MEASUREMENT OF THE TOTAL CROSS SECTION FOR THE HADRONIC PRODUCTION BY e^+e^- ANNIHILATION AT THE ENERGIES BETWEEN 2-5 GEV

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We report in this paper progress on measurements of the total cross section for e^+e^- annihilation into hadronic final states with the upgraded Beijing Spectrometer (BESII) at the Beijing Electron Positron Collider (BEPC). The center-of-mass energy values are 2.6, 3.2, 3.4, 3.55, 4.6 and 5.0 GeV. Preliminary values of R, $\sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$, from this data and future plans for a finer scan in 2-5 GeV important energy region are presented.

1 Introduction

The lowest order cross section for $e^+e^- \to \gamma^* \to hadrons$ is usually parameterized in terms of the ratio R, which is defined as $R = \sigma(e^+e^- \to hadrons)/\sigma(e^+e^- \to \mu^+\mu^-)$, where the denominator is the lowest-order QED cross section, $\sigma(e^+e^- \to \mu^+\mu^-) = 4\pi\alpha^2/3s$.

The R ratio has been measured by many experiments over the center-of-mass (cm) energy range from the hadron production threshold to the Z^0 pole[1]. The experimentally determined R values are, in general, consistent with theoretical predictions, and provide an impressive confirmation of the hypothesis of three color degrees of freedom for quarks. The existing R measurements for cm energies below 5 GeV were performed 15 to 20 years ago and have experimental uncertainties of about 15% on average [2,3,4,5]. Uncertainties in the values of R in this energy region 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 [6,7,8]. Measurements of R, particularly for cm energies below the J/Ψ mass are also required for the interpretation of the muon $(g-2)$ measurement at Brookhaven [6,7,8]. About 50% and 20% of the uncertainty in $\alpha(M_Z^2)$ and $a_\mu = (g-2)/2$, respectively, are due to the uncertainty of the values of R in the 2-5 GeV cm energy region [9]. The BES collaboration has started a program of R measurements over this energy region with the goal of reducing the present uncertainties by at least a factor of two.

2 The Detector

The measurements are being carried out with the upgraded BES detector (BESII), which is a conventional solenoidal detector that is described in some detail elsewhere [10]. The upgrades include the replacement of the central drift chamber with a vertex chamber (VC) composed of 12 tracking layers organized around a beryllium beam pipe. This chamber provides a spatial resolution of about 90 μm. The barrel time-of-flight counter (BTOF) was replaced with a new array of 48 plastic scintillators that are readout by finemesh photomultiplier tubes situated in the 0.40 T magnetic field volume. The shorter light paths improve on the BES I design and provide 180 ps resolution. A new main drift chamber (MDC) has 10 superlayers, each with four sublayers of sense wires. It provides dE/dx information for particle identification and has a momentum resolution of $\delta p/p = 1.8\%\sqrt{(1+p^2)}$ for the charged tracks with momentum p in GeV. The sampling-type barrel electromagnetic calorimeter (ECAL), which covers 80 % of 4π solid angle, is consisted of 560 cells along the ϕ direction and each cell contains 24 layer in radial direction. ECAL operates in the self-quenching streamer mode with an energy resolution of $\delta E/E = 21\%/\sqrt{E}$ (E in GeV) and a spatial resolution of 7.9 mrad in ϕ and 3.6 cm in z. The outermost component of BESII is a μ identification system consisting of three double layers of proportional tubes interspersed in the iron flux return of the magnet. These measure coordinates along the muon trajectories with resolutions of 3 cm and 5.5 cm in $r\phi$ and z, respectively.

3 Trigger

A two-level trigger system retains good events while rejecting background[10]. The trigger is derived from signals from a beam pickup electrode located upstream of the detector and from each sub-detector. Event categories are classified according to numbers of charged and neutral tracks seen at the trigger level. For beam crossings with charged tracks, two trigger channels are utilized: in (1) we require at least one hit in the 48 BTOF counter array, one track in the VC and MDC; in (2) we require back-to-back hits in the BTOF counter with one track in the VC and two tracks in the MDC and at least 150 MeV of energy deposited in the ECAL. For the neutral track trigger, we require that the sum of the deposited energy of the tracks in two cells of the ECAL is greater than 100 MeV and the total energy deposited in ECAL from all sources is greater than 800 MeV.

All coincidences were formed using 40, 120, 630, 640 ns wide gates derived from the beam pickup signal for the TOF, VC, MDC and ECAL, respectively. Event candidates fulfilling the two-level criteria are accepted.

