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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Abstract: BESIII在BEPCII所能达到的能量范围(即2.0至4.6GeV)获取了三批实验数据，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。

Key words: R值测量, 标准模型, 数据分析, 蒙特卡罗模拟.

1 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,

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

The R value is an important input parameter in test of the Standard Model (SM). The precision of R value has 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 experimetal results below 5 GeV, and they use pQCD prediction in higher energy region.

When we look over the PDG published in different years, one 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 accumulated, and in pace with the improvement of experimental methods, the precision of the R value have been evidently improved. Fig. 1 shows the current world data of R values from $2m_\pi$ to 110 GeV in PDG2014[4].

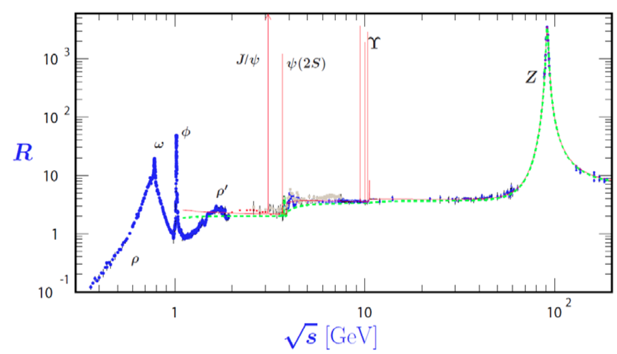

Fig. 1. The R value from $2m_\pi$ to Z^0 scale in PDG2014.

BES Collaboration has ever performed three rounds of R value measurements using the data samples taken with BESII at BEPC[5–7]. The first and second round of measurements performed the R value scan at about 100 energy ponits between 2- 5GeV and took small data samples (only about 1000 hadronic events collected at per energy point), the relative precision of R values were reduced from over 15% in earlier experiments[8–11] to 7%. The third round of measurement of R value used larger data samples at three energy points (E_{cm}=2.65, 3.07 and 3.65 GeV, the numbers of hadronic events are about 24000, 34000 and 84000 respectively), and the results reached a better precision of about 3.5%. Theorists used R values measured with BESII data in the calcu-

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lation of $\Delta\alpha^{(5)}_{had}$ in the running electromagnetic coupling constant $\alpha(s) = 1/[1 - \Delta\alpha(s)]$, the relative uncertainty contribution which result from the errors of R values between 2 to 5 GeV decreased to 35% from earlier 55%, and the relative uncertainty fraction of $a_\mu^{\rm had}$ in (g-2) reduced to about 15% from earlier 25%[1–3].

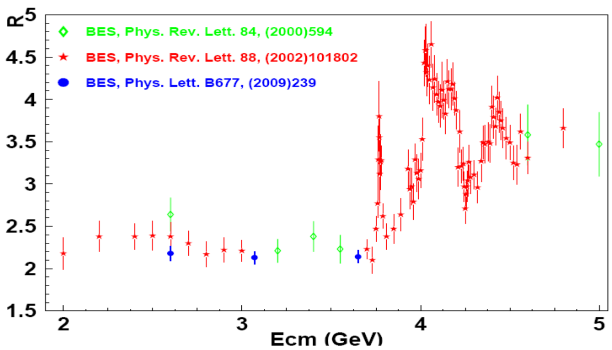

Fig. 2. The summarization R values scan with BEPC/BESII.

In the energy region above the open charm threshold, there exist several high masses ψ-family charmonium resonances ($\psi(3770)$, $\psi(4040)$, $\psi(4190)$, $\psi(4415)$) with quantum number $J^{PC} = 1^{--}$ which were well confirmed in earlier experiments (see the references cited in [12] 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 [6], the line shape and resonant parameters of $\psi(3770)$, $\psi(4040)$, $\psi(4190)$ and $\psi(4415)$ were measured[12]. Fig. 3 shows the measured R values and the fitted line-shape of these resonances. But due to the small statistics and larger scan step, the broad structure in the $\pi^+\pi^- J/\psi$, which ever called $Y(4260)$, discovered by BABAR[13] was missed in BESII scan.

