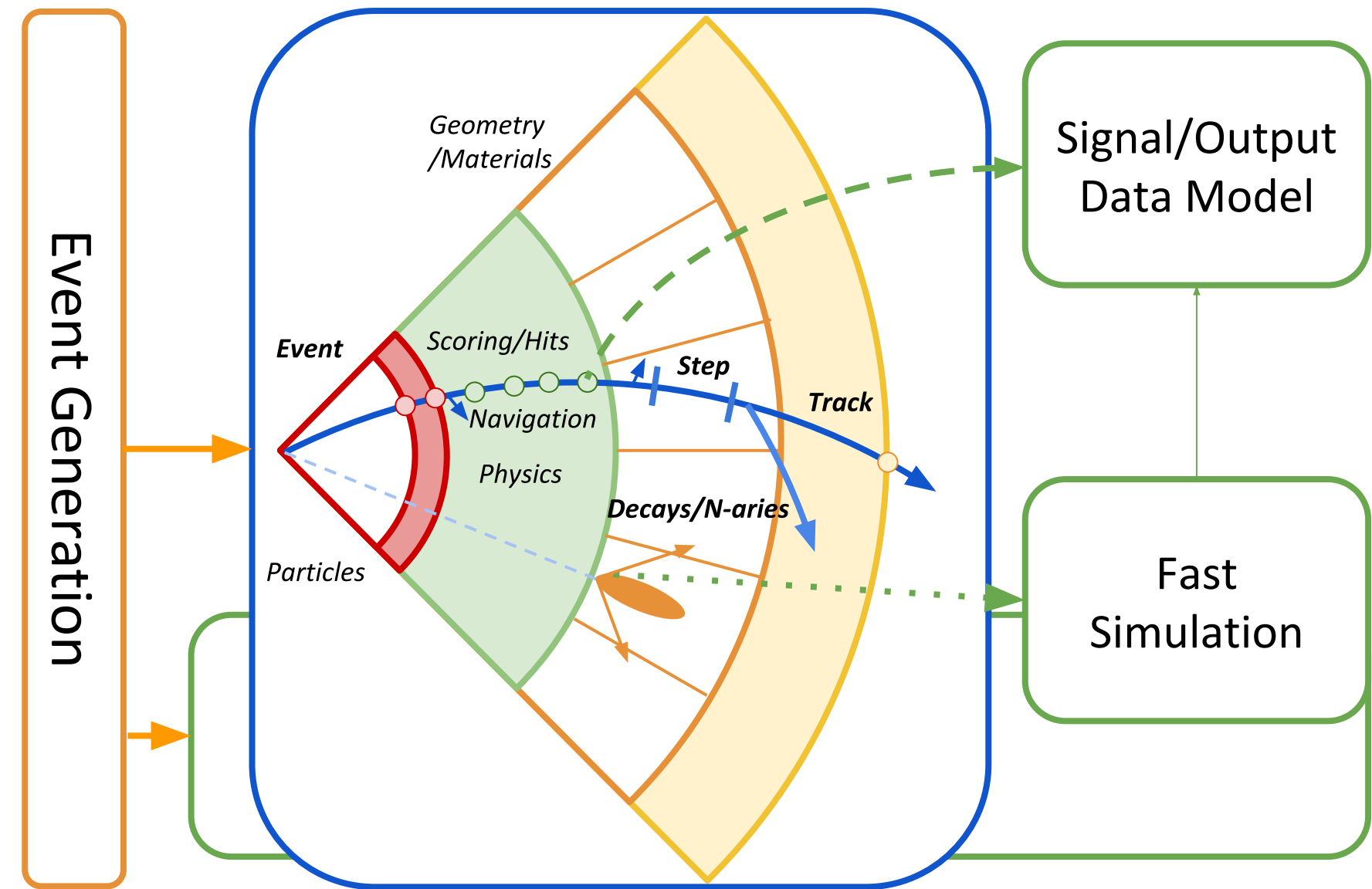




Full Simulation of HEP Detectors with Geant4

Ben Morgan

Workshop on Efficient Computing for HEP
Edinburgh 17-18 February 2020



Scope of Full Detector Simulation

Event generators and Fast
Simulation in other talks

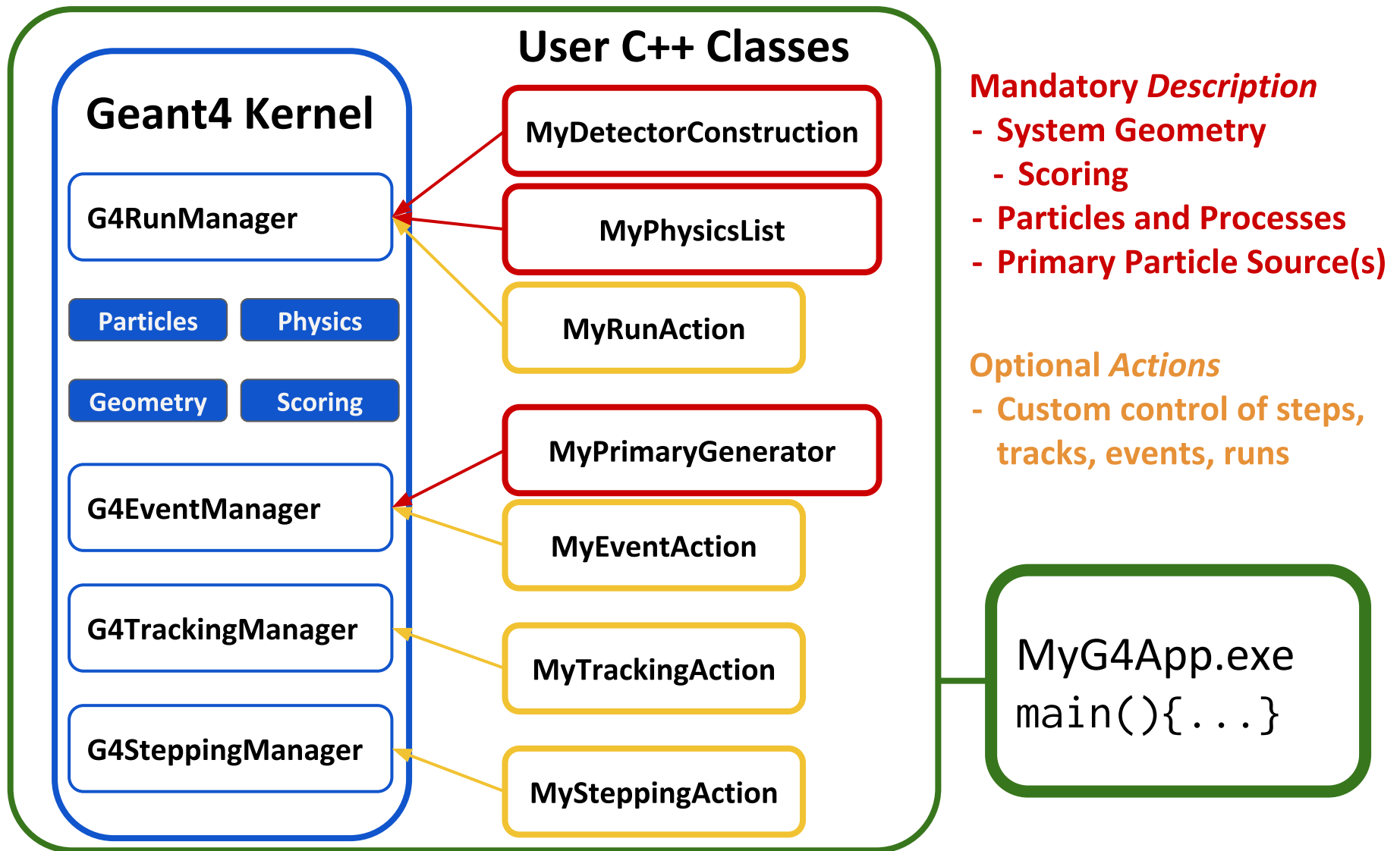
Software for Detector Simulation

- **Primary** software used by HEP is **Geant4(*)**



- *Others like Fluka, MCNPX, EGSnrc, used in limited or very specialized applications*

● (*) “Geant4” not “Geant”, “4” isn’t a version, and “Geant4” is not an acronym...

