Ultimate sensitivity on $\gamma/\phi_3$ from $B \rightarrow DK$

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Measurement of the CKM phase $\gamma$ in $B \rightarrow DK$ decays can be potentially performed with high precision due to low theoretical uncertainties. However, the precision measurement requires very large experimental samples of $B$ decays. This report covers prospects for $\gamma$ measurement at the future $e^+e^-$ facilities and upgraded LHCb detector.

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1 Introduction

Measurement of the CKM phase $\gamma$ (also known as $\phi_3$) in $B \to DK$ decays can be potentially performed with high precision due to low theoretical uncertainties. Since no loop-level diagrams are involved, this measurement provides a Standard Model reference for other determinations of CKM parameters. However, the precision measurement requires very large samples of $B$ decays. Presented here are simple estimates of $\gamma$ sensitivity in the next-generation experiments.

Two projects of the future $e^+e^-$ facilities are now approved: SuperB project in Italy [1] and upgraded KEKB collider (SuperKEKB) with the Belle II detector in KEK laboratory in Tsukuba, Japan [2]. SuperB has design luminosity of $10^{36}$ cm$^{-2}$s$^{-1}$, and aims to accumulate 75 ab$^{-1}$ during its operation. SuperKEKB has similar design goals ($8 \times 10^{35}$ cm$^{-2}$s$^{-1}$ and 50 ab$^{-1}$, respectively). Both projects plan to start data taking around 2015 and continue until 2020.

LHCb experiment [3] is a facility that will make use of large $B$ production cross section in proton collisions at LHC to study $B$ decays. After the first phase of experiments in 2009–2016 when the sample of 6–7 fb$^{-1}$ will be accumulated, there are plans to upgrade LHCb to be able to run with the increased luminosity of $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$. The expected data sample to be collected by LHCb by 2020 is 50–100 fb$^{-1}$.

The following estimates assume luminosity integrals of 50 ab$^{-1}$ for $e^+e^-$ machines operated at $\Upsilon(4S)$ (we will refer to both projects as SuperB), and 50 fb$^{-1}$ for upgraded LHCb at the centre-of-mass energy of 14 TeV. These integrals roughly correspond to $50 \times 10^9$ produced $B\overline{B}$ pairs at the SuperB and $20 \times 10^{12}$ $B\overline{B}$ pairs at LHCb. Expected numbers of events in the benchmark modes for $\gamma$ measurement are shown in Table 1. The numbers have been obtained by rescaling the signal yields at B-factories and from MC simulation studies of LHCb [4]. First results from LHCb show that the yields are roughly consistent with the MC expectation.

| Mode | SuperB (50 ab$^{-1}$) | LHCb (50 fb$^{-1}$) |
|------|-----------------------|---------------------|
| $B \to D(K\pi)K$ allowed | 200K | 4M |
| $B \to D(K_S\pi\pi)K$ | 100K | 300K |
| $B_s \to D_s(KK\pi)K$ | - | 700K |

2 Methods involving $D \to hh$

At SuperB, conventional GLW method can be applied that involves decays of $D$ to $CP$-even ($h^+h^-$) and $CP$-odd ($K_S^0\pi^0$, $K_S^0\omega$) final states. Four observables are

$$R\pm = 1 + r_B^2 \pm 2r_B \cos \delta_B \cos \gamma, \quad A\pm = \pm 2r_B \sin \delta_B \sin \gamma/R\pm,$$

where $R\pm$ is the ratio of $CP$ to flavor-specific branching ratios, and $A\pm$ is the relative charge asymmetry. The observables are not independent: $R_+A_+ = -R_-A_-$, but
there is still enough information to extract the unknown parameters $\gamma$, amplitude ratio $r_B$ and strong phase $\delta_B$. In practise, the sensitivity of GLW method alone is poor and there is a 4-fold ambiguity: $(\gamma, \delta_B) \to (\pi - \gamma, \pi - \delta_B)$ and $(\gamma, \delta_B) \to (\delta_B, \gamma)$.

Adding ADS mode that involves doubly Cabibbo-suppressed decay $D^0 \to K^+\pi^-$ helps improve the statistical sensitivity and resolve ambiguities. The observables are

$$
R_{ADS} = r_B^2 + r_D^2 + 2r_Br_D \cos \delta \cos \gamma, \quad A_{ADS} = 2r_Br_D \sin \delta \sin \gamma / R_{ADS},
$$

where $\delta$ is a sum of $\delta_B$ and the phase difference $\delta_D$ between $\overline{D}^0$ and $D^0 \to K^-\pi^+$ amplitudes, and $r_D$ is the ratio of these amplitudes. The ambiguity $(\gamma, \delta_B) \to (\pi - \gamma, \pi - \delta_B)$, however, is not resolved without external constraints on $\delta_D$ value. This constraint also improves the statistical precision significantly. Measurement of $\delta_D$ has been performed by CLEO [4] ($\delta_D = (22^{+11}_{-12} - 11)^o$), but better accuracy is required for a precision $\gamma$ measurement. The use of other $D$ decay modes, such as $K\pi\pi\pi$ or $K\pi\pi^0$, gives additional constraints on $r_B$ which also improves $\gamma$ precision.

