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Tree level γ determination at LHCb

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LHCb has been investigating several methods to measure precisely the CP-violating parameter γ. We review studies of B decays, which proceed via tree-level amplitudes, that will determine the value of γ with negligible theoretical uncertainty. From a combination of different techniques, both time-dependent and time-independent, a precision of 1.9-2.7° can be achieved with 10 fb^{-1} of data.

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1. Introduction

As of 2010, the CKM angle $\gamma \equiv arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}*}\right)$ remains the least-well measured angle of the unitarity triangle. The most recent combination of direct measurements from experiments at B-factories and the Tevatron, presented at this conference [1], gives $\gamma = (73^{+19}_{-24})^\circ$. The included measurements are from B decays, which proceed via tree-level amplitudes, with no pollution at loop level. Such measurements are largely unaffected by new physics contributions and can determine γ with negligible theoretical uncertainty.

Improving the direct measurement of γ is one of the main goals of LHCb. A precise tree-level determination will provide the Standard Model benchmark required to unravel subtle new physics effects in CP-violation searches and to disentangle different beyond-the-Standard-Model scenarios.

Here, we briefly present the studies for the first measurements which will be performed at LHCb. These include time-integrated measurements of direct CP-violation in decays of the $B \to DK$ family, where the D meson[1] is reconstructed in a mode accessible to both D^0 and $\bar{D}^0$, and time-dependent measurements of CP-violation in B_s^0 and $\bar{B}_s^0$ decays to $D_s^{\mp}K^{\pm}$. These studies are based on a realistc Monte Carlo (MC) simulation of the LHCb apparatus and a reconstruction software close to what will be used in the running experiment.

2. Common experimental aspects

These measurements are all based on the exclusive reconstruction of B hadronic decays and rely on the excellent tracking and particle identification (PID) performance of the vertex locator and ring-imaging Cherenkov detectors of the LHCb experiment [2]. The main event selection criteria reflect the basic signatures of the B-meson decays, such as the long lifetime of the B, and the high transverse momentum and large impact parameter of the decay products with regard to the primary vertex. In addition, PID criteria are extremely important to suppress the background and to distinguish the different D^0 decay channels of interest. An example of the impact of the PID in rejecting $B^+ \to D\pi^+$ events,[2] which are an important background to $B^+ \to DK^+$ for all D decays, is shown in Fig. 1 for $D \to K_S^0\pi^+\pi^-$.

3. Time-integrated measurements

Direct CP-violation measurements sensitive to γ are performed using the $B^- \to DK^-$ and the self-tagging $B^0 \to DK^{*0}$ modes (with $K^{*0} \to K^+\pi^-$). Fig. 2 shows the two tree-level diagrams for the charged B decay; the corresponding amplitudes interfere if D^0 and $\bar{D}^0$ decay to a common final state. The interference is sensitive to the weak-phase difference, γ, but also to the strong-phase difference, δ_B, to the ratio between the magnitude of the suppressed amplitude and the favoured amplitude, r_B, and to parameters of the specific D decay, which can be determined from data or taken from other measurements of the D decay. Comparison of the rates or kinematical distributions between B^+ and B^- decays allows these parameters to be determined from data, provided that a sufficient number of observables is included in the analysis.

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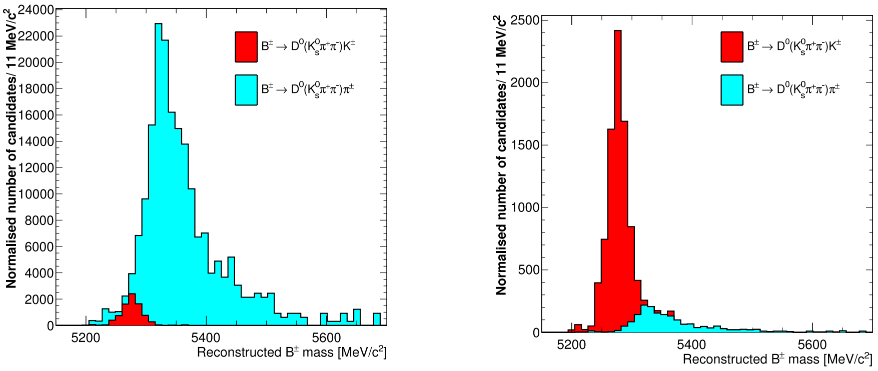
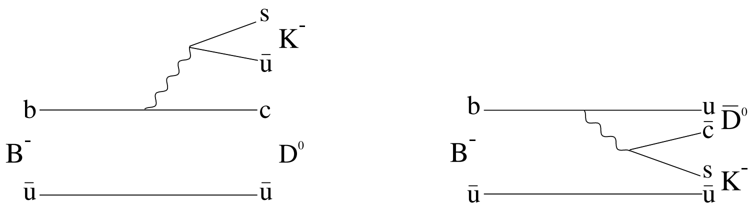
[1] Here and in the following, D indicates either a D^0 or a $\bar{D}^0$ decay.