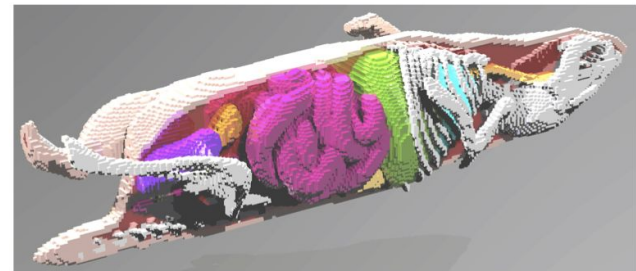
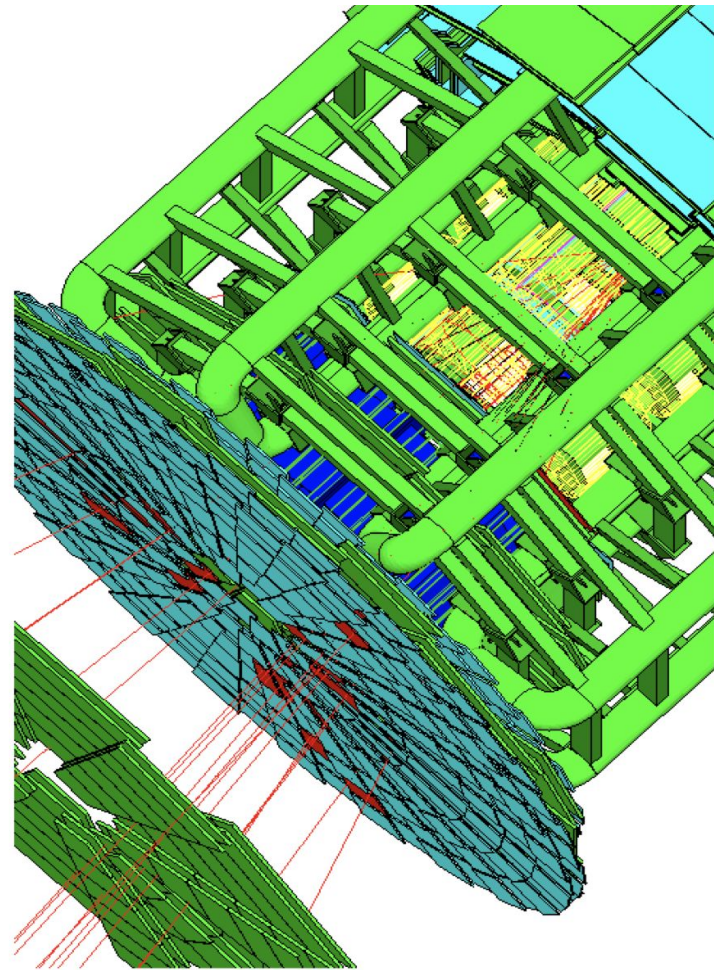


Geant4 in Brief

A general purpose C++ Monte Carlo simulation toolkit for elementary particles passing through and interacting with matter

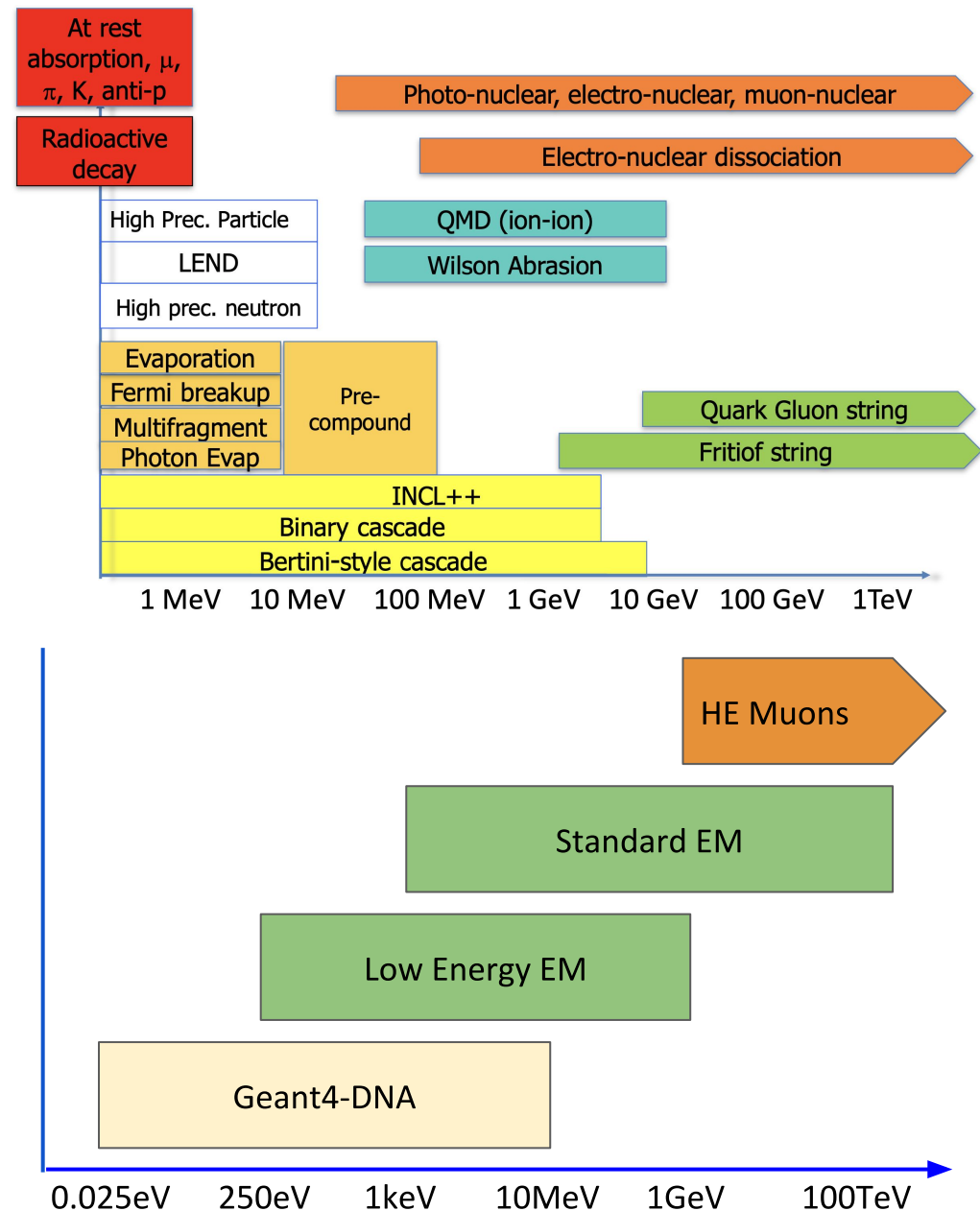
Geant4 Capabilities: Geometry

- Rich collection of shapes
 - *CSG, Union, Tessellated, User...*
- Arrange in a hierarchical or flat structure
 - *Handles up to $O(10^9)$ volumes*
 - *Tools for creating and checking complex structure*
 - *Third party tools for CAD import*
- Fast navigation in complex models via automatic voxelization
- Optional use of **VecGeom** for improved performance with some shapes



