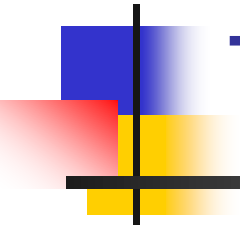
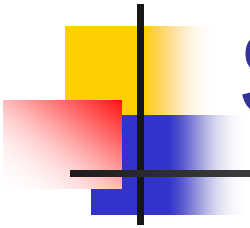


This course

Structure and logistics - 1



- This course is organized in a mixture of theoretical lectures and practical hands-on sessions
  - The hands-on sessions require real C++ coding to build up a simplified Geant4 application
  - Staged approach in tasks
  - **`http://geant4.lngs.infn.it/alghero2018/introduction`**
- A pre-installed virtual machine is provided for the hands-on sessions
  - Includes **Geant4 10.4** on a Linux environment
  - You should already have it downloaded and tested
    - Please let us know ASAP if you have problems with the VM

Structure and logistics - 2

- You can try to install Geant4 on your (Linux/Mac) laptop, if you wish
  - The course is not meant to show that, though
- All lectures (pdf) will be uploaded on-the-fly on the course indico page
  - **`https://agenda.infn.it/event/AlgheroSeminar2018`**
  - Please **feel free to ask any question**, either during the lectures , during the exercises or during the breaks
- Solutions of the exercises will be uploaded after the end of each exercise session

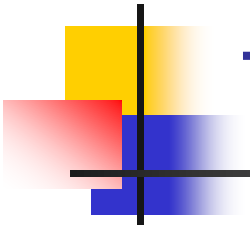
Monte Carlo techniques and GEANT4 concept

Luciano Pandola

INFN – Laboratori Nazionali del Sud

Geant4 Course, XV Seminar on Software for Nuclear, Subnuclear and Applied Physics,
Alghero, May 28th- June 1st, 2018

What Monte Carlo (MC) techniques are for?



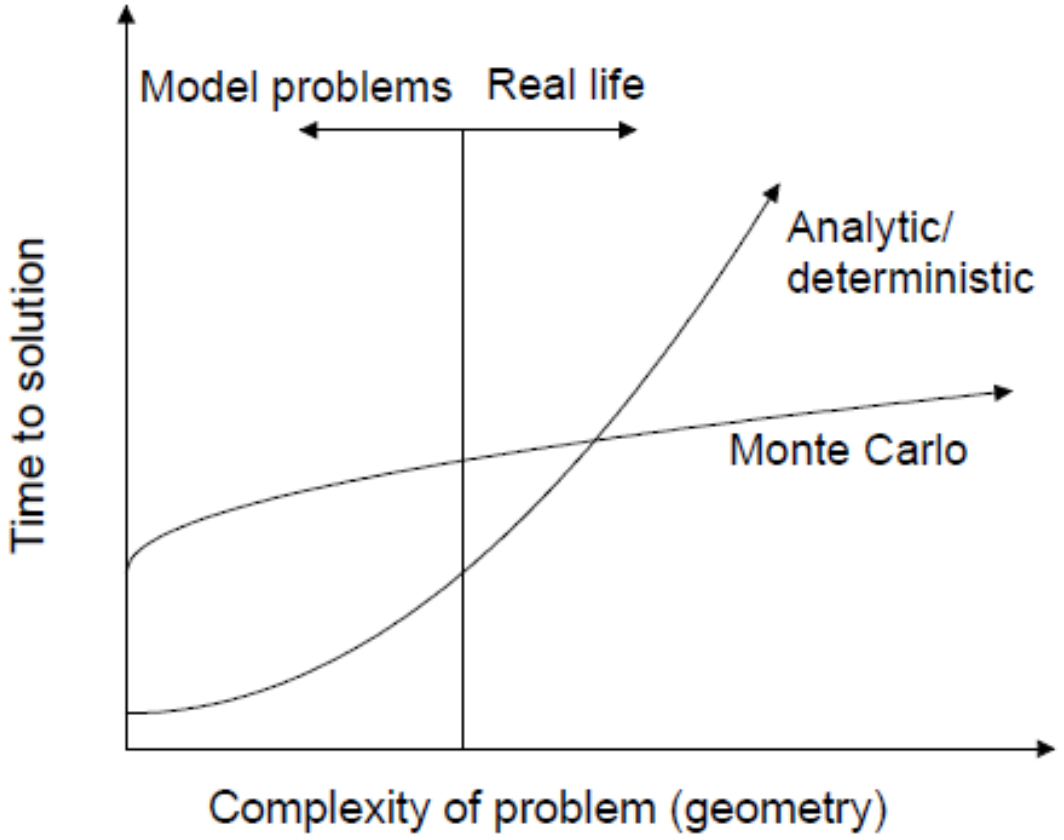
- Numerical solution of a (**complex**) macroscopic problem, by simulating the microscopic interactions among the components
- Uses random sampling, until convergence is achieved
  - Name after Monte Carlo's casino
- Applications not only in physics and science, but also finances, traffic flow, social studies
  - And not only problems that are intrisically probabilistic (e.g. numerical integration)

MC in science

- In physics, elementary laws are (typically) **known** → MC is used to predict the outcome of a (complex) experiment
  - Exact calculation from the basic laws is unpractical
  - Optimize an experimental setup, support data analysis
- Can be used to validate/disproof a theory, and/or to provide small corrections to the theory
- In this course: Monte Carlo for particle tracking (interaction of radiation with matter)

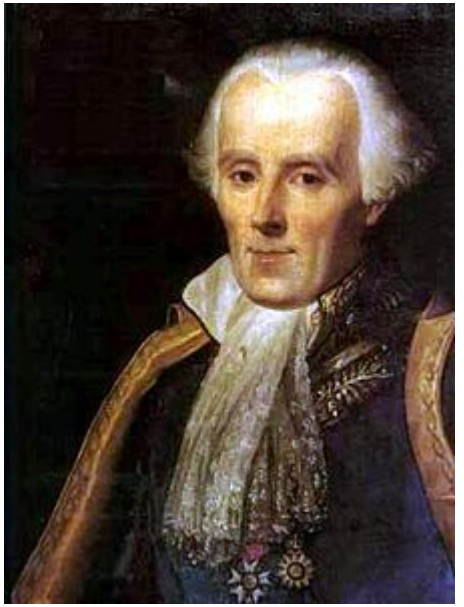
When are MC useful wrt to the math exact solution?

- Usually the Monte Carlo wins over the exact (mathematical) solution for **complex** problems



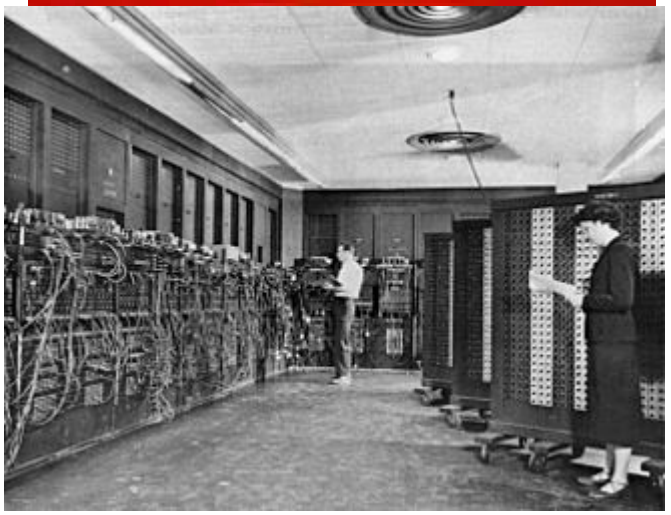
A bit of history

- Very concept of Monte Carlo comes in the XVIII century (Buffon, 1777, and then Laplace, 1786)
  - Monte Carlo estimate of π
- Concept of MC is much older than real computers
  - one can also implement the algorithms manually, with dice (= Random Number Generator)



A bit of history

- Boost in the '50 (Ulam and Von Neumann) for the development of thermonuclear weapons
- Von Neumann invented the name "Monte Carlo" and settled a number of basic theorems
- First (proto)computers available at that time
  - MC mainly **CPU load**, minimal I/O



A bit of history

JOURNAL OF THE AMERICAN STATISTICAL ASSOCIATION

Number 247 SEPTEMBER 1949 *Volume 44*

THE MONTE CARLO METHOD

NICHOLAS METROPOLIS AND S. ULAM
Los Alamos Laboratory

THE JOURNAL OF CHEMICAL PHYSICS VOLUME 21, NUMBER 6 JUNE, 1953

Equation of State Calculations by Fast Computing Machines

NICHOLAS METROPOLIS, ARIANNA W. ROSENBLUTH, MARSHALL N. ROSENBLUTH, AND AUGUSTA H. TELLER,
Los Alamos Scientific Laboratory, Los Alamos, New Mexico

AND

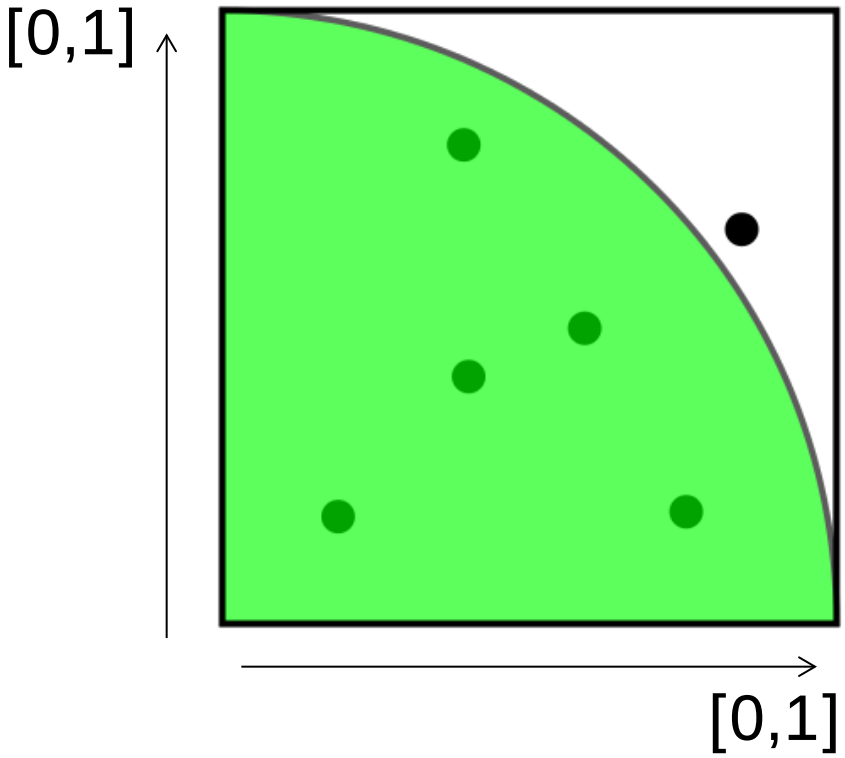
EDWARD TELLER,* *Department of Physics, University of Chicago, Chicago, Illinois*

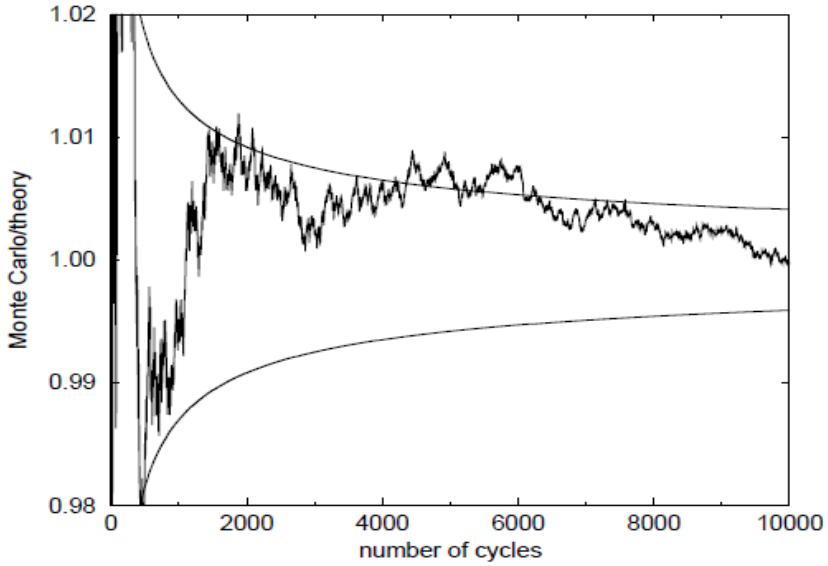
(Received March 6, 1953)

With MANIAC: the first electronic digital computer

The simplest MC application: numerical estimate of π

- Shoot N couples (x,y) randomly in [0,1]
- Count n: how many couples satisfy $(x^2+y^2 \leq 1)$

