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Measurement of J/ψ production in continuum e^+e^- annihilations near the $\Upsilon(4s)$ with the BABAR detector.

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ABSTRACT: The production of J/ψ mesons in continuum e^+e^- annihilations has been studied with the *BABAR* detector at energies near the $\Upsilon(4s)$ resonance. The mesons are distinguished from J/ψ production in B decays through their center-of-mass momentum and energy. The cross section $e^+e^- \rightarrow J/\psi X$ has been measured to be $(2.52 \pm 0.21\ (stat.) \pm 0.21\ (syst.))\ pb^{-1}$. A 90% C.L. upper limit on the branching fraction for direct $\Upsilon(4s) \rightarrow J/\psi X$ decays has been set at 4.7×10^{-4}. The angular properties and the p^* distribution of the J/ψ mesons produced in these decays are also discussed here.

1. Motivations: recent theoretical and experimental developments

The development of non-relativistic QCD (NRQCD) represents a significant advance in the theory of the production of heavy quarkonium ($q\bar{q}$) states [1]. In particular, it provides an explanation for the cross section for $\psi(2S)$ production observed by CDF, which is a factor of 30 larger than expected from previous models [2]. The enhancement is attributed to the production of a $c\bar{c}$ pair in a color octet state, which then evolves into the charmonium ($c\bar{c}$) meson along with other light hadrons. A similar contribution is expected in NRQCD for J/ψ production in e^+e^- annihilation [3, 4], but is absent in the color singlet model [5].

Significant continuum J/ψ production—as distinct from production in B decay at the $\Upsilon(4s)$ resonance—has not been observed previously in e^+e^- annihilation below the Z resonance. It therefore represents a good test of NRQCD. In particular, matrix elements extracted from different J/ψ production processes should be consistent [6]. In addition, momentum, polarization and particularly the angular distributions of the J/ψ distinguish between theoretical approaches [7]. Despite NRQCD's successes, it is not clear that it correctly explains [8] the CDF measurements of J/ψ polarization [9], or measurements of J/ψ photoproduction at HERA [10].

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The *BABAR* Collaboration has recently published [11] a study on the observation and on the measurement of the properties of J/ψ production in continuum e^+e^- annihilations near the $\Upsilon(4s)$ resonance. The results of this study tend to favor the NRQCD color octet model prediction over the color singlet model. In these proceedings we reports the results of this study. The details of the anaylsis can be found in the publication [11].

2. The *BABAR* detector at the PEP-II collider and the data sample

The study reported here uses 20.7 fb^{-1} of data collected at the $\Upsilon(4s)$ resonance (10.58 GeV) and 2.59 fb^{-1} collected at 10.54 GeV, below the threshold for $B\bar{B}$ creation. The luminosity-weighted center-of-mass (CM) energy is 10.57 GeV. The data were collected with the *BABAR* detector [12] located at the PEP-II collider at the Stanford Linear Accelerator Center.

3. J/ψ mesons reconstruction and background rejection

The J/ψ candidates are identified through their l^+l^- decays. The good performances of the *BABAR* detector in the identification of $e^\pm$ and $\mu^\pm$ and in the reconstruction of high quality tracks allow to reconstruct clean J/ψ candidates [13]. The mass of these candidates is calculated after constraining the two lepton candidates to a common origin.

To reject interactions with residual gas in the beam pipe, namely the machine background, or with the beam pipe wall, we construct an event vertex using all tracks in the fiducial volume and require it to be located within 6 cm of the beam spot in z and within 0.5 cm of the beam line. To suppress a substantial background from radiative Bhabha ($e^+e^-\gamma$) events in which the photon converts to an e^+e^- pair, five tracks are required in events with a $J/\psi \to e^+e^-$ candidate.

At this point, the data includes J/ψ mesons both from our signal—continuum-produced J/ψ mesons and J/ψ mesons from the decay of continuum-produced $\psi(2S)$ and χ_{cJ} mesons—and from other known sources. We apply additional selection criteria to suppress these other sources based on their kinematic properties.

The most copious background, $B \to J/\psi X$, is eliminated by requiring the J/ψ momentum in the CM frame (p^*) to be greater than 2 GeV/c, above the kinematic limit for B decays ($B \to J/\psi\pi$). This requirement is dropped for data recorded below the $\Upsilon(4s)$ resonance.

Other background sources include initial-state radiation (ISR) production of J/ψ mesons, $e^+e^- \to \gamma J/\psi$, or of the $\psi(2S)$, with $\psi(2S) \to J/\psi X$. ISR production of lower-mass Υ resonances is negligible. Two photon production of the χ_{c2} can produce J/ψ mesons via $\chi_{c2} \to \gamma J/\psi$. Because the out-going electron and positron are rarely reconstructed, this process, like the ISR J/ψ production, contains only two tracks. We therefore require three high-quality tracks within the fiducial volume of the tracking system.

