Results of the First R Scan Between $2.6 - 5.0$ GeV at BES

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1 Motivation

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

$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3\sum_q Q_q^2 \tag{1}$$

where the denominator is the lowest-order QED cross section,

$$\sigma(e^+e^- \to \mu^+\mu^-) = 4\pi\alpha^2/3s \tag{2}$$

which can be precisely calculated by QED theory.

A measurement of R will directly count the number of quarks, their flavors and colors, so it is a simple test of quark model. And moreover, with higher order QCD correction R can be expressed as

$$R = 3\sum_q Q_q^2[1 + (\frac{\alpha_s(s)}{\pi}) + 1.411(\frac{\alpha_s(s)}{\pi})^2 - 12.8(\frac{\alpha_s(s)}{\pi})^3 + \ldots] \tag{3}$$

The experimental R value can thus be used to determine $\alpha_s(s)$.

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.

However, 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].

2 Accelerator and Detector

The R scan measurements were carried out with the upgraded BES detector (BES-II) at the upgraded BEPC accelerator(BEPC-II). BEPC(Beijing Electron Positron Collider) is the only one accelerator running at $\tau - c$ threshold energy region in the world, and thus plays an unique role in $\tau - c$ physics. BES(Beijing Spectrometer), the only general-purpose detector at BEPC is a conventional solenoidal detector that is described in some detail in Ref. [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 read out by fine mesh photomultiplier tubes situated in the 0.40 T magnetic field volume, providing 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 (BSC), which covers 80% of 4π solid angle, consists of 560 cells along the ϕ direction, with each cell containing 24 layers in the radial direction. The BSC 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 streamer 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 the first, we require at least one hit in the 48 BTOF counter array, one track in the VC and MDC and at least 150 MeV of energy deposited in the BSC; in the second, we require back-to-back hits in the BTOF counter with one track in the VC, two tracks in the MDC, and at least 150 MeV of energy deposited in the BSC. For the neutral track trigger, we require that the sum of the deposited energy of the tracks in two cells of the BSC is greater than 80 MeV and the total energy deposited in BSC from all sources is greater than 800 MeV.

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

The trigger efficiencies are measured by comparing the responses to different trigger requirements in special runs taken at the J/ψ resonance. From the trigger measurements, the efficiencies for Bhabha, dimuon and hadronic events are determined to be 99.96%, 99.33% and 99.76%, respectively. As a cross check, the data at 3.55 GeV are used to provide independent measurements of the trigger efficiencies. These are consistent with the efficiencies determined from the J/ψ data. The errors in the trigger efficiencies for Bhabha and hadronic events are less than $\pm 0.5\%$.

4 The First R Scan and Data Analysis

The first scan of R measurements has been performed with data samples of about 1000-5000 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 value of R is determined from the number of observed hadronic events (N_{had}^{obs}) by the relation

$$R = \frac{N_{had}^{obs} - N_{bg} - \sum_l N_{ll} - N_{\gamma\gamma}}{\sigma_{\mu\mu}^0 \cdot L \cdot \epsilon_{had} \cdot \epsilon_{trg} \cdot (1+\delta)}, \tag{4}$$

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 Run Stability and Performance

A 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. Fig. 1 shows the time dependence of MDC momentum resolution, BSC energy resolution, BTOF time resolution and dE/dx pulse heights for Bhabha events.

4.2 Hadronic Event Selection

The goal of hadronic event selection is to distinguish single-photon hadron production from other processes. The following track-level selection criteria are used to define good charged tracks:

- $|\cos\theta| < 0.84$, where θ is the track polar angle;
- The track must have a reasonable three-dimensional helix fit;
- Distance of closest approach to the beam in the transverse plane and along the beam

