The Geant4 toolkit and applications

A Brief Introduction

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Contents

- Simulation packages/toolkits
  - Key capabilities and concepts
- GEANT4
  - highlights of capabilities
    - Physics
    - Setup description
- Applications

What can a simulation package or toolkit do ?

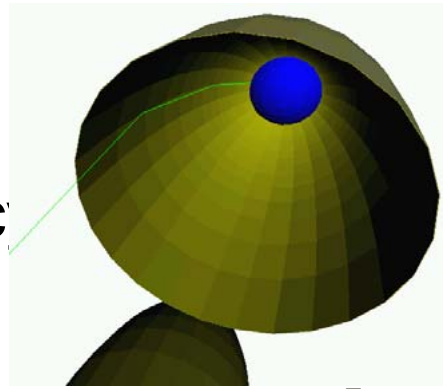
- A Package provides ‘general’ tools to undertake (some or all) of the key tasks:
  - tracking, and geometrical propagation
  - modelling of physics interactions,
  - visualization, persistency
- and enable you to describe your setup’s
  - detector geometry,
  - radiation source,
  - details of sensitive regions

GEANT 4

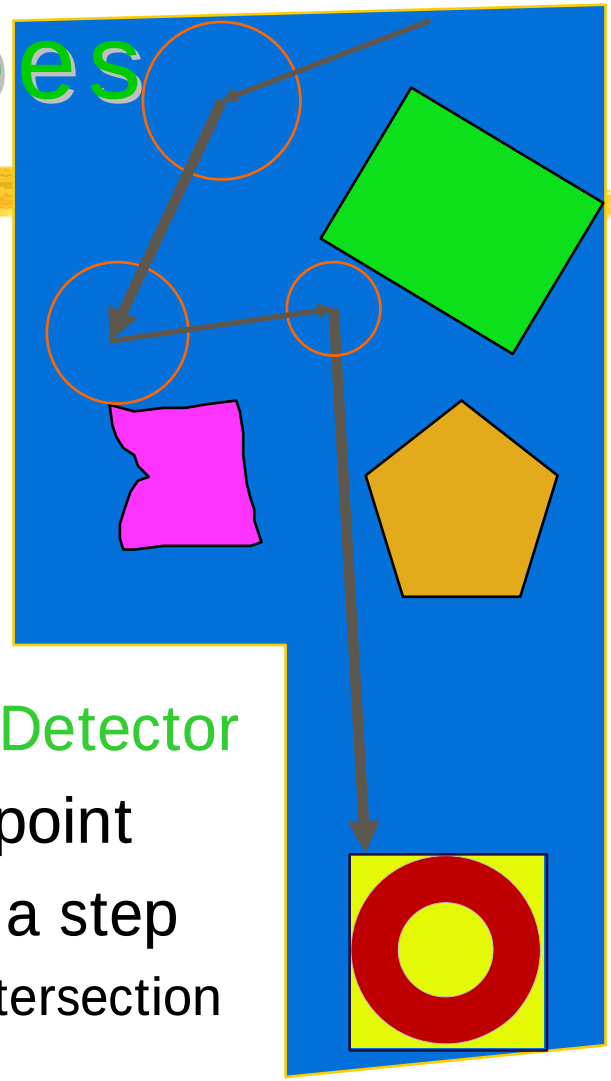
- Detector simulation tool-kit from HEP
  - full functionality: geometry, tracking, physics, I/O
  - offers alternatives, allows for tailoring
- Software Engineering and OO technology
  - provide the architecture & methods for maintaining it
- Requirements from:
  - current and future HEP experiments
  - medical and space science applications
- World-wide collaboration

Key Capabilities

- 'Kernel': create, manage, move tracks
  - tracking, stacks, geometry, hits, …
    - Extensible, flexible
- Physics Processes X-section, final-state
  - models for electromagnetic, hadronic, …
    - Can be 'assembled' for use in an application area
- Tools for faster simulation
  - 'Cuts', ramework shower parameterisation
  - Event biasing, variance reduction.
- Open interfaces for input/output
  - User commands, visualization, persistenc



Geometry: what it does



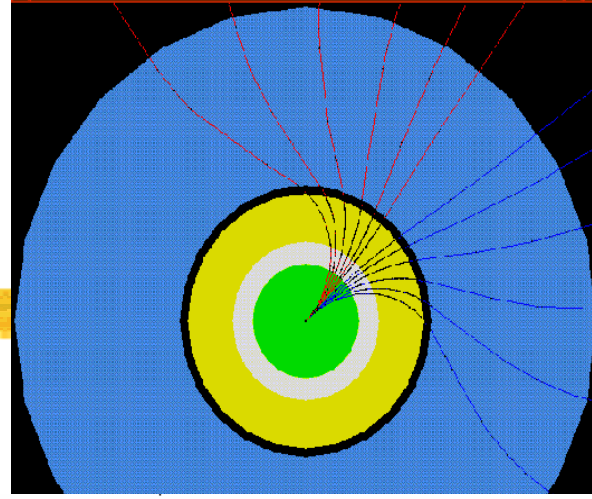
Describes a Setup

- Hierarchy of volumes
- Many volumes repeat
  - Volume & sub-tree
- Up to hundreds of thousands of volumes
- Importing solids from CAD systems

Navigates in Detector

- Locates a point
- Computes a step
  - Linear intersection

Fields. Complex geometries.

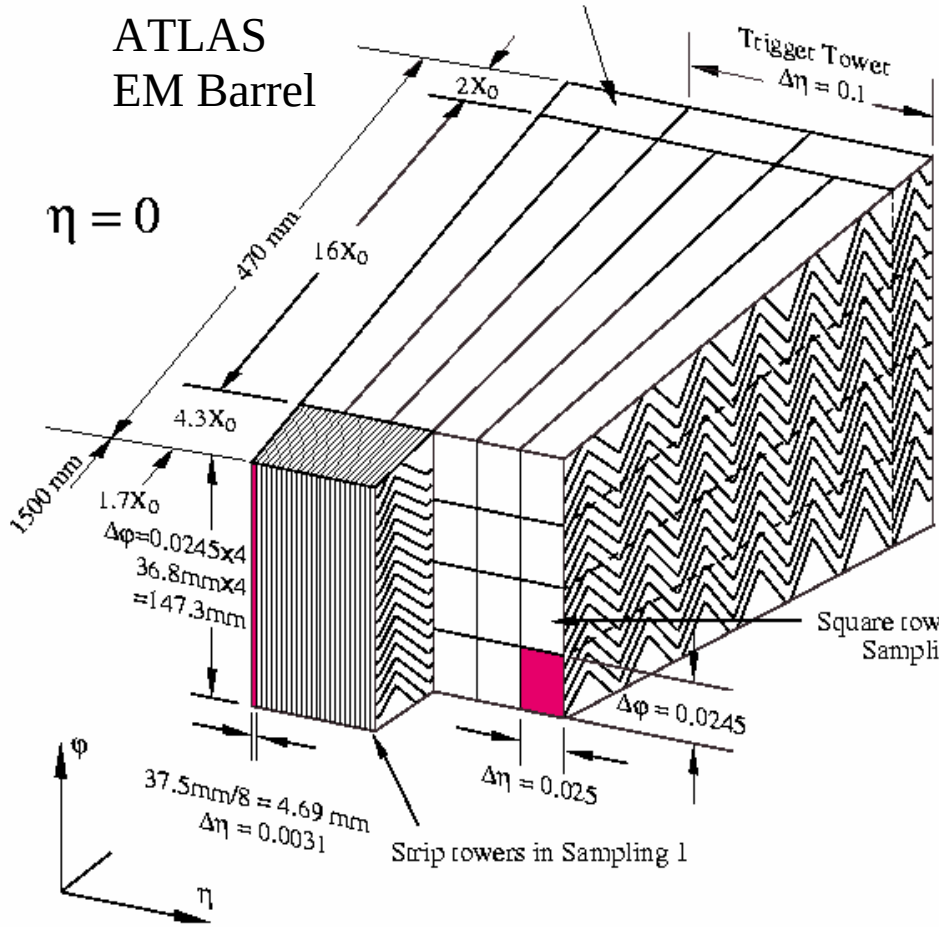


All charged particles ‘feel’ the effect of EM fields

- Automatically following paths that approximate their curved trajectories

Geometries of arbitrary complexity

- ⌘ can be described;
- ⌘ Tracking is performed efficiently for them
  - Automatically, without user assistance



