Two-Photon Interactions at Belle and BaBar

Simon Eidelman

Budker Institute of Nuclear Physics, Lavrentyev Ave. 11,
Novosibirsk, 630090, Russia
(for the Belle and BaBar Collaborations)

Results on two-photon physics obtained in experiments at the B factories are discussed. BaBar used single-tag $\gamma\gamma$ collisions to measure the transition form factor of the π^0 meson. Belle studied no-tag $\gamma\gamma$ collisions to measure cross sections of exclusive production of two baryons and two mesons. Experimental results are confronted with QCD predictions.

1 Introduction

Two experiments at B factories (BaBar at SLAC and Belle at KEK) collected huge integrated luminosities: about 560 fb^{-1} at BaBar and 950 fb^{-1} at Belle. In addition to copiously produced B meson pairs, this statistics gives access to studying two-photon physics including processes with small cross sections.

It is worth mentioning some special features of two-photon collisions:

- it is a clean source of hadrons with positive C-parity;
- peculiar kinematics: the final $e^\pm$ fly in the same direction as the initial $e^\pm$ and lose little energy; the products of $\gamma\gamma$ have small transverse momentum;
- the cross section grows as $\ln^3 E_{\rm CM}$;
- different types of experiments are possible: no-tag – both $e^\pm$ undetected, single-tag – one $e^\pm$ detected, double-tag – both $e^\pm$ detected;
- it is an excellent laboratory for QCD tests in $\gamma\gamma$ production of hadrons.

2 π^0 Transition Form Factor

BaBar used 442 fb^{-1} collected at 10.54 and 10.58 GeV to study the π^0 transition form factor in the single-tag mode, i.e. when one of the photons is almost real while the second is strongly off-shell with a momentum transfer $q^2 \equiv -Q^2$, $4 < Q^2 < 40$ GeV^2 [1]. This is serious progress compared to the previous experiments in which CELLO studied the momentum range from 0.7 to 2.2 GeV^2 [2] and CLEO from 1.6 to 8 GeV^2 [3]. The distribution of the invariant mass of two photons shows a clear peak from the π^0, Fig. 1.

About 13200 events of $\gamma\gamma^* \to \pi^0$ were selected at BaBar compared to 127 at CELLO and 1219 at CLEO. The main background comes from virtual Compton scattering, $e^+e^- \to e^+e^-\gamma$, with one final $e^\pm$ at small angles, while the other $e^\mp$ and γ scatter at large angles. The major peaking background – $e^+e^- \to e^+e^-\pi^0\pi^0$, ~ 1600 events detected.

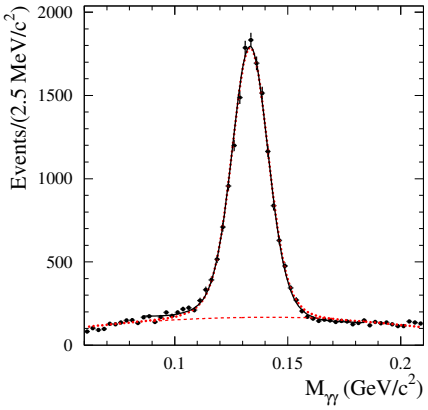

Figure 1: Invariant mass of two photons.

