STUDYING NEW PHYSICS AMPLITUDES 
IN CHARMLESS $B_s$ DECAYS

Robert Fleischer and Michael Gronau

Theor y Division, Department of Physics, CERN 
CH-1211 Geneva 23, Switzerland

ABSTRACT

A method based on flavour SU(3) is proposed for identifying and extracting New Physics (NP) amplitudes in charmless $\Delta S = 1$ $B_s$ decays using time-dependent CP asymmetries in these decays and in flavour SU(3) related $\Delta S = 0$ decays. For illustration, we assume a hierarchy, $\sim 1 : \lambda : \lambda^2$ ($\lambda = 0.2$), between a dominant $\Delta S = 1$ penguin amplitude, a NP amplitude and a Standard Model amplitude with weak phase $\gamma$. An uncertainty from SU(3) breaking corrections, reduced by using ratios of hadronic amplitudes, is further suppressed by a factor $\lambda$. We discuss examples for pairs of decays into two neutral vector mesons, $B_s \rightarrow \phi \phi$, $B_s \rightarrow \phi \bar{K}^*_{0}$ and $B_s \rightarrow K^{*0} \bar{K}^{*0}$, $B^0 \rightarrow K^{*0} \bar{K}^{*0}$, where the magnitude of the NP amplitude, its weak and strong phases can be determined.

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I. INTRODUCTION

Strangeness-changing charmless $B$ and $B_s$ decays dominated by $b \rightarrow s$ penguin amplitudes, suppressed by CKM and loop factors, are sensitive to New Physics (NP) effects [1–5]. Virtual new heavy particles at a TeV mass scale may affect Standard Model predictions [2, 6–8], $C \equiv -A_{CP} \simeq 0 + \mathcal{O}(\lambda^2), S \simeq -\eta_{CP} \sin 2\beta + \mathcal{O}(\lambda^2)$, for time-dependent asymmetries in decays to CP eigenstates with CP-eigenvalue $\eta_{CP}$. Corrections of order $\lambda^2$, $\lambda \equiv |V_{us}| = 0.2257$ [9, 10], are due to terms in decay amplitudes involving a weak phase $\gamma$. These SM predictions have been tested in a large class of processes including $B^0 \rightarrow X K_S, X = \phi, \pi^0, \eta^{'}, \omega, \rho, f_0(980), K^+ K^-, K_S \bar{K}_S, \pi^0 \pi^0$. Asymmetries measured in the first two processes [11],

$$- \eta_{CP} S(B^0 \rightarrow \phi K_S) = 0.30 \pm 0.17 \; , \quad - \eta_{CP} S(B^0 \rightarrow \pi^0 K_S) = 0.38 \pm 0.19 \; , \quad (1)$$

indicate potential discrepancies (currently at levels of 2.2$\sigma$ and 1.6$\sigma$) with respects to the value $\sin 2\beta = 0.681 \pm 0.025$ measured in $b \rightarrow c\bar{c}s$ transitions [11].

Two techniques, based on QCD factorization and flavour SU(3), have been applied to control within the Standard Model corrections of order $\lambda^2$ to $C$ and $S$. In

$^1$Permanent address: Physics Department, Technion-Israel Institute of Technology, Haifa, Israel.
an approach using QCD factorization [12–14] one calculates these terms from first
principle at leading order in $1/m_b$ and $\alpha_s$. The calculations involve uncertainties
partly due to penguin contractions, chirally-enhanced $1/m_b$ suppressed terms and
nonperturbative input parameters. In a flavour SU(3) approach one relates these
corrections to amplitudes for $\Delta S = 0$ $B^0$ decays. Using measured rates for the latter
processes one obtains upper bounds on these corrections [15–17]. The upper bounds
involve uncertainties from SU(3) breaking corrections, usually assumed to be of order
$m_s/\Lambda_{QCD}$. Under conservative assumptions about strong phases, predictions of
CP asymmetries in both methods involve theoretical uncertainties of order $\lambda^2$. This
makes it extremely difficult to identify NP amplitudes if these are of order $\lambda^2$
relative to dominant penguin amplitudes. A question seeking an answer is how to identify
and extract NP amplitudes, which in principle could be of order $\lambda$.

