Status of R vslue measurement at BESIII

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Abstract. The dominant systematic error of R value measurement comes from the hadronic generator simulations. This paper reviews the present status of R value measurement from 2.232 to 3.671 GeV at 14 energy points, especially describes the issue of the parameter tuning for the Lund string fragmentation area law generator LUARLW.

1 Introduction

R value is defined as the inclusive e^+e^- annihilation hadronic production cross section at the tree level of Feynman diagram normalized by the theoretical di-muon cross section, which is a basic input parameter for the calculations of the abnormal magnetic moment of muon $(g-2)_\mu$, and the QED running coupling constant $\alpha(s)$. In fact, the hadronic contribution for the calculations of $(g-2)_\mu$ and $\alpha(s)$ are the infinite integral about energy from $2m_\pi$ to ∞ GeV, the hadronic cross section (R value) below 5 GeV adopt the experimental value, and in higher energy region the R values predicted by pQCD are used. So, the experimental errors of R value, especially the errors below 3 GeV, will result in the dominant uncertainty of $(g-2)_\mu$ and $\alpha(s)$[1–3].

BESII ever measured R value in full full BEPC energy region. In references [4, 5], the R values between 2-5 GeV were measured with average error of about 7%, and in reference [6] the R value were measured at three energy point with error of 3.5%. At present, KEDR published the R value below open charm[7]. To reduce the error of R value measurement is still one of the the experimental goals at BESIII.

The data samples for R value measurement and QCD experimental study from 2.0 to 4.59 GeV have been collected with BESIII, the total energy points are 130 and the total integrated luminosity is about 1.3 fb^{-1}.

This note will focuses on the presentation the calculations of initial state radiative corrections and the simulation of hadronic events by the Lund area law generator LUARLW.

2 Data analysis

R value is measured with following expression

$$R_{exp} = \frac{N_{had}^{obs} - N_{bg}}{\sigma_{\mu\mu}^0 L \epsilon_{trg} \bar{\epsilon}_{had} (1+\delta)}, \tag{1}$$

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the meanings of all these quantities in above formula were explained in references[4–6]. So the work of R value measurement is to determine these quantities from data analysis and Mont Carlo simulations and give their errors.

The basic physics processes produced in e^+e^- collision have 4 types: $e^+e^- \to l^+l^-$, $\gamma\gamma$, e^+e^-X and hadrons. The scheme of events selection are similar to that of used in works[4–6]. The numbers of the residual QED background events, N_{bg} in Eq.(1) are statistically estimated by MC method:

$$N_{bg} = L[\epsilon_{ee}\sigma_{ee} + \epsilon_{\mu\mu}\sigma_{\mu\mu} + \epsilon_{\tau\tau}\sigma_{\tau\tau} + \epsilon_{\gamma\gamma}\sigma_{\gamma\gamma}], \tag{2}$$

where L is the integrated luminosity of data, σ_{ee} the cross section of Bhabha process, ϵ_{ee} the efficiency for Bhabha events that pass the hadronic event selection criteria, other symbols have corresponding meanings.

3 Initial state radiation

The hadronic cross section directly measured in experiment is the observed total cross section, which contains the total contributions of all Feynman diagrams shown in Figure 1:

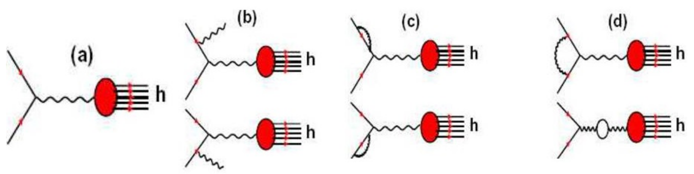

Figure 1. The picture of e^+e^- annihilation into hadrons.

