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Study of the Exclusive Initial-State Radiation Production of the $D\bar{D}$ System

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Abstract

A study of exclusive production of the $D\bar{D}$ system through initial-state radiation is performed in a search for charmonium states, where $D = D^0$ or D^+. The D^0 mesons are reconstructed in the $D^0 \rightarrow K^-\pi^+$, $D^0 \rightarrow K^-\pi^+\pi^0$, and $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ decay modes. The D^+ is reconstructed through the $D^+ \rightarrow K^-\pi^+\pi^+$ decay mode. The analysis makes use of an integrated luminosity of 288.5 fb^{-1} collected by the *BABAR* experiment. The $D\bar{D}$ mass spectrum shows a clear $\psi(3770)$ signal. Further structures appear in the 3.9 and 4.1 GeV/c^2 regions. No evidence is found for $Y(4260)$ decays to $D\bar{D}$, implying an upper limit $\frac{\mathcal{B}(Y(4260)\rightarrow D\bar{D})}{\mathcal{B}(Y(4260)\rightarrow J/\psi\pi^+\pi^-)} < 7.6$ (95% confidence level).

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1 Introduction

The $Y(4260)$ structure was discovered in the initial-state radiation (ISR) process $e^+e^- \to \gamma_{ISR}\pi^+\pi^- J/\psi$ [1] at the energy where the total e^+e^- hadronic cross section shows a local minimum [2]. Its spin-parity assignment, $J^{PC} = 1^{--}$ is inferred because it can be produced by a single-photon annhilation mechanism. The measurement $\Gamma(Y(4260) \to e^+e^-) \times \mathcal{B}(Y(4260) \to \pi^+\pi^- J/\psi) = (5.5 \pm 1.0^{+0.8}_{-0.7})$ eV$/c^2$ and an upper limit estimate of the $Y(4260)$ contribution to the total cross section gives a value for $\Gamma_{\pi\pi J/\psi}(Y(4260))$ in excess of 1 MeV$/c^2$ [3], where $\Gamma_{\pi\pi J/\psi}$ denotes the partial width to the $\pi^+\pi^- J/\psi$ final state. In contrast, $\Gamma_{\pi\pi J/\psi}$ for the $\psi(3770)$ is $(80 \pm 33 \pm 23)$ keV$/c^2$ [4], prompting suggestions that the $Y(4260)$ could be an exotic object [5]. The $Y(4260) \to \pi^+\pi^- J/\psi$ decay channel indicates $\bar{c}c$ content in the $Y(4260)$, which is energetically allowed to decay to pairs of charmed mesons. In this paper, we report a search for $Y(4260) \to D\bar{D}$ using events accompanied by initial-state radiation at the $\Upsilon(4S)$ energy.

2 Data selection

We use data from the *BABAR* detector [6] 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 288.5 fb^{-1} collected at $\sqrt{s} = 10.58$ GeV, near the peak of the $\Upsilon(4S)$ resonance, and 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 fused-silica bar radiators provides charged-particle identification. Kaon and 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. A CsI(Tl) electromagnetic calorimeter (EMC) is used to detect and identify photons and electrons. Neutral pions are reconstructed from pairs of photons, each depositing at least 100 MeV in the EMC and having an invariant mass between 115 and 155 MeV$/c^2$. Photon pairs are kinematically constrained to have the π^0 mass; pairs having a fit probability greater than 1% are retained as π^0 candidates.

Candidate $e^+e^- \to \gamma_{ISR}D\bar{D}$ events, where γ_{ISR} denotes an ISR photon, are reconstructed using four decay channels:

$$e^+e^- \to \gamma_{ISR}\ D^0\overline{D}^0, D^0 \to K^-\pi^+, \overline{D}^0 \to K^+\pi^- \quad (1)$$
$$e^+e^- \to \gamma_{ISR}\ D^0\overline{D}^0, D^0 \to K^-\pi^+\pi^0, \overline{D}^0 \to K^+\pi^- \quad (2)$$
$$e^+e^- \to \gamma_{ISR}\ D^0\overline{D}^0, D^0 \to K^-\pi^+\pi^+\pi^-, \overline{D}^0 \to K^+\pi^- \quad (3)$$
$$e^+e^- \to \gamma_{ISR}\ D^+D^-, D^+ \to K^-\pi^+\pi^+, D^- \to K^+\pi^-\pi^-. \quad (4)$$

Charge conjugate decays are implicitly included.