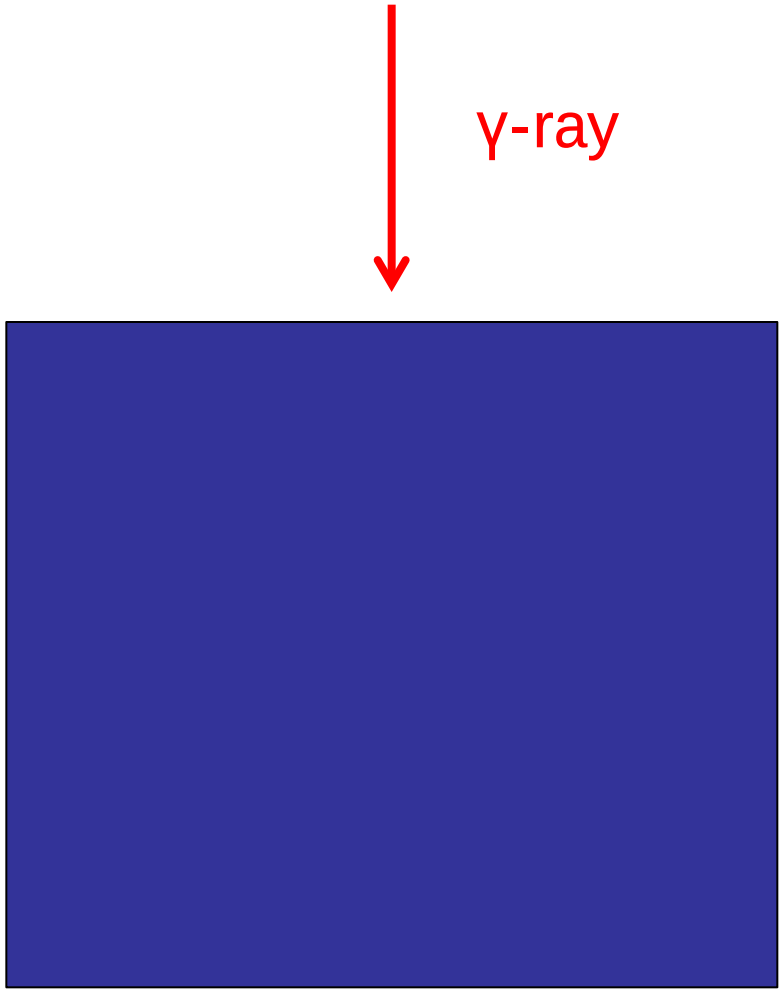




- n/N = π/4 (ratio of areas)
- Convergence as $1/\sqrt{N}$

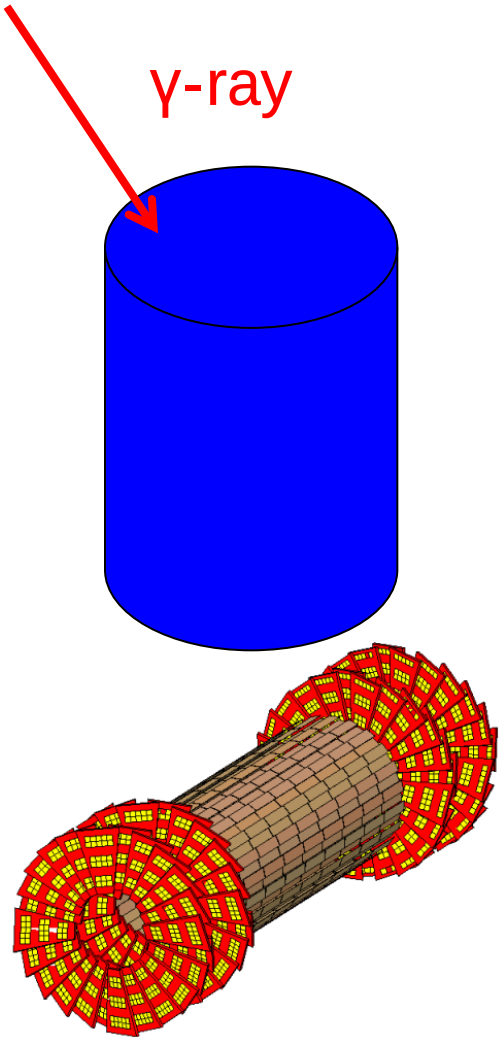
Most common application in particle physics: particle tracking

- Problem: track a γ-ray in a semi-infinite detector and determine the energy spectrum deposited
  - Still, a **model case**
- All physics is known from textbook (Compton scattering, photoelectric effect, etc.)
- Yet, the analytical calculation is a nightmare (while still possible)



Most common application in particle physics: particle tracking

- Problem v2: track a γ-ray in a finite detector (e.g. a NaI)
  - Real-life (simplified) case
- Analytical computation nearly impossible
  - Monte Carlo clearly wins
- Now make the detector more complicate, as in modern physics

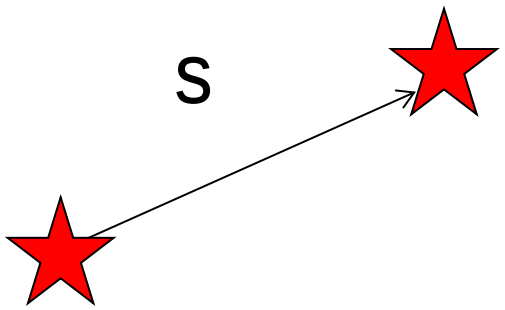


How to cook up the laws of physics into a tracking algorithm

(Bird's eye view)

Particle tracking

- Distance s between two subsequent interactions distributed as $p(s) = \mu e^{-\mu s}$



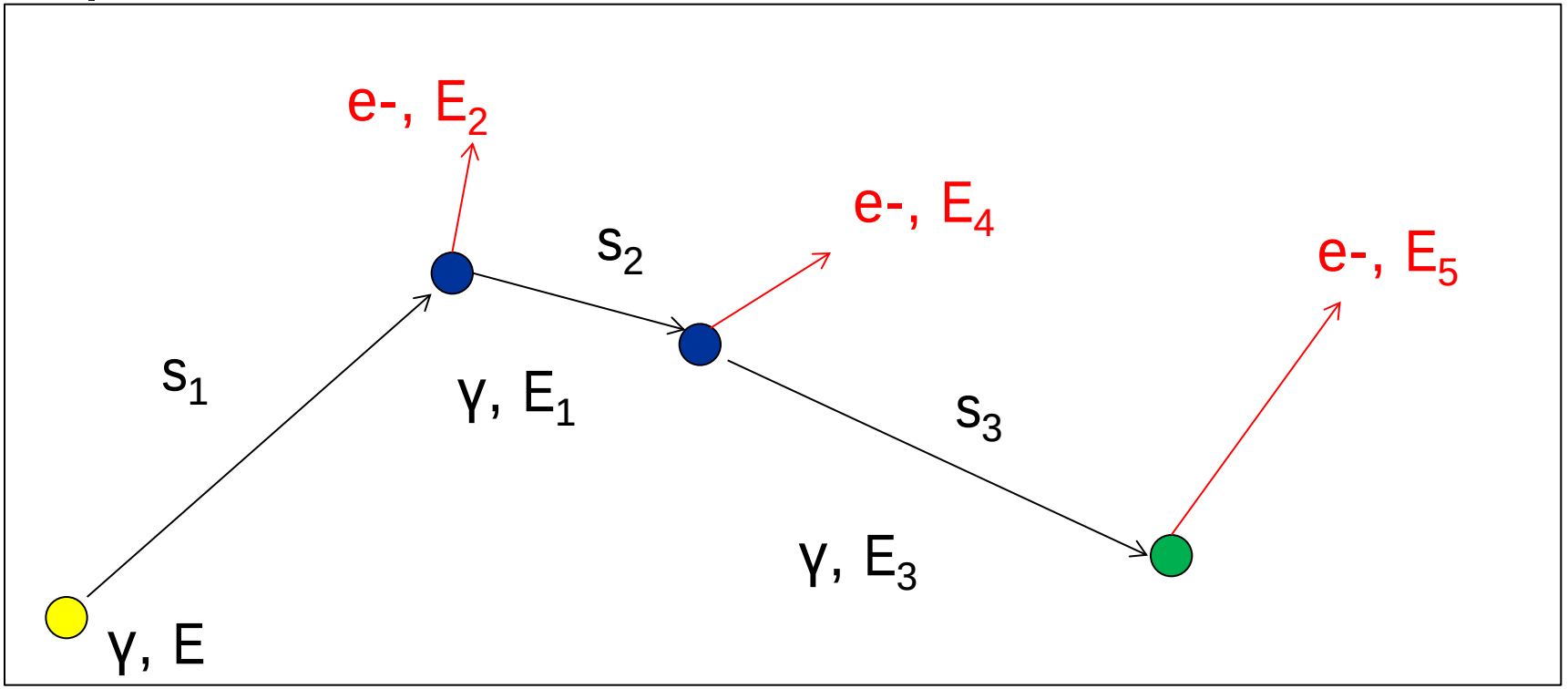
  - μ is a property of the medium (homogeneous) and of the physics
  - μ is proportional to the **total** cross section and depends on the density of the material $\mu = N\sigma = N \sum_i \sigma_i = \sum_i \mu_i$

- All competing processes contribute with their own μ_i
- Each process takes place with probability μ_i/μ → i.e. proportionally to the partial cross sections

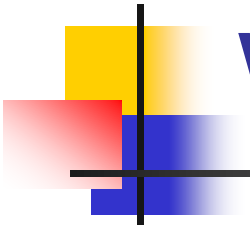
Particle tracking: basic recipe

- Divide the trajectory of the particle in **"steps"**
  - Straight free-flight tracks between consecutive physics interactions
  - Steps can also be limited by geometry boundaries
- Decide the step length s, by sampling according to $p(s) = \mu e^{-\mu s}$, with the proper μ (material+physics)
- Decide which interaction takes place at the end of the step, according to μ_i/μ
- Produce the final state according to the **physics** of the interaction ($d^2\sigma/d\Omega dE$)
  - Update direction of the primary particle
  - Store somewhere the possible secondary particles, to be tracked later on

Particle tracking: basic recipe



- Follow **all secondaries**, until absorbed or leave volume
- Notice: μ depends on energy (cross sections do!)



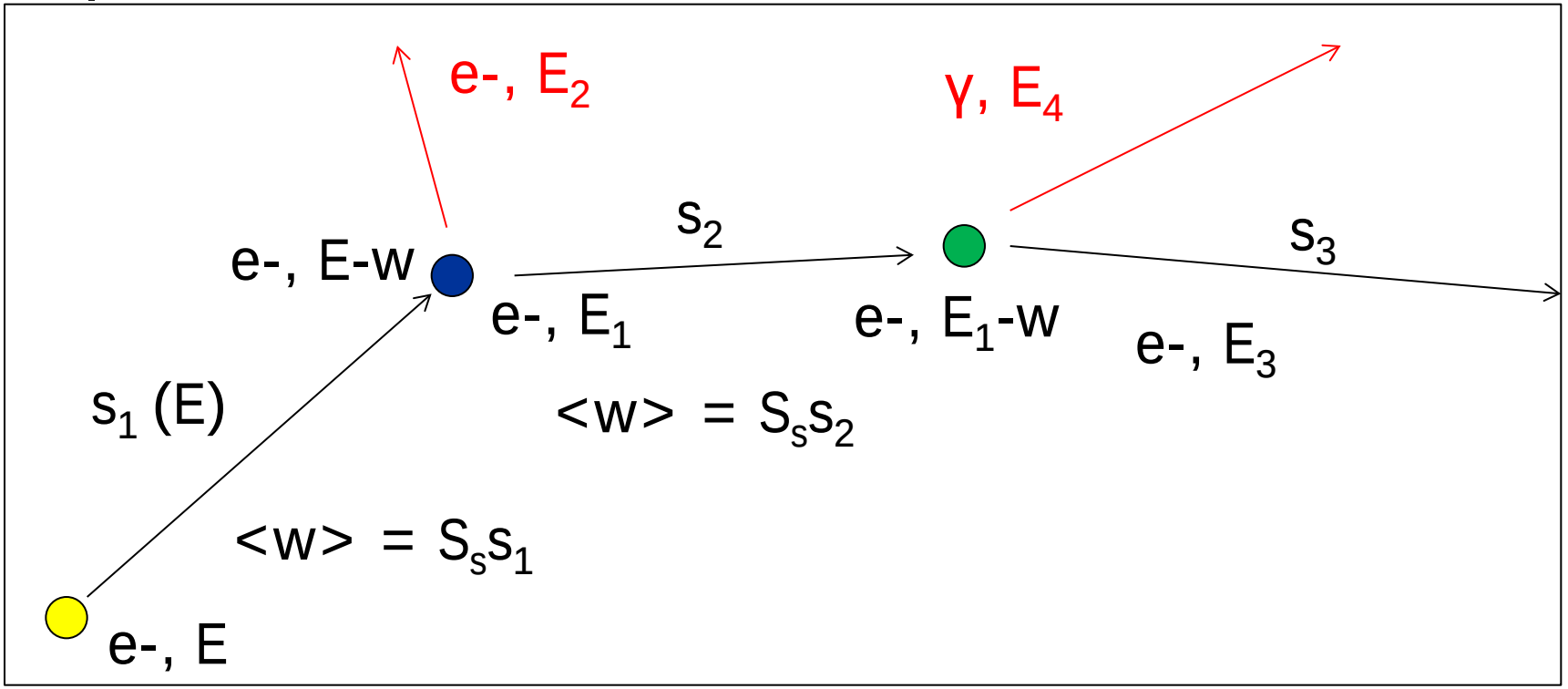
Well, not so easy

- This basic recipe works fine for γ-rays and other neutral particles (e.g. neutrons)
- Not so well for $e^{\pm}$: the cross section (ionization & bremsstrahlung) is very high, so the steps between two consecutive interactions are very small
  - CPU intensive: viable for low energies and thin material
- Even worse: in each interaction only a small fraction of energy is lost, and the angular displacement is small
  - A lot of time is spent to simulate interactions having **small effect**
  - The interactions of γ are "catastrophics": large change in energy/direction

