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Hadronic *B* Decays at *BABAR*

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Abstract. The *BABAR* collaboration has performed a number of measurements on hadronic B decays to charmonium and open charm mesons. Preliminary results based on a sample of nearly 23 million $B\overline{B}$ pairs, collected between October 1999 and October 2000, are reviewed. These include measurements of exclusive branching fractions and ratios of branching fractions, as well as angular distributions.

INTRODUCTION

Hadronic decays account for a large fraction (between ~60% and ~75%) of B meson decays. They mainly proceed through $b \to c\overline{u}d$ and $b \to c\overline{c}s$ processes[1], whence consequent hadronization leads to the formation of charmed mesons and, to a lesser extent, charmonium states and charmed baryons.

Measurement of branching fractions, momentum and angular distributions for exclusive and inclusive decays of this kind is a key to a better understanding of the underlying dynamics at the quark level and a test for phenomenological models such as the factorization hypothesis and non-relativistic QCD. Moreover, many of these channels are of particular interest in the detection of CP violation effects.

The *BABAR* collaboration has performed a number of such measurements using a sample of $B\overline{B}$ pairs produced from $\Upsilon(4S)$ decays at the PEP II asymmetric e^+e^- storage ring at the Stanford Linear Accelerator Center. Results reported here are based on data collected with the *BABAR* detector [1] between October 1999 and October 2000, for an integrated luminosity of 20.7 fb^{-1}, corresponding to $(22.74 \pm 0.36) \times 10^6$ $B\overline{B}$ pairs, at the $\Upsilon(4S)$ resonance peak, and 2.6 fb^{-1} at 40 MeV below the peak.

EVENT SELECTION

Although results presented in the next sections are the outcome of several independent analyses, the techniques employed for event selection are often common. The main criteria used are briefly described in the following.

A detailed description of the *BABAR* detector can be found in [1]. After charged tracks and neutral cluster are reconstructed, a set of track multiplicity and event shape cuts selects multi-hadron events from $B\overline{B}$ decays while rejecting large part of the continuum background.

[1] Charge conjugate states are implied throughout this paper.

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Reconstructed objects are then assigned particle types (non-exclusively) based on the information provided by all sub-detectors and on PID criteria with different levels of efficiency and purity.

"Composite" mesons are formed by combining sets of tracks and/or neutral clusters, whose mass is fixed to that of the particle type they are assigned to. A vertex constraint is usually applied before computing the invariant mass, which is then required to be compatible, within resolution, with the known meson mass. In some cases, additional criteria are applied in order to reject specific background modes or gain efficiency (*e.g.* bremsstrahlung recovery in $J/\psi \to e^+ e^-$, π^0 rejection in $\chi_{c1} \to J/\psi\gamma$). If the reconstructed meson is itself an intermediate state in the decay chain, its mass is constrained to the known mass before iterating the procedure.

Table 1 lists all decay modes used for meson reconstruction in all B decay channel considered in this paper.

Extraction of the B signal mainly relies on a pair of kinematical variables, exhibiting high discriminating power against combinatorial background and little correlation between each other:

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

$$m_{ES} = \sqrt{s/4 - p_B^{*2}}\,. \tag{2}$$

They make use of the reconstructed B energy and momentum in the center-of-mass frame, and of the total center of mass energy, known to a very good precision from the beam parameters. The signal is expected to cluster around $\Delta E = 0$ and $m_{\mathrm{ES}} = m_B$.

Candidates are considered whose ΔE and m_{ES} values lie in a broad neighborhood of this point in a two dimensional plot ($|\Delta E| < \Delta E_{\mathrm{max}}$, with ΔE_{max} tipically ~100 – 200 MeV, and 5.2 GeV/c^2 < m_{ES} < 5.3 GeV/c^2); a signal region is defined in a much smaller neighborhood, while large sidebands away from it are used for background shape evaluation. Where "cut and count" techniques are used (as opposed to likelihood fits) the background is fitted to an ARGUS[2] shape in m_{ES} and to a polynomial in ΔE in the sideband region: the extrapolated yield to the signal region is then subtracted from the total number of events found inside it.

