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Status of *R* Scan at BESIII

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Abstract: The data samples for the measurement of *R* values, hadron form factors, the line-shape scan of the high mass charmonium family and new states have been taken in the full energy region that BEPCII can reach, namely between 2.0 and 4.6 GeV. The present status of *R* value measurement is briefly reviewed.

Key words: *R* value measurement; the Standard Model; data analysis; Monte Carlo simulation

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BESIII R值扫描测量进展

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摘要：BESIII在BEPCII所能达到的能量范围(2.0～4.6 GeV)获取了3批实验数据，用于R值、强子形状因子、重粲偶素共振结构及新粒子态的测量. 本文对目前R值测量的主要工作及进展作了简要评述.

关键词：R值测量；标准模型；数据分析；蒙特卡罗模拟

0 Introduction

R value is defined as the ratio of the hadronic production cross section via the electron and positron annihilation to that of the theoretical cross section of $\mu^+\mu^-$ at the Born level,

$$R=\frac{\sigma^0(e^+e^-\rightarrow\gamma^*\rightarrow \text{hadrons})}{\sigma^0(e^+e^-\rightarrow\gamma^*\rightarrow\mu^+\mu^-)} \tag{1}$$

The *R* value is an important input parameter for testing the Standard Model (SM). The precision of *R* values has a significant influence on the uncertainties of calculations of QED running electromagnetic coupling constant $\alpha(s)$, muon anomalous magnetic moment $(g-2)$, global fit of the Higgs mass in SM[1-3]. In the calculations, *R* values adopt experimental results below 5 GeV, and the pQCD prediction was used in the higher energy region.

When we look over the PDG published in different years, we may find that *R* values have been measured by many groups from the hadronic threshold to Z^0 scale. With the increase of the luminosity of the e^+e^- colliders, more data samples with larger statistics have been

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accumulated, and in pace with the improvement of experimental methods, the precision of the R values has been evidently improved. Fig. 1 shows the current world data of R values from $2m_\pi$ to 110 GeV in PDG2014[4].

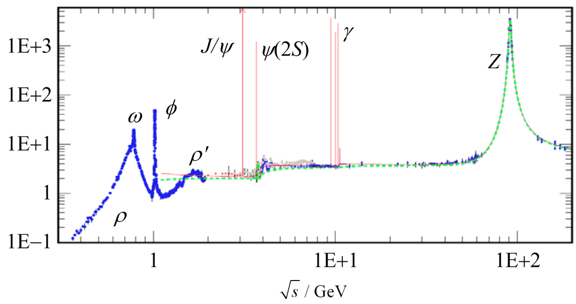


Fig. 1 The R values from $2m_\pi$ to Z^0 scale in PDG2014

BES Collaboration has performed three rounds of R value measurements using the data samples taken with BESII at BEPC[5-7], the results were shown in Fig. 2. The first and second rounds of measurements performed the R value scan at about 100 energy ponits between 2～5 GeV and took small data samples (only about 1 000 hadronic events collected at per energy point), and the relative precision of R values was reduced from over 15% in earlier experiments[8-14] to 7%. The third round of measurement of R values used larger data samples at three energy points (E_{cm} = 2.65, 3.07 and 3.65 GeV, the numbers of hadronic events were about 24 000, 34 000 and 84 000, respectively), and the results reached a better precision of about 3.5%. Theorists used R values measured with BESII data in the calculation of $\Delta\alpha^{(5)}_{\rm had}$ in the running electromagnetic coupling constant $\alpha(s) = 1/[1-\Delta\alpha(s)]$, the relative uncertainty contribution resulting from the errors of R values between 2～5 GeV decreased to 35% from earlier 55%, and the relative uncertainty of $a^{\rm had}_\mu$ in $(g-2)$ was reduced to about 15% from an earlier 25%[1-3].

