EPJ manuscript No.
(will be inserted by the editor)

Results on CP Violation from CLEO

Victor Pavlunin[1] [a]

Department of Physics, Purdue University, West Lafayette, IN 47907, USA

Received: date / Revised version: date

Abstract. We report on recent searches for CP violation from the CLEO collaboration. Searches for CP asymmetries described in this contribution are performed in the Dalitz plot of $D^0 \to \pi^-\pi^+\pi^0$ decays [1], in the space of kinematic variables in the decay $\Lambda_c^+ \to \Lambda e^+\nu$ [2] and in the decay rates for charge conjugate states of $B^0 \to K^*(892)^+\pi^-$ [3]. The data sample used in these analyses was collected with the CLEO detector at the Cornell Electron Storage Ring (CESR), Ithaca, NY.

PACS. 13.25.Ft , 13.30.Ce, 13.25.Hw

1 Introduction

In the Standard Model (SM), the origin of CP violation resides in flavor changing quark transitions and is attributed to one complex number in the Cabibbo – Kobayashi – Maskawa (CKM) matrix of quark couplings. The single source of CP violation makes the SM very predictive and experimentally testable, as within the SM, *all* CP violating measurements are correlated to *one* complex number, the weak phase. The interpretation of the experimental results is, however, difficult, because the underlying weak processes are obscured by the hadronic physics, a part of which is soft QCD physics not amenable to perturbative calculations. Therefore, to determine the fundamental parameters in the CKM matrix precisely and to reveal new physics, it is imperative to study experimentally a wide range of processes. In this contribution, we review three analyses from the CLEO collaboration on searches for CP asymmetries in c and b quark decays.

The integrated luminosity used in the analyses consists of 13.8 fb^{-1} from e^+e^- annihilation provided by CESR, a symmetric e^+e^- collider operating in the energy range of the Υ resonances. Two thirds of the data sample were taken on the $\Upsilon(4S)$ resonance and one third at energies approximately 60 MeV below it to study non $B\overline{B}$ backgrounds in B meson decays. One third of the data sample was recorded with a configuration of the CLEO detector known as CLEO II and two thirds with a detector configuration known as CLEO II.V.

The CLEO II is a general multipurpose solenoidal detector designed to provide excellent charged and neutral particle reconstruction efficiency and resolution described in detail in [4]. CLEO II.V is an upgrade of CLEO II; the most significant difference between the two configurations is a three layer double-sided silicon vertex detector [5], which replaced an inner straw tube vertex detector. Common to the two configurations are an intermediate 10 layer hexagonal cell and an outer 51 layer square cell drift chambers both operating in a 1.5 T magnetic field, the time of flight system, the CsI crystal calorimeter and muon proportional chambers behind layers of iron, serving a dual purpose as a hadron absorber and a magnetic field flux return.

2 A Search for CP Asymmetries in the Dalitz Plot of $D^0 \to \pi^-\pi^+\pi^0$

Interference of different intermediate state resonances in the Dalitz plot of multi body charm meson decays makes their amplitudes and phases experimentally accessible. Dalitz plots are therefore a sensitive way to search for CP asymmetries and new particles. Expected contributions in $D^0 \to \pi^-\pi^+\pi^0$ are from resonant decays through ρ^0, ρ^+ and ρ^- and non-resonant decays. Two points make the Dalitz plot of $D^0 \to \pi^-\pi^+\pi^0$ especially interesting. Firstly, the CP asymmetry in this Dalitz plot is predicted to be as large as $\mathcal{O}(0.1\%)$ [6]. Secondly, the Dalitz plot of $D^0 \to \pi^-\pi^+\pi^0$ allows a search for a broad neutral scalar resonance, $\sigma(500)$, evidence for which was reported in [7].

