Computing in High Energy and Nuclear Physics, 24-28 March 2003, La Jolla, California

SLAC-PUB-9862 *

Using Geant4 in the *BABAR* Simulation

D.H. Wright, D. Aston, M.L. Kocian, H. Marsiske
SLAC, Stanford, CA 94025, USA
W.S Lockman, D.C. Williams
University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, CA 95064, USA
A.W. Weidemann, J.R. Wilson
University of South Carolina, Columbia, SC 29208, USA
T.B. Moore
University of Massachusetts, Amherst, MA 01003, USA
A.J. Lyon
University of Manchester, Manchester M13 9PL, United Kingdom
on behalf of the *BABAR* Computing Group

BABAR was the first large experiment to incorporate Geant4 into its detector simulation. Since July 2001, 1.5×10^9 *BABAR* events have been produced using this simulation. In a typical $e^+e^- \rightarrow \Upsilon(4s) \rightarrow B^0\overline{B^0}$ event, between 30 and 60 tracks are produced in the generator and propagated through the detector, using decay, electromagnetic and hadronic processes provided by the Geant4 toolkit. The material model of the detector is very detailed and a special particle transportation module was developed so that minute features (on the few micron scale) would be sampled in the propagation without sacrificing performance. The propagation phase for such an event requires 5 CPU seconds on an 866 MHz processor. Execution speeds for other *BABAR* event types will also be presented. Validation of simulated events with *BABAR* data is ongoing, and results of Monte Carlo/data comparisons will be shown. A discussion of the design of the simulation code, how the Geant4 toolkit is used, and ongoing efforts to improve the agreement between data and Monte Carlo will also be presented.

1. OVERVIEW OF THE *BABAR* SIMULATION

1.1. The Detector

The primary physics goal of the *BABAR* experiment is the study of CP violation in the $B^0\overline{B^0}$ system. $B^0\overline{B^0}$ events are produced by the decay of $\Upsilon(4s)$ resonances which are produced in e^+e^- collisions. Some of the B^0s decay into CP eigenstates such as $J/\Psi K^0_s$, and the subsequent decays of the J/Ψ and K^0_s are detected and reconstructed. A typical event will produce between 30 and 60 tracks, and typical energies of the final state decay products are:

- lepton pairs: $0.3 < p < 2.3$ GeV/c
- π^0 : $0.3 < E < 2.5$ GeV
- γ : $0.1 < E < 4.5$ GeV .

Hadronic final states are also important because charged πs and Ks interact in the beam pipe and calorimeters. Typical hadron momenta are

- p < 4 GeV/c, with most < 1 GeV/c .

Background events such as Bhabha scattering produce the highest energy tracks, with $p_{e^-}, p_{e^+} < 9$ GeV/c .

The *BABAR* detector was built to collect final state tracks with high efficiency and precision, and to allow the reconstruction of B^0 decays into a wide range of exclusive final states with low background. The detector was also designed to operate at the high luminosities provided by the PEP-II accelerator.

The detector consists of a silicon vertex tracker (SVT) which surrounds the e^+e^- interaction point and provides vertex determination at the 10 μm level. Surrounding the SVT is a He-isobutane drift chamber (DCH) for the measurement of charged tracks. Outside the DCH is a detector of internally-reflected Cherenkov radiation (DRC), constructed of quartz bars and used for particle identification (PID). Outside the DRC is a CsI electromagnetic calorimeter (EMC) designed to contain showers from charged and neutral tracks. A muon tracker and instrumented flux return (IFR), built of alternating layers of iron and resistive plate chamber (RPC) detectors, surrounds all the interior detectors.

1.2. The Simulation

The simulation was designed to satisfy four main requirements. It must:

- run within the *BABAR* Framework [1]. All the tracking, physics and hit-scoring performed by Geant4 [2] is implemented as a Framework module. Because the Framework is responsible for run and event control, Geant4 must therefore relinquish this duty.
- work with existing event generators, detector response codes and reconstruction codes. At the time Geant4 became available, *BABAR* detector response and reconstruction codes were essentially complete and many event generation codes were already available.

