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Initial State Radiation Study at $\Upsilon(4S)$ in BaBar[1]

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Abstract. An analysis of the processes with initial state radiation (ISR) has been performed using 90 fb^{-1} of *BABAR* data. The selection of $\mu^+\mu^-$ and multi-hadron final states has been demonstrated accompanied with the detected ISR photon. The invariant mass of hadronic final state determines the virtual photon energy and data can be compared with direct e^+e^- cross sections. The present *BABAR* data are already competitive with e^+e^- machine data in 0.28-3.0 GeV energy range and demonstrate many interesting details usefull for low energy hadron spectroscopy.

In addition to light meson spectroscopy these data can be used for calculation of R - the ratio of $e^+e^- \to hadrons$ cross section to $e^+e^- \to \mu^+\mu^-$ - and thereby to impact the $(g-2)_\mu$ measurement.

The ISR technic gives an access to J/ψ production. The J/ψ decays to $\mu\mu$, 4π, $2K2\pi$ and 4K have been selected and new preliminary measurements of branching ratios performed with comparable or typically better accuracy than PDG.

INTRODUCTION

The possibility of using the initial state radiation (ISR) of hard photons at B-factories to study hadronic final state production at lower e^+e^- c.m. energies has been discussed previously [1, 2, 3]. The interest to this kind of study is rising up because of discrepancy between measured muon g-2 value and one predicted by Standard Model [4], where hadronic contribution is taken from e^+e^- experiments at low energies. The study of the ISR events at B-factories can give independent measurements of hadronic cross sections as well as contribute to low mass resonance spectroscopy.

The ISR cross section for a particular final state f depends on e^+e^- cross section $\sigma_f(s)$ and is obtained from:

$$\frac{d\sigma(s,x)}{dx} = W(s,x)\cdot\sigma_f(s(1-x)), \qquad (1)$$

where $x = \frac{2E_\gamma}{\sqrt{s}}$; E_γ is the energy of the ISR photon in the nominal c.m. frame, and $\sqrt{s}$ is the nominal c.m. energy. The function W(s,x) describes the energy spectrum of the virtual photons and can be calculated with better than 1% accuracy [1, 2, 3]. ISR photons are produced at all angles relative to the collision axis, and it has been shown that the *BABAR* acceptance for such photons is around 10-15 % [3].

Events corresponding to $e^+e^- \to \mu^+\mu^-\gamma$ are providing ISR luminosity for the normalization of the hadronic cross section measurements. For a hadronic final state, f, the

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normalized Born cross section at c.m. energy squared s', $\sigma_f(s')$, is obtained by relating the observed number of events in an interval ds' centered at s', $dN_{f\gamma}$, to the corresponding number of radiative di-muon events, $dN_{\mu\mu\gamma}$, by means of

$$\sigma_f(s') = \frac{dN_{f\gamma} \cdot \varepsilon_{\mu\mu} \cdot (1+\delta^{\mu\mu}_{rad})}{dN_{\mu\mu\gamma} \cdot \varepsilon_f \cdot (1+\delta^{f}_{rad})} \cdot \sigma_{e^+e^- \to \mu^+\mu^-}(s'), \tag{2}$$

where $s' = s(1-x)$; $\varepsilon_{\mu\mu}$ and ε_f are detection efficiencies, and $1+\delta^{\mu\mu}_{rad}$, $1+\delta^{f}_{rad}$ are the corrections excluding fraction of events when hard photon comes from final particles. This correction is important for di-muons and negligible for most of the hadronic final states. The Born cross section $\sigma_{e^+e^- \to \mu^+\mu^-}(s')$ is used. The radiative corrections to the initial state, acceptance for the ISR photon, and virtual photon properties are the same for $\mu^+\mu^-$ and f, and cancel in the ratio.

An advantage deriving from the use of ISR is that the entire range of effective collision energy is scanned in one experiment. This avoids the relative normalization uncertainties which can arise when data from different experiments are combined.

