Introduction to Monte Carlo methods and its applications to Particle Physics

Physics Laboratory II
27th 2020

Carlo Mancini Terracciano
carlo.mancini.terracciano@roma1.infn.it

INFN
Istituto Nazionale di Fisica Nucleare

SAPIENZA
Università di Roma

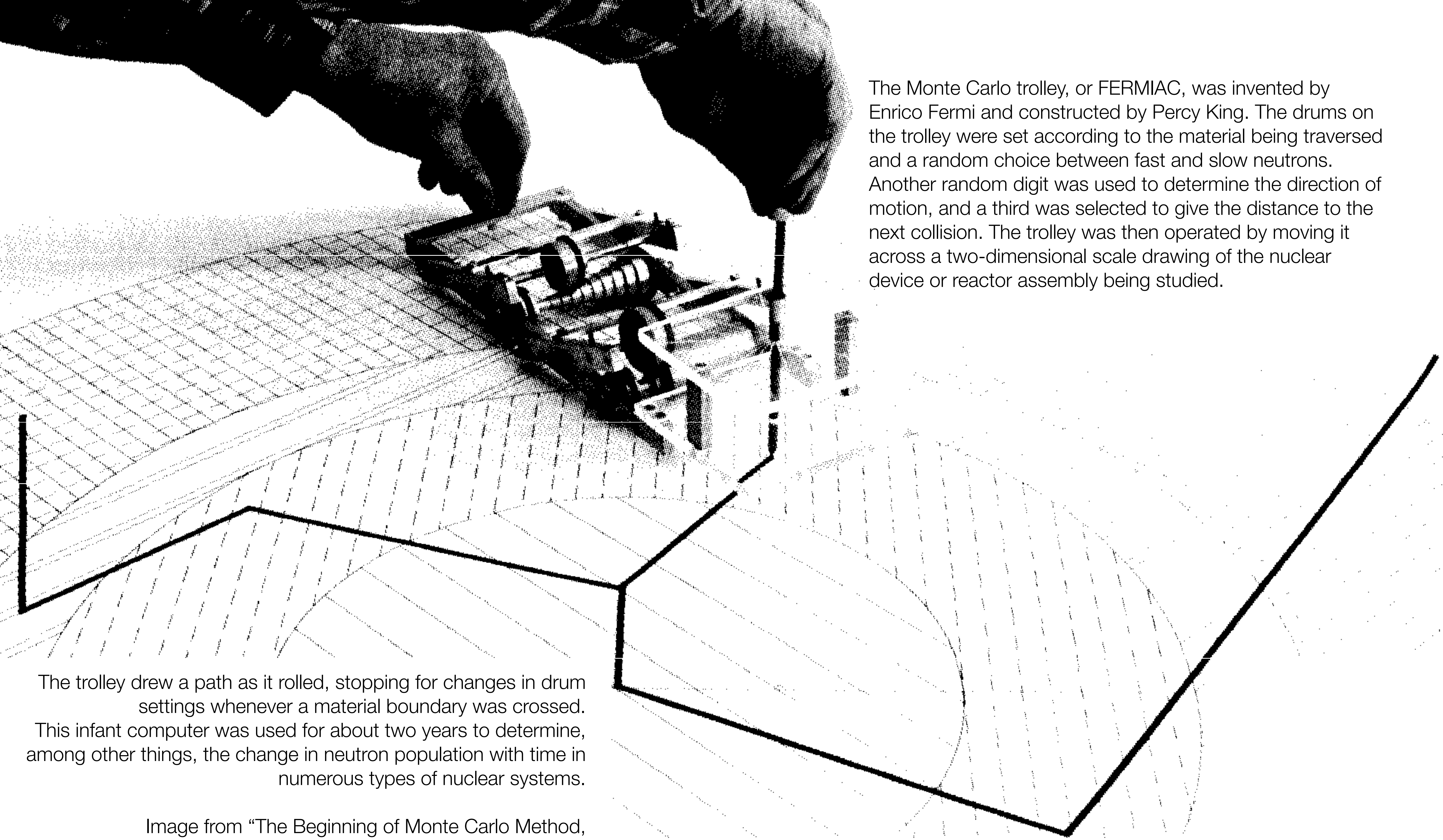
Overview

- The Monte Carlo method applied to Particle Physic
- A few tips on Geant4 installation
- Some basic features of C++ widely used in Geant4
- A short introduction to Geant4

For these slides I took inspiration from:

- M. Asai (SLAC, Stanford)
- A. Dotti (SLAC, Stanford)
- S. Incerti (CNRS, Bordeaux)
- L. Pandola (INFN-LNS, Catania)
- C. Pistillo (LHEP, Bern)
- S. Rahatlou (Sapienza, Roma)
- www.cplusplus.com

- You can download examples and slides from: http://www.roma1.infn.it/~mancinit/Teaching/LabFisNucl-2020/



The Monte Carlo trolley, or FERMIAC, was invented by Enrico Fermi and constructed by Percy King. The drums on the trolley were set according to the material being traversed and a random choice between fast and slow neutrons. Another random digit was used to determine the direction of motion, and a third was selected to give the distance to the next collision. The trolley was then operated by moving it across a two-dimensional scale drawing of the nuclear device or reactor assembly being studied.

The trolley drew a path as it rolled, stopping for changes in drum settings whenever a material boundary was crossed. This infant computer was used for about two years to determine, among other things, the change in neutron population with time in numerous types of nuclear systems.

Image from “The Beginning of Monte Carlo Method, N. Metropolis 1987

Introduction to the Monte Carlo method

The “FERMIAC”

Monte Carlo methods

- It is a mathematical approach using a sequence of random numbers to solve a problem

- Stochastic quantities (e.g.: average value of *mm* of rain)

- Deterministic problems (definite integral)

- Generate *N* random "points" $\vec{x_i}$ in the problem space

- Calculate $\langle f \rangle = \frac{1}{N} \sum_{i=1}^{N} f(\vec{x_i})$ and $\langle f^2 \rangle = \frac{1}{N} \sum_{i=1}^{N} f^2(\vec{x_i})$

Monte Carlo methods

- Comte de Buffon (1777): needle tossing experiment to calculate the π;
- Laplace (1886): random points in a rectangle to calculate π;
- Fermi (1930): random approach to calculate the properties of the newly discovered neutron;
- Manhattan project (40's): simulations during the initial developments of thermonuclear weapons;
- Von Neumann and Ulam coined the term 'Monte Carlo' (1949);
- Exponential growth of the electronic computers (40's-60's);
- Berger (1963): first complete coupled electron-photon transportation code 'ETRAN'.

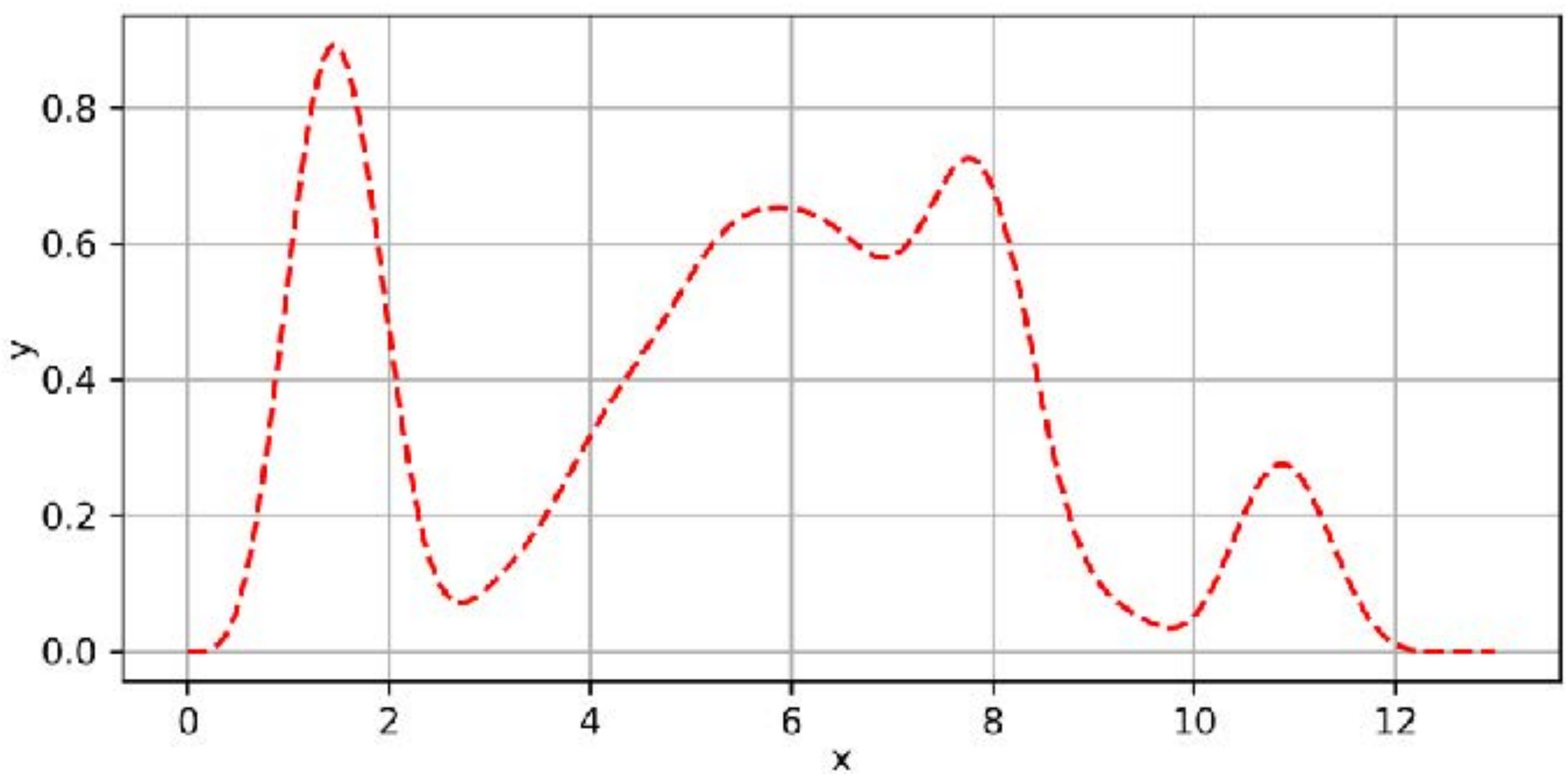
How to calculate an integral

- Randomly choose couple of numbers (x_i, y_i) from the range and the domain, respectively, of the function f
- The fraction of points where $y_i \leq f(x_i)$ is equal to the fraction of the area below the function
- Technique proposed by Von Neumann, known as the “acceptance-rejection method”
- It is used to generate random numbers for an arbitrary Probability Density Function (PDF)

Example of an integral

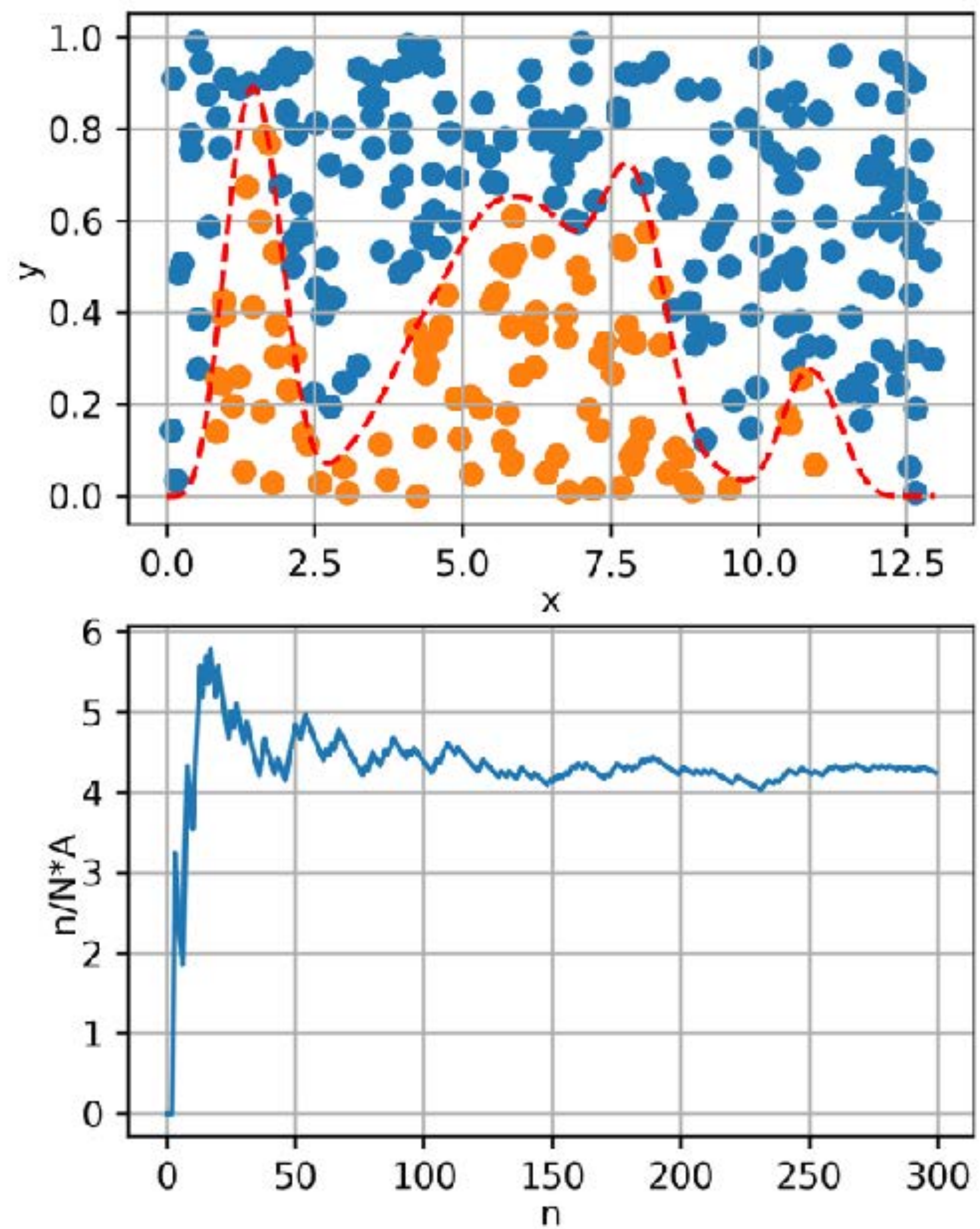
- What if you have to calculate the integral of a function as:

$$f(x) = 1.4\left[\sin^4(x)\cos^2\left(\frac{x}{3}\right) + \sin^6\left(\frac{x}{4}\right)\right]\exp\left(-\frac{x}{8}\right)$$



Example of an integral

- Using the acceptance-rejection method
- The orange points are the accepted (*n*)
- The blue are the rejected (N = accepted + rejected)



Let's calculate π

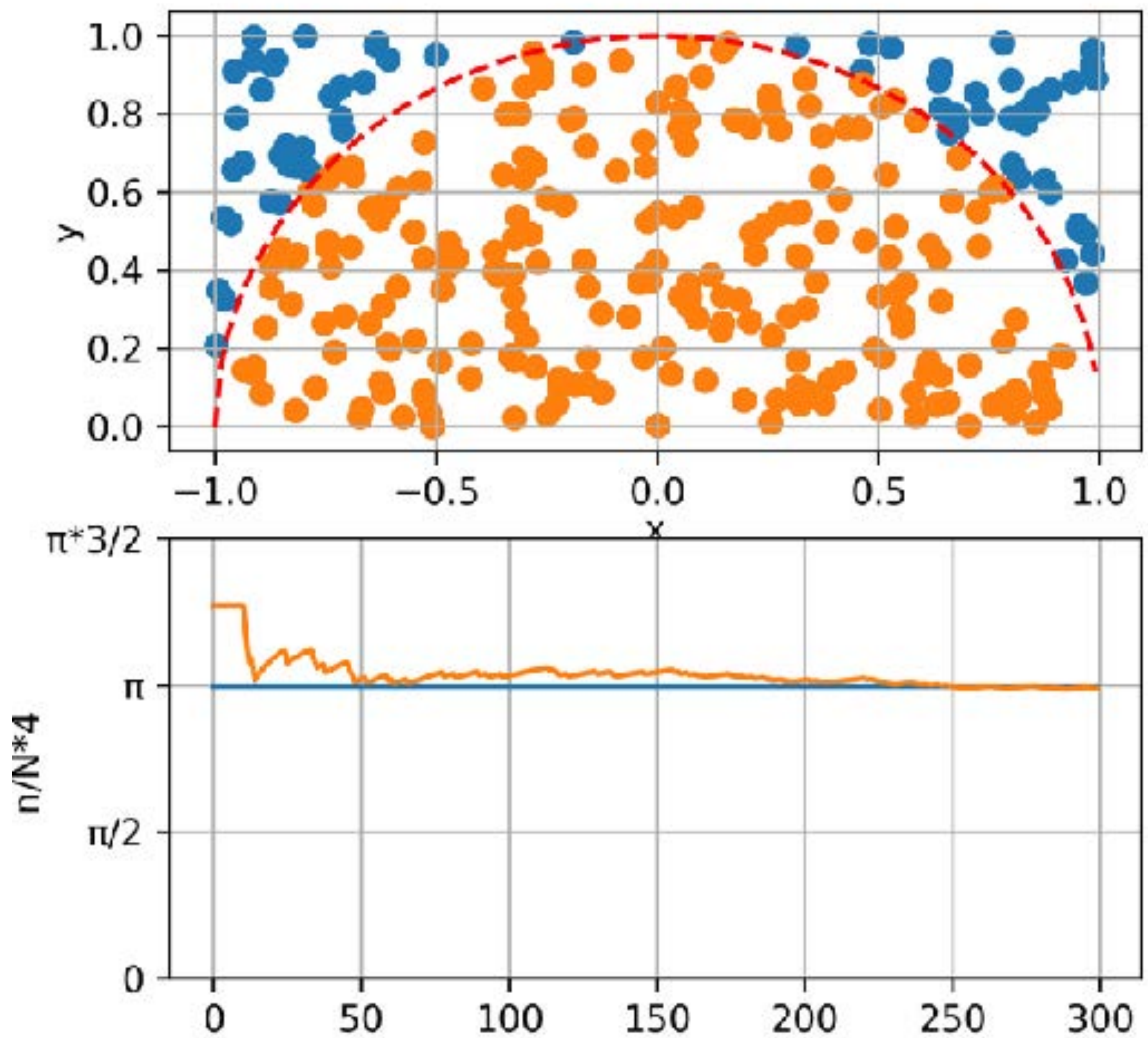
$$f(x) = \sqrt{(1-x^2)}$$

$$A_{circ} = \int_{-1}^{1} f(x)dx = \pi\frac{r^2}{2}$$

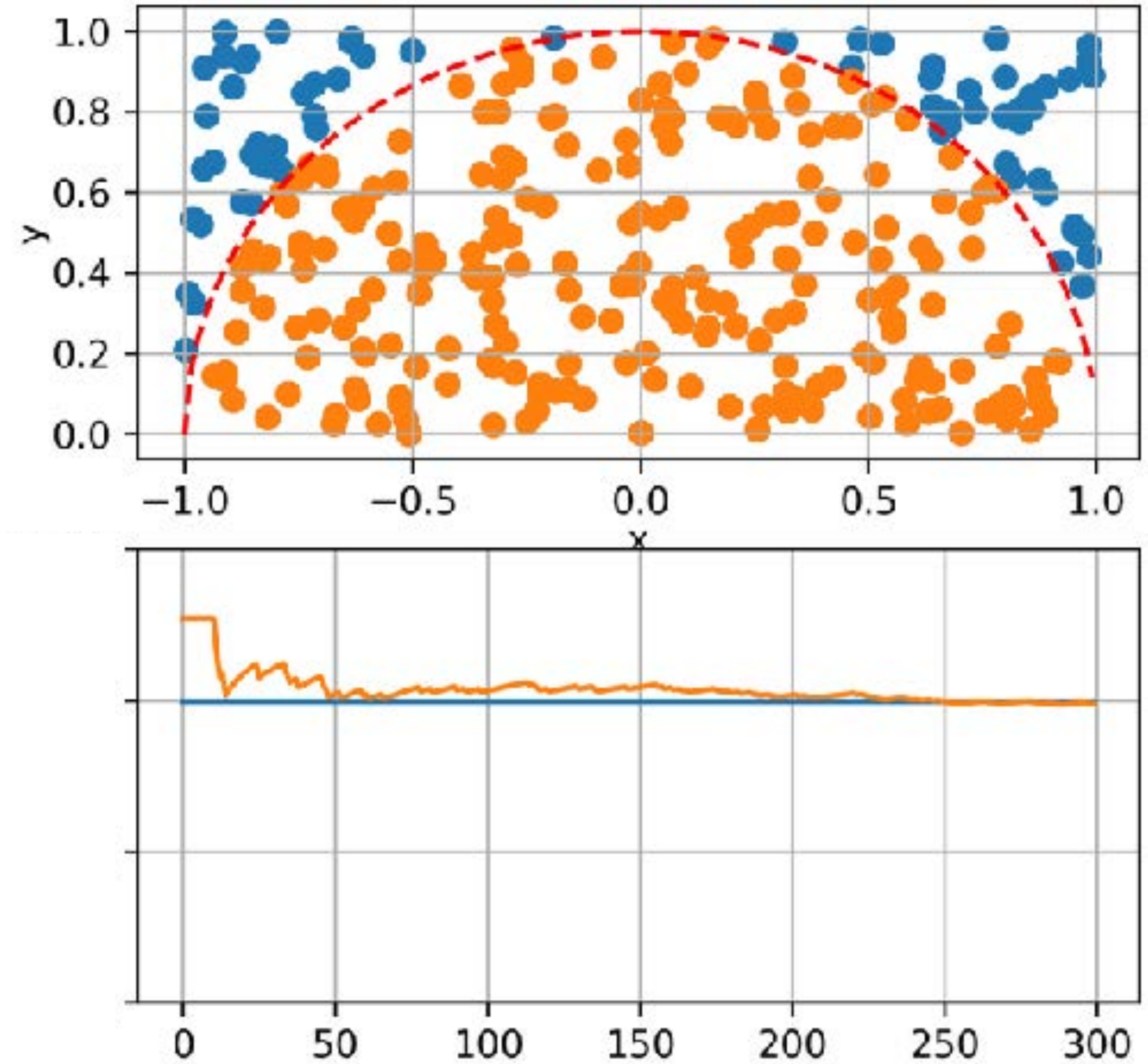
$$A_{rect} = \Delta y \cdot \Delta x$$

$$\frac{n}{N} \propto \frac{A_{circ}}{A_{rect}} = \frac{\pi r^2/2}{\Delta x \cdot \Delta y}$$

$$\pi \approx 2\frac{n}{N}\frac{\Delta x \cdot \Delta y}{r^2} = 4\frac{n}{N}$$

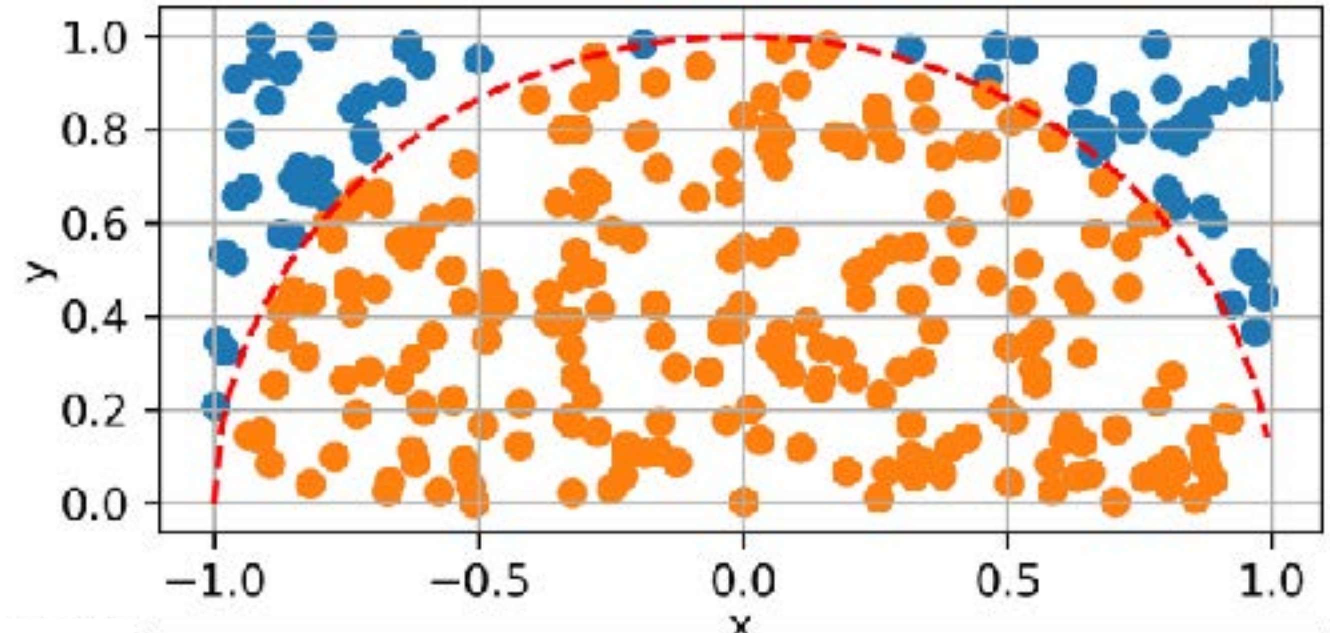


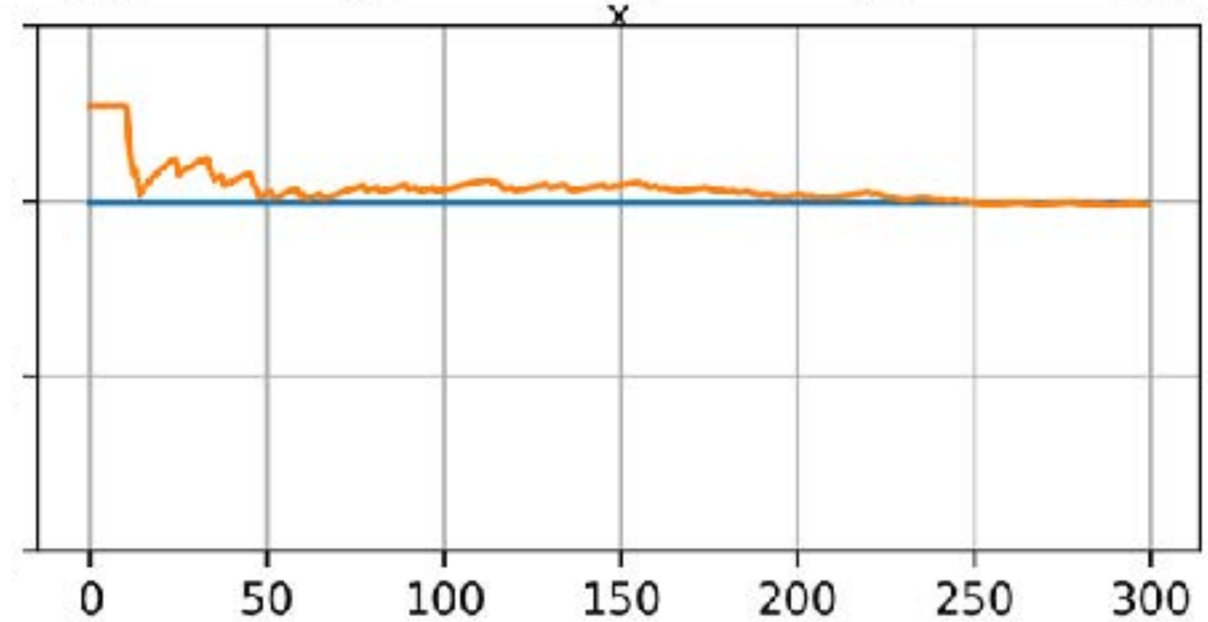
Let’s calculate π



Let's calculate π

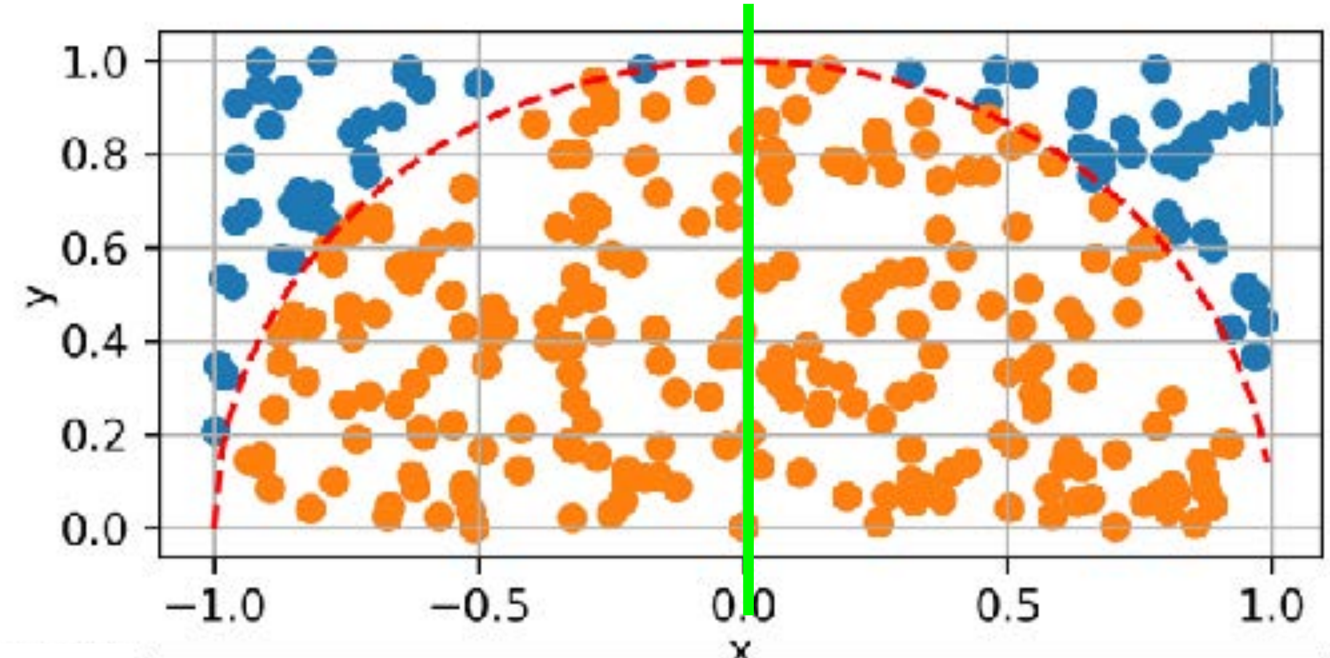
- Is there a way to speed up the convergence of the computation?





