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Reconstruction of $B^0 \rightarrow$ J/ψ K_s^0 and Measurement of Ratios of Branching Ratios Involving B $\rightarrow$ J/$\psi K^{(*)}$

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Reconstruction of $B^0 \to J/\psi K^0_S$ and Measurement of Ratios of Branching Ratios Involving $B \to J/\psi K^{(*)}$

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We report on the reconstruction of the decay mode $B^0 \rightarrow J/\psi K^0_S$ using 19.3 pb^{-1} of data collected by the Collider Detector at Fermilab in $\bar{p}p$ collisions at $\sqrt{s} =$ 1.8 TeV. A signal of 41.8 ± 6.9 events, with a signal-to-background ratio of 9:1, is observed. Three additional decay modes $B^+ \rightarrow J/\psi K^+$, $B^0 \rightarrow J/\psi K^*(892)^0$ and $B^+ \rightarrow J/\psi K^*(892)^+$ are reconstructed. We measure three ratios of branching ratios, each one relative to the $B^+ \rightarrow J/\psi K^+$ mode. We also report the ratio of production rates, $\Gamma(B \rightarrow J/\psi K^*)/\Gamma(B \rightarrow J/\psi K)$, for the vector-vector relative to the vector-pseudoscalar modes, to be 1.32 ± 0.23 (stat.) $\pm$ 0.16 (syst.).

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This Letter reports on the reconstruction of the decay $B^0 \rightarrow J/\psi K^0_S$ [1] with the subsequent decay $K^0_S \rightarrow \pi^+\pi^-$ and on three additional $B \rightarrow J/\psi K^{(*)}$ modes [2]. We reconstruct the isospin partner $B^+ \rightarrow J/\psi K^+$ and the pseudoscalar-to-vector-vector transitions, $B^0 \rightarrow J/\psi K^*(892)^0$ and $B^+ \rightarrow J/\psi K^*(892)^+$. We measure three ratios of branching ratios: $BR(B^0 \rightarrow J/\psi K^0)/BR(B^+ \rightarrow J/\psi K^+)$, $BR(B^0 \rightarrow J/\psi K^*(892)^0)/BR(B^+ \rightarrow J/\psi K^+)$, $BR(B^+ \rightarrow J/\psi K^*(892)^+)/BR(B^+ \rightarrow J/\psi K^+)$, and report the ratio formed by combining the pseudoscalar-to-vector-vector modes relative to the pseudoscalar-to-vector-pseudoscalar modes, which we refer to as the "vector-pseudoscalar ratio". By forming ratios, we minimize several systematic uncertainties, the largest of which are associated with the b-quark production cross section and transverse momentum spectrum. Together with information on the polarization in the decay $B \rightarrow J/\psi K^*$ [3–5], these decay modes are of particular interest to test theoretical predictions that depend on the factorization hypothesis [6,7] and the $B \rightarrow K^{(*)}$ form factor [8].

The decay mode $B^0 \rightarrow J/\psi K^0_S$ is expected to provide the first observation of CP violation outside the kaon system. From a theoretical point of view, the decay $B^0 \rightarrow J/\psi K^0_S$

has several properties that make it ideal for the search for CP violation in the b-quark system [9,10]. Experimentally, a large cross section for B meson production at the Tevatron collider has been measured [11]. Furthermore, the decay of the $J/\psi \to \mu^+\mu^-$ simplifies the triggering and the long lifetime of the K_S^0 permits the isolation of a clean K_S^0 signal in the hadron collider environment without explicit particle identification.

The data used in this analysis were collected with the Collider Detector at Fermilab (CDF) during the 1992-1993 run. The data correspond to an integrated luminosity of 19.3 pb^{-1} of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. The CDF detector is described in detail elsewhere [12]. We describe here only the detector components most relevant to this analysis. Two devices inside the 1.4 T solenoid are used for the tracking of charged particles: the silicon vertex detector (SVX) and the central tracking chamber (CTC). The SVX consists of four layers of silicon microstrip detectors located at radii between 3.0 and 7.9 cm from the interaction point and provides spatial measurements in the r-φ plane [13], giving a track impact parameter resolution of $(13 + 40/P_T)$ μm [14], where P_T is the transverse momentum of the track in GeV/c. The CTC is a cylindrical drift chamber containing 84 layers grouped into nine alternating superlayers of axial and stereo wires. It covers the pseudorapidity interval $|\eta| < 1.1$, where $\eta = -\ln[\tan(\theta/2)]$. The P_T resolution of the CTC combined with the SVX is $\delta(P_T)/P_T = ((0.0066)^2 + (0.0009 P_T)^2)^{1/2}$. Two muon subsystems in the central region were used, the central muon chambers and the central muon extension, which together provide coverage in the interval $|\eta| < 1.0$.

