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Using the data for 24.5×10^6 $\psi(2S)$ produced in e^+e^- annihilations at $\sqrt{s} = 3686$ MeV at the CESR-c e^+e^- collider and 8.6×10^6 J/ψ produced in the decay $\psi(2S) \to \pi^+\pi^- J/\psi$, the branching fractions for $\psi(2S)$ and J/ψ decays to pairs of pseudoscalar mesons, $\pi^+\pi^-$, K^+K^-, and $K_S K_L$, have been measured using the CLEO-c detector. We obtain branching fractions $\mathcal{B}(\psi(2S) \to \pi^+\pi^-) = (7.6 \pm 2.5 \pm 0.6) \times 10^{-6}$, $\mathcal{B}(\psi(2S) \to K^+K^-) = (74.8 \pm 2.3 \pm 3.9) \times 10^{-6}$, $\mathcal{B}(\psi(2S) \to K_S K_L) = (52.8 \pm 2.5 \pm 3.4) \times 10^{-6}$, and $\mathcal{B}(J/\psi \to \pi^+\pi^-) = (1.47 \pm 0.13 \pm 0.13) \times 10^{-4}$, $\mathcal{B}(J/\psi \to K^+K^-) = (2.86 \pm 0.09 \pm 0.19) \times 10^{-4}$, $\mathcal{B}(J/\psi \to K_S K_L) = (2.62 \pm 0.15 \pm 0.14) \times 10^{-4}$, where the first errors are statistical and the second errors are systematic. The phase differences between the amplitudes for electromagnetic and strong decays of $\psi(2S)$ and J/ψ to 0^{-+} pseudoscalar pairs are determined by a Monte Carlo method to be $\delta(\psi(2S)_{PP} = (110.5^{+16.0}_{-9.5})^\circ$ and $\delta(J/\psi)_{PP} = (73.5^{+5.0}_{-4.5})^\circ$. The difference between the two is $\Delta\delta \equiv \delta(\psi(2S))_{PP} - \delta(J/\psi)_{PP} = (37.0^{+16.5}_{-10.5})^\circ$.

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I. INTRODUCTION

Interest in final state interaction (FSI) phases originally arose from CP violation in K decays and B decays. However, recently interest has focused on the suggestion that large FSI phases are a general feature of strong decays. The electromagnetic and strong decays of the vector states of charmonium, J/ψ and $\psi(2S)$, offer good testing ground for this possibility. In a series of papers Suzuki [1–3] has studied FSI phase differences between the electromagnetic amplitude A_γ and the three-gluon strong amplitude A_{ggg}. In the decays of J/ψ to 1^-0^- vector-pseudoscalar (VP) pairs Suzuki obtained $\delta(J/\psi)_{VP} = 80^\circ$ [1], and for the 0^-0^- pseudoscalar-pseudoscalar (PP) pairs he obtained $\delta(J/\psi)_{PP} = (89.6 \pm 9.9)^\circ$ [2]. Rosner [4] confirmed Suzuki's results, obtaining $\delta(J/\psi)_{VP} = (76^{+9}_{-10})^\circ$, and $\delta(J/\psi)_{PP} = (89 \pm 10)^\circ$. Further, Gerard and Weyers [5] have argued that these differences are manifestations of what they call "universal incoherence", i.e., 90° phase difference between electromagnetic and every exclusive annihilation decay channel of J/ψ and $\psi(2S)$. In order to arrive at a deeper understanding of the origin of large phase differences it is therefore necessary to examine if what has been observed for J/ψ decays persists in the corresponding decays of $\psi(2S)$. As Suzuki has noted [3], this is particularly important in the context of the curious suppression of the ratio $\Gamma[\psi(2S) \to VP]/\Gamma[J/\psi \to VP]$ (particularly notable for $\rho\pi$ decays).

One of the best places to study the phase difference between electromagnetic and strong decays of $\psi(2S)$ and J/ψ is in their decays to pseudoscalar pairs, $\pi^+\pi^-$, K^+K^-, and $K_S K_L$. This is because the three decays sample the interactions in quite different ways. The $\pi^+\pi^-$ decay is essentially purely electromagnetic, with strong decay being forbidden by isospin invariance, the $K_S K_L$ decay is essentially purely strong and due only to SU(3) violation, and the K^+K^- decay can proceed through both the electromagnetic and strong interactions.

A particularly simple and transparent determination of the relative phase angle $\delta(\psi)$ can be made by measuring it as the *interior* angle of the triangle in the complex plane with the amplitudes for the decays to $\pi^+\pi^-$, K^+K^-, and $K_S K_L$ as its three sides. This is illustrated in Fig. 1 for the J/ψ and $\psi(2S)$ decays.

With the neglect of the small effect of SU(3)–breaking and interference between resonance and continuum amplitudes, the relative phase angle $\delta(\psi)$ is given by

$$\delta(\psi)_{\text{PP}} = \cos^{-1}\left(\frac{\mathcal{B}(K_S K_L) + \rho\mathcal{B}(\pi^+\pi^-) - \mathcal{B}(K^+K^-)}{|2\sqrt{\mathcal{B}(K_S K_L) \times \rho \times \mathcal{B}(\pi^+\pi^-)}|} \right),$$

(1)

where the phase space correction factor $\rho = (p_K/p_\pi)^3$; $\rho(\psi(2S)) = 0.902$, and $\rho(J/\psi) = 0.862$. Thus it is required to measure the three branching fractions, $\mathcal{B}(\psi(2S), J/\psi \to \pi^+\pi^-, K^+K^-,$ and $K_S K_L)$, which are proportional to the squares of the respective amplitudes.

