Study of QCD in Gamma Gamma to Pseudoscalar Meson Pair Processes at Belle

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$\gamma\gamma \to MM'$ in perturbative QCD

- $\mathcal{M}_{\lambda_1\lambda_2}(W^2,\theta^*)=\int_0^1\int_0^1 dxdy\,\phi_M(x,Q_x)\phi_{M'}(y,Q_y)T_{\lambda_1\lambda_2}(x,y,\theta^*)$

  ϕ_M Meson distribution amplitude (DA)

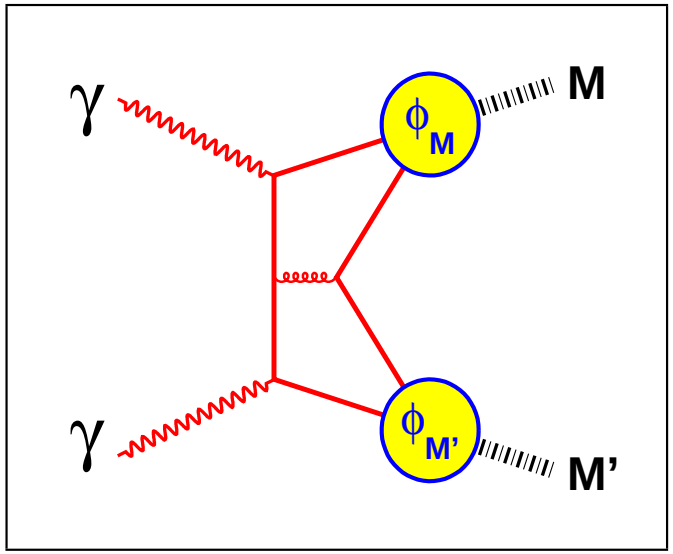
  $T_{\lambda_1\lambda_2}(x,y,\theta^*)$ Hard scattering amplitude for $\gamma\gamma \to q\bar{q}q\bar{q}$.

- $\frac{d\sigma}{d|\cos\theta^*|}=16\pi\alpha^2\frac{|F_M(W^2)|^2}{W^2}\left\{\frac{(e_1-e_2)^4}{\sin^4\theta^*}+\frac{2e_1e_2(e_1-e_2)^2}{\sin^2\theta^*}g(\theta^*)+2e_1^2e_2^2g^2(\theta^*)\right\}$

  F_M Meson form factor. $\sim 1/W^2$ at leading order.

  $g(\theta^*)$ Only unknown, non-perturbative factor.

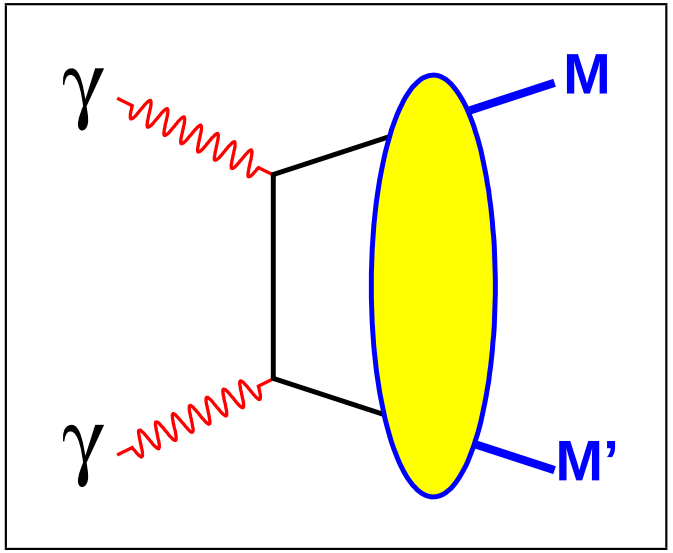
- Brodsky and Lepage (BL) [PRD24, 1808 (1981)]
- First term dominant for charged pairs. $\sim f_M^4/W^6\sin^4\theta^*$.
- $g(\theta^*)$ dominant for neutral pair.
- $d\sigma(K^+K^-)/d\sigma(\pi^+\pi^-) = (f_K/f_\pi)^4 = 2.3$
- $\sigma\sim W^{-6}$ from dimensional counting rule [PRL31,1153(1973)]
- Benayoun and Chernyak (BC) [NPB329, 285 (1990)]
  - With SU(3) symmetry breaking, different DA for π and K
  - $d\sigma(K^+K^-)/d\sigma(\pi^+\pi^-) = 1.06$
  - For neutral pair mode, $\sigma \sim W^{-10}$ because higher order effects are dominant below 4 GeV. [arxiv:0912.0623]
- pQCD is supposed to work correctly at sufficiently high energy region. Up to 4 GeV is high enough?