In the energy region above the open charm threshold, there exist several high-mass ψ-family charmonium resonances ($\psi(3770)$, $\psi(4040)$, $\psi(4190)$, $\psi(4415)$) with quantum number $J^{PC} = 1^{--}$ which were well confirmed in earlier

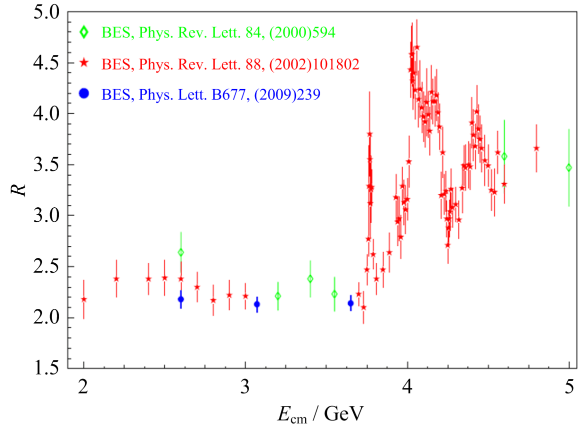


Fig. 2 The summarization R value scan with BEPC/BESII

experiments (see the references cited in Ref. [15] for details) and the newly discovered states $X(4260)$ and $X(4360)$, which can be produced directly in the $e^\pm$ annihilation. Based on the work presented in Ref. [6], the line shape and resonant parameters of $\psi(3770)$, $\psi(4040)$, $\psi(4190)$ and $\psi(4415)$ were measured[15]. Fig. 3 shows the measured R values and the fitted line-shape of these resonances. But because the small statistics and larger scan step, the broad structure in the $\pi^+\pi^- J/\psi$, called $Y(4260)$, discovered by BABAR[16], was missed in BESII scan.

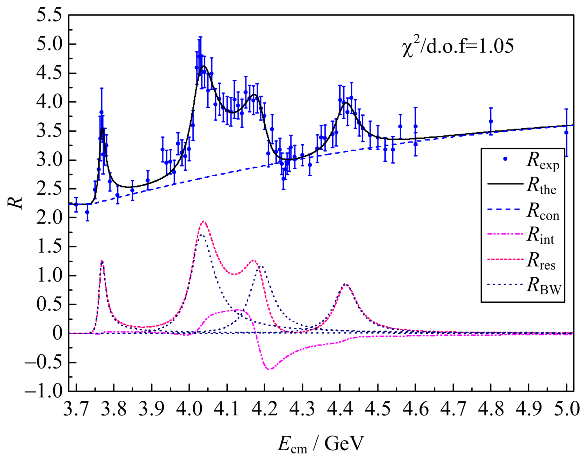


Fig. 3 The R scan of the high mass charmonium line-shape at BEPC/BESII

In the measurement of resonance parameters with BESII scan data, the fitting method was improved compared with earlier measurements (see the references cited in Ref. [15]) in the following aspects: ① intrinsic/effective initial phase angle in

Breit-Wigner amplitude was kept; ② interference terms between final states decayed from heavy ψ-family resonances were considered; ③ energy dependence of the total widths were calculated; ④ as the measurements of R values and resonant parameters are closely related and affected, they were measured using the iterative method, so that the R values and resonant parameters were updated simultaneously[15]. But due to the very small data statistics, some important information (such as, the selected numbers of various DD final states in $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$ decay) are very limited, and so the accurate expression of the interference terms can not be obtained from the data analysis, and some approximations on model describing energy dependent widthes had to be taken.

BEPCII is a double-ring e^+e^- collider running at center-of-mass energies between 2.0 and 4.6 GeV and reaches a peak luminosity of 0.85×10^{33} $\mathrm{cm^{-2}\cdot s^{-1}}$ at center-of-mass energy of 3770 MeV. The BESIII detector is located at the BEPCII[17], designed to fulfill the requirement of the τ-charm physics experiments[18]. Since the luminosity of BEPCII is about 100 times of that of BEPC, and BESIII performs much better than BESII, one may expect that R value measurement with data taken with BESIII may reach a better precision than that of BESII, and then the calculations of $\Delta\alpha(s)$ and a_μ^{had} will have less uncertainties, and the SM prediction can get more better test.

1 Data samples of R scan

BESIII Collaboration made a comprehensive plan for R value measurement and QCD experimental study, and the main objects are as follows: the measurement of R values reaches a precision about 3%; the fit of the line-shape of high mass charmonium and resonance parameters, form factors of mesons and baryons get significant improvement. The whole data taking plan was divided into three phases.