* *Work supported in part by Department of Energy contract DE--AC03--76SF00515.*

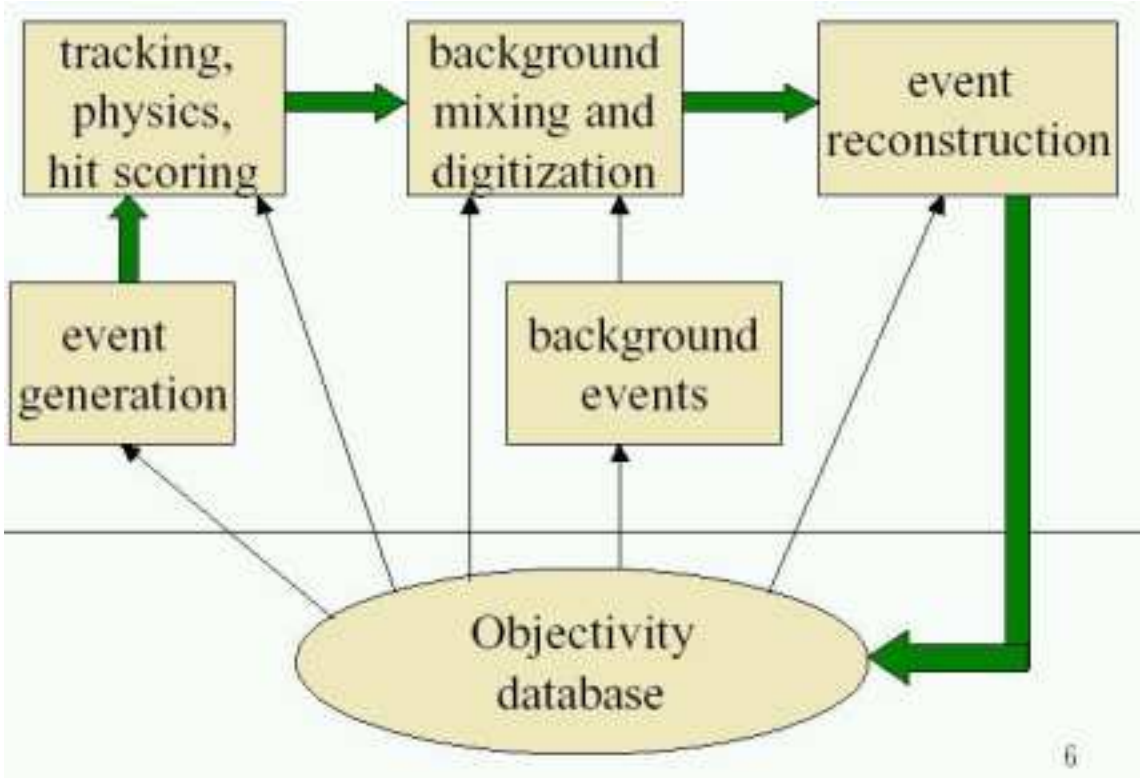

Figure 1: Simple diagram of the *BABAR* simulation. Boxes above the horizontal line represent *BABAR* Framework modules, and the wide arrows depict the event flow through the Framework. Narrow arrows indicate the retrieval of information from the database.

- use the Objectivity database [3] for persistence.
- be detailed, yet fast enough to keep up with high-luminosity event production.

A simple diagram of the main functions and operation of the resulting simulation is shown in Fig. 1.