TABLE 1. Decay channels used for the reconstruction of mesons.

***uds* mesons**	**charmonium**	**charmed mesons**
$\pi^0 \to \gamma\gamma$	$J/\psi \to e^+ e^-, \mu^+ \mu^-$	$D^+ \to K^- \pi^+ \pi^+, K_S \pi^+, K^- K^+ \pi^+$
$K_S{}^0 \to \pi^+ \pi^-, \pi^0 \pi^0$	$\psi(2S) \to e^+ e^-, \mu^+ \mu^-$	$D^0 \to K^- \pi^+, K^- \pi^+ \pi^0, K^- \pi^+ \pi^+ \pi^-, K_S \pi^+ \pi^-$
$K^{*+} \to K_S \pi^+, K^+ \pi^0$	$\psi(2S) \to J/\psi\, \pi^+ \pi^-$	$D^{*+} \to D^0 \pi^+, D^+ \pi^0$
$K^{*0} \to K_S \pi^0, K^+ \pi^-$	$\chi_{c1,2} \to J/\psi\, \gamma$	$D^{*0} \to D^0 \pi^0, D^0 \gamma$
$\phi \to K^+ K^-$		

[2] The ARGUS function is defined as $A(m_{\mathrm{ES}}; m_0, \xi) = N \cdot m_{\mathrm{ES}} \sqrt{1 - \left(\frac{m_{\mathrm{ES}}}{m_0}\right)^2} \cdot e^{\xi(1-(m_{\mathrm{ES}}/m_0)^2)}$.

BRANCHING FRACTIONS OF EXCLUSIVE *B* DECAYS

B Decays to Charmonium Mesons

Decays of *B* mesons to two-body final states containing a charmonium resonance constitute a very sensitive laboratory for the study of electroweak transitions, as well as the dynamics of strong interactions in heavy mesons systems. In particular, neutral *B* decays to these final states are expected to exhibit a significant *CP* asymmetry, the magnitude of which is cleanly related to the value of the angle β of the Unitarity Triangle [2].

We studied decay modes with a *K* or π meson accompanying the charmonium state. Due to the contributions of non-perturbative QCD interactions in the final state, theoretical estimates suffer from some degree of model dependence. Nevertheless isospin symmetry requires that the ratio of charged to neutral partial widths be unity for each type of decay, independently of the model used.

As seen in Table 1, charmonium states are reconstructed either through direct decay to $l^+ l^-$ (J/ψ and $\psi(2S)$) or through decay to a state containing a J/ψ, which in turn decays to $l^+ l^-$. The angular distribution of the lepton pair is exploited to reduce background when the light meson is a pseudoscalar, since in that case the (vector) charmonium state is longitudinally polarized.

ΔE and m_{ES} distributions are used to extract the signal yields for all channels studied, except for $B^0 \to J/\psi\, K_L$. Fig. 1(*a*) shows the distributions for the case $B^0 \to J/\psi\, K_S$, $K_S \to \pi\, \pi^-$.

The $B^0 \to J/\psi\, K_L$ case must to be treated differently since neither the K_L energy nor its momentum are measured. In this case the E_{K_L} energy is determined by constraining the *B* candidate mass to its known value, and the quantity $\Delta E_{K_L} \equiv E^*_{J/\psi} + E^*_{K_L} - E^*_{\text{beam}}$