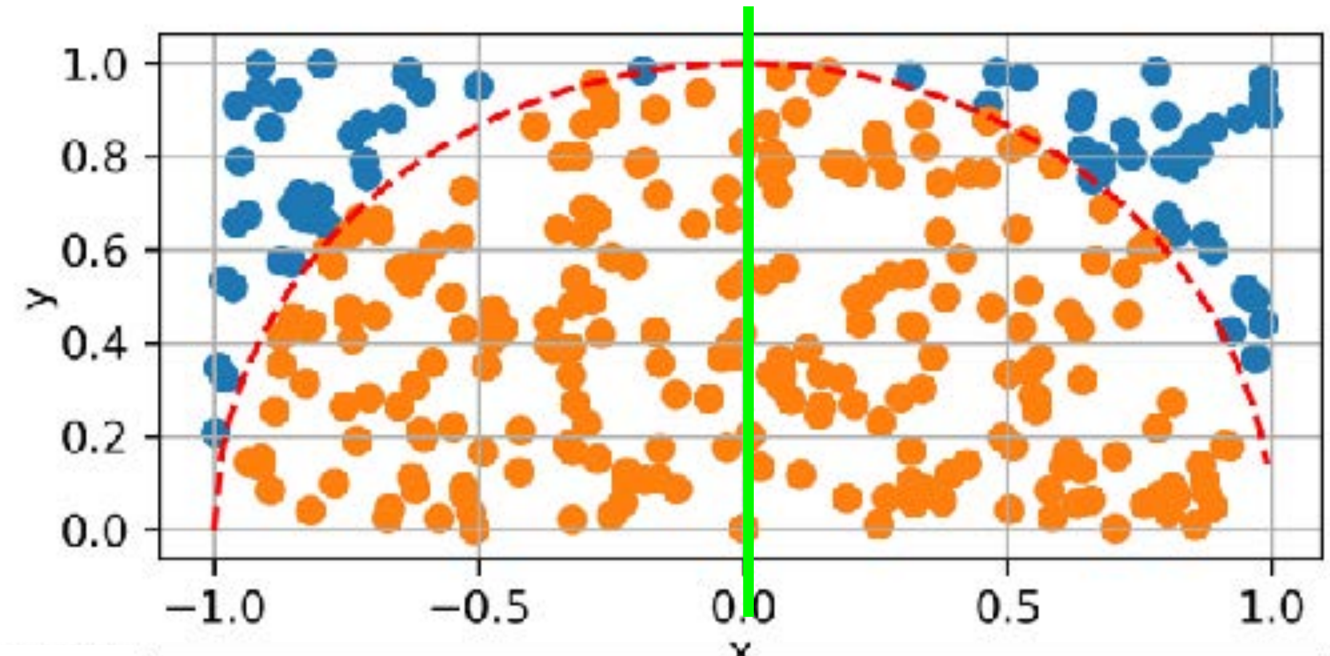
Let's calculate π

- Is there a way to speed up the convergence of the computation?
- Use the symmetry!

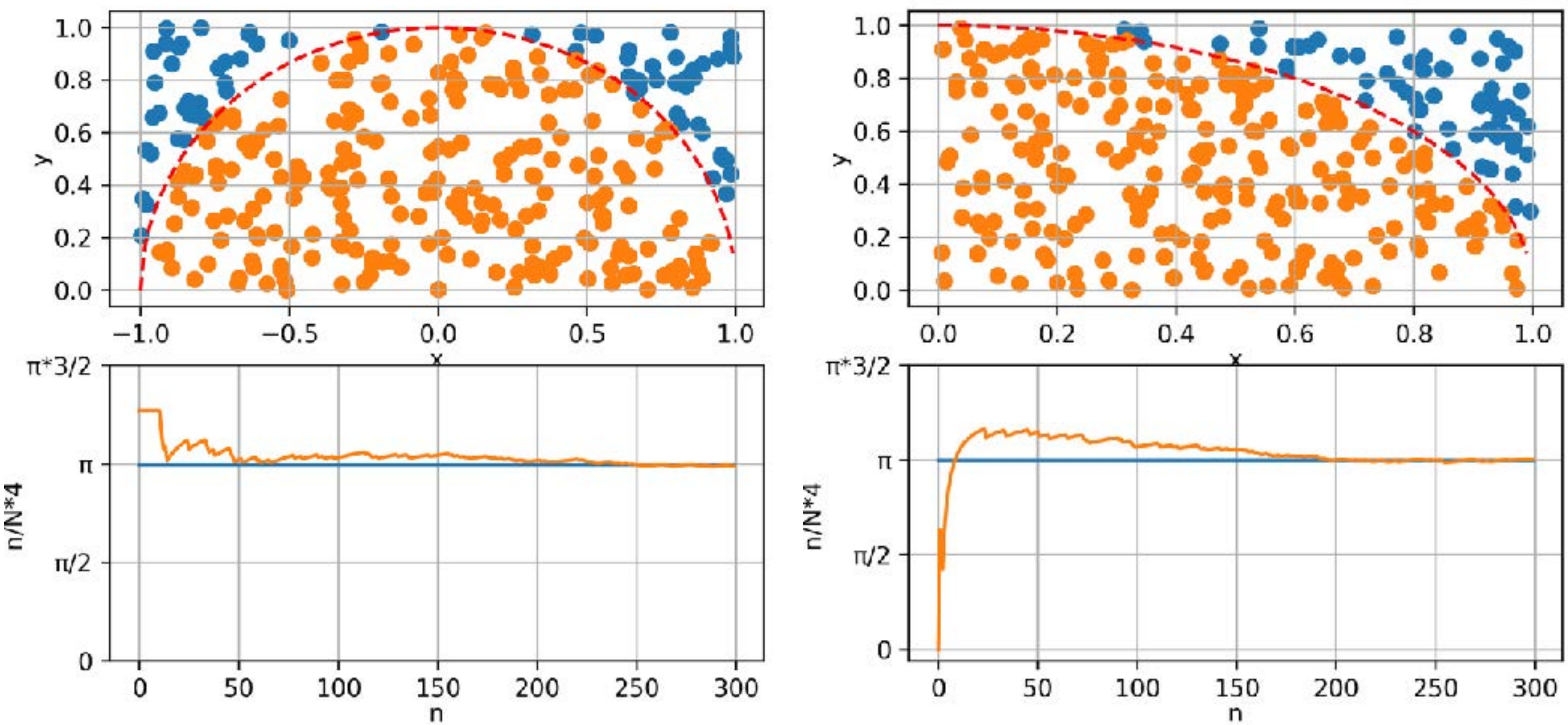


Let’s calculate π

- Is there a way to speed up the convergence of the computation?
- Use the symmetry!
- This is the method for calculating π was proposed by Laplace in “Théorie Analytique des Probabilitiés” (1825)!



Use the simmetry!



Random Numbers Generators

Random Numbers Generators

- At the core of all Monte Carlo calculations is some mechanism to produce a long sequence of random numbers r_i that are uniformly distributed over the open interval $[0,1)$

Random Numbers Generators

- At the core of all Monte Carlo calculations is some mechanism to produce a long sequence of random numbers r_i that are uniformly distributed over the open interval *[0,1)*
- Digital computers, by design, are incapable of producing random results

Random Numbers Generators

- At the core of all Monte Carlo calculations is some mechanism to produce a long sequence of random numbers r_i that are uniformly distributed over the open interval $[0,1)$

- Digital computers, by design, are incapable of producing random results

- A true random sequence could, in principle, be obtained by coupling to our computer some external device that would produce a truly random signal

Random Numbers Generators

- At the core of all Monte Carlo calculations is some mechanism to produce a long sequence of random numbers r_i that are uniformly distributed over the open interval $[0,1)$
- Digital computers, by design, are incapable of producing random results
- A true random sequence could, in principle, be obtained by coupling to our computer some external device that would produce a truly random signal
- However, use of such a random number generator would not be practical!

Random Numbers Generators

- At the core of all Monte Carlo calculations is some mechanism to produce a long sequence of random numbers r_i that are uniformly distributed over the open interval $[0,1)$
- Digital computers, by design, are incapable of producing random results
- A true random sequence could, in principle, be obtained by coupling to our computer some external device that would produce a truly random signal
- However, use of such a random number generator would not be practical!
- Imposible to debug!

Pseudo-random Number Generators

- Such a generator is a deterministic algorithm that, given the previous numbers (usually just the last number) in the sequence, the next number can be efficiently calculated

$$x_{n+1} = f(x_n, x_{n-1}, ..., x_0)$$

- x_0 is called "**seed**"
- A unique seed returns a unique random number sequence
- It is important to use a **new seed every time** that a random selection is initiated
- A typical error is the use of the same seed for multiple generation, which leads to the generation of the same sample of random numbers

Pseudo-random Number Generators

- Because the set of numbers directly representable in the computer is finite, the sequence will necessarily repeat

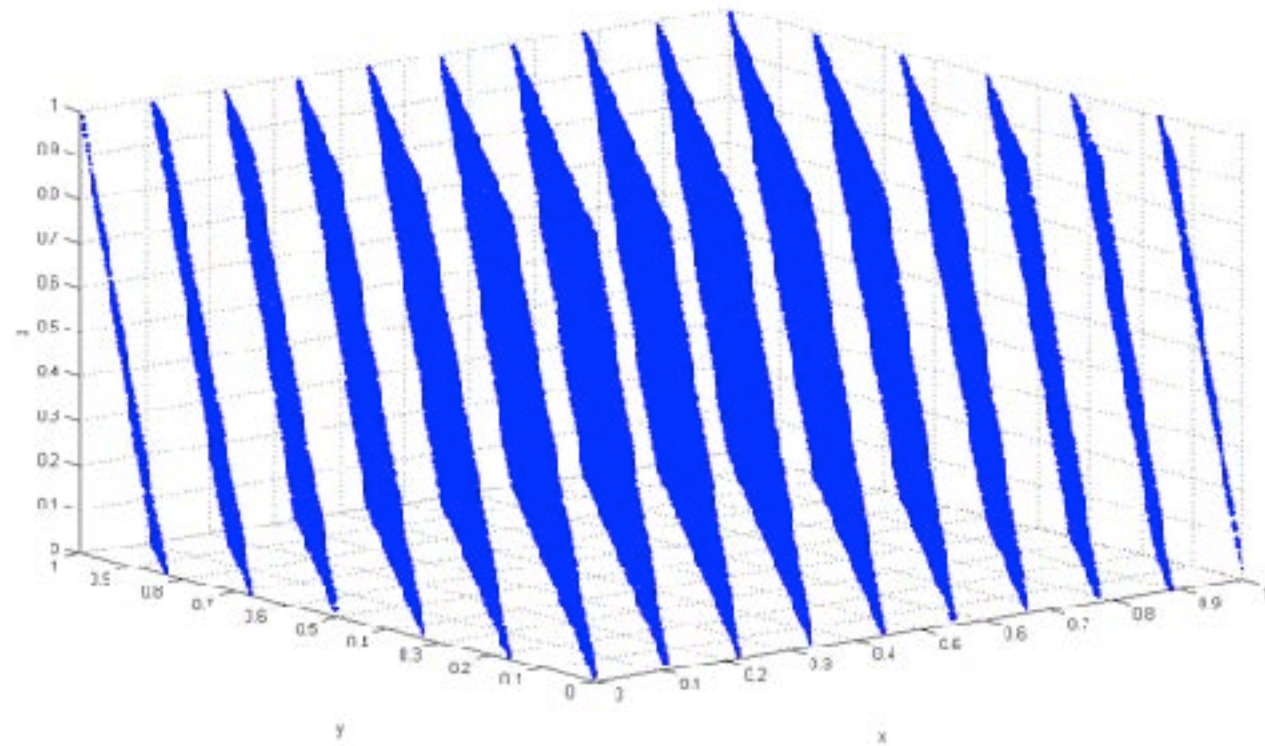
- The length of the sequence prior to beginning to repeat is called **period**

- Many pseudo-random number generators have been proposed and used over the years in a wide variety of Monte Carlo work.

- Designing better random number generators (and test them) is still an active area of research

Bad PRNG: RANDU

- Linear congruential PRNG used since '60
- Was the most widely used random number generator in the world
- Developed by IBM
- Three-dimensional plot of 100,000 values generated with RANDU
- Each point represents 3 consecutive pseudorandom values



[Image from Wikipedia]

$$x_i = 65539 \cdot x_{x-1} \mod (2^{31})$$

not only the period is important!

Simple case: decay in flight

- Suppose a π^+ with momentum *p*
- The life time is a random value with a pdf

$$f(t) = \frac{1}{\tau} \exp\left(-\frac{1}{\tau}\right)$$

- Therefore, *t* can be sampled from the inverse of the cumulative:

$$t = F^{-1}(r) = -\tau \ln(1 - r)$$

$$r \in [0, 1)$$

Simple case: decay in flight

- Select the decay channel:

Mode			Fraction (Γ_i/Γ)
Γ_1	$\mu^+\nu_\mu$	[1]	$(99.98770 \pm 0.00004)\%$
Γ_2	$\mu^+\nu_\mu\gamma$	[2]	$(2.00 \pm 0.25) \times 10^{-4}$
Γ_3	$e^+\nu_e$	[1]	$(1.230 \pm 0.004) \times 10^{-4}$
Γ_4	$e^+\nu_e\gamma$	[2]	$(7.39 \pm 0.05) \times 10^{-7}$
Γ_5	$e^+\nu_e\pi^0$		$(1.036 \pm 0.006) \times 10^{-8}$
Γ_6	$e^+\nu_e e^+ e^-$		$(3.2 \pm 0.5) \times 10^{-9}$
Γ_7	$e^+\nu_e\nu\overline{\nu}$		$< 5 \times 10^{-6}$

[table from PDG]

- In the CM frame the decay is isotropic

$$\theta \in [0, \pi); \quad \phi \in [0, 2\pi)$$

- Finally, Lorentz-boost in the Lab. frame

- 4 random numbers for one decay!

Problem

Problem

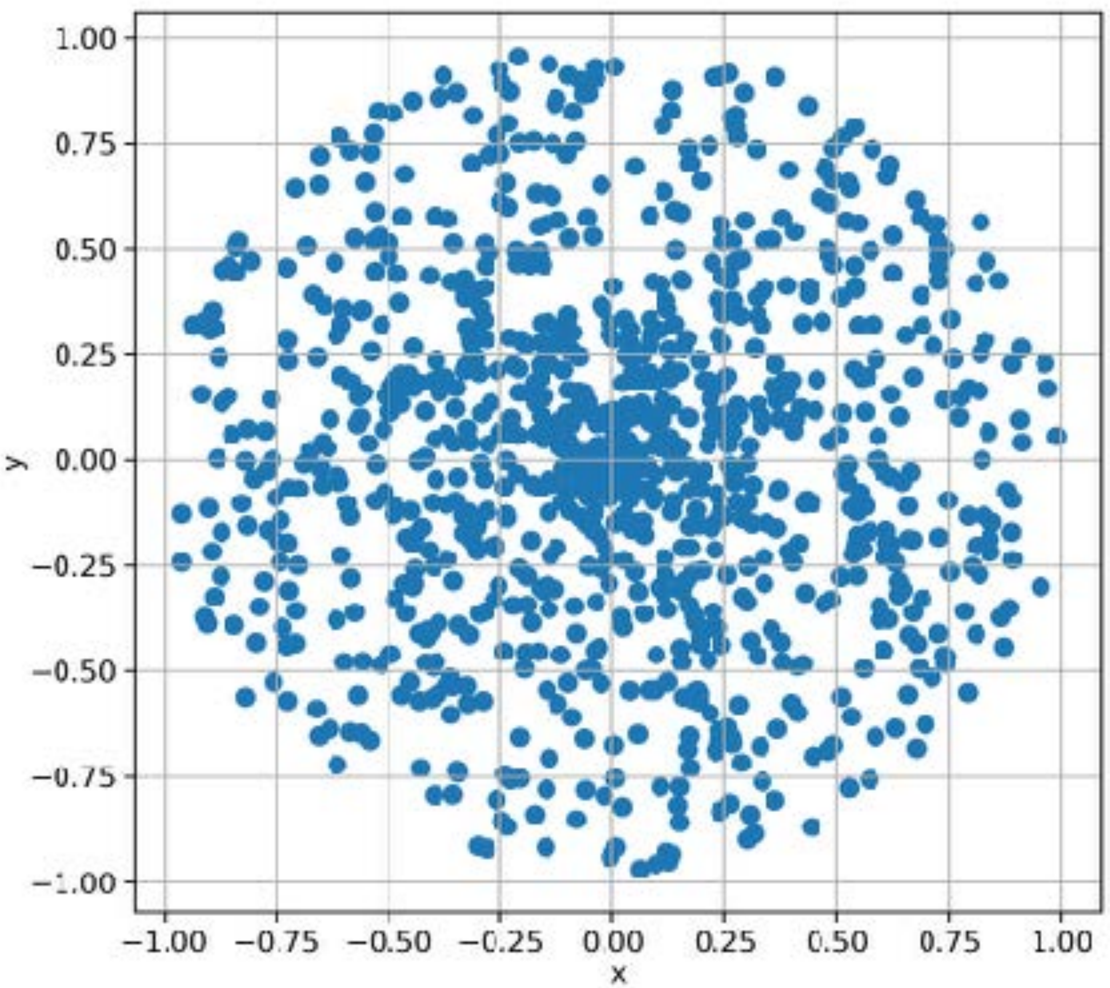
- Why did I sampled θ and ϕ in the CM frame?

Problem

- Why did I sampled θ and ϕ in the CM frame?
- What if I sample uniformly $\theta \in [0, 2\pi); \quad r \in [0, 1)$?

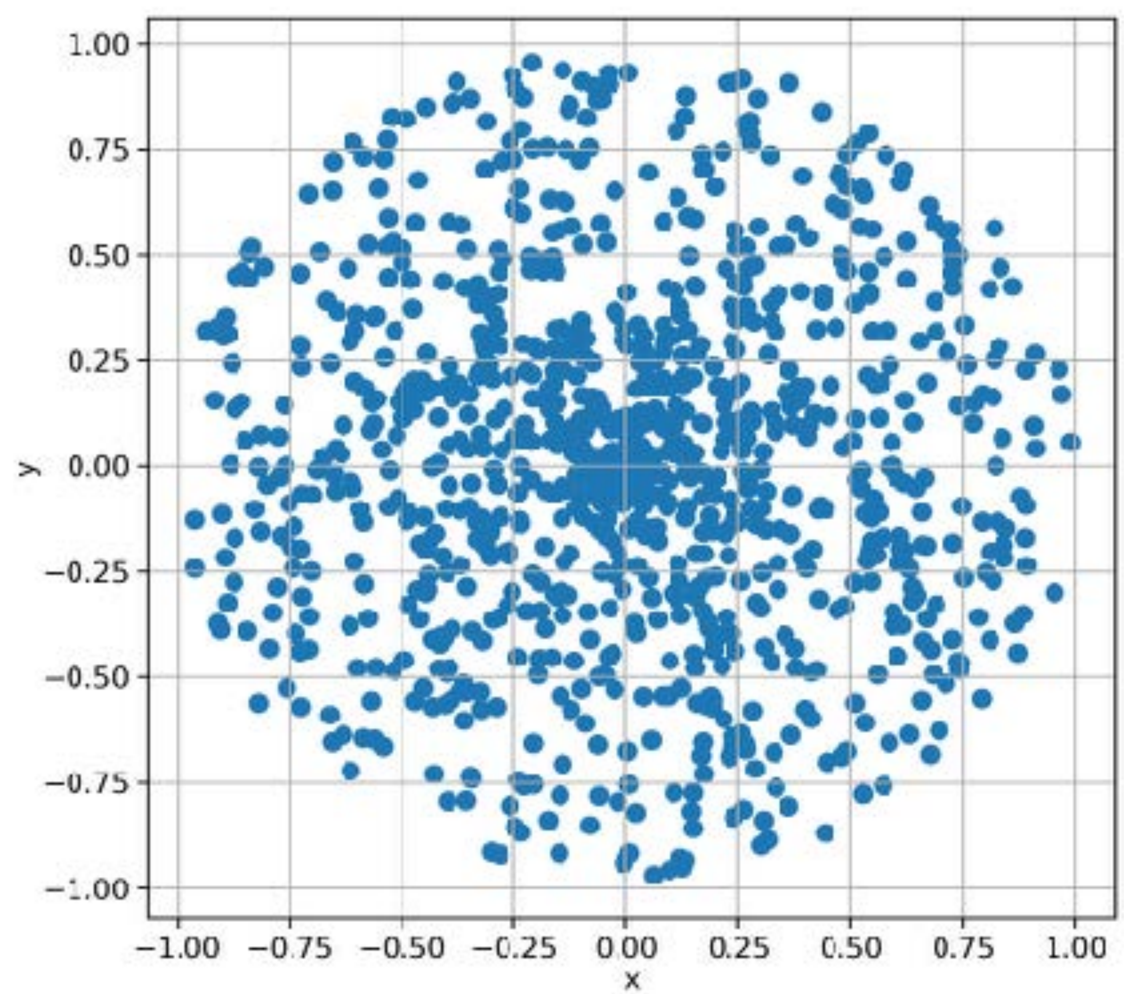
Problem

- Why did I sampled θ and ϕ in the CM frame?
- What if I sample uniformly $\theta \in [0, 2\pi); \quad r \in [0, 1)$?
- The extracted points gather in the centre



Problem

- Why did I sampled θ and ϕ in the CM frame?
- What if I sample uniformly $\theta \in [0, 2\pi); \quad r \in [0, 1)$?
- The extracted points gather in the centre



- A uniform distribution in polar coordinates is not uniform in orthogonal coordinate system

Particle tracking

- It is the most common application of MC in Particle Physic
- Assume that all the possible interactions are known
- The distance *s* between two subsequent interactions is distributed as $$p(s) = \mu \exp(-\mu s)$$
- Being μ a property of the medium

Particle tracking

- μ is proportional to the probability of an interaction per unit length, therefore:
  - is proportional to the **total cross section**

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

  - μ_i are the partial cross section of **all the competing processes**
  - depends on the **density** of the material
    (N is the number of scattering centres in the medium)

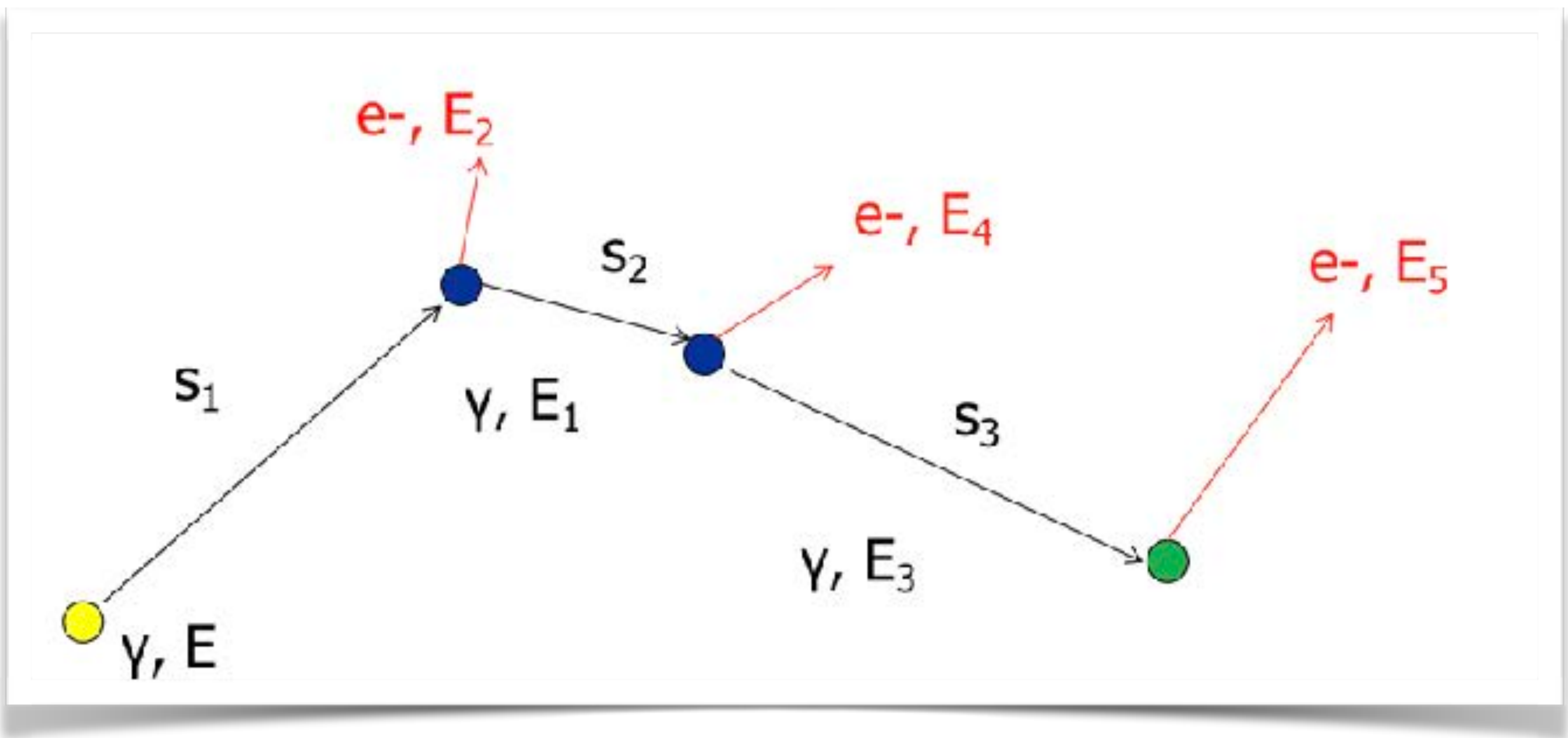
Particle tracking

- Divide the particle trajectory in **"steps"**
  - Straight free-flight tracks along the step
  - Could be limited by geometry boundaries
- Sampling the step length accordingly to $p(s)$
- Sampling the interaction at the end of the step
- Sampling the interaction accordingly to μ_i/μ
- Sampling the final state using the physics model of the interaction i
  - Update the properties of the primary particle
  - Add the possible secondaries produced (to be tracked later)

Particle tracking

- Follow all secondaries, until absorbed (or leave the geometry)

- μ depends on the energy (cross sections do!)



