R Measurement at BESIII

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Abstract. The R value is measured with a total of 14 data points with the corresponding center-of-mass energy going from 2.2324 to 3.6710 GeV. The statistical uncertainty of the measured R is less than 0.6%. Two different simulation models, the LUARLW and a new Hybrid generator, are used and give consistent detection and initial-state radiation corrections. An accuracy of better than 2.6% below 3.1 GeV and 3.0% above is achieved for the R value. The precise measurement will be an important constraint for precision tests of the Standard Model, such as calculations of the anomalous magnetic moment of the moun and the running of the QED coupling.

1 Introduction

The hadronic R value is defined as the ratio of the tree-level cross sections σ_0 of hadron production and muon pair production in electron positron annihilation

$$R = \frac{\sigma_0(e^+e^- \to \text{hadrons})}{\sigma_0(e^+e^- \to \mu^+\mu^-)}. \tag{1}$$

While the muon pair production cross section can be calculated in quantum electrodynamics (QED), the asymptotic freedom of the strong interaction only permits perturbative quantum chromodynamics (QCD) for calculations at high energies, where quarks and gluons are the degrees of freedom. In the non-perturbative region, where hadrons are the effective degrees of freedom, cross sections could be calculated using lattice QCD or could be measured in experiments. Nevertheless, R is a fundamental observable to test QCD, as it is directly related to the number of flavors and colors of the quarks. R is also an important input to current precision tests of the Standard Model (SM).

The running of the electromagnetic coupling constant at the Z-boson mass $\Delta\alpha_{\text{em}}(M_Z^2)$ is one of the essential observables in electroweak precision physics. It is also the least precisely known of these observables due to contributions of the hadronic vacuum polarization (HVP), which cannot be calculated perturbatively from QCD over the full relevant energy range. Instead, the optical theorem is exploited to relate HVP to R using dispersion theory [1, 2]. In this way, measurements of R over a wide range of center-of-mass energies $\sqrt{s}$ are used to calculate the HVP contribution. A systematic improvement of the calculation is possible by improving the accuracy of the measurements.

In a similar way, the anomalous magnetic moment of the muon a_μ depends on measurements of R. While a_μ is one of the most precisely determined observables in SM, the

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discrepancy between the direct measurement and the SM prediction [3] has been increased to more than five standard deviations with the new measurements from Fermilab [4]. The SM prediction is completely limited by the hadronic contributions, where the recent advent of competitive lattice QCD calculations [5] and new hadronic cross section measurements [6, 7] clearly point at tensions in the dispersive evaluation of the HVP contribution. New high precision measurements are called for to settle the situation. In contrast to $\Delta\alpha_{\rm em}(M_Z^2)$, the dispersion integral to determine the leading order HVP contribution to a_μ is weighted with a kernel function, emphasizing the impact of R measured at low energies [8, 9], especially at $\sqrt{s} < 1$ GeV. Due to the limited number of final states it is more common to measure exclusive reaction channels in this energy region, compared to inclusive R measurements at larger energies.

The BESIII collaboration has performed a new inclusive measurement of R at $\sqrt{s}$ between 2.2324 GeV and 3.6710 GeV [10].

2 *R* measurement at BESIII

The BESIII detector is operated at the BEPCII e^+e^- collider in Beijing, China, allowing the investigation of the τ-charm energy region at $2 \leq \sqrt{s}\,[\mathrm{GeV}] \leq 5$. Accelerator and detector are described in detail in Ref. [11]. The BESIII detector consist of a drift chamber, which surrounds the interaction region, a time-of-flight measurement system, an electro-magnetic calorimeter, a superconducting solenoid, and a muon counter, made of resistive plate chambers, which are implemented in the flux return yoke of the solenoid. The setup allows to measure momenta of charged particles with a resolution of 0.5% at 1 GeV/c, and photon energies with a resolution of 2.5% at 1 GeV. The BEPCII collider has exceeded its design luminosity of 10^{33} cm^{-2}s^{-1}, and BESIII has now obtained the world's largest data set of e^+e^- collisions in the τ-charm energy region.

In a first measurement of R, data has been collected at 14 energies between $\sqrt{s}$ = 2.2324 GeV and 3.6710 GeV. The values of R are determined from the number of hadronic events $N_{\rm had}^{\rm obs}$ observed in data. A detailed description of all selection requirements is provided in [10]. In a first step, based only on the calorimeter information, background events from the dominant QED processes of Bhabha scattering and di-gamma production are rejected. The remaining events are separated according to the number of detected tracks in the drift chamber to identify hadronic events. If only a a single track is found, the events are discarded due to the overwhelming residual background from QED processes. In case of two reconstructed tracks, these tracks are required not to be back-to-back, in order to suppress lepton pair production events, and in addition two photon candidates with at least 100 MeV energy deposit must be registered in the calorimeter. Events with three tracks are accepted, if the two tracks with highest momenta are not back-to-back and if at most one of the tracks is identified as electron. Only in the case of four or more reconstructed charged tracks is the event immediately considered a hadronic event.

