

# Hadronic Final States in $e^+e^-$ Annihilation at *BABAR*

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**Abstract.** We present recent results of studies of hadronic final states produced in  $e^+e^-$  annihilation at the *BABAR* experiment at the PEP-II asymmetric-energy storage rings.

We study the processes  $e^+e^- \rightarrow K^+K^-\pi^+\pi^-\gamma$ ,  $K^+K^-\pi^0\pi^0\gamma$ , and  $K^+K^-K^+K^-\gamma$ , where the photon is radiated from the initial state. Studying the structure of these events, we find contributions from a number of intermediate states, and we extract their cross sections where possible. In particular, we isolate the contribution from  $e^+e^- \rightarrow \phi(1020)f_0(980)$ . In the charmonium region, we observe the  $J/\psi$  in all three final states and several intermediate states, as well as the  $\psi(2S)$  in some modes, and measure the corresponding branching fractions.

We describe the preliminary measurement of the hadronic cross section  $\sigma(e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0)$  performed via Initial State Radiation in the mass range from 0.95 GeV to 4.5 GeV. We study the  $s$  dependence with small point-to-point uncertainties and the internal structure of the  $\pi^+\pi^-\pi^0\pi^0$  channel.

We report the first observation of  $e^+e^-$  annihilation into states of positive  $C$ -parity, namely  $\rho^0\rho^0$  and  $\phi\rho^0$ . The two states are observed in the  $\pi^+\pi^-\pi^+\pi^-$  and  $K^+K^-\pi^+\pi^-$  final states, respectively, at energies near  $\sqrt{s} = 10.58$  GeV. The distributions of  $\cos\theta^*$ , where  $\theta^*$  is the center-of-mass polar angle of the  $\phi$  meson or the forward  $\rho^0$  meson, suggest production by two-virtual-photon annihilation.

We present a preliminary study  $e^+e^- \rightarrow c\bar{c}$  events at  $\sqrt{s} \approx 10.6$  GeV containing both a  $\Lambda_c^+$  baryon and a  $\bar{\Lambda}_c^-$  antibaryon. We find roughly 4.2 times the number of events expected if the leading charmed hadron types are uncorrelated. These events have a 2-jet topology, but contain very few additional baryons, indicating a previously unobserved type of  $e^+e^- \rightarrow q\bar{q}$  event in which the primary  $q$  and  $\bar{q}$  are contained in a correlated baryon and antibaryon and there are multiple intermediate mesons.

## 1. Introduction

The high performance of the *BABAR* detector and the PEP-II machine required by the primary goal of the experiment, the study of  $CP$  violation in the  $b$  sector, makes *BABAR* an excellent place to study hadronic final states in  $e^+e^-$  annihilation. Of special importance are the particle identification capabilities that make it possible to cleanly study many different final states. With the method of radiative return it is possible to not only study events at the center-of-mass energy of the collider but also at low energy down to the threshold.

## 2. Hadronic Final States at $\sqrt{s} < 5$ GeV

As theoretical predictions of  $(g-2)$  of the muon and the running QED coupling constant  $\alpha$  depend on the precise knowledge of the production of hadronic final states at energies below 10 GeV, the interest in new measurements in this energy range has increased. In the past, the

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predictions of the hadronic contributions to these two quantities only used hadronic cross section data from direct  $e^+e^-$  measurements at low energies.

More recently, the use of initial state radiation (ISR) processes with hard photons at meson factories for hadron spectroscopy and the measurement of hadronic cross sections has been proposed [1]. The advantage of using ISR events is that a scan of the entire effective center of mass energy range, the available energy after radiation of a hard photon, is performed in the same experiment, avoiding uncertainties in the relative normalization when combining data from different experiments. In addition, the high transverse momentum of the particles associated with the hadronic final state recoiling against the high energy ISR photon, leads to high acceptance and detection efficiencies.

