Recent Charmonium Results from BES[†]

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This paper summarizes recent results obtained from the BES $\psi(2S)$ data, which with 3.8×10^6 events, is the world's largest data set.

I. INTRODUCTION

The BES experiment runs at the Beijing Electron Positron Collider (BEPC) which operates in the tau-charm energy range from 2 - 5 GeV. This paper is a review of recent results obtained from the $\psi(2S)$ data set, which is the world's largest sample. Many details of this work can be found in the references.

II. THE BES DETECTOR

The Beijing Spectrometer, BES, is a conventional cylindrical magnetic detector that is coaxial with the BEPC colliding e^+e^- beams. It is described in detail in Ref. [1]. A four-layer central drift chamber (CDC) surrounding the beampipe provides trigger information. Outside the CDC, the forty-layer main drift chamber (MDC) provides tracking and energy-loss (dE/dx) information on charged tracks over 85% of the total solid angle. The momentum resolution is $\sigma_p/p = 1.7\%\sqrt{1+p^2}$ (p in GeV/c), and the dE/dx resolution for hadron tracks for this data sample is $\sim 9\%$. An array of 48 scintillation counters surrounding the MDC provides measurements of the time-of-flight (TOF) of charged tracks with a resolution of ~ 450 ps for hadrons. Outside the TOF system, a 12 radiation length lead-gas barrel shower counter (BSC), operating in self-quenching streamer mode, measures the energies of electrons and photons over 80% of the total solid angle. The energy resolution is $\sigma_E/E = 22\%/\sqrt{E}$ (E in GeV). Surrounding the BSC is a solenoidal magnet that provides a 0.4 Tesla magnetic field in the central tracking region of the detector. Three double layers of proportional chambers instrument the magnet flux return (MUID) and are used to identify muons of momentum greater than 0.5 GeV/c.

III. $J/\psi \to \ell^+\ell^-$ BRANCHING FRACTION

The branching fractions for the leptonic decays $J/\psi \to e^+e^-$ (B_e) and $\mu^+\mu^-$ (B_μ) are basic parameters of the J/ψ resonance. In addition, these branching fractions are used to determine the total number of J/ψ events in a wide variety of measurements that take advantage of the clean experimental $J/\psi \to \ell^+\ell^-$ ($\ell = e$ or μ) signature.

We determine the J/ψ leptonic branching fraction from a comparison of the exclusive and inclusive processes:

$$\psi(2S) \to \pi^+\pi^- \; J/\psi$$
$$\hookrightarrow l^+l^- \qquad (I)$$

and

$$\hookrightarrow \text{anything} \qquad (II)$$

The J/ψ leptonic branching fraction is determined from the relation

$$B(J/\psi \to l^+l^-) = \varepsilon_{J/\psi} N_\ell^{obs} / \varepsilon_\ell N_{J/\psi}^{obs},$$

where N_ℓ^{obs} and $N_{J/\psi}^{obs}$ are observed numbers of events for processes I and II (see Fig. 1), and ε_ℓ and $\varepsilon_{J/\psi}$ are the respective acceptances.

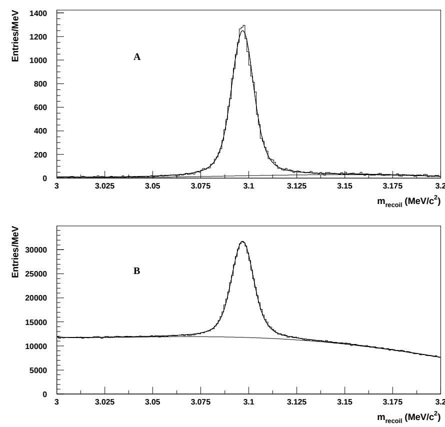

FIG. 1. The $\pi^+\pi^-$ recoil mass distributions for **a)** $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to \ell^+\ell^-$ and **b)** inclusive events.