A disadvantage is that invariant mass resolution limits the width of the narrowest structure which can be measured via ISR production.

The resolution and absolute energy scale can be monitored directly using the width of the J/ψ resonance produced in the $e^+e^- \to J/\psi\gamma$ reaction. For a narrow resonance, such as the J/ψ the total production cross section can be calculated as

$$\sigma^{tot}_{J/\psi}(s) = \frac{12\pi^2\Gamma_{ee}}{m_{J/\psi} \cdot s} \cdot W(s,x);\, x = 1 - \frac{m^2_{J/\psi}}{s}, \tag{3}$$

where $m_{J/\psi}$ and Γ_{ee} are mass and electron partial width of J/ψ. For $s = m^2_{\Upsilon(4S)}$ the cross section is equal to 0.036 nb. With 130 fb^{-1} of *BABAR* integrated luminosity about $4 \cdot 10^6$ of J/ψ's decay in the detector. The cross section for the final state f

$$\sigma^{f}_{J/\psi}(s) = \frac{12\pi^2\Gamma_{ee}B_f}{m_{J/\psi} \cdot s} \cdot W(s,x);\, x = 1 - \frac{m^2_{J/\psi}}{s}, \tag{4}$$

is propotional to the product $\Gamma_{ee} \cdot B_f$ or $\Gamma \cdot B_{ee} \cdot B_f$ where Γ and B_{ee}, B_f are the total width and branching fractions of J/ψ to e^+e^- and f.

The invariant mass of the final particles determines the position of J/ψ peak and detector mass resolution $\sim$8 MeV can be achieved by using a kinematic fit. Preliminary studies of some particular ISR processes have been performed with *BABAR* data [5, 6] showing good detector efficiency and particle identification capability for this kind of events.

THE $\mu^+\mu^-\gamma$ FINAL STATE AND ISR LUMINOSITY

The data used in this analysis were collected with the *BABAR* detector at the PEP-II asymmetric e^+e^- storage ring. The total integrated luminosity used in this analysis is $89.3 fb^{-1}$. Both data collected at $\Upsilon(4S)$ resonance and continum are used for this analysis.

The *BABAR* detector is described elsewhere [7]. The information from *BABAR* tracking system (Silicon Vertex Tracking - SVT and Drift Chamber - DCH) is used to measure angles and momenta of charged particles. Information from DIRC allows to identified kaons in final state. The IFR allows to identify muons and the photons are detected in the CsI calorimeter - EMC.