The Geant4 toolkit is used extensively in the simulation. The detector geometry is built with Geant4 simple volumes and Boolean operations. As mentioned above, Geant4 is also responsible for hit-scoring and provides all the physics processes. These include the decay, standard electromagnetic and low-energy hadronic ($E < 10GeV$) processes. Some features provided by Geant4, such as detector response code and persistence, are not used. The default Geant4 transportation/navigation process is also not used. It employs a general Runge-Kutta stepper which was found to be too slow and not precise enough for the many thin volumes in the *BABAR* simulation. Taking advantage of the slowly varying magnetic field in the *BABAR* detector, a specialized stepper was developed to meet these needs. This stepper determines how far a particle can travel before the field deviates from a locally constant value. Perfect helices are then used to propagate the particle over that distance. If that distance is large, many small steps are avoided.

2. VALIDATION

Before being put into production, the *BABAR*Geant4 simulation was subjected to a series of validation tests focusing on

- verifying the detector material model,
- electromagnetic processes,
- hadronic processes,
- tracking, resolution and reconstruction,
- particle ID,
- performance and robustness.

Since October 2000, 20 million simulated events of several types have been produced for these tests. They include generic $B^0\overline{B^0}$, Bhabha scattering and dimuon events, among others. Comparsion of these events with data has allowed a refinement of the detector material model to the point that no further changes are necessary. Understanding of particle identification and electromagnetic processes is also believed to be well in hand, although validation in these areas continues. However, additional validation is required for the hadronic processes.

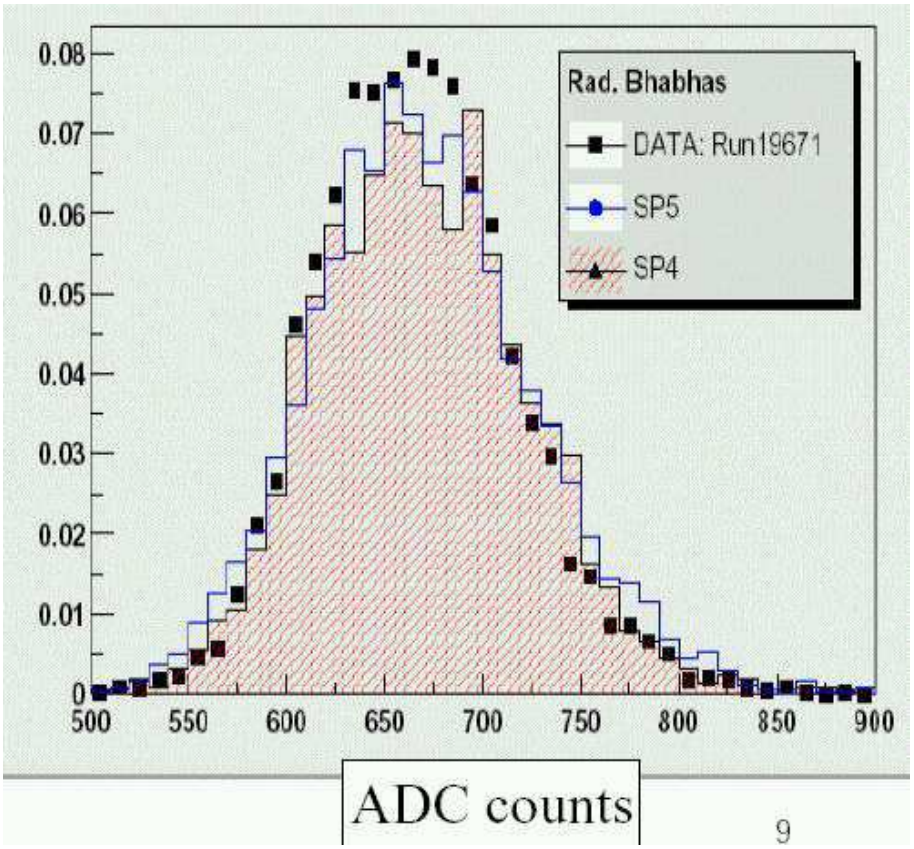

Figure 2: dE/dx for minimum ionizing electrons and positrons from Bhabha scattering. The histograms represent two different simulations of the energy loss in the drift chamber gas. The points are from a *BABAR* data run. The histograms are normalized to the number of events in the data run.

