

# CP VIOLATION WITH $B_s$

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The observation of CP violation effects is becoming more and more significant in a variety of channels, due to the impressive experimental effort of the last years. We review recent progress in  $B_s^0$  semileptonic decays and in  $B_s^0$  decays into CP eigenstates.

## 1 Introduction

There are well known differences between the  $B_s^0$  and the  $B^0$  system. The mixing parameter  $x_s \equiv \Delta m_s/\Gamma_s$  is about 30 times larger than  $x_d$ , and the mass and width difference are sizable. Another important difference is that the CP violating mixing phase probes the angle  $\beta_s$  in the unitarity triangle, which is about two order of magnitudes smaller than  $\beta$  in the Standard Model, and hence negligibly small. Any large variation due to new physics can produce observable effects, and that alone would be enough to motivate the study of CP violation in the  $B_s^0$  system. We will review a few decays where the observation of CP violation effects has recently become accessible and significant, due to the impressive experimental effort of the last years.

### 1.1 Flavour-specific decays

The mass eigenstates can be written in terms of the flavour eigenstates

$$|B_{s,H}^0\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle \quad |B_{s,L}^0\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle \quad (1)$$

where  $|p|^2 + |q|^2 = 1$ , by normalization condition. Evidence for CP violation in  $B_s^0$  mixing has been searched for, with flavor-specific decays, in samples where the initial flavor state is tagged. Flavour-specific final states are states which, due to some selection rule, can be reached directly only by  $B_s^0$  and not by  $\bar{B}_s^0$  or conversely. CP violation in the interference of mixing and decay clearly cannot occur, as only one of the two flavour eigenstates can feed the final state. Instead, CP violation in the mixing and in the decay are both possible. However, in some cases, the decay is dominated by a single amplitude, and/or there are no different strong scattering phases as required to observe CP violation in the decay. In that case, when the final state tag is also available, we can write the following asymmetry

$$a_{fs}^s = \frac{\Gamma(\bar{B}_s^0(t) \rightarrow f) - \Gamma(B_s^0(t) \rightarrow \bar{f})}{\Gamma(\bar{B}_s^0(t) \rightarrow f) + \Gamma(B_s^0(t) \rightarrow \bar{f})} = \frac{1 - |q/p|^4}{1 + |q/p|^4} \quad (2)$$

testing the “wrong” final state, accessible only through mixing. The asymmetry  $a_{fs}$  measures CP violation in mixing and it is independent from time and from the final state (to within a sign), as it can be ascribed to a property of the decaying states. In the Standard Model, one expects  $|\Gamma_{12}/M_{12}| \sim m_b^2/m_t^2 \sim 10^{-3} \ll 1$ . At lowest order in  $|\Gamma_{12}/M_{12}|$ , we have

$$\left|\frac{q}{p}\right|^2 = 1 - a \quad a \equiv \text{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right) = \frac{\Delta\Gamma_s}{\Delta m_s} \tan \phi_s \quad (3)$$

where  $\phi_s \equiv \arg(-M_{12}/\Gamma_{12})$ ,  $\Delta m_s \equiv m_H - m_L = 2|M_{12}|$  and  $\Delta\Gamma_s = \Gamma_L - \Gamma_H = 2|\Gamma_{12}| \cos \phi_s$ . Notice that the symbol  $\phi_s$  is overloaded, since in literature it is also used for the mixing phase induced by  $M_{12}$  only. Whatever the definition, the CP violating phase can be related to  $\beta_s$ , that is  $\beta_s \equiv \arg[-V_{tb}^* V_{ts}/V_{cb}^* V_{cs}]$  in the Standard Model, since the dispersive term  $M_{12}$  is mainly driven by box diagrams involving virtual top quarks and the absorptive term  $\Gamma_{12}$  is dominated by on-shell charmed intermediate states. An additional phase, e. g.  $\beta_s(SM) \rightarrow \beta_s(SM) + \tilde{\beta}_s$ , it is often used to parameterize effects of new physics or non-leading hadronic contributions.

