PROCEEDINGS OF SCIENCE

Study of QCD in gamma gamma to pseudoscalar meson pair processes

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We have measured a series of exclusive meson-pair productions in two-photon collision at the Belle experiment. Above around 3 GeV of two-photon invariant mass, the measured cross sections and angular distributions are compared with perturbative and non-perturbative QCD calculations.

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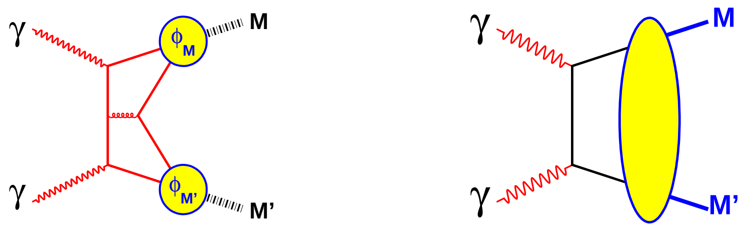

Figure 1: Factorization of the process $\gamma\gamma \to MM'$ by perturbative QCD (left) and Handbag picture (right).

Exclusive meson-pair production in two-photon collision, $\gamma\gamma \to MM'$ provides useful information for study of perturbative and non-perturbative QCD. From theoretical viewpoint, two-photon process is attractive because of the absence of strong interactions in the initial state and the possibility of calculating $\gamma\gamma \to q\bar{q}$ amplitudes.

Brodsky and Lepage (BL) [1] have computed the amplitude for the $\gamma\gamma \to MM'$ process for the first time (Fig.1 left). Their perturbative QCD calculation is obtained by factorizing the amplitude into two components,

$$\mathscr{M}_{\lambda_1\lambda_2}(s,\theta^*) = \int_0^1 \int_0^1 dxdy\phi_M(x,Q_x)\phi_{M'}(y,Q_y)T_{\lambda_1\lambda_2}(x,y,\theta^*), \tag{1}$$

where $\phi_M(x,Q_x)$ is a single-meson distribution amplitude for a meson M, the probability amplitude for finding valence partons in the meson, each carrying some fraction x of the meson's momentum. Q_x is the typical momentum transfer in the process, $\sim \min(x,1-x)\sqrt{s}|\sin\theta^*|$ with meson scattering angle θ^* in the two-photon c.m.s. By the sum rule the overall normalization is fixed as $\int_0^1 dx\phi_M(x,Q_x) = f_M/2\sqrt{3}$ where f_M is the decay constant for a meson M. $T_{\lambda_1\lambda_2}$ is a hard scattering amplitude for $\gamma_{\lambda_1}\gamma_{\lambda_2} \to q\bar{q}q\bar{q}$ with photon helicities λ_1 and λ_2.

For mesons with zero helicity leading term calculation gives the following dependence on s and scattering angle θ^*:

$$\frac{d\sigma}{d|\cos\theta^*|} = 16\pi\alpha^2\frac{|F_M(s)|^2}{s}\left\{\frac{[(e_1-e_2)^2]^2}{(1-\cos^2\theta^*)^2} + \frac{2(e_1e_2)[(e_1-e_2)^2]}{1-\cos^2\theta^*}g(\theta^*) + 2(e_1e_2)^2g^2(\theta^*)\right\}, \tag{2}$$

where e_1 and e_2 are the quark charges. Under the assumption that ϕ_K and ϕ_π are similar in shape, the differential cross section ratio depends only on the meson decay constants f_K^4/f_π^4 for the charged mode. Benayoun and Chernyak (BC) [2] employ different wave functions for $\phi_\pi(x)$ and $\phi_K(x)$ taking into account SU(3) symmetry breaking effects. Next-to-leading order calculation is done by Duplančić *et al.* [3].