[2] Charged-conjugation is implicit unless stated otherwise.



(a) (b)

Figure 1: Distributions of reconstructed B mass for $B^- \to DK^-$ and $B^- \to D\pi^-$ (a) without and (b) with PID criteria applied to the bachelor K^-. Event yields correspond to an integrated luminosity of 2 fb^{-1}.



(a) (b)

Figure 2: Feynman diagrams for (a) $B^- \to D^0K^-$ and (b) $B^- \to \bar{D}^0K^-$. The relative phase between the two amplitudes is $\delta_B - \gamma$, and the relative magnitude is r_B.

The sensitivity to γ critically depends on the size of the interference, hence on r_B. The value of r_B is naively expected to be $\frac{1}{3}|V_{ub}V_{cs}|/|V_{cb}V_{us}| \sim 0.1$, for charged B decays, where the factor $\frac{1}{3}$ is due to colour suppression. For $B^0 \to DK^{*0}$, the interfering diagrams are both colour-suppressed, therefore all branching fractions are small, but r_B is expected to be larger, about 0.3. The recent experimental measurements are in rough agreement with these expectations, but are still affected by large statistical uncertainties [3].

3.1 ADS/GLW studies

Full simulation studies indicate that LHCb can reconstruct $B^+ \to DK^+$, followed by D decay to charged kaons or pions, with high signal yields and an acceptable background level. The simplest final state topology is the one for two-body D decays to CP-even eigenstate, $\pi^+\pi^-$ or K^+K^-, used in the so-called GLW method [4], or $K^\pm\pi^\mp$, used in the ADS method [5]. The ADS technique involves measuring four separate $B \to D(K^\mp\pi^\pm)K$ rates, two suppressed (kaons of opposite charge in the final state) and two favoured (same-sign kaons). A χ^2 fit is performed to the four ADS rates and the two GLW rates to determine the five unknown parameters: γ, δ_B, r_B, the strong-phase difference between the doubly Cabibbo suppresses decay $D^0 \to K^+\pi^-$ and the Cabibbo favoured decay $D^0 \to K^-\pi^+$, δ_D, and the overall normalisation. A single normalisation parameter is required because those for the individual modes can be related together with knowledge of the D^0 branching fractions and the relative selection efficiencies. The inclusion of external constraints on δ_D has also been studied.

The event selection has been studied and optimised on large samples of simulated events of both signal and background [6].[3] The signal efficiency is found to be $(0.67 \pm 0.03)\%$ for $B^+ \to D(K^\pm\pi^\mp)K^+$, and is very similar for other D decay modes. The expected number of signal, S, and background events, B, are given in Table 1. The main background sources are from $B^+ \to D^{*0}X$ and $B^+ \to D^0(K^+\pi^+)\pi^+$ decays, where the first one is combinatorial and the second one is due to kaon/pion misidentification.

The sensitivity to γ has been determined with a toy MC study, which uses as input the above signal and background yields. This study shows that the extraction of all parameters via a fit to the six background-subtracted event yields is unbiassed. The statistical error on γ is found to be in the range 9.9-11.3° with a small dependence on δ_D, which is constrained in the fit to the CLEO-c measured value of $(-158^{+14}_{-16})^\circ$ [7].

B^+ decay	S	B
$D(K^+\pi^-)K^+$	$83,800 \pm 5800$	$50,900 \pm 3300$
$D(K^-\pi^+)K^+$	1600 ± 100	970 ± 480
$D(K^+K^-)K^+$	8400 ± 600	9760 ± 2750
$D(\pi^+\pi^-)K^+$	3000 ± 200	9520 ± 3950

Table 1: Signal and background yields expected in 2 fb^{-1} of data for the sum of B^+ and B^- decays. Signal yields are asymmetric and dependent on the parameters to be measured. Here, they are computed for $r_B = 0.1$, $\delta_B = 130^\circ$, $\gamma = 60^\circ$, $\delta_D = -158^\circ$, and $r_D = 0.0613$.

B^0 decay	S	B
$D(K^+\pi^-)K^{*0}$	3200 ± 500	780^{+1600}_{-500}
$D(K^-\pi^+)K^{*0}$	290 ± 50	2850^{+1500}_{-1400}
$D(K^+K^-)K^{*0}$	270 ± 40	<1650
$D(\pi^+\pi^-)K^{*0}$	100 ± 20	1600^{+1500}_{-950}

Table 2: Signal and background yields expected in 2 fb^{-1} of data for the sum of B^0 and $\bar{B}^0$ decays. Signal yields are computed for $r_B = 0.3$, $\gamma = 60^\circ$, $\delta_B = 0^\circ$, $\delta_D = -158^\circ$ and $r_D = 0.0613$. The upper bound is at 90% C.L.