1.1 Phase Ⅰ

The purpose of this phase is for machine study and prestudy of data analysis. The data samples were taken at 2.2324, 2.4, 2.8 and 3.4 GeV with a total luminosity of about 12 $\mathrm{pb^{-1}}$ in 2012. Based on the obtained information, the next R scan plan was optimized and the time needed for the following data taking was estimated. These data can be used for the parameter tuning of the hadronic generator LUARLW[19], and the measurement of R values and the form factors of some hadronic channels with large production cross section.

1.2 Phase Ⅱ

It is a fine scan between 3.85 and 4.59 GeV for the measurement of R values and high mass charmonium line-shape and resonant parameters. Drawing on the experience of R scans at BESII[6], the data samples collected at 104 energy points with more reasonable energy arrangement and relative smaller step-size (2～5 MeV), the total luminosity is about 800 $\mathrm{pb^{-1}}$, while 4 times of J/ψ fast scan was done for the beam energy calibration. The data samples at each energy point at least contains 10^5 hadronic events, so that the cross section of all $\overline{DD}$ final sates can be measured and the shortcoming in the BESII measurement can be overcome. Fig. 4 shows the online cross section at scan energy points.

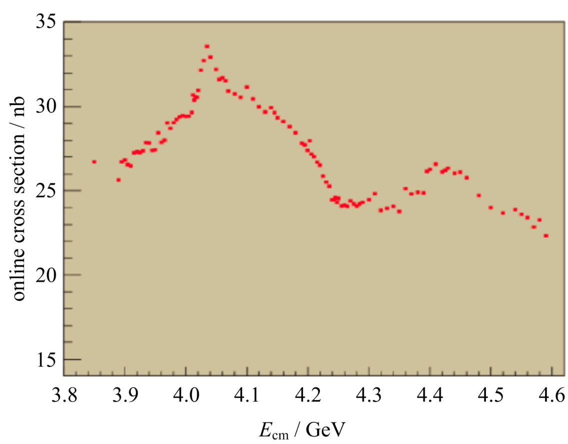


Fig. 4 The online cross section of the R scan with BESIII

1.3 Phase Ⅲ

BESIII collected the data samples at 22 energy points between 2.0 and 3.08 GeV with the total luminosity being about 500 pb^{-1}. Moreover, J/ψ fast scan was done three times for beam energy calibration, and separated beam samples were collected for the study of beam associated backgrounds. These data samples are used for the measurement of R values, meson and baryon and hyperon form factors, and the study of threshold effects of Λ, Σ, Ξ, etc.

2 Status of R value measurement

In the experiment, R value is measured with the following expression

$$R_{\text{exp}} = \frac{N_{\text{had}}^{\text{obs}} - N_{\text{bg}}}{\sigma_{\mu\mu}^{0} L \varepsilon_{\text{trg}}\, \bar{\varepsilon}_{\text{had}} (1+\delta)} \qquad (2)$$

the meanings of all these quantities in above formula having been explained in Refs. [5-7]. So the work of R value measurement is, in fact, to determine these quantities from data analysis and Mont Carlo simulations and give their errors.

2.1 Data analysis

The tree level Feynman diagrams of the physical processes produced in e^+e^- collision in BEPCII energy region can be summarized into 5 types as shown in Fig. 5. Data analysis is the most basic work for R value measurement, consisting of luminosity measurement, background subtraction and selection of hadronic events.

The luminosity of the data samples can be measured by the processes of $e^+e^-\to e^+e^-$ or $\gamma\gamma$. These two QED processes are well understood in physics, and the precision of the corresponding BABAYAGA reaches 0.5%. The signal events of e^+e^- and $\gamma\gamma$ have very clear characteristics in the detector and can be well selected, and the remaining backgrounds are very limited. The error of luminosity measurements is about 1%[21].

