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HADRON PRODUCTION IN ISR AND 2γ ANNIHILATIONS AT BaBar*

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The BaBar Collaboration studied with very high precision the LO hadronic contribution to the muon magnetic anomaly. We present recent results for $\pi^+\pi^-$, K^+K^- and $\pi^+\pi^-\pi^+\pi^-$ final states produced in ISR events. We also show the study of "exotic" states in the $\gamma\gamma$ annihilation and ISR processes.

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1. Introduction

The discrepancy between the value of the anomalous magnetic moment $a_\mu = \frac{1}{2}(g-2)_\mu$ experimentally measured by the E821 experiment at the BNL [1] and the theoretically predicted one [2] is of the order of three standard deviations (3.6 σ).

Theory delivers a very precise evaluation of QED and weak contribution to a_μ. The hadronic term, instead, cannot be calculated by a perturbative approach at low energies.

However, the dispersion integral relates the LO hadronic contribution to a_μ and the hadronic cross sections, which typically are measured in e^+e^- energy scan experiments at low energies

$$a_\mu^{\mathrm{had,LO}} = \frac{\alpha^2(0)}{3\pi^2} \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)\,, \tag{1}$$

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where $K(s) \propto \frac{1}{s}$, so that the 92% of the total contribution is for $\sqrt{s} < 1.8$ GeV. The Initial State Radiation method [3–5] allows experiments running at a fixed c.m. energy to scan from the production threshold of the hadronic system to the c.m. energy nominal value. The BaBar Collaboration ISR program [6, 7] investigates a wide range of energies and a large set of final states. In addition to the cross section measurements, these studies include many additional physics topics.

On the other side, the discovery of the $X(3872)$ opened a totally new era in charmonium sector. Many states not theoretically predicted have been observed in several decay modes and in different production processes. Many hypothesis have been done for explaining their nature but they have to be verified experimentally.

At B-factories, the production processes which deliver these "charmonium-like" states are: B-decays, double charmonium production, ISR and 2-γ annihilations. The last two processes are complementary in terms of spin and charge coniugation, in fact, they respectively lock the final states quantum numbers to be $J^{\rm PC} = 1^{--}$ and $J \neq 1$, $C = +$. This complementarity is very useful for investigating the properties of these resonances.

The results presented here are based on data collected with the BaBar detector located at the SLAC National Accelerator Laboratory. The BaBar detector is described elsewhere [8].

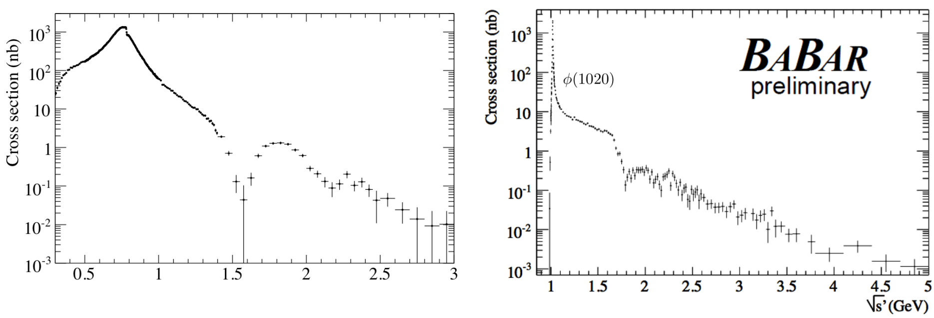
A simulation package developed for radiative processes, AFKQED, is used to determine detector acceptance and reconstruction efficiencies. Signal and background processes are simulated with Monte Carlo (MC) event generators based on [9]. Additional ISR photons are generated with the structure function method [10, 11], and additional FSR photons with PHOTOS [12]. Background events from $e^+e^- \to q\overline{q}$ $(q = u, d, s, c)$ are generated with JETSET [13], while those from $e^+e^- \to \tau^+\tau^-$ are modelled with KORALB [14]. EvtGen [15] and KK [16] generators are used to simulate the background events too. Radiative corrections and the influence of intermediate resonances on the acceptance are investigated using PHOKHARA [17, 18]. The response of the BaBar detector is simulated with GEANT4 [19]. The GAMGAM [20] generator, instead, is used to generate signal event samples for the 2-γ annihilation processes.

