Measurements of the Cross Section for $e^+e^- \to$ Hadrons at Center-of-Mass Energies from 2 to 5 GeV

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We report values of $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ for 85 center-of-mass energies between 2 and 5 GeV measured with the upgraded Beijing Spectrometer at the Beijing Electron-Positron Collider.

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In precision tests of the Standard Model (SM) [1], the quantities $\alpha(M_Z^2)$, the QED running coupling constant evaluated at the Z pole, and $a_\mu = (g - 2)/2$, the anomalous magnetic moment of the muon, are of fundamental importance. The dominant uncertainties in both $\alpha(M_Z^2)$ and a_μ^{SM} are due to the effects of hadronic vacuum polarization, which cannot be reliably calculated in the low energy region. Instead, with the application of dispersion relations, experimentally measured R values are used to determine the vacuum polarization, where R is the lowest order cross section for $e^+e^- \to \gamma^* \to$ hadrons in units of the lowest-order QED cross section for $e^+e^- \to \mu^+\mu^-$, namely, $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$, where $\sigma(e^+e^- \to \mu^+\mu^-) = \sigma^0_{\mu\mu} = 4\pi\alpha^2(0)/3s$.

Values of R in the center-of-mass (c.m.) energy ($E_{\text{c.m.}}$) range below 5 GeV were measured about 20 years ago with a precision of 15%–20% [2–4]. In this Letter, we report measurements of R at 85 c.m. energies between 2 and 4.8 GeV, with an average precision of 6.6% [5]. The measurements were carried out with the upgraded Beijing Spectrometer (BESII) [6] at the Beijing Electron-Positron Collider (BEPC).

Experimentally, the value of R is determined from the number of observed hadronic events, $N^{\text{obs}}_{\text{had}}$, by the relation

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

where N_{bg} is the number of beam-associated background events, $\sum_l N_{ll}$ ($l = e, \mu, \tau$) are the numbers of lepton-pair events from one-photon processes, $N_{\gamma\gamma}$ is the number of two-photon process events that are misidentified as hadronic events, L is the integrated luminosity, δ is the effective initial state radiative (ISR) correction, $\bar{\epsilon}_{\text{had}}$ is the average detection efficiency for hadronic events, and ϵ_{trg} is the trigger efficiency. The triggers and the integrated luminosity measurement were the same as those used in a preliminary scan that measured R at six energy points between 2.6 and 5 GeV [7].

The hadronic event selection is similar with that used in the first R scan [7] but with improvements that include the following: for good track selection, the distance of closest approach requirement (<18 cm) of a track to the interaction point along the beam axis is not imposed; for event-level selection, the selected tracks must not all point into the forward ($\cos\theta > 0$) or the backward ($\cos\theta < 0$) hemisphere. Some distributions comparing data and Monte Carlo data are shown in Figs. 1(a)–1(c). The cuts used for selecting hadronic events were varied over a wide range, e.g., $|\cos\theta|$ from 0.75 to 0.90, E_{sum} from $0.24E_{\text{beam}}$ to $0.32E_{\text{beam}}$ (E_{sum} is the total deposited energy, E_{beam} the beam energy), to estimate the systematic error arising from the event selection; this is the dominant component of the systematic error as indicated in Table II.

The numbers of hadronic events and beam-associated background events are determined by fitting the distribution of event vertices along the beam direction with a Gaussian to describe the hadronic events and a polynomial of degree one to three for the beam-associated background. This background varies from 3% to 10% of the selected hadronic event candidates, depending on the energy. The fit using a second degree polynomial, shown in Fig. 1(d), turned out to be the best. The difference between using a polynomial of degree one or three to that of degree two is about 1%, which is included in the systematic error in the event selection.

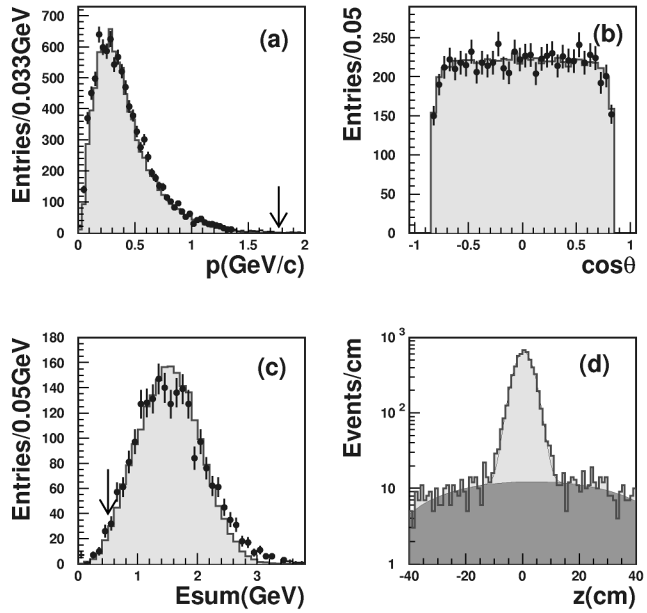

FIG. 1. Distributions for $E_{\text{c.m.}} = 3.0$ GeV of (a) track momentum, (b) track $\cos\theta$, (c) total energy deposited in the Barrel Shower Counter (BSC), and (d) event vertex position along the beam (z) axis. Histograms and dots in (a)–(c) represent Monte Carlo and real data, respectively; the beam associated background in (c) has been removed by sideband subtraction.

