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Search for X(3872) in Untagged $\gamma\gamma$ Fusion and Initial State Radiation Production with CLEO III*

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Abstract

We report on an exclusive search for the X(3872) state in the decay $\pi^+\pi^- \mathrm{J}/\psi$, $\mathrm{J}/\psi \to l^+l^-$ ($l = \mathrm{e},\mu$) from untagged $\gamma\gamma$ fusion and initial state radiation production using a 15.1 fb^{-1} data sample with the CLEO III detector. By taking advantage of the unique $\pi^+\pi^- \mathrm{J}/\psi$ decay kinematics, separate measurements for each production process are obtained. No signals are observed and preliminary upper limits have been established as $(2\mathrm{J}+1)\Gamma_{\gamma\gamma}(\mathrm{X}(3872))\mathcal{B}(\mathrm{X}(3872) \to \pi^+\pi^- \mathrm{J}/\psi)$ < 12.9 eV and $\Gamma_{\mathrm{ee}}(\mathrm{X}(3872))\mathcal{B}(\mathrm{X}(3872) \to \pi^+\pi^- \mathrm{J}/\psi) < 8.0$ eV, both at a 90% confidence level.

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The Belle Collaboration reported the observation of a narrow state, X(3872), in the decay of 152 million $B\overline{B}$ events through $B^{\pm} \to K^{\pm}$ X, X $\to \pi^+\pi^-$ J/ψ, J/$\psi \to l^+l^-$ (l = e,μ) measuring M(X) = 3872.0 ± 0.6 (stat) ± 0.5 (syst) MeV/c^2 and $\Gamma < 2.3$ MeV/c^2 at a 90% confidence level (C.L.) [1]. The observation was confirmed by the CDF II Collaboration [2] and DØ Collaboration [3] in inclusive production with X(3872) decaying to $\pi^+\pi^-$J/ψ, J/$\psi \to \mu^+\mu^-$ in $p\overline{p}$ collisions at $\sqrt{s}$ = 1.96 TeV and also by the *BaBar* Collaboration [4] using 117 million $B\overline{B}$ events with the same decay channels as the Belle observation. CDF II, DØ, and *BaBar* measured masses of 3871.3 ± 0.7 (stat) ± 0.4 (syst) MeV/c^2, 3871.8 ± 3.1 (stat) ± 3.0 (syst) MeV/c^2, and 3873.4 ± 1.4 (stat) MeV/c^2, respectively, and widths consistent with their respective detector resolutions.

A large number of theoretical papers now exist [6–18] with different interpretations of the nature of the X(3872) state and its possible quantum numbers. Among the possibilities are: (a) a charmonium state; (b) a loosely bound "molecular" state; or (c) an exotic state. Barnes and Godfrey [6] and Eichten, Lane, and Quigg [7] have examined the charmonium options in detail and conclude that, because of the small width of X(3872) and despite the larger predicted masses of the candidate charmonium states, the viable charmonium options are the negative C parity states of 1^3D_2 ($J^{PC} = 2^{--}$), 1^3D_3 (3^{--}), and 2^1P_1 (1^{+-}), and positive C states of 1^1D_2 (2^{-+}) and 2^3P_1 (1^{++}). Tornquist [9] and Swanson [10] propose that, since X(3872) is close to the $D\overline{D}^*$ threshold ($M(D^0) + M(\overline{D}^{0*}) = 3871.3 \pm 0.5$ MeV/c^2[19]) and there are no published studies in $\pi^0\pi^0$J/ψ decays, the observed decay $\pi^+\pi^-$J/ψ proceeds through ρ^0J/ψ, $\rho^0 \to \pi^+\pi^-$. They suggest 0^{-+} and 1^{++} as the most likely assignment in a molecular model. Finally, we note that Morningstar and Peardon [17] predict a three gluon 1^{--} glueball with a mass of 3850 MeV/c^2.

Searches for X(3872) have been made but no positive signals have been observed in the decay channels X(3872) $\to \gamma\chi_{c1}$, $\gamma\chi_{c2}$, γJ/ψ, ηJ/ψ, D^+D^-, $D^0\overline{D}^0$, and $D^0\overline{D}^0\pi^0$ [1, 20–22]. C. Z. Yuan, X. H. Mo, and P. Wang determined an upper limit for initial state radiation production of Γ_{ee}(X(3872))$\mathcal{B}$(X(3872) $\to \pi^+\pi^-$J/ψ) < 10 eV (90% C.L.) [23] using a previously published 22.3 pb^{-1} data sample of e^+e^- annihilations at $\sqrt{s}$ = 4.03 GeV with the BES detector [24]. With all of these searches, the new state X(3872) has only been experimentally observed decaying to $\pi^+\pi^-$J/ψ.

