

## Search for $X(3872)$ in $\gamma\gamma$ Fusion and Radiative Production at CLEO

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We report on a search for the recently reported  $X(3872)$  state using  $15.1 \text{ fb}^{-1}$  of  $e^+e^-$  data taken in the  $\sqrt{s} = 9.46\text{--}11.30 \text{ GeV}$  region. Separate searches for the production of the  $X(3872)$  in untagged  $\gamma\gamma$  fusion and  $e^+e^-$  annihilation following initial state radiation are made by taking advantage of the unique angular correlation between the leptons from the decay  $J/\psi \rightarrow l^+l^-$  in  $X(3872)$  decay to  $\pi^+\pi^-J/\psi$ . No signals are observed in either case, and 90% confidence upper limits are established as  $(2J+1)\Gamma_{\gamma\gamma}(X(3872))\mathcal{B}(X \rightarrow \pi^+\pi^-J/\psi) < 12.9 \text{ eV}$  and  $\Gamma_{ee}(X(3872))\mathcal{B}(X \rightarrow \pi^+\pi^-J/\psi) < 8.3 \text{ eV}$ .

The Belle Collaboration recently reported the observation of a narrow state,  $X(3872)$ , in the decay  $B^\pm \rightarrow K^\pm X$ ,  $X \rightarrow \pi^+ \pi^- J/\psi$ ,  $J/\psi \rightarrow l^+ l^-$  ( $l = e, \mu$ ) [1]. The observation was confirmed by the Collider Detector at Fermilab (CDF) II [2], D0 [3], and *BABAR* [4] collaborations, with consistent results,  $M(X) = 3872 \pm 1 \text{ MeV}/c^2$ , and  $\Gamma(X) \leq 3 \text{ MeV}/c^2$ .

Many different theoretical interpretations of the nature of the  $X(3872)$  state and its possible quantum numbers have been proposed [5–15]. These include that (i)  $X(3872)$  is a charmonium state [5,6]; (ii)  $X(3872)$  is a  $D^0 \bar{D}^{*0}$  loosely bound “molecular” state [7,8] since its mass is close to  $(M_{D^0} + M_{\bar{D}^{*0}}) = 3871.3 \pm 1.0 \text{ MeV}/c^2$  [16]; and (iii)  $X(3872)$  is an exotic state [9].

No positive signals for  $X(3872)$  have been observed in searches for the decay channels  $X(3872) \rightarrow \gamma \chi_{c1}$  [1],  $\gamma \chi_{c2}$ ,  $\gamma J/\psi$ ,  $\pi^0 \pi^0 J/\psi$  [17],  $\eta J/\psi$  [18],  $D^+ D^-$ ,  $D^0 \bar{D}^0$ , and  $D^0 \bar{D}^0 \pi^0$  [19], or for possible charged partners of  $X(3872)$  [20]. Yuan, Mo, and Wang [21] have used  $22.3 \text{ pb}^{-1}$  of BES data at  $\sqrt{s} = 4.03 \text{ GeV}$  to determine the upper limit of  $\Gamma_{ee}(X(3872)) \mathcal{B}(X \rightarrow \pi^+ \pi^- J/\psi) < 10 \text{ eV}$  (90% C.L.) for initial state radiation (ISR) production of  $X(3872)$ . Belle [17] has recently reported a small enhancement in the  $\pi^+ \pi^- \pi^0 J/\psi$  effective mass near the  $X(3872)$  mass.

The variety of possibilities for the structure of  $X(3872)$  suggests that, irrespective of the models, it is useful to limit the  $J^{PC}$  of  $X(3872)$  as much as possible. The present investigation is designated to provide experimental constraints for the  $J^{PC}$  of  $X(3872)$  by studying its production in  $\gamma\gamma$  fusion and ISR, and its decay into  $\pi^+ \pi^- J/\psi$ . Production of  $X(3872)$  in  $\gamma\gamma$  fusion can shed light on the positive charge parity candidate states, charmonium states  $2^3P_0$ ,  $2^3P_2$ , and  $1^1D_2$  [5,6], and the  $0^{-+}$  molecular state [7,8]. ISR production can address the  $1^{--}$  vector state.