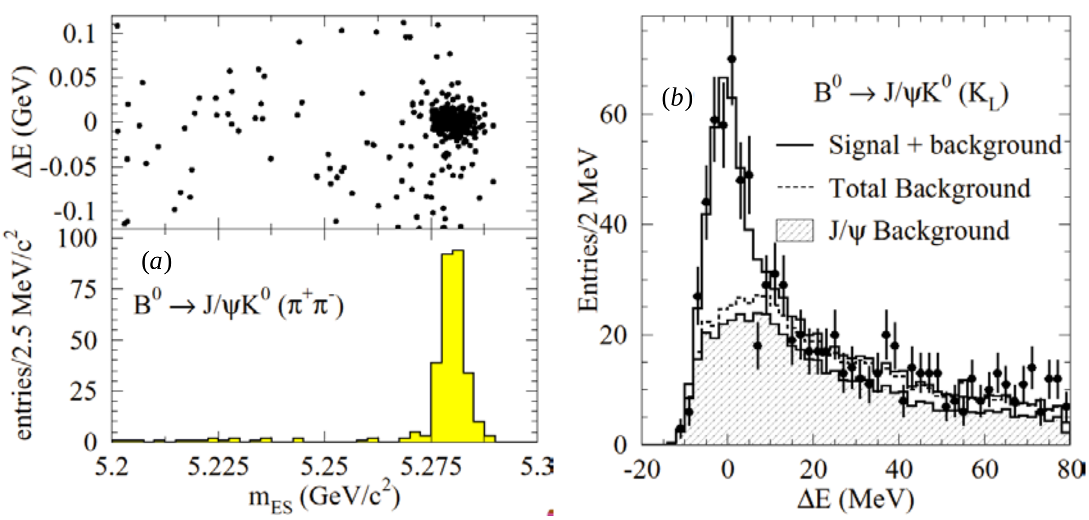

FIGURE 1. Signal evidence for two charmonium modes: (*a*) ΔE and m_{ES} distributions for $B^0 \to J/\psi\, K_S$, $K_S \to \pi^+ \pi^-$; (*b*) ΔE distribution for $B^0 \to J/\psi\, K_L$: points are from real data, histograms from Monte Carlo events.

is plotted. The large (peaking) background coming from other J/ψ channels is modeled by a detailed Monte Carlo study. The ΔE_{K_L} distribution for our sample is shown in Fig. 1(*b*).

Table 2 summarizes the branching fraction values obtained for all channels. Most of them have a better precision than published world averages [3]. The resulting values of charged-to-neutral-mode ratios differ from 1 by at most 2σ.

TABLE 2. Measured branching fractions for exclusive *B* decays involving charmonium. The first error is statistical, the second systematic.

Mode		BR ($\times 10^{-4}$)	Mode	BR ($\times 10^{-4}$)
$B^0 \to J/\psi K^0$	$K^0_S \to \pi^+ \pi^-$	$8.5 \pm 0.5 \pm 0.6$	$B^0 \to J/\psi \pi^0$	$0.20 \pm 0.06 \pm 0.02$
	$K^0_S \to \pi^0 \pi^0$	$9.6 \pm 1.5 \pm 0.7$	$B^0 \to J/\psi \pi^+ \pi^-$	$0.46 \pm 0.11 \pm 0.08$
	K^0_L	$6.8 \pm 0.8 \pm 0.8$	$B^0 \to \psi(2S) K^0$	$6.8 \pm 1.0 \pm 1.1$
	All	$8.3 \pm 0.4 \pm 0.5$	$B^+ \to \psi(2S) K^+$	$6.3 \pm 0.5 \pm 0.8$
$B^+ \to J/\psi K^+$		$10.1 \pm 0.3 \pm 0.5$	$B^0 \to \chi_{c1} K^0$	$5.4 \pm 1.4 \pm 1.1$
$B^0 \to J/\psi K^{*0}$		$12.4 \pm 0.5 \pm 0.9$	$B^+ \to \chi_{c1} K^+$	$7.5 \pm 0.8 \pm 0.8$
$B^+ \to J/\psi K^{*+}$		$13.7 \pm 0.9 \pm 1.1$	$B_0 \to \chi_{c1} K^{*0}$	$4.8 \pm 1.4 \pm 0.9$

B Decays to Open Charm Mesons

$B \to D^{(*)} \bar{D}^{(*)}$[3]

The Standard Model predicts sizeable *CP*-violating effects in the decays $B^0 \to D^{(*)+} D^{(*)-}$; in particular, time dependent asymmetries con be used to extract the value of $\sin 2\beta$, as in the case of $B^0 \to J/\psi K_S$. An independent measurement of this quantity is especially important since several extensions to the Standard Model imply differences between the values extracted from the two different classes of processes. Charged *B* decays such as $B^{\pm} \to D^{*\pm} D^{*0}$ are also important since they provide calibration and control samples.