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. Untagged $\gamma\gamma$ fusion, which only populates states of positive C parity and even values of total angular momentum, can be used to shed light on the charge parity and total angular momentum of X(3872) and its population via initial state radiation can determine its leptonic width and its likely vector character. The present investigation is designed to study the possible production of X(3872) in untagged $\gamma\gamma$ fusion and initial state radiation in the final state $\pi^+\pi^-$J/ψ, J/$\psi \to l^+l^-$ (l = e,μ).

Untagged $\gamma\gamma$ fusion and initial state radiation (ISR) resonance production have similar event characteristics. Untagged $\gamma\gamma$ fusion resonance production occurs when a photon is emitted by each incident electron/positron, the two almost real photons "fuse" to form the resonance, while the scattered electron/positron are not detected. ISR resonance production predominately occurs when either the initial electron or positron emits a hard photon which lowers the center-of-mass energy of the electron-positron system to the invariant mass of the produced resonance before annihilation. The radiated photon also has an angular distribution which is very sharply peaked along the beam axis and therefore is rarely detected. Both types of resonance production processes have a total observed energy (E_{total}) much smaller than the center-of-mass energy of the electron-positron system and a small observed transverse momentum.

The data used for this X(3872) search were collected with the detector in the CLEO III configuration [25] at the Cornell Electron Storage Ring (CESR). The CLEO III detector is a cylindrically symmetric detector designed to study e^+e^- annihilations and provide 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 fb^{-1} sample at or near the energies of the $\Upsilon(nS)$ resonances, where $n = 1$–5, and in the vicinity of the $\Lambda_b\overline{\Lambda}_b$ threshold. Table 1 lists the six different initial center-of-mass energies (CME) and integrated luminosities of the data sample.

TABLE I: Data sample used for this X(3872) search. $\langle\sqrt{s}\,\rangle$ is the integrated luminosity averaged initial CME for the Υ(1S-5S) resonance and threshold $\Lambda_b\overline{\Lambda}_b$ data samples, respectively, and $\mathcal{L}(e^+e^-)$ is the e^+e^- integrated luminosity for each CME region.

	$\langle\sqrt{s}\,\rangle$ (GeV)	$\mathcal{L}(e^+e^-)$ (fb^{-1})
Υ(1S)	9.458	1.47
Υ(2S)	10.018	1.84
Υ(3S)	10.356	1.67
Υ(4S)	10.566	8.97
Υ(5S)	10.868	0.43
$\Lambda_b\overline{\Lambda}_b$ threshold	11.296	0.72

The expected characteristics for $\gamma\gamma$ fusion and ISR resonance production are studied by generating signal Monte Carlo (MC) samples. The $\gamma\gamma$ fusion resonance signal MC process is $e^+e^- \to e^+e^-(\gamma\gamma)$, $\gamma\gamma \to$ X(3872) using the formalism of Budnev *et al.* [27]. The ISR signal MC process is $e^+e^- \to \gamma$X(3872) using the angular distribution expression from M. Benayoun *et al.* [28]. The X(3872) and J/ψ are decayed according to phase space. The MC simulation of the CLEO III detector was based upon GEANT 3.21/11 [26] with simulated events processed in the same manner as the data.

A fully reconstructed event has four charged particles and zero net charge. All charged particles must lie within the DR volume and satisfy standard requirements for track quality and distance of closest approach to the interaction point (IP). Events must also have detected $E_{\mathrm{total}} < 6$ GeV. Signal-to-background studies are performed to optimize signal efficiency and background suppression using the $\gamma\gamma$ fusion signal MC sample for the signal and background from data with $M(\pi^+\pi^-l^+l^-) - M(l^+l^-)$ above and below the X(3872) search region, i.e., $M(\pi^+\pi^-l^+l^-) - M(l^+l^-) = 0.63$–0.7 or 0.85–0.92 GeV/$c^2$. The selection variables optimized are the total neutral energy (E_{neu}) of the event, total transverse momentum of the four charged tracks (p_{tr}), lepton pair invariant mass ($M(l^+l^-)$) of the $J/\psi \to l^+l^-$ decay, and

