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

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SEARCH FOR PROMPT PRODUCTION OF $\chi_1$ AND \ldots

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We have searched for prompt production of $\chi_{c1}$, $\chi_{c2}$ 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 $\psi(2S) \rightarrow \gamma \chi_{c1,2}$, 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 $\chi_{c1}$ and 79 fb for $\chi_{c2}$, for events where the $\chi_c$ 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 $X(3872) \rightarrow \gamma J/\psi$.

**References**

[1] Belle and 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 $Y(4S)$ resonance. The integrated luminosity ($L$) consists of $349$ fb$^{-1}$ ($L_{\text{on}}$) at the $Y(4S)$ resonance and $37$ fb$^{-1}$ ($L_{\text{off}}$) 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...
$e^+e^-$ → $\chi_c$ MC events determine the selection criteria. To estimate the signal reconstruction efficiencies and PDFs, we use single $\chi_c$ MC samples decaying to $\gamma J/\psi$ with $J/\psi → e^+e^-$ or $J/\psi → \mu^+\mu^-$, which are generated with flat distributions in $p^*$ (CM frame $\chi_c$ momentum) and $\cos\theta^*$ (cosine of the polar angle of the $\chi_c$ 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 $e^+e^- → \eta_c,\eta_c(0)$, or $\eta_c(2S)$ events produced in association with either $J/\psi$ or $\psi(2S)$ mesons. $B\bar{B}$ generic and initial state radiation (ISR) $\psi(2S)$ ($e^+e^- → \gamma\psi(2S)$) MC events are used to estimate background contamination. The $\chi_c$ 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 $J/\psi$ 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 $J/\psi$ 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 $J/\psi$ 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 $\theta$ 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 $9^\circ$ in the laboratory frame (split-off rejection). The clusters satisfying these criteria come mostly from $\pi^0$ decay. We reject photon candidates that, when combined with any other photon, produce a mass between 114 and 146 MeV ($\pi^0$ 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 $p_{T,x_c}^* > 2.0$ GeV and $p_{T,j/\psi}^* > 2.0$ GeV. For the $\chi_c$ control sample, we require $p_{T,x_c}^* < 1.7$ GeV and $p_{T,j/\psi}^* < 2.0$ GeV. The combinatorial background for $J/\psi$ candidates in continuum events is reduced by requiring $|\cos\theta_H^*| < 0.9$ [6], where $\theta_H^*$ is the $J/\psi$ helicity angle, measured in the rest frame of the $J/\psi$, between the positively charged lepton daughter and the $\gamma J/\psi$ system.

The backgrounds from prompt $\psi(2S)$ radiative decay to $\gamma x_c$ 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 $\gamma x_c$, 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 ($N_{ch}$ cut). The $N_{ch}$ 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 ($\theta^\gamma$) is the angle, measured in the rest frame of the $\gamma J/\psi$ system, between the momentum of the $J/\psi$ and the momentum of the $e^+e^-$ center-of-mass in the laboratory frame. The $J/\psi$ 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 $N_{\text{sig}}^2/(N_{\text{cont}} + N_{BB})$, where $N_{\text{sig}}, N_{\text{cont}}$ and $N_{BB}$ are the numbers of events from signal, continuum, and $BB$ background expected in the data sample, respectively. The scale of $N_{\text{sig}}$ is not sensitive to the optimized cut. For $N_{\text{cont}}$ we use the yield from off-resonance data multiplied by $(L_{\text{on}} + L_{\text{off}})/L_{\text{off}}$. 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 $\Delta M$, the mass difference between the signal $\chi_c$, or $X(3872)$ candidate and the daughter $J/\psi$ candidate. We use a $\Delta M$ range [0.25, 0.60] GeV for the $\chi_c$ 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 $\chi_c$ states.

