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Measurements of the Branching Fraction and Time-Dependent *CP* Asymmetries of $B^0 \to J/\psi\,\pi^0$ Decays

The *BABAR* Collaboration

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Abstract

We present measurements of the branching fraction and time-dependent *CP* asymmetries in $B^0 \to J/\psi\,\pi^0$ decays based on $(231.8 \pm 2.6) \times 10^6$ $\Upsilon(4S) \to B\overline{B}$ decays collected with the *BABAR* detector at the PEP-II asymmetric-energy B factory at SLAC during the years 1999-2004. We obtain a branching fraction $\mathcal{B}(B^0 \to J/\psi\,\pi^0) = (1.94 \pm 0.22\ (\text{stat}) \pm 0.17\ (\text{syst})) \times 10^{-5}$. We also measure the *CP* asymmetry parameters $C = -0.21 \pm 0.26$ (stat) $\pm$ 0.09 (syst) and $S = -0.68 \pm 0.30$ (stat) $\pm$ 0.04 (syst). All results presented in this paper are preliminary.

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1 Introduction

Charge conjugation-parity (CP) violation in the B meson system has been established by the *BABAR* [1] and Belle [2] collaborations. The Standard Model (SM) of electroweak interactions describes CP violation as a consequence of a complex phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [3]. Measurements of CP asymmetries in the proper-time distribution of neutral B decays to CP eigenstates containing a charmonium and K^0 meson provide a precise measurement of $\sin 2\beta$ [4], where β is $\arg\left[-V_{\rm cd}V_{\rm cb}^*/V_{\rm td}V_{\rm tb}^*\right]$ and the V_{ij} are CKM matrix elements.

The decay $B^0 \to J/\psi\,\pi^0$ is a CP-even Cabibbo-suppressed $b \to c\overline{c}d$ transition for which, in the absence of loop (penguin) amplitudes, the SM predicts that the two CP asymmetry coefficients, S, the interference between mixing and decay, and C, the direct CP asymmetry, are $S = -\sin 2\beta$, and $C = 0$. S and C are defined as:

$$S \equiv \frac{2\,\mathcal{I}m\lambda}{1+|\lambda|^2} \qquad \text{and} \qquad C \equiv \frac{1-|\lambda|^2}{1+|\lambda|^2}, \tag{1}$$

where λ is a complex parameter that depends on both the B^0-$\overline{B}^0$ oscillation amplitude and the amplitudes describing B^0 and $\overline{B}^0$ decays to the $J/\psi\,\pi^0$ final state. The tree and penguin amplitudes expected to dominate this decay are shown in Figure 1.

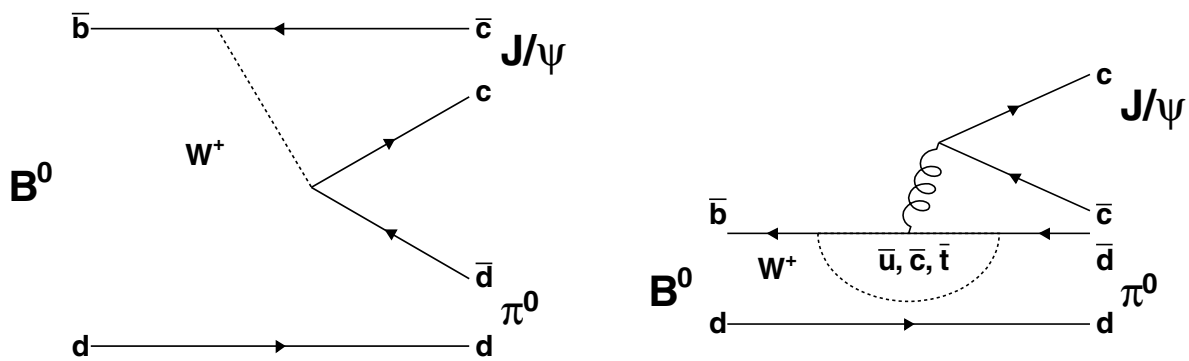

Figure 1: Feynman diagrams of the color suppressed tree (left) and gluonic penguin (right) amplitudes contributing to the $B^0 \to J/\psi\,\pi^0$ decay.