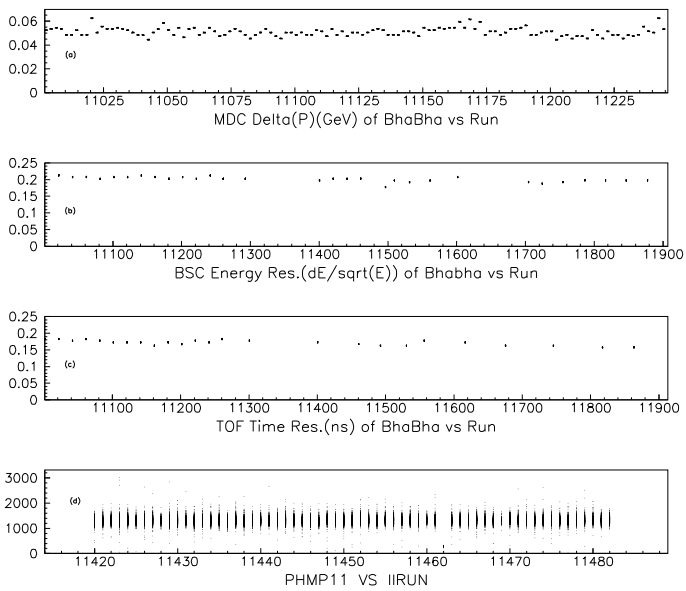

Figure 1: Plots of various BESII subsystems. (a) MDC momentum resolution; (b) BSC energy resolution; (c) BTOF time resolution; (d) MDC dE/dx of the R scan data. (a)–(c) are based on J/ψ data. All plots are produced using Bhabha events.

axis are less than 2.0 and 18 cm, respectively;

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

• $E < 0.6E_{beam}$, where E and E_{beam} are the energy of the track (as measured in the BSC) and beam, respectively;

• A track must not be definitely identified as an electron or a muon;

• $2 < t < t_p + (5 \times \sigma_t)$ (in ns), where t and t_p are the time-of-flight for the track and a nominal time-of-flight calculated for the track assuming a proton hypothesis, respectively, and σ_t is the BTOF time resolution.

After the track-level selection, a further event level selection is applied:

• At least 2 good charged tracks, with at least one track having a good helix fit;

• The total deposited energy in the BSC $> 0.28E_{beam}$.

A further selection scheme is required based on the number of good tracks in the event. For three or more prong events, the only additional requirement is that all the charged tracks not be positive (to remove beam-gas events). However, two-prong events must be distinguished from cosmic ray and lepton pair events, requiring in addition:

• The two tracks must not be back-to-back:

$$|\theta_1 + \theta_2 - 180^\circ| > 10^\circ, ||\phi_1 - \phi_2| - 180^\circ| > 4^\circ; \tag{5}$$

• There must be at least two isolated neutral tracks that fulfill the following requirements:

$$E_\gamma > 100\text{MeV}, |\phi_\gamma - \phi_c| > 15^\circ, \tag{6}$$

where ϕ_c is the ϕ angle of either of the two charged tracks.

The performance of the event selection routines was checked by hand scans, which were carried out for both the selected and rejected hadronic events, the separated-beam data, and

the Monte Carlo events. A typical hadronic event that passed the selection cuts is shown in Fig. 2. We determined the error associated with the hadronic selection criteria from changes in the event yield caused by varying the selection requirements and from the results of the hand scan.

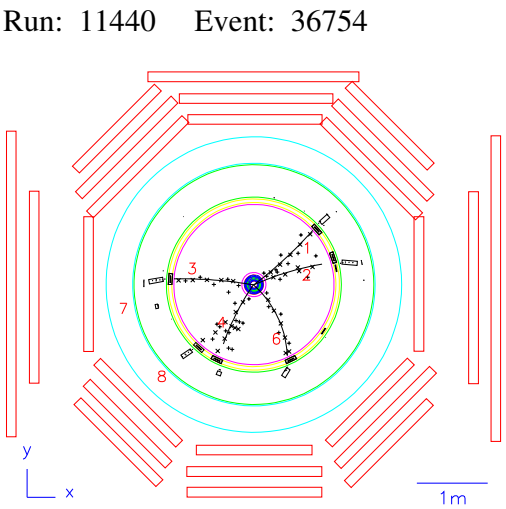

Figure 2: A typical hadronic event display from 3.55 GeV data.

4.3 Background Subtraction

There are three major types of background to be considered. One type, consisting of cosmic rays, Bhabha, dimuon events and some two-photon process events, is directly removed by the event selection. The second, consisting of tau-pair production and residual two-photon processes, is subtracted out statistically via a Monte Carlo simulation.