The data used for this  $X(3872)$  search were collected at the Cornell Electron Storage Ring (CESR) with the detector in the CLEO III configuration [22]. The detector is cylindrically symmetric and provides 93% coverage of

solid angle for charged and neutral particle identification. The detector components important for this analysis are the drift chamber (DR), CsI crystal calorimeter (CC), and muon identification system (MIS). The DR and CC are operated within a 1.5 T magnetic field produced by a superconducting solenoid located directly outside of the CC. The DR detects charged particles and measures their momenta and ionization energy loss ( $dE/dx$ ). The CC allows precision measurements of electromagnetic shower energy and position. The MIS consists of proportional chambers placed between layers of the magnetic field return iron to detect charged particles which penetrate a minimum of three nuclear interaction lengths.

The data consist of a  $15.1 \text{ fb}^{-1}$  sample of  $e^+e^-$  collisions at or near the energies of the  $Y(nS)$  resonances ( $n = 1-5$ ), and in the vicinity of the  $\Lambda_b \bar{\Lambda}_b$  threshold. Table I lists the six different initial center-of-mass energies and integrated luminosities of the data samples.

Resonance production by untagged  $\gamma\gamma$  fusion and by ISR have similar characteristics. The undetected electrons in untagged  $\gamma\gamma$  fusion and the undetected radiated photons in ISR have angular distributions sharply peaked along the beam axis. Both processes have total observed energy ( $E_{\text{tot}}$ ) much smaller than the center-of-mass energy,  $\sqrt{s}$ , of the original  $e^+e^-$  system, and have small observed transverse momentum. The detailed characteristics for  $\gamma\gamma$  fusion and ISR resonance production are studied by generating signal Monte Carlo (MC) samples using GEANT 3.21/11 [23] to simulate the CLEO III detector. For  $X(3872)$  production by  $\gamma\gamma$  fusion the formalism of Budnev *et al.* [24] is used. For ISR resonance production the formalism of M. Benayoun *et al.* [25] is used.

A fully reconstructed event has four charged particles and zero net charge. All charged particles must lie within the drift chamber volume and satisfy standard requirements for track quality and distance of closest approach to the interaction point. Events must also have detected  $E_{\text{tot}} < 6 \text{ GeV}$ . The  $X(3872)$  resonance corresponds to  $\Delta M \equiv M(\pi^+ \pi^- l^+ l^-) - M(l^+ l^-) = 0.775 \text{ GeV}/c^2$ , and

TABLE I. Data samples and MC determined detection efficiencies used for the present  $X(3872)$  search.  $\langle \sqrt{s_i} \rangle$  are the average center-of-mass energies of  $Y(1S-5S)$  and  $\Lambda_b \bar{\Lambda}_b$  threshold measurement and  $\mathcal{L}_i(e^+e^-)$  is the  $e^+e^-$  integrated luminosity at  $\sqrt{s_i}$ . The efficiencies  $\epsilon_{\gamma\gamma,i}$  and  $\epsilon_{\text{ISR},i}$  are the sums of the efficiencies  $\epsilon_{ee,i}$  and  $\epsilon_{\mu\mu,i}$  for electron and muon detection, respectively. The  $\gamma\gamma$  fusion-ISR separation, as described in the text, is applied to the respective MC samples.

