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Search for prompt production of χ_c and $X(3872)$ in e^+e^- annihilations

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We have searched for prompt production of χ_{c1}, χ_{c2} and $X(3872)$ in continuum e^+e^- annihilations using a 386 fb^{-1} data sample collected around $\sqrt{s} = 10.6$ GeV with the *BABAR* detector using the $\gamma J/\psi$ decay mode. After accounting for the feed-down from $\psi(2S) \to \gamma\chi_{c1,2}$, no significant signal for prompt $\chi_{c1,2}$ production is observed. We present improved upper limits at 90% confidence level on the production cross sections of 77 fb for χ_{c1} and 79 fb for χ_{c2}, for events where the χ_c momentum exceeds 2.0 GeV and there are at least three additional charged tracks. These limits are consistent with NRQCD predictions. We also set an upper limit on the prompt production of $X(3872)$ through the decay $X(3872) \to \gamma J/\psi$.

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Charmonium production in e^+e^- annihilation provides opportunities to study both perturbative and nonperturbative effects in QCD and to search for new charmonium states [1,2]. The prompt production of J/ψ and $\psi(2S)$ in e^+e^- annihilation [3,4] and of double charmonium [5,6] have been observed at B-factory experiments. These observations are surprising because the measured cross sections are larger than nonrelativistic QCD (NRQCD) calculations by up to an order of magnitude [1,7].

In the NRQCD production mechanism, a heavy quarkonium ($q\bar{q}$) state can be produced at short distances as a conventional color-singlet, or as a color-octet state, which then evolves into an observed quarkonium meson along with other light hadrons. With this color-octet mechanism, one may explain the enhancement for J/ψ production in e^+e^- annihilation [1]. The production of $\chi_{c1,2}$ (χ_c) in e^+e^- annihilations is an excellent probe of color-octet contributions, which are more prominent in χ_c production than in J/ψ production. This is because color-octet and color-singlet processes enter χ_c production at the same order, and C parity suppresses the process $e^+e^- \to c\bar{c}gg$, which dominates J/ψ production. Calculated cross sections for prompt χ_c production in e^+e^- annihilations are $\sigma(e^+e^- \to \chi_{c1}X) = 85$ fb and $\sigma(e^+e^- \to \chi_{c2}X) = 123$ fb, with e^+e^- center-of-mass (CM) frame J/ψ momentum $p^*_{J/\psi} > 2.0$ GeV, and where X is one of $q\bar{q}$, gg and g in the leading-order processes and J/ψ is from $\chi_c \to \gamma J/\psi$ decay [8]. More accurate measurements for χ_c states will help to clarify the discrepancy between theoretical calculations and existing measurements, and may point to other methods and mechanisms in QCD to explain the differences. The calculated cross sections in Ref. [8] violate the process independence of cross-section ratios assumed in the color evaporation model [9]. Thus an experimental upper limit on χ_c production in e^+e^- annihilations will help in understanding the mechanisms of bound-state formation [8].

Prompt production of charmonium mesons in e^+e^- annihilation has been searched for using either the reconstructed mass in an exclusive decay mode [3,4] or the mass distribution of the system recoiling against the J/ψ or $\psi(2S)$ [5,6]. Although prompt production of χ_{c0} has been observed, prompt production of the other χ_c states, χ_{c1} and χ_{c2}, has not been observed.

In this paper, we present a search for prompt χ_c production in continuum e^+e^- annihilation using the $\gamma J/\psi$ ($J/\psi \to \ell^+\ell^-$) decay mode, which is experimentally clean and is the dominant one in χ_c decay. The current limits on prompt production of χ_c are $\sigma(e^+e^- \to \chi_{c1}X) < 350$ fb and $\sigma(e^+e^- \to \chi_{c2}X) < 660$ fb with e^+e^- CM frame χ_c momentum $p^*_{\chi_c} > 2.0$ GeV, where X is the rest of the event [4]. Belle and *BABAR* recently observed an indication of the decay $X(3872) \to \gamma J/\psi$ in B decays [10], and therefore we also search for prompt $X(3872)$ production using the $\gamma J/\psi$ decay mode in e^+e^- annihilation.