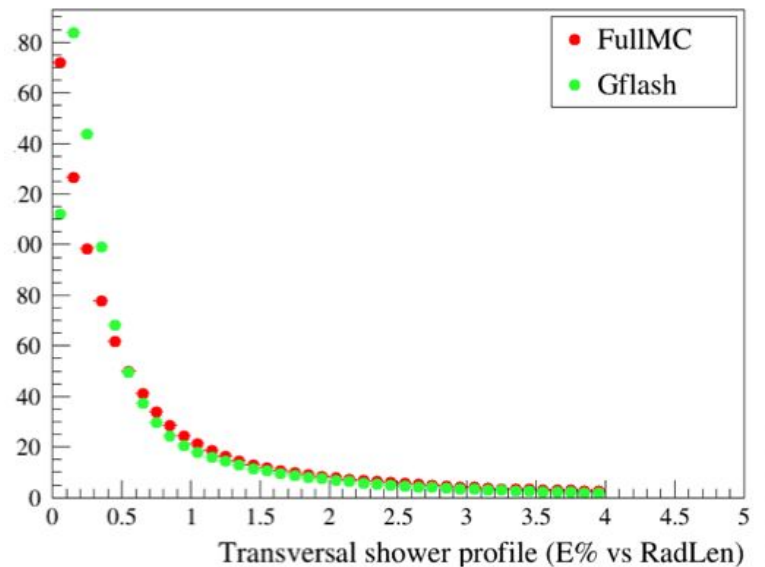
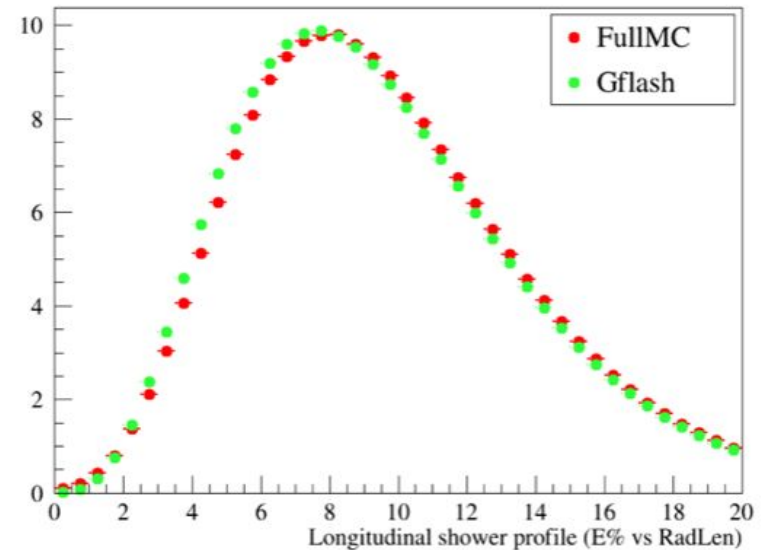
Geant4 Capabilities: Physics Models

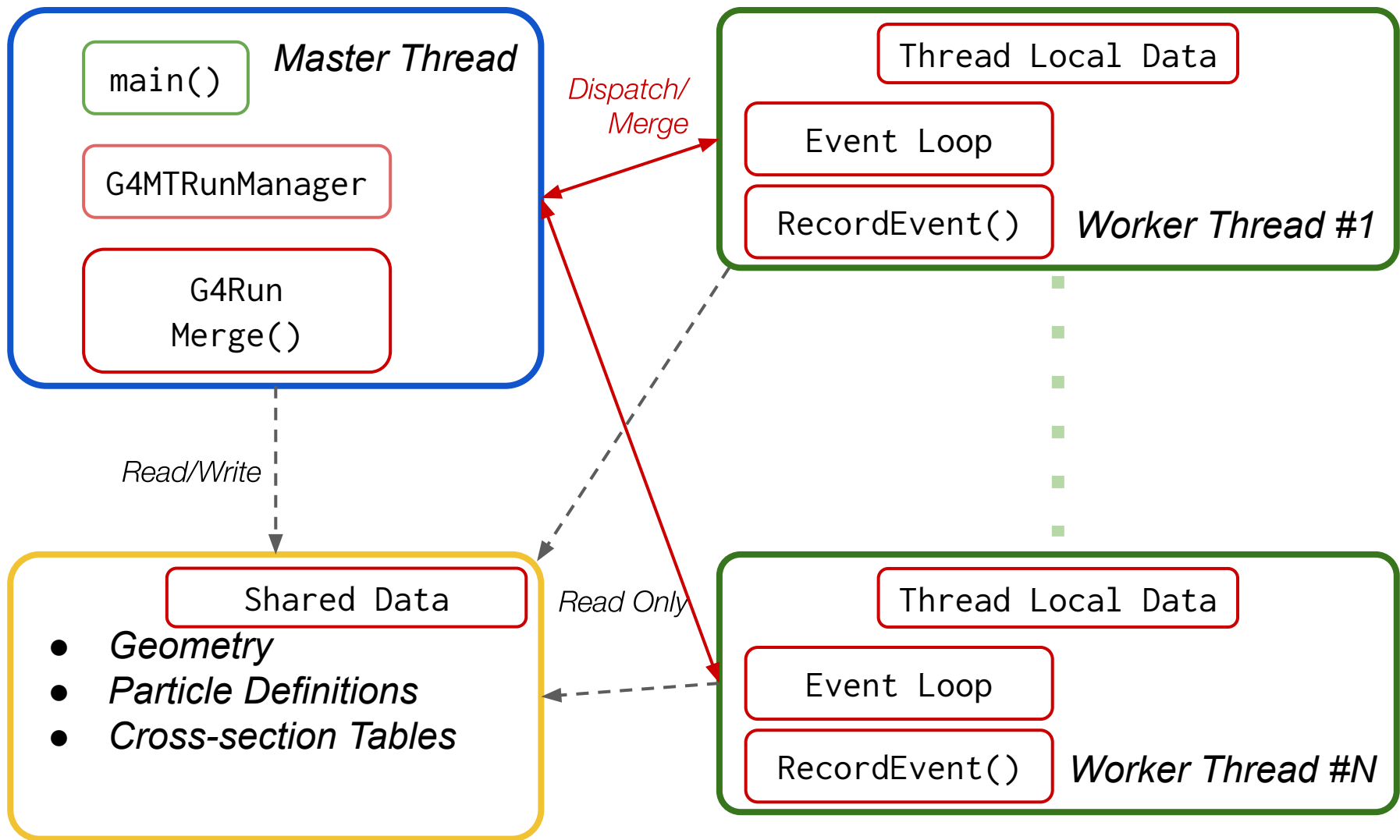
- Rich range offered:
 - *Electromagnetic*
 - *Hadronic/Nuclear*
 - *Photon/lepton-hadron*
 - *Optical photons*
 - *Decays*
 - *Shower parametrization*
 - *Event biasing*
 - *User defined*
- Cover energy ranges from sub eV to multi-TeV
- Alternative models to allow user to optimize for their application,
 - *e.g. trade speed for accuracy*



Geant4 Capabilities: Fast Methods

- **Fast simulation** hooks to override detailed tracking:
 - *In defined geometric regions...*
 - *... for given particle types...*
 - *... with a specified model*
- **Parallel world geometry**
 - *E.g. average density bulk for low energy EM particles in shower, full geometry for muons*
- **Wide range of **biasing** methods/hooks provided**
 - *Importance sampling*
 - *Primary/leading particle*
 - *Adjoint/Reverse Monte Carlo*
 - *Generic/extensible physics-based*
 - *Generic/extensible add/remove, e.g. splitting, Russian roulette*

