Study of Charmonium-like States via ISR at B Factories

X.L. Wang

Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

DOI: http://dx.doi.org/10.3204/DESY-PROC-2009-03/Wang

The ISR processes at open charm region studied at the two B factories, BaBar and Belle, are reviewed. The report focuses on charmonium-like states, including the $Y(4008)$ and $Y(4260)$ observed in $e^+e^- \to \pi^+\pi^- J/\psi$, and the $Y(4360)$ and $Y(4660)$ observed in $e^+e^- \to \pi^+\pi^-\psi(2S)$. Measurements of the $e^+e^- \to$ open charm cross sections, including $e^+e^- \to D\overline{D}$, $D^0D^-\pi^+ + c.c.$, $D^*\overline{D} + c.c.$, and $D^*\overline{D}^*$, confirm the excited ψ states $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$, but show no evidence for any of the Y states. The 4 Y states and 3 ψ states between 4.0 and 4.7 GeV/c^2 are too many to be all charmonium states from a point of view of Potential Models, indicates that our understanding of the vector charmonium states above 4 GeV/c^2 is still poor, and one or more of these states may be exotic. Measurement of $e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^-$ shows the existence of an $X(4630)$, which may be the $Y(4660)$ observed in $e^+e^- \to \pi^+\pi^-\psi(2S)$. A $Y(2175)$ is observed in $e^+e^- \to \phi f_0(980)$, this may indicate the existence of the $s\overline{s}$ version of the Y state.

1 Introduction

The Initial State Radiation (ISR) process, shown in Figure 1, is that when e^+e^- collides at $\sqrt{s_0}$, one or several photons (γ_{ISR}) emit from e^+ or e^-, and the left part is still a e^+e^- collision. Because γ_{ISR} takes away some energy, the effective collision energy is lowered down, like a new collider running at new $\sqrt{s}$, which could be much lower than $\sqrt{s_0}$.

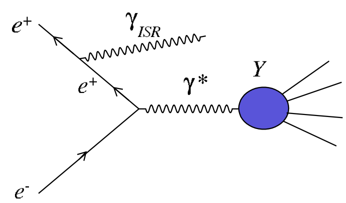

Figure 1: The ISR process at e^+e^- collider. At collision, the emitted photons make the effective $\sqrt{s}$ lower than the original $\sqrt{s_0}$.

The ISR cross section for a particular hadronic final state f (excluding the radiated γ_{ISR})

is related to the corresponding e^+e^- cross section $\sigma_f(s)$ by:

$$\frac{d\sigma_f(s_0,x)}{dx} = W(s_0,x)\cdot\sigma_f(s_0(1-x)) \ , \tag{1}$$

where $x = 2E_\gamma/\sqrt{s_0}$; E_γ is the energy of the γ_{ISR} in the nominal e^+e^- center-of-mass (CM) frame; $\sqrt{s_0}$ is the nominal e^+e^- CM energy; and $\sqrt{s_0(1-x)}$ is the effective CM energy ($\sqrt{s}$) at which the final state f is produced. The invariant mass of the hadronic final state defines the effective e^+e^- CM energy. The function $W(s_0,x)$ is calculated with better than 1% accuracy [1] and describes the probability density function for ISR photon emission, which occurs at all angles. When $\sqrt{s}$ is far from $\sqrt{s_0}$, the effective cross section $\sigma_f(s_0,x)$ is much small. And because the high energy γ_{ISR} is usually along with colliding beams, the detection efficiency is usually very low. So study via ISR needs very large data sample.

