ELSEVIER

Nuclear Physics B (Proc. Suppl.) 125 (2003) 60–68

NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS
www.elsevier.com/locate/npe

The Geant4 Toolkit: simulation capabilities and application results

M. G. Pia[a] (on behalf of the Geant4 Collaboration)

[a]INFN Sezione di Genova, Via Dodecaneso 33, 16146 Genova, Italy

Simulation plays an increasingly important role in the design and operation of high energy physics detectors. Geant4 is a toolkit for the simulation of the passage of particles through matter, developed according to advanced software engineering; it addresses the challenging requirements of new-generation experiments, as well as of other application domains. An overview of Geant4 simulation capabilities is presented.

1. The challenge of detector simulation

The simulation for high energy physics experiments faces an unprecedented challenge, determined by the complexity of the physics under study, of the detectors of the new generation and of the environments where they operate.

The complexity of the physics of the LHC experiments, related to the high machine luminosity and the significant QCD background, is the source of their enormous computational requirements, also involving the production of very high statistics of simulated events: robustness for large scale production, efficient performance and the capability to operate in a distributed computing environment are essential features for the simulation software. The complex physics environment represents a challenge for the simulation of a wide variety of particle interactions associated with multiple detection techniques (semiconductor and gaseous tracking detectors, electromagnetic and hadronic calorimeters, particle identification). The complex software environment of a large scale experiment requires a flexible integration of the simulation components within a framework.

The simulation for astroparticle experiments is also characterised by challenging requirements. These experiments embrace a wide spectrum of scientific programmes, from neutrino physics and dark matter searches to astrophysics measurements on satellites to cosmic ray physics: therefore their simulation requires a set of physics models covering an extended energy range, from the order of few eV to the PeV scale, together with a precise description of the background environment, either in space or underground. Moreover, for some of these experiments, like, for instance, those on satellites, simulation is often mission critical: therefore it should provide not only powerful functionality, but also high reliability, and it should conform to rigorous software engineering standards.

Together with the variety of requirements from application in the high energy physics domain, a growing interest in simulation is represented by the need to share functionalities across diverse fields: for instance, models to extend the simulation of electromagnetic interactions down to low energies [1] ($< 1keV$), motivated originally from medical physics applications [2], have been successfully applied to astroparticle experiments [3], and are of interest for the precise simulation of high energy physics detectors.

The intrinsic complexity of the simulation for the new generation of experiments is further complicated by the rapidly changing computing environment. The evolution of hardware, operating systems and software over the long time scale of LHC operation, as well as likely changes in the requirements of the experiments, imply that the software being built now must be able to anticipate changes.

2. The Geant4 Simulation Toolkit

The Geant4 Toolkit [4] has been developed in response to the requirements of the new genera-

doi:10.1016/S0920-5632(03)02222-9

tion of high energy physics experiments; its current applications also cover astrophysics, nuclear physics, medical physics, space science and radiation background studies.

The strategy adopted by Geant4 to cope with the challenges of the new experimental and software environment consists of the adoption of a rigorous approach to software engineering. Advanced software techniques are adopted in response to the requirements of functionality, modularity, extensibility and openness. Process assessments making reference to the ISO/IEC SPICE Model [7] are performed periodically.

The life-cycle model adopted for most domains in Geant4 is both iterative and incremental [5]. Problem domain and use-case analysis led to definition of the user requirements during the initial phase of the project, which have been systematically reviewed and updated following the ESA PSS-05 software engineering standard [6].

The adoption of object oriented technology makes the software open to extension and evolution, and facilitates its maintenance. The toolkit approach allows both the specialisation of components and their easy integration into the frameworks of the experiments, providing the flexibility to customise the software by means of alternative, interchangeable implementations. The architecture of the toolkit, resulting from the analysis of the problem domain, is shown in the class category diagram in Figure 6.

As part of the software process, the development of effective tests and testing procedures represents a significant effort in Geant4, also involving a dedicated Testing and Quality Assurance working group. Unit and system testing are critical to ensuring the integrity and correctness of the Geant4 code; various quality assurance tools, together with the adoption of coding guidelines, are also utilised to build quality in from the start.

