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New ISR Cross Section Results on $K_S^0 K_L^0 \pi^0$ and $K_S^0 K_L^0 \pi^0 \pi^0$ From BaBar

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Abstract

We present preliminary measurements of the cross sections for $e^+e^- \to K_S^0 K_L^0 \pi^0$ and $K_S^0 K_L^0 \pi^0 \pi^0$ obtained using the technique of Initial State Radiation with 469 fb^{-1} of e^+e^- collision data collected with the BaBar detector at or near the $\Upsilon(4S)$ resonance. The resonant substructure of $K_S^0 K_L^0 \pi^0$ is investigated, and branching fractions for the decays of the charmonium resonances J/ψ and $\psi(2S)$ into these final states are measured.

Keywords: BABAR, hadronic cross section, $(g-2)_\mu$, charmonium decays

1. Introduction

The anomalous magnetic moment of the electron $a_e \equiv (g_e - 2)/2$ presents an extremely precise test of Quantum Electrodynamics (QED); its experimental value and theoretical calculations agree to about one part in a billion. In contrast, there has been a long-standing tension between the standard-model (SM) expectation [1, 2] and the experimental measurement [3] for the anomalous magnetic moment of the muon a_μ. More specifically, the experimentally determined value $10^{10} \times a_\mu^{\rm exp} = 11659208.9 \pm 6.3$ and the theory value $10^{10} \times a_\mu^{\rm SM} = 11659180.2 \pm 4.9$ [1] differ by $10^{10} \times \Delta a_\mu = 28.7 \pm 8.0$, a discrepancy of about 3.6σ. New experiments planned at Fermilab [4] and J-PARC [5] are set to decrease the experimental uncertainty by factors of four or better.

The discrepancy in a_μ may be due to physics beyond the standard model, but it may also be due to the QCD contributions within the SM, in particular the hadronic vacuum polarisation (HVP) and hadronic light-by-light scattering (hLbL) (see *e.g.* [6] and references therein). Due to the non-perturbative nature of QCD at these energy scales, an *ab initio* calculation of the hadronic contributions to a_μ is impossible with current methods. However, the HVP contributions can be reliably determined using a dispersion relation and the optical theorem connecting the HVP to the total cross section for $e^+e^- \to$ hadrons at low energies. Using slightly different approaches, the HVP contribution is estimated to be $10^{10} \times a_\mu^{\rm had,LO} = 692.3 \pm 4.2$ [1] or $10^{10} \times a_\mu^{\rm had,\,LO} = 694.9 \pm 4.3$ [2]. The next-to-leading order contribution is estimated to be $10^{10} \times a_\mu^{\rm had,\,NLO} = -9.84 \pm 0.06 \pm 0.04$ [2].

One of the limiting factors in the determination of the HVP is the need to extrapolate the measured cross section for $K^+K^-\pi^0(\pi^0)$ to the process $K^0\bar{K}^0\pi^0(\pi^0)$. The new measurements presented in this talk will obviate the need for this isospin extrapolation and should help to decrease the uncertainty on the SM expectation for a_μ. This measurement is part of an extensive program at BaBar to measure exclusive cross sections of $e^+e^- \to$ hadrons for a wide range of final states, at center-of-mass energies between threshold and 4.5 GeV (see *e.g.* [7] for new measurements for the final states $\pi^+\pi^-\pi^0\pi^0$ and $\pi^+\pi^-\eta$).

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2. Experimental Setup, Event Selection and Reconstruction

The *BABAR* detector was located at the PEP-II asymmetric-energy e^+e^- collider at SLAC. Its construction and performance is described in great detail in Refs. [8, 9]. The analysis presented here uses 469 fb^{-1} of e^+e^- collision data taken at or just below the $\Upsilon(4S)$ resonance. The effective center-of-mass energy $\sqrt{s'}$ of the collision is lowered by the radiation of a hard photon from one of the initial-state leptons. This technique, which is made possible by the very high luminosity of the *BABAR* dataset, allows for the simultaneous measurement of hadronic cross sections over a large range of $\sqrt{s'}$, reducing the point-to-point systematic uncertainties compared to direct scan experiments.