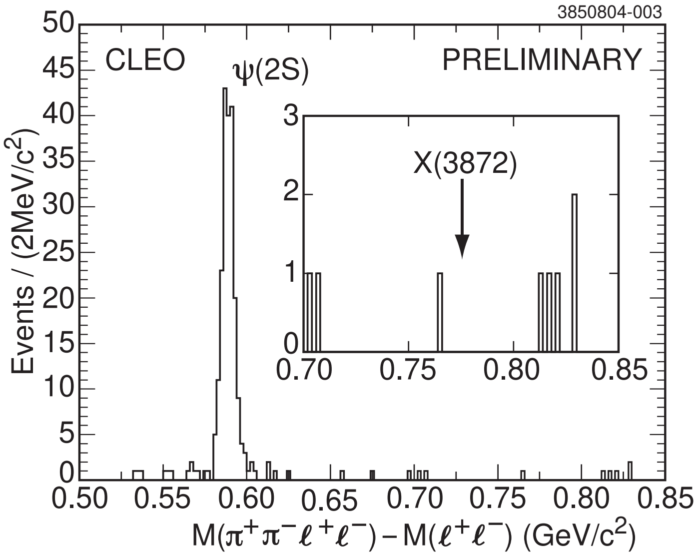

FIG. 1: $\Delta M \equiv M(\pi^+\pi^- l^+ l^-)$ - $M(l^+ l^-)$ data distribution for ΔM = 0.514–0.850 GeV/c^2. The ψ(2S) is clearly visible and there is no enhancement in the X(3872) region.

particle identification (PID) of the charged tracks. Based on the optimization studies, events are selected with $E_{neu} < 0.4$ GeV and $p_{tr} < 0.3$ GeV/c. Events with a $J/\psi \to e^+e^-$ decay have both electron candidates satisfying dE/dx and shower energy criteria consistent with the electron hypothesis and an invariant mass $M(e^+e^-)$ = 2.96-3.125 GeV/c^2. Events with a $J/\psi \to \mu^+\mu^-$ decay have both muon candidates appearing as a minimum ionizing particle in the CC, at least one muon must penetrate a number of interaction lengths in the MIS consistent with its momentum, and an invariant mass $M(\mu^+\mu^-)$ = 3.05-3.125 GeV/c^2. Each of the two pions recoiling against the J/ψ needs to individually satisfy the dE/dx pion hypothesis.

Fig. 1 shows the $\Delta M \equiv M(\pi^+\pi^- l^+ l^-)$ - $M(l^+ l^-)$ data distributions for events which pass the selection criteria and have ΔM = 0.514–0.850 GeV/c^2. A ψ(2S) signal is clearly visible while no enhancement is apparent in the X(3872) region. A MC sample of ψ(2S) produced via ISR is generated to determine the efficiency for detecting the observed ψ(2S) signal, from which an expected number of $\psi(2S) \to \pi^+\pi^- J/\psi$, $\pi^+\pi^-(l^+l^-)$ events is derived to be 226 $\pm$ 11 events, where the error is from the MC efficiency and $J/\psi \to l^+l^-$ PDG branching fraction [5] uncertainties. The observed number of ψ(2S) events is determined by fitting the ψ(2S) region with the detector resolution and a mass-independent background. The detector resolution is determined by fitting the ψ(2S) ISR MC resolution function with a double Gaussian. The narrow Gaussian width and relative area and width of the double Gaussian are fixed when the ψ(2S) is fitted. The observed number of ψ(2S) is 206 $\pm$ 15 events and consistent with expectations.

A feature unique to ISR production of charmonium-like resonances which decay via $\pi^+\pi^- J/\psi$ at initial energies of this data sample is the correlation between the tracks of the two leptons. Fig. 2 shows the two-dimensional $\cos(\theta)$ distributions for lepton tracks in the X(3872) ISR resonance and $\gamma\gamma$ fusion signal MC samples. A parabolic cut is applied to the two-dimensional lepton pair $\cos(\theta)$ distribution to separate the two phenomena and is shown in Fig. 2. This separation removes $\sim$14% of the X(3872) $\gamma\gamma$ MC fusion signal events but rejects more than 99.5% of the ISR events.

