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Recent *CP* Violation Studies from *BABAR*

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In this proceeding, results of searches for *CP* violation in charm decays using the full *BABAR* dataset are discussed. The parameter A_{CP} in the decay $D^{\pm} \to K^0_S\pi^{\pm}$ is determined to be $(-0.39 \pm 0.13 \pm 0.10)\%$. Meaurements of *CP* violation using *T*-odd correlations in the four-body decays $D^+ \to K^+K^0_S\pi^+\pi^-$ and $D^+_s \to K^+K^0_S\pi^+\pi^-$ are $(-12.0 \pm 10.0_{(\mathrm{stat})} \pm 4.6_{(\mathrm{syst})}) \times 10^{-3}$ and $(-13.6 \pm 7.7_{(\mathrm{stat})} \pm 3.4_{(\mathrm{syst})}) \times 10^{-3}$, respectively.

1. Introduction

In the Standard Model (SM), *CP* violation (*CPV*) arises from the complex phase of the CKM quark-mixing matrix [1]. Measurements of the *CPV* asymmetries in the K and B meson systems are consistent with expectations based on the SM and, together with theoretical inputs, lead to the determination of the parameters of the CKM matrix. *CPV* has not yet been observed in the charm sector, where the theoretical predictions based on the SM for *CPV* asymmetries are at the level of 10^{-3} or below [2]. An observation of *CP* asymmetries at the level of one percent or greater would be a clear indication of new physics.

2. Search for *CP* Violation in the decay $D^+ \to K^0_S\pi^+$ [3]

BABAR searched for *CPV* in the decay $D^{\pm} \to K^0_S\pi^{\pm}$ by measuring the parameter A_{CP} defined as:

$$A_{CP} = \frac{\Gamma(D^+ \to K^0_S\pi^+) - \Gamma(D^- \to K^0_S\pi^-)}{\Gamma(D^+ \to K^0_S\pi^+) + \Gamma(D^- \to K^0_S\pi^-)}, \tag{1}$$

where Γ is the partial decay width for this decay. This decay mode has been chosen because of its clean experimental signature. Although direct *CP* violation due to interference between Cabibbo-allowed and doubly Cabibbo-suppressed amplitudes is predicted to be negligible within the SM [4], $K^0 - \overline{K}^0$ mixing induces a time-integrated *CP* violating asymmetry of $(-0.332 \pm 0.006)\,\%$ [8]. Contributions from non-SM processes may reduce the value of the measured A_{CP} or enhance it up to the level of one percent [4, 5]. Therefore, a significant deviation of the A_{CP} measurement from pure $K^0 - \overline{K}^0$ mixing effects would be evidence for the presence of new physics beyond the SM. Due to the smallness of the expected value, this measurement requires a large data sample and precise control of the systematic uncertainties. Previous measurements of A_{CP} have been reported by the CLEO-c ($(-0.6\pm1.0(\mathrm{stat})\pm0.3(\mathrm{syst}))\%$ [6]) and Belle collaborations ($(-0.71\pm0.19(\mathrm{stat})\pm0.20(\mathrm{syst}))\%$ [7]).

We select $D^{\pm} \to K^0_S\pi^{\pm}$ decays by combining a K^0_S candidate reconstructed in the decay mode $K^0_S \to \pi^+\pi^-$ with a charged pion candidate. A K^0_S candidate is reconstructed from two oppositely charged tracks with an invariant mass within $\pm$ 10 MeV/c^2 of the nominal K^0_S mass [8]. To obtain the final candidate events, a Boosted Decision Tree (BDT) algorithm [9] is constructed from seven discriminating variables for each $D^{\pm}$ candidate: the measured proper decay time $\tau(D^{\pm})$, the decay distance in the transverse plane $L_{xy}(D^{\pm})$, the CM momentum magnitude $p^*(D^{\pm})$, the momentum magnitudes and transverse components with respect to the beam axis for both the K^0_S and pion candidates.

