Geant4 status and applications

John Apostolakis, CERN
for Geant4 collaboration
Contents

- Geant4’s kernel
- EM Physics processes
  - Comparisons with data
- Hadronic framework, models
- Utilization of Geant4
- Status and plans
**Geant 4**

- Detector simulation tool-kit for HEP
  - offers alternatives, allows for tailoring
- Software Engineering and OO technology
  - provide the method for building, maintaining it.
- **Requirements** from:
  - LHC
  - heavy ions, CP violation, cosmic rays
  - medical and space science applications
- **World-wide collaboration**
Geant4 Capabilities

- Powerful structure and kernel
  - tracking, stacks, geometry, hits, ...
- Extensive & transparent physics models
  - electromagnetic, hadronic, ...
- Framework for fast simulation
- Additional capabilities/interfaces
  - persistency, visualization, ...
Geant4 kernel

- Creates & manages runs, events, tracks
  - A run is configuration of geometry, physics & event generator.
- Allows particles to be prioritized easily at no cost
  - 3 default stacks, postponement.
- Tracking is general (unique)
  - Physics lists can be tailored for different use cases
- Enables the creation of user defined hits
  - Able to handle pile-up.
- Versatile volumes and navigator for Geometry
Propagating in a field

Charged particles follow paths that approximate their curved trajectories in an electromagnetic field.

- It is possible to tailor
  - the accuracy of the splitting of the curve into linear segments,
  - the accuracy in intersecting each volume boundaries.

- These can be set now to different values for a single volume or for a hierarchy.
Electromagnetic processes

Initial goal (RD44) was to create EM physics at least at equivalent to Geant-3

New concepts emerged and were implemented:

- Distinction between production threshold and tracking cut
- Expressing production cuts in terms of range instead of energy
- Creating an effective range from the distance to the nearest boundary
Electromagnetic processes

Processes new to Geant4

- Multiple Scattering: new model
  - includes lateral displacement (new)
  - no path length restriction

- New process: Transition radiation
  - from physics models

- Photo-Absorption Ionisation model
  - Alternative energy loss
Electromagnetic physics

- Gammas:
  - Gamma-conversion, Compton scattering, Photo-electric effect

- Leptons (e, μ), charged hadrons, ions
  - Energy loss (Ionisation, Bremstrahlung) or PAI model energy loss, Multiple scattering, Transition radiation, Synchrotron radiation,

- Photons:
  - Cerenkov, Rayleigh, Reflection, Refraction, Absorption, Scintillation

- High energy muons and lepton-hadron interactions

- Alternative implementation ("low energy")
  - for applications that need to 1 KeV
  - details in parallel talk (Tuesday, Track 5)
Shower profile

1 GeV electron in H₂O

G4, Data G3

Good agreement seen with the data

3rd September 2001
Cuts: production & user

- Coherent “production cuts”
  - validity range of models fully exploited
  - kernel can enforce consistent production cuts
    - yet processes can ask to override when they need to.
  - treatment of boundary effects (Figures)

- Cuts in range rather than Energy
  - Geant3 used cuts in Energy - inefficient
  - significant gain in results quality vs CPU usage

- User can cut in Energy, track length, TOF ..
GEANT4

5cm Pb, CO2, Pb, CO2

Cut: 2mm
Pb 2.5 MeV
CO2 55keV
GEANT3 run

5cm Pb, CO2, Pb, CO2
Changing cuts

- Results very stable with variation of cuts
  - even track length

- Also see shower profiles for different cuts (next slide)
  - between 10mm and 50 microns
Secondaries produced only if they could escape

<table>
<thead>
<tr>
<th>Lead</th>
<th>CO₂</th>
<th>Lead</th>
<th>CO₂</th>
</tr>
</thead>
</table>

**Range < safety**
Secondaries cannot leave Pb: not produced

**Range > safety**
Secondaries could leave Pb: produced
Confrontation with data

- Many comparisons made by WG, and results presented
  - and put in Web gallery
- A lot of comparisons are ongoing, starting
  - within the collaboration (eg in experiment groups)
  - in other experiments, groups in other fields
    - diverse uses (eg outer-space, medical, ..)
    - often small groups
Alternatives for Energy Loss

- 'Standard' differential
  - Extended down to 1 KeV
  - Creates more secondaries near volume borders

- PAI model for gases/thin absorbers

- Integral Energy Loss processes
  - Integration of cross section over Energy
    - DE/E not constrained for e+/e-
    - hadronic resonances can be seen (future)
Multiple scattering model

- A new model for multiple scattering based on the Lewis theory is implemented since public \( \beta \) release in 1998.
- It randomizes momentum direction and displacement of a track.
  - Step length, time of flight, and energy loss along the step are affected, and
  - It does not constrain the step length.
Angular distribution of 15.7 MeV e− after Au foil