Kernel: a précis

- Creates & manages tracks, events, runs,
  - run=configuration of geometry, physics & rad source
- Allows particles to be prioritised easily at no cost
  - track the most important first.
- Tracking is general (unique to G4)
  - physics ('lists') can be tailored for different uses
- Enables the user to record hits
  - using his/her own scoring of any quantity of interest
  - which can be used in calculating dose, …

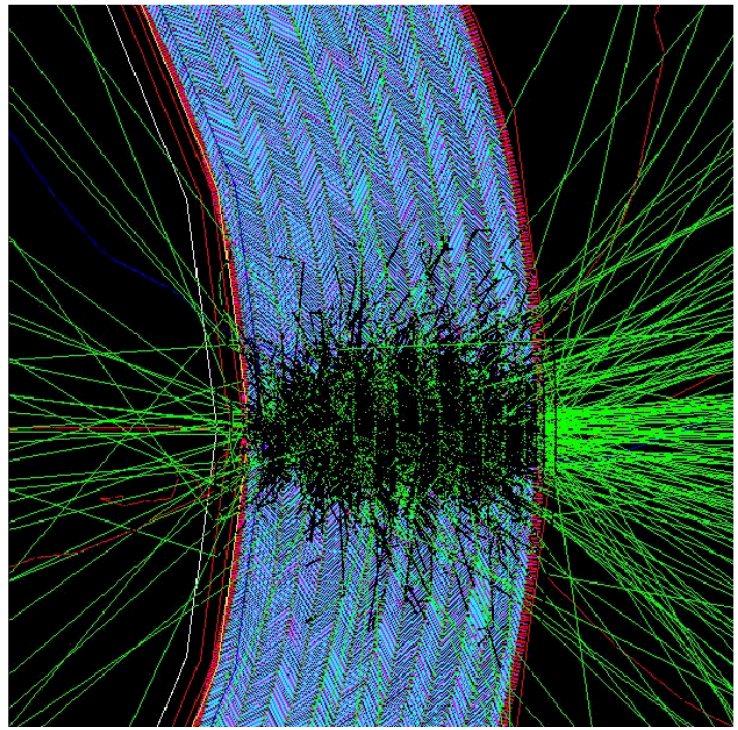
Simulating Physics in Geant4 Physics processes

- Physics in Geant4 is undertaken by ‘processes’, which the tracking calls
  - Processes implement physical interactions
  - Processes must possess cross-sections and models
- For a physical process Geant4 can have one or more ‘Geant4 processes’ simulating the physical interaction. Choice include
  - Different accuracy in cross-section
    - For example one process can model the cross-section with an approximation good to 2%, while another models it to 0.1%.
  - Modeling approach
    - Theory: fundamental or phenomenological model for interaction
    - Parameterisation: products created sampling functions used to describe data
    - data-driven: directly sampling cross-sections or end-products from ‘data-base’
- Each Geantn4 process must be
  - independent of other processes (software-wise)
  - Complementary (physics-wise), avoiding double counting of X-section

Electromagnetic physics

- Gammas:
  - Gamma-conversion, Compton scattering, Photo-electric effect
- Leptons(e, μ), charged hadrons, ions
  - Energy loss (Ionisation, Bremstrahlung), Multiple scattering, Transition radiation, Synchrotron radiation, e+ annihilation.
- Photons:
  - Cerenkov, Rayleigh, Reflection, Refraction, Absorption, Scintillation
- High energy muons
- A choice of implementations for most processes
  - "Standard": performant when relevant physics above 1 KeV
  - "Low Energy": Extra accuracy for application delving below 1 KeV

Electromagnetic physics Implementations



- Goals
  - Improved modeling of interactions, vs Geant3
  - Stability
    - with respect to variation of threshold parameters
  - Optimization of computing performance
    - Using ‘cuts’ in length
    - utilizing geometrical information

    to concentrate on radiation that ‘leaks’

Multiple scatteri

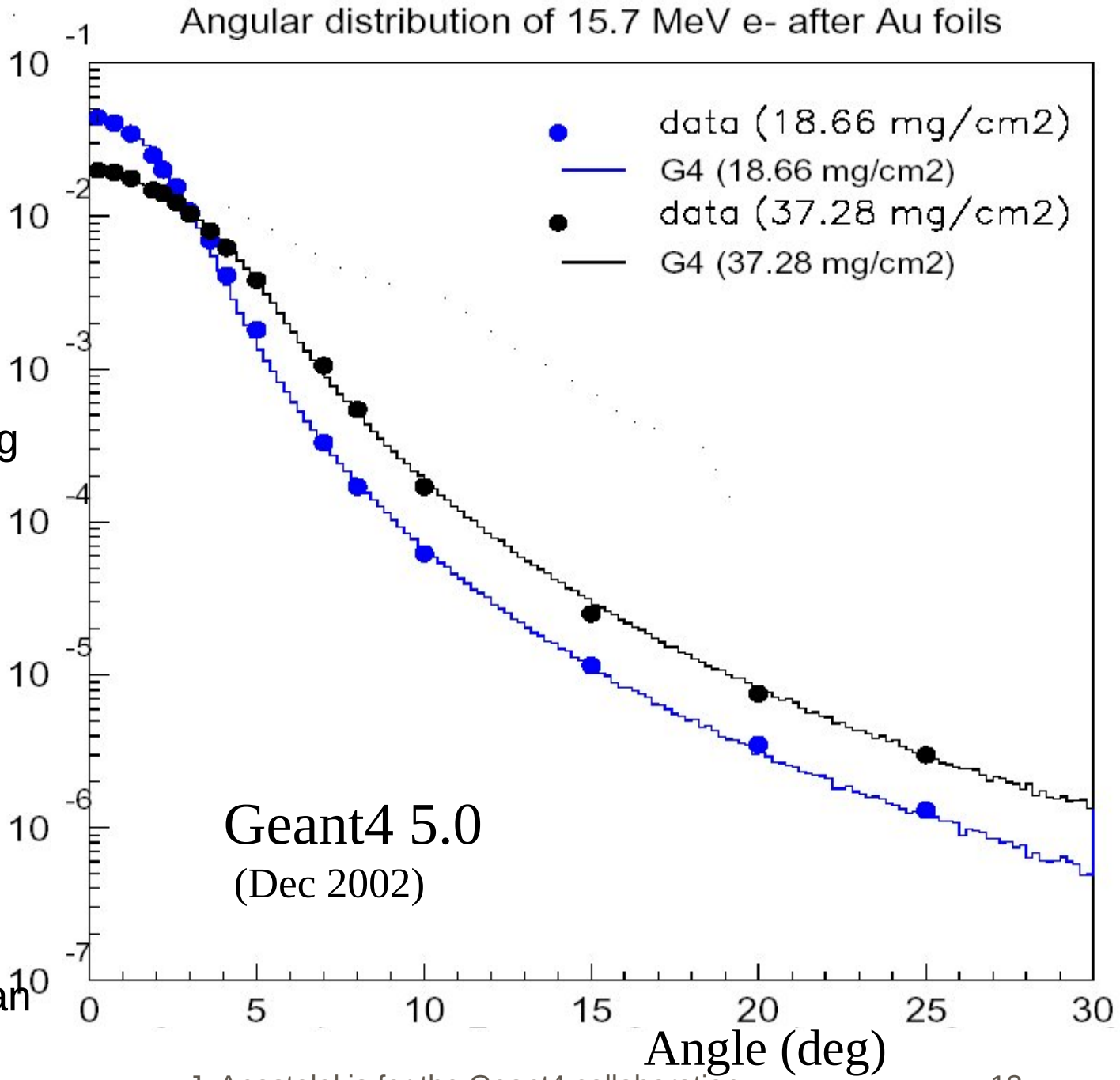
Geant4 includes a new model for multiple scattering

