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## Determination of the Spin and Parity of the $Z_c(3900)$

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The spin and parity of the  $Z_c(3900)^\pm$  state are determined to be  $J^P = 1^+$  with a statistical significance larger than  $7\sigma$  over other quantum numbers in a partial wave analysis of the process  $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ . We use a data sample of  $1.92 \text{ fb}^{-1}$  accumulated at  $\sqrt{s} = 4.23$  and  $4.26 \text{ GeV}$  with the BESIII experiment. When parametrizing the  $Z_c(3900)^\pm$  with a Flatté-like formula, we determine its pole mass  $M_{\text{pole}} = (3881.2 \pm 4.2_{\text{stat}} \pm 52.7_{\text{syst}}) \text{ MeV}/c^2$  and pole width  $\Gamma_{\text{pole}} = (51.8 \pm 4.6_{\text{stat}} \pm 36.0_{\text{syst}}) \text{ MeV}$ . We also measure cross sections for the process  $e^+e^- \rightarrow Z_c(3900)^\pm\pi^\mp + \text{c.c.} \rightarrow J/\psi\pi^+\pi^-$  and determine an upper limit at the 90% confidence level for the process  $e^+e^- \rightarrow Z_c(4020)^\pm\pi^\mp + \text{c.c.} \rightarrow J/\psi\pi^+\pi^-$ .

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A charged charmoniumlike state,  $Z_c^\pm$  [ $Z_c$  denotes  $Z_c(3900)$  throughout this Letter except when its mass is explicitly mentioned], was observed by the BESIII [1] and Belle [2] Collaborations in the process  $e^+e^- \rightarrow \pi^+\pi^-J/\psi$  and confirmed using CLEO-c's data [3]. As there are at least four quarks in the structure, many theoretical interpretations of the nature and the decay dynamics of the  $Z_c$  have been put forward [4–9].

A similar charged structure, the  $Z_c(3885)^\pm$ , was observed in the process  $e^+e^- \rightarrow (D\bar{D}^*)^\pm\pi^\mp$  [10], with a spin parity ( $J^P$ ) assignment of  $1^+$  favored over the  $1^-$  and  $0^-$  hypotheses. However, its mass and width are  $2\sigma$  and  $1\sigma$ , respectively, below those of the  $Z_c^\pm$  observed in  $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ . Are the  $Z_c(3885)^\pm$  and the  $Z_c^\pm$  the same state, and do they have the same spin and parity? This is one of the most important pieces of information desired in many theoretical analyses [6,11]. Finally, the  $Z_c(4020)$  was observed for the first time in the processes  $e^+e^- \rightarrow \pi^+\pi^-h_c$  [12] and  $e^+e^- \rightarrow (D^*\bar{D}^*)^\pm\pi^\mp$  [13], but it has not been searched for in the  $\pi^+\pi^-J/\psi$  final state yet.

In this Letter, we report on the determination of the spin and parity of the  $Z_c$  and a search for the  $Z_c(4020)^\pm$  in the process  $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ . The results are based on a partial wave analysis (PWA) of the  $e^+e^- \rightarrow \pi^+\pi^-J/\psi$  events accumulated with the BESIII detector [14]. The BESIII detector consists of a helium-gas-based drift chamber, a plastic scintillator time-of-flight system, and a CsI (TI) electromagnetic calorimeter, all enclosed in a superconducting solenoidal magnet providing a 1.0-T magnetic field. The solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identifier modules interleaved with steel. The data sample includes  $1092 \text{ pb}^{-1}$   $e^+e^-$  collision data at a center-of-mass (c.m.) energy  $\sqrt{s} = 4.23 \text{ GeV}$  and  $827 \text{ pb}^{-1}$  data at  $\sqrt{s} = 4.26 \text{ GeV}$  [15]. The precise c.m. energies are measured with the dimuon process [16].

The  $e^+e^- \rightarrow \pi^+\pi^-J/\psi$  candidate events are selected with the same selection criteria as described in Refs. [1,17] with  $J/\psi$  reconstructed from lepton pairs ( $\ell^+\ell^- = \mu^+\mu^-$ ,  $e^+e^-$ ). The numbers of selected candidate events are 4154

at  $\sqrt{s} = 4.23 \text{ GeV}$  and 2447 at  $\sqrt{s} = 4.26 \text{ GeV}$ ; the event samples are estimated to contain 365 and 272 background events, respectively, at these two points, using the  $J/\psi$  mass sidebands as has been done in Ref. [1].

