

Search for Direct CP Violation in Quasi-Two-Body Charmless B Decays

The *BABAR* Collaboration

Abstract

We have searched for direct CP violation in quasi-two-body charmless B decays observed in a sample of about 45 million B mesons collected with the *BABAR* detector at the PEP-II collider. We measure the following charge asymmetries in decay: $\mathcal{A}_{CP}(B^\pm \rightarrow \eta' K^\pm) = -0.11 \pm 0.11 \pm 0.02$, $\mathcal{A}_{CP}(B^\pm \rightarrow \omega \pi^\pm) = -0.01_{-0.31}^{+0.29} \pm 0.03$, $\mathcal{A}_{CP}(B^\pm \rightarrow \phi K^\pm) = -0.05 \pm 0.20 \pm 0.03$, $\mathcal{A}_{CP}(B^\pm \rightarrow \phi K^{*\pm}) = -0.43_{-0.30}^{+0.36} \pm 0.06$, and $\mathcal{A}_{CP}(B^0/\bar{B}^0 \rightarrow \phi K^{*0}/\bar{K}^{*0}) = 0.00 \pm 0.27 \pm 0.03$.

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1 Introduction

The phenomenon of CP violation has played an important role in understanding fundamental physics since its initial discovery in the K meson system in 1964 [1]. Recently, a significant CP violating asymmetry has been observed in the B meson system [2]. Both effects may be accounted for by a non-zero phase in the mixing of two neutral mesons ($K^0 - \bar{K}^0$ or $B^0 - \bar{B}^0$). There is a different type of CP violation due to interference among decay amplitudes which differ in both weak and strong phases. This “direct” CP violation has been observed recently in kaon decays [3]. While CP violation effects are small in the kaon system they are anticipated to be larger in B decays [4]. Direct CP violation would be evident in an asymmetry of B decay rates:

$$\mathcal{A}_{CP} = \frac{\Gamma(\bar{B} \rightarrow \bar{f}) - \Gamma(B \rightarrow f)}{\Gamma(\bar{B} \rightarrow \bar{f}) + \Gamma(B \rightarrow f)}. \quad (1)$$

Rare B meson decays are particularly interesting in searches for direct CP violation because they have significant penguin amplitudes. In the Standard Model substantial CP violation in B decays could arise from interference of penguin (P) and tree (T) amplitudes [4]:

$$\mathcal{A}_{CP} = \frac{2 |P| |T| \sin \Delta\phi \sin \Delta\delta}{|P|^2 + |T|^2 + 2 |P| |T| \cos \Delta\phi \cos \Delta\delta}, \quad (2)$$

where $\Delta\phi$ and $\Delta\delta$ are the differences in weak and strong phases. The weak phase difference, $\Delta\phi$, between the $b \rightarrow u$ tree and $b \rightarrow s$ (or $b \rightarrow d$) penguin amplitudes is γ (or $\gamma + \beta$), as in the case of the decays $B^\pm \rightarrow \eta' K^\pm$ (or $B^\pm \rightarrow \omega \pi^\pm$). Thus, \mathcal{A}_{CP} is sensitive to the CKM angles γ and $\alpha = \pi - (\gamma + \beta)$, where $\gamma = \arg(V_{ub}^*)$ and $\beta = \arg(V_{td})$ in the usual phase convention [5, 6]. However, there is large uncertainty in the strong phases, which weakens any quantitative relationship to the weak phase angles.

Even more interesting is the scenario of direct CP violation in the pure penguin modes, such as $B \rightarrow \phi K^{(*)}$. In the Standard Model, the expected \mathcal{A}_{CP} is negligible. However, new particles in loops, such as charged Higgs or SUSY particles, would provide additional amplitudes with different phases. Depending on the model parameters, \mathcal{A}_{CP} may be as large as 30% with new physics [7]. Complementary searches for new physics would involve measurements of the time-dependent asymmetries in B decays to CP eigenstates, such as $\phi K_{S(L)}^0$ and $\eta' K_{S(L)}^0$. Comparison of the value of $\sin 2\beta$ obtained from these modes with that from charmonium modes can probe for new physics participating in penguin loops. In these measurements, direct CP violation in the decay becomes highly relevant.