$\gamma\gamma \to MM'$ in Handbag Model

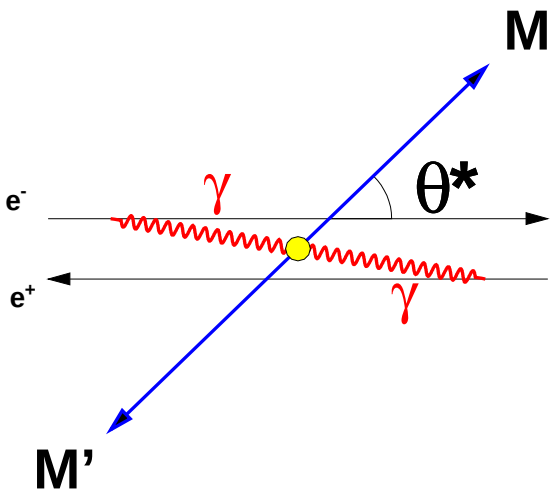
- Diehl, Kroll, Vogt (DKV) [PLB532, 99 (2002); PLB683, 165 (2010)]
- $\frac{d\sigma}{d|\cos\theta^*|}(\gamma\gamma \to MM') = \frac{8\pi\alpha^2}{W^2}\frac{1}{\sin^4\theta^*}|R_{MM'}(W^2)|^2$
  - $R_{MM'}$: Soft transition form factor that describes $q\bar{q} \to MM'$. Not calculable, taken from experiment.
- Final states cannot have $I = 2$ because intermediate state is $q\bar{q}$ (possible in pQCD where $\gamma\gamma \to q\bar{q}q\bar{q}$).

- Charge counting & flavor symmetry
  - $\sigma(K_S K_S) = \frac{2}{25}\sigma(K^+K^-)$, $\sigma(\pi^0\pi^0)/\sigma(\pi^+\pi^-) = 0.5$
- Angular distribution $\propto \sin^{-4}\theta^*$



Pseudoscalar Meson Pair Production in Two-Photon processes at Belle

mode	GeV	$<\lvert\cos\theta^*\rvert$	fb^{-1}	
$\pi^+\pi^-$, K^+K^-	3.0-4.1	0.6	88	PLB615,39(2005)
K_SK_S	2.4-4.0	0.6	398	PLB651,15(2007)
$\pi^0\pi^0$	0.6-4.1	0.8	223	PRD79,052009(2009)
$\eta\pi^0$	0.84-4.0	0.8	223	PRD80,032001(2009)
$\eta\eta$	1.096-3.8	0.9,1.0	393	PRD82,114031(2010)

