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Measurement of the $e^+e^- \to \pi^+\pi^-\pi^+\pi^-, K^+K^-\pi^+\pi^-, K^+K^-K^+K^-$ Cross Sections Using Initial State Radiation at BABAR

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Abstract. First results of a study of the $e^+e^- \to \pi^+\pi^-\pi^+\pi^-\gamma$ process with hard photon emitted from initial state are presented. About 60000 fully reconstructed events have been selected based on 89.3 fb^{-1} of BABAR data. The invariant mass of the hadronic final state defines the effective collision c.m. energy, and so BABAR ISR data can be compared to the relevant direct e^+e^- measurements. From obtained 4π mass spectrum we evaluate $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ cross section for the range of c.m.s. energy from 0.6 to 4.5 GeV. The systematic error of the cross section measurement is 5% and comparable with the best e^+e^- data. The cross sections for identified 2K2π and 4K final states also have been presented.

INTRODUCTION

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:

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

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

$$W(s,x) = \beta \cdot ((1+\delta) \cdot x^{(\beta-1)} - 1 + \frac{x}{2})$$

describes the energy spectrum of the ISR photons. $\beta = \frac{2\alpha}{\pi} \cdot (2ln\frac{\sqrt{s}}{m_e} - 1)$, and δ takes into account vertex and self-energy corrections. At the $\Upsilon(4S)$ energy, β = 0.088 and δ = 0.067.

Events corresponding to $e^+e^- \to \mu^+\mu^-\gamma$ are providing ISR luminosity for the normalization of the hadronic cross section measurements [1]. For a hadronic final state, f, the normalized Born cross section at c.m. energy squared s', $\sigma_f(s')$, is obtained by relating the observed number of events $dN_{f\gamma}$, to the corresponding number of radiative di-muon events, $dN_{\mu\mu\gamma}$, by means of

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

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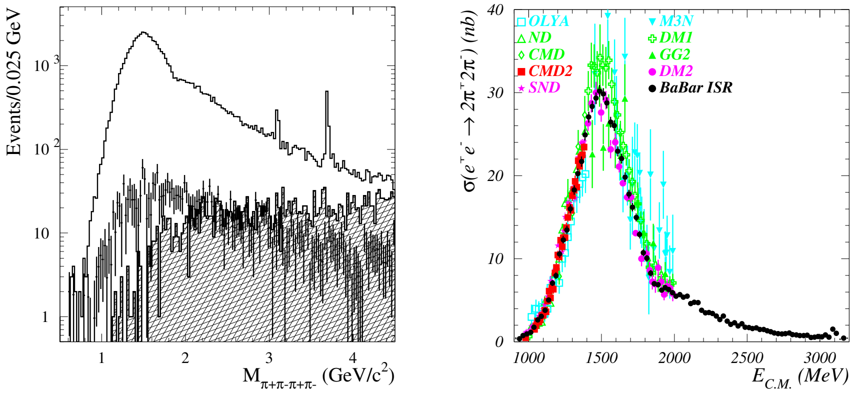

a) The four-pion invariant mass distribution for the signal region. The points indicate the estimated ISR-type background. The cross-hatched histogram corresponds to the non-ISR background.

b) The energy dependence of the $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ cross section obtained with *BABAR* ISR data (black points) in comparison with that resulting from individual e^+e^- production measurements.

FIGURE 1.

where $s' = s(1-x)$; $\varepsilon_{\mu\mu}$ and ε_f are detection efficiencies, and $1+\delta_{rad}^{\mu\mu}$, $1+\delta_{rad}^{f}$ are the corrections excluding fraction of events when hard photon comes from final particles. 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.

This paper reports the results from analysis of $\pi^+\pi^-\pi^+\pi^-$, $K^+K^-\pi^+\pi^-$ and $K^+K^-K^+K^-$ exclusive hadronic final states accompanied by a hard photon assumed to result from ISR.

DATA SELECTION AND ANALYSIS

The data used in this analysis were collected with the *BABAR* detector [2] 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 continuum are used for this analysis.

ISR events where selected requiring a high energy photon ($E_{\gamma CM}$ >3 GeV) opposite to momentum of charged tracks. A relatively clean sample of four-pion candidate events can be selected requiring that there be four charged tracks The number of detected photons (in addition to ISR photon) are not taken into account for four pion final state study. Electrons or positrons from beam losses are effectively removed from the charged track list.