The R value by definition Eq.(1) is only the cross section corresponding to the tree level Feynman diagram of Figure 1(a). The fraction contribution of higher level diagrams in Figure 1(b)(c)(d) can be calculated by the initial state radiative correction.

$$\sigma^{tot}(s) = (1+\delta)\sigma^0(s), \ \text{ or } \ (1+\delta) = \frac{\sigma^{tot}(s)}{\sigma^0(s)}, \tag{3}$$

where $\sigma^0(s)$ is the Born cross section corresponding to Figure 1(a), $\sigma^{tot}(s)$ the total cross section corresponding to all diagrams of Figure 1, and $(1+\delta)$ is called the ISR correction factor, which reflects the fraction of the contributions of the higher level processes.

The total cross section $\sigma^{tot}(s)$ can be calculated by the initial state radiation correction theory at one-loop approximation introduced in references but a little improved [11–13]

$$\sigma^{tot}(s) = (1 - x_m^\beta + \delta_{vert})\frac{\sigma^0(s)}{|1-\Pi(s)|^2} + \int_0^{x_m} dx x^\beta F_{FD}(x)\frac{\sigma_0(s')}{|1-\Pi(s')|^2}, \tag{4}$$

where $x = 2E_\gamma/E_{cm}$ is the energy fraction carried away by the bremsstrahlung photon, $x_m = 1 - 4m_\pi^2$ the maximum value of x, $s' = (1-x)s$, δ_{vert} the initial vertex correction factor, $\Pi(s)$ the vacuum polarization correction in the 1-particle-irreducible (1PI) chain approximation, and F_{FD} the radiator.

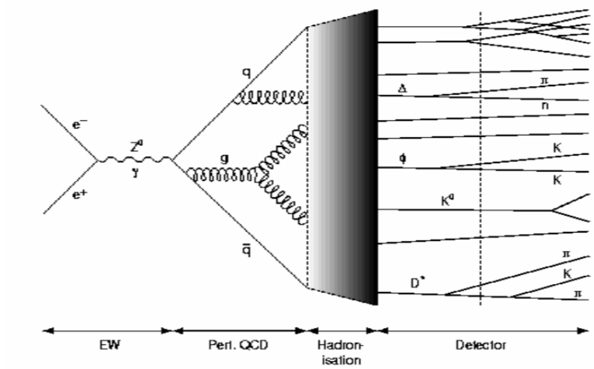

Figure 2. The picture of e^+e^- annihilation into hadrons.

4 Generator LUARLW

The general picture of e^+e^- annihilation and hadrons production are shown in Figure 2:

The nonperturbative hadronization can be described by Lund string fragmentation model[8]. The Lund area law generator LUARLW[9, 10] is built in order to simulate the few-body production processes in BEPC energy region, and is used for determining the hadronic efficiency in R value measurement. LUARLW simulation contains following constitutes: initial state radiation (ISR), string fragmentation, multiplicity and momentum-energy distributions, decay of unstable hadrons.

4.1 Simulation of ISR return processes

In the simulation of ISR return processes, the hadronic processes can be divided into two classes: the non-real bremsstrahlung and real bremsstrahlung, and their weights are

$$\sigma^{VSB}(s) = [1+\beta\ln(x_0)+\delta_{AR}]\sigma^0(s), \tag{5}$$

$$\sigma^{HB}(s) = \int_0^{4\pi} d\Omega_\gamma \int_{x_0}^{x_m} dx \frac{d\sigma^{HB}(x,\theta)}{dxd\Omega_\gamma}. \tag{6}$$

The sampling for a bremsstrahlung event which with the angle of the radiative photon and the effective squared center-of-mass energy s' can be obtained by the differential cross section[11–13]:

$$\frac{d\sigma^{HB}(x,\theta)}{dxd\Omega_\gamma} = \frac{\alpha}{\pi^2}\frac{\sin^2\theta}{(1-a^2\cos^2\theta)^2}\frac{1}{x}(1-x+\frac{x^2}{2})\sigma^0(s') \tag{7}$$

