

On the measurement of the unitarity triangle angle γ from $B^0 \rightarrow DK^{*0}$ decays

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The decay $B^0 \rightarrow DK^{*0}$ is well known to provide excellent potential for a precise measurement of the unitarity triangle angle γ in future experiments. It is noted that the sensitivity can be significantly enhanced by studying the amplitudes relative to those of the flavor-specific decay $B^0 \rightarrow D_2^{*-} K^+$, which can be achieved by analyzing the $B^0 \rightarrow D\pi^- K^+$ Dalitz plot.

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Among the fundamental parameters of the standard model of particle physics, the angle $\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$ of the Unitarity Triangle formed from elements of the Cabibbo-Kobayashi-Maskawa quark mixing matrix [1,2] has a particular importance. It is the only CP violating parameter that can be measured using only tree-level decays, and thus it provides an essential benchmark in any effort to understand the baryon asymmetry of the Universe. The precise measurement of γ is one of the main objectives of planned future B physics experiments (see, for example, [3–5]).

A method to measure γ with negligible theoretical uncertainty was proposed by Gronau, London and Wyler (GLW) [6,7]. The original method uses $B \rightarrow DK$ decays, with the neutral D meson reconstructed in CP eigenstates. It was noted that the method can be extended to use D meson decays to any final state that is accessible to both D^0 and \bar{D}^0 , and a number of potentially useful modes, including doubly-Cabibbo-suppressed decays such as $K^+\pi^-$ [8,9], multibody decays such as $K_S^0\pi^+\pi^-$ [10,11] and others [12,13] have been proposed.

The method can similarly be extended to other B decays, such as $B \rightarrow D^*K$ or $B \rightarrow DK^*$. The use of neutral B decays was noted as being particularly interesting since the amplitudes involving D^0 and \bar{D}^0 states may be of comparable magnitude, as shown in Fig. 1, potentially leading to large direct CP violation [14]. The decay $B^0 \rightarrow DK^{*0}$ is particularly advantageous since the charge of the kaon in the $K^{*0} \rightarrow K^+\pi^-$ decay unambiguously tags the flavor of the decaying B meson, obviating the need for time-dependent analysis [15]. This appears to be one of the most promising channels for LHCb to make a precise measurement of γ [16,17]. However, the natural width of the K^* meson has, until now, been considered a hindrance to the method, which could be handled by the introduction of additional hadronic parameters [18–21].

In this paper it is noted that the natural width of the K^* meson can be used to enhance the potential sensitivity to the CP violating phase γ in the analysis of $B^0 \rightarrow DK^{*0}$ decays. By studying the $B^0 \rightarrow D\pi^- K^+$ Dalitz plots with the neutral D meson reconstructed in flavor-specific and CP eigenstate modes, the complex amplitudes of the DK^{*0} decays can each be determined relative to the flavor-

specific $D_2^{*-} K^+$ amplitude, illustrated in Fig. 2, allowing a direct extraction of γ from the difference in amplitudes, rather than from the rates. Alternative approaches to measure γ using $B \rightarrow D^{**}K$ decays [22] or using amplitude analyses of $B \rightarrow DK\pi$ decays have been suggested in the literature [23,24] (the time-dependent $B^0 \rightarrow D^+ K_S^0 \pi^\pm$ Dalitz plot analysis has recently been implemented [25]), however the particular benefit of the $B^0 \rightarrow D\pi^- K^+$ Dalitz plots has not been noted until now.

Experimentally, the decay $B^0 \rightarrow \bar{D}^0 K^{*0}$ has been studied by the B factories, with the world average of its branching fraction being $\mathcal{B}(B^0 \rightarrow \bar{D}^0 K^{*0}) = (4.2 \pm 0.6) \times 10^{-5}$ [26–28]. Initial studies of the $B^0 \rightarrow \bar{D}^0 \pi^- K^+$ Dalitz plot also indicate the sizeable presence of the $B^0 \rightarrow D_2^{*-} K^+$ decay [29]. Limits on the branching fraction of the $B^0 \rightarrow D^0 K^{*0}$ decay have been set [26–28], the most restrictive limit being $\mathcal{B}(B^0 \rightarrow D^0 K^{*0}) < 1.1 \times 10^{-5}$ at 90% confidence level. First attempts to obtain constraints on γ from $B^0 \rightarrow DK^{*0}$ decays have been made using neutral D meson decays to $K_S^0\pi^+\pi^-$ [30] and to suppressed final states such as $K^-\pi^+$.