	$\langle \sqrt{s_i} \rangle$ (GeV)	$\mathcal{L}_i(e^+e^-)$ ( $\text{fb}^{-1}$ )	$\gamma\gamma$ fusion			ISR		
			$\epsilon_{ee,i}$	$\epsilon_{\mu\mu,i}$	$\epsilon_{\gamma\gamma,i}$	$\epsilon_{ee,i}$	$\epsilon_{\mu\mu,i}$	$\epsilon_{\text{ISR},i}$
$Y(1S)$	9.458	1.47	0.128(4)	0.160(4)	0.288(6)	0.065(3)	0.083(3)	0.148(4)
$Y(2S)$	10.018	1.84	0.121(3)	0.151(4)	0.272(5)	0.054(2)	0.062(3)	0.116(4)
$Y(3S)$	10.356	1.67	0.115(3)	0.137(4)	0.252(5)	0.042(2)	0.043(2)	0.085(4)
$Y(4S)$	10.566	8.97	0.123(4)	0.145(4)	0.268(6)	0.0186(14)	0.0165(13)	0.0351(19)
$Y(5S)$	10.868	0.43	0.113(3)	0.139(4)	0.252(5)	0.0025(5)	0	0.0025(5)
$\Lambda_b \bar{\Lambda}_b$ threshold	11.296	0.72	0.104(3)	0.126(4)	0.230(5)	0.0001(1)	0	0.0001(1)

we designate  $\Delta M = 0.63\text{--}0.7$  and  $0.85\text{--}0.92$   $\text{GeV}/c^2$  as background regions. Signal-to-background studies are performed to optimize signal efficiency and background suppression. Selection criteria optimized the efficiency for reconstructing  $\gamma\gamma$  fusion MC events. The selection variables optimized are the total neutral energy ( $E_{\text{neu}}$ ) of the event, total transverse momentum of the four charged tracks ( $p_{\text{tr}}$ ), lepton pair invariant mass [ $M(l^+l^-)$ ] of the  $J/\psi \rightarrow l^+l^-$  decay, and particle identification of the charged tracks. Based on the optimization studies, events are selected with  $E_{\text{neu}} < 0.4$   $\text{GeV}$  and  $p_{\text{tr}} < 0.3$   $\text{GeV}/c$ . Events with a  $J/\psi \rightarrow e^+e^-$  decay require both electron candidates to satisfy  $dE/dx$  and shower energy criteria consistent with the electron hypothesis, and to have invariant mass in the range  $M(e^+e^-) = 2.96\text{--}3.125$   $\text{GeV}/c^2$ . Events with a  $J/\psi \rightarrow \mu^+\mu^-$  decay require both muon candidates to appear as minimum ionizing particles in the CC, with at least one muon penetrating the number of interaction lengths in the MIS consistent with its momentum, and to have invariant mass in the range  $M(\mu^+\mu^-) = 3.05\text{--}3.125$   $\text{GeV}/c^2$ . Each of the two pions recoiling against the  $J/\psi$  is required to satisfy the  $dE/dx$  pion hypothesis.

Figure 1 shows the  $\Delta M$  distribution for data events which pass the selection criteria and have  $\Delta M = 0.514\text{--}0.850$   $\text{GeV}/c^2$ . A  $\psi(2S)$  signal is clearly visible while no enhancement is apparent in the  $X(3872)$  region. The observed number of  $\psi(2S)$  events is determined by fitting the  $\psi(2S)$  region with a mass-independent background and a resonance whose shape is determined by fitting the  $\psi(2S)$  peak in the ISR MC simulation. The observed number of  $\psi(2S)$  is  $N_{\text{ISR}}[\psi(2S)] = 206 \pm 15$  events. A MC simulation predicts  $N_{\text{ISR}}[\psi(2S)] = 226 \pm 11$  events.