The two B factories, BaBar at SLAC and Belle at KEK have collected more than 1 ab^{-1} e^+e^- collision data around $\Upsilon(4S)$. And the designed asymmetric collision increases the detection efficiency. So the B factories become very suitable for the studies via ISR processes, especially at open charm threshold region. At this region, there are just several ψ states established tens of years ago via inclusive production. Here we report the charmonium-like states observed from ISR studies at the B factories, including the $Y(4008)$ and $Y(4260)$ from $e^+e^-\to\pi^+\pi^-J/\psi$, the $Y(4360)$ and $Y(4660)$ from $e^+e^-\to\pi^+\pi^-\psi(2S)$. $e^+e^-\to K^+K^-J/\psi$ is also studied at Belle, no obvious signal of the Y states is observed. Cross sections of $e^+e^-\to D\overline{D}$, $D^0D^-\pi^+ + c.c.$, $D^*\overline{D} + c.c.$, and $D^*\overline{D}^*$ have been measured, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$ have been confirmed but no obvious Y states signal can be seen. Measurements on $e^+e^-\to\Lambda_c^+\overline{\Lambda}_c^-$ shows a structure at around 4.63 GeV, and in $e^+e^-\to\phi f_0(980)$ the $Y(2175)$ is observed.

2 The Y states via $e^+e^-\to h^+h^-$+charmonium

Three final states are analyzed, including $\pi^+\pi^-J/\psi$, $\pi^+\pi^-\psi(2S)$, and K^+K^-J/ψ.

2.1 Measurement on $e^+e^-\to\pi^+\pi^-J/\psi$

BaBar studied $e^+e^-\to\pi^+\pi^-J/\psi$ [2], the data sample used is 232 fb^{-1}. With a J/ψ mass constraint, the $\psi(2S)$ signal is well described by a Cauchy shape function. Figure 2 shows a new structure well above $\psi(2S)$. The new structure is called $Y(4260)$. 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 fit gives 125$\pm$23 events with a mass of $4259\pm8^{+2}_{-6}$ MeV$/c^2$, a width of $88\pm23^{+6}_{-4}$ MeV$/c^2$, and $\Gamma(Y(4260)\to e^+e^-)\cdot\mathcal{B}(Y(4260)\to\pi^+\pi^-J/\psi) = 5.5\pm1.0^{+0.8}_{-0.7}$ eV$/c^2$. The significance is more than 8σ.

Belle studied this channel with about 550 fb^{-1} data [3]. $\psi(2S)$ is used as reference signal. The calculation gives the partial width of $\psi(2S)$ $\Gamma_{e^+e^-} = 2.54\pm0.02\pm0.15$ keV$/c^2$, agrees with other experiments very well. The generator used is PHOKHARA. To increase detecting efficiency, the γ_{ISR} is not reconstructed, instead, the recoil mass of the charged track system is required to be agree with a missing massless particle. Figure 3 shows the $\pi^+\pi^-J/\psi$ invariant mass spectrum. Besides the $Y(4260)$ signal, Belle finds a broad enhancement $Y(4008)$ around 4 GeV$/s^2$. Figure 4 shows the $\pi^+\pi^-$ invariant mass distributions of events for three $m_{\pi^+\pi^-J/\psi}$

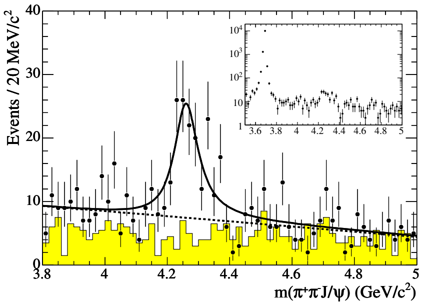

Figure 2: The $\pi^+\pi^- J/\psi$ invariant mass spectrum from BaBar in the range 3.8−5.0 GeV/c^2 and (inset) over a wider range that includes the $\psi(2S)$. The solid curve shows the result of the single-resonance fit.

regions, $[3.8, 4.2]$, $[4.2, 4.4]$, and $[4.4, 4.6]$ (unit in GeV/c^2). The $\pi^+\pi^-$ invariant mass distribution for events around 4.25 GeV/c^2 differs significantly from phase space; for other energy ranges the agreement with phase space is better. And considering the asymmetry shape of the $Y(4260)$, it is reasonable to assume that two coherent structures exist in this channel. An unbinned fit with two coherent resonances is applied to the $\pi^+\pi^- J/\psi$ invariant mass spectrum. There are two solutions with equally good fit quality (see Table 1).