2. Muon magnetic anomaly prediction using ISR method

The ISR photon is required to be detected with an energy $E^*_\gamma > 3$ GeV in the e^+e^- c.m. and polar angle with respect to the e^- beam in the range of 0.35–2.4 rad.

The $\pi^+\pi^-(\gamma)$ and $K^+K^-(\gamma)$ channels analysis has been performed with an integrated luminosity of 232 fb^{-1} considering an additional FSR photon. The measurement of $e^+e^- \to K^+K^-$ is still preliminary.

In figure 1 the cross section for the $\pi^+\pi^-$ (left) and K^+K^- (right) final states is shown. Systematic uncertainties for the $\pi^+\pi^-$ cross section are of the order of 0.5% under the ρ peak; although larger, they do not exceed statistical errors for the chosen energy intervals. In figure 1 (b), the two bins including the J/ψ and $\psi(2S)$ resonances have been removed. The overall systematic uncertainty for the K^+K^- final state is 7.2 $\times 10^{-3}$ in the [1.01; 1.03] GeV mass range, but significantly larger outside the peak region.



(a) $\pi^+\pi^-$ (b) K^+K^-

Fig. 1. Measured bare cross section for $e^+e^- \to \pi^+\pi^-$ and for $e^+e^- \to K^+K^-$. The plotted errors are from the sum of the diagonal elements of the statistical and systematic covariance matrices.

We also present results for the channel $\pi^+\pi^-\pi^+\pi^-$ which is the most significant in the 1–2 GeV region above the Φ. It has been performed using an integrated luminosity of 454 fb^{-1}. The cross section is shown in figure 2. The systematic uncertainty of this measurement is 2.4% in the peak region, increasing to 10.7% in the low energy region shown in the inlay, and to 5.5% (8.5%) for energies above 2.8 GeV (4.0 GeV).

The three respectively contributions to the anomalous magnetic moment are reported below:

$a_\mu^{\pi\pi(\gamma),\mathrm{LO}} = \left(514.1 \pm 2.2_{(\mathrm{stat})} \pm 3.1_{(\mathrm{syst})}\right) \times 10^{-10}$ [E_{CM}: thr–1.8 GeV] [7];

$a_\mu^{KK(\gamma),\mathrm{LO}} = \left(22.95 \pm 0.14_{(\mathrm{stat})} \pm 0.22_{(\mathrm{syst})}\right) \times 10^{-10}$ [E_{CM}: thr–1.8 GeV] [**preliminary**];

$a_\mu^{2(\pi^+\pi^-),\mathrm{LO}} = \left(13.64 \pm 0.03_{(\mathrm{stat})} \pm 0.36_{(\mathrm{syst})}\right) \times 10^{-10}$ [E_{CM}: 0.6–1.8 GeV] [21].

They improve both the statistical and systematic uncertainties giving the most precise results available as figure 2 clearly shows. Above 2.8 GeV, the theoretical calculations are considered.

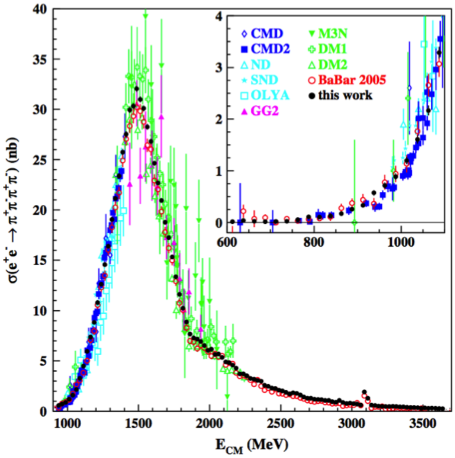


Fig. 2. Cross section for the process $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ measured by different experiments for the entire energy range. Only statistical errors are shown.

These studies are also very useful for investigating all the structures that contribute to the total cross section. Some of them are evident in the figures below, some others need to be highlighted looking at partial invariant masses of the final states.