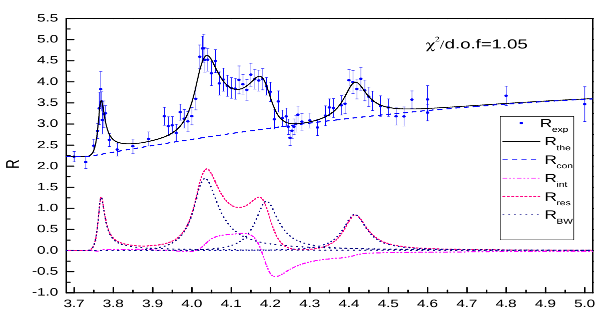

Fig. 3. The R scan of the high mass charmonium line-shape at BEPC/BESII.

In the measurement of resonance parameters with BESII scan data, the fitting method was improved compared with earlier measurements (see the references cited in [12]) in following aspects: (a) intrinsic/effective initial phase angle in Breit-Wigner amplitude was kept; (b) interference terms between final states decayed from heavy ψ-family resonances were considered; (c) energy dependence of the total widths were calculated; (d) as the measurements of R value and resonant parameters are closely related and affected, they were measured in the iterative method, so the R values and resonant parameters were updated simultaneously[12]. 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, 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 $0.85\times10^{33}{\rm cm}^{-2}{\rm s}^{-1}$ at center-of-mass energy of 3770 MeV. The BESIII detector is located at the BEPCII [14], which is designed to fulfill the requirement of the τ-charm physics experiments[15]. Due to the luminosity of BEPCII is about 100 times of that of BEPC, and the performance of BESIII is much better than BESII. One may expect that it is hopeful 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 $a_\mu^{\rm had}$ will have less uncertainties, and the SM prediction can get more better test.

2 Data samples of R scan

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

2.1 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 the total luminosity of about 12 pb^{-1} in 2012. Based on the obtained information, the further R scan plan was optimized and the needed time for the following data taking was estimated. These data can be used for the parameter tuning of the hadronic generator LUARLW[16], and the measurement of R value and the form factors of some hadronic channels which have large production cross section.

2.2 Phase II

It is a fine scan between 3.08 and 4.59 GeV for the measurement of R value and high mass charmonium line-shape and resonant parameters. Drawing on the experience of R scan 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^{-1}, meanwhile 4 times of J/ψ fast scan was did 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 $D\bar{D}$ final sates can be measured, the shortcoming in the BESII measurement can be improved. Fig. 4 shows the online cross section at scan energy points.

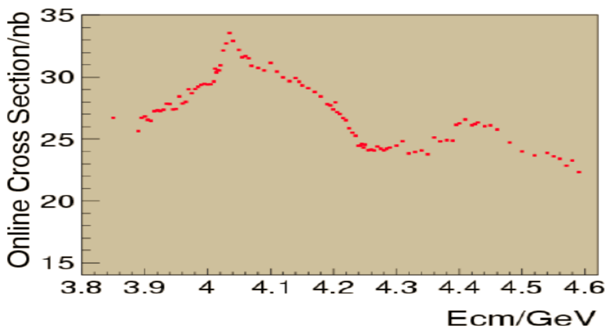

Fig. 4. The online cross section of the R scan with BESIII.

2.3 Phase III

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

3 Status of R value measurement

In experiment, R value is measured with following expression

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

the meanings all of these quantities in above formula were explained in references[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.

3.1 Data analysis

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

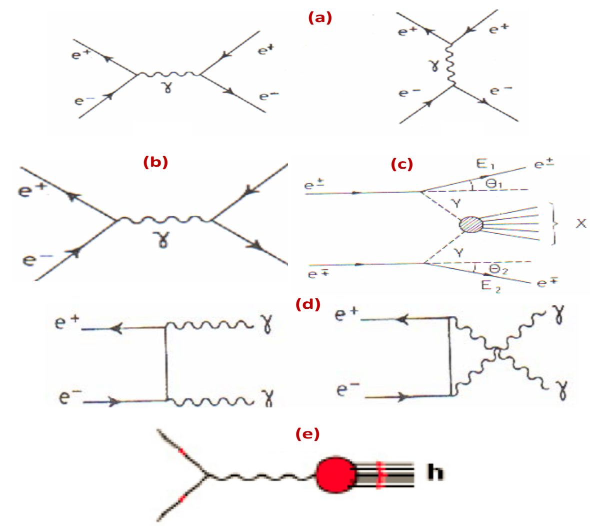

Fig. 5. The physics processes in e^+e^- collision: (a)Bhabha; (b) $\mu^+\mu^-$ and $\tau^+\tau^-$; (c) two photons; (d) $\gamma\gamma$; (e) hadrons.