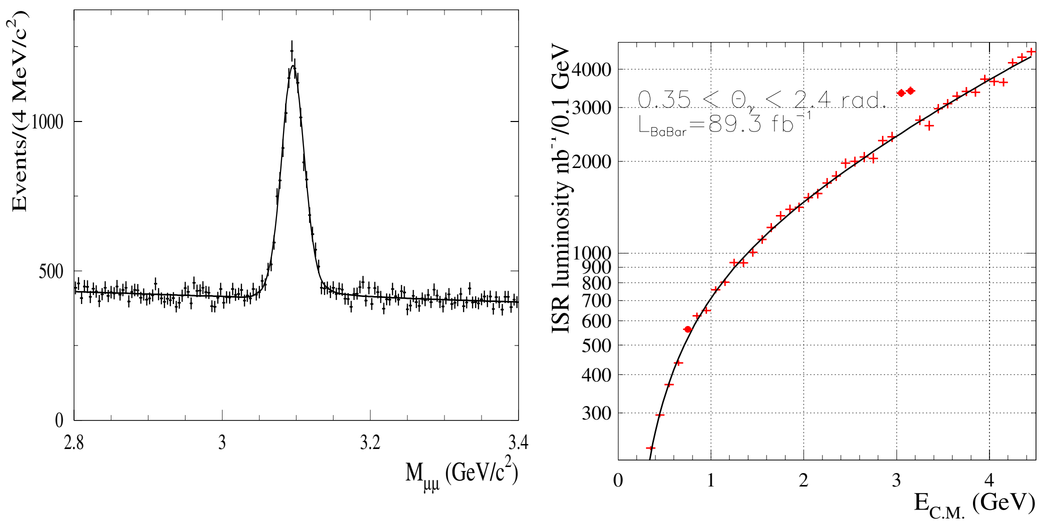

FIGURE 1. On the left: The $\mu^+\mu^-$ invariant mass distribution in J/ψ region. On the right: The calculated ISR luminosity integrated over 0.1 GeV for 89.3fb^{-1} of integrated *BABAR* luminosity.

The pair of muons from $e^+e^- \to \mu^+\mu^-\gamma$ process are easily identified and the plot in fig. 1(left) shows invariant mass distribution of muon pairs in the J/ψ region. The invariant mass of the muon pair defines the effective collision energy, i.e. the c.m. energy of the virtual photon in wide range. The energy dependence of the ISR luminosity, dL, for the interval dE_{γ^*} centred at virtual photon energy E_{γ^*} is then obtained from

$$dL(E_{\gamma^*}) = \frac{dN_{\mu\mu\gamma}(E_{\gamma^*})}{\varepsilon_{\mu\mu}(E_{\gamma^*})\cdot(1+\delta_{FSR}^{\mu\mu})(E_{\gamma^*})\cdot\sigma_{e^+e^-\to\mu^+\mu^-}(E_{\gamma^*})}, \quad E_{\gamma^*} = m_{inv}^{\mu\mu},$$

where $dN_{\mu\mu\gamma}$ is the number of experimental di-muon events observed in this interval, $\varepsilon_{\mu\mu}$ - acceptance from simulation and $(1+\delta_{FSR}^{\mu\mu})$ - correction on final state radiation (FSR). The $\sigma_{e^+e^-\to\mu^+\mu^-}(E_{\gamma^*}$ Born cross section is used. The $\mu\mu\gamma$ events with hard photon emitted by final muons contribute to total number of observed events and should be removed for limunosity calculation.

The ISR luminosity vs. effective c.m. energy for $89.3 fb^{-1}$ integrated luminosity is shown in fig. 2(left) and is used for normalization of hadronic final states according to equation 1. The present *BABAR* data are equivalent to an e^+e^- machine scan in 0.1 GeV steps with a luminosity integral per point varying from 700 nb^{-1} at 1 GeV to 4 pb^{-1} at 4.5 GeV c.m. energy. This luminosity integral is already competitive with exising e^+e^- experimental data. The systematic error is estimated as 3% and should be increased to 5% for mass region below 1 GeV.

THE HADRONIC FINAL STATES

Currently the major hadronic final states $\pi^+\pi^-\gamma$, $K\bar{K}\gamma$, $p\bar{p}\gamma$, $\pi^+\pi^-\pi^0\gamma$, $4\pi\gamma$, $K\bar{K}\pi^0\gamma$, $5\pi\gamma$, $6\pi\gamma$ are under study in the *BABAR* Collaboration. The Monte Carlo generators for these processes are based on formulae from [8, 9, 10]. The analysis procedure for $\pi^+\pi^-\pi^+\pi^-$, $K^+K^-\pi^+\pi^-$ and $K^+K^-K^+K^-$ final states is described in [12]. Figure 2(left) presents the obtained $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ cross section in comparison with all existing e^+e^- data. The estimated systematic error is about 5%.