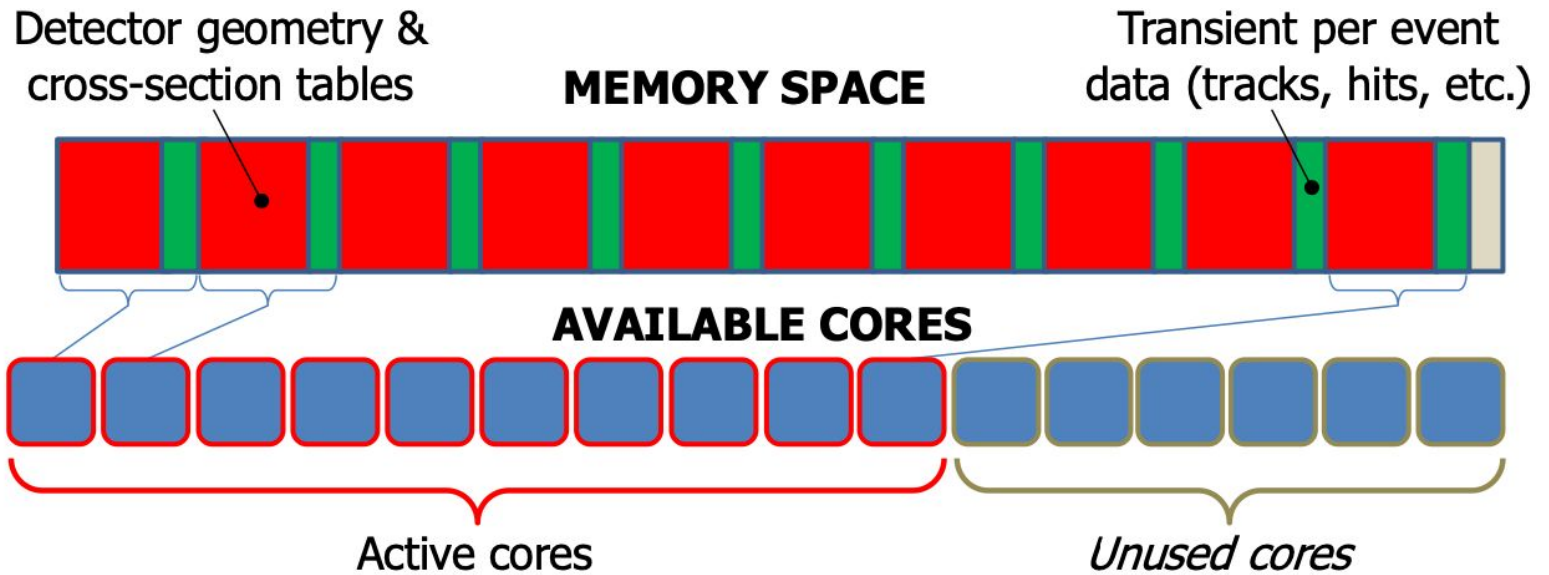




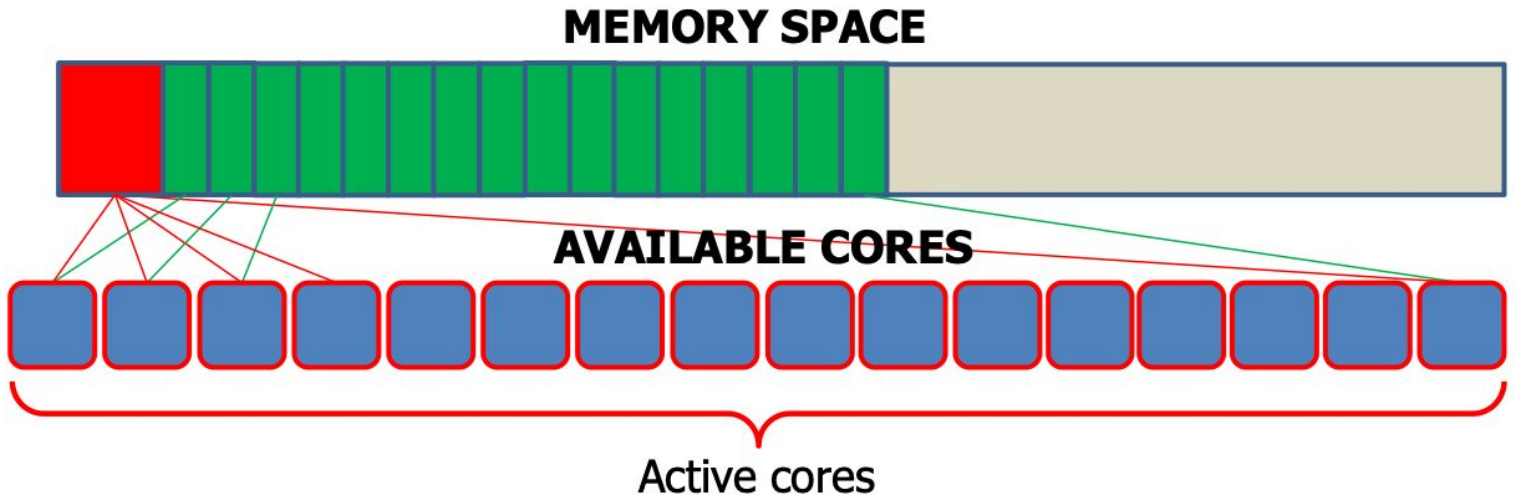
Geant4 Capabilities: Multithreading

Event level parallelism
Minimal API changes for
*Sequential->MT user code*₈

Sequential



Multithread



Multithreading: Efficient Resource Usage

Multithreading yields better usage of Cores+Memory

Geant4 Development History

R&D Phase (RD44)

- Early discussions, e.g. CHEP 94
- Dec 1994: CERN/RD44 starts
- Apr 1997: Alpha release
- Jul 1998: Beta release
- **Dec 1998: Geant4 1.0**

Production Phase

- Several major architectural changes
 - STL migration, cuts-per-region, parallel worlds...
- **Multithreading:** Developed 2011-2013 (G4MT 9.4-9.6)
- **Dec 2013: Geant4 10.0.0 public release with Multithreading**
 - *With minimal changes to user code!*
- **Dec 2019: Geant4 10.6.0**

12,644 documents have cited:

GEANT4 - A simulation toolkit

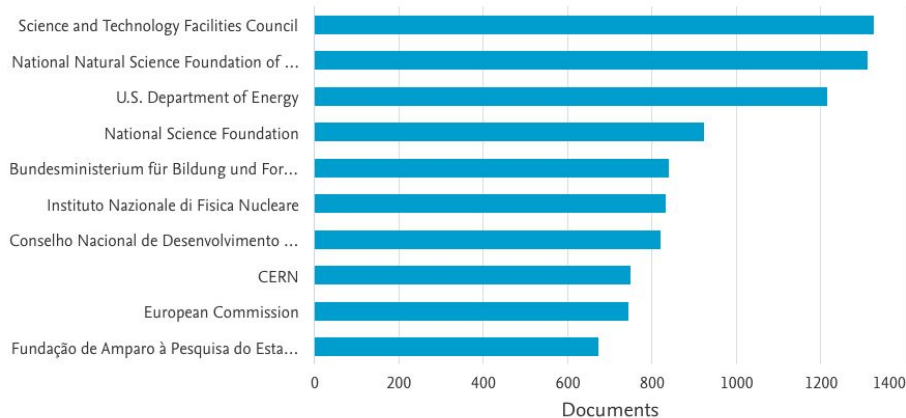
Agostinelli S., Allison J., Amako K., Apostolakis J., Araujo H., Arce P., Asai M., (...), Zschesche D.

(2003) Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 506 (3) , pp. 250-303.

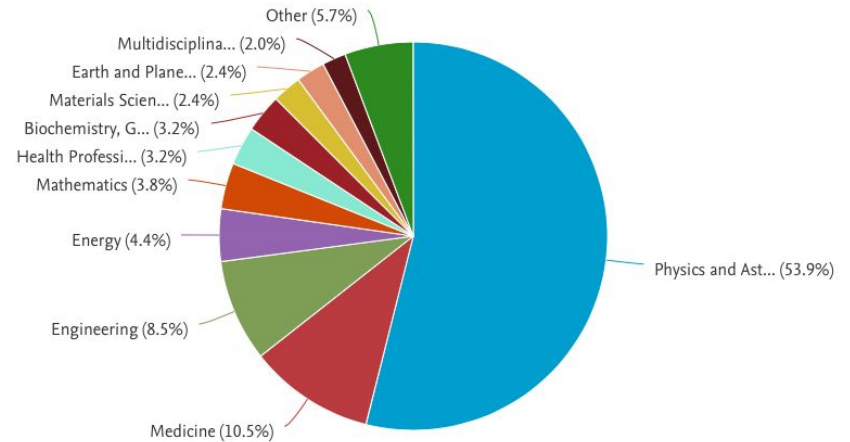
Set feed

Documents by funding sponsor

Compare the document counts for up to 15 funding sponsors.



Documents by subject area



Geant4 - A simulation toolkit
[NIM A, vol 506\(3\), pp250-303, 2003](#)

Significant use across many research areas, considered mission critical for HEP

647 documents have cited:

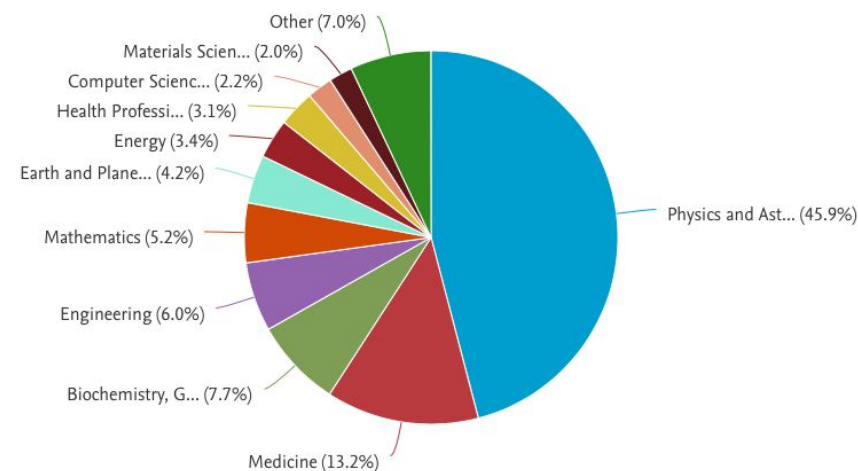
Recent developments in GEANT4

Allison J., Amako K., Apostolakis J., Arce P., Asai M., Aso T., Bagli E., (...), Yoshida H.

