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Measurement of Decay Amplitudes of $B \to (c\overline{c})\ K^*$ with an angular analysis, for $(c\overline{c})$=J/ψ, $\psi(2S)$ and χ_{c1}.

The *BABAR* Collaboration

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Abstract

We perform the first three-dimensional measurement of the amplitudes of $B \to \psi(2S)K^*$ and $B \to \chi_{c1}K^*$ decays and update our previous measurement for $B \to J/\psi\, K^*$. We use a data sample collected with the *BABAR* detector at the PEP-II storage ring, representing 232 million produced $B\overline{B}$ pairs. The longitudinal polarization of decays to the 1^{++} χ_{c1} meson together with a K^* meson, is found to be larger than that for the decay to the 1^{--} Ψ mesons. No direct *CP*-violating charge asymmetry is observed.

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1 Introduction

B decays to charmonium-containing final states (J/ψ, $\psi(2S)$, χ_{c1}) K^* are of interest for the precise measurement of $\sin 2\beta$, as for the similar decay $B \to J/\psi K^0$. Here, the final state consists of two vector particles, the K^* meson and the charmonium meson : the $L = 1$ and $L = 0, 2$ states have different *CP* eigenvalues and the related dilution of any *CP* violation must be taken into account in the measurement of $\sin 2\beta$. The amplitude for longitudinal polarization of the two vector mesons is A_0. There are two amplitudes for polarizations of the vector mesons transverse to the decay axis: $A_\parallel$ for parallel polarization of the two vector mesons and $A_\perp$ for their perpendicular polarization. Only the relative amplitudes are measured here, so that $|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2 = 1$. Previous measurements of the amplitudes by the CLEO [1], CDF [2], *BABAR* [3] and Belle [4] collaborations for the $B \to J/\psi K^*$ channels are all compatible with each other, and with a *CP*-odd intensity fraction $|A_\perp|^2$ close to 0.2.

Factorization is a framework that allows the description of heavy meson decays by assuming that a weak decay matrix element can be described as the product of two independent hadronic currents. In the case of heavy quarks present in the final state, the validity of the factorization hypothesis can be questioned. Factorization predicts that the phases of the decay amplitudes are the same (modulo π). *BABAR* has observed [3, 5] a significant departure from this prediction. The factorization-suppressed decay $B \to \chi_{c0} K^\pm$ has also been observed [6, 7] with a branching fraction of the same order of magnitude as that of the factorization-allowed $B \to \chi_{c1} K^\pm$, while the decay to χ_{c2}, predicted to have non-factorizable contributions comparable to those for decays to χ_{c0} [8], is actually not observed [9].

Precise measurements of the branching fractions of these decays are now available [10] to test the theoretical description of the non-factorizable contributions [11], but polarization measurements are also needed. In particular measurements for $\psi(2S)$ and χ_{c1}, compared to that of J/ψ, would discriminate the mass dependence from the quantum number dependence, due to the different effective Hamiltonian matrix element that describes charmonium production from vacuum under the factorization hypothesis, and to the different non-factorizable contributions [11]. CLEO has measured the longitudinal polarization of $B \to \psi(2S)\ K^*$ decays to be $|A_0|^2 = 0.45 \pm 0.11 \pm 0.04$ [12]. Belle has studied $B \to \chi_{c1}\ K^*$ decays and obtained $|A_0|^2 = 0.87 \pm 0.09 \pm 0.07$ [13].

B decays to charmonium $K^{(*)}$ provide a clean environment for the measurement of CKM angles because one tree amplitude dominates the decay. Very small direct *CP*-violating charge asymmetries are expected in these decays : the observation of a sizeable, significant signal would be a smoking gun for the presence of new physics. No such signal has been found [10]. London *et al.* have suggested that several amplitudes with both different electro-weak phases and different strong phases must be present to create a charge asymmetry in a simple branching fraction measurement, while an angular analysis of vector-vector decays can detect charge asymmetries even in the case of vanishing strong phase difference [14]. Belle has looked for, and not found, such a signal [4].

In this paper we describe the amplitude measurement of $B \to (c\overline{c})\ K^*$ with an angular analysis, for $(c\overline{c})$=J/ψ, $\psi(2S)$ and χ_{c1}, using a selection similar to that of Ref. [10] and described below, and a fitting method similar to that of Ref. [3]. Ψ candidates (any of the 1^{--} charmonia; i.e. J/ψ or $\psi(2S)$) are reconstructed in their decays to $\ell\ell$, where ℓ represents an electron or a muon, and χ_{c1} candidates to $J/\psi\gamma$. Decays to the flavor-eigenstates $K^{*0} \to K^\pm\pi^\mp$, $K^{*\pm} \to K^0_S\pi^\pm$ and $K^{*\pm} \to K^\pm\pi^0$ are used. The relative strong phases are known to have a two-fold ambiguity when measured in an angular analysis alone. In contrast with earlier publications [1, 2, 5] we use here the set of phases predicted by Suzuki [15] using arguments based on the conservation of the s quark helicity in the decay of the b quark. We have confirmed experimentally this prediction by the study of the variation with $K\pi$ invariant mass of the phase difference between the $K^*(892)$ amplitude and a non-resonant $K\pi$ S-wave amplitude [3].