Previous measurements of $\delta(\psi(2S))_{PP}$ were made by BES [6, 7] and CLEO [8]. Their results, recalculated to correspond to the internal phase angle defined by Eq. (1), are $\delta(\psi(2S))_{PP} = (91 \pm 35)^\circ$ (BES), and $\delta(\psi(2S))_{PP} = (87 \pm 20)^\circ$ (CLEO). The results for $\delta(J/\psi)_{PP}$ mentioned earlier were obtained by Suzuki and Rosner using the PDG 1998 [9] evaluation of the branching fractions measured in 1985 by Mark III [10] in the decay of their sample of 2.7×10^6 J/ψ produced directly in e^+e^- annihilations
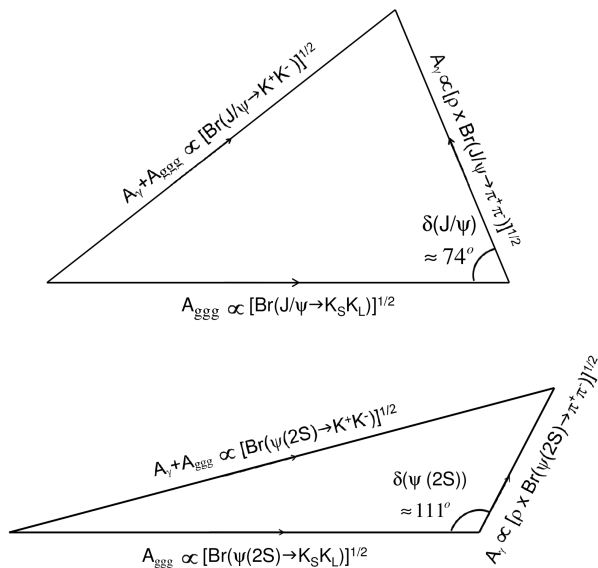
FIG. 1. Triangle representations of the amplitudes in $J/\psi \to PP$ and $\psi(2S) \to PP$ decays. The relative phase angle between the strong and electromagnetic amplitudes is $\delta(\psi)$.

at $\sqrt{s} = M(J/\psi)$. In this paper we present much more accurate results for branching fractions and $\delta(\psi(2S))_{PP}$ using the CLEO-c data of 24.5×10^6 $\psi(2S)$, eight times larger than that used in the previous CLEO measurement [8], and for branching fractions and $\delta(J/\psi)_{PP}$ using the data set of 8.6×10^6 J/ψ tagged by $\pi^+\pi^-$ recoils in the decay $\psi(2S) \to \pi^+\pi^- J/\psi$. In all cases large improvement in precision over previous measurements is obtained.

The data used in this analysis were collected at the CESR e^+e^- storage ring using the CLEO-c detector [11]. The detector has a cylindrically symmetric configuration, and it provides 93% coverage of solid angle for charged and neutral particle identification. The detector components important for the present analysis are the vertex drift chamber, the main drift chamber (DR), the Ring Imaging Cherenkov (RICH) counter, and the CsI crystal calorimeter (CC).

II. EVENT SELECTION

Event selection, particle identification, and branching fraction determination in the present paper follow closely those used by us in our published paper on the determination of $\delta(\psi(2S))$ [8].

The events for the three decay modes, $\psi(2S), J/\psi \to \pi^+\pi^-, K^+K^-, K_S(\to \pi^+\pi^-)K_L$(not detected) are required to have two charged particles for $\psi(2S)$ decays, and four charged particles for J/ψ decays, and zero net charge. The event selection criteria are identical to those in our earlier paper [8]. To recapitulate, all charged par-

ticles are required to meet the standard criteria for track quality. The $\pi^+\pi^-$, K^+K^-, and $\pi^+\pi^-$ from K_S decays (with vertex displaced by > 5 mm) are accepted in the regions $|\cos\theta| < 0.75$, 0.80 and 0.93, respectively. The invariant mass of the $\pi^+\pi^-$ from K_S decay is required to be within ± 10 MeV of $M(K_S) = 497.61$ MeV.

Particle identification is done by combining dE/dx information from the drift chamber (DR) and the likelihood information from the RICH detector for the particle species i, $j \equiv p$, K, π, μ, and e. The variable for the dE/dx information is $S_i = [(dE/dx)_{\text{measured}} - (dE/dx)_{\text{expected}}]/\sigma(dE/dx)_{\text{measured}}$, and for the RICH information it is the likelihood function, $-2\log L$. To distinguish between two particle species a joint χ^2 function, $\Delta\chi^2(i,j) = -2(\log L_i - \log L_j) + (S_i^2 - S_j^2)$ is constructed. Charged kaons in K^+K^- decays are distinguished from protons, pions, and leptons by requiring $\Delta\chi^2(K, p/\pi/\mu/e) < -9$. Looser criteria are used for pions in $\pi^+\pi^-$ decay and $\pi^+\pi^-$ daughters from K_S in $K_S K_L$ decay, $\Delta\chi^2(\pi, e/K/p) < 0$. In addition, electrons are rejected in all decays by requiring $E(\text{CC})/p < 0.9$. All these requirements are identical to those in Ref. [8].

In Ref. [12] a detailed study was made to distinguish pions from the much more prolific yield of muons. It was determined that the energy deposited in the central calorimeter by pions due to their hadronic interactions provides a very efficient means of distinguishing them from muons which deposit much smaller energy due only to dE/dx. For $\psi(2S) \to \pi^+\pi^-$ decay, it was determined that requiring every pion to deposit $E(\text{CC}) > 0.42$ GeV reduced muon contamination to $\ll 1\%$ level. This requirement was used in Ref. [8], and we impose it also in the present analysis for the channel $\psi(2S) \to \pi^+\pi^-$. For $J/\psi \to \pi^+\pi^-$, the pion yield is much larger, and the corresponding requirement is determined to be $E(\text{CC}) > 0.35$ GeV. For $K_S K_L$ decay an explicit π^0 veto was made, as in Ref. [8].

III. DETERMINATION OF $\mathcal{B}(\psi(2S) \to \pi^+\pi^-, \ K^+K^-, \ K_S K_L)$, AND $\delta(\psi(2S))$

For $\psi(2S) \to \pi^+\pi^-$ and K^+K^-, it was required that the total momentum $|\Sigma p|$ be less than 75 MeV. As expected, this requirement removes most of the J/ψ, χ_{cJ} peaks and the background which is present without it in the event distributions plotted as a function of $X(h) \equiv (E(h^+) + E(h^-))/\sqrt{s}$. The resulting $X(h)$ distributions are shown in Figs. 2(a,b) in the extended region of $X(h)$. For $\psi(2S) \to K_S K_L$ with only K_S observed no such total momentum cut can be imposed, and the different criteria developed in Ref. [8] were implemented to take account of the unobserved K_L.