The scheme of hadronic events selection is similar to that used in works[5-7] but optimized[22]. The hadronic event selection can be classified into track level and event level, which use the

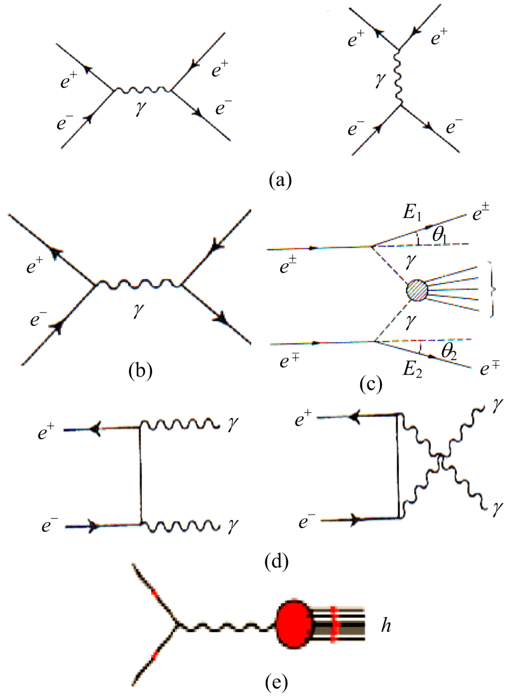


Fig. 5 The physics processes in e^+e^- collision: (a) Bhabha; (b) $\mu^+\mu^-$ and $\tau^+\tau^-$; (c) two photons; (d) $\gamma\gamma$; (e) hadrons.

information of MDC, EMC, and TOF. The combined error of event selection and MC is estimated by the ratio $\Delta(N_{\text{had}}^{\text{obs}}/\bar{\varepsilon}_{\text{had}})$ as in Ref. [7], the relative errors are preliminarily estimated as about 2.5%～3.0% dependent on energies.

The numbers of the residual QED background events, N_{bg} in Eq. (2), are determined employing the MC method,

$$N_{\text{bg}} = L[\varepsilon_{ee}\sigma_{ee} + \varepsilon_{\mu\mu}\sigma_{\mu\mu} + \varepsilon_{\tau\tau}\sigma_{\tau\tau} + \varepsilon_{\gamma\gamma}\sigma_{\gamma\gamma}] \qquad (3)$$

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. The values of ε_{ee} and $\varepsilon_{\mu\mu}$ are about 5×10^{-4}, and $\varepsilon_{\tau\tau}$ smaller than 5% depending on the difference between energy point and threshold of $\tau^+\tau^-$. The amount of background from $e^+e^-\to e^+e^-X$ is smaller than 1% of N_{bg}.

2.2 Generator LUARLW

The general picture of electron-positron annihilation and hadrons production are shown in Fig. 6. The nonperturbative hadronization can be described by the phenomenological model. In R value measurement the Lund area law generator LUARLW[26] is used for determining the hadronic efficiency. LUARLW contains the following constitutes: initial state radiation (ISR), string fragmentation, multiplicity and momentum-energy distributions, decay of unstable hadrons.

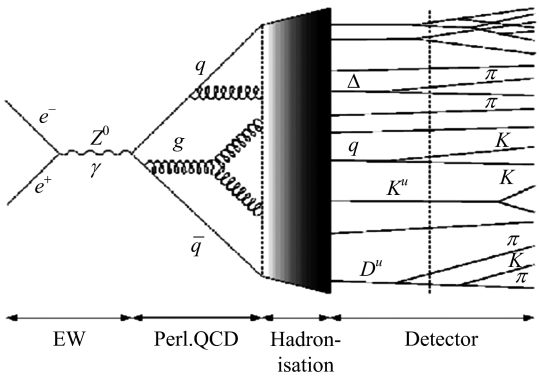


Fig. 6 The picture of e^+e^- annihilation into hadrons

In the simulation of ISR return processes, the sampling of the effective center-of-mass energy E'_{cm} for a hadronic event can be obtained by the differential cross section[23-25], or the equivalent accumulative cross section, which are shown in Fig. 7.