The trigger efficiencies are measured run by run by comparing the responses to different trigger requirements. As a cross check, data taken in special runs made at the J/Ψ and Ψ' resonances is used to provide independent measurements of the trigger efficiencies. For the R scan measurements, the trigger efficiencies for Bhabha, dimuon and hadronic events are determined to be 99.5%, 98.2% and 99.2%, respectively. These are consistent with the efficiencies determined from the J/Ψ data, where the corresponding trigger efficiencies are measured to be 99.6%, 98.2% and 99.9%, respectively. The errors in the trigger efficiencies for Bhabha and hadronic events are less than $\pm 0.5\%$.

4 The First R scan and the Data Analysis

A first scan of R measurements was performed this spring with data samples of about 1000-3000 hadronic events collected each at 2.6, 3.2, 3.4, 3.55, 4.6 and 5.0 GeV. To understand beam-associated backgrounds, separated beam data were taken at each energy point, and single beam data was accumulated at 3.55 GeV. The data taken at the J/Ψ and Ψ' resonances provide a precise energy calibration. The 3.4 GeV point was remeasured after a time interval of about two weeks to test the stability of the detector.

The 1.5M J/Ψ event sample is used for detector calibration and for monitoring the data quality and the stability of the detector performance. These data indicate that the BESII detector performance was stable and the data quality is good. Figure 1 shows the time dependence of the MDC momentum resolution, the ECAL energy resolution, the BTOF time resolution and dE/dx pulse heights for Bhabha events.

The value of R is determined from the number of observed hadronic events (N_{had}^{obs}) by the relation

$$R = \frac{N_{had}^{obs} - N_{bg} - \sum_l N_{ll} - N_{\gamma\gamma}}{\sigma_{\mu\mu}^0 \cdot L \cdot \epsilon_{had} \cdot \epsilon_{trg} \cdot (1+\delta)}, \tag{1}$$

where N_{bg} is the number of beam associated background events; $\sum_l N_{ll}$, $(l = e, \mu, \tau)$ and $N_{\gamma\gamma}$ are the numbers of misidentified lepton-pair and two-photon processes events; L is the integrated luminosity; δ is the correction for initial state radiation; and ε_{had} and ϵ_{trg} represent the detection and trigger efficiency for the hadronic events.

4.1 Hadronic Event Selection

The task of the hadronic event selection is to distinguish single-photon multihadron annihilation from all other possible mechanisms. The hadronic event sample are identified from the selected tracks. Tracks with charge ± 1 which fulfills the following criteria are selected as good charged tracks:

1. tracks in the MDC are well fit to a three-dimentional helix;

2. $|\cos\theta| < 0.84$, where θ is the track polar angle;

3. Distance of closest approach to the beam in the transverse plane and along the beam axis are less than 2.0 cm and 15 cm respectively;

4. $p < p_{beam} + 5 \times \sigma_p$, where p and p_{beam} are the momenta of the track and the beam respectively, σ_p is the momentum resolution for the beam;

5. $2 < t < t_p + 5 \times \sigma_t$ ns , where t and σ_t are the measured time-of-flight of the track and the BTOF time resolution. t_p is the time-of-flight for proton calculated according to the length and velocity of the track;

The main sources of background are cosmic rays, lepton pair production from $e^+e^- \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-$, final states produced from two photon processes and the beam associated processes, i.e. interactions of beam particles with the residual gas (beam-gas events) or the walls of the vacuum chamber (beam-wall events).

Since we require, at this time, events with tracks greater 2, the background from cosmic ray and lepton pair production is not a problem. Generally speaking, for the tracks with good MDC fits, cosmic rays are rejected on the basis of their time of flight, momentum, vertex distribution, and acollinear and acoplanar angles. Bhabha events are removed by utilizing the information of the deposited energy in the barrel ECAL, and the measured momentum, and dE/dx. Dimuon events are rejected by the response of the muon counters together with shower energy and momentum cuts. Pair production of $\tau^+\tau^-$ leptons (when E_{cm} is greater than the tau pair production threshold) are difficult to separate directly from the hadronic event sample because of their hadronic decay modes and short life time. Final states produced via two-photon processes are characterized by low momentum tracks that tend to be directed near the beam direction. These are quite distinct and, therefore, relatively easy to reject. The level of the $\tau\tau$ pair and residual two-photon backgrounds are determined by means of a Monte Carlo simulation.

