Luminosity measurements for the R scan experiment at BESIII postprint

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Abstract

By analyzing the large-angle Bhabha scattering events e+e− → ( )e+e and diphoton events e e → for the data sets collected at center-of-mass (c.m.) energies between 2.2324 and 4.5900 GeV (131 energy points in total) with the upgraded Beijing Spectrometer (BESIII) at the Beijing Electron-Positron Collider (BEPCII), the integrated luminosities have been measured at the different c.m. energies, individually. The results are the important inputs for R value and J/ resonance parameter measurements.

Full Text

Preamble

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Abstract: By analyzing large-angle Bhabha scattering events e+e → ( )e+e and diphoton events e+e → from data sets collected at center-of-mass (c.m.) energies between 2.2324 and 4.5900 GeV (131 energy points in total) with the upgraded Beijing Spectrometer (BESIII) at the Beijing Electron-Positron Collider (BEPCII), the integrated luminosities have been measured at the different c.m. energies individually. These results provide important inputs for R value and J/ resonance parameter measurements.

Key words: luminosity, Bhabha, diphoton, R value
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INTRODUCTION

Hadron production in e+e annihilation is one of the most valuable testing grounds for Quantum Chromodynamics (QCD) and serves as an important input for precision tests of the Standard Model (SM). The R value, defined as the lowest-order hadronic cross section normalized by the theoretical production cross section in e+e annihilation, is an indispensable input for determining the non-perturbative hadronic contribution to the electromagnetic coupling constant evaluated at the Z pole ((M^2_Z)) [1, 2] and the anomalous magnetic moment a_ = (g-2)/2 of the muon [3]. The dominant uncertainties in both (M^2_Z) and a_ measurements arise from 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 can determine the effect of vacuum polarization.

In experiment, the R value is determined by

$$R = \frac{N_{\text{obs}}^{\text{had}} - N_{\text{bkg}}^{\text{had}}}{\mathcal{L} \cdot \epsilon_{\text{had}} \cdot \epsilon_{\text{trig}}^{\text{had}} \cdot (1+\delta)} \cdot \frac{1}{\sigma_{\mu\mu}^{\text{Born}}}$$

where $N_{\text{obs}}^{\text{had}}$ is the number of observed hadronic events, $N_{\text{bkg}}^{\text{had}}$ is the number of background events, $\mathcal{L}$ is the integrated luminosity, ϵ_{had} is the detection efficiency for hadron event selection, $\epsilon_{\text{trig}}^{\text{had}}$ is the trigger efficiency, $1+\delta$ is the initial state radiation (ISR) correction factor, and $\sigma_{\mu\mu}^{\text{Born}}$ is the Born cross section of e+e → . Therefore, the measurement of integrated luminosity plays an important role in the R value measurement.

Quantum electrodynamics (QED) processes can usually be used to determine the integrated luminosity due to their larger production rates, simpler final state topologies, and more accurate theoretical cross section calculations relative to other processes. The integrated luminosity is measured by

$$\mathcal{L} = \frac{N_{\text{obs}}^{\text{QED}} - N_{\text{bkg}}^{\text{QED}}}{\sigma_{\text{QED}} \cdot \epsilon_{\text{QED}} \cdot \epsilon_{\text{trig}}}$$

where $N_{\text{obs}}^{\text{QED}}$ is the number of QED events observed in the experimental data, $N_{\text{bkg}}^{\text{QED}}$ is the number of background events, σ_{QED} is the cross section of the selected QED process, ϵ_{QED} is the detection efficiency, and ϵ_{trig} is the trigger efficiency.

In this paper, we present the measurements of luminosities of the R scan data samples taken at BESIII from 2012 to 2014. The measurements are performed by analyzing two QED processes: e+e → ( )e+e and e+e → . For energy points near the J/ resonance, only the e+e → process is used, because J/ → ( )e+e events cannot be distinguished from e+e → ( )e+e events experimentally.