The branching fractions are: $B_e = (5.90 \pm 0.05 \pm 0.10)\%$ and $B_\mu = (5.84 \pm 0.06 \pm 0.10)\%$. The close equality of B_μ and B_e is a verification of e-μ universality: $B_e/B_\mu = 1.011 \pm 0.013 \pm 0.016$. Assuming $B_\mu = B_e$, we find a combined leptonic branching fraction of $B_l = B(J/\psi \to \ell^+\ell^-) = (5.87 \pm 0.04 \pm 0.09)\%$ and obtain a new world average $B_l = (5.894 \pm 0.086)\%$, which has an error about half that in the 1998 PDG [2]. This work has been reported fully in Ref. [3].

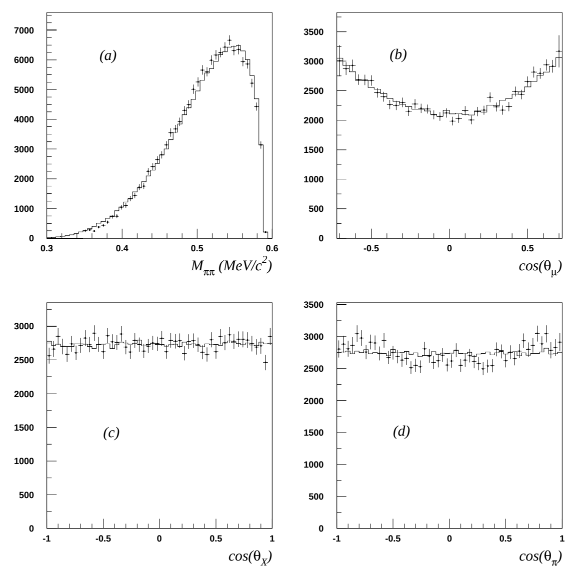

FIG. 2. Various distributions (corrected for detection efficiency) for $\psi' \to \pi^+\pi^- J/\psi$, $J/\psi \to l^+l^-$ decays. Dots with error bars are data; histogram is Monte Carlo data. **a.)** $m_{\pi^+\pi^-}$ distribution. **b.)** $\cos\theta_l^*$ distribution. The assumed distribution is a $1+\cos^2\theta_l^*$ distribution. This angle is the angle between the beam direction and the e^+ in the rest frame of the J/ψ. **c.)** $\cos\theta_X$ distribution. This is the cosine of the angle of the $\pi\pi$ system with respect to the incoming e^+e^-. **d.)** $\cos\theta^*_{\pi^+}$ distribution. This is the cosine of the angle of the π^+ with respect to the J/ψ direction in the $\pi\pi$ rest frame.

IV. $\psi(2S) \to \pi^+\pi^- J/\psi$

The dynamics of the process $\psi' \to \pi^+\pi^- J/\psi$, which is the largest decay mode of the $\psi(2S)$, can be investigated using the very clean, high statistics $\psi' \to \pi^+\pi^- J/\psi$, $J/\psi \to l^+l^-$ events ($\sim$ 23 K). This reaction may be pictured as the radiation of two gluons by the quarkonium system as it transfers to the lower energy level, followed by the hadronization of the gluons into pions. Early investigation of this decay by Mark I [4] found that the $\pi^+\pi^-$ mass distribution was strongly peaked towards higher mass values, in contrast to what is expected from phase space. Angular distributions strongly favored S-wave production of $\psi\pi\pi$, as well as an S-wave decay of the $\pi\pi$ system.

A comparison of our data and the Monte Carlo expectations based on the results of Mark I is shown in Fig. 2. We find reasonable agreement except for the $\cos\theta^*_{\pi^+}$ distribution, which is the cosine of the pion angle relative to the J/ψ direction in the $\pi\pi$ rest frame. We find that there is a D-wave contribution in addition to the S-wave.

One model that predicts a D-wave component is the Novikov-Shifman model [5]. The pions in this process are very low energy, so the process is a nonperturbative one. This model uses the scale anomaly and a multipole expansion [6]- [8] to give an amplitude:

$$A \propto \{q^2 - \kappa(\Delta M)^2(1 + \frac{2m_\pi^2}{q^2}) + \frac{3}{2}\kappa[(\Delta M)^2 - q^2](1 - \frac{4m_\pi^2}{q^2})(\cos^2\theta^*_\pi - \frac{1}{3})\},$$

