtue of Eq. (4) it follows that \( q/p \approx -M_{12}^{s*}/|M_{12}^s| = \exp(i\phi_M) \) and \(|q/p| = 1 \) (to within 1% [3]). However, experiment seems to indicate that \( \Delta \Gamma^s/\Gamma^s \) could be as large as 22% for the \( B_s^0 \) [4]. We shall return to this point shortly in Section 2.

The time-dependent \( CP \)-violating asymmetry for \( B_s^0 \to J/\psi \phi \) is defined to be,

\[
a_{J/\psi \phi}(t) = \frac{\Gamma(\bar{B}_s^0(t) \to J/\psi \phi) - \Gamma(B_s^0(t) \to J/\psi \phi)}{\Gamma(\bar{B}_s^0(t) \to J/\psi \phi) + \Gamma(B_s^0(t) \to J/\psi \phi)} ,
\]

and can be shown to be written as [2],

\[
a_{J/\psi \phi}(t) = -\left[ (1 - |\lambda_{J/\psi \phi}|^2) \cos(\Delta M^st) + 2 \text{Im} \lambda_{J/\psi \phi} \sin(\Delta M^st) \right]/(1 + |\lambda_{J/\psi \phi}|^2) ,
\]

provided \( \Delta \Gamma^s/\Gamma^s \) is small and \(|q/p| = 1\). We made use of the definition,

\[
\lambda_{J/\psi \phi} = \eta_{J/\psi \phi} \frac{q}{p} \frac{A(\bar{B}_s^0 \to J/\psi \phi)}{A(B_s^0 \to J/\psi \phi)} ,
\]

where \( A \) denotes the complex decay amplitude, \( \bar{A} \) is the \( CP \) conjugate amplitude and \( \eta_{J/\psi \phi} = \pm 1 \) describes \( CP \)-even and -odd components in the final state, the separation of which requires an angular analysis [5]. For the so-called third type of \( CP \) violation with and without mixing, one has in addition to \(|q/p| = 1\) also the condition \(|\bar{A}/A| = 1\), so that \(|\lambda_{J/\psi \phi}| = 1\):

\[
a_{J/\psi \phi}(t) = -\text{Im} \lambda_{J/\psi \phi} \sin(\Delta M^st) = \eta_{J/\psi \phi} \sin(2\beta_s) \sin(\Delta M^st) .
\]

Hence, the asymmetry directly measures the phase differences between particular CKM matrix elements and introduces no uncertainty due to strong interaction phases, which are often of non-perturbative origin and not well known; namely, the strong interaction effects all cancel exactly since \(|\lambda_{J/\psi \phi}| = 1\) or at least very close to 1. Since \( \beta_s \) is predicted to be very small in the Standard Model, no appreciable \( CP \) violation should be detected in experiment. Therefore, any large deviation from this prediction could indicate new physics (NP) contributions manifest in the modified mixing phase:

\[
2\beta_s = 2\beta_s^{SM} - \phi_s^{NP} .
\]
2 The related decay $B^0_s \rightarrow J/\psi f_0(980)$

First experimental determinations of $\beta_s$ have come from the CDF [6] and DØ [7] Collaborations and their initial values hinted at a possible large deviation (of order 2.2$\sigma$ if both results are combined) from the Standard Model. The latest DØ measurements [4] of $\Delta \Gamma^s$ and $\beta_s$ are only marginally smaller than those in [7] and in particular $\Delta \Gamma^s = 0.163^{+0.065}_{-0.064}$ ps$^{-1}$. However, an updated CDF measurement seems to be more consistent [8] with the Standard Model values. One is hopeful that LHCb will provide tighter constraints on $\beta_s$ and $\Delta \Gamma^s$ in the near future.