The phase  $\phi_s \neq 0, \pi$  implies  $|q/p| \neq 1$ . The parameter  $a$ , that is small irrespective of the value of  $\phi_s$ , implies small CP violation in the mixing. At lowest order  $a \simeq a_{fs}^s$ , and the measured value of  $a_{fs}^s$  can be translated into a constraint for both  $\Delta\Gamma_s$  and  $\phi_s$ . In the case of semileptonic decays, when the final state contains also a charged meson,  $a_{fs}^s$  is called semileptonic charge asymmetry. It has been directly measured by the experiment DØ via the decay  $B_s^0 \rightarrow D_s^- \mu^+ X^1$

$$a_{sl}^s = \left[-1.7 \pm 9.1(\text{stat})_{-2.3}^{+1.2}(\text{syst})\right] \times 10^{-3} \quad (4)$$

A related observable is the (like-sign) dimuon charge asymmetry  $\mathcal{A}_{sl}^b$ , which is the difference in the number of events with a pair of positive muons minus the number with a pair of negative muons divided by the sum. Since it arises from the meson mixing, if there is not a separation of the asymmetry due to  $B^0$  and  $B_s^0$ ,  $\mathcal{A}_{sl}^b$  can be written as

$$\mathcal{A}_{sl}^b = C_d a_{sl}^d + C_s a_{sl}^s \quad (5)$$

where the coefficients depend on mean mixing probability and the production rates of  $B^0$  and  $B_s^0$  mesons. Here  $a_{sl}^d$  is the semileptonic charge asymmetry in the  $B^0$  system, which has been measured since 2001 at  $e^+e^-$  machines; the actual averaged value is  $a_{sl}^d = 0.0105 \pm 0.0064$ <sup>2</sup>. In 2010 the experiment DØ, with  $6 \text{ fb}^{-1}$  of data, showed evidence for anomalous  $\mathcal{A}_{sl}^b$ , deviating  $3.2\sigma$  from the SM<sup>3</sup>. The 2011 DØ update at  $9 \text{ fb}^{-1}$  shows again a deviation, at  $3.9\sigma$ <sup>4</sup>, from the Standard Model value<sup>5</sup>

$$\mathcal{A}_{sl}^b = [-0.787 \pm 0.172(\text{stat}) \pm 0.093(\text{syst})] \% \quad \mathcal{A}_{sl}^b(\text{SM}) = (-0.028_{-0.006}^{+0.005}) \% \quad (6)$$

The extracted value for  $a_{sl}^s$  is in agreement with the direct determination, but improved precision or, even better, independent measurements of semileptonic asymmetries are needed to establish evidence of CP violation due to new physics. The latter could come from the LHCb experiment, which has the potential for measurements of  $B^0 \rightarrow D^\pm \mu^\mp \nu$  and  $B_s^0 \rightarrow D_s^\pm \mu^\mp \nu$  asymmetries.

## 1.2 Decays into CP eigenstates

The values of  $\Delta\Gamma_s$  and  $\phi_s$  obtained by the semileptonic charge asymmetries have to be compared with independent measurements from other channels. Particularly interesting are the so-called golden modes, which are defined as decays where the final state is a CP eigenstate and where all contributing Feynman diagrams carry the same CP violating phase. That ensures the absence of CP violation in the decays, which is often plagued by large hadronic uncertainties in the

theoretical estimates. Neglecting also the small CP violation in the mixing, golden modes exhibit interference CP violation only. A well studied process is the  $B_s \rightarrow J/\psi\phi$  decay, whose final state is an admixture of different CP eigenstates, which can be disentangled through an angular analysis of the  $J/\psi(\rightarrow l^+l^-)\phi(\rightarrow K^+K^-)$  decay products. This decay tests directly the  $B_s^0 - \bar{B}_s^0$  mixing phase, that is  $\phi_M = -2\beta_s$  in the Standard Model. In this channel, the actual world's most precise measurement of  $\phi_M$  comes from the LHCb experiment at about  $1 \text{ fb}^{-1}$  of  $pp$  collisions and it is in good agreement with Standard Model predictions<sup>6</sup>. The conflict between the  $D\bar{O}$  measurement of  $\mathcal{A}_{sl}^b$  and the newest LHCb data does not appear to be theoretically solvable with the addition of a new phase  $\tilde{\phi}_M$ , originated by new physics contributions to  $M_{12}$ , but it seems to require non-standard additions to  $\Gamma_{12}$  as well<sup>7</sup>.

