$e^+e^- \rightarrow$ HADRONS IN INITIAL STATE RADIATION AND TWO-PHOTON REACTIONS WITH BELLE AND BABAR

F. ANULLI
INFN, Sezione di Roma,
P.le Aldo Moro, 2 00185 Rome, Italy

We report on recent results of a variety of Belle and *BABAR* measurements of hadron production involving e^+e^- initial state radiation and two photon production. These include the precision measurement of the cross section of $e^+e^- \rightarrow \pi^+\pi^-$ and its implication for the hadronic vacuum polarization correction to the anomalous magnetic moment of the muon; search for new states in open-charm production; two-photon production of pairs of light pseudoscalar mesons and measurement of pseudoscalar meson transition form factors.

1 Introduction

Several aspects about the nature and production mechanisms of many hadronic states are still poorly known or controversial. Study of exclusive final states at the B-factories, thanks to the huge statistics and the clean experimental environment, can help on shedding light to that open questions. We provide here a short review of the most recent results obtained using Initial State Radiation (ISR) or two-photon fusion ($\gamma\gamma$) events, with Belle and *BABAR*, the two experiments that have operated for about ten years at the B-factories KEKB and PEP-II, respectively. Due to the limited space, we give a description of the light hadrons production only, and provide the proper references to the other results presented at the conference, namely, open-charm production with ISR ($e^+e^- \rightarrow D^{(*)}\bar{D}^{(*)}$ [1,2], $e^+e^- \rightarrow D\bar{D}^{(*)}\pi$ [3]), and the process $\gamma\gamma \rightarrow D\bar{D}$ [4].

2 Hadronic cross sections and the $(g-2)_\mu$

Precise measurements of the $e^+e^- \rightarrow$ hadrons cross section are necessary to evaluate the dispersion integrals for calculation of a_μ^{had}, the hadronic contribution to the theoretical prediction of $a_\mu = (g-2)_\mu$. Comparison of the theoretical and measured [5] values shows a discrepancy of more than three standard deviations when current e^+e^- data [6,7,8] are used, possibly hinting at new physics. The *BABAR* Collaboration [9] has an intensive program to study the e^+e^- cross section at low center-of-mass (CM) energy using ISR [10], with e^+e^- events collected at the peak of the $\Upsilon(4S)$ resonance. A number of multi-hadron processes have been measured with unprecedented accuracy, providing a major contribution to the calculation of a_μ^{had}. Among them, the recent measurement of the process $e^+e^- \rightarrow \pi^+\pi^-$ [11], which contribute for approximately 73% to a_μ^{had}, and is also the leading contributor to the uncertainty of a_μ.

The $e^+e^- \rightarrow X$ cross section, is deduced from a measurement of the radiative process $e^+e^- \rightarrow X\gamma$, where the photon is emitted by the e^+ or the e^- with a CM energy E_γ^*, and X can be any final state produced at the reduced CM energy $\sqrt{s'} = m_X$, with $s' = s(1-2E_\gamma^*/\sqrt{s})$.

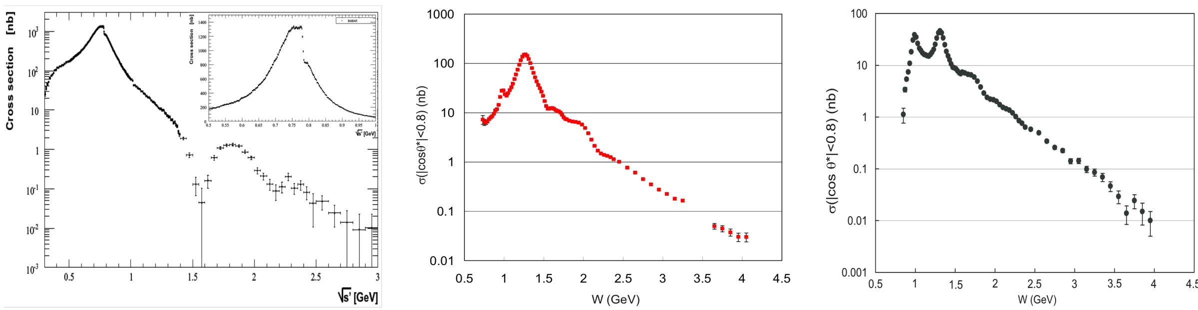

Figure 1: (Left) $e^+e^- \to \pi^+\pi^-(\gamma)$ cross section *vs* $\sqrt{s}$; in the inset, a detail of the region near the ρ peak is shown. (Center) the $\gamma\gamma \to \pi^0\pi^0$ and (right) $\gamma\gamma \to \eta\pi^0$ cross sections, shown as a function of the $\gamma\gamma$ invariant mass.