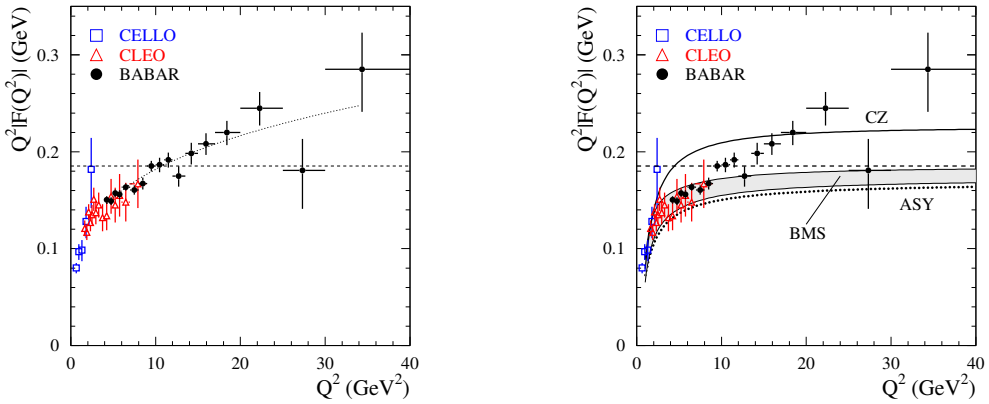

Figure 2: Q^2 dependence of the π^0 transition form factor.

To describe the Q^2 dependence, they fit the form factor using the function $Q^2|F(Q^2)| = A\left(\frac{Q^2}{10\ \mathrm{GeV}^2}\right)^{\beta}$ and obtain $A = 0.182 \pm 0.002\,\mathrm{GeV}$, $\beta = 0.25 \pm 0.02$. The effective Q^2 dependence of the form factor ($\sim 1/Q^{3/2}$) differs significantly from the leading-order pQCD prediction ($\sim 1/Q^2$) [4], demonstrating the importance of higher-order pQCD and power corrections in the Q^2 region under study.. The horizontal dashed line in Fig. 2, left, indicates the asymptotic limit $Q^2|F(Q^2)| = \sqrt{2}f_\pi \approx 0.185$ GeV for $Q^2 \to \infty$. The measured form factor exceeds the limit for $Q^2 > 10$ GeV^2 contradicting most models for the pion wave function ϕ_π, which give form factors approaching this limit from below. Fig. 2, right, shows some theoretical predictions obtained using the light-cone sum rules [5] at NLO pQCD with twist-4 for three types of ϕ_π: that of Chernyak-Zhitnitsky (CZ) [6], the asymptotic (ASY) [7] and the one derived from QCD sum rules with non-local condensates (BMS) [8]. For all three ϕ_π the Q^2 dependence is almost

flat for $Q^2 > 10$ GeV^2, whereas the data show significant growth between 8 and 20 GeV^2. This indicates that the approximation mentioned above is not adequate for Q^2 less than ~ 15 GeV^2. In the Q^2 range from 20 to 40 GeV^2, where uncertainties due to higher-order pQCD and power corrections are expected to be smaller, the BaBar data lie above the asymptotic limit and are consistent with the CZ model.

Several papers appeared after the BaBar result: in Ref. [9] it is shown that the form factor growth above 10 GeV^2 can not be explained in terms of NNLO higher-order perturbative corrections while in Refs. [10, 11] it is argued that the Q^2 dependence observed by BaBar can be explained with the flat pion wave function.

3 Results from Belle

For the exclusive pair production $\gamma\gamma \to h_1 h_2$ in the leading order (quark-counting rule) $\frac{\mathrm{d}\sigma}{\mathrm{dt}} \propto \frac{f(\cos\theta^*)}{s^{n-2}}$, where $s = W^2_{\gamma\gamma} = W^2$ and n is the number of "elementary" fields [12].

Scaling behaviour is expected in the QCD asymptotic regime ($s \to \infty$): $\sigma \propto 1/s^3$ for mesons and $\sigma \propto 1/s^5$ for baryons. The handbag model predicts that at intermediate energies amplitudes are dominated by soft non-perturbative terms [13].

Belle studied various two-body final states $\gamma\gamma \to\ p\bar{p}, \pi^+\pi^-,\ K^+K^-,\ K^0_S K^0_S,\ \pi^0\pi^0,\ \eta\pi^0$ at W up to 4 GeV [14, 15, 16, 17, 18]. These studies allow various QCD tests to be performed of which we'll discuss the energy dependence of the cross section.