Dimuon events were collected using a three-level trigger system. The first level required two charged tracks in the muon chambers. The efficiency for finding a muon at level one rises from 30% at $P_T = 1.5$ GeV/c to 93% for $P_T > 3$ GeV/c. Level two requires that at least one of the muon tracks match a charged track in the CTC found with the Central Fast Track (CFT) processor. The efficiency for finding a CTC track in the CFT at level two rises from 50% for $P_T > 2.6$ GeV/c to 94% for $P_T > 3.1$ GeV/c. The third level software trigger requires that two oppositely charged CTC tracks each match muon track segments and that the $\mu^+\mu^-$ invariant mass is between 2.8 and 3.4 GeV/c^2 to select J/ψ candidates.

The B meson reconstruction starts with the isolation of the J/ψ signal. First, the CTC track is extrapolated to the muon chambers and this position is required to match the muon track segment to within three standard deviations, which is derived from the multiple scattering and measurement errors. Only tracks measured in three dimensions by the CTC are used and good quality SVX information is added when available, which is in approximately 50% of the candidates. We calculate the invariant mass of two oppositely charged muon candidates after constraining them to originate from a common point in space ("vertex constraint"). The confidence level (CL) of the fit is required to be greater than 1%. We require one muon with $P_T > 1.8$ GeV/c and the other one with $P_T > 2.5$ GeV/c to ensure we operate in a well-measured region of the trigger efficiency. We find 62146±299 J/ψ meson candidates with a signal-to-background ratio of 5:1 [15].

After mass constraining the J/ψ to the world average value [16] and requiring the CL$>$ 1%, the next step is to search for kaon candidates from all other tracks within the CTC fiducial volume. For the $J/\psi K^+$ mode, every track is considered a kaon candidate. The K^0_S selection requires two oppositely charged tracks with $P_T > 0.35$ GeV/c, each track satisfying $d_\pi/\sigma_{d_\pi} > 2$, where d_π is the distance of closest approach to the beam position, and σ_{d_π} is the corresponding uncertainty, which includes the track measurement errors and the beam position uncertainty. The $\pi^+\pi^-$ pairs are vertex constrained, required to point to the J/ψ vertex and satisfy the requirement, CL$>$ 1%. A signed two-dimensional decay length $L_{xy}(K^0_S)$, defined as the displacement of the K^0_S vertex projected onto the direction of the $P_T(K^0_S)$, is required to be greater than 1.0 cm. We find 7733 ± 101 K^0_S candidates with a signal-to-background ratio of 7:1 [15]. The $K^*(892)^+$ candidate is formed with a K^0_S candidate plus a track, assumed to be a π^+, and the $K^*(892)^0$ candidate is formed from two charged tracks assumed to be a K^+ and a π^-. The K-π particle assignment with invariant mass closest to the world average mass [16] of the $K^*(892)^0$ is retained and combinations where the K^* mass is greater than 75 MeV/c^2 from the world average mass are rejected.

Several constraints are imposed to improve the B mass resolution. In order to maximize the combinatoric background rejection, these constraints are applied incrementally and for each added constraint we require $\mathrm{CL}(\Delta\chi^2) > 1\%$, where $\Delta\chi^2$ is the change in χ^2 due to the additional constraint. For the $J/\psi K^+$ mode, the K^+ candidate track is added to the J/ψ vertex constraint. For the $J/\psi K^0_S$ mode, K^0_S decay products are vertex and mass constrained and the K^0_S is constrained to point to the J/ψ vertex in three dimensions. For the $J/\psi K^*(892)^+$ mode, the K^0_S is constrained to point to the three-track $J/\psi\pi^+$ vertex and for the $J/\psi K^*(892)^0$ mode, the four tracks are vertex constrained. For all four modes, the B candidate system is constrained to point to the primary vertex.