The ADS/GLW analysis for $B \to D(hh')K^{*0}(K^+\pi^-)$ is similar in many aspects to that for charged B decays. The charge of the kaon from the K^{*0} decay tags the flavour of the initial B, hence there is no need for a time-dependent analysis and the full statistical power of a time-integrated analysis can be exploited. The expected number of signal and background events are given in Table 2. The signal efficiency is $(0.37 \pm 0.02)\%$, which is smaller than that of the charged B decays, due to the presence of an additional track in the final state and to the larger background level. There is, however, a large uncertainty on the background estimation due to the limited size of the MC sample and conservative assumptions have been used to compute the yields in Table 2. The corresponding uncertainty on γ is in the range 13-23°, for $r_B = 0.3$, with the variation arising from the dependence on the unknown strong-phase δ_B. More details on this measurement can be found in [8].

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[3] Here and in the following, a $b\bar{b}$ production cross-section of $500\mu b$ has been assumed. Given event yields take into account geometrical acceptance, the earliest level trigger decision, event reconstruction and selection efficiencies. The high-level trigger efficiency has not been accounted for, because performance studies have not been finalised yet for fully hadronic modes.

3.2 GGSZ Dalitz studies

The analysis of $B \to DK$ decays followed by the three-body $D \to K_S^0\pi^+\pi^-$ follows the so-called GGSZ method [9, 10], which currently gives the best constraint on γ at B-factories. The sensitivity to γ arises from differences between the $K_S^0\pi^+\pi^-$ Dalitz plot from $B^+ \to DK^+$ and $B^- \to DK^-$. Two methods are investigated [11]: a likelihood fit to the Dalitz distributions, which requires a model of the $D^0 \to K_S^0\pi^+\pi^-$ decay, and a binned method, which relies on external knowledge of the strong-phase difference between D^0 and $\bar{D}^0$ decays within those bins. The use of the model-dependent method leads to a significant systematic uncertainty, between 7° and 14°[12], due to the model assumptions, which will become the limiting error at LHCb. The binned, or model-independent, method relies on measurements of the strong-phase difference δ_D in bins of the $D \to K_S^0\pi^+\pi^-$ Dalitz plot, which have been performed at CLEO-c [13] using $\psi(3770)$ coherent decay to neutral D pairs. In this case, the uncertainty due to the experimentally-determined strong-phase parameters, which is estimated to be about 2°, replaces the large and hard-to-quantify model uncertainty.

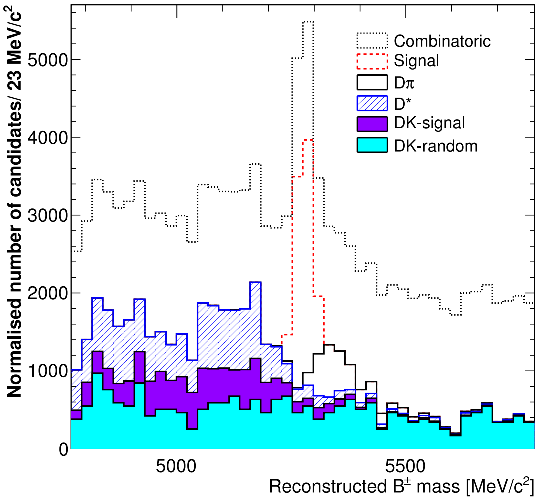

Figure 3: Expected B mass signal and background distributions for $B^- \to D(K_S^0\pi^+\pi^-)K^-$ candidates for an integrated luminosity corresponding to 2 fb^{-1}. Shown components are cumulative. For all background contributions, except for *DK-random*, the level is set to the 90% C.L. upper limit. *DK-random* denotes a background contribution where a correctly recontructed D is combined with a random kaon, i.e., a kaon which does not originate in the decay of the same B. Its estimated central value, shown in figure, could be determined from the simulation of large specific data samples.

The invariant mass distribution of the signal and the different background components are shown in Fig. 3. The specific LHCb challenge for this decay is the K_S^0 reconstruction. Due to their large boost, about $\frac{2}{3}$ of the selected K_S^0 candidates decay downstream of the vertex detector (but have hits in the downstream tracking stations). The reconstruction of these events is challenging, therefore, the overall signal efficiency is relatively small $(0.106 \pm 0.004)\%$. However, with an expected signal yield of 6,775±276 events, for 2 fb^{-1}, and a rather small background level, the achievable statistical error on γ is 9-11°, depending on the background composition, for the unbinned model-dependent fit, and about 13° for the binned model-independent fit. Due to the finite number of bins, the model-independent method leads to a decrease in the statistical precision compared to the unbinned model-dependent one. However, the former does not present any hard to quantify model-systematics, and gives a smaller total error for integrated luminosities greater than 2 fb^{-1}, including systematic uncertainties due to external inputs.