The $\gamma\gamma \to p\bar{p}$ cross section was measured for W between 2.025 and 4.0 GeV with an integrated luminosity of 89 fb^{-1} [14]. If they fit the data with a power law $\sigma \propto W^{-n}$ with n floating (Fig. 3, left), they obtain $n = 15.1^{+0.8}_{-1.1}$ at $2.5 < W < 2.9$ GeV and $n = 12.4^{+2.4}_{-2.3}$ at $3.2 < W < 4.0$ GeV. In Fig. 3, right, we show the results of the fits with n fixed at 10 and 15. Although for both ranges a good fit can be obtained at n=15, a smaller power, n=10, describes the data above 3.2 GeV reasonably well. This may imply that lower power terms become dominant at higher energies, which is an indication for the transition to asymptotics.

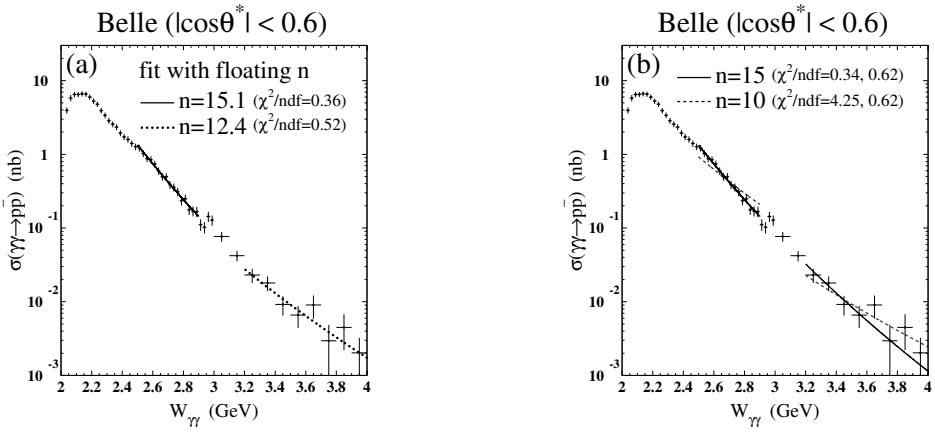

Figure 3: W dependence for the process $\gamma\gamma \to p\bar{p}$.

The $\gamma\gamma \to \pi^+\pi^-,\ K^+K^-$ cross sections were measured for W between 2.4 and 4.1 GeV with

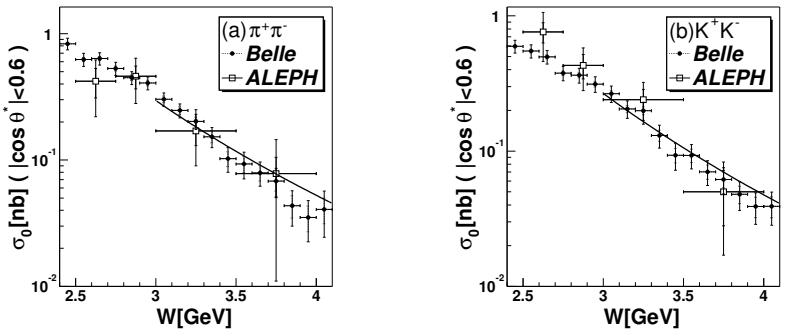

Figure 4: W dependence for the processes $\gamma\gamma \to \pi^+\pi^-$ (left) and $\gamma\gamma \to K^+K^-$ (right).