Amplitudes of the PWA are constructed with the helicity-covariant method [18]; the process  $e^+e^- \rightarrow \pi^+\pi^-J/\psi$  is assumed to proceed via the  $Z_c$  resonance, i.e.,  $e^+e^- \rightarrow Z_c^\pm\pi^\mp$ ,  $Z_c^\pm \rightarrow J/\psi\pi^\pm$ , and via the non- $Z_c$  decay  $e^+e^- \rightarrow RJ/\psi$ ,  $R \rightarrow \pi^+\pi^-$ . All processes are added coherently to obtain the total amplitude [19]. For a particle decaying to the two-body final state, i.e.,  $A(J, m) \rightarrow B(s, \lambda)C(\sigma, \nu)$ , where the spin and helicity are indicated in the parentheses, its helicity amplitude  $F_{\lambda,\nu}$  is related to the covariant amplitude via [18,20]

$$F_{\lambda,\nu} = \sum_{lS} g_{lS} \sqrt{\frac{2l+1}{2J+1}} \langle l0S\delta | J\delta \rangle \langle s\lambda\sigma-\nu | S\delta \rangle r^l \frac{B_l(r)}{B_l(r_0)}, \quad (1)$$

where  $\delta = \lambda - \nu$ , and  $g_{lS}$  is the coupling constant in the  $l - S$  coupling scheme, the angular brackets denote Clebsch-Gordan coefficients,  $r$  is the magnitude of the momentum difference between the two final state particles,  $r_0$  corresponds to the momentum difference at the nominal mass of the resonance, and  $B_l$  is a barrier factor [21]. The nonresonant process  $e^+e^- \rightarrow \pi^+\pi^-J/\psi$  is parametrized with an amplitude based on the QCD multipole expansion [22].

The relative magnitudes and phases of the complex coupling constants  $g_{lS}$  are determined by an unbinned maximum likelihood fit to the data. The minimization is performed using the package MINUIT [23], and the backgrounds are subtracted from the likelihood as in Ref. [24].

In the nominal fit, we assume the  $Z_c$  to have  $J^P = 1^+$ , and its line shape is described with a Flatté-like formula taking into account the fact that the  $Z_c^\pm$  decays are dominated by the final states  $(D\bar{D}^*)^\pm$  [10] and  $J/\psi\pi^\pm$  [1], i.e.,

$$BW(s, M, g'_1, g'_2) = \frac{1}{s - M^2 + i[g'_1\rho_1(s) + g'_2\rho_2(s)]}, \quad (2)$$

where the subscripts in  $g'_i$  ( $i = 1, 2$ ) represent the  $Z_c^\pm \rightarrow \pi^\pm J/\psi$  and  $(D\bar{D}^*)^\pm$  decays, respectively;  $\rho_i(s) = 2k_i/\sqrt{s}$

is a kinematic factor with  $k_i$  being the magnitude of the three-vector momentum of the final state particle ( $J/\psi$  or  $D$ ) in the  $Z_c$  rest frame; and  $g'_1$  and  $g'_2$  are the coupling strengths of  $Z_c^\pm \rightarrow \pi^\pm J/\psi$  and  $Z_c^\pm \rightarrow (D\bar{D}^*)^\pm$ , respectively, which will be determined by the fit to the data.

To describe the  $\pi^+\pi^-$  mass spectrum, four resonances,  $\sigma$ ,  $f_0(980)$ ,  $f_2(1270)$ , and  $f_0(1370)$ , are introduced.  $f_0(980)$  is described with a Flatté formula [25], and the others are described with relativistic Breit-Wigner (BW) functions. The width of the wide resonance  $\sigma$  is parametrized with  $\Gamma_\sigma(s) = \sqrt{1 - (4m_\pi^2/s)}\Gamma$  [26,27], and the masses and widths for the  $f_2(1270)$  and  $f_0(1370)$  are taken from the Particle Data Group [28]. The statistical significance for each resonance is determined by examining the probability of the change in log likelihood ( $\log L$ ) values between including and excluding this resonance in the fits, and the probability is calculated under the  $\chi^2$  distribution hypothesis taking the change of the number of degrees of freedom  $\Delta(\text{ndf})$  into account. With this procedure, the statistical significance of each of these states and the nonresonant process is estimated to be larger than  $5\sigma$ . All of them are therefore included in the nominal fit, which includes the  $e^+e^- \rightarrow \sigma J/\psi$ ,  $f_0 J/\psi$ ,  $f_0(1370) J/\psi$ ,  $f_2(1270) J/\psi$ ,  $Z_c^\pm \pi^\mp$ , and nonresonant processes.