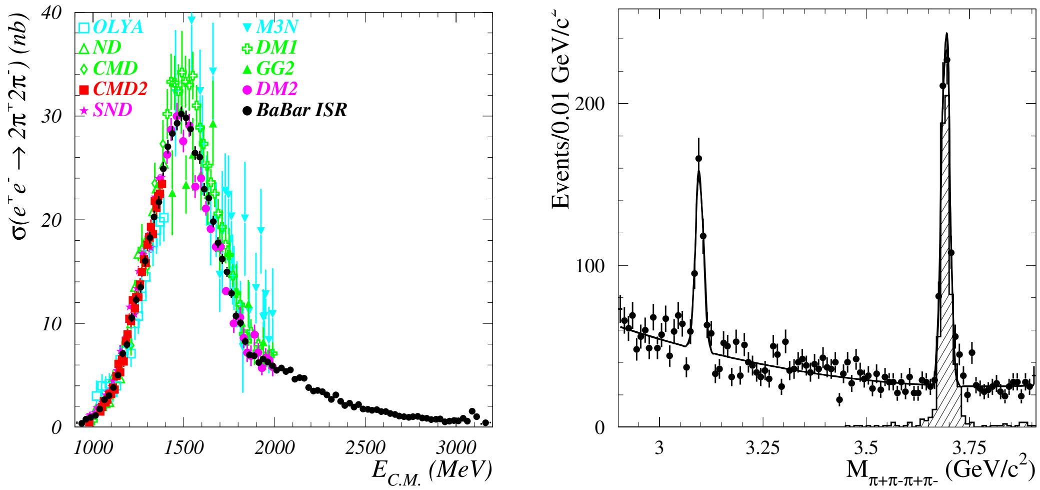

FIGURE 2. On the left: The $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ cross section obtaind from ISR at *BABAR* in comparison with all e^+e^- data. On the right: The signals from J/ψ and $\psi(2S)$ in 4π invariant mass. The shaded region at the latter corresponds to $\psi(2S) \to J/\psi\pi^+\pi^-$, with $J/\psi \to \mu^+\mu^-$.

The hadronic contribution to $(g-2)_\mu$ from this particular channel evaluated using all available e^+e^- data in 0.56-1.8 GeV range is $\alpha_\mu^{had} x10^{10} = 14.21 \pm 0.87_{exp} \pm 0.23_{rad}$. The τ decay data give $\alpha_\mu^{had} x10^{10} = 12.35 \pm 0.96_{exp} \pm 0.40_{SU2}$. The *BABAR* data in this energy range give $\alpha_\mu^{had} x10^{10} = 12.95 \pm 0.64_{exp} \pm 0.13_{rad}$ what shows a potential of the ISR measurements.

THE J/ψ DECAYS

The ratio of $\mu^+\mu^-$ events from J/ψ peak (see fig. 1(left)) to continum allows to calculate the product [6]

$$\Gamma(J/\psi \to e^+e^-) \cdot B(J/\psi \to \mu^+\mu^-) = 0.330 \pm 0.008 \pm 0.007\,\text{keV},$$

where first error is statistical from about 7800 observed events and the second one includes systematic errors from uncertainties in background estimation, line shape, radiative corrections and Monte Carlo statistic. Using the world averages for $B(J/\psi \to \mu^+\mu^-)$ and $B(J/\psi \to e^+e^-)$, we derive the J/ψ electronic and total widths: $\Gamma(J/\psi \to e^+e^-) = 5.61 \pm 0.20$ keV and $\Gamma = 94.7 \pm 4.4$ keV.

Figure 2(right) shows the J/ψ and $\psi(2S)$ signals in four charged tracks invariant mass. The later is seen due to the process $\psi(2S) \rightarrow J/\psi\pi^+\pi^- \rightarrow \mu\mu\pi^+\pi^-$ and can be easily isolated by requirement of J/ψ mass in one pair of charged particles (shaded histogram). By using 270±20 and 620±25 observed events respectively, detection efficiency from simulation and ISR luminosity the following products have been obtained:

$$B_{J/\psi\rightarrow 4\pi} \cdot \Gamma_{J/\psi ee} = (1.95 \pm 0.14 \pm 0.13) \cdot 10^{-2} \text{ keV},$$

$$B_{\psi(2S)\rightarrow J/\psi\pi^+\pi^-} \cdot B_{J/\psi\rightarrow 2\mu} \cdot \Gamma_{\psi(2S)ee} = (4.50 \pm 0.18 \pm 0.22) \cdot 10^{-2} \text{ keV}.$$