2 The *BABAR* detector and dataset

The data, collected with the *BABAR* detector at the PEP-II asymmetric e^+e^- storage ring, represent 232 million produced $B\overline{B}$ pairs, corresponding to an on-resonance integrated luminosity of about 209 fb^{-1}.

The *BABAR* detector is described in detail elsewhere [16]. Charged-particle tracking is provided by a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH). For charged-particle identification (PID), ionization energy loss in the DCH and SVT, and Cherenkov radiation detected in a ring-imaging device (DIRC) are used. Photons are identified by the electromagnetic calorimeter (EMC), which comprises 6580 thallium-doped CsI crystals. These systems are mounted inside a 1.5-T solenoidal superconducting magnet. Muons are identified in the instrumented flux return (IFR), composed of resistive plate chambers and layers of iron that return the magnetic flux of the solenoid.

We use the GEANT [17] software to simulate interactions of particles traversing the detector, taking into account the varying accelerator and detector conditions.

3 Event Selection

Event pre-selection is performed in the same way as in Ref. [10]. Multihadron events are selected by demanding a minimum of three reconstructed charged tracks in the polar-angle range $0.41 < \theta < 2.54\,\text{rad}$, where θ is defined in the laboratory frame. Charged tracks must be reconstructed in the DCH and are required to originate within 1.5 cm of the beam in the plane transverse to it and within 10 cm of the beamspot along the beam direction. Events are required to have a primary vertex within 0.5 cm of the average position of the interaction point in the plane transverse to the beamline, and within 6 cm longitudinally. Charged tracks are required to include at least 12 DCH hits and to have a transverse momentum $p_T > 100\,\text{MeV}/c$. Photon candidates are required to have a minimum energy of 30 MeV, to have a lateral energy profile compatible with that of an electromagnetic shower, and to be in the fiducial volume of the EMC, $0.41 < \theta < 2.41$ rad. Electron candidates are selected using information from the EMC, the ratio of the energy measured in the EMC to the momentum measured by the tracking system, the energy loss in the drift chamber, and the Cherenkov angle measured in the DIRC. Electrons are also required to be in the fiducial volume $0.41 < \theta < 2.41$ rad. Muon candidates are selected using information from the EMC (energy deposition consistent with a minimum ionizing particle) and the distribution of hits in the RPC. Muons are required to be in the fiducial volume $0.3 < \theta < 2.7$ rad. We select charged kaon and pion candidates using information from the energy loss in the SVT and DCH, and the Cherenkov angle measured in the DIRC. Kaon candidates are required to be in the fiducial volume $0.45 < \theta < 2.45$ rad.

B candidates are selected in a similar way as in Ref. [10]. The J/ψ candidates are required to have an invariant mass $2.95 < m_{e^+e^-} < 3.14$ GeV/c^2 or $3.06 < m_{\mu^+\mu^-} < 3.14$ GeV/c^2 for decays to e^+e^- and to $\mu^+\mu^-$ respectively. The $\psi(2S)$ candidates are required to have invariant masses $3.44 < m_{e^+e^-} < 3.74$ GeV/c^2 or $3.64 < m_{\mu^+\mu^-} < 3.74$ GeV/c^2. Electron candidates are combined with photon candidates in order to recover some of the energy lost through bremsstrahlung. In the

χ_{c1} reconstruction, the associated γ has to satisfy shower shape requirements and has to have an energy greater than 150 MeV. The χ_{c1} candidates are required to satisfy $350 < m_{\ell^+\ell^-\gamma} - m_{\ell^+\ell^-} < 450$ MeV/c^2. The $\pi^0 \to \gamma\gamma$ candidates are required to satisfy $113 < m_{\gamma\gamma} < 153$ MeV/c^2. The energy of the soft photon has to be greater than 50 MeV, and the energy of the hard photon has to be greater than 150 MeV. The $K^0_S \to \pi^+\,\pi^-$ candidates are required to satisfy $489 < m_{\pi^+\pi^-} < 507$ MeV/c^2. In addition, the K^0_S flight distance from the Ψ vertex must be larger than 3 standard deviations. The K^{*0} and K^{*+} candidates are required to satisfy $796 < m_{K\pi} < 996$ MeV/c^2 and $792 < m_{K\pi} < 992$ MeV/c^2, respectively. In addition, due to the presence of a large background of low-energy non-genuine π^0's, the cosine of the angle θ_{K^*} between the K momentum and the B momentum in the K^* rest frame has to be less than 0.8 for $K^* \to K^\pm\pi^0$. For events which reconstruct to $B_a \to VK^*_a$ and $B_b \to VK^*_b$ modes, with K^*_a decaying to π^0 and K^*_b decaying to $\pi^\pm$, the B_a candidate is discarded, as $\pi^\pm \to \pi^0$ is observed to be the dominant source of cross-feed.

