Extracting the unitarity angle $\gamma$ in $B_s \to D^0 h^0, \bar{D}^0 h^0$ Decays

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Abstract

The recently observed color-suppressed $B^0 \to D^0 \pi^0, D^0 \eta^0, D^0 K^- \pi^0 K^0, D^0 \rho^0$ and $D^0 \omega$ decay modes all have rates larger than expected. The color-suppressed $B_s \to D^0 \phi, \bar{D}^0 \phi$ modes, which were suggested for the extraction of the unitarity angle $\gamma$ in the Gronau-London method, could be larger than the previous estimation by one order of magnitude. Several new theoretical clean modes in $B_s$ decays are suggested for the extraction of $\gamma$. The proposed $B_s \to D^0 h^0, \bar{D}^0 h^0$ decay modes with $h^0 = \pi^0, \eta, \eta', \rho^0, \omega$ in addition to $h^0 = \phi$ are free from penguin contributions. Their decay rates can be estimated from the observed color-suppressed $B^0 \to D^0 h^0$ rates through SU(3) symmetry. A combined study of these $D^0 h^0, \bar{D}^0 h^0$ modes in addition to the $D^0 \phi, \bar{D}^0 \phi$ modes is useful in the extraction of $\gamma$ in the $B_s$ system without involving $B_s - \bar{B}_s$ mixing. Since the $b \to u$ and $b \to c$ transitions belong to the same topological diagram, the relative strong phase is likely to be small. In this case, the $CP$ asymmetries are suppressed and the untagged rates are very useful in the $\gamma$ extraction.

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The extraction of the unitarity angle $\gamma \equiv \arg V_{ub}^*$, where $V$ is the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix, is important in completing or testing the Standard Model (SM). Several theoretical clean ways of the weak phase extraction were proposed using interference effects. At $B$ factories, the extraction is performed in the $DK$ system, using the interference effect of $B \to D^0K$ and $\bar{D}^0K$ decays in $D_{CP}K$ final states, where $D_{CP}$ are the CP eigenstates of $D^0$ and $\bar{D}^0$ mesons, or to some common $f_{CP}K$, $f_{CP}$ states [1, 2, 3, 4, 5, 6].

Similarly, the color-suppressed $D_{CP}\phi$ mode was also proposed in the extraction of $\gamma$ in the $B_s$ system [7]. An alternative method made use of the $B_s$–$\bar{B}_s$ mixing was proposed using color-allowed $B_s \to D_s^\pm K^\mp$ decays with time-dependent tagging [7]. Due to the large rate ($10^{-4}$) in the color-allowed decays, this scenario has been seriously considered at LHCb [8].

It is well known that in the SM, the $\Delta m_{B_s}$ in the $B_s$ system is much larger than the one in the $B_d$ system. Experimental searches give $\Delta m_{B_s} > 14.5$ ps$^{-1}$ [9]. The measurement of the time-dependent asymmetry in the $B_s$ system is challenging. Furthermore, the deviation of the recently measured $\sin 2\beta_{\text{eff}}$ in penguin-dominated modes from the $\sin 2\beta$ ($\beta \equiv \arg V_{td}^*$) extracted from charmonium modes may hint at New Physics contributions in the $b \to s$ transitions [10, 11]. In this case, the $\Delta m_{B_s}$ can easily be much larger than the SM expectation (see, for example [12]). Therefore, an extraction of $\gamma$ without relaying on the $B_s$–$\bar{B}_s$ mixing is complementary to the $D_s^\pm K^\mp$ program and is indispensable to the $\gamma$ program in the $B_s$ system.

Although the Gronau-London $D_{CP}\phi$ method [1] does not need time-dependent tagging, its usefulness is questioned by the smallness of the color-suppressed decay rate, which is estimated to be as small as $10^{-6}$ [1]. However, color-suppressed $\bar{B}^0 \to D^{(*)0}\pi^0$, $D^0\eta^{(')}$, $D^0\omega$, $D^0\rho^0$, $D_s^+K^-$, $D^0\bar{K}^0$ decay modes were observed with branching ratios significantly larger than earlier theoretical expectations based on naive factorization [13].