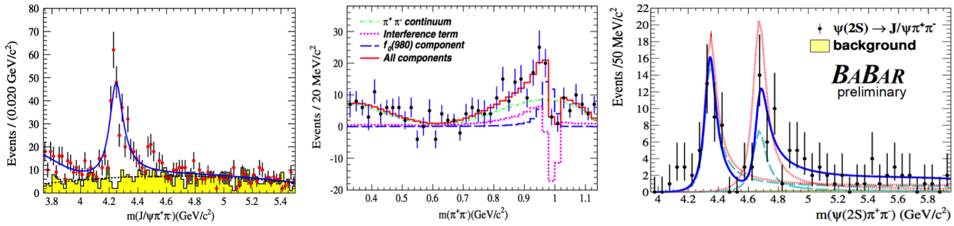
3. Exotic charmonium-like states

In the (ISR) $e^+e^- \to J/\psi\pi^+\pi^-$ the $Y(4260)$ was for the first time discovered by the BABAR using an integrated luminosity of 211 fb^{-1}.

Figure 3 (a) shows the invariant mass of the $J/\psi\pi^+\pi^-$ system studied more recently [22] at the BABAR with an integrated luminosity of 454 fb^{-1}. An extended-maximum-likelihood fit uses a relativistic Breit–Wigner (BW) signal function for the $Y(4260)$ resonant contribution, a 3$^{\mathrm{rd}}$ order polynomial to describe the background and an exponential function to describe the excess of events below 4 GeV$/c^2$; this excess may result from the $\psi(2\mathrm{S})$ tail and a possible $J/\psi\pi^+\pi^-$ non-resonant contribution. Results for the mass and width of the $Y(4260)$ are: $m_Y = 4245 \pm 5_{\mathrm{stat}} \pm 4_{\mathrm{syst}}$ MeV$/c^2$, $\Gamma_Y = 114^{+16}_{-15} \pm 7$ MeV.

The $\pi^+\pi^-$ mass distribution is studied and fitted as figure 3 (b) shows. The $Y(4260)$ decay to $J/\psi f_0(980)$ is found not to give a dominant contribution to the $J/\psi\pi^+\pi^-$ final state ($\mathcal{B} \simeq 17\%$). Another recent ISR study [23] performed by the BABAR shows up the $Y(4360)$ and the $Y(4660)$ exotic states by the chain: $e^+e^- \to Y(4260) \to \psi(2\mathrm{S})\pi^+\pi^- \to J/\psi\pi^+\pi^-\pi^+\pi^-$. This analysis has been performed using 520 fb^{-1} of collected data, the clear resonant signals are reported in figure 3 (c). The $Y(4660)$ signal has been

revealed with a confidence greater than 5σ; the resonances parameters are reported here:
$m_{Y(4360)} = 4340 \pm 16_{\rm stat} \pm 9_{\rm syst}$ MeV$/c^2$, $\Gamma_Y = 114^{+16}_{-15} \pm 7$ MeV,
$m_{Y(4660)} = 4245 \pm 5_{\rm stat} \pm 4_{\rm syst}$ MeV$/c^2$, $\Gamma_Y = 114^{+16}_{-15} \pm 7$ MeV.
In these analyses, the ISR photon is not required to be detected.



(a) (b) (c)

Fig. 3. (a) The $J/\psi\pi^+\pi^-$ mass spectrum from 3.74 GeV$/c^2$ to 5.5 GeV$/c^2$. (b) The result of the fit to the $\pi^+\pi^-$ invariant mass. (c) The $\psi(2S)\pi^+\pi^-$ invariant mass distribution from the kinematic threshold to 5.95 GeV$/c^2$ for $\psi(2S) \to J/\psi\pi^+\pi^-$. More details can be found in Refs. [22, 23].