A special joint effort was made by the Lund group and the BES Collaboration to develop the LUARLW generator, which uses a formalism based on the Lund Model Area Law, but without the extreme-high-energy approximations used in JETSET's string fragmentation algorithm [8]. The final states simulated in LUARLW are exclusive, in contrast to JETSET, where they are inclusive. Above

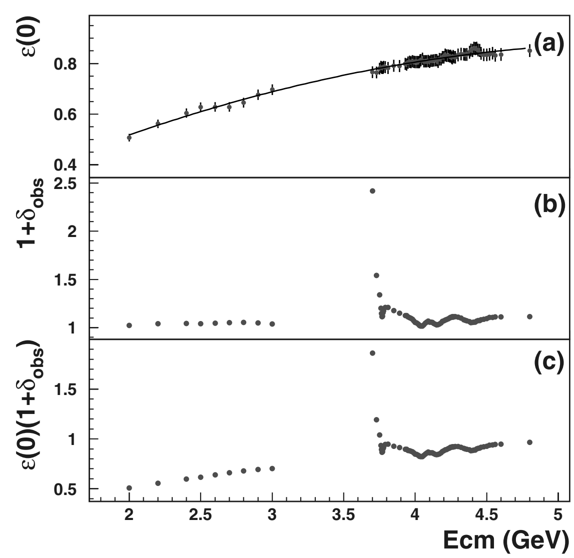

FIG. 2. (a) The c.m. energy dependence of the detection efficiency for hadronic events estimated using the LUARLW generator. The error bars are the total systematic errors. (b) The calculated radiative correction and (c) the product of (a) and (b).

TABLE I. Some values used in the determination of R at a few typical energy points.

$E_{c.m.}$ (GeV)	N_{had}^{obs}	$N_{ll}+N_{\gamma\gamma}$	L (nb^{-1})	$\epsilon(0)$ (%)	$1+\delta_{obs}$	R	Stat. error	Syst. error
2.000	1155.4	19.5	47.3	49.50	1.024	2.18	0.07	0.18
3.000	2055.4	24.3	135.9	67.55	1.038	2.21	0.05	0.11
4.000	768.7	58.0	48.9	80.34	1.055	3.16	0.14	0.15
4.800	1215.3	92.6	84.4	86.79	1.113	3.66	0.14	0.19

3.77 GeV, the production of D, D^*, D_s, and D_s^* is included in the generator according to the Eichten Model [9]. A Monte Carlo event generator has been developed to handle decays of the resonances in the radiative return processes $e^+e^- \to \gamma J/\psi$ or $\gamma\psi(2S)$ [10].

The parameters in LUARLW are tuned to reproduce 14 distributions of kinematic variables over the entire energy region covered by the scan [11]. We find that one set of parameter values is required for the c.m. energy region below open charm threshold and that a second set is required for higher energies. In an alternative approach, the parameter values were tuned point by point throughout the entire energy range. The detection efficiencies determined using individually tuned parameters are consistent with those determined with globally tuned parameters to within 2%. This difference is included in the systematic errors. The detection efficiencies were also determined using JETSET74 for the energies above 3 GeV. The difference between the JETSET74 and LUARLW results is about 1% and is also taken into account in estimating the systematic uncertainty. Figure 2(a) shows the variation of the detection efficiency as a function of c.m. energy.

We changed the fractions of D, D^*, D_s, and D_s^* production by 50% and find that the detection efficiency varies less than 1%. We also varied the fraction of the continuum under the broad resonances by 20% and find the change of the detection efficiency is about 1%. These variations are included in the systematic errors.

Different schemes for the initial state radiative corrections were compared [12–15], as reported in Ref. [7]. Below charm threshold, the four different schemes agree with each other to within 1%, while above charm threshold, where resonances are important, the agreement is within 1% to 3%. The radiative correction used in this analysis is based on Ref. [15], and the differences with the other schemes are included in the systematic error [16]. In practice, the radiative effects in the detection efficiency were moved into the radiative correction factor by making the replacement $\bar{\epsilon}_{had}(1+\delta) \to \epsilon(0)(1+\delta_{obs})$, where $\epsilon(k)$ is the efficiency for events with a radiative photon of energy k, and δ_{obs} contains a modification of the bremsstrahlung term to reflect the k dependence of the hadronic acceptance.

