Event generators at BESIII *

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Abstract We present a brief remark and introduction to event generators for tau-charm physics currently used at BESIII, including KKMC, BesEvtGen, Bhlumi, Bhwide, Babayaga and inclusive Monte-Carlo event generators. This paper provides basic information on event generators for BESIII users.

Key words event generators, BESIII, Monte-Carlo simulation

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1 Introduction

The precision of measurements will become one of the central issues or challenges for tau-charm physics analysis at BESIII. The measurement for the resonance parameters, say charmonia and light hadron states, is expected to reach the statistical accuracy of about 1% or less. For measurements of the branching fractions for charmonium transitions or exclusive decays, the precision will be highly improved by one order or more of magnitude compared with the current PDG values. For tau-mass measurement, the statistical error is expected to reduce to $\delta m_\tau \sim 0.09$ MeV, and the precision of measuring Michel parameter is expected to improve by a factor of 2 or 4. These requirements call for high precision Monte-Carlo (MC) event generators.

Event generators with high quality or precision are essential to do a reliable MC simulation to remove the systematic uncertainty as much as possible. In experiment, MC simulations are used to determine detection efficiencies or study backgrounds. For high precision measurements, one expects that the MC generators could simulate the processes under study as really as possible. Hence, the generators only with kinematic information (e.g. pure phase space) do not meet this requirement. Recently, high precision generators for QED processes are developed based on the technique of Yennie-Frautchi-Suura exponentiation to describe the process $e^+e^- \to f\bar{f}$ (f: fermion). The official precision tags of these generators are about 1% or less, e.g. KKMC, Bhlumi and so on. The generators with dynamical information for hadron decays have also been developed, such as EvtGen, for BaBar and CLEO collaborations to study B physics. These provide us with a large room to make a choice among the existent generators to simulate tau-charm physics processes.

However, most of these generators are originally designed for high energy physics above the tau-charm energy scale. Generally speaking, the MC generator is physics or model dependent. There are a few MC generators covering the full energy scale of high energy physics. So at tau-charm energy scale, the immigration of the MC generators, originally designed for the high energy scale physics, needs a fine tuning of parameters concerned, and further comparison with data is necessary. In order to generate exclusive charmonium decays, more models are needed to construct in the EvtGen framework.

In this paper, we present a general description about the BESIII generator framework, and give brief introduction to the BESIII event generators, such as KKMC, BesEvtGen, some QED generators and some inclusive generators. For details, the users are suggested to refer to the generator guides or concerned publications.

2 Generator framework

The generator framework of BESIII was approved to use KKMC + BesEvtGen to generate charmonium decay events. For charmonia produced from the e^+e^- annihilation, the process can be described

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as Fig. 1. The positron and electron can radiate some real photons before they annihilate into a virtual photon, which is the so-called initial state radiation process (ISR). Radiative corrections are crucial in e^+e^- annihilation experiments, sometimes it could change the numerical results in a profound way, such as resonances and measurements near the production threshold. In order to achieve precise results in data analyses, the generators for e^+e^- collider should carefully take this into account. The KKMC is used to simulate the e^+e^- annihilation till $c\bar{c}$ production including ISR effects, together with the beam energy spread. Then the charmonium decays are generated with BesEvtGen models.

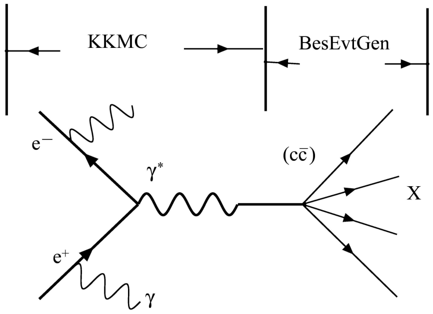

Fig. 1. Illustration of BESIII generator framework.

It should be pointed out that the events are generated in the center of mass system (CMS) of the e^+e^- beams. However, the e^+e^- beams at BEPCⅡ are not exactly aligned back to back; the cross angle between the e^+- and e^--beams is about 22 mrad. So the produced charmonium is not at rest, namely, it moves along x-direction with a small momentum¹⁾. Hence the generated events should be boosted to laboratory system before going through detector simulation. This is implemented outside the generator framework.

3 BESⅢ generators

Early generators used at BESIII are those migrated from BESⅡ, which include about 30 generators. They are now obsolete and we don't recommend to use it²⁾. In what follows, we focus on the generators currently used in the BESIII generator framework.