The *BABAR* collaboration has already published several results for hadronic cross sections at low  $\sqrt{s}$  using the radiative return method [2–6]. Here we present new results [7] for the  $K^+ K^- \pi^+ \pi^- \gamma$ ,  $K^+ K^- \pi^0 \pi^0 \gamma$ ,  $K^+ K^- K^+ K^- \gamma$  final states and preliminary results for the  $\pi^+ \pi^- \pi^0 \pi^0 \gamma$  final state.

The analysis of hadronic final states at  $\sqrt{s} < 5$  GeV require the ISR photon to be detected in the electromagnetic calorimeter of the *BABAR* detector. Recoiling against the photon, we require a set of particles with specific identification according to the final state under study.

### 2.1. The $K^+K^-\pi^+\pi^-$ , $K^+K^-\pi^0\pi^0$ , and $K^+K^-K^+K^-$ Final States

We present the measurements of the cross sections  $\sigma(e^+e^- \rightarrow K^+K^-\pi^+\pi^-)$ ,  $\sigma(e^+e^- \rightarrow K^+K^-\pi^0\pi^0)$ , and  $\sigma(e^+e^- \rightarrow K^+K^-K^+K^-)$ .

For the  $K^+K^-\pi^+\pi^-$  final state this measurement is consistent with a previous *BABAR* measurement but has significantly improved statistical precision and it is in good agreement with previous data from DM1 [8]. The substructure of this final state has been examined and we find contributions from  $K^{*0}K\pi$ ,  $\phi(1020)\pi^+\pi^-$ , and  $\phi(1020)f_0(980)$ . For these three channels the cross section is measured as a function of center-of-mass energy.

There are no previous data to compare the *BABAR* measurement of the cross section of the  $K^+K^-\pi^0\pi^0$  and  $K^+K^-K^+K^-$  final states to. For the final state with two neutral pions we find contributions from the channels  $\phi(1020)\pi^0\pi^0$ ,  $K^{*0}K\pi$ , and  $\phi(1020)f_0(980)$ . For the latter two channels we also measure the cross section. We find a contribution of  $\phi(1020)K^+K^-$  in the  $K^+K^-K^+K^-$  final state.

The  $\phi(1020)f_0(980)$  contribution is clearly visible in the  $K^+K^-\pi^+\pi^-$  and  $K^+K^-\pi^0\pi^0$  final states. Assuming one resonance interfering with a non-resonant component, we find the resonance to have a mass of  $(2.175 \pm 0.010 \pm 0.015)$  GeV/ $c^2$  and a width of  $(0.058 \pm 0.016 \pm 0.020)$  GeV/ $c^2$  as described in detail in [7, 9].

All the cross section measurements cover the charmonium region and it is possible to extract the branching fractions for 12 decay channels of the  $J/\psi$  and  $\psi(2S)$  where we present four new measurements and four with increased precision [7].

If the  $Y(4260)$  had a large branching fraction into  $\phi\pi^+\pi^-$ ,  $\phi\pi^0\pi^0$ , or  $\phi f_0$  we would expect to find an indication in the invariant mass distributions. However, we do not find evidence in either channel and calculate upper limits of  $\mathcal{B}_{Y \rightarrow \phi\pi^+\pi^-} \cdot \Gamma_{ee}^Y < 0.4$  eV and  $\mathcal{B}_{Y \rightarrow \phi f_0} \cdot \Gamma_{ee}^Y < 0.43$  eV at 90%CL which are much lower than the corresponding value for the decay  $Y(4260) \rightarrow J/\psi \pi^+\pi^-$  [10].

### 2.2. The $\pi^+\pi^-\pi^0\pi^0$ Final State

The uncertainty of the hadronic contribution to  $(g-2)_\mu$  in the energy range 1 – 2 GeV dominates the uncertainty of recent evaluations of  $(g-2)_\mu$  [11]. In this energy range the dominant source of uncertainty is the cross section of the four pion final state. While the final state with four charged pions has been measured very precisely from the threshold up to 4.5 GeV by *BABAR* [3],

the partly neutral four pion state is well known only below 1.4 GeV where results of different experiments (SND, CMD-2) are not in good agreement [12, 13].