The values of $\sigma^0(s')$ from $2m_\pi$ to 1.8 GeV use experimental values cited in PDG [14], and above 1.8 GeV

$$\sigma^0(s) = \sigma_{con}(s) + \sigma_{res}(s) = \sigma^0_\mu(s)R_{pQCD}(s) + \sigma_{BW}(s), \tag{8}$$

where $\sigma^0_\mu(s)$ is the theoretical di-muon Born cross section, $R_{pQCD}(s)$ the continuous R value predicted by pQCD, $\sigma_{BW}(s)$ the resonant cross section calculated by the Breit-Wigner formula. The Figure 3 shows the number of events distribution with different effective hadronic energies in LUARLW sampling. The left figure corresponds to the initial e^+e^- energy equals to 2.232 GeV, and the right one corresponds to the initial e^+e^- energy equals to 3.5 GeV. The peaks of resonances ρ, ϕ and j/ψ which with larger Breit-Wigner cross sections are clearly visible. It shows that the fraction of the ISR return event at lower effective energies $\sqrt{s'}$ account for more than 50% of the total number of events. These ISR return events with lower effective hadronic energies have lower efficiencies. Calculating $\sigma^{VSB}(s)$ and $\sigma^{HB}(s)$ correctly and simulating the ISR return processes are important for obtaining the correct efficiency $\bar{\epsilon}_{had}$.

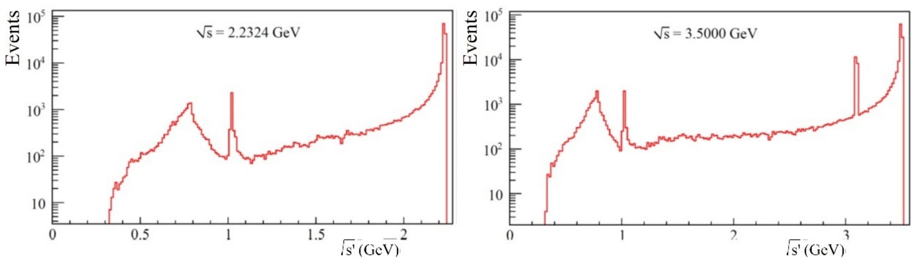

Figure 3. The event distributions of ISR return processes with the different effective hadronic energies. left: for initial $\sqrt{s}$=2.232 GeV; right: $\sqrt{s}$=3.5 GeV.

4.2 Simulation of hadronic processes

4.2.1 Physics picture

The basic physics picture of generator LUARLW is the Lund area law[8, 9]. Figure 6 shows the mesons (M) and baryons (B and $\bar{B}$) produced at the vertex of light-cone area in the string fragmentation.

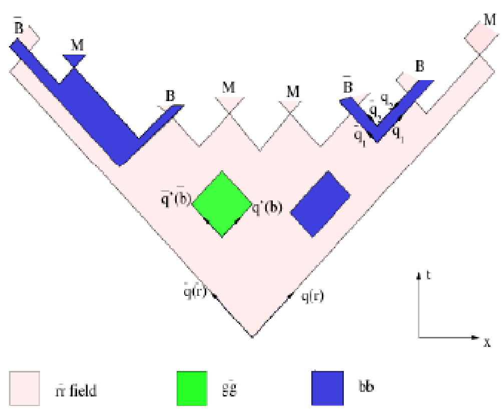

Figure 4. The mesons and baryons production in the string fragmentation, M means meson, and B means baryon.

Starting from the Lund area law, one may obtain an approximation expression of a poisson-like multiplicity distribution for the preliminary fragmentation hadrons[10]

$$P_n(s) = \frac{\mu^n}{n!} \exp[c_0 + c_1(n-\mu) + c_2(n-\mu)^2], \tag{9}$$

where n is the number of the fragmentation hadrons, the parameter μ can be understood as the average multiplicity. The energy dependence of μ can approximately quote the QCD-like prediction:

$$\mu = \alpha + \beta \exp(\gamma \sqrt{s}), \tag{10}$$

where c_1, c_2, c_3, α, β and γ are free parameters and need to be tuned.