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 signals events of e^+e^- and $\gamma\gamma$ have very clear characteristics in detector and can be well selected, the remained backgrounds are very limited. The error of luminosity measurements are about 1%[18].

The scheme of hadronic events selection are similar to that of used in works[5–7] but optimized[19]. The hadronic event selection can be classed as track level and event level, which use the information of MDC, EMC, and TOF. The combined error of event selection and MC are estimated by the ratio $\Delta(N_{had}^{obs}/\bar{\epsilon}_{had})$ as did in [7], the relative errors are preliminary 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 from MC method,

$$N_{bg} = L[\epsilon_{ee}\sigma_{ee} + \epsilon_{\mu\mu}\sigma_{\mu\mu} + \epsilon_{\tau\tau}\sigma_{\tau\tau} + \epsilon_{\gamma\gamma}\sigma_{\gamma\gamma}], \tag{3}$$

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 $\epsilon_{\mu\mu}$ are order of about 5×10^{-4}, and $\epsilon_{\tau\tau}$ 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}.

3.2 Generator LUARLW

The general picture of electron-positron annihilation and hadrons production are shown in Fig.6. The nonperturbative hadronization can be described by phenomenological model. In R value measurement the Lund area law generator LUARLW[23] is used for determining the hadronic efficiency. LUARLW contains following constitutes: initial state radiation (ISR), string fragmentation, multiplicity and momentum-energy distributions, decay of unstable hadrons.

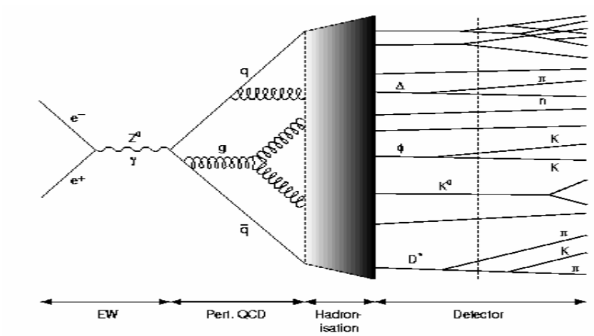

Fig. 6. The picture of e^+e^- annihilation into hadrons.

The simulation of ISR return events uses the scheme described in reference [20–22]. For example, the spectrum of effective hadronic center-of-mass energy E'_{cm} in the ISR return processes at the nominal $E_{cm} = 5$ GeV is shown in Fig. 7, which is proportional to the probability density function (pdf). The equivalent cumulative distribution function (cdf) corresponding to the hard ISR bremsstrahlung photon sampling is shown in Fig. 8.

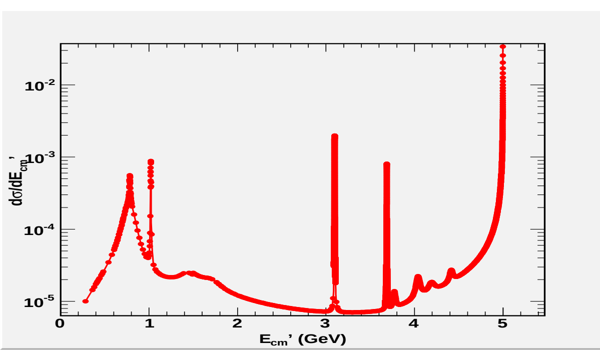

Fig. 7. The spectrum of effective hadronic center-of-mass energy of ISR return process used in scheme B.

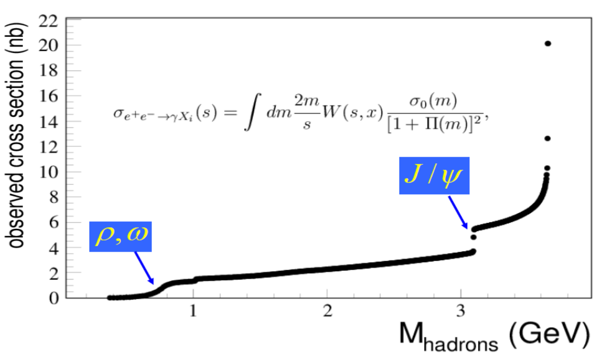

Fig. 8. The spectrum of effective hadronic center-of-mass energy of ISR return process used in scheme A.