In the present Letter we propose a more precise, yet experimentally more challeng-
ing method for controlling small Standard Model amplitudes based on flavour SU(3)
symmetry. The method requires measuring time-dependent asymmetries in pairs of
SU(3)-related $B^0$ and $B_s$ decays. Assuming given values for CKM phases,
$\beta, \gamma$ and the phase $\phi_s$ of $B_s-\bar{B}_s$ mixing, obtained for instance in $B \to J/\psi K_s, B \to D^{(*)}K^{(*)}$
and $B_s \to J/\psi \phi$, respectively, we suggest a way for analyzing and extracting NP decay
amplitudes in a class of $b \to s$ penguin-dominated decays. Our considerations do not
depend on whether $\phi_s$ obtains a NP contribution, thereby modifying the Standard
Model prediction $\phi_s = -2\lambda^2\eta$ [9]. This prediction can be tested in $B_s \to J/\psi \phi$ [18].

A formulation similar to the one presented here, neglecting NP contributions, has
been advocated in Ref. [19] as a method for determining $\gamma$ in the U-spin pair of
processes, $B_s(t) \to K^+K^-$ and $B^0(t) \to \pi^+\pi^-$. Refs. [20, 21] contain earlier studies
of NP effects in $b \to s$ penguin-dominated decays, involving different approaches and
further assumptions about negligible strong phases of NP amplitudes.

II. THE METHOD

Consider a pair of $\Delta S = 1$ and $\Delta S = 0$ charmless decay processes for $B_s$ and $B^0$,
respectively, where final states are related to each other by a U-spin transformation,
d $\leftrightarrow$ s. Let us denote a potential NP amplitude in the first process by its magni-
tude $A_{NP}$, CP-conserving phase $\delta^{NP}$ and CP-violating phase $\phi^{NP}$. Assuming no NP
contribution in $\Delta S = 0$ decays, the decay amplitudes for the two processes can be
generally expressed as

\[ A(B_s \to f)_{\Delta S=1} = A_1 \left( 1 + \xi e^{i\delta} e^{i\gamma} + \xi_{NP} e^{i\delta_{NP}} e^{i\phi_{NP}} \right), \]
\[ A(B^0 \to Uf)_{\Delta S=0} = -\tilde{\lambda} A_0 \left( 1 - \bar{\lambda}^{-2} \xi e^{i\delta} e^{i\gamma} \right), \]

where $\xi_{NP} \equiv A_{NP}/A_0, \bar{\lambda} \equiv \lambda/(1 - \lambda^2/2)$. We are using the “c-convention”, in which
the top quark in $b \to s(d)$ loop diagrams has been integrated out and the unitarity
relations $V_{tb}^*V_{ts(d)} = -V_{cb}^*V_{cs(d)} - V_{ub}^*V_{us(d)}$ have been employed. The terms $A_1$ and
$-\bar{\lambda} A_0$ include $V_{cb}^*V_{cs}$ and $V_{cb}^*V_{cd}$, respectively, while the terms involving $\xi'$ and $\xi$ include
$V_{ub}V_{us}$ and $V_{ub}V_{cd}$, respectively. The weak phases $\gamma$ and $\phi^{NP}$ change signs in decay amplitudes for $\bar{B}_s$ and $B^0$.

