$B_s^0 - \bar{B}_s^0$ Oscillations as a New Tool to Explore CP Violation in $D_s^\pm$ Decays

Robert Fleischer $^{a,b}$ and K. Keri Vos $^{a,c,d}$

$^a$Nikhef, Science Park 105, NL-1098 XG Amsterdam, Netherlands
$^b$Department of Physics and Astronomy, Vrije Universiteit Amsterdam, NL-1081 HV Amsterdam, Netherlands
$^c$Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, NL-9747 AG Groningen, Netherlands
$^d$Theoretische Physik 1, Naturwissenschaftlich-Technische Fakultät, Universität Siegen, D-57068 Siegen, Germany

Abstract

CP violation in $B_s^0 - \bar{B}_s^0$ oscillations is expected at the $10^{-5}$ level in the Standard Model but could be enhanced by New Physics. Using $B_s^0 \rightarrow D^- s \ell^+ \nu_\ell$ decays, LHCb has recently reported the new result $(0.39 \pm 0.33)\%$ of the corresponding observable $a_{s\ell}^s$. We point out that other $B_s^0$ decay data imply $a_{s\ell}^s = (0.014 \pm 0.018)\%$, which pushes this observable below accessible limits. Consequently, we propose to use $B_s^0 \rightarrow D^- s \ell^+ \nu_\ell$ and similar flavor-specific decays as a new tool to determine both the production asymmetry between $B_s^0$ and $\bar{B}_s^0$ mesons, and the CP asymmetry in the subsequent $D_s^\pm$ decays. The former serves as input for analyses of CP violation in $B_s^0$ channels, with significant room for improvement, while the latter offers an exciting laboratory for New Physics.
\[ B_s^0 - \bar{B}_s^0 \] Oscillations as a New Tool to Explore CP Violation in \( D_{\pm} \) Decays

Robert Fleischer\(^1,2\) and K. Keri Vos\(^1,3,4\)

\(^1\)Nikhef, Science Park 105, NL-1098 XG Amsterdam, Netherlands
\(^2\)Department of Physics and Astronomy, Vrije Universiteit Amsterdam, NL-1081 HV Amsterdam, Netherlands
\(^3\)Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, NL-9747 AG Groningen, Netherlands
\(^4\)Theoretische Physik 1, Naturwissenschaftlich-Technische Fakultät, Universität Siegen, D-57068 Siegen, Germany

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CP violation in \( B_s^0 - \bar{B}_s^0 \) oscillations is expected at the 10\(^{-5}\) level in the Standard Model but could be enhanced by New Physics. Using \( B_s^0 \rightarrow D_s^+ \ell^- \nu_\ell \) decays, LHCb has recently reported the new result \((0.39 \pm 0.33\%)\) of the corresponding observable \( a_{s1}^s \). We point out that other \( B_s^0 \) decay data imply \( a_{s1}^s = (0.014 \pm 0.018\%) \), which pushes this observable below accessible limits. Consequently, we propose to use \( B_s^0 \rightarrow D_s^+ \ell^- \nu_\ell \) and similar flavor-specific decays as a new tool to determine both the production asymmetry between \( B_s^0 \) and \( \bar{B}_s^0 \) mesons, and the CP asymmetry in the subsequent \( D_s^\pm \) decays. The former serves as input for analyses of CP violation in \( B_s^0 \) channels, with significant room for improvement, while the latter offers an exciting laboratory for New Physics.

Keywords: CP violation, \( B_s^0 - \bar{B}_s^0 \), mixing, flavor-specific \( B_s^0 \) decays

I. INTRODUCTION

Studies of CP violation offer interesting tests of the Standard Model (SM) of particle physics. In this respect, decays of neutral \( B_s^0 \) mesons play a key role at the Large Hadron Collider (LHC) \(^1\). These particles show \( B_s^0 - \bar{B}_s^0 \) mixing, which is absent at the tree level in the SM but is generated through quantum fluctuations. Physics beyond the Standard Model may affect \( B_s^0 - \bar{B}_s^0 \) mixing through contributions at the tree level, mediated, for instance, through \( Z^\prime \) bosons, or through new heavy particles running in the loop diagrams \(^2\).