In order to achieve maintainable software and ensure its quality, the adoption of standards, wherever possible, is promoted in Geant4.

The Geant4 software was originally developed by RD44 [8], a world-wide collaboration of physicists and computer scientists. Since 1999 the production service, user support and development of Geant4 have been managed by the international Geant4 Collaboration.

The first Geant4 production version was published in December 1998. Since then new versions have been regularly released, extending and improving the functionalities of the Toolkit.

3. Overview of Geant4 functionality

3.1. Geant4 kernel

The Geant4 kernel manages of runs, events and tracking; it enables the simulation of complex configurations, such as event pile-up. The Event package provides an abstract interface to external physics event generators for the creation of the primary particles. The kernel handles the tracking of particles taking account of the geometry, fields and physics processes. Geant4 Tracking steers the invocation of processes: it is completely general and common to all processes (including transportation) for any particle type, thus allowing great flexibility in the implementation of a variety of physics processes, as well as openness to further extensions. The management of particles is based on Particle Data Group [9] compliant definitions and data, including their decay processes and modes.

3.2. The description of the experimental set-up

The Geant4 Geometry package provides tools to describe the detailed geometrical structure of a detector; it also handles the equation of motion solvers in different fields and geometrical boundary conditions for the propagation of particles. An ISO STEP compliant solid modeller allows the exchange of models from CAD systems. Multiple solid representations, such as Constructive Solid Geometry or Boundary Represented Solids are available: these allow to model complex solids as defined by their bounding surfaces, which can be planes, second order surfaces or higher order B-spline surfaces; this variety matches those described by the ISO STEP standard for CAD systems. Boolean operations on solids (union, intersection and subtraction) are supported.

The Geant4 Materials package allows the description materials consisting of a single element or a composition of elements, which in turn can consist of a single isotope or a mixture of isotopes.

The Hits and Digi domains provide the functionality to reproduce the readout structure of a detector and its electronic response, independently from the geometry used for tracking particles.

3.3. Interactive facilities

Geant4 Visualisation provides the capability to visualise detector geometry, particle trajectories, tracking steps, hits and text. Its design, based on abstract interfaces, makes Geant4 independent from any particular graphics system; at the same time it allows multiple implementations of drivers to interface the simulation with a variety of such systems.

The User Interface domain adopts a similar approach, allowing the usage of a variety of user interfaces, from simple command-line driven ones to sophisticated GUIs.

While the Geant4 Toolkit does not directly provide any analysis facility, data analysis plays a significant role in connection with simulation, both in the testing and validation process and in the user applications. To avoid any internal dependence on any specific analysis tool, Geant4 supports the adoption of Abstract Interfaces for Data Analysis (AIDA [10]), which are used internally in the physics tests and in the advanced examples distributed together with the toolkit.

Figure 1 shows an example of a complex detector geometry modelled with Geant4, with the visualisation of tracks resulting from particle interactions.

