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Time-dependent CP asymmetries in charm decays

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The CKM paradigm has been tested thoroughly over the last 40 years in both the neutral K and B systems. The recent discovery of neutral charm meson mixing has prompted the search for CP violation in D decays. We discuss the prospects of performing time-dependent CP asymmetry measurements at facilities either taking data or under construction. Such measurements can (i) provide precision determinations of the charm mixing phase, and (ii) be used to probe for possible new physics effects (and perhaps ultimately constrain the CKM paradigm). We propose the use of the time-dependent asymmetry measurement of $D^0 \to K^+K^-$ decays to measure the phase of charm mixing, where existing experiments that are either under construction or taking data should be able to reach a precision of $< 1.5^\circ$, and to use the phase difference between $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays to constrain the angle β_c of the cu unitarity triangle up to theoretical uncertainties from long distance and loop contributions. A large phase difference measured between these modes would indicate new physics.

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1. Introduction

The Standard Model (SM) description of CP violation is encoded in a single complex phase in a 3×3 quark mixing matrix, the so-called Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix [1, 2]. In these proceedings the CKM matrix is denoted by V_{CKM} and is given by

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}. \tag{1.1}$$

As V_{CKM} is unitary it can be described by three real parameters and a complex phase. There are a number of parameterisations used in the literature, and we use the Buras model for this work [3]. The level of CP violation described by V_{CKM} was originally based on results obtained through the study of the decays of kaons. Since 1999 the B factories BABAR and Belle have tested the CKM paradigm using B mesons by measuring the angles (α, β, and γ), and constraining the sides of one of the six unitary triangles obtained via $V^{\dagger}_{CKM}V_{CKM} = I$. Two of the three angles of this '*bd*' triangle are measured using time-dependent CP asymmetries, and closure of this triangle has been tested to the 10% level. The next generation of e^+e^- collider based experiments will reduce this to the 1% level. In Ref. [4] we noted that the CERN based experiment LHCb as well as the new so-called Super Flavour Factories Super*B* and Belle II will be able to start performing equivalent measurements in the charm system. One potentially significant difference between K, B and D decays is that the latter involves an up type quark, whereas CP violating decays of the former mesons involve transitions from down type quarks. Large contributions from new physics could still be possible in charm decays. The '*cu*' triangle is given by the unitary relation $V^*_{ud}V_{cd} + V^*_{us}V_{cs} + V^*_{ub}V_{cb} = 0$. The internal angles of this are given by $\alpha_c = \arg\left[-V^*_{ub}V_{cb}/V^*_{us}V_{cs}\right]$, $\beta_c = \arg\left[-V^*_{ud}V_{cd}/V^*_{us}V_{cs}\right]$, and $\gamma_c = \arg\left[-V^*_{ub}V_{cb}/V^*_{ud}V_{cd}\right]$. These angles can be defined in a model dependent way in terms of the Buras parameters[1] A, λ, $\overline{\rho}$ and $\overline{\eta}$. It has been noted that $\gamma_c \simeq \gamma$, and that β_c is small [5]. Based on existing results from Refs. [6, 7] we deduce $\beta_c \sim 0.035^\circ$.

Given a model for the CKM matrix it is possible to infer which modes are useful to analyse in the search for CP violation. In Ref. [4] we examined the short distance contributions from tree, loop (penguin), and W exchange topologies for 36 different CP eigenstate decays of D mesons. A time-dependent CP asymmetry analysis of charm decays into a CP eigenstate can be used to determine the magnitude and phase of the underlying decay. In general this is a combination of the mixing phase ϕ_{MIX} and the weak phase(s) in the final state. The distribution of weak phases in V_{CKM} is model dependent due to re-phasing invariance.

From such an analysis it is apparent that it is unlikely that one will be able to measure γ_c from $c \to u$ loop transitions mediated by a b quark, as these always occur in conjunction with more copious loop contributions from d and s quark loops. In B decays one gains access to the angle α as a result of the interference between the short distance dominated mixing amplitude with a tree topology which have phases β and γ, respectively. In charm decays however the mixing

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[1] In order to study CP violation in charm decays one must choose a model basis. The Wolfenstein [8] and Buras [3] parameterisations of the CKM matrix differ at $O(\lambda^5)$ and we choose the latter model as this is simpler to compute and the *bd* triangle is unitary to all orders in λ in this scheme.

contribution has a significant long distance contribution, and so it is unlikely that one will be able to precisely measure α_c directly. That leaves the small angle β_c as a possible future measurement. It is clear that the measurement of this angle will not be theoretically clean, however it may be possible to determine those uncertainties given the sufficient motivation. What is clear however is that if one can make a measurement of this angle and find a significant deviation from zero that this would be incompatible with expectations from the SM. As with the analogous scenario in B decays, searches for direct CP violation use integrals of events over time and give us only part of the picture of what is happening in the decay. In order to fully explore CP violation in charm decays one should perform a time-dependent analysis of D meson decays to a given final state.