The Handbag model by Diehl, Kroll and Vogt (DKV) [4] predicted the differential cross section for the $\gamma\gamma \to MM'$ process as

$$\frac{d\sigma}{d|\cos\theta^*|}(\gamma\gamma \to MM') = \frac{8\pi\alpha^2}{s}\frac{1}{\sin^4\theta^*}|R_{MM'}(s)|^2, \tag{3}$$

where the transition amplitude is expressed as a hard scattering $\gamma\gamma \to q\bar{q}$ times a form factor $R_{MM'}(s)$ describing the soft transition $q\bar{q} \to MM'$ (Fig. 1 right). This model predicts relative magnitude of the cross sections between various modes, while it does not give absolute magnitude of the cross section.

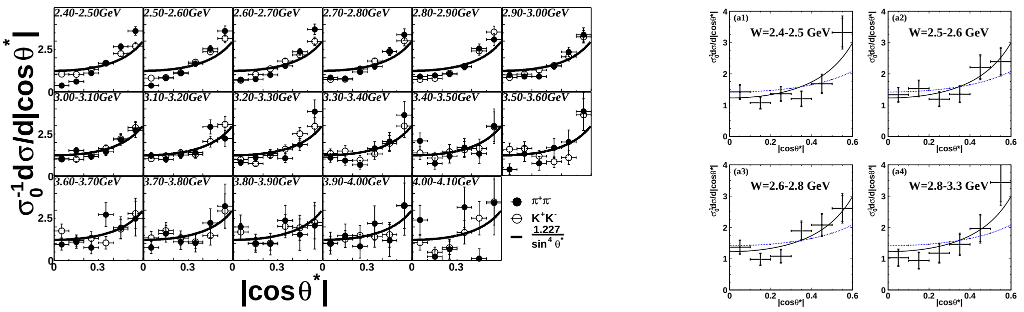

Figure 2: Angular dependence of the normalized differential cross section for $\gamma\gamma \to K^+K^-$ and $\pi^+\pi^-$ (left) and K_SK_S (right). Solid curves are $\sin^{-4}\theta^*$ dependence. Blue curves show prediction by BC.