(2016) Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 835 , pp. 186-225.

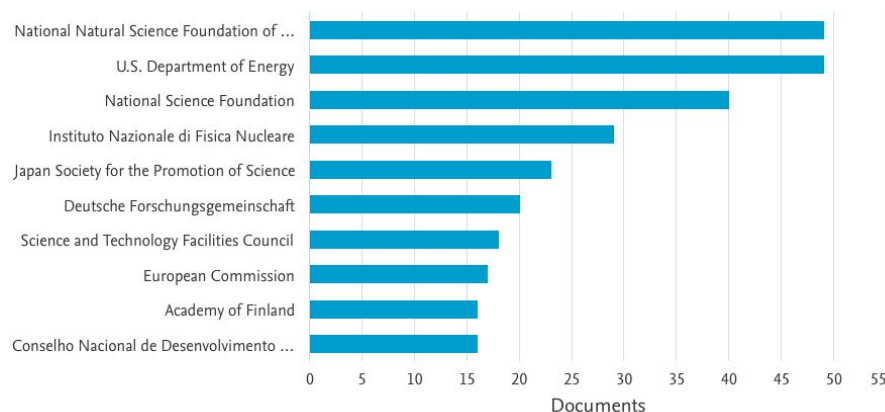
📡 Set feed

Documents by subject area



Documents by funding sponsor

Compare the document counts for up to 15 funding sponsors.



Recent developments in Geant4
[NIM A, vol 835, pp 186-225](#)

Reflects major upgrades to
capability and **usability** of
 version 10 series

Overview

Geant4 is a toolkit for the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science. The three main reference papers for Geant4 are published in Nuclear Instruments and Methods in Physics Research [A 506 \(2003\) 250-303](#), IEEE Transactions on Nuclear Science [53 No. 1 \(2006\) 270-278](#) and Nuclear Instruments and Methods in Physics Research [A 835 \(2016\) 186-225](#).

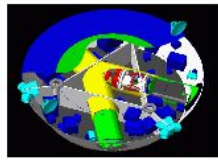
Applications



A sampling of applications, technology transfer and other uses of Geant4

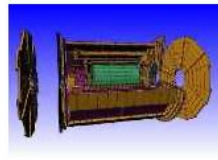
[printer-friendly version](#)

User Support



Getting started, guides and information for users and developers

Publications



Validation of Geant4, results from experiments and publications

Collaboration



Who we are: collaborating institutions, [members](#), organization and legal information

News

- **6 Dec 2019**
Release 10.6 is available from the [download area](#).
- **17 Apr 2019**
Patch-01 to release 10.5 is available from the [source archive](#) area.

Events

- [Geant4 Course at the 17th Seminar on Software for Nuclear, Sub-nuclear and Applied Physics](#), Porto Conte, Alghero (Italy), **24-29 May 2020**.
- **25th Geant4 Collaboration Meeting**, IRISA Laboratory, Rennes (France), **21-25 September 2020**.
- **4th Geant4 International User Conference** at the Physics-Medicine-Biology Frontier, Napoli (Italy), **19-21 October 2020**.

Past Events

Geant4 Collaboration

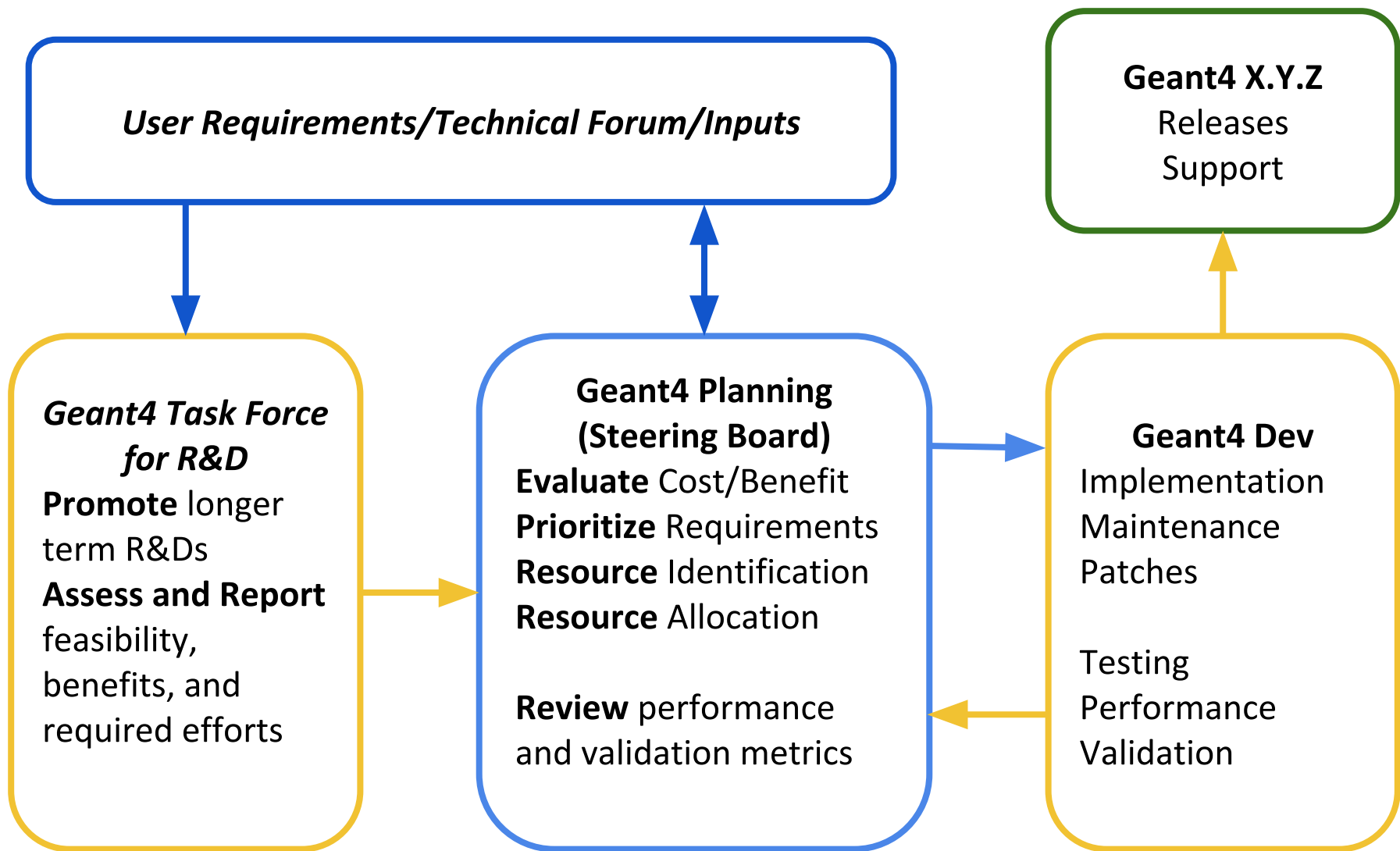
~130 members, ~30FTE
 2 UK members from HEP, 4
 from medicine, industry

Geant4 Development Principles

1. Provide excellent **support** to users
2. **Maintain** the toolkit for long-term **sustainability**
 - a. *Flexible and easy **integration** with user/project codes*
3. Improve the **precision and energy range of physics models**
4. Improve the **performance** of the toolkit