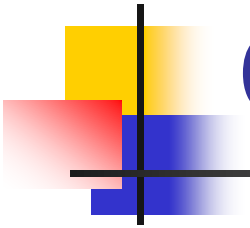
Solution: the mixed Monte Carlo

- Simulate explicitly (i.e. force step) interactions **only if** energy loss (or change of direction) is above threshold W_0
  - Detailed simulation
  - "**hard**" interaction (like γ interactions)
- The effect of all sub-threshold interactions is described **statistically** (= cumulatively)
  - Condensed simulation
  - "**soft**" interactions
- Hard interactions occur much less frequently than soft interactions
  - Fully detailed simulation restored for $W_0=0$

Particle tracking: mixed recipe



- Follow **all secondaries**, until absorbed or leave volume



Geometry

- Geometry also enters into the tracking
  - A step can never cross a geometry boundary
  - **Always stop** the step when there is a boundary, then re-start in the new medium
- Navigation in the geometry can be CPU-intensive
  - One must know to which volume each point (x,y,z) belongs to, and how far (and in which direction) is the closest boundary
- Trajectories can be affected also by EM fields, for charged particles

...luckily enough, somebody else already implemented the tracking algorithms for us (and much more)

S. Agostinelli et al., Nucl. Instr. Meth. A **506** (2003) 250
J. Allison et al., IEEE Trans. Nucl. Scie. **53** (2006) 270
J. Allison et al., Nucl. Instr. Meth. A **835** (2016) 186

What is GEANT4

A SIMULATION TOOLKIT

- Toolkit for the **Monte Carlo simulation** of the interaction of **particles** with **matter**
  - physics processes (EM, hadronic, optical) cover a comprehensive set of particles, materials and over a wide energy range
  - offers a complete set of support functionalities (tracking, geometry)
  - **Distributed** software production and management: developed by an **international Collaboration**
    - Established in 1998
    - Approximately 100 members, from Europe, America and Asia
- Written in **C++** language
  - Takes advantage from the Object Oriented software technology
- **Open source**

http://geant4.org

Collaborator Login

GEANT4
A SIMULATION TOOLKIT

Download | User Forum
Contact Us | Gallery

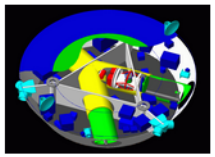
Overview

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

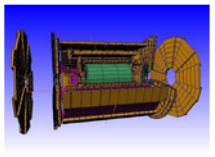
A sampling of applications, technology transfer and other uses of Geant4

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

- *12 Mar 2018*
  2018 planned developments
- *6 Mar 2018*
  Patch-01 to **release 10.4** is available from the Download area.
- *20 Oct 2017*
  Patch-03 to release 10.3 is available from the source archive area.

http://geant4.org

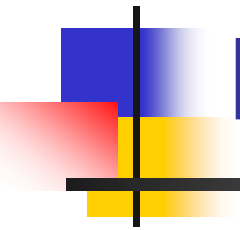
Events

- 47th Geant4 Technical Forum, CERN, Geneva (Switzerland), **10 April 2018**.
- Geant4 Beginners Course, at TUM University, Munich (Germany), **16-20 April, 2018**.
- Geant4 tutorial at Universite Paris-Saclay/LAL, Orsay (France), **14-18 May 2018**.
- Geant4 Course at the 15th Seminar on Software for Nuclear, Sub-nuclear and Applied Physics, Porto Conte, Alghero (Italy), **27 May - 1 June, 2018**.
- Geant4 Tutorial, at the University of Texas MD Anderson Cancer Center, Houston (USA), **25-27 June, 2018**.

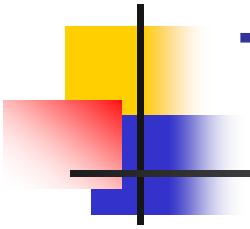
- **Code** and **documentation** available in the main **web page**
- Regular **tutorial courses** held worldwide

versions and releases

- First release (Geant4 1.0) in December 1998
  - ~Two releases per year since then
  - Major releases (**x**.y) or minor releases (x.**y**) or beta releases
  - Patches regularly issued
- Last version: Geant4 10.4
  - Released December 8th, 2017
  - Now patch **10.4.p02** (May 25th, 2018)
  - The VM used for this course has Geant4 10.4
- Requires C++11 since 10.2 (gcc > 4.8.x)
  - Native C+11 features in-place (= compilation with old compilers **fails**)

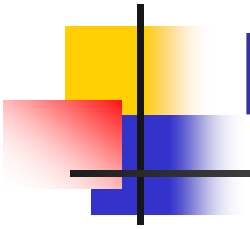


Basic concept of Geant4



Toolkit and User Application

- Geant4 is a **toolkit** (= a collection of tools)
  - i.e. you cannot “run” it out of the box
  - You must **write an application**, which uses Geant4 tools
- Consequences:
  - There are no such concepts as “Geant4 defaults”
  - You must provide the necessary information to configure your simulation
  - You must deliberately choose which Geant4 tools to use
- Guidance: many **examples** are provided

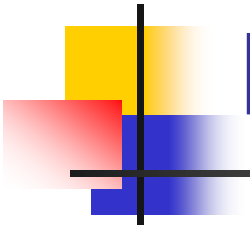


Basic concepts

- What you **MUST** do:
  - Describe your **experimental set-up**
  - Provide the **primary particles** input to your simulation
  - Decide which **particles** and **physics models** you want to use out of those available in Geant4 and the precision of your simulation (cuts to produce and track secondary particles)
- You **may also want**
  - To interact with Geant4 kernel to **control** your simulation
  - To **visualise** your simulation configuration or results
  - To produce **histograms, tuples** etc. to be further analysed

Main Geant4 capabilities

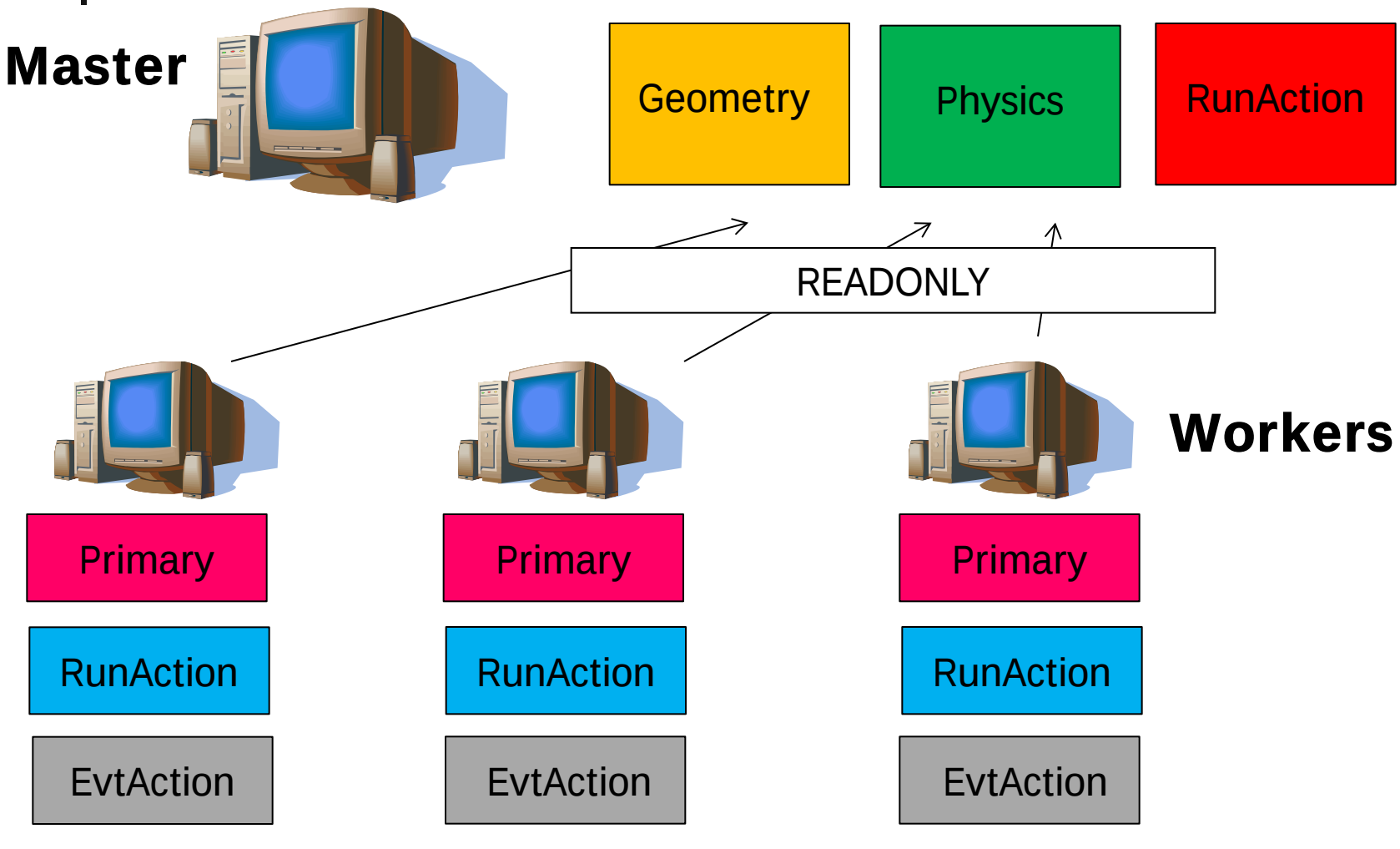
- **Transportation of a particle 'step-by-step'** taking into account all possible interactions with materials and fields
- **The transport ends** if the particle
  - is slowed down to zero kinetic energy (and it doesn't have any interaction at rest)
  - disappears in some interaction
  - reaches the end of the simulation volume
- Geant4 allows the User to access the transportation process and retrieve the results (USER ACTIONS)
  - at the beginning and end of the transport
  - at the end of each step in transportation
  - if a particle reaches a sensitive detector
  - Others...



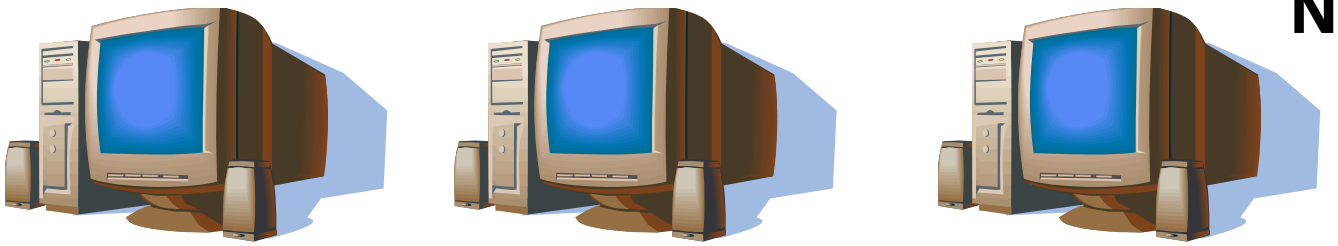
Multi-thread mode

- Geant4 10.0 (released Dec, 2013) supports multi-thread approach for multi-core machines
  - Simulation is automatically split on an event-by-event basis
    - different events are processed by different cores
  - Can fully profit of **all cores** available on modern machines → substantial **speed-up** of simulations
  - **Unique** copy (master) of geometry and physics
    - All cores have them as read-only (saves memory)
- Backwards compatible with the **sequential** mode
  - The MT programming requires some care: need to avoid conflicts between threads
  - Some modification and porting required

Concept for multi-thread ...