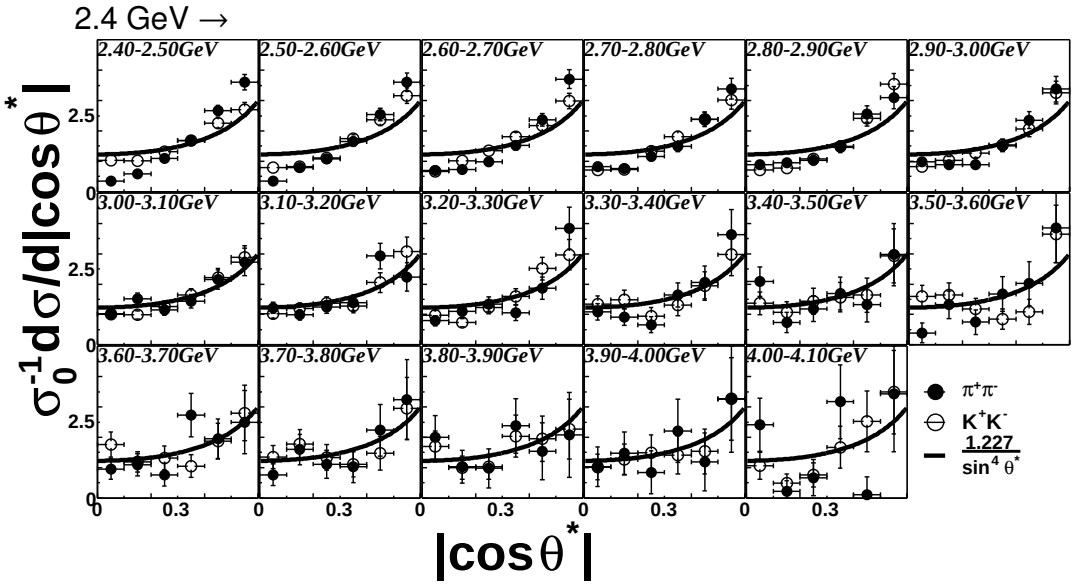


- No-tag method
- e^+e^- escape down the beam pipe at small recoil angles.
- Reactions involve almost real photons with $\left|\vec{p_t}(M)+\vec{p_t}(M')\right| \sim 0$ in e^+e^- frame.
- θ^* in MM' cms is a good approximation to the scattering angle from γ-γ axis.
- $\frac{d\sigma}{d|cos\theta^*|} = \frac{\Delta N}{\Delta W \Delta|\cos\theta^*| \frac{dL_{\gamma\gamma}}{dW} \text{ effi} \int \mathcal{L}dt}$, $\frac{dL_{\gamma\gamma}}{dW}$: Luminosity Function

$W = M(\gamma\gamma) = M(MM')$

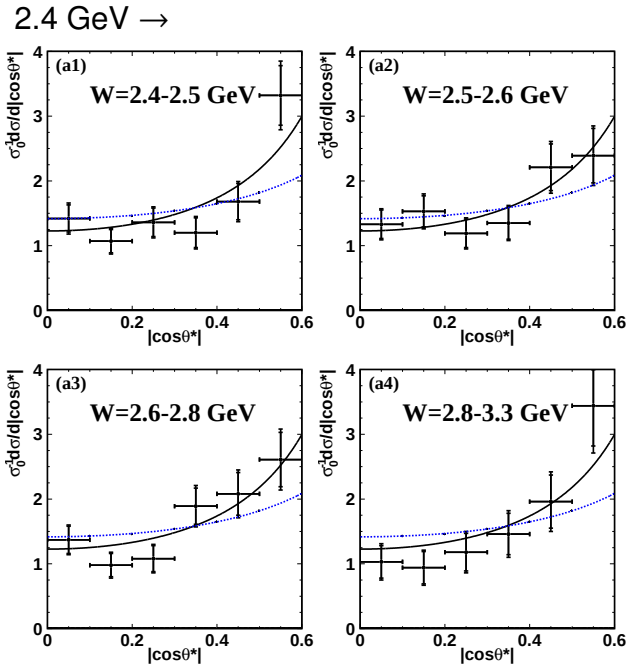
Angular Distributions for $\pi^+\pi^-, K^+K^-, K_SK_S$

$\gamma\gamma \to \pi^+\pi^-$ and K^+K^-



- Matches $\sin^{-4}\theta^*$ above 3.0 GeV.

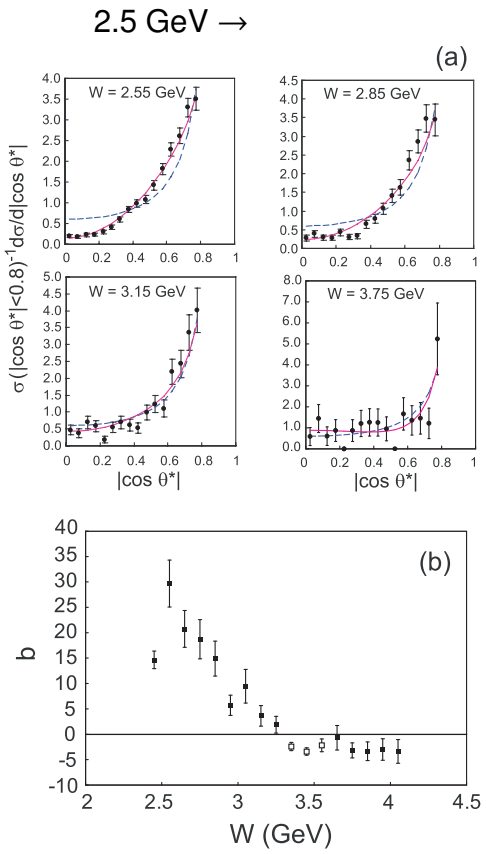
$\gamma\gamma \to K_SK_S$



- Consistent with $\sin^{-4}\theta^*$ above 2.4 GeV.