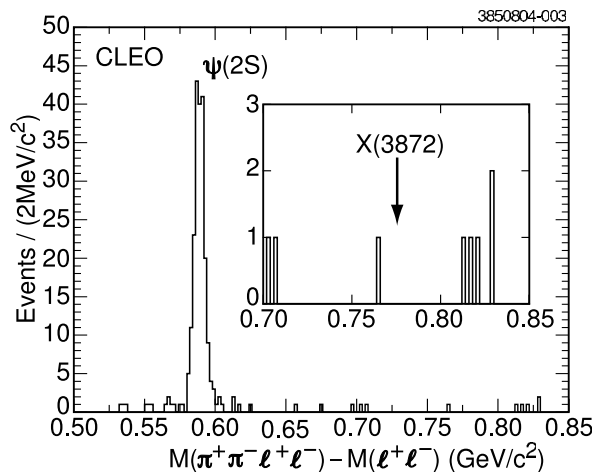


FIG. 1. Data events as a function of  $\Delta M \equiv M(\pi^+\pi^-l^+l^-) - M(l^+l^-)$ . The  $\psi(2S)$  is clearly visible and no apparent enhancement is seen in the  $X(3872)$  region.

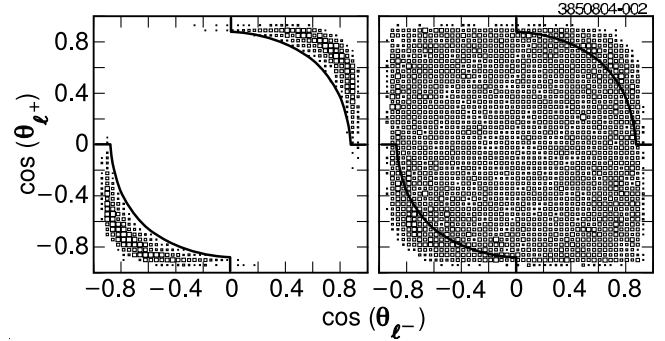


FIG. 2. MC predictions for the two-dimensional lepton pair  $\cos(\theta)$  distributions for the  $X(3872)$ : ISR (left) and  $\gamma\gamma$  fusion (right). The lines indicate how the ISR resonance and  $\gamma\gamma$  fusion samples are separated.

At  $\sqrt{s} \sim 10$   $\text{GeV}$ , a feature unique to the ISR mediated production of a vector resonance which decays via  $\pi^+\pi^-J/\psi$ ,  $J/\psi \rightarrow l^+l^-$  is the correlation between the angles  $\theta_{l+}$  and  $\theta_{l-}$  in the laboratory system. Figure 2 shows the MC prediction for the two-dimensional  $\cos(\theta)$  distributions for leptons from  $X(3872)$  decay for the ISR mediated and  $\gamma\gamma$  fusion productions. As shown in Fig. 2, a parabolic cut applied to the two-dimensional  $\cos(\theta)$  distribution efficiently separates the events from the two production processes. With this cut, the  $\gamma\gamma$  region contains a 0.6% contamination from ISR production, and the ISR sample contains a 14% contamination from  $\gamma\gamma$  fusion production if we assume for an illustrative purpose that  $(2J+1)\Gamma_{\gamma\gamma}(X) = \Gamma_{ee}(X)$ . Here  $J$  is the total spin and  $\Gamma_{\gamma\gamma}$  ( $\Gamma_{ee}$ ) is the two-photon ( $e^+e^-$ ) partial width of  $X(3872)$ .

The efficiencies as determined by MC simulations of  $X(3872)$  production and decay following  $\gamma\gamma$  fusion and ISR are listed in Table I. The  $X(3872)$  and  $J/\psi$  are decayed according to phase space in the MC simulations. The same selection criteria are applied to both MC samples except for the lepton pair  $\cos(\theta)$  cut described above.

The separate  $\Delta M$  distributions for the data in the  $X(3872)$  search region for  $\gamma\gamma$  fusion and ISR mediated resonance production are shown in Fig. 3. The number of observed  $X(3872)$  events [ $N_{\gamma\gamma, \text{ISR}}[X(3872)]$ ] is determined by maximum likelihood fits of the  $\Delta M$  data using mass-independent backgrounds and the appropriate detector resolution functions for the two production processes. The detector resolution functions are determined by the MC simulations fitted with double Gaussians which are illustrated in Fig. 3. The 90% confidence upper limits on the observed number of  $X(3872)$  events in untagged  $\gamma\gamma$  fusion and ISR mediated resonance production are determined to be  $N_{\gamma\gamma, \text{ISR}}[X(3872)] < 2.36$  for both processes.