4. Time-dependent measurements with $B_s^0 \to D_s^{\mp} K^{\pm}$

Measurements of the time-dependent *CP* asymmetries in $B_s^0 \to D_s^{\mp} K^{\pm}$ allow $\gamma - \phi_M$ to be determined [14], where ϕ_M is the B_s^0 mixing phase. The determination of γ with these decays will therefore require an independent measurement of ϕ_M, which at LHCb can be precisely constrained with $B_s^0 \to J/\psi\phi$ decays [15]. The tree-level sensitivity to γ arises from the interference between the direct decay of B_s^0 and $\bar{B}_s^0$ to $D_s^{\mp} K^{\pm}$ and decay after mixing. The ratio of the magnitudes of the two interfering amplitudes is expected to be approximately 0.4, which is large enough to be determined from data.

This measurement is likely to be unique to LHCb. Several simulation studies have been performed [16]. The best sensitivity is achieved by including both tagged and untagged events, where the latter are sensitive to γ via the non-zero width difference, $\Delta\Gamma_s$, in the B_s^0 system. The signal yield for $B_s^0 \to D_s^{\mp}(K^{\pm}K^{\mp}\pi^{\pm})K^{\pm}$ is $(14.0 \pm 5.0) \times 10^3$ events in 2 fb^{-1} of data. The combinatoric background is estimated to be in the range (0.5-4.3)$\times 10^3$. There is also a significant background from $B_s^0 \to D_s^{\mp}\pi^{\mp}$, where the bachelor π is misidentified as a K, that accounts for $(2.0 \pm 0.2) \times 10^3$ events. The weak phase, $\gamma - \phi_M$ and the B_s^0 oscillation frequency, Δm_s, are extracted from a simoultaneous fit to the proper time distributions of $B_s^0 \to D_s^{\mp} K^{\pm}$ and $B_s^0 \to D_s^{\mp}\pi^{\pm}$. The error on $\gamma - \phi_M$ is expected to be about 10° for 2 fb^{-1} of data.

5. Global precision on γ

A combination of several LHCb measurements of γ has been performed to give an estimate of the achievable precision [17].[4] The optimal sensitivity is achieved via a global fit where γ and other parameters, which are common to several $B \to DK$ modes, are simultaneously extracted. The global fit includes the binned model-independent method for the $B^+ \to D(K_S^0\pi^+\pi^-)K^+$ analysis, the ADS/GLW measurements of $B^+ \to D(hh')K^+$ and $B^0 \to D(hh')K^{*0}$, and an additional ADS measurement of $B^+ \to D(K^{\pm}\pi^{\mp}\pi^+\pi^-)K^+$, described in ref. [18]. Its result is combined with the time-dependent measurements from $B_s^0 \to D_s^{\pm}K^{\mp}$, which has no other parameter in common apart from γ. The combined uncertainty on γ is found to be about 10° for 0.5 fb^{-1}, 5° for 2 fb^{-1}, and 1.9-2.7° for 10 fb^{-1} of data, with small dependence on the physics parameters involved. This error includes uncertainties on the external inputs, such as the measurements of the strong-phase difference between D^0 and $\bar{D}^0$ decays by CLEO-c [7, 13]. It is expected that experimental uncertainties, not yet included in the error, will be significantly smaller than the statistical ones. Systematic errors will be estimated on data using control channels.

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[4] The combination has not been completely updated to include the latest estimate of signal yields reported here, however, since the experimental performance is overall similar compared to previous studies, if not improved, it is expected that the sensitivity has not significantly changed.

6. Conclusions

LHCb has been investigating different techniques to measure the *CP* violating parameter γ at tree-level. Studies have shown that several measurements, which can be performed with first data, give a comparable sensitivity. From a combination of various time-dependent and time-independent measurements, a precision of 1.9-2.7° can be achieved with 10 fb^{-1} of data, corresponding to the expected total LHCb data set. This is around an order of magnitude improvement upon the current measurements. Many additional channels, that are sensitive to γ at tree-level and have not been accounted for in this estimation, can be exploited. These include: $B^+ \to D(K^+K^-\pi^+\pi^-)K^+$, $B^+ \to D(K_S^0K^+K^-)K^+$, $B^+ \to D(K^+\pi^-\pi^0)K^+$, $B_s^0 \to D\phi$, and other promising decays. These many additions will further enhance the LHCb sensitivity from large data sets.

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