The preliminary measurement of  $\sigma(e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0)$  presented here covers the energy range from 0.95 GeV up to 4.5 GeV. It is the first measurement of the cross section above 2.4 GeV. Since one experiment now covers the entire energy range without uncertainties in the point-to-point normalization, this measurement can help to fix the normalization scale of the measurements below 1.8 GeV. We observe good agreement with the SND measurement and new preliminary data also suggest a good agreement with CMD-2 [14].

This cross section measurement has achieved a preliminary systematic uncertainty in the peak region around 1.8 GeV of about 7.9% which is already an improvement over previous measurements that have achieved 10 – 15% in the peak region. Above 1.4 GeV the systematic error shows an improvement of more than an order of magnitude with respect to previous measurements. We expect further improvements of the systematic uncertainty for the final result.

In addition to the cross section the internal structure of the  $\pi^+\pi^-\pi^0\pi^0$  channel was also studied. Strong contributions from the  $\omega\pi^0$  and  $a_1(1260)\pi$  have been observed. Two previously unknown contributions from the  $\rho^+\rho^-$  and  $f_0(980)\rho^0$  channels were also found.

Since this measurement covers the charmonium region it is possible to determine the branching fraction of  $J/\psi \rightarrow \pi^+\pi^-\pi^0\pi^0$  for the first time. We find  $\mathcal{B}_{J/\psi \rightarrow 4\pi} \cdot \Gamma_{ee}^{J/\psi} = (3.19 \pm 0.40) \times 10^{-2}$  keV and with the PDG value of  $\Gamma_{ee}^{J/\psi} = (5.55 \pm 0.14)$  keV we can extract the branching fraction  $\mathcal{B}_{J/\psi \rightarrow 4\pi} = (5.74 \pm 0.74) \times 10^{-3}$ .

The final measurement of the cross section  $\sigma(e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0)$  will help to reduce the uncertainty of the hadronic contribution to  $(g-2)_\mu$ . However, since the contribution of the partly neutral four pion channel is relatively small, an improvement of the systematic error of this measurement cannot reconcile the SM prediction with the measurement of  $(g-2)_\mu$  [15].

### 3. Hadronic Final States at $\sqrt{s} \approx 10.6$ GeV

Studying hadronic final states at  $\sqrt{s} \approx 10.6$  GeV helps to improve our understanding of QCD. The large data sample of *BABAR* makes it possible to study rare processes such as events with  $\Lambda_c^+ \bar{\Lambda}_c^- X$  pairs or  $C = +1$  final states in  $e^+e^-$  annihilation.

#### 3.1. The $\rho^0\rho^0$ and $\phi\rho^0$ Final States

The final states of the exclusive reactions  $e^+e^- \rightarrow \rho^0\rho^0$  and  $e^+e^- \rightarrow \phi\rho^0$  are even under charge conjugation and thus cannot be produced in single-virtual-photon annihilation (SVPA). However, the production of  $C = +1$  final states is possible in two-virtual-photon annihilation (TVPA). The  $\rho^0\rho^0$  and  $\phi\rho^0$  final states are reconstructed in events with either two  $\pi^+\pi^-$  pairs or  $K^+K^-$  and  $\pi^+\pi^-$  pairs, respectively. We find clear indications for the production of the  $\rho^0\rho^0$  and  $\phi\rho^0$  final states [16]. From a fit to nine rectangular regions of the two dimensional mass distributions of the  $\pi^+\pi^-$  and  $K^+K^-$  pairs, we extract the number of  $1243 \pm 43$   $\rho^0\rho^0$  and  $147 \pm 13$   $\phi\rho^0$  signal events.