The B candidates, reconstructed by combining charmonium and K^* candidates, are characterized by two kinematic variables: the difference between the reconstructed energy of the B candidate and the beam energy in the center-of-mass frame $\Delta E = E^*_B - E^*_{beam}$, and the beam energy-substituted mass $m_{\rm ES}$, defined as $m_{\rm ES} \equiv \sqrt{E^{*2}_{beam} - \mathbf{p}^{*2}_B}$, where the asterisk refers to quantities in the center-of-mass and $\mathbf{p}_B$ is the B momentum. For a correctly reconstructed B meson, ΔE is expected to peak at zero and the energy-substituted mass $m_{\rm ES}$ at the B meson mass, 5.279 GeV/c^2. Only one reconstructed B meson is allowed per event. For events that have multiple candidates, the candidate having the smallest $|\Delta E|$ is chosen. The analysis is performed in a region of the $m_{\rm ES}$ vs ΔE plane defined by $5.2 < m_{\rm ES} < 5.3$ GeV/c^2 and $-120 < \Delta E < 120$ MeV. The signal region is defined as $m_{\rm ES} > 5.27$ GeV/c^2 and $|\Delta E|$ smaller than 40 or 30 MeV for channels with or without a π^0 respectively. Figure 1 shows the $m_{\rm ES}$ distributions for both data and Monte Carlo, within the ΔE signal region.

4 Angular Analysis

The B decay amplitudes are measured from the differential decay distribution, expressed in the transversity basis with angles $(\theta_{K^*}, \theta_{tr}, \phi_{tr})$ defined as follows ([3, 5], Fig. 2) [5]:

- θ_{K^*} is the helicity angle of the K^* decay. It is defined in the rest frame of the K^* meson, and is the angle between the kaon and the opposite direction of the B meson in this frame;
- θ_{tr} and ϕ_{tr} are defined in the Ψ (χ_{c1}) rest frame and are the polar and azimutal angle of the positive lepton (J/ψ daughter of χ_{c1}) , with respect the axis defined by:
  - $\boldsymbol{x}_{tr}$: opposite direction of the B meson;
  - $\boldsymbol{y}_{tr}$: perpendicular to $\boldsymbol{x}_{tr}$, in the $(\boldsymbol{x}_{tr}, \boldsymbol{p}_{K^*})$ plane, with a direction such that $\boldsymbol{p}_{K^*} \cdot \boldsymbol{y}_{tr} > 0$;
  - $\boldsymbol{z}_{tr}$: to complete the frame, ie: $\boldsymbol{z}_{tr} = \boldsymbol{x}_{tr} \times \boldsymbol{y}_{tr}$.

In terms of the angular variables $\boldsymbol{\omega} \equiv (\theta_{K^*}, \theta_{tr}, \phi_{tr})$, the time-integrated differential decay rate for the decay of the B meson is

$$g(\boldsymbol{\omega}; \boldsymbol{A}) \equiv \frac{1}{\Gamma} \frac{\mathrm{d}^3\Gamma}{\mathrm{d}\cos\theta_{K^*}\mathrm{d}\cos\theta_{tr}\mathrm{d}\phi_{tr}} = \sum_{i=1}^{6} \mathcal{A}_i f_i(\boldsymbol{\omega}), \tag{1}$$

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[5] The conventions regarding these frame definitions are detailed in [19, 20].

