Progress on R Measurement through ISR with BABAR

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The status of the ISR analysis with BABAR is presented. Preliminary results are presented on the process $e^+e^- \rightarrow 2\pi^+2\pi^-$ and $3/\psi$ decays including a determination of its total width and the branching ratios into $2\pi^+2\pi^-$, $K^+K^-\pi^+\pi^-$ and $2K^+2K^-$ modes.

1. Introduction

High-luminosity $e^+e^-$ storage rings designed for the study of CP violation, such as KEK-B, PEP-B, and DAΦNE, have opened a new possibility to measure $e^+e^-$ annihilation using initial-state radiation (ISR) [1–3]. A large mass range becomes accessible in a single experiment, especially at B factories, contrary to the case with fixed energy machines which are optimized only in a limited region. The broad-band coverage may result into a better understanding of systematic effects since only one experimental set-up is involved.

Apart from their own physics interest, ranging from hadronic spectroscopy to tests of QCD, measurements of the ratio $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma_{pt}$ provide the necessary input to dispersion integrals for computing hadronic vacuum polarization contributions. This is indeed the case when calculating the theoretical prediction for the muon magnetic anomaly $a_\mu$ and the running of the electromagnetic coupling to the Z mass, $\alpha(M_Z^2)$, one of several ingredients in precision tests of the electroweak theory bearing on such fundamental issues as the structure of the Higgs sector.

The cross section for the ISR process $e^+e^- \rightarrow f\gamma$ with a particular final state $f$ is related to the cross section $\sigma_f(s)$ for the direct annihilation $e^+e^- \rightarrow f$ through

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

where $x = 2E_\gamma/\sqrt{s}$, $E_\gamma$ being the radiated photon energy in the $e^+e^-$ frame and $\sqrt{s}$ the nominal centre-of-mass energy of the collider. The quantity $s' = s(1 - x)$ represents the mass squared of the final-state $f$ system. The radiator function $W(s,x)$ providing the virtual photon spectrum can be computed including radiative corrections to an accuracy better than 1\% [4]. The production of ISR photons is strongly peaked along the initial beams, but for $\sqrt{s} \sim 10$ GeV the fraction at large angle is relatively large, i.e. 10 – 15\% in the BABAR central detector.

The measurement of the corresponding leptonic process $e^+e^- \rightarrow \mu^+\mu^-\gamma$ provides the ISR luminosity. Thus the Born cross section $\sigma_f(s')$ is obtained through

$$\sigma_f(s') = \frac{\Delta N_f\gamma}{\Delta N_{\mu\mu\gamma}} \frac{\epsilon_{\mu\mu}(1 + \delta_{\gamma}^{FSR})}{\epsilon_f(1 + \delta_{FSR}^{\gamma})} \sigma_{\mu\mu}(s') \quad (2)$$

where $\Delta N_f\gamma$ is the number of detected $f\gamma$ events in the bin of width $\Delta s'$ centred at $s'$, $\epsilon_f$ is the detection efficiency for the final state $f$ and $\delta_{FSR}$ is the fraction of the cross section for $e^+e^- \rightarrow f\gamma$ where the photon is emitted by the final-state particles. The latter quantity can be sizeable for the $\mu\mu$ channel, but negligible for most of the low-energy hadronic states which have vanishingly small cross sections at the nominal energy $\sqrt{s}$. The radiative corrections for the initial state and vacuum polarization effects cancel in the ratio (2), as does the photon efficiency.

The BABAR detector at the PEP-II asymmet-
ric $e^+e^-$ storage ring is well suited for this study. The different triggers routinely used allow one to select ISR processes with a $95-98\%$ efficiency. A complete description of $\text{BABAR}$ can be found elsewhere $[5]$. All main detector components are used in this analysis as particle identification plays a crucial role in separating the different channels. It is also important in correctly computing the $s'$ value for each event as it is obtained from the produced particles momenta since the photon energy is rather insensitive to $s'$ in the low-energy regime of interest. In particular, K-$\pi$ separation in quartz radiators (DIRC) is an essential ingredient. The information from the tracking system (silicon vertex detector and drift chamber) is used to measure the angles and the momentum of the charged particles. Muons are identified in the instrumented flux return (IFR) of the superconducting solenoidal magnet, while photons are detected in the fine-grain CsI calorimeter.

