We report results from five analyses based on data taken with the \textit{BABAR} detector at the PEP-II asymmetric $e^+e^-$ collider. Included are branching fraction measurements for many $B$-meson decays involving $\eta$, $\eta'$, $\omega$, $\phi$ or $a_0$ mesons and the final state $K_S^0 \pi^+\pi^-$, and a full angular analysis of the decay $B^0 \to \phi K^{*0}$.

1 Introduction

Many interesting new results from \textit{BABAR} for charmless hadronic $B$ decays were presented previously at the Electroweak session of the XXXIXth Rencontres de Moriond. For new measurements of $\sin^2\beta$ from four final states ($\phi K^0$, $K^+K^-K^0_s$, $\pi^0 K^0_s$, $f_0 K^0$), see the writeup by Marc Verderi. Also a new preliminary result for the decay $B^0 \to \rho^+\rho^-$, with a measurement of the CKM angle $\alpha$ was presented in a talk by Lydia Roos. Finally a measurement of the time-dependent asymmetry of the decay $B^0 \to \pi^0 K^0_s$ was shown by Eugenio Paoloni. With adequate data, the latter mode can provide interesting constraints on new physics.

In this paper I will report on five other new analyses of charmless hadronic $B$ decays. The first involves $B$ decays to $\eta(\prime)K^*$, $\eta(\prime)\rho$, $\eta(\prime)\pi^0$, $\omega\pi^0$, and $\phi\pi^0$.

Substantial signals are seen for $B \to \eta K^*$ and limits are provided for the other modes. The decay $B \to \eta'K^*$ is particularly interesting since it provides limits on a flavor-singlet amplitude.\footnote{2} The second analysis searches for eight isoscalar final states.\footnote{3} In addition to the interest in observing signals should the branching fractions be large enough, these channels are interesting because they can provide constraints on the expected value of $\sin^2\beta$ for the modes $B^0 \to \eta'K^0$ and $B^0 \to \phi K^0$.\footnote{4} These channels provide constraints on the size of the color-suppressed tree amplitudes for these penguin-dominated channels. The third analysis involves a search for $B$ decays to the scalar $a_0$ meson accompanied by pions or kaons. Little is known about decays involving scalars. The fourth analysis is a fairly precise measurement of the decay $B \to K_S^0\pi^+\pi^-$. The last analysis measures the polarization and potential CP-violating terms in the full angular analysis of the decay $B \to \phi K^{*0}$.

2 Datasets and analysis details

The results presented here are based on data collected with the \textit{BABAR} detector\footnote{4} at the PEP-II asymmetric $e^+e^-$ collider located at the Stanford Linear Accelerator Center. Most analyses
use a sample of 89 million $B\overline{B}$ pairs, recorded at the $\Upsilon(4S)$ resonance (center-of-mass energy $\sqrt{s} = 10.58$ GeV). The $B \rightarrow \phi K^{*0}$ analysis uses a sample of 124 million $B\overline{B}$ pairs.

A $B$-meson candidate is characterized kinematically by the energy-substituted mass $m_{ES}$ and by the energy difference $\Delta E$, defined as

$$m_{ES} = \sqrt{\frac{1}{4} s - p_B^2} \quad \text{and}$$

$$\Delta E = E_B^* - \frac{1}{2} \sqrt{s},$$

where $(E_B, p_B)$ is the $B$-candidate four vector and $s$ is the square of the invariant mass of the electron-positron system; the asterisk denotes the value in the $\Upsilon(4S)$ frame. All analyses use these two quantities in unbinned maximum-likelihood fits which also have invariant masses of quasi-two-body resonances in the final states and a Fisher discriminant that is sensitive to event shape.

3 Measurements of $\eta^{(i)} K^*$ and related decays

We have searched for the $B$ decays to $\eta^{(i)} K^*$, $\eta^{(i)} \rho$, $\eta^{(i)} \pi^0$, $\omega \pi^0$, and $\phi \pi^0$. We find a substantial signal for both charge states of the $B \rightarrow \eta K^*$ decay as shown in the projection plots in Fig. 1. These results are tabulated in Table 1 along with previous results for the $\eta^{(i)} K$ and $\eta^{(i)} \pi$ decays. Thus we have completed the measurement of the four $(\eta, \eta')(K, K^*)$ final states with a sensitivity in the branching fraction of a few times $10^{-6}$. We find no significant signal for $B \rightarrow \eta' K^*$; the 90% C.L. upper limit is not yet precise enough to determine whether a flavor-singlet component is present for this decay, though we do restrict the size of such a contribution. See Ref. 2 and references therein for a discussion of this issue. We also have evidence for the decay $B^+ \rightarrow \eta \rho^+$ with a significance of 3.5$\sigma$.

