PROCEEDINGS OF SCIENCE

Two-photon collisions at Belle

Hideyuki Nakazawa (Belle Collaboration)
National Central University (R.O.C.)
E-mail: nkzw@post.kek.jp

We report recent measurements of two-photon processes at Belle experiment, cross section measurements for $\gamma\gamma$ to vector meson pair and $\gamma\gamma \to \eta'\pi^+\pi^-$ processes and measurement of π^0 transition form factor in the $\gamma\gamma* \to \pi^0$ process.

36th International Conference on High Energy Physics,
July 4-11, 2012
Melbourne, Australia

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PoS(ICHEP2012)356

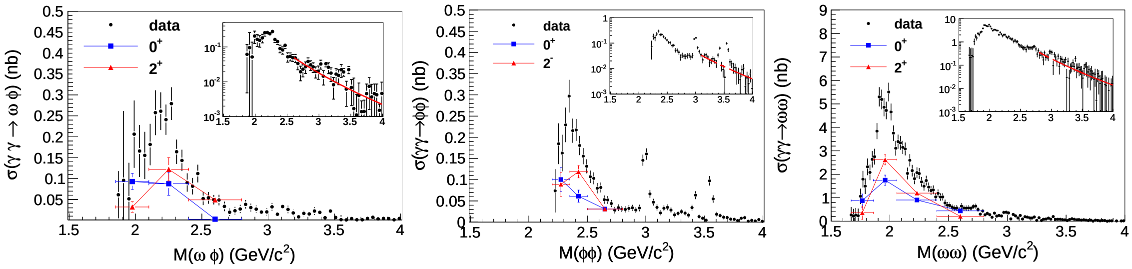

Figure 1: Measured cross sections for $\gamma\gamma \to \phi\phi$, $\omega\phi$ and $\omega\omega$ modes. Fit results to W^{-n} dependence are shown in red curves in insets.

1. $\gamma\gamma \to \phi\phi, \omega\phi$ and $\omega\omega$

Vector meson pair productions in two-photon process, $\gamma\gamma \to VV (V = \rho, \omega, \phi, K^*)$ have been measured by TASSO, CELLO and ARGUS experiments (see [1] for review). In most of these measurements, large cross sections are observed not far above threshold. Various models, such as $q^2\bar{q}^2$ tetraquark states, Regge exchange, an s-channel $\rho^0\rho^0$ resonance, and one-pion-exchange models were proposed to explain the structures.

We measure $\gamma\gamma \to \phi\phi$, $\omega\phi$, and $\omega\omega$ modes followed by $\phi \to K^+K^-$ or $\omega \to \pi^+\pi^-\pi^0$ decays [2] using an 870 fb^{-1} data sample. Non resonant background events are subtracted by studying ϕ- or ω-sideband events. Figure 1 shows measured cross sections. η_c (in $\phi\phi$ and $\omega\phi$ modes) and χ_{c0} and χ_{c2} (in $\phi\phi$ mode) are seen. The products of the two-photon decay width and branching fraction for the charmonia are measured to be $\Gamma_{\gamma\gamma}\mathscr{B}(\eta_c \to \phi\phi) = 7.75 \pm 0.66 \pm 0.62$ eV, $\Gamma_{\gamma\gamma}\mathscr{B}(\chi_{c0} \to \phi\phi) = 1.72 \pm 0.33 \pm 0.14$ eV, $\Gamma_{\gamma\gamma}\mathscr{B}(\chi_{c2} \to \phi\phi) = 0.62 \pm 0.07 \pm 0.05$ eV, and $\Gamma_{\gamma\gamma}\mathscr{B}(\eta_c \to \omega\omega) = 8.67 \pm 2.86 \pm 0.96$ eV.

In all three modes structures are seen near threshold. Their peak position and cross sections measured are summarized in Table 1. Any existing models cannot explain observed structures systematically. We perform spin-parity analysis for the structures. Mixture of 0^+ (S wave) and 2^- (P wave) is favored for $\phi\phi$ and $\omega\omega$, and mixture of 0^+ (S wave) and 2^+ (S wave) for $\omega\phi$.

In higher energy region, W^{-n} dependence of the cross section is measured where W is the invariant mass of the two-photon system. Fit results are shown in insets of Fig. 1. n values obtained, 7.2 ± 0.6 for $\omega\phi$ ($W > 3.2$GeV), 8.4 ± 1.1 for $\phi\phi$ ($W > 3.1$GeV), and 9.1 ± 0.6 for $\omega\omega$ ($W > 2.8$GeV) are consistent with perturbative and non perturbative QCD predictions.

