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Measurements of the center-of-mass energies of e^+e^- collisions at BESIII *

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Abstract

During the 2016-17 and 2018-19 running periods, the BESIII experiment collected 7.5 fb $^{-1}$ of e^+e^- collision data at center-of-mass energies ranging from 4.13 to 4.44 GeV. These data samples are primarily used for the study of excited charmonium and charmoniumlike states. By analyzing the di-muon process $e^+e^- \to e^+e^- \to$, we measure the center-of-mass energies of the data samples with a precision of 0.6 MeV. Through a run-by-run study, we find that the center-of-mass energies were stable throughout most of the data-collection period.

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I. INTRODUCTION

The BESIII experiment [1] was designed to study physics in the τ-charm energy region (2.0 – 4.9 GeV) [2] through e^+e^- annihilations produced by the BEPCII storage ring [3]. Since it started running in 2008, a variety of data samples have been collected at different center-of-mass (CM) energies for the study of light hadron spectroscopy, charmonium and charmoniumlike states (also called XYZ states), charm physics, τ physics, various QCD-related studies, and the search for new physics beyond the standard model [4].

The Beam Energy Measurement System (BEMS) [5] was designed to precisely measure BESIII CM energies (E_{cm}) using a method based on Compton back-scattered photons. However, its capability at high energy (E_{cm} above 4 GeV) is degraded by its detection efficiency and limited calibration sources for high-energy gamma rays. Therefore, an alternative algorithm was developed to measure the E_{cm} for data samples above 4 GeV. This method uses the well-understood QED process $e^+e^- \rightarrow (\gamma_{\mathrm{ISR/FSR}})\mu^+\mu^-$ (the di-muon process), where $\gamma_{\mathrm{ISR/FSR}}$ is a radiative photon due to initial state radiation (ISR) and/or final state radiation (FSR). Using this method, a precision of 0.8 MeV was previously achieved for data from 2011 to 2014 [6].

In this paper, we present the E_{cm} measurement for the XYZ data samples taken at BESIII from 2017 to 2019. The method used in Ref. [6] is followed, but the precision of the momentum calibration is improved, and the E_{cm} is measured with an uncertainty of 0.6 MeV.

Using the selected di-muon events, $e^+e^- \rightarrow (\gamma_{\mathrm{ISR/FSR}})\,\mu^+\mu^-$, we determine E_{cm} using

$$E_{\mathrm{cm}} = (M_{\mathrm{p}}(\mu^+\mu^-) + \Delta M_{\mathrm{ISR/FSR}} + \Delta M_{\mathrm{cal}}) \times c^2, \qquad (1)$$

where $M_{\mathrm{p}}(\mu^+\mu^-)$ is the peak position of the $\mu^+\mu^-$ invariant mass of selected di-muon events; $\Delta M_{\mathrm{ISR/FSR}}$ is the mass shift due to the emission of ISR or FSR photons, estimated from Monte Carlo (MC) simulation of the di-muon process by turning the ISR/FSR processes on and off in MC generation; and ΔM_{cal} is the correction introduced by the momentum calibration of the $\mu^+\mu^-$ tracks, obtained from an analysis of the process $e^+e^- \rightarrow \gamma_{\mathrm{ISR}} J/\psi$.

II. THE BESIII DETECTOR AND DATA SETS

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The BESIII detector is described in detail in Ref. [1]. The cylindrical core of the detector covers 93% of the full solid angle and consists of a helium-based multilayer drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), all of which are enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. The solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identification modules interleaved with steel. The charged-particle momentum resolution at $1\ \mathrm{GeV}/c$ is 0.5, and the $\mathrm{d}E/\mathrm{d}x$ resolution is 6% for electrons from Bhabha scattering. The EMC measures photon energies with a resolution of 2.5% (5%) at 1 GeV in the barrel (end cap) region. The time resolution in the TOF barrel region is 68 ps, and that in the end cap region is 60 ps [7-9].

The data samples analyzed in this work are listed in Table 1. They include 16 different CM energies from 4.13 to 4.44 GeV and were collected in two running years: from December 2016 to May 2017 (labelled as "2017XYZ" hereafter, the integrated luminosities are measured using the Bhabha events in Ref. [10]) and from February 2019 to June 2019 (labelled as "2019XYZ" hereafter, the integrated luminosities are estimated by using online monitoring information). The column "Sample" lists the nominal CM energy in MeV used during online data collecting. The true CM energy is generally within a few MeV of the nominal value. Run numbers are used to divide the data into subsamples. Other columns, such as ( ), are illustrated below.