2.1. Electromagnetic Process Validation

The *BABAR* simulation uses the following Geant4 electromagnetic processes

- for photons: photo-electric effect, Compton scattering and e^+e^- pair production;
- for electrons and positrons: electron ionization, electron bremsstrahlung and e^+ annihilation;
- for muons: μ ionization, μ bremsstrahlung and e^+e^- pair production by muons;
- for hadrons: hadron ionization;
- for all charged particles: multiple scattering.

One of the most basic validation tests is to reproduce the expected energy loss due to ionization processes. In this case, minimum ionizing electrons and positrons from radiative Bhabha scattering were examined in the He-Isobutane gas of the drift chamber. Simulated events are compared to data from a recent run in Fig. 2, where it is seen that both the shape and normalization of the dE/dx distributions are in agreement to within 15%. This indicates that fluctuations in the energy loss are reasonably well-reproduced. More importantly, the mean values of dE/dx agree to within 1%.

It is also important to study electromagnetic showers in the CsI calorimeter. Measuring shower shapes provides a cumulative test of the photon and electron processes listed above. Radiative Bhabha scattering was used to examine the distribution of azimuthal and lateral shower parameters as a function of electron/positron energy. Fig. 3 shows the lateral distribution parameter (LAT). With the exception of a few energy bins, distributions of both of these parameters were found to show good agreement between data and simulation for all electron and positron energies up to 4 GeV.

2.2. Reconstruction

The comparison of reconstructed events from data and simulation provides a stringent validation test. In *BABAR* an accurate reconstruction of the π^0 mass and width provides a test of many detector performance features, including tracking, energy scale, shower development, shower containment and detector response.

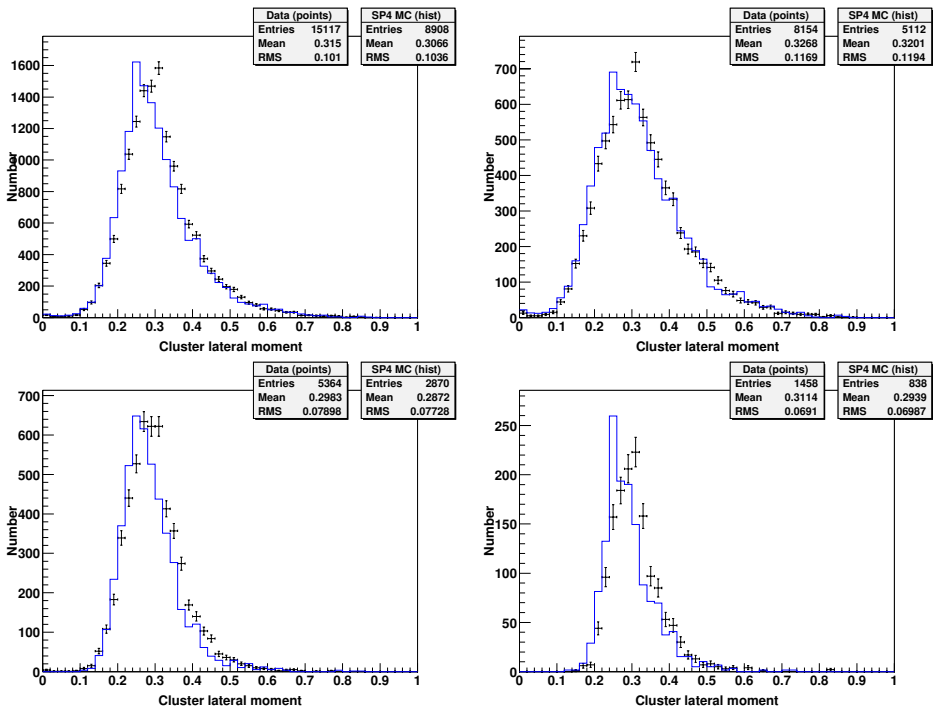

Figure 3: Distribution of the LAT parameter as a function of incident electron or positron energy. Top left: all energies; top right: 0 to 1 GeV; bottom left: 1 to 3 GeV; bottom right: 3 to 5 GeV. The histograms represent a simulated sample of Bhabha events and the points are taken from *BABAR* data.