Latest:

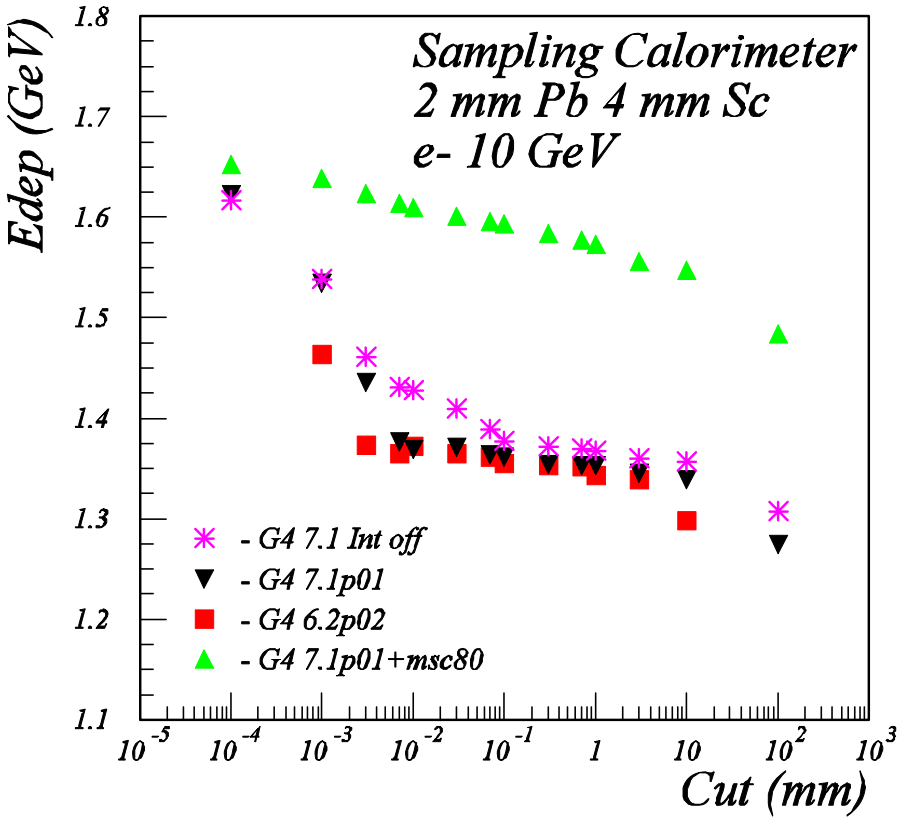
- Refinement of angular distributions
  - in Geant4 5.0

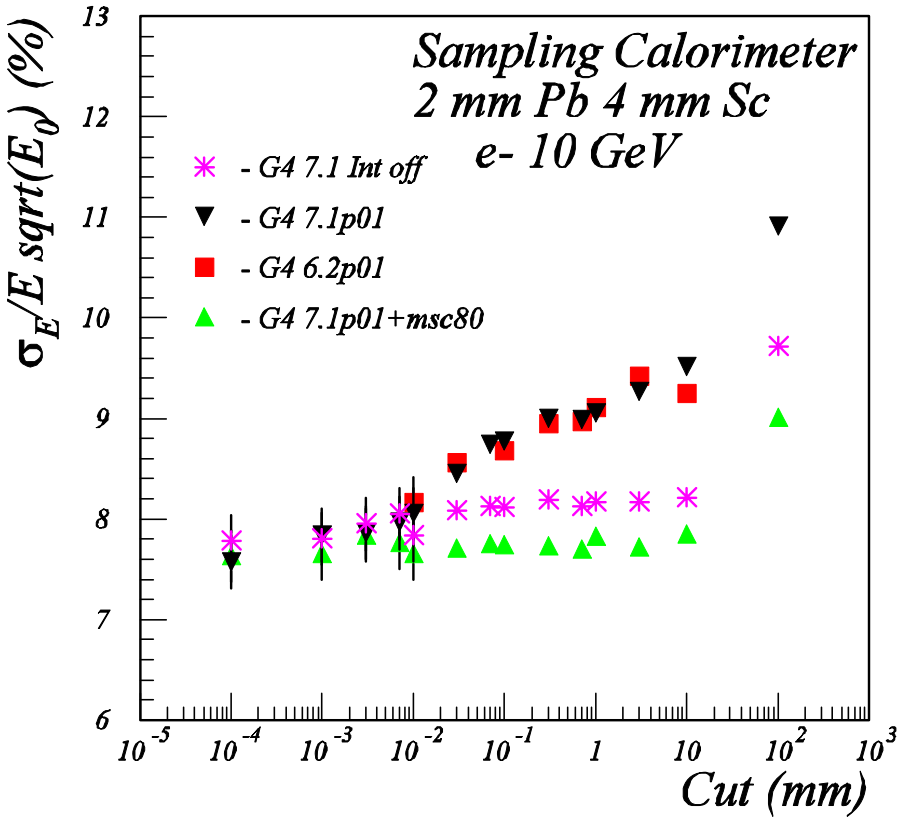
Modeling & comparisons:

L. Urban



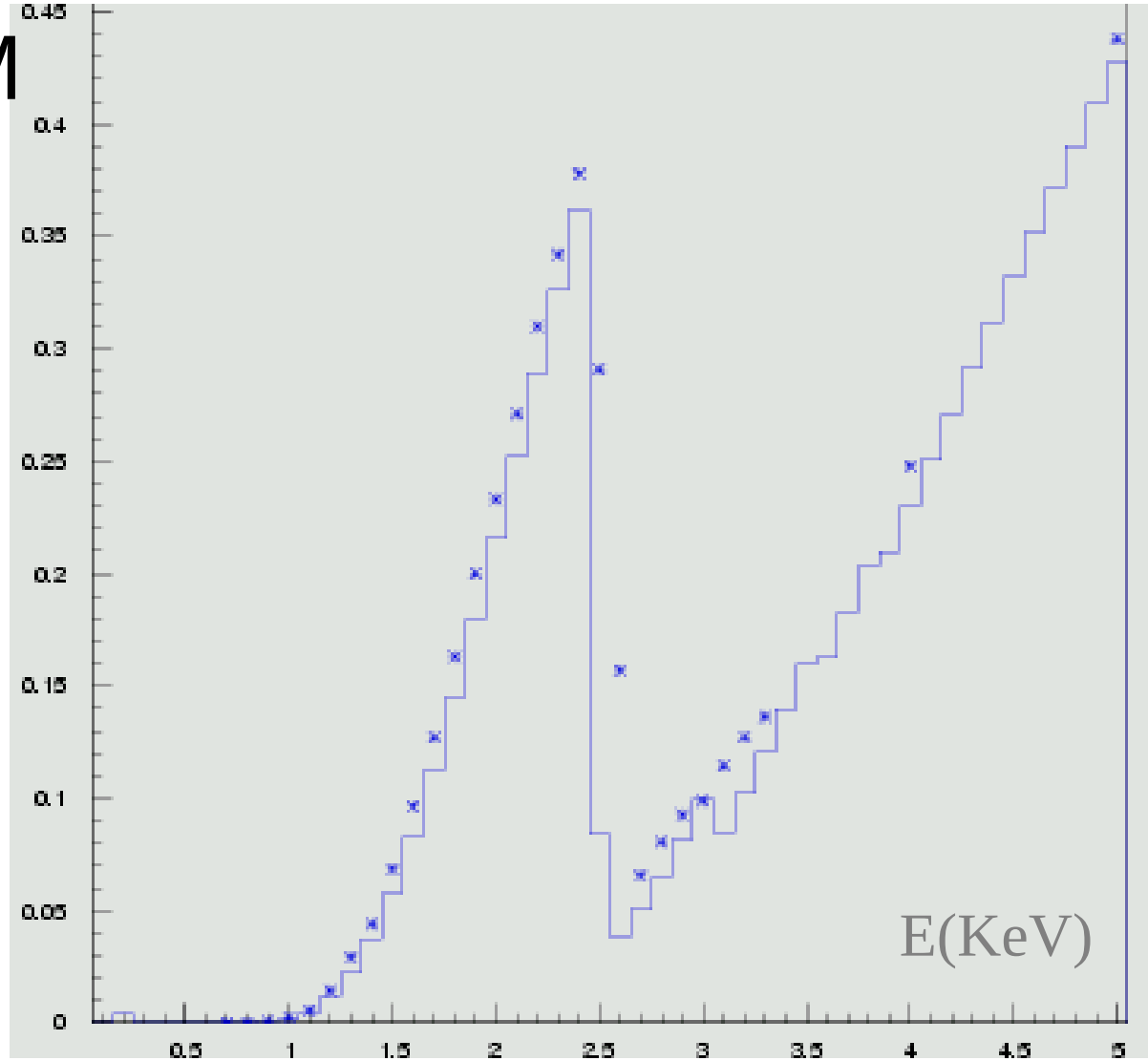
Improvement in model fo Multiple Scattering (Geant4 8.0)