Table 1: Peak position and cross section for the observed near-threshold structures in $\gamma\gamma \to VV$ processes.

mode	peak [GeV/c^2]	nb
$\omega\phi$	$\sim$2.2	0.27 ± 0.05
$\phi\phi$	$\sim$2.35	0.30 ± 0.04
$\omega\omega$	$\sim$1.91	5.30 ± 0.42

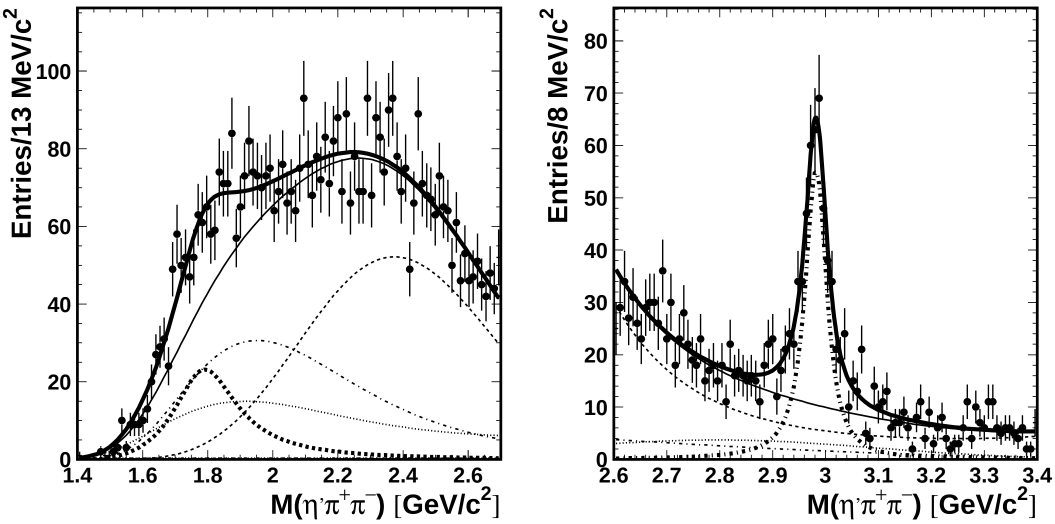

Figure 2: $\gamma\gamma \to \eta'\pi^+\pi^-$ invariant mass distributions in lower energy (left) and η_c (right) region. Thick solid curve shows best fit, and other curves show resonance, two background, and non resonant components.

2. $\gamma\gamma \to \eta'\pi^+\pi^-$

The BES II and BES III collaborations observed $X(1835)$ resonance in $\eta'\pi^+\pi^-$ invariant mass distribution with more than 20σ using $J/\psi \to \gamma\eta'\pi^+\pi^-$ decay mode. Spin-parity of 0^{-+} is preferred for the resonance. Measured mass and width are not compatible with known resonances. Theoretical consideration on the nature of the $X(1835)$ includes baryonium, glueball and a radial excitation of the η'. The two-photon decay width $\Gamma_{\gamma\gamma}$, which can be measured using two-photon process, is important parameter to study the nature of the resonance.

We reconstruct $\eta'\pi^+\pi^-$ in two-photon collisions using $\eta' \to \eta\pi^+\pi^-$ and $\eta \to \gamma\gamma$ decay modes based on a 673 fb^{-1} data sample [5]. Figure 2 shows $\eta'\pi^+\pi^-$ invariant mass distributions.

In the lower energy region, an enhanced shoulder is seen around 1.8 GeV. We perform an unbinned maximum likelihood fit to the mass distribution taking into account two background, non resonant and peak components. Assuming one peak we obtained $M = (1768^{+24}_{-25})\text{MeV}/c^2$ and $\Gamma = (224^{+62}_{-56})$MeV with 4.8σ and denote this peak as $\eta(1760)$. If we additionally assume presence of the $X(1835)$ and interference with the $\eta(1760)$, and fix the mass and width of the $X(1835)$ to the values from BES, we found constructive and destructive solutions with the statistical significance of 4.1σ for $\eta(1760)$ and 2.9σ for $X(1835)$. We also made fits without interference with fixing or floating masses and widths for the resonances. In any fit configurations above, the significance of the $\eta(1760)$ exceeds 4.0σ. The fit results are summarized in Table 2.

For the resonant region the angular distribution of the η' in the two-photon rest frame is compatible with the assumption that the resonances are pseudoscalars.