In the U-spin symmetry limit, without neglecting any small terms such as annihilation amplitudes, one has [19,22]

$$A_1 = A_0 , \quad \xi' = \xi , \quad \delta' = \delta.$$  \hspace{1cm} (4)

The first equality is susceptible to U-spin breaking correction of order $m_s/\Lambda_{QCD}$. Corrections to the second and third relations applying to ratios of amplitudes are expected to be smaller than 30% because certain SU(3) breaking factors including ratios of meson decay constants and ratios of form factors cancel in the factorization approximation [19]. Our discussion below will be restricted to CP asymmetries alone, in which the common factors in amplitudes $A_0$ and $\tilde{\lambda}A_1$ cancel. Thus, our approximation relies only on the latter two relations in (4). As we will explain, the theoretical uncertainty in extracting NP amplitudes is reduced further if these amplitudes occur at order $\lambda$.

We note the large enhancement by a factor $\tilde{\lambda}^{-2} = 18.6$ of the interference between amplitudes with weak phases 0 and $\gamma$ in the $\Delta S = 0$ process relative to the corresponding interference in the $\Delta S = 1$ decay. This enhancement is effective when using CP asymmetries in the $\Delta S = 0$ process for controlling the small amplitude $\xi' \exp(i\delta') \exp(i\gamma)$ in the $\Delta S = 1$ decay. For comparison, in earlier suggestions for using decay rates in $\Delta S = 0$ decays to control the small amplitude [15,16], the effective enhancement factor is only $\tilde{\lambda}^{-1} = 4.3$. This is the ratio of amplitudes with weak phase $\gamma$ in $\Delta S = 0$ and $\Delta S = 1$ decays. As we demonstrate below, the larger enhancement factor in the new method is one of two factors leading to a higher precision in controlling the small amplitude. A second ingredient, related to the determination of a strong phase difference, will be discussed below.

Denoting

$$\lambda_{B_s} \equiv e^{-i\phi_s} \frac{A(\bar{B}_s \to f)}{A(B_s \to f)} = \eta_{CP} e^{-i\phi_s} \frac{A(\bar{B}_s \to \bar{f})}{A(B_s \to f)},$$  \hspace{1cm} (5)

$$\lambda_{B^0} \equiv e^{-2i\beta} \frac{A(\bar{B}^0 \to Uf)}{A(B^0 \to Uf)} = \eta_{CP} e^{-2i\beta} \frac{A(\bar{B}^0 \to \bar{Uf})}{A(B^0 \to Uf)},$$  \hspace{1cm} (6)

where $\eta_{CP}$ is the common CP eigenvalue of $f$ and $Uf$, it is straightforward to calculate the four CP asymmetries in the two processes,

$$C(B_s \to f) \equiv \frac{1 - |\lambda_{B_s}|^2}{1 + |\lambda_{B_s}|^2}, \quad S(B_s \to f) \equiv \frac{2\text{Im}(\lambda_{B_s})}{1 + |\lambda_{B_s}|^2},$$  \hspace{1cm} (7)

$$C(B^0 \to Uf) \equiv \frac{1 - |\lambda_{B^0}|^2}{1 + |\lambda_{B^0}|^2}, \quad S(B^0 \to Uf) \equiv \frac{2\text{Im}(\lambda_{B^0})}{1 + |\lambda_{B^0}|^2}.$$  \hspace{1cm} (8)

In the U-spin symmetry limit $\xi' = \xi, \delta' = \delta$, one obtains expressions for the four asymmetries which are functions of $\xi, \delta, \xi^{NP}, \delta^{NP}, \phi^{NP}$ and the three phases, $\beta, \gamma$ and
\( \phi_s: \)
\[
\begin{align*}
C(B_s \to f) &= f_1(\gamma, \xi, \delta, \xi^{\text{NP}}, \delta^{\text{NP}}, \phi^{\text{NP}}), \\
- \eta_{\text{CP}} S(B_s \to f) &= g_1(\phi_s, \gamma, \xi, \delta, \xi^{\text{NP}}, \delta^{\text{NP}}, \phi^{\text{NP}}), \\
C(B^0 \to U f) &= f_0(\gamma, \xi, \delta), \\
- \eta_{\text{CP}} S(B^0 \to U f) &= g_0(\beta, \gamma, \xi, \delta).
\end{align*}
\]

