Observation of a Broad Structure in the $\pi^+\pi^- J/\psi$ Mass Spectrum around 4.26 GeV/c^2

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We study initial-state radiation events, $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^- J/\psi$, with data collected with the *BABAR* detector. We observe an accumulation of events near 4.26 GeV/c^2 in the invariant-mass spectrum of $\pi^+\pi^- J/\psi$. Fits to the mass spectrum indicate that a broad resonance with a mass of about 4.26 GeV/c^2 is required to describe the observed structure. The presence of additional narrow resonances cannot be excluded. The fitted width of the broad resonance is 50 to 90 MeV/c^2, depending on the fit hypothesis.

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Recent observations of the $X(3872)$, decaying into $\pi^+\pi^- J/\psi$ [1–4], and the $Y(3940)$, decaying into $\omega J/\psi$ [5], have renewed experimental interest in charmonium spectroscopy. We have previously reported a search for direct $X(3872)$ production in e^+e^- annihilation through initial-state radiation (ISR): $e^+e^- \to \gamma_{\rm ISR}X$ [6]. No signal is observed, suggesting that the $X(3872)$ is not a 1^{--} state, just as expected for a narrow state well above the $D\bar{D}$ threshold. In this Letter, we present a study of the $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^- J/\psi$ process across the charmonium mass range.

We use data collected with the *BABAR* detector [7] at the PEP-II asymmetric-energy e^+e^- storage rings, located at the Stanford Linear Accelerator Center (SLAC). These data represent an integrated luminosity of 211 fb^{-1} collected at $\sqrt{s} = 10.58$ GeV, near the peak of the $\Upsilon(4S)$ resonance, plus 22 fb^{-1} collected approximately 40 MeV below this energy.

Charged-particle momenta are measured in a tracking system consisting of a five-layer double-sided silicon vertex tracker (SVT) and a 40-layer central drift chamber (DCH), both situated in a 1.5 T axial magnetic field. An internally reflecting ring-imaging Cherenkov detector (DIRC) with quartz bar radiators provides charged-particle identification. A CsI 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 deposited in the EMC to the momentum, the shower shape, the specific ionization 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. Pion candidates are selected based on a likelihood calculated from the specific ionization in the DCH and SVT, and the Cherenkov angle measured in the DIRC. Photon candidates are identified with clusters in the EMC that have a shape consistent with an electromagnetic shower but without an associated charged track.

A candidate J/ψ meson is reconstructed via its decay to e^+e^- or $\mu^+\mu^-$. The lepton tracks must be well reconstructed, and at least one must be identified as an electron or a muon. An algorithm to associate and combine the energy from bremsstrahlung photons with nearby electron tracks is used when forming a $J/\psi \to e^+e^-$ candidate. An e^+e^- ($\mu^+\mu^-$) pair with an invariant mass within $^{+33}_{-95}$ ($^{+33}_{-40}$) MeV/$c^2$of the nominal J/ψ mass is taken as a J/ψ candidate and is combined with a pair of oppositely charged tracks that are identified as pions.

Following an observation of an enhancement in the $\pi^+\pi^- J/\psi$ mass spectrum during an earlier search for ISR $X(3872)$ production in a 124 fb^{-1} subsample of the available data, we chose to exclude the mass region from 4.2 to 4.4 GeV/c^2 from consideration during optimization of the selection criteria with the full sample to avoid the introduction of statistical or other biases in the analysis of this region. Radiative production of the $\psi(2S)$ serves as a clean benchmark process [8] for a data-driven optimization. Selection criteria are chosen to maximize $N/(3/2 + \sqrt{B})$ [9], where N is the total number of $\gamma_{\rm ISR}\psi(2S)$, $\psi(2S) \to \pi^+\pi^- J/\psi$ candidates in the 20 MeV/c^2 $\pi^+\pi^- J/\psi$ mass range that brackets the $\psi(2S)$ mass, and B is the number of events in the $\pi^+\pi^- J/\psi$ mass regions [3.8, 4.2] GeV/c^2 and [4.4, 4.8] GeV/c^2, scaled to the width of the originally observed peak. Simulated ISR events are validated with the $\psi(2S)$ data and are used to extrapolate the selection criteria to the excluded mass region as appropriate for small kinematic differences due to the higher mass.