To further reduce the combinatoric background, we require $P_T(K^{(*)}) > 1.5$ GeV/c, $P_T(B) > 7$ GeV/c, and $c\tau(B) > 100$ μm, where $c\tau(B)$ is computed using the displacement of the J/ψ vertex projected onto the direction of the $P_T(B)$. The normalized mass distributions are shown in Fig. 1 for $J/\psi K^+$, $J/\psi K^0_S$, and in Fig. 2 for the $J/\psi K^*(892)^0$ and $J/\psi K^*(892)^+$. The normalized mass is computed for each candidate by dividing the difference between the invariant mass and the world average B mass [16] by the error on the mass, where the error is determined using the full covariance matrix for each candidate. The normalized mass follows a Gaussian shape more closely than the invariant mass distribution. The number of signal events is obtained by fitting a Gaussian of width fixed to 1.0 and a flat background to the normalized mass distributions. The binned maximum likelihood method gives 169 ± 18, 41.8 ± 6.9, 71 ± 12, and 17.0 ± 4.7 signal events in the $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^0_S$, $B^0 \to J/\psi K^*(892)^0$, and $B^+ \to J/\psi K^*(892)^+$ channels, respectively. The signal-to-background ratios [15] are given in Table I.

The ratio of branching ratios is computed using the relation:

$$\frac{BR(B^0 \to J/\psi K^0)}{BR(B^+ \to J/\psi K^+)} = \frac{2N(J/\psi K^0_S)}{N(J/\psi K^+)} \times \frac{\epsilon_{J/\psi K^+}}{\epsilon_{J/\psi K^0_S}} \times \frac{1}{BR(K^0_S \to \pi^+\pi^-)},$$

where the factor of two corrects for $K^0 \to K^0_L$, which is not reconstructed, and we assume equal production rates of B^+ and B^0 mesons. World average branching ratios are used for all $K^{(*)}$ daughter decays [16], an isospin analysis determines $BR(K^*(892)^0 \to K^+\pi^-) = 2/3$ and $BR(K^*(892)^+ \to K^0\pi^+) = 2/3$.

The reconstruction efficiencies are factorized as:

$$\epsilon_{J/\psi K^+} = \epsilon_{P_T(B)} \times \epsilon_{c\tau(B)} \times \epsilon_{J/\psi} \times \epsilon_{P_T(K^+)} \times \epsilon^R_{J/\psi K^+}$$

$$\epsilon_{J/\psi K^0_S} = \epsilon_{P_T(B)} \times \epsilon_{c\tau(B)} \times \epsilon_{J/\psi} \times \epsilon_{P_T(K^0_S)} \times \epsilon^R_{J/\psi K^0_S}.$$

The efficiency of the $P_T(B)$ cut ($\epsilon_{P_T(B)}$), the $c\tau(B)$ cut ($\epsilon_{c\tau(B)}$), the $P_T(K)$ cut ($\epsilon_{P_T(K)}$), and the efficiency for finding the J/ψ ($\epsilon_{J/\psi}$), all cancel in the ratio. However, some of the efficiencies associated with the K^0_S decay do not cancel in the ratio. The superscript R denotes the remaining terms. To further facilitate cancellation, these terms are factorized as:

$$\epsilon^R_{J/\psi K^+} = \epsilon^G_{K^+} \times \epsilon_{\mathrm{Trk}(K^+)} \times \epsilon_{\Delta\chi^2(J/\psi K^+)}$$

$$\epsilon_{\Delta\chi^2(J/\psi K^+)} = \epsilon_{V(\mu^+\mu^-)} \times \epsilon_{M(\mu^+\mu^-)} \times \epsilon_{V(K^+)} \times \epsilon_{P_{xy}(J/\psi K^+)} \times \epsilon_{P_z(J/\psi K^+)}$$

and

$$\epsilon^R_{J/\psi K^0_S} = \epsilon_{K^0_S} \times \epsilon_{\Delta\chi^2(J/\psi K^0_S)}$$

$$\epsilon_{K^0_S} = \epsilon^G_{\pi} \times \epsilon_{P_T(\pi)} \times \epsilon_{\mathrm{Trk}(K^0_S)} \times \epsilon_{L_{xy}} \times \epsilon_{d_\pi}$$

$$\epsilon_{\Delta\chi^2(J/\psi K^0_S)} = \epsilon_{V(\mu^+\mu^-)} \times \epsilon_{M(\mu^+\mu^-)} \times \epsilon_{V(\pi^+\pi^-)} \times \epsilon_{P(\pi^+\pi^-)} \times \epsilon_{M(\pi^+\pi^-)} \times \epsilon_{P_{xy}(J/\psi K^0_S)} \times \epsilon_{P_z(J/\psi K^0_S)}$$