A binned maximum likelihood (ML) fit to the $m(K^0_S\pi^{\pm})$ distribution for the retained $D^{\pm}$ candidates is used to extract the signal yield. The total probability distribution function (PDF) is the sum of signal and background components. The signal PDF is modeled as a sum of three Gaussian functions, the first two of them with common mean. The background PDF is taken as a sum of two components: a background from $D^{\pm}_s \to K^0_S K^{\pm}$, where the $K^{\pm}$ is misidentified as $\pi^{\pm}$, and a combinatorial background from other sources. The data and the fit are shown in Fig. 1. All of the fit parameters are extracted from the fit to the data sample apart from the normalization of the background due to $D^{\pm}_s \to K^0_S K^{\pm}$, which is fixed to the value predicted by the MC simulation. We determine A_{CP} by measuring the signal yield asymmetry A defined as:

$$A = \frac{N_{D^+} - N_{D^-}}{N_{D^+} + N_{D^-}}, \tag{2}$$

where $N_{D^+}(N_{D^-})$ is the number of fitted $D^+ \to K^0_S\pi^+(D^- \to K^0_S\pi^-)$ decays. The quantity A is the result of two other contributions in addition to A_{CP}. There is a physics component due to the forward-backward (FB)

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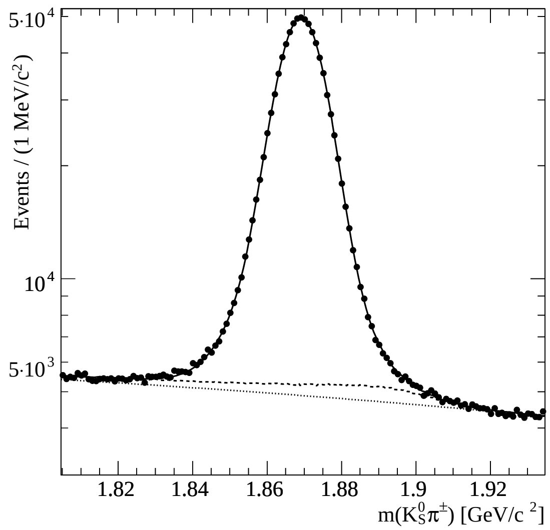

Figure 1: Invariant mass distribution for $K_S^0\pi^\pm$ candidates in the data (black points). The solid curve shows the fit to the data. The dashed line is the sum of all backgrounds, while the dotted line is combinatorial background only. The vertical scale of the plot is logarithmic.

asymmetry (A_{FB}) in $e^+e^- \to c\bar{c}$, arising from γ^*-Z^0 interference and high order QED processes in $e^+e^- \to c\bar{c}$. This asymmetry will create a difference in the number of reconstructed D^+ and D^- decays due to the FB detection asymmetries arising from the boost of the center-of-mass (CM) system relative to the laboratory frame. There is also a detector-induced component due to the difference in the reconstruction efficiencies of $D^+ \to K_s^0\pi^+$ and $D^- \to K_s^0\pi^-$ generated by differences in the track reconstruction and identification efficiencies for π^+ and π^-. While A_{FB} is measured together with A_{CP} using the selected dataset, we correct the dataset itself for the reconstruction and identification effects using control data sets. BABAR developed a data-driven method to determine the charge asymmetry in track reconstruction as a function of the magnitude of the track momentum and its polar angle which is shown along with the associated errors in Fig. 2.

Neglecting the second-order terms that contain the product of A_{CP} and A_{FB}, the resulting asymmetry can be expressed simply as the sum of the two. The parameter A_{CP} is independent of kinematic variables, while A_{FB} is an odd function of $\cos\theta_D^*$, where θ_D^* is the polar angle of the $D^\pm$ candidate momentum in the e^+e^- CM frame. If we compute $A(+|\cos\theta_D^*|)$ for the $D^\pm$ candidates in a positive $\cos\theta_D^*$ bin and $A(-|\cos\theta_D^*|)$ for the candidates in its negative counterpart, the contribution to the two asymmetries from A_{CP} is the same, while the contribution from A_{FB} has the same magnitude but opposite sign. Therefore A_{CP} and A_{FB} can be written as a function of $|\cos\theta_D^*|$ as follows:

$$A_{FB}(|\cos\theta_D^*|) = \frac{A(+|\cos\theta_D^*|) - A(-|\cos\theta_D^*|)}{2} \tag{3}$$

and

$$A_{CP}(|\cos\theta_D^*|) = \frac{A(+|\cos\theta_D^*|) + A(-|\cos\theta_D^*|)}{2}. \tag{4}$$

The selected sample is divided into ten subsamples corresponding to ten $\cos\theta_D^*$ bins of equal width and a simultaneous binned ML fit is performed on the invariant mass distributions of D^+ and D^- candidates for each subsample to extract the signal yield asymmetries. Using the asymmetry measurements in five positive and in five negative $\cos\theta_D^*$ bins, we obtain five A_{FB} and five A_{CP} values. As A_{CP} does not depend upon $\cos\theta_D^*$, we compute a central value of this parameter using a χ^2 minimization to a constant. The A_{CP} and A_{FB} values are shown in Fig. 3, together with the central value and $\pm 1\,\sigma$ confidence interval for A_{CP}. We determine A_{CP} to be:

$$A_{CP} = (-0.39 \pm 0.13 \pm 0.10)\% \tag{5}$$

where the first error is statistical and the second systematic.