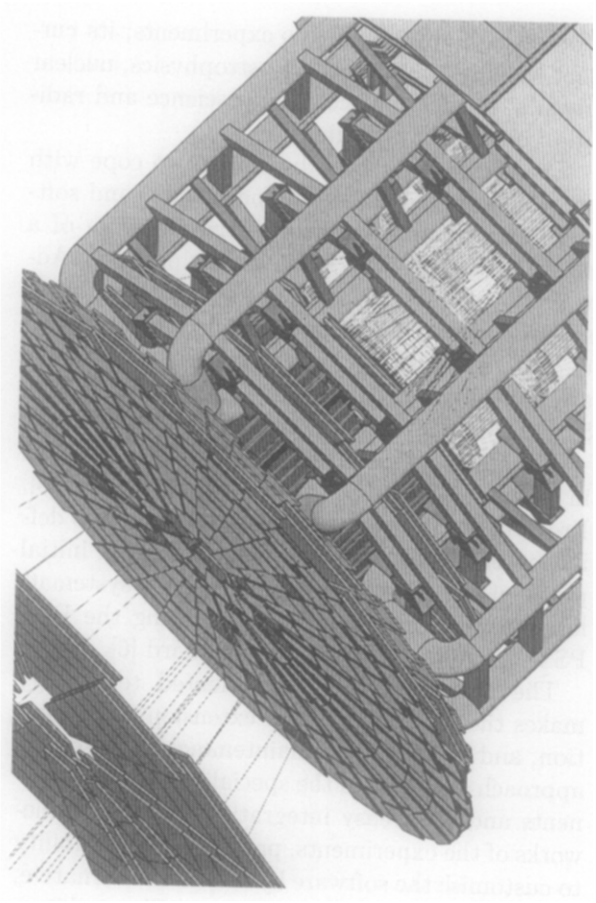

Figure 1. A complex detector geometry is modelled with Geant4; the tracks resulting from particle interactions in the detector are visualised.

3.4. Other features

A Fast Parameterisation facility is integrated with the full simulation, allowing independent and simplified detector descriptions and direct production of hits.

The Persistency category provides an interface for storing and retrieving run, event, hits, digits and geometry information in and from ODMG-compliant object databases.

Extensive possibilities for interaction with the Geant4 system are offered to the user via a set of dedicated user-action classes.

4. Geant4 physics

One of the most important goals of Geant4 consists in making the design and implementation of the physics open and transparent. The Geant4 design makes physics data, models and assumptions transparently accessible to the user, rather than hard-coded in black-box packages, thus improving the verification and the reliability of simulation results. It also exposes the granular implementation of the physics, each component of which can be inspected at source code level.

Thanks to object oriented technology, a variety of alternative or complementary physics models can be provided for the same physical process, with openness to further extensions.

4.1. Electromagnetic physics

Geant4 electromagnetic physics [11] provides a variety of implementations of electron, positron, photon, charged hadron and ion interactions. Photon processes include Compton and Rayleigh scattering, γ-conversion and the photoelectric effect. Electron/positron processes include bremsstrahlung, ionisation, positron annihilation and synchrotron radiation. The ionisation and energy loss are available for hadrons and ions as well. A significant feature is an algorithm [12] which can generate low energy δ-rays only near the boundaries of volumes, which can lead to an improved performance while keeping the quality of physics.

The multiple scattering process handles all charged particles, computing the mean path length correction and the mean lateral displacement. Figure 2 shows how well the multiple scattering model implemented in Geant4 performs with respect to experimental data [13] and to the model in Geant3 [14].

A shower profile resulting from Geant4 *standard* electromagnetic physics processes is compared to Geant3 and experimental data [15] in Figure 3. Standard electromagnetic processes average the effects of the shell structure of atoms and cannot expected to simulate details below 1 keV.

To complement the *standard* electromagnetic processes, Low energy extensions [1] are implemented, down to 250 eV for photons and electrons, and to the energy corresponding to the ionisation potential of the material for hadrons and ions. In addition, fluorescence and Auger electron emission from excited atoms is generated.

The implementation of the processes for electrons and photons is based on the exploitation of evaluated data libraries (EPDL97 [16], EEDL [17] and EADL [18]), that provide data for the determination of cross-sections and the sampling of the final state. A simulation of the energy distribution of electrons transmitted through an Al foil,

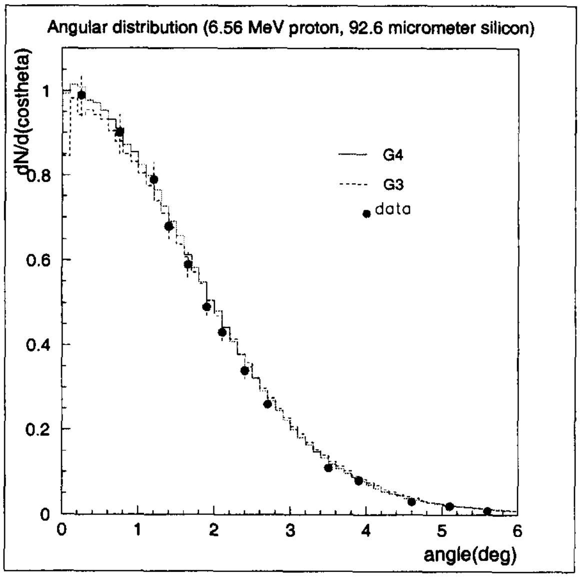

Figure 2. Multiple scattering of 6.56 MeV protons by 92.6 μm of silicon: comparison of Geant4, Geant3 and experimental data from [13]