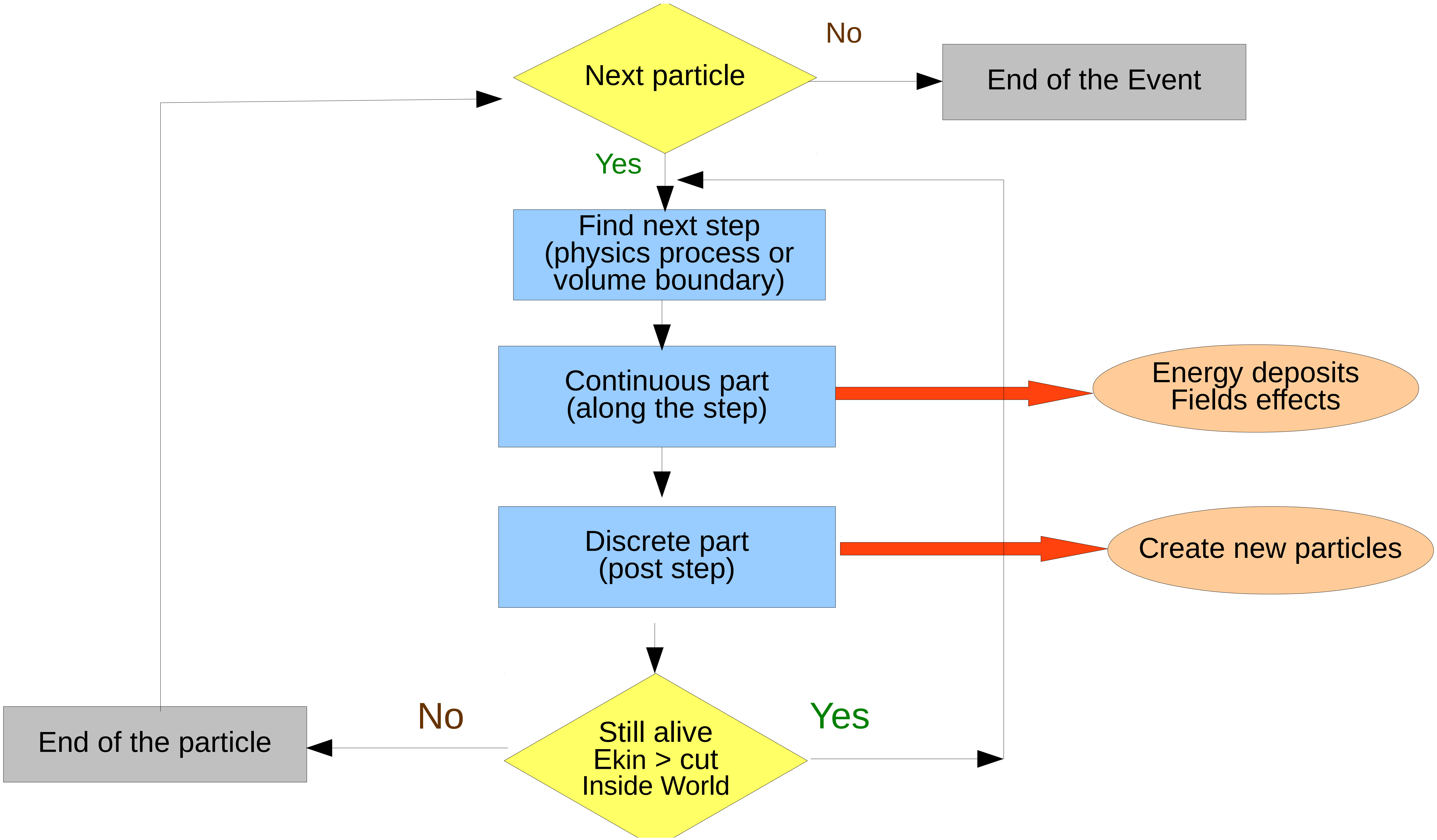
Tracking, not so easy…

- This basic recipe doesn't work well for charged particles
- The **cross sections** of some processes (ionisation and bremsstrahlung) **is very high**, so the **steps** would be very **small**
- In each interaction **only a small fraction of energy is lost** and the effect on the particle are small
- A lot of CPU time used to simulate many interactions having small effects

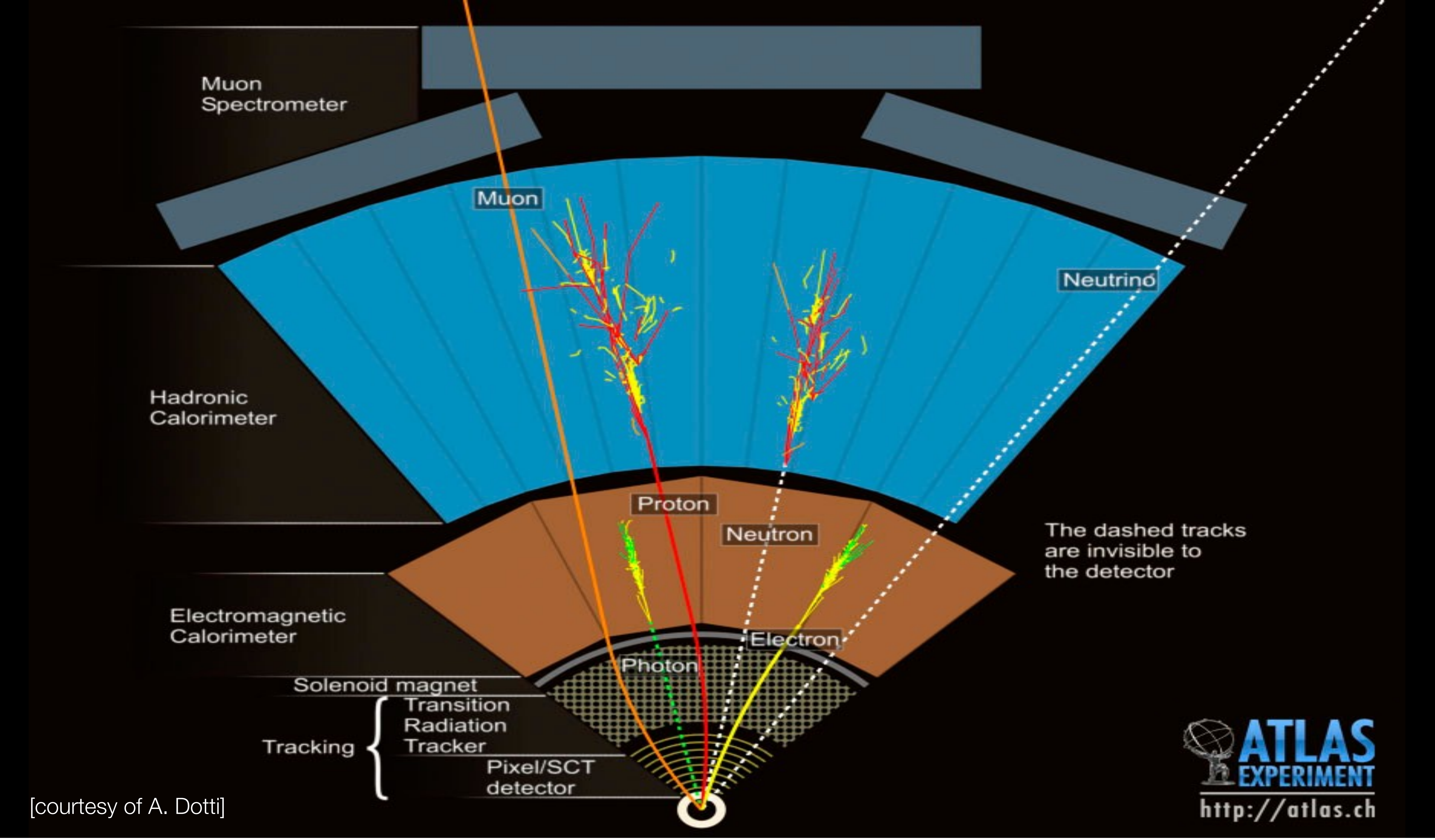
The solution: approximate

- Simulate explicitly interactions only if the energy loss is above a threshold E_0 (**hard** interactions)
    - Detailed simulation
- The effects of all sub-threshold interactions is described cumulatively (**soft** interactions)
- Hard interactions occur much less frequently than soft interactions

Flowchart of an event



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



[courtesy of A. Dotti]

A short introduction to Geant4

A sketch of the ATLAS MC simulation

Geant4 (GEometry ANd Traking)

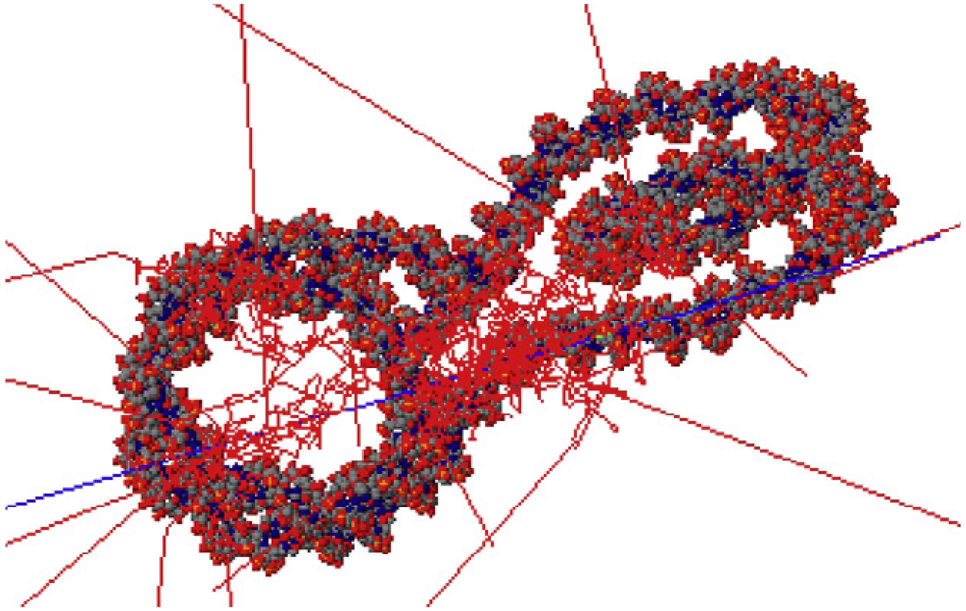
- Developed by an International Collaboration
  - Established in 1998
  - Approximately 100 members, from Europe, US and Japan
  - http://geant4.org
- Open source
- Written in C++ language
  - Takes advantage from the Object Oriented software technology

[Geant4, a simulation toolkit Nucl. Inst. and Methods Phys. Res. A, 506 250-303

Geant4 developments and applications Transaction on Nuclear Science 53, 270-278]

Geant4 applications

- Physics experiments
- but also:
  - Hadrontherapy
  - Radiobiology
  - and many others…



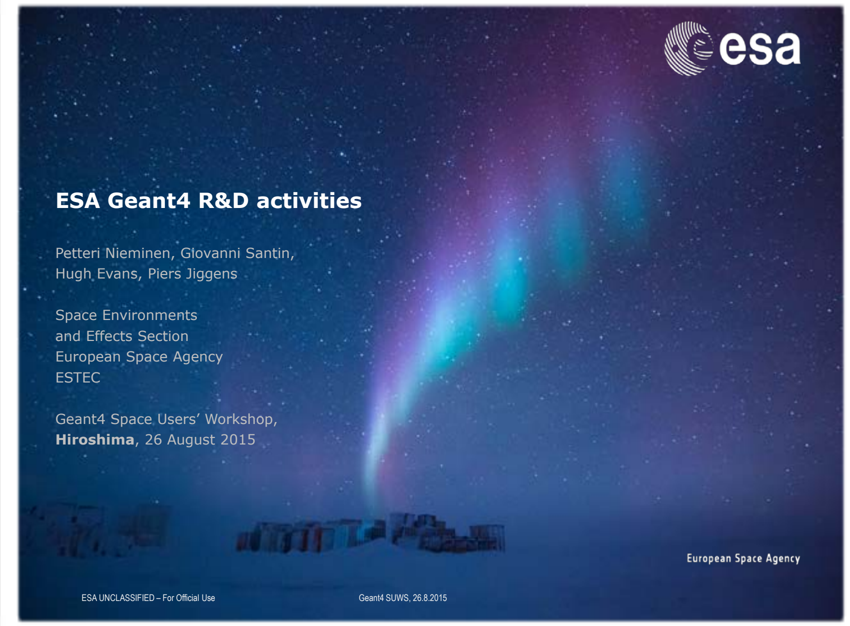
atomistic view of a dinucleosome irradiated by a single 100 keV proton

Image from M. A. Bernal et al Physica Medica, vol. 31, no. 8, pp. 861–874, Dec. 2015.

Geant4, further applications

- Radio-protection in space mission
- Shielding for satellites
- Single event upset and radiation damages to electronics
- Simulations for nuclear spallation sources
- Radioactive waste

First slide of the talk "ESA Geant4 R&D Activities from the Geant4 Space User Workshop Hiroshima, 26 August 2015



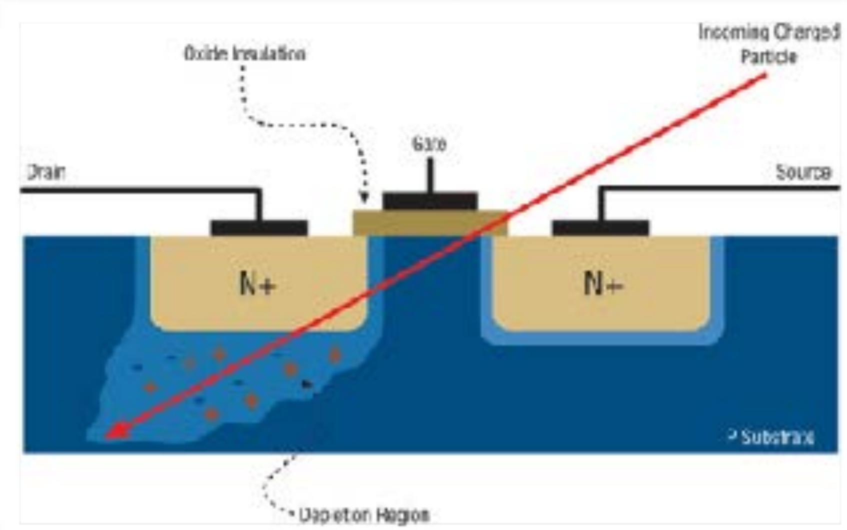
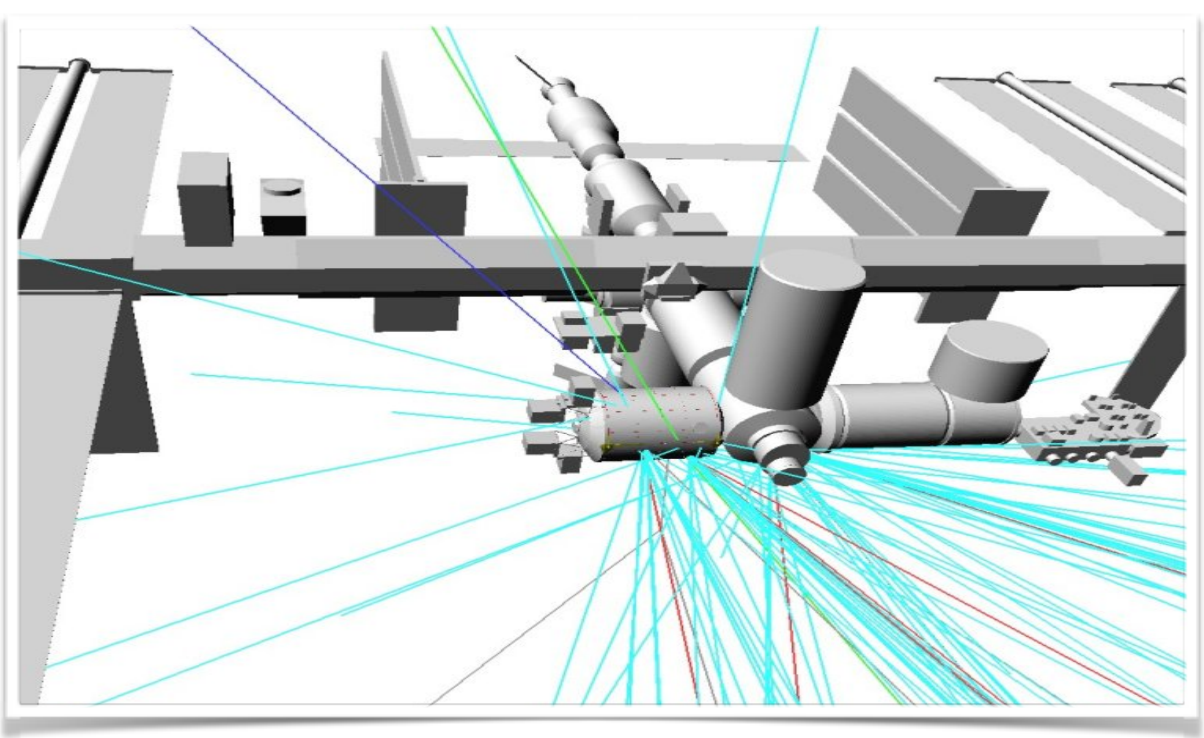


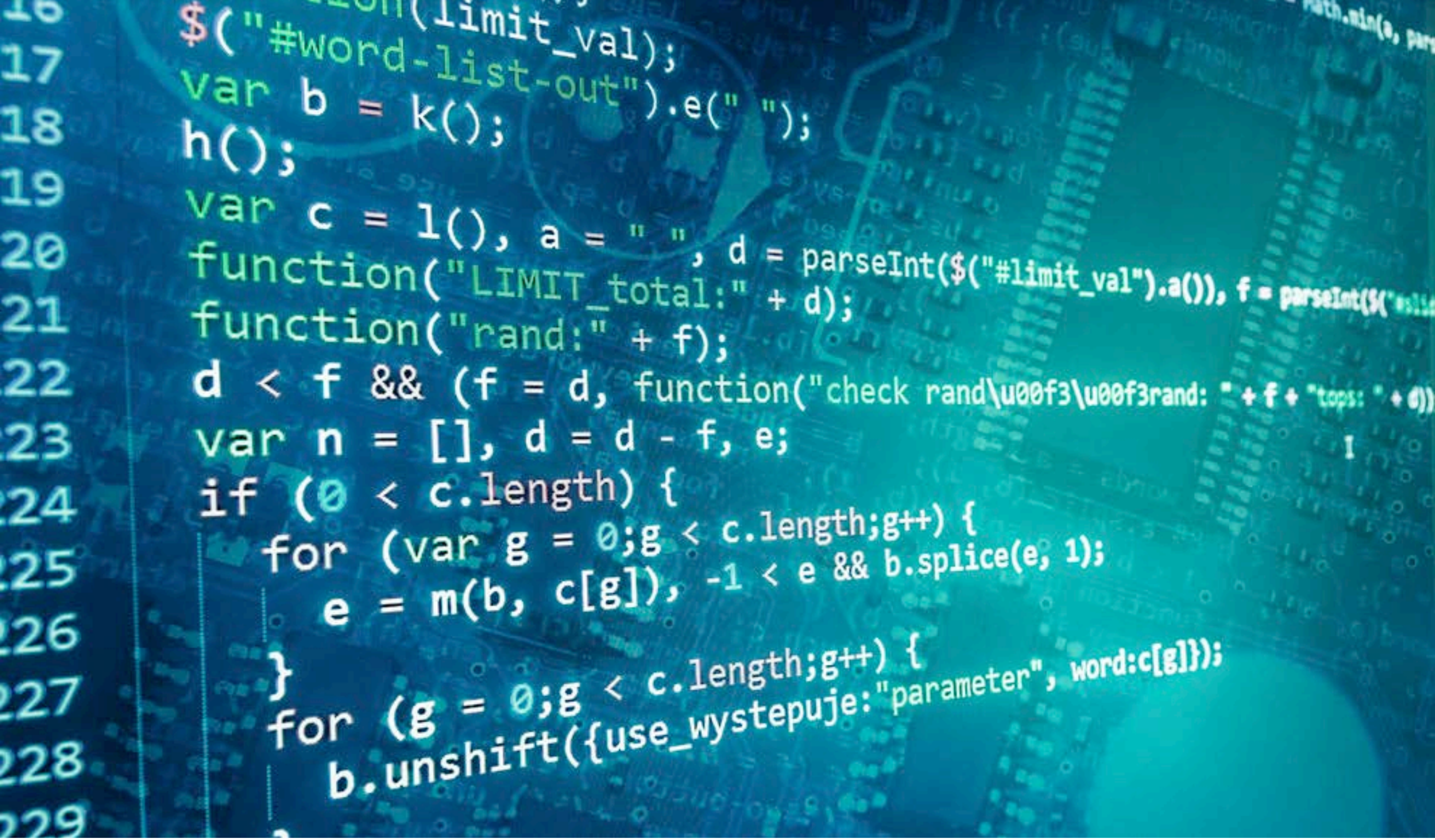
Figure from M. Sawant, COTS Journal Jan. 2012

How to install Geant4

- You can find the most recent tips on:

  http://www.roma1.infn.it/~mancinit/?action=3Teaching/Suggestions_on_Geant4_installation





Some basic features of C++

[slides made getting inspiration from http://www.cplusplus.com]

Just an introduction

- This is not a C++ course
- Just few information useful to understand the Geant4 examples
- For a complete course:
  http://www.roma1.infn.it/people/rahatlou/programmazione++/

Few things about C++

- A general-purpose programming language
- Has imperative, **object-oriented** and generic programming features
- Provides facilities for low-level memory manipulation
- In 1983, "C with Classes" was renamed to "C++" (++ being the increment operator in C)
- Initially standardised in 1998 (current standard is C++17 but the most used is C++11)

Classes

- Classes are an expanded concept of data structures: like data structures, they can contain data members, but they can also contain functions as members

Like Plato's ideas (the idea of apple), classes have generic attributes (e.g. color).
Each instance (this Golden Delicious apple) of the class have a specific attribute (e.g. yellow)

```
class Apple {
public:
   void setColor(color);
   color getColor();

private:
   color fColor;
   double fWeight;
```

Example of class usage

```
#include <iostream>
using std::cout;

class Rectangle {
    int width, height;
  public:
    void set_values (int,int);
    int area() {return width*height;}
};

void Rectangle::set_values (int x, int y)
{
  width = x;
  height = y;
}

int main () {
  Rectangle rect;
  rect.set_values (3,4);
  cout << "area: " << rect.area();
```

Idea of rectangle

An instance of rectangle

Example of class usage

```
#include <iostream>
using std::cout;

class Rectangle {
    int width, height;
  public:
    void set_values (int,int);
    int area() {return width*height;}
};

void Rectangle::set_values (int x, int y)
{
  width = x;
  height = y;
}

int main () {
  Rectangle rect;
  rect.set_values (3,4);
  cout << "area: " << rect.area();
```

Declaration

Namespace

Implementation

Usage of the methods

Example of class usage

```
#include <iostream>
using std::cout;

class Rectangle {
    int width, height;
  public:
    void set_values (int,int);
    int area() {return width*height;}
};

void Rectangle::set_values (int x, int y)
{
  width = x;
  height = y;
}

int main () {
  Rectangle rect;
  rect.set_values (3,4);
  cout << "area: " << rect.area();
```

Hyperuranion

(ὑπερουράνιος τόπος)

literally: "place beyond heaven"

“Real” world

What if I want to protect the rectangle properties (the dimensions), once instantiated?