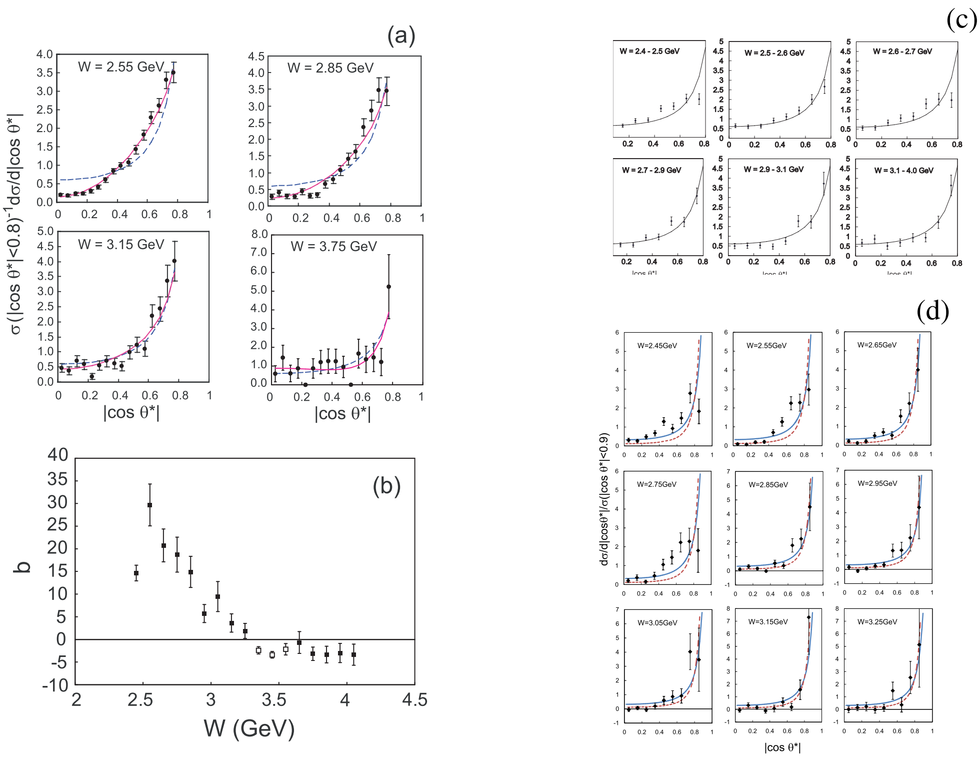

Figure 3: Angular dependence of the normalized differential cross section: (a) $\gamma\gamma \to \pi^0\pi^0$, (c) $\eta\pi^0$, and (d) $\eta\eta$. (a): Dotted (solid) curves show $\sin^{-4}\theta^*$ (fit to $\sin^{-4}\theta^* + b\cos\theta^*$) dependence. W dependence of b is shown in (b). (c): Curves show $\sin^{-4}\theta^*$. (d): Dotted (solid) curves show $\sin^{-6}\theta^*$ ($\sin^{-4}\theta^*$) dependence.

The Belle experiment has measured $\gamma\gamma \to \pi^+\pi^-$ [5], $\pi^0\pi^0$ [7], K^+K^- [5], K_SK_S [6], $\eta\pi^0$ [8], and $\eta\eta$ [9] processes. The results are compared with perturbative and non perturbative QCD predictions.

1. Angular Dependence of Differential Cross Section

In Equation (2) the first term is dominant for charged pair mode, and the angular distribution is thus expected to have $\sim \sin^{-4}\theta^*$ dependence. But for neutral pair mode for which the first term vanishes the angular dependence is directly determined by the shape of $g(\theta^*)$ and the value of

Table 1: Angular dependence of differential cross sections in comparison with $\sin^{-4}\theta^*$ dependence.

mode	$\sin^{-4}\theta^*$	energy range	$\lvert\cos\theta^*\rvert$ range	reference
$\pi^+\pi^-$	Match well.	3.0 - 4.1	< 0.6	[5]
K^+K^-	Match well.	3.0 - 4.1	< 0.6	[5]
K_SK_S	Consistent.	2.4 - 3.3	< 0.6	[6]
$\pi^0\pi^0$	$\sin^{-4}\theta^* + b\cos\theta^*$ better. Approaches $\sin^{-4}\theta^*$ above 3.1 GeV.	2.4 - 4.1†	< 0.8	[7]
$\eta\pi^0$	Good agreement above 2.7 GeV.	3.1 - 4.1	< 0.8	[8]
$\eta\eta$	Poor agreement. $\sin^{-6}\theta^*$ better above 3.0 GeV.	2.4 - 3.3	< 0.9	[9]

$\dagger$ χ_{cJ} region, 3.3 - 3.6 GeV is excluded.

$F_M(s)$, which depend on incalculable factor ϕ_M. On the other hand, the handbag model predicts $\sin^{-4}\theta^*$ dependence for large t both for charged and neutral meson pairs.

The measured angular dependence are consistent with $\sin^{-4}\theta^*$ around 3 GeV or higher energy region except $\eta\eta$ mode. Figure 2 shows the measured angular dependence for $\pi^+\pi^-$, K^+K^-, and K_SK_S. For $\gamma\gamma \to \pi^0\pi^0$ and $\eta\eta$, $\sin^{-4}\theta^* + b\cos\theta^*$ and $\sin^{-6}\theta^*$ dependence, respectively, show better agreement than $\sin^{-4}$ while $\eta\pi^0$ is in agreement with $\sin^{-4}\theta^*$ above 2.7 GeV (Fig. 3). Comparison with $\sin^{-4}\theta^*$ dependence is summarized in Table 1.

2. Energy Dependence of Cross Section and ratio of Cross Sections

It is found that existing calculations do not agree with absolute normalization of the cross sections even with next-to-leading-order term [3]. However, power-low dependence of cross section $\sigma_0 \sim W^{-n}$ and their ratio, summarized in Table 2, provide useful information to test QCD predictions.