where q^2 is the four-momentum squared of the dipion system and $\Delta M = M_{\psi(2S)} - M_{J/\psi}$. The parameter $\kappa = (9/6\pi)\alpha_s(\mu)\rho^G_\mu(\mu)$, where ρ^G is the gluon fraction of the π's momentum, and κ is predicted to be ≈ 0.15 to 0.2. The first terms in the amplitude are the S-wave part and the last is the D-wave part. Note that parity and charge conjugation invariance require that the spin be even. Fits using this amplitude are shown in Fig. 3, and the fit results are given in Table I. Our result for κ based on the $m_{\pi\pi}$ distribution is in good agreement with that of ARGUS [9] using Mark I data for $\psi' \to \pi^+\pi^- J/\psi$: $\kappa = 0.194 \pm 0.010$ with a χ^2/DOF of 38/24. Our results are preliminary.

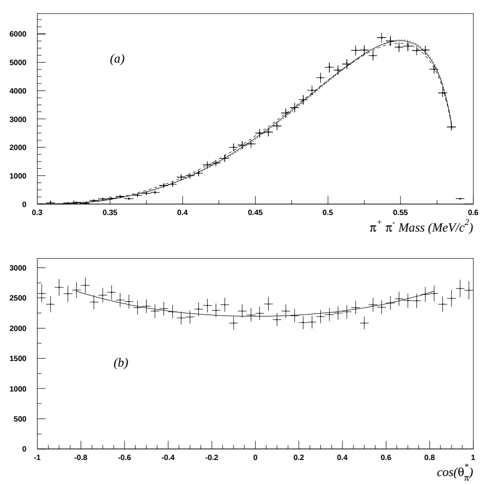

FIG. 3. Fits to 1D distributions. **(a)** $m_{\pi\pi}$ distribution. **(b)** $\cos\theta^*_\pi$ distribution.

TABLE I. Preliminary fit results for κ for the Novikov-Shifman model.

Distribution	κ	χ^2/DOF
$m_{\pi\pi}$	$0.186 \pm 0.003 \pm 0.010$	55/45
$\cos\theta^*_\pi$	$0.23^{+0.07}_{-0.04} \pm 0.11$	26/40
$m_{\pi\pi}$ vs $\cos\theta^*_\pi$	$0.183 \pm 0.003 \pm 0.005$	1618/1482

V. HADRONIC $\psi(2S)$ DECAYS

Both J/ψ and $\psi(2S)$ decays are expected to proceed via $\psi \to ggg$, with widths that are proportional to the square of the $c\bar{c}$ wave function at the origin [11]. This yields the expectation that

$$\frac{B(\psi(2S) \to X_h)}{B(J/\psi \to X_h)} \approx \frac{B(\psi(2S) \to e^+e^-)}{B(J/\psi \to e^+e^-)} = (14.1 \pm 1.2)\%$$

It was first observed by MarkII [10] that the vector-pseudoscalar (VP) $\rho\pi$ and $K^*\overline{K}$ channels are suppressed with respect to the 14% expectation - the "$\rho\pi$ puzzle".

TABLE II. ψ_{2S} Branching Ratios for Decays to Hadrons (Preliminary).