The large color-suppressed decay rates have attracted much attention [14, 15, 16, 17, 18]. Similar enhancement in the color-suppressed decay rates in the $B_s$ system is expected. In particular, the $D^0\phi$ rate is expected to be larger than the previous estimation. In addition to the $D\phi$ mode, several other theoretical clean modes are suggested in this work. The proposed tree $D^0h^0$, $\bar{D}^0h^0$ decay modes, where $h^0 = \pi^0$, $\eta$, $\eta'$, $\rho^0$, $\omega$, in addition to the $D^0\phi$, $\bar{D}^0\phi$ modes are useful to extract $\gamma$ without time-dependent tagging. As we shall see later, the extraction done only with untagged rates can also be useful.

In this study, the $\gamma$ extraction method is similar to the $B_d \to DK$ and $B_s \to D\phi$ method.
FIG. 1: Color-allowed and color-suppressed amplitudes for $B^- \to D^0 K^-$ decay, and color-suppressed amplitude for the $B^- (B_s) \to D^0 K^-(\phi, \eta, \eta')$ decay.

It will be useful to briefly review the $DK$ method and the present experimental status at $B$ factories. To be specific, the amplitude ratio $r_B$ and the strong phase difference $\delta_B$ for the color-allowed $B^- \to D^0 K^-$ and color-suppressed $D^0 K^-$ decays, which are governed by different CKM matrices as depicted in Fig. 1 are defined as

$$r_B = \frac{|A(B^- \to D^0 K^-)|}{|A(B^- \to D^0 K^-)|}, \quad \delta_B = \text{arg} \left[ \frac{e^{i\gamma} A(B^- \to D^0 K^-)}{A(B^- \to D^0 K^-)} \right]. \quad (1)$$

The weak phase $\gamma$ is removed from $A(B^- \to D^0 K^-)$ in the $\delta_B$ definition. Since the strong phase difference arises from that in the color-suppressed and color-allowed amplitudes, it is expected to be non-vanishing. The $r_B$ and $\delta_B$ parameters are common to the $\gamma$ determination methods of Gronau-London-Wyler (GLW) \cite{1, 2}, Atwood-Dunietz-Soni (ADS) \cite{3} and “$DK$ Dalitz plot” \cite{4, 5}, where one exploits the interference effects of $B^- \to D^0 K^- \to f_{CP} K^-$ and $B^- \to D^0 K^- \to f_{CP} K^-$ amplitudes. Note that the $r_B$ parameter, which governs the strength of interference, is both color and CKM suppressed, hence hard to measure directly.

Through the $DK$ Dalitz plot method, BaBar and Belle experiments already find $\gamma = \ldots$
In addition to the color-suppressed diagram the $B^0 \rightarrow K_S \pi^+ \pi^-$, and the BaBar measurement includes the $DK^*$ analysis. Although similar results on $\gamma$ are obtained, the corresponding $r_B$ values are quite different for BaBar and Belle. Belle reports $r_B = 0.21 \pm 0.08 \pm 0.03 \pm 0.04$ and $\delta_B = (157 \pm 19 \pm 11 \pm 21)^\circ$, while BaBar gives $r_B = 0.118 \pm 0.079 \pm 0.034^{+0.036}_{-0.034}$ and $\delta_B = (104 \pm 45^{+17+16}_{-21-24})^\circ$. Note that an average of $r_B = 0.10 \pm 0.04$ is found by the UT$_{fit}$ group, by combining analyses using all three methods [20]. As the strength of interference is governed by the size of the ratio $r_B$, the larger error in the $\gamma$ value of BaBar reflects the smallness of their $r_B$. Given the present experimental situation that Belle and BaBar have quite different $r_B$ values and that the critical role it plays in the $\gamma$ extraction, it is important to compare with a theoretical or phenomenological prediction of $r_B$. In a recent work, we obtained $r_B = 0.09 \pm 0.02$ [18]. The predicted $r_B$ agrees with the UT$_{fit}$ extraction [20] and does not differ much from the naive factorization expectation. Furthermore, the $r_B$ value prefers the lower value of the BaBar experiment and disfavors the Belle result. A similar $r_B$ was found experimentally in the $DK^*$ analysis [10, 19].