based on Geant4 *low energy* package, is compared with experimental data [19] in figure 4; it shows evidence of shell effects.

A *low energy* process is available in Geant4 to handle the ionisation by hadrons and ions [1]. It implements different models depending on the energy range and the particle charge: in the high energy ($E > 2\ MeV$) domain the Bethe-Bloch formula and in the low energy one ($E < 1\ keV$ for protons) the free electron gas model are applied respectively; in the intermediate energy range parameterised models based on experimental data from the Ziegler [20] and ICRU [22] reviews are implemented; corrections due to the molecular structure of materials [21] and to the effect of the nuclear stopping power [22] are taken into account. Figure 5 shows the simulation of energy deposition of a 175 MeV proton beam in water with Geant4 *low energy* package, compared to experimental data from [24].

Specialised *low energy* processes are available

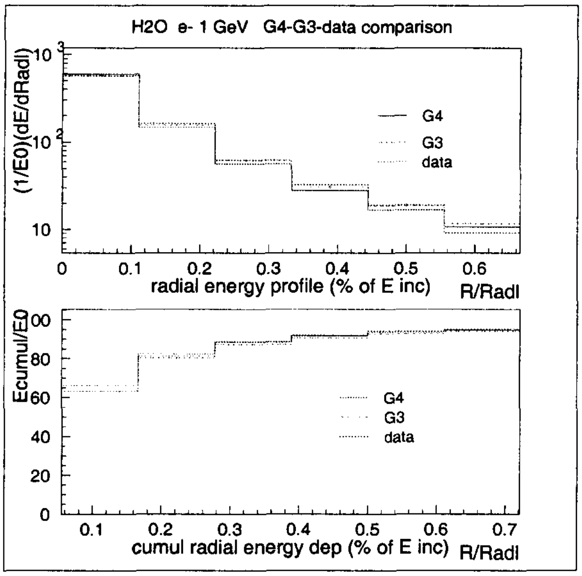

Figure 3. Shower profile of 1 GeV electrons in water: comparison of Geant4, Geant3 and experimental data from [15].

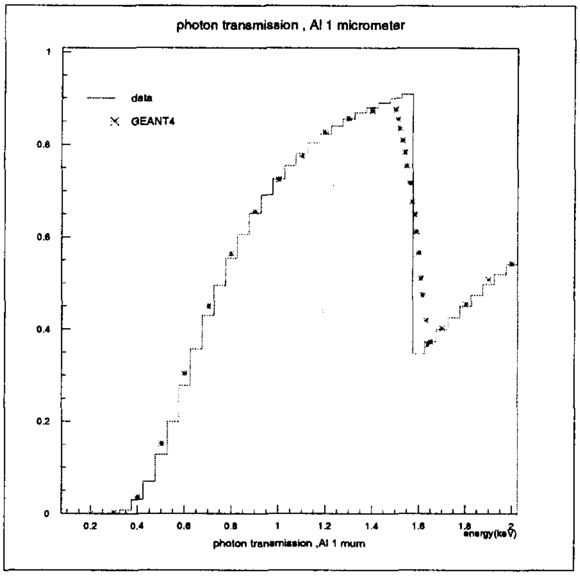

Figure 4. Energy distribution of electrons transmitted through an Al foil, simulated with Geant4 *low energy* package and compared to experimental data from [19].

to handle polarisation [25] and charge dependent hadron ionisation [26].

The validity range of all the muon processes, based on theoretical models, scales up to the thousand PeV region, allowing the simulation of ultra-high energy and cosmic ray physics.