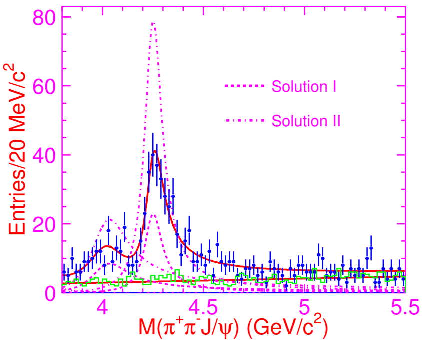

Figure 3: The plot shows the $\pi^+\pi^- J/\psi$ mass spectrum and the fit with two coherent resonances.

2.2 Measurement on $e^+e^- \to \pi^+\pi^-\psi(2S)$

After the discovery of the $Y(4260)$, BaBar searches for it in $e^+e^- \to \pi^+\pi^-\psi(2S)$ with about 300 fb^{-1} data [5]. Figure 5 shows the $\pi^+\pi^-\psi(2S)$ invariant mass spectrum and the $\pi^+\pi^-$ invariant mass distribution. The state $Y(4360)$ was observed around 4.3 GeV/c^2. Fit with one resonance give the mass (4324 ± 24) MeV/c^2 and the width (172 ± 33) MeV/c^2, where systematic errors not included. BaBar tried to fit with a $Y(4260)$, but the conclusion is negative. The statistics didn't allow BaBar fit the spectrum with two resonances.

Belle study this spectrum with a data sample of about 673 fb^{-1} [6]. Figure 6 shows the $\pi^+\pi^-\psi(2S)$ invariant mass spectrum. Belle confirms the $Y(4360)$ and observes the $Y(4660)$ for the first time. Fitting with two coherent resonances gives the results in Table 2, there are

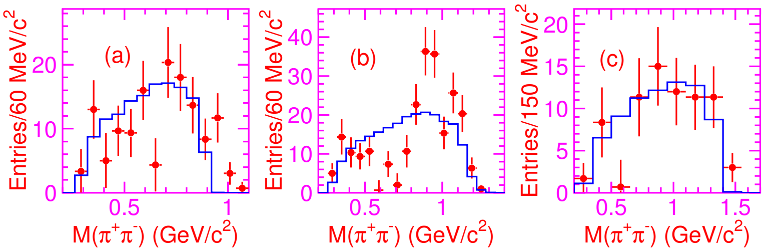

Figure 4: The $\pi^+\pi^-$ invariant mass distribution of events for different $\pi^+\pi^- J/\psi$ mass regions. (a): $m_{\pi^+\pi^- J/\psi} \in [3.8, 4.2]$ GeV$/c^2$, (b): $m_{\pi^+\pi^- J/\psi} \in [4.2, 4.4]$ GeV$/c^2$, and (c): $m_{\pi^+\pi^- J/\psi} \in [4.4, 4.6]$ GeV$/c^2$. The points with errors bars are pure signal events, the histograms are MC simulations made using phase space distributions.

Parameters	Solution I	Solution II
$M(Y(4008))$	$4008 \pm 40^{+114}_{-28}$	
$\Gamma_{\rm tot}(Y(4008))$	$226 \pm 44 \pm 87$	
$\mathcal{B} \cdot \Gamma_{e^+e^-}(Y(4008))$	$5.0 \pm 1.4^{+6.1}_{-0.9}$	$12.4 \pm 2.4^{+14.8}_{-1.1}$
$M(Y(4260))$	$4247 \pm 12^{+17}_{-32}$	
$\Gamma_{\rm tot}(Y(4260))$	$108 \pm 19 \pm 10$	
$\mathcal{B} \cdot \Gamma_{e^+e^-}(Y(4260))$	$6.0 \pm 1.2^{+4.7}_{-0.5}$	$20.6 \pm 2.3^{+9.1}_{-1.7}$
ϕ	$12 \pm 29^{+7}_{-98}$	$-111 \pm 7^{+28}_{-31}$

Table 1: Fit results of the $\pi^+\pi^- J/\psi$ invariant mass spectrum from Belle.