The following decay sequence is reconstructed: $D^{*+} \to D^0\pi^+_{\rm slow}$, $D^0 \to \pi^-\pi^+\pi^0$, $\pi^0 \to \gamma\gamma$. The requirement that the D^0 must come from D^{*+} provides a constraint that is important for suppressing background and necessary for determining the flavor of the D-meson needed for measuring a CP asymmetry. Reconstruction of the D^{*+} utilizes the silicon vertex detector information, and therefore only the CLEO II.V data are used in this analysis. D^0 candidates are selected based on the candidate mass and the mass difference of the candidate and that of its parent, D^{*+}. The momentum of the D^{*+} is required to satisfy

[a] *Present address:* Laboratory for Elementary Particle Physics (Purdue Group), Cornell University, Ithaca, NY 14853, USA. email: victor@mail.lns.cornell.edu

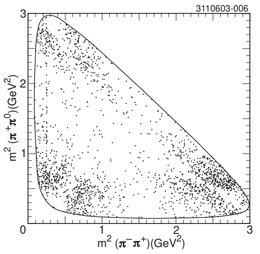

Fig. 1. The Dalitz plot of $D^0 \to \pi^-\pi^+\pi^0$ for events satisfying the selection criteria.

$p_{D^*}/p_{D^*}^{max} > 0.7$. Approximately 1,100 events pass the selection criteria, 20% of which are consistent with background. The Dalitz plot for the selected events is shown in Figure 1.

A fit is made to the Dalitz plot using a likelihood function of the form

$$\mathcal{L} = \{F\frac{\epsilon(m^2_{\pi^-\pi^+}, m^2_{\pi^+\pi^0})|\mathcal{M}_{D^0\to\pi^-\pi^+\pi^0}|^2}{N_{\text{signal}}} + \qquad (1)$$
$$(1-F)\frac{\mathcal{B}(m^2_{\pi^-\pi^+}, m^2_{\pi^+\pi^0})}{N_{\text{background}}}\},$$

where F is the fraction of signal events, ϵ and $\mathcal{B}$ are the reconstruction efficiency and the background level as functions of the event location in the Dalitz plot, N_{signal} and $N_{\text{background}}$ are the signal and background normalizations. The matrix element $\mathcal{M}_{D^0\to\pi^-\pi^+\pi^0}$ is a sum of matrix elements for each of the expected resonant and non-resonant decays, with each such matrix element contributing an amplitude and a phase to the list of free parameters in the fit. For the amplitudes, phases and fit fractions returned by the fit consult [1]. Here, we only have space to note that including the $\sigma(500)$ scalar did not result in a significant improvement to the likelihood and yielded a fit fraction consistent with zero. The CP asymmetry is integrated across the Dalitz plot in the following way:

$$\mathcal{A}_{CP} \sim \int \frac{|\mathcal{M}_{D^0}|^2 - |\mathcal{M}_{\bar{D}^0}|^2}{|\mathcal{M}_{D^0}|^2 + |\mathcal{M}_{\bar{D}^0}|^2} dm^2_{\pi^-\pi^+} dm^2_{\pi^+\pi^0}, \qquad (2)$$

and, once normalized to a unit area on the Dalitz plot, it is found to be $\mathcal{A}_{CP} = 0.01^{+0.09}_{-0.07}(\text{stat}) \pm 0.09(\text{sys})$. These results are preliminary. More information is available in [1].

3 Measurement of Form Factor and Search for CP Violation in the Decay $\Lambda_c^+ \to \Lambda e^+\nu$

The main goal of this analysis is to measure the form factors parameterizing the hadronic current in the decay $\Lambda_c^+ \to \Lambda e^+\nu$, as the predictions of Heavy Quark Effective Theory (HQET) for the Λ type baryons are especially simple. In HQET, the heavy flavor and spin symmetries reduce the number of form factors required to parameterize the hadronic current for the heavy to light Λ type baryon transitions to two, $f_1(q^2)$ and $f_2(q^2)$:

$$\langle\Lambda|J_\mu^{V+A}|\Lambda_c\rangle = \qquad (3)$$
$$\overline{u}(\Lambda)[f_1(q^2)\,\gamma_\mu(1-\gamma_5) + \not{v}_c\, f_2(q^2)\gamma_\mu(1-\gamma_5)]u(\Lambda_c^+),$$

where q^2 is the invariant mass squared of the virtual W^+. A dipole dependence of form factors on q^2 ($f(q^2) \sim 1/(1-q^2/m^2_{pole})^2$) is assumed according to [8], where the pole mass is taken to be $m_{D_s^*(1^-)} = 2.11$ GeV$/c^2$. A fit in a manner similar to [9] is performed simultaneously for the form factor ratio ($R = f_2/f_1$) and the pole mass (M_{pole}) in a four dimensional space of kinematic variables, defined in [8], describing a quasi two body decay: $\Lambda_c^+ \to \Lambda W^+$, where $\Lambda \to p^+\pi^-$ and $W^+ \to e^+\nu$.