The most serious sources of background in the hadronic event sample are beam-gas and beam-wall interactions. Most of the beam-gas and beam-wall background events are rejected by the vertex cut (figure 3). The salient feature of the beam associated background are that their tracks are very much along the beam pipe direction, the energy deposited in ECAL is small, and most of the tracks are protons. The same hadronic event selection criteria are applied to the separated-beam data, and the number of separated-beam events N_{sep} surviving these criteria are obtained. The number of the beam associated background events N_{bg} in the corresponding hadronic event sample is given by $N_{bg} = f \times N_{sep}$, where f can be determined by the ratio of the products of the pressure P at the collision region times the integrated beam currents I, i.e. $N_{bg} = N_{sep} \cdot (\int_{run} P_{run} \cdot I_{run}\, dt)/(\int_{sep} P_{sep} \cdot I_{sep}\, dt)$.

We limit ourself, at least for the time being, to events with at least three charged tracks. For the events with one or two prongs, more effort is needed to develop criteria to separate hadronic and background events. The hadronic event should then fulfill: at least three good charged tracks but not all of them carry positive charge(this requirement rejects most of the remaining beam-gas background); the ratio between the total energy deposited in ECAL and the beam energy is greater than 0.225. Figure 2 shows a typical hadronic event selected.

We determine the error associated with the hadronic selection criteria from changes in the event yield caused by varying the selection requirements. The event selection error is estimated to be 4.0%.

4.2 Luminosity

The integrated luminosity is determined using large-angle Bhabha scattering events. The MDC, BTOF and ECAL can be used to identify Bhabha events. Using only the ECAL information, we select two clusters with largest deposited energy in the polar angle $|\cos\theta| \leq 0.55$ of the the ECAL and each cluster has an energy greater than 1.0 GeV (for 3.55 GeV data). In adddition, it is required that $2^\circ < |\delta\phi| < 16^\circ$, where $\delta\phi = |\phi_1 - \phi_2| - 180^\circ$, of which ϕ_1 and ϕ_2 are the azimuthal angle of the two clusters measured by ECAL.

The error of the integrated luminosity is conservatively estimated to be 4.0%. This includes the statistical error, the uncertainties from varying the selection criteria and in the theoretical calculation of the cross section. Luminosities , which are determined using only the MDC dE/dx information, are consistent with those measured using the ECAL information within 2.5%. This difference is also taken into account as systematical error.

4.3 Detection Efficiency

The detection efficiency for hadronic events, denoted as ϵ_{had}, was determined by Monte Carlo simulation using the JETSET7.4 event generator [12]. The parameters in the JETSET7.4 generator were tuned using the more than 40,000 hadronic event selected from the tau mass measurement data sample[13]. The parameters of the generator were adjusted to reproduce distributions of kinematic variables such as multiplicity, sphericity, transverse momentum, etc. Figure 5 shows the charge multiplicity, the sphericity, the aplanarity and the transverse momentum distributions for the real and simulated event samples. The generator-dependent error on the acceptance is estimated to be 5.5%.

4.4 Radiative Corrections

Radiative corrections have to be applied to account for the effects of high order processes on the observed multi-hadronic event rate. We follow the approach given by Bonneau and Martin [14]. In addition, a method proposed by E. A. Kuraev and V. S. Fadin [15], which represents the cross section for single photon annihilation with inclusion of radiative correction as the form of the cross section for the Drell-Yan process, was investigated. This method is valid for the energy interval of 0.2-10 GeV, and the theoretical accuracy is 0.1%. We also determined the radiative correction using the method given by Berends and Kleiss [16]. The radiative correction calculated by these methods are all consistent with each other to within $\pm$ 1%; The error of the radiative correction is estimated to be 3.5%, including the contribution of the uncertainty in the values of R, which are used to estimate the hadronic vacuum polarization.

4.5 Preliminary Results

The errors from all different sources discussed previously to the R values are listed in table 1. Table 2 lists the selected hadronic events N_{had}, the corresponding detection efficiencies ϵ_{had}, the measured luminosities L, the radiative correction $1 + \delta$, and the R values at 2.6 and 3.55 GeV.

The total errors on R are obtained by adding all the error sources mentioned previously in quadrature. The R values presented here are preliminary, and the errors are estimated conservatively. This analysis is continuing; a final result with smaller uncertainies and using lower charged multiplicity events is expected.