The $\Delta M$ distribution for signal candidates is described by a crystal ball line shape (CBL) which is a Gaussian (described by the peak value $\Delta M_0$ and resolution $\sigma_{\Delta M}$) with a power law tail $1/(\Delta M_0 - \Delta M + \text{const})$, at a value of $\Delta M_0 - \alpha \cdot \sigma_{\Delta M}$. We use different PDFs for $\chi_{c1}$, $\chi_{c2}$, 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 $\chi_{c1}$, $\chi_{c2}$, and $X(3872)$ respectively and these are scaled by $\beta$, a scale factor for the $\Delta M$ resolution. The mean $\Delta M_0$ for each of $\chi_{c1}$, $\chi_{c2}$, and $X(3872)$ is given by the known mass shift by $\delta$, an offset of the PDF in $\Delta M$. The difference of the $\chi_{c1}$ and $\chi_{c2}$ masses is constrained to the known value 45.5 MeV [16]. The $\beta$ and $\delta$ parameters are determined as $\beta = 0.89 \pm 0.03$ and $\delta = (2.7 \pm 0.4)$ MeV using a control data sample of $\chi_{c}$ 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 $\chi_{c1}$ and $\chi_{c2}$ searches, we analyze 1417 events after all selection criteria. The number of $\chi_{c1}$ candidates is $134 \pm 23$ and the number of $\chi_{c2}$ candidates is $56 \pm 19$. 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 $\chi_{c1}$ and 5.1 events for $\chi_{c2}$. 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 $\chi_{c}$ production and feed-down from prompt $\psi(2S)$ production.

To estimate the signal detection efficiency $\epsilon$, we decompose it into three factors: efficiencies of reconstruction ($\epsilon_r$), $p^+$ veto ($\epsilon_v$), and split-off rejection ($\epsilon_s$). The efficiency becomes smaller in low $p^+$ bins and high $\cos \theta^*$ bins owing to the $p^+_{ij}/\phi > 2.0$ GeV requirement and lower detector coverage near the end cap region. To get an estimate of $\epsilon$, 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 $\epsilon = w_i \epsilon_{ij} w_j^{\cos \theta^*}$ where $w_i$ and $w_j^{\cos \theta^*}$ are weights and $\epsilon_{ij}$ 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

$$w_i = \frac{N^p_i / \epsilon^p_i}{\sum_k N^p_k / \epsilon^p_k}, \quad w_j = \frac{N^{\cos \theta^*}_j / \epsilon^{\cos \theta^*}_j}{\sum_k N^{\cos \theta^*}_k / \epsilon^{\cos \theta^*}_k}$$

where $\epsilon^p_i$ and $\epsilon^{\cos \theta^*}_j$ are efficiencies in bins of $p^*$ and $\cos \theta^*$, determined from the single $\chi_c$ MC samples, and $N^p_i$ and $N^{\cos \theta^*}_j$ 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 $\chi_{c1}$ and $\chi_{c2}$ are used, because of the limited statistics for the number of $X(3872)$ candidates. The $\epsilon_{ij}$ values are determined from the single $X(3872)$ MC sample. With these corrections, the $\epsilon_r$ values are 10.1%, 9.3%, and 8.4% for $\chi_{c1}$, $\chi_{c2}$, and $X(3872)$, respectively.

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

$$\epsilon = \frac{\sum_i N_{pi} \cdot \epsilon(N_{i})}{\sum_i N_{pi}} = \frac{\sum_i N_{pi} \cdot \epsilon(N_{i})}{\sum_i N_{pj}}$$

where $N_{pi}$ stands for the number of photons or charged tracks produced in the $i$th bin, $N_{pj}$ for the number of photons or charged tracks observed in the $i$th bin, $N_{pi} = N_{pi} / \epsilon(N_{i})$, and $\epsilon(N_{i})$ is the efficiency of the $i$th bin in the distribution of $N_{s\gamma}$ or $N_{ch}$. For the $X(3872)$ search, we use the same $\epsilon_v$ and $\epsilon_s$ as for the $\chi_c$. The total efficiency $\epsilon$ is
the product $\varepsilon_c \cdot \varepsilon_u \cdot \varepsilon_s$ and is estimated to be 7.7%, 7.1%, and 6.4%, respectively, for the $\chi_{c1}$, $\chi_{c2}$, and $X(3872)$.