where the superscript G indicates the term is a geometrical acceptance, V, M, and P indicate a vertex, mass, or pointing constraint, respectively, while P_{xy} and P_z refer to pointing constraints in the x-y plane and z direction. We cancel the $\epsilon_{V(K^+)}$ against the $\epsilon_{P(\pi^+\pi^-)}$ term and have verified the cancellation by Monte Carlo simulation. Canceling the remaining terms in the expansion of $\epsilon_{\Delta\chi^2(J/\psi K^+)}$ against similar terms in $\epsilon_{\Delta\chi^2(J/\psi K^0_S)}$, leaves the efficiency product $\epsilon^R_{\Delta\chi^2(J/\psi K^0_S)} = \epsilon_{V(\pi^+\pi^-)} \times \epsilon_{M(\pi^+\pi^-)}$.

The geometrical acceptances, the $\epsilon_{P_T(\pi)}$ term, the tracking efficiencies (ϵ_{Trk}), and the $\epsilon_{L_{xy}}$ are calculated using a Monte Carlo simulation that incorporates the following:

(1) The b-quark P_T and rapidity distributions follow the next-to-leading order QCD [17] calculation with MRS D0 [18] proton structure functions. We generate b quarks with rapidity $|y| < 1.0$.

(2) The $B^+ \to J/\psi K^+$ and the $B^0 \to J/\psi K^0$ decays involve a pseudoscalar-to-vector-pseudoscalar decay. In the J/ψ rest frame, the decay muons follow a $\sin^2\theta$ angular distribution with respect to the kaon direction in the rest frame of the B meson.

(3) We measure the efficiency of the CTC track reconstruction algorithm by embedding simulated tracks in real data J/ψ events. The tracks are generated so as to permit the reconstruction of the B mass [2]. The kaons are required to have $P_T > 1.5$ GeV/c. Only tracks within the CTC fiducial volume are embedded. We measure a tracking efficiency of $\epsilon_{\mathrm{Trk}(K^+)} = (92.0 \pm 2.0 \text{ (syst.)})\%$ for K^+. This result includes the effect of the K^+ finite lifetime. The K^0_S tracking efficiency is $\epsilon_{\mathrm{Trk}(K^0_S)} = (86.0 \pm 2.0 \text{ (syst.)})\%$ for $P_T(\pi) > 0.35$ GeV/c.

The efficiency of the $d_\pi/\sigma_{d_\pi} > 2$ cut (ϵ_{d_π}), and the efficiencies of the CL($\Delta\chi^2$) $> 1\%$ requirement on the vertex and mass constraints of the $\pi^+\pi^-$ pairs ($\epsilon_{V(\pi^+\pi^-)}$, $\epsilon_{M(\pi^+\pi^-)}$), were obtained from the inclusive K^0_S sample. In summary we determine the ratio of efficiencies to be $\epsilon_{J/\psi K^+}/\epsilon_{J/\psi K^0_S} = 1.57 \pm 0.08$ (syst.).

For the $J/\psi K^*(892)^0$ and the $J/\psi K^*(892)^+$ decay modes, the efficiencies are factorized in the same manner. For both ratios, $J/\psi K^*(892)^0/J/\psi K^+$ and $J/\psi K^*(892)^+/J/\psi K^+$, the efficiencies for the cuts on $c\tau(B)$ and $P_T(B)$, will cancel.

The efficiency for finding the J/ψ and the efficiency of the $P_T(K^{(*)})$ cut do not completely cancel because of the K^* polarization and the K^*–K mass difference. Both of these ratios are corrected for the acceptance of the K^* mass window, which is computed by integrating a Breit-Wigner distribution.

Each $J/\psi K^*/J/\psi K^+$ ratio also has unique non-canceling efficiencies. For the $K^*(892)^0$ case, there is the effect of slightly different geometrical acceptances and efficiencies for the K^+, as well as four terms associated with the π^-: the efficiency of the $P_T(\pi)$ cut, the track and geometric efficiencies, and the efficiency of adding an extra track to the vertex constraint.