3.1 KKMC

KKMC[1] is the event generator based on precise predictions of the Electroweak Standard Model for the process $e^+e^- \rightarrow f\bar{f} + n\gamma$, $f = \mu, \tau, d, u, s, c, b$ at centre-of-mass energies from τ lepton threshold to 1 TeV. KKMC is originally designed for LEP, SLC, but also suitable for the future linear colliders, b, c, τ− factories, and so on.

In KKMC, the most important features are the ISR-FSR interference, the second-order subleading corrections, and the exact matrix element for the two hard photons. Effects due to photon emission from the initial beams and the outgoing fermions are calculated in QED up to the second order, including all interference effects, within the Coherent Exclusive Exponentiation (CEEX), which is based on Yennie-Frautschi-Suura exponentiation. Electroweak corrections are included in the first order, with higher-order extensions, using the DIZET 6.21 library. Final-state quarks hadronize according to the parton shower model using PYTHIA. Decays of the τ lepton are simulated using the TAUOLA library, taking into account the spin polarization effects as well. The code and more information on the program are available at the KKMC web page[2].

In the generator framework at BESIII, KKMC is used to generate charmonium states by including ISR effects and the spread of the beam energy. The resonances supportable by KKMC include J/ψ, $\psi(2S)$, $\psi(3770)$, $\psi(4030)$, $\psi(4160)$, $\psi(4415)$ and other low-lying resonances, like ρ, ρ', ρ'', ω, ω', ϕ and ϕ'. Though KKMC also supports the event generation of resonance decays, we have more powerful models in BesEvtGen to generate resonance decay events, and the final state radiation (FSR) effects are included in the simulation at the BesEvtGen level by using the package PHOTOS.

3.2 BesEvtGen

BesEvtGen[3] is the event generator for tau-charm physics, which is developed from the generator EvtGen³⁾, originally designed for studying B physics by BaBar and CLEO collaborations. EvtGen is a powerful interface to generate events for a given decay by specifying a model easily created by users; it also allows the access to other generators, such as PYTHIA and PHOTOS.

The EvtGen interface uses the dynamical information to generate a sequential decay events chain by chain through the accept-reject algorithm, which is based on the amplitude probability with the combination of the forward and/or backward spin-density matrix information. The EvtGen interface is designed to have functionality to automatically calculate these spin-density matrixes. To illustrate how the event selection algorithm works consider the sequential decay

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1) The z-axis is defined along the beam direction in the laboratory system.

2) Currently, the McTruths of these generators are not available in the simulation

3) The version is V00-11-07

$J/\psi \to \rho^0\pi^0$, $\rho^0 \to \pi^+\pi^-$ and $\pi^0 \to \gamma\gamma$.

The first chain of the decay is selected based on the probability

$$P_\psi = \sum_{\lambda_\psi,\lambda_\rho} |M^{J/\psi\to\rho^0\pi^0}_{\lambda_\psi,\lambda_\rho}|^2 , \tag{1}$$

where M stands for the amplitude for $J/\psi \to \rho^0\pi^0$ with the helicity indexes λ_ψ and λ_ρ. After decaying the J/ψ, one has the forward spin-density matrix

$$\mathcal{D}^{\rho^0}_{\lambda_\rho,\lambda'_\rho} = \sum_{\lambda_\psi} M^{J/\psi\to\rho^0\pi^0}_{\lambda_\psi,\lambda_\rho}\left[M^{J/\psi\to\rho^0\pi^0}_{\lambda_\psi,\lambda'_\rho}\right]^* . \tag{2}$$

To generate the $\rho^0 \to \pi^+\pi^-$ decay, one proceeds as with the J/ψ, including also $\mathcal{D}^{\rho^0}_{\lambda_\rho,\lambda'_\rho}$

$$P_\rho = \frac{1}{\mathrm{Tr}\mathcal{D}^{\rho^0}} \sum_{\lambda_\rho,\lambda'_\rho} \mathcal{D}^{\rho^0}_{\lambda_\rho,\lambda'_\rho} A^{\rho^0\to\pi^+\pi^-}_{\lambda_\rho}\left[A^{\rho^0\to\pi^+\pi^-}_{\lambda'_\rho}\right]^* . \tag{3}$$