The sources of systematic uncertainty are summarized in Table I. The dominant uncertainty is from the reconstruction efficiency ($\varepsilon_s$) correction from the $p^*$ and $\cos \theta^*$ distributions. For the $\chi_c$ search, we assign the systematic uncertainty as the rms spread of 10,000 simulated experiments (each experiment gives one $\varepsilon_s$ 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 $\chi_{c1}$ and $\chi_{c2}$, 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 $\pm 1$ standard deviation of the uncertainties in the measured $\delta$ and $\beta$ in the $\chi_c$ 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 $\pm 1$ 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 $\tau^+ \rightarrow \pi^+ \nu$ and $\tau^+ \rightarrow \rho(\pi^+ \pi^0)\nu$ samples. We assign half of the ISR $\psi(2S)$ background estimate as systematic uncertainty for the $\chi_c$ search. The uncertainty of the ISR background is neglected for the $X(3872)$ search. The $\prod B_i$ is a product of subdecay mode branching fractions, that is $B(\chi_c \rightarrow \gamma J/\psi) \cdot [B(J/\psi \rightarrow e^+ e^-) + B(J/\psi \rightarrow \mu^+ \mu^-)]$. The systematic error related to $\prod B_i$ is estimated from the reference values [16]. The systematic uncertainties from $\varepsilon_u$ and $\varepsilon_s$ evaluations are estimated by a quadratic sum over the deviations in two cases: when the data-to-MC correction is not used and when $N_\gamma$ 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 $\sigma_{N_{ch}=3}$ that is the cross section of prompt $\chi_c$ or $X(3872)$ production ($\sigma(e^+ e^- \rightarrow c\bar{c}X)$) times the probability of the rest of the event ($X$) having more than two charged tracks, $P_{N_{ch}=3}$. 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 $\sigma_{N_{ch}=3}$ is derived from the formula $N_{sg} = L \cdot e \cdot \sigma_{N_{ch}=3} \cdot \prod B_i$ where $N_{sg}$ is the number of $\chi_c$ or $X(3872)$ candidates from $e^+ e^-$ annihilation. In the case of $\chi_c$, $\sigma_{N_{ch}=3}$ includes the prompt $\psi(2S)$ feed-down contribution. For the $X(3872)$, we measure the product $\sigma_{N_{ch}=3} \cdot B(X(3872) \rightarrow \gamma J/\psi)$ because the $X(3872) \rightarrow \gamma J/\psi$ BF is unknown.

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

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

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

| $p^*/\cos \theta^*$ correction | $\chi_{c1}$ | $\chi_{c2}$ | $X(3872)$ |
|-------------------------------|-------------|-------------|-----------|
| 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       |
| $\pi^0$ veto efficiency ($\varepsilon_u$) | 2.3       | 2.3         | 2.3       |
| Split-off rejection efficiency ($\varepsilon_s$) | 0.4       | 0.4         | 0.4       |
| PDF                          | 3.5         | 11.2        | 15.1      |
| ISR background               | 3.8         | 5.0         | $\cdots$ |
| $\prod B_i$                  | 5.4         | 5.0         | 0.7       |
| Total                        | 17.1        | 30.6        | 38.8      |

### Table II. Signal yield $N_{sg}$ from the nominal fit after subtracting the ISR $\psi(2S)$ estimate; signal detection efficiency ($\varepsilon = \varepsilon_c \cdot \varepsilon_u \cdot \varepsilon_s$) product of subdecay mode BF's ($\prod B_i$); integrated on- and off-resonance luminosity ($L$); $\sigma_{N_{ch}=3}$ (defined in the text) and its upper limit including systematic uncertainties; $\sigma_{N_{ch}=3}^{\text{prompt}}$ (for the prompt production) and its upper limit including systematic uncertainties. Upper limits are at the 90% C.L.

| $N_{sg}$ | $\chi_{c1}$ | $\chi_{c2}$ |
|----------|-------------|-------------|
| 125 ± 23 | 51 ± 19     | $-8 \pm 11$ |
| ($< 75$) | ($< 15$)    |             |

| $\varepsilon$ (%) | 7.7 | 7.1 | 6.4 |
|--------------------|-----|-----|-----|
| $\prod B_i$ (%)    | 4.2 | 2.4 | 11.9|
| $L$ (fb$^{-1}$)    | 386 | 386 | 386 |
| $\sigma_{N_{ch}=3}$ (fb) | $99 \pm 18 \pm 17$ | $78 \pm 28 \pm 24$ | $-3 \pm 4 \pm 1$ |
|                  | $< 125$ | $< 5$ | $< 5$ |

| $\sigma_{N_{ch}=3}^{\text{prompt}}$ (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 $P_{N_{ch} \geq 3}$ 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 $\chi_{c1}$ and $\chi_{c2}$ in e^+e^- annihilation near $\sqrt{s} = 10.6$ GeV. We observe candidates for these $\chi_c$ states, but the measured cross sections are compatible, within statistics, with the expected contributions of $\chi_c$ feed-down from prompt $\psi(2S)$ production. The 90% confidence level upper limits on prompt $\chi_c$ 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 $\chi_c$ in comparison with $J/\psi$ 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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