For $\psi(2S) \to K_S K_L$, the direction of K_L is inferred from that of the observed K_S. We require that there be no shower associated with neutrals closest to this direction with energy > 1.5 GeV. Further, we require that in a cone of 0.35 radians around the K_L direction there be no

more than one shower with $E_{\rm in} > 100$ MeV. We require that outside this cone there be no single shower with $E_{\rm out} > 100$ MeV and the sum of all showers $\Sigma E_{\rm out} < 300$ MeV. These selections remove events with neutral particles other than K_L accompanying the detected K_S. As shown in Fig. 2 (c), the remaining background is featureless, and very small in the signal region, $X(K_S) \approx 1.0$.

In Figs. 2 (d,e,f) we show the $X(h)$ distributions of Figs. 2 (a,b,c) in detail in the smaller region of $X(h)$ in which we fit the data with MC–generated peak shapes and linear backgrounds. The fit results are presented in Table I. The observed peak counts, $N(\rm obs)$, are 70.8±8.8, 1431.3 ± 39.4, and 478.0 ± 23.0 for $\pi^+\pi^-$, K^+K^-, and $K_S K_L$, respectively.

The MC signal events were generated assuming $\sin^2\theta$ angular distributions, where θ is the angle between a meson and the positron beam. In Figs. 2 (g,h,i) we show that the angular distributions of the data events are in excellent agreement with the MC distributions in all three cases for $\psi(2S) \to \pi^+\pi^-$, K^+K^-, and $K_S K_L$ decays.

The observed peaks for $\pi^+\pi^-$ and K^+K^- decays contain contributions from continuum, or form factor production $e^+e^- \to \gamma^* \to \pi^+\pi^-, K^+K^-$ in addition to the resonance contributions. Continuum contribution in $K_S K_L$ decays can, however, only arise from higher order processes, and is expected to be very small. The continuum contributions have to be estimated, and subtracted from the observed peak yields of $\pi^+\pi^-$ and K^+K^- before the corresponding branching fractions can be determined. This is particularly challenging for the $\pi^+\pi^-$ decays.

The main limitation in the measurement of the interference phase difference angle in earlier publications came from the determination of the branching fraction for $\pi^+\pi^-$ decay, $\mathcal{B}(\psi(2S) \to \pi^+\pi^-)$. As mentioned earlier, the three–gluon strong decay $\psi(2S) \to \pi^+\pi^-$ is forbidden by isospin conservation, and the branching fraction $\mathcal{B}(\psi(2S) \to \pi^+\pi^-)$ is consequently small. The problem of the intrinsically small branching fraction is compounded by the fact that no good–statistics measurements of the continuum $\pi^+\pi^-$ contribution were available. As a result all three previous measurements had very large $(60 - 100)\%$ errors:

$$\mathcal{B}(\pi^+\pi^-) \times 10^6 = 80 \pm 50 \ (\text{DASP [15]}),$$
$$= 8.4 \pm 6.5 \ (\text{BES [6]}), \text{ and}$$
$$= 8 \pm 8 \ (\text{CLEO [8]}).$$

In the DASP [15] and BES [6] measurements no attempt was made to subtract the continuum contribution. In our published paper [8] with 3 million $\psi(2S)$ (corresponding to integrated luminosity $\int \mathcal{L}dt = 5.6$ pb^{-1}), only 11 $\pi^+\pi^-$ counts were observed. From these the scaled continuum contribution of 7 counts, based on data with e^+e^- integrated luminosity of 20.7 pb^{-1} taken off–$\psi(2S)$ at $\sqrt{s} = 3670$ MeV, was subtracted to get $N(\pi^+\pi^-) = 4\pm 4$. This led to the poor determination of $\mathcal{B}(\psi(2S) \to \pi^+\pi^-) = (8 \pm 8 \pm 2) \times 10^{-6}$ [8].

Our present analysis has two big advantages over the old analysis. We now have available a much larger data set of 24.5 million $\psi(2S)$ corresponding to an integrated e^+e^- luminosity of 48 pb^{-1}. Also, we are able to make a much better estimate of the continuum contributions in the yields of $\pi^+\pi^-$ and K^+K^- based on our large-statistics form factor measurements with luminosity of 805 pb^{-1} at $\sqrt{s} = 3772$ MeV and 586 pb^{-1} at $\sqrt{s} = 4170$ MeV.

The widths of $\psi(3770)$ and $\psi(4160)$ are $\Gamma(\psi(3770)) = (27.3 \pm 1.0)$ MeV and $\Gamma(\psi(4160)) = (103 \pm 8)$ MeV, respectively [13]. They are about two orders of magnitude or more larger than $\Gamma(\psi(2S)) = (0.304 \pm 0.009)$ MeV, and the estimates of the resonance branching fractions for the decays of $\psi(3770)$ and $\psi(4160)$ to $\pi^+\pi^-$, K^+K^-, and $K_S K_L$ range from 1×10^{-8} to 8×10^{-8}. These lead to the conclusion that the resonance contributions in $\pi^+\pi^-$ and K^+K^- decays of $\psi(3770)$ and $\psi(4160)$ are less than 0.01% of the total, i.e., the total observed counts $N'(\rm tot.\ obs)$ are entirely due to continuum or form factor contribution. They can therefore be confidently extrapolated to estimate continuum contribution in the measured counts at $\psi(2S)$. The extrapolation is done as

$$C \equiv \frac{N(\text{cont}, \sqrt{s})}{N'(\text{obs}, \sqrt{s'})} = \frac{\mathcal{L}(\sqrt{s})\epsilon(\sqrt{s})}{\mathcal{L}(\sqrt{s'})\epsilon(\sqrt{s'})} \times \left(\frac{\sqrt{s'}}{\sqrt{s}}\right)^6. \quad (2)$$

where $\sqrt{s} = M(\psi(2S)) = 3686$ MeV and $\sqrt{s'} = 3772$ MeV and 4160 MeV. Here $\mathcal{L}(\sqrt{s}, \sqrt{s'})$ are the luminosities, and $\epsilon(\sqrt{s}, \sqrt{s'})$ are efficiencies determined by Monte Carlo (MC) simulations, and the factor $(\sqrt{s'}/\sqrt{s})^6$ is the conventional extrapolation based on the constancy of $Q^2 F(Q^2)$ for vector meson form factors [14]. The observed K^+K^- and $\pi^+\pi^-$ counts at $\sqrt{s'} = 3772$ MeV and 4170 MeV have statistical and systematic uncertainties [12]. Using the counts at 3772 and 4170 MeV in Eq. (2) leads to estimated continuum contributions at $\sqrt{s} = 3686$ MeV which are 105.7±3.6±4.7 and 109.2±4.9±4.8 counts respectively for kaons, and 41.8±2.2±4.3 and 37.6±3.1±3.9 counts respectively for pions (the first errors are statistical and the second errors are systematic). We use their averages, taking account of the fact that systematic errors are correlated, as 106.9±5.5 counts for kaons, and 40.4±4.6 counts for pions as our best estimates of continuum contributions at 3686 MeV.