To illustrate the method, consider first of all the Dalitz plot of the $B^0 \rightarrow \bar{D}^0 \pi^- K^+$ decay, in which the \bar{D}^0 is reconstructed in the $K^+\pi^-$ final state. Initially, this is treated as a flavor-specific decay (hence the flavor of the D meson is indicated—the notation D is used to indicate a

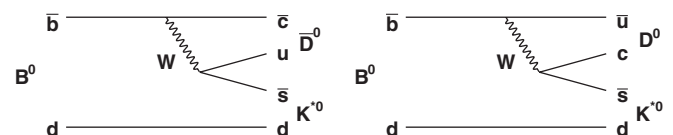


FIG. 1. Feynman diagrams for $B^0 \rightarrow DK^{*0}$, via (left) a $\bar{b} \rightarrow \bar{c}u\bar{s}$ transition and (right) a $\bar{b} \rightarrow \bar{c}u\bar{s}$ transition.

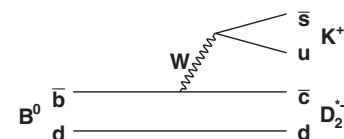


FIG. 2. Feynman diagram for the flavor-specific $B^0 \rightarrow D_2^{*-} K^+$ decay.

neutral charm meson that is some admixture of D^0 and \bar{D}^0 . The effect of the doubly-Cabibbo-suppressed $D^0 \rightarrow K^+ \pi^-$ amplitude will be considered later. Recall that the charge of the prompt kaon in the $\bar{D}^0 \pi^- K^+$ final state unambiguously identifies the flavor of the decaying B meson, so that it is not necessary to consider effects due to B^0 - \bar{B}^0 mixing [31].

The $B^0 \rightarrow \bar{D}^0 \pi^- K^+$ Dalitz plot will, of course, contain $\pi^- K^+$ resonances such as $K^{*0}(892)$, $K_0^{*0}(1430)$ and $K_2^{*0}(1430)$. One advantage of the Dalitz plot approach is that the hadronic parameters of each resonance can be determined, avoiding the complications that arise due to the use of effective hadronic parameters in the quasi-two-body DK^* analysis [18–21]. Furthermore, CP violation effects can be studied simultaneously in all of the contributing $\pi^- K^+$ resonances, enhancing the sensitivity to γ . However, more importantly, the Dalitz plot will also contain significant contributions from $\bar{D}^0 \pi^-$ resonances such as $D_0^{*-}(2400)$ and $D_2^{*-}(2460)$ (contributions from $D^{*-}(2010)K^+$ are not considered, since the $D^{*-}(2010)$ is too narrow to interfere with other resonances). The crucial point is that for such resonances the flavor of the D meson is unambiguously identified by the charge of the accompanying pion, independent of the D decay mode. Resonances of $\bar{D}^0 K^+$ are not possible (at least, not as simple quark-antiquark mesons), and the presence of any D_s^{*+} -type contributions to the Dalitz plot would indicate the presence of amplitudes involving the D^0 meson.

It is sufficient to consider a toy model of the Dalitz plot containing only $K^{*0}(892)$ and $D_2^{*-}(2460)$ resonances. The amplitude of the $\bar{D}^0 K^{*0}$ decay relative to that of the $D_2^{*-} K^+$ decay can be determined, as illustrated in Fig. 3 (left), where the relative phase between the two amplitudes is denoted by Δ . The complex amplitudes of any other contributions to the Dalitz plot can be and should be determined simultaneously, so as not to bias the extraction of the amplitudes of interest, but this does not affect the principle of the measurement. Since the neutral D meson is

flavor-specific, all contributions to the Dalitz plot are dominated by the $b \rightarrow c\bar{u}s$ tree-level transition, i.e., all have the same weak phase. Therefore, no direct CP violation is expected, and the same relation between amplitudes should be obtained for B^0 decays and for the conjugate \bar{B}^0 decays.

Consider now the amplitudes that will be determined when a similar analysis is applied to the $D\pi^- K^+$ Dalitz plot when the neutral D meson is reconstructed in CP -even eigenstates such as $D \rightarrow K^+ K^-$. (As mentioned later, CP -odd decays such as $D \rightarrow K_S^0 \pi^0$ can also be included in the analysis if they are experimentally accessible.) Since the $D_2^{*-} K^+$ amplitude is flavor-specific, the reference amplitude remains the same. In Fig. 3 (right) this amplitude is denoted as $\sqrt{2}A(D_{2CP}^{*-} K^+)$ where D_{2CP}^{*-} denotes that the neutral D meson produced in the decay of the D_2^{*-} is reconstructed in a CP -even eigenstate. Neglecting trivial phase factors, $|D_{CP}\rangle = \frac{1}{\sqrt{2}}(|D^0\rangle + |\bar{D}^0\rangle)$ so that the relation $\sqrt{2}A(D_{2CP}^{*-} K^+) = A(D_2^{*-} K^+)$ holds.