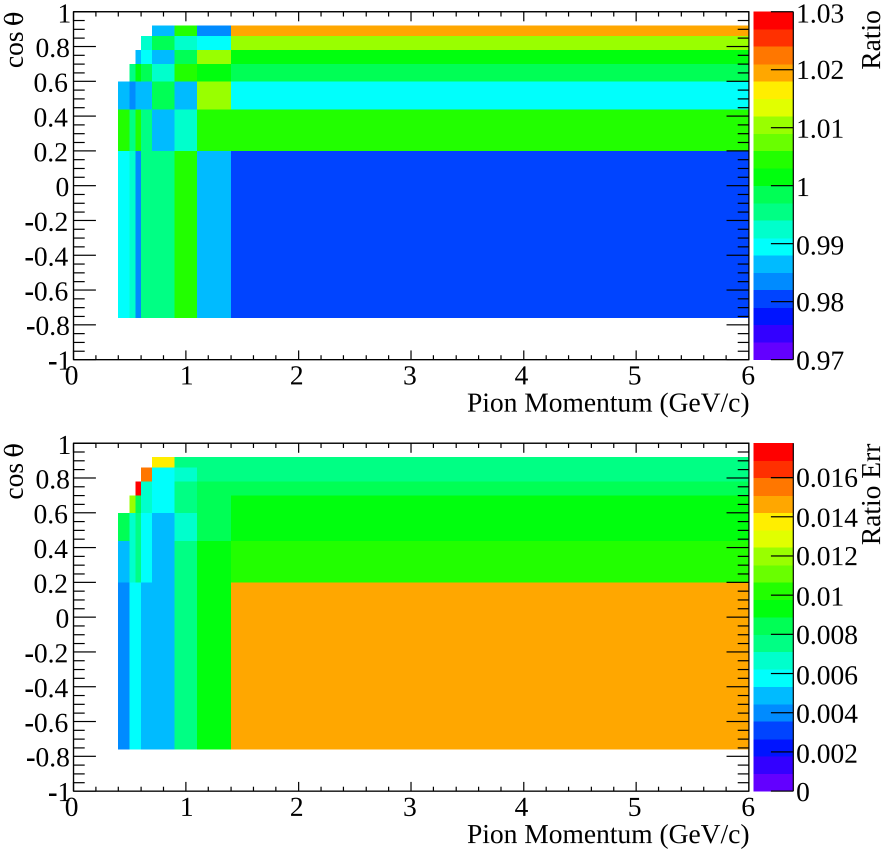

Figure 2: Map of the ratio between detection efficiency for π^+ and π^- (top) plus the corresponding statistical errors (bottom). The map is produced using the numbers of π^- and π^+ tracks in the selected control sample.

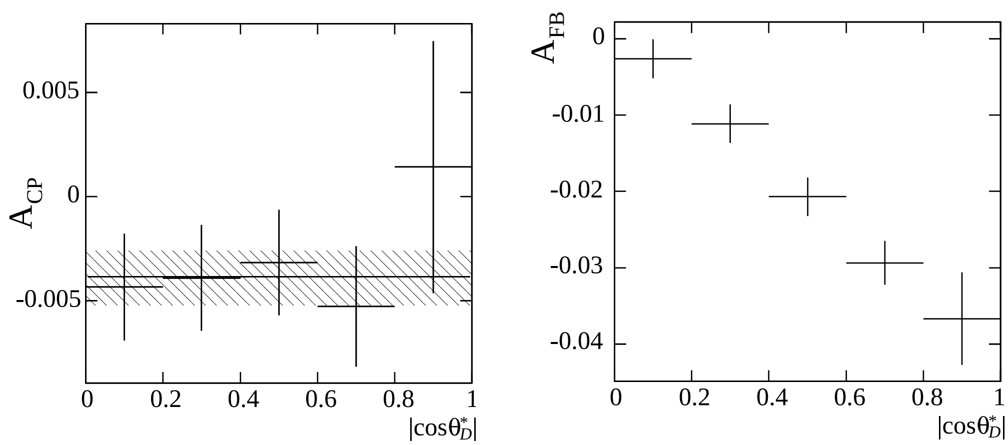

Figure 3: A_{CP} (top) and A_{FB} (bottom) asymmetries for $D^\pm \to K^0_S \pi^\pm$ candidates as a function of $|\cos\theta^*_D|$ in the data sample. The solid line represents the central value of A_{CP} and the hatched region is the $\pm 1\,\sigma$ interval, both obtained from a χ^2 minimization assuming no dependence on $|\cos\theta^*_D|$.