Assuming known values for the two CKM phases, \( \beta, \gamma \) and the \( B_s \bar{B}_s \) mixing phase \( \phi_s \), one is left with five parameters describing the four observables. Two of the parameters, \( \xi \) and \( \delta \), are determined from the two asymmetries in \( B^0 \to U f \). This is the proposed prescription for controlling through the latter process both \( \xi \) and \( \delta \) describing the small amplitude with weak phase \( \gamma \) in \( B_s \to f \). Using \( \xi \) and \( \delta \) as inputs in \( C(B_s \to f) \) and \( S(B_s \to f) \), one can calculate their effect on the latter asymmetries in the limit of a vanishing NP amplitude, \( \xi^{\text{NP}} = 0 \). As we have pointed out, this should be more precise than estimating this effect by using the rate for the \( \Delta S = 0 \) process. This follows from both the larger enhancement factor \( \lambda^{-2} \) mentioned above and information obtained about the strong phase \( \delta \), which is unavailable when using the rate.

In principle, a disagreement between the predicted asymmetries in \( B_s \to f \) and their experimental values for \( \xi^{\text{NP}} = 0 \) would provide evidence for NP. The discrepancy, for the predetermined values of \( \xi \) and \( \delta \), can then be used to study the three NP parameters \( \xi^{\text{NP}}, \delta^{\text{NP}} \) and \( \phi^{\text{NP}} \).

We now demonstrate more explicitly the application of our proposed method, evaluating the theoretical precision involved in identifying and potentially extracting the NP amplitude. For this purpose we will assume a hierarchy between the dominant penguin amplitude \( A_1 \), the smaller NP amplitude \( A_{\text{NP}} \) and a still smaller amplitude with weak phase \( \gamma \),
\[
1 : \xi^{\text{NP}} : \xi \sim 1 : \lambda : \lambda^2.
\]
We write exact expressions for \( C(B^0 \to U f), S(B^0 \to U f) \) and expressions for \( C(B_s \to f), S(B_s \to f) \) which are true to order \( \lambda \), keeping for illustration also terms of order \( \xi \):
\[
\begin{align*}
f_0 &= \frac{2 \lambda^{-2} \xi \sin \delta \sin \gamma}{1 - 2 \lambda^{-2} \xi \cos \delta \cos \gamma + \left( \lambda^{-2} \xi \right)^2}, \\
g_0 &= \frac{\sin 2\beta - 2 \lambda^{-2} \xi \cos \delta \sin(2\beta + \gamma) + \left( \lambda^{-2} \xi \right)^2 \sin 2(\beta + \gamma)}{1 - 2 \lambda^{-2} \xi \cos \delta \cos \gamma + \left( \lambda^{-2} \xi \right)^2}. \\
f_1 &= -2 \xi^{\text{NP}} \sin \phi^{\text{NP}} \sin \delta^{\text{NP}} - 2 \xi \sin \gamma \sin \delta + O(\lambda^2), \\
g_1 &= - \sin \phi_s + 2 \cos \phi_s (\xi^{\text{NP}} \sin \phi^{\text{NP}} \cos \delta^{\text{NP}} + \xi \sin \gamma \cos \delta) + O(\lambda^2).
\end{align*}
\]
Assuming arbitrary strong phases, one notes two interesting and useful features:
- The asymmetry \( C(B^0 \to U f) \equiv f_0 \) and the deviation of \( - \eta_{\text{CP}} S(B^0 \to U f) \equiv g_0 \) from \( \sin 2\beta \) are formally of order one. This is encouraging for a determination of \( \xi \) and \( \delta \) from these two asymmetries.
- At order $\lambda$, $C(B_s \rightarrow f) \equiv f_1$ and $-\eta_{\text{CP}} S(B_s \rightarrow f) \equiv g_1$ depend on the combination $\xi^{\text{NP}} \sin \phi^{\text{NP}}$ and not on $\xi^{\text{NP}}$ and $\phi^{\text{NP}}$ independently. This feature holds only to leading order in $\lambda$. At this order, $\xi^{\text{NP}} \sin \phi^{\text{NP}}$ and $\delta^{\text{NP}}$ can be determined from these asymmetries when $\xi$ and $\delta$ are used as inputs obtained from $B^0 \rightarrow Uf$.