The smallness of the ratio $r_B$ would demand larger statistics of data for the $\gamma$ program in the $DK^{(*)}$ system. In fact, the smallness of $r_B$ is precisely the reason that ADS and $DK$ Dalitz methods are needed in addition to the original GLW method. However, these methods usually bring in additional uncertainties, such as the fourth uncertainties in the extracted $\gamma$ value quoted above.

We now return to the $B_s$ system. By replacing the spectator quark in the previous case, we have $\overline{B}_s \rightarrow D \phi$ decays replacing the role of $\overline{B} \rightarrow D K^{(*)}$ decays, as depicted in Fig. 1 in the $\gamma$ program [1]. Unlike the $\overline{B}$ case, both $\overline{B}_s \rightarrow D^0 \phi$ and $\overline{B}^0 \phi$ modes are color suppressed decays. Consequently, the corresponding $b \rightarrow u$ and $b \rightarrow c$ amplitude ratio is estimated as $r_{B_s} \simeq R_b \equiv \sqrt{\rho^2+\eta^2} \simeq 0.4$ [9, 10], which is several times greater than $r_B$, giving a much prominent interference effect [1]. The $\overline{B}_s \rightarrow D^0 \phi$ decay can be related to other decays by using the topological approach [21], which is closely related to SU(3) symmetry. Indeed the $\overline{B}_s \rightarrow D^0 \phi$ decay is similar to other color-suppressed modes, such as $\overline{B}^0 \rightarrow D^0 \rho^0$, $D^0 \omega$, as one can see by replacing $s\bar{s}$ and $V_{us}$ in the second diagram of Fig. 1 by $d\bar{d}$ and $V_{ud}$, respectively. These modes were observed with $\mathcal{B}(\overline{B}^0 \rightarrow D^0 \rho^0) = (2.9 \pm 1.1) \times 10^{-4}$ and $\mathcal{B}(\overline{B}^0 \rightarrow D^0 \omega) = (2.5 \pm 0.6) \times 10^{-4}$ [22], which are larger than naive factorization expectations. In addition to the color-suppressed diagram the $\overline{B}^0 \rightarrow D^0 \rho^0$ and $D^0 \omega$ amplitudes receive
annihilation diagram contributions (similar to the second diagram shown in Fig. 2), but with different relative signs. The measured rates roughly satisfy $\mathcal{B}(\bar{B}^0 \to D^0 \rho^0) \simeq \mathcal{B}(\bar{B}^0 \to D^0 \omega)$ and, consequently, imply the sub-dominant role of the annihilation contribution plays in these modes. Assuming SU(3) symmetry and neglecting the annihilation contribution, the $\bar{B}_s \to D^0 \phi$ rate can be estimated from these decay rates by using

$$\mathcal{B}(\bar{B}_s \to D^0 \phi) \simeq \frac{\tau_{B_d}}{\tau_{B_s}} \left( \frac{V_{us}}{V_{ud}} \right)^2 \mathcal{B}(\bar{B}^0 \to D^0 \rho^0) + \mathcal{B}(\bar{B}^0 \to D^0 \omega) \right] \simeq 3 \times 10^{-5}, \quad (2)$$

where $\tau_{B_d,B_s}$ are the lifetime of $B_{d,s}$ mesons with $\tau_{B_s}/\tau_{B_d} \simeq 0.95 [9]$. Our estimation of the $\bar{B}_s \to D^0 \phi$ rate is one order of magnitude larger than the previous one [7]. The Gronau-London method should be useful in the extraction of $\gamma$ in the $B_s$ system.