... vs. parallelisation



Nodes

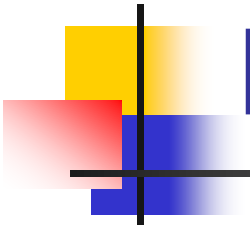
Geometry	Geometry	Geometry
Physics	Physics	Physics
Primary	Primary	Primary
RunAction	RunAction	RunAction
EvtAction	EvtAction	EvtAction

- Each node hosts a complete simulation
- Many copies of geometry and physics tables
- More memory-thristy

Interaction with the Geant4 kernel - 1

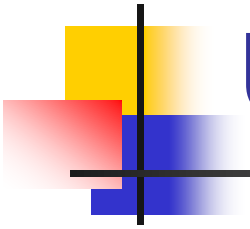
- Geant4 design provides **tools** for a user application
  - To tell the kernel about your simulation configuration
  - To interact with Geant4 kernel itself
- Geant4 tools for user interaction are **base classes**
  - You create **your own concrete class** derived from the base classes → interface to the Geant4 kernel
  - Geant4 kernel handles your own derived classes transparently through their base class interface (polymorphism)

Interaction with the Geant4 kernel - 2



Two types of Geant4 base classes:

- **Abstract base classes** for user interaction (classes starting with G4V)
  - User derived concrete classes are **mandatory**
  - User to implement the purely virtual methods
- **Concrete base classes** (with **virtual** dummy default methods) for user interaction
  - User derived classes are **optional**



User Classes

Initialisation classes

Invoked at the initialization

- G4VUserDetectorConstruction
- G4VUserPhysicsList

Global: only one instance of them exists in memory, shared by all threads (**readonly**). Managed only by the master thread.

Action classes

Invoked during the execution loop

- G4VUserActionInitialization
  - G4VUserPrimaryGeneratorAction
  - G4UserRunAction (*)
  - G4UserEventAction
  - G4UserTrackingAction
  - G4UserStackingAction
  - G4UserSteppingAction

Local: an instance of each action class exists **for each thread**.

(*) Two RunAction's allowed: one for master and one for threads

The mandatory user classes

Mandatory classes in ANY Geant4 User Application

- G4VUserDetectorConstruction
  describe the experimental set-up
- G4VUserPhysicsList
  select the physics you want to activate
- G4VUserActionInitialization
  takes care of the user initializations
  G4VUserPrimaryGeneratorAction

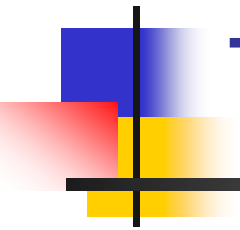
Will be described in detail in the next lectures (Tue-Wed)

Optional user classes

- Five concrete base classes whose virtual member functions the user may override to gain **control** of the simulation at various stages
  - G4User**Run**Action
  - G4User**Event**Action
  - G4User**Tracking**Action
  - G4User**Stacking**Action
  - G4User**Stepping**Action

e.g. actions to be done at the beginning and end of each event

- Each member function of the base classes has a dummy implementation (not purely virtual)
  - Empty implementation: does nothing
  - Override only the methods that you need
- User action classes must be **registered** to the Run Manager via the **`G4VUserActionInizialization`**



The mandatory user classes

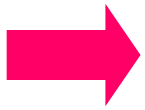
The geometry

- User class which describes the geometry must inherit from **`G4VUserDetectorConstruction`** and registered in the Run Manager
- Virtual base class: the purely virtual method must be implemented
  - **`G4VPhysicalVolume* Construct() = 0;`**
    - Must return the pointer to the world volume: all other volumes are contained in it
- Optionally, implement the virtual method
  - **`void ConstructSDandField();`**
    - Defines sensitive volumes and EM fields

Select physics processes

- Geant4 doesn't have any default particles or processes
- Derive your own concrete class from the **`G4VUserPhysicsList`** abstract base class
  - define all necessary particles
  - define all necessary processes and assign them to proper particles
  - define γ/δ production thresholds (in terms of range)
- Pure virtual methods of **`G4VUserPhysicsList`**

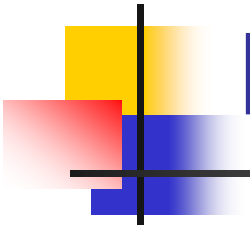
ConstructParticles()
ConstructProcesses()
SetCuts()



must be implemented by the user in his/her concrete derived class

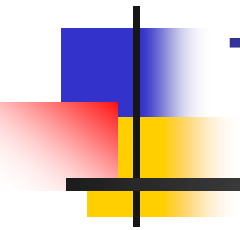
Action Initialization

- User class must inherit from **`G4VUserActionInitialization`** and registered in the Run Manager
- Implement the purely virtual method
  - **`void Build() = 0;`**
  - Invoked in sequential mode and in MT mode by all workers
  - Must instantiate at least the primary generator
- Optional virtual method
  - **`void BuildForMaster();`**
  - Invoked by the master in MT mode. Applies **only** to Run Action (all other user actions are thread-local)

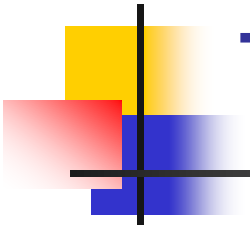


Primary generator

- User class must inherit from **`G4VUserPrimaryGeneratorAction`**
  - Registered to the Run Manager via the ActionInizialitation (MT mode)
  - Register directly to the RunManager in seq-mode
- Implement the purely virtual method
  - **`void GeneratePrimaries(G4Event*)=0;`**
  - Called by the RunManager during the event loop, to generate the primary vertices/particles
- Uses internally a concrete instance of **`G4VPrimaryGenerator`** (e.g. **`G4ParticleGun`**) to do the job

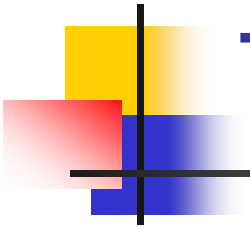


The main() program



The main() program - 1

- Geant4 does **not** provide the **main()**
  - Geant4 is a toolkit!
  - The main() is part of the user application
- In his/her main(), the user **must**
  - construct **`G4RunManager`** (or his/her own derived class)
  - notify the **`G4RunManager`** mandatory user classes derived from
    - **`G4VUserDetectorConstruction`**
    - **`G4VUserPhysicsList`**
    - **`G4VUserActionInitialization`** (takes care of Primary)
  - In MT mode, use **`G4MTRunManager`**



The main() program - 2

- The user may define in his/her main()
  - optional user action classes
  - VisManager, (G)UI session
- The user also has to take care of retrieving and saving the relevant information from the simulation (Geant4 will not do that by default)
- Don’t forget to delete the G4RunManager at the end

An example of (sequential) main()

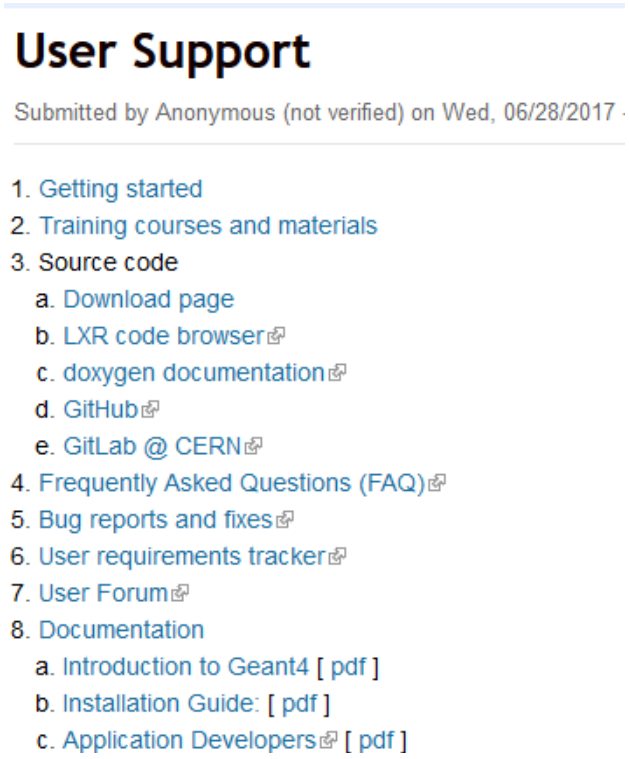
```
{
  …
  // Construct the default run manager
  G4RunManager* runManager = new G4RunManager;
  // Set mandatory user initialization classes
  MyDetectorConstruction* detector = new MyDetectorConstruction;
  runManager->SetUserInitialization(detector);
  MyPhysicsList* physicsList = new MyPhysicsList;
  runManager->SetUserInitialization(myPhysicsList);
  // Set mandatory user action classes
  runManager->SetUserAction(new MyActionInitialization);
  // Set optional user action classes
  MyEventAction* eventAction = new MyEventAction();
   runManager->SetUserAction(eventAction);
  MyRunAction* runAction = new MyRunAction();
   runManager->SetUserAction(runAction);
  …
}
```

http://geant4.org

Documentation

- A few manuals available in the Geant4 webpage
  - Application developer manual
  - Physics manual
- Other tools available
  - LXR code repository
  - User forum
  - Bugzilla
  - GitHub code repo

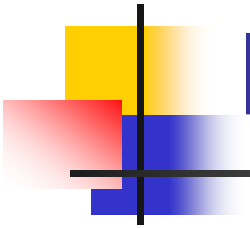
https://github.com/Geant4



User Support

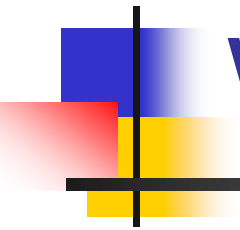
Submitted by Anonymous (not verified) on Wed, 06/28/2017

1. Getting started
2. Training courses and materials
3. Source code
   a. Download page
   b. LXR code browser
   c. doxygen documentation
   d. GitHub
   e. GitLab @ CERN
4. Frequently Asked Questions (FAQ)
5. Bug reports and fixes
6. User requirements tracker
7. User Forum
8. Documentation
   a. Introduction to Geant4 [pdf]
   b. Installation Guide: [pdf]
   c. Application Developers [pdf]



Examples

- Ready-for-the-use Geant4 applications (examples) are distributed with Geant4
  - Very good starting point for new users
- Three suites of examples:
  - **"basic"**: oriented to novice users and covering the most typical use-cases of a Geant4 application with keeping simplicity and ease of use.
  - **"extended"**: covers many specific use cases for actual detector simulation.
  - **"advanced"**: where real-life complete applications for different simulation studies are provided
- See dedicated presentation on Friday

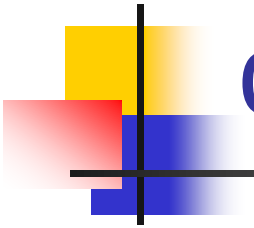


Who/why is using Geant4?

Experiments and MC

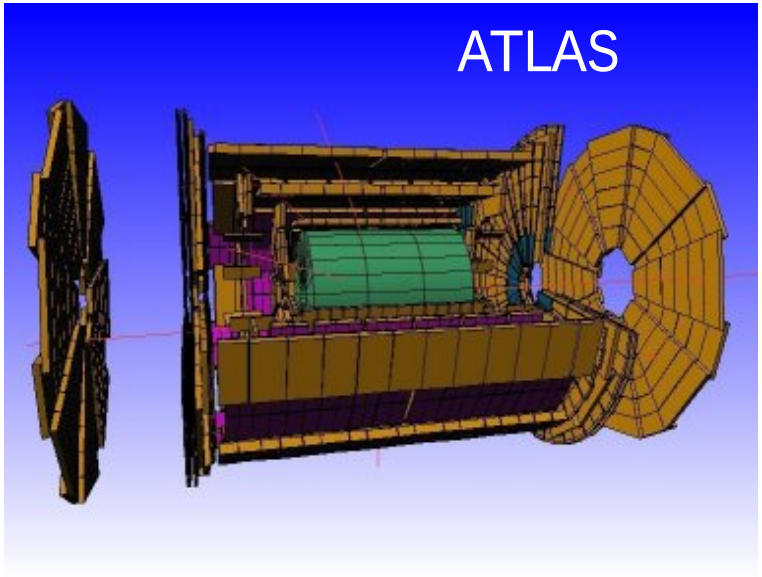
- In my knowledge, **all experiments** have a (more or less detailed) full-scale Monte Carlo simulation
- Design phase
  - Evaluation of background
  - Optimization of setup to maximize scientific yield
    - Minimize background, maximize signal efficiency
- Running/analysis phase
  - Support of data analysis (e.g. provide efficiency for signal, background, coincidences, tagging, ...).
    - Often, Monte Carlo is the only way to convert *relative rates* (events/day) in *absolute yields*