All charged daughter tracks of D meson candidates must be well-reconstructed; however there may be one additional track having fewer than twelve DCH hits, having a transverse momentum below 0.1 GeV$/c$, or having a distance of closest approach to the interaction point of greater than 1 cm in the plane transverse to the beam or 10 cm along the beam direction. Events having an extra π^0 candidate are vetoed. The tracks of each D candidate are topologically constrained to come from a common vertex; D candidates with a vertex fit probability greater than 0.1% are retained. Subsequently, each $D\bar{D}$ pair is refit to a common vertex with a beam spot constraint;

$D\bar{D}$ candidates with a fit probability of greater than 0.1% are retained. When calculating kinematic properties of $D\bar{D}$ pairs, the energy of the D mesons with daughter tracks that are all charged is recomputed using the nominal D mass value [7]. For candidate $D^0 \to K^-\pi^+\pi^0$ decays, a one-constraint fit to the nominal D^0 mass is performed. Events having a $D\bar{D}$ pair with an invariant mass below 6.0 GeV/c^2 are retained.

A distinguishing characteristic of $e^+e^- \to \gamma_{ISR}D\bar{D}$ events is that the squared invariant mass of the recoil to the $D\bar{D}$ system (MM^2) is that of the initial-state photon. The peak centered on MM^2= 0 in Fig. 1, summed over all four reconstructed channels, provides clear evidence for exclusive ISR production. The shaded histogram shows a background estimate derived from the two-dimensional D and $\bar{D}$ mass sidebands.

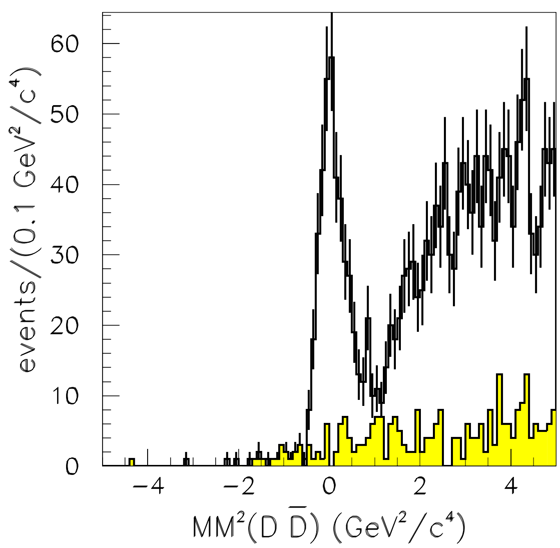

Figure 1: The recoil mass squared for ISR event candidates (MM^2) summed over all the four reconstructed final states. The shaded histogram is the background distribution estimated from D and $\bar{D}$ mass sidebands.

Candidate events in the ISR region, defined as $|MM^2| < 1.0$ GeV$^2/c^4$ are retained. Observation of the ISR photon is not required since these photons are emitted preferentially along the beam directions; approximately 10% are reconstructed in the EMC. In Fig. 2, we show the mass of the D vs. that of the $\bar{D}$, for each reconstructed channel and projections for each reconstructed D decay mode.

The number of observed events for each reconstructed channel is given in Table 1. The same table also shows the resolution from a single-Gaussian fit to the D-candidate mass spectra and the experimental $D\bar{D}$ mass resolution at the mass of the $Y(4260)$. The mass resolution for each channel agrees with values found for simulated $e^+e^- \to \gamma_{ISR}D\bar{D}$ events. A $\pm 2.5\sigma$ signal region is defined for each D channel, with sideband regions defined from –6.0 σ to –3.5 σ and 3.5 σ to 6.0 σ. Background estimates for each channel are inferred from the two-dimensional D and $\bar{D}$ sidebands.