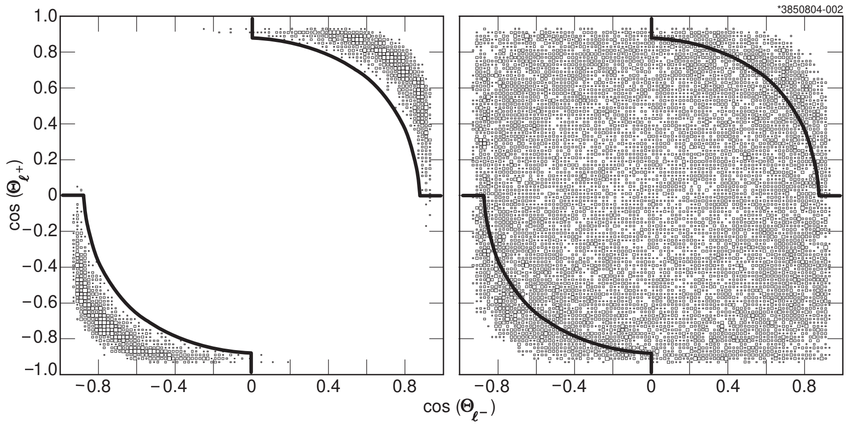

FIG. 2: Two dimensional lepton pair $\cos(\theta)$ distribution for the X(3872) ISR (left) and $\gamma\gamma$ fusion (right) resonance MC samples. The lines indicate where the ISR resonance and $\gamma\gamma$ fusion samples were separated.

The total efficiencies in the six different initial CME regions are listed in Table 2. The efficiencies are determined from the X(3872) $\gamma\gamma$ fusion and ISR resonance signal MC samples. The same selection criteria is applied to both MC samples except with their appropriate two-dimensional lepton pair $\cos(\theta)$ correlation.

TABLE II: Detection efficiencies determined from the signal $\gamma\gamma$ fusion and ISR resonance MC samples. ϵ_{ee} ($\epsilon_{\mu\mu}$) is the total efficiency for detecting X(3872) in events with a $\pi^+\pi^-$J/ψ, J/$\psi \to$ e$^+$e$^-$ (J/$\psi \to \mu^+\mu^-$) decay. The appropriate $\gamma\gamma$ fusion/ISR separation is applied to the respective signal MC sample.

		$\gamma\gamma$ Fusion		ISR	
	$\langle\sqrt{s}\,\rangle$ (GeV)	ϵ_{ee}	$\epsilon_{\mu\mu}$	ϵ_{ee}	$\epsilon_{\mu\mu}$
Υ(1S)	9.458	0.128(4)	0.160(4)	0.065(3)	0.083(3)
Υ(2S)	10.018	0.121(3)	0.151(4)	0.054(2)	0.062(3)
Υ(3S)	10.356	0.115(3)	0.137(4)	0.042(2)	0.043(2)
Υ(4S)	10.566	0.123(4)	0.145(4)	0.0186(14)	0.0165(13)
Υ(5S)	10.868	0.113(3)	0.139(4)	0.0025(5)	0
$\Lambda_b\overline{\Lambda}_b$ threshold	11.296	0.104(3)	0.126(4)	0.0001(1)	0

The ΔM data distributions in the X(3872) search region for $\gamma\gamma$ fusion and ISR resonance production are shown in Fig. 3. The number of observed events (N$_{\rm obs}$) is determined by a maximum likelihood fit of the ΔM data distribution using a production-mode-dependent detector resolution and mass-independent background. The respective detector resolutions are determined by a double Gaussian fit of the signal MC resolution functions and their shapes are illustrated in Fig. 3. For each resolution function, the mean is fixed to the Belle observation of ΔM $= 0.7751$ GeV/c^2 with the narrow Gaussian width and the double Gaussian relative area and width also fixed. The upper limits on the observed number of X(3872) events in untagged $\gamma\gamma$ fusion and ISR resonance production are N$_{\rm obs} < 2.36$ and N$_{\rm obs} < 2.1$ at 90% C.L., respectively.

