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The EvtGen particle decay simulation package

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Abstract

With several new B-physics experiments now taking data, the physics of B-meson decays will be studied in greater detail than previously possible. It is important to have a simulation of the underlying physics processes that is able to accurately describe this data. The EvtGen package provides a framework for the implementation of physics processes relevant to decays of B mesons and other resonances. Models of time dependent CP asymmetries in neutral B meson decays, semileptonic form-factor models, and a full decay table for B decays are a few of the implemented features. © 2001 Published by Elsevier Science B.V.

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1. Introduction

There are several event generators available for the simulation of particle decays in high energy physics experiments. This paper describes the EvtGen package [1], which we hope will be a useful tool for the simulation of decays of B mesons and other resonances. With several new B-physics experiments now taking data, the physics of B mesons will be studied in greater detail than previously possible. It is important to have tools for the simulation of the underlying physics processes at these experiments.

Decay amplitudes, instead of probabilities, are used for the simulation of decays. The amplitude for each node in a decay tree is used to simulate the entire decay chain, including all angular and time-dependent correlations. For example, in the CP violating decay $B \to J/\psi K^*$, $J/\psi \to ll$, and $K^* \to K\pi$, illustrated in Fig. 1, only the decay amplitudes for $B \to J/\psi K^*$, $J/\psi \to ll$, and $K^* \to K\pi$ must be provided. The implementation of each decay amplitude is independent of how the mother particle was generated or how the daughter particles are to decay.[1]

Section 2 describes the algorithm that simulates correlations given individual decay amplitudes, as described above. Currently implemented decay models and comparisons with data are described in Section 3. The framework of EvtGen provides tools so that additional models can be easily implemented.

2. Algorithm

To illustrate how the event selection algorithm works, consider the decay $B \to D^* \tau \bar{\nu}$, $D^* \to D\pi$,

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[1] One exception to this is the case where the amplitude for a decay depends on the decay of the daughter particles in some way. An example of this is $B \to J/\psi K^*$, where the CP of the final state depends on if the K^* decays to $K_S\pi$, $K_L\pi$, or $K^{\pm}\pi$. This type of decay is handled as a special case in the decay table.

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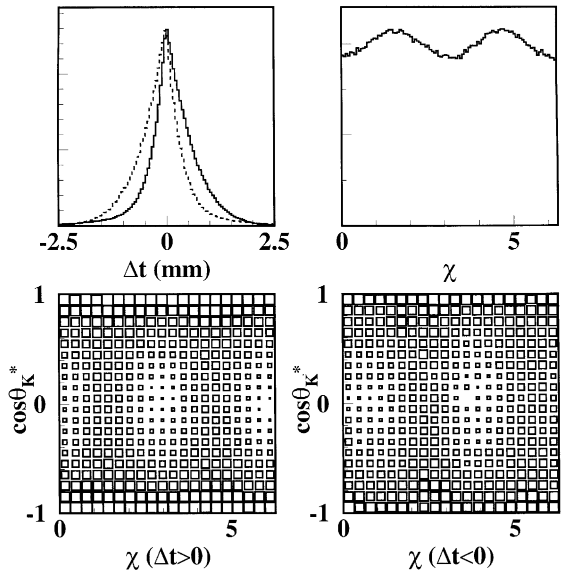

Fig. 1. Distributions for the CP violating decay $B \to J/\psi K^*$ ($J/\psi \to ll$ and $K^* \to K\pi$). The upper-left plot shows the Δt distribution for B^0 and $\bar{B}^0$ (at $t = 0$) decays. χ, shown in the upper-right distribution, is the angle between the decay plane of the J/ψ and that of the K^*. The lower plots show $\cos\theta_{K^*}$ vs. χ for $\Delta t > 0$ and $\Delta t < 0$. $\cos\theta_{K^*}$ is the decay angle of the K^*.

and $\tau \to \pi\nu$. The general case is a straight forward generalization of this example. The decay amplitude can be written as

$$A = \sum_{\lambda_{D^*}\lambda_\tau} A^{B\to D^*\tau\nu}_{\lambda_{D^*}\lambda_\tau} \times A^{D^*\to D\pi}_{\lambda_{D^*}} \times A^{\tau\to\pi\nu}_{\lambda_\tau} \tag{1}$$

where λ_{D^*} and λ_τ label the states of spin degrees of freedom of the D^* and the τ, respectively. Thus, $A^{B\to D^*\tau\nu}_{\lambda_{D^*}\lambda_\tau}$ represents the decay amplitude for $B \to D^*\tau\nu$ for the six different combinations of D^* and τ states.

A possible implementation of Eq. (1) is to generate kinematics according to phase space for the entire decay chain and to calculate the probability, the amplitude squared, which is used in an accept–reject algorithm. This approach has two serious limitations. First, the maximum probability of the decay chain must be known. This is logicistally difficult given the large number of potential decay chains in B decays. Second, for long decay chains the accept–reject algorithm can be very inefficient as the entire chain must be regenerated if the event is rejected. We have implemented an algorithm that generates a decay chain as a sequence of sub-decays, thus avoiding both of these limitations.