Table 1: Errors contributed from different sources to R at 2.6 GeV

Source	Error to R (%)
Hadronic event selection	4.0
Beam gas subtraction	2.5
Hadron efficiency	5.5
Luminosity	4.0
Radiative correction	3.5
Trigger efficiency	0.5
Systematic quadrature sum	9.0

Table 2: Preliminary R values at 2.6 and 3.55 GeV

E_{cm}	N_{had}	$L(nb^{-1})$	ϵ_{had}	$1+\delta$	R
2.6	3499	292.8	0.397	1.055	2.22±0.20
3.55	1655	198.8	0.557	1.136	1.86± 0.17

5 Future Plan

The main goal of the first scan was a careful understanding of the trigger and hadronic event acceptances, as well as the hadronic event selection and the background subtraction, which are central to a total cross section measurement. This fall, BES-II will carry out a finer scan from 2 to 5 GeV as indicated by figure 6. Our goal is to reduce the present uncertainties of R by at least a factor of two over this entire energy region.

6 References

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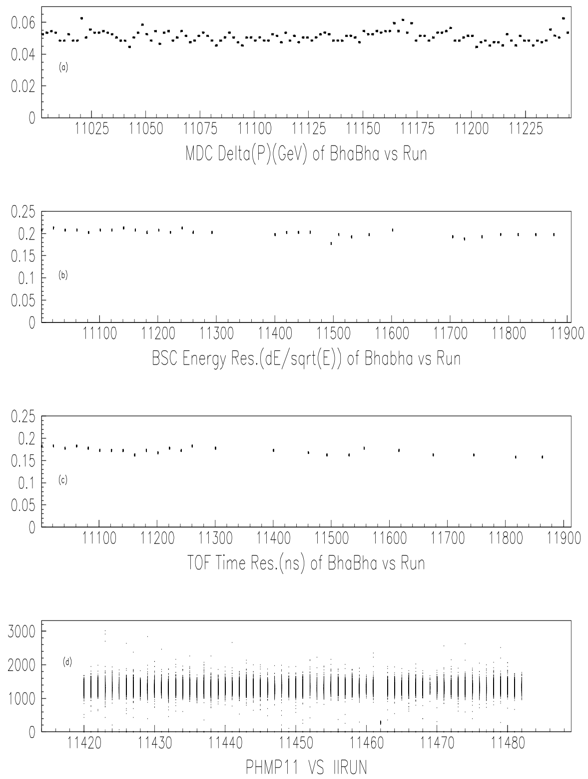

Figure 1: Plots showing the stable performance of BESII. (a) MDC momentum resolution; (b) ECAL energy resolution; (c) time resolution of BTOF; (d) MDC $dE/dx(\propto PHMP)$ of the R scan data. (a)-(c) are based on J/Ψ data collected before taking R scan data for the calibration of BESII. All the plots are produced using Bhabha events.

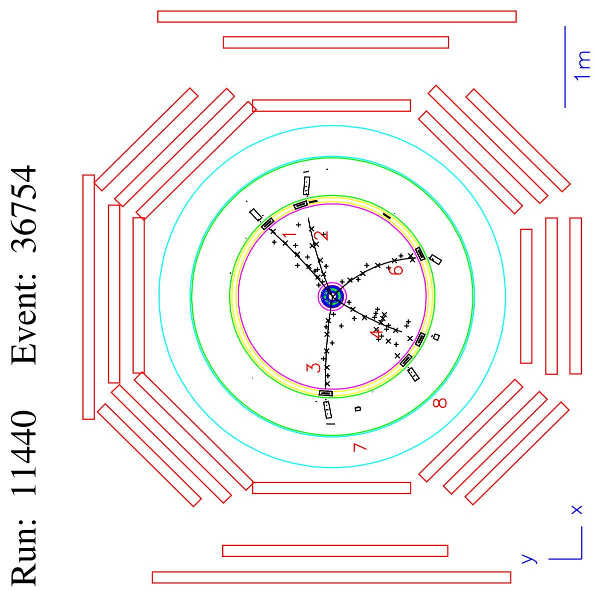

Figure 2: A typical selected hadronic event display from E_{cm} = 3.55 GeV data.