We distinguish between different manifestations of CP violation in \( B_s^0 \) meson decays: “direct” CP violation arising directly at the decay amplitude level through interference between different decay contributions, “mixing-induced” CP violation originating from interference between \( B_s^0 - \bar{B}_s^0 \) mixing and \( B_s^0, \bar{B}_s^0 \) decay processes, and CP violation in the \( B_s^0 - \bar{B}_s^0 \) oscillations themselves \(^3\).

The latter phenomenon is described by an observable \( a_{s1}^s \), which can be measured through semileptonic \( B_s^0 \rightarrow D_s^- \ell^+ \nu_\ell \) and \( \bar{B}_s^0 \rightarrow D_s^+ \ell^- \bar{\nu}_\ell \) decays \(^4\). It is usually assumed that such transitions are flavor-specific:

\[
A(B_s^0 \rightarrow D_s^- \ell^+ \nu_\ell) = A(\bar{B}_s^0 \rightarrow D_s^+ \ell^- \bar{\nu}_\ell) = 0, \quad (1)
\]

which is satisfied with excellent precision in the SM. The final states of the “wrong-sign” decays \( B_s^0 \rightarrow D_s^- \ell^+ \nu_\ell \) and \( \bar{B}_s^0 \rightarrow D_s^+ \ell^- \bar{\nu}_\ell \) can then only be reached through \( B_s^0 - \bar{B}_s^0 \) mixing, thereby probing \( a_{s1}^s \) \(^4\). As the relations in \(^1\) have interestingly not yet been tested experimentally, we shall give formulae to accomplish this task.

Employing such decays, LHCb has recently reported the world’s best measurement for \( a_{s1}^s \) using the full 3 fb\(^{-1}\) data set collected at run 1 of the LHC \(^5\):

\[
a_{s1}^s = (0.39 \pm 0.26 \text{(stat)} \pm 0.20 \text{(syst)}) \times 10^{-2}. \quad (2)
\]

The average of the previous results made by the “Heavy Flavor Averaging Group” (HFAG) is given as follows \(^6\):

\[
a_{s1}^s = -(0.48 \pm 0.48) \times 10^{-2}. \quad (3)
\]

Here the DO dimuon result \( a_{s1}^s = -(1.33 \pm 0.58) \times 10^{-2} \) \(^7\), which differs from the SM picture at the 3\(\sigma\) level and has led to attention in the community (see \(^1\)\(^8\) and references therein), was not included.

Using the most recent input parameters, the following SM prediction for \( a_{s1}^s \) was obtained \(^9\):

\[
a_{s1}^s|_{\text{SM}} = (2.22 \pm 0.27) \times 10^{-5}. \quad (4)
\]

The LHCb result \(^2\) agrees with the SM within the uncertainties, and does not support the DO result.

We propose a new method to utilize flavor-specific \( B_s^0 \) decays, with a focus on \( B_s^0 \rightarrow D_s^- \ell^+ \nu_\ell \) although it can also be implemented with other flavor-specific modes, such as \( B_s^0 \rightarrow D_s^- \pi^+ \). We point out that the experimental information for the \( B_s^0 - \bar{B}_s^0 \) mixing parameters and CP violation in \( B_s^0 \rightarrow J/\psi \phi \) decays constrain \( a_{s1}^s \) to be vanishingly small. Exploiting this feature, we present a strategy allowing us to determine a CP-violating asymmetry, which probes direct CP violation both in the \( B_s^0 \) and in the subsequent \( D_s^- \rightarrow f_D \) decays, and the production asymmetry between the \( B_s^0 \) and \( \bar{B}_s^0 \) mesons.

The latter is defined as

\[
A_P(B_s) \equiv \frac{\sigma(\bar{B}_s^0) - \sigma(B_s^0)}{\sigma(\bar{B}_s^0) + \sigma(B_s^0)} \quad (5)
\]

with \( \sigma(\bar{B}_s^0) \) and \( \sigma(B_s^0) \) denoting the production cross sections for the \( \bar{B}_s^0 \) and \( B_s^0 \) mesons, respectively. It enters studies of CP violation and is a non-perturbative, hadronic quantity which is characteristic for the environment where the mesons are produced. Making certain assumptions and a time-dependent analysis of \( B_s^0 \rightarrow D_s^- \pi^+ \) decays, LHCb has extracted