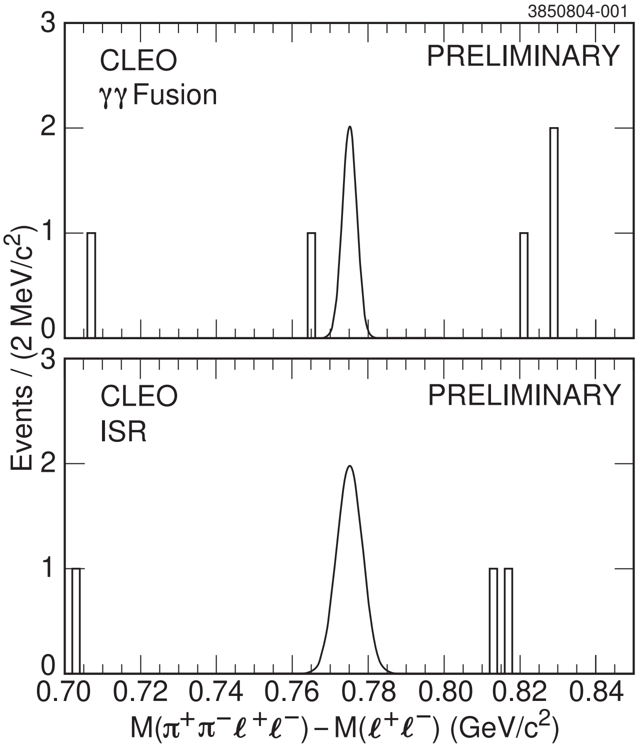

FIG. 3: $\gamma\gamma$ fusion (top) and ISR (bottom) ΔM data distributions with $\Delta\mathrm{M} = 0.7$–0.85 GeV/c^2 satisfying respective selection criteria. The corresponding MC-determined resolution functions are illustrated with the means fixed at $\Delta\mathrm{M} = 0.7751$ GeV/c^2.

The X(3872) production results need to incorporate the six different CME regions of the data sample. The cross section for a $\gamma\gamma$ fusion or ISR produced resonance of mass $\mathrm{m_R}$ decaying to $\pi^+\pi^-\mathrm{J}/\psi$, $\mathrm{J}/\psi \to l^+l^-$ is

$$\sigma(\mathrm{R})_{\gamma\gamma,\mathrm{ISR}}\mathcal{B}(\mathrm{R}\to\pi^+\pi^-\mathrm{J}/\psi) = \frac{\mathrm{N_{obs}}}{\sum_i \mathrm{f}_i[\epsilon_{ee,i}\mathcal{B}(\mathrm{J}/\psi\to\mathrm{e^+e^-}) + \epsilon_{\mu\mu,i}\mathcal{B}(\mathrm{J}/\psi\to\mu^+\mu^-)]} \quad (1)$$

where $\mathrm{f}_i = \mathcal{L}_i(\mathrm{e^+e^-})\sigma(\mathrm{s}_i,\mathrm{m_R})_{\gamma\gamma,\mathrm{ISR}}$ is the flux for $\gamma\gamma$ fusion or ISR production, $\mathcal{L}_i(\mathrm{e^+e^-})$ is the $\mathrm{e^+e^-}$ integrated luminosity, and $\epsilon_{ee,i}$ ($\epsilon_{\mu\mu,i}$) is the detection efficiency for events with $\pi^+\pi^-\mathrm{J}/\psi$, $\mathrm{J}/\psi\to\mathrm{e^+e^-}$ ($\mathrm{J}/\psi\to\mu^+\mu^-$) decays at an initial CME, $\sqrt{\mathrm{s}_i}$. $\mathcal{B}(\mathrm{R}\to\pi^+\pi^-\mathrm{J}/\psi)$ is the $\mathrm{R}\to\pi^+\pi^-\mathrm{J}/\psi$ branching fraction while $\mathcal{B}(\mathrm{J}/\psi\to\mathrm{e^+e^-})$ and $\mathcal{B}(\mathrm{J}/\psi\to\mu^+\mu^-)$ are the PDG branching fractions [5]. For a narrow resonance, $\sigma(\mathrm{s}_i,\mathrm{m_R})_{\gamma\gamma}$ is defined as [27]

$$\sigma(\mathrm{s}_i,\mathrm{m_R})_{\gamma\gamma} = \left(\frac{\alpha}{\pi\mathrm{m_R}}\right)^2 \left[\mathrm{f}\left(\frac{\mathrm{m_R^2}}{\mathrm{s}_i}\right)\left(\ln\left(\frac{\mathrm{s}_i}{\mathrm{m_e^2}}\right)-1\right)^2 - \frac{1}{3}\left(\ln\left(\frac{\mathrm{s}_i}{\mathrm{m_R^2}}\right)\right)^3\right], \quad (2)$$