A clear η_c peak is seen (Fig. 2). Measured mass and width are consistent with the world average values. The product of two-photon decay width and branching fraction is measured to

Table 2: Summary of the results for $\eta(1760)$ and $X(1835)$: M and Γ are the mass and width; Y is the yield; $\Gamma_{\gamma\gamma}\mathscr{B}$ is the product of the two-photon decay width and branching fraction; $(\Gamma_{\gamma\gamma}\mathscr{B})_{90}$ are the upper limits at 90% confidence level with systematic error included; ϕ is the relative phase between the resonances. S is the signal significance including systematic errors.

Parameter	One resonance	Two interfering resonances		World Average
		Solution I	Solution II	
		$X(1835)$		
M, MeV$/c^2$		1836.5 (fixed)		$1836.5 \pm 3.0^{+5.6}_{-2.1}$ [3]
Γ, MeV$/c^2$		190 (fixed)		$190 \pm 9^{+38}_{-36}$ [3]
Y		$332^{+140}_{-122} \pm 73$	$632^{+224}_{-231} \pm 139$	
$\Gamma_{\gamma\gamma}\mathscr{B}$, eV$/c^2$		$18.2^{+7.7}_{-6.7} \pm 4.0$	$35^{+12}_{-13} \pm 8$	
$(\Gamma_{\gamma\gamma}\mathscr{B})_{90}$ eV$/c^2$		$<$ 35.6	$<$ 83	
S, σ		2.8		
		$\eta(1760)$		
M, MeV$/c^2$	$1768^{+24}_{-25} \pm 10$	$1703^{+12}_{-11} \pm 1.8$		1756 ± 9 [4]
Γ, MeV$/c^2$	$224^{+62}_{-56} \pm 25$	$42^{+36}_{-22} \pm 15$		96 ± 70 [4]
Y	$465^{+131}_{-124} \pm 60$	$52^{+35}_{-20} \pm 15$	$315^{+223}_{-165} \pm 88$	
$\Gamma_{\gamma\gamma}\mathscr{B}$, eV$/c^2$	$28.2^{+7.9}_{-7.5} \pm 3.7$	$3.0^{+2.0}_{-1.2} \pm 0.8$	$18^{+13}_{-10} \pm 5$	
S, σ	4.7	4.1		
ϕ		$(287^{+42}_{-51})^{\circ}$	$(139^{+19}_{-9})^{\circ}$	

be $\Gamma_{\gamma\gamma}\mathscr{B}(\eta_c \to \eta'\pi^+\pi^-) = (50.5^{+4.2}_{-4.1} \pm 5.6)\mathrm{eV}/c^2$. In the case the interference effect is included, constructive and destructive solutions are found.

3. $\gamma\gamma* \to \pi^0$

The BABAR experiment measured the $e^+e^- \to e^+e^-\pi^0$ process in single-tag mode and obtained differential cross section, $d\sigma/dQ^2$, and the π^0 transition form factor (TFF) for $\gamma\gamma* \to \pi^0$, $F(Q^2)$, with virtuality of the tagged photon, Q^2, up to 40 GeV^2 [6]. The result is consistent with previous CELLO and CLEO measurements [7] in $Q^2 < 8$ GeV^2. However in $Q^2 > 10$ GeV^2, the measured transition form factor exceeds asymptotic limit of perturbative QCD by at most 50%. This result has been a hot subject for the last several years, and would imply new physics if confirmed [8]. BABAR also reported TFFs for η and η' [9], and the results are consistent with QCD prediction.

We measure $e^+e^- \to e^+e^-\pi^0$ in single-tag mode for 4 GeV$^2 < Q^2 < 40$ GeV^2 using a 759 fb^{-1} data sample [10]. Signal candidates with one $e^{\pm}$ and two gamma's are selected. e^- tag (e-tag) and e^+ tag (p-tag) modes are analyzed separately. We select events in specific angular regions determined with angular correlation between polar angle of $e^{\pm}$ and $\gamma\gamma$ system to avoid harmed region by Bhabha-veto trigger and to ensure sufficient detection efficiency.

π^0 signal yield is obtained by fitting $\gamma\gamma$ mass distribution. Figure 3 (left) shows signal yields. Figure 3 (right) is the differential cross section $d\sigma/dQ^2$ in comparison with results from CLEO and BABAR measurements, where e-tag and p-tag modes are combined, as we find that the obtained $d\sigma/dQ^2$ is consistent between the two modes.

