Chapter 4

Monte Carlo

The response of an individual spectrometer component (e.g., SMD plane or Čerenkov counter) upon passage of an energetic charged particle through its volume is in general well understood through first principles, direct measurement, or some combination of the two. Tracing the life history of a particle through multiple detector components, from its birth in, say, the target until its decay or escape further downstream, is considerably more complicated. Multiple scattering and energy loss due to interactions with the detector material must be considered. In addition, the effective efficiencies of the detector components are typically impacted by the presence of other particles in the event.

In this analysis, charm particle signals are extracted from raw data by reconstructing their charged decay products (see Chapter 5 for a description of this process). Absolute normalization of cross-sections requires that the correlated detector responses from each particle in the event (charm decay products as well as particles from the "underlying" event) be linked to yield an overall average detection efficiency or "acceptance" (see Section 7.1 for a precise definition). The final acceptance is an average over several distributions that can only be defined probabilistically; in addition to the variable detector responses alluded to above, we must average over the momentum and lifetime distributions of the produced charm particle, the Dalitz distribution of its decay products, and relevant distributions characterizing the underlying event. This last aspect of the problem is especially difficult: final-state particles and intermediate-state partons are connected by hadronization, a process which cannot be treated perturbatively.

Acceptance is essentially given by a tremendously complicated n-dimensional integral, one for which an expression cannot even be written down, much less evaluated. The standard solution to this dilemma is to create a computer model of the complex interaction between an event containing a given charm decay and the spectrometer. By generating[1] N events and determining what fraction of them make it into the final invariant mass plot (Monte Carlo integration), the acceptance is calculable to a precision which depends on N.

This Monte Carlo (MC) simulation can be divided into two parts: event generation and digitization. In the first, the complete history of an event containing a specified charm decay is spelled out step-by-step, leading to a "truth table" representation of the event: a list of the 4-momenta and positions of all produced particles. In the digitizer, the characteristics of the individual detector components allow conversion of the truth table into the raw data format used in the actual E769 data set. From this point forward, this "fake" data is analyzed like real data, except that MC events are weighted to incorporate effects that are not simulated with sufficient accuracy (or at all) in the MC program itself. These weighting procedures are detailed in Section 7.2. Event generation and digitization are described more fully in Sections 4.1 and 4.2, respectively.

4.1 Event generation

The first task of the E769 event generator is to create a $c\bar{c}$ pair. Although the program is set up to simulate collisions of different beam hadrons (at 250 GeV momentum) on the nuclear target, in practice only π^- is used. For target protons and neutrons (beam pions), momentum distributions of the constituent partons are given by the PDFs of Duke and Owens (Owens) [24]. LO QCD amplitudes for gg fusion and $q\bar{q}$ annihilation are used to generate the momentum distribution of the produced

[1] At each "decision point" in the event, a random number generator is used to pick a value from the relevant probability distribution.

charm pair. To LO, charm correlations are trivial: the c and $\bar{c}$ quarks are created back-to-back in the partonic center-of-mass frame. The underlying partonic event is modelled using the Lund software package FRITIOF 1.3 [14]. FRITIOF is designed to simulate hadron-nucleus collisions; it allows multiple soft interactions to occur between spectator quarks, taking into account the effects of the nuclear environment.

Hadronization of the quarks into particles is modelled using the Lund program JETSET 6.3, which implements a string fragmentation model [13]. Those particles which are unstable are decayed assuming 1990 Particle Data Group (PDG) average lifetime values and branching fractions.[2] At this point, it is not crucial that the MC simulation return charm particle momentum distributions; as detailed in Section 7.2.3, MC events are weighted in x_F and p_T in order to bring in line generated and measured distributions in these variables.[3] Lifetime weighting (Section 7.2.4) is also used to update assumed charm lifetimes to 1994 PDG[4] values.

The final phase of event generation is simulation of the interactions of the particles with the detector itself. In addition to propagating charged particles through the magnetic fields of M1 and M2, the MC program generates Čerenkov photons in C1 and C2 and electromagnetic and hadronic showers in the calorimeters. The effects of multiple scattering and secondary interactions on particle trajectories are also modelled. The resulting truth table list of particle momenta and locations (birth and death) is input to the digitization stage of the MC program.