$$\mathrm{f}\left(\frac{\mathrm{m_R^2}}{\mathrm{s}_i}\right) = \left(1+\frac{\mathrm{m_R^2}}{2\mathrm{s}_i}\right)^2 \ln\left(\frac{\mathrm{s}_i}{\mathrm{m_R^2}}\right) - \frac{1}{2}\left(1-\frac{\mathrm{m_R^2}}{\mathrm{s}_i}\right)\left(3+\frac{\mathrm{m_R^2}}{\mathrm{s}_i}\right)$$

and $\sigma(\mathrm{s}_i,\mathrm{m_R})_{\mathrm{ISR}}$ is [28]

$$\sigma(\mathrm{s}_i,\mathrm{m_R})_{\mathrm{ISR}} = \frac{2\alpha}{\pi\mathrm{x}_i\mathrm{s}_i}\left(2\ln\frac{\sqrt{\mathrm{s}_i}}{\mathrm{m_e}} - 1\right)\left(1-\mathrm{x}_i+\frac{\mathrm{x}_i^2}{2}\right) \quad (3)$$

where x_i is the ratio of the ISR photon energy to the initial beam energy ($\frac{2E_{\gamma,i}}{\sqrt{s_i}}$) and m_e is the electron mass. $\sigma(R)_{\gamma\gamma}$ is related to the $\gamma\gamma$ fusion resonance production by

$$\sigma(R)_{\gamma\gamma} = \frac{8\pi^2(2J+1)\Gamma_{\gamma\gamma}(R)}{m_R} \tag{4}$$

and $\sigma(R)_{ISR}$ is related to the ISR resonance production by

$$\sigma(R)_{ISR} = \frac{12\pi^2\Gamma_{ee}(R)}{m_R} \tag{5}$$

where $\Gamma_{\gamma\gamma}(R)$ ($\Gamma_{ee}(R)$) is the two-photon (e^+e^-) partial width of the resonance.

The sources of systematic uncertainty arise from possible biases in the detection efficiency and estimated background level. These are studied by varying the track quality, IP, $\gamma\gamma$ fusion/ISR separation, and selection criterion optimized in the signal-to-background studies. Other systematic uncertainties are from the e^+e^- luminosity measurement and PDG $J/\psi \to l^+l^-$ branching fractions. The total systematic uncertainty contributing to $\gamma\gamma$ fusion (ISR) resonance production is 18.5% (23.4%), determined by summing individual contributions in quadrature, and is incorporated into the final results by increasing the measured upper limits by the respective systematic uncertainties. The specific X(3872) angular distributions for a given J^{PC} have not been considered in this analysis.

Untagged $\gamma\gamma$ fusion resonance production tests the possibility of a state having positive C parity and an even value of total angular momentum. The preliminary upper limit for X(3872) $\gamma\gamma$ fusion production is

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

at a 90% C.L. Assuming $\mathcal{B}(B^\pm \to K^\pm X(3872)) \approx \mathcal{B}(B^\pm \to K^\pm\psi(2S)) = (6.8\pm0.4)\times10^{-4}$ [19] leads to $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) \approx 0.02$ for both the Belle [1] and BaBar [4] results. This translates into $(2J+1)\Gamma_{\gamma\gamma}(X(3872)) < 0.645$ keV (90% C.L.) for this analysis. The X(3872) $(2J+1)\Gamma_{\gamma\gamma}(R)$ is more than four times smaller than for η_c, χ_{c0}, and χ_{c2}, i.e., $(2J+1)\Gamma_{\gamma\gamma}(\eta_c) = 7.4 \pm 2.3$ keV, $(2J+1)\Gamma_{\gamma\gamma}(\chi_{c0}) = 2.6 \pm 0.5$ keV, and $(2J+1)\Gamma_{\gamma\gamma}(\chi_{c2}) = 2.6 \pm 0.3$ keV [19], respectively. If X(3872) is a vector meson, the preliminary 90% C.L. upper limit for ISR resonance production is

$$\Gamma_{ee}(X(3872))\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) < 8.0 \text{ eV}.$$

From the observed $\psi(2S)$ signal, the upper limit for the X(3872) ISR production yield is $N_{X(3872)}/N_{\psi(2S)} < 0.011$ (90% C.L.). The ISR production upper limit from this X(3872) search includes our estimated systematic uncertainty and is comparable to the ISR upper limit of $\Gamma_{ee}(X(3872))\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) < 10$ eV (90% C.L.) using the BES data [23].

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