\[
A_P(B_s) = (1.09 \pm 2.61 \pm 0.66)\% \quad (6)
\]
for \( pp \) collisions at \( \sqrt{s} = 7 \text{ TeV} \) [10]. The CP asymmetry is tiny in the SM but may be enhanced through New Physics (NP). Our new method can be applied to any \( D_s^0 \) decays which can be experimentally reconstructed. Particularly interesting are modes with penguin loop contributions where new particles may well contribute. However, also NP contributions to pure tree decays are not yet too strongly constrained, as was recently emphasized for the B-meson system [11] [12]. The impact of possible CP violation in \( D_s^0 \) decays has not been included in the experimental value in [2]. We shall take this effect into account in our analysis.

II. A CLOSER LOOK AT \( a_{s1}^a \)

The observable \( a_{s1}^a \) takes the following form [4]:

\[
a_{s1}^a = \left| \frac{\Gamma^{(s)}_{12}}{M^{(s)}_{12}} \right| \sin \tilde{\phi}_s, \tag{7}
\]

where \( \Gamma^{(s)}_{12} \) and \( M^{(s)}_{12} \) are the off-diagonal elements of the decay and mass matrices describing \( B_s^0 \rightarrow B_s^0 \) mixing, and

\[
\tilde{\phi}_s = \arg(-M^{(s)}_{12}/\Gamma^{(s)}_{12}). \tag{8}
\]

As \( M^{(s)}_{12} \) is governed by short-distance contributions, NP may have a significant impact. On the other hand, the matrix element

\[
\Gamma^{(s)}_{12} = \sum_f N_f \langle B_s^0 | f \rangle \langle f | B_s^0 \rangle \tag{9}
\]

is dominated by tree decays originating from \( b \rightarrow c\bar{c}s \) quark-level processes which are favored by the Cabibbo–Kobayashi–Maskawa (CKM) matrix. Consequently, \( \Gamma^{(s)}_{12} \) is expected to be insensitive to NP contributions [4] [8].

Detailed theoretical analyses of \( \Gamma^{(s)}_{12} \) and its \( B_d^0 \) counterpart \( \Gamma^{(d)}_{12} \) were performed in [13] [14], motivated in particular by the DO result [17]. These studies found indeed small room for NP effects in \( \Gamma^{(s)}_{12} \) also through poorly constrained \( (s\bar{b})(\tau\tau) \) operators. On the other hand, NP effects in \( \Gamma^{(d)}_{12} \) may still be significant.

As we aim at the high-precision era of B physics, it is useful to have a closer look at NP effects entering through \( b \rightarrow c\bar{c}s \) processes. We write the amplitude of a \( B_s^0 \) decay caused by such transitions as

\[
(f | B_s^0) = A(B_s^0 \rightarrow f) = V_{cb} V^*_{cs} A_{SM}^{\bar{s}} \left[ 1 + \rho_{NP} e^{i\phi_{NP}} e^{i\delta_{NP}} \right]. \tag{10}
\]

Here the parameter

\[
\rho_{NP} e^{i\phi_{NP}} e^{i\delta_{NP}} = \left( \frac{\epsilon e^{i\phi_{NP}}}{V_{cb} V^*_{cs}} \right) \frac{A_{NP}^f}{A_{SM}^{\bar{s}}} \tag{11}
\]

describes a NP contribution with a CP-violating phase \( \phi_{NP} \) and a CP-conserving strong phase difference \( \delta_{NP} \).

Neglecting doubly Cabibbo-suppressed \( b \rightarrow u\bar{u}s \) decay contributions to \( [9] \) and assuming, for simplicity, that the dependence on \( f \) cancels in the ratio \( \Gamma_{12}^{(s)} \), we obtain

\[
\Gamma_{12}^{(s)} = e^{i(2\arg(V_{cb} V^*_{cs}) - \Delta\psi_s^{NP})} \sum_f N_f |A_f||\tilde{A}_f|. \tag{12}
\]

While \( V_{cb} V^*_{cs} \) is the corresponding CKM factor,

\[
\Delta\psi_s^{NP} = -2\rho_{NP} \cos \delta_{NP} \sin \phi_{NP} \tag{13}
\]

is generated through the CP-violating NP contributions to the dominant \( b \rightarrow c\bar{c}s \) decay processes.