18.66 mg/cm²
37.28 mg/cm²
Energy deposit of 976 keV e⁻ in 0.148 mm Si

data \( E_{mp} = 40.3 \text{ keV} \)
data \( w = 18.6 \text{ keV} \)

- **GEANT4** \( \text{cut} = 0.01 \text{ mm} \)
- **GEANT3** \( \text{cut} = 0.01 \text{ mm} \)
Energy deposit of 1 MeV $e^-$ in 0.530 mm Si

- GEANT4 cut=0.01 mm
- GEANT3 cut=0.01 mm
- exp.data
Under development

backscattering coeff. of e-/e+ backscattered from gold

cback %

E(keV)^2

electron

- data
- G4new
- G4std
- G3

3rd September 2001

J. Apostolakis for Geant4 collaboration
Low energy EM processes

- Photons, electrons down to 250 eV
  - Xsec from EADL libr.
  - Thanks to M.G. Pia, P. Nieminen, ..
- Hadron EM interactions
- See 5-001 for an overview of Geant4 Low Energy EM Physics

Photon transmission through 1 mm Pb, showing shell effects
Comparison projects

- Established joint projects for comparing Geant4 results with experimental/test-beam data.
- Collaboration with experiments
  - ATLAS (projects with data of test beams of 4 calorimeters)
  - BaBar (with experiment data for tracker, drift chamber)
- Following slides are taken from presentations at conferences & workshops
  - For details: see presentation of D. Salihagic (Tuesday in Track5)
Atlas FCal1 electron Energy resolution

Thanks to
Rachid Manzini
& Peter Loch
& Atlas FCAL
Thanks to Gaston Parrou, Kostas Kordas and Atlas LAr

Muons in EMB

G4.3.0R1

incompatibility washed out because of the limited size of the test beam sample - More muons in the analysis pipe line.

G3/G4 distributions statistically incompatible - K-S tests fail
Hadronic processes

- Five level implementation framework
  - allows models to be used in combination at different levels
    - Solving the mix and match problem in the framework
- Variety of models and cross-sections
  - for each energy regime, particle type, material
  - alternatives with different strengths and computing resource requirements
- Components can be assembled in an optimized way for each use case.
  - A simple example is illustrated in figure (next page)
Assembling processes

Illustrative example of assembling models into an inelastic process for set of particles

- Uses levels 1 & 2 of framework
Hadronic processes

Each hadronic process may have one or more
- cross section data sets and
- final state production models

associated with it. Each one has its own applicability.

We define “data set” and “model” broadly
- A “data set” is an object that encapsulates methods and data for calculating total cross sections.
- A “model” is an object that encapsulates methods and data for calculating final states.
Hadronic processes at rest

■ At Rest processes
  ▪ pion absorption
  ▪ kaon absorption
  ▪ neutron capture
  ▪ antiproton annihilation
  ▪ antineutron annihilation
  ▪ mu capture

■ At Rest processes may generate secondaries after some time interval.
Hadronic processes in flight

Four types of processes
- Elastic scattering
- Inelastic scattering
- Fission
- Capture

Examples
- Parameterization driven models originally based on GHEISHA with many improvements
- Data driven models based on ENDF/B-VI
- Theory driven models for inelastic scattering
Modeling approaches

1. Data driven approach

- Neutrons
  - from numerous evaluated data libraries
  - down to thermal energies, up to 20 MeV
- Isotope production (see next slide)
- Induced Fission & Capture (H.Fesefeldt)
  - used above 20 MeV

- Photon-evaporation, radioactive decay, etc.

2. Parameterized models

- Gheisha + fixes + new parameterizations (H.F, TRIUMF)
Modeling approaches (cont.)

3. **Theoretical models**, from low E to high E

- Pre-Compound Model + Evaporation Phase
- Cascades, CHIPS and QMD models
- String models
  - Excitation, fragmentation, hadronisation models
- Interface to event generator(s)
  - In future
Pre-Compound Model & Evaporation Phase

- Traditional pre-equilibrium model
  - as good as existing ones

- Evaporation:
  - Weisskopf-Ewing model
  - Fermi breakup model
  - Model for fission
  - Multi-fragmentation model (Bondorf)
  - Photon Evaporation
  - only missing Internal Conversion
    - (suppressed by more than $10^4$, funding expected)

- Future: 2nd Pre-Compound, from HETC re-eng. (in 2002)
Cascade energy range

- Parameterized
- Bertini cascade (from HETC)
  - collaboration milestone for 2001 (Helsinki)
- Chiral Invariant Phase Space decay, "CHIPS"
  - 1st implementation now (Jefferson Lab.)
  - collaboration milestone 2001
- Kinetic model (INFN, Frankfurt)
- Further future: Relativistic QMD (Frankfurt), rewrite of INUCL code (Helsinki)
String models