The data used in this analysis were collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider, where 9.0 GeV electrons and 3.1 GeV positrons are collided at a CM energy of 10.58 GeV, the mass of the $\Upsilon(4S)$ resonance. The integrated luminosity ($\mathcal{L}$) consists of 349 fb^{-1} ($\mathcal{L}_{\text{on}}$) at the $\Upsilon(4S)$ resonance and 37 fb^{-1} ($\mathcal{L}_{\text{off}}$) at a center-of-mass energy 40 MeV below the resonance.

The *BABAR* detector is described elsewhere [11] and here we give only a brief overview. The momenta of charged particles are measured by the silicon vertex tracker, consisting of five layers of double-sided silicon strip sensors, and the central drift chamber (DCH) with 40 wire layers, both operating in a 1.5 T magnetic field of a solenoid. The tracking system covers 92% of the solid angle in the CM frame. An internally reflecting ring-imaging Cherenkov detector (DIRC) with quartz bar radiators provides charged particle identification (PID). A CsI(Tl) electromagnetic calorimeter (EMC) is used to detect and identify photons and electrons, while muons are identified in the instrumented magnetic flux return system (IFR).

Electron candidates are identified by the ratio of the shower energy measured in the EMC to the track momentum measured in the DCH, the shower shape, the specific ionization energy loss in the DCH, and the Cherenkov angle measured by the DIRC. Muons are identified by the depth of penetration into the IFR, the IFR cluster geometry, and the energy deposited in the EMC. Photon candidates are identified by EMC clusters that have a shape consistent with an electromagnetic shower and are not associated with a charged track.

We use a Monte Carlo (MC) simulation of the *BABAR* detector based on GEANT4 [12] to validate the analysis procedure, to evaluate signal detection efficiencies, to model probability density functions (PDFs), and to estimate background contributions. We use samples of

$e^+e^- \to \chi_{c1,2} + J/\psi$ or $\psi(2S)$ MC events to determine the selection criteria. To estimate the signal reconstruction efficiencies and PDFs, we use single χ_c MC samples decaying to $\gamma J/\psi$ with $J/\psi \to e^+e^-$ or $J/\psi \to \mu^+\mu^-$, which are generated with flat distributions in p^* (CM frame χ_c momentum) and $\cos\theta^*$ (cosine of the polar angle of the χ_c momentum to the beam axis in the CM frame). Data are used to greatly reduce the dependence of the efficiency on specific models; the procedure used will be described in detail. To understand combinatorial background, we use MC generated $e^+e^- \to \eta_c$, χ_{c0}, or $\eta_c(2S)$ events produced in association with either J/ψ or $\psi(2S)$ mesons. $B\bar{B}$ generic and initial state radiation (ISR) $\psi(2S)$ ($e^+e^- \to \gamma\psi(2S)$) MC events are used to estimate background contamination. The χ_c candidates from B decay are used as a control data sample to correct for differences in the photon energy measurements between MC simulation and data.

Charged particles are required to have a point of closest approach to the beam spot of less than 10 cm along the beam axis and less than 1.5 cm in the plane transverse to the beam. The J/ψ mesons are reconstructed in the dilepton channel using two oppositely charged tracks identified as electrons or muons. An algorithm to recover the energy loss due to bremsstrahlung is applied to electron candidates. The invariant mass of the reconstructed J/ψ is required to be within the range [3.07, 3.13] GeV for the $\mu^+\mu^-$ channel and [3.05, 3.13] GeV for the e^+e^- channel. The asymmetric selection in the e^+e^- channel is due to initial and final state radiation. The J/ψ candidate is subjected to a vertex constrained fit and is combined with a photon candidate that satisfies standard reconstruction quality criteria as described below. Multiple signal candidates in the event are allowed.