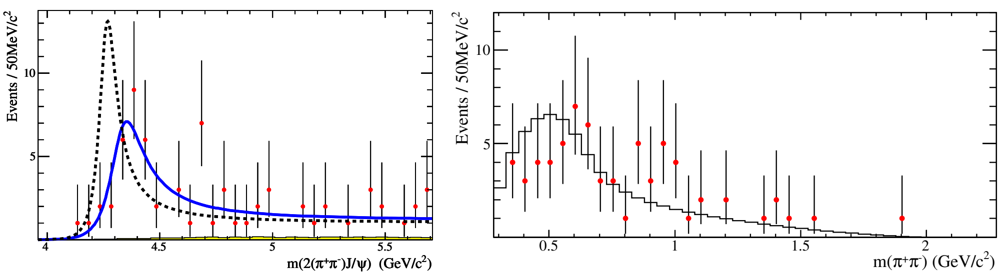

Figure 5: The left plot shows the $\pi^+\pi^-\psi(2S)$ invariant mass spectrum up to 5.7 GeV$/c^2$ from BaBar. The right plot shows the corresponding $\pi^+\pi^-$ invariant mass distribution.

also two solutions with equal quality and different $\Gamma_{e^+e^-}$. Figure 7 shows the scattering plot of M($\pi^+\pi^-$) versus M($\pi^+\pi^-\psi(2S)$). From the scattering plot, there is a concentration around 1 GeV/c^2 at M($\pi^+\pi^-$). If it is the scalar particle $f_0(980)$, the decay of $Y(4660)$ should be dominated by $\psi(2S) + f_0(980)$. So there is an assumption that $Y(4660)$ is a $\psi(2S)f_0(980)$ bound state [7]. For both $Y(4360)$ and $Y(4660)$, M($\pi^+\pi^-$) distributions tend to be large. And the one of $Y(4360)$ happens to be around 600 MeV/c^2, which looks similar to that from $\psi(2S) \to \pi^+\pi^- J/\psi$. At $\psi(2S)$ decay, an assumption is that $\pi^+\pi^-$ is from scalar particle $\sigma(600)$.

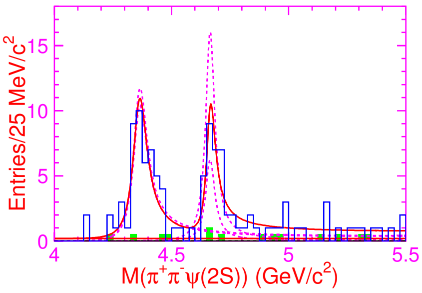

Figure 6: The plot shows the $\pi^+\pi^-\psi(2S)$ invariant mass distribution.

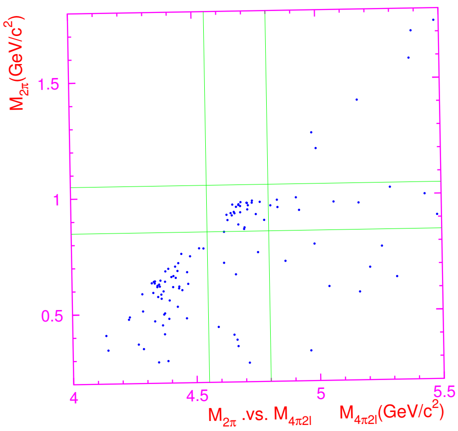

Figure 7: The plot is the scattering plot of M($\pi^+\pi^-$) vs. M($\pi^+\pi^-\psi(2S)$), which indicates a clear signal at M($\pi^+\pi^-$) near 1 GeV/c^2. This structure may be $f_0(980)$.

