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Initial State Radiation and Two-photon results from Belle

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Abstract

We review recent results from initial state radiation and two-photon processes at the Belle experiment. The results include the measurements of $e^+e^- \to \pi^+\pi^- J/\psi$, $\pi^+\pi^-\psi(2S)$, $K^+K^- J/\psi$, and $\gamma\chi_{cJ}$ from initial state radiation processes and the measurement of $\gamma\gamma \to p\bar{p}K^+K^-$ from two-photon process. We also summarize all the published results from these two kinds of processes. Moreover, we point out some golden channels that will be studied firstly with larger statistic at Belle II in the near future.

Keywords
Initial State Radiation; Two-photon; Belle experiment.

1 Initial state radiation results from Belle

The idea of utilizing initial state radiation (ISR) from a high-mass state to explore electron-positron processes at all energies below that state was outlined in Ref. [1]. The possibility of exploiting such processes in high luminosity $\phi-$ and B- factories was discussed in Refs. [2–4] and motivates the hadronic cross section measurement. The traditional way of measuring of the hadronic cross section via the energy scan has one disadvantage - it needs dedicated experiments. An alternative way, the study of ISR events at B-factories provides independent and contiguous measurements of hadronic cross sections in this energy region and also contributes to the investigation of low-mass resonances spectroscopy. So states with $J^{PC} = 1^{--}$ can be studied with ISR in Belle's and BaBar's large $\Upsilon(4S)$ data samples or via direct production in e^+e^- collisions at BESIII.

The study of charmoniumlike states via ISR at the B-factories has proven to be very fruitful. Many of them show properties different from the naive expectation of conventional charmonium states. The first vector charmoniumlike state $Y(4260)$ was observed and confirmed by BaBar [5], CLEO [6] and Belle experiments [7]. Besides the $Y(4260)$, Belle also observed a broad excess near 4 GeV, called $Y(4008)$ [8]. With full of BaBar data sample 454 fb^{-1}, the $Y(4008)$ structure was not confirmed [9]. The difference on the measured cross section from BaBar and Belle at around 4.01 GeV is large. For $Y(4260) \to \pi^+\pi^- J/\psi$ decays, Belle also observed a clear charged signal in the distributions of $M_{\rm max}(\pi^\pm J/\psi)$, the maximum of $M(\pi^+ J/\psi)$ and $M(\pi^- J/\psi)$ [10]. The measured mass and width are $(3899.0 \pm 3.6 \pm 4.9)$ MeV$/c^2$ and $(63 \pm 24 \pm 26)$ MeV/c^2 with a signal significance greater than 5σ. This state is close to the $D\bar{D}^*$ mass threshold and is called $Z_c(3900)$.

The $Y(4360)$ was firstly found by BaBar [11], while Belle observed two resonant structures at 4.36 and 4.66 GeV/c^2, denoted as the $Y(4360)$ and $Y(4660)$ [12]. BaBar confirmed the existence of the $Y(4660)$ state later [13]. Besides the $Y(4360)$ and $Y(4660)$ parameters are measured with improved precision with full 980 fb^{-1} data sample [14], Belle also noticed there are a number of events in the vicinity of the $Y(4260)$ mass. But the signal significance of the $Y(4260)$ is only 2.4σ. Evidence for a charged charmoniumlike structure at 4.05 GeV$/c^2$, denoted as the $Z_c(4050)$, was observed in the $\pi^\pm\psi(2S)$ intermediate state in the $Y(4360)$ decays, which might be the excited state of the $Z_c(3900)$.

Using a data sample of 673 fb^{-1}, Belle observed abundant $e^+e^- \to K^+K^- J/\psi$ signal events [15]. There is one very broad structure in the $K^+K^- J/\psi$ mass spectrum; fits using either a single Breit-

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Wigner (BW) function, or the $\psi(4415)$ plus a second BW function yield resonant parameters that are very different from those of the currently tabulated excited ψ states. To examine possible structures in the K^+K^-J/ψ, K^+K^- and $K^\pm J/\psi$ systems, updated measurement of $e^+e^- \to K^+K^-J/\psi$ between threshold and 6.0 GeV/c^2 with an integrated luminosity of 980 fb^{-1} was performed, but no clear structure is observed in any system [16].