In this analysis, $X = \pi^+\pi^-(\gamma)$ and $X = \mu^+\mu^-(\gamma)$ are measured, with the charged pair possibly accompanied by a final state radiation (FSR) photon. The ISR photon is detected at large angle; the $\pi^+\pi^-$ cross section are obtained from the ratio of pion to muon yield. In this way the main systematic uncertainties cancel (e^+e^- integrated luminosity, ISR photon efficiency, additional ISR). The measured $\pi^+\pi^-(\gamma)$ bare cross section, including FSR, $\sigma^0_{\pi\pi(\gamma)}(\sqrt{s'})$, is shown in Fig. 1(left). Systematic uncertainties are about 0.5% in the region dominated by the ρ peak, and do not exceed the statistical errors over the full measured spectrum. The leading-order contribution to a_μ is obtained integrating the measured cross section (up to $1.8\,\mathrm{Ge}V$) and amounts to

$$a_\mu^{\pi^+\pi^-(\gamma),LO} \;=\; \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds'\, K(s')\, \sigma^0_{\pi\pi(\gamma)}(\sqrt{s'}) \;=\; (514.1 \pm 2.2 \pm 3.1) \times 10^{-10}, \qquad (1)$$

where $K(s')$ is a known kernel [12], and the errors are statistical and systematic, respectively. This value is larger than from a combination of previous e^+e^- data, $(503.5 \pm 3.5) \times 10^{-10}$, while it is in good agreement with the updated value extracted from τ spectral functions [13].

Combining *BABAR* result with the previous e^+e^- data and including all other contributions, the discrepancy between the Standard Model prediction and the experimental value of a_μ is reduced to $a_\mu^{exp} - a_\mu^{SM} = (25.5 \pm 8.0) \times 10^{-10}$, still above three standard deviations [13].

3 $\gamma\gamma$ in no-tag mode

Studies of exclusive final states in two-photon fusion processes, $e^+e^- \to e^+e^-\gamma^\star\gamma^\star \to e^+e^-X$, provide valuable information concerning the physics of light- and heavy-quark hadrons, perturbative and non perturbative QCD, and hadron production mechanism. The beam particles are generally scattered at small angles, most of the times escaping undetected along the beam-line. In such a case (no-tag mode) two *quasi-real* photons are produced with $q^2 = (p - p')^2 \simeq 0$, where p and p' are the electron's initial and final four momenta. At a B-factory, $\gamma\gamma$ invariant masses up to $W \sim 5\,\mathrm{Ge}V$ can be effectively studied; the final states are produced with even C-parity and angular momentum $J \neq 1$. The Belle Collaboration [14] measured the production cross section for several pairs of light mesons. Both experiments have also measured a number of final states in the charm and charmonium sector.

The $\gamma\gamma \to \pi^0\pi^0$ and $\gamma\gamma \to \eta\pi^0$ [15], extracted from the corresponding $e^+e^- \to e^+e^-X$ cross sections, and integrated over a CM angular range $|cos\theta^*_{\gamma\gamma}| < 0.8$, are shown as a function of W in Fig. 1. For $W < 2\,\mathrm{Ge}V$ the production is dominated by intermediate resonances with even angular momentum and $I^G = 0^+$ (that is $f_0, f_2 ...$) in the $\pi^0\pi^0$, and $I^G = 1^-$ (that is $a_0, a_2 ...$) in the $\eta\pi^0$ final state. Full partial wave analyses have been performed to disentangle the different contributions and extract information on these states. The cross section at higher energies can be compared to perturbative QCD predictions. At leading order, the $\pi^0\pi^0$ cross section is predicted