Finally, 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 a vertex cut. The salient features of the beam associated background are that their tracks were very much along the beam pipe direction, the energy deposited in BSC 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 is determined by the ratio of the products of the pressure P at the collision region times the integrated beam currents I, i.e. $N_{bg} = N_{sep} \cdot (\int_{run} P_{run} \cdot I_{run}\, dt)/(\int_{sep} P_{sep} \cdot I_{sep}\, dt)$.

4.4 Luminosity

The integrated luminosity is determined using large-angle Bhabha events with the following selection criteria, using only BSC information:

- Two clusters in the BSC with largest deposited energy in the polar angle $|\cos\theta| \leq 0.55$;
- Each cluster with energy > 1.0 GeV (for 3.55 GeV data, scaled for other energy points);
- $2^\circ < ||\phi_1 - \phi 2| - 180^\circ| < 16^\circ$, where ϕ_1 and ϕ_2 are the azimuthal angles of the clusters.

A cross check using only MDC information (dE/dx) was generally consistent with the BSC measurement; the difference was taken into account in the systematic error.

4.5 Hadronic Detection Efficiency

The detection efficiency for hadronic events is determined via a Monte Carlo simulation using the JETSET7.4 event generator[11]. Parameters in the JETSET7.4 generator are tuned[12] using more than 40,000 hadronic events selected from the tau mass measurement data sample[13]. The parameters of the generator are adjusted to reproduce distributions of kinematic variables such as multiplicity, sphericity, transverse momentum, etc. Fig. 3 shows the charge multiplicity, the sphericity, the aplanarity and the transverse momentum distributions for the real and simulated event samples.

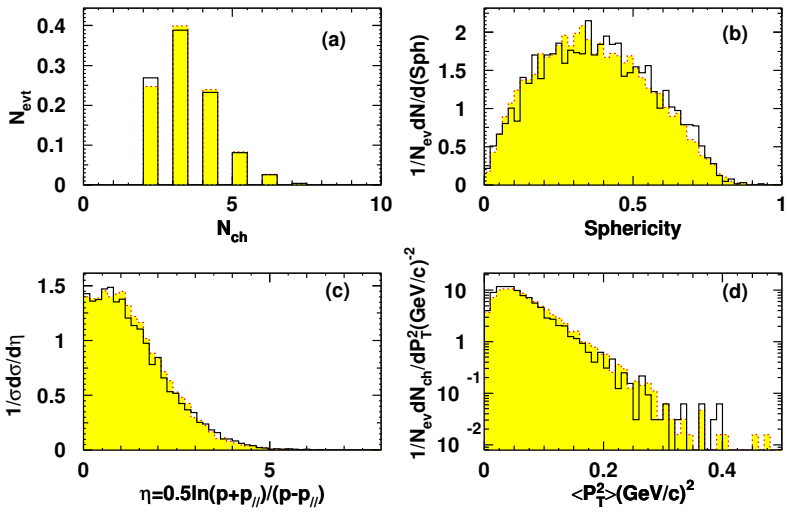

Figure 3: Comparison of hadronic event shapes between data (shaded region) and Monte Carlo (histogram). (a) Multiplicity; (b) Sphericity; (c) Rapidity; (d) Transverse momentum.

4.6 Initial State Radiation

The effect of radiative corrections on the measured cross-section was examined in detail. Four different schemes were used: Berends and Kleiss[14], Kuraev and Fadin[15], Bonneau and Martin[16], and a method used by the Crystal Ball[17]. Radiative corrections calculated by all these methods are consistent to within 1% for off-resonance points, but could differ by 1-3% in resonance regions.

We used the approach of Bonneau and Martin, with the differences from the other schemes included in the systematic error.

4.7 Results

The R values obtained at the six energy points are shown in Table 1 and graphically displayed in Fig. 4. A further breakdown of contributions to the systematic errors is given in Table 2.

Table 1: Summary of R data and values.

E_{cm}	N_{had}^{obs}	N_{bg}	$\mathcal{L}$ nb^{-1}	$\epsilon_{had}(\%)$	$(1+\delta)$	R value	Sys. error	Stat. error
2.60	5617	127	292.9	0.5482	1.009	2.61	6.7%	1.8%
3.20	2051	100	109.3	0.6430	1.447	2.25	5.6%	3.2%
3.40	2149	178	135.3	0.6961	1.173	2.36	6.8%	3.1%
3.55	2672	216	200.2	0.6840	1.125	2.29	6.9%	2.7%
4.60	1497	282	87.7	0.8227	1.079	3.53	8.2%	5.6%
5.00	1648	463	102.3	0.8453	1.068	3.42	8.4%	9.4%

Table 2: Contributions to systematic errors. All errors are in percentages (%).