Constructors

```
#include <iostream>
using std::cout;

class Rectangle {
    int width, height;
  public:
    Rectangle(int x, int y);
    int area() {return width*height;}
};

Rectangle::Rectangle(int x, int y)
{
  width = x;
  height = y;
}

int main () {
  Rectangle rect(3,4);
  cout << "area: " << rect.area();
  return 0;
```

Using the constructor and removing the setting method

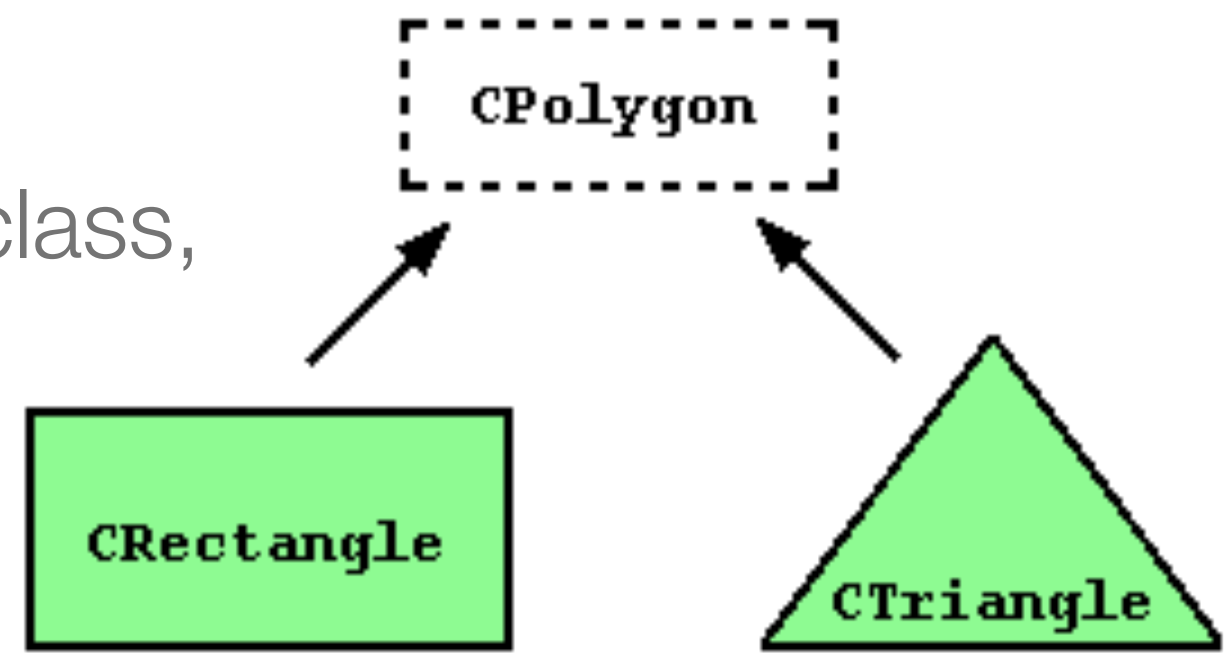
Constructors

```
#include <iostream>
using std::cout;

class Rectangle {
     int width, height;
   public:
     Rectangle(int x, int y);
     int area() {return width*height;}
};

Rectangle::Rectangle (int x, int y) :
width(x), height(y) { }


int main () {
   Rectangle rect(3,4);
   cout << "area: " << rect.area();
   return 0;
}
```

Better implementation!

Inheritance

- Classes in C++ can be extended, creating new classes which retain characteristics of the base class
- This process, known as inheritance, involves a base class and a derived class
- The derived class inherits the members of the base class, on top of which it can add its own members



Inheritance, an example

```
class Polygon {
  protected:
    int width, height;
  public:
    void set_values (int a, int b)
      { width=a; height=b;}
 };
```

```
class Rectangle: public Polygon
{
 public:
  int area ()
  {
   return width*height;
  }
};
```

```
class Triangle: public Polygon
{
 public:
  int area()
  {
   return width*height/2;
  }
};
```

Protected and not private!

- The protected access specifier used in class Polygon is similar to private. Its only difference occurs in fact with inheritance:

- When a class inherits another one, the members of the derived class can access the protected members inherited from the base class, but not its private member

- By declaring width and height as protected instead of private, these members are also accessible from the derived classes Rectangle and Triangle, instead of just from members of Polygon

- If they were public, they could be accessed just from anywhere

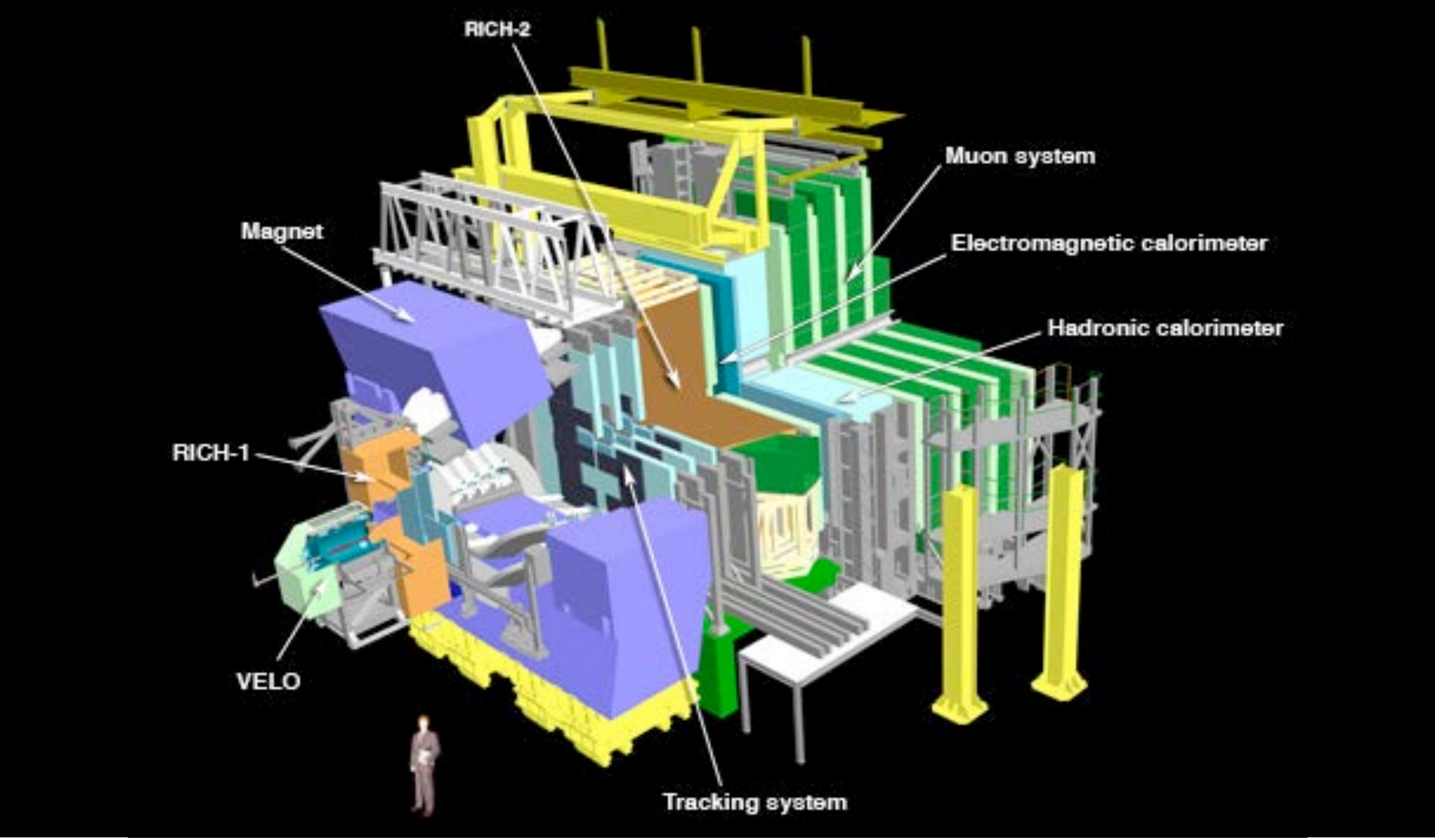
Let’s use the classes…

```
#include <iostream>
using std::cout;
using std::endl;

int main () {
  Rectangle rect;
  Triangle trgl;
  rect.set_values (4,5);
  trgl.set_values (4,5);
  cout << rect.area() << endl;
  cout << trgl.area() << endl;
  return 0;
}
```

have a look at the example
https://github.com/carlomt/inheritance_example
for more details

CMake

- a cross-platform free and open-source software application for managing the build process of software using a compiler-independent method
- supports directory hierarchies and multiple libraries
- can locate executables, files, and libraries
- https://cliutils.gitlab.io/modern-cmake/
- use a version of CMake that came out after your compiler
- since CMake will dumb itself down to the minimum required version in your CMake file, installing a new CMake, even system wide, is pretty safe



Lets get back to Geant4

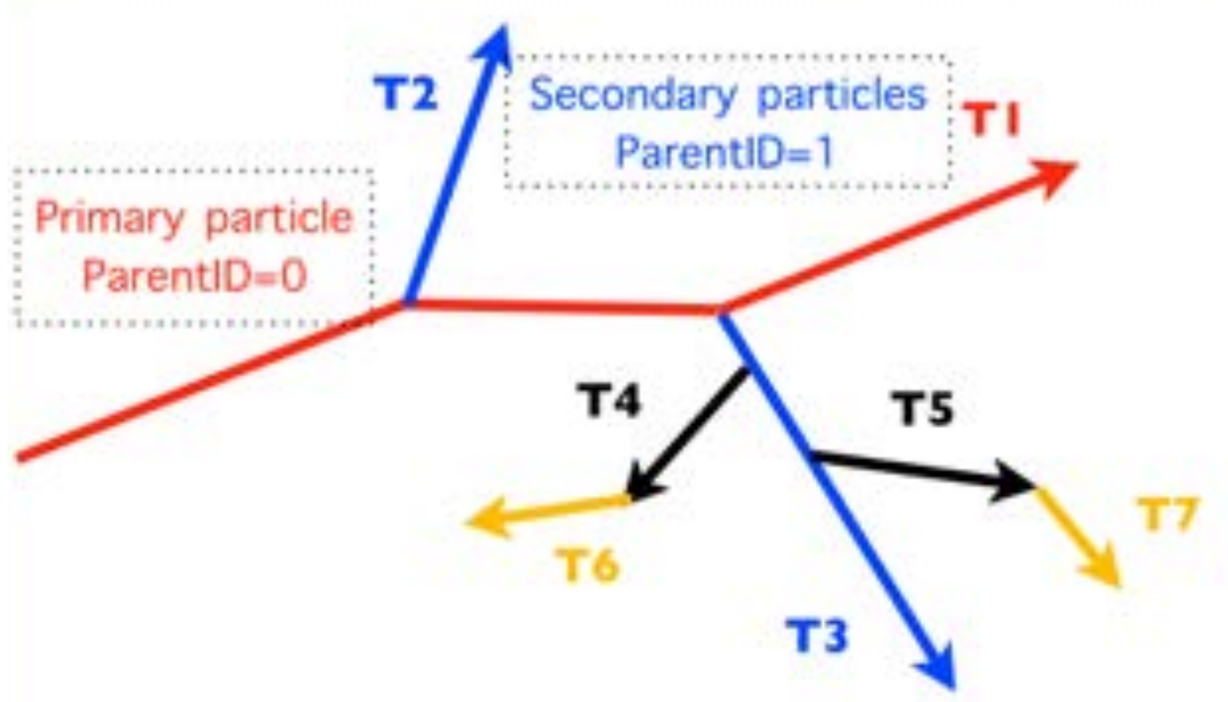
Geant4 is a toolkit

Reminder…

- 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
- 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 Examples**: overview of Geant4 tools
  - Advanced Examples: Geant4 tools in real-life applications

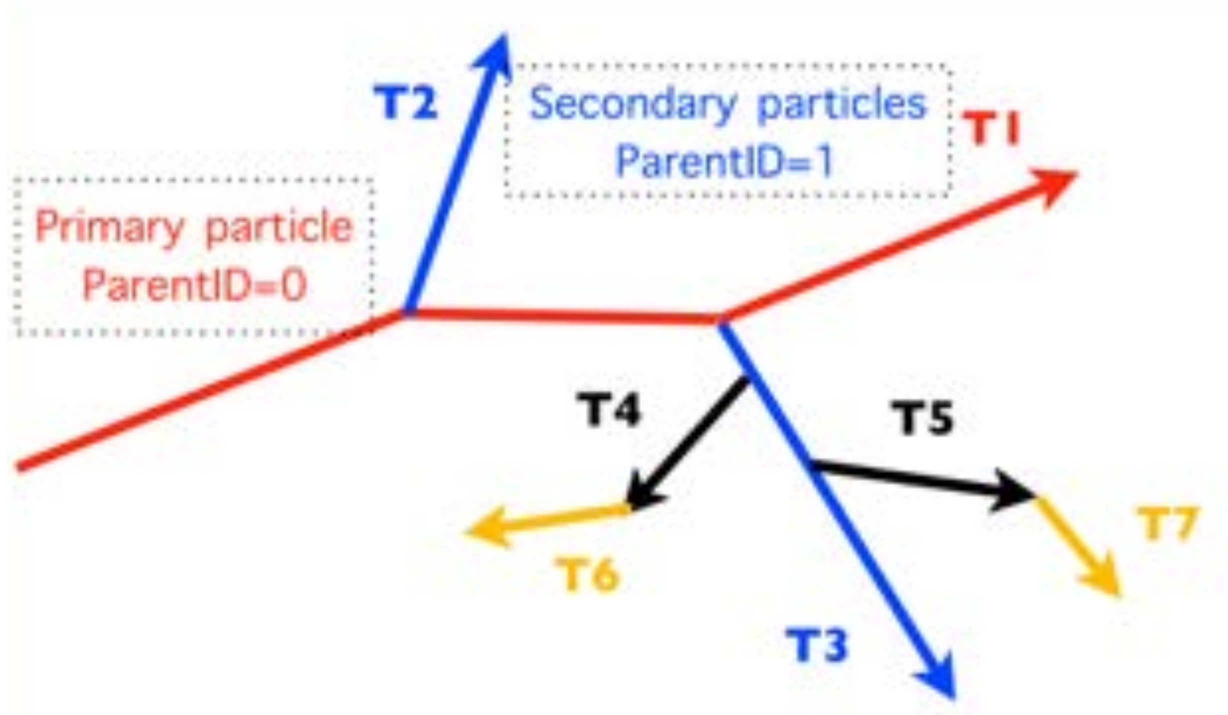
Geant4 way of tracking

- Force step ending at **geometry boundaries**
- All **AlongStep** processes **co-occur**
- The **PostStep** compete, i.e.: **only one** is selected



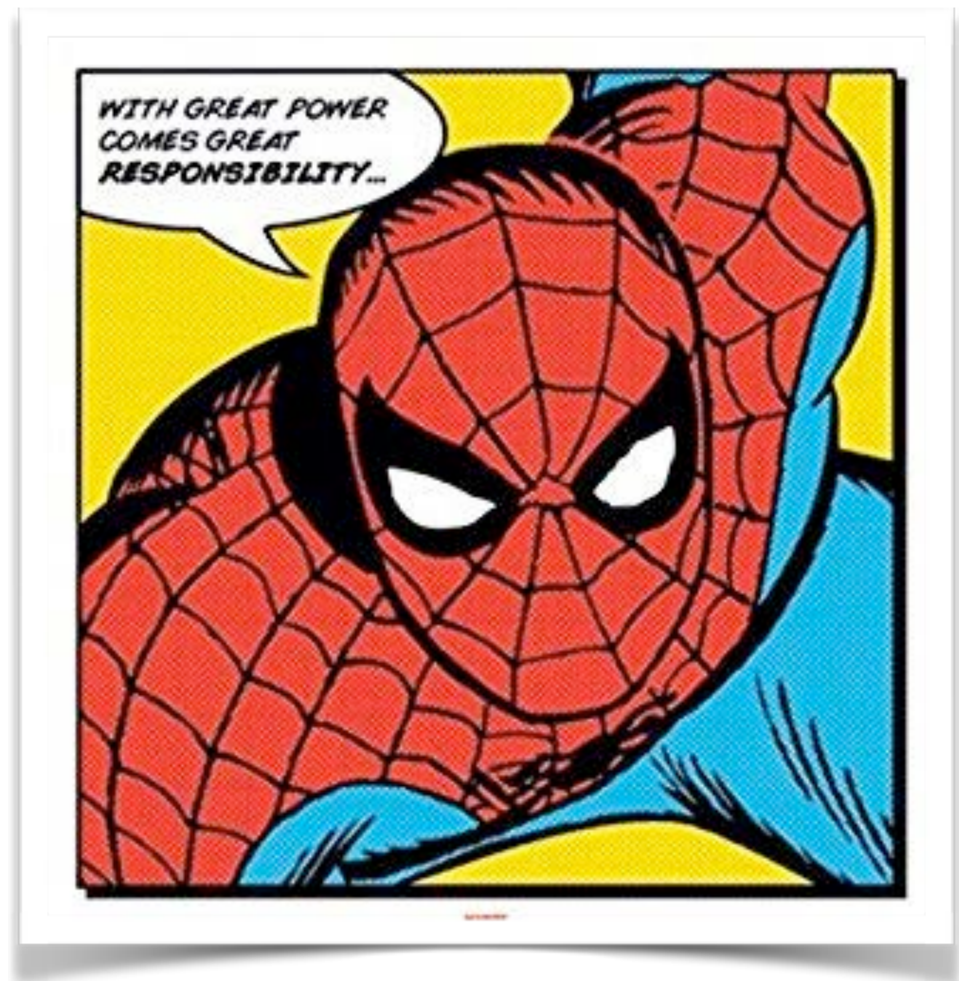
Geant4 way of tracking

- **If particle is at rest** chose one of the **AtRest** processes
- The secondaries are saved in the stack
- To be further tracked with a **last in first out** approach



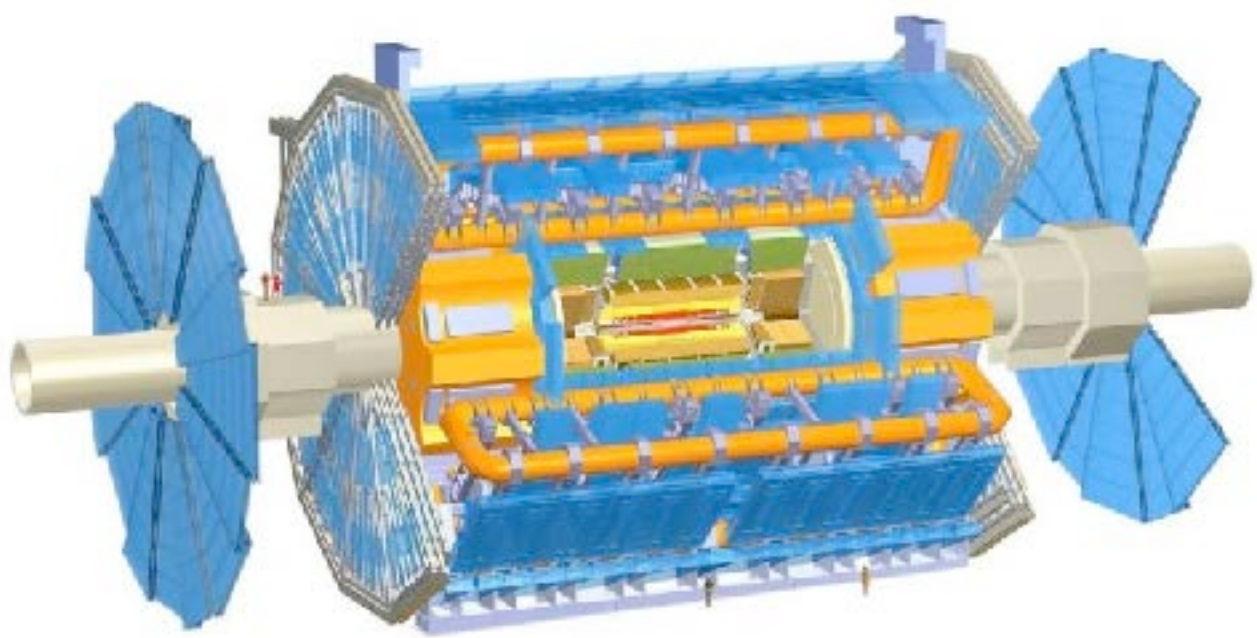
You MUST:

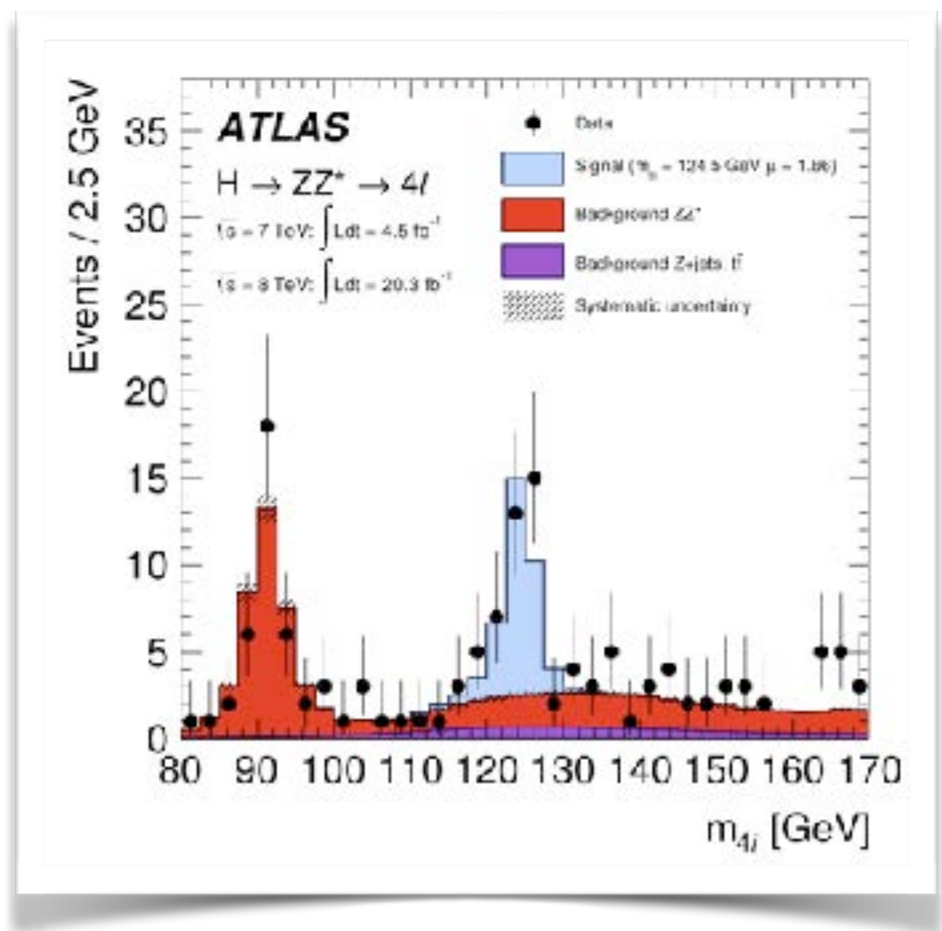
- Describe your experimental set-up
- Provide the primary particles input to your simulation
- Decide **which particles** and **physics models** you want to use out of those available in Geant4 and the precision of your simulation (cuts to produce and track secondary particles)



You may also want to:

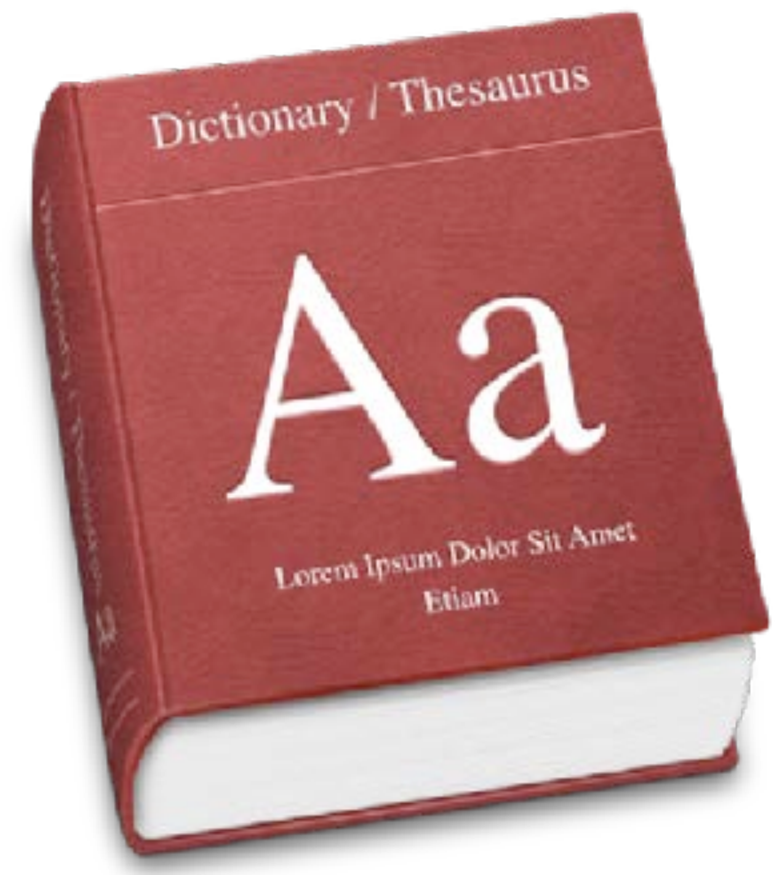
- Interact with Geant4 kernel to control your simulation
- Visualise your simulation configuration or results
- Produce histograms, tuples etc. to be further analysed





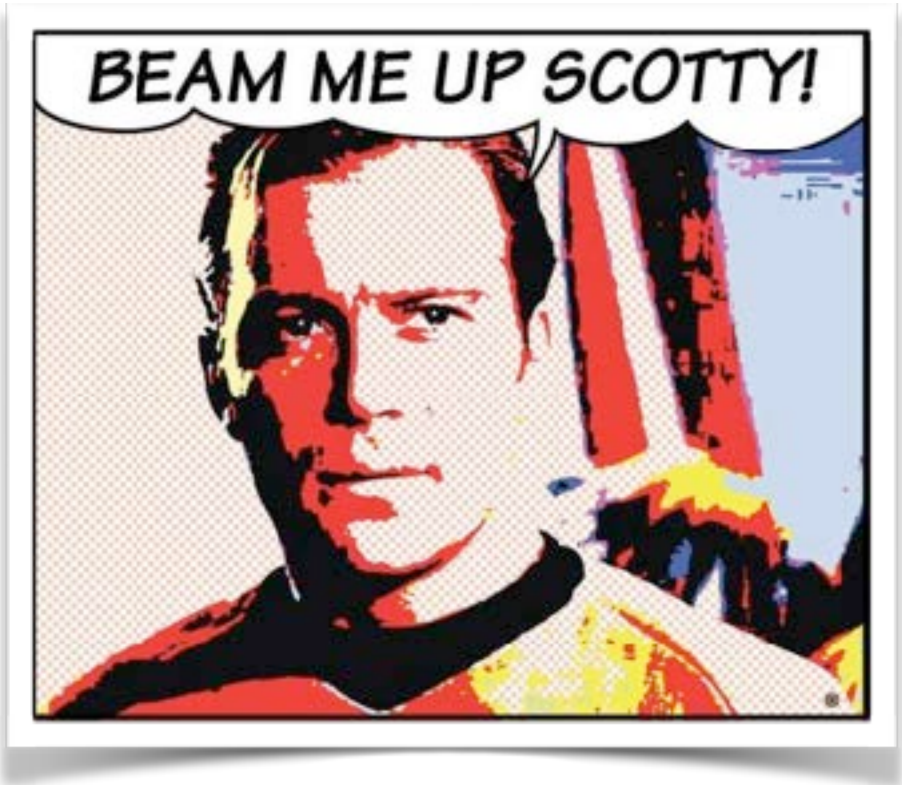
Jargons

- Run, event, track, step, step point
- Process
  - At rest, along step, post step
- Cut = production threshold
- Sensitive detector, score, hit, hits collection,