Figure 4 (Figure 5) shows cross sections integrated over sensitive angular region for $\gamma\gamma \to K_SK_S$ and $\pi^0\pi^0$ ($\eta\pi^0$ and $\eta\eta$) and their ratios to charged ($\pi^0\pi^0$) mode. The range of all measured n value, from 7 to 10, is not far above the asymptotic pQCD prediction of 6 [10]. At present energies, the leading term may be small and dominated by the first power correction, therefore energy dependence can be much steeper, $n \sim 10$ [2]. Cross section ratio, $\sigma_0(K^+K^-)/\sigma_0(\pi^+\pi^-)$ is constant in present energy region, while neutral-to-charged ratios, $\sigma_0(K_SK_S)/\sigma_0(K^+K^-)$ and $\sigma_0(\pi^0\pi^0)/\sigma_0(\pi^+\pi^-)$ seem to approach constant. Cross sections for $\eta\pi^0$, $\eta\eta$, K^+K^-, and K_SK_S satisfy well $SU(3)$ relation in Handbag approach [11]. Further discussion can be found in [12].

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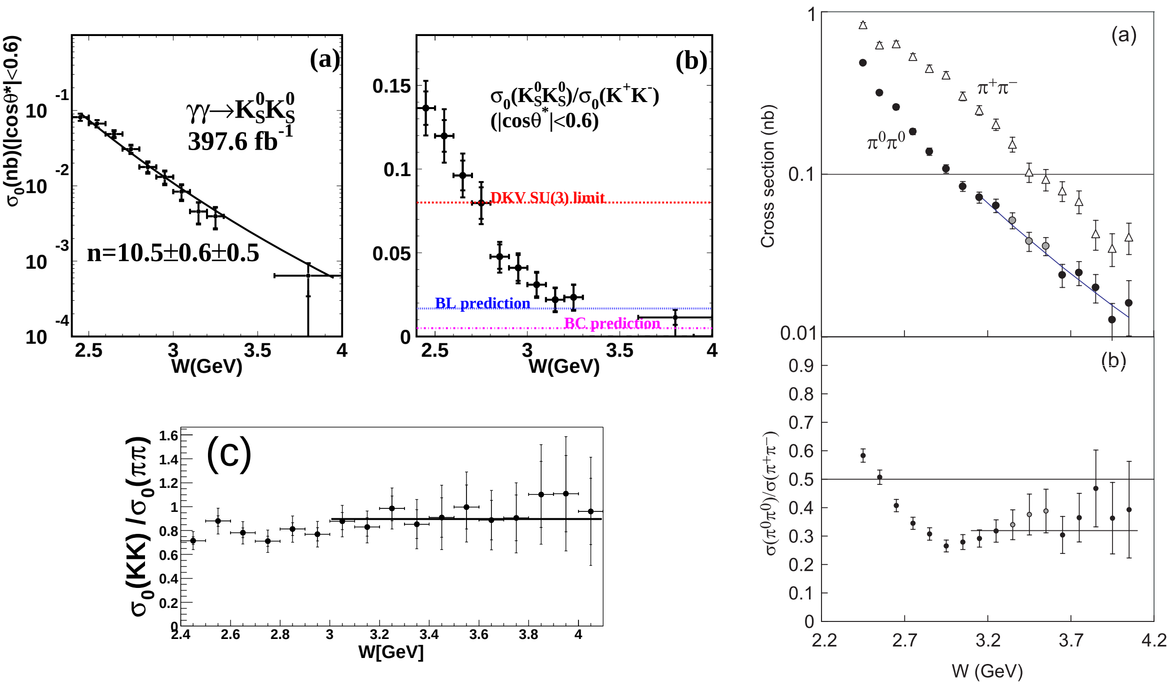

Figure 4: Left: (a) Cross section for $\gamma\gamma \to K_S K_S$, (b) its ratio to K^+K^-, $\sigma_0(K_S K_S)/\sigma_0(K^+K^-)$ and (c) $\sigma_0(K^+K^-)/\sigma_0(\pi^+\pi^-)$. Right: (a) Cross section for $\pi^0\pi^0$ and $\pi^+\pi^-$ and (b) their ratio $\sigma_0(\pi^0\pi^0)/\sigma_0(\pi^+\pi^-)$. Curves in (a) show fits to W^{-n}. Fit result to a constant value is shown for $\sigma_0(K^+K^-)/\sigma_0(\pi^+\pi^-)$ and $\sigma_0(\pi^0\pi^0)/\sigma_0(\pi^+\pi^-)$.