These contributions are illustrated as dotted histograms in Figs. 2 (d,e).

In Table I, for $\psi(2S)$ decays we list the number $N(\rm obs)$ of counts observed in the $\pi^+\pi^-$, K^+K^- and $K_S K_L$ peaks, the number $N(\rm cont)$ of continuum counts estimated as described above, the net signal counts $N(\rm signal) = N(\rm obs) - N(\rm cont)$, the event selection efficiencies ϵ, and the branching fractions calculated as

$$\mathcal{B}(\psi(2S) \to PP) = N(\text{signal})/[\epsilon \times N(\psi(2S))], \quad (3)$$

where the number of $\psi(2S)$ is $N(\psi(2S)) = 24.5 \times 10^6$. We note that these branching fractions have been obtained
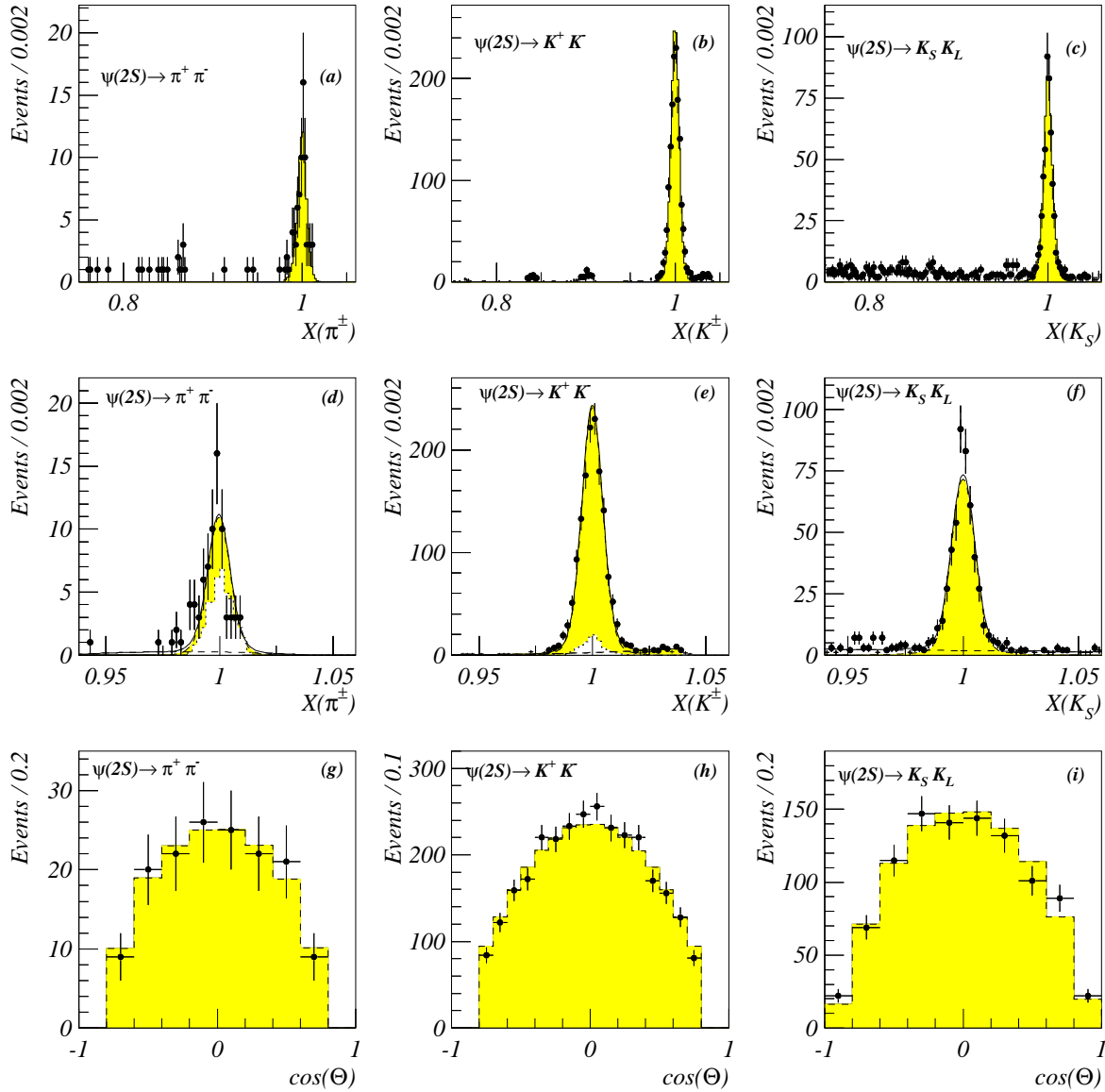
FIG. 2. Event distributions for $\psi(2S) \to \pi^+\pi^-$, K^+K^-, and $K_S K_L$. Panels (a,b,c) show $X(h)$ distributions in the extended range $X(h)$. Panels (d,e,f) show enlarged $X(h)$ distributions in the region in which we fit the data with MC–determined peak shapes and linear backgrounds. Panels (g,h,i), show the corresponding angular distributions. Points with errors represent data; shaded histograms represent MC fits to the data. In panels (d,e) the dotted histograms indicate continuum contributions.

without taking account of possible interference between continuum and resonance contributions.