A separate set of MC events must be generated for each charm decay mode of interest. For each of the decay modes $D^+ \to K\pi\pi$, $D^0 \to K\pi$, and $D_s \to \phi\pi$, 150K MC events were generated; 200K $D_s \to K^*K$ MC events were generated. The two D_s decays, however, were not specified completely; the secondary decays $\phi \to K^+K^-$ and $K^* \to K^-\pi^+$ were not forced during event generation. As a result, the numbers of useful MC events for the D_s modes are reduced to the number of generated events

[2]The mode to which the charm particle decays is fixed by the user.

[3]In nonresonant three-body decays, the Dalitz distributions of charm decay products depend on the decay model used by the MC generator. In studying D^+ and D_s decays to three pions, however, the E691 collaboration determined that, for these modes, acceptance of the TPL spectrometer is "uniform" over the 3π Dalitz plot [15].

[4]Full citations for the 1990 and 1994 editions of the PDG Review of Particle Properties are given in [34] and [35], respectively.

multiplied by the Lund branching fractions of their secondary decays, 49.5% and 66.7% respectively. No separate D^* MC was generated; that fraction of the generated D^0's produced from D^* decays (about 30%) is used.

4.2 Digitization

In the digitization phase of the MC, the fully-specified event of the truth table is translated into the language of the experiment itself: responses in thousands of SMD, DC, PWC, and PMT channels. The presence or absence of a "hit" in a particular channel is a function not only of the track geometry but also of the efficiency of the relevant detector component. In order to simulate a real raw data event accurately, detector contingencies such as hot or dead channels and the presence of random noise hits must also be taken into account. After measuring each of the aforementioned aspects of spectrometer performance, the corresponding parameters in the digitizer program are tuned to bring about the same result. However, in two important experimental areas (Čerenkov counters and transverse-energy triggers), the MC simulation is not sufficient to return reliable estimates of average efficiency. In these cases, therefore, MC event weighting is implemented, as described in Sections 7.2.2 and 7.2.1, respectively.

Experimental conditions did not remain constant over the entire period of data collection. The most important changes were to the average SMD and DC plane efficiencies; as the average beam flux increased in the second half of the experimental running (i.e., positive beam polarity), these efficiencies decreased. Therefore, average efficiencies measured in these separate time periods are each used to create a corresponding version of the digitizer code. These are called the "negative" and "positive" digitizers; the difference in the overall efficiencies returned by these two versions is significant, as seen in the geometric acceptances compiled in Table 7.5.

Due to the problematic history of two DC planes, specifically the u and v views of assembly 2 of D1 (D12u and D12v), the positive "default" digitizer as originally written had to be modified. About halfway through the positive running (by flux), these two planes became inoperative, reducing their average efficiencies from 85-90%

down to zero. This condition persisted for some period thereafter (corresponding to roughly 15% of the positive flux); then the v view plane was fixed, returning it to its previous efficiency. The u view plane remained down for the rest of the experiment. These three operating conditions are labelled "on/on", "off/off", and "on/off", respectively.

The default digitizer did not use correct average efficiencies for these two planes. It was determined, however, that even upon correction of these average efficiencies, the "modified" digitizer does not return accurate values for acceptance (the $D^+ \to K\pi\pi$ mode was used in these studies); the dependence of the acceptance on these plane efficiencies is sufficiently non-linear to require separate digitizers be used for each operating period. In other words, the flux-weighted average of "on/on", "off/off", and "on/off" acceptances is found *not* to equal (within statistics) the acceptance returned by the modified digitizer, which used flux-weighted average D12u and D12v plane efficiencies. Moreover, these three operating regions overlap quite differently with the two positive run regions used in the analysis (see Chapter 6 for the definitions of the four E769 run regions). Threefold digitization of positive beam events for all decay modes in this analysis would have been prohibitive. The results obtained with the $D^+ \to K\pi\pi$ mode are therefore used to calculate correction factors for the acceptances returned by the positive digitizer for the other modes; these factors are described and given in Section 7.2.5.

Generated events for all decay modes undergo both negative and positive digitization. In the case of the $D^+ \to K\pi\pi$ and $D^0 \to K\pi$, the modified positive digitizer is used; MC events for the D_s modes, however, are digitized using the default positive digitizer. As described above, the positive running $D^+ \to K\pi\pi$ acceptances are calculated using three separate digitizers; the acceptance returned by the modified digitizer is used only to obtain correction factors for the other decay modes.