The $b \to c\overline{c}d$ tree amplitude has the same weak phase as the $b \to c\overline{c}s$ modes (e.g. the CP-odd decay $B^0 \to J/\psi\,K^0_S$). The $b \to c\overline{c}d$ penguin amplitudes have a different weak phase than the tree amplitude. If there is a significant penguin amplitude in $B^0 \to J/\psi\,\pi^0$, then one will measure a value of S that differs from $-\sin 2\beta$, and a value of C that differs from zero [5].

In this paper, we present an update of previous *BABAR* measurements of the branching fraction and time-dependent CP violating (CPV) asymmetries in $B^0 \to J/\psi\,\pi^0$ [6, 7]. The preliminary results presented here are obtained using 210.6 fb^{-1} of data. *BABAR* and Belle have both previously presented measurements of the $B^0 \to J/\psi\,\pi^0$ branching fraction using $\Upsilon(4S) \to B\overline{B}$ decays. These are:

BABAR:	$(2.0 \pm 0.6\ (\text{stat}) \pm 0.2\ (\text{syst}))\times 10^{-5}$	(from 20.7 fb^{-1})	[6],
Belle:	$(2.3 \pm 0.5\ (\text{stat}) \pm 0.2\ (\text{syst}))\times 10^{-5}$	(from 29.4 fb^{-1})	[8].

Both the *BABAR* and Belle notations in denoting the magnitude of the direct *CP* asymmetry, where C (*BABAR*) $= -A$ (Belle), the previous measurements of S and C (A) are:

BABAR:	$S = 0.05 \pm 0.49 \pm 0.16$	$C = 0.38 \pm 0.41 \pm 0.09$	(from 81.1 fb^{-1})	[7],
Belle:	$S = -0.72 \pm 0.42 \pm 0.09$	$A = -0.01 \pm 0.29 \pm 0.03$	(from 140.0 fb^{-1})	[9].

2 The *BABAR* detector and dataset

The data used in this analysis were collected with the *BABAR* detector at the PEP-II asymmetric e^+e^-storage ring from 1999 to 2004. This represents a total integrated luminosity of 210.6 fb^{-1} taken at the Υ(4S) resonance (onpeak), corresponding to a sample of 231.8 ± 2.6 million $B\overline{B}$ pairs. An additional 21.6 fb^{-1} of data, collected at approximately 40 MeV below the Υ(4S) resonance, is used to study background from $e^+e^- \to q\overline{q}$ ($q = u, d, s, c$) continuum events.

The *BABAR* detector is described elsewhere [10]. Surrounding the interaction point is a 5 layer double-sided silicon vertex tracker (SVT) which provides precise reconstruction of track angles and B decay vertices. A 40 layer drift chamber (DCH) surrounds the SVT and provides measurements of the transverse momenta for charged particles. Both the SVT and the DCH operate in a 1.5 T solenoidal magnetic field. Charged hadron identification is achieved through measurements of particle energy-loss (dE/dx) in the tracking system and Čerenkov angle obtained from a detector of internally reflected Čerenkov light (DIRC). This is surrounded by a segmented CsI(Tl) electromagnetic calorimeter (EMC) which provides photon detection, electron identification, and is used to reconstruct neutral hadrons. Finally, the instrumented flux return (IFR) of the magnet allows discrimination of muons from pions.