The cross section for  $\gamma\gamma$  fusion or ISR mediated production of the  $X(3872)$  resonance with total angular momentum  $J$ , and decay through  $\pi^+\pi^-J/\psi$ ,  $J/\psi \rightarrow l^+l^-$ , is

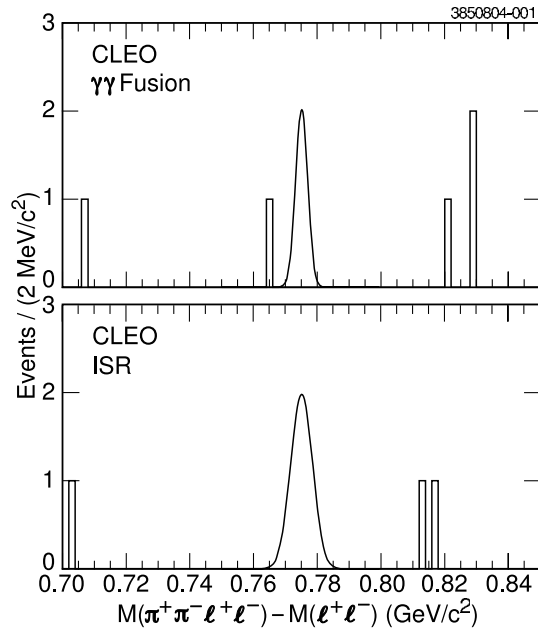


FIG. 3. Distributions of data events as a function of  $\Delta M \equiv M(\pi^+\pi^-l^+l^-) - M(l^+l^-)$  for  $\gamma\gamma$  fusion (top) and ISR (bottom) events in the region  $\Delta M = 0.7\text{--}0.85$   $\text{GeV}/c^2$ . The mass resolution functions determined from MC simulations are shown on an arbitrary scale at  $\Delta M = 0.775$   $\text{GeV}/c^2$ .

$$\begin{aligned} & \left( \frac{C_{\gamma\gamma, \text{ISR}}}{M} \right) (2J+1) \Gamma_{\gamma\gamma, ee}(X) \mathcal{B}(X \rightarrow \pi^+\pi^-J/\psi) \\ &= \frac{N_{\gamma\gamma, \text{ISR}}[X(3872)]}{\mathcal{B}(J/\psi \rightarrow l^+l^-) \sum_i \mathcal{L}_i(e^+e^-) \epsilon_{\gamma\gamma, \text{ISR}, i} \sigma(\sqrt{s_i})_{\gamma\gamma, \text{ISR}}} \end{aligned} \quad (1)$$

where  $C_{\gamma\gamma, \text{ISR}}$  are constants,  $M = 3872$   $\text{MeV}/c^2$ ,  $\sqrt{s_i}$ ,  $\mathcal{L}_i(e^+e^-)$ , and  $\epsilon_{\gamma\gamma, \text{ISR}, i}$  are as listed in Table I, and  $\sigma(\sqrt{s_i})_{\gamma\gamma, \text{ISR}}$  are as shown in Fig. 4. The branching fraction  $\mathcal{B}(J/\psi \rightarrow l^+l^-) = (5.91 \pm 0.07)\%$  is the average Particle Data Group branching fraction of  $J/\psi \rightarrow e^+e^-$  and  $J/\psi \rightarrow \mu^+\mu^-$  [16]. This leads to the 90% confidence upper limits

$$(2J+1) \Gamma_{\gamma\gamma}(X(3872)) \mathcal{B}(X \rightarrow \pi^+\pi^-J/\psi) < 10.9 \text{ eV}$$

for  $X(3872)$  production in  $\gamma\gamma$  fusion, and

$$\Gamma_{ee}(X(3872)) \mathcal{B}(X \rightarrow \pi^+\pi^-J/\psi) < 7.3 \text{ eV}$$

for  $X(3872)$  production via ISR.