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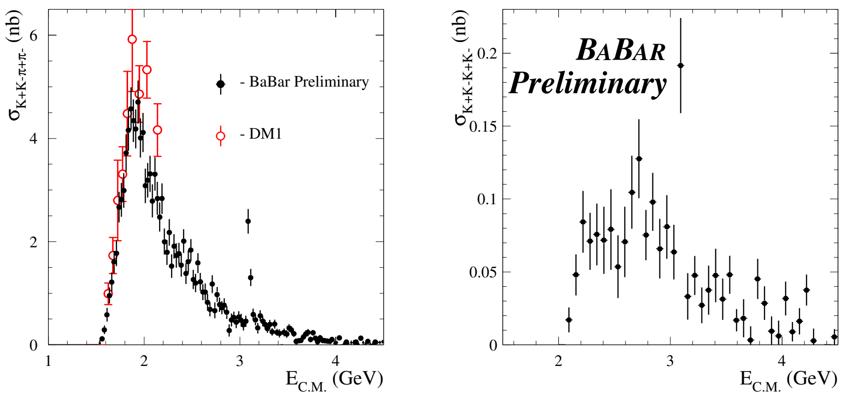


a) The c.m. energy dependence of the $e^+e^- \to K^+K^-\pi^+\pi^-$ cross section obtained from ISR events at BaBar.

b) The c.m. energy dependence of the $e^+e^- \to K^+K^-K^+K^-$ cross section obtained from ISR events at BaBar.

FIGURE 2.

To calculate acceptance and efficiencies a special package of Monte Carlo generators for radiative processes has been developed. The $4\pi\gamma$ final state simulation is based on the code developed by Kuehn and Czyz [3]. For the 2K2π and 4K final states a phase-space model has been used.

The radiative corrections - multiple (real) photon emission by initial and final particles have been added with the technique of structure functions [4, 5] and "PHOTOS" package. The accuracy of radiative corrections is better or about 1%.

For the background estimation a relatively big sample of the main ISR processes ($2\pi\gamma$, $3\pi\gamma$ ... $6\pi\gamma$, $2K2\pi\gamma$) has been simulated. General simulation (JETSET) with quark-antiquark and $\tau - \tau$ final states to estimate non-ISR type background were also used.

The constrained fit procedure uses the measured momenta and angles of charged particles and error matrix to solve four energy-momentum equations with the photon mass as the only constraint.

The four track sample can contain events with four pions, 4 kaons and events with 2 kaons plus 2 pions in the final state. To discriminate between these three possibilities, the three fits are performed for each event.

The main sources of background are other ISR multipion processes and non-ISR multipion production from e^+e^- collision. The background was studied using simulation and events from the χ^2 control sample.

The mass resolution obtained by simulation is $\sigma_{M4\pi}$=0.0062 GeV and $\sigma_{M4\pi}$=0.0075 for 1.5 GeV and 3 GeV regions respectively. This is confirmed by the data where the J/ψ width in 4π is 0.0080 GeV [1]. Figure 1a presents the invariant mass distribution.

Figure 1b presents the obtained cross section in 0.025 GeV step which is corresponding to about $3\sigma_{M4\pi}$ and bin-to-bin correlations are less than 1%.

The following corrections and systematic errors discussed above have to be added to the measured cross section determined from 4 track sample:

- Luminosity from $\mu\mu\gamma$ [1]: $\pm$3%; 5% for $m_{4\pi}$ <1.0 GeV.

- $\chi^2 < 30$ cut MC-DATA difference: +3±2%
- Background subtraction: ±1%; ±10% for $m_{4\pi}$ <1.0 GeV; ±3% for $m_{4\pi}$ >3.0 GeV
- MC-DATA difference in track losses: +3±2%
- Radiative (multiple FSR) correction accuracy: ±1%
- Acceptance from simulation (model dependent): ±2% for <3 GeV; ±15% for the rest

Assuming no correlation the total systematic error in the cross section is calculated to be 12% for $m_{4\pi}$ <1.0 GeV, 5.0% for 1-3 GeV mass region and 16% for higer masses.

$K^+K^-\pi^+\pi^-$ final state

The constrained fit in 2K2π hypothesis (kaon ID is required for one or two particles) allows to separate this final state with relatively low background. A χ^2 based selection is applied leaving negligible number of background events.