The rate of the Cabibbo-suppressed decays $B \to D^{(*)} \bar{D}^{(*)}$, can be estimated from the measured rate of the Cabibbo-favored decays $B \to D_s^{(*)} \bar{D}^{(*)}$, leading to values of the order of 0.1%. Previous measurements of branching fractions and upper limits for these modes were reported by CLEO [4] and ALEPH [5].

To search for signal in these channels the variable $\chi^2_{\mathrm{Mass}} \equiv \Sigma\,[(m_i - m_i^{\mathrm{PDG}}) / \sigma_{m_i}]^2$ was used, in addition to ΔE and m_{ES}, where m_i is the mass of the reconstructed $D^{(*)}$ candidate, σ_{m_i} its error, and m_i^{PDG} the corresponding PDG value and the sum is performed on all reconstructed D and D^* in the decay chain.

A clean signal is observed in the $B \to D^{*+} D^{*-}$ channel (Fig. 2); evidence for a peak is also seen in the m_{ES} plots for the $B \to D^{*+} D^-$ and $B^+ \to D^{*+} D^{*0}$ channels. Table 3 summarizes results for these 3 modes. We report a branching fraction only for $B^0 \to D^{*+} D^{*-}$: for the other two modes we quote the probability that the observed distribution be due to background fluctuation.

[3] Here and in the following, the symbol $D^{(*)}$ refers to either a D or a D^* state.

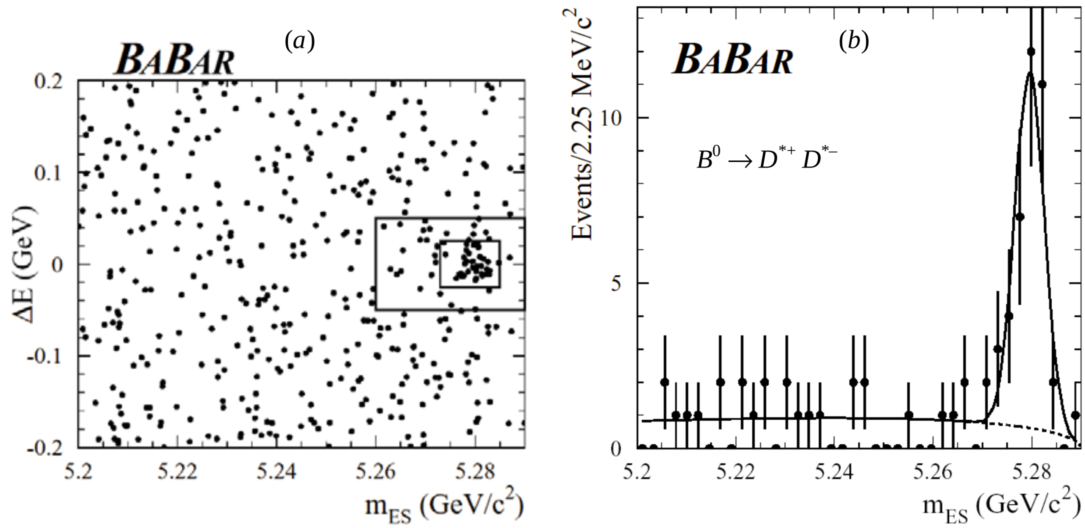

FIGURE 2. Evidence of signal for $B^0 \to D^{*+} D^{*-}$: (*a*) distribution in the m_{ES}-ΔE plane and (*b*) projection in m_{ES}.