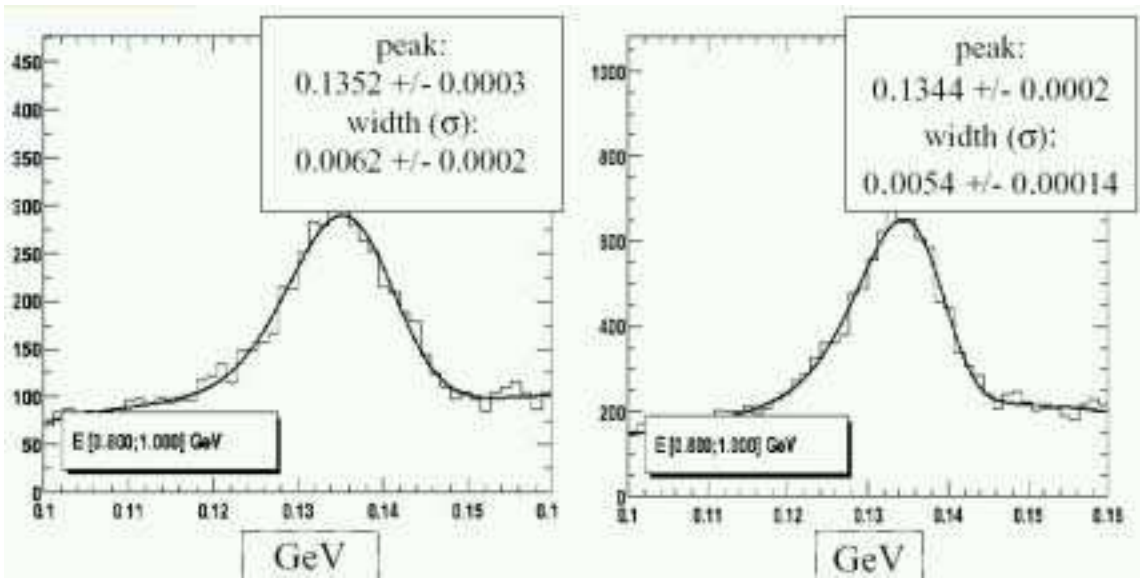

Figure 4: π^0 mass reconstruction for data (left) and simulation (right). Histograms represent the reconstructed samples and the curves are fits to the samples. The total pion energy is between 0.8 and 1.0 GeV. The fitted mass and width values are stable over the range 0.3 - 2.1 GeV.

In $B^0\overline{B^0}$ events, the decay $K_s \rightarrow \pi^0\pi^0$ provides π^0s with energies between 0.3 and 2.1 GeV. Fig. 4 shows the reconstructed mass for π^0s with total energies between 0.8 and 1.0 GeV. For both data and simulated samples the mass is close to the expected value, which indicates that tracking, energy scale and shower containment are well-understood. The widths, however, are significantly different and point to problems in shower development or detector response. Since it is believed that the shower development is under-