There are some phenomenological parameters in LUARLW. In the BEPC energy, the main parameters are those which determine the ratios of mesons and baryons with different quantum numbers (s, L, J) in the string fragmentation process. In LUARLW these parameters are stored in array PARJ(1—20) as in JETSET[28], their default values were set with the values from fitting the data measured with DELPHI at LEP[20]. Fig. 8 shows the mesons (M) and baryons (B and $\bar{B}$) produced at the vertex of the light-cone area in the string fragmentation. The values of PARJ(1—20) are tuned to make the MC agree with the experimental data taken with BESIII.

Starting from the Lund area law, one may obtain an approximation expression of a poisson-like multiplicity distribution for the preliminary fragmentation hadrons[26]

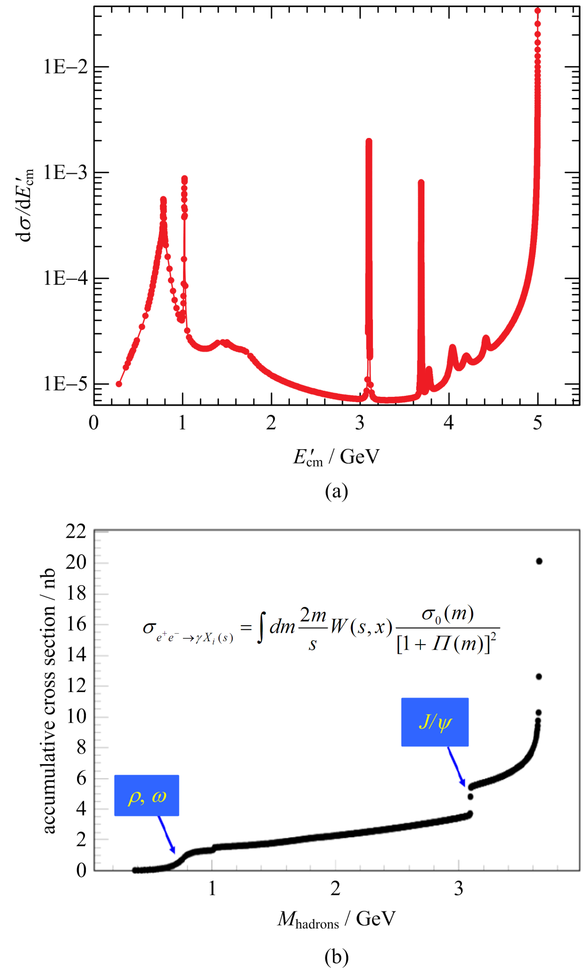


Fig. 7 (a) The differential cross section of ISR return process at E_{cm} =5 GeV (in any scale); (b) the accumulative cross section at E_{cm} =3.65 GeV

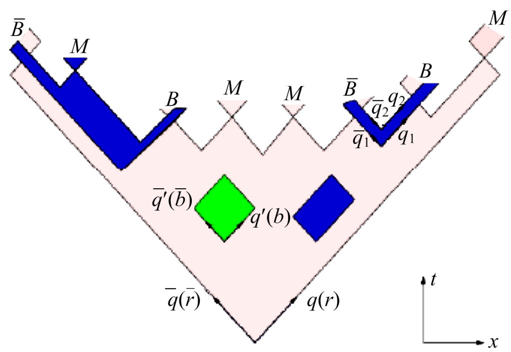


Fig. 8 The mesons and baryons production in the string fragmentation. M means meson, and B means baryon

$$P_n(s) = \frac{\mu^n}{n!}\exp[c_0 + c_1(n-\mu) + c_2(n-\mu)^2] \tag{4}$$

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

$$\mu = \alpha + \beta\exp(\gamma\sqrt{s}) \quad (5)$$

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

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

$$e^+e^- \to \gamma^* \to \begin{cases} q\bar{q} \to \text{string} \to \text{hadrons} \\ gq\bar{q} \to 2\text{strings} \to \text{hadrons} \end{cases}$$

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

$$e^+e^- \to \gamma^* \to \rho(770), \omega(782), \phi(1020) \cdots \rho(1700) \quad (6)$$