In the absence of contributions from $D^0 K^{*0}$ one would expect to find exactly the same amplitude for DK^{*0} relative to that for $D_2^{*-} K^+$ as found for flavor-specific D decays. The extracted relative amplitude therefore contains information about the ratio of the $B^0 \rightarrow D^0 K^{*0}$ and $B^0 \rightarrow \bar{D}^0 K^{*0}$ amplitudes, $r_B = |A(B^0 \rightarrow D^0 K^{*0})/A(B^0 \rightarrow \bar{D}^0 K^{*0})|$, their relative strong phase difference δ_B , and their relative weak phase difference γ . This is illustrated in Fig. 3 (right), for both B^0 and \bar{B}^0 decays, where the sign of the weak phase difference between the amplitudes is flipped.

It is clear that the triangle constructions shown in Fig. 3 (right) are exactly those regularly drawn to illustrate the GLW method [6,7], except rotated by a constant angle Δ . To reiterate the advantage of the approach outlined here, in the typical quasi-two-body DK^* analysis, one must reconstruct these triangles from measurements only of the lengths of the long sides and the base; in this approach,

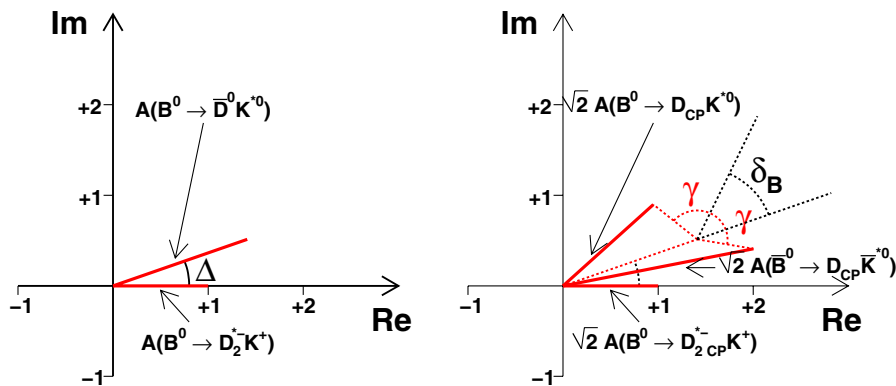


FIG. 3 (color online). Argand diagrams illustrating the measurements of relative amplitudes and phases from analysis of the Dalitz plots of (left) $\bar{D}^0 \pi^- K^+$ and (right) $D_{CP} \pi^- K^+$. In these illustrative examples the following values are used: $|A(B^0 \rightarrow \bar{D}^0 K^{*0})/A(B^0 \rightarrow D_2^{*-} K^+)| = 1.5$, $\Delta = \arg(A(B^0 \rightarrow \bar{D}^0 K^{*0})/A(B^0 \rightarrow D_2^{*-} K^+)) = 20^\circ$, $\gamma = 75^\circ$, $\delta_B = 45.0^\circ$ and $r_B = 0.4$. These are in line with expectation and current measurements, though Δ and δ_B are unconstrained at present.

one determines directly the positions of the apexes of the triangles. Thus this approach provides significant additional information to constrain γ , as well as resolving ambiguities in the strong phase difference. As a further elaboration of this point, note that the rate and asymmetry measurements in the usual GLW analysis can be translated into measurements of the parameters $x_{\pm} = r_B \cos(\delta_B \pm \gamma)$ conventionally used in studies of $B \rightarrow D^{(*)}K^{(*)}$ decays with subsequent multibody D decays such as $D \rightarrow K_S^0 \pi^+ \pi^-$ [32,33]. However, this is only possible if asymmetries and rates for both CP -even and CP -odd D decays have been measured, and furthermore no constraints on $y_{\pm} = r_B \sin(\delta_B \pm \gamma)$ are obtained (except indirectly from a constraint on $r_B^2 = x_{\pm}^2 + y_{\pm}^2$). With Dalitz plot analysis of the $D\pi^-K^+$ Dalitz plots, both problems are solved: from the relation