3. Search for CP Violation using T-Odd Correlations in $D^+_{(s)} \to K^0_S K^+ \pi^+ \pi^+$ [10]

A search for CP violation in the decays $D^+ \to K^+ K^0_S \pi^+ \pi^-$ and $D^+_s \to K^+ K^0_S \pi^+ \pi^-$ using T-odd correlations is described here. We define a kinematic triple product that is odd under time reversal using the vector momenta of the final state particles in the $D^+_{(s)}$ rest frame as

$$C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})\,. \tag{6}$$

Under the assumption of CPT invariance, T violation is equivalent to CP violation.

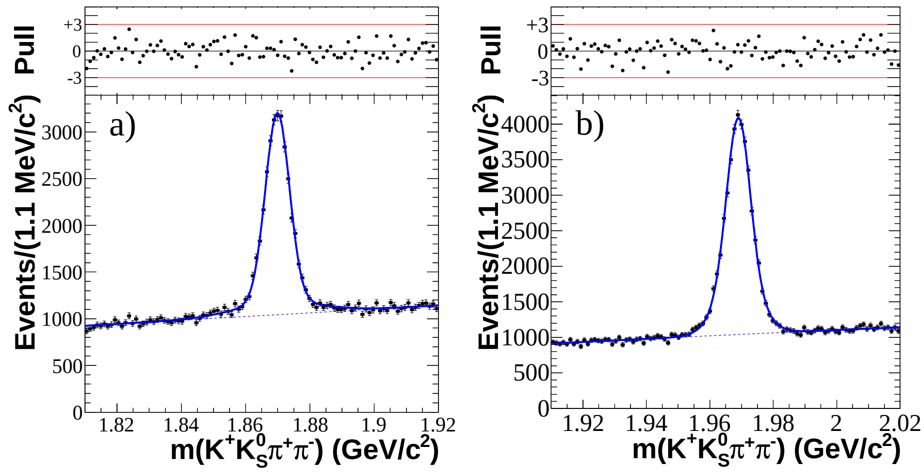

Figure 4: The $K^+K^0_S\pi^+\pi^-$ mass spectrum a) in the D^+, and b) in the D^+_s mass region. The curves result from the fits described in the text. The distributions of the Pull values are also shown.

We study the T-odd correlations by measuring the observable expressed in Eq. (6) and then evaluating the asymmetry

$$A_T \equiv \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}, \tag{7}$$

where Γ is the decay rate for the process under study. The observable defined in Eq. (7) can have a non-zero value due to final state interactions even if the weak phases are zero [11]. The T-odd asymmetry measured in the *CP*-conjugate decay process, $\bar{A}_T$, is defined as:

$$\bar{A}_T \equiv \frac{\Gamma(-\bar{C}_T > 0) - \Gamma(-\bar{C}_T < 0)}{\Gamma(-\bar{C}_T > 0) + \Gamma(-\bar{C}_T < 0)}, \tag{8}$$

where $\bar{C}_T \equiv \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})$. We can then construct:

$$\mathcal{A}_T \equiv \frac{1}{2}\left(A_T - \bar{A}_T\right), \tag{9}$$

which is an asymmetry that characterizes T violation in the weak decay process [12–14].

At least four different particles are required in the final state so that the triple product may be defined using momentum vectors only [15]. The D meson decays suitable for this analysis method are $D^+ \to K^+K^0_S\pi^+\pi^-$, $D^+_s \to K^+K^0_S\pi^+\pi^-$ and $D^0 \to K^+K^-\pi^+\pi^-$. The search for *CP* violation using T-odd correlations in $D^0 \to K^+K^-\pi^+\pi^-$ has recently been carried out by the *BABAR* Collaboration, and no evidence of *CP* violation has been observed [16].

The D^+ and D^+_s meson decay candidates are reconstructed in the production and decay sequence:

$$e^+e^- \to XD^+_{(s)}; D^+_{(s)} \to K^+K^0_S\pi^+\pi^-; K^0_S \to \pi^+\pi^-, \tag{10}$$

using the events with at least five charged particles. To obtain the final set of signal candidates, the p^*, the difference in vertex probabilities that the parent meson originates from a common vertex and the primary vertex, and the signed transverse decay length are combined in a likelihood-ratio test. Fig. 4 shows the resulting $K^+K^0_S\pi^+\pi^-$ mass spectra in the D^+ and D^+_s regions. For each region, the signal is described by the superposition of two Gaussian functions with a common mean value. The background is parametrized by a first-order polynomial in the D^+ region, and by a second-order polynomial in the D^+_s region. We extract the integrated yields $N(D^+) = 21210 \pm 392$ and $N(D^+_s) = 29791 \pm 337$ from the fits, where the uncertainties are statistical only.