For the $J/\psi K^*(892)^+/J/\psi K^+$ ratio, both modes have a charged track originating from the B decay vertex. However, the geometric acceptance, track reconstruction, kinematic and

CL($\Delta\chi^2$) cut efficiencies are slightly different. The efficiencies associated with the K^0_S do not cancel, and are determined in the same manner outlined previously. We use the Monte Carlo method described above to compute the ratio of the remaining efficiencies. The efficiencies and numbers of events for all four modes are summarized in Table I.

Six sources of systematic uncertainty contribute to the ratio of efficiencies. Each uncertainty in the lifetimes, τ_{B^+} and τ_{B^0}, contributes a 2% uncertainty to the $c\tau(B) > 100\ \mu$m cut. This contributes a 2.8% systematic error for the ratio of efficiencies. The ratio of tracking efficiencies has a 2–3.5% systematic error, depending on the mode. The CL($\Delta\chi^2$)> 1% requirement adds 2–2.8% and was determined from the inclusive K^0_S sample. Polarization, (Γ_L/Γ), uncertainties contribute 1.9–2.4% and the variation of the b-quark P_T spectrum in the Monte Carlo simulation contribute 1.7–7.6%. In the two cases where the J/ψ trigger efficiencies do not cancel due to different polarization effects in the ratio, we determine the ratio of the number of events with and without a trigger requirement, and assign an additional 5% uncertainty due to the difference in the ratios. The uncertainties are combined in quadrature, and are summarized in Table II.

We find the ratios of branching ratios to be:

$$BR(B^0 \to J/\psi K^0)/BR(B^+ \to J/\psi K^+) = 1.13 \pm 0.22\ (\text{stat.}) \pm 0.06\ (\text{syst.})$$
$$BR(B^0 \to J/\psi K^*(892)^0)/BR(B^+ \to J/\psi K^+) = 1.33 \pm 0.27\ (\text{stat.}) \pm 0.11\ (\text{syst.})$$
$$BR(B^+ \to J/\psi K^*(892)^+)/BR(B^+ \to J/\psi K^+) = 1.55 \pm 0.46\ (\text{stat.}) \pm 0.16\ (\text{syst.}).$$

We also determine the combined vector-to-pseudoscalar ratio using all four modes to be

$$R = \Gamma(B \to J/\psi K^*)/\Gamma(B \to J/\psi K) = 1.32 \pm 0.23\ (\text{stat.}) \pm 0.16\ (\text{syst.}),$$

where we assume equal production of B^+ and B^0 mesons and the systematic error is summarized in Table II. The dominant systematic uncertainty of 9% comes from the B meson lifetime ratio, τ_{B^+}/τ_{B^0} [16]. In addition we use the world average value $BR(B^+ \to J/\psi K^+) = (1.02 \pm 0.14) \times 10^{-3}$ [16] to obtain three branching ratios

$$BR(B^0 \to J/\psi K^0) = [1.15 \pm 0.23\ (\text{stat.}) \pm 0.17\ (\text{syst.})] \times 10^{-3}$$

$$BR(B^0 \to J/\psi K^*(892)^0) = [1.36 \pm 0.27 \text{ (stat.)} \pm 0.22 \text{ (syst.)}] \times 10^{-3}$$

$$BR(B^+ \to J/\psi K^*(892)^+) = [1.58 \pm 0.47 \text{ (stat.)} \pm 0.27 \text{ (syst.)}] \times 10^{-3},$$

where the quoted systematic error includes the uncertainty in the $BR(B^+ \to J/\psi K^+)$. These results are consistent with the current world average values [16].

In conclusion, we have presented the details of the reconstruction of the CP eigenstate $B^0 \to J/\psi K^0_S$ in a hadron collider environment and demonstrated that a good signal-to-background ratio is achieved. We have reported three branching ratios using $B^0 \to J/\psi K^*(892)^0$, $B^+ \to J/\psi K^*(892)^+$, and $B^0 \to J/\psi K^0$ relative to $B^+ \to J/\psi K^+$, which are comparable in precision and in good agreement with the current world average values [16].

We also combine these four decay modes to determine the vector-to-pseudoscalar ratio and confirm a previous determination of $R = 1.64 \pm 0.34$ [19], where naive spin counting would predict a value of three for the vector-to-pseudoscalar ratio. Theoretical models [6–8] that assume the factorization hypothesis and use current meson form factors are presently not able to simultaneously accommodate a low vector-to-pseudoscalar ratio and the polarization data [5]. This measurement reinforces the need for a better understanding of these models.