To investigate the production mechanism, we examine the production angle  $\theta^*$ , the center-of-mass polar angle of  $\phi$  or  $\rho^0$  in the forward hemisphere. The strongly forward peaking angular distributions are consistent with the TVPA expectation of  $\frac{d\sigma}{d\cos\theta^*} \propto \frac{1+\cos^2\theta^*}{1-\cos^2\theta^*}$ . Other distributions like  $1 + \cos^2\theta^*$  are disfavored. TVPA predicts the  $\phi$  and the  $\rho^0$  to be transversely polarized which translates to a  $\sin^2\theta_H$  distribution of the decay helicity angle  $\theta_H$ . The  $\theta_H$  distributions of the  $\phi$  and the  $\rho^0$  are in good agreement with a  $\sin^2\theta_H$  distribution.

We also extract the fiducial cross section within  $|\cos\theta^*| < 0.8$  near  $\sqrt{s} = 10.58$  GeV and find  $\sigma_{\text{fid}}(e^+e^- \rightarrow \rho^0\rho^0) = (20.7 \pm 0.7 \pm 2.7)$  fb and  $\sigma_{\text{fid}}(e^+e^- \rightarrow \phi\rho^0) = (5.7 \pm 0.5 \pm 0.8)$  fb which is in good agreement with the calculation from a vector-dominance two-photon exchange model [17].

We conclude that we have observed non-SVPA production of exclusive final states. The effect of the TVPA contribution on the Standard Model predictions of  $(g - 2)_\mu$ , which assume the low-energy  $e^+e^-$  hadronic cross section to be entirely due to SVPA processes, is estimated to be small compared with the current precision [11].

### 3.2. The $\Lambda_c^+ \bar{\Lambda}_c^- X$ Final State

Baryon number conservation in high energy jets produced in  $e^+e^-$  annihilation can be realized either locally through a baryon antibaryon pair that is produced in one step of the hadronization chain with a small value of rapidity difference or through the production of a primary diquark and antidiquark where the jets contain a leading baryon and antibaryon, respectively, with a high rapidity difference. Most previous experimental data have shown no evidence for primary production.

We present a preliminary study of  $e^+e^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- X$  events near  $\sqrt{s} = 10.6$  GeV where  $\Lambda_c^+$  candidates are reconstructed in the channels  $pK^-\pi^+$  and  $pK_s^0$  where charge conjugation is implied. Clear  $\Lambda_c^+$  signals are visible in the  $pK^-\pi^+$  and  $pK_s^0$  invariant mass distributions. Plotting the  $pK^-\pi^+$  ( $pK_s^0$ ) vs. the  $\bar{p}K^+\pi^-$  ( $\bar{p}K_s^0$ ) mass we find  $649 \pm 31$   $\Lambda_c^+ \bar{\Lambda}_c^- X$  signal events in the overlap of the  $\Lambda_c$  and  $\bar{\Lambda}_c$  mass bands. Under the assumption of no correlation between the  $c$  and  $\bar{c}$  hadron types we expect about 155 signal events. The ratio of observed to expected events of 4.2 is consistent with an observation by CLEO [18].

We investigate the structure of the  $\Lambda_c^+ \bar{\Lambda}_c^- X$  events and find that the majority of the events do not contain any additional baryons and therefore the conservation of the baryon number is realized with the primary  $c$  and  $\bar{c}$  hadrons. Only  $13 \pm 8$  events are true 4-baryon events, well below the expectation of 155 events. The 4-baryon process is strongly suppressed indicating the dominance of a different process.

We find events in the single  $\Lambda_c^+$  sidebands where the  $\Lambda_c^+$  are the decay products of heavier  $c$  baryons, i.e.  $\Sigma_c^{++/0}$  and excited  $\Lambda_c^+$  states. Studying  $e^+e^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- X$  events with additional mesons we find that the  $K : \pi$  ratio is much lower than in typical hadronic events.

We conclude that we find direct evidence for a new class of events where the baryon number is conserved by the primary baryon and antibaryon and not locally along the hadronization chain.

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