Low energy EM processes

- Photons, electrons down to 250 eV
  - Based on EPDL97, EEDL and EADL evaluated data libraries
  - New approach based on physics models of PENELOPE (2001), also includes positrons.



Photon transmission through 1 mm Pb, showing shell effects

Hadronic processes

- Hadronic physics is included in Geant4
  - a powerful and flexible framework and
  - implementations of physics X-sections & models.
- A 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 optimised way for each use case.

Tailored Physics 'lists'

- Created and distribute "educated guess" physics lists
  - That correspond to the major use cases of Geant4 involving hadronic physics,
  - to use directly, and as a starting point for users to modify,
    - facilitate the specialization of those parts of hadronic physics lists that vary between use cases.
- First released in September 2002
  - Using physics models of Geant4 4.1.
- Revised with experience of comparisons with data
  - This provide 'tested' options, with performance guarantees;
  - Latest:
    - updated with physics models of Geant4 5.0 in March 2003
- Find them on the G4 hadronic physics web pages
  http://cmsdoc.cern.ch/~hpw/GHAD/HomePage

Hadronic Use cases and Physics Lists

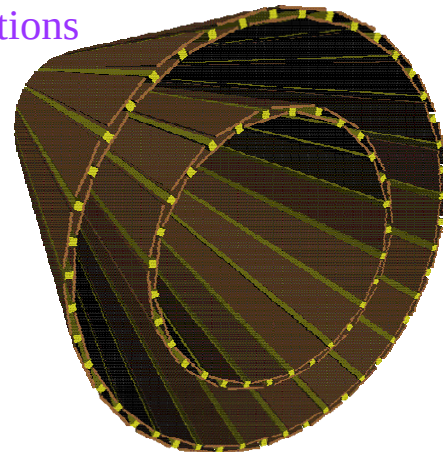
- Manage the complexity of hadronics
  - Identified major use cases of Geant4 involving hadronic physics,
- Created and distribute "educated guess" physics lists
  - that correspond to these use cases
  - to use directly
    - Or as a starting point for more advanced users to modify,
  - provide 'tested' options, with performance guarantees;
- They evolve
    - Revised from comparisons with data
- Where to find them
  - For the use cases see
    - the G4 hadronic physics web http://cmsdoc.cern.ch/~hpw/GHAD/HomePage
  - The source is available
    - In each release
    - Latest updates on hadronics web

Most relevant Use cases

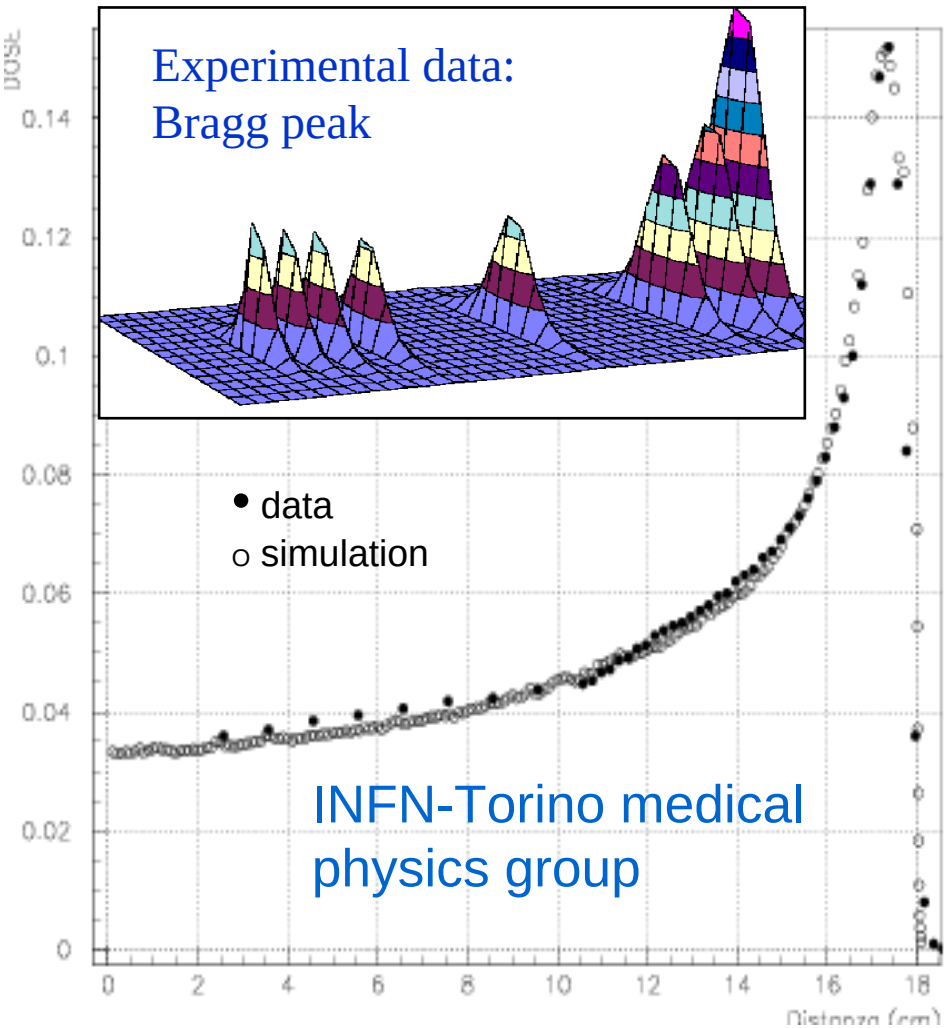
- Low energy dosimetric applications with neutrons
- shielding
- medical and life-saving neutron applications
- low energy dosimetric applications
- Other
  - HEP trackers.
  - HEP calorimeter.
  - low energy nucleon penetration shielding
  - Air shower applications

Physics 'Lists'