Radiative $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^- J/\psi$ events are characterized by a small mass recoiling against the $\pi^+\pi^- J/\psi$ system and by low missing transverse momentum. These properties are reflected in (1), (2), and (3) of the selection criteria: (1) there must be no additional well-reconstructed charged tracks in the event; (2) the transverse component of the visible momentum in the e^+e^- center-of-mass frame, including the ISR photon when it is reconstructed, must be less than 2.5 GeV/c; (3) the inferred value of the square of the mass recoiling against the $\pi^+\pi^- J/\psi$ combination ($m^2_{\rm Rec}$) must be within $[-1.04, +3.27]$ GeV$^2/c^4$ for $J/\psi \to e^+e^-$ candidates and $[-1.04, +1.25]$ GeV$^2/c^4$ for $J/\psi \to \mu^+\mu^-$ candidates; (4) $\cos\theta_\ell$, where θ_ℓ is the angle between the ℓ^+ momentum in the J/ψ rest frame and the J/ψ momentum in the e^+e^- center-of-mass frame, must satisfy $|\cos\theta_\ell| < 0.90$. In addition, (5) for the e^+e^- mode, $\cos\theta_\pi$, where θ_π is the angle between the π^- momentum and the J/ψ momentum in the $\pi^+\pi^-$ rest frame, is required to be less than 0.90 to reject background from misidentified low momentum e^- in the forward region of the detector. We do not require the ISR photon to be detected in the EMC since it is produced preferentially along the beam direction.

Candidate $\pi^+\pi^-\ell^+\ell^-$ tracks are refitted, constrained to a common vertex, while the lepton pair is kinematically constrained to the J/ψ mass. The resulting $\pi^+\pi^-J/\psi$ mass-resolution function is well described by a Cauchy distribution [10] with a full width at half maximum of 4.2 MeV/c^2 for the $\psi(2S)$ and 5.3 MeV/c^2 at 4.3 GeV/c^2.

The $\pi^+\pi^-J/\psi$ invariant-mass spectrum for candidates passing all criteria is shown in Fig. 1 as points with error bars. Events that have an e^+e^- ($\mu^+\mu^-$) mass in the J/ψ sidebands [2.76, 2.95] or [3.18, 3.25] ([2.93, 3.01] or [3.18, 3.25]) GeV/c^2 but pass all the other selection criteria are represented by the shaded histogram after being scaled by the ratio of the widths of the J/ψ mass window and sideband regions. An enhancement near 4.26 GeV/c^2 is clearly observed; no other structures are evident at the masses of the quantum number $J^{PC} = 1^{--}$ charmonium states, i.e., the $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$ [11], or the $X(3872)$. The Fig. 1 inset includes the $\psi(2S)$ region with a logarithmic scale for comparison; $11\,802 \pm 110$ $\psi(2S)$ events are observed, consistent with the expectation of $12\,142 \pm 809$ $\psi(2S)$ events. We search for sources of backgrounds that contain a true J/ψ and peak in the $\pi^+\pi^-J/\psi$ invariant-mass spectrum. The possibility that one or both pion candidates are misidentified kaons is checked by reconstructing the K^+K^-J/ψ and $K^\pm\pi^\mp J/\psi$ final states; we observe featureless mass spectra. Similar studies of ISR events with a $\pi^+\pi^-J/\psi$ candidate plus one or more additional pions reveal no structure that could feed down to produce a peak in the $\pi^+\pi^-J/\psi$ mass spectrum. Two-photon events are studied directly by reversing the requirement on the missing mass; the number of events inferred for the signal region is a small fraction of those observed and their mass spectrum shows no structure. Hadronic $e^+e^- \to q\bar{q}$ events produce J/ψ at a rate that is surprisingly large [12–15], but no structure is observed for this background.

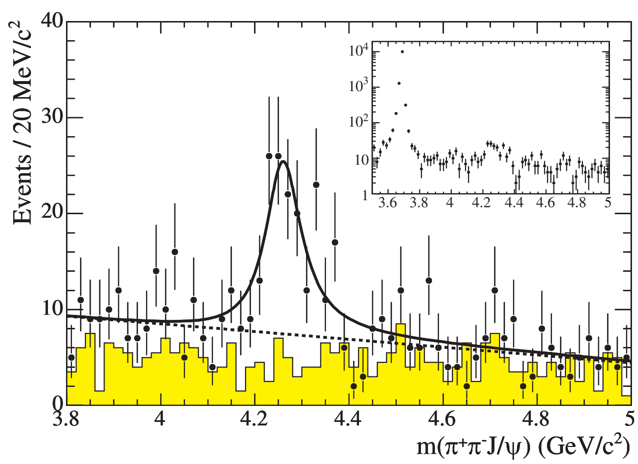

FIG. 1 (color online). The $\pi^+\pi^-J/\psi$ invariant-mass spectrum in the range 3.8–5.0 GeV/c^2 and (inset) over a wider range that includes the $\psi(2S)$. The points with error bars represent the selected data and the shaded histogram represents the scaled data from neighboring e^+e^- and $\mu^+\mu^-$ mass regions (see text). The solid curve shows the result of the single-resonance fit described in the text; the dashed curve represents the background component.