A simultaneous fit is performed to the two data sets. The coupling constants are set as free parameters and are allowed to be different at the two energy points except for the common ones describing  $Z_c$  decays. The oppositely charged  $Z_c$  states are regarded as isospin partners; they share a common mass and coupling parameters  $g'_1$  and  $g'_2$ . Figure 1 shows projections of the fit results at  $\sqrt{s} = 4.23$  and 4.26 GeV, with a fit goodness of the Dalitz plot  $\chi^2/\text{ndf} = 1.3$  and 1.2, respectively. The mass of  $Z_c^\pm$  is measured to be  $M_{Z_c} = (3901.5 \pm 2.7_{\text{stat}})$  MeV/ $c^2$ , and the coupling parameters  $g'_1 = (0.075 \pm 0.006_{\text{stat}})$  GeV $^2$  and  $g'_2/g'_1 = 27.1 \pm 2.0_{\text{stat}}$ . This measurement is consistent with the previous result  $g'_2/g'_1 = 27.1 \pm 13.1$  estimated based on the measured decay width ratio  $\Gamma(Z_c^\pm \rightarrow (D\bar{D}^*)^\pm)/\Gamma(Z_c^\pm \rightarrow J/\psi\pi^\pm) = 6.2 \pm 2.9$  [10]. If the  $Z_c^\pm$  is parametrized as a constant-width BW function, the simultaneous fit gives a mass of  $(3897.6 \pm 1.2_{\text{stat}})$  MeV/ $c^2$  and a width of  $(43.5 \pm 1.5_{\text{stat}})$  MeV, but the value of  $-\ln L$  increases by 22 with  $\Delta(\text{ndf}) = 1$ . The BW parametrization is thus disfavored with a significance of  $6.6\sigma$ .

Figure 2 shows the polar angle ( $\theta_{Z_c^\pm}$ ) distribution of  $Z_c^\pm$  in the process  $e^+e^- \rightarrow Z_c^\pm \pi^- + \text{c.c.}$  and the helicity angle ( $\theta_{J/\psi}$ ) distribution in the decay  $Z_c^\pm \rightarrow \pi^\pm J/\psi$  for the