- FTF string model, derived from Fritiof
  - but no Rutherford scattering
- Quark Gluon String model (~ Dual Parton)
  - for proton, neutron, $\pi$, $K^+/K^-$ induced reaction
    - string decay as in JETSET
    - following Kaidalov’s formulation
    - using FTF algorithm for energy transfer in case of single diffraction (~6% cases)
  future: $K_0$, $\gamma$, anti-nucleon induced reactions
Future additions

- Quark molecular dynamics model (Frankfurt)
- Nucleus-Nucleus
  - via QMD (Frankfurt)
  - for light nuclei using pre-compound and cascades
  - ablation/abration model
- Parton cascade (ansatz of K. Geiger)
- ‘Re-use’ of Pythia7
  - for hadron-nuclear & hadron-hadron interactions
Some of the Improved Hadronic Physics 1999-2001

- Neutron & proton induced isotope production models
  - up to 100 MeV (J.P. Wellisch)
- Multi-fragmentation and pre-compound
  - redesign & refinement (V. Lara)
- Additional string model (J.P. Wellisch)
  - for proton, neutron, π, K+/K- induced reactions
- Special cross-section classes for neutron, proton, and ion induced reactions (D. Axen, M. Laidlaw, J.P.W.)
- Retuning of High Energy Models (H. Fesefeldt) (JPW)
- Doppler broadening of neutron X-section on the fly

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Isotope Production

- Isotopes produced by neutrons on Lead 208

- Small dots: evaluated data
- Circles with error bars: Geant4
  - latest model
  - included since Geant4 1.0

J.P. Wellisch
CHIPS

- New physics model/event generator
- From ~100 MeV to ~10 GeV
- Applications to date:
  - Pbar annihilation at rest
  - Pi capture
  - Gamma-nucleus interactions
  - Intranuclear transport
    - after high energy interaction
- Schedule for release end 2001
Pion capture on $^{12}$C nucleus

- Neutrons: $E_{\text{kin}}/E_{\text{e/m}} = 79.8 / 59.4$ MeV
- Deuterons: $E_{\text{kin}}/E_{\text{e/m}} = 5.2 / 7.2$ MeV
- Protons: $E_{\text{kin}}/E_{\text{e/m}} = 8.7 / 9.9$ MeV
- Tritium: $E_{\text{kin}}/E_{\text{e/m}} = 2.5 / 2.7$ MeV
- Helium-3: $E_{\text{kin}}/E_{\text{e/m}} = 0.6 / 1.0$ MeV
- Lithium: $E_{\text{kin}}/E_{\text{e/m}} = 1.0 / 1.3$ MeV

$k = (p+E_{\text{kin}})/2$ (MeV)
\[^{12}\text{C}(\gamma,p)\] reaction at \(E_\gamma = 123\) MeV

Thanks to M. Kossov, J.P. Wellisch, P.V. Degtaryenko

For more on Hadronic Physics in Geant4, see the presentation in Track 5 by J.P. Wellisch, 5-004

“Hadronic Shower Models in Geant4: Validation strategy and Results”
Other processes

- Decay
- Optical processes
  - Reflection, refraction, absorption
- Photolepton-hadron
- Transportation
  - interrogates geometry, field motion
Parameterization/Fast Simulation

- Fast Simulation Manager
  - Framework for parameterization
  - Takes over from detailed simulation
  - Can return to detailed simulation (e.g., cracks)
- Can trigger on particle, volume, ..
  - Parallel geometrical description
- User must create his/her own (for now)
- This parameterisation scheme utilised
  - For fast simulation of TR, PAI
Interface to external tools

Through abstract interfaces

-No dependence

-Minimize coupling of components

Example: AIDA & Analysis Tools

Similar approach:

- graphics
- (G)UI
- persistency
- etc.
Visualization

- Much functionality is implemented
- Several drivers:
  - OpenGL, VRML, Open Inventor, Opacs, DAWN renderer (G4)
- Also choice of User Interfaces:
  - Terminal (text) or
  - GUI: Momo (G4), OPACS
  - Editors for geometry, EM physics code generation
Object Persistency: Hits & other

- To store hits, use object persistency
- Abstract interface
  - ODBMS solution via RD45 (Objectivity)
  - Tracker-type and calorimeter-type hits
  - Saw minimal performance & storage overhead
- Minimal modifications
  - G4 kernel untouched

Also store:
- Trajectories, Runs,
- Events, Geometry
Use of Geant4

Two and a half years from the first Geant4 public release, major experiments has already started to use Geant4 intensively:

- BaBar: Full migration from G3 based simulator
- HARP: Running today with G4 as only simulation
- Atlas : G4 validation for all detector test beams 2000/1
- CMS : Simulation of full detector based on G4 in 2001

Usage of Geant4 has expanded to fields other than HEP.