In the analysis presented here, the reconstruction of events proceeds through the selection of an ISR photon γ_{ISR} with an energy of at least 3 GeV in the e^+e^- center-of-mass (CM) frame. The neutral pions and kaons are reconstructed in their decays $\pi^0 \to \gamma\gamma$ and $K^0_S \to \pi^+\pi^-$, respectively. The long-lived, neutral K^0_L cannot be fully reconstructed. Therefore, this analysis uses K^0_L interacting in the electromagnetic calorimeter; the direction of the cluster is used, but the momentum of the K^0_L is determined by a kinematic fit [10, 11] imposing overall energy-momentum conservation with additional mass constraints for the $\pi^0 \to \gamma\gamma$ candidate(s). The resolution in the $K^0_S K^0_L \pi^0(\pi^0)$ invariant mass is about 25 MeV/c^2.

3. Results

For both processes under consideration, the reconstruction efficiency is estimated using Monte Carlo (MC) simulated data. These MC derived efficiencies are then corrected to match efficiencies measured on real data in a range of control channels. Backgrounds from known ISR processes seem only to describe about half the background visible in data; these additional backgrounds are subtracted using events in the χ^2 control region.

3.1. $K^0_S K^0_L \pi^0$ Cross Section

Events with $\chi^2(K^0_S K^0_L \pi^0) < 25$ of the kinematic fit are selected for further analysis, while events in the control region $25 < \chi^2(K^0_S K^0_L \pi^0) < 50$ are used to determine the background. After subtracting the background and correcting for the reconstruction efficiency, the measured cross section for $e^+e^- \to K^0_S K^0_L \pi^0$ is obtained as shown in Fig. 1, where the error bars indicate the statistical uncertainty only. No previous measurements of this process have been reported. The cross section is dominated

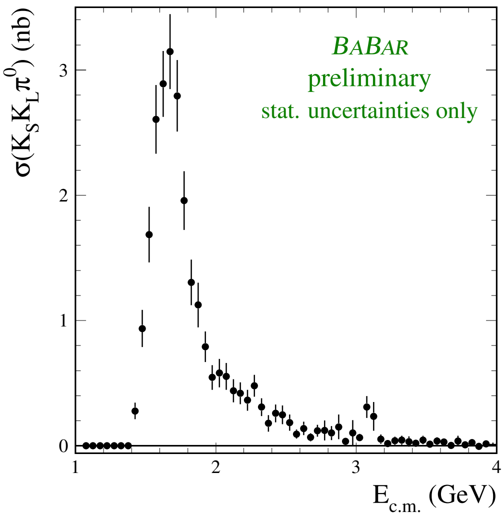

Figure 1: Measured cross section for $e^+e^- \to K^0_S K^0_L \pi^0$. The uncertainties shown are statistical only.

by a broad structure around 1.7 GeV/c^2, and a small contribution from the process $J/\psi \to K^0_S K^0_L \pi^0$ is visible.

Systematic uncertainties arise mainly due to the uncertainty in the background yields. The corrections applied to the reconstruction efficiency determined from simulation contribute a systematic uncertainty of 1.6%. For $K^0_S K^0_L \pi^0$ invariant masses below 2.2 GeV/c^2, the systematic uncertainty due to the background subtraction is below 10%, rising to 80–100% above 3.2 GeV/c^2, where the event yield is dominated by background processes. Radiative corrections are within one percent of unity, with an overall uncertainty of 1%.

3.2. $K^0_S K^0_L \pi^0$ Resonant Substructure

A study of the $K^0_S \pi^0$ and $K^0_L \pi^0$ invariant mass distributions reveals that the cross section is dominated by the process $e^+e^- \to K^*(892)^0 \overline{K}^0 + c.c.$, with a small contribution from $K^*_2(1430)\overline{K}^0 + c.c.$ (Fig. 2). We fit the mass spectra with a sum of two Breit-Wigner functions together with a function describing the non-resonant contribution. On closer inspection, we find that the process $K^*(892)^0 \overline{K}^0 + c.c.$ almost saturates the cross section.