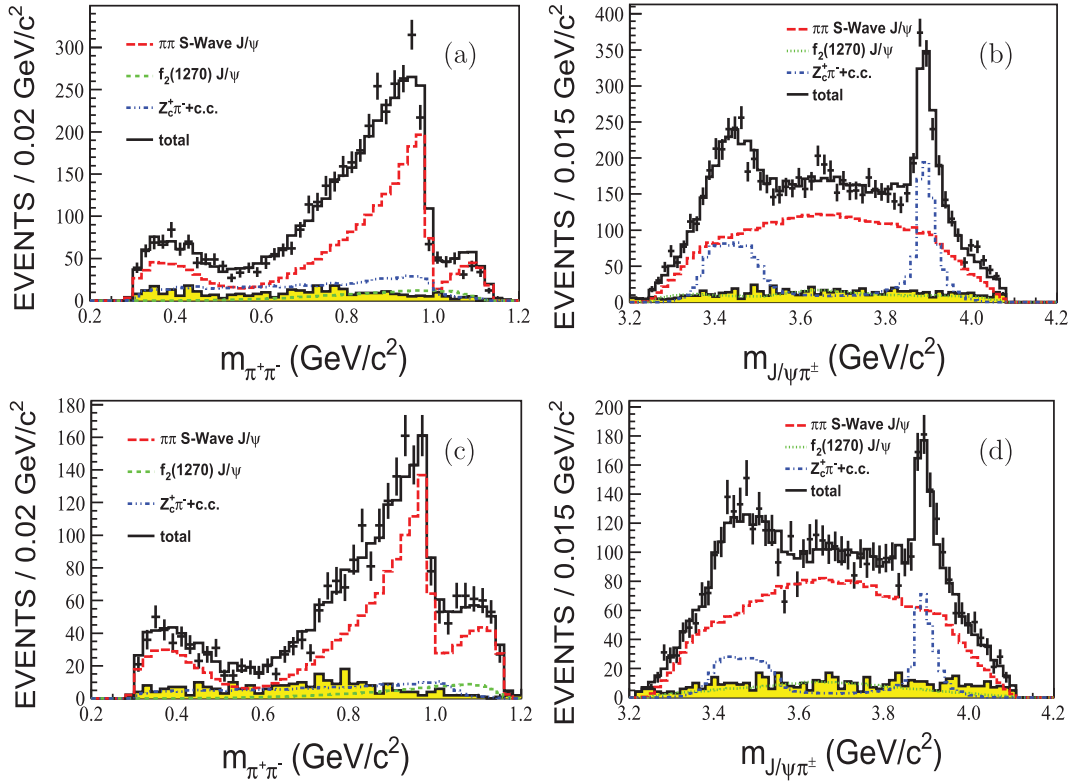


FIG. 1. Projections to  $m_{\pi^+\pi^-}$  (a),(c) and  $m_{J/\psi\pi^\pm}$  (b),(d) of the fit results with  $J^P = 1^+$  for the  $Z_c$ , at  $\sqrt{s} = 4.23$  GeV (a),(b) and  $\sqrt{s} = 4.26$  GeV (c),(d). The points with error bars are data, and the black histograms are the total fit results including backgrounds. The shaded histogram denotes backgrounds. The contributions from the  $\pi^+\pi^-$  S-wave  $J/\psi$ ,  $f_2(1270)J/\psi$ , and  $Z_c^\pm \pi^\mp$  are shown in the plots. The  $\pi^+\pi^-$  S-wave resonances include the  $\sigma$ ,  $f_0(980)$ , and  $f_0(1370)$ . Plots (b) and (d) are filled with two entries ( $m_{J/\psi\pi^+}$  and  $m_{J/\psi\pi^-}$ ) per event.

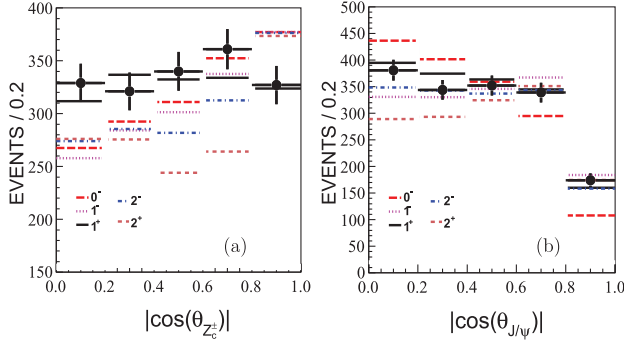


FIG. 2. (a) Polar angle distribution of  $Z_c^\pm$  in the process  $e^+e^- \rightarrow Z_c^\pm \pi^\mp + \text{c.c.}$ ; (b) helicity angle distribution of  $J/\psi$  in the  $Z_c^\pm \rightarrow \pi^\pm J/\psi$ . The dots with error bars show the combined data with the requirement  $m_{J/\psi\pi^\pm} \in (3.86, 3.92) \text{ GeV}/c^2$  and compared to the total fit results with different  $J^P$  hypotheses.

combined data within the  $Z_c$  mass region  $m_{J/\psi\pi^\pm} \in (3.86, 3.92) \text{ GeV}/c^2$ , where  $\theta_{J/\psi}$  is the angle between the momentum of  $J/\psi$  in the  $Z_c$  rest frame and the  $Z_c$  momentum in the  $e^+e^-$  rest frame. The fit results, using different assumptions for the  $Z_c$  spin and parity, are drawn with a global normalization factor. The distribution indicates that data favor a spin and parity assignment of  $1^+$  for the  $Z_c^\pm$ . The significance of the  $Z_c^\pm(1^+)$  hypothesis is further examined using the hypothesis test [29], in which the alternative hypothesis is our nominal fit with an additional  $Z_c^\pm(J^P \neq 1^+)$  state. Possible  $J^P$  assignments, other than  $1^+$ , are  $0^-, 1^-, 2^-$ , and  $2^+$ . The changes  $-2\Delta \ln L$  when the  $Z_c(1^+)\pi^\mp$  amplitude is removed from the alternative hypothesis are listed in Table I. Using the associated change in the ndf when the  $Z_c^\pm(1^+)$  is excluded, we determine the significance of the  $1^+$  hypothesis over the alternative  $J^P$  possibilities to be larger than  $7\sigma$ .