The fit is made to a sample of 4060 events passing a set of tight selection criteria described in [2]; approximately 20% of the selected events are background. For each reconstructed event, the four kinematic variables need to be estimated because of the unknown momentum of the neutrino. An estimate is obtained using the kinematic constraints in the decay, the thrust vector of the event, which can be associated with the directions of the $c\bar{c}$ jets, and the fragmentation function of Λ_c. The values for the form

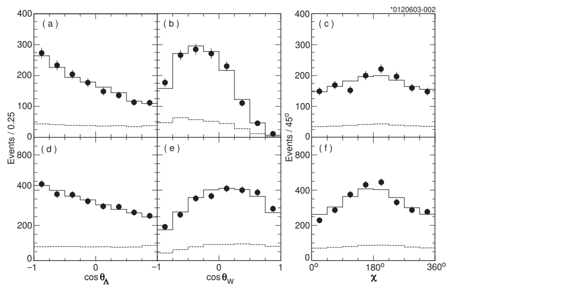

Fig. 2. Projections of kinematic variables and the fit in two bins of $t = q^2/q^2_{max}$. Plots (a), (b) and (c) are for $t < 0.5$, and plots (d), (e) and (f) are for $t > 0.5$. The dashed lines show the background contribution. The plotted kinematic variables are defined in [8].

factor ratio and the pole mass are found to be $-0.31 \pm 0.05(\text{stat}) \pm 0.04(\text{sys})$ and $(2.13 \pm 0.07(\text{stat}) \pm 0.10(\text{sys}))$ GeV$/c^2$, respectively. Figure 2 shows projections of the data and the fit.

If there are two or more contributions to the helicity amplitudes in the decay rate with differing CP-odd phases, there can exist, for example, a CP-violating asymmetry in the CP-odd interference terms in the decay rate, which would lead to CP asymmetries in the space of kinematic variables, even though the total decay rate may stay CP conserving. Such asymmetries are expected to be absent in the SM, and their observation should be attributed to new physics. Following [10] and by extension, a CP violating asymmetry of the Λ_c^+ is defined as $\mathcal{A}_{\Lambda_c} = (\alpha_{\Lambda_c} + \alpha_{\overline{\Lambda}_c})/(\alpha_{\Lambda_c} - \alpha_{\overline{\Lambda}_c})$, where α_{Λ_c} is the decay asymmetry parameter of $\Lambda_c^+ \to \Lambda e^+\nu$. Fitting charge conjugate states separately, we obtain $\mathcal{A}_{\Lambda_c} = 0.01 \pm 0.03(\text{stat}) \pm 0.01(\text{sys}) \pm 0.02_{\mathcal{A}_\Lambda}$, where correlations among the systematic uncertainties for the charge conjugate states are taken into account and the third error is from the uncertainty in $\mathcal{A}_\Lambda$, for $\Lambda \to p\pi^-$. These results are preliminary. For more information the reader is referred to [2].

4 Measurement of the Charge Asymmetry in $B \to K^*(892)^\pm\pi^\mp$

In the SU(3) symmetry limit, the amplitudes for the charge conjugate states of $B \to K^*(892)^\pm\pi^\mp$ can be written as $\mathcal{A}(B^0 \to K^*(892)^+\pi^-) = |P| - |T|e^{i(\gamma+\delta)}$ and $\bar{\mathcal{A}}(\bar{B}^0 \to K^*(892)^-\pi^+) = |P| - |T|e^{i(-\gamma+\delta)}$, where P and T stand for a penguin and a tree amplitudes. Measuring a CP averaged branching fraction and a CP asymmetry in the decay rate allows extraction of $\gamma = arg(-V_{ub}^* V_{ud}/V_{cb}^* V_{cd})$ and the strong phase, δ. CLEO has measured the CP averaged branching fraction of $B \to K^*(892)^\pm\pi^\mp$ in [11]. Measurement of a CP asymmetry in the decay rate of $B \to K^*(892)^\pm\pi^\mp$, defined as

$$\mathcal{A}_{CP} \equiv \frac{\mathcal{B}(\bar{B}^0 \to K^*(892)^-\pi^+) - \mathcal{B}(B^0 \to K^*(892)^+\pi^-)}{\mathcal{B}(\bar{B}^0 \to K^*(892)^-\pi^+) + \mathcal{B}(B^0 \to K^*(892)^+\pi^-)}, \quad (4)$$

described here, is an extension of that previous analysis.