To calculate δ_{obs}, a cutoff in s', the effective c.m. energy after ISR to produce hadrons, has to be made. In our calculation, the minimum value of s' should be the threshold for producing two pions, corresponding to $k_{max} = 1 - s'/s = (0.9805 - 0.9969)$ in the 2–5 GeV range. Our criteria to select hadronic events is such that ϵ approaches zero when k is close to 0.90, which makes us insensitive to events with high ISR photon energy.

In calculating the radiative correction for the narrow resonances J/ψ and $\psi(2S)$, the theoretical cross section is convoluted with the energy distribution of the colliding beams, which is treated as a Gaussian with a relative beam energy spread of $1.32 \times 10^{-4} E_{c.m.}$ ($E_{c.m.}$ in GeV). For the broad resonances at 3770, 4040, 4160, and 4416 MeV, the interferences and the energy dependence of total widths were taken into consideration. Initially the resonance parameters from PDG2000 [17] were used; then the parameters were allowed to vary and were determined from our fit. The calculation converged after a few iterations.

We varied the input parameters (masses and widths) of the J/ψ, $\psi(2S)$, and the broad resonances used in the radiative correction determination by 1 standard deviation from the values quoted in Ref. [17] and find that the changes in the R value are less than 1% for most points. Points close to the resonance at 4.0 GeV have errors from 1% to 1.7%. Figure 2(b) shows the radiative correction as a function of c.m. energy, where the structure at higher energy is related to the radiative tail of the $\psi(2S)$ and the broad resonances in this energy region. Tables I and II

TABLE II. Contributions to systematic errors: experimental selection of hadronic events, luminosity determination, theoretical modeling of hadronic events, trigger efficiency, radiative corrections, and total systematic error. All errors are in percentages (%).

$E_{c.m.}$ (GeV)	Hadron selection	L	MC modeling	Trigger	Radiative correction	Total
2.000	7.07	2.81	2.62	0.5	1.06	8.13
3.000	3.30	2.30	2.66	0.5	1.32	5.02
4.000	2.64	2.43	2.25	0.5	1.82	4.64
4.800	3.58	1.74	3.05	0.5	1.02	5.14

TABLE III. Values of R from this experiment; the first error is statistical, the second systematic ($E_{\mathrm{c.m.}}$ in GeV).