The fit results shown in Fig. 1 indicate that process is dominated by the  $\pi\pi$   $S$ -wave resonances, i.e., the  $\sigma$ ,  $f_0(980)$ , and  $f_0(1370)$ . The fraction of all  $\pi^+\pi^-$   $S$ -wave

TABLE I. Significance of the spin parity  $1^+$  over other quantum numbers for  $Z_c^\pm$ . The significance is obtained for given change in ndf,  $\Delta(\text{ndf})$ . In each case,  $\Delta(\text{ndf}) = 2 \times 4 + 5$ , where  $2 \times 4$  ndf account for the coupling strength for  $e^+e^- \rightarrow Z_c^\pm \pi^\mp$  at the two data sets and the additional five ndf are the contribution of the common degrees of freedom for the  $Z_c$  resonant parameters and the coupling strength for  $Z_c^\pm \rightarrow J/\psi\pi^\pm$ .

Hypothesis	$\Delta(-2 \ln L)$	$\Delta(\text{ndf})$	Significance
$1^+$ over $0^-$	94.0	13	$7.6\sigma$
$1^+$ over $1^-$	158.3	13	$10.8\sigma$
$1^+$ over $2^-$	151.9	13	$10.5\sigma$
$1^+$ over $2^+$	96.0	13	$7.7\sigma$

components including the interference between them is measured to be  $(61.7 \pm 2.1_{\text{stat}})\%$  of the total  $\pi^+\pi^-J/\psi$  events at  $\sqrt{s} = 4.23 \text{ GeV}$  and  $(71.4 \pm 4.1_{\text{stat}})\%$  at  $\sqrt{s} = 4.26 \text{ GeV}$ . The signal yields  $N_{Z_c^\pm}$  of  $Z_c^\pm$  are calculated by scaling its partial signal ratio with the total number of signal events. They are measured to be  $N_{Z_c^\pm} = 952.3 \pm 39.3_{\text{stat}}$  at  $\sqrt{s} = 4.23 \text{ GeV}$  and  $343.3 \pm 23.3_{\text{stat}}$  at  $\sqrt{s} = 4.26 \text{ GeV}$ . Here, the errors are statistical only, and they are estimated using the covariance matrix from the fits.

To measure amplitudes associated with the polarization of  $Z_c^\pm$  in  $e^+e^- \rightarrow Z_c^\pm \pi^\mp$  and that of  $J/\psi$  in  $Z_c^\pm \rightarrow J/\psi\pi^\pm$  decays in the nominal fit, the ratios of helicity amplitudes with different polarizations as defined in Eq. (1) are calculated to be  $|F_{1,0}^{Z_c}|^2/|F_{0,0}^{Z_c}|^2 = 0.22 \pm 0.05_{\text{stat}}$  at 4.23 GeV and  $0.21 \pm 0.11_{\text{stat}}$  at 4.26 GeV for  $e^+e^- \rightarrow Z_c^\pm \pi^\mp$ , and  $|F_{1,0}^{J/\psi}|^2/|F_{0,0}^{J/\psi}|^2 = 0.45 \pm 0.15_{\text{stat}}$  for  $Z_c^\pm \rightarrow J/\psi\pi^\pm$ , at both energy points. Here  $F_{1,0}^{Z_c/\psi}$  and  $F_{0,0}^{Z_c/\psi}$  correspond to transverse and longitudinal polarization amplitudes in the decay, respectively. The results show that the  $Z_c$  polarization is dominated by the longitudinal component.

The Born cross section for  $Z_c$  production is measured with the relation  $\sigma = N_{Z_c^\pm}/[\mathcal{L}(1+\delta)\epsilon\mathcal{B}]$ , where  $N_{Z_c^\pm}$  is the signal yield for the process  $e^+e^- \rightarrow Z_c^\pm \pi^\mp + \text{c.c.} \rightarrow \pi^+\pi^-J/\psi$ ,  $\mathcal{L}$  is the integrated luminosity, and  $\epsilon$  is the detection efficiency obtained from a Monte Carlo (MC) simulation which is generated using the amplitude parameters determined in the PWA. The radiative correction factor  $(1+\delta)$  is determined to be 0.818 [1]. The Born cross section is measured to be  $(22.0 \pm 1.0_{\text{stat}}) \text{ pb}$  at  $\sqrt{s} = 4.23 \text{ GeV}$  and  $(11.0 \pm 1.2_{\text{stat}}) \text{ pb}$  at  $\sqrt{s} = 4.26 \text{ GeV}$ .