Under our assumption (13), the asymmetries $C(B_s \rightarrow f)$ and $-\eta_{\text{CP}} S(B_s \rightarrow f) + \sin \phi_s$ are dominated by NP contributions, $-2 \xi^{\text{NP}} \sin \phi^{\text{NP}} \sin \delta^{\text{NP}}$ and $2 \cos \phi_s \xi^{\text{NP}} \sin \phi^{\text{NP}} \cos \delta^{\text{NP}}$, which are of order $\lambda^2$. Standard Model terms, $-2 \sin \gamma \xi \sin \delta$ and $2 \cos \phi_s \sin \gamma \xi \cos \delta$, are of order $\lambda^2$. Consequently, theoretical errors from SU(3) breaking in the ratios of amplitudes, $\xi \sin \delta$ and $\xi \cos \delta$, are diluted by another factor $\lambda$ in the determination of NP quantities, $\xi^{\text{NP}} \sin \phi^{\text{NP}}$, $\cos \delta^{\text{NP}}$ and $\sin \delta^{\text{NP}}$. Therefore, initial U-spin breaking effects of order $m_s/\Lambda_{\text{QCD}}$ lead to very small uncertainties of order $\lambda^3$ in the extracted amplitudes.

**III. A FEW EXAMPLES**

**a. Decays involving one or two pseudoscalar mesons**

We list a few examples of pairs of U-spin related $\Delta S = 1$ and $\Delta S = 0$ decays to CP-eigenstates involving two pseudoscalars [22]:

\begin{align}
B_s &\rightarrow K^+ K^- , & B^0 &\rightarrow \pi^+ \pi^- , \\
B_s &\rightarrow K^0 \bar{K}^0 , & B^0 &\rightarrow K^0 \bar{K}^0 , \\
B^0 &\rightarrow K_S \pi^0 , & B_s &\rightarrow K_S \pi^0 .
\end{align}

(18) (19) (20)

Time-dependent asymmetries $C$ and $S$ in $B^0 \rightarrow \pi^+ \pi^-$ have been measured at $e^+ e^-$ $B$ factories [11]. Similar measurements for $B_s \rightarrow K^+ K^-$ are being planned at Fermilab and CERN. This pair of processes, usually considered within the Standard Model for a determination of the weak phase $\gamma$ [19], can in principle also be studied in a broader context for potential NP effects as described above. In $B_s \rightarrow K^+ K^-$ one has $\xi \simeq 0.2 \simeq \lambda$ [19, 23] because this decay involves an ordinary tree amplitude. While certain SU(3) breaking corrections cancel in the ratio $\xi$, the hierarchy (13) does not hold in $B_s \rightarrow K^+ K^-$. Therefore, SU(3) breaking corrections in the determination of a potential NP amplitude are not further suppressed by $\lambda$.

Time-dependent asymmetry measurements are very challenging for the processes (19) and (20) involving only neutral pions and kaons, and will not be discussed much further. Such measurements have been made for $B^0 \rightarrow K_S \pi^0$ at $B$ factories [11], interpreted in terms of a CKM amplitude with weak phase $\gamma$ [17] and in terms of potential NP contributions [24]. Measuring time-dependence in $B_s \rightarrow K_S \pi^0$ seems less feasible at hadronic colliders. Somewhat easier are decays involving corresponding pairs of pseudoscalar and vector mesons, e.g.,

\begin{align}
B^0 &\rightarrow K_S \rho^0 , & B_s &\rightarrow K_S \rho^0 .
\end{align}