The production and decay of the charmonium adopt the standard pictures[27]. For example, the simulation of J/ψ contain following channels

$$e^+e^- \to \gamma^* \to J/\psi \to \begin{cases} \gamma^* \to e^+e^-, \mu^+\mu^- \\ \gamma^* \to q\bar{q} \to \text{string} \to \text{hadrons} \\ ggg \to 3\text{strings} \to \text{hadrons} \\ \gamma gg \to 2\text{strings} \to \text{hadrons} \\ \gamma\eta_c \to gg \to 2\text{strings} \to \text{hadrons} \\ \gamma + \text{radiative decay channels.} \end{cases}$$

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

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

$$d\sigma(s) = d\sigma(e^+e^- \to q\bar{q}) \cdot d\mathscr{P}(q\bar{q} \to m_1, m_2 \cdots m_n; s) \quad (7)$$

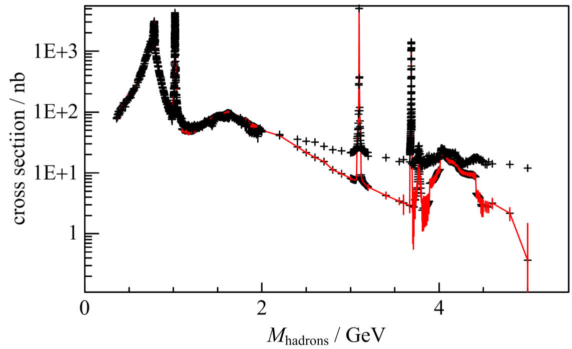
The $d\sigma(e^+e^- \to q\bar{q})$ is the QED cross section, $d\mathscr{P}$ is the probability for string fragmentation into n hadrons and the energy-momentum distributions of the fragmentation hadrons are determined by Lund area law[26].

2.3 Parameter tuning of LUARLW

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

2.3.1 Scheme A: ConExc+LUARLW

The red points in Fig. 9 show the sum of cross sections of the measured exclusive processes, and the black points the total cross sections measured inclusively. The differences between them show that only parts of the exclusive processes were measured above 2 GeV.



The black points are the total cross section measured in inclusive method, and the red points are the sum of the measured exclusive cross sections.

Fig. 9 The Born cross section of $e^+e^- \to$ hadrons below 5 GeV

We have a hadronic generator ConExc + LUARLW. The simulations for the measured processes adopt the exclusive way, the weights of events are proportional to the corresponding cross sections, and the momentums of the hadrons are determined by the phase-space method for multi-hadrons states and the specific angular distributions for two-hadrons states. But the remaining unmeasured or unknown processes will be generated via LUARLW in an inclusive way.

Choose m important parameters to be tuned, assume that their optimal values can be obtained by fitting the distributions of the final state observables x. In order to make the fit effective, the distributions of x should be sensitive to those chosen parameters. Parameter tuning is an iterative process. At the beginning, the default values are used as the initial values. Let $\boldsymbol{p}$ denote the parameters vector with m components, and change the chosen parameters around the initial value $\boldsymbol{p}_0$ by $\delta\boldsymbol{p}$, then the final state distributions for each bin of each distribution can be expressed as the functions of the parameters[20]

$$f(\boldsymbol{p}_0+\delta \boldsymbol{p},x)=$$

$$a_0^{(0)}(x)+\sum_{i=1}^{m} a_i^{(1)}(x)\delta p_i+\sum_{i,j=1}^{m} a_{ij}^{(2)}\delta p_i \delta p_j \tag{8}$$

$$\approx M(\boldsymbol{p}_0+\delta \boldsymbol{p},x) \tag{9}$$

The fit is equivalent to solving a system of linear equations

$$F \cdot \boldsymbol{a}(x)=\boldsymbol{M}(x) \tag{10}$$

where $\boldsymbol{M}(x)$ is the vector of model predictions corresponding to the vector of parameters $\boldsymbol{p}_0+\delta\boldsymbol{p}$, $\boldsymbol{a}(x)$ the vector of coefficients $a_{i(j)}^{(k)}(x)$, F the matrix containing parameter variations. The effective tuning should choose those parameters which are sensitive to the distributions of $\boldsymbol{M}(x)$. The sensitivity can be quantified as

$$S_i(x)=\frac{\delta M(x)}{M(x)}\Big/\frac{\delta p_i}{p_i},\ i=1,\cdots,m) \tag{11}$$

For the purpose of R value measurement, sensitive distributions may be charged and photon multiplicities, momentum of charged particles, polar angle cos θ, meson and baryon ratio, momentum, etc.