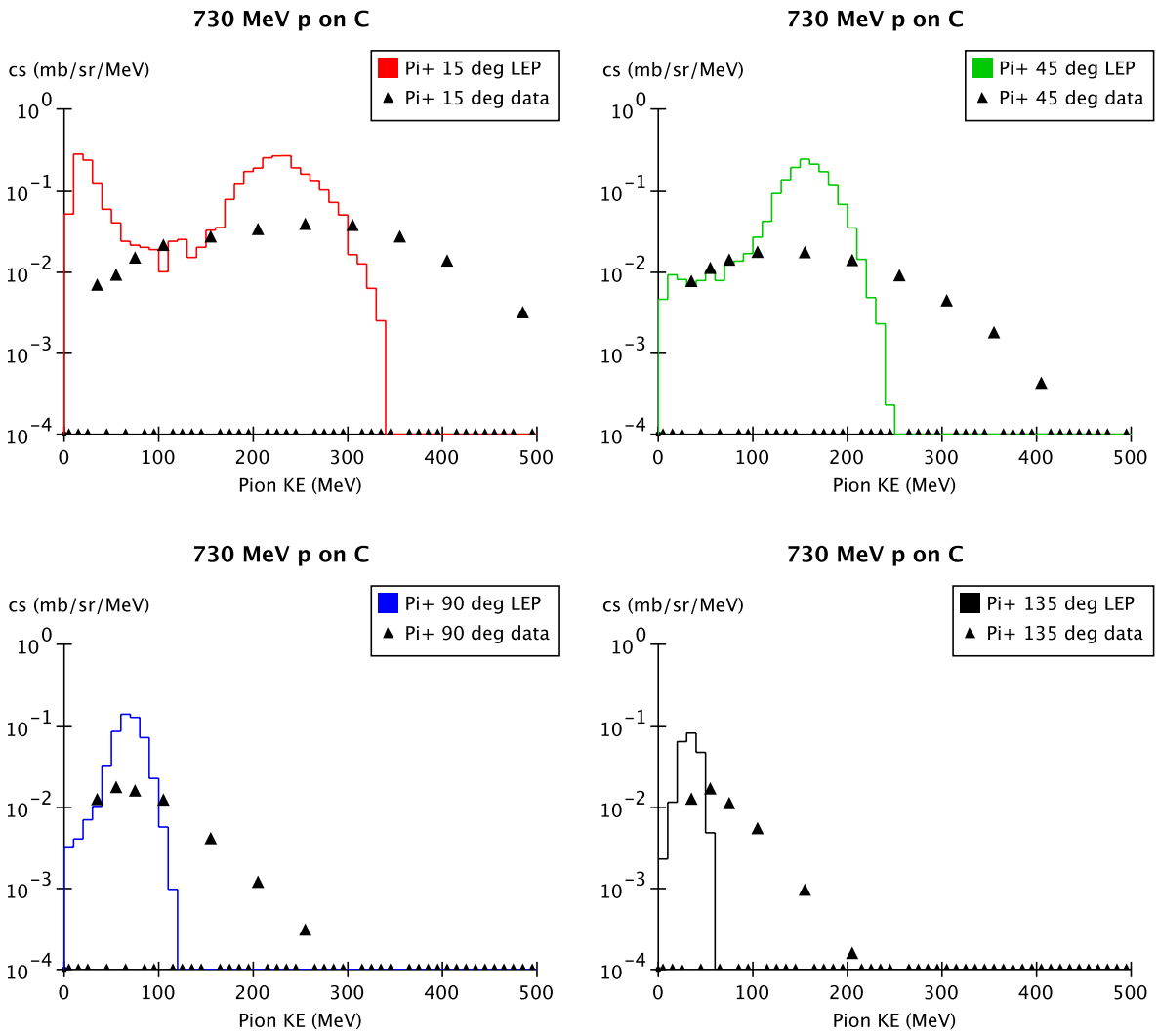

Figure 5: Cross section for π^+ production from 730 MeV protons on carbon at 15°, 45°, 90° and 135°. Histogram: prediction of the Low Energy Parameterized (LEP) model in Geant4. Data points are from Ref. [5].

stood, detector response should be examined in future validation tests.

2.3. Hadronic Process Validation

The electromagnetic processes of hadron ionization and multiple scattering are of primary importance in the propagation of long-lived hadrons through the detector. Hadronic interactions are still important, however, because scattering from nuclei and the production of hadronic secondaries in the dense material of the EMC and IFR can affect the energy deposition.