We have considered various sources of systematic uncertainties in our branching fraction results. As in Ref. [8], for all three decay channels, $\psi(2S) \to \pi^+\pi^-$, K^+K^-, and $K_S K_L$ the common uncertainties are $\pm 2\%$ in number of $\psi(2S)$, $\pm 1\%$ per track in track finding, and $\pm 1\%$ per track in charged particle identification. Uncertainties in trigger efficiency are $\pm 1\%$ in $\pi^+\pi^-$ and K^+K^-, and $\pm 2\%$ in $K_S K_L$. The systematic uncertainty in determination of the factor C in Eq. (2) comes from the uncertainties in the total integrated luminosity val-

ues of the data taken at $\psi(2S)$ and at $\sqrt{s} = 3772$ MeV and $\sqrt{s} = 4170$ MeV, which correspond to 1% for each. Thus, we assign 1.4% systematic uncertainty to the value C, determined in Eq. (2).

Variation of the total momentum $\Sigma p_i < 75$ MeV requirement by ± 15 MeV resulted in no statistically significant change in $\mathcal{B}(\psi(2S) \to \pi^+\pi^-)$, and a $\pm 3.5\%$ change in $\mathcal{B}(\psi(2S) \to K^+K^-)$, which we assign as systematic uncertainty. For $\psi(2S) \to \pi^+\pi^-$ changing the requirement $E(CC) > 0.42$ GeV by $\pm 10\%$ resulted in $\pm 7\%$ change in $\mathcal{B}(\psi(2S) \to \pi^+\pi^-)$. The effect of the implementation of K_L-related constraints in $K_S K_L$ decay was determined as the ratio of fitted peak counts in the spectra in Fig. 2(f)/Fig. 2(c). It was determined to be 0.835 ± 0.042. The 5% uncertainty in this determination was assigned as a systematic error in $\mathcal{B}(\psi(2S) \to K_S K_L)$.

The total systematic uncertainties are 8.0%, 5.2%, and 6.5% for $\psi(2S) \to \pi^+\pi^-$, K^+K^-, and $K_S K_L$ decays, respectively.

The resulting branching fractions are

$$\mathcal{B}(\psi(2S) \to \pi^+\pi^-)$$
$$= [7.6 \pm 2.5(\text{stat}) \pm 0.6(\text{syst})] \times 10^{-6},$$
$$\mathcal{B}(\psi(2S) \to K^+K^-)$$
$$= [7.48 \pm 0.23(\text{stat}) \pm 0.39(\text{syst})] \times 10^{-5},$$
$$\mathcal{B}(\psi(2S) \to K_S K_L)$$
$$= [5.28 \pm 0.25(\text{stat}) \pm 0.34(\text{syst})] \times 10^{-5}. \quad (4)$$

These are listed in Table I. In Table II the errors are listed with the statistical and systematic errors combined in quadrature, together with results from previous investigations by DASP [15], BES [7, 16], and CLEO [8]. The uncertainties in our branching fractions results are factors two to five smaller than those in the published results. In Table II, we also list the phase angle difference $\delta(\psi(2S)) = (113.4 \pm 11.5)^\circ$, calculated using Eq. (1). All the published values of $\delta(\psi(2S))$ are also listed, as recalculated using Eq. (1).

In Sec. V we present the determination of the phase angle differences using a MC method which allows us to take account of the distributions in the values of the branching fractions.

IV. DETERMINATION OF $\mathcal{B}(J/\psi \to \pi^+\pi^-, K^+K^-, K_S K_L)$ AND $\delta(J/\psi)$

The 24.5 million $\psi(2S)$ in our data set lead to 8.6 million J/ψ events tagged by $\pi^+\pi^-$ recoil in the decay $\psi(2S) \to \pi^+\pi^- J/\psi$. This sample is automatically free of any contamination of e^+e^-, $\mu^+\mu^-$, K^+K^-, or $p\bar{p}$ events produced in direct measurement at $\sqrt{s} = 3097$ MeV. The subsequent J/ψ decays to $\pi^+\pi^-$, and K^+K^- also do not contain any continuum contributions. As such, these data are cleaner and simpler to analyze than the data from e^+e^- collisions at $\sqrt{s} = 3097$ MeV.

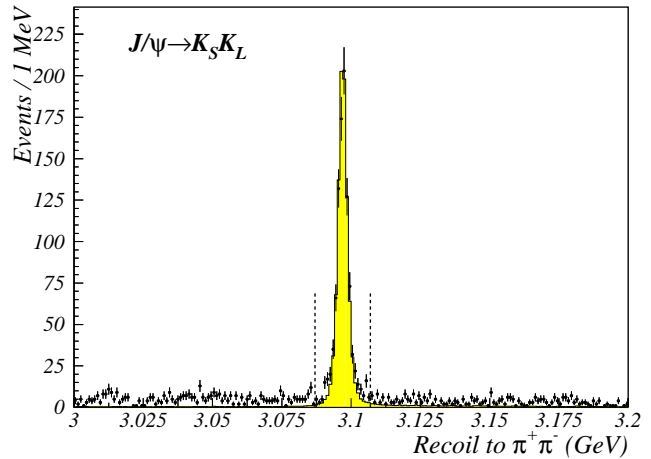As stated earlier, to select events for J/ψ decays our event selection criteria are modified to require four

FIG. 3. For the decay $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to K_S K_L$, $K_S \to \pi^+\pi^-$, distributions of the recoil invariant mass against $\pi^+\pi^-$ pair which does not come from the K_S decay. Points are for the data, shaded histogram corresponds to the signal MC. Normalization is arbitrary.

charged particles instead of two. Recoil mass is then constructed for every pair of two oppositely charged particles. This is dominated by the production of J/ψ, as shown in Fig. 3 for the channel $J/\psi \to K_S K_L$, which is similar to those obtained for the channels $J/\psi \to \pi^+\pi^-$, K^+K^-. We define the clean J/ψ sample as consisting of events with $M(\text{recoil}) = M(J/\psi) \pm 10$ MeV. Selection of events for $J/\psi \to \pi^+\pi^-$, K^+K^-, and $K_S K_L$ is done exactly in the same manner as described for $\psi(2S)$. As mentioned earlier, the most efficient $E(CC)$ cut to reject $\mu^+\mu^-$ from J/ψ decays is to require that each pion satisfy $E(CC) > 350$ MeV. The MC–estimated muon contamination with this requirement is $< 1\%$.