A search for direct CP violation in B meson decays to πK , $\eta' K$, and $\omega \pi$ was performed previously by the CLEO experiment [8]. In this paper we improve the precision of the measurements and extend the search for direct CP violation to new modes with data from the BABAR experiment. We present measurements of the charge asymmetry in the quasi-two-body charmless B decays [9, 10]: $B^\pm \rightarrow \eta' K^\pm$, $B^\pm \rightarrow \omega \pi^\pm$, $B^\pm \rightarrow \phi K^\pm$, $B^\pm \rightarrow \phi K^{*\pm}$, and $B^0/\bar{B}^0 \rightarrow \phi K^{*0}/\bar{K}^{*0}$. We choose modes where the B flavor is tagged by its charge, except for the $\phi K^{*0}/\bar{K}^{*0}$ final state where the flavor is tagged by the charge of the kaon from the $K^{*0} \rightarrow K^+ \pi^-$ decay. A measurement from BABAR of the πK charge asymmetry may be found elsewhere [11].

2 Detector and Data

The data were collected with the BABAR detector [12] at the PEP-II asymmetric e^+e^- collider [13] located at the Stanford Linear Accelerator Center. The results presented in this paper are based on

data taken in the 1999–2000 run. An integrated luminosity of 20.7 fb^{-1} was recorded corresponding to 22.7 million $B\bar{B}$ pairs at the $\Upsilon(4S)$ resonance (“on-resonance”) and 2.6 fb^{-1} about 40 MeV below this energy (“off-resonance”).

The asymmetric beam configuration in the laboratory frame provides a boost to the $\Upsilon(4S)$ increasing the momentum range of the B -meson decay products up to $4.3 \text{ GeV}/c$. Charged particles are detected and their momenta are measured by a combination of a silicon vertex tracker (SVT) consisting of five double-sided layers and a 40-layer central drift chamber (DCH), both operating in a 1.5 T solenoidal magnetic field. With the SVT, a position resolution of about $40 \text{ }\mu\text{m}$ is achieved for the highest momentum charged particles near the interaction point, allowing the precise determination of decay vertices. The tracking system covers 92% of the solid angle in the center-of-mass system (CM). The track finding efficiency is, on average, $(98\pm 1)\%$ for momenta above $0.2 \text{ GeV}/c$ and polar angle greater than 0.5 rad . Photons are detected by a CsI electromagnetic calorimeter (EMC), which provides excellent angular and energy resolution with high efficiency for energies above 20 MeV [12].

Charged particle identification is provided by the average energy loss (dE/dx) in the tracking devices and by a unique, internally reflecting ring imaging Cherenkov detector (DIRC) covering the central region. A Cherenkov angle K – π separation of better than 4σ is achieved for tracks below $3 \text{ GeV}/c$ momentum, decreasing to 2.5σ at the highest momenta in our final states. Electrons are identified with the use of the tracking system and the EMC.

3 Event Selection

All the selection requirements are identical to those used in the branching fraction measurements [9, 10]. Hadronic events are selected based on track multiplicity and event topology. We fully reconstruct B meson candidates from their charged and neutral decay products, where we recover the intermediate states $\eta' \rightarrow \eta\pi^+\pi^-$ ($\eta'_{\eta\pi\pi}$) or $\rho^0\gamma$ ($\eta'_{\rho\gamma}$), $\omega \rightarrow \pi^+\pi^-\pi^0$, $\phi \rightarrow K^+K^-$, $K^{*+} \rightarrow K^0\pi^+$ ($K_{K^0}^{*+}$) or $K^+\pi^0$ ($K_{K^+}^{*+}$), $K^{*0} \rightarrow K^+\pi^-$, $\rho^0 \rightarrow \pi^+\pi^-$, $\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$, and $K^0 \rightarrow K_S^0 \rightarrow \pi^+\pi^-$. Candidate charged tracks are required to originate from the interaction point, and to have at least 12 DCH hits and a minimum transverse momentum of $0.1 \text{ GeV}/c$. Looser criteria are applied to tracks forming K_S^0 candidates to allow for displaced decay vertices. Kaon tracks are distinguished from pion and proton tracks via a likelihood ratio that includes, for momenta below $0.7 \text{ GeV}/c$, dE/dx information from the SVT and DCH, and, for higher momenta, the Cherenkov angle and number of photons as measured by the DIRC.