(21)

While the $\rho^0 \rightarrow \pi^+ \pi^-$ decay vertex permits a time-dependent measurement, one would have to fight against a background from incidental pairs of charged pions lying
under the wide $\rho^0$. One may expect a cleaner signal for the pair of processes involving an $\omega$ instead of a $\rho^0$,

$$B^0 \rightarrow K_S\omega, \quad B_s \rightarrow K_S\omega.$$  \hspace{1cm} (22)

**b. Decays involving two vector mesons**

Decays into two charmless neutral vector mesons, each decaying to a pair of charged particles, are slightly more challenging than decays involving pseudoscalar mesons, but are very interesting theoretically and experimentally. Identifying CP-eigenstates requires studying both the time and angular dependence for the four final decay particles. These processes provide a high potential for probing NP effects.

The number of amplitudes increases by a factor three relative to decays to two pseudoscalars due to three independent polarization states. The number of asymmetry observables is six times larger (see discussion below). The additional information permits controlling more accurately small Standard Model terms and studying potential NP amplitudes with fewer ambiguities.

Consider a generic pair of $\Delta S = 1$ and $\Delta S = 0$ processes, $B_s \rightarrow V_1 V_2$, $B^0 \rightarrow U(V_1 V_2)$. The decay amplitudes for a given polarization can be written in the U-spin symmetry limit in analogy with (2) and (3),

$$A_k(B_s \rightarrow V_1 V_2) = (A_1)_k \left( 1 + \xi_k e^{i\delta_k} e^{i\gamma} + \xi_{NP} e^{i\delta_{NP}} e^{i\phi_{NP}} \right),$$  \hspace{1cm} (23)

$$A_k(B^0 \rightarrow U(V_1 V_2)) = -\tilde{\lambda}(A_0)_k \left( 1 - \tilde{\lambda} - 2\xi_k e^{i\delta_k} e^{i\gamma} \right).$$  \hspace{1cm} (24)

The amplitudes $A_k$ with $(\eta_{CP})_k = +1, +1, -1$, for $k = L, ||, \perp$, correspond to two vector mesons which are either longitudinally polarized ($L$), or transversely polarized with linear polarization parallel ($||$) or perpendicular ($\perp$) to one another [25]. We are assuming a single NP weak phase $\phi_{NP}$ which is independent of the vector meson polarization.

Time-dependent decay distributions depend on transversity angles defining directions for the final outgoing particles [25]. CP asymmetries $C_{kl}$ and $S_{kl}$ ($k, l = L, ||, \perp$) multiplying $\cos \Delta m t$ and $\sin \Delta m t$ can be defined for each of six independent functions of transversity angles [26]. The measurable asymmetries $C_{kl}$ and $S_{kl}$ are given by expressions analogous to (7) and (8) (details will be given elsewhere [27]),

$$C_{kl} = \frac{\mathcal{F}(1 - \lambda_k^{*} \lambda_l)}{\mathcal{F}(1 + \lambda_k^{*} \lambda_l)},$$  \hspace{1cm} (25)

$$S_{kl} = \frac{\mathcal{F}[i(\lambda_k^{*} - \lambda_l)]}{\mathcal{F}(1 + \lambda_k^{*} \lambda_l)}, \quad k, l = L, ||, \perp,$$  \hspace{1cm} (26)

where

$$\mathcal{F} = \begin{cases} \text{Re} : & k = L, \quad l = || \\ \text{Im} : & k = L, ||, \quad l = \perp \end{cases},$$  \hspace{1cm} (27)