![Figure 1](image-url)
Table 1: We show the significance $S(\sigma)$ (including systematic errors), fit branching fractions $B$, 90% C.L. upper limits, and charge asymmetries for the 12 new measurements as well as six related measurements (above the line) that were published recently.\[30\]

| Mode       | $S(\sigma)$ | $B(10^{-6})$ | UL ($10^{-6}$) | $A_{ch}$ |
|------------|-------------|--------------|----------------|----------|
| $B^+ \rightarrow \eta'K^+$ | $> 10$ | $76.9 \pm 3.5$ | $0.037 \pm 0.045$ |
| $B^0 \rightarrow \eta'K^0$ | $> 10$ | $60.6 \pm 5.6$ |
| $B^+ \rightarrow \eta\pi^+$ | $7.9$ | $5.3 \pm 1.0 \pm 0.3$ | $-0.44 \pm 0.18 \pm 0.01$ |
| $B^+ \rightarrow \eta K^+$ | $6.1$ | $3.4 \pm 0.8 \pm 0.2$ | $-0.52 \pm 0.24 \pm 0.01$ |
| $B^0 \rightarrow \eta K^0$ | $3.3$ | $2.9 \pm 1.0 \pm 0.2$ | $< 5.2$ |
| $B^+ \rightarrow \eta \pi^+$ | $3.4$ | $2.7 \pm 1.2 \pm 0.3$ | $< 4.5$ |
| $B^+ \rightarrow \eta K^{*+}$ | $9$ | $25.6 \pm 4.0 \pm 2.4$ | $+0.13 \pm 0.14 \pm 0.02$ |
| $B^0 \rightarrow \eta K^{*0}$ | $11$ | $18.6 \pm 2.3 \pm 1.2$ | $+0.02 \pm 0.11 \pm 0.02$ |
| $B^+ \rightarrow \eta \rho^+$ | $3.5$ | $9.2 \pm 3.4 \pm 1.0$ | $< 14$ |
| $B^0 \rightarrow \eta \rho^0$ | $-$ | $-1.1^{+0.7}_{-0.4}$ | $< 1.5$ |
| $B^0 \rightarrow \eta \pi^0$ | $0.8$ | $0.7^{+1.1}_{-0.9} \pm 0.3$ | $< 2.5$ |
| $B^+ \rightarrow \eta' K^{*+}$ | $1.9$ | $6.3^{+4.6}_{-3.6} \pm 1.8$ | $< 14$ |
| $B^0 \rightarrow \eta' K^{*0}$ | $2.1$ | $4.1^{+2.1}_{-1.8} \pm 1.2$ | $< 7.6$ |
| $B^+ \rightarrow \eta' \rho^+$ | $2.6$ | $12.9^{+6.2}_{-5.5} \pm 2.0$ | $< 22$ |
| $B^0 \rightarrow \eta' \rho^0$ | $0.5$ | $0.8^{+1.7}_{-1.2} \pm 0.9$ | $< 4.3$ |
| $B^0 \rightarrow \eta' \pi^0$ | $0.7$ | $1.0^{+1.4}_{-1.0} \pm 0.8$ | $< 3.7$ |
| $B^0 \rightarrow \omega \pi^0$ | $-$ | $-0.6^{+0.7}_{-0.2}$ | $< 1.2$ |
| $B^0 \rightarrow \phi \pi^0$ | $0.7$ | $0.2^{+0.4}_{-0.3} \pm 0.1$ | $< 1.0$ |

4 Search for isoscalar charmless decays

We have searched for eight isoscalar charmless decays. These decays are particularly interesting because they can provide constraints on the expected value of $\sin 2\beta$ for the modes $B^0 \rightarrow \eta'K^0$ and $B^0 \rightarrow \phi K^{*0}$.\[50\] Results are summarized in Table 2. The $4.3\sigma$ signal in $B^0 \rightarrow \eta\omega$ is unexpected and may be a fluctuation; more data will be required to see if this is interesting. The limits on all of these modes have improved the understanding of the expected value of $\sin 2\beta$ for $B^0 \rightarrow \eta'K^0$ so that the model-independent precision is now 0.10.\[10\] This is an improvement of about a factor of five on the previous limits.\[5\]

Table 2: Significance $S(\sigma)$ (including systematic uncertainties), measured branching fraction $B$, and 90% C.L. upper limits (UL) from this and previous measurements by CLEO.