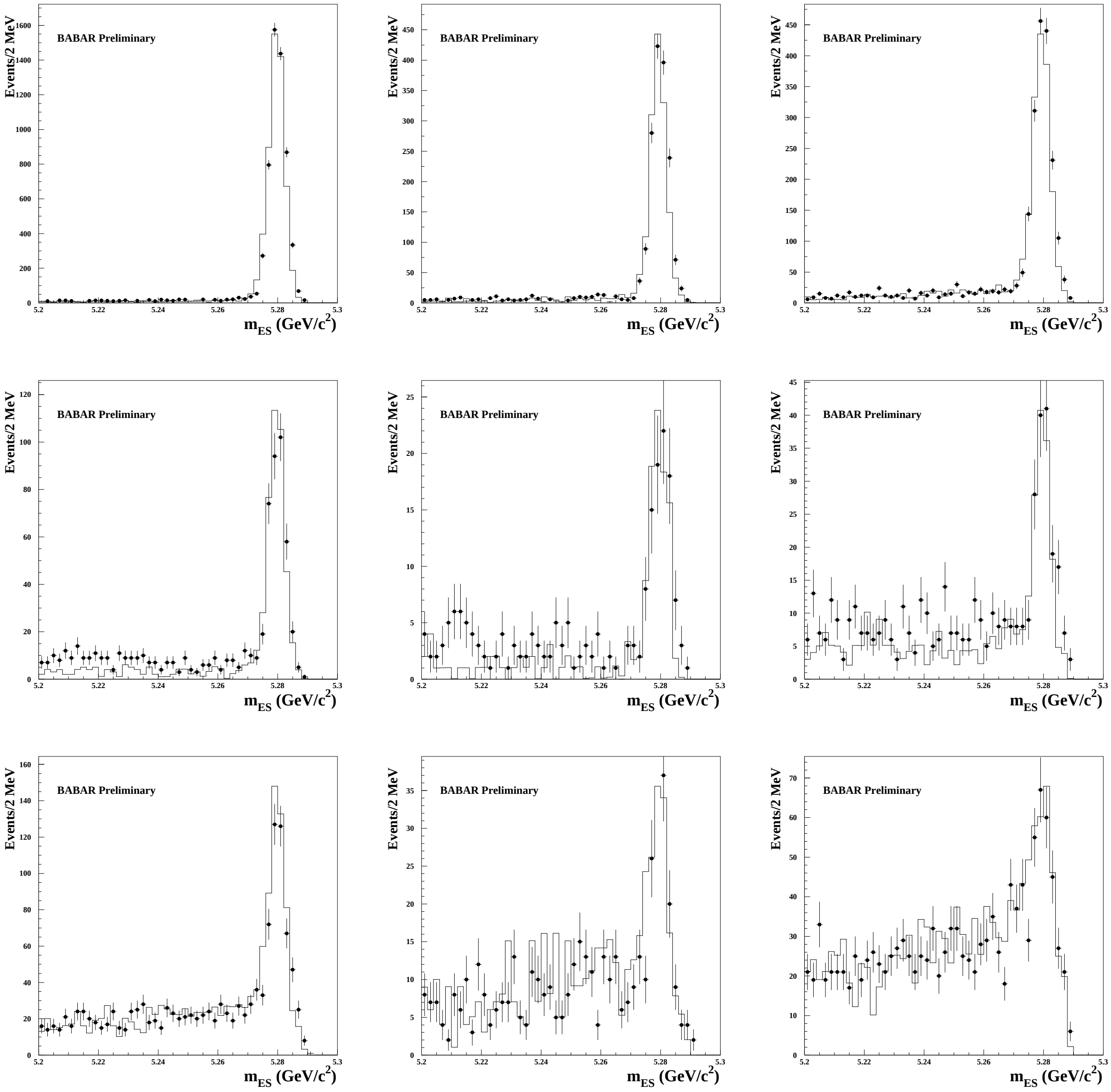

Figure 1: m_{ES} distributions within the ΔE signal region. From top to bottom the rows represent the J/ψ, $\psi(2S)$ and χ_{c1} channel. From left to right, the columns represent the $K^{*0}(K^+\pi^-)$, $K^{*+}(K^0_S\pi^+)$ and $K^{*+}(K^+\pi^0)$ channels. The points represent the data and the histograms represent the Monte Carlo.

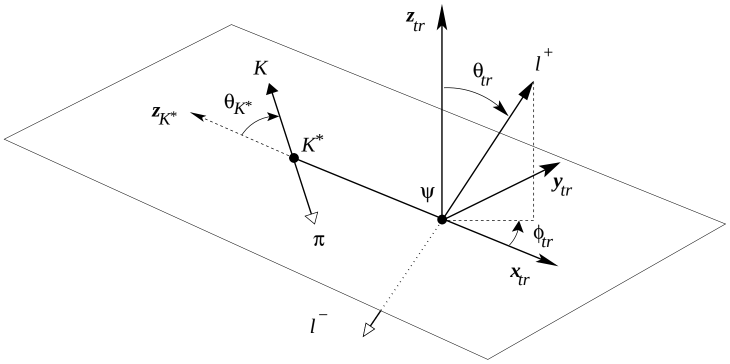

Figure 2: Definition of the transversity angles. Details are given in the text.

Table 1: Amplitude coefficients $\mathcal{A}_i$ and angular functions $f_i(\boldsymbol{\omega})$, that contribute to the differential decay rate of a B meson. An overall normalization factor $9/32\pi$ (for Ψ) and $9/64\pi$ (for χ_{c1}) has been omitted. In the case of a $\overline{B}$ decay, the $\Im m$ terms change sign.

i	$\mathcal{A}_i$	$f_i(\boldsymbol{\omega})$ for Ψ [3, 5]	$f_i(\boldsymbol{\omega})$ for χ_{c1} [19]
1	$\lvert A_0\rvert^2$	$2\cos^2\theta_{K^*}\left[1-\sin^2\theta_{tr}\cos^2\phi_{tr}\right]$	$2\cos^2\theta_{K^*}\left[1+\sin^2\theta_{tr}\cos^2\phi_{tr}\right]$
2	$\lvert A_\parallel\rvert^2$	$\sin^2\theta_{K^*}\left[1-\sin^2\theta_{tr}\sin^2\phi_{tr}\right]$	$\sin^2\theta_{K^*}\left[1+\sin^2\theta_{tr}\sin^2\phi_{tr}\right]$
3	$\lvert A_\perp\rvert^2$	$\sin^2\theta_{K^*}\sin^2\theta_{tr}$	$\sin^2\theta_{K^*}\left[2\cos^2\theta_{tr}+\sin^2\theta_{tr}\right]$
4	$\Im m(A_\parallel^* A_\perp)$	$\sin^2\theta_{K^*}\sin 2\theta_{tr}\sin\phi_{tr}$	$-\sin^2\theta_{K^*}\sin 2\theta_{tr}\sin\phi_{tr}$
5	$\Re e(A_\parallel A_0^*)$	$-\frac{1}{\sqrt{2}}\sin 2\theta_{K^*}\sin^2\theta_{tr}\sin 2\phi_{tr}$	$\frac{1}{\sqrt{2}}\sin 2\theta_{K^*}\sin^2\theta_{tr}\sin 2\phi_{tr}$
6	$\Im m(A_\perp A_0^*)$	$\frac{1}{\sqrt{2}}\sin 2\theta_{K^*}\sin 2\theta_{tr}\cos\phi_{tr}$	$-\frac{1}{\sqrt{2}}\sin 2\theta_{K^*}\sin 2\theta_{tr}\cos\phi_{tr}$