The photon candidates are EMC clusters in the angular region $0.41 < \theta < 2.41$ radians where θ is the polar angle with respect to the beam axis in the laboratory frame. The lateral energy distribution (LAT) [13] measures the transverse energy profile of a cluster; requiring this to be less than 0.5 suppresses clusters due to both electronic noise and hadronic interactions. The azimuthal asymmetry of the energy deposition in a cluster is measured by the A_{42} Zernike moment [14]. Requiring A_{42} less than 0.1 further rejects clusters from hadronic interactions. In addition, the angular separation between the direction of the candidate and of any charged track in the event should be at least 9° in the laboratory frame (split-off rejection). The clusters satisfying these criteria come mostly from π^0 decay. We reject photon candidates that, when combined with any other photon, produce a mass between 114 and 146 MeV (π^0 veto). The partner photon must have energy greater than 30 MeV and $LAT < 0.8$ without any requirement on A_{42} and split-off rejection.

Backgrounds arise from combinatorial background in B decays and continuum events, and decays of $\psi(2S)$ mesons produced either promptly or in ISR events. To suppress B-background contributions, we require $p^*_{\chi_c} > 2.0$ GeV and $p^*_{J/\psi} > 2.0$ GeV. For the χ_c control sample, we require $p^*_{\chi_c} < 1.7$ GeV and $p^*_{J/\psi} < 2.0$ GeV. The combinatorial background for J/ψ candidates in continuum events is reduced by requiring $|\cos\theta_H^{J/\psi}| < 0.9$ [6], where $\theta_H^{J/\psi}$ is the J/ψ helicity angle, measured in the rest frame of the J/ψ, between the positively charged lepton daughter and the $\gamma J/\psi$ system.

The backgrounds from prompt $\psi(2S)$ radiative decay to $\gamma\chi_c$ are indistinguishable from the signal. The estimated contribution from prompt $\psi(2S)$ production will be subtracted from the measured cross sections.

Substantial backgrounds are due to ISR production of $\psi(2S)$ decaying to $\gamma\chi_c$, which produces low multiplicity and a jetlike event shape. To suppress such backgrounds, the ratio R_2 of second and zeroth Fox-Wolfram moments of the event [15] is required to be less than 0.8 and the number of charged particles in the event is required to be at least five ($N_{\rm ch}$ cut). The $N_{\rm ch}$ cut is also effective to suppress QED background contributions. We estimate the possible contributions from ISR production using MC samples and subtract them from the signal yield. Two-photon background contributions are estimated to be negligible with all selection criteria applied.

The helicity angle of the $\gamma J/\psi$ system (θ_H) is the angle, measured in the rest frame of the $\gamma J/\psi$ system, between the momentum of the J/ψ and the momentum of the e^+e^- center-of-mass in the laboratory frame. The J/ψ mesons from combinatorial background tend to be along the direction of the boost vector which makes $\cos\theta_H$ close to unity whereas the distribution of signal events is flat. We optimize the $\cos\theta_H$ cut using MC samples by maximizing the figure of merit $N_{\rm sig}^2/(N_{\rm cont} + N_{B\bar{B}})$, where $N_{\rm sig}$, $N_{\rm cont}$ and $N_{B\bar{B}}$ are the numbers of events from signal, continuum, and $B\bar{B}$ background expected in the data sample, respectively. The scale of $N_{\rm sig}$ is not sensitive to the optimized cut. For $N_{\rm cont}$ we use the yield from off-resonance data multiplied by $(\mathcal{L}_{\rm on} + \mathcal{L}_{\rm off})/\mathcal{L}_{\rm off}$. The optimized cut is found to be $\cos\theta_H < 0.4$. The same cut is applied for the $X(3872)$ search which has similar kinematics.

We extract the signal yield using an unbinned maximum likelihood (UML) fit (nominal fit) for the distribution of ΔM, the mass difference between the signal χ_c or $X(3872)$ candidate and the daughter J/ψ candidate. We use a ΔM range [0.25, 0.60] GeV for the χ_c searches and [0.60, 0.95] GeV for the $X(3872)$ search in the nominal fit. To estimate the systematic uncertainty, we use [0.25, 0.35] GeV and [0.50, 0.60] GeV as sideband regions and [0.35, 0.50] GeV as the core signal region for the χ_c states.