The remaining background is primarily ISR $\psi(2S)$ decays to $J/\psi\ \pi^+\pi^-$, plus some ISR J/ψ events in which the ISR photon converts. To suppress these, we require the visible energy E to be greater than 5 GeV, and the ratio of the second to the zeroth Fox-Wolfram moment [14], R_2, to be less than 0.5. Both are calculated from tracks and neutral clusters in the fiducial volume.

Approximately 3.5% of the J/ψ meson events that satisfy all criteria are from this background; an additional $\sim 1.6\%$ are ISR events with the photon in the fiducial volume.

4. J/ψ yields and production cross section

The mass distributions of the selected J/ψ candidates show clear signals for both e^+e^- and $\mu^+\mu^-$ final states, both on and below resonance (Fig. 1).

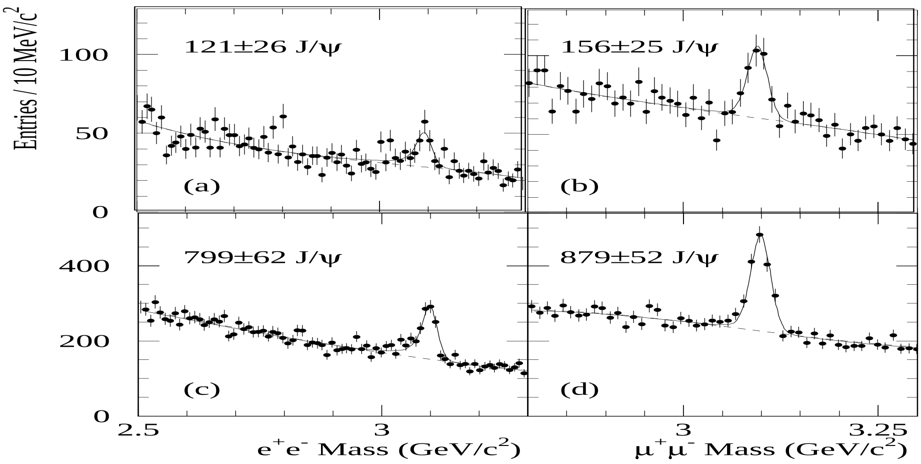

Figure 1: Mass distribution of J/ψ candidates reconstructed in data recorded below the $\Upsilon(4s)$ resonance in the (a) e^+e^- and (b) $\mu^+\mu^-$ final states. Mass distributions for $p^* > 2\ GeV/c$ in data at the $\Upsilon(4s)$ resonance in (c) e^+e^- and (d) $\mu^+\mu^-$ final states. The number of J/ψ mesons extracted by a fit to the distribution is shown on each graph.

To determine the production cross section, we perform mass fits on these distributions, separately for $J/\psi \to e^+e^-$ and $\mu^+\mu^-$. The fit uses a polynomial function for the background distribution. The J/ψ mass function is obtained from a complete simulation of $B \to J/\psi X$ events, convolved with a Gaussian distribution to match the resolution of $12\ MeV/c^2$ observed in data in a sample of approximately 14,000 $B \to J/\psi X$ events. The predicted ISR background contribution to the signal part of the fits is also subtracted in the cross section calculation.

The events yields are then corrected for the event selection and reconstruction efficiencies. The total product of these efficiencies is respectively $\sim 37\%$ and $\sim 43\%$ for $J/\psi \to e^+e^-$ and $\mu^+\mu^-$. The $J/\psi \to e^+e^-$ or $\mu^+\mu^-$ branching fractions [15], and the integrated luminosity (sum of on plus off-resonance for $p^* > 2\ GeV/c$, off-resonance only for $p^* < 2\ GeV/c$) are also taken into account in the cross section computation.

The calculations of the $J/\psi X$ cross section from the e^+e^- and $\mu^+\mu^-$ final states are consistent: the ratio $\sigma(\mu^+\mu^-)/\sigma(e^+e^-)$ is 0.93 ± 0.11 for $p^* > 2\ \ GeV/c$. The two values are combined, accounting for common systematic errors, to obtain:

$$\sigma_{e^+e^- \to J/\psi X} = (2.52 \pm 0.21\ (stat.) \pm 0.21\ (syst.))\ pb. \tag{4.1}$$

With existing values for matrix elements, color singlet cross section estimates range from 0.45 to 0.81 pb [3, 4, 5], while NRQCD cross sections, including a color octet component, range from 1.1 to 1.6 pb [3, 4].

The dominant component of the 8.3% systematic error is a 7.2% uncertainty on event selections common to both the e^+e^- and $\mu^+\mu^-$ cases and a 4.9% uncertainty due to the five track requirement. Other contributions include 2.4% due to track quality cuts; 1.5% from the luminosity; 1.8% (electrons) or 1.4% (muons) from particle identification; and 1.2% from the ISR background.

The statistical error is dominated by the uncertainty on the contribution below p^* of 2 GeV/c. When restricting the measurement to $p^* > 2\ GeV/c$, the value of the $e^+e^- \to J/\psi X$ cross section becomes $(1.87 \pm 0.10\ (stat.) \pm 0.15\ (syst.))\ pb$.