A small contribution to the cross section comes from the isospin $I = 1$, OZI suppressed process $e^+e^- \to \phi\pi^0 \to K^0_S K^0_L \pi^0$ (see Fig. 3). The measured cross section is compatible with the one measured in $K^+K^-\pi^0$ [12] and shows a similar peaking structure around 1.6 GeV/c^2.

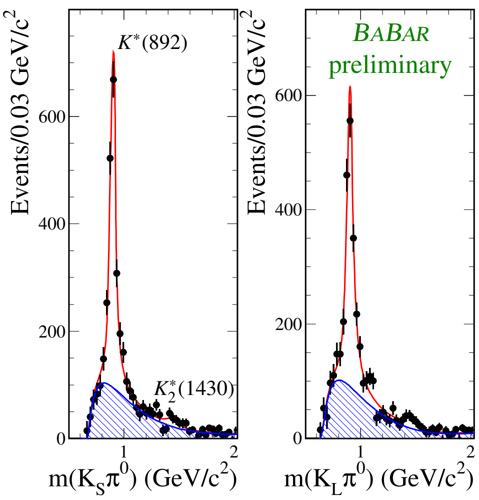

Figure 2: Invariant masses of the $K_S^0\pi^0$ and $K_L^0\pi^0$ subsystems in $e^+e^- \to K_S^0K_L^0\pi^0$. Black points represent background-subtracted data, the (red) curve shows the result of the fit described in the text, and the hatched area shows the non-resonant component.

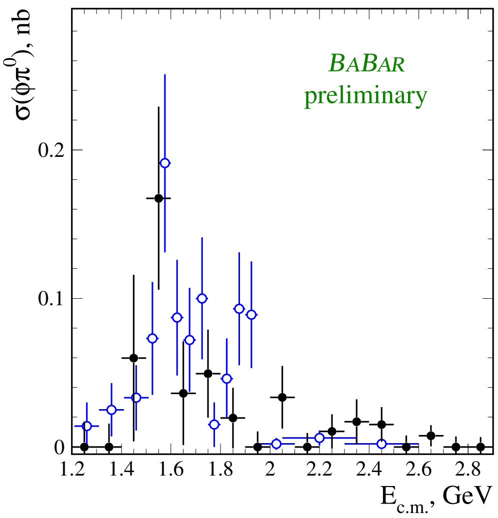

Figure 3: Cross section for $e^+e^- \to \phi\pi^0$. The black filled points show this measurement, the blue open points show the cross section obtained in the final state $K^+K^-\pi^0$ [12]. In both final states, a possible resonant structure near 1.6 GeV/c^2 is clearly visible.

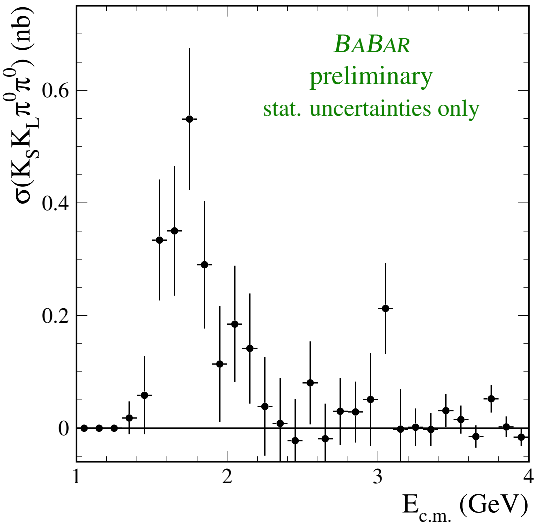

Figure 4: Measured cross section for $e^+e^- \to K_S^0K_L^0\pi^0\pi^0$. The uncertainties shown are statistical only.

3.3. $K_S^0K_L^0\pi^0\pi^0$ Cross Section

The cross section for $e^+e^- \to K_S^0K_L^0\pi^0\pi^0$ is measured in an analogous fashion. For this channel, the region $\chi^2(K_S^0K_L^0\pi^0\pi^0) < 30$ is taken as the signal region, and the control region is taken as $30 < \chi^2(K_S^0K_L^0\pi^0\pi^0) < 60$. Dominant backgrounds are from the ISR processes $e^+e^- \to K_S^0K_L^0$, $K_S^0K_L^0\pi^0$, and $K_S^0K_L^0\eta$; they are subtracted using simulated data normalised to our measurements. Additional backgrounds are estimated from the χ^2 control region. The resulting cross section is shown in Fig. 4. It rises from threshold at 1.4 GeV to a maximum of about 0.5 nb near 1.8 GeV and then decreases with increasing CM energy, except for a J/ψ and (possibly) $\psi(2S)$ signal.