The two-photon annihilation into $J/\psi\ \omega$ has been studied for searching the $X(3915)$ and $X(3872)$ as intermediate states [24]. 519.2 fb^{-1} have been analized for this purpose. Figure 4 shows the evidence for the $X(3872)$ and a clear resonant peak for the $X(3915)$; its parameters are obtained by the fit, we report them just below: $m_{X(3915)} = (3919.4 \pm 2.2 \pm 1.6)$ MeV$/c^2$ $\Gamma_X = (13 \pm 6 \pm 3)$ MeV. The PDF for the signal component is defined by the convolution of an S-wave relativistic Breit–Wigner distribution with a detector resolution function.

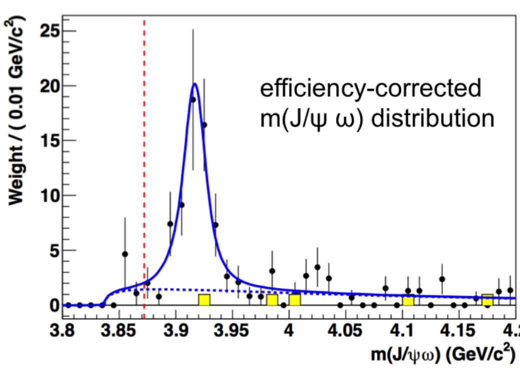


Fig. 4. The efficiency-corrected $m_{J/\psi\omega}$ distribution of selected events (solid points). The vertical dashed (red) line is placed at $m_{J/\psi\omega} = 3.872$ GeV$/c^2$. For details, see Ref. [24].

An angular analysis has been performed using the Rosner predictions to discriminate the most probable quantum numbers of the state. The χ^2 probability is in favour of $J^{\mathrm{P}} = 0^+$.

The $X(3915)$, $X(3872)$, $\chi_{c2}(1\mathrm{P})$, $\eta_c(2\mathrm{S})$, and $\chi_{c2}(2\mathrm{P})$ have been searched as intermediate states of the chain $\gamma\gamma \to X \to \eta_c\pi^+\pi^-$ [25]. Figure 5 shows no clear evidence of these states into the decay. Very precious upper limits have been measured, they are between 10 and 135 eV.

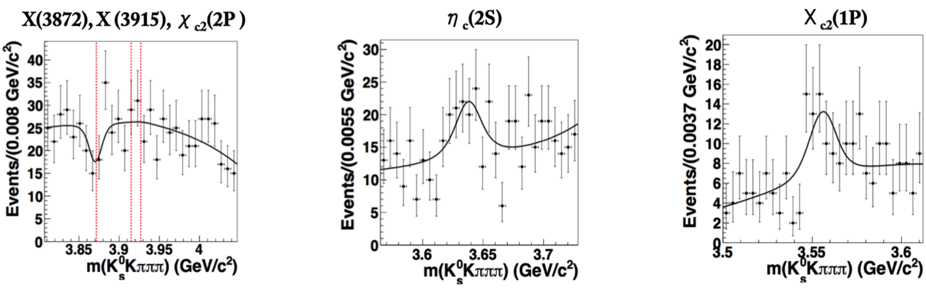


Fig. 5. Distributions of $m(K^0_{\mathrm{S}}K^+\pi^-\pi^+\pi^-)$ with the PDF overlaid. The vertical dashed lines indicate the peak mass positions of the $X(3872)$, $X(3915)$, and $\chi_{c2}(2\mathrm{P})$.

4. Conclusions

Measurement of hadronic cross sections via ISR is a very productive field in addition to B-physics at the BaBar. Many measurements were performed or are still ongoing for the first time with high accuracy delivering the most complete theoretical determination of the hadronic contribution to a_μ: $a_\mu^{\mathrm{SM}} = (11659180.2 \pm 4.2 \pm 2.6 \pm 0.2(4.9_{\mathrm{tot}})) \times 10^{-10}$ [2].

$(g-2)_\mu$ discrepancy between experimental measurement and theoretical evaluation should be further explored. Should the discrepancy be confirmed, it would unambiguously signal physics beyond the Standard Model.

Exotic charmonium-like states are still a physical open issue, ISR and 2-γ annihilation processes are a precious mean for delineating their properties and nature. Many other studies are in progress, and the BaBar is still producing very interesting results.

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