E_{cm}	Had. sel.	Back.	$\mathcal{L}$	τ-pair	Bhabhas	Had. eff.	Trig.	Rad. corr.
2.60	5.25	0.06	2.12	0.00	0.04	2.60	0.50	2.6
3.20	4.03	0.15	2.83	0.00	0.04	1.90	0.50	2.2
3.40	5.06	0.27	2.83	0.00	0.04	2.90	0.50	3.0
3.55	6.05	0.27	2.32	0.00	0.04	2.30	0.50	2.4
4.60	7.58	0.75	2.16	0.32	0.00	3.60	0.50	4.1
5.00	9.00	1.26	2.81	0.32	0.00	3.20	0.50	3.8

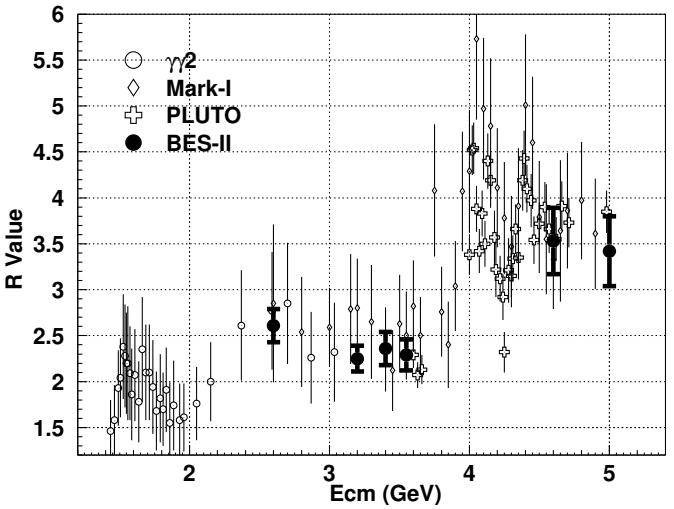

Figure 4: Plot of R values at the 6 data points vs E_{cm}.

5 The Second Run of R Scan

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. BES-II began carrying out the finer scan from 2 to 5 GeV since Feb. 1999, and finished the scan early in June, 85 energy points measured altogether. Our goal is to reduce the present uncertainties of R by at least a factor of two over this entire energy region, —that is about 7%.

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References

[1] C. Caso et al., European Phys. Journal **C 3** (1998) 1.

[2] F. Ceradini *et al.*, *Phys. Lett.* B **47**, 80 (1973)
B. Batoli *et al.*, *Phys. Rev.* D **6**, 2374 (1972)
M. Bernardini *et al.*, *Phys. Lett.* B **51**, 200 (1974)

[3] G. Cosme *et al.*,*Phys. Lett.* B **40**, 685 (1972)

[4] M. Kurdadze *et al.*, *Phys. Lett.* B **42**, 515 (1972)

[5] A. Litke *et al.*, Phys. Rev. Lett. **30** (1973) 1189.

[6] A. Blondel, plenary talk at ICHEP'96, Warsaw.

[7] B. Pietrzyk, Rad. Corr. Conf., Cracow 1996.

[8] M. Davier and A. Hoeker, LAL 97-85.

[9] M. Davier and A. Hoeker, LAL 97-02.

[10] J.Z. Bai *et al.*, *Nucl. Instrum. Methods* A **344**, 319 (1994)

[11] Torbjoen Sjoestrand, LU TP 95-20.

[12] X.R. Qi *et al.*, High Energy Physics and Nuclear Physics (in Chinese), 23, 1(1999)

[13] J.Z. Bai *et al.*, *Phys. Rev.* D **53**, 20 (1996)

[14] F.A. Berends and R. Kleiss, *Nucl. Phys.* B **178**, 141 (1981)

[15] E. A. Kuraev *et al.*, Sov. J. Nucl. Phys. 41 3(1985)

[16] G. Bonneau and F. Martin, *Nucl. Phys.* B **27**, 387 (1971)

[17] C.Edwards et al. SLAC-PUB-5160, (1990) (T/E)