Channel	$\mathcal{B}(\psi' \to X_h)(\times 10^{-4})(PDG)$	$\mathcal{B}(\psi' \to X_h)(\times 10^{-4})$ (BES)	$S = 0.14\frac{\mathcal{B}_{J/\psi}(PDG)}{\mathcal{B}_{\psi'}(BES)}$
$\rho\pi$	< 0.83	< 0.28	> 64
$K^+\overline{K}^*(892)^- + c.c.$	< 0.54	< 0.30	> 23
$K^0\overline{K}^*(892)^0 + c.c.$	–	$0.81 \pm 0.24 \pm 0.16$	7.3 ± 2.7
$\omega\pi^0$	–	$0.38 \pm 0.17 \pm 0.11$	1.5 ± 0.8
$\omega\eta$	–	< 0.33	> 6.7
$\omega\eta^{'}(958)$	–	$0.76 \pm 0.44 \pm 0.18$	0.3 ± 0.2
$\gamma\eta$	–	$0.53 \pm 0.31 \pm 0.08$	2.3 ± 1.4
$\gamma\eta^{'}(958)$	–	$1.54 \pm 0.31 \pm 0.20$	3.9 ± 1.2
ωf_2	–	< 1.7	> 3.5
ρa_2	–	< 2.3	> 6.6
$K^*(892)^0\overline{K}_2^*(1430)^0 + c.c.$	–	< 1.2	> 7.8
$\phi f_2'(1525)$	–	< 0.45	> 2.5
$\gamma f_2(1270)$	–	$3.01 \pm 1.12 \pm 1.07$	0.6 ± 0.3
$K^*(892)^0\overline{K}^*(892)^0$	–	$0.45 \pm 0.25 \pm 0.07$	< 1.6
$\phi\phi$	–	< 0.26	
$b_1\pi$	–	$5.3 \pm 0.8 \pm 0.8$	0.8 ± 0.2
$K_1(1270)\overline{K}$	–	$10.0 \pm 1.8 \pm 1.8$	< 0.41
$K_1(1400)\overline{K}$	–	< 2.9	> 1.8
$\pi^+\pi^-K^+K^-$	16 ± 4.0	$6.9 \pm 0.3 \pm 1.2$	1.5 ± 0.5
$K^+K^-K^+K^-$	–	$0.65 \pm 0.10 \pm 0.11$	1.5 ± 0.7
$\pi^+\pi^-\pi^0$	0.9 ± 0.5	$1.06 \pm 0.11 \pm 0.16$	2.0 ± 0.7
$K\overline{K}\pi$	–	$1.25 \pm 0.18 \pm 0.26$	6.8 ± 2.1
$K^*(892)^0K^-\pi^+$ $c.c.$	–	$4.8 \pm 0.5 \pm 0.7$	
ϕK^+K^-	–	$0.51 \pm 0.13 \pm 0.09$	4.0 ± 1.4
$\phi\pi^+\pi^-$	–	$1.3 \pm 0.2 \pm 0.2$	0.9 ± 0.2
$\omega\pi^+\pi^-$	–	$4.7 \pm 0.7 \pm 1.0$	2.1 ± 0.5
$\rho^0\pi^+\pi^-$	4.2 ± 1.5	$3.7 \pm 0.6 \pm 0.9$	
$\Lambda\overline{\Lambda}$	< 4.0	$2.11 \pm 0.23 \pm 0.26$	0.9 ± 0.2
$\Sigma^0\overline{\Sigma^0}$	–	$0.94 \pm 0.30 \pm 0.38$	1.5 ± 0.5
$\Xi\overline{\Xi}$	< 2.0	$0.83 \pm 0.28 \pm 0.12$	1.5 ± 0.6
$\Delta^{++}\overline{\Delta}^{--}$	–	$0.89 \pm 0.10 \pm 0.24$	1.7 ± 0.5

We have measured, as shown in Table II, the $\psi(2S)$ branching fractions for a large number of meson final states - many for the first time. We confirm the $\rho\pi$ puzzle but with a bigger suppression factor and note the following:

1. The branching fraction for $\psi(2S) \to \omega\pi^0$ is larger than the one for the isospin-conserving, $SU(3)$-allowed, $\psi(2S) \to \rho\pi$ decay.

2. Large isospin violations are seen between the branching fractions for charged and neutral $\psi(2S) \to K^*\overline{K}$ decays, as shown in Fig. 4.

3. A clear signal is seen in $\psi(2S) \to \gamma\eta'$, but with a suppression factor of about four with respect to the 14% expectation [12].

4. Decays to vector plus tensor final states, such as $\psi(2S) \to \omega f_2, \rho a_2, K^{*0}\overline{K_2^{*0}}$, and $\phi f_2^{'}$ are also suppressed, with suppression factors relative to the J/ψ of at least about three or more [13]. This is the first evidence for suppression in a channel other than VP.

5. The $\psi(2S) \to AP$ decays $b_1^+\pi^-$ and $K_1^+(1270)K^-$ are relatively strong decay channels of the $\psi(2S)$ [14]. For $\psi(2S) \to b_1^+\pi^-$, the result is higher than, but consistent with what is expected from the 14 % rule. See Fig. 5. This rules out explanations for the $\rho\pi$ puzzle that suppress all $\psi(2S)$ decays to lowest lying two-body meson final states.