A run in Geant4

- As an analogy of the real experiment, a run of Geant4 starts with **"Beam On"**

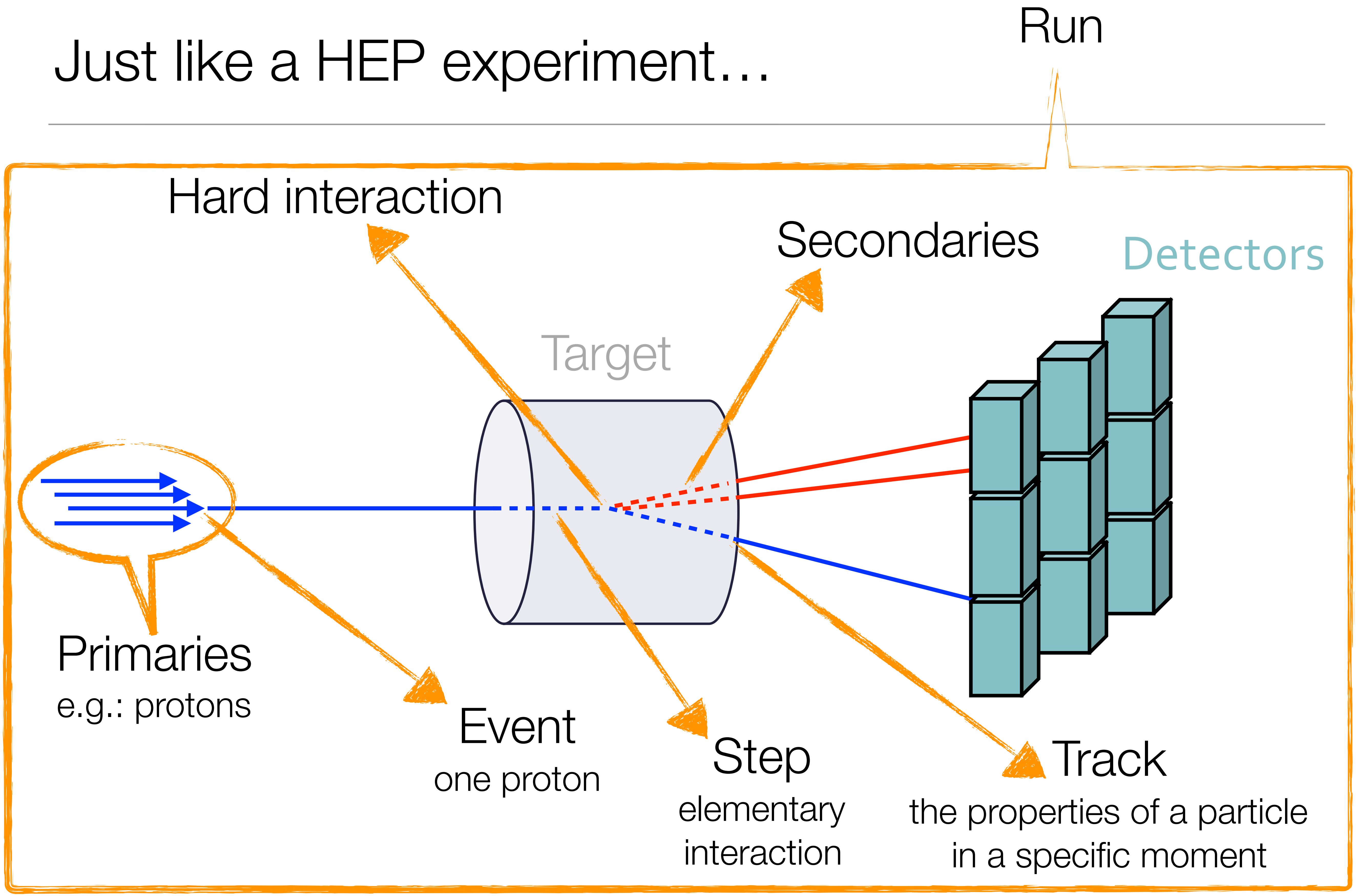


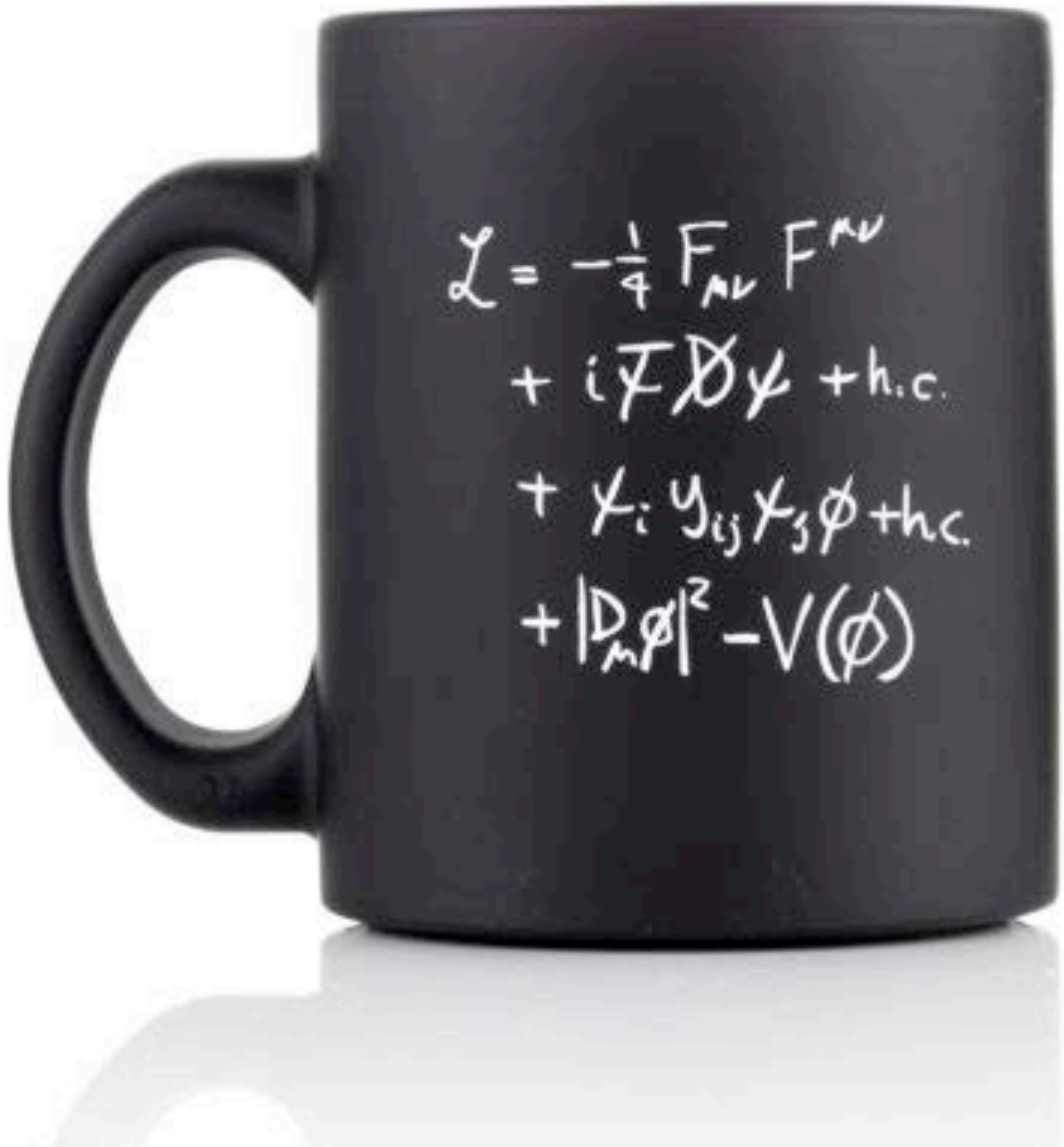
- A run is a collection of events which share the same detector and physics conditions

- **G4RunManager** class manages processing a run

- **G4UserRunAction** is the optional user hook

Just like a HEP experiment…



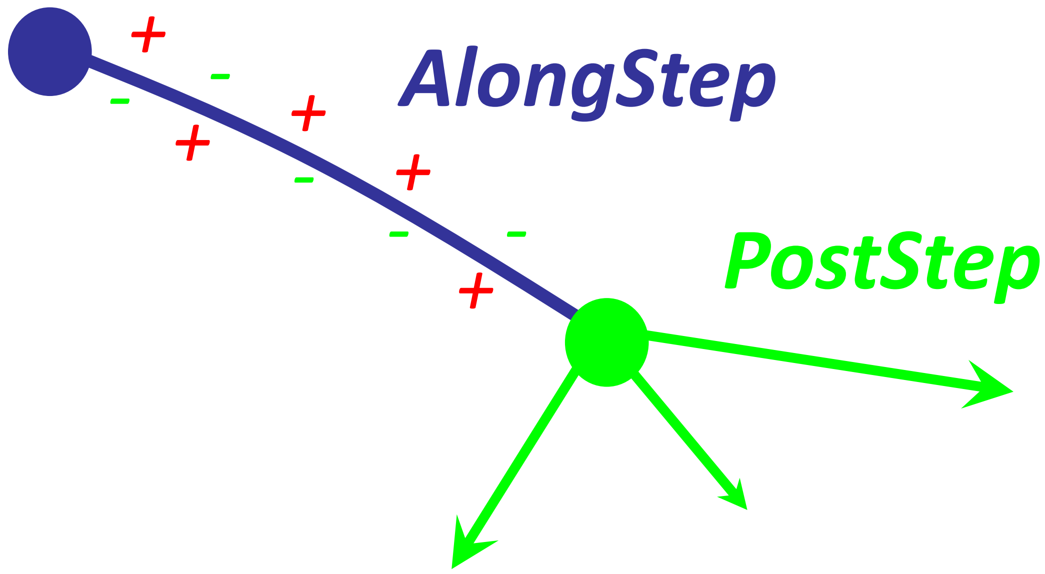


Physics processes

an overview…

The `G4VProcess`

- All physics processes derive from `G4VProcess`
- `G4VProcess` is an abstract class
- It defines the common interface of all processes in Geant4
- Three kind of "actions":
  - **AlongStep**
    all the soft interactions
  - **PostStep**
    all the hard interactions
  - **AtRest**
    decays, e+ annihilation



γ model inventory

- Many models available for each process
- Differ for energy range, precision and CPU speed
- Final state generators

Model	E_{min}	E_{max}
G4LivermoreRayleighModel	100 eV	10 PeV
G4PenelopeRayleighModel	100 eV	10 GeV
G4KleinNishinaCompton	100 eV	10 TeV
G4KleinNishinaModel	100 eV	10 TeV
G4LivermoreComptonModel	100 eV	10 TeV
G4PenelopeComptonModel	10 keV	10 GeV
G4LowEPComptonModel	100 eV	20 MeV
G4BetheHeitlerModel	1.02 MeV	100 GeV
G4PairProductionRelModel	10 MeV	10 PeV
G4LivermoreGammaConversionModel	1.02 MeV	100 GeV
G4PenelopeGammaConversionModel	1.02 MeV	10 GeV
G4PEEFluoModel	1 keV	10 PeV
G4LivermorePhotoElectricModel	10 eV	10 PeV
G4PenelopePhotoElectricModel	10 eV	10 GeV

ElectroMagnetic models

- The same physics processes can be described by different models
- For instance: Compton scattering can be described by
  - `G4KleinNishinaCompton`
  - `G4LivermoreComptonModel` (low-energy, based on the Livermore database)
  - `G4PenelopeComptonModel` (low-energy, based on the Penelope analytical model)
  - `G4LivermorePolarizedComptonModel` (low-energy, Livermore database with polarization)
  - `G4PolarizedComptonModel` (Klein-Nishina with polarization)
  - `G4LowEPComptonModel` (full relativistic 3D simulation)
- Different models can be combined, so that the appropriate one is used in each given energy range (à performance optimization)

EM Physics constructors

G4EmStandardPhysics – default
G4EmStandardPhysics_option1 – HEP fast but not precise
G4EmStandardPhysics_option2 – Experimental
G4EmStandardPhysics_option3 – medical, space
G4EmStandardPhysics_option4 – optimal mixture for precision
G4EmLivermorePhysics
G4EmLivermorePolarizedPhysics
G4EmPenelopePhysics
G4EmLowEPPhysics
G4EmDNAPhysics_option…
…

Combined Physics
Standard > 1 GeV
LowEnergy < 1 GeV

- Advantage of using of these classes – they are tested on regular basis and are used for regular validation

Hadronic processes

- At rest
  - Stopped muon, pion, kaon, anti-proton
  - Radioactive decay
  - Particle decay (decay-in-flight is PostStep)
- Elastic
  - Same process to handle all long-lived hadrons (multiple models available)
- Inelastic
  - Different processes for each hadron (possibly with multiple models vs. energy)
  - Photo-nuclear, electro-nuclear, mu-nuclear
- Capture
  - Pion- and kaon- in flight, neutron
- Fission

Hadronic physics challenge

- Three energy regimes
  - < 100 MeV
  - resonance and cascade region (100 MeV - 10 GeV)
  - > 20 GeV (QCD strings)
- Within each regime there are several models
- Many of these are phenomenological

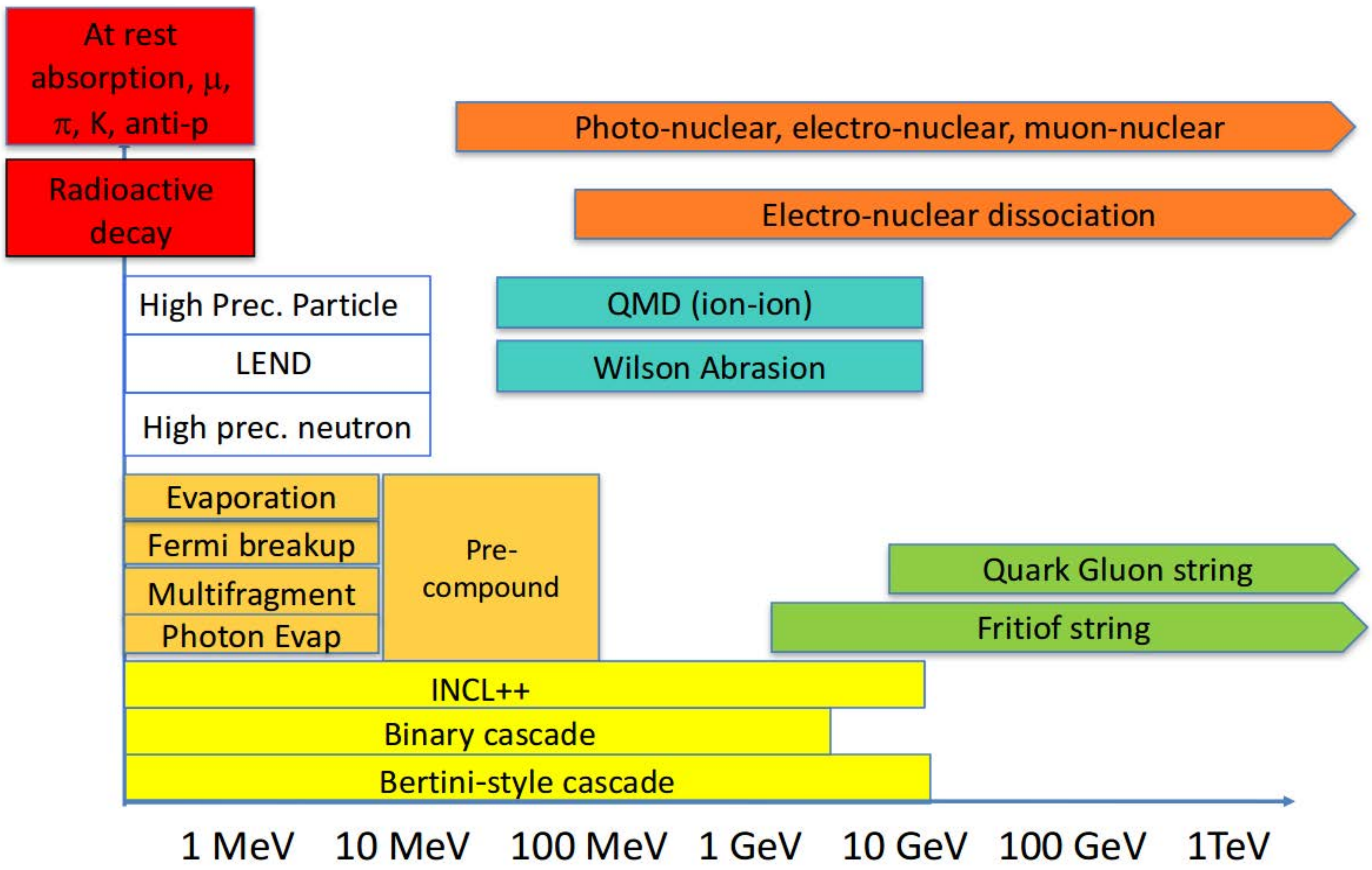
Hadronic models

- Two families of builders for the high-energy part
  - **QGS**, or list based on a model that use the Quark Gluon String model for high energy hadronic interactions of protons, neutrons, pions and kaons
  - **FTF**, based on the FTF (FRITIOF like string model) for protons, neutrons, pions and kaons
- Three families for the cascade energy range
  - **BIC**, binary cascade
  - **BERT**, Bertini cascade
  - **INCLXX**, Liege Intranuclear cascade model

ParticleHP

- Data-driven approach for inelastic reactions for n (in place since many years, named NeutronHP) p, d, t, ^{3}He and α
- Data based on TENDL-2014 (charged particles) and ENDFVII.r1 (neutrons).
- For neutrons, includes information for elastic and inelastic scattering, capture, fission and isotope production
- Range of applicability: from thermal energies up to 20 MeV
- Very precise tracking, but also very slow
- Use it with care: thermal neutron tracking is very CPU-demanding

Hadronic model inventory



Physics List

- A class which collects all the particles, physics processes and production thresholds needed for your application
- It tells the run manager how and when to invoke physics
- It is a very flexible way to build a physics environment
  - user can pick the particles he wants
  - user can pick the physics to assign to each particle
- But, **user must have a good understanding of the physics required**
- Omission of particles or physics could cause errors or **poor simulation**

There is not default, but…

- Geant4 provides several “production physics lists” which are routinely validated and updated with each release these should be considered only as starting points which you may need to validate or modify for your application

- There are currently 19 packaged physics lists available

- 6 reference physics lists:

  - FTFP_BERT, FTFP_BERT_HP QGSP_BERT, QGSP_BERT_HP, QGSP_BIC QGSP_FTFP_BERT

Naming…

- The following acronyms refer to various hadronic options
  - QGS -> Quark Gluon String model (>~20 GeV) FTF -> Fritiof string model (>~5 GeV)
    BIC -> Binary Cascade (<~ 10 GeV)
    BERT -> Bertini-style cascade (<~ 10 GeV)
- HP -> High Precision neutron model (< 20 MeV) P -> G4Precompund model used for de-excitation
- EM options designated by
  - no suffix: standard EM physics
  - EMV suffix: older but faster EM processes
    – other suffixes for other EM options

Production Physics Lists

- FTFP_BERT
  - recommended by Geant4 for HEP
  - contains all standard EM processes
  - uses Bertini-style cascade for hadrons < 5 GeV
  - uses FTF (Fritiof) model for high energies (> 4 GeV)
- QGSP_BERT
  - all standard EM processes
  - Bertini-style cascade up to 9.9 GeV
  - QGS model for high energies (> ~18 GeV) FTF in between

Production Physics Lists

- QGSP_BIC
  - same as QGSP_BERT, but replaces Bertini cascade with Binary cascade and G4Precompound model
  - recommended for use at energies below 200 MeV (many medical applications)

- FTFP_BERT_HP
  - same as FTFP_BERT, but with high precision neutron model used for neutrons below 20 MeV
  - signifcantly slower than FTFP_BERT when full thermal cross sections used there’s an option to turn this of
  - for radiation protection and shielding applications

Other Physics Lists

- If primary particle energy in your application is < 5 GeV (for example, clinical proton beam of 150 MeV)
  - start with a physics list which includes BIC or BERT
  - e.g. QGSP_BIC, QGSP_BERT, FTFP_BERT, etc.

- If neutron transport is important
  - start with physics list containing “HP”
  - e.g. QGSP_BIC_HP, FTFP_BERT_HP, etc.

- If you’re interested in Bragg curve physics
  - use a physics list ending in “EMV” or “EMX” or “EMY”
  - e.g. QGSP_BIC_EMY

Let's cut it out… (cuts in MC)

- The traditional Monte Carlo solution is to set a tracking cut-off in energy:
  - a particle is stopped when its energy goes below it
  - its residual energy is deposited at that point

- Imprecise stopping and energy deposition location
- Particle and material dependence

Let’s cut it out… (cuts in Geant4)

- Geant4 does not have tracking cuts
  i.e.: all tracks are tracked down to 0 energy
- A Cut in Geant4 is a production threshold
- It is applied only for physics processes that have infrared divergence
  - Bremsstrahlung
  - Ionisation e^- (δ rays)
  - Protons from hadronic elastic scattering

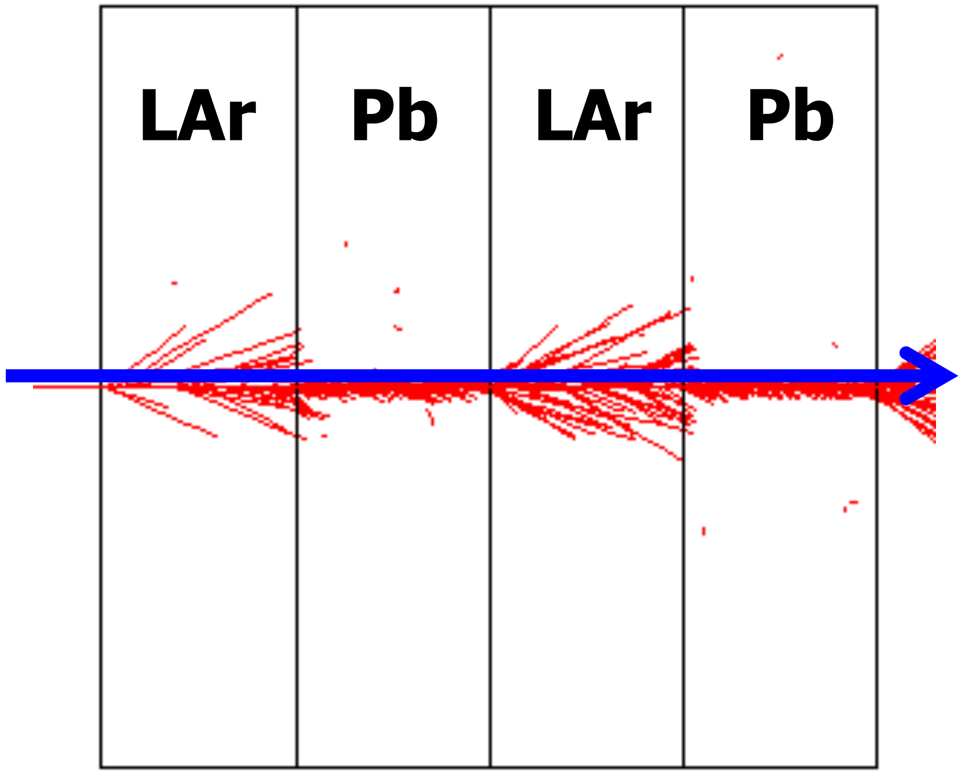
A range cut

- The threshold is a **distance**!
- Default = 1 mm
- Particles unable to travel at least the range cut value are not produced

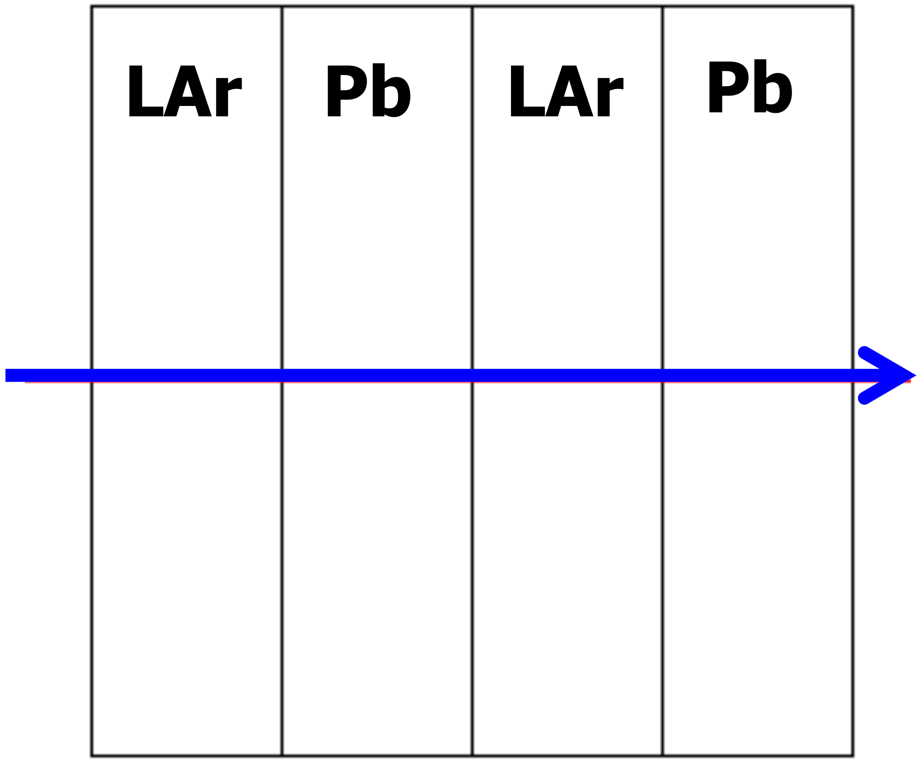
- Sets the "spatial accuracy" of the simulation
- Production threshold is internally converted to an energy threshold for each material

Cut in energy

- 460 keV
- good for LAr
- not for Pb

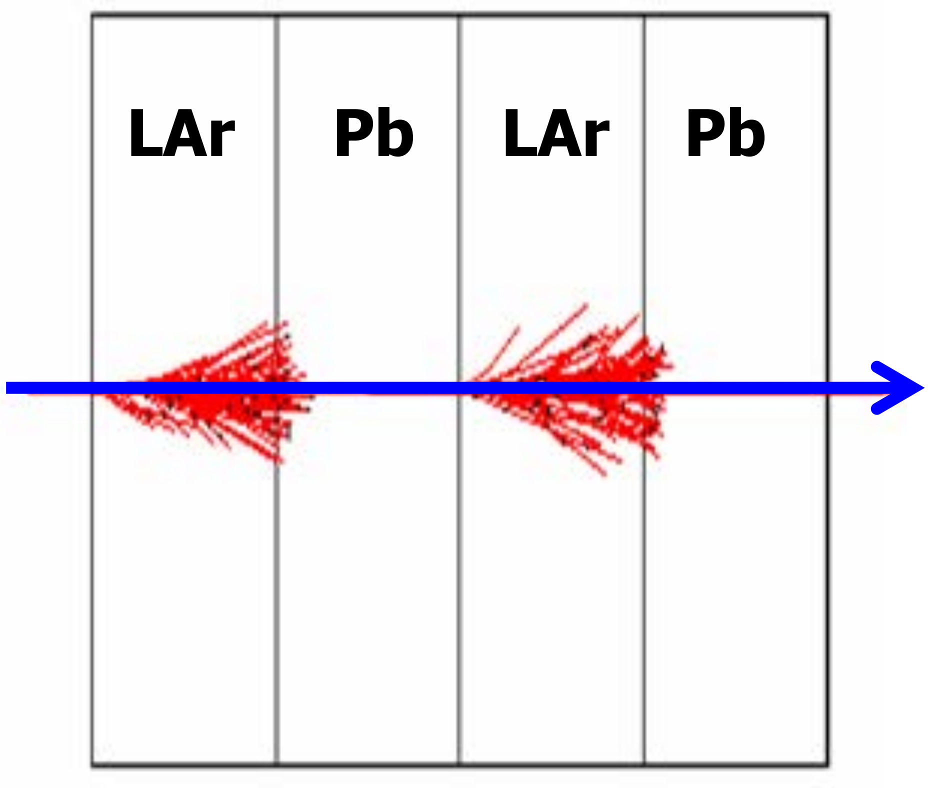


- 2 MeV
- good for Pb
- not for LAr



Cut in range

- 1.5 mm
- ~460 KeV in LAr
- ~2 MeV in Pb



run with the hares and hunt with the hounds...
(good for both!)