Using number of events, efficiency and ISR luminosity. the $e^+e^- \rightarrow K^+K^-\pi^+\pi^-$ cross section is calculated. Figure 2a shows the obtained cross section.

The systematic errors dominate by not correct acceptance simulation (10%) and a difference in kaon ID for data and MC (up to 5%/track) and estimated to be ≈15%.

$K^+K^-K^+K^-$ final state

The constrained fit in 4K hypothesis allows to separate this final state. Main background for this process are $2K2\pi$ events. But requirements of 3 or 4 particles to have the kaon IDs and χ^2 cuts leave small number of these background events.

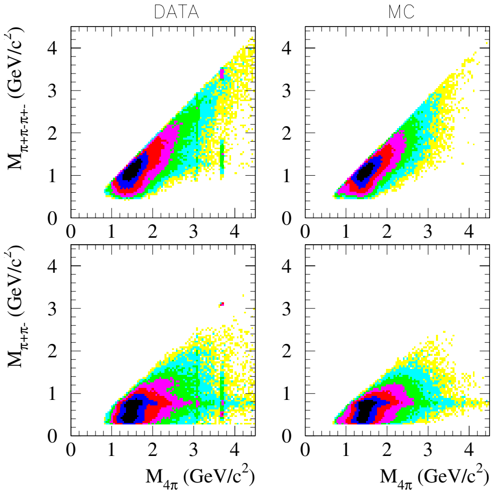
Using number of events, acceptance and ISR luminosity the $e^+e^- \rightarrow K^+K^-K^+K^-$ cross section is calculated. Figure 2b shows the obtained cross section. There are no e^+e^- data available for comparison.

Systematic errors dominate by not correct acceptance simulation and background subtraction procedure (10%) and difference in kaon ID for data and MC (up to 5% per track) and estimated to be ≈25%.

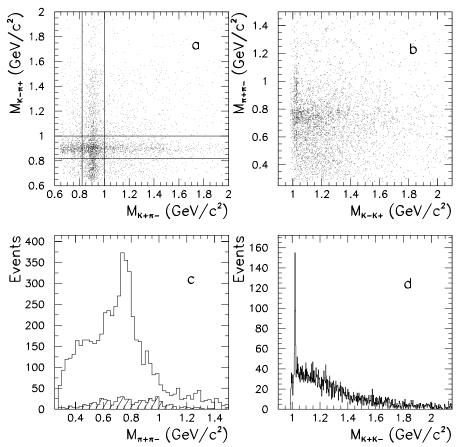
Mass substructures

The different mass combinations were studied for data and MC to search for the states not included to the model. Figures 3a show the scatter plots of 3 pions and 2 pions vs. 4π mass for data and MC. Good agreement in general is seen except the narrow regions for J/ψ and $\psi(2S)$ whose decays are not simulated. From fig. 3a it's clearely visible a contribution from $a_1(1260)$ and $f_2(1270)$, a detailed PWA is needed to confirm it.

Figure 3b shows $\pi\pi$, K^+K^- and $K\pi$ mass combinations. The production seems to be dominated by $K^{*+}(892)K^{*-}(892)$ final state as it is seen in fig. 3b(a). If events in the $K^*(892)$ bands are removed the scatter plot $M_{\pi^+\pi^-}$ vs. $M_{K^+K^-}$ shows the presence of



a) The $\pi^+\pi^-$ and three-pion vs. four-pion invariant mass distributions for data (left) and simulation (right) for the 4π data sample.



b) Invariant mass distributions for the $K^+K^-\pi^+\pi^-$ data sample.

FIGURE 3.

ρ^0 and ϕ resonancies - fig. 3b(b). One dimentional plot fig. 3b(c) shows $\pi^+\pi^-$ mass distribution for events not associated with ϕ and shaded hist for events from ϕ spike shown in fig. 3b(d). No evidence of $\phi f_0(980)$ has been observed so far.

CONCLUSIONS

The good detector resolution and PID capabilities of *BABAR* allow the measurement of the $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ cross section with ISR data in the energy range 0.6 to 4.5 GeV with a systematic error of about 5% in the central region. This can be compared with all e^+e^- data, which are available only up to 2.0 GeV - the maximum c.m. energy where exclusive studies of this channel have been performed. Figure 1b shows obtained cross section in comparison with all existing e^+e^-. It's the first time that the cross section for the process $e^+e^- \to K^+K^-K^+K^-$ has been measured.

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