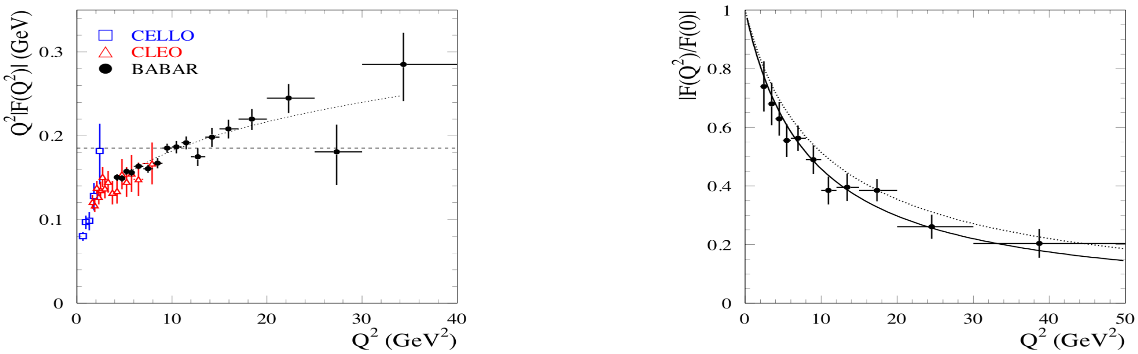

Figure 2: (Left) $\gamma^\star\gamma \to \pi^0$ TFF shown as a function of Q^2; the horizontal dashed line refers to the asymptotic value predicted by pQCD. (Right) $\gamma^\star\gamma \to \eta_c$ TFF normalized to the FF for zero transferred momentum; the solid line is the result of the fit described in the text, while the dotted line refer to a LO pQCD prediction.

to be much smaller than of $\pi^+\pi^-$, and the ratio of $\pi^0\pi^0$ to $\pi^+\pi^-$ to be in the range $0.03 - 0.06$. The observed ratio shows a fast decrease for $W < 3\,GeV$, and then flatten to a roughly constant value of 0.3, which is significantly higher than the LO pQCD prediction, while it is not far from the value of 0.5 as expected if the amplitudes for the two processes are the same. A prediction of this kind is provided for example by the handbag model [16]. A fit to a power law, W^{-n}, of the $\gamma\gamma \to \pi^0$ differential cross section integrated over the polar angle $|cos\theta^*_{\gamma\gamma}| < 0.6$, in the CM energy region $3.1 < W < 4.1\,GeV$, gives a value of $n = 6.9 \pm 0.6 \pm 0.7$, which is compatible with the results found for the $\pi^+\pi^-$ and K^+K^- channels, while a significantly higher value is found for the $\eta\pi^0$ channel.

4 $\gamma\gamma$ in single-tag mode

If one of the electron is scattered at large angle and detected, the emitted photon is highly off-shell, and the momentum transfer $q_1^2 = -Q^2$ is large. The cross section for pseudoscalar meson (P) production depends on only one form factor, $F(Q^2)$, which describe the $\gamma^\star\gamma \to P$ transition [17]. At large enough Q^2, the form factor can be represented as a convolution of a calculable hard scattering $\gamma^\star\gamma \to q\bar{q}$, with a non perturbative meson distribution amplitude (DA), $\phi_P(x, Q^2)$ [18], which describe the transition of the meson into two quarks, carrying a fraction x and $(1-x)$ of the meson momentum. Measurements of the transition form factors (TFF) can be used to determine its dependence on x. The *BABAR* Collaboration has measured the TFF for the neutral pion and the η_c.

The π^0 is reconstructed from its decay into two photons. A total of about 14000 $\gamma\gamma \to \pi^0$ events are selected in 442 fb^{-1} of data, and divided in 17 Q^2 bins of different width, from 4 to 40 GeV^2. The TFF extracted from the measured cross section is shown in Fig. 2(left). The *BABAR* results [19] are in agreement with a previous measurement by the CLEO Collaboration [20] in the Q^2 range from 4 to 9 GeV^2, but have significantly better precision. The horizontal dashed line shown in the plot indicates the asymptotic limit $Q^2F(Q^2) = \sqrt{2}f_\pi \approx 0.185\,GeV$ for $Q^2 \to \infty$, as predicted by pQCD [18]. The measured TFF exceeds the limit for $Q^2 > 10\ GeV^2$, contradicting most models for the pion DA which predict form factors approaching the asymptotic limit from below.