Figures 4 (g,h,i), show that the angular distributions of the data events for all three J/ψ decays are in excellent agreement with the MC $\sin^2\theta$ distributions, as in the case of $\psi(2S)$ decays in Figs. 2 (g,h,i).

The systematic errors for J/ψ decays were determined in exactly the same manner as for $\psi(2S)$ decays. Their totals are 9%, 6.8%, and 5.5% for $\pi^+\pi^-$, K^+K^-, and $K_S K_L$, respectively.

Figure 4 shows the results for J/ψ decays to $\pi^+\pi^-$, K^+K^-, $K_S K_L$ as Fig. 2 does for the corresponding $\psi(2S)$ decays. Figures 4 (a,b,c) show the data in the extended range of $X(h)$ with arbitrarily normalized MC predictions. The distribution of the K_S events as a function of $X(K_S)$ in the rest frame of J/ψ, shown in Fig. 4 (c), needs comment. The $K_S K_L$ peak at $X(K_S) = 1.0$ is clearly separated from the smaller peak at $X \approx 0.94$ which arises from the J/ψ decays into $\overline{K}^{*0}(892) K_S$, $K^{*0} \to K_L \pi^0$, $K_S \to \pi^+\pi^-$, despite π^0 rejection. The clear separation of the $K_S K_L$ peak from
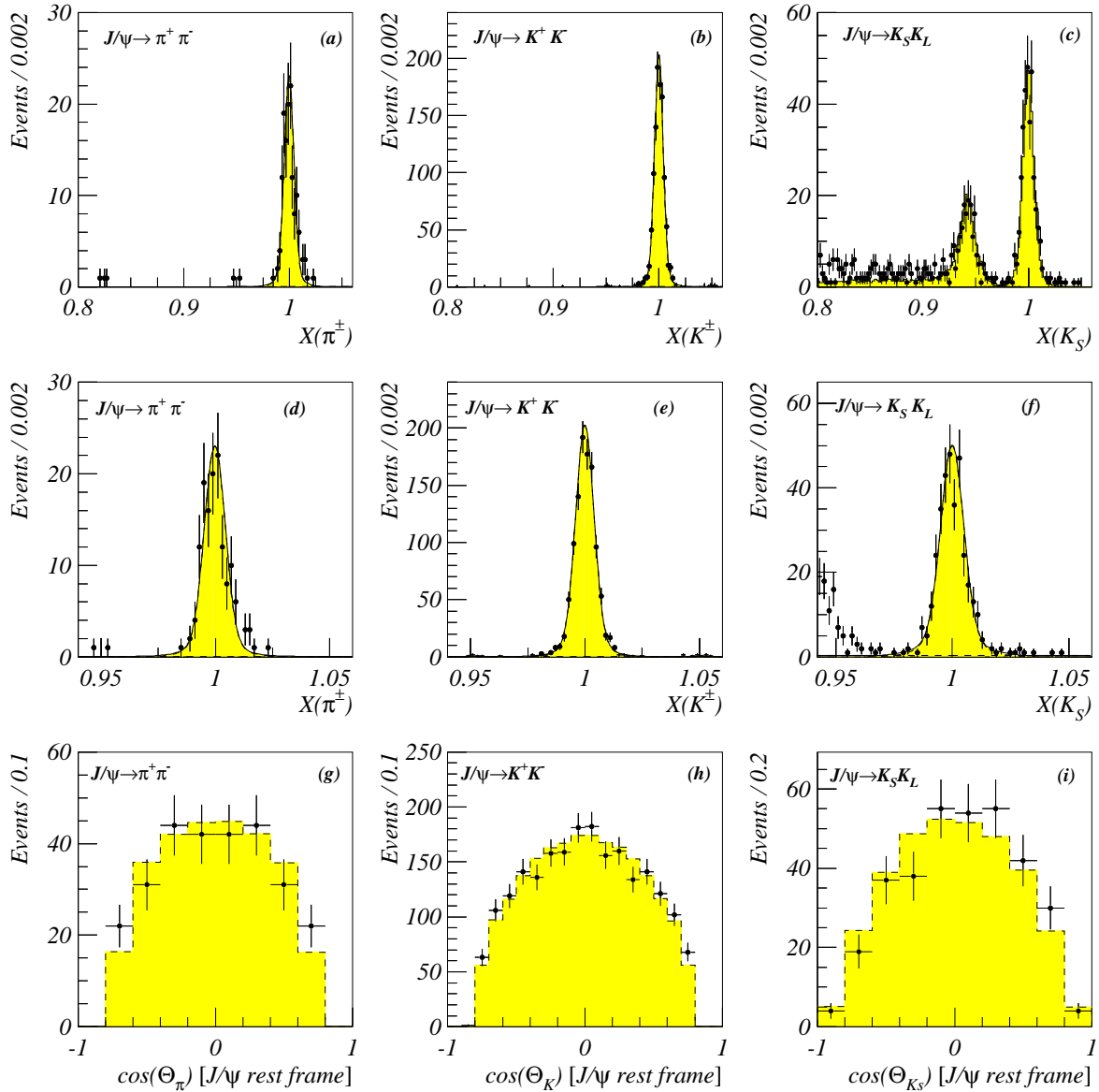
FIG. 4. Event distributions for $J/\psi \to \pi^+\pi^-$, K^+K^-, and $K_S K_L$. Panels (a,b,c) show $X(h)$ distributions in the extended range $X(h) = 0.8 - 1.1$. Panels (d,e,f) show enlarged $X(h)$ distributions in the region $X(h) = 0.94 - 1.06$ with fits with MC determined peak shape and linear background. Panels (g,h,i) show the corresponding angular distributions. Points with errors represent data, shaded histograms represent MC fits to the data.

the $\overline{K}^0(892)K_S$ peak is confirmed by the MC simulation whose result is superposed on the data in Fig. 4 (c). In Figs. 4 (d,e,f), the event distributions of Figs. (a,b,c) are shown in detail in the smaller region of $X(h)$. Also shown are the fits using MC–determined peak shapes and linear backgrounds. The fits give 137.6 ± 11.8, 1057.0 ± 32.8,

and 334.3 ± 19.3 counts for $\pi^+\pi^-$, K^+K^-, and $K_S K_L$, respectively. These compare with 84, 107 and 74 counts in the Mark III measurements with a factor three smaller sample of J/ψ [10]. These counts, the MC determined efficiencies ϵ, and $N(J/\psi) = (8.57 \pm 0.07) \times 10^6$ [17], lead to the branching fractions listed in Table I.

