PROCEEDINGS OF SCIENCE

R value measurements at BESIII

Frederic Stieler[a,*] **for the BESIII Collaboration**

[a] *Institute for Nuclear Physics, Johannes Gutenberg University Mainz, Johann-Joachim-Becher-Weg 45, 55128 Mainz, Germany*

E-mail: frstiele@uni-mainz.de

The R value is defined as the ratio of the leading-order cross-section of hadron muon pair production in electron-positron annihilation. It is crucial for the precise determination of several quantities in the Standard Model (SM), including the QED running coupling constant evaluated at the Z-boson pole and the muon magnetic moment (a_μ), where the current uncertainties are dominated by hadronic vacuum polarization, that cannot be calculated using perturbative theory at low energy regions. This paper presents a discussion of the current status of R measurements at BESIII based on e^+e^- annihilations detected at the BESIII detector within an energy range of 2.23 to 3.67 GeV.

The 11th International Workshop on Chiral Dynamics (CD2024)
26-30 August 2024
Ruhr University Bochum, Germany

*Speaker

https://pos.sissa.it/

PoS(CD2024)053

1. Introduction

The R value is defined as the ratio of the leading-order cross-section of hadron and muon pair production in positron-electron annihilation

$$R = \frac{\sigma_0(e^+e^- \to \text{hadrons})}{\sigma_0(e^+e^- \to \mu^+\mu^-)} = N_C \sum_f Q_f^2. \tag{1}$$

While the born cross-section of $e^+e^- \to \mu^+\mu^-$ can be calculated in quantum electrodynamics (QED), the hadronic cross-section cannot be calculated reliably in the low-energy region due to the asymptotic freedom of the strong interaction allowing perturbative quantum chromodynamics (QCD) only for high energies where quarks and gluons are the degrees of freedom. To determine the hadronic cross-section for lower energies, one has to rely on lattice QCD or direct measurements. The R value is directly related to the number of flavors and colors of quarks at a given energy. Thus, it serves as a fundamental observable to test QCD and is used as input to current high-precision tests of the Standard Model (SM).

The running of the fine structure constant at the Z-boson mass $\Delta\alpha_{\text{em}}(M_Z^2)$ is one of the three essential observables for electroweak precision physics. Three parts contribute to the calculation of this quantity, the leptonic part, the hadronic vacuum polarisation (HVP) part, and the top quark part. Here, the HVP dominates the uncertainty as it cannot be calculated perturbatively. Instead, a dispersive approach exploits the optical theorem, relating the HVP contribution directly to the R value [1, 2]. To further narrow down the uncertainty of $\Delta\alpha_{\text{em}}(M_Z^2)$, the R value has to be measured over a wide center-of-mass energy.

The anomalous magnetic moment of the muon (a_μ) also depends on measurements of the R value. While a_μ is one of the most precisely studied quantities in the SM, recent results from Fermilab [3] have pushed the discrepancy between experimental measurements and SM predictions [4] beyond five standard deviations. The theoretical precision of a_μ is primarily limited by hadronic contributions. Advances such as improved lattice QCD calculations [5] and updated hadronic cross-section data [6, 7] have revealed tensions in the dispersive evaluation of the HVP contribution. Resolving these discrepancies requires new, high precision measurements. For the leading-order HVP contribution to a_μ, the dispersion integral employs a kernel function that enhances the impact of low-energy R data [8, 9], particularly for $\sqrt{s} < 1$ GeV. In this energy range, the restricted number of possible final states makes it more practical to focus on exclusive reaction channels, whereas inclusive R measurements are more common at higher energies

To enhance the measurement of the R value, BESIII performed an inclusive measurement at an energy range of 2.2324 to 3.6710 GeV adding up to $\sim 100\,\text{pb}^{-1}$ [10].

2. R measurement at BESIII

The BESIII detector [11] records symmetric e^+e^- collisions provided by the BEPCII storage ring [12] in the center-of-mass energy range from 1.84 to 4.95 GeV, with a peak luminosity of $1.1 \times 10^{33}\,\text{cm}^{-2}\text{s}^{-1}$ achieved at $\sqrt{s} = 3.773$ GeV. BESIII has collected large data samples in this energy region [13]. The cylindrical core of the BESIII detector covers 93% of the full solid angle and consists of a helium-based multilayer drift chamber (MDC), a time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), which are all 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 GeV/c is 0.5%, and the dE/dx 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 plastic scintillator TOF barrel region is 68 ps, while that in the end cap region was 110 ps. In the experiment, the R value is determined by