After realizing the applicability of the Gronau-London method in the $B_s$ system, we propose several additional theoretical clean modes adding to the $\gamma$ program. The tree $B_s \to D^0 h^0$, $\bar{B}^0 h^0$ decays with $h^0 = \pi^0, \eta, \eta', \rho^0, \omega$, do not contain any penguin contribution. The $B_s \to D^0 \eta$, $\bar{B}^0 \eta'$ modes receive contributions from color-suppress tree and $W$-exchange diagrams as depicted in Fig. 1 and 2 while others are pure weak annihilation modes.

The $B_s \to D^0 h^0$ rates can be estimated by using the $\bar{B}^0 \to D^0 h^0$ rates in the topological amplitude approach [21]. We have

$$A(\bar{B}^0 \to D^0 \pi^0) = \frac{V_{cb}V_{ud}^*}{\sqrt{2}}(E - C),$$

$$A(\bar{B}^0 \to D^0 \eta) = \frac{V_{cb}V_{ud}^*}{\sqrt{2}} \cos \psi(E + C),$$

$$A(\bar{B}^0 \to D^0 \eta') = \frac{V_{cb}V_{ud}^*}{\sqrt{2}} \sin \psi(E + C),$$

$$A(\bar{B}^0 \to D_s^+ K^-) = V_{cb}V_{ud}^*E, \quad (3)$$

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1 In the right-hand-side of the equation, the annihilation amplitude only enters quadratically. Its contribution can be safely neglected. Also note that the $\bar{B}^0 \to D^0 \rho^0(\omega)$ amplitude has an additional factor of $1/\sqrt{2}$ due to the $\rho^0(\omega)$ wave function.
and

\[ A(B_s \to D^0 \pi^0) = \frac{V_{ub} V_{ub}^*}{\sqrt{2}} E', \]
\[ A(B_s \to D^0 \eta) = \frac{V_{ub} V_{ub}^*}{\sqrt{2}} (-\sin \psi \sqrt{2} C' + \cos \psi E'), \]
\[ A(B_s \to D^0 \eta') = \frac{V_{ub} V_{ub}^*}{\sqrt{2}} (\cos \psi \sqrt{2} C' + \sin \psi E'), \]
\[ A(B_s \to D^0 \eta^0) = \frac{V_{ub} V_{ub}^*}{\sqrt{2}} E'', \]
\[ A(B_s \to D^0 \eta') = \frac{V_{ub} V_{ub}^*}{\sqrt{2}} (\cos \psi \sqrt{2} C'' + \sin \psi E''), \]

where \( C, C', C'' \) and \( E, E', E'' \) are (complex) color-suppressed and \( W \)-exchange amplitudes, respectively, containing possible final-state-interaction (FSI) effects, and \( \psi = 39.3^\circ \) is the mixing angle of the \( \eta \) and \( \eta' \) non-strange and strange contents \( 22 \).

\[
\begin{pmatrix}
\eta \\
\eta'
\end{pmatrix} = \begin{pmatrix} \cos \psi & -\sin \psi \\ \sin \psi & \cos \psi \end{pmatrix} \begin{pmatrix} \eta_q \\ \eta_s \end{pmatrix}
\]