We evaluate the statistical significance of the enhancement using unbinned maximum likelihood fits to the $\pi^+\pi^-J/\psi$ mass spectrum. To evaluate the goodness of fit, the fit probability is determined from the χ^2 and the number of degrees of freedom for bin sizes of 5, 10, 20, 40, and 50 MeV/c^2. Bins are combined with higher mass neighbors as needed to ensure that no bin is predicted to have fewer than seven entries. We try first-, second-, and third-order polynomials as null-hypothesis fit functions. The χ^2-probability estimates for these fits range from 10^{-16} to 10^{-11}. No substantial improvement is obtained by including $\psi(4040)$, $\psi(4160)$, or $\psi(4415)$ [11] terms in the fit. We conclude that the structure near 4.26 GeV/c^2 is statistically inconsistent with a polynomial background. Henceforth, we refer to this structure as the $Y(4260)$.

It is important to test the ISR-production hypothesis because the $J^{PC} = 1^{--}$ assignment for the $Y(4260)$ follows from it. The ISR photon is reconstructed in $(24 \pm 8)\%$ of the $Y(4260)$ events, in agreement with the 25% observed for ISR $\psi(2S)$ events. Kinematic distributions for the signal are obtained by subtracting scaled distributions for events with $\pi^+\pi^-J/\psi$ mass in the regions [3.86, 4.06] GeV/c^2 and [4.46, 4.66] GeV/c^2 from those with $\pi^+\pi^-J/\psi$ mass in the signal region, defined as [4.16, 4.36] GeV/c^2. The distribution of $m^2_{\rm Rec}$ is shown in Fig. 2, along with corresponding distributions for ISR $\psi(2S)$ data events and for

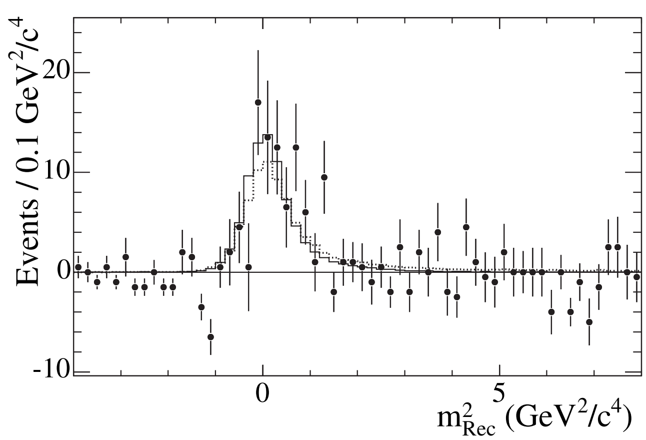

FIG. 2. The distribution of $m^2_{\rm Rec}$. The points represent the data events passing all selection criteria except that on $m^2_{\rm Rec}$ and having a $\pi^+\pi^-J/\psi$ mass near 4260 MeV/c^2, minus the scaled distribution from neighboring $\pi^+\pi^-J/\psi$ mass regions (see text). The solid histogram represents ISR Y Monte Carlo events, and the dotted histogram represents the ISR $\psi(2S)$ data events.

ISR $Y(4260)$ Monte Carlo events. Good agreement is found for these distributions and for all other quantities studied to test that initial-state radiation is responsible for these events.

An unbinned likelihood fit to the $\pi^+\pi^- J/\psi$ mass spectrum is performed using a single relativistic Breit-Wigner signal function and a second-order polynomial background. The signal function is multiplied by a phase space factor and convoluted with the previously described resolution function. The fit gives 125 ± 23 events with a mass of $4259 \pm 8(\text{stat})^{+2}_{-6}(\text{syst})\ \text{MeV}/c^2$ and a width of $88 \pm 23(\text{stat})^{+6}_{-4}(\text{syst})\ \text{MeV}/c^2$. Systematic uncertainties include contributions from the fitting procedure, the mass scale, the mass-resolution function, and dependence on the model of the $Y(4260) \to \pi^+\pi^- J/\psi$ decay. They have been added in quadrature. Under this single-resonance hypothesis we calculate a value of $\Gamma(Y(4260) \to e^+e^-)\mathcal{B}(Y(4260) \to \pi^+\pi^- J/\psi) = 5.5 \pm 1.0^{+0.8}_{-0.7}\ \text{eV}/c^2$. The fit probability determined from the χ^2 and the number of degrees of freedom ranges from 0.3% to 6.6% for the same set of binning choices and background parametrizations used to evaluate the null hypothesis. To estimate the significance of the $Y(4260)$ structure conservatively, we use, instead of our optimized selection criteria, the criteria developed in analyzing just the first $124\ \text{fb}^{-1}$ of data. Using these, we compare fits to the remaining $109\ \text{fb}^{-1}$ of data sample with and without the resonance parameters determined by the first data sample. Using the binnings described above, we find a significance in the second and independent data sample alone of 5σ to 7σ. The likelihood and χ^2 differences between signal and null-hypothesis fits to the full sample correspond to significances of at least 8σ.