The primary pion ($\pi^\mp$) produced as a result of a $B \to K^*(892)^\pm\pi^\mp$ decay is the fastest track in that decay 99.99% of the time; its sign is used to determine the flavor of the B meson. The $K^*(892)^\pm$ is reconstructed in two submodes $K^*(892)^+ \to K^0\pi^+$ and $K^*(892)^+ \to K^+\pi^0$. The signal yields are extracted from an unbinned maximum likelihood fit, as described below, applied to a sample of events satisfying loose selection requirements. In both topologies, charged daughters of $K^*(892)^+$ are identified as π^+ or K^+ by consistency with the expected dE/dx values. The momentum of π^0 must be greater than 1.0 GeV/c to reduce combinatorial background. B meson candidates are selected based on the difference between the total energy and the beam energy, and the beam constrained mass ($M_B \equiv \sqrt{E_{\rm beam}^2 - \boldsymbol{p}_B^2}$). The $b \to c$ background of $B \to D\pi$ with $D \to K\pi$ and $B \to \psi K^0$ with $\psi \to \mu^+\mu^-$ is vetoed by excluding regions of the Dalitz plot it populates. The continuum $e^+e^- \to q\bar{q}$ background is suppressed by a cut on the angle between the sphericity axis of the candidate and the rest of the event. Further suppression is achieved by exploiting a Fisher discriminant formed from variables describing the momentum distribution of event products over the solid angle in the detector.

The fit is made for two hypotheses for the fastest track, which is denoted as $h^\pm$ below, in a B candidate, for a pion and a kaon hypothesis. The likelihood function has the form

$$\mathcal{L} = \prod_{i=1}^{\rm candidates} \sum_{j=1}^{\rm components} [f_j(1 \pm \mathcal{A}_{+-}^j) \prod_{k=1}^{\rm variables} P_{ijk}] \quad (5)$$

where P_{ijk} are candidate PDF values, $\mathcal{A}_{+-}^j$ are the charge asymmetries, defined as $(N_{h^+}^j - N_{h^-}^j)/(N_{h^+}^j + N_{h^-}^j)$, and f_j are component fractions. The fit is made for f_j and A_{+-}^j, subject to the constraint to sum to the known number of $h^\pm$ tags. Variables used in the fit are M_B, E_B, the Fisher discriminant, $\cos\theta_B$, where θ_B is the angle a B flight direction in the lab forms with the beam line, dE/dx for the $h^\pm$ track in a B decay, and the Dalitz plot variables. Components used in the fit are the $K^{*\pm}(892)h^\mp$, the continuum background, the $B\bar{B}$ background, B decays through a variety of resonances other than $K^{*\pm}(892)$, as well as a non-resonant contribution. The two reconstructed final state topologies, $K^0\pi^+h^-$ and $K^+\pi^0h^-$, are fit simultaneously with the branching fractions and the CP asymmetries constrained to be equal for the components that are reconstructed in each topology.

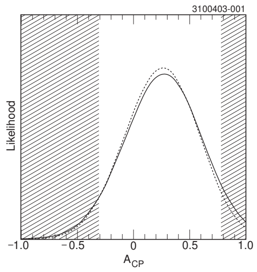

Fig. 3. The likelihood function for $\mathcal{A}_{CP}$ with (dashed) and without (solid) including systematic uncertainties. The dashed regions are excluded at 90% confidence level.

The combined statistical significance of the yield and the CP asymmetry for $B \to K^*(892)^\pm\pi^\mp$ are found to be 4.6σ and $\mathcal{A}_{CP} = 0.26^{+0.33}_{-0.34}({\rm stat})^{+0.10}_{-0.08}({\rm sys})$, respectively. The dominant contribution to the systematic uncertainties are associated with the PDF shapes and the fitting method. The latter result corresponds to $\mathcal{A}_{CP} \in [-0.31; 0.78]$ at 90% CL (Figure 3), which is consistent with theoretical predictions [12]. For more information consult [3].

5 Acknowledgments

The author thanks I.Shipsey, R.Galik, W.Sun and C.Plager for their help in preparing the conference presentation.

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