The application of methods involving two-body $D$ decays at LHCb is different, since $CP$-odd final states are not readily available. LHCb will therefore use a combination of GLW ($D \to KK, \pi\pi$) and ADS ($D \to K\pi$) modes to constrain the free parameters $\gamma, r_B, \delta_B$ [4]. The numbers of events in these modes are:

$$
N(B^\pm \to D(K^{\pm}\pi^\mp)K^\pm) = N_{K\pi}[1 + r_B^2 r_D^2 + 2r_Br_D \cos(\delta_B - \delta_D \pm \gamma)],
$$

$$
N(B^\pm \to D(K^{\pm}\pi^\mp)K^\pm) = N_{K\pi}[r_B^2 + r_D^2 + 2r_Br_D \cos(\delta_B + \delta_D \pm \gamma)],
$$

$$
N(B^\pm \to D(h^+h^-)K^\pm) = N_{hh}[1 + r_B^2 + 2r_Br_D \cos(\delta_B \pm \gamma)].
$$

If the ratio of normalisation factors $N_{K\pi}/N_{hh}$ is fixed (using the efficiency ratio obtained from MC or control samples), these equations provide enough constraints to obtain unknown parameters $r_B, \delta_{B,D}$ and $\gamma$.

Expected $\gamma$ sensitivity for $D \to hh$ modes is given in Table 2. The numbers are obtained for $\gamma = 70^o$, $r_B = 0.1$, $\delta_B = 130^o$, $\delta_D = 22^o$. Significant disadvantage of the method involving $D \to hh$ decays is in its precision being dependent on the values of the strong phases. The precision degrades significantly for the combinations of phases $\delta_B + \delta_D \pm \gamma$ close to 0 or $\pi$ — in these cases the number of events in ADS mode becomes insensitive to the values of phases, and one needs to use additional constraints (e. g. other $D$ decay modes, such as $K\pi\pi\pi$, to constrain $r_B$).

Additional modes with neutrals can be used at SuperB: $B^\pm \to D^\star(D\pi^0, D\gamma)K^\pm$, $B^\pm \to DK^{*\pm}$. Using these modes can double the $\gamma$ precision and provides a fallback solution for the “unlucky” phase combinations in $B^\pm \to DK^\pm$.
3 Dalitz plot analyses

The $\gamma$ measurement using the Dalitz plot analysis of $D \to K_S^0 hh$ decay provides the best constraint on $\gamma$ with $B$-factories data, but in the case of LHCb its contribution is suppressed by relatively low trigger efficiency for modes involving $K_S^0$ reconstruction. The observables in this method are Dalitz plot densities of $D$ decay from $B^\pm \to DK^\pm$:

$$p_\pm(m_{K_S^0\pi^+}^2, m_{K_S^0\pi^-}^2) = |A_D(m_{K_S^0\pi^+}^2, m_{K_S^0\pi^-}^2) + r_B e^{i(\delta_B \pm \gamma)} A_D(m_{K_S^0\pi^-}^2, m_{K_S^0\pi^+}^2)|^2.$$  \hspace{1cm} (4)

The advantage of this method is in its precision being only weakly dependent on the values of phases because of significant strong phase variation in the amplitude $A_D$.

The analyses performed so far use $D \to K_S^0 \pi^+ \pi^-$ and $D \to K_S^0 K^+ K^-$ amplitudes obtained from the flavor-tagged sample $D^{*\pm} \to D^0 \pi^\pm$ with model assumptions. The associated model uncertainty reaches a few degrees, and would dominate the future precision measurements. To avoid it, a modification of the Dalitz plot analysis method has been proposed, where all the information about the amplitude $A_D$ is obtained from the analysis of quantum-correlated $\psi(3770)$ decays. Using the binning inspired by the measured $D^0$ Dalitz plot, and $x_\pm + iy_\pm = r_B e^{i(\delta_B \pm \gamma)}$. Average cosine $c_i$ and sine $s_i$ of the strong phase difference between the bins $i$ and $-i$ can be obtained from the analysis of quantum-correlated $\psi(3770) \to D^0 \overline{D}^0$ decays. Using the binning inspired by the measured $D^0$ amplitude allows to reach the precision only 10 – 20% worse than in the unbinned approach [6].

Extrapolation of the sensitivity reached at the B-factories to the SuperB and LHCb data samples gives the statistical precision of 1–2°. This clearly means that the analysis should be done in a model-independent way. The precision of $c_i$, $s_i$ obtained by CLEO [7] with 800 pb$^{-1}$ translates to 2–3° error in $\gamma$. Therefore one needs a larger (of the order 10 fb$^{-1}$) sample of $e^+e^- \to \psi(3770)$ data that can be provided by e. g. BES-III experiment.