It was already mentioned that $CP$ violation can be measured using angular analyses since the final state $J/\psi \phi$ is not a $CP$ eigenstate. This requires more events to acquire a similar sensitivity to that obtained if the decay proceeds solely via $CP$-even or $CP$-odd channels. The related channel $B^0_s \rightarrow J/\psi f_0(980)$ is in that sense advantageous, as the decay is to a single $CP$-odd eigenstate and does not require an angular analysis. As in the case of $B^0_s \rightarrow J/\psi \phi$, its $CP$ violating phase is given by $-2\beta_s$ up to higher corrections. However, as for other scalar mesons, the exact flavor and constituent content is not known to date.$^2$ The mass of the $f_0(980)$ is well estimated at $m_{f_0} = 980 \pm 10$ MeV, yet its width is only poorly known due to the nearby opening of the $KK$ channel and its dependence on a given final state. It can be rather narrow in the case of $B^\pm \rightarrow K^\pm f_0(980)$ decays and estimates of the width are in the range $40 - 100$ MeV [3]. For a general overview of scalar mesons we refer to the review by C. Amsler et al. in the Particle Data Group book [3] and references therein.

It has also been argued that the angular analysis in the decay $B^0_s \rightarrow J/\psi \phi$ is complicated by the $J/\psi f_0(980)$ channel, since it contributes $S$-wave $K^+K^-$ pairs which can interfere with those originating from the $\phi$. This $S$-wave should also be manifest in the appearance of $f_0(980) \rightarrow \pi^+\pi^-$ decays. Following this observation, the level of $S$-wave “contamination” was proposed to be estimated by the following ratio [12]:

$$\mathcal{R}_{f_0/\phi} = \frac{\Gamma(B^0_s \rightarrow J/\psi f_0(980), f_0(980) \rightarrow \pi^+\pi^-)}{\Gamma(B^0_s \rightarrow J/\psi \phi, \phi \rightarrow K^+K^-)}.$$  \hspace{1cm} (12)

Initial estimates based on similar decays in the charm sector show this ratio to be of the order of 20% - 30% [12]. These estimates rely on experimental data on $D_s^+ \rightarrow f_0(980)\pi^+$ and $D_s^+ \rightarrow \phi\pi^+$ decay rates and seem to indicate that the $S$-wave contribution of $f_0(980) \rightarrow K^+K^-$ cannot be ignored when analyzing the angle $\beta_s$ in $B_s^0 \rightarrow J/\psi \phi$. Likewise, Xie et al. found the effect of an $S$-wave component on $-2\beta_s$ to be of the order of 10% in the $\phi$ resonance region [13]. A first calculation of this ratio based on decay amplitudes derived in QCD factorization (QCDF) and a model calculation of the non-perturbative transition amplitude $A(B_s \rightarrow f_0(980))$ [14, 15] are discussed in the following sections.

A treatment of possible $S$-wave contributions in experimental analyses was presented in a recent analysis of $\beta_s$ [8]. In there, the CDF Collaboration finds that $S$-wave contribution within $\pm 10$ MeV about the $\phi$ meson is less that 6.7% at 95% confidence level. Incidentally, these preliminary CDF results [8] on $\beta_s$ and $\Gamma^s$ point at a reconciliation with the Standard Model values and it remains to be clarified which impact on the analyses the additional $S$-wave contribution have.

$^2$ Notwithstanding popular descriptions of scalar mesons as molecular bound-states of mesons as well as tetra-quarks, a Dyson-Schwinger equation approach to the scalar $qq$ ground state with a non-perturbative kernel beyond the rainbow-ladder truncation determines the mass of the flavor-pure scalar to be $m_s = 900$ MeV [9]. A more sophisticated description in terms of a mixing angle between $uu\bar{d}d$ and $ss$ components has not been realized yet but is feasible. Further improvements include pion- and kaon-loop effects in the non-perturbative kernel which can shift the pole mass by about 8% [10]. In short, viewing scalar mesons, such as the $f_0(980)$, exclusively as a $\bar{q}q$ or $q^2\bar{q}^2$ state may simply be too naive [11].
3 Nonperturbative aspects in decay amplitudes