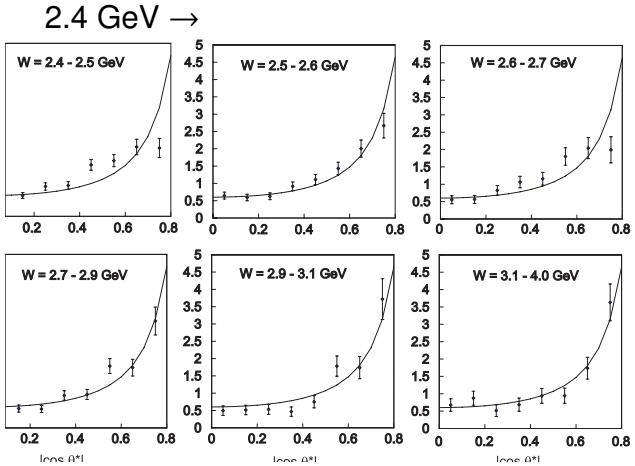
Angular Distributions for $\pi^0\pi^0, \eta\pi^0, \eta\eta$

$\gamma\gamma \to \pi^0\pi^0$



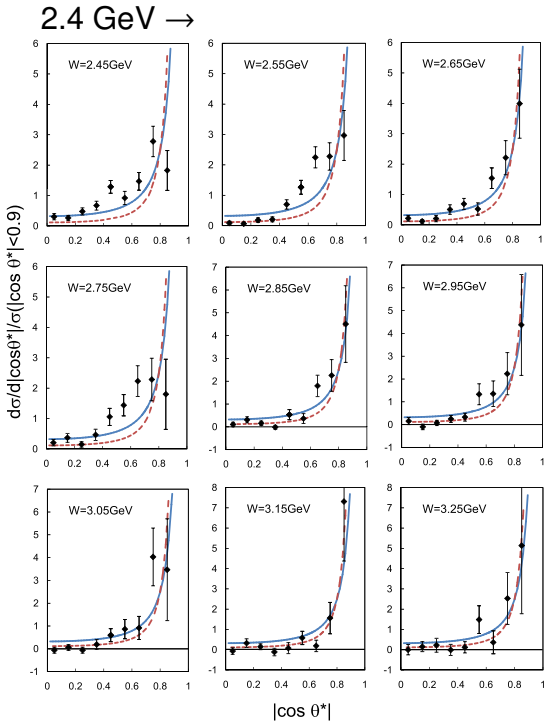
- $\sin^{-4}\theta^* + b\cos\theta^*$ better.
- Approaches $\sin^{-4}\theta^*$ above 3.1 GeV.

$\gamma\gamma \to \eta\pi^0$



- Good agreement with $\sin^{-4}\theta^*$ above 2.7 GeV.

$\gamma\gamma \to \eta\eta$



- Poor agreement with $\sin^{-4}\theta^*$.
- $\sin^{-6}\theta^*$ better above 3.0 GeV.

Angular Distributions

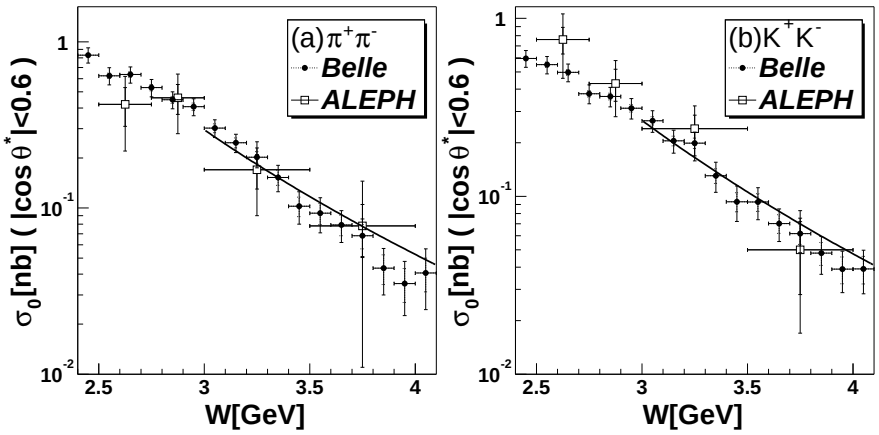
mode	$\sin^{-4}\theta^*$	GeV	$\lvert\cos\theta^*\rvert$
$\pi^+\pi^-$	Match well.	3.0 - 4.1	< 0.6
K^+K^-	Match well.	3.0 - 4.1	< 0.6
K_SK_S	Consistent.	2.4 - 3.3	< 0.6
$\pi^0\pi^0$	$\sin^{-4}\theta^* + b\cos\theta^*$ better. Approaches $\sin^{-4}\theta^*$ above 3.1 GeV.	2.4 - 4.1†	< 0.8
$\eta\pi^0$	Good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