Geant4 can also handle the optics of scintillation and Cherenkov detectors and their associated light guides, including a set of dedicated processes for optical photons: refraction and reflection at medium boundaries, absorption and Rayleigh scattering.

4.2. Hadronic physics

The Geant4 Toolkit provides a rich set of physics models for the simulation of hadronic interactions [27], covering the energy ranges from thermal for neutron cross-sections and interactions, through 7 TeV (in the laboratory) for LHC experiments, to even higher for cosmic ray physics. The complex nature of hadronic showers and the particular needs of the experiment require the user to be able easily to vary the models for particular particles and materials depending on the situation.

The hadronic models in Geant4 follow three different basic approaches: data-driven, parameterisation-driven and theory-driven modelling; in the overall framework they offer both complementary and alternative options. Data driven modelling is used in the context of neutron transport, photon evaporation, absorption at rest, calculation of inclusive cross-sections, and isotope production. Parameterisations and extrapolations of cross-sections and interactions are widely used in the full range of hadronic shower energies, and for all kinds of reactions. Models in Geant4 adopting this paradigm are based on those available from Geant3, predominantly GHEISHA [28]. They include induced fission, capture, and elastic scattering, as well as inelastic

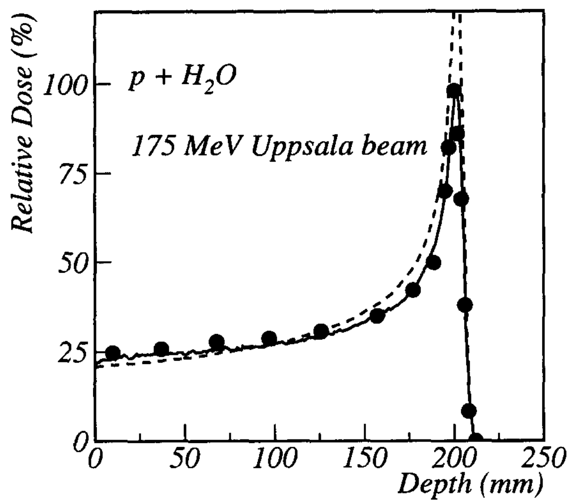

Figure 5. The energy deposition of a 175 MeV proton beam in water: the points represent data from [24], the dashed histogram is Geant4 simulation including *low energy* electromagnetic interactions only, the solid histograms also includes the simulation of hadronic interactions.

final state production. Theory based modelling is the basic approach in many models currently available, or under development, in Geant4. A variety of models address different energy ranges and computing performance needs. Figure 7 shows the branchings into two-particle final states in proton-antiproton annihilation predicted by the Chiral Invariant Phase Space (CHIPS) decay model [29–31].

5. Support facilities

The wide user community of Geant4, encompassing users in diverse application domains and characterized by a wide level of expertise, requires a significant investment in the support processes and related facilities.

The Geant4 Toolkit provides an extensive documentation, including installation, user and reference guides, and a range of training kits.

An ample set of examples is distributed together with the toolkit; the advanced ones consist of full scale applications, demonstrating the simulation capabilities of Geant4 in the context of high energy physics experiments, astrophysics and medical physics.

6. Conclusions

Geant4 represents a versatile and comprehensive toolkit for simulation applications that involve the interaction and passage of particles through matter. It can handle complex geometries efficiently, and provides models for a wide range of physics processes based on theory, data or parameterisation. It has demonstrated that rigorous software engineering practices can be profitably applied to the production of a coherent and maintainable software product, even with the fast-changing and open-ended requirements presented by physics research. The adoption of an object-oriented design allows it to be easily extended to meet further requirements of the users.

Geant4 has been adopted by several experiments, space science and medical physics projects as the basis for their simulations. Such a wide domain of applications offers also the opportunity for technology transfer [2] from high energy physics to other fields. Various results of application of Geant4 are presented in other contributions to these proceedings [32–36], as well as a preliminary demonstration of integration in a distributed computing environment [37].