*Recognizes **mission critical** nature of Geant4 for HEP*

*First three principles are **crucial** to realize the fourth*



Geant4 Development Process

Provides balance between the four principles

Geant4 Task Force for R&D

- Promote and survey research activities:
 - *Potential **software architect** updates to Geant4*
 - *use of **emerging technologies/computing architectures** of benefit to Geant4*
- Ensure the visibility of such explorations and act as the focal point for such **activities inside and outside of the Collaboration**
- Where appropriate, conduct benchmarking comparison and provide/assist communication/support among R&D activities
- Make timely assessment reports to Steering Board with **solid proof of benefits**
- *Based on assessments of this Task Force, once a concrete and beneficial architectural revision is identified, the Steering Board launches a new, dedicated, task force to create workflow, estimate required resources and drive that particular development for integration into the code base.*
 - *As was done for Multithreading and prior revisions*

geant4-forum.web.cern.ch

GEANT4

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all categories Latest Top Categories

Topic Replies Views Activity

Strange visualisation Geant4.10.6 Recording, Visualizing and Persisting Data	0	2	1h
Multi target in the B1 example Getting Started	0	2	3h
How to get track starting point Particles, Track, Event, Run and Biasing	3	37	9h
Underestimating neutron flux Physics Processes, Models and Cross Sections	5	112	17h
Using Qt with OpenGL Getting Started	6	57	1d
How to find optical properties? Geometry, Fields and Transportation	1	21	1d
G4Trap coplanarity problem with GEANT4 version >=10.4 Geometry, Fields and Transportation	1	11	2d
How to remove error? Getting Started	6	80	2d
First event has enhanced inelastic interaction probability Physics Processes, Models and Cross Sections	0	9	2d
Define optical properties of materials in gdmf files Geometry, Fields and Transportation	1	27	2d

bugzilla-geant4.kek.jp

GEANT4

Geant4 Problem Tracking System

Bugzilla/Geant4 - Main Page

Home | New | Browse | Search | Search [7] | Reports | New Account | Log In | Forgot Password

Geant4 Problem Tracking System

This is Geant4 problem tracking system which files details of problems reported by users and developers. Each report is given a number, and is kept on file until it is marked as having been dealt with. For participating you need a personal account which will gain you the ability to post reports and comments as well as voting for specific reports and observe development. You'll need to enable cookies for this site for staying logged in.

Problem Reports

Report a new problem
Components list

Searching

Find a specific problem
Query problem reports (advanced)
Quick search

Tracking

Open problems
New problems (not yet responded)
The latest updated problems (in the past 120 days)
The latest fixed problems (in the past 120 days)

New Account

To submit a new problem, you need to have an account in Bugzilla/Geant4. Login ID is a legitimate e-mail address, which will be used for communication during bug tracking.

Create a new account

Problem #: Go

Not Secure - geant4-userdoc.web.cern.ch

Book For Application Developers

10.6

Search docs

- Introduction
- Getting Started with Geant4 - Running a Simple Example
- Toolkit Fundamentals
- Detector Definition and Response
- Tracking and Physics
- User Actions
- Control
- Visualization
- Analysis
- Examples
- Appendix
- Bibliography

Docs » Geant4 Book For Application Developers

Geant4 Book For Application Developers

Scope of this manual

The User's Guide for Application Developers is the first manual the reader should consult when learning about GEANT4 or developing a GEANT4 -based detector simulation program. This manual is designed to:

- introduce the first-time user to the GEANT4 object-oriented detector simulation toolkit,
- provide a description of the available tools and how to use them, and
- supply the practical information required to develop and run simulation applications which may be used in real experiments.

This manual is intended to be an overview of the toolkit, rather than an exhaustive treatment of it. Related physics discussions are not included unless required for the description of a particular tool. Detailed discussions of the physics included in GEANT4 can be found in the [Physics Reference Manual](#). Details of the design and functionality of the GEANT4 classes can be found in the [User's Guide for Toolkit Developers](#).

GEANT4 is a detector simulation toolkit written in the C++ language. The reader is assumed to have a basic knowledge of object-oriented programming using C++. Although GEANT4 is a fairly complicated software system, only a relatively small part of it needs to be understood in order to begin developing detector simulation applications. An understanding of radiation physics and associated processes is beneficial.

Status of this Document

Guide for Application Developers using the GEANT4 toolkit.

Indico.cern.ch

Europe/Zurich English Login

Geant4 Advanced Course @ CERN

24-26 March 2020
CERN
Europe/Zurich timezone

Search...

Overview

- Timetable
- Contribution List
- Registration
- Access Cards
- How to get to CERN (link)
- Laptops and Wireless access
- On-site Information
- Accommodation
- Local Committee

Geant4 Training 2020

GEANT4

A SIMULATION TOOLKIT

Tutorial on Geant4 for users interested to improve their understanding and usage of Geant4. Appropriate for creating intermediate and advanced applications in any domain, with emphasis on topics most relevant to experiments in High Energy or Nuclear Physics. This is a tutorial course based on Geant4 version 10.6.

Lectures will cover the most advanced features of Geant4 starting from the basic building blocks covered in the beginners course, interspersed with discussion sessions.

The course is expected to be of interest to users with intermediate experience in Geant4 and familiarity with the toolkit. Participants are expected to have a reasonable knowledge of C++.

Support and Sustainability

A critical foundation for performance: best practice, early problem reporting

Why GitHub?EnterpriseExplore

Geant4 / geant4

CodePull requests 2Actions

Project overviewDetailsActivityReleasesCycle Analytics

Geant4 toolkit for the simulation of the passage of particles through matter

59 commits37 branches

Branch: masterNew pull request

gcosmo Import Geant4 10.6.0 source tree

.githubAdd missing

ReleaseNotesImport Gear

cmakeImport Gear

configImport Gear

environmentsImport Gear

examplesImport Gear

sourceImport Gear

.gitignoreImport Git/H

CHANGELOGImport Gear

CMakeLists.txtImport Gear

CONTRIBUTING.mdGeant4 10.6

LICENSEImport Gear

README.rstImport Gear

README.rst

Geant4: A Simulation

gitlab.com

GitLabProjectsGroupsSnippetsHelp

Search or jump to...Sign in

G4 geant4

Project ID: 8366

59 Commits37 Branches101 Tags271.4 MB Files

Geant4 toolkit for the simulation of the passage of particles through matter

NIM A 506 (2003) 250-303 - IEEE TNS 53 No. 1 (2006) 270-278 - NIM A 835 (2016) 186-225

mastergeant4HistoryFind file

Import Geant4 10.6.0 source treeGabriele Cosmo authored 2 months ago5baee230

READMELICENSECHANGELOGCONTRIBUTING

Name	Last commit	Last update
.github	Add missing source/parameterisations to github owners	7 months ago
ReleaseNotes	Import Geant4 10.6.0 source tree	2 months ago
cmake	Import Geant4 10.6.0 source tree	2 months ago
config	Import Geant4 10.6.0 source tree	2 months ago
environments	Import Geant4 10.6.0 source tree	2 months ago
examples	Import Geant4 10.6.0 source tree	2 months ago
source	Import Geant4 10.6.0 source tree	2 months ago
.gitignore	Import Git/Hub support files	7 months ago
CHANGELOG	Import Geant4 10.3.0 source tree	3 years ago
CMakeLists.txt	Import Geant4 10.6.0 source tree	2 months ago
CONTRIBUTING.md	Geant4 10.6.0 beta	7 months ago

GitLab/Hub

Releases/Patches/Betas

Overview

Timetable

Contribution List

Participant List

Videoconference Rooms

Timetable

< Thu 16/01 >

Print

PDF

Full screen

Detailed view

Filter

Session legend

16:00	Introduction <i>Makoto Asai</i> link 13/2-005, CERN 16:00 - 16:08
	What's new in 10.6 - non-physics part <i>Dr Gabriele Cosmo</i> link 13/2-005, CERN 16:08 - 16:21
	What's new in 10.6 - EM physics part <i>Prof. Vladimir Ivantchenko</i> link 13/2-005, CERN 16:21 - 16:34
	What's new in 10.6 - Hadronic physics part <i>Alberto Ribon</i> link 13/2-005, CERN 16:34 - 16:47
	Open requirements <i>Marc Verderi</i> link 13/2-005, CERN 16:47 - 17:00
17:00	ATLAS <i>Marilena Bandieramonte</i> link 13/2-005, CERN 17:00 - 17:12
	CMS <i>Sunanda Banerjee et al.</i> link 13/2-005, CERN 17:12 - 17:24
	Geant4 in LArTPC simulation <i>Tingjun Yang</i> link 13/2-005, CERN 17:24 - 17:36
	"pyg4ometry" to load/manipulate/save/visualise/convert GDML/Fluka/CAD geometry <i>Prof. Stewart Takashi Boogert et al.</i> link 13/2-005, CERN 17:36 - 17:48
	Tetrahedral mesh navigator <i>Hassan Hachimi</i> link