where the amplitude coefficients $\mathcal{A}_i$ and the angular functions $f_i(\boldsymbol{\omega})$, $i = 1\cdots 6$ are listed in Table 1. The Ψ decays to two spin-1/2 particles, while the χ_{c1} decays to two vector particles. The angular functions obtained are therefore different [19].

The symbol $\boldsymbol{A}$ denotes the transversity amplitudes for the decay of the B meson: $\boldsymbol{A} \equiv (A_0, A_\parallel, A_\perp)$. We denote by $\overline{\boldsymbol{A}}$ the amplitudes for the $\overline{B}$ meson decay. In the absence of direct *CP* violation, we can choose a phase convention in which these amplitudes are related by $\overline{A}_0 = +A_0$, $\overline{A}_\parallel = +A_\parallel$, $\overline{A}_\perp = -A_\perp$, so that $A_\perp$ is *CP*-odd and A_0 and $A_\parallel$ are *CP*-even. The phases δ_j of the amplitudes, where $j = 0, \parallel, \perp$, are defined by $A_j = |A_j|e^{i\delta_j}$. Phases are defined relative to $\delta_0 = 0$.

5 Acceptance Correction

We perform an unbinned likelihood fit of the three-dimensional angle PDF. The acceptance of the detector and the efficiency of the event reconstruction may vary as a function of the transversity angles, in particular as the angle θ_{K^*} is strongly correlated with the momentum of the final kaon and pion. The PDF of the observed events, g^{obs}, is :

$$g^{obs}(\boldsymbol{\omega};\boldsymbol{A}) = g(\boldsymbol{\omega};\boldsymbol{A})\frac{\varepsilon(\boldsymbol{\omega})}{\langle\varepsilon\rangle(\boldsymbol{A})}, \tag{2}$$

where $g(\boldsymbol{\omega};\boldsymbol{A})$ is given by Eq. (1), $\varepsilon(\boldsymbol{\omega})$ is the angle-dependent acceptance, and

$$\langle\varepsilon\rangle(\boldsymbol{A}) \equiv \int g(\boldsymbol{\omega};\boldsymbol{A})\varepsilon(\boldsymbol{\omega})\mathrm{d}\boldsymbol{\omega} \tag{3}$$

is the average acceptance. The presence of cross-feed from the companion channels which have, as a consequence of isospin symmetry, the same $\boldsymbol{A}$ dependence as that of the signal, is taken into account. The observed PDF for channel b ($b = K^{\pm}\pi^{\mp}, K^0_S\pi^{\pm}, K^{\pm}\pi^0$) is then

$$g^{b,obs}(\boldsymbol{\omega};\boldsymbol{A}) \quad = \quad g(\boldsymbol{\omega};\boldsymbol{A})\frac{\varepsilon^b(\boldsymbol{\omega})}{\sum_{k=1}^{6}\mathcal{A}_k(\boldsymbol{A})\Phi^b_k} \tag{4}$$

$\varepsilon^b(\boldsymbol{\omega})$ is the efficiency for reconstructed channel b considering $B \to (c\bar{c})K^*$ channels as a whole (for the three charmonium states separately), that is counting cross-feed events as signal. The Φ^b_k are the $f_k(\boldsymbol{\omega})$ moments of the "whole" efficiency ε^b. The expressions for $\varepsilon^b(\boldsymbol{\omega})$ and Φ^b_k are available and discussed in section IV.A of Ref. [3].

The acceptance $\varepsilon^b(\boldsymbol{\omega})$ can be expressed as in Eq. (4), and only the coefficients Φ^b_k are needed, under the approximations that the angular resolution can be neglected, including for cross-feed events, and that the double misidentification of the daughters of the $K^{*0} \to K^{\pm}\pi^{\mp}$ candidate (K–π swap) can be neglected. The biases induced by these approximations have been estimated with Monte Carlo (MC) based studies, and found to be negligible (see table IV of [3]).

