Simulation of a High Energy Detector
for Undergraduate Physics Students

Gideon Bella and Erez Etzion

School of Physics and Astronomy,
Raymond and Beverly Sackler Faculty of Exact Sciences,
Tel Aviv University,
Tel Aviv 69778, ISRAEL

1994

Abstract

A simulation program suitable for study of high energy particle detectors is described in this article. It can demonstrate some theoretical phenomena, but mainly gives the opportunity to practice a modern experimental work. The using the GEANT3 package and running on a workstation, has been program, at the Tel Aviv University for the undergraduate advanced laboratory developed course.

Introduction

The research of elementary particles is currently held with giant machines, which accelerate particle beams in very long paths up to several tens of kilometers until they reach the region where they interact with a target, or with a crossing particle beam. The interaction point is surrounded by arrays of computer-controlled detectors, which collect the process details. There are only few laboratories of this type in the world and therefore it is very difficult to expose this important research field to undergraduate students.

In this article we introduce a method for studying the basic tools of experimental high energy physics with the use of a detector simulation program, demonstrating the particle detection methods. The detector simulation program uses the GEANT3 package [1] developed at CERN. GEANT provides tools to allow the user to define the geometrical parameters of his detector using standard shapes. It also deals with tracking of particles through this detector, including all the relevant physics processes such as energy loss, multiple scattering, radiation, interactions and decays. With a simple workstation, or an Xterminal connected to a workstation, the student can analyze the data in a similar way to real data processing. The work reported here has the following goals:

- Demonstration of some basic concepts of high energy physics

- Presentation of the structure and the operation principle of high energy detectors such as magnetic spectrometers and electromagnetic (EM) calorimeters

- Analysis of elementary particle interactions and decays using the laws of classical mechanics and special relativity

- Practice of detector calibration techniques

- Identification of elementary particles and measurement of their characteristic features such as momentum, energy, mass, life time and decay branching ratios

- Investigation of the detector characteristics such as resolution, efficiencies and background levels

The program is used since 1993 in a laboratory course for third year undergraduate physics students at the Tel Aviv University. A student spends 4 sessions of about 6 hours each in the laboratory, after some preliminary reading. No other equipment aside from the workstation or graphical terminal is needed.

Setup of the Simulated Experiment

The simulated detector has a default structure, which can be modified by the user. It was designed using the main elements contained in most present high energy detectors. It consists, as shown in fig. 1, of magnetic spectrometer, EM calorimeter, iron yoke and muon detector [2]. Each event starts with a generation of a neutral or charged particle injected into the detector. For particles traversing sensitive areas, the program stores "hits" which contain information to allow the subsequent simulation of the detector response. At the end of the event processing, the program uses the digitized hits to simulate the data produced by the detector for subsequent reconstruction and analysis. The data is reconstructed into some useful parameters (see below). The output of each event consists of lists of the raw data and the reconstructed parameters. In addition there is a graphical display as shown in fig. 1.

The coordinate system of the detector is indicated in the figure. The x-axis is horizontal, and the incoming particles are injected within a small random angle around this axis. The z-axis is the direction of the magnetic field.

The *Magnetic Spectrometer* consists of 10 drift chambers inside a uniform magnetic field. A chamber dimensions are $3 \times 62 \times 60$ cm^3 and the distance between two chambers is 8 cm. It consists of two planes of 5 anode and 6 cathode wires made of tungsten with a thickness of 100 µm and 30 µm respectively. The wires are strung parallel to the z-axis on a frame made of G10 material. It is filled with a mixture of Argon (88%), Methane (10%) and Isobutane (2%). Two sheets of mylar, 0.2 mm thick, close the chamber. A measurement of the drift time on the sense wires allows the y position, needed for the curvature determination, to be calculated rather accurately. Measuring the charge division between the two ends of the sense wires allows a relatively coarse z coordinate measurement. The "measured" hit positions are displayed in the graphical output as crosses. The program to reconstruct tracks using a pattern recognition algorithm uses their coordinates. The hits associated with each track are fitted to a helix and the helix parameters, along with their error matrix are printed on the screen. The program also tries to fit for secondary vertices.