Technical Forum

Regular meetings to collect user requirements to guide **workplan** and **priorities**, and update the community on new developments 19

HEP Requirements (LHC, CALICE, FCC)

- Only a flavour!
 - *Hadronic models for c and b -mesons*
 - *“Sub-event” parallelism to handle high-memory events*
 - *Very high energy physics effects (FCC-hh)*
 - *Navigation with VecGeom*
 - *Gamma polarization in high energy EM models*
- Plus bug reports and general support

Neutrino/Low Background Requirements

- Again, only a selection
 - *Specialized physics models for Liquid Argon detectors*
 - *Detailed output from hadronic cascades*
 - *Better performance for optical photons*
 - *Built-in neutrino interactions*
 - *Neutron self-shielding*
 - *Gamma induced neutron backgrounds*
- Plus bug reports and general support
 - *Particularly valuable for data-driven decays/cross-sections*

Continuous Testing

On each new GitLab Merge Request:

- *Code review by developers, quality checks (clang tools)*
- *Each change compiled and simple unit tests/applications run, ~45mins per change*

Nightly Testing

Set of pre-approved MRs: Unit/FPE/BoundsChecking tests, Valgrind, low statistics benchmarking and validation

- *~500 CPU hours per night on shared CERN-SFT resources*

Monthly/Release Candidate/Release Tests

Detailed static analysis with Coverity

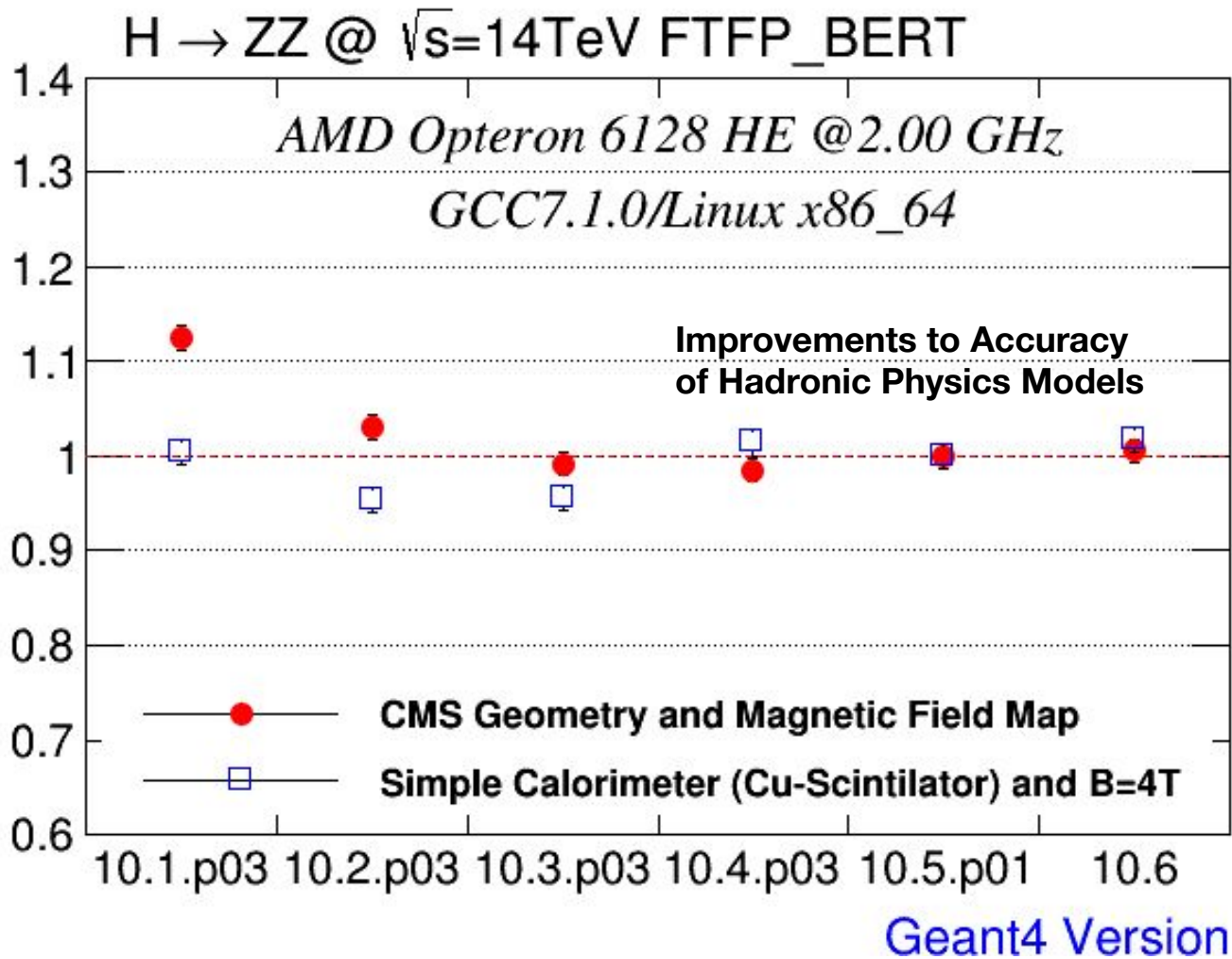
*High statistics **benchmarking** (OpenSpeedShop, IgProf) and **validation** on FNAL Wilson Cluster*

- *~60 profiling rounds per year, ~320000 CPU hours*
- *~23 validation rounds, ~23000 CPU hours*
- <https://g4cpt.fnal.gov>

Maintaining Physics Precision and Performance

Dedicated [Testing and Quality Assurance Working Group](#)

Ratio of CPU Time/Event to 10.5.p01



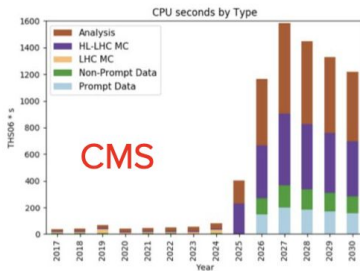
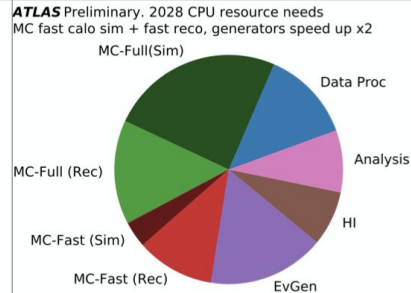
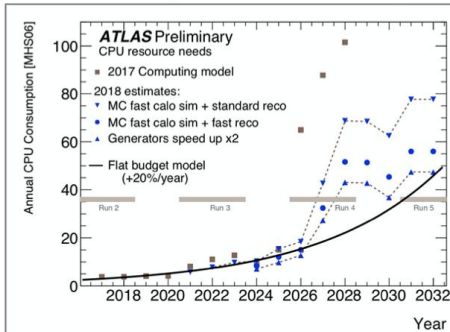
<https://g4cpt.fnal.gov>

20% speedup from 9.6-10.0
Further speedups **plus** better
physics accuracy

Many physics and performance studies require large datasets of simulated events

- Geant4 is highly CPU-intensive
- Already lacking statistics -- increasing luminosity poses greater challenges