5. Limit on the $\Upsilon(4s) \to J/\psi X$ branching fraction

In determining the previous cross sections, we assume that there are no J/ψ mesons from direct $\Upsilon(4s)$ decays. We quantify this statement using the $p^* > 2\ GeV/c$ component. We scale the off-resonance event yield to the on-resonance luminosity and subtract it from the on-resonance yield. The excess, attributable to $\Upsilon(4s)$ decays, is consistent with zero. We obtain $\mathcal{B}_{\ \Upsilon(4s)\to J/\psi X} = (1.5 \pm 2.2 \pm 0.1) \times 10^{-4}$. A Bayesian 90% confidence level upper limit with a uniform prior above zero is:

$$\mathcal{B}_{\ \Upsilon(4s)\to J/\psi X} < 4.7 \times 10^{-4}\ (90\%\ \text{C.L.}). \tag{5.1}$$

This result disagrees with a previous publication [16]. In NRQCD, the expected partial width is similar to that for the $\Upsilon(1S)$ [4, 17], implying a branching fraction of a few $\times 10^{-6}$. Note that a true branching fraction of 10^{-4} would correspond to an effective cross section of 0.10 pb.

6. Signal properties

Production and decay properties of the J/ψ have also been studied. The p^* distribution is obtained by dividing the sample into 500 MeV/c wide intervals, fitting the resulting mass distribution, subtracting predicted ISR backgrounds, correcting for the reconstruction efficiency, and normalizing for different luminosities (Fig. 2).

The distribution of the signal in $\cos\theta^*$ has been extracted and fit with $1 + A \cdot \cos^2\theta^*$. Both NRQCD and color singlet calculations predict a flat distribution ($A \approx 0$) at low p^*. At high momentum, NRQCD predicts $0.6 < A < 1.0$ while the color singlet model predicts $A \approx -0.8$ [7]. We measure the distribution separately for low and high momentum mesons, selecting $p^* = 3.5\ GeV/c$ as the boundary. We proceed as for the p^* distribution, with mass fits performed in $\cos\theta^*$ intervals of width 0.4. The distributions are then normalized to unit area (Fig. 3a). We find $A = (0.05 \pm 0.22)$ for $p^* < 3.5\ GeV/c$ and $A = (1.5 \pm 0.6)$ for $p^* > 3.5\ GeV/c$, clearly favoring NRQCD.

Finally, we obtain the helicity angle θ_H distribution for the two p^* ranges by fitting mass distributions in intervals of width 0.4 in $\cos\theta_H$ (Fig. 3b). The helicity is the angle, measured in the rest frame of the J/ψ, between the positively charged lepton daughter and the direction of the J/ψ measured in the CM frame. Fitting the function $3\left(1 + \alpha \cdot \cos^2\theta_H\right)/2\,(\alpha + 3)$, we obtain a J/ψ polarization $\alpha = (-0.46 \pm 0.21)$ for $p^* < 3.5\ GeV/c$ and $\alpha = (-0.80 \pm 0.09)$ for $p^* > 3.5\ GeV/c$. $\alpha = 0$ indicates an unpolarized distribution, $\alpha = 1$ transversely polarized, and $\alpha = -1$ longitudinally polarized.

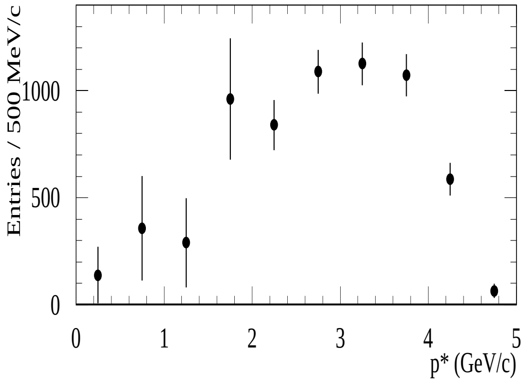

Figure 2: Center of mass momentum distribution of J/ψ mesons produced in continuum e^+e^- annihilation.

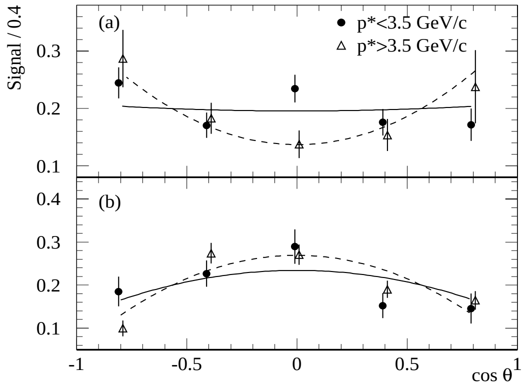

Figure 3: (a) Production angle ($\cos\theta^*$) distribution for J/ψ mesons produced in continuum e^+e^- annihilation; (b) helicity ($\cos\theta_H$) distribution. Solid curve is the fit to $p^* < 3.5$ GeV/c; dashed curve is for $p^* > 3.5$ GeV/c.

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