Table 1. Summary of the data samples, including run numbers, integrated luminosity [10], the measured mass after FSR correction (in MeV/), (in MeV/), and . Superscripts represent data from different periods: "1" denotes 2017XYZ data, and "2" denotes 2019XYZ data. The first uncertainties are statistical and the second systematic.

Sample	Run Number	/	/MeV
4130	59163-59573	400	
4160	59574-59896	400	
4190	47543-48170		
4200	48172-48713		
4210	48714-49239		
4220	49270-49787		
4237	49788-50254		
4246	50255-50793		
4270	50796-51302		
4280	51305-51498		
4290	59902-60363	500	
4315	60364-60805	500	
4340	60808-61242	500	
4380	61249-61762	500	
4400	61763-62285	500	
4440	62286-62823	570	

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A GEANT4 [11] based detector simulation package is developed to model the detector response for MC events. In our analysis, the di-muon sample is generated with BABAYAGA3.5 [12], and the sample is generated with KKMC [13, 14]. One million events are generated for each process at each CM energy.

III. EVENT SELECTION AND MEASUREMENT OF

The di-muon process is selected by requiring two oppositely charged tracks in the detector, each positively identified as a muon. Both charged tracks are reconstructed from hits in the MDC within the polar angle range and their extrapolations to the interaction point (IP) within 10 cm along the beam direction and 1 cm in the plane perpendicular to the beam. The energy deposition in the EMC for each charged track is required to be less than 0.4 GeV to suppress backgrounds from radiative Bhabha events.

The sample after these selections includes di-muon events with no photon emission or with very low-energy radiative photons, ISR with , and ISR events with a smooth invariant mass ( ) distribution. The events in the mass region are used for track momentum calibration and those with high invariant mass are used to measure the after additional selection criteria are applied, as described below.

To suppress di-muon events with high energy radiative photons, a requirement on the cosine of the opening angle between the two tracks, is applied. To further remove cosmic ray events, the TOF time difference between the two tracks is required to be ns. The background contribution after these selection criteria is less than 0.1% compared with the signal and is therefore neglected in the following analysis.

The distribution for the 4190 data sample is shown in Fig. 1 as an example. The distributions of the other samples are very similar. The distribution is a Gaussian due to the momentum resolution of the , though it is distorted by ISR and FSR effects, producing a tail on the left side of the peak. The central part of the distribution can be approximated with a Gaussian function. We measure the peak position of the distribution ( ) by fitting it with a Gaussian function in the range of around the peak, where is the standard deviation of the Gaussian. If the goodness of the fit, (is the number of degrees of freedom of the fit), the fit range is slightly reduced until , guaranteeing a good fit quality. The fit result for the 4190 data sample is shown in Fig. 1. The values of for the other data samples are obtained using a similar method and are listed in Table 1.

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Fig. 1 (color online) The invariant mass distribution and the fit result of the 4190 sample. Dots with error bars are data, and the solid red curve is the fit.

To examine the stability of the over the data-taking period for each data sample, the fit procedure is repeated for each run of the data sample. The measured peak values of the invariant mass distribution versus run number for all 16 samples are shown in Fig. 2. There are small jumps of less than 1 MeV in the 4130, 4200, 4210, 4246, 4380, and 4400 samples. Before and after the jumps, the energy is stable. We fit each stable part of the distribution with a linear function and Table 2 summarizes the average, , for each period of time. The deviation of from the peak position obtained in the full data sample is considered as one source of systematic uncertainty.

Fig. 2 (color online) Measured run-by-run values for the of di-muon events in each data sample. The red solid lines show the fit results for the data samples of each stable period of time. The green dotted lines are the fit results of the entire sample when there is an energy jump.

Table 2. Average value (in MeV/) for each stable data-taking period within each data sample.

Sample	Run Number	Run Number
4130	59163-59190	59191-59573
4160	59574-59896	
4190	47543-48170	
4200	48172-48290	48291-48713
4210	48174-49065	49066-49239
4220	49270-49787	
4237	49788-50254	
4246	50255-50520	50521-50793
4270	50796-51302	
4280	51305-51498	
4290	59902-60363	

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Sample	Run Number	Run Number
4315	60364-60805	
4340	60808-61242	
4380	61249-61400	61401-61762
4400	61763-61980	61981-62285
4440	62286-62823	

IV. MOMENTUM CALIBRATION WITH ISR SIGNAL

The momentum measurement of the muon tracks is validated with candidates produced via the process selected in the previous section. The distribution of for each sample is fitted with a crystal-ball function [15] for the signal and a linear function to model the background from continuum production of . Figure 3(a) shows the fit result for the 4190 data sample as an example. The peak position of the signal, , is used to calibrate the momentum measurement of the muon tracks.