$$R = \frac{N^{\text{obs}}_{\text{had}} - N_{\text{bkg}}}{\sigma^0_{\mu\mu} \cdot \mathcal{L}_{\text{int}} \cdot \epsilon_{\text{trig}} \cdot \epsilon_{\text{had}} \cdot (1+\delta)}, \tag{2}$$

where $N^{\text{obs}}_{\text{had}}$ is the number of observed hadronic events, N_{bkg} is the number of background events, $\sigma^0_{\mu\mu}$ is the leading order cross-section of $e^+e^- \to \mu^+\mu^-$ events calculated from QED, $\mathcal{L}_{\text{int}}$ is the integrated luminosity, ϵ_{trig} is the trigger efficiency for hadronic events of close to 100% [14], ϵ_{had} is the detection efficiency, and $(1+\delta)$ are radiative corrections.

There are two different contributions to the number of background events, beam related contribution from data and QED background processes. The beam related background events include beam-gas and beam-wall interactions. They are estimated using the sideband method, which relies on the average event vertex in z-direction. Background events from QED processes like Bhabha and di-gamma events are estimated with Monte Carlo (MC) samples scaled with the luminosity of experimental data.

The integrated luminosity $\mathcal{L}_{\text{int}}$ is determined by exploiting the well-known large angle Bhabha scattering $e^+e^- \to (\gamma)e^+e^-$ and diphoton process $e^+e^- \to (\gamma)\gamma\gamma$ and simulated using the Babayaga v3.5 generator. The uncertainty of the measured (simulated) luminosity is about 0.7% (0.5%) and 1.1% (1.0%) for Bhabha scattering and diphoton process, respectively [15, 16].

To determine the R value, it is necessary to apply corrections for higher-order Feynman diagrams, as the leading order hadronic cross-section is required, rather than the total hadronic cross-section. The radiative correction factor $(1+\delta)$ is calculated using the Feynman diagram and the structure function scheme [17], both being consistent within 1.2%.

The analysis strategy of counting the total number of observed hadronic events $N^{\text{obs}}_{\text{had}}$ is shown in Figure 1. In the first step, a large fraction of Bhabha and di-gamma events are rejected using information from the electromagnetic calorimeter (EMC) only. At the second stage, good charged hadronic tracks referred to as *prongs*, and isolated photon candidates are selected by adding track-based requirements. In the third step, the analysis strategy differs depending on the number of prongs in one event. In the case of only one identified prong, the events are discarded due to the high QED background contributions and only used for tuning the generator. If two prongs are reconstructed, the tracks are required not to be back-to-back to suppress lepton pair production events and more than one reconstructed isolated photon candidate. Events with three tracks are accepted, provided that the two tracks with the highest momenta are not back-to-back and that no more than one of the tracks is identified as an electron. As soon as four or more prongs are identified in one event, the event is considered a hadronic event without further requirements.