Why Geant4 is a common choice in the market



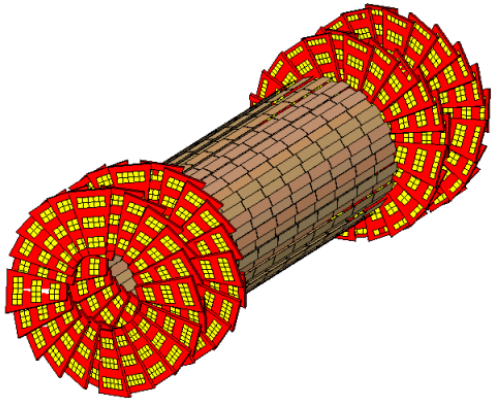
- Open source and object oriented/C++
  - No black box
  - Freely available on all platforms
  - Can be easily extended and customized by using the existing interfaces
    - New processes, new primary generators, interface to ROOT analysis, ...
- Can handle complex geometries
- Regular development, updates, bug fixes and validation
- Good physics, customizable per use-cases
- End-to-end simulation (all particles, including optical photons)

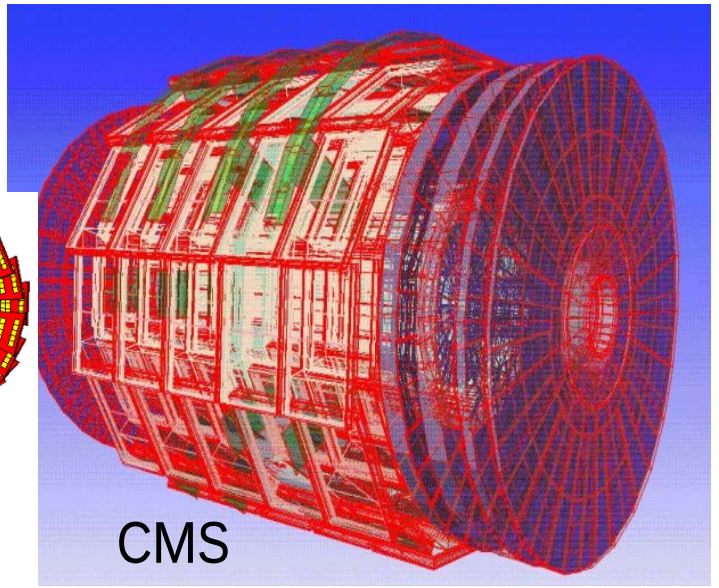
LHC @ CERN



- All four big **LHC experiments** have a Geant4 simulation
  - M of volumes
  - Physics at the TeV scale

- Benchmark with test-beam data
- Key role for the Higgs searches

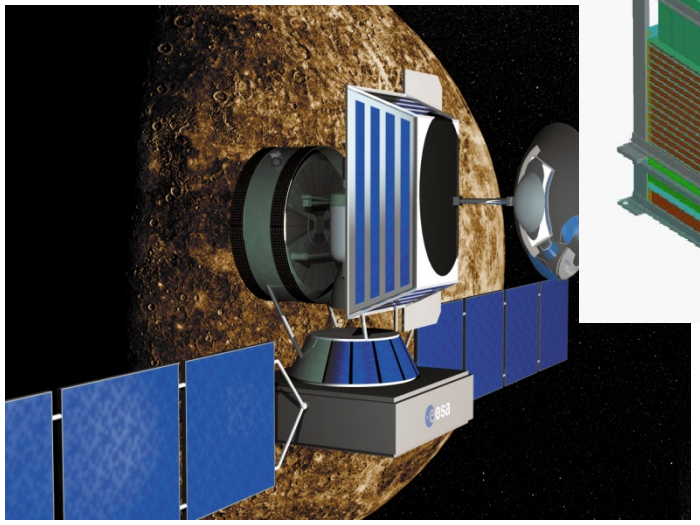


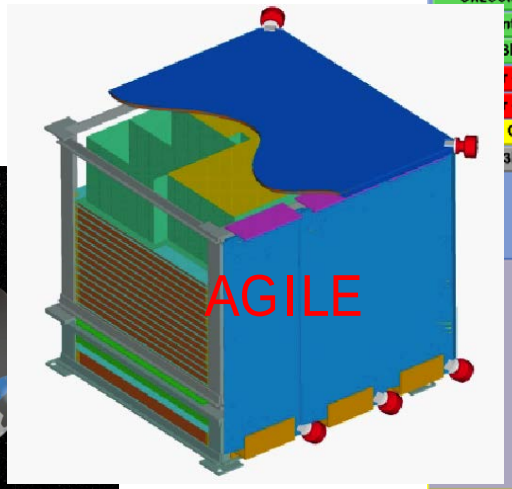


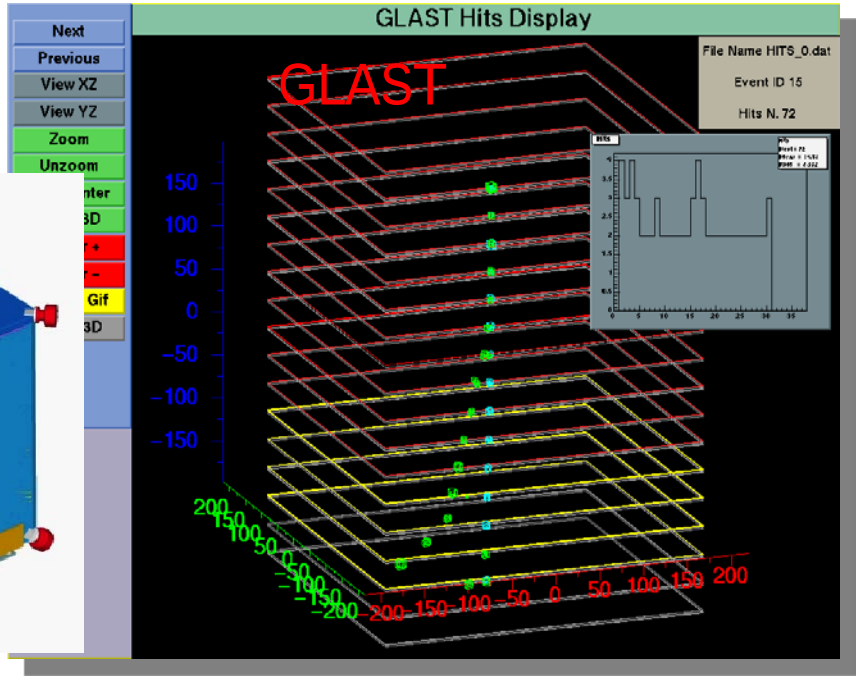
Space applications

- Satellites (γ astrophysics, planetary sciences)
- Funding from ESA

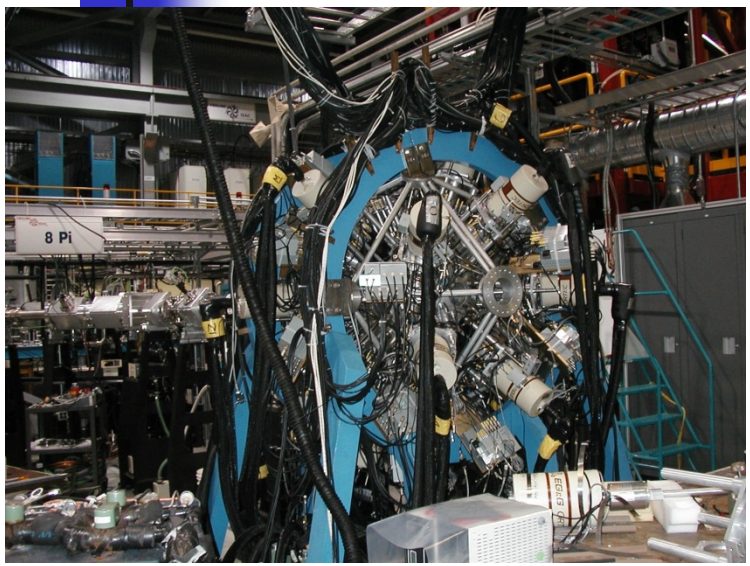
Typical telescope:
Tracker
Calorimeter
Anticoincidence

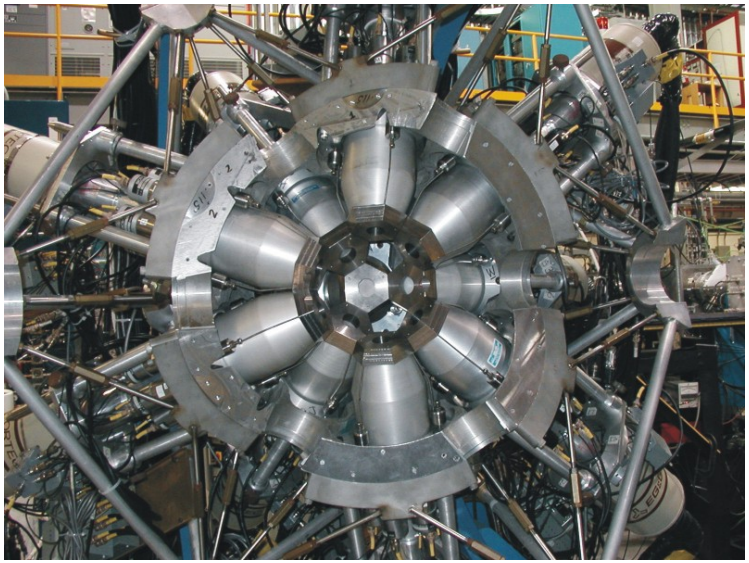


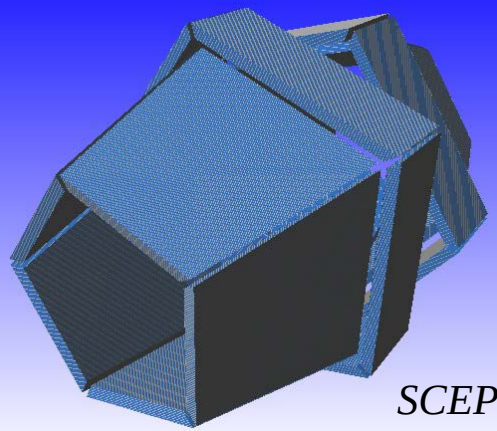




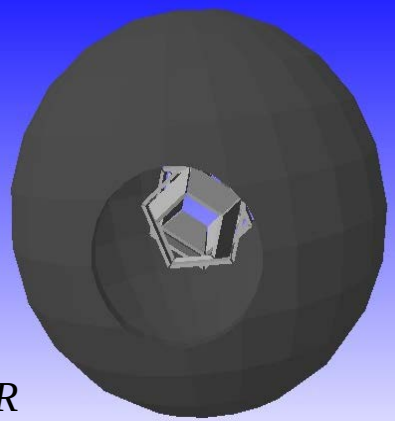
Nuclear spectroscopy

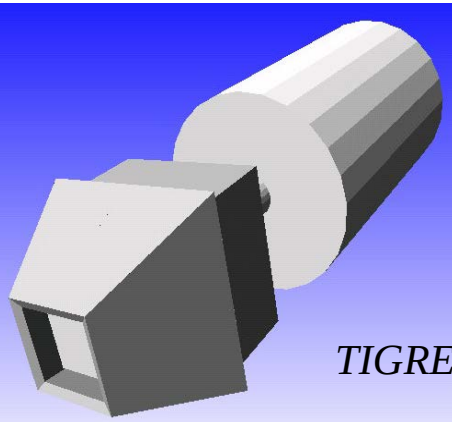




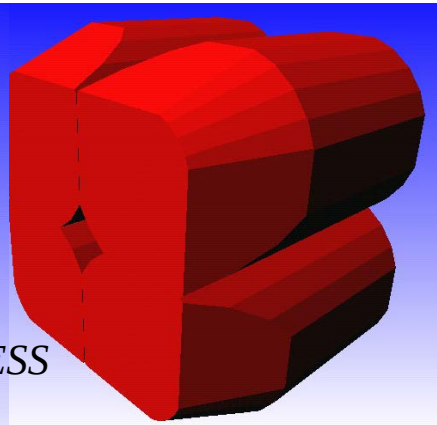


SCEPTAR

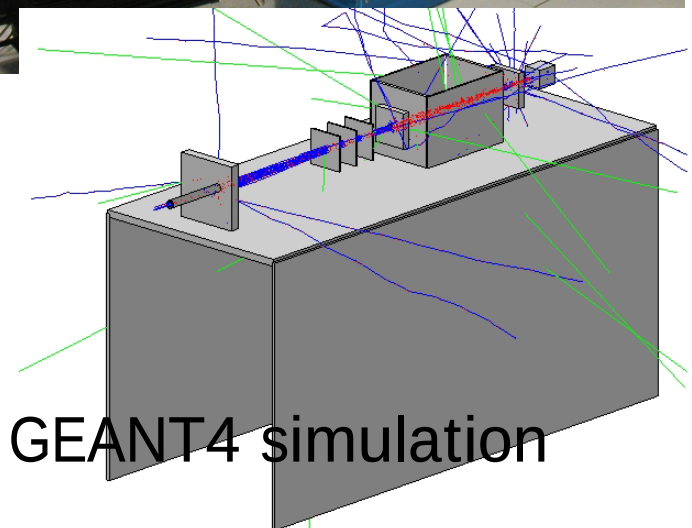




TIGRESS

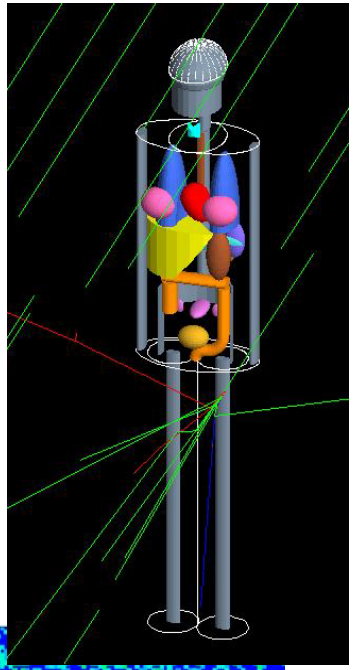


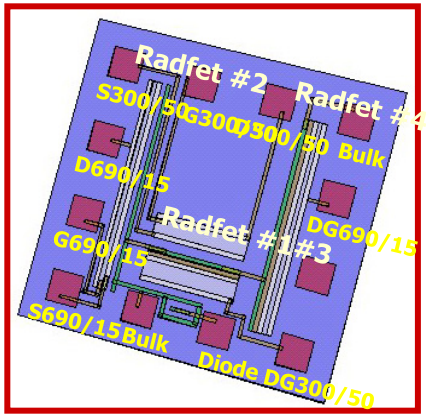
Medical applications



- **Treatment planning** for hadrontherapy and proton-therapy systems
  - Goal: deliver dose to the tumor while sparing the healthy tissues
  - Alternative to less-precise (and commercial) TP software
- Medical imaging
- Radiation fields from medical accelerators and devices
  - **`medical_linac`**
  - **`gamma-knife`**
  - **`brachytherapy`**