Hadronic interactions in the *BABAR* simulation are currently handled by the so-called "low energy parameterized", or LEP, model. This is a re-engineered version of the GHEISHA code [4], which has been tuned for hadrons with incident energies below 20 GeV. Even so, it is not particularly appropriate at *BABAR* hadron energies which are typically below 1 GeV. This is demonstrated in Fig. 5 which shows the pion production cross section for 730 MeV protons on a thin carbon target. Large, qualitative differences between the LEP model and data are evident. Recently, however, better models, such as the Bertini cascade [6], have become available. As shown in Fig. 6, much better agreement with the data is achieved at all angles. A current limitation of this model is that it is not valid for kaons.

The hadronic process validation in *BABAR* has so far concentrated on the comparison of results from various models to published data from other experiments in which the incident hadron energies are in the *BABAR* range. Validations using *BABAR* data are just beginning.

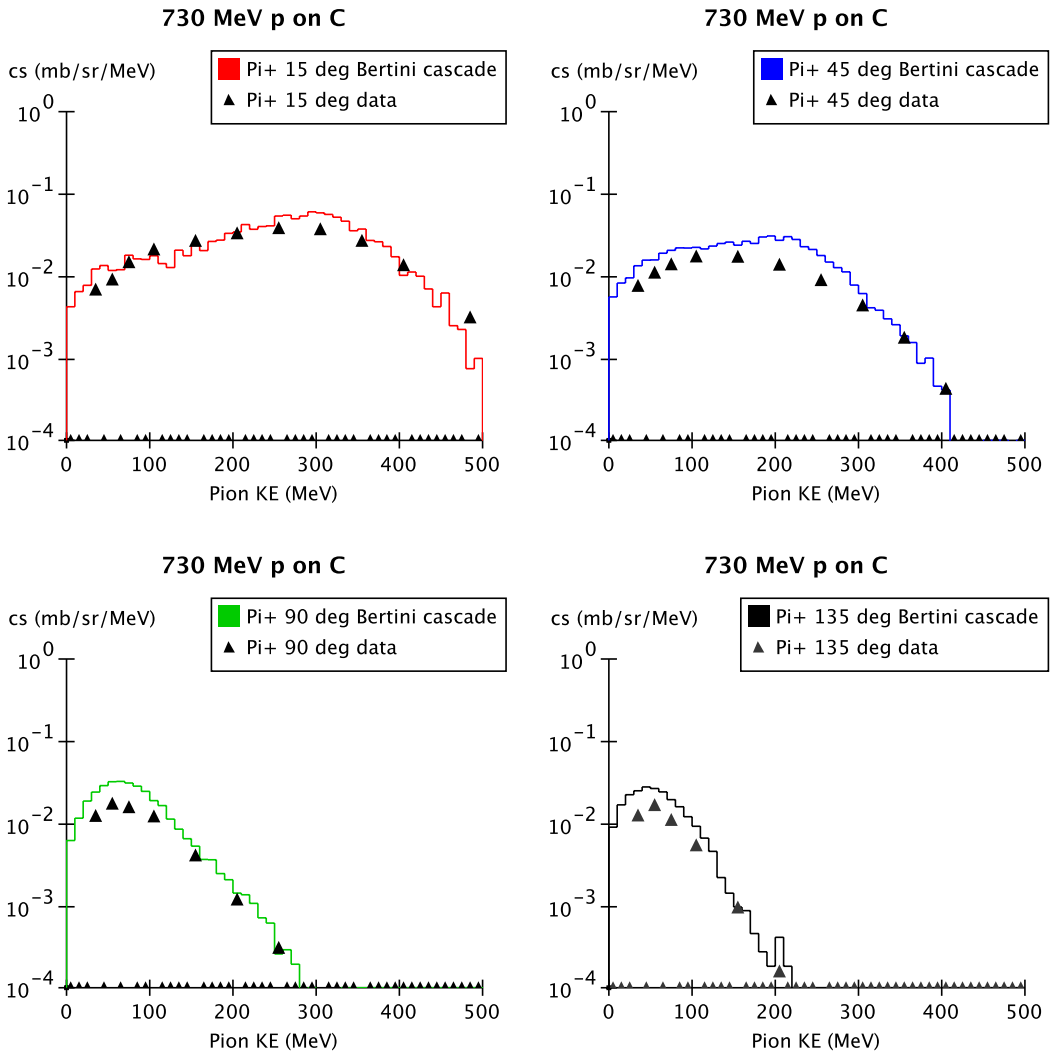

Figure 6: Cross section for π^+ production from 730 MeV protons on carbon at 15°, 45°, 90° and 135°. Histogram: prediction of the Bertini cascade model in Geant4. Data points are from Ref. [5].

While *BABAR* is certainly not optimized for hadronic physics validation, two regions of the detector are useful for tests. The beam pipe support tube is a cylinder of carbon fiber and the inner wall of the drift chamber is a cylinder of beryllium. Tests are just beginning which use these regions as thin targets for incident hadrons.

Table I Execution Time for *BABAR* Events

Event type	**CPU time (sec)**
$B0\overline{B0}$	5.0
bhabha	7.0
dimuon	0.6

3. PERFORMANCE

The simulation stage of *BABAR* event production includes event generation, tracking and hit-scoring. A Pentium III 866 MHz PC currently requires 5.0 seconds on average to simulate a $B^0\overline{B}^0$ event. Average execution times for other *BABAR* event types are given in Table I.

Up to now, relatively little effort has been devoted to optimizing performance because validation was the main concern. However, some increase in speed is expected with

- improvements in *BABAR* geometry models,