A combined fit has been performed on BaBar and Belle's measurements, which are also shown in Table 2. From the fits, and the comparison with other vector charomnium(-like) states, the $Y(4660)$ has the highest mass and the narrowest width. This may be because of the narrow width of $f_0(980)$ decays from the $Y(4660)$, or indicates the $Y(4660)$ is a different state.

2.3 $e^+e^- \to K^+K^-J/\psi$

CLEO-c observed 3 K^+K^-J/ψ events at $\sqrt{s}$ = 4.26 GeV/c^2, and assumed them from the $Y(4260)$. Limited by statistics, only Belle scans $e^+e^- \to K^+K^-J/\psi$ via ISR [8]. Figure 8

Parameters	Belle fit Solution I	Belle fit Solution II	Combined fit Com. Sol.I	Combined fit Com. Sol.II
$M(Y(4350))$	$4361 \pm 9 \pm 9$		4355^{+9}_{-10}	
$\Gamma_{\rm tot}(Y(4350))$	$74 \pm 15 \pm 10$		103^{+17}_{-15}	
$\mathcal{B} \cdot \Gamma_{e^+e^-}(Y(4350))$	$10.4 \pm 1.7 \pm 1.5$	$11.8 \pm 1.8 \pm 1.4$	$11.1^{+1.3}_{-1.2}$	12.3 ± 1.2
$M(Y(4660))$	$4664 \pm 11 \pm 5$		4661^{+9}_{-8}	
$\Gamma_{\rm tot}(Y(4660))$	$48 \pm 15 \pm 3$		42^{+17}_{-12}	
$\mathcal{B} \cdot \Gamma_{e^+e^-}(Y(4660))$	$3.0 \pm 0.9 \pm 0.3$	$7.6 \pm 1.8 \pm 0.8$	$2.2^{+0.7}_{-0.6}$	5.9 ± 1.6
ϕ	$39 \pm 30 \pm 22$	$-79 \pm 17 \pm 20$	18^{+23}_{-24}	-74^{+16}_{-12}

Table 2: Results of the fits to the $\pi^+\pi^-\psi(2S)$ invariant mass spectrum from Belle's unbinned fit and a combined fit on BaBar and Belle's results.

shows the K^+K^-J/ψ invariant mass distribution, together with the background estimated from the J/ψ mass sidebands. There is a broad enhancement around 4.4-5.5 GeV/c^2. In addition, there are two events near $\sqrt{s} = 4.26$ GeV, where CLEO observes three K^+K^-J/ψ events [4].

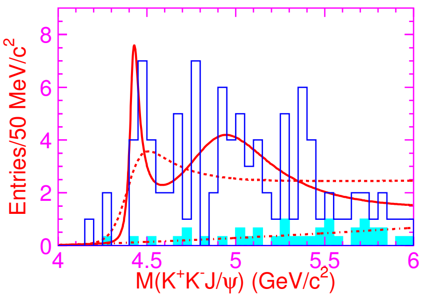

Figure 8: The K^+K^-J/ψ invariant mass distribution from Belle.

Fit the spectrum with a single resonance, The resonance parameters are $M = 4430^{+38}_{-43}$ MeV/c^2, $\Gamma_{\rm tot} = 254^{+55}_{-46}$ MeV/c^2, $\mathcal{B}(R \to K^+K^-J/\psi) \cdot \Gamma_{e^+e^-} = 1.9 \pm 0.3$ eV/c^2, where the errors are statistical only. Since there is a small concentration around 4.4 GeV/c^2, another fit with two resonance has been applied. One resonance is $\psi(4415)$ fixed according to PDG. The fit shows that the other resonance has mass 4875 ± 132 MeV/c^2 and width 630 ± 126 MeV/c^2. The spectrum and fit results are still not very clear. Like previous processes, the K^+K^- invariant mass also tends to be large. No clear $Y(4260)$ signal is observed, and Belle gives an upper limit on $\mathcal{B}(Y(4260) \to K^+K^-J/\psi)\Gamma(Y(4260) \to e^+e^-) < 1.2$ eV/c^2 at the 90% C.L.