In order to improve the understanding of the nature of vector charmoniumlike states and search for more new states, Belle studied $e^+e^- \to \gamma\chi_{cJ}$ process using ISR events with χ_{cJ} reconstructed via $\gamma J/\psi$ [17]. The integrated luminosity used in this analysis is 980 fb^{-1}. After all the event selections, no significant signal is observed in either $\gamma\chi_{c1}$ or $\gamma\chi_{c2}$ mode in $M(\gamma\gamma J/\psi)$ distributions for $\gamma\chi_{c1}$ and $\gamma\chi_{c2}$ candidate events as well as the sum of them. The measured upper limits on the cross sections are around a few pb to a few tens of pb.

Figure 1 shows the measured $e^+e^- \to \pi^+\pi^-J/\psi$, $\pi^+\pi^-\psi(2S)$ and K^+K^-J/ψ cross sections from Belle with full of data sample. Table 1 also summarized all the published ISR results at Belle for those processes with information of used total integrated luminosity, the range of center-of-mass (C.M.) energy, the related physics topics and the corresponding reference paper.

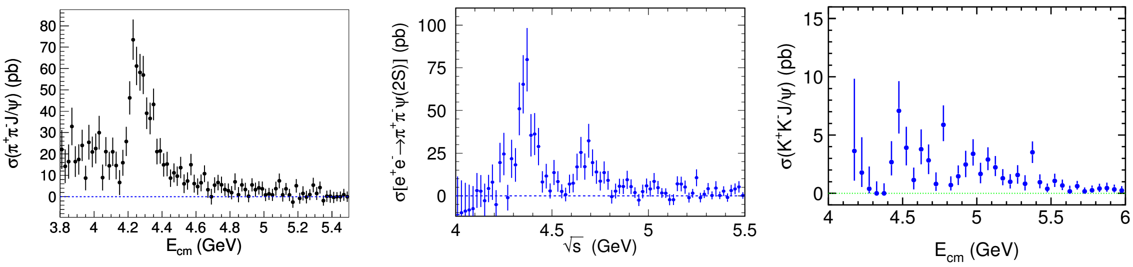

Fig. 1: The measured $e^+e^- \to \pi^+\pi^-J/\psi$ [10], $\pi^+\pi^-\psi(2S)$ [14] and K^+K^-J/ψ [16] cross sections from Belle.

Table 1: Published ISR results at Belle for those processes with total integrated luminosity (Int. Lum.), the range of center-of-mass energy (C.M. energy), the related physics topics and the corresponding reference paper.

Process	Int. Lum.	C.M. energy	Physics Covered	Reference
$D^{(*)\pm}D^{(*)\mp}$	547.8 fb^{-1}	(3.9-5.0) GeV	cross sections	PRL 98, 092001(2007)
$DD_2^*(2460)$	673 fb^{-1}	(4.0-5.0) GeV	$\psi(4415)$	PRL 100, 062001 (2008)
$\Lambda_c^+\Lambda_c^-$	695 fb^{-1}	(4.8-5.4) GeV	Y(4630)	PRL 101, 172001 (2008)
$D^0D^{*-}\pi^+$	695 fb^{-1}	(4.1-5.2) GeV	Y(4260)	PRD80 101, 091101(R) (2009)
$D\bar{D}$	673 fb^{-1}	(3.8-5.0) GeV	cross sections	PRD 77, 011103 (2008)
$\pi^+\pi^-J/\psi$	548 fb^{-1}	(3.8-5.5) GeV	Y(4008),Y(4260)	PRD 99, 182004 (2007)
$\pi^+\pi^-\psi(2S)$	673 fb^{-1}	(4.0-5.5) GeV	Y(4360),Y(4660)	PRD 99, 142002 (2007)
K^+K^-J/ψ	673 fb^{-1}	(4.2-6.0) GeV	Y(4260)	PRD 77, 011105(R) (2008)
$\pi^+\pi^-\phi$	673 fb^{-1}	(1.3-3.0) GeV	Y(2175),ϕ(1680)	PRD 80, 031101 (2009)
$\eta J/\psi$	980 fb^{-1}	(3.8-5.3) GeV	$\psi(4040)$, $\psi(4160)$	PRD 87, 051101(R) (2013)
$\pi^+\pi^-J/\psi$	980 fb^{-1}	(3.8-5.5) GeV	Y(4008),Y(4260), $Z_c(3900)$	PRL 110, 252002 (2013)
K^+K^-J/ψ	980 fb^{-1}	(4.4-5.2) GeV	Y(4260)	PRD 89, 072015 (2014)
$\pi^+\pi^-\psi(2S)$	980 fb^{-1}	(4.0-5.5) GeV	Y(4260),Y(4360),Y(4660)	PRD 91, 112007 (2015)
$\gamma\chi_{cJ}$	980 fb^{-1}	(3.8-5.6) GeV	cross sections	PRD 92, 012011 (2015)