The robustness of the $Y(4260)$ signal is tested with single-resonance fits to the $\pi^+\pi^- J/\psi$ mass spectrum for e^+e^- and $\mu^+\mu^-$ modes separately, which yield 49 ± 16 and 76 ± 13 signal events, respectively. Fits give 76 ± 18 events for the original $124\ \text{fb}^{-1}$ data set and 56 ± 13 events for the next, independent $109\ \text{fb}^{-1}$ data set. Fits to samples with and without reconstructed ISR photons give 30 ± 11 and 96 ± 15 events, respectively. We find consistent values for the $Y(4260)$ and the $\psi(2S)$ when determining the fraction of the total signal found in each of these subsets.

Several additional systematic checks have been performed. Each selection criterion has been tightened (loosened) and the decrease (increase) in the signal yield is consistent with that for the $\psi(2S)$ data. Events selected when the selection criteria are reversed, individually or in pairs, are studied; in no case is there a significant dip in the signal-mass region that might indicate a bias in the selection procedure.

Since the single-resonance fit probability is low, we consider the possibility that the observed signal is due to two interfering resonances. Two-resonance fits with an interference term find one resonance mass close to the mass from the single-resonance fit, but with a width as low as $50\ \text{MeV}/c^2$, plus a second narrow resonance around $4.33\ \text{GeV}/c^2$. However, the fit probabilities are not significantly improved by two-resonance hypotheses. The size of our sample does not allow a statistically significant discrimination; we can neither exclude nor establish a multi-resonance hypothesis.

The dipion invariant-mass distribution for the $Y(4260)$ is shown in Fig. 3. Each point represents the yield of a single-resonance fit to the $\pi^+\pi^- J/\psi$ mass distribution for that $\pi^+\pi^-$ mass bin.

No enhancement has been observed in the cross section for $e^+e^- \to$ hadrons [11] at energies corresponding to the $Y(4260)$. We compute the cross section for $e^+e^- \to \pi^+\pi^- J/\psi$ production at 4.25 GeV, corresponding to the highest bin in our data, to be about 50 pb. The inclusive hadronic cross section at $\sqrt{s} = 4.25$ GeV is 14.2 nb [11]. The ratio, approximately 0.34%, is smaller than the 4% experimental uncertainty for the hadronic cross section, so this mode would not have been visible. However, if the branching fraction of $Y(4260)$ to $\pi^+\pi^- J/\psi$ is very small, decays to other hadronic modes such as $D\bar{D}$ would have been observable. This indicates that the branching fraction to $\pi^+\pi^- J/\psi$ must be large compared to that for $\psi(3770)$ [16].

In summary, we have used initial-state radiation events to study the process $e^+e^- \to \pi^+\pi^- J/\psi$ across the charmonium mass range. In addition to the expected $\psi(2S)$ events, we observe an excess of 125 ± 23 events centered at a mass of $\sim 4.26\ \text{GeV}/c^2$, signifying the presence of one or more previously unobserved $J^{PC} = 1^{--}$ states containing hidden charm. At the current level of statistics we are unable to distinguish the number of new states; the data can be characterized by a single resonance of mass $\sim 4.26\ \text{GeV}/c^2$ and of width $\sim 90\ \text{MeV}/c^2$.

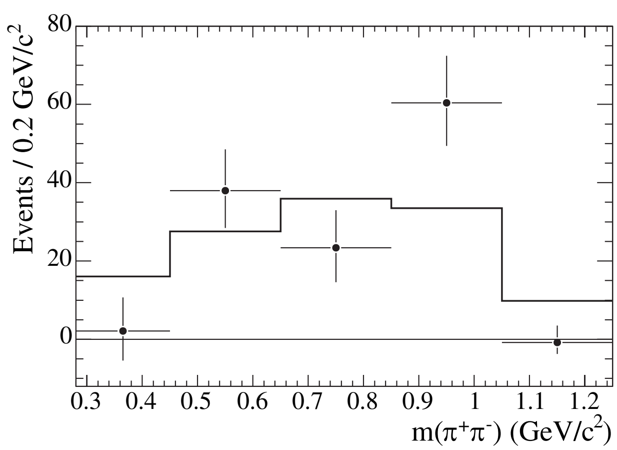

FIG. 3. The dipion mass distribution for $Y(4260) \to \pi^+\pi^- J/\psi$ data is shown as points with error bars. The histogram shows the distribution for Monte Carlo events where $Y(4260) \to \pi^+\pi^- J/\psi$ is generated according to an S-wave phase space model.

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