The ΔM distribution for signal candidates is described by a crystal ball line shape (CBL) which is a Gaussian (described by the peak value ΔM_0 and resolution $\sigma_{\Delta M}$) with a power law tail $1/(\Delta M_0 - \Delta M + \text{const})^n$, at a value of $\Delta M_0 - \alpha \cdot \sigma_{\Delta M}$. We use different PDFs for χ_{c1}, χ_{c2}, and $X(3872)$, averaged over the e^+e^- and $\mu^+\mu^-$ modes.

The parameter values used in the CBL are determined using MC simulation and are then fixed in the nominal fit. The resolution $\sigma_{\Delta M}$ is 14.0 MeV, 15.3 MeV and 20.5 MeV for χ_{c1}, χ_{c2}, and $X(3872)$ respectively and these are scaled by β, a scale factor for the ΔM resolution. The mean ΔM_0 for each of χ_{c1}, χ_{c2}, and $X(3872)$ is given by the known mass shifted by δ, an offset of the PDF in ΔM. The difference of the χ_{c1} and χ_{c2} masses is constrained to the known value 45.5 MeV [16]. The β and δ parameters are determined as $\beta = 0.89 \pm 0.03$ and $\delta = (2.7 \pm 0.4)$ MeV using a control data sample of χ_c mesons from B decay and fixed in the nominal fit. The background line shape is described by a third-order Chebyshev polynomial with free coefficients.

The results for the nominal fit are presented in Fig. 1. For the χ_{c1} and χ_{c2} searches, we analyze 1417 events after all selection criteria. The number of χ_{c1} candidates is 134 ± 23 and the number of χ_{c2} candidates is 56 ± 19. For the $X(3872)$ search, we find $N_{X(3872)} = -8 \pm 11$ from 293 events.

The ISR $\psi(2S)$ backgrounds are estimated using MC samples to be 9.4 events for χ_{c1} and 5.1 events for χ_{c2}. Subtracting these from the fitted yields we find $N_{\chi_{c1}} = 125 \pm 23$ and $N_{\chi_{c2}} = 51 \pm 19$, which we attribute to the sum of prompt χ_c production and feed-down from prompt $\psi(2S)$ production.

To estimate the signal detection efficiency ϵ, we decompose it into three factors: efficiencies of reconstruction (ϵ_r), π^0 veto (ϵ_v) and split-off rejection (ϵ_s). The efficiency becomes smaller in low p^* bins and high $\cos\theta^*$ bins owing to the $p^*_{J/\psi} > 2.0$ GeV requirement and lower detector coverage near the end cap region. To get an estimate of ϵ_r, we divide the region $2.0 < p^* < 5.0$ GeV into 6 bins and $-1.0 < \cos\theta^* < 1.0$ into 5 bins. We correct using the formula $\epsilon_r = w_i^{p^*} \epsilon_{ij} w_j^{\cos\theta^*}$ where $w_i^{p^*}$ and $w_j^{\cos\theta^*}$ are weights and ϵ_{ij} is an efficiency matrix ($i = 1, 6$; $j = 1, 5$), averaged over the e^+e^- and $\mu^+\mu^-$ modes using single particle MC samples. The weights are defined by

$$w_i = \frac{N_i^{p^*}/\epsilon_i^{p^*}}{\sum_{k=1}^{6} N_k^{p^*}/\epsilon_k^{p^*}}, \qquad w_j = \frac{N_j^{\cos\theta^*}/\epsilon_j^{\cos\theta^*}}{\sum_{k=1}^{5} N_k^{\cos\theta^*}/\epsilon_k^{\cos\theta^*}},$$

where $\epsilon_i^{p^*}$ and $\epsilon_j^{\cos\theta^*}$ are efficiencies in bins of p^* and $\cos\theta^*$, determined from the single χ_c MC samples, and $N_i^{p^*}$ and $N_j^{\cos\theta^*}$ are the yields in each bin, extracted from the binned fit to the data sample. For the $X(3872)$ search, we use the averaged efficiency when the weights for χ_{c1} and χ_{c2} are used, because of the limited statistics for the number of $X(3872)$ candidates. The ϵ_{ij} values are determined from the single $X(3872)$ MC sample. With these corrections, the ϵ_r values are 10.1%, 9.3%, and 8.4% for χ_{c1}, χ_{c2}, and $X(3872)$, respectively.