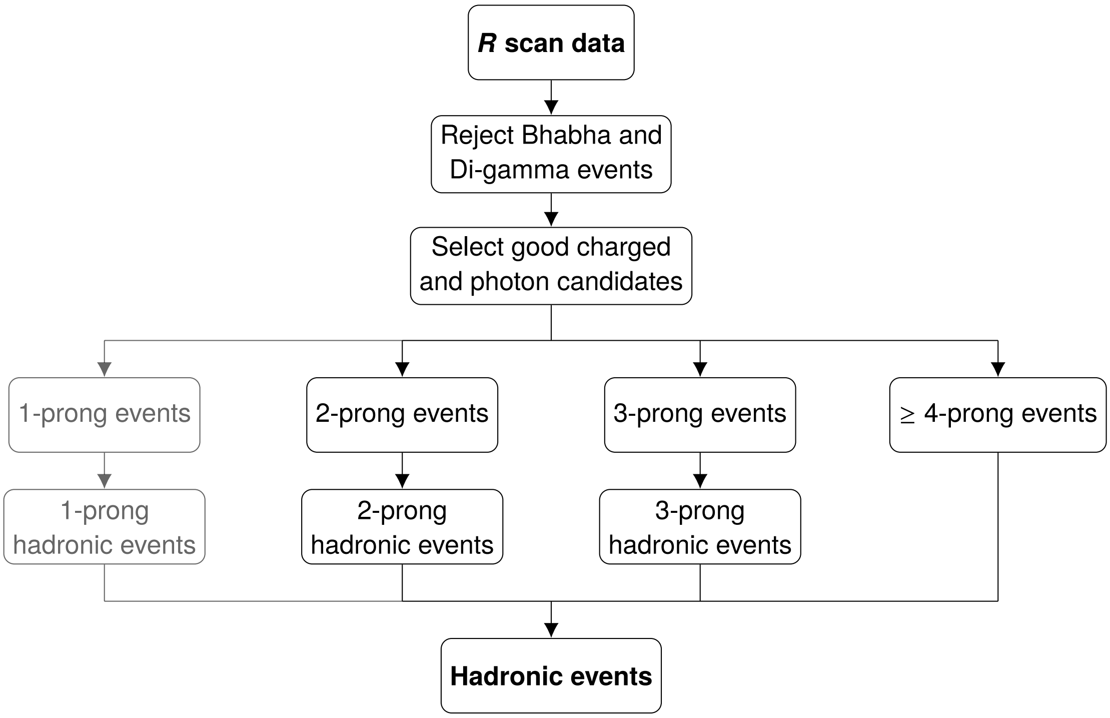

Figure 1: Flow chart indicating the analysis strategy, where *prong* refers to the number of identified good charged tracks in one event.

The most crucial source for uncertainties of the R value is the detection efficiency for hadronic events ϵ_{had}. To evaluate this efficiency, two conceptually different event generators Lund area law (LUARLW) [18] and a Hybrid generator [19] are developed.

LUARLW is a self-consistent inclusive generator. Compared to the well-known generator JETSET on which LUARLW is based, LUARLW simulates few body production processes of hadronic events in e^+e^- annihilations and decays of resonant and continuous hadronic states from $2m_\pi$ up to 5 GeV. The model's phenomenological parameters are adjusted by aligning simulated kinematical distributions, such as multiplicities and angular distributions, with experimental data. The simulation of generic hadronic events and the calculation of the ISR correction represent the major source of systematic uncertainty. Therefore, an alternative hybrid generator is developed which contains as much experimental information as possible and consists of a combination of three generators. PHOKHARA [20, 21] generates events of 10 exclusive channels with hadronic models, that are tuned to data. CONEXC [22, 23] generates events of more than 50 channels with cross-sections determined in experiments. The remaining unknown processes are again generated by LUARLW. Double counting in the cross sections is avoided by removing duplicate channels and prioritizing experimental data. The results obtained from both generators are in good agreement with each other and with the data.

Figure 2 depicts the resulting values of R derived from the 14 data points between 2.2324 to 3.6710 GeV. The results demonstrate an accuracy of better than 2.6% below the J/ψ mass, which exceeds the precision of previous KEDR measurements in this energy region [24]. At higher

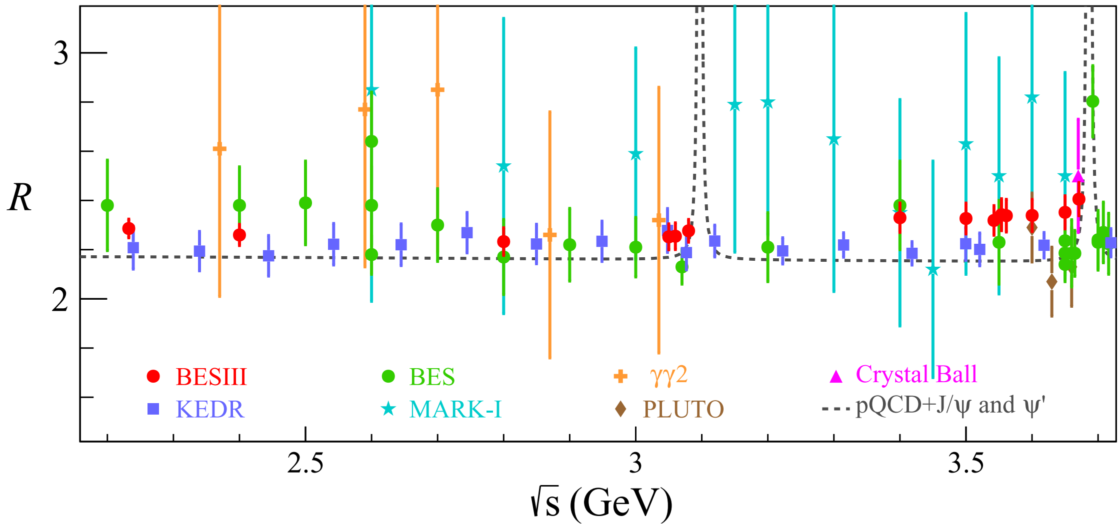

Figure 2: R-values in the center-of-mass region range from 2.2 to 3.7 GeV. The recent BESIII measurements discussed in this paper are represented by red, while data from other earlier experiments are depicted using various colors and symbols, as indicated in the legend.

energies, an accuracy of better than 3% is achieved, which is competitive with the recent KEDR measurements [25]. While the absolute values of the BESIII measurements are consistently larger than those of KEDR and the predictions of perturbative QCD, the new measurements, in particular, exceed the theory prediction at energies between 3.4 and 3.6 GeV by 2.7 standard deviations. To gain further insight into these discrepancies, additional data measured at BESIII can be subjected to further analysis.