Using these two data sets, we also search for the process  $e^+e^- \rightarrow Z_c(4020)^\pm \pi^\mp + \text{c.c.} \rightarrow \pi^+\pi^-J/\psi$ , with the  $Z_c(4020)^\pm$  assumed to be a  $1^+$  state. In the PWA, its mass is taken from Ref. [12], and its width is taken as the observed value, which includes the detector resolution. The statistical significance for  $Z_c(4020)^\pm \rightarrow J/\psi\pi^\pm$  is found to be  $3\sigma$  in the combined data. The Born cross sections are measured to be  $(0.2 \pm 0.1_{\text{stat}}) \text{ pb}$  at 4.23 GeV and  $(0.8 \pm 0.4_{\text{stat}}) \text{ pb}$  at  $s = 4.26 \text{ GeV}$ , and the corresponding upper limits at the 90% confidence level are estimated to be 0.9 and 1.4 pb, respectively.

Systematic errors associated with the event selection, including the luminosity measurement, tracking efficiency of charged tracks, kinematic fit, initial state radiation correction factor, and the branching fraction of  $Br(J/\psi \rightarrow \ell^+\ell^-)$ , have been estimated to be 4.8% for the cross section measurement and 1.8 MeV for the  $Z_c$  mass in the previous analysis [1].

Uncertainties associated with the amplitude analysis come from the  $\sigma$  and  $Z_c$  parametrizations, the background estimation, the parameters in the  $f_0(980)$  Flatté formula, the barrier radius in the barrier factor, the mass resolution, and the component of nonresonant amplitude.

The systematic uncertainty due to the  $\sigma$  line shape is estimated by comparing the nominal fit with two other parametrizations, the PKU ansatz [30] and the Zou-Bugg approach [31]. The differences in the  $Z_c$  signal yields and mass measurement are taken as the errors, which are 2.5% (31.0%) for the signal yields at 4.23 (4.26) GeV and 19.5 MeV for the  $Z_c$  mass.

The uncertainty due to the  $f_0(980)$  line shape is estimated by varying the couplings by  $1\sigma$  as determined in the decays  $J/\psi \rightarrow \phi\pi^+\pi^-$  and  $\phi K^+K^-$  [25]. Uncertainties associated with the  $f_0(1370)$  are estimated by varying the mass and width by one standard deviation around the world average values [28].

The uncertainty due to the  $Z_c$  parametrization is estimated by using a constant-width relativistic BW function. The simultaneous fit gives the  $Z_c$  mass of  $(3897.6 \pm 1.2_{\text{stat}})$  MeV/ $c^2$  and the width of  $(43.5 \pm 1.5_{\text{stat}})$  MeV. The difference in the  $Z_c$  signal yields is 15.5% (7.9%) for the data taken at 4.23 (4.26) GeV.

The uncertainty due to the background level is estimated by changing the number of background events by  $1\sigma$  around the nominal value, that is,  $\pm 25$  around 637 events.

The barrier radius is usually taken in the range  $r_0 \in (0.25, 0.76)$  fm, with 0.6 fm being used in the nominal fit. Uncertainties at both ends are checked. For a conservative estimation, the radius  $r_0 = 0.76$  fm, which results in the larger difference, is used to estimate the uncertainty.

The uncertainty due to the mass resolution in the  $J/\psi\pi$  invariant mass is estimated with an unfolded  $Z_c$  width. A truth width is unfolded from the observed  $Z_c$  width using a relation determined by the MC simulation, and its difference from the unfolded width,  $\delta\Gamma/\Gamma = \delta g'_1/g'_1$ , is taken as the systematic uncertainty for the coupling constant  $g'_1$ . The uncertainties in the signal yields and the  $Z_c$  mass are determined with the truth coupling constant.