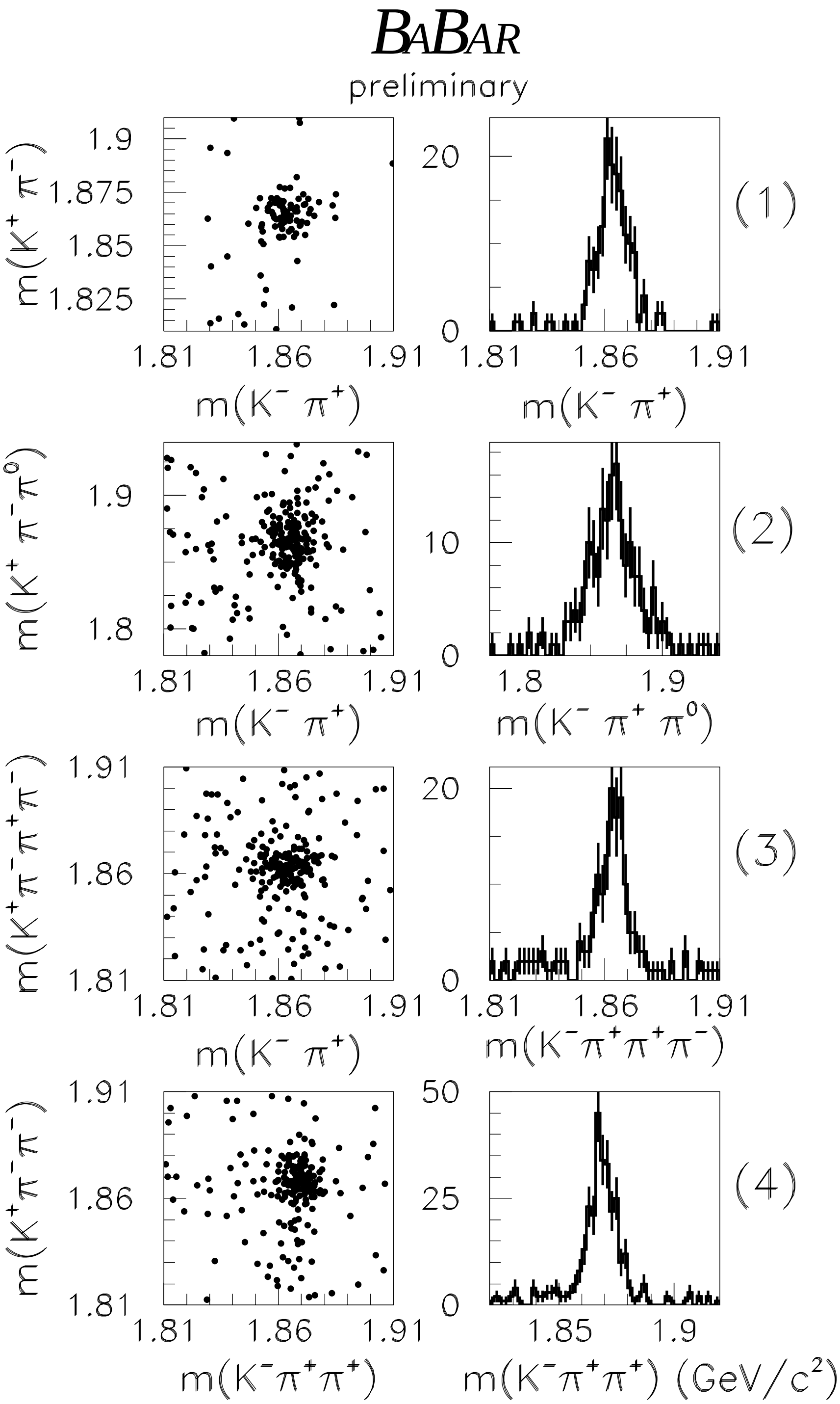

Figure 2: Scatter plots for each channel and projections of the candidate D mass.