The data used in this analysis correspond to an integrated luminosity of $89.3 \text{fb}^{-1}$, collected both at the $\Upsilon(4S)$ and in the nearby continuum.

2. Event preselection

ISR events are preselected requiring a large-angle photon in the central part of the detector with an energy in the centre-of-mass larger than 3 GeV. This requirement is loosened down to 0.5 GeV for 2-track events which have at least one track identified as a muon, in order to collect a large statistics of muon tracks for calibrating the muon-identification performance. The number of tracks pointing well to the interaction region is required to be even and larger than two, and their total charge should be equal to zero. A loose kinematic constraint is applied by asking the ISR photon candidate to be inside a 0.3 radian cone whose axis is along the missing momentum vector constructed from all the recorded recoiling particles. Essentially all low-energy exclusive ISR final states are retained by these general selection criteria, while about $2\%$ of all $\text{BABAR}$ events are kept.

3. The di-muon final state

The process $e^+e^- \rightarrow \mu^+\mu^-\gamma$ plays an important role in this analysis. For $\mu\mu$ masses less than a few GeV, it provides the measurement of the ISR luminosity, while for masses larger than 2 GeV, where hadron pairs are negligible, it enables one to measure the muon identification efficiency. For this latter purpose, a muon candidate is tagged by the opposite identified muon. The large statistics of muons collected in this way efficiently covers the acceptance of the detector so that fine-grained efficiency maps in momentum, polar and azimuthal angles can be constructed.

A $1C$ kinematic fit using the two muon events. After the $\mu\mu$ mass and $\chi^2$ cuts, the purity of the muon sample is found to be better than 0.999. In addition, the fit improves the $\mu\mu$ mass resolution which decreases from 16 MeV down to 8 MeV at the $J/\psi$ mass.

Fig. 1 shows the derived spectrum of ISR luminosity per 100 MeV energy bins. Thus, the $\text{BABAR}$ luminosity of $89.3 \text{fb}^{-1}$ corresponds to an $e^+e^-$ energy scan taken all together with 0.7 pb$^{-1}$/100 MeV at 1 GeV and 3.6 pb$^{-1}$/100 MeV at 4 GeV. It provides a statistically competitive hadron sample, especially in the range between 1.4 and 3 GeV.

4. Hadronic channels

The main approach to the R measurement is the study of exclusive hadronic channels, constrained by a kinematic fit and with identified charged particles. Work is in progress along these lines, including the measurement of the following final states: $\pi^+\pi^-, K^+K^-, \rho\rho, \pi^+\pi^-\pi^0, 4\pi, 5\pi, 6\pi, \pi\pi\eta, K\bar{K}\pi, K\bar{K}\pi\pi, 2K2\bar{K}, K\bar{K}\eta, \text{with charged and neutral (K}_0^0\text{) kaons. Another approach, based on an inclusive method where the hadronic mass is deduced from the ISR photon energy, is also in progress, with the difficulty that the resolution deteriorates rapidly for low recoil masses.}

The study of the $\pi^+\pi^-$ final state is an important part of the programme, especially in view of persisting discrepancies between existing $e^+e^-$
Figure 1. The differential ISR luminosity in 100-MeV bins obtained from the measurement of $e^+e^- \rightarrow \mu^+\mu^-\gamma$. The points near the $\rho(770)$ and $J/\psi$ resonances are excluded, because of pion misidentification as muon in the first case and the non-QED nature of the second process.

results and isospin-corrected $\tau$ data [6,7]. Such a study requires a good control of systematic uncertainties at the 1% level or better. The ISR method has several advantages compared to the standard fixed-energy annihilation: (i) a large mass range is simultaneously covered in a single experiment, (ii) the cross section can be measured down to threshold with excellent acceptance, and (iii) easier particle identification can be achieved, thanks to the Lorentz boost given to the hadronic system.