To decay the π^0 with the full correlations between all kinematic variables in the decay, the EvtGen interface automatically calculates the backward spin-density matrix by

$$\tilde{\mathcal{D}}^{\rho^0}_{\lambda_\rho,\lambda'_\rho} = A^{\rho^0\to\pi^+\pi^-}_{\lambda_\rho}\left[A^{\rho^0\to\pi^+\pi^-}_{\lambda'_\rho}\right]^* , \tag{4}$$

then the spin-density matrix for the π^0 is

$$\mathcal{D}^{\pi^0} = \sum_{\lambda_\psi,\lambda_\rho,\lambda'_\rho} \tilde{\mathcal{D}}^{\rho^0}_{\lambda_\rho,\lambda'_\rho} M^{J/\psi\to\rho^0\pi^0}_{\lambda_\psi,\lambda_\rho}\left[M^{J/\psi\to\rho^0\pi^0}_{\lambda_\psi,\lambda'_\rho}\right]^* , \tag{5}$$

this is a constant for a spin-0 particle. So the π^0 decay is selected by the probability

$$P_{\pi^0} = \frac{1}{\mathrm{Tr}\mathcal{D}^{\pi^0}} \sum_{\lambda_1,\lambda_2} \mathcal{D}^{\pi^0} A^{\pi^0\to\gamma\gamma}_{\lambda_1,\lambda_2}\left[A^{\pi^0\to\gamma\gamma}_{\lambda_1,\lambda_2}\right]^* = \sum_{\lambda_1,\lambda_2} A^{\pi^0\to\gamma\gamma}_{\lambda_1,\lambda_2}\left[A^{\pi^0\to\gamma\gamma}_{\lambda_1,\lambda_2}\right]^* . \tag{6}$$

BesEvtGen extends the baryon to the spin-3/2 case, and adds about 30 models for simulating the exclusive decays of tau-charm physics. The amplitudes of these models are constructed with the helicity amplitude method, and constrained by imposing the *P*-parity conservation. One of the most powerful models is DIY, which can generate any decay event in terms of the amplitude provided by users. The other useful models are those which generate decay events using the histogram distributions, such as MassH1, MassH2 and Body3 1). BesEvtGen allows the access to the inclusive generators, e.g. PYTHIA and LUNDCHARM, to generate the unknown decay events for a given resonance.

3.3 QED generators

3.3.1 Bhlumi and Bhwide

The generators Bhlumi[4] and Bhwide[5] are used to generate the events for Bhabha scattering processes $e^+e^- \to e^+e^- + n\gamma$. They are full energy scale generators, though originally designed for LEP1/SLC and LEP2 at high energy scale. The generator Bhlumi is suitable for generating the low angle Bhabha events ($\theta < 6°$), while the generator Bhwide is suitable for the wide angle Bhabha events ($\theta > 6°$). Here the "suitable" means that these generators working within the suitable region will achieve the tagged precision, out of the region their precisions will decrease. The precision of the Bhlumi is quoted as 0.11% at LEP1 energy scale and 0.25% for LEP2 experiments. This estimate is based on the comparison with other MC calculations[4]. The precision of the Bhwide is quoted as 0.3% at the Z boson peak and 1.5% at LEP2 energies.

Bhlumi is a multiphoton Monte Carlo event generator for low angle ($\theta < 6°$) Bhabha processes providing four-momentum of outgoing electron, positron and photons. The first $\mathcal{O}(\alpha^1)_{\mathrm{YFS}}$ version was described in Ref. [6]. The matrix elements are based on the Yennie-Frautschi-Suura exponentiation. These matrix elements include exactly the photonic first order and second order leading-log corrections. The other higher order and subleading contributions are included in the approximate form.

Bhwide is a wide angle ($\theta > 6°$) generator for Bhabha scattering. The theoretical formulation is based on $\mathcal{O}(\alpha)$ YFS exponentiation, with $\mathcal{O}(\alpha)$ virtual corrections from Ref. [7]. The YFS exponentiation is realized via Monte Carlo methods based on the BHLUMI-type Monte-Carlo algorithm, but with some important extensions: (1) QED interferences between the electron and positron lines had to be reintroduced as they are important in the large angle Bhabha scattering; (2) the full YFS form factor for the $2 \to 2$ process, including all s-, t- and u-channels was implemented; (3) the exact $\mathcal{O}(\alpha)$ matrix element for the full Bhabha process was included.