- Accelerator applications (T9 Harp, Muon fact.)
- Space (see 5-002) and medical applications
BaBar full simulator ‘BOGUS’

BaBar Object-oriented Geant4-based Unified Simulator

- 2.5 million events generated
  - Robust - Crash rate of 3 events / 1 million
  - No significant memory leaks
  - As good performance as BBSIM (Geant3)

- Comparisons with experimental data and BBSIM, were undertaken, using the full reconstruction chain.

- Decision to move to Geant4 and plan to utilize it exclusively for 2001 data.
  - Full production with BOGUS is starting soon: plans to simulate 200 million events by early 2002.
Conversions in $\gamma\gamma$ events

G3 8series over Data (points)

G4 10series over Data (points)
Atlas TRT tracker

Simulating energy deposition in thin straw tubes of gas.

- Precision requirements led to adoption of PAI model of energy loss for gas,
  - For remainder of detector the standard energy loss is applied (tailored physics list)
  - Good agreement in many comparisons.
  - Validated use of new concrete PAI parameterisations for fast simulation.
- Utilising transition radiation models.
Geant4 latest releases

- Geant4 3.0 released December 2000
  - with additional physics models
    - and refinements/improvements/corrections in existing ones
  - with new functionality, eg
    - first Analysis module, to use AIDA histograms+
      • create manager of AIDA objects
    - new examples with visualisation, analysis

- Geant4 3.2 on June 29th, 2001
Performance?

- Geometry navigation
  - Geant4 automatically optimizes the user’s geometrical description. And it provides faster navigation than optimized Geant3 descriptions.

- EM Physics computing performance goals
  - For the same physics performance, we seek speed at the level of Geant3 or better.
  - Keeping physics performance constant, optimise the speed that maintains the performance.
    - In two current speed benchmarks (thin silicon & simplified sampling calorimeter) these goals are achieved.
Performance?

- In experimental setups
  - Atlas EM Barrel: comparable performance
  - Atlas FCAL: Geant4 is 3x faster than Geant3
  - BaBar: comparable performance.

- Our goal is that Geant4 is at least as fast as Geant3 in almost every case
  - when its power and features are well exploited.
  - And, where required, ‘new’ techniques including shower parameterisation can be used to obtain large speedups (in acceptable trade-off with accuracy)
Future directions

The next major release, Geant4 4.0 in December, is scheduled to include

- New theoretical hadronic models
  - Re-engineered from HETC
  - CHIPS for gamma-Nucleus, π capture and intranuclear transport

- Ability to reduce initialisation time
  - By saving/retrieving physics processes’ tables

- Ability to set different Cuts for different regions
Future directions

We plan

- To facilitate the specialization of those parts of hadronic physics lists that vary between use cases.
- To create and distribute “educated guess” physics lists corresponding to the major use cases of Geant4 involving hadronic physics,
  - As an aid and starting point for users.
Software process

- Geant4 has been the first software development in HEP to fully apply most recent software engineering methodologies.

- Current focus of Process Improvement in Geant4:
  - Q/A & Optimization activity
    - apply Q/A to the software product
  - Analysis & Design software cycle
    - identify the well established OOP procedure for development and maintenance
  - Testing
    - assure constant improvement and continuity to system testing

- For more on this see 8-008 (Wed.)
Geant4 Collaboration

Collaborators also from non-member institutions, including
Budker Inst. of Physics
IHEP Protvino
MEPHI Moscow
Pittsburg University
Summary

- Geant4 is in use today in running HEP experiments (BaBar, HARP)
- Results of comparing Geant4 versus data are growing month by month,
  have provided important ‘yardsticks’.
- Geant4 has demonstrated important strengths:
  - stability of results, flexibility, transparency.
- Refinements & development are ingoing.
### Geant4 releases: timeline

<table>
<thead>
<tr>
<th>Date</th>
<th>Release Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec ’94</td>
<td>Project start</td>
</tr>
<tr>
<td>July 98</td>
<td>First beta release</td>
</tr>
<tr>
<td>Dec ’98</td>
<td>Geant4 0.0 release</td>
</tr>
<tr>
<td>Jul ’99</td>
<td>Geant4 0.1 release</td>
</tr>
<tr>
<td>Dec ’00</td>
<td>Geant4 3.0 release</td>
</tr>
<tr>
<td>June 01</td>
<td>Geant4 3.2 release</td>
</tr>
<tr>
<td></td>
<td>Two public releases per year</td>
</tr>
<tr>
<td></td>
<td>Plus monthly development tags for collaboration users</td>
</tr>
</tbody>
</table>

- CERN
- RD44
- MoU-based collaboration
THE END

Note that it was not possible to give credit to all those who have contributed to Geant4 ...