$$\lambda_k = \begin{cases} e^{-i\phi_s} A_k(\bar{B}_s \rightarrow V_1 V_2)/A_k(B_s \rightarrow V_1 V_2) : & B_s \\ e^{-2i\beta} A_k(B^0 \rightarrow U(V_1 V_2))/A_k(B^0 \rightarrow U(V_1 V_2)) : & B^0 \end{cases}.$$  \hspace{1cm} (28)
The twelve observables $C_{kk}$, $S_{kk}$ ($k = L, ||, \perp$), combining $B_s$ and $B^0$ decays, are analogous to the four asymmetries $C$ and $S$ in $\Delta S = 1$ and $\Delta S = 0$ decays to two pseudoscalars. They permit mutually independent determinations for the three sets of four hadronic parameters, $\xi_k, \delta_k$ and $\xi^\text{NP}_k \sin \phi^\text{NP}_k, \delta^\text{NP}_k$, assuming a hierarchy as in [13]. The other twelve asymmetries, $C_{kl}, S_{kl}$ ($k \neq l$), depend on the same twelve parameters and on four relative strong phases, two among $(A_1)_k$ and two among $(A_0)_k$. This information may improve precision and resolve discrete ambiguities obtained when using only $C_{kk}$ and $S_{kk}$. Furthermore, while $C_{kk}$ and $S_{kk}$ have been shown to depend on $\xi^\text{NP}_k \sin \phi^\text{NP}_k$, “mixed” asymmetries such as $C_{14}$ ($i = L, ||$) depend also on $\xi^\text{NP}_k \cos \phi^\text{NP}_k$ [27]. This permits determining separately the magnitude $\xi^\text{NP}_k$ and weak phase $\phi^\text{NP}_k$ of the NP amplitude.

Examples of pairs of SU(3)-related decays to which our proposed method may be applied include the following:

$$B_s \to K^{*0} \bar{K}^{*0} \ (K^{*0} \to K^+ \pi^-) \ , \quad B^0 \to \bar{K}^{*0} K^{*0} \ (K^{*0} \to K^+ \pi^-) \ ,$$

$$B^0 \to K^{*0} \rho^0 (K^{*0} \to K_S \pi^0) \ , \quad B_s \to K^{*0} \rho^0 (K^{*0} \to K_S \pi^0) \ ,$$

$$B_s \to \phi \phi \ (\phi \to K^+ K^-) \ , \quad B_s \to \phi \bar{K}^{*0} \ (\bar{K}^{*0} \to K_S \pi^0) \ .$$

Decay rates and CP asymmetries in the first pair of processes [29] have been suggested very recently as tests for consistency within the Standard Model [28]. Our method for studying potential NP amplitudes avoids the use of decay rates, which are expected to introduce sizable SU(3) breaking corrections. While $B^0 \to K^{*0} \bar{K}^{*0}$ has already been observed with a branching ratio of about $0.5 \times 10^{-6}$ [29], the decay $B_s \to K^{*0} \bar{K}^{*0}$ is expected to have an order of magnitude larger branching ratio [30,31].

The contribution of an amplitude with weak phase $\gamma$ in this process is expected to be very small, $\xi \sim \lambda^2$. Thus, our suggested analysis of a potential NP amplitude in $B_s \to K^{*0} \bar{K}^{*0}$ should work well in this case.

A very interesting $B_s$ decay mode involving $\xi \sim \lambda^2$ is $B_s \to \phi \phi$. A handful of events have been observed in this mode a few years ago by the CDF collaboration at the Fermilab Tevatron, corresponding to a branching ratio of $(14^{+6}_{-5} \pm 6) \times 10^{-6}$ [32]. It is estimated that by now the signal has grown to about 150 events [33]. A proposal for studying time and angular dependence in this decay mode has been made by the LHCb collaboration at the CERN Large Hadron Collider [34]. The proposal is based on an estimated sample of about 3100 events collected in one year of running.