The relative systematic uncertainty is dominated by the background subtraction; it ranges from 25% in the peak region of the cross section to 60% around 2 GeV/c^2 and 100% at higher CM energies.

The statistics is too low to investigate the resonant substructure in detail. A contribution from $K^*(892)^0\bar{K}\pi^0 + c.c$ is evident, but there is no indication for $K^*(892)^0\bar{K}^*(892)^0$. This is consistent with the expectation from a study of the final state $K^+K^-\pi^+\pi^-$ [13].

3.4. Charmonium Decays to $K_S^0K_L^0\pi^0(\pi^0)$

A clear signal of $J/\psi \to K_S^0K_L^0\pi^0(\pi^0)$ is visible in the cross sections (Figs. 1 and 4). Furthermore, there is some indication of the $\psi(2S)$ decaying to $K_S^0K_L^0\pi^0\pi^0$ but not to $K_S^0K_L^0\pi^0$. Using the PDG values for $\Gamma_{ee}(J/\psi) =$ 5.55 keV and $\Gamma_{ee}(\psi(2S)) = 2.35$ keV [14], we obtain the

	$\mathcal{B}/10^{-3}$		
	BABAR prelim.	PDG 2014	
$J/\psi \to K^0_S K^0_L \pi^0$	$2.06 \pm 0.24 \pm 0.10$		
$J/\psi \to K^0_S K^0_L \pi^0\pi^0$	$1.86 \pm 0.43 \pm 0.10$	2.35 ± 0.41	(from $K^+K^-\pi^0\pi^0$)
$\psi(2S) \to K^0_S K^0_L \pi^0$	< 0.3	—	
$\psi(2S) \to K^0_S K^0_L \pi^0\pi^0$	$1.24 \pm 0.54 \pm 0.06$	—	

Table 1: Branching fractions of the charmonium resonances J/ψ and $\psi(2S)$ decaying to the final states observed in this analysis. For the decay $J/\psi \to K^0_S K^0_L \pi^0\pi^0$ only, there is an estimate of the branching fraction in the 2014 edition of the Review of Particle Physics [14], which was inferred from $\mathcal{B}(J/\psi \to K^+K^-\pi^0\pi^0)$.

branching fractions shown in Table 1. The systematic uncertainty of 5% comes from the correction of the MC-derived efficiencies to match data, and from variations in the procedure to determine the signal yield.

Our measurements are the first observations of these J/ψ decay modes. The process $\psi(2S) \to K^0_S K^0_L \pi^0\pi^0$ is seen with a significance of about two standard deviations; this decay has not been reported previously.

4. Summary

We present studies of the processes $e^+e^- \to K^0_S K^0_L \pi^0$ and $e^+e^- \to K^0_S K^0_L \pi^0\pi^0$ at center-of-mass energies below 4 GeV, using the technique of initial-state radiation on a data sample of 469 fb^{-1} collected with the *BABAR* detector. The cross sections for both processes are measured for the first time over the full energy range from threshold to 4 GeV, and the resonant sub-structure is investigated. We observe the decays $J/\psi \to K^0_S K^0_L \pi^0$ and $J/\psi \to K^0_S K^0_L \pi^0\pi^0$ for the first time and see evidence for $\psi(2S) \to K^0_S K^0_L \pi^0\pi^0$ at a significance of 2σ.

These results complete the study of the reactions $e^+e^- \to K\bar{K}\pi\pi$ by *BABAR* in all possible charge combinations (except the final states containing $K^0_L K^0_L$). This will allow a much more precise calculation of the contribution of the $K\bar{K}\pi\pi$ final states to the hadronic vacuum polarisation without the need to rely on isospin relations.

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