Setting the cuts

- Optional method in G4VPhysicsList

```
void MyPhysicsList::SetCuts()
{
    //G4VUserPhysicsList::SetCuts();
    defaultCutValue = 0.5 * mm;
    SetCutsWithDefault();

    SetCutValue(0.1 * mm, "gamma");
    SetCutValue(0.01 * mm, "e+");
  G4ProductionCutsTable::GetProductionCutsTable()
        ->SetEnergyRange(100*eV, 100.*GeV);
}
```

- not all models are able to work with very low production thresholds
- an energy threshold limit is used,
- its default value is set to 990 eV.
- You can change this value

Cuts UI command

```
# Universal cut (whole world, all particles)
/run/setCut 10 mm

# Override low-energy limit
/cuts/setLowEdge 100 eV

# Set cut for a specific particle (whole world)
/run/setCutForAGivenParticle gamma 0.1 mm

# Set cut for a region (all particles)
/run/setCutForARegion myRegion 0.01 mm

# Print a summary of particles/regions/cuts
/run/dumpCouples
```

Cuts per region

- Complex detector may contain many different sub-detectors involving:
    - finely segmented volumes
    - position-sensitive materials (e.g. Si trackers)
    - large, undivided volumes (e.g. calorimeters)
- The same cut may not be appropriate for all of these
- User can define regions (independent of geometry hierarchy tree) and assign different cuts for each region
- A region can contain a subset of the logical volumes

To limit the step

- To have more precise energy deposition
- To increase precision in magnetic field
- Include `G4StepLimiter` in your physics list
  - as a Physics process
  - compete with the others

System of Units

- Internal unit system used in Geant4 is completely hidden not only from user's code but also from Geant4 source code implementation

- Each hard-coded number must be multiplied by its proper unit:
  - `radius = 10.0 * cm; E = 1.*GeV;`

- To get a number, it must be divided by a proper unit:
  - `G4cout<< “E dep: “<< eDep/MeV <<“ [MeV]”<<G4endl;`

User classes

- You **have** to write the **main**()
- Initialisation classes:
  - **G4VUserDetectorConstruction**
  - **G4VUserPhysicsList**
  - **G4VUserActionInitialization**
- Action classes
  - **G4VUserPrimaryGeneratorAction**
  - **G4UserRunAction**
  - **G4UserEventAction**
  - **G4UserStackingAction**
  - **G4UserTrackinAction**
  - **G4UserSteppingAction**

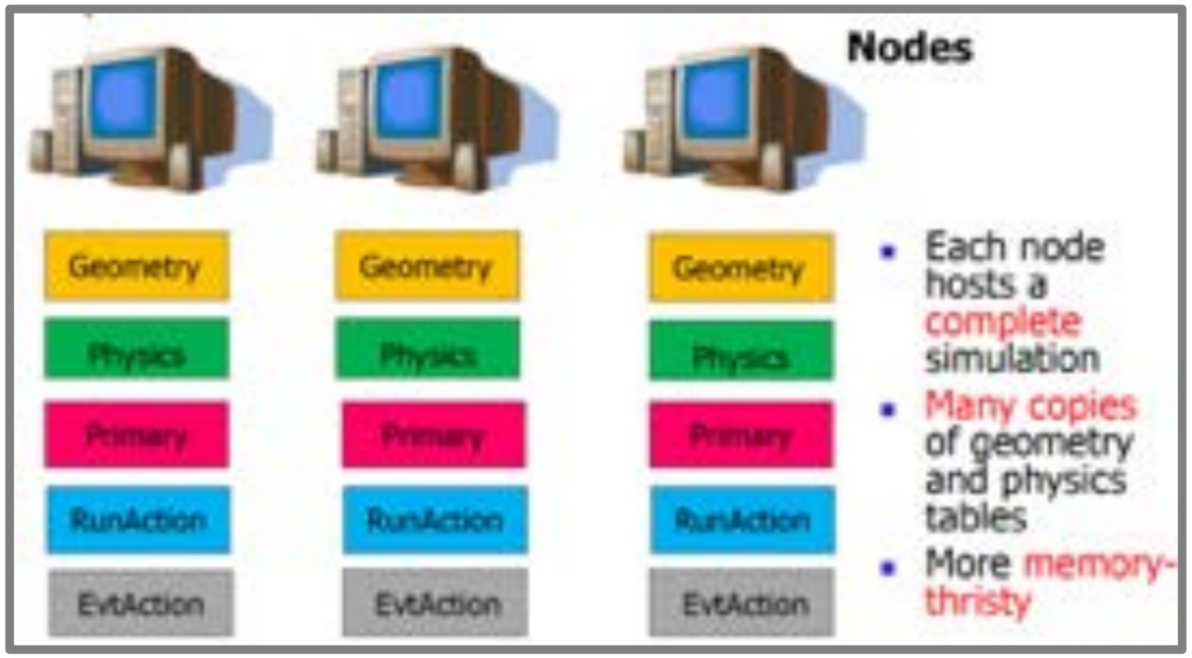
classes written in red are mandatory!

Your program

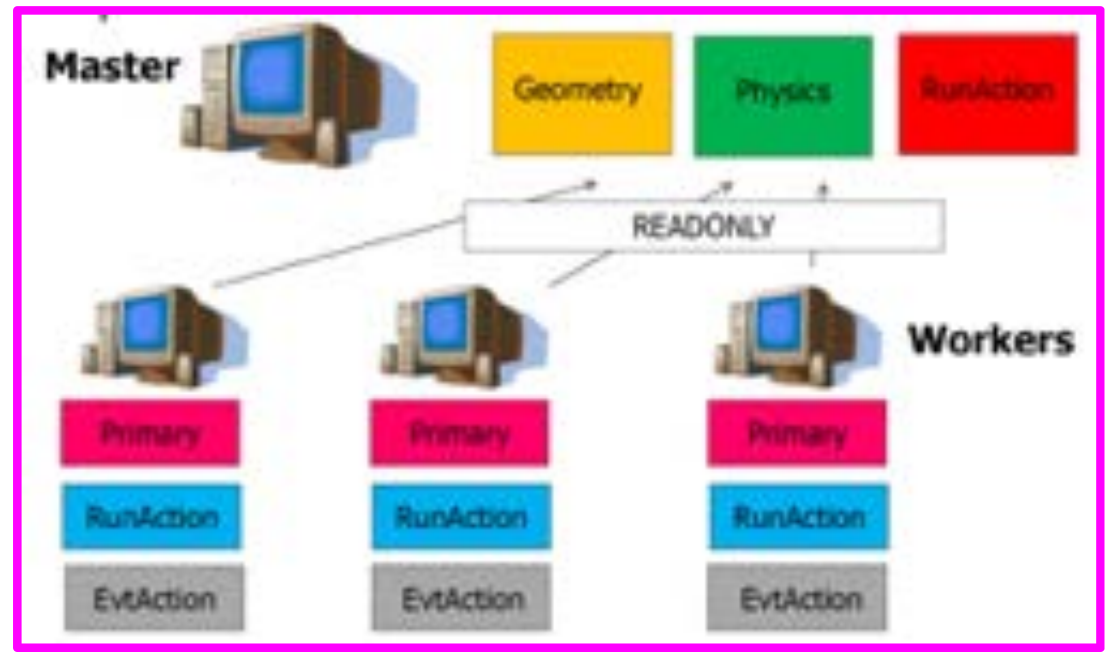
- Geant4 does not provide a main()
- In your main(), you have to
- Construct `G4RunManager` (sequential mode)
- Set user mandatory initialisation classes to RunManager
  - **`G4VUserDetectorConstruction`**
  - **`G4VUserPhysicsList`**
  - **`G4VUserActionInitialization`**
- You can define VisManager, (G)UI session,
- You can initialise optional user action classes

Multi-threading in Geant4

Parallel



Multithread

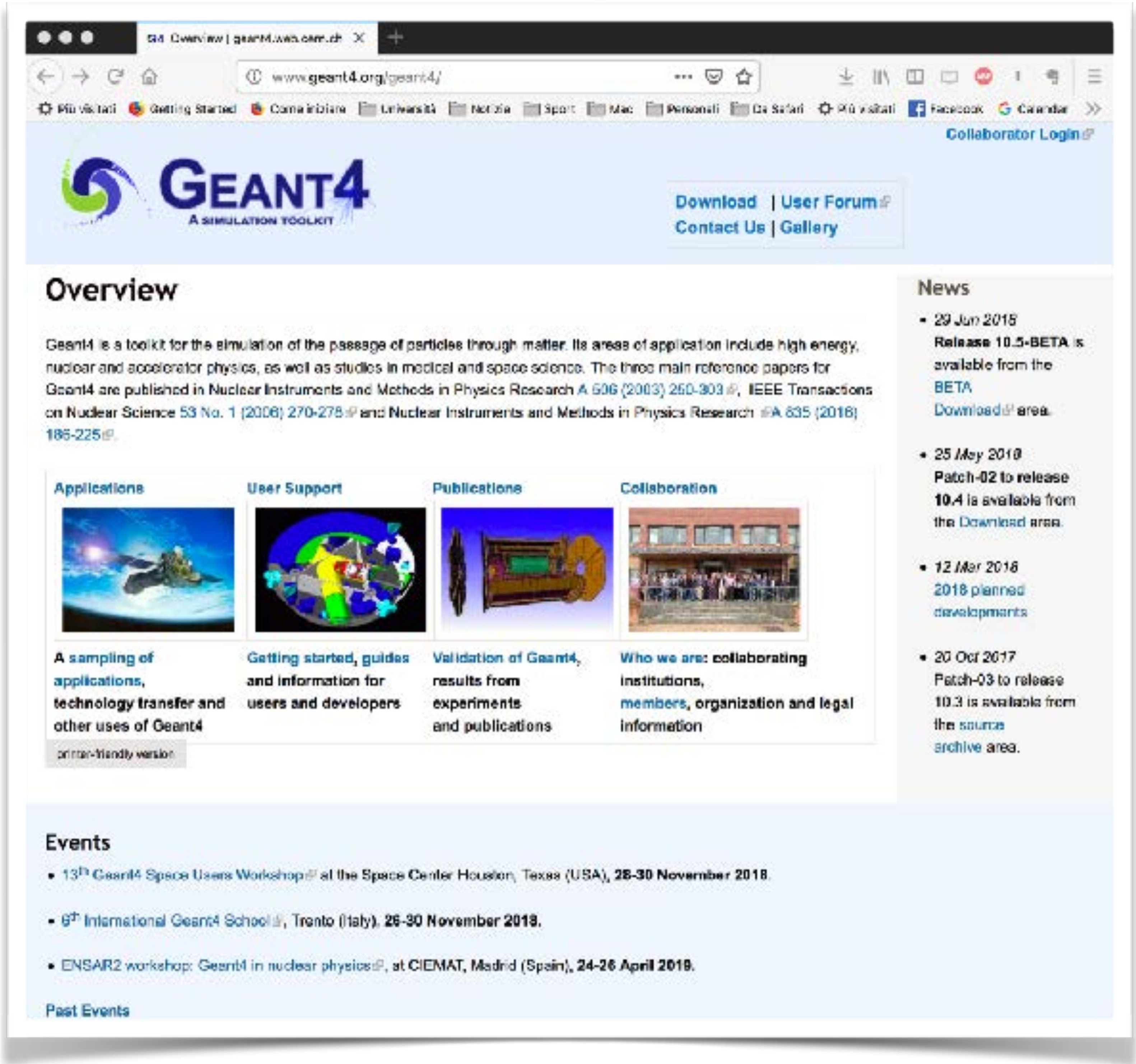


- Speed-up of simulations even on a laptop
- More efficient usage of memory: all cores only read geometry and physics of the Geant4 simulation (no duplication)

How to survive in the real life

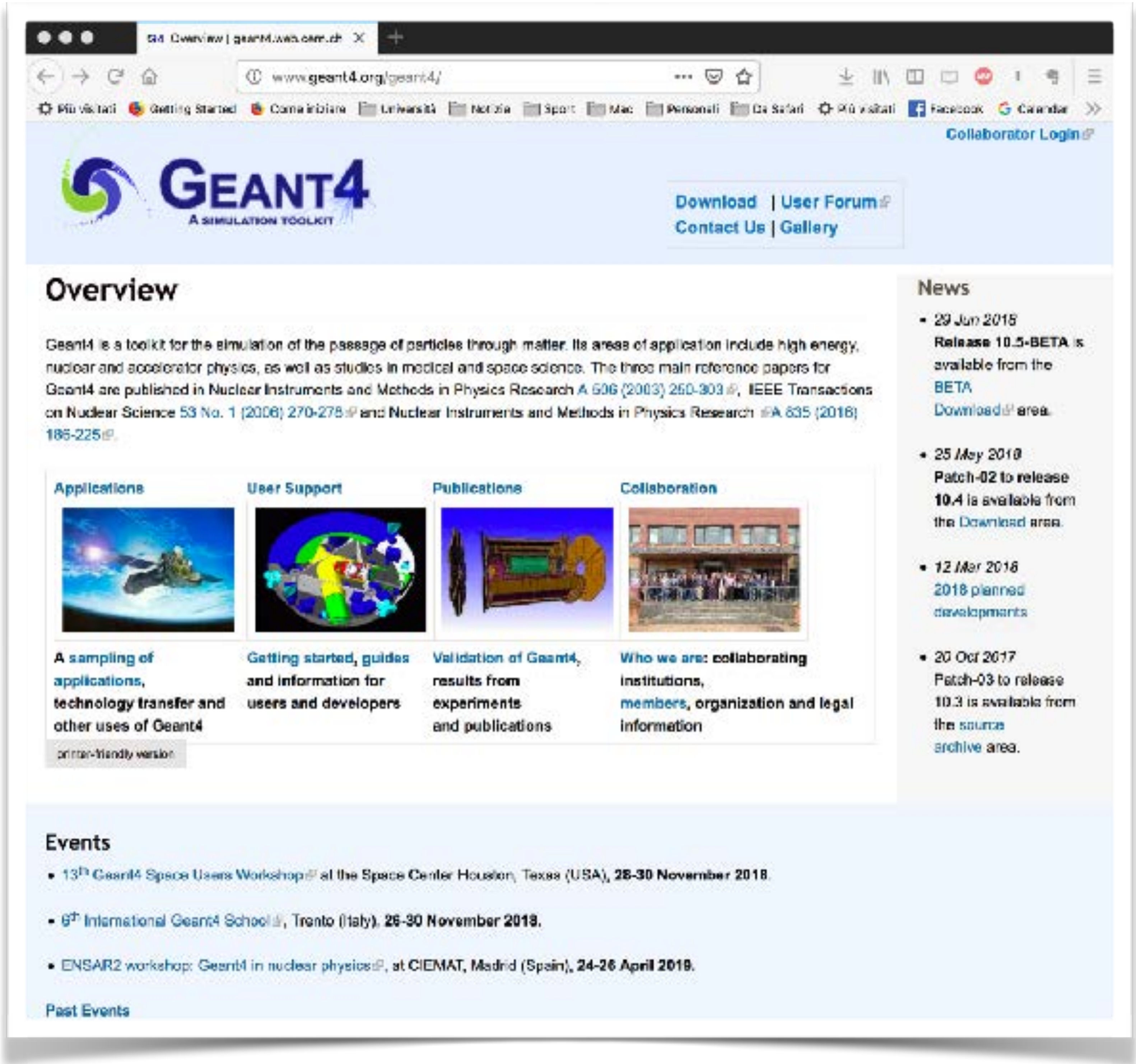
Some tips, you will find your way…

The Geant4 website



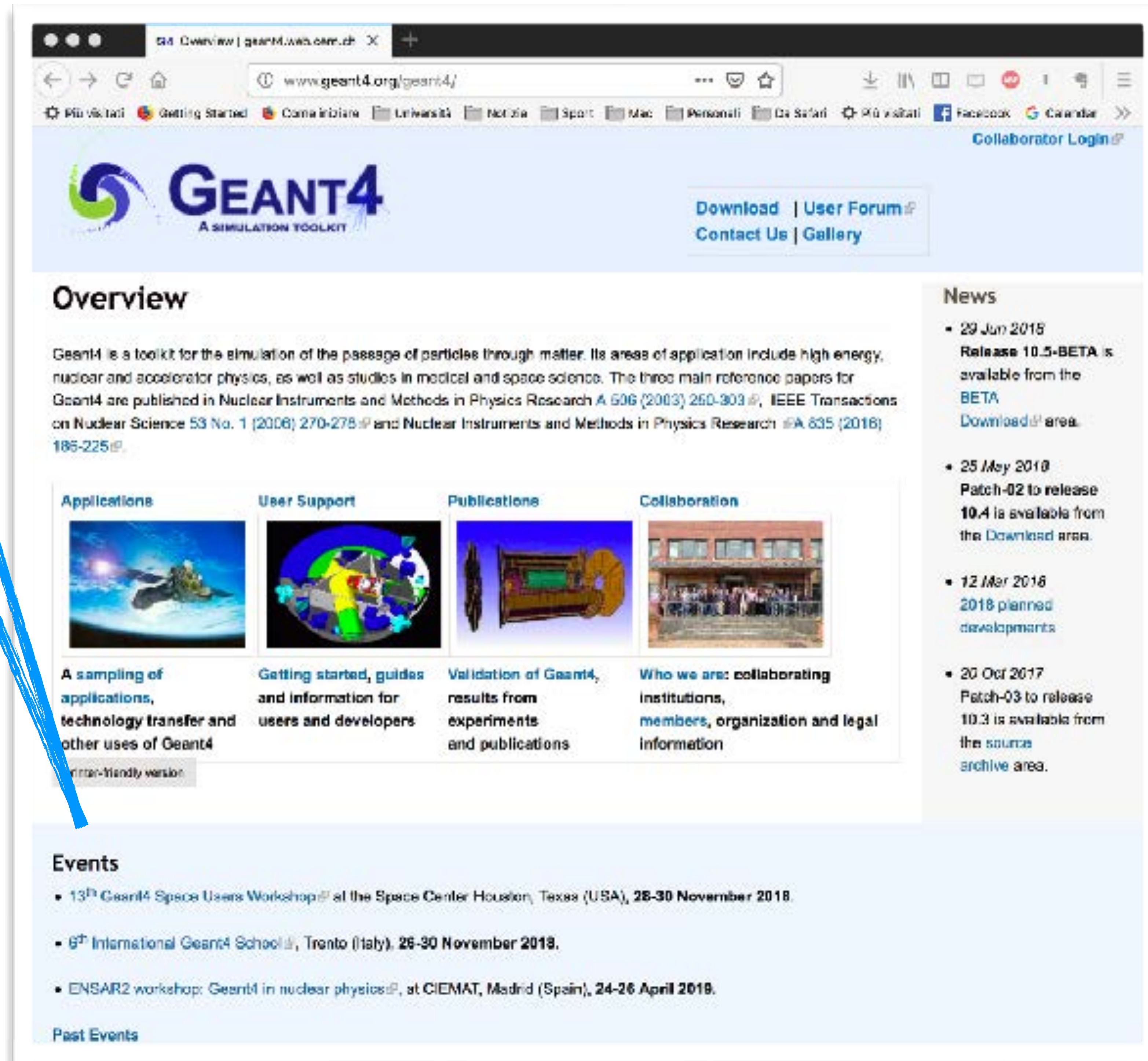
The Geant4 website

- www.geant4.org



The Geant4 website

- www.geant4.org
- Future and past events (e.g.: this course)

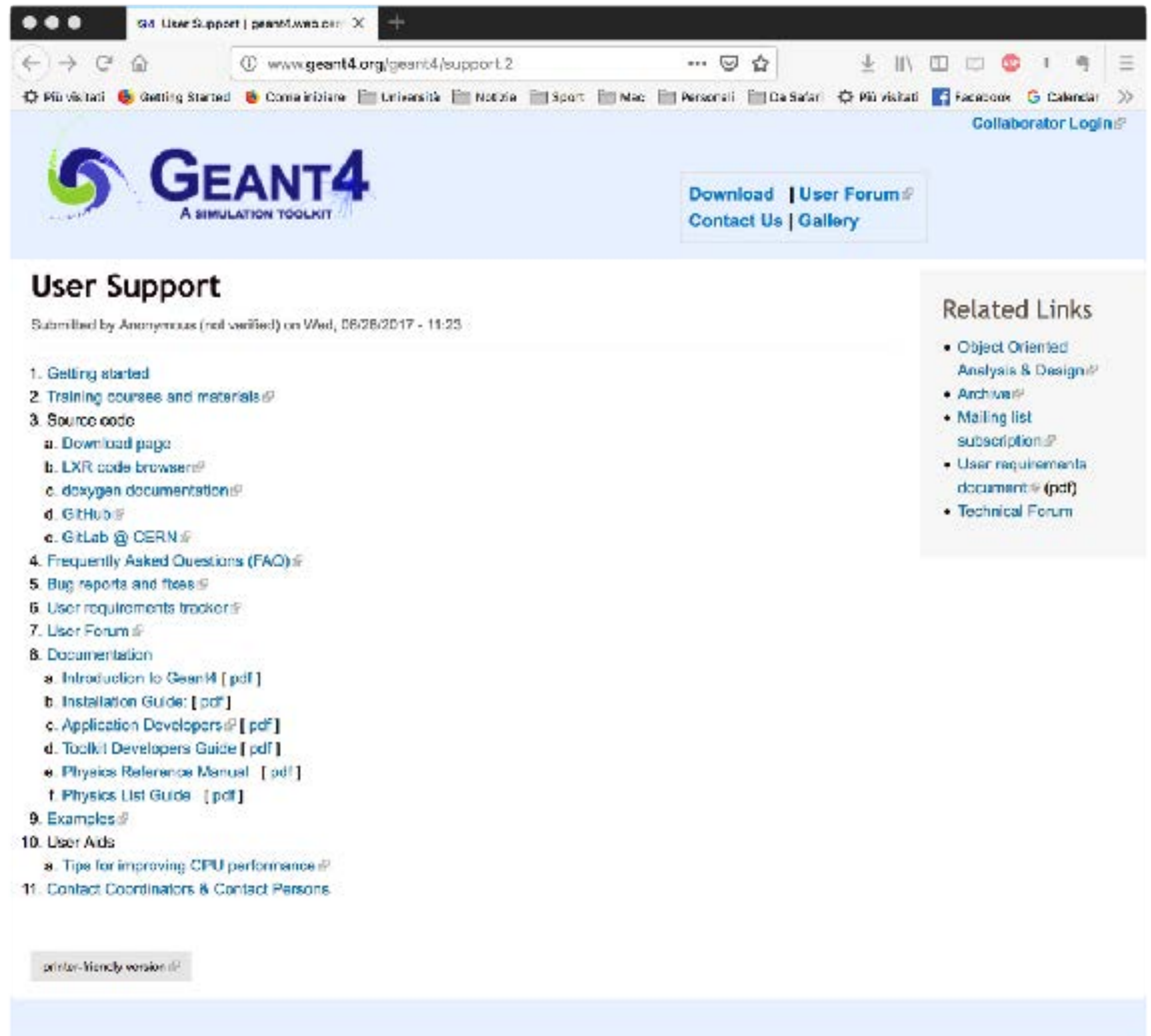


The Geant4 website

- www.geant4.org
- Future and past events (e.g.: this course)
- User support (one of the best friends for Geant4 users…)