To estimate ϵ_v and ϵ_s, we need to have knowledge of the efficiency as a function of photon (N_γ) or charged track multiplicity ($N_{\rm ch}$), and the N_γ or $N_{\rm ch}$ fractional distribution of signal events, because ϵ_v and ϵ_s are strongly dependent on the number of photons or charged tracks in the event. We estimate efficiencies for each N_γ and $N_{\rm ch}$ bin using signal MC simulation corrected by the data-to-MC difference using χ_c candidates from B decays. The distributions of N_γ and $N_{\rm ch}$ for signal events are estimated from the sideband-subtracted data sample. The N_γ distribution ranges from 1 to 18 and the $N_{\rm ch}$ distribution ranges from 5 to 14. We estimate $\epsilon_v = 0.80$ and $\epsilon_s = 0.96$ from an average calculated by the following formula:

$$\epsilon = \frac{\sum_i N_{pi} \cdot \epsilon(N_i)}{\sum_j N_{pj}} = \frac{\sum_i N_{oi}}{\sum_j N_{pj}}$$

where N_{pi} stands for the number of photons or charged tracks produced in the ith bin, N_{oi} for the number of photons or charged tracks observed in the ith bin, $N_{pi} = N_{oi}/\epsilon(N_i)$, and $\epsilon(N_i)$ is the efficiency of the ith bin in the distribution of N_γ or $N_{\rm ch}$. For the $X(3872)$ search, we use the same ϵ_v and ϵ_s as for the χ_c. The total efficiency ϵ is

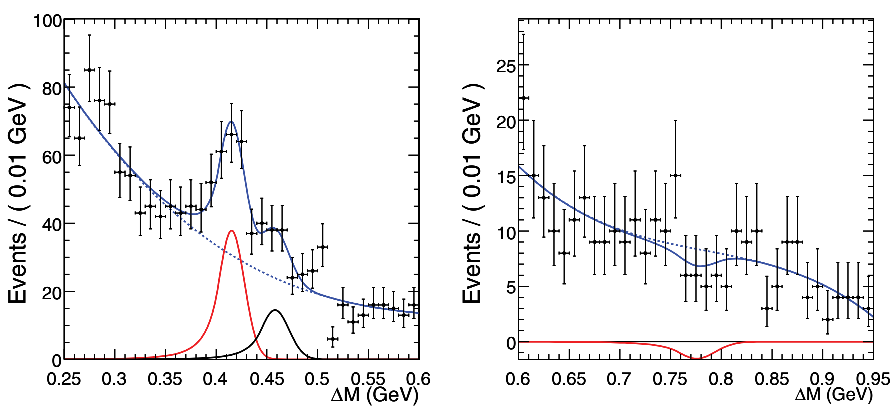

FIG. 1 (color online). Nominal fit result for the χ_c search (left) and the $X(3872)$ search (right) from the 386 fb^{-1} data sample ($p^* > 2.0$ GeV). The points represent the data, the dashed lines are background PDFs, the solid lines below the points are signal PDFs, and the solid lines on the points are the total PDFs.

TABLE I. Systematic uncertainties (quoted in %) on $\sigma_{N_{ch}\geq 3}$ defined in the text.

	χ_{c1}	χ_{c2}	$X(3872)$
$p^*/\cos\theta^*$ correction	13.3	26.5	34.9
Track efficiency	0.5	0.5	0.5
Charged PID	7.2	7.2	7.2
Photon PID	1.8	1.8	1.8
π^0 veto efficiency (ϵ_v)	2.3	2.3	2.3
Split-off rejection efficiency (ϵ_s)	0.4	0.4	0.4
PDF	3.5	11.2	15.1
ISR background	3.8	5.0	. . .
$\prod \mathcal{B}_i$	5.4	5.0	0.7
Total	17.1	30.6	38.8

the product $\epsilon_r \cdot \epsilon_v \cdot \epsilon_s$ and is estimated to be 7.7%, 7.1% and 6.4%, respectively, for the χ_{c1}, χ_{c2}, and $X(3872)$.