TABLE 3. Yields and branching fractions for $B \to D^{(*)}\,\overline{D}^{(*)}$ modes.

Mode	N. signal events	Bkg.	BR [or prob. of bkg. fluctuation]
$B^0 \to D^{*+}D^{*-}$	38	6.2	$(8.0 \pm 1.6 \pm 1.2) \times 10^{-4}$
$B^0 \to D^{*+}D^{-}$	31	10.5	$[9.7 \times 10^{-7}$ $(> 4.3\ \sigma)]$
$B^+ \to D^{*+}D^{*0}$	39	20.3	$[2.9 \times 10^{-6}$ $(> 4.1\ \sigma)]$

$B \to D^{(*)}\,\overline{D}^{(*)}K$

Until 1994 it was believed that the $c\bar{s}$ pair in the process $b \to c\bar{c}s$ would hadronize dominantly as $D_s^{(*)+}$ mesons. If this conjecture is used in computing the total hadronic branching fraction of the B, it leads to an inconsistency with the measured value of the inclusive semileptonic branching fraction: their contributions sum up to about 80%, albeit with a large uncertainty [6]. In recent years, CLEO [7] and ALEPH [5] have reported evidence for a small number of completely reconstructed decays of the type $B \to D^{(*)}\ \overline{D}^{(*)}K$: this would point to a larger $b \to c\bar{c}s$ branching fraction, which would help solve the puzzle.

We have reconstructed $B \to D^{(*)}\,\overline{D}^{(*)}K$ events using all possible charge combinations. In the case of $B^0 \to D^{*-}\,D^{*0}K^+$, a partial reconstruction technique is adopted: the D^0 is reconstructed but not combined with the γ or π^0 to form the D^{*0}. The ΔE distribution peaks in this case at -154 MeV instead of 0. We found a significant number of events in 3 exclusive channels: m_{ES} distributions are shown in Fig. 3 for two of them, while resulting branching fractions are reported in Table 4. Moreover, several candidates have been observed in the semi-exclusive mode $B^0 \to D^{(*)}\,\overline{D}^{(*)}K_{\mathrm{S}}$, which could be used for $\sin 2\beta$ measurements.