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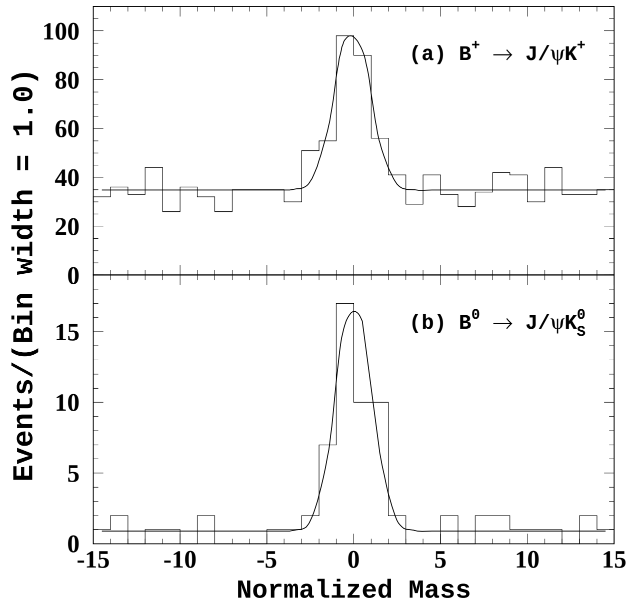

FIG. 1.

The normalized mass distribution for (a) $J/\psi K^{+}$ and (b) $J/\psi K_S^0$ after all cuts.

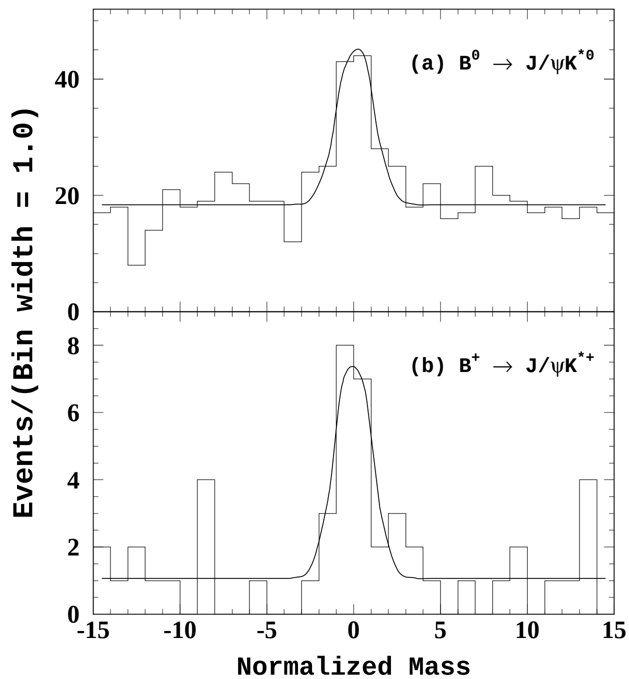

FIG. 2.

The normalized mass distribution for (a) $J/\psi K^*(892)^0$ and (b) $J/\psi K^*(892)^+$ after all cuts.

TABLE I. Summary of number of events, signal-to-background (S/B), and ratios of efficiencies relative to the $B^+ \to J/\psi K^+$ decay mode.

	$J/\psi K^+$	$J/\psi K_S^0$	$J/\psi K^*(892)^0$	$J/\psi K^*(892)^+$
Number of Events	169 ± 18	41.8 ± 6.9	71 ± 12	17.0 ± 4.7
S/B	0.97	9.23	0.77	3.12
Ratio of efficiencies	-	1.57 ± 0.08	2.11 ± 0.18	3.53 ± 0.37

TABLE II. Summary of systematic uncertainties (%) for the ratios of branching ratios.

	$\epsilon_{J/\psi K^+}/\epsilon_{J/\psi K_S^0}$	$\epsilon_{J/\psi K^+}/\epsilon_{J/\psi K^{*0}}$	$\epsilon_{J/\psi K^+}/\epsilon_{J/\psi K^{*+}}$	ϵ_V/ϵ_P
τ_{B^+}/τ_{B^0}	2.8	2.8	-	9
Trk Efficiency	2.8	2	3.5	2.1
CL($\Delta\chi^2$)	2.8	2	3.5	2.1
Γ_L/Γ	-	1.9	2.4	1.9
$P_T(b)$ Variations	1.7	5.4	7.6	5.5
Trigger	-	5	5	5
Total	5.0%	8.6%	10.6%	12%