- improvements in the Geant4 electromagnetic processes, and

- fine tuning of the secondary particle production cuts.

On the other hand, the improved hadronic models are much more CPU-intensive than the currently used LEP model, and will cause some slowdown.

After the production of 20 million validation events, many of the bugs in both the *BABAR* simulation code and in Geant4 have been shaken out. To date, *BABAR* simulation production has generated more than 1.5 billion events of all types at roughly 20 production sites in North America and Europe, with a failure rate of less than one event per million in the simulation stage.

4. CONCLUSION

BABAR is the first large experiment to develop and use a Geant4-based simulation. A detailed detector model has been developed using the Geant4 geometry, and both electromagnetic and hadronic interactions are implemented with Geant4 physics processes. The simulation was designed to run within the *BABAR* Framework application.

Comparisons of simulated event samples and *BABAR* data indicate that the electromagnetic processes perform largely as expected in the few GeV energy range. Validation tests of the LEP hadronic model show that more detailed models will be required before good agreement with data can be achieved.

The *BABAR* simulation has proven to be robust, with 1.5 billion events generated so far at a low failure rate. Future efforts will concentrate on improving the overall speed of the simulation.

5. ACKNOWLEDGMENTS

This work was supported by Department of Energy contract DE-AC03-76SF00515.

References

[1] http://www.slac.stanford.edu/BFROOT/www/doc/workbook/framework1/framework1.html
[2] S.Agostinelli et al., CERN-IT-20020003, KEK Preprint 2002-85, SLAC-PUB-9350; submitted to Nuclear Instruments and Methods NIM A, 2003.
[3] Objectivity database, Release 7.0, November, 2001.
[4] H. Fesefeldt, The Simulation of Hadronic Showers, Physics and Applications Report PITHA 85/02, Aachen 1985;
Geant4 Physics Reference Manual, Chapter 15. http://geant4.web.cern.ch/geant4/G4UsersDocuments/UsersGuides/PhysicsReferenceManual
[5] D.R.F. Cochran et al., Phys. Rev. D6, 3085 (1972).
[6] Geant4 Physics Reference Manual, Chapter 19. http://geant4.web.cern.ch/geant4/G4UsersDocuments/UsersGuides/PhysicsReferenceManual