The details of the $B_s^0 \rightarrow J/\psi f_0(980)$ and $B_s^0 \rightarrow J/\psi \phi$ decay amplitudes calculated in QCDF can be found in Ref. [14]. We here concentrate on the nonperturbative matrix element that emerges from the factorized amplitude. The amplitude of interest is the heavy-to-light transition between a $B_s^0$ and the scalar $f_0(980)$ meson which decomposed into Lorentz invariants gives rise to two form factors,

$$\langle f_0(p_2)|\bar{s} \gamma_\mu (1 - \gamma_5)b|B_s^0(p_1)\rangle = \left(p_\mu - \frac{m_{B_s^0}^2 - m_{f_0}^2}{q^2} q_\mu\right) F_1^{B_s^0\rightarrow f_0}(q^2) + \frac{m_{B_s^0}^2 - m_{f_0}^2}{q^2} q_\mu F_0^{B_s^0\rightarrow f_0}(q^2), \quad (13)$$

with $p_1^2 = m_{B_s^0}^2$, $p_2^2 = m_{f_0}^2$, $q = p_1 - p_2$ and $p = p_1 + p_2$. The matrix element of the $B_s^0 \rightarrow \phi$ transition amplitude is given by a similar decomposition and introduces five more form factors [14].

Common relativistic quark-model approaches represent heavy-to-light transition amplitudes by triangle diagrams, a 3-point function between the Bethe-Salpeter amplitudes (BSA) of a heavy ($H$) and a light ($M$) meson and the weak coupling represented by the transition amplitude $\langle M(p_2) | q \bar{f} H | H(p_1) \rangle$. This is the generalized impulse approximation, which in the language of Dyson-Schwinger equations [16] is the leading term in their systematic and symmetry preserving truncation:

$$A(p_1, p_2) = \text{tr} \int \frac{d^4 k}{(2\pi)^4} \Gamma_M(k; -p_2) S_M(k + p_2) \Gamma_I(p_1, p_2) S_M(k + p_1) \Gamma_H(k; p_1) S_Q(k), \quad (14)$$

where $S(k)$ are (dressed) quark propagators, $Q = c, b$; $q = q' = u, d, s$; $\Gamma_M$ is the light meson BSA with $M = S, P, V, A$ and the index $\mu$ indicates its possible vector structure. $\Gamma_I = \gamma_\mu (1 - \gamma_5)$ or $\sigma_\mu q' (1 + \gamma_5)$ is the interaction vertex and $\Gamma_H$ is the heavy meson BSA. The trace is over Dirac and color indices. Calculation of these matrix elements in lattice-regularized QCD or with QCDF sum rules follows a somewhat different approach based on heavy-light correlation functions. A brief review on effective and non-perturbative approaches to heavy-light transition form factors and in particular discrepancies between model predictions at large time-like momentum transfer, $q^2$, can be found in Ref. [17]

As discussed earlier, the lack of a precise constituent picture of the scalar $f_0(980)$ makes a precision calculation of the transition matrix element in Eq. (13) impossible for the time being. Nevertheless, the $B_s \rightarrow f_0(980)$ form factors have recently been obtained in QCD sum rules [18, 19] and pQCD [20] for $q^2 = 0$, where an extrapolation to the value $F_{0.1}^{B_s \rightarrow f_0}(m_{J/\psi}^2)$ is required. They have also been calculated by some of us [15] from the constituent quark three-point function, the vertices of which are the weak interaction coupling, $\gamma_\mu (1 - \gamma_5)$, and two BSA for the $B_s$ and $f_0(980)$ mesons. In this relativistic dispersion-relation model, a phenomenological parametrization of the $B_s$ is obtained from the simultaneous calculation of the weak decay constant $f_{B_s}$ (known from lattice-QCD simulations). In an attempt to find a suitable form of the $f_0(980)$ BSA, we constrained the mixing angle between strange and non-strange $\bar{q}q$ components and appropriate width parameters by means of experimental data on the branching fractions of the decays $D_s \rightarrow f_0(980)P$ with $P = \pi, K$. The scalar $F_0^{B_s \rightarrow f_0}(q^2)$ and vector $F_1^{B_s \rightarrow f_0}(q^2)$ form factors are then obtained for any physical time-like momentum transfer $q^2$ and no extrapolation is needed. We recall that only the vector form factor $F_1^{B_s \rightarrow f_0}(q^2)$ enters the decay amplitude $A(B_s^0 \rightarrow J/\psi f_0(980))$. We deduce from the extrapolation parametrization in Ref. [19] that $F_1^{B_s \rightarrow f_0}(m_{J/\psi}^2) \simeq 0.3$, which is compatible with our prediction $F_1^{B_s \rightarrow f_0}(m_{J/\psi}^2) \simeq 0.4$ [15] within theoretical errors.