3 ψ States at $e^+e^- \to$ Open Charm

Since masses of the Y states are well above the charm threshold, the Y states are expected to decay to open charms easily. Four final states are measured using ISR data, they are $D\overline{D}$ [9, 13], $D\overline{D}\pi + c.c.$ [10], $D\overline{D}^* + c.c.$ [11, 13], and $D^*\overline{D}^*$ [11, 13]. For comparison, cross sections from Belle of $e^+e^- \to$ open charm are shown in Figure 9, as well as the cross sections of $e^+e^- \to h^+h^-$ + charmonium. From Belle's results, there are $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$ at open charm final states, and one state could just appear at one or two channel obviously. $D\overline{D}\pi$ is dominated by $D\overline{D}^*(2460) + c.c.$, and $\psi(4415)$ could only decay to $DD(2460)$.

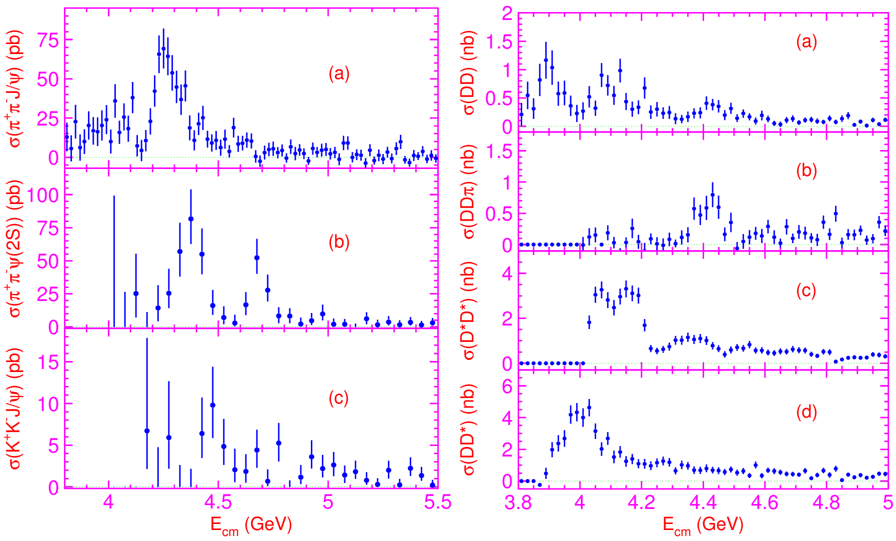

Figure 9: The left plot shows the measured $e^+e^- \to \pi^+\pi^- J/\psi$ (a), $\pi^+\pi^-\psi(2S)$ (b), and K^+K^-J/ψ (c) cross sections. The right plot shows the measured $D\overline{D}$ (a), $D^0D^-\pi^+ + c.c.$ (b), $D^{*+}D^{*-}$ (c), and $D^+D^{*-} + c.c.$ (d) cross sections.

BaBar got similar results on $e^+e^- \to$ open charm measurement. Figure 10 shows the sum of the $e^+e^- \to D\overline{D}$, $D\overline{D}^*$, and $D^*\overline{D}^*$ cross sections, the arrow indicates the position of the $Y(4260)$, which falls in a local minimum, in agreement with the cross section measured for hadron production in e^+e^- annihilation [14]. BaBar also obtains $\frac{\mathcal{B}(Y(4260)\to D\overline{D})}{\mathcal{B}(Y(4260)\to J/\psi\pi^+\pi^-)} < 34$ and $\frac{\mathcal{B}(Y(4260)\to D^*\overline{D}^*)}{\mathcal{B}(Y(4260)\to J/\psi\pi^+\pi^-)} < 40$ at the 90% confidence level.