The sources of systematic uncertainty are summarized in Table I. The dominant uncertainty is from the reconstruction efficiency (ϵ_r) correction from the p^* and $\cos\theta^*$ distributions. For the χ_c search, we assign the systematic uncertainty as the rms spread of 10 000 simulated experiments (each experiment gives one ϵ_r value) with weights generated according to the central values and errors from the p^* and $\cos\theta^*$ binned fit results. For the $X(3872)$ search, we adopt a conservative approach. We calculate separately the rms values corresponding to the binned fit results for χ_{c1} and χ_{c2}, and assign the sum of rms values as the systematic uncertainty for the $X(3872)$ reconstruction efficiency.

The error from the PDF modeling is estimated by a quadratic sum over the changes in the yield from an alternative background line shape $e^{-[p_0+p_1(\Delta M)+p_2(\Delta M)^2]}$, and ± 1 standard deviation of the uncertainties in the measured δ and β in the χ_c control sample from B decay. We take the data-to-MC difference in track reconstruction efficiency as a source of systematic uncertainty. To estimate systematic uncertainties in charged PID efficiencies, we assign the difference when taking ± 1 standard deviation of each error depending on momentum and azimuthal angle of tracks measured using control samples. The systematic uncertainty of photon identification is estimated by comparing data with MC simulations of $\tau^+ \to \pi^+\nu$ and $\tau^+ \to \rho(\pi^+\pi^0)\nu$ samples. We assign half of the ISR $\psi(2S)$ background estimate as systematic uncertainty for the χ_c search. The uncertainty of the ISR background is neglected for the $X(3872)$ search. The $\prod \mathcal{B}_i$ is a product of subdecay mode branching fractions, that is $\mathcal{B}(\chi_c \to \gamma J/\psi) \cdot [\mathcal{B}(J/\psi \to e^+e^-) + \mathcal{B}(J/\psi \to \mu^+\mu^-)]$. The systematic error related to $\prod \mathcal{B}_i$ is estimated from the reference values [16]. The systematic uncertainties from ϵ_v and ϵ_s evaluations are estimated by a quadratic sum over the deviations in two cases: when the data-to-MC correction is not used and when N_γ and N_{ch} distributions are taken without sideband subtraction to see the effect of backgrounds on the distribution.

Table II summarizes the measurements and all the quantities we need to calculate $\sigma_{N_{ch}\geq 3}$, that is the cross section of prompt χ_c or $X(3872)$ production ($\sigma(e^+e^- \to c\bar{c}X)$) times the probability of the rest of the event (X) having more than two charged tracks, $\mathcal{P}_{N_{ch}\geq 3}$. We obtain 90% confidence level upper limits assuming the measurements are Gaussian distributed and restricted to the physical region. Where systematic errors are given, we combine them in quadrature with the statistical errors before obtaining the upper limit. The result $\sigma_{N_{ch}\geq 3}$ is derived from the formula $N_{sg} = \mathcal{L} \cdot \epsilon \cdot \sigma_{N_{ch}\geq 3} \cdot \prod \mathcal{B}_i$ where N_{sg} is the number of χ_c or $X(3872)$ candidates from e^+e^- annihilation. In the case of χ_c, $\sigma_{N_{ch}\geq 3}$ includes the prompt $\psi(2S)$ feed-down contribution. For the $X(3872)$, we measure the product $\sigma_{N_{ch}\geq 3} \cdot \mathcal{B}(X(3872) \to \gamma J/\psi)$ because the $X(3872) \to \gamma J/\psi$ BF is unknown.