More data are necessary and better for ISR studies. Belle II will accumulate 10 ab^{-1} (50 ab^{-1}) data at around $\Upsilon(4S)$ by 2020 (2024). Compared to the current BESIII, with ISR events the whole hadron spectrum is visible so that the line shape of the resonance and fine structures can be investigated. The disadvantage is the effective luminosity and detection efficiency are relative low although we have huge data sample. Figure 2 shows the effective luminosity from 3 to 5 GeV in the Belle II data samples.

We can see that, for 10 ab^{-1} Belle II data, we have about 400–500 pb^{-1} data for every 10 MeV in the range 4–5 GeV. Of course, the ISR analyses have a lower efficiency than in direct e^+e^- collisions because of the extra ISR photons and the boost given to events along the beam direction. Even taking these effects into account, the full Belle II data sample, which corresponds to about 2,000–2,300 pb^{-1} data for every 10 MeV from 4–5 GeV, will result in similar statistics for modes like $e^+e^- \to \pi^+\pi^- J/\psi$ at BESIII currently. Belle II has the advantage that data at different energies will be accumulated at the same time, making the analysis much simpler than at BESIII at 60 data points. In addition, Belle II can produce events above 4.6 GeV, which is currently the maximum energy of BEPCII.

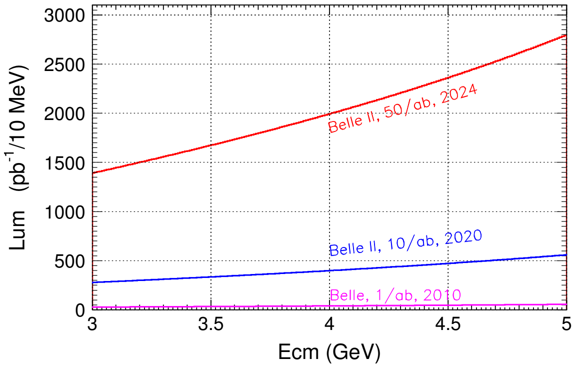

Fig. 2: Effective luminosity at low energy in the Belle and Belle II $\Upsilon(4S)$ data samples.

2 Two-photon results from Belle

At e^+e^- collider, two-photon interactions are studied via the process $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-R$. Almost all of the beam energy is caught by scattered electron and positron and usually they are not detected (no-tagged events). If the scattering angle is sufficiently large, they can be detected in the forward region (tagged events). Many two-photon processes have been done by Belle. Table 2 summarizes the published results from two-photon processes with information of the analyzed mode, the used integrated luminosity (Int. Lum.), the $\gamma\gamma$ C.M. energy, the studied light mesons/baryons and charmonium states, and the corresponding reference paper.

The latest published two-photon results are from $\gamma\gamma \to p\bar{p}K^+K^-$ in order to search for exotic baryons. The LHCb observed two exotic structures, $P_c(4380)^+$ and $P_c(4450)^+$, in the $J/\psi p$ system in $\Lambda_b^0 \to J/\psi K^- p$ [18]. These two P_c states must consist of at least five quarks. Several theoretical interpretations of these states have been developed, such as the diquark picture and hadronic molecules. Actually, the first strong experimental evidence for a pentaquark state, referred to as the $\Theta(1540)^+$, was reported in the reaction $\gamma n \to nK^+K^-$ in the LEPS experiment [19]. It was a candidate for a $uudd\bar{s}$ pentaquark state. However, it was not confirmed in larger-statistics data samples in the same experiment and was most probably not a genuine state [20].