	N(obs)	N(cont)	N(signal)	ϵ (%)	$\mathcal{B}(\psi(2S) \to PP) \times 10^6$	χ^2/dof
$\psi(2S) \to \pi^+\pi^-$	70.8 ± 8.8	40.4 ± 4.6	30.4 ± 9.9	16.4	$\mathbf{7.6 \pm 2.5 \pm 0.6}$	0.68
$\psi(2S) \to K^+K^-$	1431.3 ± 39.4	106.9 ± 5.5	1324.4 ± 39.8	72.4	$\mathbf{74.8 \pm 2.3 \pm 3.9}$	1.11
$\psi(2S) \to K_S K_L$	478.0 ± 23.0		478.0 ± 23.0	53.5	$\mathbf{52.8 \pm 2.5 \pm 3.4}$	1.00
					$\mathcal{B}(J/\psi \to PP) \times 10^4$	
$J/\psi \to \pi^+\pi^-$	137.6 ± 11.8		137.6 ± 11.8	10.9	$\mathbf{1.47 \pm 0.13 \pm 0.13}$	1.09
$J/\psi \to K^+K^-$	1057.7 ± 32.8		1057.7 ± 32.8	43.1	$\mathbf{2.86 \pm 0.09 \pm 0.19}$	1.00
$J/\psi \to K_S K_L$	334.3 ± 19.3		334.3 ± 19.3	21.5	$\mathbf{2.62 \pm 0.15 \pm 0.14}$	1.03

TABLE I. Fit results for $\psi(2S)$, $J/\psi \to \pi^+\pi^-$, K^+K^-, and $K_S K_L$ decays, and the corresponding branching fractions.

	DASP [15] 1979	BES [6, 7] 2004	CLEO [8] 2005	This analysis	This analysis MC result
$\mathcal{B}(\psi(2S) \to \pi^+\pi^-) \times 10^6$	80 ± 50	8.4 ± 6.5	8 ± 8	$\mathbf{7.6 \pm 2.6}$	
$\mathcal{B}(\psi(2S) \to K^+K^-) \times 10^6$	100 ± 70	61 ± 21	63 ± 7	$\mathbf{74.8 \pm 4.5}$	
$\mathcal{B}(\psi(2S) \to K_S K_L) \times 10^6$	—	52.4 ± 6.7	58.0 ± 9.0	$\mathbf{52.8 \pm 4.2}$	
$\delta(\psi(2S))$	—	$(91 \pm 35)^\circ$	$(87 \pm 20)^\circ$	$\mathbf{(113.4 \pm 11.5)^\circ}$	$\mathbf{(110.5^{+16.0}_{-9.5})^\circ}$
	Mark III[10]	BES [16]		This analysis	This analysis MC result
$\mathcal{B}(J/\psi \to \pi^+\pi^-) \times 10^4$	1.58 ± 0.25	—		$\mathbf{1.47 \pm 0.18}$	
$\mathcal{B}(J/\psi \to K^+K^-) \times 10^4$	2.39 ± 0.33	—		$\mathbf{2.86 \pm 0.21}$	
$\mathcal{B}(J/\psi \to K_S K_L) \times 10^4$	1.01 ± 0.18	1.82 ± 0.13		$\mathbf{2.62 \pm 0.21}$	
$\delta(J/\psi)$	$(88 \pm 11)^\circ$	—		$\mathbf{(73.6 \pm 5.6)^\circ}$	$\mathbf{(73.5^{+5.0}_{-4.5})^\circ}$

TABLE II. Summary of results for $\psi(2S)$ and J/ψ decays to pseudoscalar pairs: branching fractions and the phase difference angles $\delta(\psi(2S))$ and $\delta(J/\psi)$ using central values of branching fractions. The BES [7] and CLEO [8] results for $\delta(\psi(2S))$ have been recalculated to correspond to the internal angle of the amplitude triangle. In the last column $\delta(\psi)$ results based on Monte Carlo calculation described in the text are presented.

Thus the final branching fractions are

$$\mathcal{B}(J/\psi \to \pi^+\pi^-)$$
$$= [1.47 \pm 0.13(\text{stat}) \pm 0.13(\text{syst})] \times 10^{-4},$$
$$\mathcal{B}(J/\psi \to K^+K^-)$$
$$= [2.86 \pm 0.09(\text{stat}) \pm 0.19(\text{syst})] \times 10^{-4},$$
$$\mathcal{B}(J/\psi \to K_S K_L)$$
$$= [2.62 \pm 0.15(\text{stat}) \pm 0.14(\text{syst})] \times 10^{-4}. \quad (5)$$

These are listed in Table I, and in Table II with the statistical and systematic errors combined in quadrature. The above branching fractions for $J/\psi \to \pi^+\pi^-$ and K^+K^- are consistent with those reported by Mark III [10], and have factors two and three smaller uncertainties, respectively. Our branching fraction for $J/\psi \to K_S K_L$ based on 334 ± 19 well resolved events, as shown in Fig. 4 (f), is a factor 2.6 larger than $\mathcal{B}(J/\psi \to K_S K_L) = (1.01\pm0.18)\times 10^{-4}$ reported by Mark III with 74 identified counts, obtained by "stringent cuts" to remove $J/\psi \to \rho^0\pi^0$ and $J/\psi \to K_S \bar{K}^*(898)$ decays, and is $\sim 40\%$ larger than $\mathcal{B}(J/\psi \to K_S K_L) = (1.82 \pm 0.13) \times 10^{-4}$ reported by BES II [7] with 2155 ± 45 identified events. In the large statistics BES II measurements the peak due to $J/\psi \to \overline{K}^{*0}(892)K_S$, $\overline{K}^{*0} \to K_L\pi^0$, $K_S \to \pi^-\pi^+$, overlapped with the direct $J/\psi \to K_S K_L$, $K_S \to \pi^+\pi^-$ peak, and strong cuts had to be made to resolve the two peaks.