4 The ratio $\mathcal{R}_{f_0/\phi}$ and new physics contributions in the light of recent measurements

Equipped with an estimate of the $F_1^{B_s \rightarrow f_0}(m_{J/\psi}^2)$ form factor value and the QCDF expression for $\mathcal{R}_{f_0/\phi}$ in Eq. (12), we can predict this ratio in dependence of different inputs in the $B_s^0 \rightarrow J/\psi f_0(980)$ and $B_s^0 \rightarrow$
**Figure 1**: The ratio $R_{f_0/\phi}$ as a function of the transition form factor $F_1^{B_s^0 \to f_0}(m_{J/\psi}^2)$ based on the $B_s^0 \to J/\psi f_0(980)$ and $B_s^0 \to J/\psi \phi$ decay amplitudes in Eqs. (2) and (4) of Ref. [14] for $\zeta^{(h)} = 0$. The area between the two dashed lines accounts for the uncertainty of the decay constants ($f_{B_s} = 260 \pm 30$ MeV and $\bar{f}_{f_0} = 380 \pm 40$ MeV) while the solid lines include in addition the uncertainties on the decay rates $f_0(980) \to \pi^+ \pi^-$ and $\phi \to K^+ K^-$. The single dotted line is the prediction for the central values of the decay constants. The shaded area between the two dot-dashed horizontal lines represents the window of experimentally motivated estimates for $R_{f_0/\phi}$ [12, 21].

$J/\psi \phi$ decay amplitudes. To account for the main source of uncertainty, we do so by plotting this ratio as a function of $F_1^{B_s^0 \to f_0}(m_{J/\psi}^2)$ in Figs. 1 and 2. Two other sources of uncertainties are included in both figures which are due to the theoretical errors of the vector decay constant, $f_{B_s}$, the scalar decay constant, $\bar{f}_{f_0}$, and the experimental error on the decay rates $f_0(980) \to \pi^+ \pi^-$ [15, 21] and $\phi \to K^+ K^-$ [3]. We plot the evolution of $R_{f_0/\phi}$ for a rather large window of form factor values, though the domain of interest due to the theoretical estimates [15, 19] is in the range $F_1^{B_s^0 \to f_0}(m_{J/\psi}^2) \simeq 0.3 - 0.4$. As seen in Figure 1, in this particular range the central value of $R_{f_0/\phi}$ is about $0.35 \pm 0.05$ which is compatible with the estimates based on the ratio of (differential) decay rates, $\Gamma(D_s^+ \to f_0(980)\pi^+)/\Gamma(D_s^+ \to \phi\pi^+)$ [12, 21], depicted by the shaded area.

Additional short-distance amplitudes $\zeta^{(h)}$, where $h$ denotes the helicity of the $J/\psi \phi$ state, proportional to the dominant CKM term were introduced in the QCDF amplitudes for $B_s^0 \to J/\psi f_0(980)$ and $B_s^0 \to J/\psi \phi$ [14]. In a sense, these phenomenological amplitudes mock up other or beyond Standard Model physics contributions to the decays. In addition, we assume that whatever these other amplitudes are, they contribute equally to all helicities states of $J/\psi \phi$ and to $J/\psi f_0(980)$, as they originate in the same flavor-changing neutral current, $b \to sc\bar{c}$, of the corresponding penguin diagrams: $\zeta^{(h)}_{J/\psi \phi} = \zeta_{J/\psi f_0} = \zeta_{J/\psi f_0}$. Generically, we write the amplitudes as,

$$A = |\mathcal{A}^{SM}| e^{i\beta_2^{SM}} + |\mathcal{A}^{NP}| e^{i(2\beta_2^{SM} - \phi_N^{NP})} = |\mathcal{A}^{SM}| e^{i\beta_2^{SM}} \left(1 + \mathcal{R} e^{-i\phi_N^{NP}}\right),$$

(15)

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3 See Section IV in Ref. [14] for a discussion of the scalar decay constant $\bar{f}_{f_0}$ defined by $m_{f_0} \bar{f}_{f_0} = (0|\bar{q}q|f_0)$ and its relation to the vector decay constant $f_{f_0}$.  