4 $e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^-$ and $\phi\pi^+\pi^-$

It is important to search these exotic Y states in charm baryon-antibaryon pair production. The first study is $e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^-$ from Belle [15]. Figure 11 shows the cross section with statistical uncertainties only. There is a peak slightly above mass threshold. One possible interpretation of it is a new structure, $X(4630)$. Belle gives the mass $M = (4634^{+8+5}_{-7-8})$ MeV/c^2 and the total width $\Gamma_{\rm tot} = (92^{+40+10}_{-24-21})$ MeV/c^2. The significance for this structure is 8.8σ. The $X(4630)$ is close to the $Y(4660)$, and they have the same quantum number, $J^{PC} = 1^{--}$, so it is possible that they are the same structure.

It seems that there exists an $s\overline{s}$ version of the Y states from the study on $e^+e^- \to \phi\pi^+\pi^-$ via ISR. Like $\pi^+\pi^-\psi(2S)$, there are signals $\phi f_0(980)$ in $\phi\pi^+\pi^-$ final state. Figure 12 shows the cross sections on $e^+e^- \to \phi f_0(980)$ from BaBar [16] and Belle [17]. There is a structure

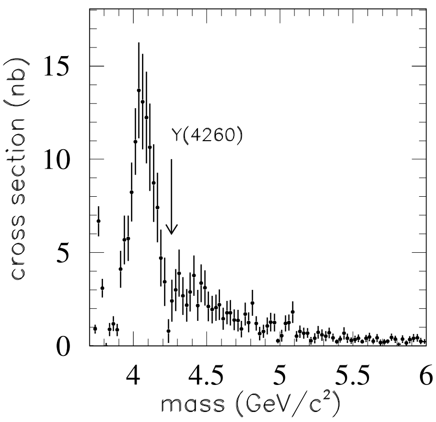

Figure 10: Sum of $e^+e^- \to D\overline{D}$, $D\overline{D}^*$, and $D^*\overline{D}^*$ cross sections. The arrow indicates the position of the $Y(4260)$.

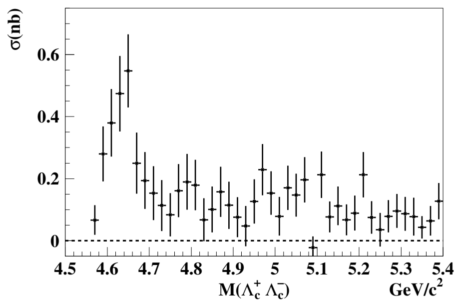

Figure 11: The cross section for the exclusive process $e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^-$.

at 2.17 GeV/c^2. BaBar measures $M = (2175 \pm 10)$ MeV/c^2 and $\Gamma = (58 \pm 16)$ MeV/c^2 with only statistic errors, and Belle obtains $M = (2133^{+69}_{-115})$ MeV/c^2 and $\Gamma = (169^{+105}_{-92})$ MeV/c^2 where the uncertainties include both statistical and systematic errors. BES also confirmed this state in $J/\psi \to \eta\phi f_0(980)$ decay [18], and reports $M = (2186 \pm 10 \pm 6)$ MeV/c^2 and $\Gamma = (65 \pm 23 \pm 17)$ MeV/c^2.