Finally, we get

\[
\tilde{\phi}_s = \phi_s^{SM} + \phi_s^{NP} + \Delta\psi_s^{NP}, \tag{14}
\]

where \( \phi_s^{NP} \) enters through \( M^{(s)}_{12} \) and originates from CP-violating NP contributions to \( B_s^0 \rightarrow B_s^0 \) mixing [2] [4]. An overview of the status of the SM value \( \tilde{\phi}_s^{SM} \), including also \( b \rightarrow u\bar{u}s \) contributions, is given in [9]:

\[
\tilde{\phi}_s^{SM} = (0.26 \pm 0.07)^\circ. \tag{15}
\]

Using the mass and decay width differences \( \Delta M_s \) and \( \Delta\Gamma_s \) of the \( B_s \) mass eigenstates, we obtain

\[
a_{s1}^a = \left( \frac{\Delta\Gamma_s}{\Delta M_s} \right) \tan(\tilde{\phi}_s^{SM} + \phi_s^{NP} + \Delta\psi_s^{NP}). \tag{16}
\]

The Particle Data Group (PDG) [15] gives the averages

\[
\frac{\Delta\Gamma_s}{\Delta M_s} = 0.124 \pm 0.011, \quad x_s = \frac{\Delta M_s}{\Gamma_s} = 26.81 \pm 0.10, \tag{17}
\]

where \( 1/\Gamma_s = (1.510 \pm 0.005) \times 10^{-12} s \) is the \( B_s^0 \) lifetime. The experimental results for \( \Delta\Gamma_s \) and \( \Delta M_s / \Delta M_s \) are consistent with the SM predictions although the theoretical uncertainties are still at the 20% level [9]. Inserting these experimental results into \( [16] \) yields

\[
a_{s1}^a = [(0.46 \pm 0.04) \times 10^{-2}] \times \tan(\tilde{\phi}_s^{SM} + \phi_s^{NP} + \Delta\psi_s^{NP}). \tag{18}
\]

It is interesting to note that the numerical pre-factor has the same size as the central value of the current LHCb measurement [2].

CP violation in \( B_s^0 \rightarrow J/\psi\phi \) and other modes originating from \( b \rightarrow c\bar{c}s \) processes [4] allows the extraction of

\[
\phi_s = \phi_s^{SM} + \phi_s^{NP} + \Delta\psi_s^{NP}, \tag{19}
\]

which takes the following SM value [9]:

\[
\phi_s^{SM} = -(2.1 \pm 0.1)^\circ. \tag{20}
\]

As in [10], we have allowed for NP contributions at the decay amplitude level, which introduce the phase shift \( \Delta\psi_s^{NP} \). The theoretical precision of these measurements is limited by contributions from doubly Cabibbo-suppressed penguin topologies, which can be determined with the help of control channels (see [10] and references
supported by the feature that the data for constrained to vanish at the 0.3% level \[15\].

violation within the current precision of both NP phases are small. The picture for \(\Delta \psi\) which implies a SM prediction in (4).

FIG. 1: The dependence of \(a_s^0\) on \(\phi_s\) following from \[18\] and \[19\]. The vertical band corresponds to the experimental range in \[21\], while the horizontal bands show the experimental LHCb and HFAG results in \[2\] and \[3\], respectively.

therein). The current experimental situation is summarized as follows \[15\]:

\[\phi_s = -(0.68 \pm 2.2)^\circ, \quad (21)\]

which implies \(\phi_s^{NP} + \Delta \psi_s^{NP} = (1.4 \pm 2.2)^\circ\). Since an accidental cancellation is not plausible, we conclude that both NP phases are small. The picture for \(\Delta \psi_s^{NP}\) is also supported by the feature that the data for \(B_s^0 \rightarrow J/\psi f\) and \(B_d^0 \rightarrow J/\psi K\) modes show no sign of direct CP violation within the current precision of \(O(1\%)\). For \(B^\pm \rightarrow J/\psi K^\pm\) decays, the direct CP asymmetry is even constrained to vanish at the 0.3% level \[15\].