First the decay of the B is considered. Kinematics are generated according to phase space and the probability is calculated

$$P_B = \sum_{\lambda_{D^*}\lambda_\tau} |A^{B\to D^*\tau\nu}_{\lambda_{D^*}\lambda_\tau}|^2. \tag{2}$$

The kinematics are regenerated until the event passes an accept–reject algorithm based on P_B. After decaying the B we form the spin density matrix

$$\rho^{D^*}_{\lambda^*_D\lambda'_{D^*}} = \sum_{\lambda_\tau} A^{B\to D^*\tau\nu}_{\lambda_{D^*}\lambda_\tau}[A^{B\to D^*\tau\nu}_{\lambda'_{D^*}\lambda_\tau}]^*, \tag{3}$$

which describes a D^* from the $B \to D^*\tau\nu$ decay after summing over the degrees of freedom for the τ. To generate the $D^* \to D\pi$ decay, proceed as with the B, including also ρ^{D^*}

$$P_{D^*} = \frac{1}{\mathrm{Tr}\,\rho^{D^*}} \times \sum_{\lambda_{D^*}\lambda'_{D^*}} \rho^{D^*}_{\lambda_{D^*}\lambda'_{D^*}} A^{D^*\to D\pi}_{\lambda_{D^*}}[A^{D^*\to D\pi}_{\lambda'_{D^*}}]^*, \tag{4}$$

where the scale factor, $1/\mathrm{Tr}\,\rho^{D^*}$, is proportional to the decay rate, and does not affect the angular distributions. This scale factor makes the maximum decay probability of each sub-decay independent of the full decay chain.

Finally, we decay the τ. We form the density matrix

$$\tilde{\rho}^{D^*}_{\lambda_{D^*}\lambda'_{D^*}} = A^{D^*\to D\pi}_{\lambda_{D^*}}[A^{[D^*\to D\pi}_{\lambda'_{D^*}}]^*, \tag{5}$$

which encapsulates the information about the D^* decay needed to properly decay the τ with the full correlations between all kinematic variables in the decay. Using the $\tilde{\rho}^{D^*}$ matrix we calculate the spin density matrix of the τ

$$\rho^{\tau}_{\lambda_\tau\lambda'_\tau} = \sum_{\lambda_{D^*}\lambda'_{D^*}} \tilde{\rho}^{D^*}_{\lambda_{D^*}\lambda'_{D^*}} A^{B\to D^*\tau\nu}_{\lambda_{D^*}\lambda_\tau}[A^{B\to D^*\tau\nu}_{\lambda'_{D^*}\lambda'_\tau}]^*. \tag{6}$$

As in the other decays, kinematics are generated according to phase space and the accept–reject is based on the probability calculated as in Eq. (4), replacing D^* with τ.

3. Decay models

The computation of the spin density matrices and the decay probability in the above example are performed by the EvtGen framework. Decay models, which implement a single node in a decay tree, must only specify the decay amplitude for each combination of mother and daughter spin states. A simple example is $D^* \to D\pi$, whose amplitude is $A_{\lambda_{D^*}}^{D^* \to D\pi} \propto \varepsilon_{\lambda_{D^*}} p_\pi$, where $\varepsilon_{\lambda_{D^*}}$ is the polarization of the D^* and p_π is the momentum of the π. In this case, three amplitudes must be provided, one for each basis state of λ_{D^*}.

Many decay models are currently maintained in the EvtGen package. These include generic models, models for specific CP violating channels, Dalitz decay models (Fig. 2), mixing, and semileptonic form factor models. Generic models handle either decays to specific sets of spin states, such as a pseudoscalar to a vector plus pseudoscalar, or more inclusive models, such as a helicity basis or partial wave model. In these models, a parent particle is decayed to specified daughters, both with arbitrary spins, according to a specified combination of specified partial wave or helicity basis states.

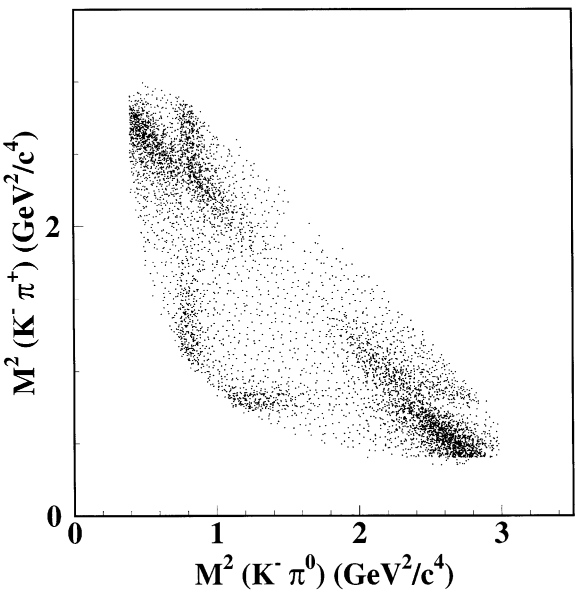

Fig. 2. The Dalitz distribution for the decay $D \to K^-\pi^+\pi^0$ from EvtGen. The resonance parameters used are measurements from the CLEO Collaboration (Ref. [2]).