Dosimetry with Geant4

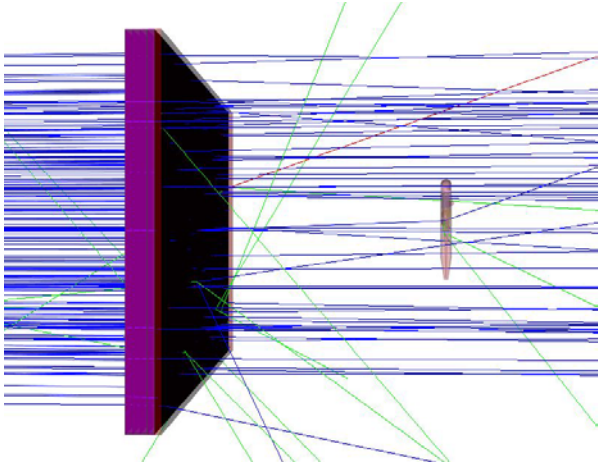


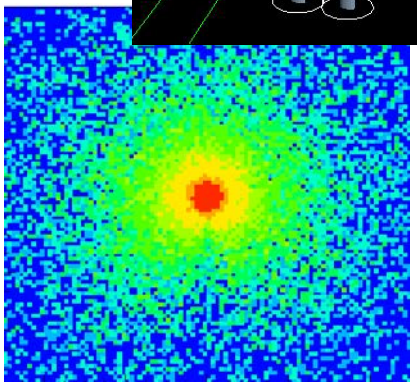


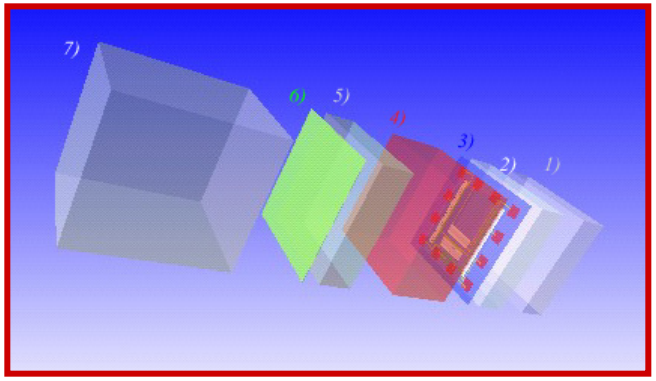
Space science

Radiotherapy

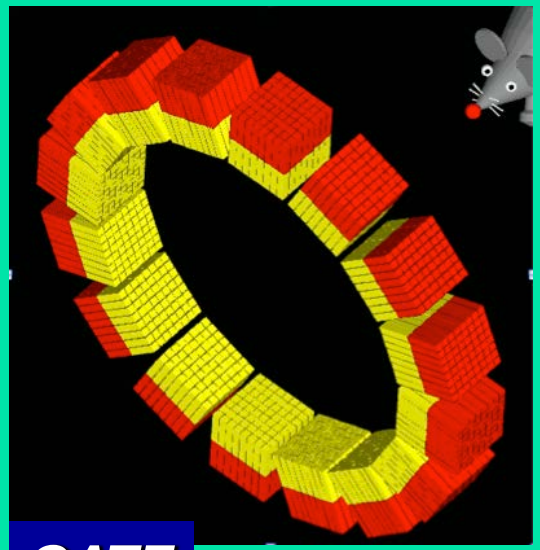
Effects on electronics components



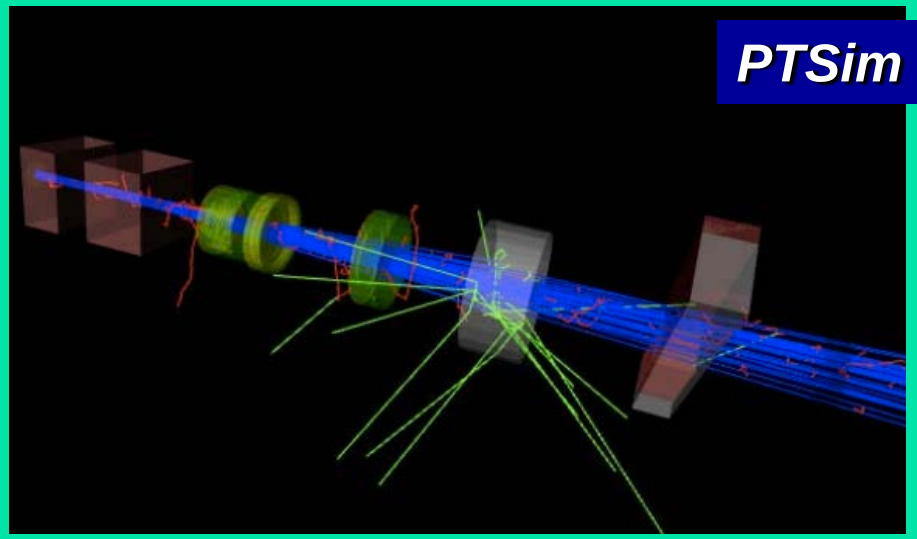




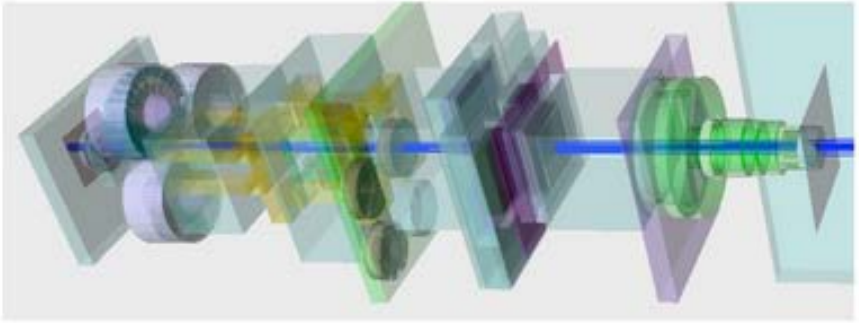
Geant4-based frameworks in the medical physics

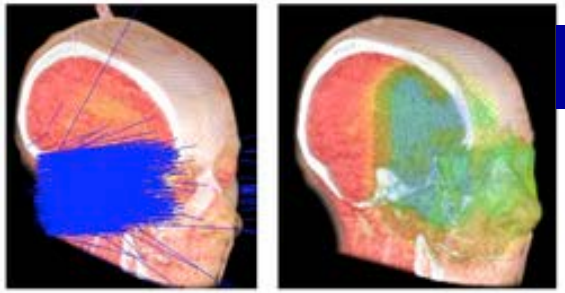


GATE

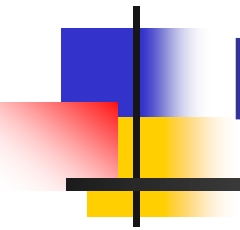


PTSim



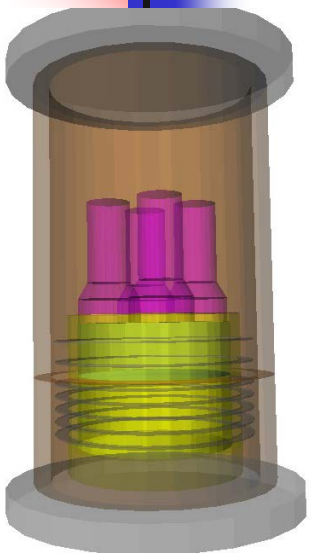


TOPAS



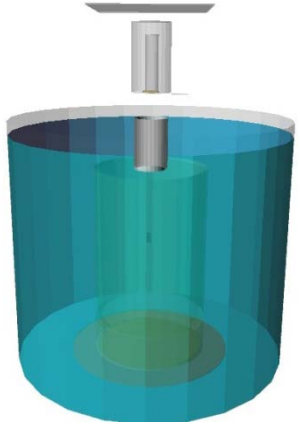
Backup

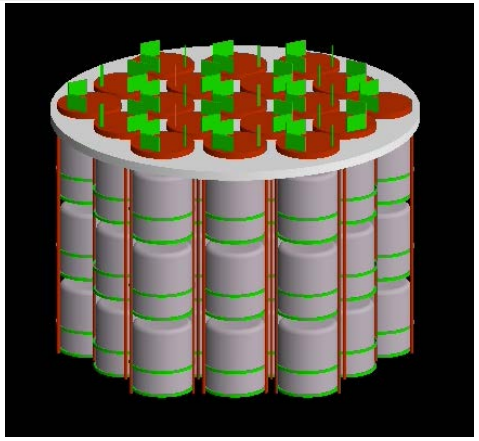
Low background experiments

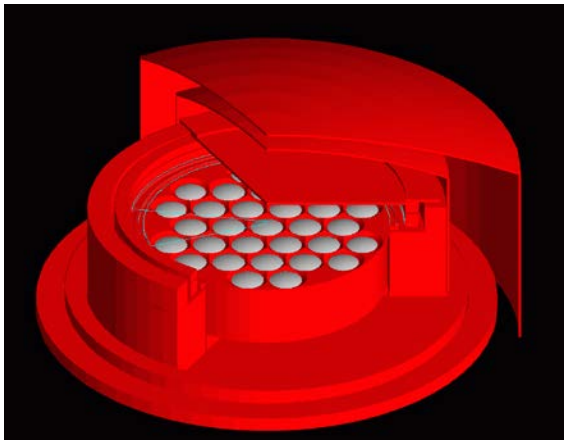


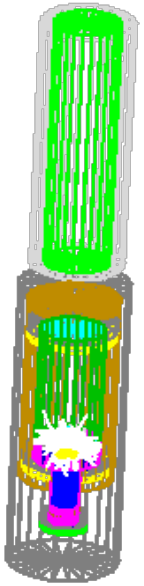
Neutrinoless ββ decay:

GERDA, Majorana
COBRA, CUORE, EXO







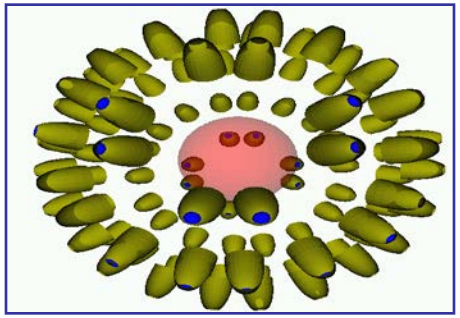


Dark matter detection:

Zeplin-II/III, Drift, Edelweiss, ArDM, Xenon, CRESST, Lux, Elixir,

Solar neutrinos:

Borexino, …

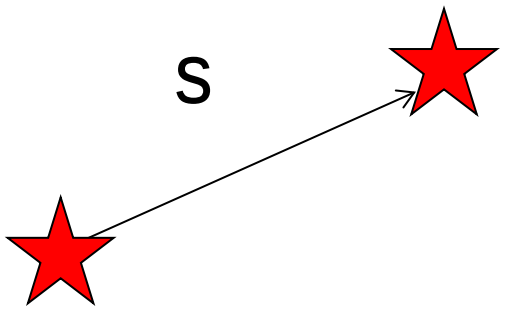


How to cook up the laws of physics into a tracking algorithm

(Bird's eye view)

Particle tracking

- Distance s between two subsequent interactions distributed as $p(s) = \mu e^{-\mu s}$