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 number (s, L, J) in the string fragmentation process. In LUARLW these parameters are stored in array PARJ(1-20) as did in JETSET[25], their default values were set with the values from fitting the data measured with DELPHI at LEP[17]. Fig. 9 shows the mesons (M) and baryons (B and $\bar{B}$) produced at the vertex of 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.

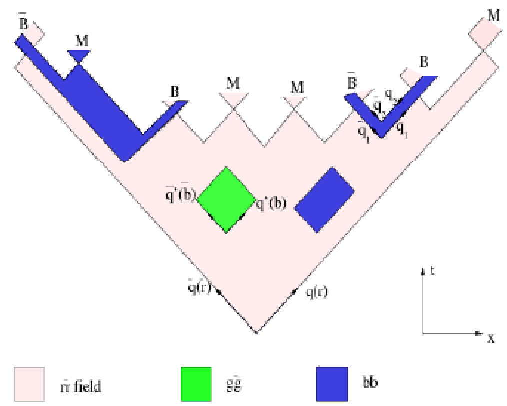

Fig. 9. The mesons and baryons production in the string fragmentation, M means meson, and B means baryon.

Starting from the Lund area law, one may obtain an approximation expression of a poisson-like multiplicity distribution for the preliminary fragmentation hadrons[23]

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

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 continous 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 smaller than 2 GeV and with $J^{PC} = 1^{--}$ can directly couple to virtual photon in ISR return process

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

The production and decay of the charmonium adopt the standard pictures[24]. 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 in the similar way.

The cross section 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

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

The $d\sigma(e^+e^- \to q\bar{q})$ is the QED cross section, $d\mathcal{P}$ is the probability for string fragmentation into n hadrons and the energy-momentum distributions of the fragmentation hadrons are determined by Lund area law[23].

3.3 Parameter tuning of LUARLW

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

3.3.1 Scheme A: ConExc+LUARLW

The red points in Fig. 10 show the sums of cross sections of the measured exclusive processes, and the black points the total cross sections measured inclusively. The differences between them show only parts of exclusive processes were measured above 2 GeV.

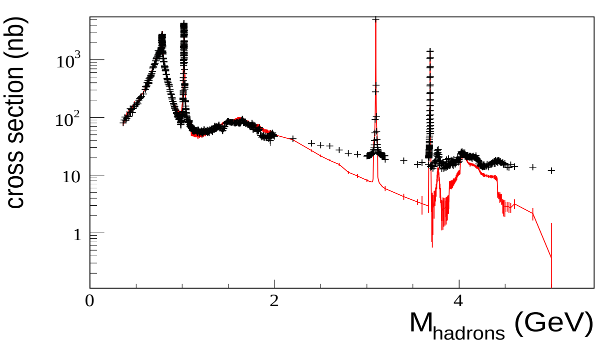

Fig. 10. The Born cross section of $e^+e^- \to$ hadrons below 5 GeV. The black points are the total inclusive cross section, the red points are the sum of the measured exclusive cross section.

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 phase-space method for multi-hadrons states and the specific angular distributions for two-hadrons states. But for the remaining unmeasured or unknown processes will be generated via LUARLW in 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 about x should be sensitive to those chosen parameters. Parameter tuning is an iterative process. At beginning, the default values are used as the initial values. Let $\mathbf{p}$ denote the parameters vector with m components, and change the chosen parameters around the initial value $\mathbf{p}_0$ by $\delta\mathbf{p}$, then the final state distributions for each bin of each distribution can be expressed as the functions of the parameters[17]

$$f(\mathbf{p}_0 + \delta\mathbf{p}, x) = a_0^{(0)}(x) + \sum_{i=1}^{m} a_i^{(1)}(x)\delta p_i + \sum_{i,j=1}^{m} a_{ij}^{(2)} \delta p_i \delta p_j \quad (8)$$
$$\approx M(\mathbf{p}_0 + \delta\mathbf{p}, x), \quad (9)$$