Systematic uncertainty in the above limits arises from possible biases in the detection efficiency and estimated background level. These are studied by varying the track quality,  $\gamma\gamma$  fusion/ISR separation, and selection criterion optimized in the signal-to-background studies. Other systematic uncertainties are from the  $e^+e^-$  luminosity measurement and  $J/\psi \rightarrow l^+l^-$  branching fractions. Adding these in quadrature, the total systematic uncertainties in

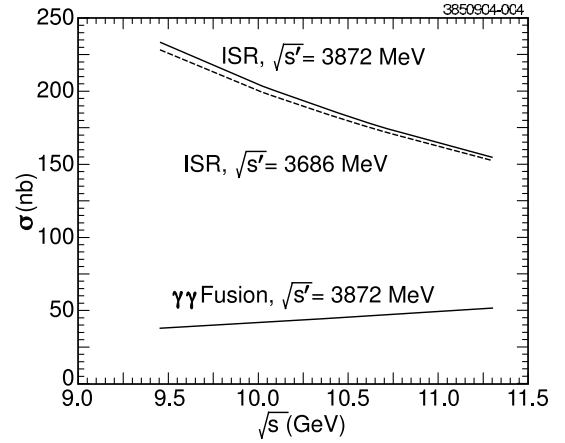


FIG. 4. Cross sections for  $e^+e^-$  collisions at  $\sqrt{s}$  to produce reduced c.m. energy,  $\sqrt{s'}$ , for  $\gamma\gamma$  fusion [24] with  $\sqrt{s'} = 3872$   $\text{MeV}$  and ISR [25] with  $\sqrt{s'} = 3872$   $\text{MeV}$  and  $\sqrt{s'} = 3686$   $\text{MeV}$ .

$\gamma\gamma$  fusion and ISR are 18.5% and 13.2%, respectively. A conservative way to incorporate these systematic uncertainties is to increase the measured upper limits by these amounts. This leads to the 90% confidence upper limits

$$(2J+1) \Gamma_{\gamma\gamma}(X(3872)) \mathcal{B}(X \rightarrow \pi^+\pi^-J/\psi) < 12.9 \text{ eV}$$

for  $X(3872)$  which has positive  $C$  parity, and

$$\Gamma_{ee}(X(3872)) \mathcal{B}(X \rightarrow \pi^+\pi^-J/\psi) < 8.3 \text{ eV}$$

for  $X(3872)$  being a vector meson with  $J^{PC} = 1^{--}$ .

If  $\mathcal{B}(B^\pm \rightarrow K^\pm X(3872)) \approx \mathcal{B}(B^\pm \rightarrow K^\pm \psi(2S)) = (6.8 \pm 0.4) \times 10^{-4}$  [16] is assumed, we obtain  $\mathcal{B}(X \rightarrow \pi^+\pi^-J/\psi) \approx 0.02$  from both the Belle [1] and BABAR [4] results. This leads to 90% confidence upper limits

$$(2J+1) \Gamma_{\gamma\gamma}(X(3872)) < 0.65 \text{ keV},$$

and

$$\Gamma_{ee}(X(3872)) < 0.42 \text{ keV}.$$

The  $(2J+1) \Gamma_{\gamma\gamma}(X(3872))$  upper limit is almost 1/4 the corresponding values for  $\chi_{c0}$  and  $\chi_{c2}$ , but it is nearly 6 times larger than the prediction for the  $1^1D_2$  state of charmonium [26]. The upper limit for  $\Gamma_{ee}(X(3872))$  is comparable to the measured electron width of  $\psi(3770)$  and is about 1/2 that of  $\psi(4040)$ . We also note that the ratio  $N_{\text{ISR}}[X(3872)]/N_{\text{ISR}}[\psi(2S)] < 0.01$  (90% C.L.).

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