Using the world averages for $\Gamma_{J/\psi\rightarrow e^+e^-}$, $\Gamma_{\psi(2S)\rightarrow e^+e^-}$ and $B_{J/\psi\rightarrow 2\mu}$ we derive the values $B_{J/\psi\rightarrow 4\pi} = (3.70 \pm 0.27 \pm 0.36) \cdot 10^{-3}$ and $B_{\psi(2S)\rightarrow J/\psi\pi^+\pi^-}$=0.361±0.015±0.037.

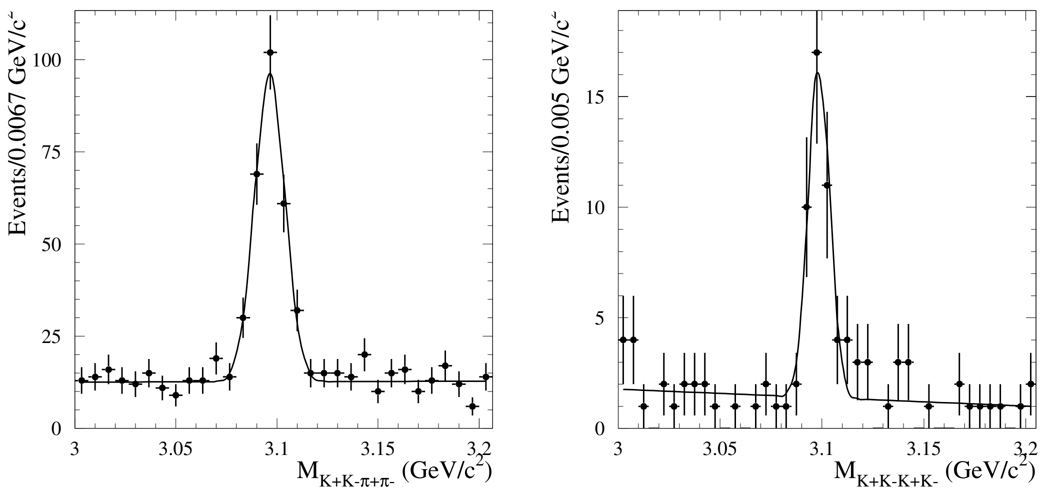

FIGURE 3. On the left: The signals from J/ψ in 2K2π invariant mass. On the right: The signals from J/ψ in 4K invariant mass.

Figures 3 show J/ψ signals in the $K^+K^-\pi^+\pi^-$ and $K^+K^-K^+K^-$ final states. 233±19 and 38.5±6.7 events have been observed respectively. Using Monte Carlo efficiency and ISR luminosity the following products have been obtained:

$$B_{J/\psi\rightarrow 2K2\pi} \cdot \Gamma_{J/\psi ee} = (3.29 \pm 0.27 \pm 0.27) \cdot 10^{-2} \text{ keV},$$

$$B_{J/\psi\rightarrow 4K} \cdot \Gamma_{J/\psi ee} = (3.6 \pm 0.6 \pm 0.5) \cdot 10^{-3} \text{ keV}.$$

Taking into accout world average value for $\Gamma_{J/\psi\rightarrow e^+e^-}$ we derive the relative decay rates

$$B_{J/\psi\rightarrow 2K2\pi} = (6.25 \pm 0.50 \pm 0.62) \cdot 10^{-3},$$

$$B_{J/\psi\rightarrow 4K} = (6.9 \pm 1.2 \pm 1.1) \cdot 10^{-4}.$$

CONCLUSION

The studies of some particular ISR processes have been performed with *BABAR* data showing good detector efficiency and particle identification capability for this kind of events. The preliminary $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ cross section with about 5% systematic error has been obtained from threshold to 4.5 GeV c.m. energy. The radiative return to J/ψ resonance allows to measure the relative brunching fractions with best to date accuracy.

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