Since the $\pi^+\pi^-$ and $\mu^+\mu^-$ final states have the same topology, it is advantageous to directly measure the ratio $N_{\pi\pi}/N_{\mu\mu}$ since many effects cancel: the $e^+e^-$ luminosity, ISR and vacuum polarization radiative corrections, the photon detection efficiency. Small corrections still need to be applied concerning trigger efficiencies (calorimeter triggers are more efficient for pions), tracking efficiency (because pions can produce secondary interactions in the tracking detector), FSR corrections. All these effects can in fact be studied directly on the data. The major experimental task remains the determination of the particle identification efficiency matrix, using pure samples of known particles, as outlined above for the muons, as a function of momentum and the 2-dimensional location of the particle in the relevant detectors. Such a detailed study is still in progress.

Preliminary results are available for the final state with four charged particles, namely $2\pi^+2\pi^-$, $K^+K^-\pi^+\pi^-$, and $2K^+2K^-$. Fig. 2 shows the mass distribution of the events satisfying the $2\pi^+2\pi^-$ kinematics and $K/\pi$ identification constraints. No muon identification was applied as no corresponding background is expected in this four-track sample. The data are seen to be dominated by a broad peak at 1.5 GeV originating from the $\rho(1450)$ and $\rho(1700)$ resonances, a shoulder near 2 GeV, and sharp peaks at the $J/\psi$ and $\psi'$ masses. The latter signal is the result of the decay chain $\psi' \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow \mu^+\mu^-$. The background from other hadronic channels is small and subtracted in each mass bin. Overall, about 70k events are obtained leading to small statistical uncertainties. The normalization uncertainty is estimated to be 5%, dominated by the luminosity determination and the dependence of the detection efficiency on the dynamics (below 2 GeV the intermediate state $\pi a_1$ is found to be dominant). The derived cross section is given in Fig. 3. The accuracy of the BABAR data is comparable to the latest most precise results from CMD-2 [8] and SND [9] below 1.4 GeV and the agreement is good. Between 1.4 and 2 GeV the quality of the BABAR data exceeds that from DCI and Adone. The range above 2 GeV is only covered by BABAR.

One can illustrate the impact of the BABAR results on the $2\pi^+2\pi^-$ annihilation cross section obtained through ISR by computing its contributions to the lowest-order hadronic component of the muon magnetic anomaly. Using the same energy range from threshold up to 1.8 GeV as in Ref. [10] for a convenient comparison, one gets

\[
a_{\mu}^{\text{had,LO}}[4\pi] = (12.95 \pm 0.64 \text{_{exp}} \pm 0.13 \text{_{rad}}) \times 10^{-10}(3)
\]

to be compared to the values [10] obtained us-
Figure 2. The 4-pion invariant mass distribution for kinematically constrained events of the type $e^+e^- \rightarrow 2\pi^+2\pi^-\gamma$. No muon/pion separation is applied. The points with error bars indicate the level of background obtained from a study of the $\chi^2$ distribution of the kinematical fit. The cross-hatched histogram corresponds to the non-ISR background as given by the JETSET simulation of annihilation events. Sharp signals are seen at the $J/\psi$ and $\psi'$ masses.

Figure 3. The $e^+e^- \rightarrow 2\pi^+2\pi^-$ cross section obtained from ISR at BABAR in comparison with all existing $e^+e^-$ data.

with $x_0 = 1 - M^2/s$. The total $J/\psi$ ISR cross section amounts to 0.036 nb for $s = (10.58)^2$ GeV$^2$, leading to $4 \times 10^6$ events for the present 130 fb$^{-1}$ of BABAR luminosity (the angular acceptance of the detected ISR photon is about 0.1).