- QGSP
- QGSP_BIC



Validation


Experimental data:
Bragg peak
• data
o simulation
INFN-Torino medical physics group
0.14
0.12
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16
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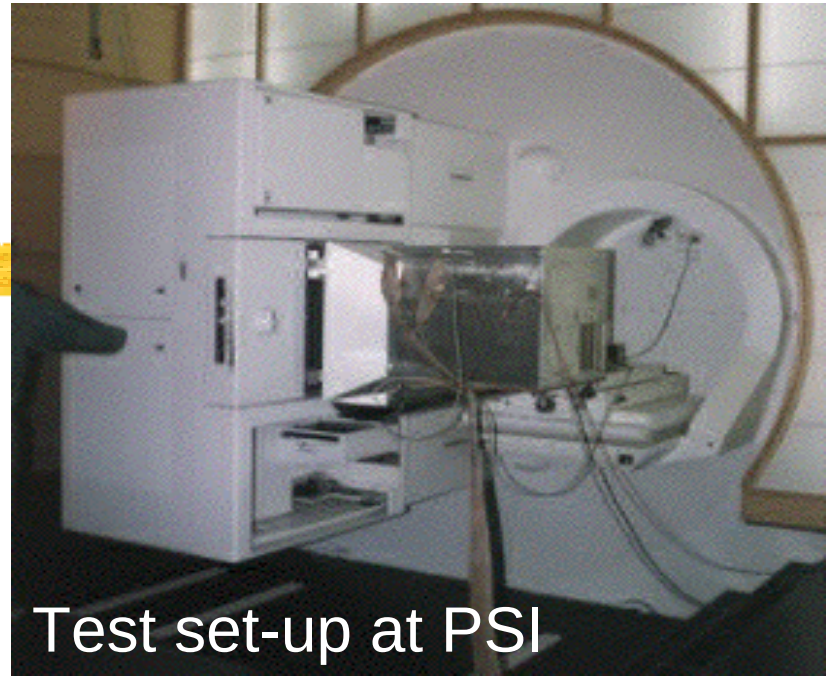
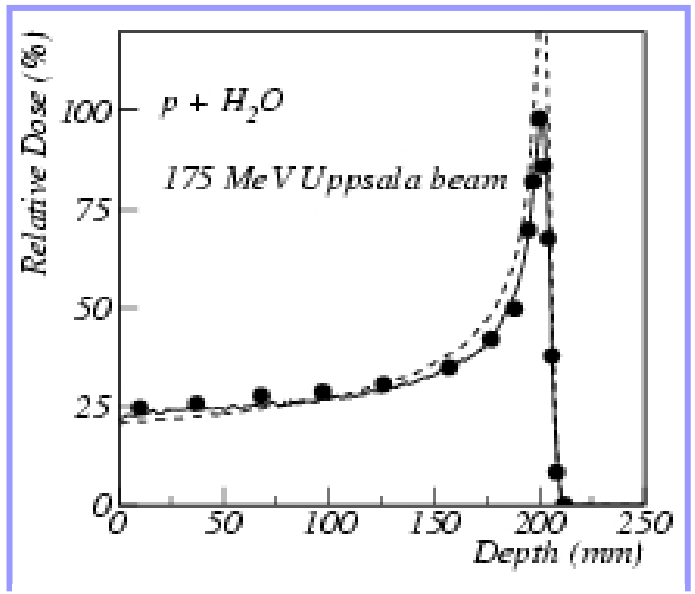
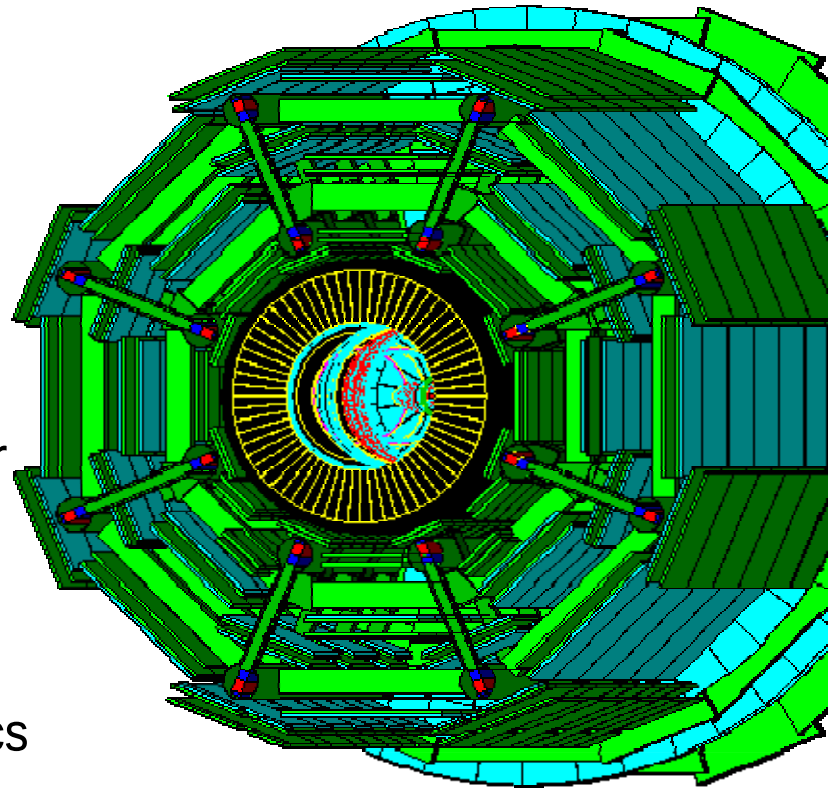

Test set-up at PSI


p + H2O
175 MeV Uppsala beam
Relative Dose (%)
100
75
50
25
0
0
50
100
150
200
250
Depth (mm)

Visualization

- Much functionality
  - Visualise detector, tracks
  - Specify view, angles, …
  - Transparency, ray tracing
- Several drivers:
  - ***DAWN renderer (S. Tanaka)***
  - OpenGL, ***VRML,*** Open Inventor
- Choice of User Interfaces:
  - Terminal (text) or
  - GUI: Momo (G4), OPACS
  - Editors for geometry, EM physics code generation

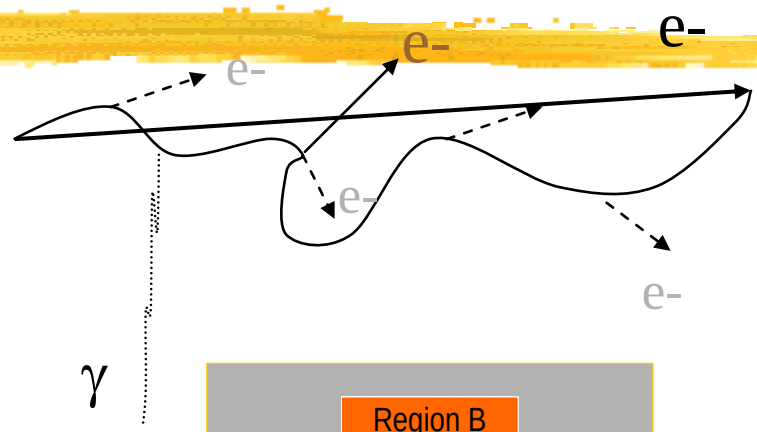


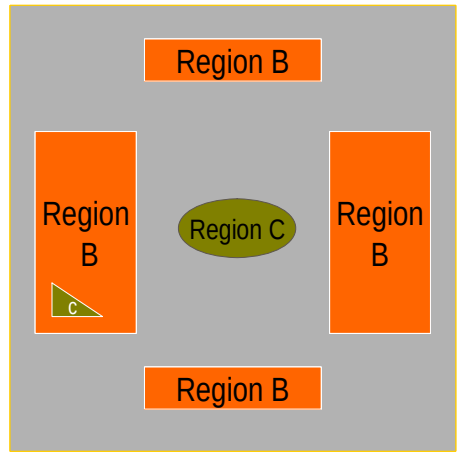
Performance?