4.2.2 Production modes

The simulations of the continuum states include lowest and leading order QCD correction

$$e^+e^- \to \gamma^* \to \left\{ \begin{array}{l} q\bar{q} \to \text{string} \to \text{hadrons} \\ gq\bar{q} \to 2\ \text{strings} \to \text{hadrons} \end{array} \right.$$

The final states for a chosen exclusive process $e^+e^- \to q\bar{q}(g) \to$ string(s) $\to m_1 + m_2 ... + m_n$ can be factorized as

$$d\sigma_n(s) = d\sigma(e^+e^- \to q\bar{q}) \cdot d\mathcal{P}_n(q\bar{q}(g) \to m_1, m_2 ... m_n; s). \tag{11}$$

The $d\sigma(e^+e^- \to q\bar{q})$ is the QED cross section, $d\mathcal{P}_n$ is the probability for string fragmentation into n hadrons and the energy-momentum distributions of the fragmentation hadrons are determined by Lund area law[10].

The vector mesons whose masses smaller than 2 GeV and with $J^{PC} = 1^{--}$ can directly couple to virtual photon in ISR return process:

$$e^+e^- \to \gamma^* \to \rho(770), \omega(782), \phi(1020) \cdots \rho(1700). \tag{12}$$

The decay fractions of these vector mesons take PDG values, and the polar angles distribution depends on their decay final states.

The production and decay of the charmonium adopt the standard pictures[15, 16]. For example, the simulation of J/ψ contain following channels

$$e^+e^- \to \gamma^* \to J/\psi \to \left\{ \begin{array}{l} \gamma^* \to e^+e^-, \mu^+\mu^- \\ \gamma^* \to q\bar{q} \to \text{string} \to \text{hadrons} \\ ggg \to 3\text{strings} \to \text{hadrons} \\ \gamma gg \to 2\text{strings} \to \text{hadrons} \\ \gamma\eta_c \to gg \to 2\text{strings} \to \text{hadrons} \\ \gamma + \text{radiative decay channels} \quad (\text{citePDG}) \end{array} \right.$$

The simulations for $\psi(3686)$, $\psi(3770)$, $\psi(4040)$, $\psi(4190)$ and $\psi(4415)$ are in the similar ways.

4.3 Parameter tuning of LUARLW

Two schemes used for parameter tuning and optimization will be described below.

4.3.1 Scheme A: hybrid PHOKHARA+ConExc+LUARLW

The red points in Figure 5 show the sum of cross sections of the measured exclusive processes, and the black points the total cross sections measured inclusively.

MC code PHOKHARA+ConExc+LUARLW is a hybrid generator. The processes ever measured exclusively are simulated by the exclusive package PHOKHARA[18–20] or ConExc[21], the weights of events are proportional to the corresponding cross sections, and the remaining unmeasured or unknown processes are simulated by LUARLW in inclusive way. In PHOKHARA and ConExc, there is no free parameter, the all free parameters to be tuned are in LUARLW.

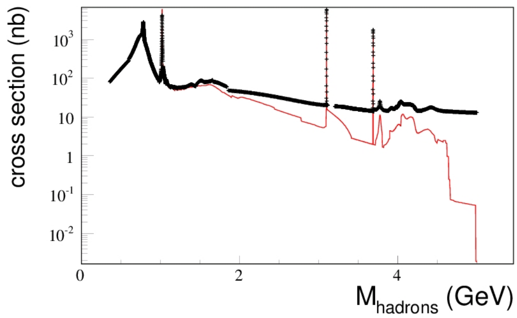

Figure 5. he Born cross section of $e^+e^- \rightarrow$ hadrons below 5 GeV. The black points are the total cross section measured in inclusive method, the red points are the sum of the measured exclusive cross sections.