We combine pairs of tracks with opposite charge from a common vertex to form K_S^0 , ϕ , K^{*0} , and ρ^0 candidates. We further combine a pair of charged tracks with a π^0 or η candidate to select ω or $\eta'_{\eta\pi\pi}$ candidates. The selection of K_S^0 candidates is based on the invariant two-pion mass ($|M_{\pi\pi} - m_{K^0}| < 12 \text{ MeV}/c^2$), the angle α between the reconstructed flight and momentum directions ($\cos \alpha > 0.995$), and the measured lifetime significance ($\tau/\sigma_\tau > 3$).

We reconstruct π^0 (η) mesons as pairs of photons with a minimum energy deposition of 30 MeV (100 MeV). The typical width of the reconstructed π^0 mass is $7 \text{ MeV}/c^2$. A $\pm 15 \text{ MeV}/c^2$ interval is applied to select π^0 candidates. We combine a ρ^0 candidate with a photon of energy above 200 MeV to obtain an $\eta'_{\rho\gamma}$ candidate.

We select ϕ , ω , η' , and η candidates with the following requirements on the invariant masses of their final states (in MeV/c^2): $990 < m(K^+K^-) < 1050$, $735 < m(\pi^+\pi^-\pi^0) < 830$, $930 < m(\eta\pi^+\pi^-) < 990$, $900 < m(\rho\gamma) < 1000$, and $490 < m(\gamma\gamma) < 600$. The natural widths of the K^* and ρ dominate the resolution in the invariant mass spectrum. We require the invariant ρ mass to

be between $500 \text{ MeV}/c^2$ and $995 \text{ MeV}/c^2$. For K^* candidates the $K\pi$ invariant mass interval is either ± 100 or $150 \text{ MeV}/c^2$ [9].

The helicity angle θ_H of a ϕ , K^* , or ω is defined as the angle between the direction of one of the two daughters, or the normal to the ω decay plane, and the parent B direction in the resonance rest frame. To suppress combinatorial background we restrict the $K^{*+} \rightarrow K^+\pi^0$ helicity angle ($\cos\theta_H > -0.5$). This effectively requires the π^0 momentum to be above $0.35 \text{ GeV}/c$.

We identify B meson candidates kinematically using two nearly independent variables [12], the energy-substituted mass $m_{\text{ES}} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$ and $\Delta E = (E_i E_B - \mathbf{p}_i \cdot \mathbf{p}_B - s/2)/\sqrt{s}$, where \sqrt{s} is the total e^+e^- CM energy. The initial-state four-momentum (E_i, \mathbf{p}_i) derived from the beam kinematics and the four-momentum (E_B, \mathbf{p}_B) of the reconstructed B candidate are all defined in the laboratory. An alternative to m_{ES} is the energy constrained mass m_{EC} , which is obtained from the kinematic fit of the measured candidate four momentum in the $\Upsilon(4S)$ frame with the constraint of the B energy to the beam energy. Both m_{ES} and m_{EC} provide almost identical background separation, while m_{EC} is less correlated to ΔE than is m_{ES} . For signal events ΔE peaks at zero and m_{ES} and m_{EC} at the B mass.