Expressing \(\phi_s^{NP} + \Delta \psi_s^{NP}\) in terms of \(\phi_s\) yields

\[a_s^0 = \left( \frac{\Delta \Gamma_s}{\Delta M_s} \right) \tan(\phi_s + \phi_{s,SM}^{CP} - \phi_{s,SM}^{CP}), \quad (22)\]

which gives

\[a_s^0 = (0.104 \pm 0.018) \times 10^{-2}, \quad (23)\]

when using the numerical values listed above. Consequently, we observe that the strong experimental constraint on the CP-violating phase \(\phi_s\) suppresses \(a_s^0\) with respect to the numerical factor in \[18\] by another factor of about 50. The result in \[23\] is in agreement with the SM prediction in \[4\].

In Fig. 1 we illustrate the impact of the experimental information on \(\phi_s\) for the observable \(a_s^0\), taking also the measurements of \(\Delta \Gamma_s\) and \(\Delta M_s\) into account. The comparison with the LHCb and HFAG bands shows impressively that \(a_s^0\) has already been constrained to be experimentally out of reach.

Further refinements of \[23\] concerning SM penguin contributions and NP effects at the decay amplitude level are possible. However, these effects can only impact the determination of \(\phi_s^{NP} + \Delta \psi_s^{NP}\) in the \(O(1\%)\) level, thereby not affecting the general picture in Fig. 1.

In view of this finding, we propose a new way to utilize flavor-specific \(B_s^0\) decays. Although this method applies to any channel of this kind, we will focus on semileptonic decays. On the other hand, our method does not hold for flavor-specific \(B_d^0\) decays, where \(\Delta \Gamma_d\) is vanishingly small and current data still leave sizeable room for NP effects in \(a_s^0\) describing CP violation in \(B_d^0\)–\(\bar{B}_d^0\) mixing.

III. DECAY RATE ASYMMETRIES

Assuming \[1\], as is usually done in the literature, \(B_s^0 \rightarrow D^- s \ell^- \bar{\nu}_\ell\) and \(\bar{B}_s^0 \rightarrow D^+_s \ell^- \bar{\nu}_\ell\) are flavor-specific decays. In the SM, \[1\] receives corrections from processes of higher order in electroweak interactions, which are extremely small, and NP may in principle have some impact. Interestingly, the relations in \[1\] have not yet been tested. We will therefore give the most general expressions for the relevant observables, allowing us to search for violations of \[1\] through characteristic decay-time dependences. To simplify the discussion, we keep only leading-order terms of small parameters.

Following \[4\], we introduce

\[\lambda = -e^{-i\phi_s^{(s)}} \frac{\left[ A(B_s^0 \rightarrow D_s^- \ell^+ \nu_\ell) \right]}{\left[ A(\bar{B}_s^0 \rightarrow D^+_s \ell^+ \nu_\ell) \right]}, \quad (24)\]

\[\bar{\lambda} = -\frac{1}{e^{-i\phi_s^{(s)}}} \frac{\left[ A(B_s^0 \rightarrow D_s^- \ell^- \bar{\nu}_\ell) \right]}{\left[ A(\bar{B}_s^0 \rightarrow D^+_s \ell^- \bar{\nu}_\ell) \right]}, \quad (25)\]

where \(\phi_s^{(s)}\) denotes the CP-violating phase associated with \(B_s^0\)–\(\bar{B}_s^0\) mixing, and

\[\Delta A_{\text{mix}}^{\text{CP}} = -2 \text{Im}(\lambda - \bar{\lambda}), \quad \Delta A_{\Delta \Gamma} = -2 \text{Re}(\lambda - \bar{\lambda}). \quad (26)\]

If \[1\] holds, \(\lambda, \bar{\lambda}\) and the observables in \[26\] vanish.

Let us now consider the following “wrong-sign” asymmetry for the time-dependent decay rates:

\[a_{\text{WS}} \equiv \frac{\Gamma(\bar{B}_s^0(t) \rightarrow D_s^- \ell^+ \nu_\ell) - \Gamma(B_s^0(t) \rightarrow D^+_s \ell^- \bar{\nu}_\ell)}{\Gamma(B_s^0(t) \rightarrow D_s^- \ell^+ \nu_\ell) + \Gamma(B_s^0(t) \rightarrow D^+_s \ell^- \bar{\nu}_\ell)}, \quad (27)\]