Table 1: Mass resolutions and event yields for each reconstructed channel.

Channel	D Mass Res. (MeV/c^2)	Candidates	Background	Signal	$D\bar{D}$ Mass Res. (MeV/c^2)
$D^0 \to K^-\pi^+, \overline{D}^0 \to K^+\pi^-$	6.8 ± 0.2	68	4	64 ± 8	5.1 ± 0.1
$D^0 \to K^-\pi^+\pi^0, \overline{D}^0 \to K^+\pi^-$	13.0 ± 0.4	121	22	99 ± 12	5.2 ± 0.2
$D^0 \to K^-\pi^+\pi^+\pi^-, \overline{D}^0 \to K^+\pi^-$	5.0 ± 0.04	111	16	95 ± 11	4.6 ± 0.1
$D^+ \to K^-\pi^+\pi^+, \overline{D}^0 \to K^+\pi^-\pi^-$	5.6 ± 0.1	116	14	102 ± 11	4.6 ± 0.1

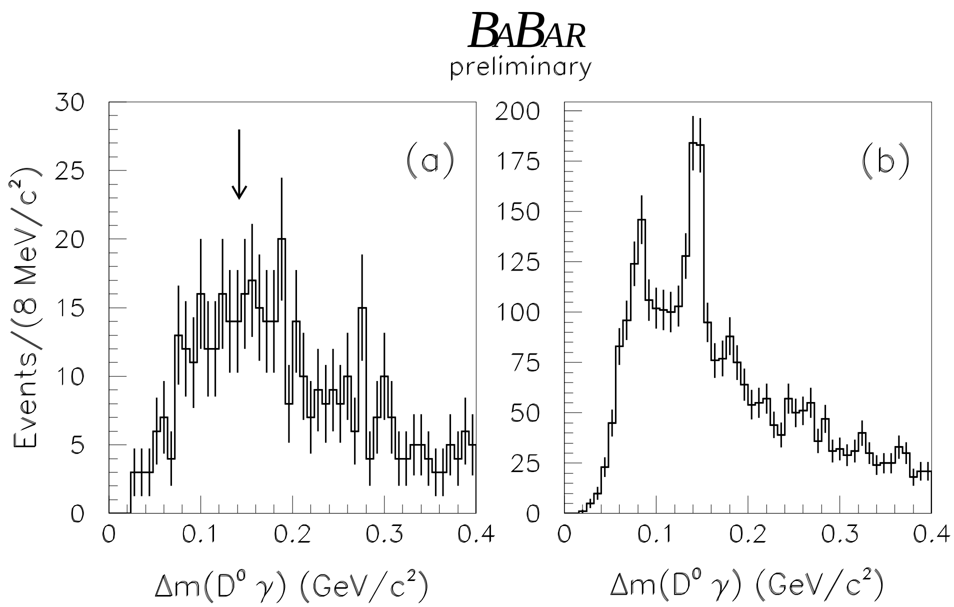

Figure 3: Spectra of $\Delta m(D^0\gamma) \equiv m(D^0\gamma) - m(D^0)$ for (a) all events inside and (b) $D^0 \to K^-\pi^+, \overline{D}^0 \to K^+\pi^-$ events outside the exclusive ISR region. The arrow indicates the expected position of D^{*0}.