To confirm the pentaquark states discovered by LHCb, further experimental searches for exotic baryons are necessary. The possibility of observing additional hypothetical exotic baryons in $\gamma\gamma$ collisions is discussed in Ref. [21]. The cross section for the reaction $\gamma\gamma \to p\bar{p}K^+K^-$ is predicted to be around 0.1 nb for $W_{\gamma\gamma} \geq 2(m_p + m_K)$ [21], where $W_{\gamma\gamma}$ is the C.M. energy of two-photon system. This presents the opportunity to search for novel exotic baryons, denoted as $\Theta(1540)^0 \to pK^-$ and $\Theta(1540)^{++} \to pK^+$ which are similar to $\Theta(1540)^+$, in intermediate processes in two-photon annihilations.

The process $\gamma\gamma \to p\bar{p}K^+K^-$ and its intermediate processes are measured for the first time using a 980 fb^{-1} data sample by Belle [22]. The production of $p\bar{p}K^+K^-$ and a $\Lambda(1520)^0$ ($\bar{\Lambda}(1520)^0$) signal in the pK^- ($\bar{p}K^+$) invariant mass spectrum are clearly observed. However, no evidence for

Table 2: Published results from two-photon processes with information of the analyzed mode (Process), the used integrated luminosity (Int. Lum.), the $\gamma\gamma$ C.M. energy, the studied light mesons/baryons and charmonium states (Charm.), and the corresponding reference paper.

Process	Int. Lum.	$\gamma\gamma$ C.M. energy	Light mesons/baryons	Charm.	Reference
$\gamma J/\psi$	32.6 fb^{-1}	(3.2-3.8) GeV	—	—	PLB 540, 33(2002)
K^+K^-	67 fb^{-1}	(1.4-2.4) GeV	$f_2'(1525)$	—	EPJC 32, 323(2003)
$\pi^+\pi^-/K^+K^-$	87.7 fb^{-1}	(2.4-4.1) GeV	—	$\chi_{c0,c2}$	PLB 615, 39(2005)
$p\bar{p}$	89 fb^{-1}	(2.03-4.0) GeV	—	η_c	PLB 621, 41(2005)
$D\bar{D}$	395 fb^{-1}	(3.7-4.3) GeV	—	χ_{c2}'	PRL 96, 082003(2006)
$\pi^+\pi^-$	85.9 fb^{-1}	(0.8-1.5) GeV	$f_0(980)$, $f_2(1270)$, η'	—	PRD 75, 051101(2007)
$K_s^0K_s^0$	397.6 fb^{-1}	(2.4-4.0) GeV	—	$\chi_{c0,c2}$	PLB 651, 15(2007)
four mesons	395 fb^{-1}	(1.4-3.4) GeV	—	$\chi_{c0,c2}$	EPJC 53, 1(2008)
				$\eta_c(1S, 2S)$	
$\pi^0\pi^0$	95 fb^{-1}	(0.6-4.0) GeV	$f_0(980)$, $f_2(1270)$	$\chi_{c0,c2}$, η_c	PRD 78, 052004(2008)
			$f_2'(1525)$		
$\pi^0\pi^0$	223 fb^{-1}	(0.6-4.1) GeV	$f_4(2050)$, $f_2(1950)$	$\chi_{c0,c2}$	PRD 79, 052009(2009)
$\eta\pi^0$	223 fb^{-1}	(0.84-4.0) GeV	$a_0(980)$, $a_0(1450)$	—	PRD 80, 032001(2009)
			$a_2(1320)$	—	
$\phi J/\psi$	825 fb^{-1}	(4.2-5.0) GeV	—	$X(4350)$	PRL 104, 112004(2010)
$\omega J/\psi$	694 fb^{-1}	(3.9-4.2) GeV	—	$X(3915)$	PRL 104, 092001(2010)
$\eta\eta$	393 fb^{-1}	(1.096-3.8) GeV	$f_2(1270)$, $f_2'(1525)$	$\chi_{c0,c2}$	PRD 82, 114031(2010)
$\omega\omega$, $\omega\phi$, $\phi\phi$	870 fb^{-1}	< 4.0 GeV	—	$\chi_{c0,c2}$, η_c	PRL 108, 232001(2012)
$\gamma\gamma^* \to \pi^{0a}$	759 fb^{-1}	$4 < Q^2 < 40$ GeV^{2b}	—	—	PRD 86, 092007(2012)
$\eta'\pi^+\pi^-$	673 fb^{-1}	(1.4-3.4) GeV	$\eta(1760)$, $X(1835)$	η_c	PRD 86, 052002(2010)
$K_s^0K_s^0$	972 fb^{-1}	(1.04-4.0) GeV	$f_2(1270)$, $a_2(1320)$	$\chi_{c0,c2}$	PTEP 2013, 123C01 (2013)
			$f_2'(1525)$, $f_0(1710)$	$\eta_c(2S)$	
$\gamma\gamma^* \to \pi^0\pi^{0a}$	759 fb^{-1}	$Q^2 < 30$ GeV^{2b}	$f_0(980)$, $f_2(1270)$	—	PRD 93, 032003(2016)
$p\bar{p}K^+K^-$	980 fb^{-1}	(3.2-5.6) GeV	$\Lambda(1520)$, $\Theta(1540)$	$\chi_{c0,c2}$	PRD 93, 112017(2016)