A similar analysis has been performed to measure the $\gamma^\star\gamma \to \eta_c$ TFF, with η_c reconstructed through the decay $\eta_c \to K_S K^\pm\pi^\mp$. This channel has been studied also in no-tag mode, in order to measure the parameters of the resonance, in particular the product of the two-photon width times the branching fraction, and normalize $F(Q^2)$ to $F(Q^2 = 0)$. The $\gamma^\star\gamma \to \eta_c$ TFF measured [21] in the single-tag analysis is shown in Fig. 2(right). Experimental data are well described by the monopole form $|F(Q^2)/F(0)| = 1/(1 + Q^2/\Lambda)$. The fitted value for the pole is

$\Lambda = (8.5 \pm 0.6 \pm 0.7)$ GeV^2, consistent with that expected from vector dominance, $\Lambda = m^2_{J/\psi} =$ 9.6 GeV^2, and with a lattice QCD calculation [22]. The data lie instead systematically below a calculation at leading-order pQCD [23], but within the quoted theoretical uncertainties.

5 Conclusions

ISR and $\gamma\gamma$ processes have proved to be very effective tools for studying hadronic interactions at low energies, when combined with the high statistics provided by the modern B-factories. Here, we have reported about a small fraction of the numerous measurements performed, with unprecedented accuracy, by the Belle and *BABAR* experiments.

Acknowledgments

I wish to thank the Organizing Committee of the Conference for the warm hospitality. I am also grateful to the colleagues from the *BABAR* and Belle collaborations for the fruitful discussions during the preparation of the talk, with particular thanks to Galina Pakhlova, Sadaharu Uehara and Pavel Pakhlov.

References

1. G. Pakhlova *et al*, Belle Collaboration, *Phys. Rev.* D **77**, 011103 (2008); *Phys. Rev.* D **98**, 092001 (2007).
2. B. Aubert *et al*, *BABAR* Collaboration, *Phys. Rev.* D **76**, 111105(R) (2007); *Phys. Rev.* D **79**, 092001 (2009).
3. G. Pakhlova *et al*, Belle Collaboration, arXiv:0908.0231 [hep-ex] (2009).
4. S. Uehara *et al*, Belle Collaboration, *Phys. Rev. Lett.* **78**, 082003 (2006);
   B. Aubert *et al*, *BABAR* Collaboration, *Phys. Rev.* D **81**, 092003 (2010).
5. G.W. Bennet *et al*, *Phys. Rev.* D **73**, 072003 (2006).
6. R.R. Akhmetshin *et al*, CMD-2 Collaboration, *Phys. Lett.* B **648**, 28 (2007).
7. M.N. Achasov *et al*, SND Collaboration, JETP Lett. 2006, **103**, 380.
8. F. Ambrosino *et al*, KLOE Collaboration, *Phys. Lett.* B **670**, 285 (2009).
9. B. Aubert *et al*, *BABAR* Collaboration, *Nucl. Instrum. Methods* A **479**, 1 (2002).
10. A.B. Arbuzov *et al*, J. High Energy Phys., **9812**, 009 (1998);
    S. Binner, J.H. Kuhn, and K. Melnikov, *Phys. Lett.* B **459**, 279 (1999).
11. B. Aubert *et al*, *BABAR* Collaboration, *Phys. Rev. Lett.* **103**, 231801 (2009).
12. S.J. Brodsky and E. de Rafael, *Phys. Rev.* **168**, 1620 (1968).
13. M. Davier *et al*, arXiv:0908.4300 (2010),
14. A. Abashian *et al*, Belle Collaboration, *Nucl. Instrum. Methods* A **479**, 117 (2002).
15. S. Uehara *et al*, Belle Collaboration, *Phys. Rev.* D **78**, 052004 (2008); *Phys. Rev.* D **79**, 052009 (2009); *Phys. Rev.* D **80**, 032001 (2009).
16. M. Diehl, P. kroll, and C. Vogt, *Phys. Lett.* B **532**, 99 (2002).
17. S.J. Brodsky, T. Kinoshita, and H. Terazawa, *Phys. Rev.* D **4**, 1532 (1971).
18. G.P. Lepage and S.J. Brodsky, *Phys. Rev.* D **22**, 2157 (1980).
19. B. Aubert *et al*, *BABAR* Collaboration, *Phys. Rev.* D **80**, 052002 (2009).
20. J. Gronberg *et al*, CLEO Collaboration, *Phys. Rev.* D **57**, 33 (1998).
21. J.P.Lees *et al*, *BABAR* Collaboration, *Phys. Rev.* D **81**, 052010 (2010).
22. J.J. Dudek and R.G. Edwards, *Phys. Rev.* D **97**, 172001 (2006).
23. T. feldmann and P. Kroll, *Phys. Lett.* B **413**, 410 (1997).