For \(t > 0\), it takes the form

\[a_{\text{WS}} = a_{\text{CP}}(\ell^+ \nu_\ell; f_{D_s}) + a_s^0 + F_-(t), \quad (28)\]

with

\[F_\pm(t) = \frac{\Delta A_{\text{mix}}^{\text{CP}} \sin \Delta M_s t \pm \Delta A_{\Delta \Gamma} \sinh \Delta \Gamma_s t/2}{2(\cos \Delta M_s t \pm \cosh \Delta \Gamma_s t/2)}. \quad (29)\]

The time dependence of \[28\] allows us to test the relations in \[1\]. If we assume their validity, the time dependence cancels and the time-dependent rates in \[27\] can actually be replaced by their time-integrated counterparts, which is an advantage from the experimental point of view. The CP asymmetry \(a_{\text{CP}}(\ell^+ \nu_\ell; f_{D_s})\), where \(f_{D_s}\) is the final state of the subsequent \(D_s^-\) decay, will be discussed in Section IV.

The observable \(a_{\text{WS}}\) can be complemented with the “right-sign” lepton asymmetry

\[a_{\text{RS}} \equiv \frac{\Gamma(\bar{B}_s^0(t) \rightarrow D^+_s \ell^- \bar{\nu}_\ell) - \Gamma(B_s^0(t) \rightarrow D_s^- \ell^+ \nu_\ell)}{\Gamma(B_s^0(t) \rightarrow D^+_s \ell^- \bar{\nu}_\ell) + \Gamma(B_s^0(t) \rightarrow D_s^- \ell^+ \nu_\ell)}, \quad (30)\]

where the final states can be accessed directly, i.e. without \(B_s^0\)–\(\bar{B}_s^0\) oscillations or a violation of \[1\]. It takes the following form:

\[a_{\text{RS}} = A_{\text{F}}(B_s) - a_{\text{CP}}(\ell^+ \nu_\ell; f_{D_s}) - F_+(t), \quad (31)\]
where the time-dependent function allows us to probe \( \frac{1}{2} \). Assuming the relations given there, \( a_{\text{RS}} \) can be extracted – as in the case of \( a_{\text{WS}} \) – from the tagged, time-integrated rates.

As we have seen in Section 11, \( a_{\text{al}}^0 \) is constrained by \( B_0^0 \) decay data to be too small to be accessible in measurements of decay rate asymmetries. On the other hand, we may extract \( A_\ell(B_s) \) and \( a_{\text{CP}}(\ell^+ \nu; f_{D_s}) \) from a combined analysis of \( a_{\text{WS}} \) and \( a_{\text{RS}} \):

\[
A_\ell(B_s) = \frac{1}{2} (a_{\text{WS}} + a_{\text{RS}} - a_{\text{al}}^0),
\]

\[
a_{\text{CP}}(\ell^+ \nu; f_{D_s}) = \frac{1}{2} (a_{\text{WS}} - a_{\text{RS}} - a_{\text{al}}^0),
\]

where we have neglected the \( F_{\pm}(t) \) terms and \( a_{\text{al}}^0 \) is given by (23), playing a negligible role.

From the experimental point of view, it is interesting to consider the untagged rate asymmetry [

\[
a_{\text{um}}(t) \equiv \frac{\Gamma[D^-_s \ell^+ \bar{\nu}_t, t] - \Gamma[D^+_s \ell^+ \bar{\nu}_t, t]}{\Gamma[D^-_s \ell^+ \bar{\nu}_t, t] + \Gamma[D^+_s \ell^+ \bar{\nu}_t, t]}
\]

\[
= a_{\text{CP}}(\ell^+ \nu; f_{D_s}) + a_{\text{al}}^0 \left[ \frac{\cos(\Delta M_s t)}{\cosh(\Delta \Gamma_s t/2)} \right] + \frac{1}{2} \Delta A \Delta \tau \tanh(\Delta \Gamma_s t/2),
\]

where \( \Gamma[f, t] \equiv \Gamma(B_0^0(t) \to f) + \Gamma(B_{-1}^0(t) \to f) \). In the experimental analysis to determine (2), LHCb has employed (34) for the time-integrated untaged rates. Thanks to the rapid \( B_0^0-B_{-1}^0 \) oscillations, the term involving the production asymmetry (which suffers from a large error (6)) is then essentially washed out (17). On the other hand, the decay-time dependence of (34) would allow us to extract \( A_\ell(B_s) \) and \( a_{\text{CP}}(B_s; f_{D_s}) \), thereby complementing the determination through the time-integrated, tagged rate asymmetries \( a_{\text{WS}} \) and \( a_{\text{RS}} \). We advocate to implement these analyses at LHCb and future runs of Belle II at the \( \Upsilon(5S) \) resonance.