(5)

with \( \eta_q = (u\bar{u} + d\bar{d})/\sqrt{2} \) and \( \eta_s = s\bar{s} \). The color suppressed rates are measured to be \( B(B^0 \to D^0 \pi^0) = (2.53 \pm 0.20) \times 10^{-4}, B(B^0 \to D^0 \eta) = (2.11 \pm 0.33) \times 10^{-4}, B(B^0 \to D^0 \eta') = (1.26 \pm 0.23) \times 10^{-4} \) and \( B(B^0 \to D_s^+ K^-) = (3.8 \pm 1.3) \times 10^{-5} \) \([9,13]\). These decay rates are much larger than the naive factorization expectations. There are some theoretical efforts in understanding the largeness of these decay modes \([14,15,16,18]\). Considering, for example, the \( B^0 \to D_s^+ K^- \) decay, in the rescattering approach \([18]\). Its large rate is feed from the color-allowed \( D^+ \pi^- \) one, through the rescattering process \( D^+(c\bar{u})\pi^-(u\bar{d}) \to D_s^+(c\bar{s})K^-(s\bar{u}) \) with the annihilation (creation) of \( u\bar{u} \) (\( s\bar{s} \)) quark pair in the initial (final) state.

The measured \( B^0 \to D^0 h^0 \) rates are useful in estimating \( B_s \to D^0 h^0 \) rates. In the SU(3) limit, we have \( C = C' \) and \( E = E' \). For \( B_s \to D^0 \eta, D^0 \eta' \) modes, we have

\[
B(B_s \to D^0 \eta, D^0 \eta') \equiv B(B_s \to D^0 \eta) + B(B_s \to D^0 \eta')
\]
\[
\simeq \frac{\tau_{B_s}}{\tau_{B_d}} \left| \frac{V_{us}}{V_{ud}} \right|^2 \left[ B(B^0 \to D^0 \pi^0) + B(B^0 \to D^0 \eta) 
+ B(B^0 \to D^0 \eta') - \frac{1}{2} B(B^0 \to D_s^+ K^-) \right]
\simeq 3 \times 10^{-5}.
\] 

(6)
FIG. 2: W-exchanged amplitudes for $B^0 \rightarrow D^+_s K^-$ and $B_s \rightarrow D^0 h^0$ decays.

To further estimate $D^0 \eta$ and $D^0 \eta'$ rates, we need information on $R \equiv E'/C'$. Using the measured color-suppressed $B^0$ decay rates and Eq. (3), it is straightforward to obtain the best fitted value of $E/C = 0.26 e^{\pm i72^\circ}$. By assuming $R(\equiv E'/C') \simeq E/C$ under SU(3), we estimate

$$\mathcal{B}(B_s \rightarrow D^0 \eta) \simeq \mathcal{B}(B_s \rightarrow D^0 \eta, D^0 \eta') \left| \frac{-\sqrt{2} \sin \psi + \cos \psi R}{2 + |R|^2} \right|^2 \simeq 1 \times 10^{-5},$$

$$\mathcal{B}(B_s \rightarrow D^0 \eta') \simeq \mathcal{B}(B_s \rightarrow D^0 \eta, D^0 \eta') \left| \frac{\sqrt{2} \cos \psi + \sin \psi R}{2 + |R|^2} \right|^2 \simeq 2 \times 10^{-5}, \quad (7)$$

which are of the same order as $\mathcal{B}(\bar{B}_s \rightarrow D^0 \phi)$.

The pure W-exchange $\bar{B}_s \rightarrow D^0 \pi^0$ decay rate can be estimated in a similar manner as

$$\mathcal{B}(\bar{B}_s \rightarrow D^0 \pi^0) \simeq \frac{\tau_{B_s}}{\tau_{B_d}} \left| \frac{V_{us}}{\sqrt{2} V_{ud}} \right|^2 \mathcal{B}(\bar{B}^0 \rightarrow D^+_s K^-) \simeq 1 \times 10^{-6}. \quad (8)$$

In fact, when take into account the SU(3) breaking effects, the $\bar{B}_s \rightarrow D^0 \pi^0$ decay rate could be larger than the above estimation, since unlike the $\bar{B}^0 \rightarrow D_s K$ decay no creation of the $s\bar{s}$ pair is needed in the final state (see Fig. 2).
Note that our estimation of the $\overline{B}_s \to D^0\pi^0$ rate is similar to a recent one \cite{23}, while our predicted $\overline{B}_s \to D^0\eta, D^0\eta$ rates are smaller than theirs by a factor of 20. This is because, the CKM factor $V_{ud}$ instead of $V_{us}$ was used in \cite{23} for the $\overline{B}_s \to D^0\eta(0)$ amplitudes.