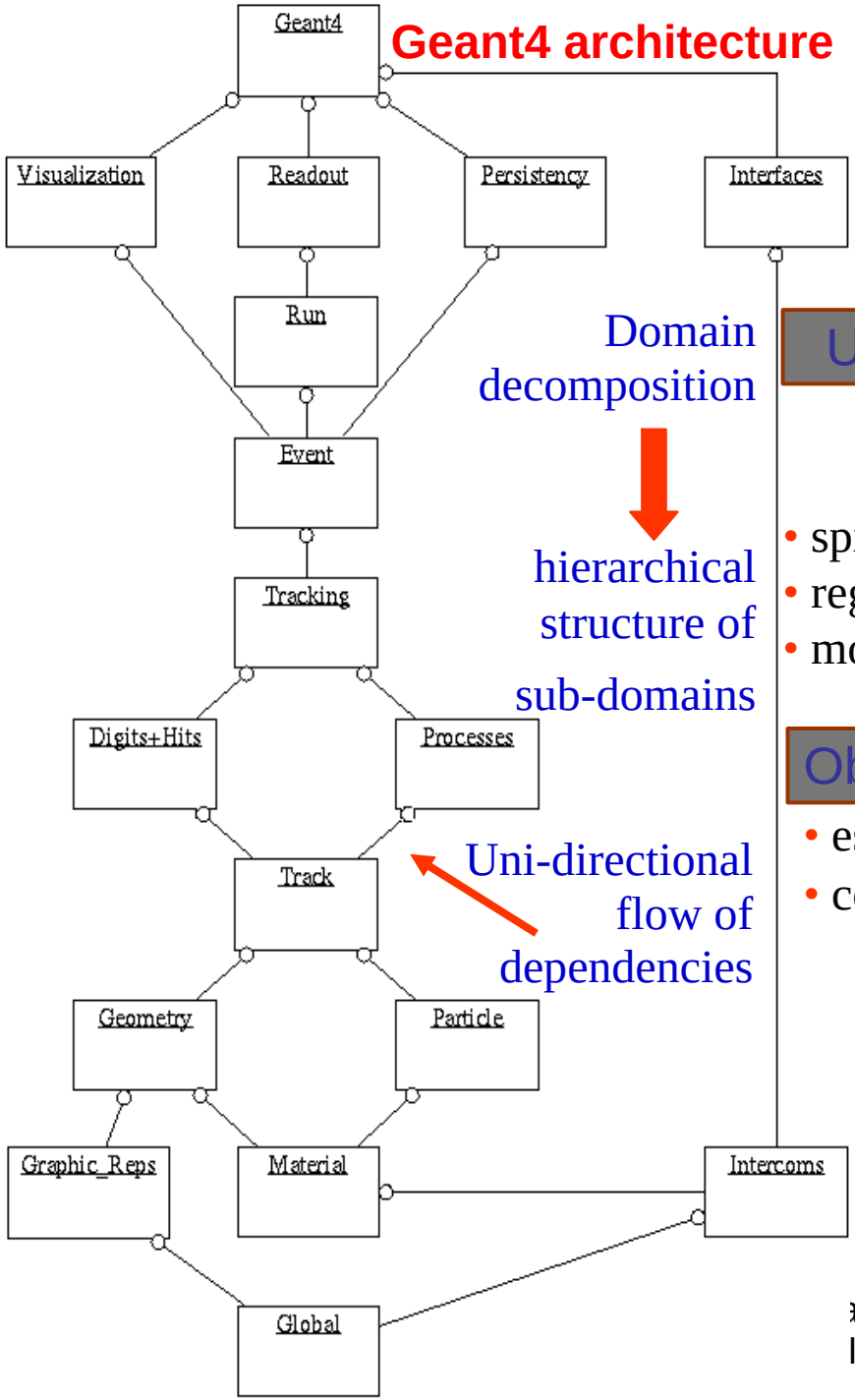
- Geometry navigation
  - Geant4 automatically optimizes the user's geometrical description. And it provides as fast or faster navigation than obtained in G3 with geometries optimized by experts.
- EM Physics computing performance goals
  - For same physics performance, seek speed of Geant3 or better.
  - 'STD' EM in HEP experiments/test beams
    - Some showed competitive performance.
    - Latest studies show a penalty (~50%)
  - Low energy comes at a performance cost
    - In exchange for improved precision

‘Tools’ for CPU performance

- Using the production thresholds (‘production cut’)
  - To limit creation of ‘uninteresting’ tracks
    - Eg elec, with range 10μm, γ with 1 μm
  - Using regions
    - To customise cut values (ie lower in critical areas)
- Shower parameterization
  - Replacing detailed simulation of e-/ γ showers
    - Eg in crystal calorimeters
- Parallel Processing
  - Event based ‘trivial’ parallelisation
    - Example based on TopC in distribution
    - Grid parallelisations
- Event Biasing / Variance Reduction
  - Geometrical (importance) biasing
  - Leading particle
  - Weight window







Geant4 architecture

Domain decomposition

hierarchical structure of sub-domains

Uni-directional flow of dependencies

Software Engineering

plays a fundamental role in Geant4

User Requirements
- formally collected
- systematically updated
- PSS-05 standard

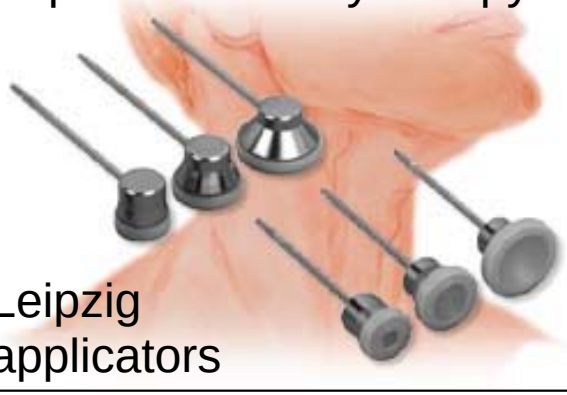
Software Process
- spiral iterative approach
- regular assessments and improvements
- monitored following the ISO 15504 model

Object Oriented methods
- OOAD
- use of CASE tools
- essential for distributed parallel development
- contribute to the transparency of physics

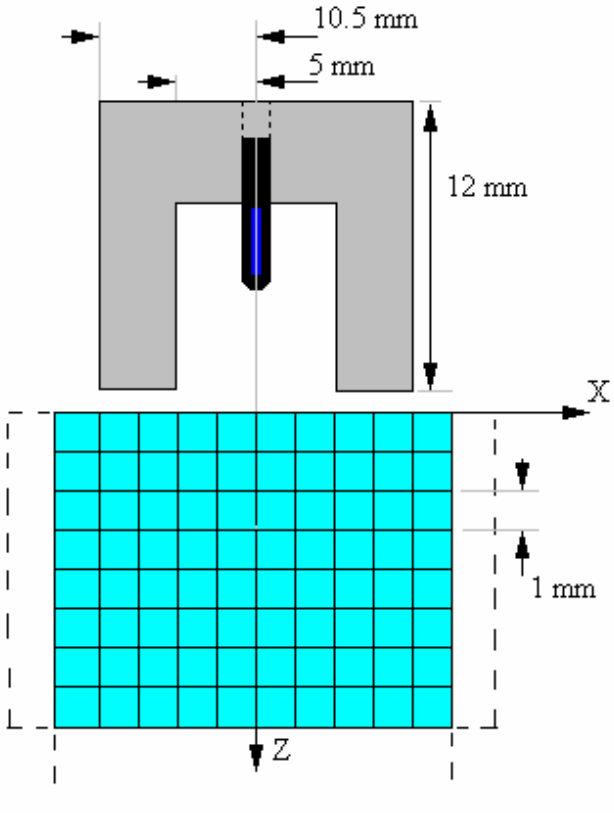
Quality Assurance
- commercial tools
- code inspections
- automatic checks of coding guidelines
- testing procedures at unit and integration level
- dedicated testing team