REFERENCES

1. S. Chauvie et al., Geant4 low energy electromagnetic physics, Proceedings of CHEP2001, Beijing, 2001.
2. S. Chauvie et al., G. Cosmo, From HEP computing to biomedical research and vice-versa: technology transfer and application results, Proceedings of CHEP2001, Beijing, 2001.
3. P. Nieminen et al., Low-Energy Proton Effects on Detectors on X-Ray Astronomy Missions, Proceedings of Computing in High Energy and Nuclear Physics CHEP2000 Padova, 2000.

4. S. Agostinelli et al., GEANT4: a simulation toolkit, SLAC-PUB-9350.
5. G. Booch, Object-Oriented Analysis and Design with Applications, The Benjamin/Cummings Publishing Co., 1994, ISBN 0-805-35340-2.
6. ESA, Guide to User Requirements Definition Phase, ESA PSS-05, 1994.
7. ISO/IEC Joint Technical Committee 1 (JTC1), ISO/IEC DTR 15504 Software Process Assessment.
8. RD44 Collaboration, Status Report, CERN/LHCC-98-44, 1998.
9. Review of Particle Physics, The European Physical Journal C, 15 (2000).
10. G. Barrand et al., Abstract Interfaces for Data Analysis: Component Architecture for Data Analysis Tools, Proceedings of Computing in High Energy Physics CHEP2001, Beijing, 2001.
11. S. Chauvie et al., Geant4 electromagnetic physics, Proceedings of the Monte Carlo 2000 Conference, Springer, 2000.
12. J. Apostolakis et al., CERN-OPEN-99-299 (1999)
13. J. Vincour and P. Bem, Nucl. Instr. Meth. 148 (1978) 399.
14. R. Brun, F. Bruyant, A.C. McPherson, M. Maire, P. Zanarini, CERN Data Handling Division, DD/EE/84–1, 1987.
15. J. H. Crannel, Phys. Rev. 184 (1969) 2.
16. D. Cullen et al., EPDL97, the Evaluated Photon Data Library, 97 version, UCRL–50400, Vol. 6, Rev. 5 (997.
17. S.T. Perkins et al., Tables and Graphs of Electron-Interaction Cross Sections from 10 eV to 100 GeV Derived from the LLNL Evaluated Electron Data Library (EEDL), UCRL-50400 Vol. 31, 1997.
18. S.T. Perkins et al., Tables and Graphs of Atomic Subshell and Relaxation Data Derived from the LLNL Evaluated Atomic Data Library (EADL), Z=1-100, UCRL-50400 Vol. 30, 1997.
19. J. Baro et al., NIM B 100 (1995) 31.
20. H.H. Andersen and J.F. Ziegler, The Stopping and Ranges of Ions in Matter. Vol.3, Pergamon Press, 1977.
21. J.F. Ziegler, J.P. Biersack, U. Littmark, The Stopping and Ranges of Ions in Solids. Vol.1, Pergamon Press, 1985.
22. ICRU (A. Allisy et al), Stopping Powers and Ranges for Protons and Alpha Particles, ICRU Report 49, 1993.
23. J.F. Ziegler and J.M. Manoyan, Nucl. Instr. and Meth. B35 (1988) 215.
24. S. N. Boon, Dosimetry and quality control of scanning proton beams, Thesis, University of Groningen, 1998.
25. G.O. Depaola et al., A new Monte Carlo method for Compton scattering by polarised gamma rays, in preparation.
26. S. Chauvie et al., Geant4 simulation of the energy loss of slow negatively charged hadrons, in preparation.
27. J.P. Wellisch, Hadronic shower models in Geant4: the frameworks, Comp. Phys. Comm. No. 140 (2001) 65.
28. H. C. Fesefeldt, Simulation of hadronic showers, physics and application, Technical report PITHA 85–02, 1985.
29. P. V. Degtyarenko et al., Eur. Phys. J. A 8 (2000) 217.
30. P. V. Degtyarenko et al., Eur. Phys. J. A 9 (2000) 411.
31. P. V. Degtyarenko et al., Eur. Phys. J. A 9 (2000) 421.
32. A. Howard et al., Simulation and analysis for astroparticle experiments, these Proceedings.
33. G. Barca et al., A powerful simulation tool for medical physics applications: Geant4, these Proceedings.
34. G. Santin, GATE (Geant4 Application for Tomographic Emission): a PET/SPECT general-purpose simulation platform, these Proceedings.
35. G. Santin, New Geant4 based simulation tools for space radiation shielding and effects analysis, these Proceedings.
36. S. Chauvie et al., Dose calculation for radiotherapic treatment on a distributed computing environment, these Proceedings.
37. J. Moscicki et al., Parallel Geant4 simulation in medical and space science applications, these Proceedings.