II. DETECTOR

BEPCII [4] is a double-ring e+e collider designed to provide a peak luminosity of 10^{33} cm ^{2}s ^{1} at the center-of-mass (c.m.) energy ($\sqrt{s}$) of 3770 MeV. The BESIII [4] detector has a geometrical acceptance of 93% of 4 and consists of four main sub-components: (1) A small-cell, helium-based (60% He, 40% C H) main drift chamber (MDC) with 43 layers providing an average single-hit resolution of 135 m and charged-particle momentum resolution in a 1 T magnetic field of 0.5% at 1 GeV/c. (2) An electromagnetic calorimeter (EMC) consisting of 6240 CsI(Tl) crystals arranged in a cylindrical structure with a barrel and two end-caps. The energy resolution at 1.0 GeV/c is 2.5% (5%) in the barrel (endcaps), and the position resolution is 6 mm (9 mm) in the barrel (endcaps). (3) A time-of-flight

(TOF) system for particle identification composed of a barrel part made of two layers with 88 pieces of 5 cm thick, 2.4 m long plastic scintillators in each layer, and two endcaps with 96 fan-shaped, 5 cm thick plastic scintillators in each endcap. The time resolution of 80 ps (110 ps) for barrel (endcap) provides 2 K/ separation for momenta up to 1.0 GeV/c. (4) A muon system (MUC) consisting of 1000 m^2 of resistive plate chambers in nine (eight) layers in the barrel (endcap) providing 2 cm position resolution.

III. DATA SAMPLE AND MONTE CARLO SIMULATION

The luminosity measurements are performed for 131 data samples, including 4 energy points at 2.2324, 2.4000, 2.8000, and 3.4000 GeV taken during the 2012 run, 104 energy points from 3.8500 to 4.5900 GeV taken during the 2013-2014 runs, 15 energy points near the J/ production threshold, 4 energy points during the mass measurement, and 4 energy points for charmonium studies.

The e+e → ( )e+e , e+e → , and e+e → ( ) events are simulated with the generator Babayaga v3.5 [5]. The background process e+e → is generated with KKMC [6], while the e+e → hadrons + X (where X can be hadrons or leptons) events are generated with LUARLW [7] and BesTwogam [8], respectively.

To estimate the numbers of background events, N_{bkg}, two different methods are applied for the e+e → ( )e+e and e+e → processes individually. For the e+e → ( )e+e process, the numbers of background events are estimated by applying the same selection requirements to the background MC samples, which yields a background level of 10 after normalization. For the e+e → process, the background level is relatively large due to contamination from hadronic processes. The normalized numbers of background events from e+e → are estimated from the sideband region defined as 2.5° < |Δ | < 5.0°. The distributions of the Δ sideband are expected to be flat based on analysis of the background MC samples.

IV. ANALYSIS

Table I shows the input numbers used to calculate the luminosities at $\sqrt{s}$ = 2.2324 and 3.0969 GeV. The e+e → ( )e+e events are required to have two good charged tracks with opposite charge. Each charged track is required to be within 10 cm of the interaction point in the beam direction and 1 cm in the plane perpendicular to the beam. In addition, the charged tracks are required to satisfy $|\cos\theta| < 0.8$, where θ is the polar angle, in the MDC. Without applying further particle identification, the tracks are assigned as electron and positron depending on their charges. The deposited energies of the electron and positron ($E_{e^\pm}$) in the EMC are required to be larger than $0.65E_{\text{beam}}$ to suppress backgrounds, where E_{beam} is the beam energy. To ensure that the selected charged tracks are back-to-back in the detector, requirements of $|\theta_1 + \theta_2 - 180°| < 10.0°$ and $|\phi_{1/2}| < 5.0°$ are applied, where $\theta_{1/2}$ and $\phi_{1/2}$ are the polar and azimuthal angle differences between the two charged tracks, respectively. Figure 1 [Figure 1: see original paper] shows comparisons of the momentum and polar angle distributions of electrons and positrons between experimental data and Monte Carlo (MC) simulation at $\sqrt{s} = 2.2324$ GeV, where good agreement is observed.