While the decay mode $B_s \to \phi \phi$ has no U-spin counterpart, it may be related through flavour SU(3) to $B_s \to \phi \bar{K}^{*0}$. The two processes involve each a penguin amplitude, a singlet penguin amplitude and an electroweak penguin amplitude, related to each other through an operator replacement $(\bar{s}b) \leftrightarrow (\bar{d}b)$ and a similar quark replacement $s \leftrightarrow d$ in the final state [35]. An assumption about a negligible penguin annihilation contribution in $B_s \to \phi \phi$ may be verified by obtaining a stringent upper bound on $\mathcal{B}(B^0 \to \phi \phi)$ which is dominated by penguin annihilation. As we have noted, an SU(3) breaking correction cancels largely in the ratios $\xi^\text{NP}_k$, and the effect of this correction on extracting a potential NP amplitude of order $\lambda$ is further suppressed by $\lambda$ and can thus be neglected. Thus, expressions analogous to (23) and
apply to this case involving $B_s \rightarrow \phi \phi$ and $B_s \rightarrow \phi \bar{K}^{*0}$. The first amplitude must be multiplied by a factor $\sqrt{2}$ to account for identical particles.

The decay $B_s \rightarrow \phi \bar{K}^{*0}$ is expected to have a branching ratio of about $0.5 \times 10^{-6}$ [30, 31]. This corresponds to observing an order of one hundred signal events in one year at the LHCb. An analysis involving both time and angular dependence requires several years of running at the LHC. The direct asymmetries $C_{kl}$ in $B_s \rightarrow \phi \bar{K}^{*0}$ can be measured through the self-tagging flavour state, $\bar{K}^{*0} \rightarrow K^- \pi^+$. The mixing-induced asymmetries $S_{kl}$ would have to be measured in decays to a CP eigenstate, $\bar{K}^{*0} \rightarrow K_S \pi^0$. This may be challenging for experiments at hadron colliders and can also be done at a Super-$B$ $e^+e^-$ collider running at the $\Upsilon(5S)$ [36]. The case of $B_s \rightarrow \phi \phi$ versus $B_s \rightarrow \phi \bar{K}^{*0}$ will be studied in detail elsewhere [27].

IV. CONCLUSION

We have suggested a method for studying NP amplitudes in penguin-dominated strangeness-changing $B_s$ decays by comparing time-dependent CP asymmetries in these decays to asymmetries in SU(3) related strangeness-conserving decays. Assuming that a NP amplitude of order $\lambda$ occurs in $\Delta S = 1$ processes but not in $\Delta S = 0$ decays, we have shown that these asymmetries determine with high precision small Standard Model amplitudes with weak phase $\gamma$ and potential NP amplitudes. Corrections from SU(3) breaking, usually assumed to be of order $m_s/\Lambda_{QCD}$, are suppressed by two factors:

1. The method depends on ratios of hadronic amplitudes in which certain SU(3) breaking factors cancel.

2. The uncertainty in the extracted NP amplitude from SU(3) breaking is suppressed by another factor of $\lambda$.

Decays into two vector mesons are particularly appealing. They permit both time-dependent and angular-dependent analyses, and can be used to extract both the magnitudes of the NP amplitudes and their strong and weak phases. Two pairs of processes which are first on our list are $B_s \rightarrow \phi \phi$, $B_s \rightarrow \phi \bar{K}^{*0}$ and $B_s \rightarrow K^{*0}\bar{K}^{*0}$, $B^0 \rightarrow \bar{K}^{*0}K^{*0}$. These $\Delta S = 1$ penguin-dominated $B_s$ decays hold great promise for carrying out the proposed study because of their rich polarization structure. Unlike $B^0 \rightarrow \rho^+\rho^-$ which involves a dominant longitudinally polarized amplitude and much smaller transverse amplitudes, in these $\Delta S = 1$ processes the three polarization amplitudes are expected to have comparable magnitudes, $|A_L| \sim \sqrt{2}|A_|| \sim \sqrt{2}|A_\perp|$ [30,31], similar to the situation observed in $B^0 \rightarrow \phi K^{*0}$ [11].

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