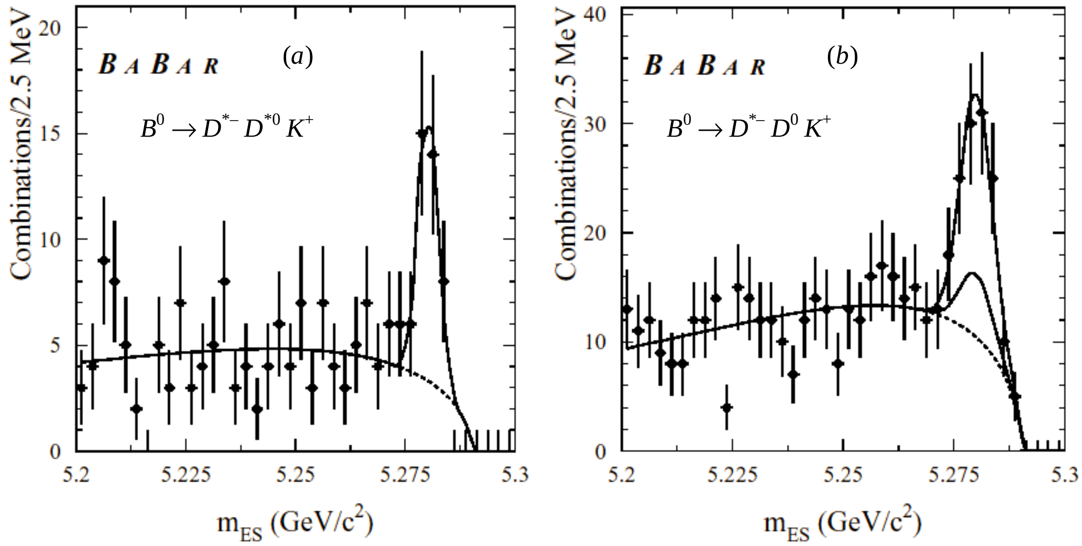

FIGURE 3. Evidence of signal for two exclusive $B \to D^{(*)} \bar{D}^{(*)} K$ modes: m_{ES} distribution for (*a*) $B^0 \to D^{*-} D^{*0} K^+$ and (*b*) $B^0 \to D^{*-} D^0 K^+$. The smaller peak in (*b*) represents the background contribution from $B^+ \to D^{**+} D^{*-} K^+$ decays, where the π^+ from the D^{**} is not reconstructed.

TABLE 4. Yields and branching fractions for $B \to D^{(*)} \bar{D}^{(*)} K$ modes.

Mode	Signal (fit)	Bkg. (fit)	BR ($\times 10^{-3}$)
$B^+ \to D^{*-} D^{*+} K^+$	8.2 ± 3.5	1.7	3.4 ± 1.6 ± 0.9
$B^0 \to D^{*-} D^0 K^+$	29.6 ± 7.2	24.8	2.8 ± 0.7 ± 0.5
$B^0 \to D^{*-} D^{*0} K^+$	80.2 ± 15.3	20.6 ± 9.7	6.8 ± 1.7 ± 1.7
$B^0 \to D^{(*)-} D^{(*)+} K_S$	10.1 ± 3.7	3.4	

Measurement of Ratio of Branching Fractions with K/π Separation

In cases where two different final states differ only by the presence of either a charged K or π, the correct reconstruction of the decay depends on how well the two modes can be separated, based on PID information and kinematics. As one of the two decays is typically Cabibbo-suppressed with respect to the other, their branching fractions can differ by order of magnitudes, thus making the task hardly achievable by means of ordinary "cut and count" methods.

BABAR has measured two ratios of branching fractions of this kind, by using unbinned maximum likelihood fits on samples of reconstructed events where no K/π identification has been applied in the selection.

$$B(B^\pm \to J/\psi\, \pi^\pm)/\, B(B^\pm \to J/\psi\, K^\pm)$$

Contribution from the tree diagrams alone would give a ratio of ~5% between the $B^\pm \to J/\psi\ \pi^\pm$ and $B^\pm \to J/\psi\ \ K^\pm$ branching fractions. A substantially different value of the measured ratio would point to significant interference with penguin diagrams. This could be the source of a sizeable direct CP-asymmetry [8].

A likelihood function based on p.d.f. for ΔE, m_{ES} and the bachelor track momentum for the π, K and background case was built and the number of events of each type fitted for. The result of the fit yields

$$\mathrm{B}(B^{\pm} \rightarrow J/\psi\, \pi^{\pm}) \,/\, \mathrm{B}(B^{\pm} \rightarrow J/\psi\, K^{\pm}) = (3.91 \pm 0.78 \pm 0.19)\ \%.$$

Fig. 4(a) shows the m_{ES} distribution for a sample where the $J/\psi\, \pi^{\pm}$ content has been enriched by applying tight PID cuts.

$B(B^{\pm} \rightarrow D^{0}\, K^{\pm}) / B(B^{\pm} \rightarrow D^{0}\, \pi^{\pm})$

Measurement of the $B^{\pm} \rightarrow D^{0}\, K^{\pm}$ branching fraction can in principle be used, in conjunction with other rarer B decays, to extract the value of the CKM angle γ in a theoretically clean way. A prediction for its ratio to the $B^{-} \rightarrow D^{0}\, \pi^{-}$ branching fraction can be obtained from $\mathrm{B}(\tau^{-} \rightarrow K^{-} \nu_{\tau}) \,/\, \mathrm{B}(\tau^{-} \rightarrow \pi^{-}\, \nu_{\tau})$, giving $(7.4 \pm 0.3)\%$. The first observation of the $B^{\pm} \rightarrow D^{0}\, K^{\pm}$ decay has been reported by CLEO [9].