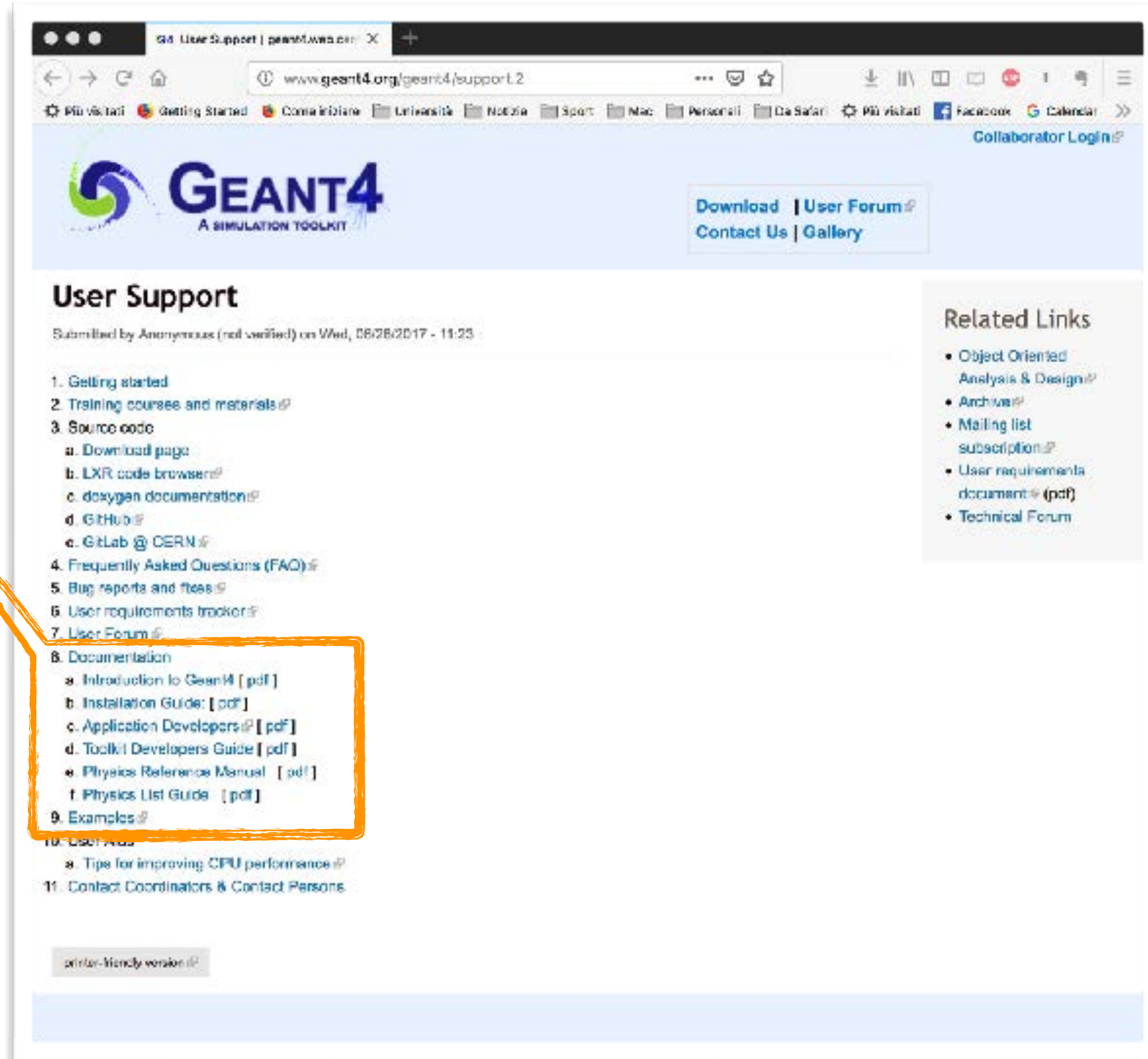
The Geant4 website

- http://www.geant4.org/geant4/node/52



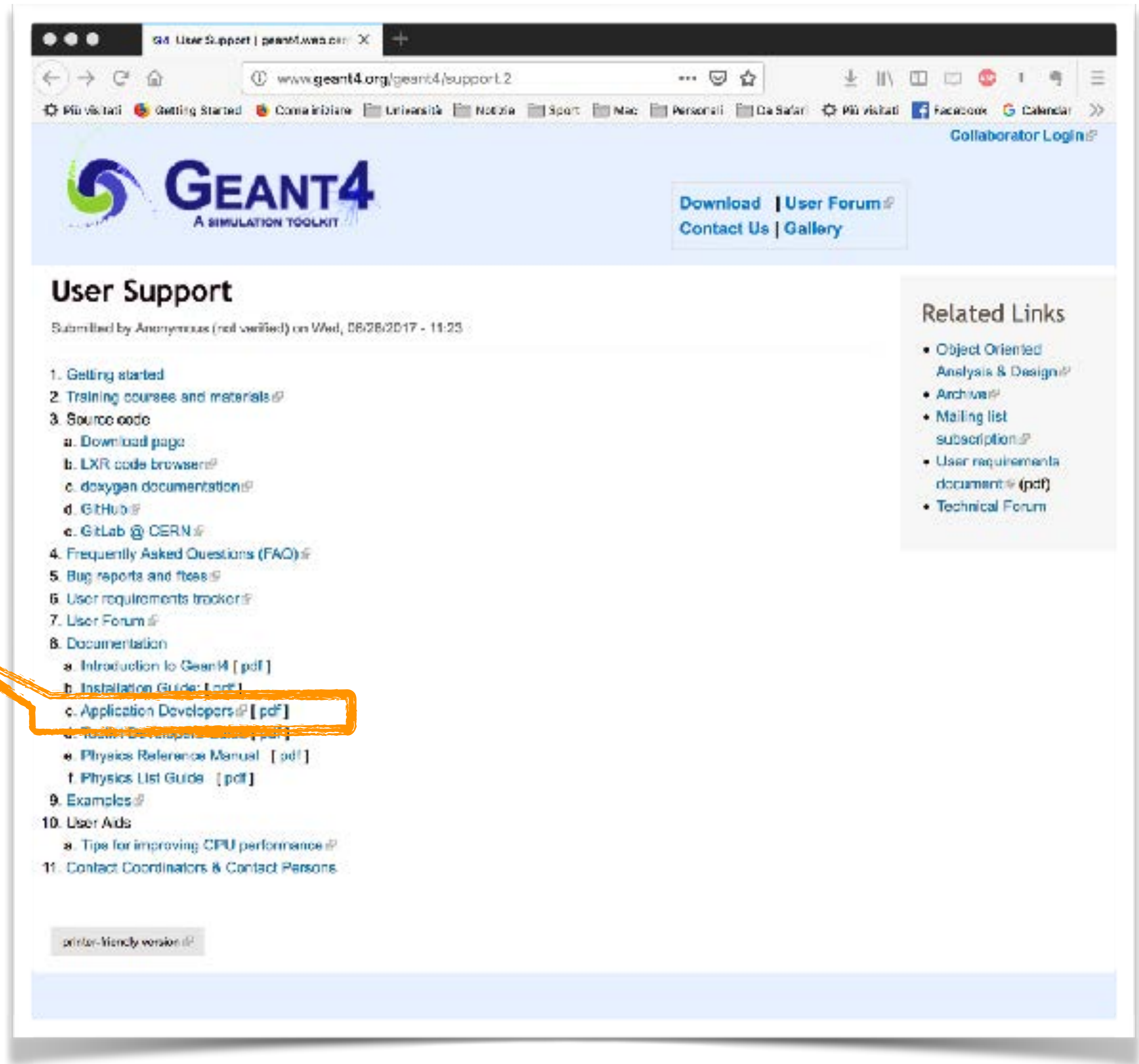
The Geant4 website

- http://www.geant4.org/geant4/node/52
- Documentation



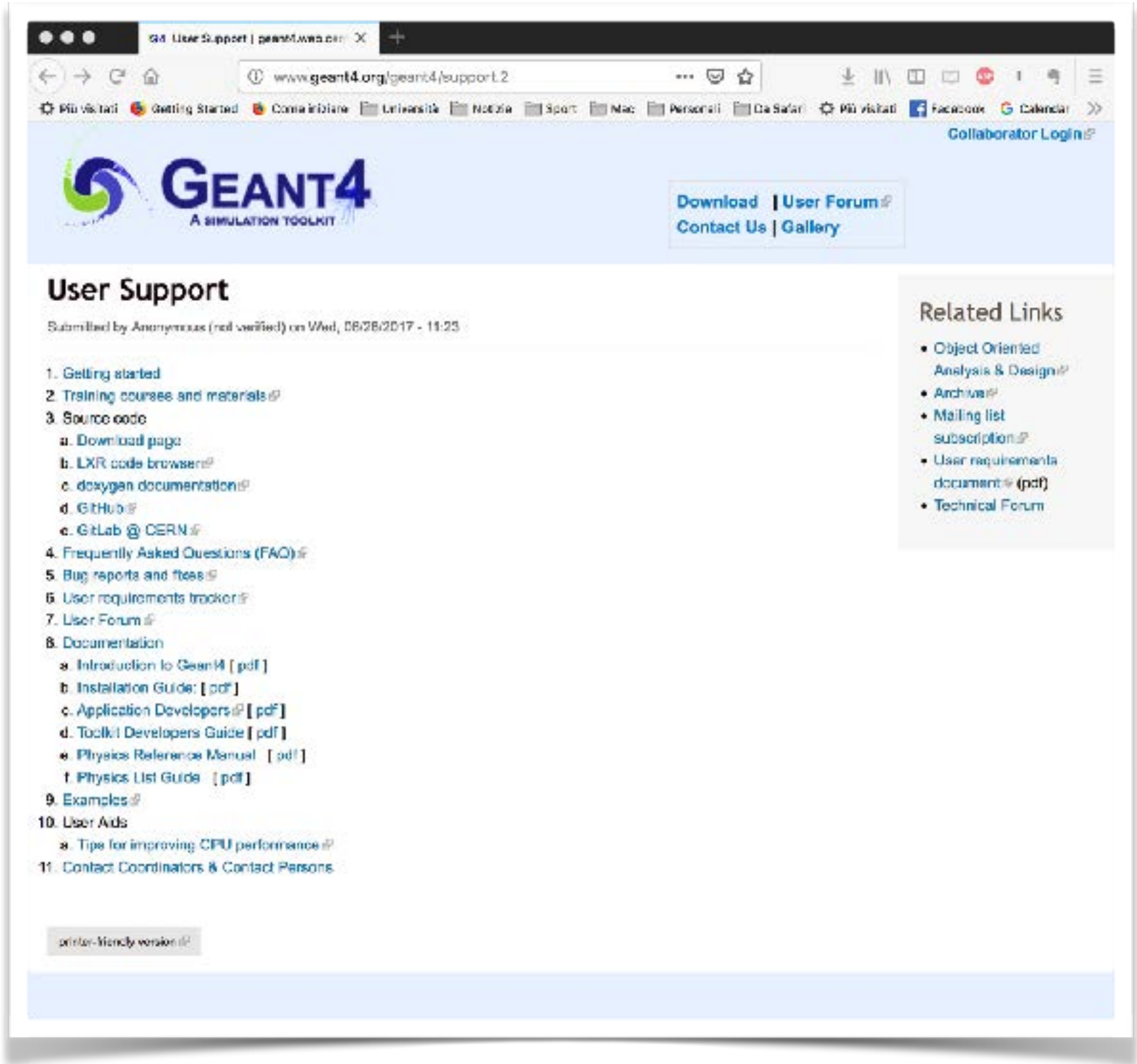
The Geant4 website

- http://www.geant4.org/geant4/node/52
- Documentation
- Application Developers (you!) guide

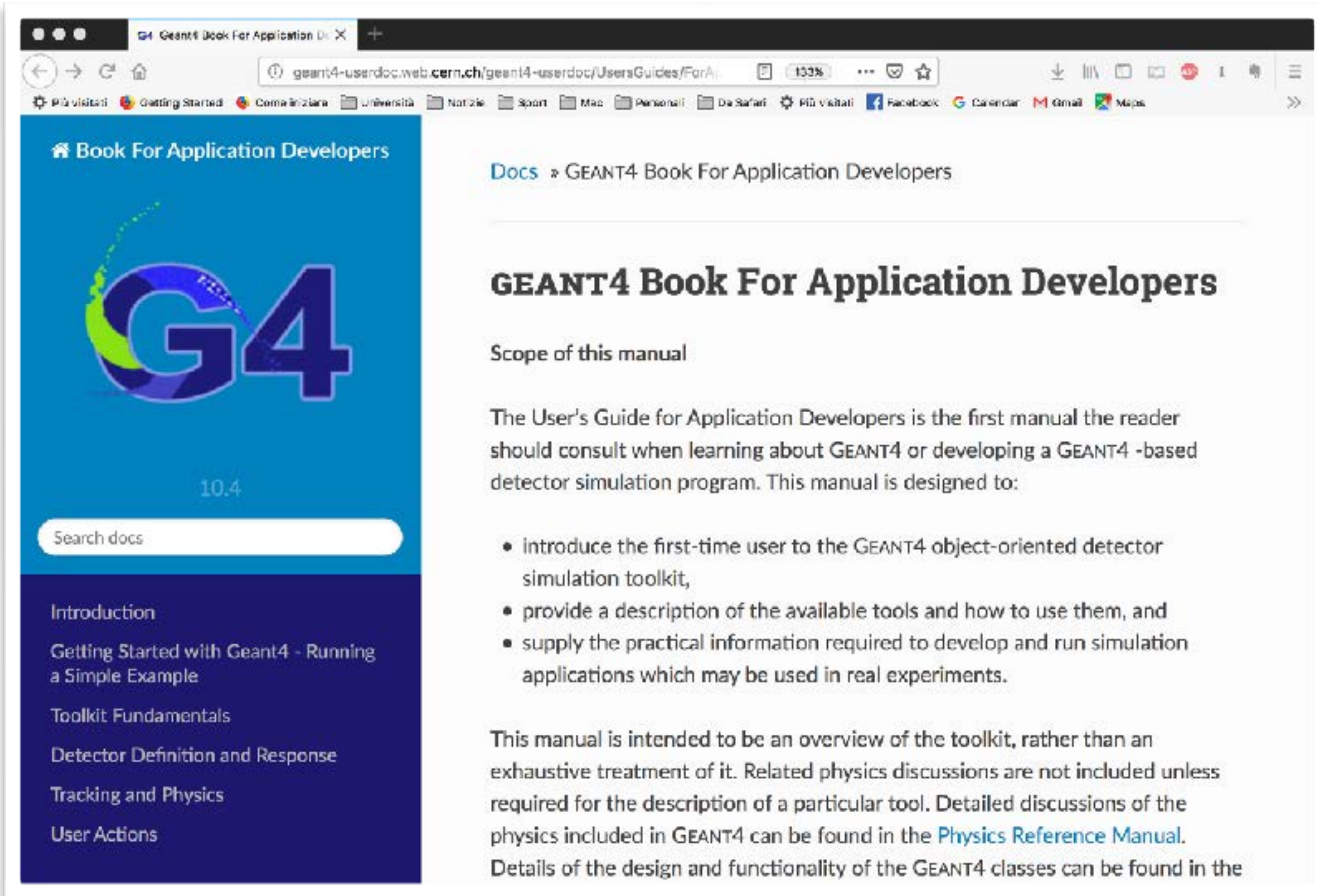


The Geant4 website

- http://www.geant4.org/geant4/node/52
- Documentation
- Application Developers (you!) guide



Application Developers user guide

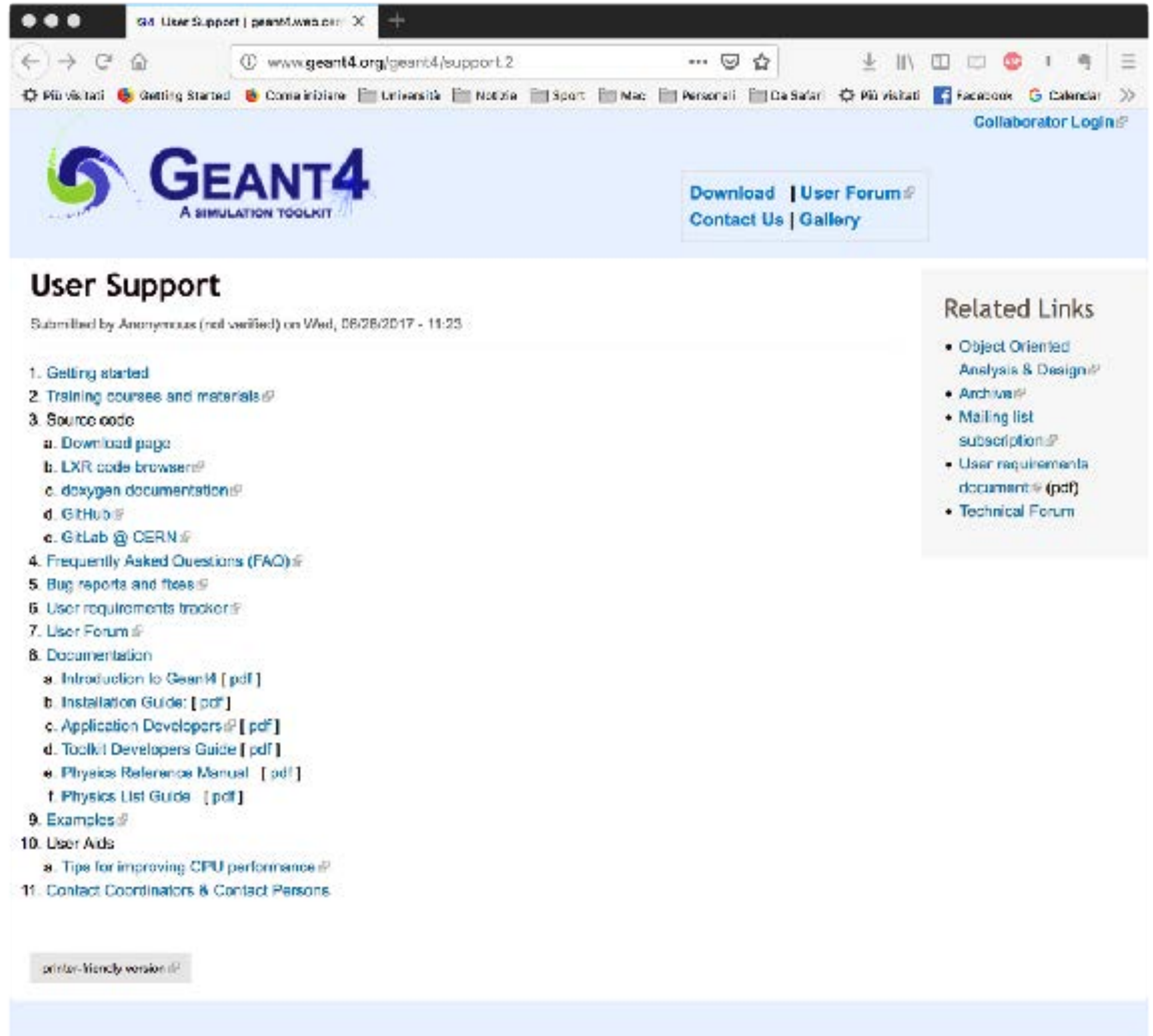


Application Developers user guide

- http://geant4-userdoc.web.cern.ch/geant4-userdoc/UsersGuides/ForApplicationDeveloper/html/index.html
- Introduces new Users to the Geant4 toolkit
- Describes the most useful tools
- Describes hoot set-up and run a simulation application
- Intended as an overview of the toolkit, not an exhaustive treatment

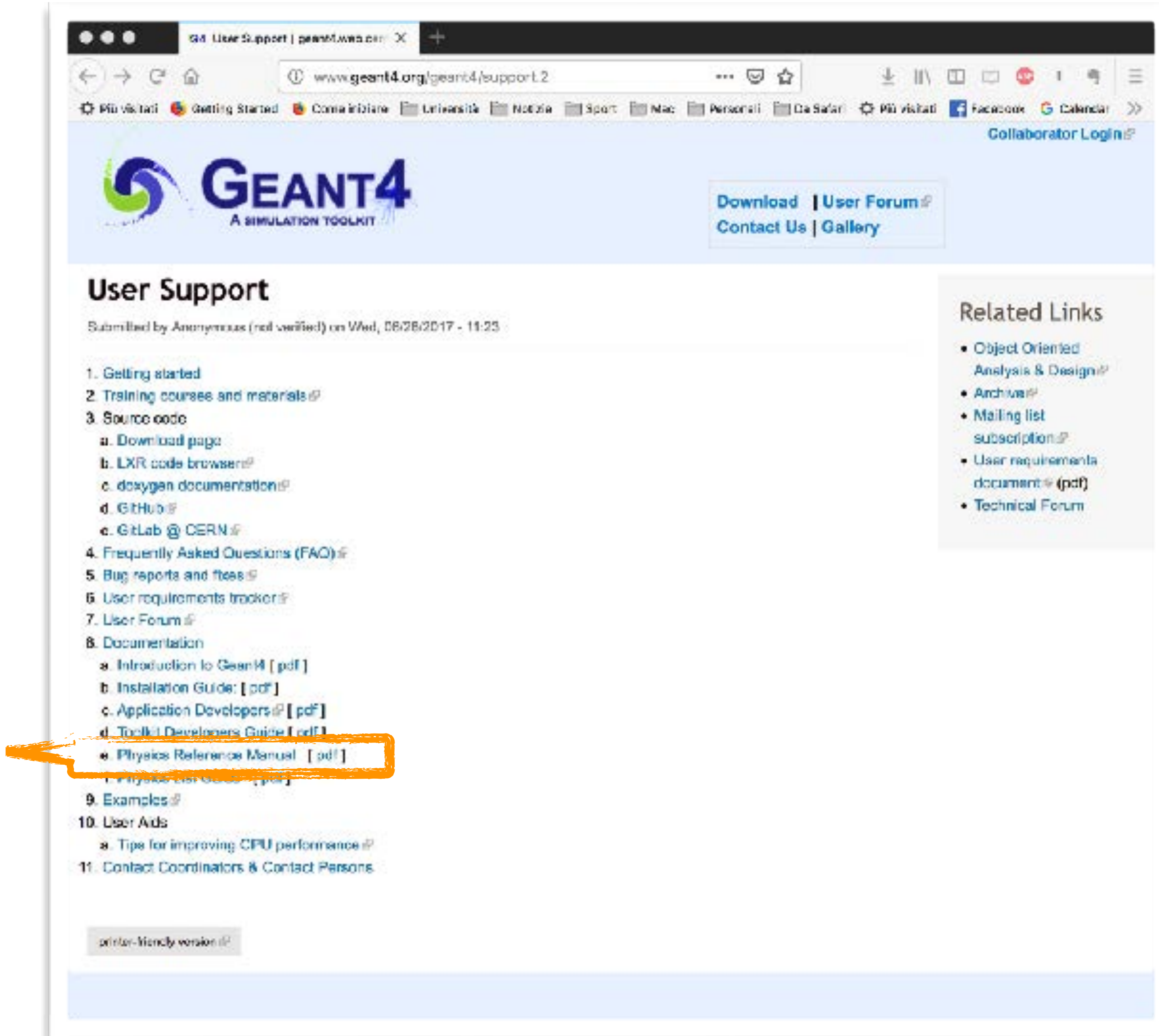
The Geant4 website

- www.geant4.org
- Documentation
- Application Developers (you!) guide

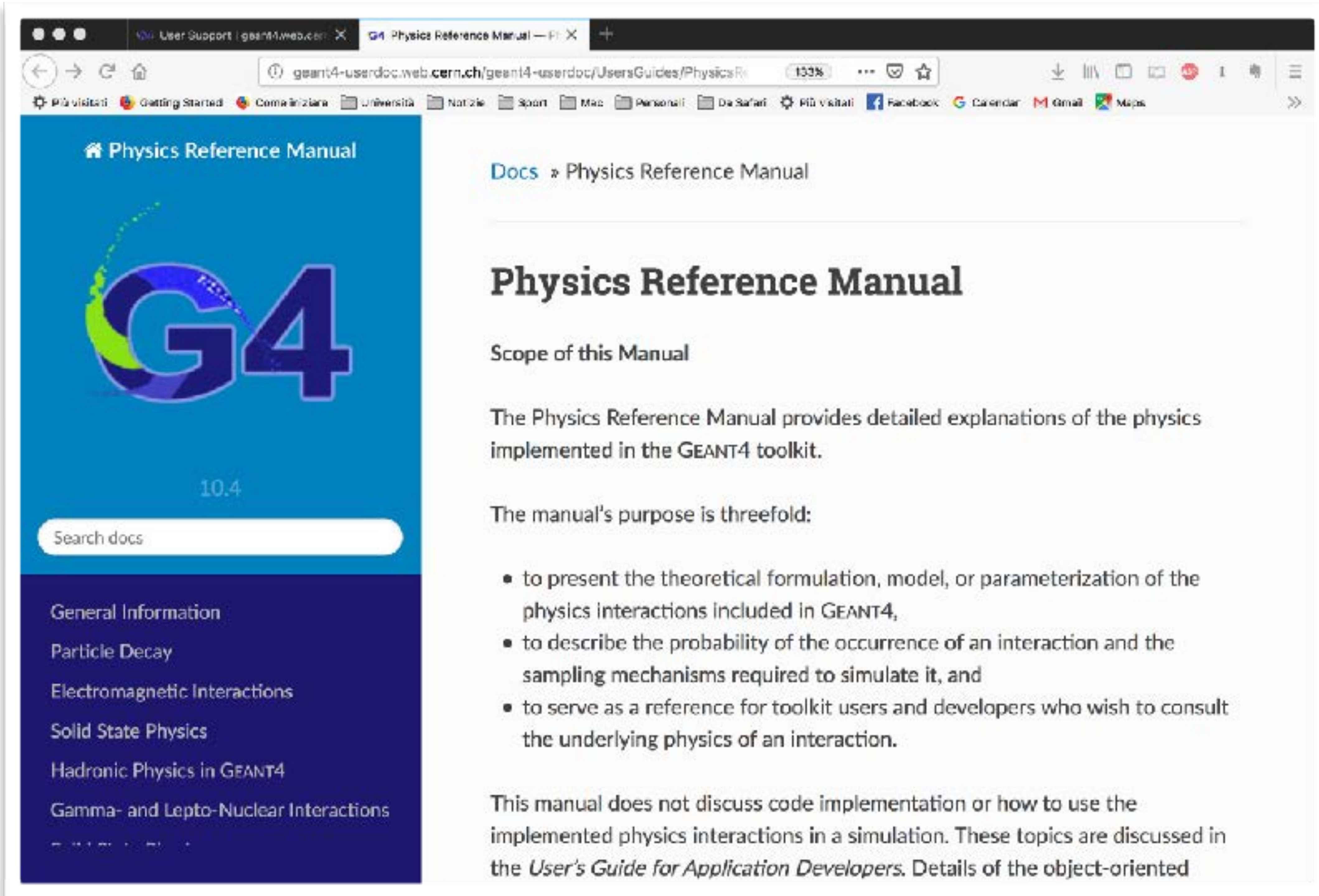


The Geant4 website

- www.geant4.org
- Documentation
- Application Developers (you!) guide
- Physics Reference Manual