[a] γ^* denotes a virtual photon.
[b] -Q^2 is the invariant-mass squared of a virtual (spacelike) photon.

an exotic baryon near 1540 MeV/c^2, i.e., $\Theta(1540)^0$ ($\bar{\Theta}(1540)^0$) or $\Theta(1540)^{++}$ ($\Theta(1540)^{--}$), is seen in the pK^- ($\bar{p}K^+$) or pK^+ ($\bar{p}K^-$) invariant mass spectra. Cross sections for $\gamma\gamma \to p\bar{p}K^+K^-$, $\Lambda(1520)^0\bar{p}K^+ + c.c.$ and the products $\sigma(\gamma\gamma \to \Theta(1540)^0\bar{p}K^+ + c.c.)\mathcal{B}(\Theta(1540)^0 \to pK^-)$ and $\sigma(\gamma\gamma \to \Theta(1540)^{++}\bar{p}K^- + c.c.)\mathcal{B}(\Theta(1540)^{++} \to pK^+)$ are measured. The cross sections for $\gamma\gamma \to p\bar{p}K^+K^-$ are lower by a factor 2.5 or more than the theoretical prediction of 0.1 nb in Ref. [21].

Experimental studies for two-photon physics at Belle II have merits since all the data at any energy point can be used to investigate the lower invariant mass region. Physics at higher invariant mass region, $W_{\gamma\gamma} > 5$ GeV, is not suitable because the luminosity fucntion for two-photon collisions steeply decreases with increasing $W_{\gamma\gamma}$ and the backgrounds from single photon annihilation processes are considerable.

With the total integrated luminosity larger than 10 ab^{-1} at Belle II, the below two-photon processes are our priorities: (1) $\gamma\gamma \to D\bar{D}$ to study $Z(3930)$ and search for $\chi_{c0}(2P)$. We expect obvious contributions from $\gamma\gamma \to D\bar{D}^* \to D\bar{D}\pi$ and $\gamma\gamma \to D\bar{D}(n)\gamma$. All of these processes are cross contaminated. Their cross sections can be measured by doing independent analysis and using iteration method. (2) $\gamma\gamma \to \phi J/\psi$ to confirm $X(4350)$ and search for other X states.

3 Summary and discussion

Although dramatic progresses have been made on the study of the ISR and two-photon processes, which has improved the understanding of the light mesons, light baryons, XYZ states and the conventional charmonium states greatly, there are more questions to be answered with the currently available data. All of above mentioned processes will be updated to give improved precision and more new reactions will be measured on the cross sections and search for more resonances or decay modes with larger statistic at Belle II.

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