Using $N_{\rm had}^{\rm obs}$, R is determined according to

$$R = \frac{1}{\sigma^0_{\mu\mu}} \frac{N_{\rm had}^{\rm obs} - N_{\rm bkg}}{\mathcal{L} \cdot \varepsilon_{\rm trig} \cdot \varepsilon_{\rm had} \cdot (1+\delta)}. \tag{2}$$

From the observed number of hadronic events, the number of residual background events $N_{\rm bkg}$ is subtracted. The number is estimated from Monte Carlo simulations of lepton pair production and two-photon processes for e^+e^- reactions and directly from data in the case of beam-associated background contributions. The integrated luminosity $\mathcal{L}$ is determined using large angle Bhabha scattering events with an uncertainty of 0.8%. The event yield needs to

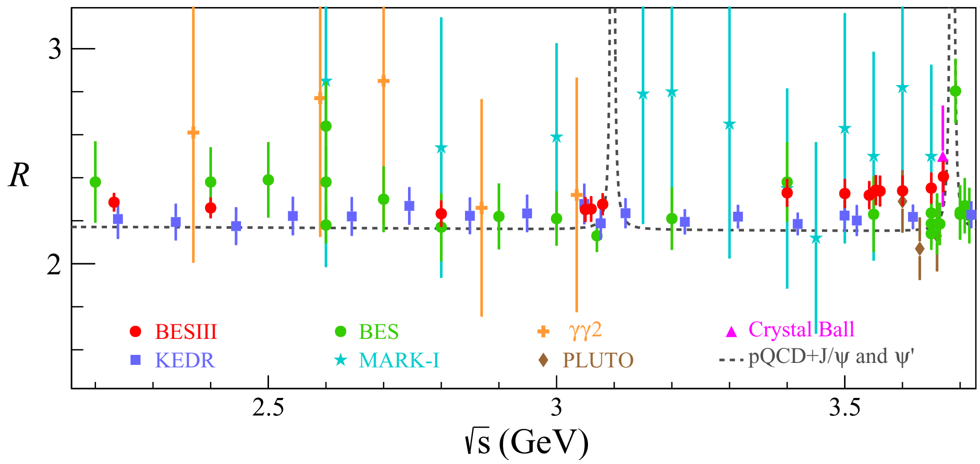

Figure 1. Comparison of R, measured by different experiments at $2.2 \leq \sqrt{s}\,[\text{GeV}] \leq 3.7$. The results of the work reported here are shown in red. Previous high precision results by the KEDR collaboration [17, 18] are shown with squares. The black dashed line illustrates the prediction of perturbative QCD, including the charmonium resonances. The references for the other experimental information shown here can be found in Ref. [10], where this figure is taken from.

be corrected for trigger efficiency $\varepsilon_{\text{trig}}$, which is close to 100% for hadronic events with an uncertainty of 0.1%, the hadronic detection efficiency ε_{had}, and radiative effects. The latter are considered using the Feynman diagram approach as well as the structure function approach, which agree on a level of better than 1.3%.

The most crucial aspect in the evaluation of the systematic uncertainties is the hadronic efficiency ε_{had}. It is evaluated using the LUARLW event generator [12], which is a self-consistent generator based on the Lund string fragmentation model. The phenomenological parameters of the model are tuned to data by comparing various kinematical distributions including multiplicities and angular distributions from simulation and experiment. The uncertainty of ε_{had} determined from the LUARLW generated events is assessed by comparing it to results obtained with another generator, which is developed to be conceptually different. In contrast to the purely theoretical LUARLW, it should contain as much information from experiment as available. To achieve this, three event generators are combined. The PHOKHARA generator [13, 14] is able to generate events of 10 exclusive channels according to models, which are tuned to existing measurements to also describe intermediate states. The CONEXC generator [15, 16] is a phase space generator for multi-particle final states, which reproduces the measured cross sections of more than 50 hadronic processes. The remaining fraction of events is again generated using LUARLW, tuning it to data. Double counting in the cross sections has been excluded by filtering out reappearing channels, giving priority to the experimental information. Both event generators agree well with each other and with data. The deviations in ε_{had} are considered as the systematic uncertainty, which is below 2.3% at all energies.

The resulting values of R are presented in Fig. 1. The accuracy of the measurements is better than 2.6% at $\sqrt{s} < 3.1$ GeV, also exceeding the accuracy of previous measurements for example KEDR [18], shown with squares in Fig. 1. It is still better than 3% at higher energies and is competitive with the recent KEDR measurements [17]. The absolute values of the BESIII result are consistently larger, not only compared to the previous results of the KEDR collaboration, but also compared to the prediction of perturbative QCD, indicated with the dashed line. Especially, at energies in the region $3.4 \leq \sqrt{s}\,[\mathrm{GeV}] \leq 3.6$, the new measurement exceeds the theory prediction by 2.7 standard deviations. Additional high accuracy measurements of R at BESIII in the charmonium and open-charm region may help to understand this discrepancy.

3 Outlook

In addition to the 14 energy points used in the first R measurement [10], the BESIII collaboration has collected data at about 140 additional energies. These cover $\sqrt{s}$ from 2.0000 GeV to 4.9500 GeV and provide more than 10^5 hadronic events at each individual data point. New high accuracy R measurements using this data in the continuum region and the open-charm regions are in preparation.

In addition, an alternative approach to the energy scan measurement is being developed using the initial state radiation (ISR) method [19]. The distinctive kinematics of ISR events allows for a better detection efficiency. The effective $\sqrt{s}$ after radiating ISR photons also allows to perform an inclusive measurement of R at $\sqrt{s} < 2\,\mathrm{GeV}$, which is not accessible with the BEPCII accelerator when applying the conventional energy scan method. A comparison of such an inclusive measurement with the sum of exclusive measurements, usually quoted for $\sqrt{s} < 2\,\mathrm{GeV}$ might help to settle tensions found in this energy region [1].

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