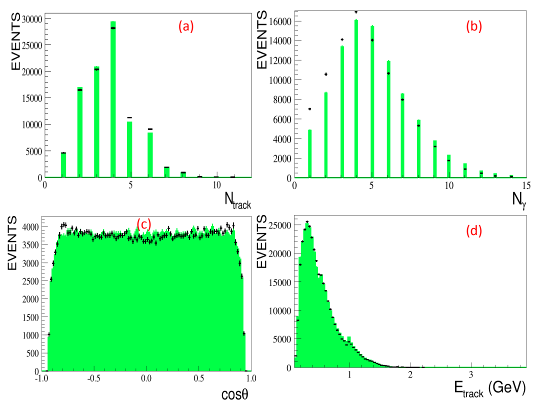

Figure 6. Comparison between data and MC in scheme A at 3.65 GeV. (a) multiplicity of charged track; (b) multiplicity of photon; (c) polar angle $\cos\theta$; (d) momentum of charged track.

4.3.2 Scheme B: Pure LUARLW

There are some phenomenological parameters in LUARLW. In the BEPC energy, the main parameters are those about the multiplicity of the preliminary hadrons in Eq.(9) and Eq.(10), and those which determine the ratios of mesons and baryons with different quantum number (s, L, J) in the string fragmentation process. In LUARLW these parameters are stored in array PARJ(1-20) as did in JETSET[17]. The above mentioned parameters are tuned to make the MC agree with the experimental data taken with BESIII. This work is in progress.

5 Summary

The three phases data taking plan has already been carried out, and the data analysis has almost been finished. The challenging work is still parameters tuning, which will continue to be done till the MC agree data well and the error of hadronic efficiency reach a acceptable level, for example 2%. The total errors of R value reduce to 3%.

References

[1] B.Pietrzyk, Nucl. Phys. **B162**(Proc. Suppl.), 2006, 18

[2] F. Jegerlehner, Nucl. Phys. **B162**(Proc. Suppl.), 2006, 22

[3] F. Jegerlehner, hep-ph/0104304

[4] BES Collaboration, J.Z.Bai *et al.*, Phys. Rev. Lett. **84**, 2000, 594

[5] BES Collaboration, J.Z.Bai *et al.*, Phys. Rev. Lett. **88**, 2002, 101802

[6] BES Collaboration, M. Ablikim *et al.*, Phys. Lett. **B677**, 2009, 239

[7] Phys. Lett. **B** 788, 42 (2019)

[8] Bo Andersson, *The Lund Model* (Cambrindge University Press, 1998)

[9] B. Andersson and H. Hu, hep-ph/9810285

[10] H. Hu *et al.*, High Energy Physics and Nuclear Physics, **25**, 2001, 1035 (in Chinese)

[11] A.Osterheld *el al.*, SLAC-PUB-4160(1986)(T/E)

[12] C.Edward *el al.*, SLAC-PUB-5160(1990)(T/E)

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

[14] Paticle Data Group, Chinese Physics C, **38**, 2014

[15] L. K*ö*pke and N. Wermes, Phys. Reprt. **174** 67 (1989)

[16] H. Hu *et al.*, High Energy Physics and Nuclear Physics, **27**, 2003, 673 (in Chinese)

[17] T.Sjöstrand, PYTHIA 5.7 and JETSET 7.4 Physics and Manual, CERN-TH.7112/93, Decenber 1993

[18] G.Rodrigo *et al.*, Eur. Phys. J. **C24**, 2002, 71

[19] H.Czyz *et al.*, Eur. Phys. J. **C27**, 2003, 563

[20] H.Czyz *et al.*, hep-ph/0308312

[21] R.Ping, Chin. Phys. **C40**, 2016, 113002

[22] Journal Author, Journal **Volume**, page numbers (year)

[23] Book Author, *Book title* (Publisher, place, year) page numbers