**IV. DIRECT CP VIOLATION**

The \( D_s^- \) mesons, which are produced in \( \bar{B}_s^0 \to D_s^- \ell^+ \bar{\nu}_t \), will decay further as \( D_s^- \to f_{D_s} \) and are observed correspondingly in the detector. Keeping only leading-order terms in CP-violating effects, we obtain

\[
a_{\text{CP}}(\ell^+ \nu; f_{D_s}) = a_{\text{CP}}^{(B_s)}|_{\ell^+ \nu} + a_{\text{CP}}^{(D_s)}|_{f_{D_s}},
\]

where

\[
a_{\text{CP}}^{(B_s)}|_{\ell^+ \nu} \equiv \frac{\Gamma(B_0^0 \to D_s^- \ell^+ \bar{\nu}_t) - \Gamma(B_{-1}^0 \to D_s^- \ell^+ \bar{\nu}_t)}{\Gamma(B_0^0 \to D_s^- \ell^+ \bar{\nu}_t) + \Gamma(B_{-1}^0 \to D_s^- \ell^+ \bar{\nu}_t)}
\]

(36)

probes CP violation at the \( B_0^0 \) amplitude level, whereas

\[
a_{\text{CP}}^{(D_s)}|_{f_{D_s}} \equiv \frac{\Gamma(D_s^- \to f_{D_s}) - \Gamma(D_s^+ \to f_{D_s})}{\Gamma(D_s^- \to f_{D_s}) + \Gamma(D_s^+ \to f_{D_s})}
\]

(37)

measures CP violation in the \( D_s^- \to f_{D_s} \) processes.

Such “direct” CP asymmetries can be generated through the interference between at least two decay amplitudes with non-trivial CP-conserving and CP-violating phase differences [3]. The CP-conserving phases can be induced through strong interactions or absorptive parts of loop diagrams. In the charm sector, significant CP-violating phases would be associated with NP effects.

In the SM, \( a_{\text{CP}}^{(B_s)}|_{\ell^+ \nu} \) is zero at leading order in weak interactions and takes a vanishingly small value through higher-order effects [18,20]. Even in the presence of NP, this CP asymmetry cannot take sizeable values. For the non-leptonic decay \( B_0^0 \to D_s^+ \pi^- \) things have to be assessed more carefully, as there may still be room for NP at the decay amplitude level [11,12] and strong interactions are at work. It would be interesting to measure

\[
a_{\text{CP}}(\pi^+; f_{D_s}) - a_{\text{CP}}(\ell^+ \nu; f_{D_s}) = a_{\text{CP}}^{(B_s)}|_{\pi^+}
\]

(38)

with our method, where the CP asymmetry in \( D_s^- \to f_{D_s} \) cancels.

In the non-leptonic \( D_s \) channels, CP-conserving phase differences can be induced – in contrast to \( B_0^0 \to D_s^+ \ell^+ \bar{\nu}_t \) modes – through strong interactions. Direct CP asymmetries in \( D_s \) decays are small in the SM but may be enhanced through NP contributions [21,22]. Predictions suffer generally from hadronic uncertainties, where the SU(3) flavor symmetry offers a useful framework [23].

For the LHCb analyses, \( D_s^\pm \to K^\pm K^- \pi^\mp \) transitions are used, such that the experimental value in [24] should actually read

\[
(a_{\text{al}}^0)_{\text{eff}} = a_{\text{al}}^0 + 2a_{\text{CP}}^{(D_s)}|_{K^+K^-\pi^\mp}.
\]

(39)

Consequently, in order to extract \( a_{\text{al}}^0 \), we need information on the CP asymmetry of the subsequent \( D_s \) decay. The PDG [15] gives the following average of CLEO measurements [24,25]:

\[
(a_{\text{CP}}^{(D_s)})|_{K^+K^-\pi^\mp} = (0.5 \pm 0.9) \times 10^{-2}.
\]

(40)

Using (23), we can convert the LHCb result into

\[
a_{\text{CP}}^{(D_s)}|_{K^+K^-\pi^\mp} = (0.20 \pm 0.16) \times 10^{-2},
\]

(41)

which is consistent with (40) but five times more precise. Moreover, it is consistent with the SM picture.