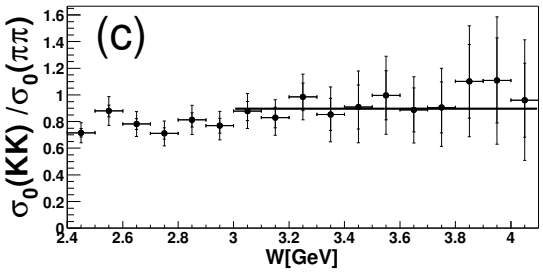

Figure 5: The ratio of the cross sections $\gamma\gamma \to \pi^+\pi^-$ and $\gamma\gamma \to K^+K^-$.

an integrated luminosity of 87.7 fb^{-1} [15]. Fig. 4 shows the observed cross sections for $\gamma\gamma \to \pi^+\pi^-$ (left) and $\gamma\gamma \to K^+K^-$ (right) and compares them to the ALEPH measurement [19]. Above 3 GeV ALEPH data as well as much more precise data from Belle (more than 6000 events for each of the processes) agree with $\sigma \propto 1/W^6$. Direct fits of the Belle data to $\sigma \propto W^n$ for W between 3.0 and 4.1 GeV give somewhat steeper dependence $n = -7.9 \pm 0.4 \pm 1.5$ for $\pi^+\pi^-$ and $n = -7.3 \pm 0.3 \pm 1.5$ for K^+K^-, but still not contradicting to the W^{-6} dependence.

Fig. 5 shows the ratio of the cross sections $\sigma(\gamma\gamma \to K^+K^-)/\sigma(\gamma\gamma \to \pi^+\pi^-)$ as a function of W. The ratio is energy independent above 3.0 GeV in accordance with the QCD prediction. The obtained value of the ratio is $0.89 \pm 0.04 \pm 0.15$ consistent with 1.08 predicted in Ref. [20] and significantly lower than 2.23 following from Ref. [12]. The value predicted in [20] is based on consistent consideration of SU(3) breaking effects using different wave functions for pions and kaons derived from the QCD sum rules whereas in [12] the same wave functions are used so that the ratio behaves as the fourth power of the ratio of the kaon and pion decay constants.

Belle has also measured for the first time the cross section of $\gamma\gamma \to K^0_S K^0_S$ cross sections for W from 2.4 to 4.0 GeV using a data sample of 397.6 fb^{-1} [16]. Fig. 6, left, shows the observed cross section. The fit to the data gives a W^{-n} dependence with $n = 10.5 \pm 0.6 \pm 0.5$ and suggests that the values of W are not yet large enough to neglect power corrections not taken into account in Refs. [12, 20]. The ratio $\sigma_0(K^0_S K^0_S)/\sigma_0(K^+K^-)$ shown in Fig. 6 decreases from ~ 0.13 to ~ 0.01. Such energy dependence is inconsistent with the prediction of Ref. [13] that

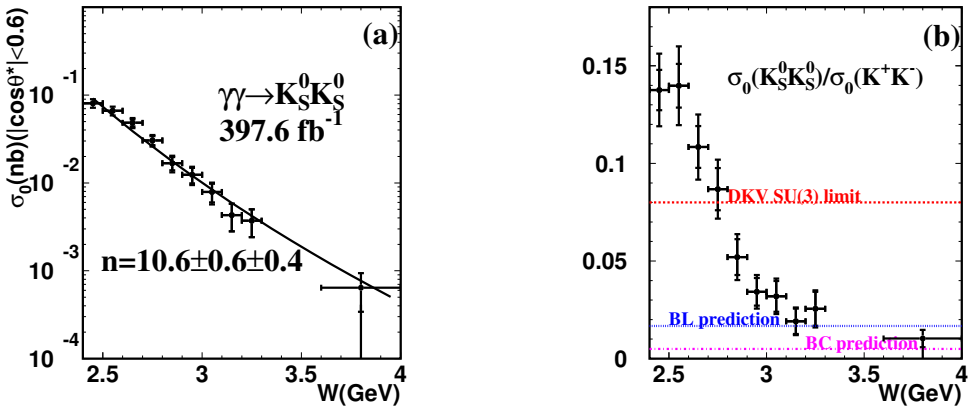

Figure 6: The cross section of $\gamma\gamma \to K^0_S K^0_S$ and its ratio to the cross section of $\gamma\gamma \to K^+K^-$.

the ratio should be $\approx 2/25$ in the SU(3) symmetry limit.