As shown in Figs. 4 (c,f), in our measurements the two peaks are completely resolved. Further, MC calculations confirm that with our selections the decay $J/\psi \to \pi^0\rho^0$, $\rho^0 \to \pi^+\pi^-$ also does not make any contribution under the $J/\psi \to K_S K_L$, $K_S \to \pi^+\pi^-$ peak at $X(K_S) = 1.0$.

As for $\psi(2S)$, we calculate $\delta(J/\psi)$ using Eq. (1), and obtain $\delta(J/\psi) = (73.6 \pm 5.6)^\circ$, as compared to $(88 \pm 11)^\circ$ obtained using the branching fractions measured by Mark III. These are listed in Table II.

V. MONTE CARLO BASED EVALUATION OF $\delta(\psi)$ AND THE DIFFERENCE $\Delta\delta \equiv \delta(\psi(2S)) - \delta(J/\psi)$

The individual measured branching fraction values have distributions which are conventionally stated in terms of 1σ errors, as listed in Table I. Using only the central values to evaluate $\delta(\psi)$ according to Eq. (1) is not correct. The more correct procedure is to make Monte Carlo evaluation of Eq. (1) taking account of random associations of the branching fraction values in the distributions for the three decays. We have made such toy MC evaluations of both $\delta(\psi(2S))$ and $\delta(J/\psi)$. As shown in Fig. 5 (left), the large error ($\pm30\%$) in $\psi(2S) \to \pi^+\pi^-$ branching fraction leads to a very asymmetric MC distribution for $\delta(\psi(2S))$, whereas the much smaller error
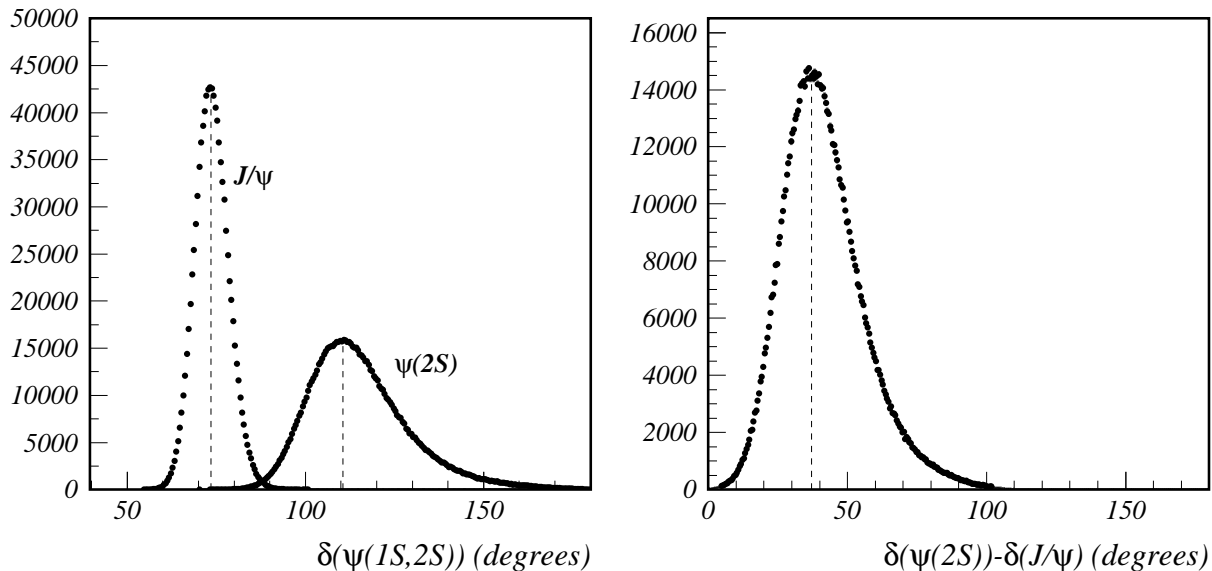
FIG. 5. (Left) The relative phase angle distributions $\delta(\psi)$ for $\psi(2S)$ and J/ψ obtained from toy MC simulations. The results are $\delta(\psi(2S)) = (110.5^{+16.0}_{-9.5})^\circ$ and $\delta(J/\psi) = (73.5^{+5.0}_{-4.5})^\circ$. (Right) Toy MC distribution of the difference of relative phase angles for $\psi(2S)$ and J/ψ, $\Delta\delta = \delta(\psi(2S)) - \delta(J/\psi) = (37.0^{+16.5}_{-10.5})^\circ$.

$(\pm 12\%)$ for $J/\psi \to \pi^+\pi^-$ results in a much smaller asymmetry in the distribution for $\delta(J/\psi)$. If we adopt the usual definition of the 1σ error as that which includes 68% of the area on each side of the peak of a distribution, our results are

$$\delta(\psi(2S))_{PP} = (110.5^{+16.0}_{-9.5})^\circ, \quad \text{and}$$
$$\delta(J/\psi)_{PP} = (73.5^{+5.0}_{-4.5})^\circ. \qquad (6)$$

The difference, whose MC distribution is illustrated in Fig. 5 (right), is

$$\Delta\delta \equiv \delta(\psi(2S))_{PP} - \delta(J/\psi)_{PP} = (37.0^{+16.5}_{-10.5})^\circ. \quad (7)$$

We consider the above estimates of $\delta(\psi(2S))_{PP}$, $\delta(J/\psi)_{PP}$, and their difference to be our final results.

VI. CONCLUSIONS

We have made large statistics measurements of the branching fractions for the decays of $\psi(2S)$ and J/ψ to pseudoscalar pairs $\pi^+\pi^-$, K^+K^-, and $K_S K_L$. Our branching fraction results have errors which are factors two to five smaller than the previously published results. Using these branching fractions we have made calculations of the phase angle differences between the electromagnetic and strong decays for both $\psi(2S)$ and J/ψ, taking proper account of the distributions of the branching fraction values. Our results are nearly a factor two more precise than the previously published results.

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