2. Analysis

There are two experimental environments that one can use to perform time-dependent CP asymmetry studies in charm decays. These are correlated decays created in a coherent $J^P = 1^-$ state via the decay of a $\psi(3770)$ meson at threshold, and uncorrelated decays of D mesons produced in a $D^* \to D\pi_S$ decay, where π_S denotes that the pion from the D^* decay has low momentum and is often referred to as a slow-pion. The ingredients required in order to measure a time-dependent asymmetry are (i) a sample of D decays to a CP eigenstate (or admixture) in conjunction with ancillary information that can be used to infer the flavor of the D meson at some point in time (i.e. flavour tagging), and (ii) information about the time difference between the creation of the D meson involved in the CP decay and the decay of that meson. The time variable for events created in the decay $\psi(3770) \to D^0\overline{D}^0$ arises as the proper time difference Δt between the decay of the two D mesons. The reason for this is that when the $\psi(3770)$ decays the $D\overline{D}$ pair are created in a correlated EPR state. This state evolves such that there is always one D^0 and one $\overline{D}^0$ meson in an oscillating system until such time that one of the D's decays. When that happens the coherent wave function collapses and the remaining D oscillates with a mixing frequency $\Delta M = x\Gamma_D$, where $x \sim 0.5\%$. The time variable used for D mesons tagged with a slow pion from a D^* decay is the difference between the creation and decay times of the D, denoted by t. The charge of the slow pion indicates the flavour (D or $\overline{D}$) of the charm meson when created, and this subsequently oscillates until it decays into an interesting final state. Here we consider the asymmetry for D^* tagged mesons, however the formalism for correlated mesons is similar and can be found in Ref. [4].

The asymmetry between the rate of decay $\overline{\Gamma}$ of $\overline{D}$ mesons to that of D mesons (Γ) is given by

$$\mathscr{A}(t) = \frac{\overline{\Gamma}(t) - \Gamma(t)}{\overline{\Gamma}(t) + \Gamma(t)} = 2e^{\Delta\Gamma t/2}\frac{(|\lambda_f|^2 - 1)\cos\Delta M t + 2Im\lambda_f \sin\Delta M t}{(1+|\lambda_f|^2)(1+e^{\Delta\Gamma t}) + 2Re\lambda_f(1-e^{\Delta\Gamma t})},$$

where $\Delta\Gamma$ is the width difference between CP even and odd decays, and λ_f is related to the mixing parameters q and p and the ratio of amplitudes for the D ($\overline{D}$) decays into a common final state f.

The phase of λ_f is ϕ_{MIX} for $D \to K^+K^-$ decays, and $\phi_{MIX} - 2\beta_c$ for $D \to \pi^+\pi^-$ (neglecting penguin contributions). The difference between these two measured phases will give us a measure of $2\beta_c$ up to theoretical uncertainties arising from penguin and long distance contributions. This is something that can be tested at LHCb, Belle II and Super*B*. The context of these measurements is threefold (i) provide a precision measurement of ϕ_{MIX} to complement existing methods using $D \to K_S h^+ h^-$ decays, (ii) constrain the weak angle β_c via the phase difference in K^+K^- and $\pi^+\pi^-$

decays, and (iii) test for possible NP effects should the phase difference be large. There are a number of other time-dependent asymmetries that can be measured, where many are null tests like the $D \to K^+K^-$ mode, where one should measure only the mixing phase. Others include non-trivial weak phase differences that can be used to test the SM. The tables in Ref. [4] summarise the interesting structure of those final states.

From ensembles of simulated experiments based on the physical time-evolution of decays, along with reasonable estimates for event yields we estimate that Super$B$ will be able to make a measurement of ϕ_{MIX} with a precision of $\sim 1.3^\circ$, and of $\beta_{c,\mathrm{eff}} \sim 1.3^\circ$. This is obtained by combining results from a $500 fb^{-1}$ run at the $\psi(3770)$ and a $75 ab^{-1}$ run at the $\Upsilon(4S)$. In comparison LHCb would be able to measure the mixing phase and $\beta_{c,\mathrm{eff}}$ to $\sim 1.4^\circ$. The Belle II experiment should be able to obtain similar precision, $\sim 1.6^\circ$. More copious decays such as $D \to K_S\pi^0$ could also be used to measure the mixing phase, and would probably result in a more precise constraint than the other modes proposed here. However one should note that those decays would be challenging to study even in an e^+e^- environment as one would need to understand the experimental resolution on the D vertex using tracking information from the K_S which itself decays in flight. The fact that the B factories have been able to measure time-dependent asymmetries for $B \to K_S\pi^0$ indicates that Belle II and Super$B$ should be able to make the equivalent measurements of $D \to K_S\pi^0$ decays.

3. Summary

One should be able to extract a model dependent measurement of the charm mixing phase from a time-dependent analysis of $D \to K^+K^-$ decays with a precision comparable to that of the $D \to K_S h^+h^-$ approach at Super$B$ and Belle II (1.3° and $\sim 1.6^\circ$, respectively). LHCb should be able to reach a similar precision ($\sim 1.4^\circ$). It may be possible to obtain a more precise result using $D \to K_S\pi^0$ decays for the e^+e^- collider based experiments, however such measurements would require a good understanding of the experimental resolution on t or Δt. The measurement of the difference in phase obtained between $D \to K^+K^-$ and $D \to \pi^+\pi^-$ decays is related to the angle β_c, up to theoretical uncertainties. The large value of th $D \to \pi^0\pi^0$ branching fraction [9] suggests that this has to be studied in detail. Given that $\beta_c \sim 0$ in the SM a large non-zero phase difference measured would be a clear indication of NP.

References

[1] N. Cabibbo, Phys. Rev. Lett. **10** (1963) p531-533.

[2] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49** (1973) p652-657.

[3] A. Buras *et al.*, Phys. Rev. D**50** (1994) p3433-3446.

[4] A. Bevan *et al.*, arXiv:1106.5075 (submitted to Phys. Rev. D).

[5] I. Bigi and A. Sanda, hep-ph/9909479.

[6] M. Bona *et al.*, `http://www.utfit.org/`.

[7] A. Hocker *et al.*, Eur. Phys. J. C**12** (2001) p225-259.

[8] L. Wolfenstein, Phys. Rev. Lett. **51** (1983) p1945.

[9] J. P. Lees (*BaBar* Collaboration), arXiv:1110.6480.