A summary of the models [15] - [22], attempting to solve the $\rho\pi$ puzzle, and related BES results, are reported in Table III.

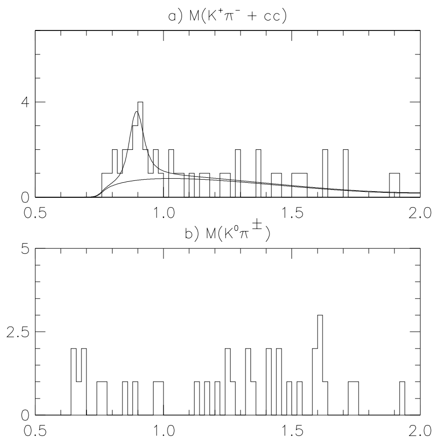

FIG. 4. Invariant **a)** $K^{\pm}\pi^{\mp}$ and **b)** $K^{o}\pi^{\pm}$ mass distributions.

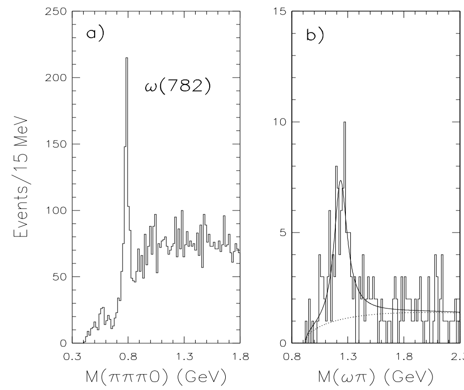

FIG. 5. **a)** The $\pi^+\pi^-\pi^0$ and **b)** the $\omega\pi^{\pm}$ mass distributions from $\psi(2S) \to \pi^+\pi^-\pi^+\pi^-\pi^0$ events. The b_1 is clearly visible in **b)**.

TABLE III. Theoretical models related to the "$\rho\pi$ puzzle" and BES results.

Authors	Model predictions	BES results
Brodsky, Lepage, Tuan [15] (1981, 1987)	Hadron Helicity Conservation suppresses $\psi(2S)$ and $J/\psi \to VP$	$\psi(2S) \to \omega\pi^0$ not suppressed. $\psi(2S) \to VT$ are suppressed (these do not violate H.H.C.)
Freund and Nambu [16] (1975) Hou and Soni [17] (1983)	J/ψ-glueball (o) mixing explains $J/\psi \to VP$ enhancement	$\mid m_o - m_{J/\psi} \mid < 80 MeV$ $4MeV < \Gamma_o < 50MeV$
Chen and Braaten [18] (1998)	color-octet $c\bar{c}$ production (requires H.H.C): $\psi(2S) \to \omega\pi^0$ not suppressed	$\psi(2S) \to \omega\pi^0$ not suppressed
Brodsky and Karliner [19] (1997)	intrinsic charm component in the light mesons (requires H.H.C.)	$\psi(2S) \to \omega\pi^0$ not suppressed
Pinsky [20] (1990)	$\psi(2S) \to VP$ are hindered M1 transitions : $\psi(2S) \to \omega f_2$ not suppressed $\psi(2S) \to \gamma\eta' < 1 \times 10^{-5}$	$\psi(2S) \to \omega f_2$ is suppressed $\psi(2S) \to \gamma\eta' \sim 1.5 \times 10^{-4}$
Li, Bugg and Zhou [21] (1997)	Final State Interactions: strong $\psi' \to VT$ signals	$\psi' \to VT$ suppressed
Chaichian and Tornquist [22] (1989)	invokes a form factor to suppress all 2-body meson modes	$J/\psi \to K_1(1400)\overline{K}$, $\psi(2S) \to b_1\pi$, etc.. not suppressed

VI. STUDIES OF $\chi_{C_{0,1,2}}$ DECAYS

The large sample of $\psi(2S)$ decays permits studies of $\chi_{c0,1,2}$ decays with unprecedented precision ($\sim 1 \times 10^6 \chi$'s). Some theoretical papers of interest are given in Refs. [23] - [28], and a summary of branching fractions is given in Table IV. Many branching fractions, like $B(\chi_{c0} \to p\bar{p})$ [29], are measured for the first time. Using $\chi_{c0} \to \pi^+\pi^-$, we find $\Gamma_{\chi_0} = 14.3 \pm 3.6$ MeV [29], which is an improvement on the PDG value (14 ± 5 MeV) [2] based on two discrepant measurements.