The coefficients Φ^b_k are computed with exclusive signal MC samples obtained using a full simulation of the experiment [17, 21]. PID efficiencies measured with data control samples are used to adjust the MC simulation to the actual behavior of the detector. Separate coefficients are used for different charges of the final state mesons, in particular to take into account the charge dependence of the interaction of charged kaons with matter, and a possible charge asymmetry of the detector. Writing the expression for the log-likelihood $L^b(\boldsymbol{A})$ for the PDF $g^{b,obs}(\boldsymbol{\omega}_i;\boldsymbol{A})$ for a pure signal sample of N_S events, the relevant contribution is

$$L^b(\boldsymbol{A}) = \sum_{i=1}^{N_S}\ln\left(g(\boldsymbol{\omega}_i;\boldsymbol{A})\right) - N_S\ln\left(\sum_k \mathcal{A}_k(\boldsymbol{A})\Phi^b_k\right), \tag{5}$$

since the remaining term $\sum_{i=1}^{N_S}\ln\left(\varepsilon^b(\boldsymbol{\omega}_i)\right)$ does not depend on the amplitudes.

6 Background Correction

We use a background correction method described in section IV.B of Ref. [3], in which background events are added with a negative weight to the log-likelihood that is maximized

$$L^{b\prime}(\boldsymbol{A}) \equiv \sum_{i=1}^{n_B+N_S}\ln(g^{b,obs}(\boldsymbol{\omega}_i;\boldsymbol{A})) - \frac{\tilde{n}_B}{N_B}\sum_{k=1}^{N_B}\ln(g^{b,obs}(\boldsymbol{\omega}_k;\boldsymbol{A})). \tag{6}$$

The fit is performed within the m_{ES} signal region ($m_{\mathrm{ES}} > 5.27\,\mathrm{GeV}/c^2$) which contains N_B signal events. $\tilde{n}_B$ is an estimate of the unknown number n_B of background events that are present in the signal region in the data sample. In Ref. [3] background events were estimated from the data by fitting the $m_{\rm ES}$ distribution in the sideband region and extrapolating in the $m_{\rm ES}$ signal region. This method assumed that the background has only a combinatorial contribution and no peaking contribution. This is a valid argument for the J/ψ channels, but not the $\psi(2S)$ and χ_{c1} channels where peaking backgrounds are known to have a non-negligigle contribution. Therefore, in this analysis, the background (combinatorial and peaking) has been taken from generic MC. As $L^{b\prime}$ is not a log-likelihood, the uncertainties yielded by the minimization program `Minuit` [22] are biased estimates of the actual uncertainties. An unbiased estimation of the uncertainties is described and validated in Appendix A of Ref. [3]. With this pseudo-log-likelihood technique, we avoid parametrizing the acceptance as well as the background angular distributions.

7 Systematics

The measurement is affected by several systematic uncertainties. The branching ratios that are used in the cross-feed part of the acceptance cross section are varied by $\pm 1\sigma$, and the largest variation is retained. The uncertainty induced by the finite size of the MC sample used to compute the coefficients Φ_k^b is estimated by the statistical uncertainty of the angular fit on that MC sample (shift additivity [5]). The uncertainty due to our limited understanding of the PID is estimated by using two different methods to correct for the MC-vs-data differences. The background uncertainty is obtained by comparing MC and data shapes of the $m_{\rm ES}$ distributions for the combinatorial component and by using the corresponding branching errors for the peaking component. The uncertainty due to the presence of a $K\pi$ S wave under the $K^*(892)$ peak is estimated by a fit including it. The differential decay rate is described by eqs. (6–9) of Reference [3].

8 Results

The results are summarized in Table 2. The values of $|A_0|^2$, $|A_\parallel|^2$, $|A_\perp|^2$ turn out to be negatively correlated, as is expected for quantities the sum of which is unity. In particular, $|A_\parallel|^2$, which would be the least precisely measured parameter in separate one-dimensional fits, is strongly anti-correlated with $|A_0|^2$, which would be the best measured. The one-dimensional (1D) distributions, acceptance-corrected with an 1D Ansatz [6] , and background-subtracted, are overlaid with the fit results and shown on figure 4. As in lower statistics studies, the $\cos\theta_{K^*}$ forward backward asymmetry due to the interference with the S wave is clearly visible.

Table 2: Summary of the amplitudes measured. In the case of decays to χ_{c1}, $A_\perp$ is compatible with zero, and therefore its phase is not defined.

Channel	$\lvert A_0\rvert^2$	$\lvert A_\parallel\rvert^2$	$\lvert A_\perp\rvert^2$	$\delta_\parallel$	$\delta_\perp$
$J/\psi K^*$	$0.556 \pm 0.009 \pm 0.010$	$0.211 \pm 0.010 \pm 0.006$	$0.233 \pm 0.010 \pm 0.005$	$-2.93 \pm 0.08 \pm 0.04$	$2.91 \pm 0.05 \pm 0.03$
$\psi(2S)K^*$	$0.48 \pm 0.05 \pm 0.02$	$0.22 \pm 0.06 \pm 0.02$	$0.30 \pm 0.06 \pm 0.02$	$-2.8 \pm 0.4 \pm 0.1$	$2.8 \pm 0.3 \pm 0.1$
$\chi_{c1}K^*$	$0.77 \pm 0.07 \pm 0.04$	$0.20 \pm 0.07 \pm 0.04$	$0.03 \pm 0.04 \pm 0.02$	$0.0 \pm 0.3 \pm 0.1$	–

A graphical representation is given in Fig. 3.