The nonresonant process is described with a formula derived from the QCD multipole expansion [22]. It includes the  $S$ - and  $D$ -wave components. The uncertainty associated with this amplitude is estimated by removing the insignificant  $D$ -wave component and using the  $S$ -wave component only.

Table II summarizes the systematic uncertainties. Assuming all of these sources are independent, the total systematic uncertainties are 38.0 MeV for the measurement of the  $Z_c$  mass and 20.3% (49.2%) for the measurement of  $Z_c$  cross sections at  $\sqrt{s} = 4.23$  (4.26) GeV.

In summary, with  $1.92 \text{ fb}^{-1}$  data taken at  $\sqrt{s} = 4.23$  and 4.26 GeV, the  $Z_c^\pm$  state is studied with an amplitude fit to the  $e^+e^- \rightarrow \pi^+\pi^- J/\psi$  samples, and its spin and parity have been determined to be  $1^+$  with a statistical significance larger than  $7\sigma$  over other quantum numbers. The mass is measured to be  $M_{Z_c} = (3901.5 \pm 2.7_{\text{stat}} \pm 38.0_{\text{sys}})$  MeV/ $c^2$  in the parametrization of a Flatté-like formula with parameters  $g'_1 = 0.075 \pm 0.006_{\text{stat}} \pm 0.025_{\text{sys}}$  GeV $^2$  and  $g'_2/g'_1 = 27.1 \pm 2.0_{\text{stat}} \pm 1.9_{\text{sys}}$ , which corresponds to the  $Z_c$  pole

TABLE II. Summary of systematic uncertainties on the  $Z_c(J^P = 1^+)$  mass  $M_{Z_c}$  (MeV/ $c^2$ ), parameters  $g'_1$  (GeV $^2$ ) and  $g'_2/g'_1$ , and the signal yields at 4.23 ( $N_{Z_c}^I$ ) and 4.26 GeV ( $N_{Z_c}^{II}$ ). The uncertainties shown for the  $Z_c$  mass, parameter  $g'_1$ , and the ratio  $g'_2/g'_1$  are absolute values, while the uncertainties for  $N_{Z_c}^I$  and  $N_{Z_c}^{II}$  are relative ones.

Sources	$M_{Z_c}$	$g'_1 \times 10^3$	$g'_2/g'_1$	$N_{Z_c}^I$ (%)	$N_{Z_c}^{II}$ (%)
Event selection	1.8	...	...	4.8	4.8
$\sigma$ line shape	19.5	12.0	0.3	2.5	31.0
$Z_c$ parametrization	3.9	...	...	15.5	7.9
Backgrounds	13.9	8.0	0.1	1.9	9.3
$f_0(980)$ , $g_1$ , $g_2/g_1$	17.5	14.0	0.6	2.4	24.6
$f_0(1370)$	16.7	11.0	0.4	11.5	14.0
Barrier radius	7.9	2.0	1.7	0.5	12.9
$Z_c$ mass resolution	1.0	2.0	...	0.4	0.5
Nonresonance	14.3	9.0	0.0	0.1	18.0
Total	38.0	24.8	1.9	20.3	49.2

mass  $M_{\text{pole}} = (3881.2 \pm 4.2_{\text{stat}} \pm 52.7_{\text{sys}})$  MeV/ $c^2$  and pole width  $\Gamma_{\text{pole}} = (51.8 \pm 4.6_{\text{stat}} \pm 36.0_{\text{sys}})$  MeV, where  $M_{\text{pole}} - i\Gamma_{\text{pole}}/2$  is the solution for which the denominator of the Flatté-like formula is zero. The pole mass is consistent with the previous measurement [10]. The Born cross sections for the process  $e^+e^- \rightarrow \pi^+Z_c^- + \text{c.c.}$  are measured to be  $(21.8 \pm 1.0_{\text{stat}} \pm 4.4_{\text{sys}})$  pb at  $\sqrt{s} = 4.23$  GeV and  $(11.0 \pm 1.2_{\text{stat}} \pm 5.4_{\text{sys}})$  pb at  $\sqrt{s} = 4.26$  GeV. The contributions from  $Z_c(4020)^\pm$  are also searched for, but no significant signals are observed, and an upper limit for the  $e^+e^- \rightarrow \pi^+Z_c(4020)^- + \text{c.c.}$  process is determined to be 0.9 (1.4) pb at  $\sqrt{s} = 4.23$  (4.26) GeV.

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