The extraction of $\gamma$ in $\overline{B}_s \to D^0h^0$ modes can be performed by employing the GLW method. It should be clear that other methods, such as ADS \cite{3} and DK Dalitz \cite{4, 5} can also be used. However, as $r_{B_s}$ is several times greater than $r_B$, the GLW method should be more favorable in reducing additional uncertainties. By the standard construction, we have

$$A(\overline{B}_s \to D^0h^0) = a,$$

$$A(\overline{B}_s \to D^0h^0) = be^{-i\gamma}e^{i\delta},$$

$$\sqrt{2}A(\overline{B}_s \to D_{CP\pm}h^0) = (a \pm be^{-i\gamma}e^{i\delta}),$$

$$\sqrt{2}A(B_s \to D_{CP\pm}h^0) = \mp(a \pm be^{i\gamma}e^{i\delta}),$$

where $D_{CP\pm}$ are defined as $(D^0 \pm \overline{D}^0)/\sqrt{2}$, $a, b$ are real numbers with suitable phase convention and $\delta$ is the strong phase difference. All four unknowns $\gamma, a, b, \delta$ can be obtained by measuring the four tagged $\overline{B}_s \to D_{CP\pm}h^0$ and $B_s \to D_{CP\pm}h^0$ decay rates. It is useful to define \cite{1}

$$A_\pm \equiv \frac{\Gamma(\overline{B}_s \to D_{CP\pm}h^0) - \Gamma(B_s \to D_{CP\pm}h^0)}{\Gamma(\overline{B}_s \to D_{CP\pm}h^0) + \Gamma(B_s \to D_{CP\pm}h^0)} = \frac{\pm 2r_{B_s} \sin \gamma \sin \delta}{1 + r_{B_s}^2 \pm 2r_{B_s} \cos \gamma \cos \delta},$$

$$R_\pm \equiv \frac{\Gamma(\overline{B}_s \to D_{CP\pm}h^0) + \Gamma(B_s \to D_{CP\pm}h^0)}{\Gamma(\overline{B}_s \to D^0h^0) + \Gamma(B_s \to D^0h^0)} = \frac{1 + r_{B_s}^2 \pm 2r_{B_s} \cos \gamma \cos \delta}{1 + r_{B_s}^2},$$

where $r_{B_s} \simeq R_b \simeq 0.4$. It should be noted that the measurement of the asymmetry $A_\pm$ requires tagging, while the measurement of $R_\pm$ is untagged. In \cite{24}, weak annihilation modes of $B_s \to D^\pm\pi^\mp$ having rate similar to $\mathcal{B}(B_s \to D^0\pi^0, \overline{D}^0\pi^0)$ were proposed for extracting $\gamma$. However, contrary to our case, time-dependent tagged rates are necessary \cite{24}.

As a result of the same topological amplitudes for $b \to u$ and $b \to c$ transitions, the strong phase difference $\delta$ is likely to be small. In this case, a large $r_{B_s}$ value does not necessary lead to a large $CP$-asymmetry $A_\pm$, but it is still very useful in producing the interference effects in the $D_{CP\pm}h^0$ rates. For illustration, using $\delta = 0$, $r_{B_s} = 0.4$ and $\gamma = 60^\circ$, we obtain \cite{24},

$$R_+ = 1.34, \quad R_- = 0.66.$$

\footnote{Note that an additional negative sign in the last equation is due to the $CP$ quantum number of $h^0$ and a $(-)^L$ factor, where $L$ is the orbital angular momentum.}
The measurements of $R_\pm$ provide $\gamma$ and $r_{B_s}$ values. The vanishing strong phase approximation is useful in extracting or constraining $\gamma$ using less data. It can be verified by measuring $A_\pm$, when more data is available. Since the $b \to u$ and $b \to c$ amplitudes are of similar size, the direct $CP$ asymmetry will be very sensitive to the strong phase difference. In fact, similar arguments also apply to $B^0 \to D^0 K^0, \bar{D}^0 K^0$ decays. The measurement of direct $CP$ violation in $B^0 \to D_{CP} K^0$ decays, will provide the information of the usefulness of the vanishing strong phase approximation.