3 Analysis Method

We study $B^0 \to J/\psi\,\pi^0$ decays in $B\overline{B}$ candidate events from combinations of $J/\psi \to \ell^+\ell^-$ ($\ell =$ e, μ) and $\pi^0 \to \gamma\gamma$ candidates. A detailed description of the $J/\psi \to \ell^+\ell^-$ selection can be found elsewhere [6]. For the $J/\psi \to e^+e^-$ ($J/\psi \to \mu^+\mu^-$) channel, the invariant mass of the lepton pair is required to be between 3.06 and 3.12 GeV/c^2 (3.07 and 3.13 GeV/c^2).

We form $\pi^0 \to \gamma\gamma$ candidates with an invariant mass $100 < m_{\gamma\gamma} < 160$ MeV/c^2 from pairs of photon candidates which have been identified as clusters in the EMC. These clusters are required to be isolated from any charged tracks, carry a minimum energy of 30 MeV, and have a lateral energy distribution consistent with that of a photon. Each π^0 candidate is required to have a minimum energy of 200 MeV and is constrained to the nominal mass [11].

The $B^0 \to J/\psi\,\pi^0$ candidates (B_{rec}) are reconstructed from these J/ψ and π^0 candidates and constrained to originate from the e^+e^- interaction point using a geometric fit. Finally, the J/ψ and π^0 candidates are combined using 4-momentum addition.

We use two kinematic variables, $m_{\rm ES}$ and ΔE, in order to isolate the signal.
$m_{\rm ES} = \sqrt{(\sqrt{s}/2)^2 - (p^*_B)^2}$ is the beam-energy substituted mass, where $\sqrt{s}$ is the center-of-mass

(CM) energy, and therefore $\sqrt{s}/2$ is the beam energy in the CM frame. p_B^* is the B-candidate momentum in the CM frame. ΔE is the difference between the B-candidate energy and the beam energy in the e^+e^- CM frame. We require $m_{\rm ES} > 5.2\,{\rm GeV}/c^2$ and $|\Delta E| < 0.3\,{\rm GeV}$.

A significant source of background is due to $e^+e^- \to q\overline{q}$ ($q = u, d, s, c$) continuum events. We combine several kinematic and topological variables into a Fisher discriminant (F) to provide additional separation between signal and continuum. The three variables L_0, L_2 and $\cos(\theta_H)$ are inputs to F. L_0 and L_2 are the zeroth- and second-order Legendre polynomial moments; $L_0 = \sum_i |\mathbf{p}_i^*|$ and $L_2 = \sum_i |\mathbf{p}_i^*| \frac{3\cos^2\theta_i - 1}{2}$, where $\mathbf{p}_i^*$ are the CM momenta for the tracks and neutral calorimeter clusters that are not associated with the signal candidate. The θ_i are the angles between $\mathbf{p}_i^*$ and the thrust axis of the signal candidate. θ_H is the angle between one of the leptons and the B candidate in the J/ψ rest frame.

We use multivariate algorithms to identify signatures of B decays that determine (tag) the flavor of the decay of the other B in the event (B_{tag}) to be either a B^0 or $\overline{B}^0$. The flavor tagging algorithm used is described in more detail elsewhere [12]. In brief, we define seven mutually exclusive tagging categories. These are (in order of decreasing signal purity) `Lepton`, `Kaon 1`, `Kaon 2`, `Kaon-Pion`, `Pion`, `Other`, and `No-Tag`. The total effective tagging efficiency of this algorithm is $(30.5 \pm 0.4)\%$.

The decay rate f_+ (f_-) of B^0 decays to a CP eigenstate, when B_{tag} is a B^0 ($\overline{B}^0$), is:

$$f_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}[1 \pm S\sin(\Delta m_d \Delta t) \mp C\cos(\Delta m_d \Delta t)], \tag{2}$$

where Δt is the difference between the proper decay times of the B_{rec} and B_{tag} mesons, $\tau_{B^0} = 1.536 \pm 0.014$ ps is the B^0 lifetime and $\Delta m_d = (0.502 \pm 0.007) \times 10^{-12}$s is the B^0-$\overline{B}^0$ oscillation frequency [11]. The decay width difference between the B^0 mass eigenstates is assumed to be zero.