We have studied $\chi_c \to 4\gamma$'s and measured preliminary branching ratios for $Br(\chi_{c0} \to \pi^0\pi^0)$, $Br(\chi_{c2} \to \pi^0\pi^0)$, $Br(\chi_{c0} \to \eta\eta)$, and place an upper limit on $Br(\chi_{c2} \to \eta\eta)$. Fig. 6 shows clearly the χ_{c0} and χ_{c2} in the $\pi^o\pi^o$ invariant mass distribution. We find $Br(\chi_{c0} \to \eta\eta)/Br(\chi_{c0} \to \pi^0\pi^0) = 0.73 \pm 0.31 \pm 0.24$, where 0.95 would be expected assuming SU(3) flavor symmetry.

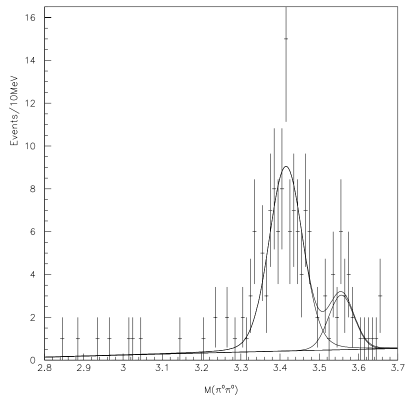

FIG. 6. Invariant Mass of $\pi^o\pi^o$. The χ_{c0} and χ_{c2} peaks are visible.

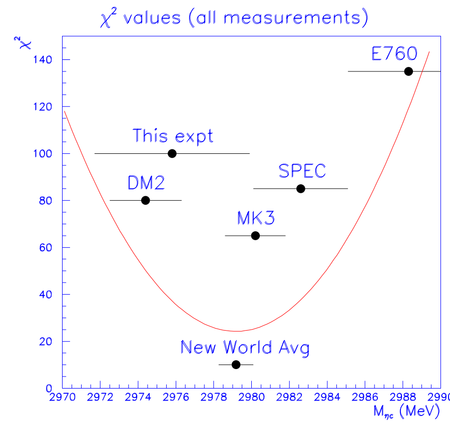

FIG. 7. M_{η_c} Results

Using many decay modes of the χ_{c0}, we have determined $M_{\chi_{c0}} = 3414.1 \pm 0.6 \pm 0.8$ MeV. This is a big improvement over the PDG value which has an error of 2.8 MeV. We have also measured the η_c mass using $\eta_c \to \pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-K^+K^-$, $K_sK^\pm\pi^\mp$, and $K^+K^-K^+K^-$, and find $M_{\eta_c} = 2975.8 \pm 3.9 \pm 1.2$ MeV. Our result and the previous ones are shown in Fig. 7. This work is described fully in Ref. [30]. Using J/ψ data, BES finds a preliminary value of M_{η_c} that agrees well with the one obtained using the $\psi(2S)$ data.

VII. SUMMARY

Using the BES $\psi(2S)$ data set, which is the world's largest, we have presented many results, including the measurement $B(J/\psi \to \ell^+\ell^-) = 5.87 \pm 0.04 \pm 0.09$, many $\psi(2S)$ and χ_c branching ratios, more information concerning the $\rho\pi$ puzzle, $M_{\chi_{c0}} = 3414.1 \pm 0.6 \pm 0.8$ MeV, and $M_{\eta_c} = 2975.8 \pm 3.9 \pm 1.2$ MeV.