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

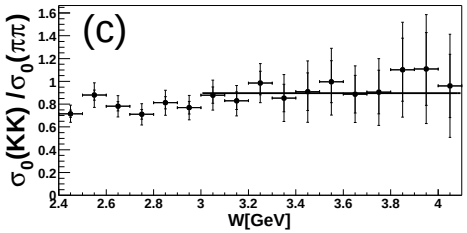
All modes show $\sin^{-4}\theta^*$ or similar dependence above 3.0 GeV except the $\eta\eta$ mode.

Cross sections (W^{-n} dependences) and their ratios for $\gamma\gamma \to \pi^+\pi^-, K^+K^-, K_SK_S$

$\gamma\gamma \to \pi^+\pi^-, K^+K^-$

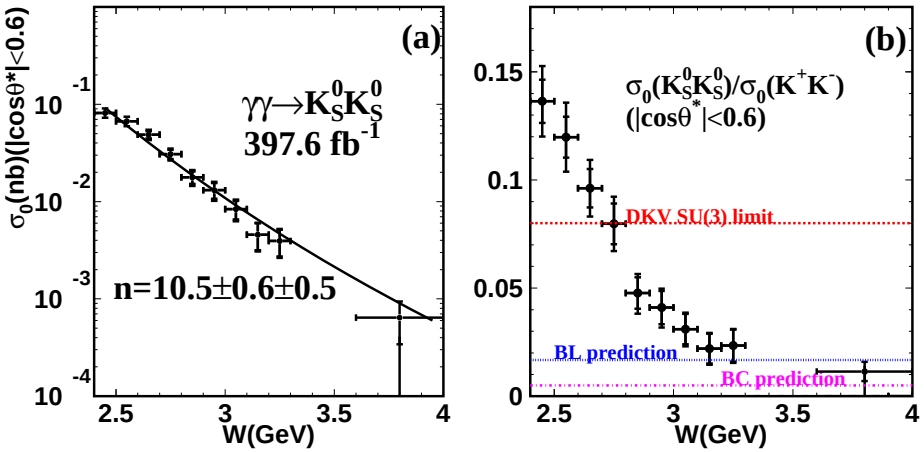


$\sigma(K^+K^-)/\sigma(\pi^+\pi^-) = 0.89 \pm 0.04 \pm 0.15$



- $\pi^+\pi^-$ $\quad n = 7.9 \pm 0.4 \pm 1.5$
  K^+K^- $\quad n = 7.3 \pm 0.3 \pm 1.5$
- A bit higher than theoretical prediction of 6.

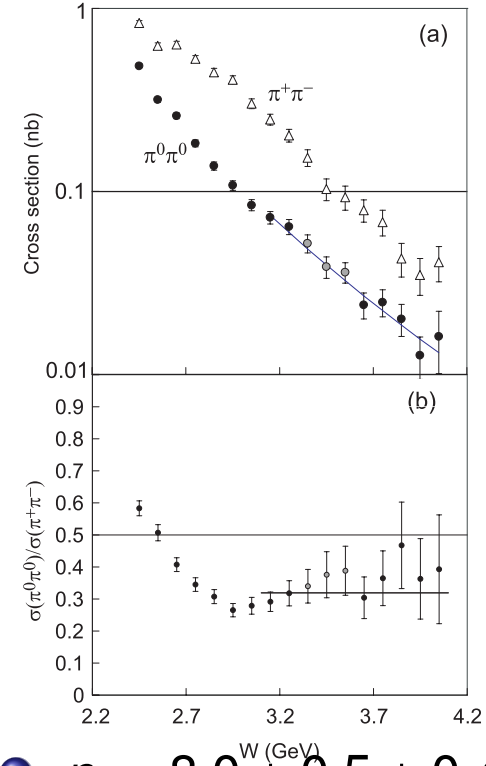
$\gamma\gamma \to K_SK_S$



- $n = 10.5 \pm 0.6 \pm 0.5$
- $\sigma(K_SK_S)/\sigma(K^+K^-)$ approaches BC prediction asymptotically.