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[6] In contrast with the dedicated method used in the fit, for the plots, we simply computed the 1D efficiency maps from the distributions of the accepted events divided by the 1D PDF.

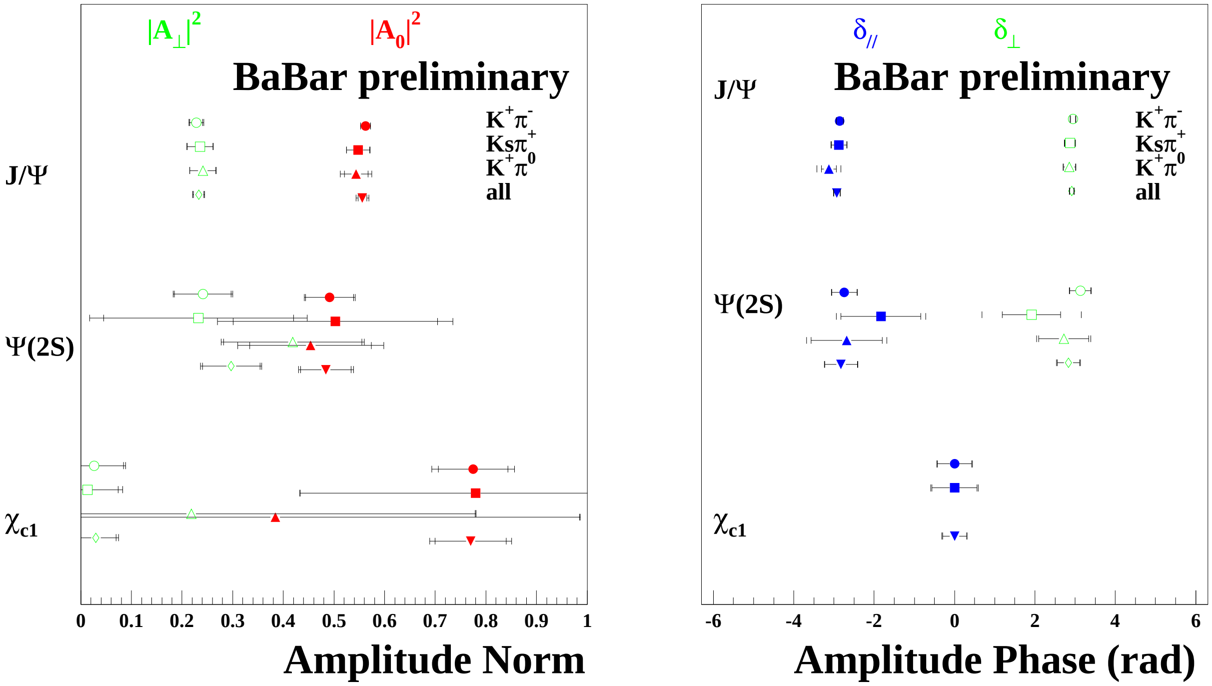

Figure 3: Data : Results of the fits. Left : norms ($|A_0|^2$ in red, $|A_\parallel|^2$ in green), Right : phases ($\delta_\parallel$ in blue, $\delta_\perp$ in green). Circles :$K^\pm\ \pi^\mp$; Squares : $K^0_S\ \pi^+$; Up triangles : $K^\pm\ \pi^0$, Down triangles : all K^*'s combined. In the case of decays to χ_{c1}, $A_\perp$ is compatible with zero, and therefore its phase is not defined. (the $K^+\pi^0$ contribution is removed in computing $\delta_\parallel$ for χ_{c1}, as $|A_\parallel|^2$ is compatible with zero). For each charmonium and each measurement, the results for the individual channels are shown together with the average.

Table 3: Difference between the interference terms measured in B and $\overline{B}$ decays to J/ψ.

	$(K^+\pi^-)$	$(K^+\pi^0)$	$(K^0_S\pi^+)$
$\delta\mathcal{A}_4$	$0.002 \pm 0.025 \pm 0.005$	$-0.017 \pm 0.047 \pm 0.023$	$-0.008 \pm 0.049 \pm 0.011$
$\delta\mathcal{A}_6$	$-0.011 \pm 0.043 \pm 0.016$	$-0.051 \pm 0.098 \pm 0.064$	$0.075 \pm 0.089 \pm 0.009$