Finally, Belle used a data sample of 223 fb^{-1} to measure the cross sections of $\gamma\gamma \to \pi^0\pi^0$ for W from 0.6 to 4.1 GeV [17] and of $\gamma\gamma \to \eta\pi^0$ for W from 0.84 to 4.0 GeV [18].

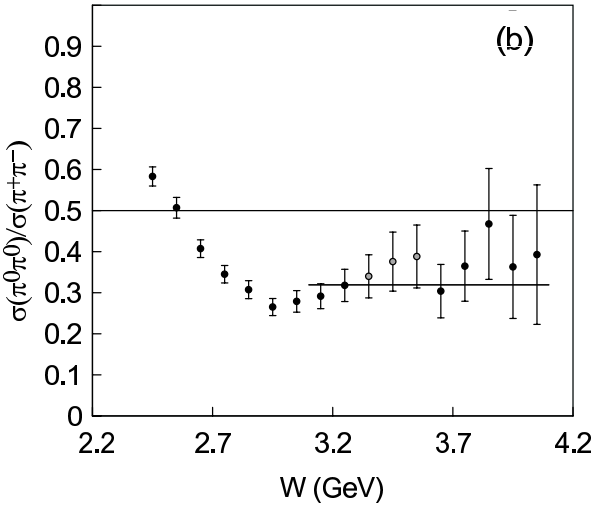

Figure 7: The ratio of the cross sections of $\gamma\gamma \to \pi^0\pi^0$ and $\gamma\gamma \to \pi^+\pi^-$.

Fig. 7 shows the ratio of the cross sections of $\gamma\gamma \to \pi^0\pi^0$ and $\gamma\gamma \to \pi^+\pi^-$. The ratio is falling at low energies, but above 3.1 GeV is almost constant with an average of $0.32\pm0.03\pm0.05$ that is significantly larger than the leading-order QCD prediction [12, 20] and lower than 0.5 suggested by isospin invariance [13].

For $\gamma\gamma \to \eta\pi^0$, a fit with W^{-n} gives $n = 10.5 \pm 1.2 \pm 0.5$ compatible with $K^0_S K^0_S$, but

higher than for $\pi^0\pi^0$. A fit of the ratio of the $\gamma\gamma \to \eta\pi^0$ and $\gamma\gamma \to \pi^0\pi^0$ cross sections gives $0.48 \pm 0.05 \pm 0.04$ with 0.46 predicted in QCD.

We summarise all results on the W dependence in Table 1.

Mode	n	$\int L\,dt$, fb^{-1}	W range, GeV	$\lvert\cos\theta^*\rvert$ range
$\pi^+\pi^-$	$7.9 \pm 0.4 \pm 1.5$	87.7	[3.0,4.1]	< 0.6
K^+K^-	$7.3 \pm 0.3 \pm 1.5$	87.7	[3.0,4.1]	< 0.6
$K^0_SK^0_S$	$10.5 \pm 0.6 \pm 0.5$	397.6	[2.4,3.3],[3.6,4.0]	< 0.6
$\pi^0\pi^0$	$6.9 \pm 0.6 \pm 0.7$	223	[3.1,3.3],[3.6,4.1]	< 0.6
$\pi^0\pi^0$	$8.0 \pm 0.5 \pm 0.4$	223	[3.1,3.3],[3.6,4.1]	< 0.8
$\eta\pi^0$	$10.5 \pm 1.2 \pm 0.5$	223	[3.1,4.1]	< 0.8
$p\bar{p}$	$15.1^{+0.8}_{-1.1}$	89	[2.5,2.9]	< 0.6
	$12.4^{+2.4}_{-2.3}$	89	[3.2,4.0]	< 0.6