Physics Reference Manual

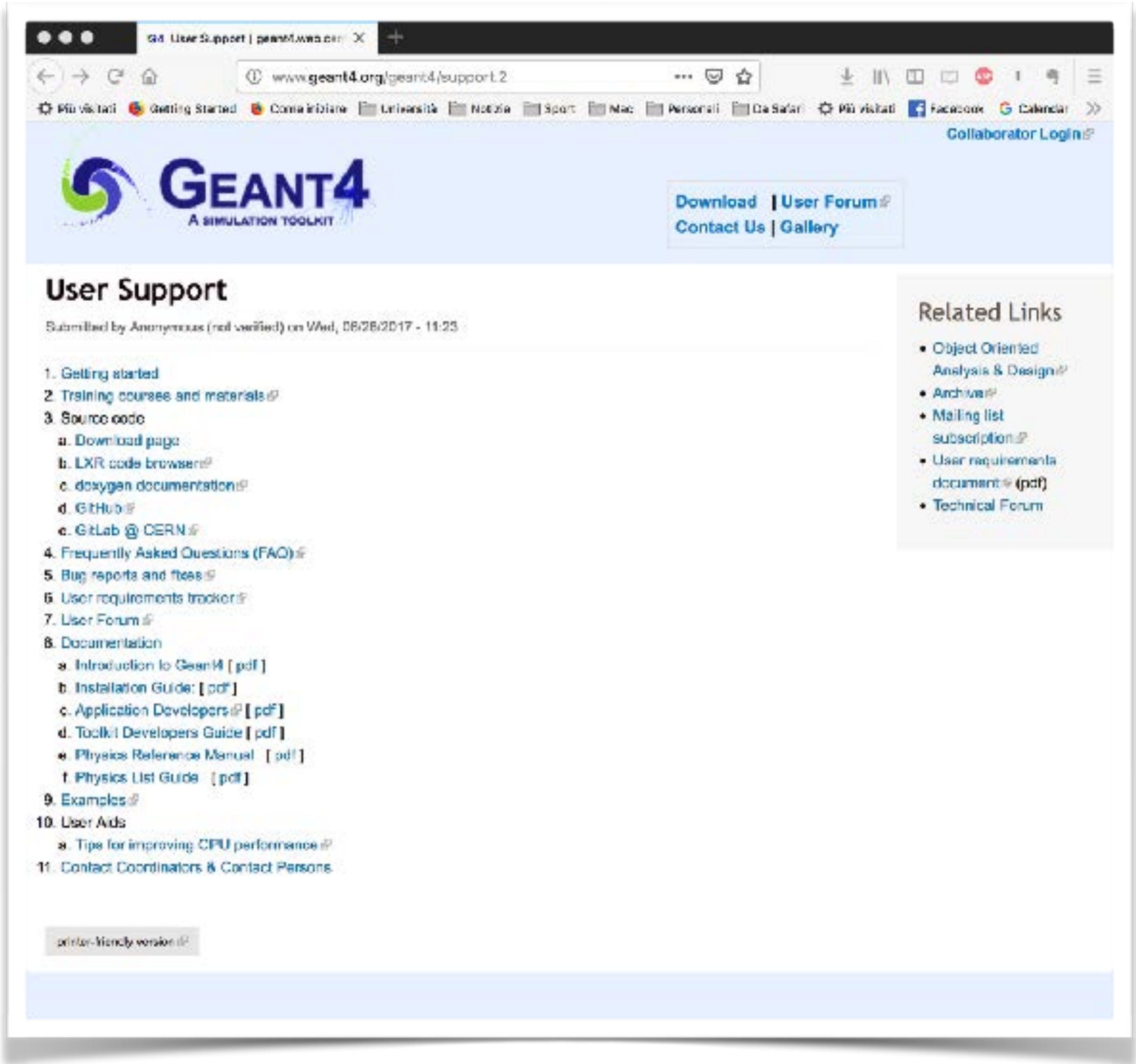


Physics Reference Manual

- http://geant4-userdoc.web.cern.ch/geant4-userdoc/UsersGuides/PhysicsReferenceManual/html/index.html
- A reference for toolkit Users and developers who wish to consult and study the physics of an interaction/model
- Present the theoretical formulation, model or parameterisation of the physics interactions provided by Geant4

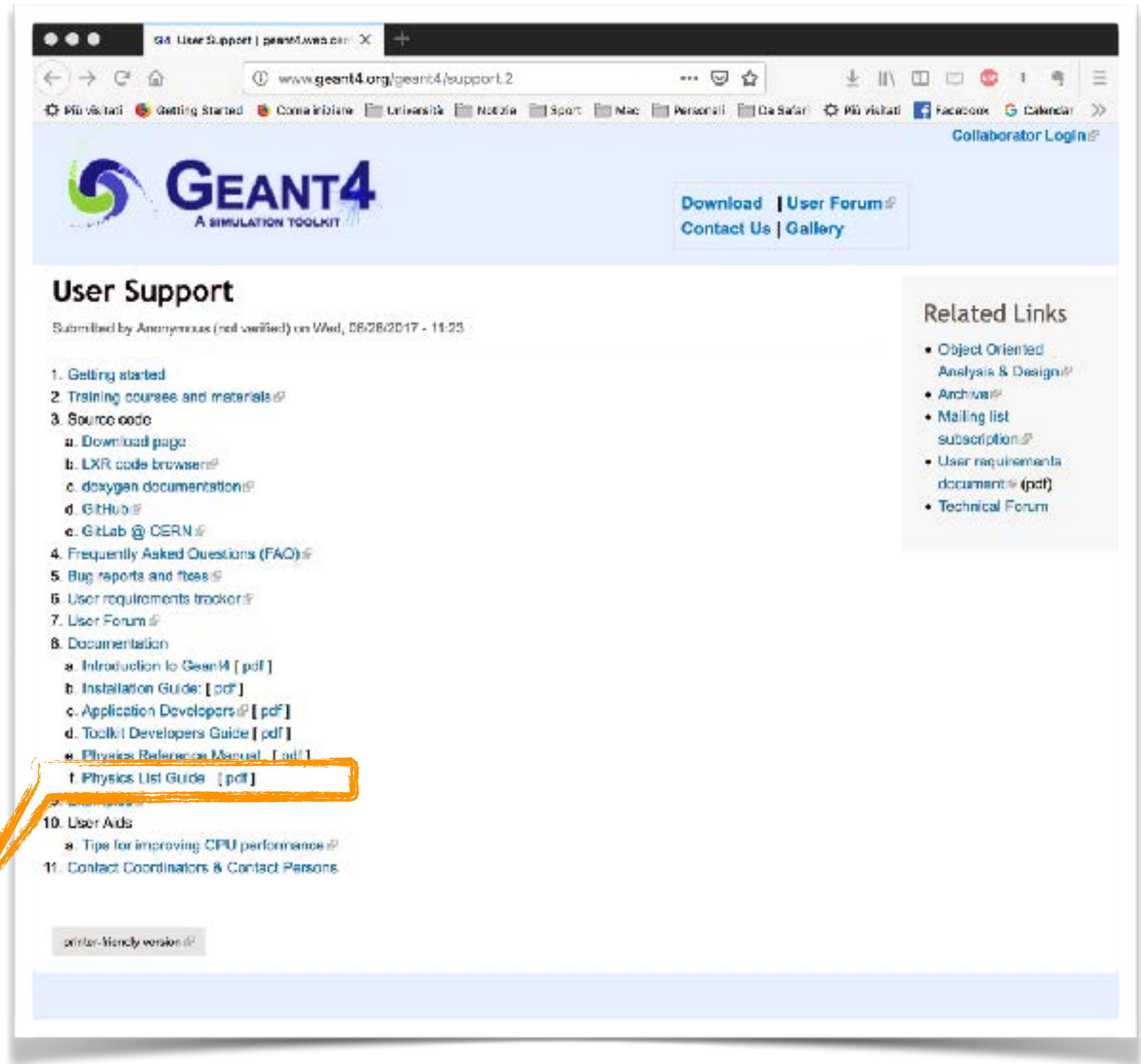
The Geant4 website

- www.geant4.org
- Documentation
- Application Developers (you!) guide
- Physics Reference Manual

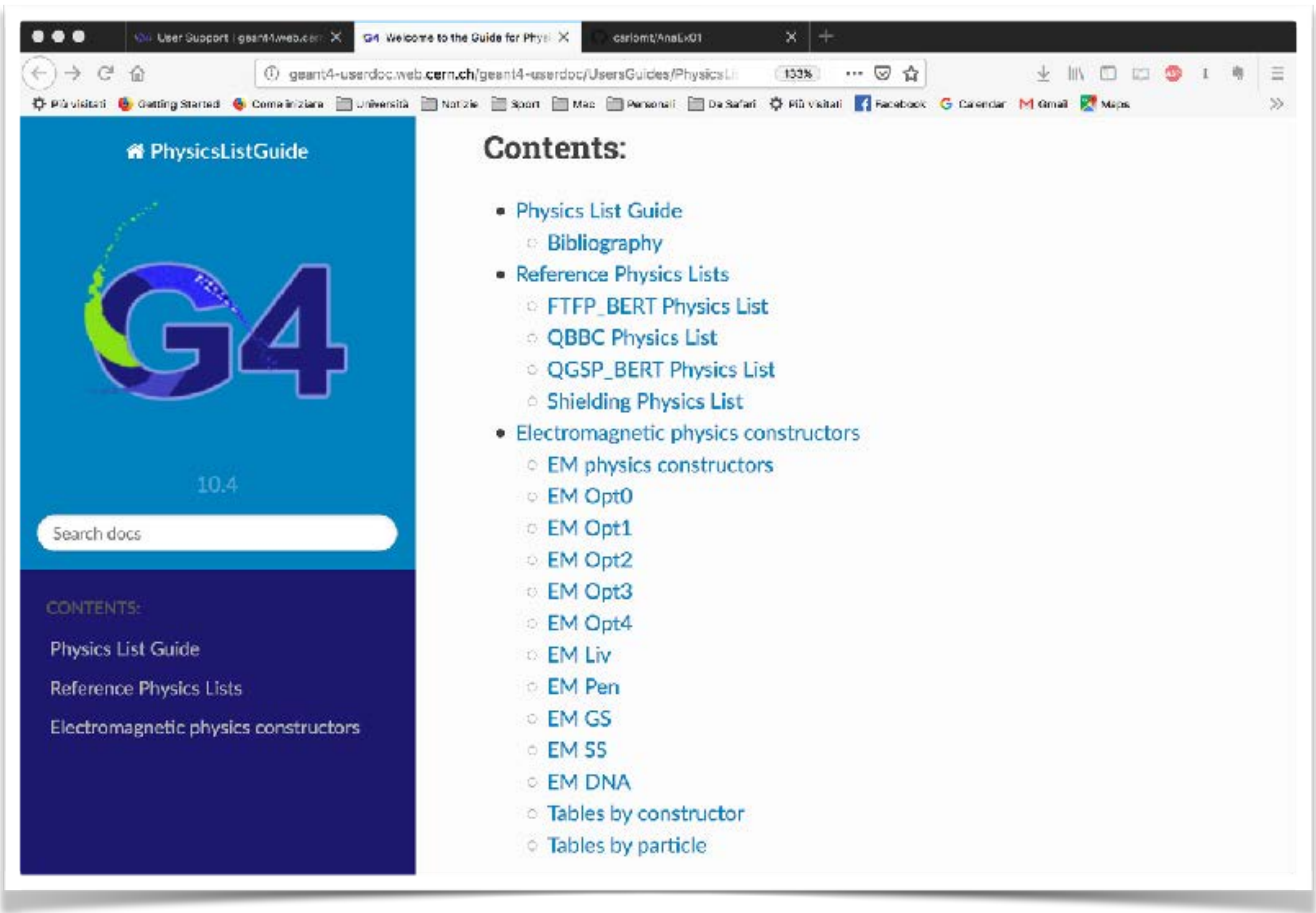


The Geant4 website

- www.geant4.org
- Documentation
- Application Developers (you!) guide
- Physics Reference Manual
- Physics Lists Guide

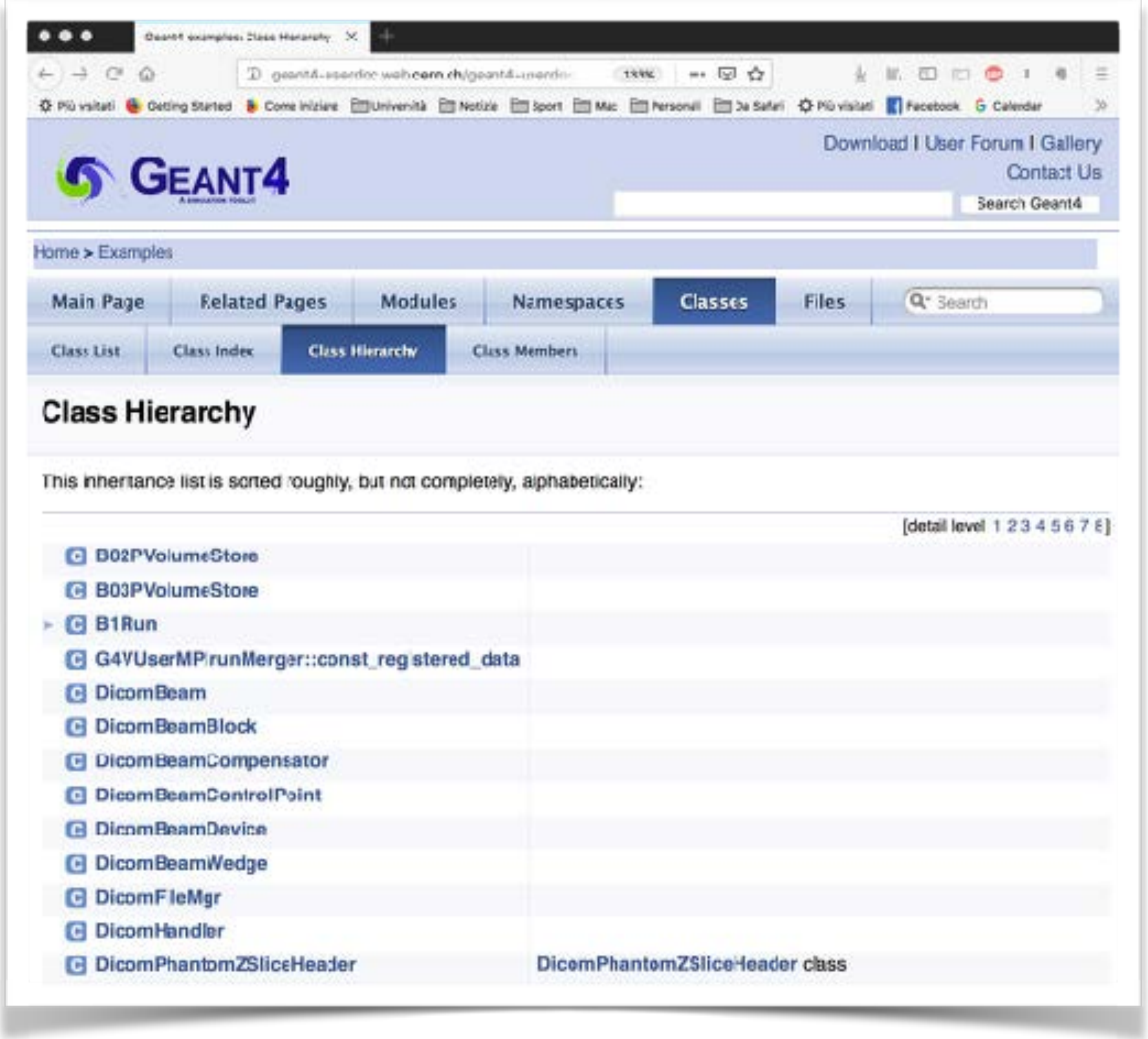


Physics List Guide



Doxygen

- http://geant4-userdoc.web.cern.ch/geant4-userdoc/Doxygen/examples_doc/html/hierarchy.html
- All the class interfaces



Examples

an overview…

Examples omnia divisa est in partes trees…

- **Basic** set of examples is oriented to novice users and covering the most typical use-cases of a Geant4 application with keeping simplicity and ease of use
- **Extended** set of examples may require some additional libraries besides of Geant4. This set covers many specific use cases for actual detector simulation
- **Advanced** set of examples covers the use-cases typical of a "toolkit"- oriented kind of development, where real complete applications for different simulation studies are provided; may require additional third party products to be built

Where?

- Where to find the examples:
  - `$G4DIR/examples/basic`
  - `$G4DIR/examples/extended`
  - `$G4DIR/examples/advanced`

Basic examples

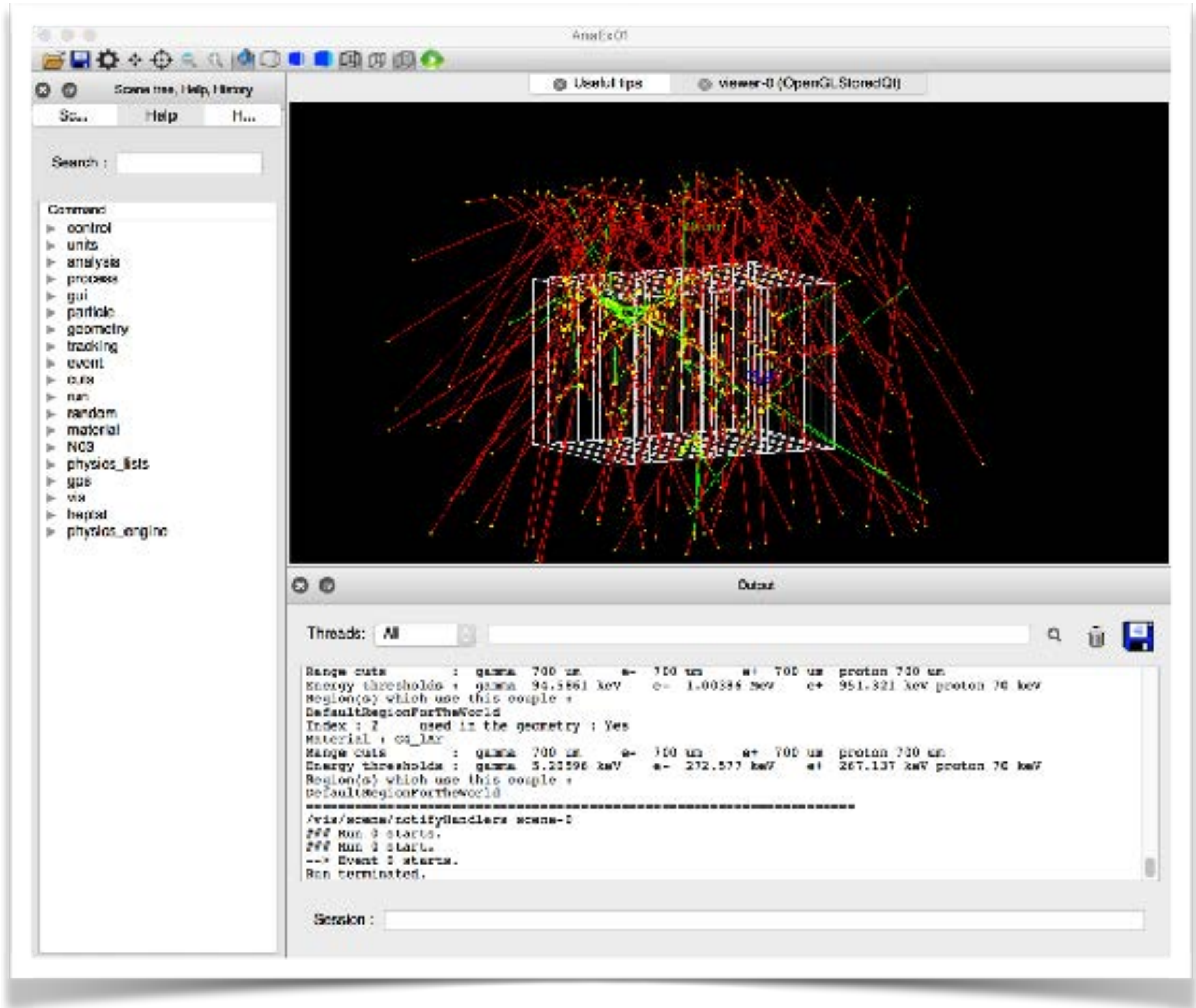
Code name	Few Characteristics
Example B1	• Simple geometry with a few solids • Geometry with simple placements (G4PVPlacement) • Scoring total dose in a selected volume user action classes • Geant4 physics list (QBBC)
Example B2	• Simplified tracker geometry with global constant magnetic field • Geometry with simple placements (G4PVPlacement) and parameterisation (G4PVParameterisation) • Scoring within tracker via G4 sensitive detector and hits • Geant4 physics list (FTFP_BERT) with step limiter • Started from novice/N02 example
Example B3	• Schematic Positron Emitted Tomography system • Geometry with simple placements with rotation (G4PVPlacement) • Radioactive source • Scoring within Crystals via G4 scorers • Modular physics list built via builders provided in Geant4
Example B4	• Simplified calorimeter with layers of two materials • Geometry with replica (G4PVReplica) • Scoring within layers in four ways: via user actions, via user own objects via G4 sensitive detector and hits and via scorers • Geant4 physics list (FTFP_BERT) • Histograms (1D) and ntuple saved in the output file • Started from novice/N03 example
Example B5	• A double-arm spectrometer with wire chambers, hodoscopes and calorimeters with a local constant magnetic field • Geometry with placements with rotation, replicas and parameterisation • Scoring within wire chambers, hodoscopes and calorimeters via G4 sensitive detector and hits • Geant4 physics list (FTFP_BERT) with step limiter • UI commans defined using G4GenericMessenger • Histograms (1D, 2D) and ntuple saved in the output file • Started from extended/analysis/A01

Basic examples

	Code name	Few Characteristics
Basic!	Example B1	• Simple geometry with a few solids • Geometry with simple placements (G4PVPlacement) • Scoring total dose in a selected volume user action classes • Geant4 physics list (QBBC)
	Example B2	• Simplified tracker geometry with global constant magnetic field • Geometry with simple placements (G4PVPlacement) and parameterisation (G4PVParameterisation) • Scoring within tracker via G4 sensitive detector and hits • Geant4 physics list (FTFP_BERT) with step limiter • Started from novice/N02 example
A bit complex	Example B3	• **Schematic Positron Emitted Tomography system** • Geometry with simple placements with rotation (G4PVPlacement) • Radioactive source • Scoring within Crystals via G4 scorers • Modular physics list built via builders provided in Geant4
	Example B4	• Simplified calorimeter with layers of two materials • Geometry with replica (G4PVReplica) • Scoring within layers in four ways: via user actions, via user own objects via G4 sensitive detector and hits and via scorers • Geant4 physics list (FTFP_BERT) • Histograms (1D) and ntuple saved in the output file • Started from novice/N03 example
	Example B5	• **A double-arm spectrometer with wire chambers, hodoscopes and calorimeters with a local constant magnetic field** • Geometry with placements with rotation, replicas and parameterisation • Scoring within wire chambers, hodoscopes and calorimeters via G4 sensitive detector and hits • Geant4 physics list (FTFP_BERT) with step limiter • UI commans defined using G4GenericMessenger • Histograms (1D, 2D) and ntuple saved in the output file • Started from extended/analysis/A01

My example

- https://github.com/carlomt/AnaEx01
- A modified version of extended/AnaEx01
- output in root files
- input in GPS
- example of cosmic muons…



Courses

- Geant4 Advanced Course @ CERN, CERN (Geneva), ~~24-26 March 2020~~ POSTPONED. https://indico.cern.ch/e/geant4_advanced_course_2020

- Geant4 Course at the 17th Seminar on Software for Nuclear, Sub-nuclear and Applied Physics, Porto Conte, Alghero (Italy), 24-29 May 2020. https://agenda.infn.it/e/AlgheroSeminar2020 thank you for your attention!

Inverse transform sampling

- If a PDF f is integrable (called **cumulative**, F)
- and the cumulative is invertible F^{-1}
- It is possible to sample x accordingly to f :

$$x = F^{-1}(u)$$

where *u* is uniformly distributed

An event in Geant4

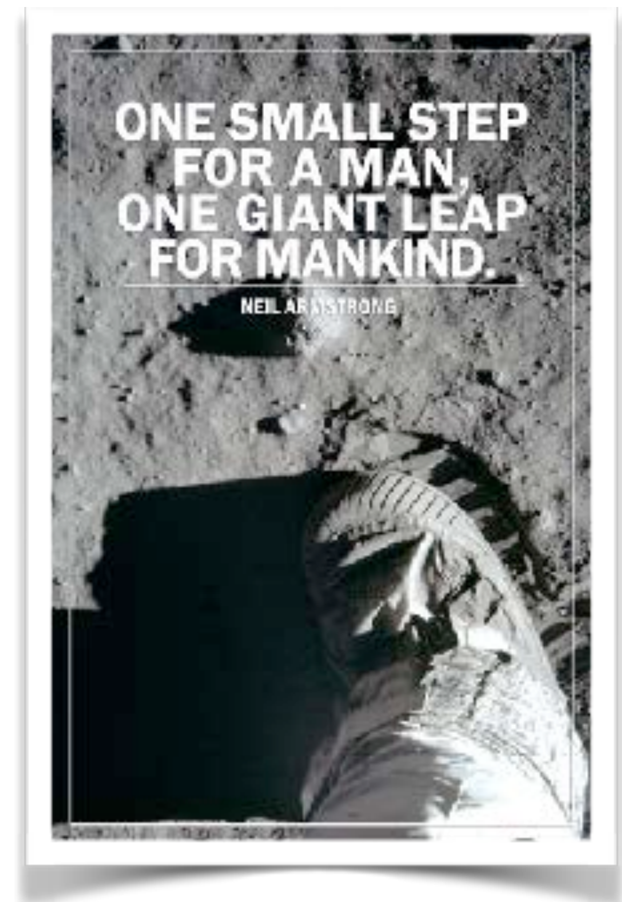
- An event is the basic unit of simulation in Geant4
- **G4Event** class represents an event. It has following objects at the end of its (successful) processing
    - List of primary vertices and particles (as input)
    - Hits and Trajectory collections (as output)
- **G4EventManager** class manages processing an event
- **G4UserEventAction** is the optional user hook

A track in Geant4

- Track is a snapshot of a particle
- It has physical quantities of current instance only. It does not record previous quantities
- It's not a collection of steps. Instead, a track is being updated by steps
- G4TrackingManager manages processing a track, a track is represented by G4Track class
- G4UserTrackingAction is the optional user hook

A step in Geant4

- A step is a variation of a track
- Has two points (pre and post step points)
- In case a step is limited by a boundary, the end point stands on the boundary, and it logically belongs to the next volume
- Boundary processes such as transition radiation or refraction could be simulated



- **G4SteppingManager** class manages processing a step, a step is represented by **G4Step** class
- **G4UserSteppingAction** is the optional user hook

Particle in Geant4

- A particle in Geant4 is represented by three layers of classes:
  - **G4Track**
    - Geometrical information (position)

  - **G4DynamicalParticle**
    - Dynamic physical properties (momentum, energy, spin…)
  - **G4ParticleDefinition**
    - Static properties (charge, mass, life time)

Sampling the step size

- In Geant4, particle transportation is a process as well, by which a particle interacts with geometrical volume boundaries and field of any kind
- Each particle has its own list of applicable processes. At each step, all processes listed are invoked to get proposed physical interaction lengths
- The process which requires the shortest interaction length limits the step