For the $\mu^+\mu^-$ final state, one can directly compare the rate in the $J/\psi$ peak (about 8000 events) to the continuum (see Fig. 4) and derive the value of the product

$$\Gamma_{J/\psi \rightarrow e^+e^-} B_{J/\psi \rightarrow \mu^+\mu^-} = (0.330 \pm 0.008_{\text{stat}} \pm 0.007_{\text{syst}}) \text{ keV}$$

The systematic error receives contributions from the background estimation, the $J/\psi$ line shape, the radiative corrections and Monte Carlo statistics. Using the world averages for $B_{J/\psi \rightarrow \mu^+\mu^-}$ and $B_{J/\psi \rightarrow e^+e^-}$, one can derive the $J/\psi$ electronic and total widths, $\Gamma_{J/\psi \rightarrow e^+e^-} = (5.61 \pm 0.20)$ keV and $\Gamma_{J/\psi} = (94.7 \pm 4.4)$ keV, to be compared to the world average values [11] of $(5.26 \pm 0.37)$ keV and $(87 \pm 5)$ keV, respectively.
From the mass spectrum given in Fig. 2, the following quantities can be derived:

\[
\Gamma_{J/\psi \rightarrow e^+e^-} - B_{J/\psi \rightarrow 4\pi} = (1.95 \pm 0.14_{\text{stat}} \pm 0.13_{\text{syst}}) \times 10^{-2} \text{ keV}
\]

(6)

\[
\Gamma_{\psi' \rightarrow e^+e^-} - B_{\psi' \rightarrow \mu^+\mu^-} - B_{\psi' \rightarrow J/\psi\pi^+\pi^-} = (4.50 \pm 0.18_{\text{stat}} \pm 0.22_{\text{syst}}) \times 10^{-2} \text{ keV}
\]

(7)

Using the world averages [11] for the \(J/\psi\) and \(\psi'\) electronic widths, the results \(B_{\psi' \rightarrow 4\pi} = (3.70 \pm 0.27 \pm 0.36) \times 10^{-3}\) and \(B_{\psi' \rightarrow J/\psi\pi^+\pi^-} = 0.361 \pm 0.015 \pm 0.037\) are obtained, in agreement with the world average values [11] of \((4.0 \pm 1.0) \times 10^{-3}\) and \(0.305 \pm 0.016\), respectively.

Taking advantage of the \(K/\pi\) Cherenkov identification, one can measure the \(J/\psi\) decay rate into final states involving \(K^+K^-\) pairs. The corresponding mass spectra are given in Figs. 5 and 6. Using again the world average value for the electronic width, the following branching ratios are measured: \(B_{\psi \rightarrow K^+K^-\pi^+\pi^-} = (6.25 \pm 0.50 \pm 0.62) \times 10^{-3}\) and \(B_{\psi \rightarrow K^+K^-K^+K^-} = (6.9 \pm 1.2 \pm 1.1) \times 10^{-4}\). Both determinations are more precise than the current world averages [11] of \((7.2 \pm 2.3) \times 10^{-3}\) and \((7.3 \pm 3.) \times 10^{-4}\), respectively.
6. Conclusions

Preliminary results from BABAR on final states produced through ISR show the high physics potential of this sample which should yield precise measurements of $e^+e^-$ annihilation cross sections. The ISR method will allow one to cross check the results of the ‘direct’ experiments, with the significant advantage that the important energy range from threshold to 3-4 GeV can be covered in a single experiment, thereby reducing systematic uncertainties.

The ratio $R$ will be measured from the sum of exclusive channels, providing input for vacuum polarization calculations, QCD studies and investigations in hadronic spectroscopy. Amazingly, the current data is already providing very competitive results for $J/\psi$ and $\psi'$ decays.

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