Monte Carlo (MC) simulation [15] demonstrates that contamination from other B decays is negligible. However, charmless hadronic modes suffer from large backgrounds due to random combinations of tracks produced in the quark-antiquark ($q\bar{q}$) continuum. This background is distinguished by its jet structure as compared to the spherical decay of the Υ . To reject continuum background we make use of the angle θ_T between the thrust axes of the B candidate and the rest of the tracks and neutral clusters in the event, calculated in the center-of-mass frame. The distribution of $\cos\theta_T$ is sharply peaked near ± 1 for combinations drawn from jet-like $q\bar{q}$ pairs, and nearly uniform for the isotropic B meson decays. Thus we require $|\cos\theta_T| < 0.9$ (0.8 for ϕK^{*+}). We also construct a Fisher discriminant [14] which combines eleven variables: the angles of the B momentum vector and the B two-body decay axis with respect to the beam axis in the $\Upsilon(4S)$ frame, and a nine bin representation of the energy flow about the B decay axis.

4 Maximum Likelihood Fit

We use an extended unbinned maximum likelihood (ML) fit to extract signal yields and charge asymmetries simultaneously. The extended likelihood for a sample of N events is

$$\mathcal{L} = \exp\left(-\sum_{i=1}^M \sum_{k=1}^2 n_{ik}\right) \prod_{j=1}^N \left(\sum_{i=1}^M \sum_{k=1}^2 n_{ik} \mathcal{P}_{ik}(\vec{x}_j; \vec{\alpha})\right), \quad (3)$$

where $\mathcal{P}_{ik}(\vec{x}_j; \vec{\alpha})$ describes the probability for candidate event j to belong to category i and flavor state k , based on its measured variables \vec{x}_j , and fixed parameters $\vec{\alpha}$ that describe the expected distributions of these variables in each of the M categories. This probability is non-zero only for the right final state flavor ($k = 1$ for $\bar{B} \rightarrow \bar{f}$ and $k = 2$ for $B \rightarrow f$). In the simplest case, the probabilities are summed over two categories ($M = 2$), signal and background. The decays with the charged primary daughter h^\pm (K^\pm or π^\pm) are fit simultaneously with two signal and two corresponding background categories ($M = 4$). These are: $B^\pm \rightarrow \eta' h^\pm$, ωh^\pm , and ϕh^\pm . We rewrite the event yields n_{ik} in each category in terms of the asymmetry \mathcal{A}_i and the total event yield n_i : $n_{i1} = n_i \times (1 + \mathcal{A}_i)/2$ and $n_{i2} = n_i \times (1 - \mathcal{A}_i)/2$. The event yields n_i and asymmetries \mathcal{A}_i in each category are obtained by maximizing \mathcal{L} [16]. Statistical errors correspond to unit changes in the quantity $\chi^2 = -2 \ln \mathcal{L}$ around its minimum value. The significance of non-zero asymmetry is

defined by the square root of the change in χ^2 when constraining the asymmetry to zero in the likelihood fit. The 90% C.L. limits correspond to a change in χ^2 of 2.69. When more than one channel is measured for the same primary B decay, the channels are combined with χ^2 distributions.

The probability $\mathcal{P}_{ik}(\vec{x}_j; \vec{\alpha})$ for a given event j is the product of independent probability density functions (PDFs) in each of the fit input variables \vec{x}_j . These are ΔE , m_{ES} or m_{EC} , invariant masses of intermediate resonances (η' , ω , ϕ , K^* , and η), Fisher discriminant, and the ϕ and ω helicity angles for pseudoscalar-vector decays. For the simultaneous fit to the decays with the charged primary daughter h^\pm we include normalized residuals derived from the difference between measured and expected DIRC Cherenkov angles for the h^\pm . Additional separation between the two final states is provided by ΔE , where the separation depends on the momentum of the charged primary daughter in the laboratory and it is about 45 MeV on average.

The fixed parameters $\vec{\alpha}$ describing the PDFs are extracted from signal and background distributions from MC simulation, on-resonance ΔE - m_{ES} sidebands, and off-resonance data. The MC resolutions are adjusted by comparisons of data and simulation in abundant calibration channels with similar kinematics and topology, such as $B \rightarrow D\pi, D\rho$ with $D \rightarrow K\pi, K\pi\pi$. The simulation reproduces the event-shape variable distributions found in data. The Cherenkov angle residual parameterizations are determined from samples of $D^0 \rightarrow K^-\pi^+$ originating from D^* decays.