The time interval Δt is calculated from the measured separation Δz between the decay vertices of B_{rec} and B_{tag} along the collision axis (z). The vertex of B_{rec} is from the lepton tracks that come from the J/ψ and the vertex of B_{tag} is constructed from the remaining tracks in the event that do not belong to B_{rec}, whilst using constraints from the beam spot location and the B_{rec} momentum. We accept events with $|\Delta t| < 20\,$ps whose uncertainty is less than $2.5\,$ps.

After all of the selection cuts mentioned above have been applied, the average multiplicity is approximately 1.1, indicating some events still have multiple candidates. In these events, we randomly choose one candidate to be used in the fit. After this step, the signal efficiency is 22.0% and a total of 1318 onpeak events are selected.

In addition to signal and continuum background events, there are also B backgrounds present in the data after applying the selection cuts above. We divide the B backgrounds into the following types: (i) $B^0 \to J/\psi\, K_S$, (ii) generic neutral B meson decays, and (iii) generic charged B meson decays. From Monte Carlo (MC) we expect 153 ± 9, 68 ± 14 and 314 ± 63 events of these background types, respectively. The generic neutral B meson decays do not include signal or $B^0 \to J/\psi\, K_S$ events. The generic B decay backgrounds are dominated by contributions from $B \to J/\psi X$ (inclusive charmonium final states). In particular the generic charged B meson decay backgrounds are dominated by $B^\pm \to J/\psi\rho^+$ decays. The $B^0 \to J/\psi\, K_S$ background was studied separately since it is a well understood decay with respect to time-dependent analysis.

We perform an extended unbinned maximum likelihood fit to the B candidate sample, where the discriminating variables used in the fit are $m_{\rm ES}$, ΔE, F and Δt. The values of the signal yield, S and C are simultaneously extracted.

The signal $m_{\rm ES}$ distribution is described by a Gaussian with an exponential tail [13]. We parameterise the $m_{\rm ES}$ distribution for continuum and neutral generic B background with a phase

space distribution [14]. As there are significant correlations between $m_{\rm ES}$ and ΔE for the charged generic B background, we parameterise these variables with two-dimensional non-parametric probability density functions (PDFs). We use two-dimensional non-parametric PDFs when describing the $m_{\rm ES}$-ΔE distribution for $B^0 \to J/\psi\, K_S$. The ΔE distribution for signal events is modeled with a Gaussian with an exponential tail on the negative side to model energy leakage in the EMC, plus a polynomial contribution. The ΔE distribution for continuum and neutral generic B background are described by polynomials. The F distributions for the signal and the backgrounds are described by a Gaussian with different widths above and below the mean (a bifurcated Gaussian).

The signal decay rate distribution of Equation 2 is modified to account for dilution coming from incorrectly assigning the flavor of B_{tag} and is convoluted with a triple Gaussian resolution function, whose core width is about 1.1 ps. The decay rate distribution for B backgrounds is similar to that for signal. To account for their mis-reconstruction, the generic B backgrounds are assigned an effective lifetime instead of their respective measured B lifetimes. When evaluating systematic uncertainties, we allow for *CP* violation in the generic B background. This is described later in the text. The decay rate distribution for $B^0 \to J/\psi\, K_S$ is the same as that for signal and accounts for the known level of *CP* violation in that decay. The continuum background is modeled with a prompt lifetime component convoluted with a triple Gaussian resolution function.

The results from the fit are 109 ± 12 (stat) signal events, with $S = -0.68 \pm 0.30$ (stat) and $C = -0.21 \pm 0.26$ (stat). We also obtain for the aforementioned mutually exclusive tagging categories, the following numbers of continuum events: $\mathrm{N}_{\texttt{Lepton}} = 17 \pm 5$, $\mathrm{N}_{\texttt{Kaon1}} = 38 \pm 8$, $\mathrm{N}_{\texttt{Kaon2}} = 101 \pm 12$, $\mathrm{N}_{\texttt{KaonPion}} = 102 \pm 12$, $\mathrm{N}_{\texttt{Pion}} = 115 \pm 12$, $\mathrm{N}_{\texttt{Other}} = 94 \pm 11$ and $\mathrm{N}_{\texttt{NoTag}} = 227 \pm 17$.

