Physics with the initial state radiation events at B-factory experiments

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Initial state radiation (ISR) events produced in e^+e^- collisions at the $\Upsilon(4S)$ energy region can provide access to e^+e^- annihilations at lower C. M. energies. At B-factory experiments the data rate is substantial for physics at all energies below the $\Upsilon(4S)$. This paper describes the tagging of the ISR events, and identifies several physics topics that can be studied with the ISR data.

1. INTRODUCTION

The B factory experiments are designed to study primarily the CP asymmetries in neutral B meson decays. One of the requirements is that the machine must operate with a luminosity in excess of 10^{33} cm^{-2}s^{-1} in order to produce sufficient B mesons. At this unprecedented high luminosity, hadronic event rates produced via ISR followed by $e^+e^-\to q\overline{q}$ at C. M. energies below the $\Upsilon(4S)$ can be substantial. Meanwhile, these ISR data contains $e^+e^-\to q\overline{q}$ interactions at all energies below the $\Upsilon(4S)$, providing excellent experimental opportunities to study a broad spectrum of physics topics at low energies, topics that are normally explored by a tau-charm facility.

2. INITIAL STATE RADIATION EVENTS AT THE $\Upsilon(4S)$

In the C. M. frame of reference of the e^+e^- at the $\Upsilon(4S)$ ($\sqrt{s}$=10.58 GeV), an ISR reduces the C. M. energy of e^+e^- annihilations to[1]

$$s' = \sqrt{s}(\sqrt{s} - 2E_\gamma) \tag{1}$$

where E_γ is the energy of the ISR photon, which uniquely identifies the C. M. energy, $\sqrt{s'}$, of the subsequent e^+e^- annihilation. The differential production cross section for a specific process from ISR has been evaluated to be[1]

$$\frac{d\sigma}{dk} = f(s,k)\sigma(s') \tag{2}$$

where $k = 2E_\gamma/\sqrt{s}$, $f(s,k)$ is a sampling function and $\sigma(s')$ is the nominal cross section for this process at C. M. energy $\sqrt{s'}$. The total ISR cross section can be calculated by substituting $\sigma(s')$ with $R(s')\cdot\sigma_{\mu\mu}(s')$, where $R(s')$ is the ratio between the total hadronic cross section and the $e^+e^-\to\mu\overline{\mu}$ cross section, $\sigma_{\mu\mu}(s')$.

A narrow resonance with mass M_R has a spin averaged Breit-Wigner production cross section

$$\sigma(s') = F\frac{3\pi}{s'}\frac{\Gamma_{ee}\Gamma_0}{(\sqrt{s'}-M_R)^2+\frac{\Gamma_0^2}{4}} \tag{3}$$

wheres F=0.38938×10^6 nb, and Γ_0, Γ_{ee} are the full width and partial width to e^+e^- (in GeV) of the resonance. Eq.s (2) and (3) can be used to evaluate the rate of resonances like charmonia produced via ISR.

3. TAGGING OF ISR EVENTS AT B-FACTORY EXPERIMENTS

ISR events are characterized by a very high energy photon that is mostly along the beam direction. About 11% of the ISR photons are contained within $|cos\theta| < 0.85$ (in the C. M. system)[3], that are within detector acceptance, where θ is the angle between the photon and the beam direction

The tagging of ISR events with $E_\gamma > 3$ GeV in the C. M. system, and background contributions from B decays, continuum $e^+e^- \to q\overline{q}$ events and radiative $\Upsilon(1S)$ decays have been studied using the JETSET7.4 simulation program[3]. For each of the processes 10 M events are generated. The main backgrounds are found to be photons from decays of the π^0. The ISR tag requires $E_\gamma > 3$ GeV ($\sqrt{s'}$ <6.94 GeV) and $|cos\theta| < 0.85$. The energy of the photon is smeared according to the resolution of the *BABAR* detector[4].

Table I. Numbers of Events in 100 fb^{-1} of Data

interaction type	cross section (nb)	No of events produced (M)	No of events pass selection (M)
ISR hadronic event ($5 < \sqrt{s'} < 7$)	2.1	210	24.0
B decays	1.05	105	0.00028
continuum $q\overline{q}$	3.39	339	0.778
$\Upsilon(1S)$	0.0215	2.15	0.015
total background	4.4615	446.15	0.7933

The results are summarized in Table I, where the generated events in the simulation have been normalized to their production cross sections. The backgrounds considered represent only 3.3% of the total tagged events. The rms resolution on the $\sqrt{s'}$ is found to be 80 MeV at $\sqrt{s'}$=7 GeV and 110 MeV at $\sqrt{s'}$=5 GeV, respectively, assuming a photon energy resolution of the *BABAR* detector.

4. PHYSICS TOPICS WITH ISR DATA

High statistics R scan between 5 - 7 GeV, model independent measurement of the decays of the D_s^+ and Λ_c^+ hadrons, and searches for heavy hybrids are discussed in this section.[1]

[1]Note that although τ, charmonium and other charm physics topics are not covered here, they can also be studied with a similar approach.

4.1. High Statistics R Scan Between 5 - 7 GeV

Uncertainties on the lowest order cross section for $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ in the low energy region are rather large[2]. These uncertainties limit the precision of the QED running coupling constant evaluated at the mass of the Z boson, $\alpha(M_Z^2)$, which in turn limits the precision of the determination of the Higgs mass from radiative corrections in the Standard Model[5]. Current and planed R scans will reduce the uncertainties on R at energies below 5 GeV [6]. However in the 5 - 7 GeV region data are sparse and the precisions are poor[2]. An improved measurement is needed.