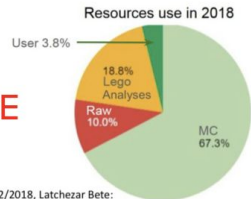
ATLAS



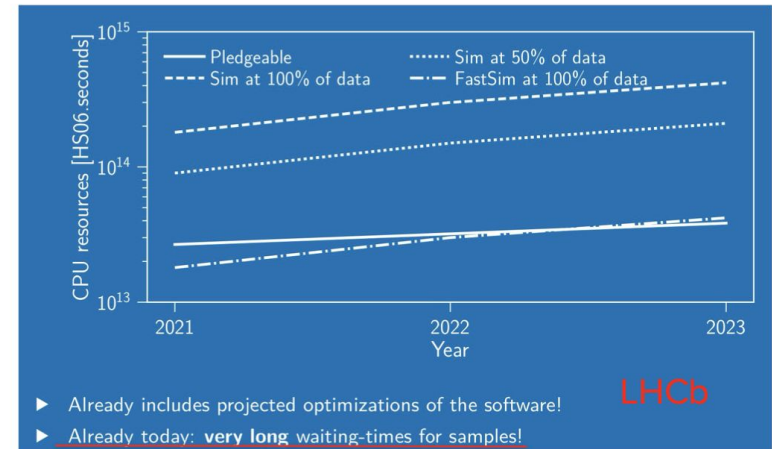
- Simulate more events to keep up with HL-LHC data volumes: 10x(Phase1)
- May also need to improve accuracy of physics lists to simulate HGCal
- Reconstruction will take longer due to high pileup and granular detectors
- Need more events, more accuracy, in more complicated geometry... w/ relatively smaller fraction of total CPU usage

- 2/3 of the computing resources are dedicated to MC simulation, all full sim
- fast sim not used in production yet
- fully parametrised fast simulation approach for upgrade studies
- expected 10-100 times more data in Runs 3 and 4
- cannot cover that with current usage of full sim

ALICE



ALICE Week, 12/12/2018, Latchezar Bete:



- Already includes projected optimizations of the software!
- Already today: very long waiting-times for samples!

4

HL-LHC Needs on Simulation Performance

Don't forget Neutrino, Low Background, Beamlines. Some specific challenges/differences

24

Near/Longer Term Developments

- Near term modernization/optimization of Geant4
 - *Tasking framework*
 - *Physics/Geometry/Kernel algorithms*
 - *Code/data layout, call sequencing, reduce state*
- R&D on **tooling to assist fast simulation development**
- R&D on potential **use of accelerators** such as GPUs and/or FPGAs

Tasking Framework

- Pool of threads without predefined call stack
- “Tasks” ~ function calls placed on a queue
- Pooled threads idle until tasks pushed to queue
- No major API changes
- Potential for sub-Event parallelism
 - *E.g. each primary G4Track could be processed as a task*
- May be important for leveraging accelerators
 - *Thread pools for “CPU” and “Accelerator”*
 - *Offload suitable tasks to accelerator queue*
- ***On Geant4’s workplan for 2020/21***

Usage of VecGeom

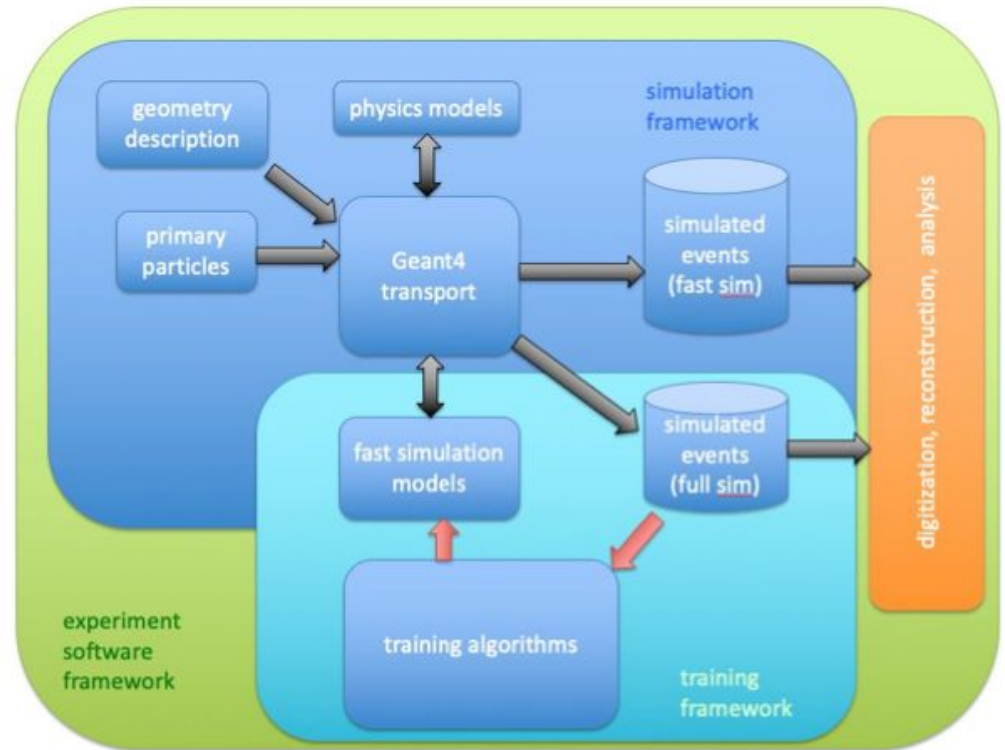
- Common library for HEP to describe geometry
 - *Improved scalar algorithms*
 - *Uses SIMD where possible*
 - *Shapes + distance/containment algorithms*
 - *Modelling + navigation: “ray tracing”*
- VecGeom **Shapes** as optional feature in Geant4 since 10.4, planned to become **production default in 2020**
 - *7-13(2-4)% speedup in CMS(ATLAS)*
- VecGeom **Navigation** as **optional feature (Beta version) in Geant4’s 2020 release**

Refactoring Transportation

- A core process in Geant4, navigates particles through geometry and fields
- Only one transportation in memory, and handles all particle types (neutral/charged/photons)
 - *Results in frequent if/else branches*
 - *... On charge to decide on field computation*
 - *... On type to compute group velocity*
- **Study underway on transportation per-type**
 - *One each for neutral/charged particles*
 - *Eventually one for optical photons*
 - *Reduces branching and redundant calls*

Integrating Full/ Fast Simulation

- “Fast” (non-stepping) methods essential at HL-LHC to gain statistics
- Geant4’s fast/biasing hooks allow easy integration of models **once developed**
- R&D on tooling/methods to assist users develop or train their experiment dependent models



R&D on Use of Accelerators

- Full simulation not a natural candidate for GPUs/FPGAs
 - *Few localized hotspots*
 - *Many branches, special cases, large data tables*
 - *Work unknown in advance (Monte Carlo!)*
- Some success for limited use cases over the past 5-7 years
 - *Low-Energy EM in simple geometries, Neutron/Optical Photon transport*
- Portability, usability, flexibility, sustainability **must** be retained
 - *Otherwise any gains could easily be lost in maintenance/support*
- *Accelerators are here to stay for the near future though, so where might benefits be found for full simulation?*

Existing Studies with Accelerators

- MPEXS, MPEXS-DNA for radiotherapy/biology
 - *Voxelized phantom and single material only, only $e^-/e^+/g$ at energies up to $\sim 100\text{MeV}$*
- GATE for PET/CT applications
 - *Voxelized phantom only, very limited set of EM processes at low energies*
- Opticks for optical photons using NVidia OptiX
 - *“Offload” photon processes/tracing to GPU, plus handlers for ray tracing with CSG/binary tree geometries (GDML)*
- Project at ORNL studying thermal and colder neutron transport with tessellated geometries
- ***Highlight many of the challenges involved with general Monte Carlo on accelerators***

Potential Accelerator R&D Explorations

- Geant4 work on Tasking, Transportation, Geometry
 - *Providing enhancements to users **right now** in addition to steps in reducing issues for Accelerators such as branching*
 - *Tasking may be important in “offloading” work*
- Further exploration of Neutron/Optical Photon transport
- EM physics at higher energies in restricted volumes
- VecGeom navigation and algorithms such as ray tracing
- APIs such as oneAPI/Alpaka/Kokkos for portability/sustainability
- See Geant4 R&D Task Force Meetings for more
 - *<https://indico.cern.ch/category/11208/>*

Summary

- Geant4 the primary full simulation toolkit for HEP
- *Architectural, performance, and physics enhancements delivered to experiments over >20 years*
- Near and longer term developments plus R&D underway on performance enhancements
 - *Geant4 work on kernel tasking, transportation, geometry, important stepping stone to future enhancements*
 - *Task Force for R&Ds on longer term work, inc accelerators*
 - ***Whilst maintaining physics accuracy, usability, and sustainability for experiments over the coming decade***