3. Summary and Outlook

The R value measurements using 14 e^+e^- collision data samples collected by BESIII at center-of-mass energies ranging from 2.2324 to 3.6710 GeV exceed the theory prediction and latest KEDR measurements and show very good accuracy. The dominant uncertainties in the R value calculations arise from the hadron production model and are determined using two conceptually different generators that are in agreement.

In addition to the 14 energy points adding up to $\sim 100\,\text{pb}^{-1}$ discussed in this paper, BESIII collected 21 more data points between 2.00 and 3.08 GeV of $\sim 550\,\text{pb}^{-1}$ and 104 data points between 3.85 and 4.59 GeV of $\sim 800\,\text{pb}^{-1}$, each consisting of more than 10^5 hadrons. High-precision R measurements are being developed using this data in both the continuum and open-charm regions.

Moreover, an alternative analysis is currently being conducted, where data can be analyzed using the ISR method [26]. For this purpose, a large charmonium data set from BESIII can be employed. Due to the ISR kinematics, a more effective detection efficiency can be achieved. Furthermore, tensions in the transition region of exclusive measurements below 2 GeV and inclusive measurements above 2 GeV can be analyzed, as the effective energy after radiation of ISR photons allows for inclusive measurements of R below 2 GeV.

References

[1] M. Davier, A. Hoecker, A. Malaescu, Z. Zhang. Eur. Phys. J. C. **80**, 241 (2020), [Erratum: Eur.Phys.J.C 80, 410 (2020)], 1908.00921

[2] A. Keshavarzi, D. Nomura, T. Teubner, Phys. Rev. **D97**, 114025 (2018), 1802.02995

[3] D. Aguillard *et al.*, (Muon g-2), Phys. Rev. Lett. **131**, 161802 (2023), 2308.06230

[4] T. Aoyama *et al.*, Phys. Rept. **887**, 1 (2020), 2006.04822

[5] S. Borsanyi *et al.*, Nature **593**, 51 (2021), 2002.12347

[6] F.V. Ignatov *et al.*, (CMD-3) (2023) 2302.08834

[7] F.V. Ignatov *et al.*, (CMD-3) (2023) 2309.12910

[8] S.J. Brodsky, E. de Rafael, Phys. Rev. **168**, 1620 (1968)

[9] B.E. Lautrup, E. de Rafael, Phys. Rev. **174**, 1835 (1968)

[10] M. Ablikim *et al.*, (BESIII), Phys. Rev. Lett. **128**, 062004 (2022), 2112.11728

[11] M. Ablikim *et al.*, (BESIII), Nucl. Instrum. Meth. **A614**, 345 (2010), 0911.4960

[12] C. H. Yu *et al.*, in 7th International Particle accelerator Conference (2016) p. TUYA01

[13] M. Ablikim *et al.* (BESIII), Chin. Phys. C **44**, 040001 (2020).

[14] N. Berger *et al.*, Chin. Phys. **C34**, 1779 (2010)

[15] M. Ablikim *et al.*, [BESIII Collaboration], Chin. Phys. **C41**, 063001 (2017)

[16] G. Balossini *et al.*, Phys. Lett. **B663**, 209 (2008)

[17] H. Hu *et al.*, High Energy and Nuclear Physics, **25**, 701 (2001) in chinese

[18] B. Andersson, H.M. Hu (1999), hep-ph/9910285

[19] R.G. Ping *et al.*, Chin. Phys. **C40**, 113002 (2016), 1605.09208

[20] G. Rodrigo, H. Czyz, J.H. Kuhn, M. Szopa, Eur. Phys. J. **C24**, 71 (2002), hep-ph/0112184

[21] F. Campanario *et al.*, Phys.Rev. **D100**, 076004 (2019), 1903.10197

[22] R.G. Ping, Chin. Phys. **C38**, 083001 (2014), 1309.3932

[23] R.G. Ping et al., Chin. Phys. **C40**, 113002 (2016), 1605.09208

[24] V.V. Anashin et al., Phys. Lett. **B770**, 174 (2017), 1610.02827

[25] V.V. Anashin et al., Phys. Lett. **B753**, 533 (2016), 1510.02667

[26] T. Lenz *et al.* [BESIII], EPJ Web Conf. **303**, 05003 (2024) doi:10.1051/epjconf/202430305003