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TABLE IV. BES results on decay branching fractions of the $\chi_{c0,1,2}$ charmonium states

	BES ($\times 10^{-3}$)	PDG ($\times 10^{-3}$)
$B(\chi_{c0} \to \pi^+\pi^-)$	$4.68 \pm 0.26 \pm 0.65$	7.5 ± 2.1
$B(\chi_{c0} \to \pi^o\pi^o)$	$2.80 \pm 0.32 \pm 0.51$	–
$B(\chi_{c2} \to \pi^+\pi^-)$	$1.49 \pm 0.14 \pm 0.22$	1.9 ± 1.0
$B(\chi_{c2} \to \pi^o\pi^o)$	$0.92 \pm 0.27 \pm 0.52$	–
$B(\chi_{c0} \to \eta\eta)$	$2.03 \pm 0.84 \pm 0.58$	–
$B(\chi_{c2} \to \eta\eta)$	< 2.5	–
$B(\chi_{c0} \to K^+K^-)$	$5.68 \pm 0.35 \pm 0.85$	7.1 ± 2.4
$B(\chi_{c2} \to K^+K^-)$	$0.79 \pm 0.14 \pm 0.13$	1.5 ± 1.1
$B(\chi_{c0} \to p\overline{p})$	$0.159 \pm 0.043 \pm 0.053$	< 0.9
$B(\chi_{c1} \to p\overline{p})$	$0.042 \pm 0.022 \pm 0.028$	0.086 ± 0.012
$B(\chi_{c2} \to p\overline{p})$	$0.058 \pm 0.031 \pm 0.032$	0.10 ± 0.01
$B(\chi_{c0} \to \pi^+\pi^-\pi^+\pi^-)$	$15.4 \pm 0.5 \pm 3.7$	37 ± 7
$B(\chi_{c1} \to \pi^+\pi^-\pi^+\pi^-)$	$4.9 \pm 0.4 \pm 1.2$	16 ± 5
$B(\chi_{c2} \to \pi^+\pi^-\pi^+\pi^-)$	$9.6 \pm 0.5 \pm 2.4$	22 ± 5
$B(\chi_{c0} \to K_s^0K_s^0)$	$1.96 \pm 0.28 \pm 0.52$	-
$B(\chi_{c2} \to K_s^0K_s^0)$	$0.61 \pm 0.17 \pm 0.16$	-
$B(\chi_{c0} \to \pi^+\pi^-K^+K^-)$	$14.7 \pm 0.7 \pm 3.8$	30 ± 7
$B(\chi_{c1} \to \pi^+\pi^-K^+K^-)$	$4.5 \pm 0.4 \pm 1.1$	9 ± 4
$B(\chi_{c2} \to \pi^+\pi^-K^+K^-)$	$7.9 \pm 0.6 \pm 2.1$	19 ± 5
$B(\chi_{c0} \to \pi^+\pi^-p\overline{p})$	$1.57 \pm 0.21 \pm 0.54$	5.0 ± 2.0
$B(\chi_{c1} \to \pi^+\pi^-p\overline{p})$	$0.49 \pm 0.13 \pm 0.17$	1.4 ± 0.9
$B(\chi_{c2} \to \pi^+\pi^-p\overline{p})$	$1.23 \pm 0.20 \pm 0.35$	–
$B(\chi_{c0} \to K^+K^-K^+K^-)$	$2.14 \pm 0.26 \pm 0.40$	–
$B(\chi_{c1} \to K^+K^-K^+K^-)$	$0.42 \pm 0.15 \pm 0.12$	–
$B(\chi_{c2} \to K^+K^-K^+K^-)$	$1.48 \pm 0.26 \pm 0.32$	–
$B(\chi_{c0} \to \phi\phi)$	$0.92 \pm 0.34 \pm 0.38$	–
$B(\chi_{c2} \to \phi\phi)$	$2.00 \pm 0.55 \pm 0.61$	–
$B(\chi_{c0} \to K_s^0K^+\pi^- + c.c.)$	< 0.71	–
$B(\chi_{c1} \to K_s^0K^+\pi^- + c.c.)$	$2.46 \pm 0.44 \pm 0.65$	–
$B(\chi_{c2} \to K_s^0K^+\pi^- + c.c.)$	< 1.06	–
$B(\chi_{c0} \to 3(\pi^+\pi^-))$	$11.7 \pm 1.0 \pm 2.3$	15 ± 5
$B(\chi_{c1} \to 3(\pi^+\pi^-))$	$5.8 \pm 0.7 \pm 1.2$	22 ± 8
$B(\chi_{c2} \to 3(\pi^+\pi^-))$	$9.0 \pm 1.0 \pm 2.0$	12 ± 8