A recent player, first observed in 2011 by the LHCb<sup>8</sup> and Belle experiments<sup>9</sup>, is the  $B_s^0 \rightarrow J/\psi f_0(980)$  decay. Data have been reported for  $B_s^0 \rightarrow J/\psi f_0(980)$  with  $f_0(980) \rightarrow \pi^+\pi^-$ , which is the dominant channel. LHCb has not measured the branching ratio directly, but instead its fraction,  $R_{f_0/\phi}$ , with respect to the branching ratio for  $B_s^0 \rightarrow J/\psi\phi$  with  $\phi \rightarrow K^+K^-$ . The same ratio has been measured afterwards by the  $D\bar{O}$ <sup>10</sup> and CDF<sup>11</sup> collaborations. All these results are in general agreement and point to a fraction  $R_{f_0/\phi}$  between about 1/5 and 1/3. The disadvantage of a smaller branching ratio is compensated by the fact that the  $B_s^0 \rightarrow J/\psi f_0(980)$  channel, unlike the  $B_s^0 \rightarrow J/\psi\phi$  one, does not require a time-dependent angular analysis. Indeed, because the  $f_0(980)$  is a scalar state with quantum numbers  $J^{PC} = 0^{++}$ , the final state of  $B_s^0 \rightarrow J/\psi f_0(980)$  is a  $p$ -wave state with the CP eigenvalue  $-1$ .

In addition to the branching ratio result, the CDF collaboration has reported a first measurement for the effective  $B_s^0 \rightarrow J/\psi f_0(980)$  lifetime<sup>11</sup>, and the LHCb collaboration has presented a first analysis of CP violation in  $B_s^0 \rightarrow J/\psi f_0(980)$ <sup>12</sup>. Experimental investigations are still progressing, leading towards more and more precise measurements of relevant observables. It should be noted that the composition of the scalar  $f_0(980)$  as a conventional  $\bar{q}q$  meson is still under debate as of today, since alternative interpretations, e.g. as a tetraquark or a molecular state, are deemed possible. The dominant contributions to the amplitude of  $B_s^0 \rightarrow J/\psi f_0$  is given by the color-suppressed tree diagram  $b \rightarrow c\bar{c}s$ , where  $f_0(980)$  is originated by the couple  $\bar{s}s$ . Penguin and exchange diagrams give additional contributions, that add to hadronic uncertainties. The details of the composition of  $f_0(980)$  affect the amplitudes, introducing additional topologies<sup>13</sup>. It becomes important to look for observables that are quite robust with respect to hadronic effects and thereby allow searching for a large (i.e. non-standard) CP violating mixing phase. It has been demonstrated<sup>13</sup> that useful candidates in that respect are the effective lifetime of  $B_s^0 \rightarrow J/\psi f_0(980)$  and the CP violating observable  $S$ . The effective lifetime is defined as

$$\tau_{J/\psi f_0} \equiv \frac{\int_0^\infty t \langle \Gamma(B_s(t) \rightarrow J/\psi f_0(980)) \rangle dt}{\int_0^\infty \langle \Gamma(B_s(t) \rightarrow J/\psi f_0(980)) \rangle dt}. \quad (7)$$

and it can be written in terms of  $y_s \equiv \Delta\Gamma_s/2\Gamma_s$ , which in turn depends on the mixing phase. One can investigate the dependence on the hadronic uncertainties, finding a robust behavior under a generous range of the parameters describing contributions from topologies different than the tree diagram<sup>13</sup>. The dominant uncertainty comes from the theoretical error on  $\Delta\Gamma_s$  in the Standard Model.