Table 1: W dependence of the cross sections of various processes

4 Conclusions

- Huge integrated luminosity collected at the B factories has already resulted in high-statistics studies of some rare phenomena
- BaBar measured the $\gamma\gamma^* \to \pi^0$ transition form factor from 4 to 40 GeV^2; below 15 GeV^2 the NLO pQCD with twist-4 is inadequate, above 20 GeV^2 the data lie above the asymptotic limit; the η_c form factor will appear soon; the η, η' form factors are under study. These results can be important for models of form factors in the light-by-light contribution to the muon anomaly.
- Belle performed tests of QCD at $3 < W < 4$ GeV with
  $\gamma\gamma \to p\bar{p},\ \pi^+\pi^-,\ K^+K^-,\ K^0_SK^0_S,\ \pi^0\pi^0,\ \eta\pi^0$;
  for $\sigma(W) \sim W^{-n}$ n follows pQCD
- There were also many interesting studies of hadronic resonances: f_0's in $\pi^+\pi^-$, $\pi^0\pi^0$, a_0's in $\eta\pi^0$, f_2's in K^+K^- at Belle; η_c and $\eta_c(2S)$ at BaBar and Belle, $\chi_{c2}(2P)$ was discovered at Belle in $\gamma\gamma \to D\bar{D}$
- High-statistics $\gamma\gamma$ production has good potential for discovering new states, measuring transition form factors and $\mathcal{B}$'s, testing QCD predictions

Acknowledgements

I'm grateful to M. Deile for excellent organisation of the Conference. Thanks are also due to V. Chernyak, V. Druzhinin, K. Trabelsi and S. Uehara for useful discussions.
This work was supported in part by grants RFBR 07-02-00816, 08-02-13516, 08-02-91969 and 09-02-01143 and PST.CLG.980342.

References

[1] B. Aubert et al. (BaBar Collab.), Phys. Rev. D **80** 052002 (2009).

[2] H.J. Behrend et al. (CELLO Collab.), Z. Phys. C **49** 401 (1991).

[3] J. Gronberg et al. (CLEO Collab.), Phys. Rev. D **57** 33 (1998).

[4] G.P. Lepage and S.J. Brodsky, Phys. Rev. D **22** 2157 (1980).

[5] A.P. Bakulev, S.V. Mikhailov and N.G. Stefanis, Phys. Rev. D **67** 074012 (2003).

[6] V.L. Chernyak and A.R. Zhitnitsky, Nucl. Phys. B **201** 492 (1982), Erratum-ibid B **214** 547 (1983).

[7] G.P. Lepage and S.J. Brodsky, Phys. Lett. B **87** 359 (1979).

[8] A.P. Bakulev, S.V. Mikhailov and N.G. Stefanis, Phys. Lett. B **508** 279 (2001), Erratum-ibid, B **590** 309 (2004).

[9] S.V. Mikhailov and N.G. Stefanis, Nucl. Phys. B **821** 291 (2009).

[10] A.V. Radyushkin, arXiv:hep-ph/0906.0323 (2009).

[11] M.V. Polyakov, arXiv:hep-ph/0906.0538 (2009).

[12] S. Brodsky, P. Lepage, Phys. Rev. D **24** 1808 (1981).

[13] M. Diehl, P. Kroll, C. Vogt, Phys. Lett. B **532** 99 (2002).

[14] C.C. Kuo et al. (Belle Collab.), Phys. Lett. B **621** 41 (2005).

[15] H. Nakazawa et al. (Belle Collab.), Phys. Lett. B **615** 39 (2005).

[16] W.T. Chen et al. (Belle Collab.), Phys. Lett. B **651** 15 (2005).

[17] S. Uehara et al. (Belle Collab.), Phys. Rev D **79** 052009 (2009).

[18] S. Uehara et al. (Belle Collab.), Phys. Rev. D **80** 032001 (2009).

[19] A. Heister et al. (ALEPH Collab.), Phys. Lett. B **569** 140 (2003).

[20] M. Benayoun, V.L. Chernyak, Nucl. Phys. B **329** 285 (1990).