It is interesting to give the $\delta = 0$ argument in the rescattering picture. For example, as in the $\bar{B}^0 \to D_s^+ K^-$ case, the $\bar{B}_s \to D_s^0 \pi^0 (\bar{D}^0 \pi^0)$ rate is mainly feed from the color-allowed $D_s^+ K^- (D^- K^+)$ one, through the rescattering $D_s^+ (\bar{c}s) K^- (\bar{s}u) \to D^0 (\bar{c}u) \pi^0 (u\bar{u}) [D_s^- (\bar{c}s) K^+ (\bar{s}u) \to \bar{D}^0 (\bar{c}u) \pi^0 (u\bar{u})]$ with the annihilation and creation of $s\bar{s}$ and $u\bar{u}$ quark pair in the initial and final states, respectively [18]. The tree-allowed $D_s^\pm K^\mp$ amplitudes do not have any strong phase difference, while the $D_s^+ (\bar{c}s) K^- (\bar{s}u) \to D^0 (\bar{c}u) \pi^0 (u\bar{u})$ and $D_s^- (\bar{c}s) K^+ (\bar{s}u) \to \bar{D}^0 (\bar{c}u) \pi^0 (u\bar{u})$ annihilation rescattering amplitudes are related by charge conjugation, which is respected by strong interactions. Consequently, the strong phase difference in $\bar{B}_s \to D^0 \pi^0$ and $\bar{D}^0 \pi^0$ amplitudes should be small. The above consideration also applies to other modes, including those with $C', C''$, as long as they are long distant dominated (as hinted by the $\bar{B}^0 \to D^0 h^0$ data). For the case of $D_{CP}V$, the amplitudes $C'$ and $C''$, $E'$ and $E''$ can be different in signs [25], but we do not expect a large strong phase difference.

In conclusion, we point out that the large enhancement in color-suppress decay rates observed in $\bar{B}$ decays suggest similar enhancement in the color-suppress $B_s$ decay rates. The GLW method in extracting $\gamma$ using $B_s \to D^0 \phi, \bar{D}^0 \phi$ is not limited to the color suppressed decay modes as previously believed. We also suggest several new theoretical clean modes in the extraction of $\gamma$ in $B_s$ decays. These modes are color-suppressed $B_s \to D^0 h^0, \bar{D}^0 h^0$ decays, with $h^0 = \pi^0, \eta, \eta', \rho^0, \omega$, in addition to the $h^0 = \phi$ case. They are free of penguin contributions. The extraction of $\gamma$ can be performed as in the $D_{CP} \phi$ case. These $D^0 h^0$ rates are of order $10^{-6} \sim 10^{-5}$. A combined analysis could be useful in reducing the statistical uncertainties in the $\gamma$ extraction. No information on the $B_s-\bar{B}_s$ mixing is required. While the mixing is sensitive to New Physics, the $\gamma$ extraction in this case is expected to be insensitive to NP and does not require a $\Delta m_{B_s}$ value as predicted by the standard model. It can be considered as a complementary to the $D_s^\pm K^\mp$ method. The $r_{B_s}$ value is expected to
be $R_b \approx 0.4$, while the strong phase difference between $b \to u$ and $b \to c$ amplitudes, both are of the same topological types, are likely to be small. In this case, the $CP$ asymmetries are suppressed and the untagged measurements will provide very useful information in the extraction of $\gamma$.

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