We next divide the data sample into four sub-samples depending on $D_{(s)}$ charge and whether C_T ($\bar{C}_T$) is greater or less than zero, and fit the corresponding mass spectra simultaneously to extract the yields and the values of the asymmetry parameters A_T and $\bar{A}_T$. The triple product asymmetries for Cabibbo-suppressed decays

$D^0 \to K^+K^-\pi^+\pi^+$ [16], $D^+ \to K^+K^0_S\pi^+\pi^-$ and Cabibbo-favored decays $D^+_s \to K^+K^0_S\pi^+\pi^-$ are summarized in Tab. I. The average of the triple product asymmetries is also included in the table

$$\Sigma_T = \frac{1}{2}(A_T + \bar{A}_T) \tag{11}$$

which is not a CP violating parameter but may provide more information on the final-state interactions in these decays.

Table I: Triple-product asymmetries A_T, $\bar{A}_T$, $\mathcal{A}_T$, and Σ_T for the Cabibbo-suppressed decays $D^0 \to K^+K^-\pi^+\pi^-$ [16], $D^+ \to K^+K^0_S\pi^+\pi^-$ [10] and the Cabibbo-favored decays $D^+_s \to K^+K^0_S\pi^+\pi^-$ [10]. The values quoted in units 10^{-3}.

Asymmetry	$D^0/\overline{D}^0$	D^+/D^-	D^+_s/D^-_s
A_T	-68.5 ± 7.3 ± 5.8	11.2 ± 14.1 ± 5.7	-99.2 ± 10.7 ± 8.3
$\bar{A}_T$	-70.5 ± 7.3 ± 3.9	35.1 ± 14.3 ± 7.2	-72.1 ± 10.9 ± 10.7
$\mathcal{A}_T$	1.0 ± 5.1 ± 4.4	-12.0 ± 10.0 ± 4.6	-13.6 ± 7.7 ± 3.4
Σ_T	-69.5 ± 6.2	23.1 ± 11.0	85.6 ± 10.2

The final measurements for $\mathcal{A}_T$ in all decays are consistent with zero, however, the values for the T-odd asymmetries are considerably larger in D^0 and D^+_s decays. The differences in these values for the various decays may indicate a difference in the final-state interactions. The final-state interactions may be responsible for the hierarchy of lifetimes and branching fractions [17].

4. Conclusion

Measurements with the final *BABAR* dataset achieve the precision at the SM prediction for *CP* violation in charm decays. The systematic uncertainties are at the level of the statistical uncertainties. Current and future measurements from LHCb, Belle, and SuperB will face the challenge of reducing these systematic uncertainties.

References

1 N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).
2 F. Buccella *et al.*, Phys. Rev. D **51**, 3478 (1995).
3 P. del Amo Sanchex *et al.* [BABAR Collaboration], Phys. Rev. D 83 071103 (2011).
4 H. J. Lipkin and Z. Xing, Phys. Lett. B **450**, 405 (1999).
5 I. I. Bigi and H. Yamamoto, Phys. Lett. B **349**, 363 (1995).
6 S. Dobbs *et al.* (CLEO Collaboration), Phys. Rev. D **76**, 112001 (2007).
7 B. R. Ko *et al.* (Belle collaboration), Phys. Rev. Lett. **104**, 181602 (2010).
8 K. Nakamura *et al.* (Particle Data Group), J. Phys. G **37**, 075021 (2010).
9 P. Speckmayer, A. Hocker, J. Stelzer and H. Voss, J. Phys. Conf. Ser. **219**, 032057 (2010).
10 P. del Amo Sanchez *et al.* (*BABAR* Collaboration), hep-ex/1105.4410 (2011).
11 I. I. Bigi and H.-B. Li, Int. J. Mod. Phys. A **24S1**, 657 (2009).
12 W. Bensalem, A. Datta, D. London, Phys. Rev. D **66**, 094004 (2002).
13 W. Bensalem, A. Datta, D. London, Phys. Lett. B **538**, 309 (2002).
14 W. Bensalem and D. London, Phys. Rev. D **64**, 116003 (2001).
15 E. Golowich and G. Valencia, Phys. Rev. D **40**, 112 (1989).
16 P. del Amo Sanchez *et al.* (*BABAR* Collaboration), Phys. Rev. D **81**, 111103 (2010).
17 M. Gronau and J. Rosner, hep-ph/1107.1232v2 (2011).