Users to run these generators are required to specify the CMS energy, as well as other cuts on the electron, positron and soft photons in their job option files. At tau-charm energy scale, the precisions are not given by authors, but anyhow they are the most precise generators we have for Bhabha processes.

3.3.2 Babayaga

Babayaga[8] is a Monte Carlo event generator for $e^+e^- \to e^+e^-$, $\mu^+\mu^-$, $\gamma\gamma$ and $\pi^+\pi^-$ processes for

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1) They correspond to generate events with 1-D diagram, Dalitz plot and to generate 3-body decays with a Dalitz plot plus two angular distribution plots.

energies below 12 GeV. It's a high-precision calculation of the Bahbha process in quantum electrodynamics, of interest for precise luminosity determination of electro-positron colliders involved in R measurements in the region of hadronic resonances. The calculation is based on the matching of exact next-to-leading order corrections with a parton shower algorithm. The accuracy of the approach is demonstrated in comparison with the existing independent calculations and through a detailed analysis of the main components of theoretical uncertainty, including two-loop corrections, hadronic vacuum polarization and light pair contributions. The theoretical accuracy of Babayaga is quoted as 0.1%[9]. The current version of BABAYAGA at BESIII is V3.5[9].

To use the generator Babayaga, user are required to specify the CMS energy of the $\mathrm{e}^+\mathrm{e}^-$ beams, together with the cuts on the electron, positron and photons.

3.4 Inclusive generators

The PYTHIA program is frequently used as inclusive event generators in high-energy physics for $\mathrm{e}^+\mathrm{e}^-$, pp and ep colliders. Historically, the family of event generators from the Lund group was begun with JETSET in 1978. The PYTHIA program followed a few years later. The recent version available is PYTHIA 6.4. The code and further information may be found on the Pythia web page[10].

For simulating charmonium J/ψ and $\psi(2S)$ inclusive decays, Lundcharm model has been well adjusted at BESII, on which the constraints of C- and G-parity are imposed, and further compared with the experimental data[11]. So it is officially decided in BES collaboration to use this modified Lundcharm model to generate J/ψ and $\psi(2S)$ inclusive decays in the BesEvtGen framework.

Advantage to generate inclusive MC sample in the EvtGen framework is that the decay widths in the Lundcharm model can be controlled by user. The branching fractions and the models of known decays can be specified in the decay dictionary of the EvtGen, while the unknown decays are generated with the Lundcharm models. When the Lundcharm model is called, a complete chain of the decay is generated, but only the first chain of the J/ψ or $\psi(2S)$ decay is read out and returned to the EvtGen interface. The EvtGen interface has a functionality to check whether the decay is included in the EvtGen exclusive decay models. Only the decay not included in the exclusive decay models is accepted, then the decays of the daughter particles are simulated with the EvtGen Models.

EvtGen also allows the access to the PYTHIA model to generate the QED inclusive decays with the model "PYCONT". At tau-charm energy scale, the area law of the Lundcharm model should be implemented to constraint the decays, however this has not been implemented in the EvtGen model.

4 Summary and outlook

We present a general description on the generator framework and event generators currently used at BESIII, which include KKMC, BesEvtGen, Bhlumi, Bhwide, Babayaga and the inclusive generators. The cosmic ray generator, CORSIKA[12], is under immigrating. Though some event generators for QED processes, such as $\mathrm{e}^+\mathrm{e}^- \rightarrow \mu^+\mu^-$ and $\tau^+\tau^-$ in KKMC, and $\mathrm{e}^+\mathrm{e}^- \rightarrow \gamma\gamma$, $\mu^+\mu^-$ and $\pi^+\pi^-$ in Babayaga, are available, they still don't satisfy the requirement on measurements of hadronic cross-section at BESIII. Migrating other generators is necessary, for example, MCGPJ ($\pi^+\pi^-$, $\mathrm{K}^+\mathrm{K}^-$ and $\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{L}$ available) and PHOKHARA ($\pi^+\pi^-$, $\pi^+\pi^-\pi^0$, $\pi^+\pi^-\pi^+\pi^-$, $\mathrm{K}^+\mathrm{K}^-$, $\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{L}$, $\mathrm{p}\bar{\mathrm{p}}$, $\mathrm{n}\bar{\mathrm{n}}$ and $\Lambda\bar{\Lambda}$ available) with the precision of (0.1—0.2)%.

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