In this case the likelihood function includes, along with the ΔE and m_{ES} p.d.f., a PID variable exploiting the K/π separation power provided by the DIRC. Contribution from both combinatorial and resonant background are fitted for. The result is:

$$\mathrm{B}(B^{\pm} \rightarrow D^{0}\, K^{\pm}) \,/\, \mathrm{B}(B^{\pm} \rightarrow D^{0}\, \pi^{\pm}) = (8.3 \pm 0.6 \pm 0.3)\ \%.$$

Fig. 4(b) shows the ΔE distribution for a sample where the $D^{0}\, K^{\pm}$ content has been enriched by applying tight PID cuts.

ANGULAR DISTRIBUTIONS

B decays to such states as $J/\psi\, K^{*0}$ and $D^{*+}\, D^{*-}$ are potentially sensitive to CP violation effects [10], [11]. Since the vector-vector final state has both a CP-even and a CP-odd component, a direct extraction of the CP-violating parameter ($\sin 2\beta$ in this case) would be affected by some dilution, unless an angular analysis is carried out.

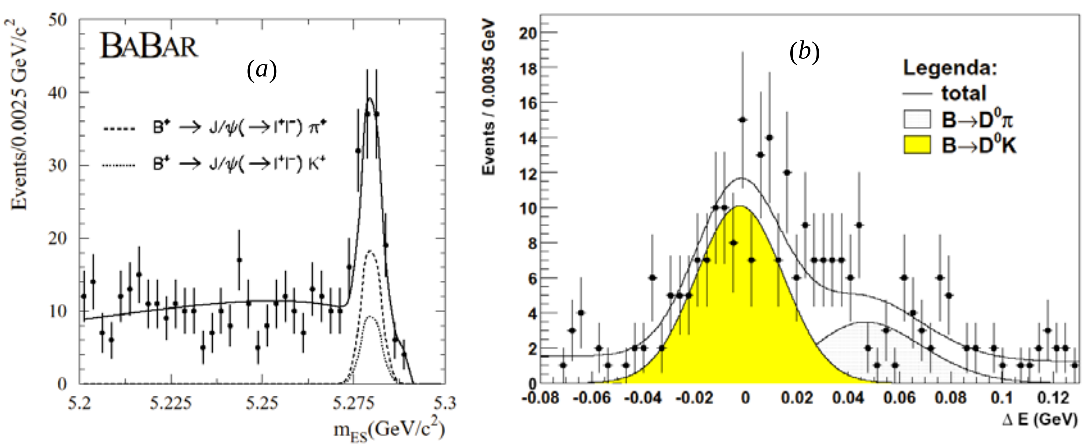

FIGURE 4. (a) m_{ES} distribution for $B^{+} \rightarrow J/\psi\, \pi^{+}$ ($J/\psi\, K^{+}$) for a π-enriched sample; (b) ΔE distribution for $B^{0} \rightarrow D^{0}\, K^{+}$ ($D^{0}\, \pi^{+}$) for a K-enriched sample; in both cases fit results are superimposed.

In the transversity basis formalism [12], the angular distribution is described by three amplitudes A_0, $A_\parallel$, $A_\perp$ with *CP* eigenvalues +1, +1 and –1 respectively. The parameter

$$R_\perp \equiv \frac{|A_\perp|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}; \tag{3}$$

describes the fraction of *P*-odd component: if this is neglected, the resulting dilution amounts to $1 - 2R_\perp$.