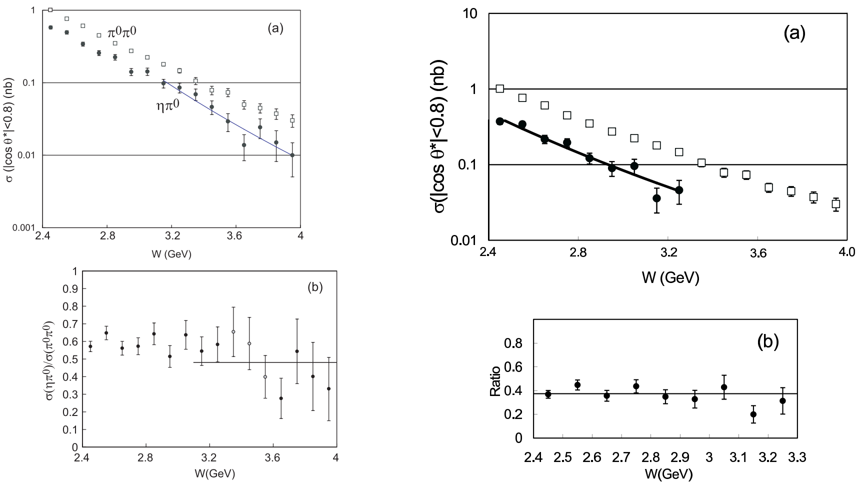

Figure 5: Cross section and its ratio to $\pi^0\pi^0$ for $\eta\pi^0$ (left) and $\eta\eta$ (right). In (a), $\sigma_0(\pi^0\pi^0)$ is shown in open squares. Curves are fit result to W^{-n} dependence.

Table 2: The value of n of $\sigma_0 \propto W^{-n}$ in various reactions fitted in the W and $|\cos\theta^*|$ ranges indicated and the ratio of the cross sections in comparison with QCD predictions. The first and second errors are statistical and systematic, respectively.

Process	n or σ_0 ratio	W(GeV)	$\lvert\cos\theta^*\rvert$	BL [1]	BC [2]	DKV [4]
$\pi^+\pi^-$	$7.9 \pm 0.4 \pm 1.5$	3.0 - 4.1	< 0.6	6	6	
K^+K^-	$7.3 \pm 0.3 \pm 1.5$	3.0 - 4.1	< 0.6	6	6	
$K_S^0K_S^0$	$10.5 \pm 0.6 \pm 0.5$	2.4 - 4.0[1]	< 0.6	6	10	
$\pi^0\pi^0$	$8.0 \pm 0.5 \pm 0.4$	3.1 - 4.1†	< 0.8	6	10	
$\eta\pi^0$	$10.5 \pm 1.2 \pm 0.5$	3.1 - 4.1	< 0.8	6	10	
$\eta\eta$	$7.8 \pm 0.6 \pm 0.4$	2.4 – 3.3	< 0.8	6	10	
$K^+K^-/\pi^+\pi^-$	$0.89 \pm 0.04 \pm 0.15$	3.0 - 4.1	< 0.6	2.3	1.06	
K_SK_S/K^+K^-	~ 0.13 to ~ 0.01	2.4 - 4.0	< 0.6		0.005	2/25
$\pi^0\pi^0/\pi^+\pi^-$	$0.32 \pm 0.03 \pm 0.06$	3.1 - 4.1	< 0.6		0.04-0.07	0.5
$\eta\pi^0/\pi^0\pi^0$	$0.48 \pm 0.05 \pm 0.04$	3.1 - 4.0	< 0.8	$0.24R_f(0.46R_f)^\ddagger$		
$\eta\eta/\pi^0\pi^0$	$0.37 \pm 0.02 \pm 0.03$	2.4 - 3.3	< 0.8	$0.36R_f^2(0.62R_f^2)^\ddagger$		

† χ_{cJ} region, 3.3 – 3.6 GeV is excluded.

‡ η meson as a pure SU(3) octet (mixture of octet and singlet with $\theta_p = -18^\circ$), $R_f = f_\eta^2/f_{\pi^0}^2$.

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