$$\begin{aligned} x_+ + iy_+ &= r_B e^{i(\delta_B + \gamma)} \\ &= \frac{(\sqrt{2}A(D_{CP}K^{*0})) / (\sqrt{2}A(D_{2CP}^*K^+))}{(A(\bar{D}^0K^{*0})) / (A(D_2^{*-}K^+))} - 1 \\ &= \frac{\sqrt{2}A(D_{CP}K^{*0})}{A(\bar{D}^0K^{*0})} - 1, \end{aligned} \quad (1)$$

both x_+ and y_+ can be obtained using only CP -even and flavor-specific D decays reconstructed in B^0 decays, with $x_- + iy_-$ similarly obtained from the conjugate \bar{B}^0 decays. In Eq. (1), the fact that both $D_{CP}K^{*0}$ and \bar{D}^0K^{*0} amplitudes must be determined relative to $D_2^{*-}K^+$ is made explicit. (If CP -odd D decays are also used, to add statistics and to provide a useful experimental cross-check, the right-hand side of the last two relations of Eq. (1) will be multiplied by a minus sign.) Note that all relevant normalization factors and subdecay branching fractions are automatically taken into account since the complex amplitudes $A(D_{CP}K^{*0})$ and $A(\bar{D}^0K^{*0})$ of Eq. (1) are both obtained relative to the flavor-specific $D_2^{*-}K^+$ amplitude. Therefore this approach, which does not require reconstruction of CP -odd D decay modes, appears highly promising for LHCb where reconstruction of states such as $K_S^0 \pi^0$ will be extremely challenging in the hadronic environment. Indeed, previous studies of the potential of LHCb to measure γ from $B^0 \rightarrow DK^{*0}$ decays [16,17] have shown a strong dependence of the sensitivity on the unknown value of the hadronic parameter δ_B . Since the origin of this dependence is related to the absence of information from CP -odd D decays, it is to be expected that it will be appreciably reduced using the Dalitz plot analysis suggested here.

The precise gain in sensitivity to γ compared to the quasi-two-body analysis is difficult to estimate, since it depends on how precisely the relative phase Δ can be measured. Dalitz plot analyses of $B^0 \rightarrow D\pi^-K^+$ have not yet been carried out, so there is no experimental information with which to assess this issue. However, a study of $B^0 \rightarrow \bar{D}^0 \pi^+ \pi^-$ shows that the relative phase between $D_2^{*-} \pi^+$ and $\bar{D}^0 \rho^0$ can be well measured [34].

This interference can also be exploited to obtain weak phase information, as recently noted [35]. Furthermore, studies of $K\pi$ resonances produced in B decays have revealed a rich structure (see, for example, [36,37]). These results provide confidence that the phase Δ can be accurately determined, and that the Dalitz plot $B^0 \rightarrow D\pi^-K^+$ analysis advocated in this paper promises a substantial improvement over the quasi-two-body $B^0 \rightarrow DK^{*0}$ approach. Moreover, the analysis advocated herein obtains γ with only a single unresolved ambiguity ($\gamma \rightarrow \gamma + \pi$, $\delta_B \rightarrow \delta_B + \pi$), whereas the quasi-two-body approach suffers an eight-fold ambiguity (note that other methods to reduce the ambiguities exist).

The discussion above has neglected the fact that neutral D decays to π^-K^+ are not completely flavor-specific, due to the existence of doubly-Cabibbo-suppressed $D^0 \rightarrow \pi^-K^+$ amplitudes. The ratio of this suppressed amplitude to its Cabibbo-favored counterpart has been precisely measured to be $r_D = |A(D^0 \rightarrow \pi^-K^+)/A(D^0 \rightarrow \pi^+K^-)| = (5.8 \pm 0.2)\%$ [38–41]; moreover the strong phase difference between these decay amplitudes has recently been determined by CLEOc to be $\delta_D = (22_{-12}^{+11+9})^\circ$ [42,43] (a more precise constraint is found from a global fit including measurements of charm mixing parameters [28]). When the $D \rightarrow \pi^-K^+$ decay mode is used there will therefore be a contribution from the $B^0 \rightarrow D^0K^{*0}$ amplitude with magnitude suppressed by $r_B \times r_D$ compared to that of $B^0 \rightarrow \bar{D}^0K^{*0}$; the strong phase and weak phase differences will be $\delta_B + \delta_D$ and γ , respectively (CP conservation in D decay is assumed). This could, if neglected, potentially bias the extracted value of γ . Any bias would be small, due to the factor of $r_B \times r_D$, but could nonetheless be significant in an era of precision measurements.