For the parameterization of the PDFs for ΔE , m_{ES} or m_{EC} , and resonance masses we employ Gaussian and Breit-Wigner functions to describe the signal distributions. For the background we use low-degree polynomials or, in the case of m_{ES} or m_{EC} , an empirical phase-space function [17]. The background parameterizations for resonance masses also include a resonant component to account for resonance production in the continuum. In the B decays into vector-vector states, the $\cos\theta_H$ distribution is the result of an *a priori* unknown superposition of transverse and longitudinal polarizations, and thus it is not used for background suppression in the fit. For pseudoscalar-vector B decay modes, angular momentum conservation results in a $\cos^2\theta_H$ distribution for signal. The background shape is again separated into contributions from combinatorics and from real mesons, both fit by nearly constant low-degree polynomials. The Cherenkov angle residual PDFs are Gaussian for both the pion and kaon distributions. The Fisher discriminant is described by an asymmetric Gaussian for both signal and background.

5 Results

The results of our ML fit analyses are summarized in Table 1. The signal yields along with branching fraction results have been reported earlier [9, 10]. In all cases we find significant signal event yields, and hence proceed with asymmetry measurements. The dependence of the χ^2 on \mathcal{A}_{CP} for each decay mode and sub-channel is shown in Fig. 1 and asymmetry measurements are summarized in Fig. 2. We see no significant asymmetries and set 90% C.L. intervals.

Most of the systematic error contributions relevant to branching fraction analyses cancel for the ratio in Eq. 1. Some level of charge asymmetry bias is inevitable as neither the *BABAR* detector nor PEP-II is perfectly charge symmetric. However these effects are mostly very small for the final states considered here. Charge biases in the detector and track reconstruction have been studied in a sample of more than a billion charged tracks in multi-hadron events. After proton and electron rejection we find an asymmetry consistent with zero with an uncertainty of less than 1% for a wide range of momenta. Taking into account particle identification requirements, this consistency is still better than 2%. The $D^{*\pm}$ control sample of kaon and pion tracks is used to estimate systematic uncertainties in the asymmetries arising from possible charge biases in the Cherenkov angle residual,