For prompt χ_c production, it is necessary to subtract prompt $\psi(2S)$ feed-down to χ_c. The contribution of prompt $\psi(2S)$ production is estimated to be (58 ± 12) fb for χ_{c1} and (54 ± 11) fb for χ_{c2} using $\sigma(e^+e^- \to \psi(2S)X) = (0.67 \pm 0.13)$ pb for $p^* > 2.0$ GeV [4] and the $\psi(2S) \to \gamma\chi_c$ BF [16]. The errors are included as systematic uncertainties in the prompt χ_c production cross section. Feed-down from other $\psi(2S)$ decay modes with photons is checked using MC simulation: $J/\psi\pi^0\pi^0$, $J/\psi\eta(\gamma\gamma)$, $J/\psi\eta(\gamma\pi^+\pi^-)$, $J/\psi\eta(\pi^+\pi^-\pi^0)$, and $J/\psi\eta(\pi^0\pi^0\pi^0)$. No background from these decays is seen in the MC simulation. The resultant cross sections, $\sigma^{\rm prompt}_{N_{ch}\geq 3}$, for χ_c production are shown in Table II.

Our measurements use an additional kinematic cut $p^*_{\chi_c} > 2.0$ GeV which has little effect on the cross section because leading-order contributions are from two-body

TABLE II. Signal yield N_{sg} from the nominal fit after subtracting the ISR $\psi(2S)$ estimate; signal detection efficiency ($\epsilon = \epsilon_r \cdot \epsilon_v \cdot \epsilon_s$); product of subdecay mode BF's ($\prod \mathcal{B}_i$); integrated on- and off-resonance luminosity ($\mathcal{L}$); $\sigma_{N_{ch}\geq 3}$ (defined in the text) and its upper limit including systematic uncertainties; $\sigma^{\rm prompt}_{N_{ch}\geq 3}$ ($\sigma_{N_{ch}\geq 3}$ for the prompt production) and its upper limit including systematic uncertainties. Upper limits are at the 90% C.L. Note that $\sigma_{N_{ch}\geq 3}$ for $X(3872)$ denotes $\sigma_{N_{ch}\geq 3} \cdot \mathcal{B}(X(3872) \to \gamma J/\psi)$.

	χ_{c1}	χ_{c2}	$X(3872)$
N_{sg}	125 ± 23	51 ± 19	-8 ± 11
		(<75)	(<15)
ϵ (%)	7.7	7.1	6.4
$\prod \mathcal{B}_i$ (%)	4.2	2.4	11.9
$\mathcal{L}$ (fb^{-1})	386	386	386
$\sigma_{N_{ch}\geq 3}$ (fb)	$99 \pm 18 \pm 17$	$78 \pm 28 \pm 24$	$-3 \pm 4 \pm 1$
		<125	<5
$\sigma^{\rm prompt}_{N_{ch}\geq 3}$ (fb)	$41 \pm 18 \pm 21$	$23 \pm 28 \pm 26$	$-3 \pm 4 \pm 1$
	<77	<79	<5

e^+e^- annihilation processes. To compare these results with the theoretical predictions in Ref. [8], the value of $\mathcal{P}_{N_{ch}\geq 3}$ should be estimated correctly. Nevertheless, our upper limits are comparable with the NRQCD cross-section predictions.

In summary, we have searched for prompt production of χ_{c1} and χ_{c2} in e^+e^- annihilation near $\sqrt{s} = 10.6$ GeV. We observe candidates for these χ_c states, but the measured cross sections are compatible, within statistics, with the expected contributions of χ_c feed-down from prompt $\psi(2S)$ production. The 90% confidence level upper limits on $\sigma^{\text{prompt}}_{N_{ch}\geq 3}$ are 77 fb for χ_{c1} and 79 fb for χ_{c2} with $p^*_{\chi_c} > 2.0$ GeV. We find no evidence for prompt $X(3872)$ production via the decay $X(3872) \to \gamma J/\psi$. We set the 90% confidence level upper limit on $\sigma_{N_{ch}\geq 3} \cdot \mathcal{B}(X(3872) \to \gamma J/\psi)$ to be 5 fb. The upper limits presented on prompt χ_c production are significant improvements on the previously reported results [4]. These limits are comparable to the theoretical cross-section predictions of Ref. [8]. Upper limits on prompt production of χ_c in comparison with J/ψ and $\psi(2S)$ prompt production [3,4] can be used to further our understanding of the charmonium prompt production mechanism [1,2,8].

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