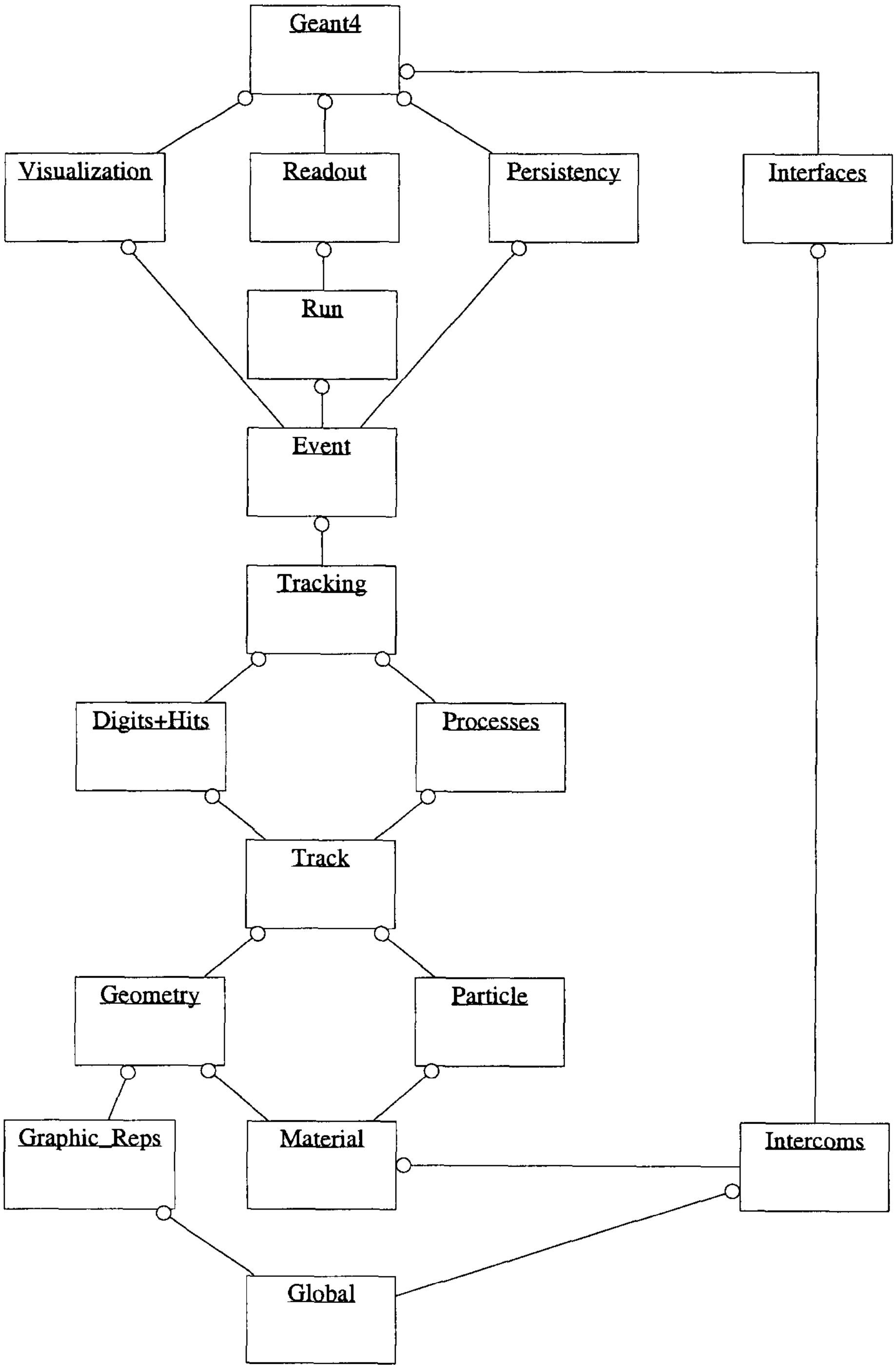

Figure 6. The top level class category diagram of the Geant4 Toolkit. The open circle on the joining lines represents a using relationship; the category at the circle end uses the adjoined category.