The function of the *Electromagnetic Calorimeter* is to detect and measure the energy and location of electrons, positrons and photons. It is simulated as an array of 650 (26×25) crystals positioned 10 cm behind the magnetic spectrometer. The crystals are made of a BGO ($Bi_4 Ge_3 O_{12}$) scintillating material. Each crystal is 2×2 cm^2 wide and 22.4 cm long corresponding to about 20 radiation lengths (X_0). The information provided from this part is the pulse height, which presents the energy deposited in each crystal. The hits are represented on a front view of the detector as circles. The size of each circle is proportional to the signal height in the corresponding crystal. An initial stage of reconstruction is done by the program, which attempts to associate the hit crystals into clusters. The output consists of the clusters locations and pulse heights.

The *Iron Magnet Return Yoke* is 100 cm long, designed also to stop the hadrons by hadronic interactions. It is placed 10 cm behind the EM calorimeter. Two additional drift chambers similar to those of the magnetic spectrometer serve as a *Muon Detector*. These chambers are placed behind the iron in order to measure the position of all charged particles that have traversed the iron absorber. The probability of a pion not interacting before reaching this part is very small.

The Operational Procedure

For using the simulator, the user has to operate an interactive program on an X-terminal or a workstation. The program was written in the Fortran language on a Unix workstation, and is very easy to use. With a small list of self-explained commands, the student can utilize all the simulator facilities.

Before injecting a particle into the detector, the student can select the type of the particle to be injected and its initial momentum. For each event the graphical display consists of the detector including the hits in the drift chambers and the calorimeter crystals. The display is organized in three projections (see fig. 1): a side view on the x-y plane, a top view on the x-z plane, and a front view of the EM calorimeter on the y-z plane. Lists of all hits in the three sensitive detectors are given in the operation window including the results of the fits to tracks and vertices and the clusters found in the calorimeter.

During the first session the student is required to calibrate the experimental equipment He has first to calculate the magnetic field in the spectrometer by using the known momenta of the incoming particles and the measured curvatures. Then he performs the calibration of the calorimeter, calculating the relation between the pulse height and the energy of the electron or photon stopping in the calorimeter.
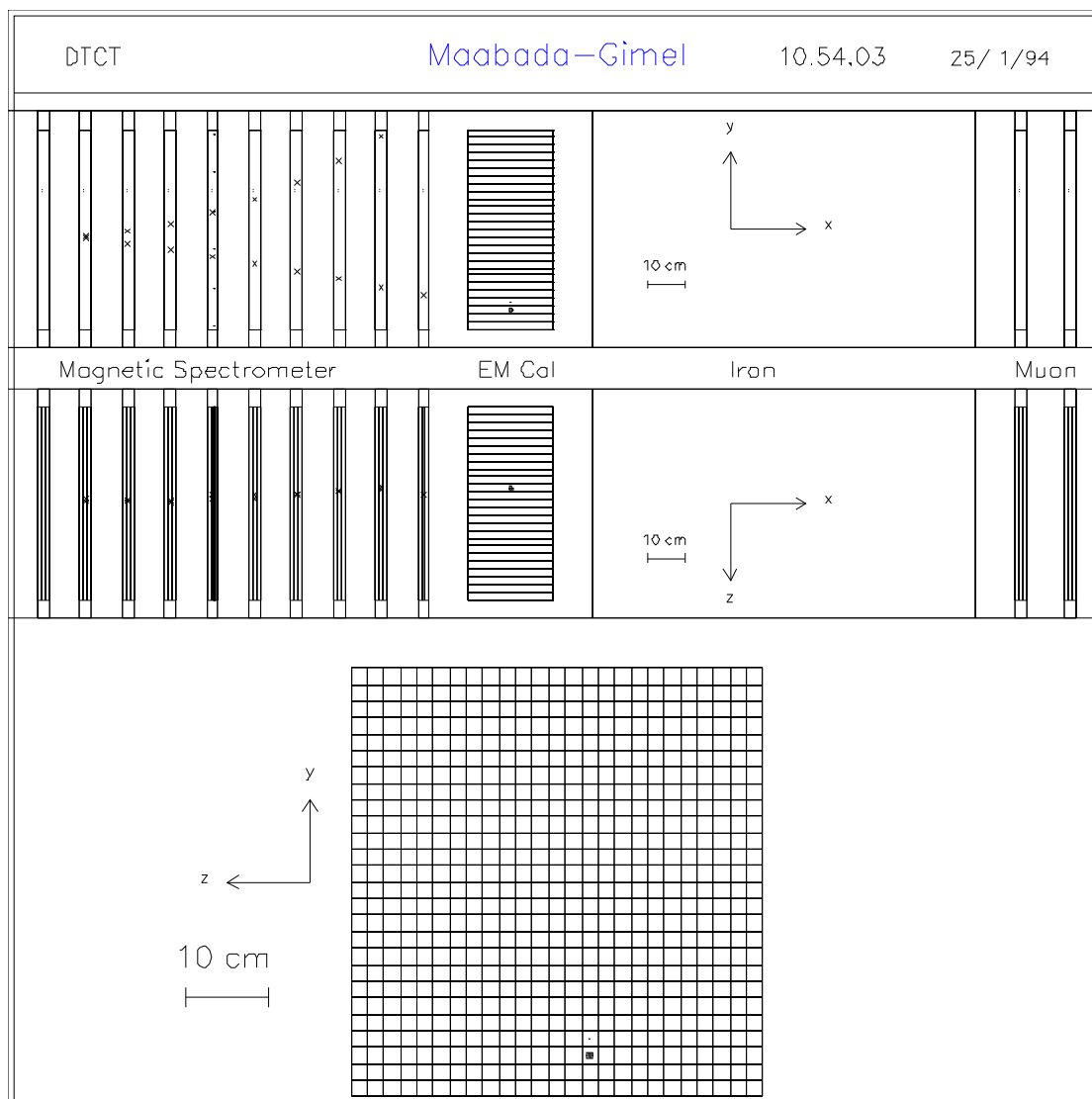

