Precision measurement of the integrated luminosity of the data taken by BESIII at center of mass energies between 3.810 GeV and 4.600 GeV (Postprint)

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Abstract

From December 2011 to May 2014, about 5 fb−1 of data were taken with the BESIII detector at center-of-mass energies between 3.810 GeV and 4.600 GeV to study the charmoniumlike states and higher excited charmonium states. The time integrated luminosity of the collected data sample is measured to a precision of 1% by analyzing events produced by the large-angle Bhabha scattering process.

Full Text

Preamble

Precision measurement of the integrated luminosity of the data taken by BESIII at center of mass energies between 3.810 GeV and 4.600 GeV

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From December 2011 to May 2014, about 5 fb^{-1} of data were taken with the BESIII detector at center-of-mass energies between 3.810 GeV and 4.600 GeV to study the charmoniumlike states and higher excited charmonium states. The time-integrated luminosity of the collected data sample is measured to a precision of 1% by analyzing events produced by the large-angle Bhabha scattering process.

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INTRODUCTION

The charmoniumlike states discovered in recent years have drawn great attention from both theorists and experimentalists due to their exotic properties, as reviewed in Ref. [1]. Being well above the open charm threshold, the strong coupling of these states to hidden charm processes makes their interpretation as conventional charmonium states very difficult. On the other hand, the theory of the strong interaction, Quantum Chromodynamics (QCD), does not prohibit the existence of exotic states beyond the quark model, such as molecular states, tetraquark states, hybrid states, etc. Either the verification or exclusion of the existence of such states will help evaluate the quark model and improve our understanding of QCD. Even though some states have been identified as higher excited charmonium states, such as the (4040), (4160), and (4415), their large widths and mutual interference make precise study complicated. In addition, the relationship between the charmoniumlike states and higher excited charmonium states remains unclear. Precise knowledge of the time-integrated luminosity is essential for quantitative analysis of these states.

As a τ-charm factory, the BESIII experiment has collected the world's largest sample of e^+e^- collision data at center-of-mass (CM) energies between 3.810 GeV and 4.600 GeV. In this energy region, charmoniumlike states and higher excited charmonium states are produced copiously, enabling comprehensive studies. In this paper, we present a measurement of the integrated luminosity based on analysis of the Bhabha scattering process $e^+e^- \to (\gamma)e^+e^-$. A similar method was used for luminosity measurement of (3770) data at BESIII [2]. This process has a simple and clean signature with a large production cross section, allowing for small systematic and negligible statistical uncertainties. A cross-check of the result is performed by analyzing the di-gamma process $e^+e^- \to \gamma\gamma$.

II. THE DETECTOR

BESIII is a general-purpose detector covering 93% of the solid angle, operating at the $\mathrm{e^+e^-}$ collider BEPCII. A detailed description of the facilities is given in Ref. [3]. The detector consists of four main components: (a) A small-cell, helium-based main drift chamber (MDC) with 43 layers provides an average single-hit resolution of 135 µm and a momentum resolution of 0.5% for charged tracks at 1 GeV/c in a 1 T magnetic field. (b) An electromagnetic calorimeter (EMC) consisting of 6240 CsI(Tl) crystals in a cylindrical structure (barrel and two endcaps). The energy resolution for 1.0 GeV photons is 2.5% (5%) in the barrel (endcaps), while the position resolution is 6 mm (9 mm) in the barrel (endcaps). (c) A time-of-flight system (TOF) constructed of 5 cm thick plastic scintillators, arranged in 88 detectors of 2.4 m length in two layers in the barrel and 96 fan-shaped detectors in the endcaps. The barrel (endcap) time resolution of 80 ps (110 ps) provides 2σ K/π separation for momenta up to about 1.0 GeV/c. (d) A muon counter (MUC) consisting of nine layers of resistive plate chambers in the barrel and eight layers for each endcap, incorporated in the iron return yoke of the superconducting magnet. Its position resolution is about 2 cm. A GEANT4 [4, 5] based detector simulation package has been developed to model the detector response. Due to the crossing angle of the beams at the interaction point, the $\mathrm{e^+e^-}$ CM system is slightly boosted with respect to the laboratory frame.

III. DATA SAMPLE AND MONTE CARLO SIMULATION

Twenty-one data samples were taken at CM energies between 3.810 GeV and 4.600 GeV. Six of these data sets exceed the others in accumulated statistics by an order of magnitude. These samples were taken on the peaks of charmoniumlike states, such as the Y(4260), Y(4360), and Y(4630), or higher excited charmonium states, such as (4040) and (4415), to study these resonances and their decays in detail. The data samples taken at other CM energies serve as scan points to study the behavior of the cross section around these resonances. All individual data samples are listed in Table I.