$E_{\mathrm{c.m.}}$	R	$E_{\mathrm{c.m.}}$	R	$E_{\mathrm{c.m.}}$	R	$E_{\mathrm{c.m.}}$	R
2.000	2.18 ± 0.07 ± 0.18	3.890	2.64 ± 0.11 ± 0.15	4.120	4.11 ± 0.24 ± 0.23	4.340	3.27 ± 0.15 ± 0.18
2.200	2.38 ± 0.07 ± 0.17	3.930	3.18 ± 0.14 ± 0.17	4.130	3.99 ± 0.15 ± 0.17	4.350	3.49 ± 0.14 ± 0.14
2.400	2.38 ± 0.07 ± 0.14	3.940	2.94 ± 0.13 ± 0.19	4.140	3.83 ± 0.15 ± 0.18	4.360	3.47 ± 0.13 ± 0.18
2.500	2.39 ± 0.08 ± 0.15	3.950	2.97 ± 0.13 ± 0.17	4.150	4.21 ± 0.18 ± 0.19	4.380	3.50 ± 0.15 ± 0.17
2.600	2.38 ± 0.06 ± 0.15	3.960	2.79 ± 0.12 ± 0.17	4.160	4.12 ± 0.15 ± 0.16	4.390	3.48 ± 0.16 ± 0.16
2.700	2.30 ± 0.07 ± 0.13	3.970	3.29 ± 0.13 ± 0.13	4.170	4.12 ± 0.15 ± 0.19	4.400	3.91 ± 0.16 ± 0.19
2.800	2.17 ± 0.06 ± 0.14	3.980	3.13 ± 0.14 ± 0.16	4.180	4.18 ± 0.17 ± 0.18	4.410	3.79 ± 0.15 ± 0.20
2.900	2.22 ± 0.07 ± 0.13	3.990	3.06 ± 0.15 ± 0.18	4.190	4.01 ± 0.14 ± 0.14	4.420	3.68 ± 0.14 ± 0.17
3.000	2.21 ± 0.05 ± 0.11	4.000	3.16 ± 0.14 ± 0.15	4.200	3.87 ± 0.16 ± 0.16	4.430	4.02 ± 0.16 ± 0.20
3.700	2.23 ± 0.08 ± 0.08	4.010	3.53 ± 0.16 ± 0.20	4.210	3.20 ± 0.16 ± 0.17	4.440	3.85 ± 0.17 ± 0.17
3.730	2.10 ± 0.08 ± 0.14	4.020	4.43 ± 0.16 ± 0.21	4.220	3.62 ± 0.15 ± 0.20	4.450	3.75 ± 0.15 ± 0.17
3.750	2.47 ± 0.09 ± 0.12	4.027	4.58 ± 0.18 ± 0.21	4.230	3.21 ± 0.13 ± 0.15	4.460	3.66 ± 0.17 ± 0.16
3.760	2.77 ± 0.11 ± 0.13	4.030	4.58 ± 0.20 ± 0.23	4.240	3.24 ± 0.12 ± 0.15	4.480	3.54 ± 0.17 ± 0.18
3.764	3.29 ± 0.27 ± 0.29	4.033	4.32 ± 0.17 ± 0.22	4.245	2.97 ± 0.11 ± 0.14	4.500	3.49 ± 0.14 ± 0.15
3.768	3.80 ± 0.33 ± 0.25	4.040	4.40 ± 0.17 ± 0.19	4.250	2.71 ± 0.12 ± 0.13	4.520	3.25 ± 0.13 ± 0.15
3.770	3.55 ± 0.14 ± 0.19	4.050	4.23 ± 0.17 ± 0.22	4.255	2.88 ± 0.11 ± 0.14	4.540	3.23 ± 0.14 ± 0.18
3.772	3.12 ± 0.24 ± 0.23	4.060	4.65 ± 0.19 ± 0.19	4.260	2.97 ± 0.11 ± 0.14	4.560	3.62 ± 0.13 ± 0.16
3.776	3.26 ± 0.26 ± 0.19	4.070	4.14 ± 0.20 ± 0.19	4.265	3.04 ± 0.13 ± 0.14	4.600	3.31 ± 0.11 ± 0.16
3.780	3.28 ± 0.12 ± 0.12	4.080	4.24 ± 0.21 ± 0.18	4.270	3.26 ± 0.12 ± 0.16	4.800	3.66 ± 0.14 ± 0.19
3.790	2.62 ± 0.11 ± 0.10	4.090	4.06 ± 0.17 ± 0.18	4.280	3.08 ± 0.12 ± 0.15		
3.810	2.38 ± 0.10 ± 0.12	4.100	3.97 ± 0.16 ± 0.18	4.300	3.11 ± 0.12 ± 0.12		
3.850	2.47 ± 0.11 ± 0.13	4.110	3.92 ± 0.16 ± 0.19	4.320	2.96 ± 0.12 ± 0.14		

list some of the values used in the determination of R and the contributions to the uncertainty in the value of R at a few typical energy points in the scanned energy range, respectively.

Table III lists the values of R from this experiment. They are displayed in Fig. 3, together with BESII values

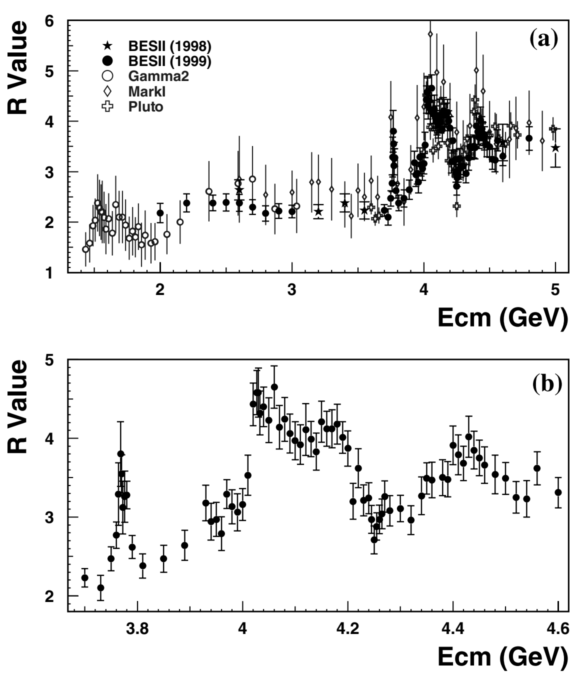

FIG. 3. (a) A compilation of measurements of R in the c.m. energy range from 1.4 to 5 GeV. (b) R values from this experiment in the resonance region between 3.7 and 4.6 GeV.

from Ref. [7] and those measured by Mark I Collaboration, $\gamma\gamma 2$ Collaboration, and Pluto Collaboration [2–4]. The R values from BESII have an average uncertainty of about 6.6%, which represents a factor of 2 to 3 improvement in precision in the 2 to 5 GeV energy region. Of this error, 3.3% is common to all points. These improved measurements have a significant impact on the global fit to the electroweak data and the determination of the SM prediction for the mass of the Higgs particle [18]. In addition, they are expected to provide an improvement in the precision of the calculated value of a_μ^{SM} [19,20] and test the QCD sum rules down to 2 GeV [21,22].

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