$B^0 \to J/\psi K^{*0}$

For the $B^0 \to J/\psi K^{*0}$ decay, an unbinned maximum likelihood fit to the data has been performed using a full angular distribution for both signal and background. Moduli and phases of the three amplitudes have been extracted from the fit, leading to

$$R_\perp = 0.160 \pm 0.032 \pm 0.014.$$

Fitted distributions are illustrated in Fig. 5(*a*). Two relative phases $\phi_\perp \equiv \arg(A_\perp/A_0)$ and $\phi_\parallel \equiv \arg(A_\parallel/A_0)$ are defined: if factorization holds, their value would be 0 or π. Our measurement of $\phi_\parallel = 2.50 \pm 0.20 \pm 0.08$, is inconsistent with this hypothesis. In general, all measurements significantly improve on previous ones by CLEO [13] and CDF [14].

$B^0 \to D^{*+} D^{*-}$

In the case of $B^0 \to D^{*+} D^{*-}$ decay, the angular distribution is integrated over two of the three angular variables, leaving a function with a single parameter, $R_\perp$. An unbinned maximum likelihood fit to the selected events yields

$$R_\perp = 0.22 \pm 0.18 \pm 0.03$$

The fitted distribution is shown in Fig. 5(*b*).

SUMMARY

Using a sample of 22.7 million $B\overline{B}$ pairs, *BABAR* has reconstructed a number of charged and neutral *B* decays to states containing charmonium or open charm mesons. Signals have been observed and branching fractions have been measured for several exclusive decays to $(c\overline{c})$ + light mesons, $D^{(*)}\overline{D}^{(*)}$, $D^{(*)}\overline{D}^{(*)}K$. The precision of these (preliminary) results is in most cases better than currently published world averages [3]. We also report measurements of the ratios of branching fractions $\mathrm{B}(B^\pm \to J/\psi\,\pi^\pm)$ / $\mathrm{B}(B^\pm \to J/\psi\,K^\pm)$ and $\mathrm{B}(B^\pm \to D^0 K^\pm)$ / $\mathrm{B}(B^\pm \to D^0\,\pi^\pm)$. Finally, angular distributions for $B^0 \to J/\psi K^{*0}$ and $B^0 \to D^{*+} D^{*-}$ have been studied and their parameters determined, with a substantial improvement over existing published results.

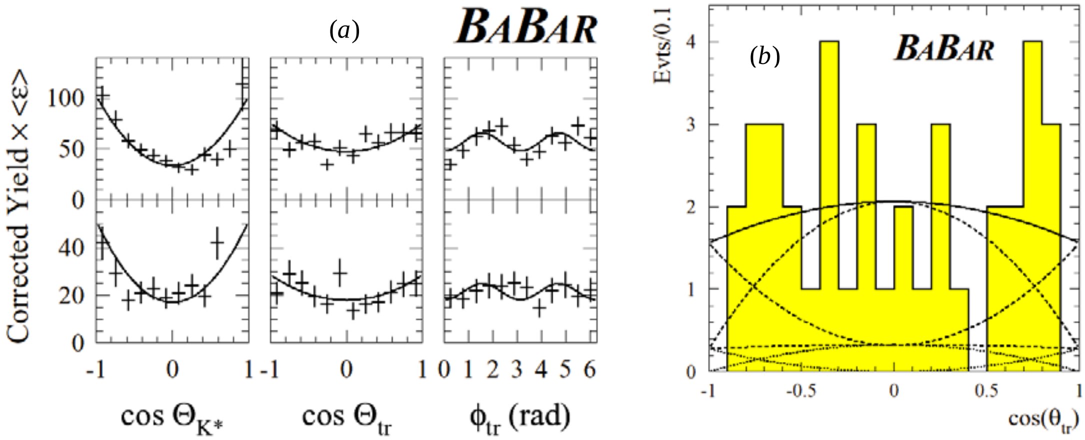

FIGURE 5. Fit results for angular distributions of (*a*) $B^0 \to J/\psi\, K^{*0}$ for channels without (top) and with (bottom) a π^0, and (*b*) $B^0 \to D^{*+} D^{*-}$. Solid curves are the fitted signal + background distributions.

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