A potential source of contamination in this sample of $e^+e^- \to \gamma_{ISR} D\bar{D}$ candidates could arise from the low MM^2 tail from $e^+e^- \to \gamma_{ISR} D^{(*)}\bar{D}^{(*)}$. This background is partially suppressed by the extra-π^0 veto; however radiative D^{*0} decays or $D^{*0} \to \pi^0 D^0$ decays with an unreconstructed photon daughter of the π^0 could survive. A direct search for D^{*0} is made by plotting $\Delta m(D^0\gamma) \equiv m(D^0\gamma) - m(D^0)$ in Fig. 3(a) for all D^0 and $\overline{D}^0$ candidates within the ISR MM^2 region. For comparison, the same quantity is shown for $D^0 \to K^-\pi^+, \overline{D}^0 \to K^+\pi^-$ candidates outside the ISR MM^2 region in Fig. 3(b). A clear peak in Fig. 3(b) corresponding to $D^{*0} \to \gamma D^0$ is visible, but there is no evidence for any D^{*0} contamination in the ISR $D\bar{D}$ sample.

3 $D\bar{D}$ mass spectrum

The $D\bar{D}$ invariant mass spectrum for the ISR sample is shown by the data points in Fig. 4. A clear signal is seen for the $\psi(3770)$, which decays predominantly to $D\bar{D}$. Additional enhancements coincide with the $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$ masses, which are observed in measurements of the total e^+e^- hadronic cross section. Finally, a broad enhancement is evident near 3.9 GeV/c^2. This structure has not been seen in the hadronic cross section measurements but is in qualitative agreement with coupled-channel model predictions [8].

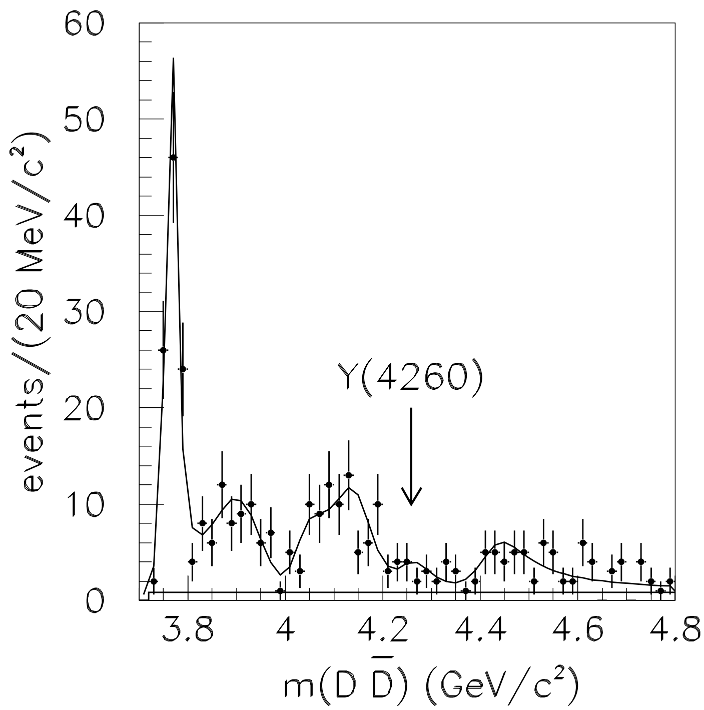

Figure 4: The $D\bar{D}$ invariant mass spectrum, summed over all four reconstructed final states, with a fit that includes the $Y(4260)$ contribution. The arrow indicates the expected position of the $Y(4260)$.

An unbinned maximum likelihood fit is performed using a signal shape described by four relativistic P-wave Breit-Wigner distributions convoluted with a P-wave phase space function. The Breit-Wigner parameters are fixed to the values from a fit to the hadronic cross section [9]. A Gaussian term is used to parameterize the enhancement near 3.9 GeV/c^2. All Breit-Wigner and Gaussian terms are allowed to interfere by assigning them a free phase. A constant background is fixed to a value of 0.84 events per 20 MeV/c^2 bin as determined from a fit to the D and $\bar{D}$ mass sidebands. The fit yields a Gaussian-term mass of (3.909 ± 0.021) GeV/c^2 with $\sigma = (0.050 \pm 0.007)$

GeV/c^2. The $D\bar{D}$ mass resolution at the $Y(4260)$ mass, determined from Monte Carlo studies and shown in Table 1, is small compared to the widths of the fit structures and is neglected.