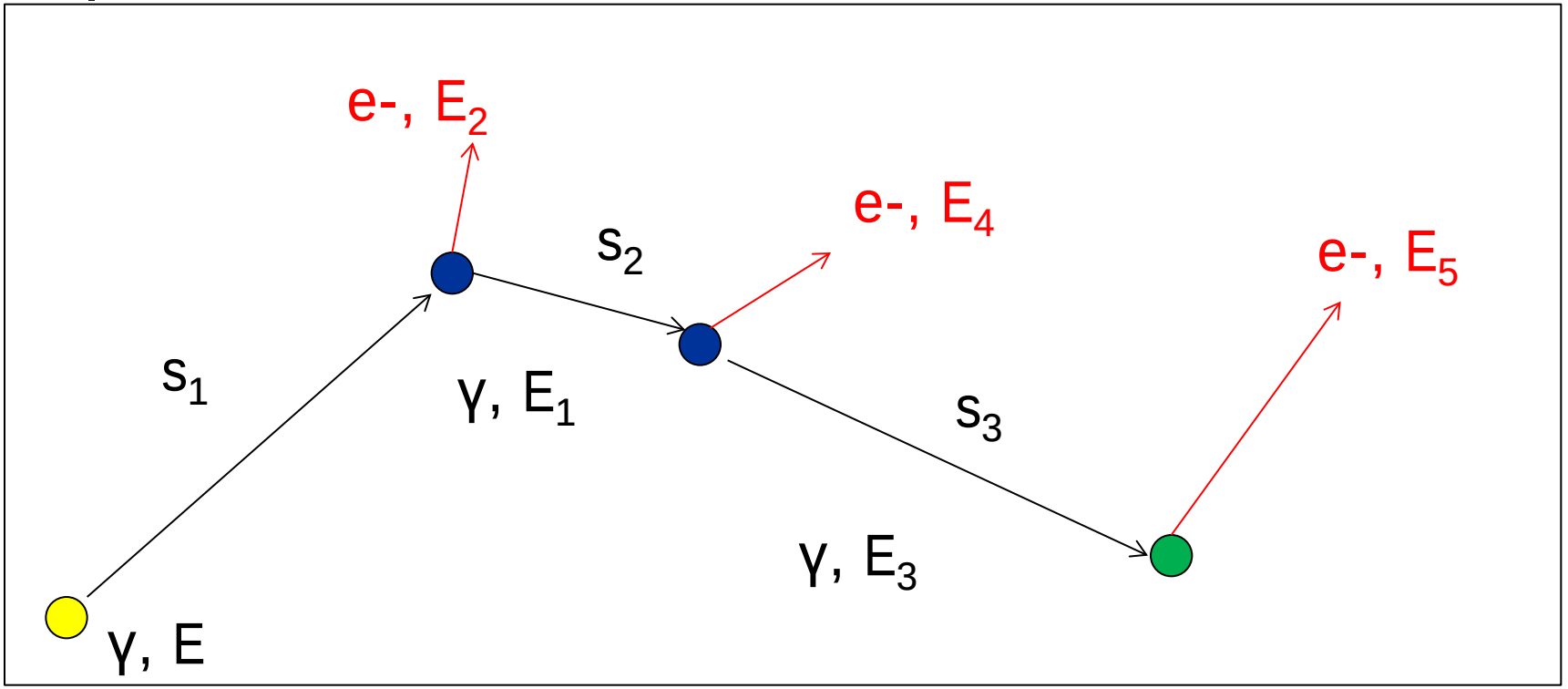
  - μ is a property of the medium (homogeneous) and of the physics
  - μ is proportional to the **total** cross section and depends on the density of the material $\mu = N\sigma = N \sum_i \sigma_i = \sum_i \mu_i$

- All competing processes contribute with their own μ_i
- Each process takes place with probability μ_i/μ → i.e. proportionally to the partial cross sections

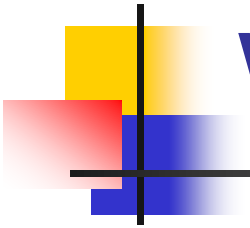
Particle tracking: basic recipe

- Divide the trajectory of the particle in **"steps"**
  - Straight free-flight tracks between consecutive physics interactions
  - Steps can also be limited by geometry boundaries
- Decide the step length s, by sampling according to $p(s) = \mu e^{-\mu s}$, with the proper μ (material+physics)
- Decide which interaction takes place at the end of the step, according to μ_i/μ
- Produce the final state according to the **physics** of the interaction ($d^2\sigma/d\Omega dE$)
  - Update direction of the primary particle
  - Store somewhere the possible secondary particles, to be tracked later on

Particle tracking: basic recipe



- Follow **all secondaries**, until absorbed or leave volume
- Notice: μ depends on energy (cross sections do!)



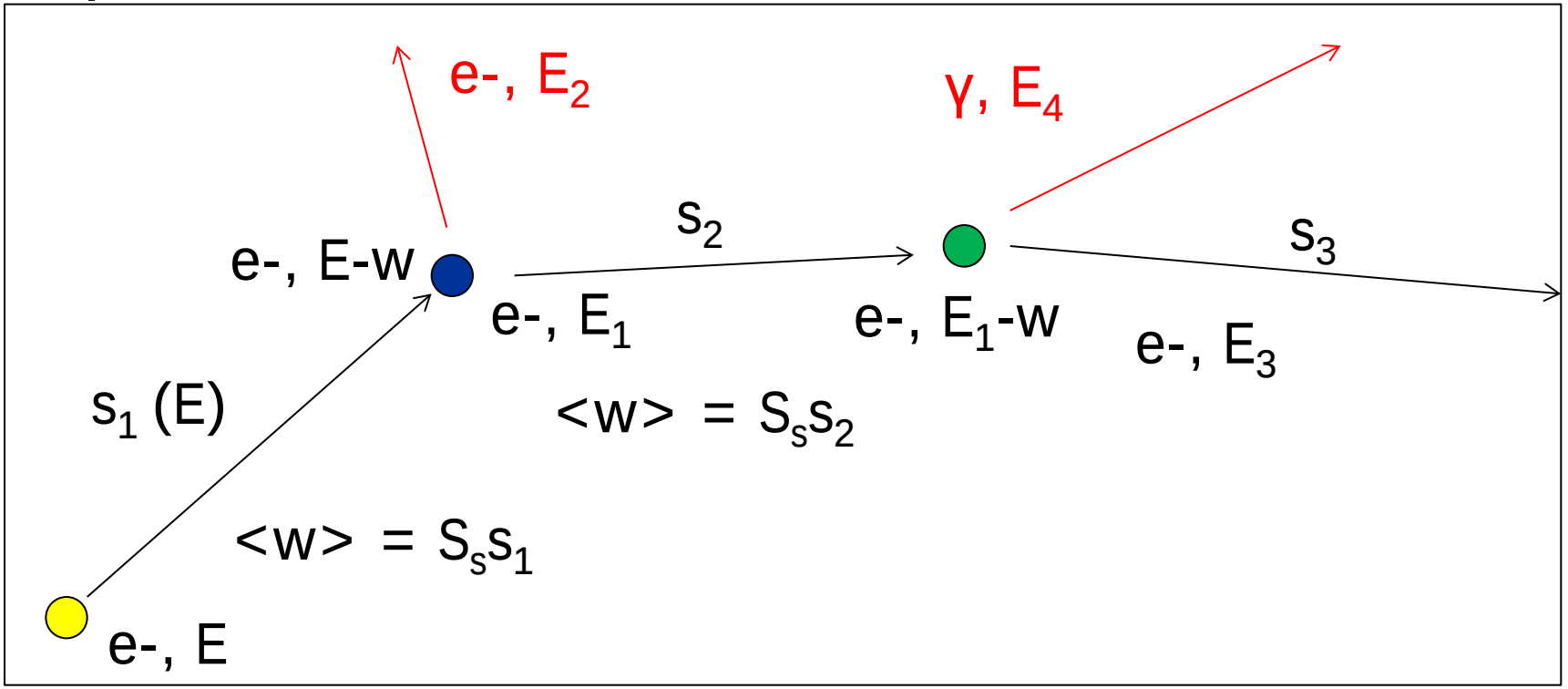
Well, not so easy

- This basic recipe works fine for γ-rays and other neutral particles (e.g. neutrons)
- Not so well for $e^{\pm}$: the cross section (ionization & bremsstrahlung) is very high, so the steps between two consecutive interactions are very small
  - CPU intensive: viable for low energies and thin material
- Even worse: in each interaction only a small fraction of energy is lost, and the angular displacement is small
  - A lot of time is spent to simulate interactions having **small effect**
  - The interactions of γ are "catastrophics": large change in energy/direction

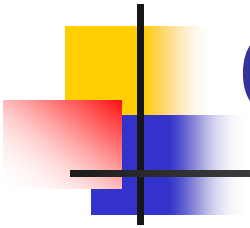
Solution: the mixed Monte Carlo

- Simulate explicitly (i.e. force step) interactions **only if** energy loss (or change of direction) is above threshold W_0
  - Detailed simulation
  - "**hard**" interaction (like γ interactions)
- The effect of all sub-threshold interactions is described **statistically** (= cumulatively)
  - Condensed simulation
  - "**soft**" interactions
- Hard interactions occur much less frequently than soft interactions
  - Fully detailed simulation restored for $W_0=0$

Particle tracking: mixed recipe



- Follow **all secondaries**, until absorbed or leave volume



Geometry

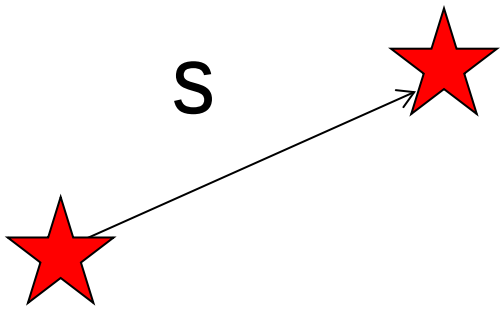
- Geometry also enters into the tracking
  - A step can never cross a geometry boundary
  - **Always stop** the step when there is a boundary, then re-start in the new medium
- Navigation in the geometry can be CPU-intensive
  - One must know to which volume each point (x,y,z) belongs to, and how far (and in which direction) is the closest boundary
- Trajectories can be affected also by EM fields, for charged particles

...luckily enough, somebody else already implemented the tracking algorithms for us (and much more)

Particle tracking

- μ is proportional to the **total** cross section and depends on the density of the material

$$\mu = N\sigma = N\sum_i \sigma_i = \sum_i \mu_i$$



- All competing processes contribute with their own μ_i
- Each process takes place with probability μ_i/μ → i.e. proportionally to the partial cross sections

The mixed Monte Carlo

- Has some technical tricks:
  - since energy is lost along the step due to soft interactions, the sampled step s cannot be too long ($s < s_{max}$)
- Parameter μ_h between hard collisions

$$\mu_h = N \int_{W_0}^{E} \frac{d\sigma}{dW}(E) dW$$

  - Has $\boldsymbol{\mu_h << \mu}$ because the differential cross section is strogly peaked at low W (= soft secondaries)
  - Much longer step length

The mixed Monte Carlo

- Stopping power due to **soft** collisions (dE/dx)

$$S_s = N \int_0^{W_0} W \frac{d\sigma}{dW}(E) dW$$

- Average energy lost along the step: $\langle w \rangle = sS_s$
  - Must be $\langle w \rangle << E$
- Fluctuations around the average value $\langle w \rangle$ have to be taken into account
  - Appropriate random sampling of w with mean value $\langle w \rangle$ and variance (straggling)

Extended recipe

1. Decide the step length s, by sampling according to $p(s) = \mu_h e^{-\mu_h s}$, with the proper μ_h
2. Calculate the cumulative effect of the **soft** interactions along the step: sample the energy loss w, with $\langle w \rangle = sS_s$, and the displacement
3. Update *energy and direction* of the primary particle at the end of the step E → E-w
4. Decide which interaction takes place at the end of the step, according to $\mu_{i,h}/\mu_h$
5. Produce the final state according to the **physics** of the interaction ($d^2\sigma/d\Omega dE$)

Applications in the rare-event physics

Experiment backgrounds
internal detector radioactivity
rock radioactivity
μ-induced neutron production
shielding and veto systems