Our new method can actually be applied to any \( D_s \)-meson decay \( D_s^- \to f_{D_s} \). In contrast to conventional analyses of CP violation in such transitions, our strategy is not affected by the production asymmetry [26]

\[
A_\ell(D_s) \equiv \frac{\sigma(D_s^-) - \sigma(D_s^+)}{\sigma(D_s^-) + \sigma(D_s^+)} = (-0.33 \pm 0.22 \pm 0.10)\%.
\]

(42)

Concerning direct CP violation, non-leptonic decays play the key role as we discussed above. With respect to the impact of NP, transitions with penguin loop contributions are particularly interesting. Prominent examples are \( D_s^+ \to \pi^+ K^0, \pi^0 K^+, K^+ \phi, \ldots \) where the final-state particles may also be replaced by vector mesons or
higher resonances. The corresponding CP asymmetries are small in the SM because of the CKM structure of the decay amplitudes and having down-type quarks in the loops [21, 22].

Taking as an example the recent LHCb measurement of the direct CP asymmetry of $D_s^+ \to \pi^+ K_S$ [27]:

$$a_{CP}^{(D_s)}|_{K_S \pi^\pm} = -(0.38 \pm 0.46 \pm 0.17)\%,$$  \hspace{0.5cm} (43)

we see that it has an uncertainty three times larger than the result in [41]. The CP violation in $K^0 - \bar{K}^0$ mixing has to be included when comparing the SM prediction with experiment [28]. Taking these known contributions aside, the CP violation in $D_s^+ \to \pi^+ K_S$ is expected at the $10^{-4}$ level. New-Physics contributions may enhance this CP asymmetry [29].

V. CONCLUSIONS

We have shown that current $B^0_s$ data constrain the CP violation in $B^0_s - \bar{B}^0_s$ oscillations as $a_{CP}^3 = (0.014 \pm 0.018)\%$, thereby pushing it below experimentally accessible limits. In order to utilize flavour-specific $B^0_s \to D^-_s \ell^+ \nu_\ell$ decays, which have played the key role to measure $a_{CP}^3$, we propose a new method. With this method, the $B^0_s$ production asymmetry $A_P(B_s)$ and the CP-violating asymmetry $a_{CP}^{(D^-)}(\ell^+ \nu_\ell; f_{D^-})$ can be extracted.

The current experimental situation for $A_P(B_s)$ leaves room for significant improvement, while $a_{CP}^{(D^-)}(\ell^+ \nu_\ell; f_{D^-})$ is governed by the direct CP violation in $D_s^- \to f_{D^-}$, thereby opening a completely new avenue for the exploration of this phenomenon. In our strategy, the CP violation measurement is not affected by a production asymmetry of the $D_s^-$ mesons, which is a major limitation for the conventional analyses.

The observables $A_P(B_s)$ and $a_{CP}^{(D^-)}(\ell^+ \nu_\ell; f_{D^-})$ can be extracted either through a simultaneous measurement of the time-integrated, tagged wrong- and right-sign asymmetries or through a time-dependent analysis of the untagged asymmetry. We advocate to implement these analyses already with the currently available LHCb data. The new method can also be applied to other flavor-specific modes, such as $B^0_s \to D^- \pi^+$. Further applications may address $B^0_s \to K^- \pi^+$ and $B^0_s \to K^- \ell^+ \nu_\ell$.

Interestingly, the assumption that such decays are flavor-specific, which appears on solid ground, has not yet been tested experimentally. We have given expressions allowing us to probe the validity of this assumption through time dependences of rate asymmetries.

The new method shifts flavor-specific $B^0_s$ decays from their well-known role as probes of $a_{CP}^3$ to new tools for the exploration of direct CP violation, in particular in $D_s^-$ decays. As CP violation in these decays might be enhanced by New Physics, our method gives a new framework to search for such signatures, thereby allowing us to take full advantage of the corresponding physics potential in the high-precision era of heavy-flavor studies.

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