The fit is equivalent to solving a system of linear equations

$$F \cdot \mathbf{a}(x) = \mathbf{M}(x) \quad (10)$$

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

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

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

3.3.2 Scheme B: Pure LUARLW

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

3.3.3 Comparisons between data and MC

If the event generator is correct and the detector simulation is real, good parameter set should make MC agree with data well for most distributions, especially for those which are sensitive to the hadronic efficiency, such as charged and neutral multiplicities, $\cos\theta$, momentum. The Fig. 11 and Fig. 12 are the comparison between data and MC for some selected distributions. The differences mean further tuning are needed.

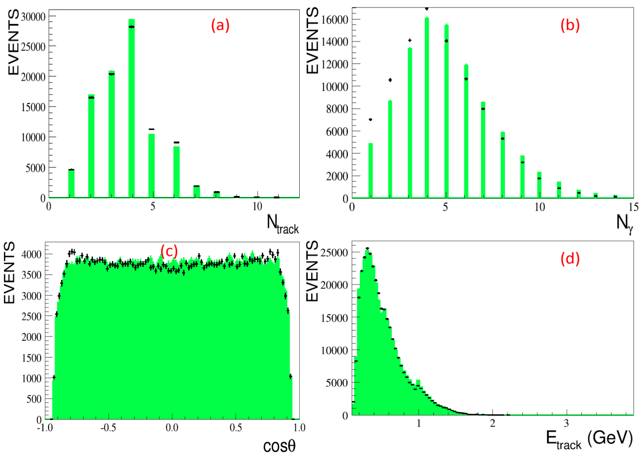

Fig. 11. Comparison between data and MC in scheme A at 3.65 GeV. (a) multiplicity of charged track; (b) multiplicity of photon; (c) polar angle $\cos\theta$; (d) momentum of charged track.

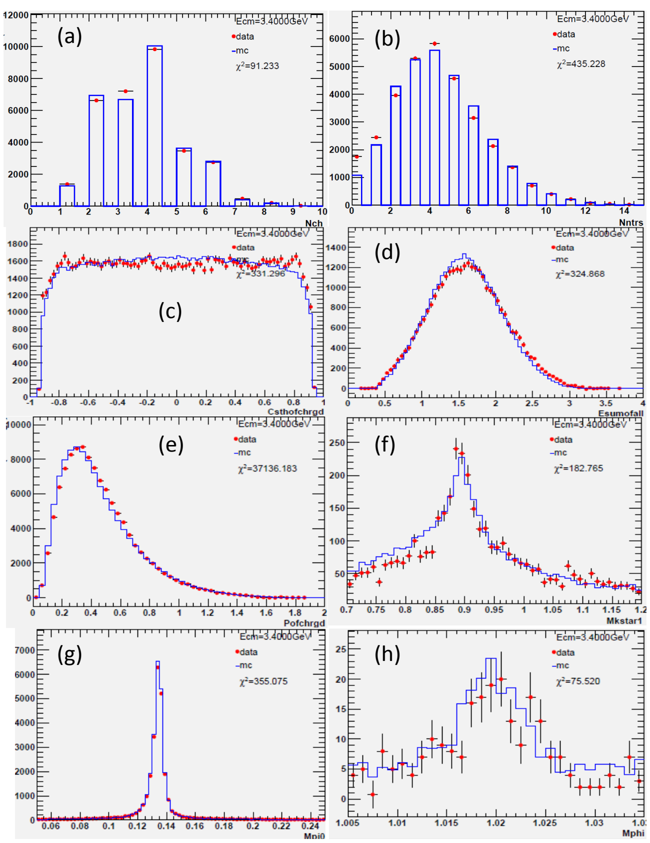

Fig. 12. Comparison between data and MC in scheme B at 3.400 GeV. (a) multiplicity of charged track; (b) multiplicity of photon; (c) polar angle $\cos\theta$; (d) deposit energy of charged and neutral tacks; (e) momentum of charged track; (f) invariant mass of $K^*(892) \to K\pi$; (g) number of π^0; (h) invariant mass of $\phi \to K^+K^-$.

4 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%.

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