| Mode       | $S(\sigma)$ | $B(10^{-6})$ | UL ($10^{-6}$) | CLEO UL ($10^{-6}$) |
|------------|-------------|--------------|----------------|---------------------|
| $B^0 \rightarrow \eta\eta$ | $0.0$ | $-0.9^{+1.6}_{-1.4} \pm 0.7$ | $< 2.8$ | $< 18$ |
| $B^0 \rightarrow \eta'\eta'$ | $0.3$ | $0.6^{+2.1}_{-1.7} \pm 1.1$ | $< 4.6$ | $< 27$ |
| $B^0 \rightarrow \eta'\eta$ | $0.4$ | $1.7^{+1.8}_{-1.2} \pm 0.6$ | $< 10$ | $< 47$ |
| $B^0 \rightarrow \eta\omega$ | $4.3$ | $4.0^{+1.3}_{-1.2} \pm 0.4$ | $< 6.2$ | $< 12$ |
| $B^0 \rightarrow \eta'\omega$ | $0.0$ | $-0.2^{+1.3}_{-0.9} \pm 0.4$ | $< 2.8$ | $< 60$ |
| $B^0 \rightarrow \eta\phi$ | $0.0$ | $-1.4^{+0.7}_{-0.4} \pm 0.2$ | $< 1.0$ | $< 9$ |
| $B^0 \rightarrow \eta'\phi$ | $0.8$ | $1.5^{+1.5}_{-1.3} \pm 0.4$ | $< 4.5$ | $< 31$ |
| $B^0 \rightarrow \phi\phi$ | $0.3$ | $0.3^{+0.7}_{-0.4} \pm 0.1$ | $< 1.5$ | $< 12$ |
5 Search for $B$ decays involving $a_0$ mesons

Very little is known about charmless $B$ decays with a scalar meson in the final state. There are also few predictions for these decays. We have searched for quasi-two-body $B$ decays with an $a_0$ meson and a pion or kaon. This follows a previous preliminary search where evidence for the decay $B^0 \to a_0^- \pi^+$ was found. The results of the present search are summarized in Table 8. We do not confirm the previous result which was obtained with one-quarter of this data sample. The difference appears to be a fluctuation. We provide preliminary upper limits on this and five related decay channels. This are the first measurements for these decays and seem to rule out the largest predictions for the $B^- \to a_0^- K^0$ decay from one recent paper.

Table 3: Significance $S(\sigma)$ (including systematic uncertainties), measured branching fraction $B$, and 90% C.L. upper limits (UL) for $B$ decays involving $a_0$ mesons.

| Mode         | $S(\sigma)$ | $B(10^{-6})$ | UL $(10^{-6})$ |
|--------------|-------------|--------------|----------------|
| $B^0 \to a_0^- \pi^+$ | 2.0         | $2.8^{+1.5}_{-1.3} \pm 0.7$ | $< 5.1$         |
| $B^0 \to a_0^- K^+$ | 0.4         | $0.4^{+1.0}_{-0.8} \pm 0.2$ | $< 2.1$         |
| $B^- \to a_0^+ K^0$ | 0.6         | $-1.5^{+2.4}_{-1.8} \pm 0.8$ | $< 3.9$         |
| $B^+ \to a_0^0 \pi^+$ | 1.9         | $3.6^{+2.1}_{-1.9} \pm 0.8$ | $< 6.7$         |
| $B^+ \to a_0^0 K^+$ | 0.0         | $-3.7^{+1.6}_{-1.3} \pm 0.5$ | $< 1.8$         |
| $B^0 \to a_0^0 K^0$ | 1.0         | $2.8^{+3.1}_{-2.4} \pm 1.1$ | $< 7.8$         |

6 Measurement of the branching fraction for the decay $B \to K^0 \pi^+ \pi^-$

We measure the branching fraction of the decay $B \to K^0 \pi^+ \pi^-$. Corrections are made for the efficiency variation across the Dalitz plot. From 310 ± 27 signal events, we measure $B(B \to K^0 \pi^+ \pi^-) = 43.8 \pm 3.8 \pm 3.4 \times 10^{-6}$. This is in good agreement with, but more precise than, previous results. An analysis of the Dalitz plot structure is in progress.

7 Measurement of polarization and $CP$-violating terms in a full angular analysis of $B \to \phi K^{*0}$

We present a full angular analysis of the decay $B \to \phi K^{*0}$. The angular distribution of the $B \to \phi K^*$ decay products can be expressed in the helicity representation with $H_i = \cos \theta_i$ and $\Phi$, where $\theta_i$ is the angle between the direction of one of the vector meson daughters ($i = 1$ for the $K^* \to K \pi$, $i = 2$ for the $\phi \to KK$) and the direction opposite the $B$ in the resonance rest frame, and $\Phi$ is the angle between the two resonance decay planes. The differential decay width has three complex amplitudes $A_\lambda$ for the vector meson helicity $\lambda = 0$ or $\pm 1$. The decay width can be written, in terms of $A_\parallel = (A_+ + A_-)/\sqrt{2}$, and $A_\perp = (A_+ - A_-)/\sqrt{2}$, as