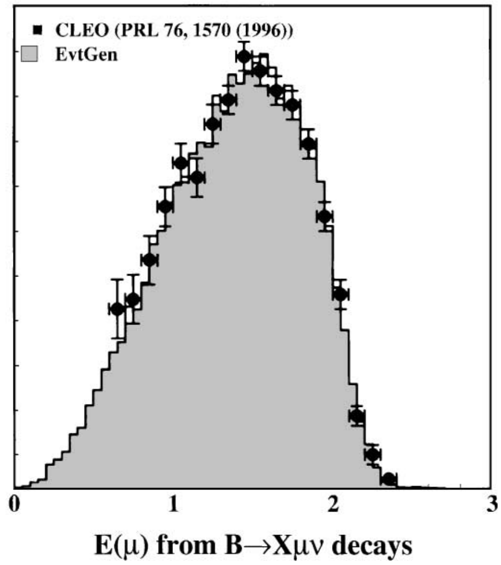

Fig. 3. The inclusive lepton energy distribution from $B \to Xl\nu$ decay. The points are from Ref. [4] and the histogram shows the EvtGen prediction. The inclusive branching fraction has been tuned to agree with the PDG2000 [5] value.

Two body CP violating decays, including scalar–scalar, scalar–vector, scalar–tensor, and vector–vector final states, have been implemented. Model parameters include the value of the CKM angle and the amplitude for B^0 or $\bar{B}^0$ mesons to decay to the specified final state. For vector–vector final states, such as $B \to J/\psi K^*$, transversity amplitudes are specified. See Fig. 1.

Semileptonic models include form-factor implementations for specific theoretical models [3] or more generic models, where the user specifies parameters for the form factors. For example, there is a model for $B \to D^* l\nu$ based on HQET with parameters for ρ^2, R_1, and R_2. Fig. 3 shows the $B \to Xl\nu$ lepton energy spectrum from EvtGen.

4. Outlook

The EvtGen generator has been designed to correctly simulate the angular and time-dependent distributions in sequential B decays. To implement

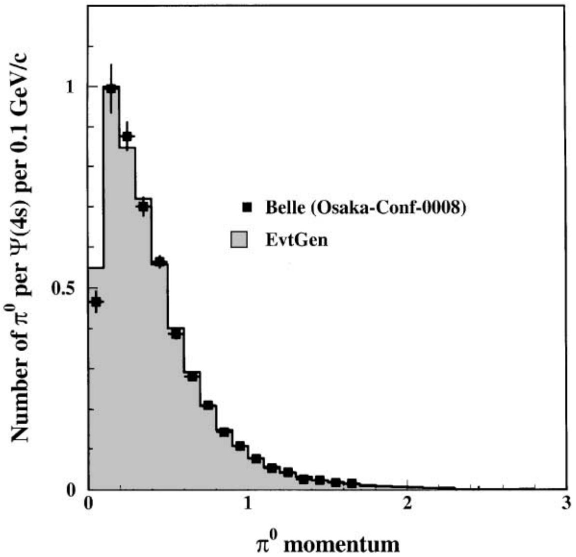

Fig. 4. The inclusive π^0 energy distribution from B decays. The points are from Ref. [7] and the histogram shows the EvtGen simulation. The error bars are statistical only.

a decay chain, only the decay amplitude for each step in the chain is needed. This design is efficient and leads to reusable decay models.

The BABAR experiment uses the EvtGen package to for generic B and D decays in its Monte Carlo production. Approximately 60% of B decays are specified in the decay table and handled by EvtGen models. The remainder are handled by an interface to JETSET [6]. Figs. 3 and 4 illustrate the agreement between experimental data and EvtGen. In addition, the charged track multiplicity agrees with the measurements in Ref. [8]. With new data soon to be available, we hope that the decay table can be further improved.

The development of models within EvtGen has focused on B decays at the Υ(4S). There are several additional issues in the generation of B_s and b baryon decays:

- A non-zero value of $\Delta\Gamma$ must be considered in B_s decays. While B_s mixing is treated correctly by EvtGen, we have not yet found a generic solution for the large number of common final states of the B_s system. Exclusive models for important CP violating final states (as described above) are sufficient in the B_d system, but not for developing a generic decay table for the B_s.
- PYTHIA/JETSET interactions. The program used for production should not affect the outcome of EvtGen decays. When PYTHIA is used to produce a B meson, which is passed to EvtGen to decay, the PYTHIA initialization can affect EvtGen due to the usage of JETSET for generic decays.

The EvtGen package provides a framework for efficient simulation of complex decay chains, where only the amplitude of each step in the decay chain must be specified. A complete decay table for B_d physics has been developed, and shows good agreement with experimental measurements in many distribution. The implementation of additional features needed for the simulation of B physics at hadronic machines is ongoing.

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