Figure 2 shows the distributions of $m_{\rm ES}$, ΔE, and F for the data. In these plots the signal has been enhanced by cutting on $|\Delta E| < 0.1\,\mathrm{GeV}$ for the $m_{\rm ES}$ plot, $m_{\rm ES} > 5.275\,\mathrm{GeV}/c^2$ for the ΔE plot and by applying both of these constraints for the F plot. After applying these requirements to the signal (background) samples that are used in the fit, they are reduced to a relative size of 83.1% (24.3%), 85.0% (21.1%) and 73.1% (2.8%) for the $m_{\rm ES}$, ΔE, and F distributions respectively.

Figure 3 shows the Δt distribution for B^0 and $\overline{B}^0$ tagged events. The time-dependent decay-rate asymmetry $[N(\Delta t) - \overline{N}(\Delta t)]/[N(\Delta t) + \overline{N}(\Delta t)]$ is also shown, where N ($\overline{N}$) is the decay-rate for B^0 ($\overline{B}^0$) tagged events and the decay-rate takes the form of Equation 2.

4 Systematic Studies

Table 1 summarises the systematic uncertainties on the signal yield, S and C. Each entry in the table indicates one systematic effect and these are added in quadrature to give the totals presented. These include the uncertainty due to the PDF parameterisation, evaluated by fixing both the signal and the background PDF parameters to their nominal values and varying them within uncertainties; the effect of SVT mis-alignment; the uncertainty due to knowledge of the Lorentz boost and z-scale of the tracking system, and knowledge of the event-by-event beam spot position.

The uncertainty coming from the fit bias is estimated by performing ensembles of mock experiments using signal MC which is generated using the GEANT based *BABAR* MC simulation [15], embedded into MC samples of background generated from the PDF. The deviation from input values is added in quadrature to the error on the deviation in order to obtain the fit bias uncertainty. Most, but not all of the inclusive charmonium final states which dominate the generic B background, are precisely known from previous measurements. Their yields are then fixed in the fit. As a crosscheck, we allow the backgrounds to vary in the fit to data to validate the expected yields and to provide a systematic uncertainty. We also apply an additional systematic uncertainty