We consider a possible $Y(4260)$ contribution by performing a second fit, adding a fifth Breit-Wigner term with parameters determined from the $Y(4260)$ observation in the $J/\psi\pi^+\pi^-$ mode: $m(Y(4260)) = 4.260$ GeV/c^2 and $\Gamma(Y(4260)) = 0.088$ GeV/c^2 [1]. The Gaussian term is fixed to parameters from the first fit. The result, shown in Fig. 4, yields a $Y(4260)$ component with 7 ± 13 events. The systematic uncertainty is evaluated as ± 8 events by varying the mass and width of the four ψ resonances, the $Y(4260)$, and the Gaussian enhancement near 3.9 GeV/c^2 by one standard deviation, and by removing the phase space factor from the fit. All the resulting deviations are added in quadrature.

The $D\bar{D}$ reconstruction efficiency for each channel, determined from Monte Carlo studies, increases with $D\bar{D}$ mass as shown in Fig. 5.

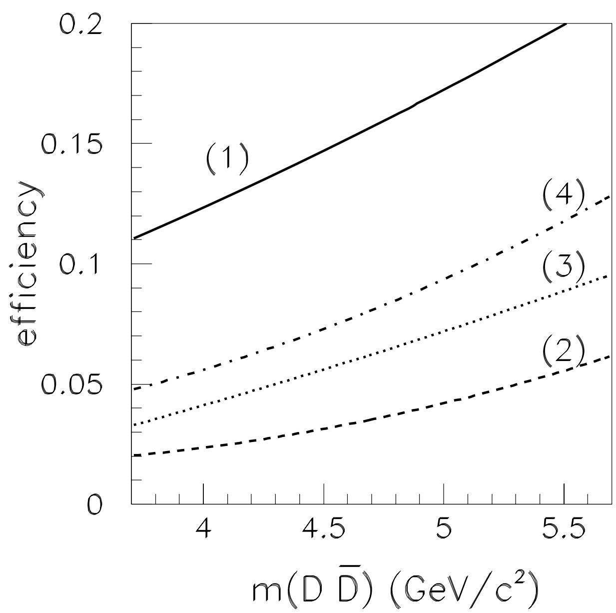

Figure 5: Reconstruction efficiency for the four channels as defined in Eqs. (1)-(4) as a function of the $D\bar{D}$ invariant mass.

Combining the fit result with world average D branching fractions, reconstruction efficiency, and the result from the *BABAR* $\gamma_{ISR}\psi\pi^+\pi^-$ analysis [1] yields

$$\frac{\mathcal{B}(Y(4260) \to D\bar{D})}{\mathcal{B}(Y(4260) \to J/\psi\pi^+\pi^-)} = 1.4 \pm 3.1, \tag{5}$$

where statistical and systematic uncertainties have been added in quadrature. Because a statistically significant signal for $Y(4260) \to D\bar{D}$ has not been established, this result can be recast as an upper limit:

$$\frac{\mathcal{B}(Y(4260) \to D\bar{D})}{\mathcal{B}(Y(4260) \to J/\psi\pi^+\pi^-)} < 7.6 \text{ at } 95\% \text{ C.L.} \tag{6}$$

This limit is over an order of magnitude smaller than the value found for the $\psi(3770)$, another indication that the $Y(4260)$ is not a conventional vector charmonium state.

4 Conclusions

In summary, ISR events have been used to explore $D\bar{D}$ production in e^+e^- annhilation from charm threshold to 6 GeV/c^2. We find evidence for $D\bar{D}$ decays of the $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$, and a broad enhancement of $D\bar{D}$ production near 3.9 GeV/c^2 in qualitative agreement with coupled-channel model predictions. No statistically significant signal for $Y(4260) \to D\bar{D}$ is seen, leading to a 95% confidence level upper limit, $\frac{\mathcal{B}(Y(4260)\to D\bar{D})}{\mathcal{B}(Y(4260)\to J/\psi\pi^+\pi^-)} < 7.6$.

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