At each energy point, one million Bhabha events were generated using the BABAYAGA3.5 [6] generator with the options presented in Table II. For the BABAYAGA3.5 generator, the uncertainty in calculating the cross section is 0.5%, which meets the demand for the total uncertainty of the luminosity measurement. The kinematic distributions of the final-state particles from the BABAYAGA3.5 generator are consistent with those from data. In the simulation, the scattering angles of the final-state particles were limited to a range from 20 degrees to 160 degrees, which slightly exceeds the sensitive volume of the detector, to save computing resources. An energy threshold of 0.04 GeV was applied to the final-state particles. The acolinearity of the events was not constrained. Finally, the generation accounted for the running of the electromagnetic coupling constant and final-state radiation (FSR).

To study background and optimize event selection criteria, an inclusive Monte Carlo (MC) sample corresponding to a luminosity of 500 pb^{-1} at the CM energy of 4.260 GeV was generated, including QED processes, continuum hadron production, and initial-state radiation (ISR) to J/ and (3686) resonance processes. The BABAYAGA3.5 generator was used to simulate QED processes, both signal and background. Other processes, such as decays of J/ , were generated with specialized models packaged and customized for the BESIII Offline Software System (BOSS) (see [7] for an overview).

IV. EVENT SELECTION AND RESULTS

Signal candidates are required to have exactly two oppositely charged tracks originating from a cylindrical volume centered around the interaction point, defined by a radius of 1 cm perpendicular to the beam axis and a length of $±$10 cm along the beam axis. The charged tracks must be within |cos | < 0.8, where is the polar angle measured by the MDC. Without further particle identification, the tracks are assigned as electron and positron based on their charge. The deposited energies of the electron and positron in the EMC must be larger than 4.26 × 1.55 (GeV) to remove di-muon background, where √s is the CM energy in GeV. The momenta of the electron and positron are required to be larger than 4.26 × 2 (GeV/c) to suppress background events from lighter vector resonances produced in the ISR process, such as J/ , (3686), and other resonances decaying into e^+e^- pairs. For data samples with CM energies of 3.810 or 3.910 GeV, the effect of remaining (3686) events is studied by applying a 20% larger momentum requirement and found to be negligible. The requirements on deposited energies and momenta are not optimized in detail, as the number of signal events in such an analysis is sufficiently large. All variables mentioned above are determined in the initial e^+e^- CM frame. The ratio of remaining background events to signal events, estimated from the inclusive MC sample, is less than 2×10^{-4}, which is negligible. Thus all selected events are taken as Bhabha events.

Figure 1 [Figure 1: see original paper] shows comparisons between data and MC simulation for the kinematic variables of the leptons, using data at the CM energy of 4.260 GeV as an example. Reasonable agreement is observed in the angular and momentum distributions. The striking difference between data and simulation found in the distributions of energies deposited by the leptons in the EMC arises from imperfections in simulating the energy response of individual detector channels. At the CM energies analyzed in this work, a single shower in the calorimeter can be so energetic that the deposited energy per crystal exceeds the dynamic range of the analog-to-digital converter (ADC), causing individual ADC channels to saturate. In the analysis presented here, conditions applied to energy deposits are not affected. Relevant deviations between data and MC are considered as contributions to systematic uncertainties.

The integrated luminosity is calculated using

$$\mathcal{L} = \frac{N_{\text{obs}}^{\text{Bhabha}}}{\sigma_{\text{Bhabha}} \times \epsilon}$$

where $N_{\text{obs}}^{\text{Bhabha}}$ is the number of observed Bhabha events, σ_{Bhabha} is the cross section of the Bhabha process, and ϵ is the efficiency determined by analyzing the signal MC sample. The cross sections are calculated with the BABAYAGA3.5 generator using the parameters listed in Table II and decrease with increasing energy. The efficiencies are almost independent of CM energy, as intended by the choice of relative conditions on lepton momenta and deposited energies. The luminosity results calculated with Equation (1) are listed in Table I. The statistical accuracy of the resulting integrated luminosity is better than 0.1% at all energy points.

V. SYSTEMATIC UNCERTAINTY

The following sources of systematic uncertainties are considered: tracking efficiency uncertainty, uncertainty related to requirements on kinematic variables, statistical uncertainty of the MC sample, beam energy measurement uncertainty, trigger efficiency uncertainty, and systematic uncertainty of the event generator.

To estimate the systematic uncertainty related to tracking efficiency, the Bhabha event sample is selected using information from the EMC only, without using tracking information from the MDC. The selection criteria are: at least two clusters in the EMC for each candidate, with the two most energetic clusters assumed to originate from the e^+e^- pair; the deposited energies of the two clusters are required to be larger than 4.26 × 1.8 (GeV). At CM energies above 4.420 GeV, the requirement is changed to 4.26 × 1.55 (GeV). This adjustment avoids additional systematic uncertainties that would be introduced by deviations between data and simulation in deposited energy in the EMC, as discussed in Section IV. The polar angle of each cluster is required to be within |cos _{EMC}| < 0.8, where _{EMC} is the polar angle measured by the EMC. To remove background from the di-photon process, $\Delta\phi$ is required to be in the range of [−40°, −5°] or [5°, 40°], where $\Delta\phi = |\phi_1 - \phi_2| - 180°$ and $\phi_{1,2}$ are the azimuthal angles of the clusters in the EMC boosted to the CM frame. The efficiency for selected Bhabha events to pass the track requirements applied in the nominal analysis is calculated for both data and MC samples, and the difference between them is taken as the systematic uncertainty associated with tracking efficiency.