5 Summary

Here we report ISR precesses studied at BaBar and Belle, focusing on charmonium-like states found above 4 GeV/c^2 region. There are four exotic states, $Y(4008)$ and $Y(4260)$ are only observed at $e^+e^- \to \pi^+\pi^- J/\psi$, and $Y(4360)$ and $Y(4660)$ are only observed at $e^+e^- \to \pi^+\pi^-\psi(2S)$. There is no evidence of these state in $e^+e^- \to D\overline{D}$, $D\overline{D}\pi$, $D\overline{D}^*$, and $D^*\overline{D}^*$,

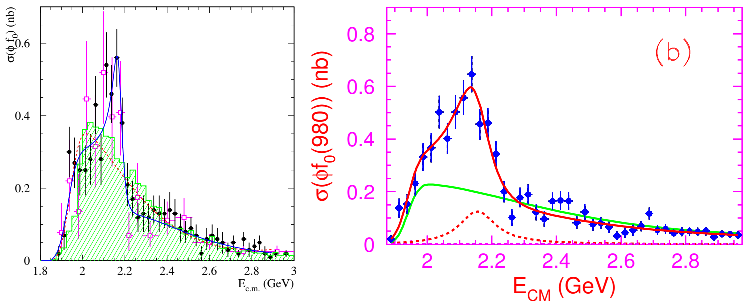

Figure 12: The cross sections of $e^+e^- \to \phi f_0(980)$ from BaBar(left) and Belle(right). Each plot also shows best fit on the spectrum, and give the evidence for Y(2175).

instead, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$ are confirmed at these channels. The 4 Y states and 3 ψ states too many for the charmonium states predicted in potential models, which may indicate one or several of them are exotic states. Belle observes a structure $X(4630)$ in charm baryon-antibaryon pair $\Lambda_c^+\overline{\Lambda}_c^-$ production. The $X(4630)$ and $Y(4660)$ are consist with each other in mass and width. There looks an $s\bar{s}$ version of the Y state, $Y(2175)$ in $e^+e^- \to \phi f_0(980)$.

6 Acknowledgments

This work is supported in part by NSFC (10825524) and 100 Talents Program of CAS (U-25).

References

[1] M. Benayoun *et al.*, Mod. Phys. Lett. **A14**, 2605 (1999).

[2] Aubert B *et al.* (BaBar Collaboration), Phys. Rev. Lett. (2005) **95**:142001.

[3] Yuan C Z *et al.* (Belle Collaboration), Phys. Rev. Lett. (2007) **99**:182004.

[4] Coan T E *et al.* (CLEO Collaboration). Phys. Rev. Lett. (2006) **96**:162003.

[5] Aubert B *et al.* (BaBar Collaboration), Phys. Rev. Lett. (2007) **98**:212001.

[6] Wang X L *et al.* (Belle Collaboration), Phys. Rev. Lett. (2007) **99**:142002.

[7] Guo F K *et al.*, Phys.Lett.B (2008)665:26-29.

[8] Yuan C Z *et al.* (Belle Collaboration), Phys. Rev. D (2008) **77**:011105(R).

[9] G. Pakhlova *et al.* (Belle Collaboration), Phys. Rev. D (2007) **77**:011103(R).

[10] G. Pakhlova *et al.* (Belle Collaboration), Phys. Rev. Lett. (2008) **100**:062001.

[11] G. Pakhlova *et al.* (Belle Collaboration), Phys. Rev. Lett. (2007) **98**:092001.

[12] Aubert B *et al.* (BaBar Collaboration), Phys. Rev. D (2009) **79**:092001.

[13] Aubert B *et al.* (BaBar Collaboration), arXiv:0607083 [hep-ex].

[14] C. Amsler *et al.*, Review of Particle Physics, Phys. Lett. **B667**, 1 (2008).

[15] G. Pakhlova *et al.* (Belle Collaboration), Phys. Rev. Lett. (2008) **101**:172001.

[16] Aubert B *et al.* (BaBar Collaboration), Phys. Rev. D (2007) **77**:012008.

[17] Shen C P *et al.* (Belle Collaboration), arXiv:0808.0006v1 [hep-ex].

[18] M. Ablikim *et al.* (BES Collaboration), Phys. Rev. Lett. (2008) **100**:102003.