As shown in sections 2 and 3 the high energy photon tagged events are dominated by ISR events, the rate of which is directly related to R(s'). On an event-by-event basis the resolution on the $\sqrt{s'}$ is accurate to 80 - 110 MeV. An effective R scan can be extracted from the tagged ISR events and the photon energy spectrum. For a precision measurement of R between 5 - 7 GeV, radiative corrections would be needed to relate the event rate to R.

The production via ISR of $J\psi$ and ψ(2S) are estimated to be 3.73 M and 1.34 M in 100 fb^{-1} of data, using eq.s (2) and (3). These charmonia can be used for the validation and calibration for a R measurement.

4.2. Measurement of decays of charm hadrons

Branching fractions of exclusive decays of the $\mathrm{D_s^+}$ meson and the Λ_c^+ baryon are only poorly known, and few experimental results exist on the their inclusive decays[2]. It is important to improve the knowledge on these processes to understand the dynamics of charm decays, and to make possible precision measurements of B decays which proceed dominantly through charmed hadrons.

The C. M. energy region for threshold production of $\mathrm{D_s^+D_s^-}$ ($\Lambda_c^+\Lambda_c^-$) is 3.937 - 4.334 GeV (4.569 - 5.088 GeV) where the lower energy bound is twice the mass of the $\mathrm{D_s^+}$ (Λ_c^+), and the upper bound is determined by the minimum energy necessary to produce the mixed interaction $\mathrm{e^+e^-} \rightarrow \mathrm{D_s^+\overline{D}\overline{K}}$ ($\mathrm{e^+e^-} \rightarrow \Lambda_c^-\mathrm{Dp}$). The actual upper energies might be higher due to phase space limitation for the mixed interactions. They can be directly determined from the ISR data where the threshold energy for $e^+e^- \rightarrow \mathrm{D_s^+}\overline{\mathrm{D}}X$ (Λ_c^-DpX) corresponds to this upper bound. Using eq. (1) and the $\mathrm{D_s^+}$ cross section evaluated in[7], and an assumed cross section of 0.25 nb for the Λ_c^+, 2 M $\mathrm{D_s^+D_s^-}$ pairs and 1.5 M $\Lambda_c^+\Lambda_c^-$ pairs are estimated to be produced via ISR in 100 fb^{-1} of data, respectively.

Within these windows pairs of $\mathrm{D_s^+D_s^-}$ and $\Lambda_c^+\Lambda_c^-$ provide unique and exclusive correlation between the same type hadrons, where an inclusive signal establishes the underlying pairs in the data, and a double tag, in which both charmed hadrons in a pair are fully reconstructed, make it possible to determine the branching fraction independent of models.

Kinematic fits can be explored to improve the resolution on $\sqrt{s'}$. The ISR photon needs to be reconstructed for the single tag ($\mathrm{D_s^+}$, Λ_c^+), while the double tag analysis might not need this ISR photon tag, and the detection efficiency might be increased. Unique to leptonic decays of the $\mathrm{D_s^+}$, large missing energy together with the requirement of exactly 1-prong recoiling against the $\mathrm{D_s^+}$ will be powerful criteria for background rejection.

4.3. Search for heavy hybrids

QCD has predicted the existence of hybrid states $\mathrm{c\bar{c}g}$[8]. However they have not been established experimentally. Theoretical calculations of the $\mathrm{c\bar{c}g}$ hybrids have yielded consistent mass values. For the lowest lying $c\bar{c}g$ with $J^{PC}=1^{1+}$ its mass has been determined to be 4.1 GeV by QCD sum rule[9], and 4.4 GeV by lattice[8]. The two calculations agree within a 10% systematic uncertainty associated with each method.

While the $c\bar{c}g$ states can be searched in the continuum data at B-factory experiments, an additional channel of production is possible via ISR where e^+e^- annihilations occur just above the masses of the $c\bar{c}g$ hybrids.

Signatures of the $c\bar{c}g$ include anomalous inclusive production of charmonia J/ψ and $\psi(2S)$[10,11], beyond those from B decays, which have low momenta, and the direct ISR $e^+e^- \to \gamma\psi$ events, which have single momentum values. Events of charmonia outside kinematic ranges of B decays and direct ISR events can serve as indication of new production mechanism for charmonia that include the decays of $c\bar{c}g$ hybrids.

A direct and more conclusive way to search for the $c\bar{c}g$ hybrids is to reconstruct their exclusive decays into final states $J/\psi\pi^0$[10], $D^*\overline{D}$, and $D^{**}\overline{D}$[12]. Masses and resonance parameters can be obtained from the exclusive study.

For both inclusive and exclusive searches, the ISR hybrid events have low multiplicity that should result in low combinatorial background, and large missing neutral energy ($\sim$4.4 GeV), which can be used to reject continuum and $B\overline{B}$ backgrounds.

5. SUMMARY

A research program using the ISR data at B factory experiments is promising. The physics program includes a high statistics R scan between 5 - 7 GeV, model independent study of decays of the D_s^+ meson and the Λ_c^+ baryon, and searches for quark-gluon hybrids. Estimates are made for hadronic production between 5 - 7 GeV, and pair production of the $D_s^+D_s^-$ and $\Lambda_c^+\Lambda_c^-$ just above their thresholds. A procedure for selecting the ISR hadronic events is presented.

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