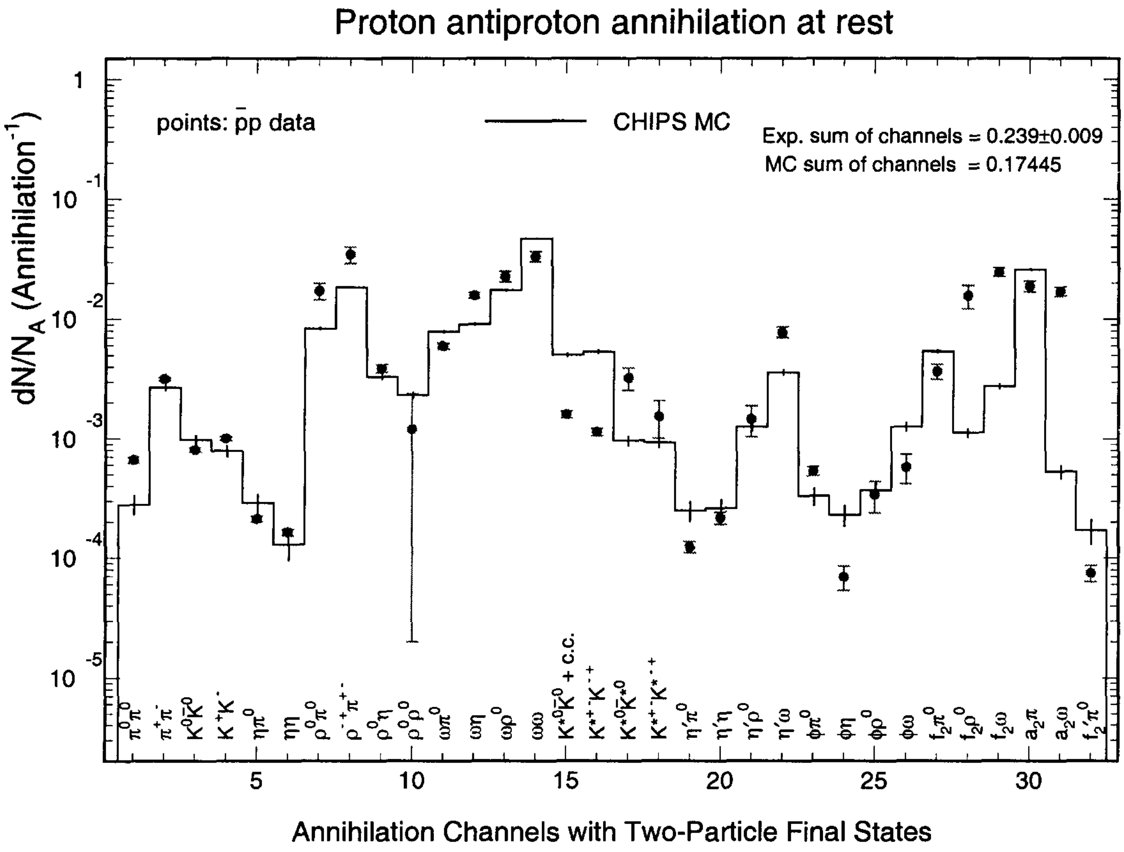

Figure 7. Comparison of the branchings in two-particle final states in proton anti-proton annihilation with the predictions of the CHIPS model.