Measurement of the Total Cross Section for Hadronic Production by e^+e^- Annihilation at Energies between 2.6–5 GeV

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Using the upgraded Beijing Spectrometer, we have measured the total cross section for e^+e^- annihilation into hadronic final states at center-of-mass energies of 2.6, 3.2, 3.4, 3.55, 4.6, and 5.0 GeV. Values of R, $\sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$, are determined.

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The lowest order cross section for $e^+e^- \to \gamma^* \to$ hadrons is usually parametrized in terms of the ratio R, which is defined as $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$, where the denominator is the lowest-order QED cross section, $\sigma(e^+e^- \to \mu^+\mu^-) = \sigma^0_{\mu\mu} = 4\pi\alpha^2/3s$. This ratio has been measured by many experiments over the center-of-mass (cm) energy range from the hadron production threshold to the Z pole [1]. The measured 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 17 to 25 years ago [2–8] and have average experimental uncertainties of about 15% [9]. 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 [9–15]. 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 [9–15]. About 50% and 20% of the error 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 [15].

In this Letter, we report measurements of R at cm energies of 2.6, 3.2, 3.4, 3.55, 4.6, and 5.0 GeV. The measurements were carried out with the Beijing Spectrometer (BESII), which is a conventional solenoidal detector

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that is described in detail in Ref. [16]. 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 ten superlayers, each with four sublayers of sense wires. It provides dE/dx information for particle identification and has a momentum resolution of $\sigma_p/p = 1.8\%\sqrt{(1 + p^2)}$ for charged tracks with momentum p in GeV. The sampling-type barrel electromagnetic calorimeter (BSC), which covers 80% of 4π solid angle, consists of 24 layers of self-quenching streamer tubes interspersed with lead and with each layer having 560 tubes. The BSC has an energy resolution of $\sigma_E/E = 21\%/\sqrt{E}$ (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 and 5.5 cm in $r\phi$ and z, respectively.

Triggers are formed from signals derived from the BTOF, VC, MDC, and BSC and referenced in time to signals from a beam pickup electrode located upstream of the detector [16]. 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 topologies are utilized: in the first, we require at least one hit in the 48 BTOF counterarray, one track in the VC and MDC, and at least 100 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 and two tracks in the MDC. For the neutral track trigger, we require that the sum of the deposited energy of the tracks in two adjacent towers of the BSC is greater than 80 MeV in the first level trigger and that the total energy deposited in BSC from all sources is greater than 800 MeV in the second level trigger. A tower in the BSC is one tube in ϕ (11 mrad) by 24 layers radially.

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

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

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 pairs from one-photon and two-photon processes events, respectively, L is the integrated luminosity, δ is the radiative correction, and ϵ_{had} and ϵ_{trg} represent, respectively, the detection and trigger efficiency for hadronic events.

The J/ψ resonance is a convenient source of large numbers of hadronic events. A sample of 1.5×10^6 J/ψ events, accumulated intermittently throughout the experimental running period, was used for monitoring the detector performance. These data indicate that the detector components and triggers remained stable throughout the run [17].

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: (i) $|\cos\theta| < 0.84$, where θ is the track polar angle; (ii) the track must have a reasonable three-dimensional helix fit; (iii) distances of closest approach to the beam in the transverse plane and along the beam axis are less than 2.0 and 18 cm, respectively; (iv) $p < p_{\text{beam}} + (5 \times \sigma_p)$, where p and p_{beam} are the momenta of the track and the beam, respectively, and σ_p is the momentum resolution for charged tracks with $p = p_{\text{beam}}$; (v) $E < 0.6E_{\text{beam}}$, where E is the energy in the BSC that is associated with the track, and E_{beam} is the beam energy; (vi) a track must not be definitely identified as an electron or a muon; (vii) $2 < t < t_p + (5 \times \sigma_t)$ (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: (i) at least two charged tracks, with at least one good track satisfying the requirements listed above; (ii) the total deposited energy in the BSC $>0.28E_{\text{beam}}$.

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: (i) the two tracks must not be back-to-back; (ii) there must be at least two isolated neutral tracks that have more than 100 MeV of energy and are at least 15° from the closest charged track in azimuthal angle.

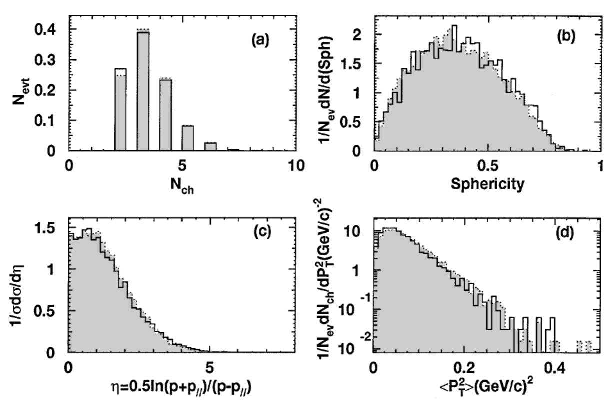

FIG. 1. Comparison of hadronic event shapes between data (shaded region) and Monte Carlo (histogram): (a) multiplicity; (b) sphericity; (c) rapidity; (d) transverse momentum.

TABLE I. Summary of R data and values.