To select e+e → events, the number of good charged tracks is required to be zero. Two neutral clusters are required to have a polar angle $|\cos\theta| < 0.8$ with deposited energy E_γ satisfying $0.7 < E_\gamma/E_{\text{beam}} < 1.16$. The two selected photon candidates are further required to be back-to-back by applying the requirement $|\phi_{\gamma 1/2}| < 2.5°$, where $\phi_{\gamma 1/2}$ is the azimuthal angle difference between the photons. Figure 2 [Figure 2: see original paper] shows comparisons of the energy deposition, polar angle, and Δ distributions of the two selected photons between experimental data and MC simulation at $\sqrt{s} = 2.2324$ GeV.

The numbers of observed QED events, $N_{\text{obs}}^{\text{QED}}$, are obtained by event counting after applying the event selection requirements to experimental data at different c.m. energies individually. The detection efficiencies of signals, ϵ_{QED}, are obtained by analyzing the corresponding signal MC events in the same manner as the data analysis. The cross sections of selected QED processes are calculated with the Babayaga v3.5 generator, and the trigger efficiencies are quoted from Ref. [9].

TABLE I. Summaries of the input numbers in luminosity calculation at $\sqrt{s} =$ 2.2324 and 3.0969 GeV.

$\sqrt{s}$ (GeV)	QED process	$N_{\text{obs}}^{\text{QED}}$	N_{bkg}	σ_{QED} (nb)	ϵ_{QED}	ϵ_{trig}
2.2324	( )e+e					
2.2324						
3.0969	( )e+e					
3.0969						

V. SYSTEMATIC UNCERTAINTY

The main systematic uncertainties of the integrated luminosity originate from uncertainties related to requirements on kinematic variables, tracking efficiency, cluster reconstruction efficiency, c.m. energy, MC statistics, background estimation, trigger efficiency, and generators.

For the systematic uncertainty from requirements on each kinematic variable, we re-measure the luminosity by altering the required values–i.e., $|\cos\theta| < 0.8$, $|\phi_{1/2}| < 10°$, $|\phi_{\gamma 1/2}| < 2.5°$, $E_{e^\pm}/E_{\text{beam}} > 0.65$, $|\theta_1 + \theta_2 - 180°| < 5°$, and $0.7 < E_\gamma/E_{\text{beam}} < 1.16$–individually. The resultant differences in measured luminosity relative to the nominal value are taken as the systematic uncertainty.

To study the uncertainty of tracking efficiency, a Bhabha event sample is selected using only EMC information [10]. Candidate events are selected by requiring two clusters registered in the EMC with deposited energy larger than $0.65E_{\text{beam}}$ and lying within the polar angle $|\cos\theta| < 0.8$, corresponding to the angular coverage of the barrel EMC. Since the two clusters originating from e± in e+e → ( )e+e candidate events are bent in the magnetic field, the two shower clusters in the xy-plane of the EMC are not back-to-back. Δ _{e^±}$ is required to be in the range of [5°, 40°] to remove e+e → events. We further apply MDC information to the selected candidates, and the ratio of surviving events is regarded as the tracking efficiency. The average difference in tracking efficiency between data and signal MC simulation, 0.41%, is taken as the systematic uncertainty.

The systematic uncertainty due to cluster reconstruction efficiency in the EMC is determined to be 0.05% for e± by comparing cluster reconstruction efficiencies between data and signal MC (both for e and e). Since high-energy and e± behave similarly in the EMC, the value of 0.05% is also taken as the systematic uncertainty due to cluster reconstruction efficiency for a single .

The uncertainty of c.m. energy is estimated to be 2 MeV [11]. For each energy point, an alternative MC simulation sample of 1 million events with a c.m. energy 2 MeV above the nominal value is generated to re-estimate the detection efficiency; the resulting difference is regarded as the systematic uncertainty from c.m. energy.

The uncertainty from MC statistics is 0.17% for the e+e → ( )e+e process and 0.15% for the e+e → process, estimated as $\sqrt{N}/N \cdot \epsilon$ where N is the number of signal MC events and ϵ is the detection efficiency.