Use of Standards
- de jure and de facto

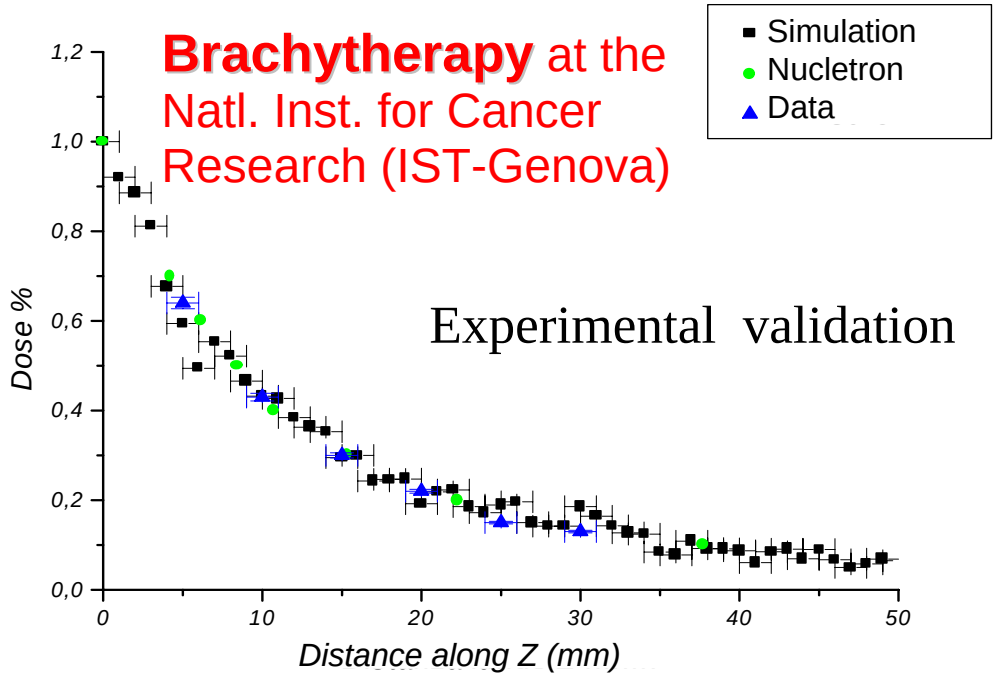
Superficial brachytherapy



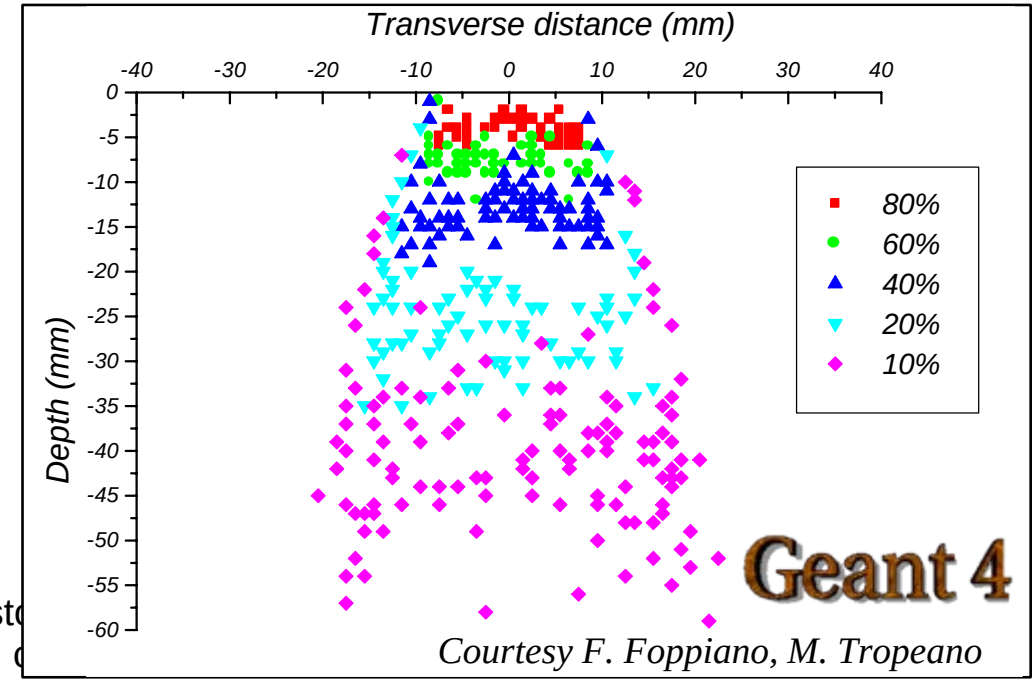
Leipzig applicators



Brachytherapy at the Natl. Inst. for Cancer Research (IST-Genova)



Experimental validation



J. Aposto

Role of the simulation:

precise evaluation of the effects of source anisotropy in the dose

Transverse axis of the source

Comparison with experimental data

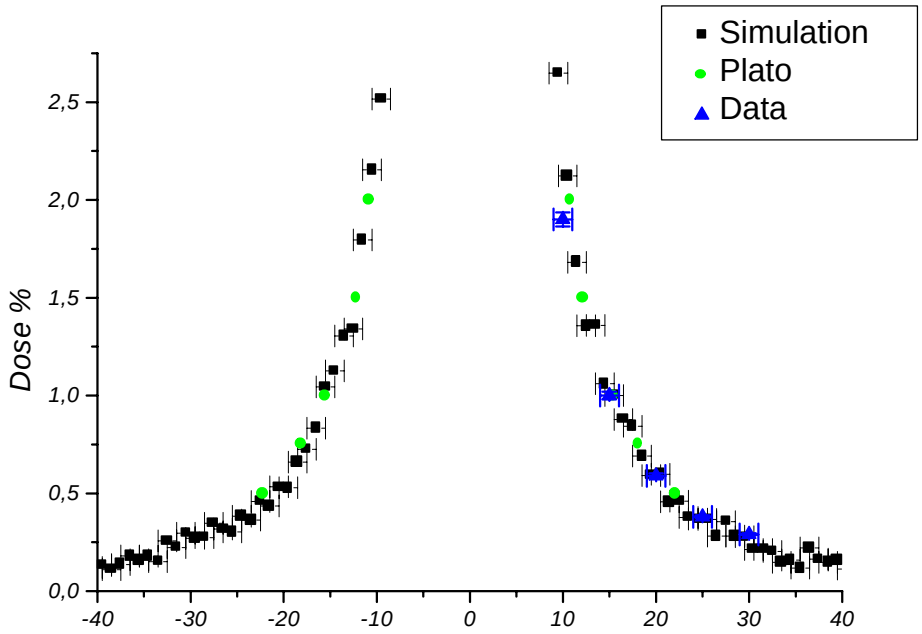
↑ validation of the software

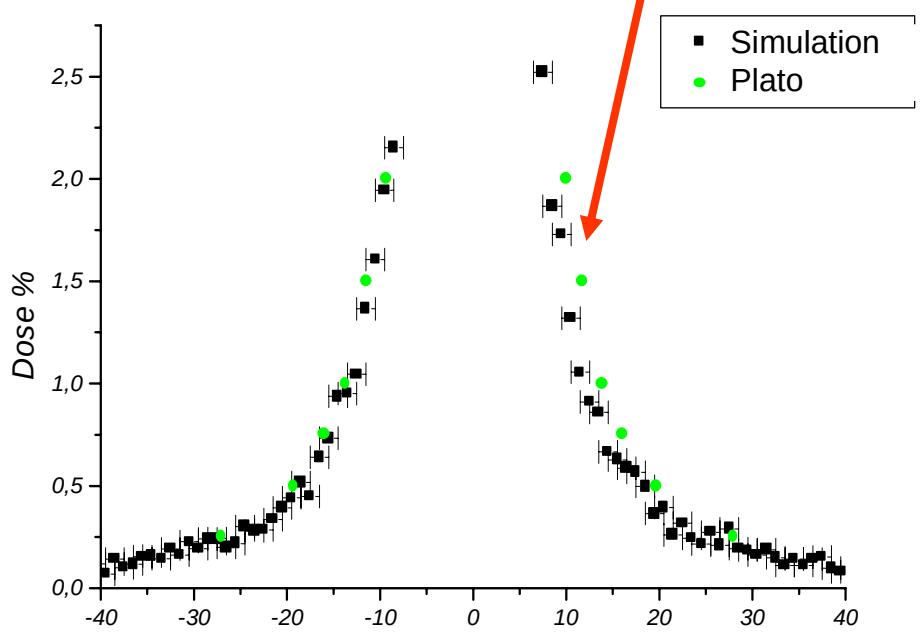
Longitudinal axis of the source

Difficult to make direct measurements

↑ rely on simulation to get better accuracy than conventional treatment planning software