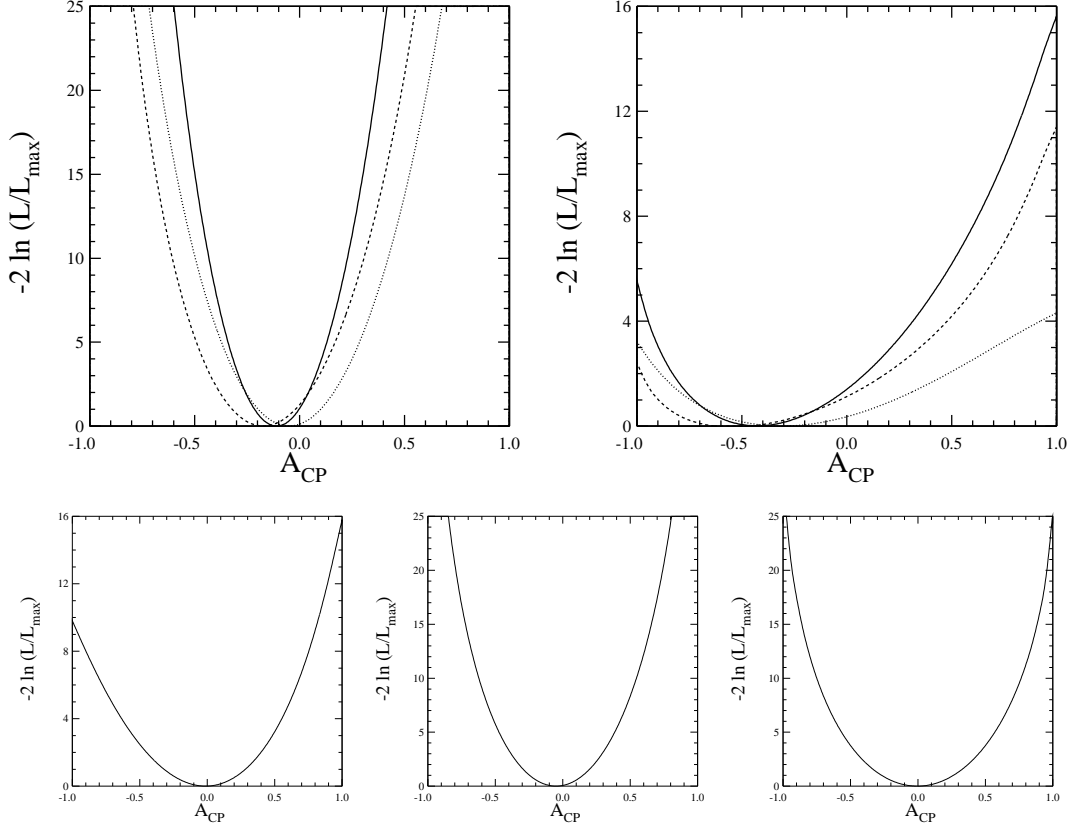


Figure 1: Distribution of χ^2 for the charge asymmetries \mathcal{A}_{CP} in the physically allowed range. Top plots: two secondary channels (dashed and dotted lines) are combined to produce a final result (solid line); left plot: $\eta' K^\pm$ with $\eta'_{\eta\pi\pi} K^\pm$ (dashed) and $\eta'_{\rho\gamma} K^\pm$ (dotted); right plot: $\phi K^{*\pm}$ with $\phi K_{K^0}^{*\pm}$ (dashed) and $\phi K_{K^+}^{*\pm}$ (dotted). Bottom plots, from left to right: $\omega\pi^\pm$, ϕK^\pm , and $\phi K^{*0}/\bar{K}^{*0}$.

Table 1: Results of the ML fits: number of signal events (n_{sig}), their charge asymmetry (\mathcal{A}_{CP}), asymmetry 90% C.L. limits and significance ($S_{\mathcal{A}}$). All results include systematic errors.

Mode	n_{sig}	\mathcal{A}_{CP}	90% C.L.	$S_{\mathcal{A}}$ (σ)
$\eta' K^{\pm}$	–	$-0.11 \pm 0.11 \pm 0.02$	$[-0.28; +0.07]$	1.0
$\eta'_{\eta\pi\pi} K^{\pm}$	$49.5^{+8.1}_{-7.3} \pm 1.5$	$-0.17 \pm 0.15 \pm 0.01$	–	1.1
$\eta'_{\rho\gamma} K^{\pm}$	$87.6^{+13.4}_{-12.5} \pm 3.7$	$-0.05 \pm 0.15 \pm 0.03$	–	0.3
$\omega\pi^{\pm}$	$27.6^{+8.8}_{-7.7} \pm 1.9$	$-0.01^{+0.29}_{-0.31} \pm 0.03$	$[-0.50; +0.46]$	0.0
ϕK^{\pm}	$31.4^{+6.7}_{-5.9} \pm 2.3$	$-0.05 \pm 0.20 \pm 0.03$	$[-0.37; +0.28]$	0.2
$\phi K^{*\pm}$	–	$-0.43^{+0.36}_{-0.30} \pm 0.06$	$[-0.88; +0.18]$	1.2
$\phi K_{K^0}^{*\pm}$	$4.4^{+2.7}_{-2.0} \pm 0.4$	$-0.55^{+0.51}_{-0.35} \pm 0.05$	–	1.1
$\phi K_{K^+}^{*\pm}$	$7.1^{+4.3}_{-3.4} \pm 1.2$	$-0.31^{+0.54}_{-0.43} \begin{smallmatrix} +0.10 \\ -0.06 \end{smallmatrix}$	–	0.6
ϕK^{*0}	$20.8^{+5.9}_{-5.1} \pm 1.3$	$0.00 \pm 0.27 \pm 0.03$	$[-0.43; +0.43]$	0.0

which are found to be less than 1%.