The rate of background events in selected e+e → ( )e+e candidate events is very small (10). Therefore, the uncertainty due to background contamination is neglected. For e+e → events, the background event rate is the normalized number of selected background events in the sideband region divided by the number of signal events, which are (1.53 ± 0.04)% for experimental data and (1.31 ± 0.03)% for MC simulation, respectively. Therefore, the difference of 0.23% is taken as the uncertainty from background contamination.

The trigger efficiencies for barrel e+e → ( )e+e events and e+e → events are 100% with an uncertainty of less than 0.1% [9]. The uncertainty due to the Babayaga generator v3.5 is 0.5% for e+e → ( )e+e and 1.0% for e+e → [5].

Systematic uncertainties at $\sqrt{s} = 2.2324$ GeV for e+e → ( )e+e and e+e → are listed in Table II. Assuming all sources of systematic uncertainties are uncorrelated, the total uncertainty is calculated to be 0.7% for e+e → ( )e+e and 1.1% for e+e → by adding all contributions in quadrature. The uncertainties related to tracking efficiency, cluster reconstruction efficiency, trigger efficiency, and generators are common between different c.m. energy points, while others are c.m. energy dependent and are determined for different c.m. energy points individually.

TABLE II. Summary of systematic uncertainties at $\sqrt{s} = 2.2324$ GeV.

Source	e+e → ( )e+e	e+e →
$\lvert\cos\theta\rvert < 0.8$		
$\lvert\phi_{1/2}\rvert < 2.5°$		
$E_{e^+}/E_{\text{beam}} > 0.65$		
$E_{e^-}/E_{\text{beam}} > 0.65$		
$0.7 < E_\gamma/E_{\text{beam}} < 1.16$		
Tracking efficiency		
Cluster reconstruction		
Beam energy		
MC statistics		
Background estimation		
Trigger efficiency		
Generator		
Total	0.7%	1.1%

VI. SUMMARY

The integrated luminosities have been measured for 131 data samples with c.m. energies between 2.2324 and 4.5900 GeV. The precision of the integrated luminosity is approximately 0.7% for e+e → ( )e+e and approximately 1.1% for e+e → . The total luminosity is 1036.3 pb ^{1}, and the luminosities at individual c.m. energy points are summarized in Table III. The ratio of measured luminosities from the two processes is illustrated in Figure 3 [Figure 3: see original paper]. The ratios are close to 1 within uncertainties, indicating that the results from the two measurements are consistent with each other. For each energy point outside the J/ resonance region, the luminosity measured by e+e → ( )e+e is more precise and thus is recommended. For energy points around J/ (from 3.0930 to 3.1200 GeV), only luminosities measured by e+e →   are obtained. These measured results provide important inputs for physics studies such as R value measurement and J/ resonance parameter measurement.

TABLE III. Summaries of measured integrated luminosities from the two QED processes. The first uncertainty is statistical and the second is systematic.

$\sqrt{s}$ (GeV)	e+e → ( )e+e (pb ^{1})	e+e → (pb ^{1})

By using the QED processes e+e → ( )e+e and e+e → , the integrated luminosities have been measured.

TABLE III. (continued) Summaries of measured integrated luminosities from the two QED processes.

$\sqrt{s}$ (GeV)	e+e → ( )e+e (pb ^{1})	e+e → (pb ^{1})

TABLE III. (continued) Summaries of measured integrated luminosities from the two QED processes.

$\sqrt{s}$ (GeV)	e+e → ( )e+e (pb ^{1})	e+e → (pb ^{1})

TABLE III. (continued) Summaries of measured integrated luminosities from the two QED processes.

$\sqrt{s}$ (GeV)	e+e → ( )e+e (pb ^{1})	e+e → (pb ^{1})

FIGURE 3. Ratios of luminosities measured by e+e → ( )e+e and e+e → . The main plot shows data samples with c.m. energy larger than 3.8500 GeV, while others are shown in the insert plot. The two methods give fully compatible results within the quoted uncertainties.

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Note: Figure translations are in progress. See original paper for figures.