5
Figure 2: The ratio $R_{f_0/\phi}$ as in Figure 1 but including possible new physics contributions $\zeta^{(h)}$ in Eqs. (2) and (4) of Ref. [14].

with $R = |A^{NP}/A^{SM}|$. The amplitudes $A^{NP} \sim \zeta^{(h)}$ are adjusted so they give the best possible agreement with experimental data on $B_s^0 \to J/\psi \phi$, which includes the branching ratio, the longitudinal, parallel and perpendicular polarization fractions, $f_L$, $f_\parallel$ and $f_\perp$, and two relative phases, $\phi_\parallel$ and $\phi_\perp$ [3, 22, 23]. They are then inserted in the $B_s^0 \to J/\psi f_0(980)$ decay amplitude. The evolution of $R_{f_0/\phi}$ including the $\zeta^{(h)}$ amplitudes as a function of $F_{1B_s^0\to f_0}^{B_0\to f_0}(q^2=m_{J/\psi}^2)$ is presented in Figure 2 from which it obvious that the ratio is strongly enhanced. For the same range as previously, $F_{1B_s^0\to f_0}^{B_0\to f_0}(m_{J/\psi}^2) \simeq 0.3 - 0.4$, the central value of $R_{f_0/\phi}$ is of the order $0.6 \pm 0.05$. Taking into account the theoretical uncertainties this is still within an acceptable range from the estimates in the shaded area.

On the other hand, recent first measurements of the ratio $R_{f_0/\phi}$, consistent with each other, seem to favor our calculation for $\zeta^{(h)} = 0$ and a form factor $F_{1B_s^0\to f_0}(m_{J/\psi}^2) < 0.4$:

\[
\begin{align*}
R_{f_0/\phi} & = 0.275 \pm 0.041 \pm 0.061 & (D\emptyset \text{ Collaboration [24]}) , \\
R_{f_0/\phi} & = 0.257 \pm 0.020 \pm 0.014 & (CDF \text{ Collaboration [25]}) , \\
R_{f_0/\phi} & = 0.252_{-0.032}^{+0.046+0.027} & (LHCb \text{ Collaboration [26]}) ,
\end{align*}
\]

where in each case the errors are statistical and systematic, respectively. The calculated value $F_{1B_s^0\to f_0}^{B_0\to f_0} \simeq 0.4$ [15] actually leads to a bigger ratio, $R_{f_0/\phi} = 0.42$, which rises to 0.63 when the $\zeta^{(h)}$ amplitudes are included. Clearly, as Figure 1 instructs us, if the decays $B_s^0 \to J/\psi f_0(980)$ and $B_s^0 \to J/\psi \phi$ are merely due to Standard Model interactions (save for $\Lambda_{QCD}/m_b$ corrections neglected in our decay amplitudes based on QCDF), then $0.15 - 0.2$ is a more likely value for $F_{1B_s^0\to f_0}^{B_0\to f_0}$. If, however, these decays receive contributions from a yet unknown source then it is not plausibile that they should be equal in magnitude and phase for both final states unless one admits a rather unrealistic value for $F_{1B_s^0\to f_0}^{B_0\to f_0} < 0.1$. Even if this was the case, the new physics amplitudes $A^{NP}$ must necessarily contribute different phases to the $B_s^0 \to J/\psi f_0(980)$ and $B_s^0 \to J/\psi \phi$ amplitudes which results in interferences so that $R_{f_0/\phi}$ comes close the observed values in Eq. (16).
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