$$
\frac{8\pi}{9\Gamma} \frac{d^3\Gamma}{dH_1 dH_2 d\Phi} = \frac{1}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2} \times \left[ |A_0|^2 H_1^2 H_2^2 + \frac{1}{4} (|A_\parallel|^2 + |A_\perp|^2) (1 - H_1^2) (1 - H_2^2) \right. \\
+ \frac{1}{4} (|A_\parallel|^2 - |A_\perp|^2) (1 - H_1^2) (1 - H_2^2) \cos 2\Phi - \text{Im}(A_\parallel A_\perp^*)(1 - H_1^2) (1 - H_2^2) \sin 2\Phi \\
+ \sqrt{2} \text{Re}(A_\parallel A_0^*) \sqrt{1 - H_1^2} H_1 \sqrt{1 - H_2^2} H_2 \cos \Phi - \sqrt{2} \text{Im}(A_\parallel A_0^*) \sqrt{1 - H_1^2} H_1 \sqrt{1 - H_2^2} H_2 \sin \Phi \left. \right].
$$

We measure the polarization parameters $f_\parallel = |A_0|^2/|\Sigma|A_\lambda|^2$, $f_\perp = |A_\parallel|^2/|\Sigma|A_\lambda|^2$, $\phi_\parallel = \text{arg}(A_\parallel/A_0)$, and $\phi_\perp = \text{arg}(A_\perp/A_0)$. We also allow for $CP$-violating differences between the $B^0$.
Table 4: We show results for the ten primary signal fit parameters and the secondary triple-product asymmetries. All results include systematic errors quoted last. The dominant correlations coefficients are also shown.

| Fit param. | Fit result | Corr. | Fit param. | Fit result | Corr. |
|------------|------------|-------|------------|------------|-------|
| $n_{\text{sig}}$ (events) | 129 $\pm$ 14 $\pm$ 9 |       | $A_{\text{CP}}$ | $-0.12$ $\pm$ 0.10 $\pm$ 0.03 |       |
| $f_L$ | 0.52 $\pm$ 0.07 $\pm$ 0.02 | $-52\%$ | $A_{0\text{CP}}$ | $-0.02$ $\pm$ 0.12 $\pm$ 0.01 | $-52\%$ |
| $f_\perp$ | 0.27 $\pm$ 0.07 $\pm$ 0.02 | $+59\%$ | $\Delta r_{\parallel}$ (rad) | 0.38 $\pm$ 0.23 $\pm$ 0.04 | $+59\%$ |
| $\phi_{\parallel}$ (rad) | 2.63 $\pm$ 0.24 $\pm$ 0.04 | $+59\%$ | $\Delta r_{\perp}$ (rad) | 0.30 $\pm$ 0.22 $\pm$ 0.03 |       |
| $\phi_{\perp}$ (rad) | 2.71 $\pm$ 0.24 $\pm$ 0.03 | $+59\%$ |       |       |       |

$(Q = +1)$ and the $B^0 (Q = -1)$ decay amplitudes, where the flavor sign $Q$ is determined in the self-tagging final state with a $K^*$ or $K^*$:

$$n_{\text{sig}}^Q = n_{\text{sig}}(1 + QA_{\text{CP}})/2; \quad f_L^Q = f_L(1 + QA_{0\text{CP}}); \quad f_\perp^Q = f_\perp(1 + QA_{CP}^\perp);$$
$$\phi_{\parallel}^Q = \phi_{\parallel} + Q\Delta \phi_{\parallel}; \quad \phi_{\perp}^Q = \phi_{\perp} + \frac{\pi}{2} + Q(\Delta \phi_{\perp} + \frac{\pi}{2}).$$

From the above parameters one can derive triple-product asymmetries $A_T^\parallel$ and $A_T^0$ as discussed in Ref. [15]

$$A_T^\parallel = \frac{1}{2} \left( \frac{\text{Im}(A^*_T A_{T\parallel}^\parallel)}{\Sigma |A_m|^2} + \frac{\text{Im}(A^*_T A_{T\perp}^\perp)}{\Sigma |A_m|^2} \right).$$

The longitudinal polarization in this decay is found to be 0.52 $\pm$ 0.07 $\pm$ 0.02 as seen in Table 2 and Fig. 2(a); this value is surprising since naive expectations and measurements for $B \to \rho\rho$ indicate a value very close to 1. This confirms earlier measurements by BABAR\cite{16} and Belle\cite{17} and is still not understood theoretically. Also shown in Fig. 2(b)-(d) are measurements involving the other quantities determined in the fit.

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Figure 2: Contour plots with 1σ intervals derived from the fit −2 ln L distributions for (a) polarization fractions \( f_L = |A_0|^2/\Sigma |A_m|^2 \) and \( f_L = |A_0|^2/\Sigma |A_m|^2 \), (b) CP-even and CP-odd transverse phases \( [\pi, \pi] \) point expected if no final-state interactions), (c) asymmetry parameters sensitive to direct CP violation; (d) phases of the triple-product asymmetries that are sensitive to new physics.