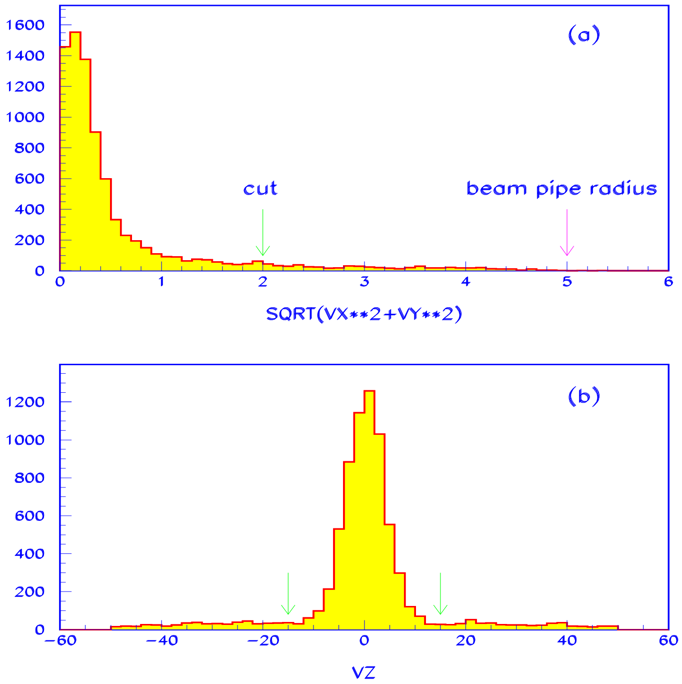

Figure 3: Track vertex distribution in radical (a) and z (b) directions in cm.

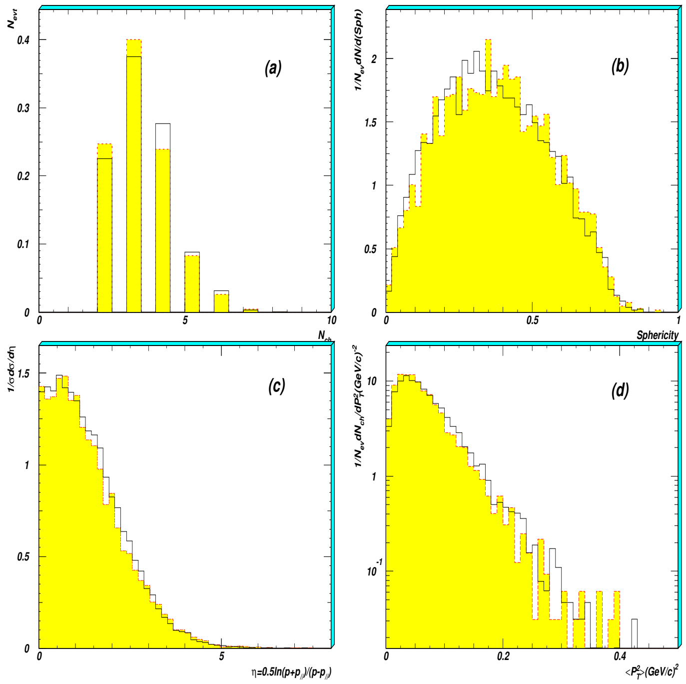

Figure 5: Hadronic event shape of the real data (hatched region) and Monte Carlo data(histogram). (a) multiplicity (b) sphericity (c) rapidity (d) transverse momentum.

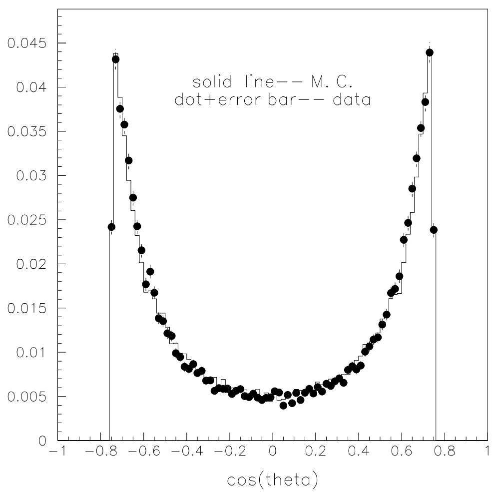

Figure 4: Angular distribution of the selected Bhabha events.

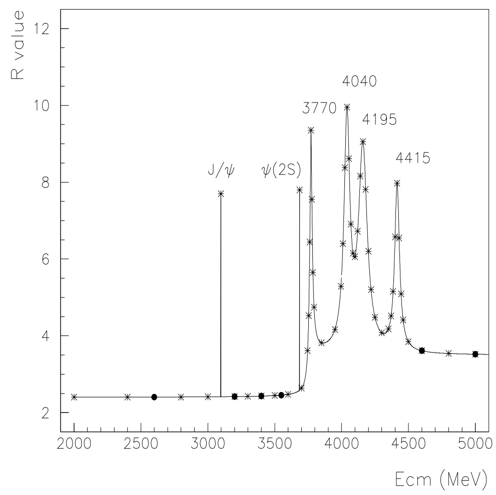

Figure 6: Energy scan points presented in this work (solid circles) and points that will be scanned during the BES II 1998-1999 run. The R curve shown is a representation of the resonance region and should not be treated as a measurement. The values at the J/Ψ and $\Psi(2S)$ would be off scale.