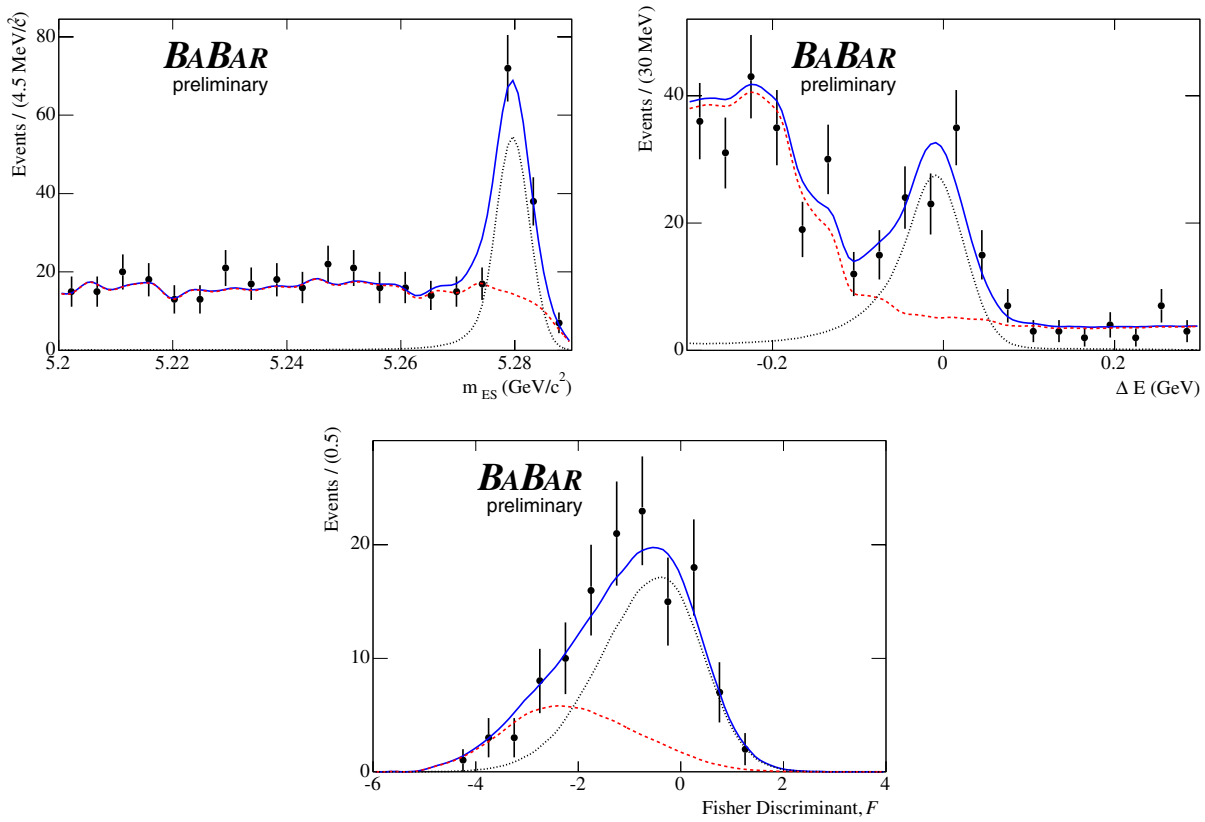

Figure 2: Signal enhanced distributions of $m_{\rm ES}$ (top), ΔE (center) and F (bottom) for the data (black points). The (blue) solid line represents the total likelihood, the (red) dashed line is the sum of the backgrounds and the (black) dotted line is the signal. The undulations in the background model are the result of limited MC statistics available for defining the two-dimensional non-parametric PDFs.

to account for neglecting the small correlation between $m_{\rm ES}$ and ΔE in signal and neutral generic B background events.

In order to evaluate the uncertainty coming from CP violation in the B background, we have allowed S and C to vary between $+1$ and -1 for the neutral generic B background, and for the direct CP asymmetry to vary between $+0.5$ and -0.5 for the charged generic B background. The CP parameters in $B^0 \to J/\psi\, K_S$ are varied within current experimental knowledge [12].

The generic B background uses an effective lifetime in the nominal fit. We replace this with the B lifetime to evaluate the systematic error due to CP background lifetime. There is also a small asymmetry in the tagging efficiency between B^0 and $\overline{B}^0$ tagged events, for which a systematic uncertainty is evaluated. We also study the possible interference between the suppressed $\overline{b} \to \bar{u}c\overline{d}$