The systematic uncertainty in the polar angle requirement is estimated by changing the requirement from |cos | < 0.8 to |cos | < 0.7. The difference between the resulting luminosity and the nominal value is taken as the associated systematic uncertainty. The systematic uncertainty from the energy deposit requirement in the EMC is estimated by changing the threshold from 4.26 × 1.55 (GeV) to 4.26 × 1.71 (GeV). The systematic uncertainty from the momentum requirement is estimated by changing the threshold from 4.26 × 2 (GeV/c) to 4.26 ×

2.06 (GeV/c). These ranges are chosen as they cause the largest deviations from the nominal luminosity result near the applied requirements.

The statistical uncertainty of the efficiency determined from MC simulations is 0.25%. The CM energy is determined using $e^+e^- \rightarrow (\gamma)\ ^{+}\ ^{-}$ events. The invariant mass of the di-muon system is calculated taking into account ISR and FSR effects [8]. The difference between the CM energy listed in Table I and that measured with the di-muon process is about 2 MeV, and the corresponding systematic uncertainty is estimated by shifting the CM energy by 2 MeV in the MC simulation. The trigger efficiency for the Bhabha process is 100% with an uncertainty of less than 0.1% [9]. The theoretical uncertainty of the cross section calculated by the BABAYAGA3.5 generator is given as 0.5% [6].

The same systematic uncertainty estimation method is applied to all sub-samples. The largest relative uncertainty among them is taken as the associated uncertainty for all sub-samples. The systematic uncertainties considered in this work are summarized in Table III. Assuming the sources of systematic uncertainties to be uncorrelated, the total uncertainty is calculated as 0.97% by adding the contributions in quadrature.

VI. CROSS CHECK

To verify the result, a cross-check is performed using di-gamma events. The event selection criteria are the same as those used to estimate the systematic uncertainty from tracking efficiency, except for the requirement on $\Delta\phi$. To reduce Bhabha background, $\Delta\phi$ is required to be in the range of $[-0.8°, 0.8°]$, since photons are not deflected by the magnetic field.

The luminosity results from this cross-check (L_{ck}) are shown in Table I, together with the relative differences from the nominal results. Both results are in good agreement for all individual measurements, indicating the robustness of the result.

VII. SUMMARY

The integrated luminosity of the data samples taken at BESIII for studying charmoniumlike states and higher excited charmonium states is measured to a precision of 1% using Bhabha events. The total uncertainty is dominated by systematic uncertainties. A cross-check with di-gamma events yields consistent results. The result presented here is essential for future cross-section measurements with these data and has already been used in the discovery of charged charmoniumlike states [10–13].

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REFERENCES

[1] N. Brambilla, S. Eidelman, B. K. Heltsley, R. Vogt, G. T. Bodwin, E. Eichten, A. D. Frawley and A. B. Meyer et al., Eur. Phys. J. C 71, 1534 (2011).

[2] M. Ablikim et al. [BESIII Collaboration], Chin. Phys. C 37, 032007 (2013).

[3] M. Ablikim et al. [BESIII Collaboration], Nucl. Instrum. Meth. A 614, 345 (2010).

[4] S. Agostinelli et al. [GEANT4 Collaboration], Nucl. Instrum. Meth. A 506, 250 (2003).

[5] J. Allison, K. Amako, J. Apostolakis, H. Araujo, P. A. Dubois, M. Asai, G. Barrand and R. Capra et al., IEEE Trans. Nucl. Sci. 53, 270 (2006).

[6] G. Balossini, C. M. Carloni Calame, G. Montagna, O. Nicrosini and F. Piccinini, Nucl. Phys. B 758, 227 (2006).

[7] R. G. Ping, Chin. Phys. C 32, 599 (2008).

[8] M. Ablikim et al. [BESIII Collaboration], Measurement of the center-of-mass energy of the data taken by BESIII at center of mass energies between 3.81 GeV and 4.60 GeV, Paper in preparation.

[9] N. Berger, K. Zhu, Z. -A. Liu, D. -P. Jin, H. Xu, W. -X. Gong, K. Wang and G. -F. Cao, Chin. Phys. C 34, 1779 (2010).

[10] M. Ablikim et al. [BESIII Collaboration], Phys. Rev. Lett. 110, 252001 (2013).

[11] M. Ablikim et al. [BESIII Collaboration], Phys. Rev. Lett. 111, 242001 (2013).

[12] M. Ablikim et al. [BESIII Collaboration], Phys. Rev. Lett. 112, 022001 (2014).

[13] M. Ablikim et al. [BESIII Collaboration], Phys. Rev. Lett. 112, 132001 (2014).

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