In the analysis where the suppressed D decay amplitudes are neglected, one has four observables (which can, for convenience, be taken to be (x_+, y_+, x_-, y_-) and three unknowns (r_B, δ_B, γ)). Introducing suppressed amplitudes adds two more parameters (r_D, δ_D) but also adds two new observables, since one can now measure CP violating differences between the $B^0 \rightarrow \bar{D}^0K^{*0}$ decay amplitude and its conjugate (both measured relative to the flavor-specific D_2^*K amplitudes). Furthermore, external constraints on these new parameters can be used in the analysis. Therefore, it is still possible to extract γ with a precision that should not be significantly worse than that when the suppressed amplitudes are neglected. (A more precise measurement of δ_D would, however, be useful.)

One may consider whether studying the $B^0 \rightarrow D\pi^-K^+$ Dalitz plot with the D meson reconstructed in the suppressed modes will add additional useful information. Although this appears promising, there will be a complication since the flavor-specific D_2^*K amplitude that has, until now, been used as a reference will no longer be one of the larger contributions to the Dalitz plot. There could, potentially, be D_s^{*+} -type resonances of DK^+ that could

provide an alternative flavor-specific reference, though these would be expected to be broader than one would wish for such a reference amplitude. If it were possible to use such a reference, its phase relative to $D_2^* K$ could be determined in the Dalitz plot where the D meson is reconstructed in CP eigenstates. Thus it might be possible to use information about the suppressed D decay modes, additional to that on the rates, to further improve the sensitivity to γ .

In passing, it is worthwhile to note that the method described above can easily be extended to $B^0 \rightarrow D^* \pi^- K^+$ decays, where the neutral D^* meson can be reconstructed in decays to either $D\pi^0$ or $D\gamma$ [44]. However, in this case there will be an additional complication due to the different helicity amplitudes that are possible in the $B^0 \rightarrow D^* K^{*0}$ decay [45]. The method can also be extended to use other D decays, including multi-body decays such as $D \rightarrow K_S^0 \pi^+ \pi^-$ [19] or others [13] or single-Cabibbo-suppressed decays such as $D \rightarrow K^{*\pm} K^\mp$ [12,46]. Another possible extension would be to use $DK^+(n\pi)^-$ final states [23].

Finally, it should be noted that the method discussed above does not, unfortunately, work well when applied to charged B decays. The K^{*+} produced in $B^+ \rightarrow DK^{*+}$ can decay to $K^+ \pi^0$ or $K^0 \pi^+$. In the former case, $D\pi^0$ resonances do not identify the flavor of the D meson. While D_s^{*+} -type resonances of DK^+ are possible, the amplitudes for $B^+ \rightarrow D_s^{*+} \pi^0$ decays are expected to be rather small (by extrapolation from published results on $B^+ \rightarrow D_s^+ \pi^0$, for example [47]). The $DK^+ \pi^0$ Dalitz plot can, however, benefit from a possible alleviation of the suppression of the $D^0 K^+ \pi^0$ amplitude [24]. In the case that the K^{*+} decays to

$K^0 \pi^+$, neutral DK^0 resonances are not possible (at least, not as simple quark-antiquark mesons), and amplitudes for $B^+ \rightarrow D^{*+} K^0$ are expected to be negligible (by extrapolation from limits on $B^+ \rightarrow D^{(*)+} K^0$ decays, for example [48]). Thus, there is no significant flavor-specific amplitude to provide the necessary reference point by which to obtain information about γ in the Dalitz plot analysis.

In summary, it has been shown that a potentially significant improvement in the measurement of γ can be achieved by measuring the complex amplitudes of $B^0 \rightarrow DK^{*0}$ decays relative to that of the flavor-specific decay $B^0 \rightarrow D_2^{*-} K^+$, which can be achieved by analyzing $B^0 \rightarrow D\pi^- K^+$ Dalitz plots. Compared to previously suggested techniques to measure γ from $B^0 \rightarrow DK^{*0}$ decays, this approach helps to resolve ambiguities, solves problems related to interferences between various resonances while avoiding the need for the introduction of effective hadronic parameters and provides a potentially significant overall improvement in the sensitivity while reducing its dependency on currently unknown parameters. This method can be used at LHCb and other future B physics experiments to make a precise measurement of this fundamental parameter of the standard model.

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