Figure 1: Example of an event (Λ decays into proton and π) on the graphical display. It consists of three projections: a side view on the x-y plane, a top view on the xz plane, and a front view of the EM calorimeter on the y-z plane. The particles are injected in the positive x direction, and the magnetic field is parallel to the z coordinate. The display includes the axis orientation, and scales for each projection. The crosses stand for the hits in the drift chambers (the magnetic spectrometer, or the muon chambers). The size of the circles in the EM calorimeter is proportional to the pulse height in the corresponding BGO crystal.

In the following sessions the student is asked to analyze series of events in order to study the interactions of the tested particles in various energy scales. He has to study the particle identification criteria using the detector outputs, and to measure energies, mass, lifetime and branching ratios of particles decaying inside the detector. Additional study that can be held with this apparatus is the subdetector responses,

namely their resolution, efficiencies and their ability to distinguish between the various particle types. To this end, the student may also control some parameters of the subdetectors such as:

- The magnetic field

- The length of the iron

- The length of the BGO crystals

- The calorimeter granularity (number of BGO crystals in the array)

In the last session the program selects the injected particles and their momenta randomly. The student is then required to use all the knowledge he has gained during the previous sessions to identify the injected particles and measure their characteristic parameters.

Summary

An introduction to modern high energy experimental physics is given by this simulation program of a simple elementary particle experiment. This program can be used for pedagogical presentations in the first course on elementary particles, and for students in the laboratory to practice working with modern techniques of particle physics.

References

1. R. Brun, F. Bruyant and A.C. McPherson, GEANT3, CERN DD/EE/841.

2. A detailed introduction to detectors can be found in:

   - T. Ferbel (ed.), Experimental Techniques in High Energy Physics, AddisonWelsley, Menlo Park, CA 1987.

   - K. Kleinknecht, Detectors for Particle Radiation,Cambridge University Press, 1987.

   - R.C. Frenow, Introduction to Experimental Particle Physics, Cambridge University Press, 1986.