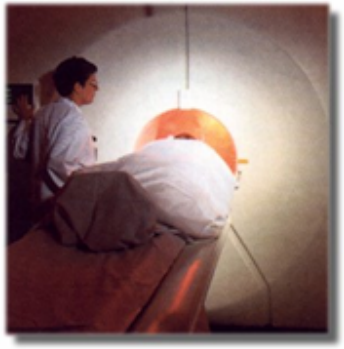
Effects of source anisotropy



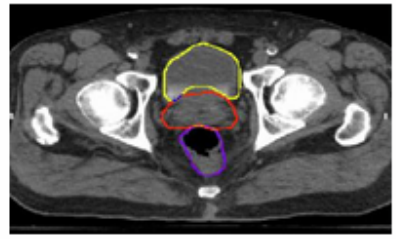


f
collaboration

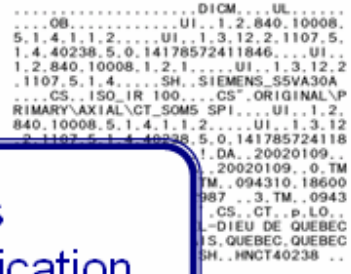
Geant4 DICOM Interface



Modeling complex structures



file



Reproduce patient's anatomy in a Geant4 application

UNIVERSITÉ LAVAL

Authors: L. Archambault, L. Beaulieu, V.-H. Tremblay

(Univ. Laval and l'Hôtel-Dieu, Québec)

Geant 4

Building a Geant4 application

How do you create a Geant4 simulation ?

- Get a ready-made application (eg GATE), or
  - GATE=Geant4 Application for Tomographic Emission
- Modify a similar, existing, application, or
  - Eg examples/advanced/brachytherapy
- Piece together a custom application

What are the key steps for creating an application

- Describing the setup: geometry, material, ..
- Description the primaries
- Choosing the physics to use
- Designating the “sensitive” volumes
  - And collecting physics observables

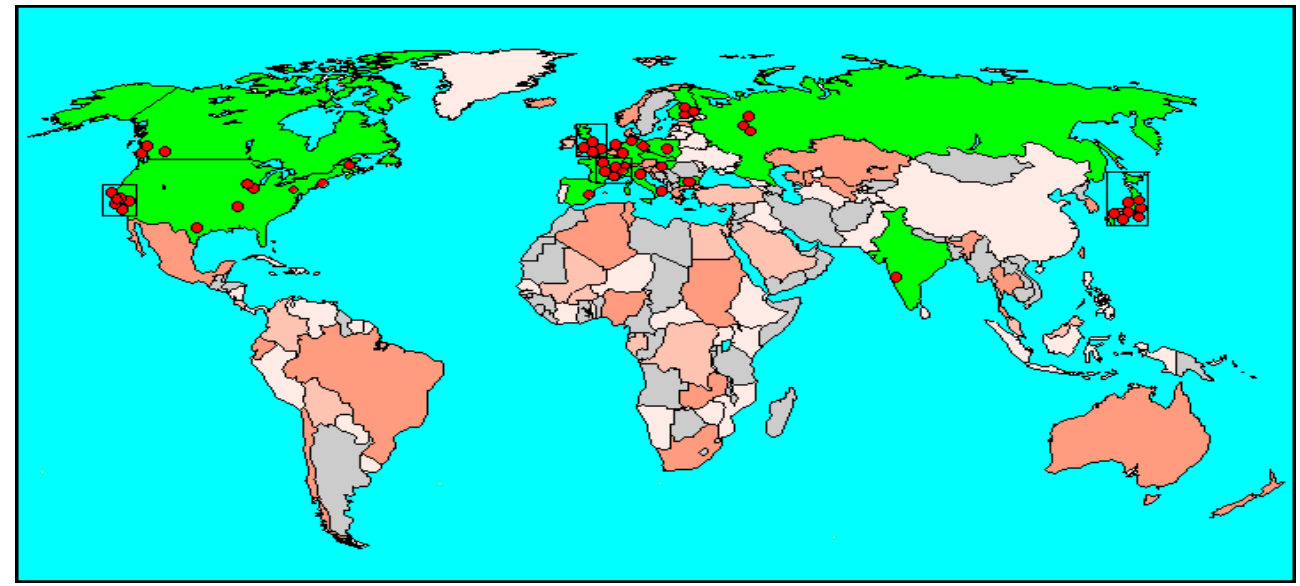
Practical considerations

- Starting off / Installation
  - Need CLHEP, vis ‘drivers’
  - Compatible platform
- Interacting with an application
  - Command line interface
    - /gun/particle proton
    - /run/beamOn 10
  - GUI
- ‘Coding’ (if necessary)
  - Modifying existing C++ ‘code’ to describe your setup
  - For advanced uses, creating you own class to describe eg a magnetic field.

Platforms

- What works ‘best’
  - Linux and gcc 3.2.3
    - most developers & HEP institutions use this
    - We test on ‘Scientific Linux’ 3
  - Windows (XP) & Vis C++ 7.1
    - numerous users
- What we expect to work
  - Other Linux flavours with
    - gcc 3.4.3, 3.4.4
- What others ‘ported’ and check
  - Mac OS X, AIX,

Geant4 Collaboration



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

Resources for more information

- Geant4 web site
  - http://cern.ch/geant4/
- Geant4 Training Page
  - http://cern.ch/geant4/support/ and follow “Training” link,
  - Geant4 training INFN / EM ‘Low-energy’
    - http://www.ge.infn.it/geant4/training/
- Geant4 Workshops and Users Workshops presentations
  - http://geant4.in2p3.fr/2005/
  - Latest at the home page, previous at http://cern.ch/geant4/collaboration/meetings_minutes.html#G4workshops

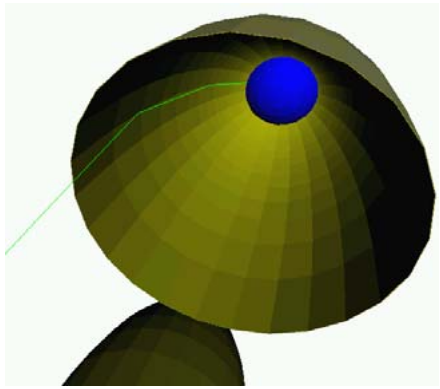
Note: “Training” page is also directly accessed at http://cern.ch/geant4/milestones/training/training-milestone.html

- Geant4 Physics WG web sites
  - Which can all be found at http://cern.ch/geant4/organisation/working_groups.html
  - Geant4 Low-Energy Electromagnetic WG web site
    - http://www.ge.infn.it/geant4/lowE/
  - Geant4 EM (standard) see below
  - Geant4 Hadronic WG home
- Papers on G4 and its validation
  - “Geant4: a simulation toolkit”, Nucl Instr and Methods **A** 506 (2003), 250-303
  - “Validation of GEANT4, an object-oriented MC toolkit for simulations in medical physics” J.F. Carrier et al, Med Phys 32 (2004), p 484.

ElectroMagnetic (standard) WG home page is at http://cern.ch/geant4/working_groups/electromagnetic/electromagneticWG.html

Geant4 Capabilities & Use

- Kernel: create geometry, hits, …
- Physics Processes
  - models for EM, hadronics, …
  - ‘assembled’ into physics lists for application area
- Tools for faster simulation
  - Shower parameterisation & Event biasing.
- Open interfaces for input/output
  - User commands, visualization
- Verification and validation for use cases
- Using it
  - via ready applications (eg GATE)
  - by starting with examples & customising



The END

Newest resource / results

- **Geant4 2005**
  - **user conference and 10th G4 workshop**
    November 3-10, 2005, Bordeaux, France
    - URL http://geant4.in2p3.fr/2005/
  - **Sessions**
    - **Imaging**
    - **External beam therapy**
    - **Hadrontherapy**
    - **Space and biology applications**
    - **Dosimetry**
    - **Computing**
  - **‘Short’ tutorial course (4 sessions)**
  - Presentations will be available on WWW shortly

Acknowledgements

Thanks to those who have contributed

-to creating slides for tutorials / talk, that I borrowed

Thanks to all those who have contributed

-to the development of Geant4,

-to its validation for these and other application areas,

-to those who have applied it

-particularly those who have given feedback.

Note that it is a large task to give credit to all of them individually.