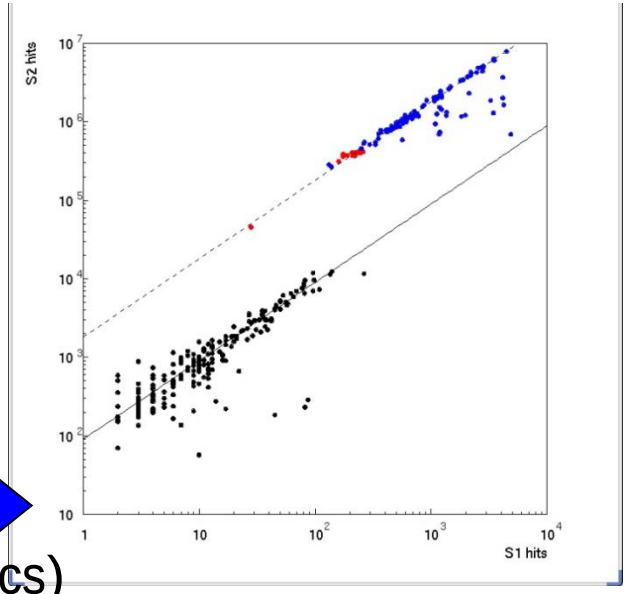
Geant4 is uniquely suited for **integrated** simulations of underground and low-background detectors (e.g. dark matter)

Optics
Photon generation
Light collection

Detector response
Scintillation
Ionisation

Simulated Data
Visualisation
Run-time analysis
Input to data analysis software

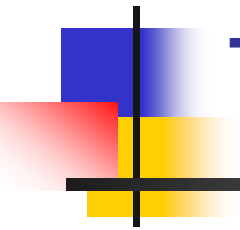
Calibration
Neutrons
Gammas



A dedicated advanced example (underground_physics) is **released** with Geant4 (ZEPLIN experiment)

Geant4-based frameworks in astroparticle/neutrino physics

- Geant4 is a **toolkit** → can be used in software projects of **wider scope**
  - Flexibility in selecting geometries, physics, outputs, ...
- A few examples in astroparticle physics:
  - MaGe (GERDA/Majorana): double beta decay
  - LUXSim (LUX): dark matter and undeground experiments
  - DCGLG4sim (Double Chooz): liquid scintillator and reactor neutrinos
  - artG4 (FermiLab)
  - VENOM (COBRA): double beta decay
  - Just google "Geant4-based"
- (Many more for HEP, space physics, medical physics)



The mandatory user classes

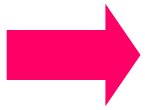
The geometry

- User class which describes the geometry must inherit from **`G4VUserDetectorConstruction`** and registered in the Run Manager
- Virtual base class: the purely virtual method must be implemented
  - **`G4VPhysicalVolume* Construct() = 0;`**
    - Must return the pointer to the world volume: all other volumes are contained in it
- Optionally, implement the virtual method
  - **`void ConstructSDandField();`**
    - Defines sensitive volumes and EM fields

Select physics processes

- Geant4 doesn't have any default particles or processes
- Derive your own concrete class from the **`G4VUserPhysicsList`** abstract base class
  - define all necessary particles
  - define all necessary processes and assign them to proper particles
  - define γ/δ production thresholds (in terms of range)
- Pure virtual methods of **`G4VUserPhysicsList`**

ConstructParticles()
ConstructProcesses()
SetCuts()

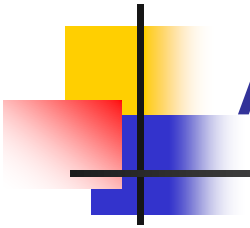


must be implemented by the user in his/her concrete derived class

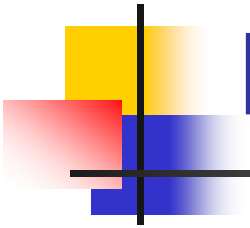
Physics Lists

- Geant4 doesn't have any default particles or processes
- *Partially true*: there is no default, but there are a set of **"ready-for-use" physics lists** released with Geant4, tailored to different use cases. Mix and match:
  - Different sets of hadronic models (depending on the energy scale and modeling of the interactions)
  - Different options for neutron tracking
    - Do we need (CPU-intensive) description of thermal neutrons, neutron capture, etc?
  - Different options for EM physics
    - Do you need (CPU-intensive) precise description at the low-energy scale (< 1 MeV)? E.g. fluorescence, Doppler effects in the Compton scattering, Auger emission, Rayleigh diffusion
    - Only a waste of CPU time for LHC, critical for many low-background experiments

Action Initialization

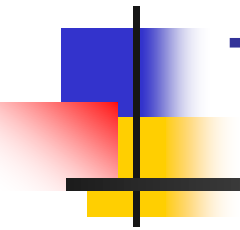


- New in Geant4 10.0 (supports multi-thread)
- User class must inherit from **`G4VUserActionInitialization`** and registered in the Run Manager
- Implement the purely virtual method
  - **`void Build() = 0;`**
  - Invoked in sequential mode and in MT mode by all workers
  - Must instantiate at least the primary generator
- Optional virtual method
  - **`void BuildForMaster();`**
  - Invoked by the master in MT mode. Applies **only** to Run Action (all other user actions are thread-local)



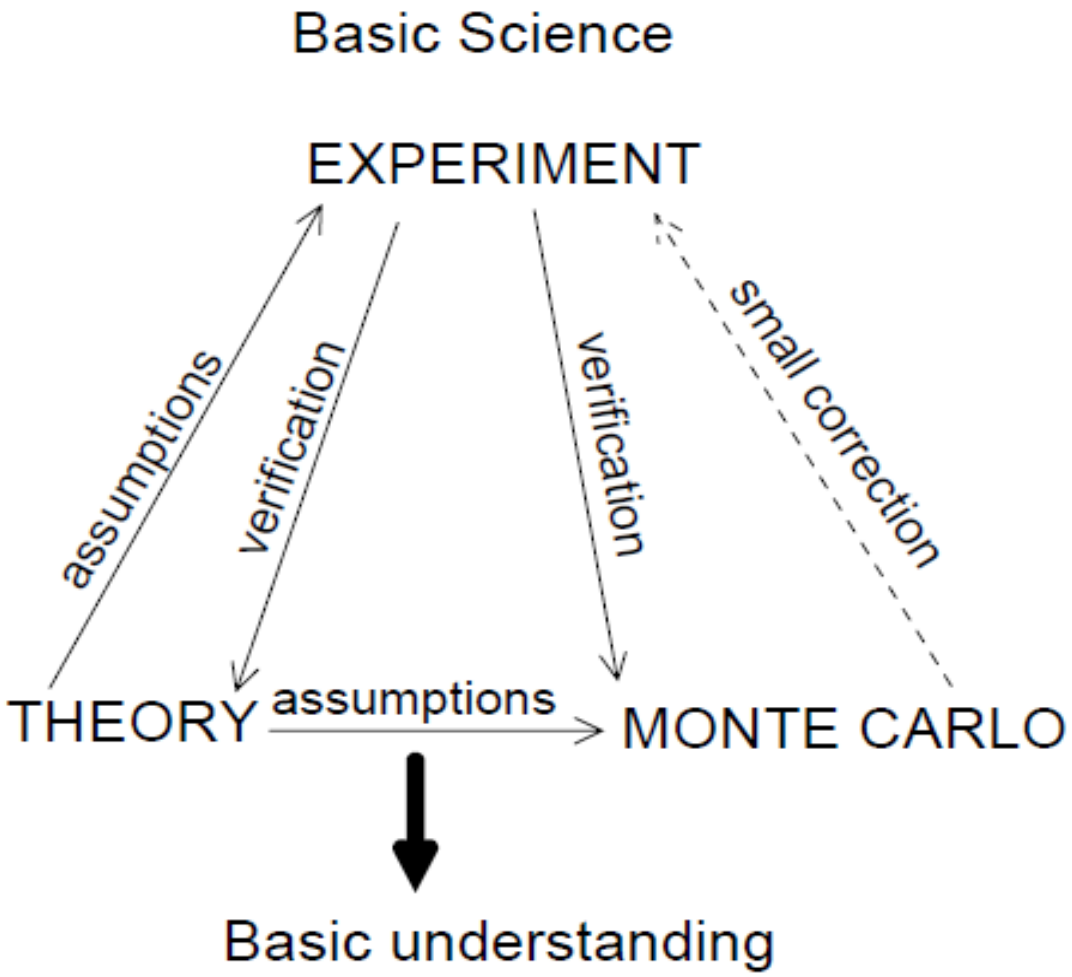
Primary generator

- User class must inherit from **`G4VUserPrimaryGeneratorAction`**
  - Registered to the Run Manager via the ActionInizialitation (MT mode)
  - Register directly to the RunManager in seq-mode
- Implement the purely virtual method
  - **`void GeneratePrimaries(G4Event*)=0;`**
  - Called by the RunManager during the event loop, to generate the primary vertices/particles
- Uses internally a concrete instance of **`G4VPrimaryGenerator`** (e.g. **`G4ParticleGun`**) to do the job



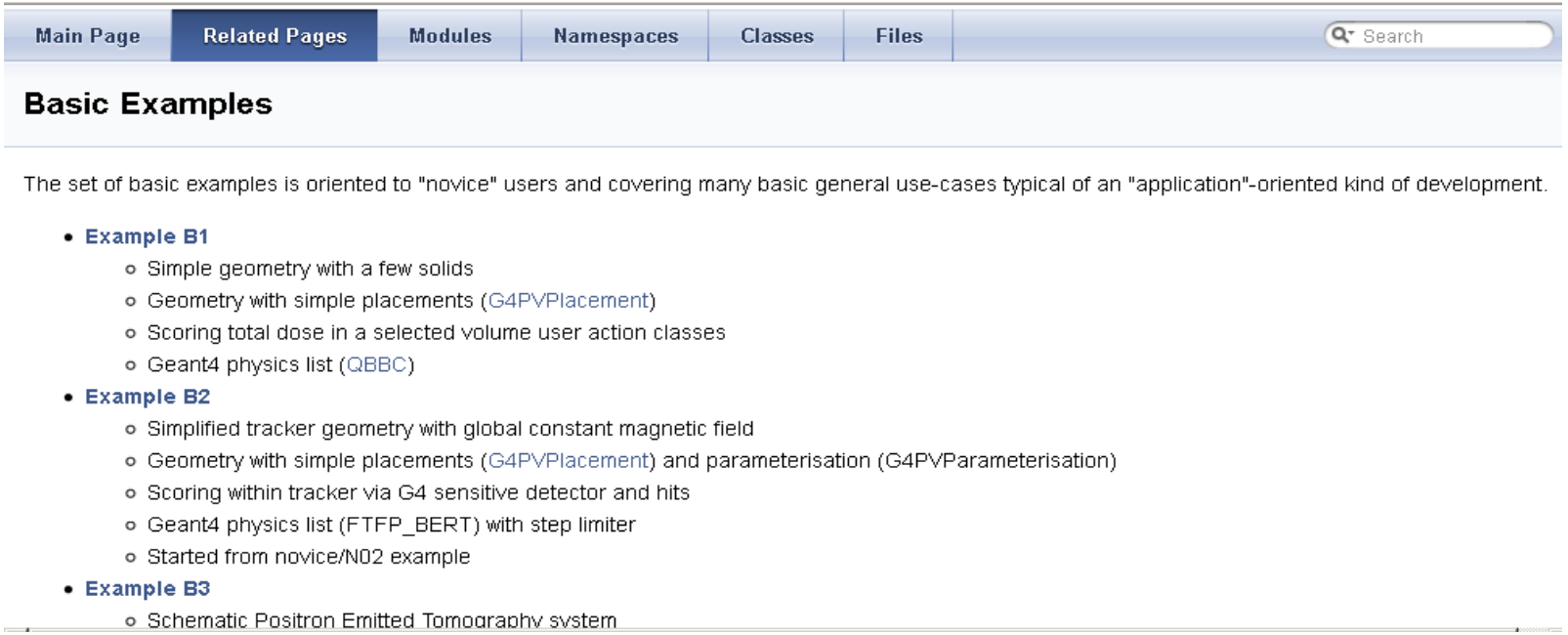
The optional user classes

Interplay between theory, simulation and experiments



Examples

- A webpage with doxygen documentation is available for the basic/extended examples



http://cern.ch/geant4/UserDocumentation/Doxygen/examples_doc/html

Sequential vs. MT main()

- The MT vs. sequential mode can be chosen in the main() by picking the appropriate RunManager:
  - **G4RunManager** for sequential
  - **G4MTRunManager** for multi-thread

```
  // Construct the default run manager. Pick the proper run
  // manager depending if the multi-threading option is
  // active or not.
#ifdef G4MULTITHREADED
  G4MTRunManager* runManager = new G4MTRunManager;
#else
  G4RunManager* runManager = new G4RunManager;
#endif
```

General recipe for novice users

Experienced users may do **much more**, but the conceptual process is still the same...

- Design your application... requires some preliminar **thinking** (what is it supposed to do?)
- Create your derived **mandatory** user classes
  - My**DetectorConstruction**
  - My**PhysicsList**
  - My**ActionInitialization** (must register My**PrimaryGenerator**)
- Create optionally your derived user action classes
  - My**UserRunAction**, My**UserEventAction**, ...
- Create your **`main()`**
  - Instantiate **`G4RunManager`** or your own derived MyRunManager
  - Notify the RunManager of your mandatory and optional user classes
  - Optionally initialize your favourite User Interface and Visualization
- That's all!