Fig. 3 (color online) (a) Fit to the distribution in the signal region for the 4190 data sample. Black dots with error bars are data, the red curve shows the fit result, the blue curve indicates the signal, and the green dashed line indicates the background. (b) The difference between and the world average mass of [16], for each data sample.

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Due to FSR, , the measured is slightly lower than the world average mass ( ) given by the PDG [16]. The mass shift due to the FSR photon(s) of the process at each is obtained by using the generator PHOTOS [17] with FSR turned on or off. The shift is around 0.3 MeV/ with minimal dependence on the CM energy of the data sample.

Comparing the (as shown in Table 1) with the world-average mass value in the Particle Data Book (PDG), we measure the bias in the mass measurement ( ) due to the muon track momentum calibration, as shown in Fig. 3(b). It can be seen that the bias in the invariant mass is stable throughout one running year, but is quite different in the 2017XYZ and 2019XYZ samples. This may indicate that the calibrations in these two periods of time have significant differences.

Through MC simulation we find that the bias in the measurement depends linearly on (see Fig. 4), and there exists with no radiation, so the correction to the due to calibration is expressed as

Fig. 4 (color online) (a) The distribution of of different for the MC simulation of process without FSR. The average value is MeV/ . (b) is the difference between the reconstructed and generated center-of-mass energy ( ) reported as a function of (is equal to for events without radiation). The di-muon events are generated without radiation emission. The bias at mass given from (b) is MeV/ , which is consistent with the result provided in (a). The linear fit to the points provides the dependence of the bias on (slope) due to track momentum calibration, which is assumed to be the same for data and simulation.

where the slopes and correspond to the 2017XYZ and 2019XYZ samples, respectively. They agree within the statistical uncertainties of the MC samples, which indicates that the momentum dependence of the calibration constants is very similar in the 2017XYZ and 2019XYZ samples.

V. THE MASS SHIFT

of the initial pair is measured via the di-muon process . However, due to the emission of radiative photons, the invariant mass of the pair is smaller than by . This correction is estimated with MC simulation using BABAYAGA3.5 [12].

We generate one million di-muon events for each sample with ISR/FSR turned on or off, apply the same event selection criteria to the di-muon events as in the data (described in Sec. III), and fit the distributions of from the samples with ISR/FSR on and off with a Gaussian function in the range around the peak (same as in Sec. III). The difference in is taken as the mass shift caused by ISR or FSR. versus shown in Fig. 5 indicates that the ISR/FSR effect depends linearly on . The data are fitted with a linear function to provide an improved precision measurement of the correction. From the fit,

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Fig. 5 (color online) Mass shift versus CM energy for MC samples. The solid red line is the linear fit.

with a correlation factor of between the slope and the intercept, and the goodness of the fit is .

VI. SYSTEMATIC UNCERTAINTIES

The systematic uncertainty in is from the momentum calibration of , the estimation of the mass shift due to ISR/FSR, the open angle cut of , the corresponding fit procedure, and the generator. The bias of the momentum measurement of and the estimation of the mass shift due to ISR/FSR both have a linear relationship with , and the uncertainty produced by the uncertainty of the parameters is regarded as the systematic uncertainties.

To reduce the influence of the events with high radiation, we required . Different cut values will give different and corresponding radiation correction values . The changes in these two parts cancel each other out. The largest difference comes from the data between and , and is MeV. We take 0.14 MeV as the uncertainty due to this requirement.

 is measured by fitting with a Gaussian function in the range of around the peak with fit quality . If the fit range is smaller than the standard range, the difference in the fit results is less than 0.1 MeV. We take this as the uncertainty due to the fit method.

The contribution to the systematic uncertainty of the ISR/FSR correction from the generator is negligibly small, as claimed in Ref. [12]. The uncertainties from other sources, such as background and other event selection criteria, are negligible.

Assuming all sources of systematic uncertainty are independent, the total systematic uncertainty is obtained by adding all the items in quadrature, which is listed in Table 1. The uncertainty is smaller than 0.6 MeV for all data samples.

VII. SUMMARY

The center-of-mass energies, , of the data samples are obtained using Eq. (1), with the correction factors in Eqs. (2) and (3). The final results are listed in Table 1, including the statistical and systematic uncertainties. The corresponding statistical uncertainty is very small, and the systematic uncertainty is less than 0.36 MeV everywhere, with the exception of the point at 4280 MeV, where the error on is much larger than the rest. The stability of over time for the data samples is also examined.

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The results presented in this work are essential for the discovery of new states and the investigation of the transitions of charmonium and charmoniumlike states [18] using the BESIII data. Some of the analyses have been presented in Refs. [19-24].

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Footnotes

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