2.3.2 Scheme B: Pure LUARLW

In scheme A, the generated number of MC samples increases rapidly with the number of the chosen parameters to be tuned. In practice, an acceptable number of parameters to be tuned is around 10. In the model, every parameter has a specific function and can not be replaced by others. Therefore the number of parameters in need of tuning is much larger than 10. In fact, any number of parameters can be tuned manually, as long as its tuning can improve the MC simulations. At last, the fit method in scheme A was used to optimize them further.

2.3.3. Comparisons between data and MC

If the event generator is correct and the detector simulation is real, a good parameter set should make MC agree well with data for most of the distributions, especially for those which are sensitive to hadronic efficiency, such as charged and neutral multiplicities, cos θ, momentum. Fig. 10 and Fig. 11 show the comparisons between data and MC for some selected distributions. The differences mean further tuning is needed.

3 Conclusion

The three-phase data collection plan has been

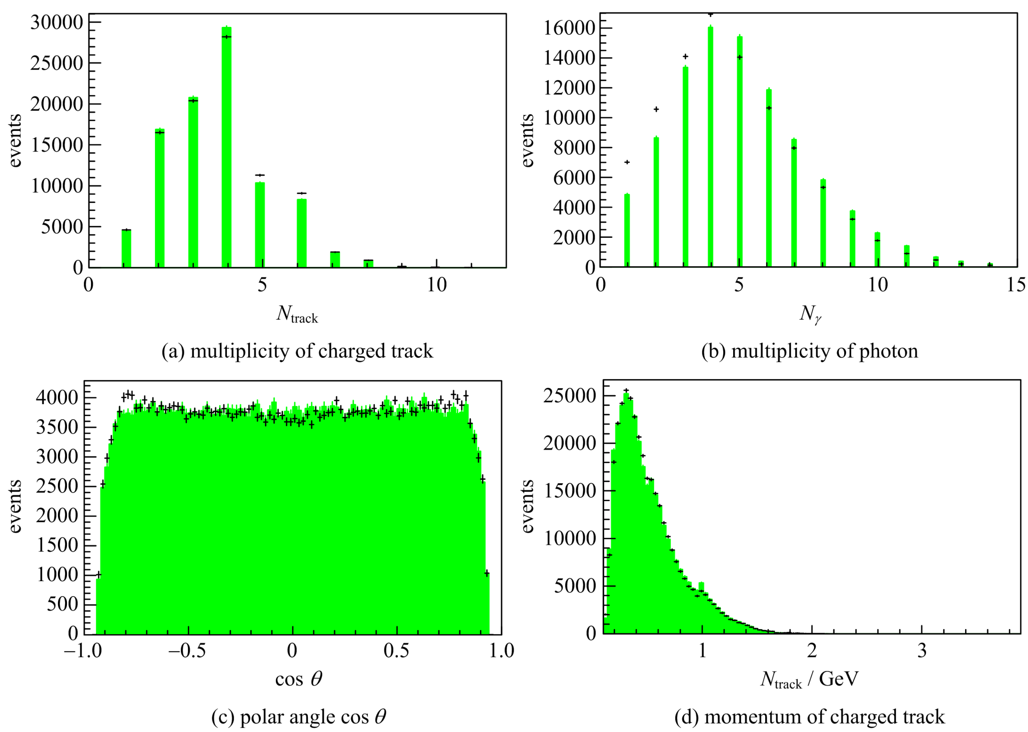
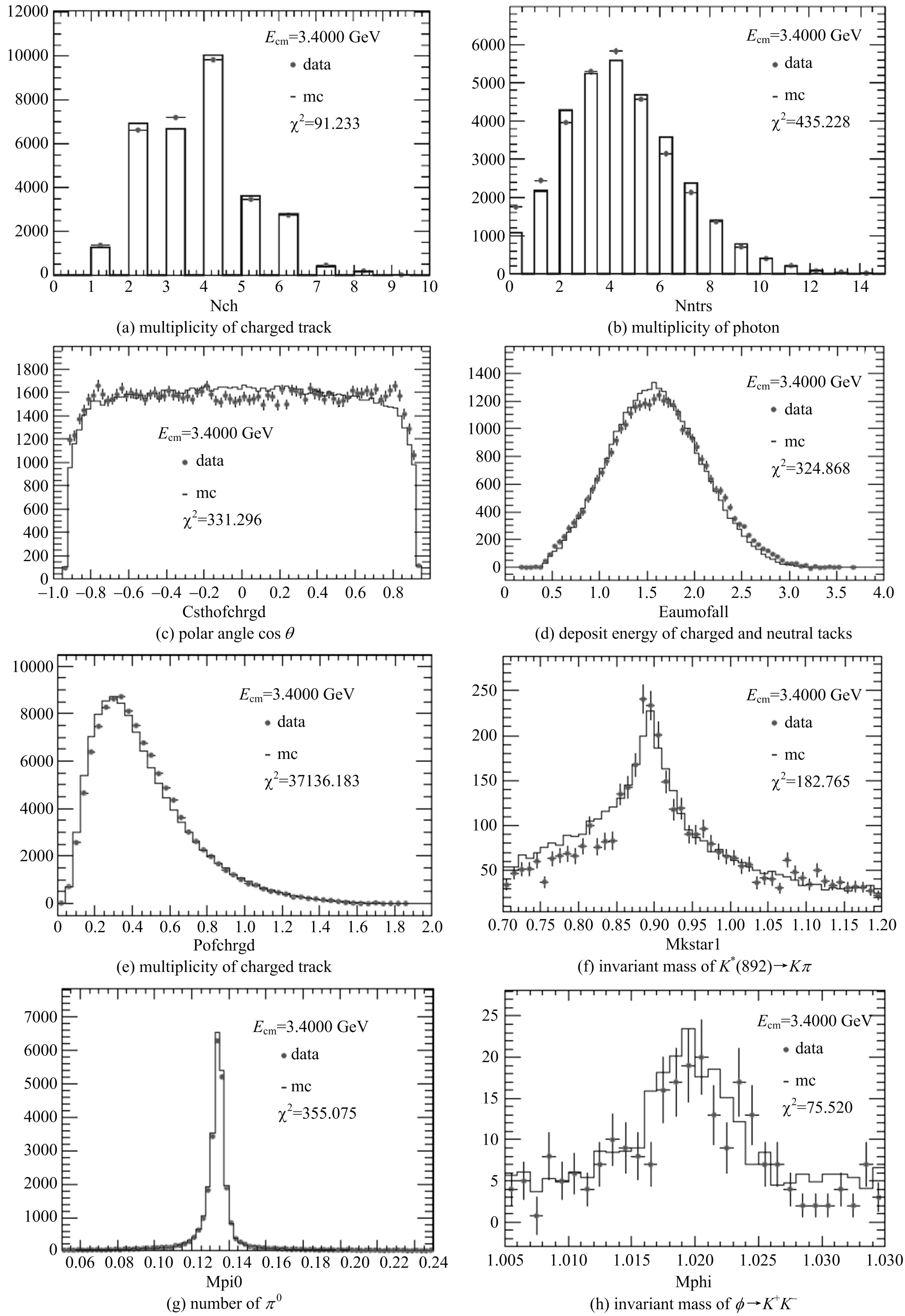


Fig. 10 Comparison between data and MC in scheme A at 3.65 GeV



(a) multiplicity of charged track

(b) multiplicity of photon

(c) polar angle cos θ

(d) deposit energy of charged and neutral tacks

(e) multiplicity of charged track

(f) invariant mass of $K^*(892)\to K\pi$

(g) number of π^0

(h) invariant mass of $\phi\to K^+K^-$

Fig. 11 Comparison between data and MC in scheme B at 3. 400 GeV

carried out, and the data analysis is almost finished. Parameter tuning still remains a challenging task, which will continue to be done till the MC agrees well with data and the errors of hadronic efficiency reaches an acceptable level, for example, 2%, and the total error of R values is reduced to 3%.

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