E_{cm} (GeV)	N_{had}^{obs}	N_{bg}	L (nb^{-1})	ϵ_{had} (%)	$(1+\delta)$	R	Stat. error	Syst. error
2.60	5617	127	292.9	54.11	1.009	2.64	0.05	0.19
3.20	2051	100	109.3	65.71	1.447	2.21	0.07	0.13
3.40	2149	178	135.3	69.33	1.173	2.38	0.07	0.16
3.55	2672	216	200.2	70.66	1.125	2.23	0.06	0.16
4.60	1497	282	87.7	81.75	1.079	3.58	0.20	0.29
5.00	1648	463	102.3	83.94	1.068	3.47	0.32	0.29

The background involved in our measurement is from cosmic rays, lepton pair production, two-photon processes, and beam associated processes. The cosmic rays and part of the lepton pair production events are directly removed by the event selection. The remaining background from lepton pair production and two-photon processes is then subtracted out statistically according to Monte Carlo simulation.

The most serious source of background in the hadronic event sample is beam associated background. To understand this, separated beam data were taken at each energy point, and single beam data were accumulated at 3.55 GeV. Most of the beam associated background events are rejected by a vertex cut. The salient features of the beam associated background are that their tracks are 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 the ratio of the product of the pressure at the collision region times the integrated beam currents for colliding beam runs and that for the separated beam runs.

The integrated luminosity is determined using large-angle Bhabha events with the following selection criteria, using only BSC information: (i) two clusters in the BSC with largest deposited energy in the polar angle $|\cos\theta| \leq 0.55$; (ii) each cluster with energy >1.0 GeV (for 3.55 GeV data, scaled for other energy points); (iii) $2° < \|\phi_1 - \phi_2| - 180°| < 16°$, where ϕ_1 and ϕ_2 are the azimuthal angles of the clusters. The 2° cut removes $e^+e^- \rightarrow \gamma\gamma$ events. A cross-check using only dE/dx information from the MDC to identify electrons was generally consistent with the BSC measurement; the difference was taken into account in the overall systematic error of 2.1%–2.8%.

The detection efficiency for hadronic events is determined via a Monte Carlo simulation using the JETSET7.4 event generator [18]. Parameters in the generator are tuned [19] using a 40×10^3 hadronic event sample collected near 3.55 GeV for the tau mass measurement done by this experiment [20]. The parameters of the generator are adjusted to reproduce distributions of kinematic variables such as multiplicity, sphericity, transverse momentum, etc. Figure 1 shows these distributions for the real and simulated event samples. The parameters have also been obtained using the 2.6 GeV data ($\approx 5 \times 10^3$ events). The difference between the two parameter sets and between the data and the Monte Carlo data based on these parameter sets is used to determine a systematic error of 1.9%–3.2% in the hadronic efficiency.

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 trigger information from the 2.6 and 3.55 GeV data samples 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 $\pm 0.5\%$.

Radiative corrections determined using four different schemes [21–24] agreed with each other to within 1% below charm threshold. Above charm threshold, where resonances are important, the agreement is within 1%–3%. The major uncertainties common to all models are due to errors in previously measured R values and in the choice of values for the resonance parameters. For the measurements reported here, we use the formalism of Ref. [23]

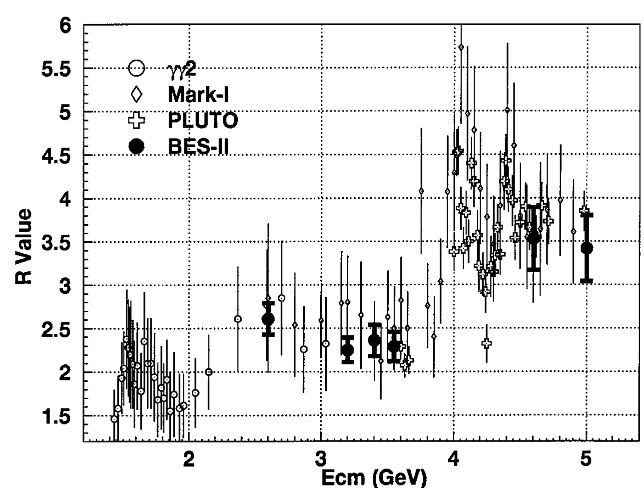

FIG. 2. Plot of R values vs E_{cm}. The R values from BES are taken from Table I with an error which combines statistical and systematic errors in quadrature.

TABLE II. Contributions to systematic errors: hadronic selection, f factor, luminosity determination, τ-pair background, background from Bhabha events, hadronic efficiency determination, trigger efficiency, and radiative corrections. All errors are in percentages (%).

E_{cm} (GeV)	Had. sel.	f factor	L	τ-pair	Bhabhas	Had. eff.	Trig.	Rad. corr.
2.60	5.1	0.06	2.12	0.00	0.04	4.10	0.50	2.6
3.20	3.8	0.15	2.83	0.00	0.04	1.90	0.50	2.2
3.40	4.6	0.27	2.83	0.00	0.04	2.90	0.50	3.0
3.55	5.5	0.27	2.32	0.00	0.04	2.30	0.50	2.4
4.60	5.7	0.75	2.16	0.32	0.00	3.60	0.50	4.1
5.00	6.0	1.26	2.81	0.32	0.00	3.20	0.50	3.8

and include the differences with the other schemes in the systematic error of 2.2%–4.1%.

The R values obtained at the six energy points are shown in Table I and graphically displayed in Fig. 2. A breakdown of contributions to the systematic errors is given in Table II. The largest systematic error is due to the hadronic event selection and is determined to be 3.8%–6.0% by varying the selection criteria. The systematic errors on the measurements below 4.0 GeV are similar and are a measure of the amount of error common to all points. We have also done the analysis including only events with greater than two charged tracks; although the statistics are smaller, the results obtained agree well with the results shown here. The R values for E_{cm} below 4 GeV are in good agreement with results from $\gamma\gamma2$ [6] and Pluto [8] but are below those from Mark I [7]. Above 4 GeV, our values are consistent with previous measurements.

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