From these studies we assign a systematic uncertainty of 1% on \mathcal{A}_{CP} for all the modes with a charged primary daughter: $B^{\pm} \rightarrow \eta' h^{\pm}$, ωh^{\pm} , and ϕh^{\pm} . For the modes with a K^* we account for the broader momentum spectrum of the charged daughters and particle identification applied to the kaon candidates with a 2% systematic error. All measured background asymmetries and signal asymmetries in MC are consistent with zero within statistical uncertainties.

A different type of uncertainty originates in the ML fit from assumptions about the signal and background distributions. We vary the PDF parameters within their respective uncertainties, and derive the associated systematic errors in the event yield and its asymmetry. Corresponding systematic errors on asymmetry are found to be 2% for $\eta' K^{\pm}$ and ϕK^{*0} , 3% for $\omega\pi^{\pm}$ and ϕK^{\pm} , and 6% for $\phi K^{*\pm}$, the latter being dominated by the mode with a π^0 . These systematic errors are conservatively estimated and may be improved with higher statistics.

We combine the correlated (due to selection requirements) and uncorrelated (due to PDF variations) systematic errors, and convolute systematic errors into χ^2 distributions in order to obtain results with systematics. We also treat the correlated and uncorrelated systematic errors separately when we combine the sub-channels. The uncertainties in the final results presented in Table 1 are dominated by statistical errors.

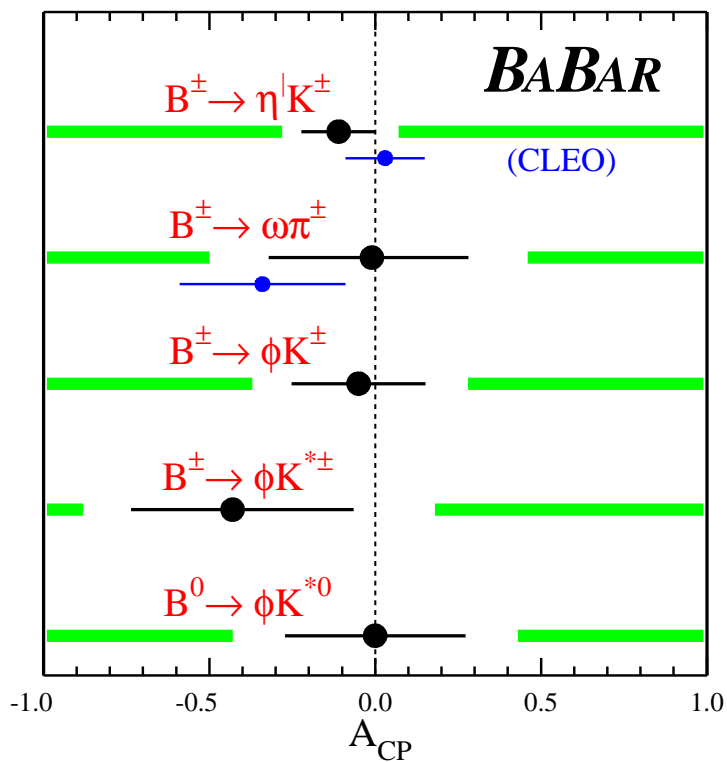


Figure 2: Results of the direct CP violation search in the B decays into final states $\eta'K^\pm$, $\omega\pi^\pm$, ϕK^\pm , $\phi K^{*\pm}$, and $\phi K^{*0}/\bar{K}^{*0}$. Points with error bars represent experimental measurements of \mathcal{A}_{CP} . Solid thick lines delimit the 90% C.L. intervals. For the modes $\eta'K^\pm$ and $\omega\pi^\pm$ smaller points with error bars show results of the CLEO experiment [8].

6 Conclusions

We have searched for direct CP violation in quasi-two-body charmless B decays observed in *BABAR* data. The measured charge asymmetries of the B decays into final states $\eta'K^\pm$, $\omega\pi^\pm$, ϕK^\pm , $\phi K^{*\pm}$, and $\phi K^{*0}/\bar{K}^{*0}$ are summarized in Table 1 and Fig. 2. The 90% C.L. limits rule out a significant part of the physical \mathcal{A}_{CP} region.

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