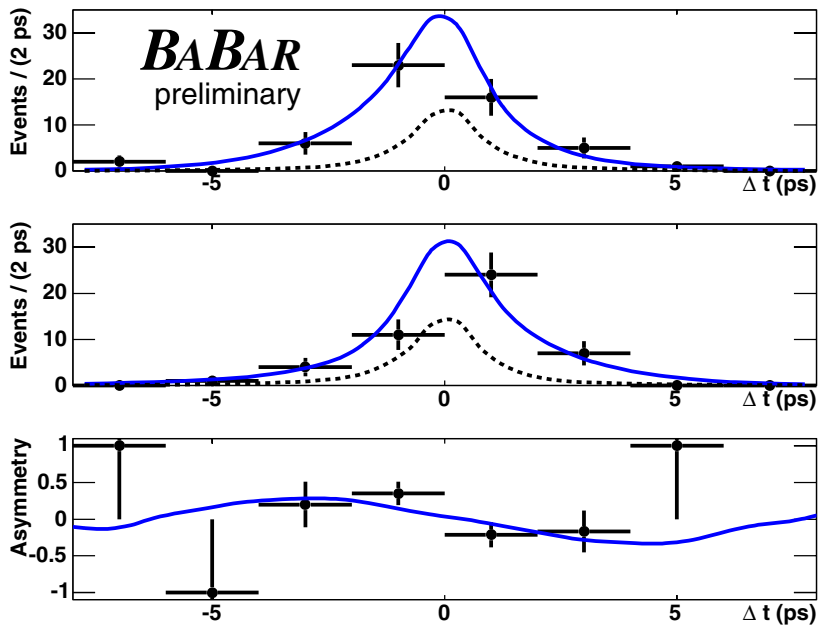

Figure 3: The Δt distribution for a sample of events enriched in signal for B^0 (top) and $\overline{B}^0$ (middle) tagged events. The dotted lines are the sum of backgrounds and the solid lines are the sum of signal and backgrounds. The time-dependent CP asymmetry (see text) is also shown (bottom), where the curve is the measured asymmetry.

amplitude with the favored $b \to c\bar{u}d$ amplitude for some tag-side B decays [16]. The difference in the distribution of F between data and MC is evaluated with a large sample of $B \to D^\star \rho$ decays.

There are additional systematic uncertainties that contribute only to the branching fraction. These come from uncertainties in charged particle identification (5.2%), π^0 meson reconstruction (3%), the $J/\psi \to \ell^+\ell^-$ branching fractions (2.4%), tracking efficiency (1.2%) and the number of B meson pairs (1.1%). The systematic error contribution from MC statistics is negligible.

5 Summary

The 109 ± 12 signal events correspond to a preliminary branching fraction of

$$\mathcal{B}(B^0 \to J/\psi\, \pi^0) = (1.94 \pm 0.22(\text{stat}) \pm 0.17(\text{syst})) \times 10^{-5}$$

which is consistent with previous measurements from the B Factories. We determine the preliminary CP asymmetry parameters

$$C = -0.21 \pm 0.26(\text{stat}) \pm 0.09(\text{syst}),$$
$$S = -0.68 \pm 0.30(\text{stat}) \pm 0.04(\text{syst}),$$

where the correlation between S and C is 8.3%. The value of S is consistent with SM expectations for a tree-dominated $b \to c\bar{c}d$ transition of $S = -\sin 2\beta$ and $C = 0$.

Table 1: Contributions to the systematic errors on the signal yield, S and C. Additional systematic uncertainties that are applied only to the branching fraction are discussed in the text.

Contribution	Signal yield	S	C
SVT mis-alignment	$-$	± 0.002	± 0.002
Boost and z-scale	$^{+0.08}_{-0.16}$	± 0.004	± 0.001
Beam spot position	$-$	± 0.007	± 0.002
PDF parameterisation	$^{+3.21}_{-2.88}$	± 0.013	$^{+0.009}_{-0.012}$
Fit bias	± 3.00	± 0.030	± 0.060
Generic B background yields	± 3.52	± 0.003	± 0.020
Choice of 1D v 2D PDFs	± 2.92	± 0.020	± 0.002
CP content of B background	$^{+0.40}_{-0.26}$	$^{+0.020}_{-0.018}$	± 0.058
CP background lifetime	± 0.67	± 0.010	± 0.010
Tagging efficiency asymmetry	± 0.02	± 0.000	± 0.020
Tag-side interference	$-$	± 0.004	± 0.014
Fisher data/MC comparison	± 0.70	± 0.004	± 0.004
Total	$^{+6.43}_{-6.26}$	$^{+0.044}_{-0.043}$	± 0.093

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