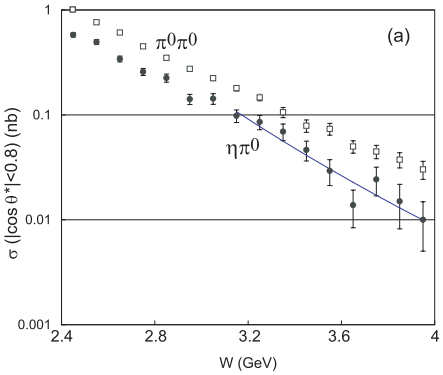
Cross sections (W^{-n} dependences) and their ratios for $\gamma\gamma \to \pi^0\pi^0, \eta\pi^0, \eta\eta$

$\gamma\gamma \to \pi^0\pi^0$

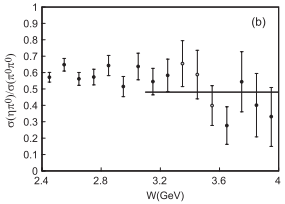


- $n = 8.0 \pm 0.5 \pm 0.4$
- $\sigma(\pi^0\pi^0)/\sigma(\pi^+\pi^-) = 0.32 \pm 0.03 \pm 0.06$

$\gamma\gamma \to \eta\pi^0$

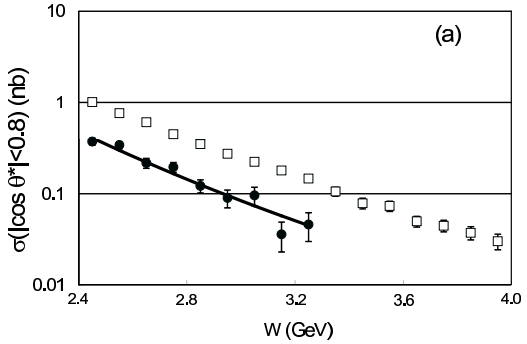


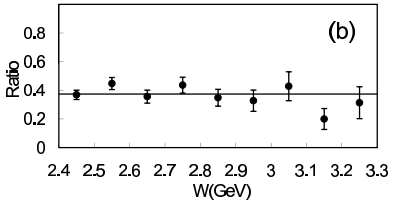
$\sigma(\eta\pi^0)/\sigma(\pi^0\pi^0) = 0.48 \pm 0.05 \pm 0.04$



- $n = 10.5 \pm 1.2 \pm 0.5$

$\gamma\gamma \to \eta\eta$





- $n = 7.8 \pm 0.6 \pm 0.4$
- $\sigma(\eta\eta)/\sigma(\pi^0\pi^0) = 0.37 \pm 0.02 \pm 0.03$

Cross sections (W^{-n} dependences) and their ratios

Process	n or σ_0 ratio	W(GeV)	$\lvert\cos\theta^*\rvert$	BL	BC	DKV
$\pi^+\pi^-$	$7.9 \pm 0.4 \pm 1.5$	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	
$K^0_S K^0_S$	$10.5 \pm 0.6 \pm 0.5$	2.4 - 4.0	< 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	
$K_S K_S/K^+K^-$	~ 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	$0.36R_f^2(0.62R_f^2)^\ddagger$		

$\dagger$ χ_{cJ} region, 3.3 – 3.6 GeV is excluded.
$\ddagger$ η meson as a pure SU(3) octet (mixture of octet and singlet with $\theta_p = -18°$), $R_f = f_\eta^2/f_{\pi^0}^2$.

- Similar n values ranging 7 to 10
- Most cross section ratios constant above $\sim$ 3 GeV.

Conclusions

- The Belle experiment has measured pseudoscalar meson pair production in two-photon collisions, $\gamma\gamma \to \pi^+\pi^-, K^+K^-, K_SK_S, \pi^0\pi^0, \eta\pi^0$, and $\eta\eta$.
- Our data are compared with (p)QCD predictions.
- The angular distribution of most modes follow a $\sin^{-4}\theta^*$ or similar θ^* dependence above 3 GeV.
- n values of W^n dependence range 7 to 10, a bit higher than the dimensional counting rule.
- Cross section ratios are close to constant above ~3 GeV except $\sigma(K_SK_S)/\sigma(K^+K^-)$
- No single theory can describe these measurements systematically.