Although $D \to K_S \pi \pi$ presently dominates the sensitivity among the multibody modes, other three-body (and possibly four-body) $D^0$ final states can be used for $\gamma$ extraction using Dalitz plot analyses: $K_S^0 K^+ K^-$ ($c_i$, $s_i$ measurement by CLEO is available for this mode [7]) , $K_S^0 K \pi$, $\pi^+ \pi^- \pi^0$, $K^+ K^- \pi^+ \pi^-$, $K_S^0 \pi^+ \pi^- \pi^0$ etc.

4 Time-integrated $B^0$ analyses

Self-tagged decays of the neutral $B$ ($B^0 \to DK^{*0}$) can be used in the same way as the $B^\pm \to DK^\pm$ decays. The branching ratio of this mode is smaller by a factor 4–5,
but since both interfering amplitudes are colour-suppressed, larger CP violation with \( r_B \sim 0.3 \) is expected, thus giving the \( \gamma \) sensitivity similar to \( B^+ \to DK^+ \) mode. A complication in \( B^0 \to DK^{*0} \) analyses is in \( K^{*0} \) being a wide state. An interference with other states in \( B^0 \to DK\pi \) amplitude affects the results of the \( \gamma \) measurement. This effect can be corrected in a model-independent way by introducing an additional free parameter — coherence factor \( \kappa < 1 \) in the interference term.

This complication turns into advantage if one performs a simultaneous Dalitz plot analysis of \( B^0 \to DK\pi \) amplitudes with \( D \to K\pi \) and \( D \to hh \) final states [8]. The interference with the flavor-specific \( D_s^*K \) mode resolves discrete ambiguities and provides additional sensitivity compared to ADS- and GLW-like techniques. An attempt has been made to make this approach model-independent using the double Dalitz plot analysis \( B^0 \to D(K_0^S\pi^+\pi^-)K\pi \) [9]. Feasibility studies show the precision of \( \gamma \) measurement with upgraded LHCb around 1–1.5\(^\circ\), but this number has a large uncertainty since the amplitudes \( B^0 \to DK\pi \) are not well-measured yet.

5 Time-dependent analyses

In the time-dependent analyses, \( \gamma \) is obtained from the interference of \( B^0 \to D^{(s)-}\pi^+ \) and \( \overline{B}^0 \to D^{(s)-}\pi^+ \) amplitudes through \( B \) mixing. Although the \( CP \) violation in now well-established in this mode, precise determination of \( \gamma \) is difficult due to smallness of the amplitude containing \( V_{ub} \). In \( B_s \to D_s^+K^+ \) decays accessible at LHCb both interfering amplitudes are of the same order, which makes them competitive to the time-integrated \( B \to DK \) measurements [4]. Low cross section of \( B_s \) production in \( e^+e^- \) collisions does not allow SuperB to compete here.

Measurements of flavor-tagged \( B_s \to D_sK \) decay rate as a function of time are sensitive to \( \gamma + \phi_s \). The \( CP \)-violating phase \( \phi_s \) will be measured precisely in \( B_s \to J/\psi\phi \) analysis; no other external inputs are needed for \( \gamma \) measurement. MC studies give the sensitivity of 10\(^\circ\) with 2 fb\(^{-1}\) at LHCb, which scales to 1.5–2\(^\circ\) with upgraded LHCb data. It still needs to be understood, however, if there are systematic effects that can limit this precision.

6 Influence of charm mixing

Mixing in charm sector can affect the precision \( \gamma \) measurements that use neutral \( D \) mesons in the final state. The magnitude of the effect depends on how the charm data are used in \( \gamma \) measurement. All ADS and Dalitz \( B \to DK \) analyses performed so far ignore \( D \) mixing in both charm and \( B \) parameters. In that case, the mixing correction is of the second order in \( x_D, y_D \) and thus can be safely ignored even for one-degree \( \gamma \) precision [10]. Model-independent Dalitz plot analysis is however a special case: \( c_i \) and \( s_i \) parameters extracted from quantum-correlated \( \psi(3770) \to D^0\overline{D}^0 \) decays...
where neutral $D$ mesons are produced in $C = -1$ state appear to be unaffected by mixing \[11\]. Using these values in $B \to DK$ analysis results in linear mixing effects in $\gamma$ that are, however, additionally suppressed by $r_B$ and other small factors. The resulting $\gamma$ bias is estimated to be of the order $0.2^\circ$ and can be corrected once the $D$ mixing parameters will be measured.

7 Conclusion

Various independent methods allow measurements of CKM phase $\gamma$ with the precision of 1–3$^\circ$ at the future $e^+e^-$ and hadron facilities. While the upgraded LHCb sensitivity potentially looks more promising than that of SuperB, it can be affected by higher backgrounds and degenerate combinations of parameters. In addition, both facilities have their own auxiliary modes: $D^*$ states (SuperB), $B_s$ and $\Lambda^*_b$ decays (LHCb).

Having a large 10 fb$^{-1}$ sample of $\psi(3770) \to D\bar{D}$ decays is desirable for the model-independent extraction of hadronic parameters in $D$ decays. This can be achieved by taking a significant fraction of BES-III sample at open charm threshold, by building a high-luminosity charm-tau factory, or by running SuperB at low energy.

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