A tagged analysis, from which we can distinguish between initially present  $B_s^0$  or  $\bar{B}_s^0$  mesons, allows to measure the time-dependent, CP-violating rate asymmetry

$$\frac{\Gamma(B_s(t) \rightarrow J/\psi f_0(980)) - \Gamma(\bar{B}_s(t) \rightarrow J/\psi f_0(980))}{\Gamma(B_s(t) \rightarrow J/\psi f_0(980)) + \Gamma(\bar{B}_s(t) \rightarrow J/\psi f_0(980))} = \frac{C \cos(\Delta M_s t) - S \sin(\Delta M_s t)}{\cosh(\Delta\Gamma_s t/2) + \mathcal{A}_{\Delta\Gamma} \sinh(\Delta\Gamma_s t/2)}, \quad (8)$$

where the ‘‘mixing-induced’’ CP-violating observable  $S$

$$S \equiv \frac{-2 \text{Im} \lambda_{J/\psi f_0}}{1 + |\lambda_{J/\psi f_0}|^2} \quad \lambda_{J/\psi f_0} \equiv \frac{q}{p} \frac{A(\bar{B}_s^0 \rightarrow J/\psi f_0(980))}{A(B_s^0 \rightarrow J/\psi f_0(980))} \quad (9)$$

originates from interference between  $B_s^0-\bar{B}_s^0$  mixing and decay processes, and depends on the mixing phase. The Standard Model prediction gives<sup>13</sup>  $S(B_s^0 \rightarrow J/\psi f_0(980))|_{\text{SM}} \in [-0.086, -0.012]$ , and a measurement of a sizably different  $|S|$  would give us unambiguous evidence for new physics. Still, should its value fall into the range  $-0.1 \lesssim S \lesssim 0$ , the Standard Model effects related to the hadronic parameters would preclude conclusions on the presence or absence of CP violating new physics contributions to  $B_s^0$  mixing. It should be noted that the decay  $B^0 \rightarrow J/\psi f_0(980)$ , which has not yet been observed, may be used to obtain insights into the size of such hadronic parameters. The leading contributions of the  $B^0 \rightarrow J/\psi f_0(980)$  decay emerge from the  $d\bar{d}$  component of the  $f_0(980)$ . Its estimated branching ratio with  $f_0(980) \rightarrow \pi^+\pi^-$  is at the few times  $10^{-6}$  level<sup>13</sup>, which is not outside the reach of future experimental data taking.

New terrain for exploring CP violation is provided by the  $B_{(s)}^0 \rightarrow J/\psi\eta^{(\prime)}$  decays. The only data come from the Belle Collaboration, that this year has given the measured values for branching fractions (of order  $\sim 10^{-4}$ ) with  $121.4 \text{ fb}^{-1}$  of data at the  $\Upsilon(5S)$  resonance<sup>14</sup>, following the first observation for  $B_s^0 \rightarrow J/\psi\eta$  and the first evidence for  $B_s^0 \rightarrow J/\psi\eta'$  in 2009<sup>15</sup>. As before, CP violation can be investigated analyzing the effective lifetimes and mixing-induced CP asymmetries. As far as the latter are concerned, measured values within the range  $0.03 \lesssim S_{J/\psi\eta^{(\prime)}} \lesssim 0.09$  would not allow us to distinguish CP violating new physics contributions to  $B_s^0-\bar{B}_s^0$  mixing from Standard Model effects, unless we can control the hadronic Standard Model corrections. This can be accomplished by using e.g. the  $B^0 \rightarrow J/\psi\eta^{(\prime)}$  as a control channel and the  $SU(3)_F$  flavour symmetry. Very recently Belle has analyzed the branching fractions of  $B^0 \rightarrow J/\psi\eta^{(\prime)}$  decays with the complete Belle data sample of  $772 \times 10^6$   $B\bar{B}$  events collected at the  $\Upsilon(4S)$  resonance<sup>16</sup>. Only an upper limit is obtained for  $B^0 \rightarrow J/\psi\eta'$ , while the branching fractions of  $B^0 \rightarrow J/\psi\eta$  is measured to be of order  $O(10^{-6})$ , in agreement with theoretical predictions<sup>17</sup>. The most prominent  $\eta^{(\prime)}$  decays involve photons or neutral pions in the final states, which is a very challenging signature for  $B$ -decay experiments at hadron colliders and appears well suited for the future  $e^+e^-$  SuperKEKB and SuperB projects.

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