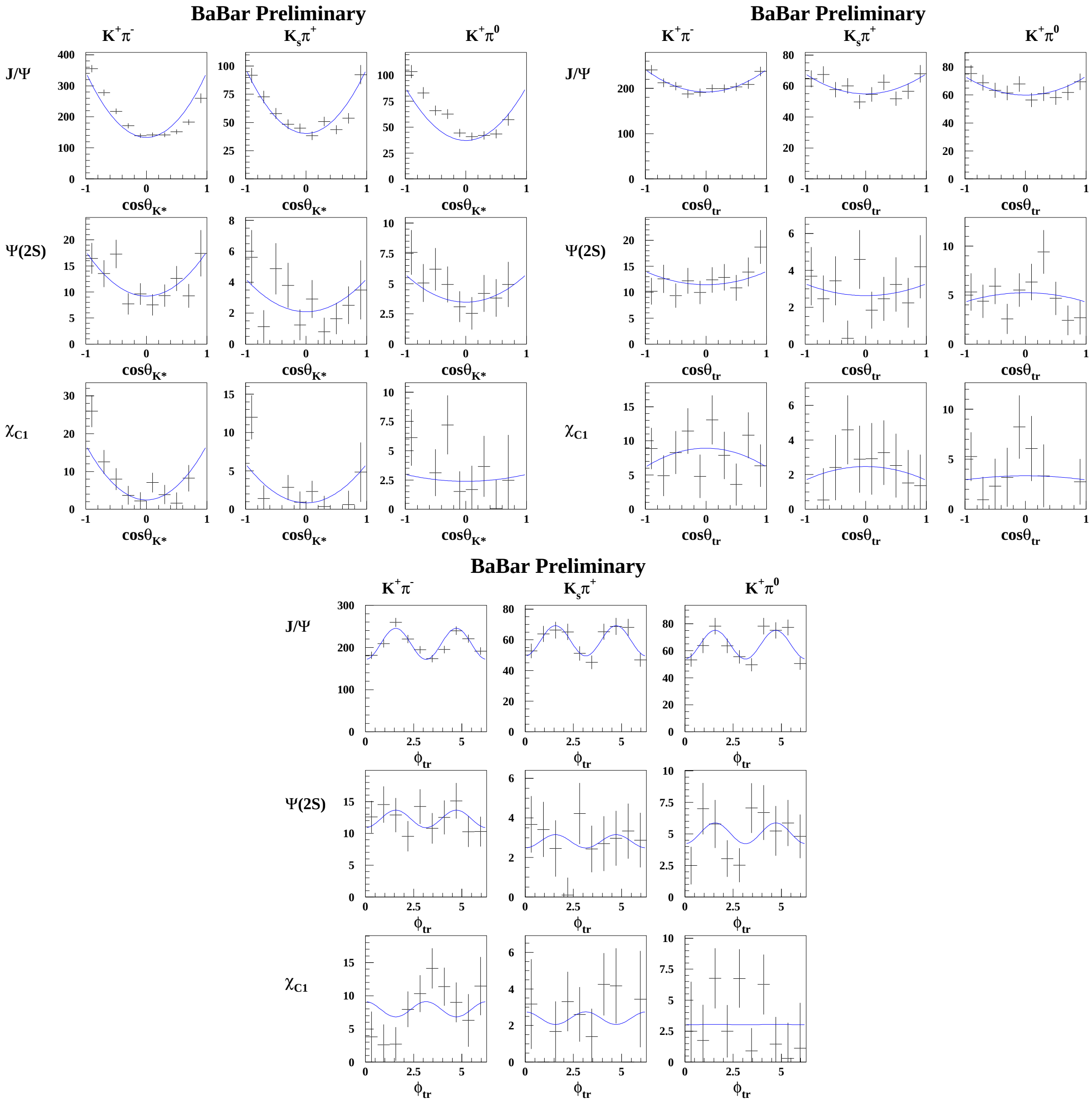

Figure 4: Angular distributions with PDF from fit overlaid. The asymmetry of the $\cos\theta_{K^*}$ distributions induced by the S-wave inteference is clearly visible.

In summary,

- Our measurement of the amplitudes of B decays to J/ψ are compatible with, and of better precision than, previous measurements.
- From a comparison of B^0 and B^+ decays, isospin is seen to be conserved in the decay.
- We confirm our previous observation that the strong phase differences are significantly different from zero, in contrast with what is predicted by factorization. For $B \rightarrow J/\psi K^*$, it amounts to $\delta_{\parallel} - \delta_{\perp} = 0.45 \pm 0.05 \pm 0.02$, an 8σ effect.
- The presence of direct *CP*-violating triple-products in the amplitude would produce a B to $\overline{B}$ difference in the interference terms $\mathcal{A}_4$ and $\mathcal{A}_6$: $\delta\mathcal{A}_4$ and $\delta\mathcal{A}_6$. This is not observed as all the measurement are compatible with zero (see Table 3), with an improved precision with respect to the BELLE measurement [23].
- We have performed the first three-dimensional analysis of the decays to $\psi(2S)$ and χ_{c1}. The longitudinal polarization of the decay to $\psi(2S)$ is smaller than that of the J/ψ, while the *CP*-odd intensity fraction of the two decays are similar. This is compatible with the prediction of models of meson decays in the framework of factorization.

  The longitudinal polarization of the decay to χ_{c1} is found to be larger than that to J/ψ, in contrast with the predictions of Ref. [11] which include non-factorizable contributions. The *CP*-odd intensity fraction of this decay is compatible with zero. The phases of the parallel and of the longitudinal amplitudes are observed to be compatible with each other, in contrast with decays to Ψ.

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