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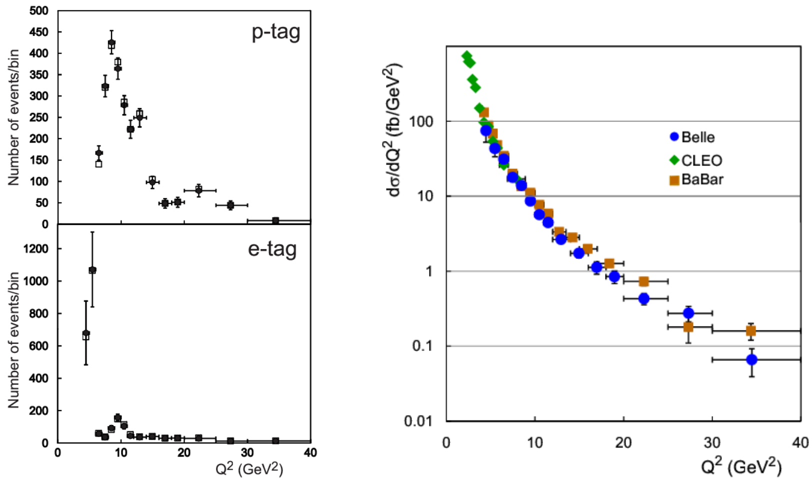

Figure 3: Signal yield (left). Before (open squares) and after (dots with error bars) the Q^2 unfolding. Differential cross section for $e^+e^- \to e^+e^-\pi^0$, $d\sigma/dQ^2$ (right).

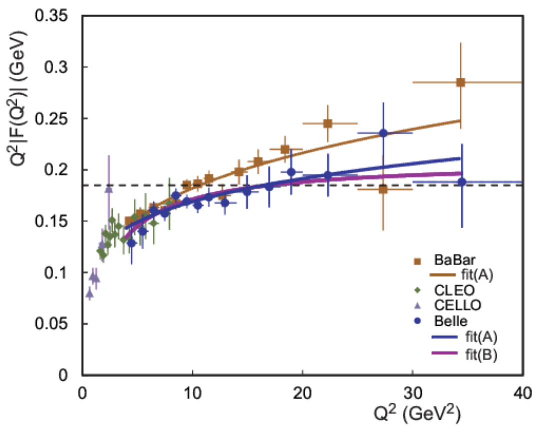

Figure 4: π^0 transition form factor $Q^2|F(Q^2)|$. Curves are fit results. The dotted line shows the asymptotic prediction from pQCD.

The π^0 TFF for the $\gamma\gamma* \to \pi^0$ process is extracted as

$$Q^2|F(Q^2)| = Q^2\sqrt{\frac{d\sigma/dQ^2(Q^2)}{2A(Q^2)}} \tag{3.1}$$

where a function $A(Q^2)$ is calculated numerically following Ref. [11]. Figure 4 shows the obtained π^0 TFF. In $Q^2 < 9$ GeV^2 region measured results are consistent with each other. However, in the higher Q^2 region, the Belle results do not show rapid growth observed by *BABAR*.

We perform fits to $Q^2|F(Q^2)|$ with two different models, one proposed by *BABAR* [6] (fit(A)) and the other in asymptotic form, $BQ^2/(Q^2+C)$ (fit(B)). The fit results are summarized in Table 3 and shown in Fig. 4.

In fit(A), the difference of parameter A and β between Belle and *BABAR* results is about 1.5σ. We also estimate the difference in 9 GeV^2 $< Q^2 <$ 20 GeV region by fitting the data from both experiments together using a function of fit(B), and the difference between deviations of each

Table 3: Fit results to measured π^0 transition form factor, $Q^2|F(Q^2)|$.

	$Q^2\|F(Q^2)\|$	BABAR	Belle
Fit(A)	$A\left(Q^2/10\ \mathrm{GeV}^2\right)^\beta$	$A = 0.182 \pm 0.005^\dagger$ GeV $\beta = 0.25 \pm 0.02$	$A = 0.169 \pm 0.006$ GeV $\beta = 0.18 \pm 0.05$
Fit(B)	$BQ^2/(Q^2+C)$		$B = 0.209 \pm 0.016$ GeV $C = 2.2 \pm 0.8\ \mathrm{GeV}^2$

$^\dagger Q^2$-independent systematic error included.

experiment from the simultaneous fit is found to 2.3σ. From Belle data, the asymptotic value B obtained from fit(B) is 0.209 ± 0.016 GeV that is consistent with pQCD prediction of ~ 0.185 GeV.

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