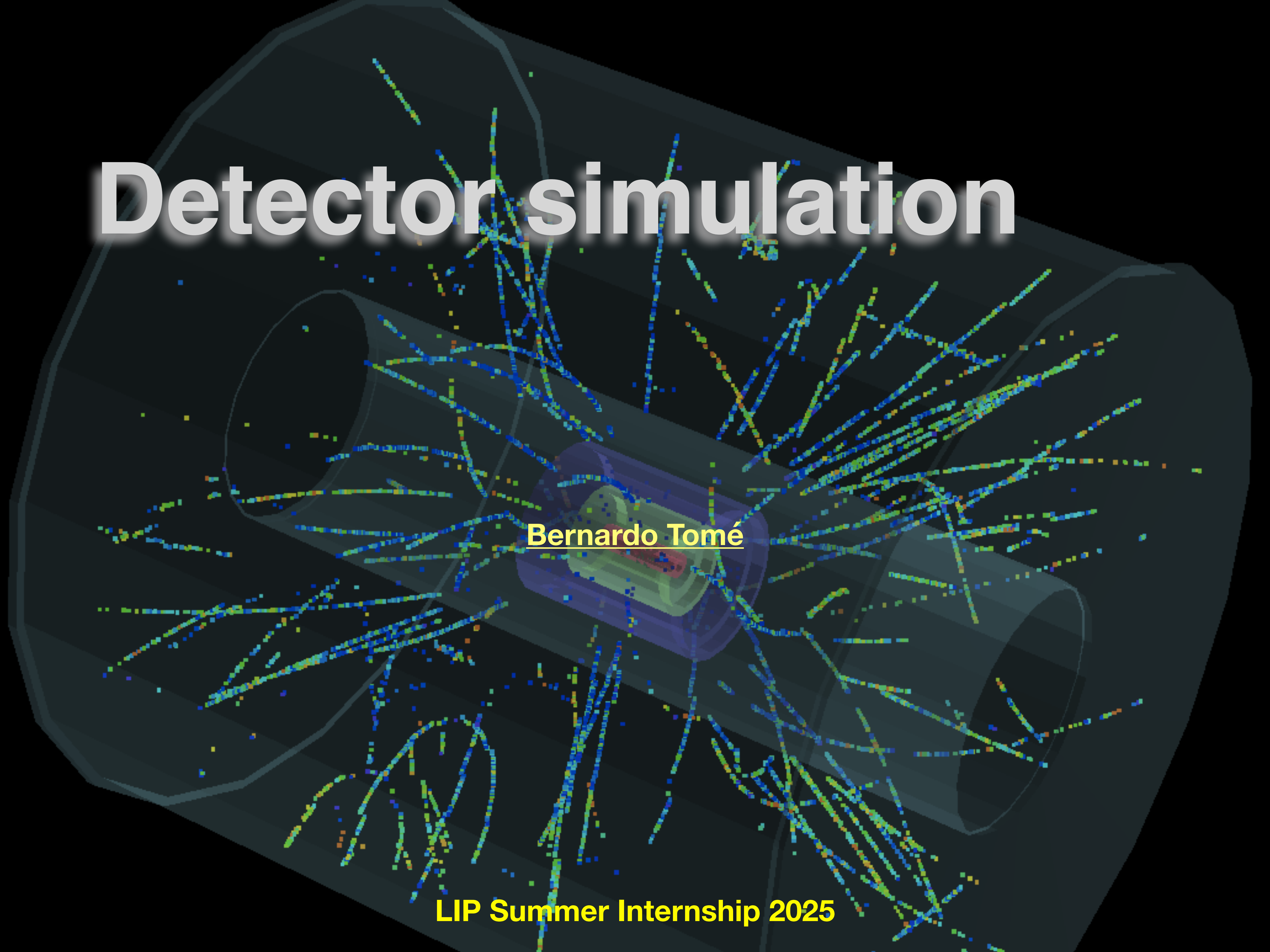


Detector simulation

Bernardo Tomé

LIP Summer Internship 2025

Why we need simulations ?

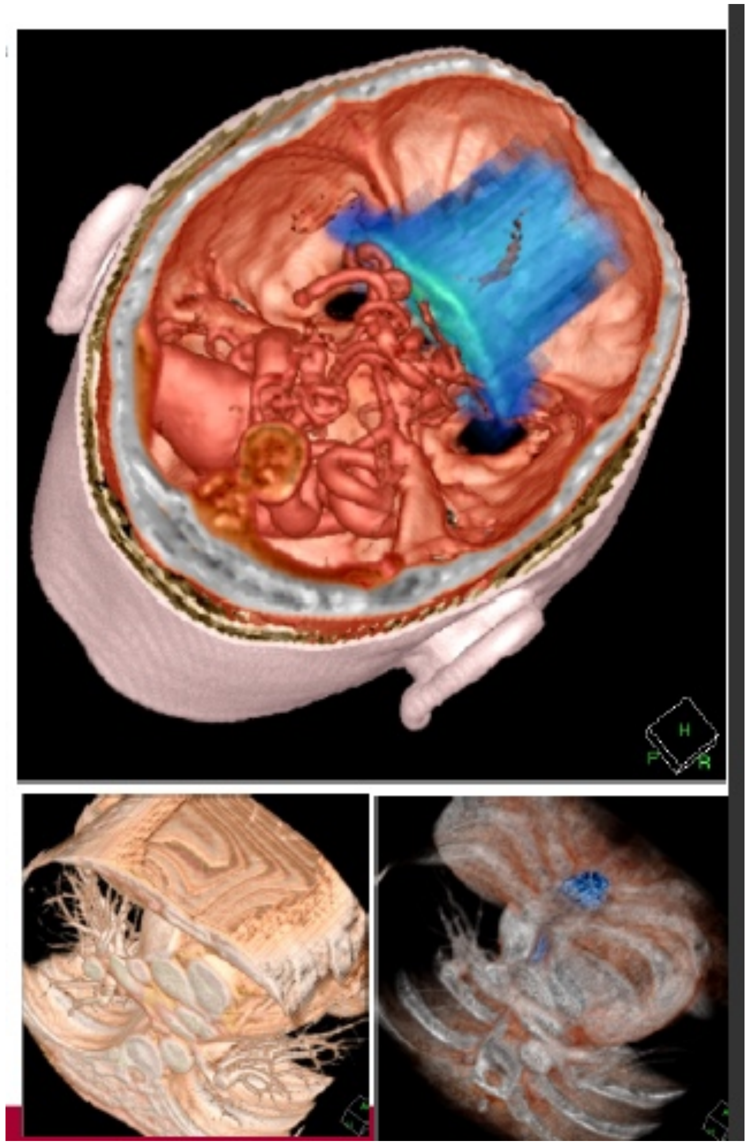
- Simulation is a modern and essential tool to :
    - Design a new experiment, allowing to predict very realistically the performance of the future yet unbuilt apparatus;
    - Analyse and understand the data of ongoing experiments;
    - Develop new data analysis methods, train neural networks, etc.
    - Simulate new physics models, understanding how a particular detector design could detect these;
- Detector configurations can vary a lot but the physics is the same;
- General codes exist that can be used for simulating "any" detector :

Monte Carlo radiation transportation codes

Monte Carlo simulation tools

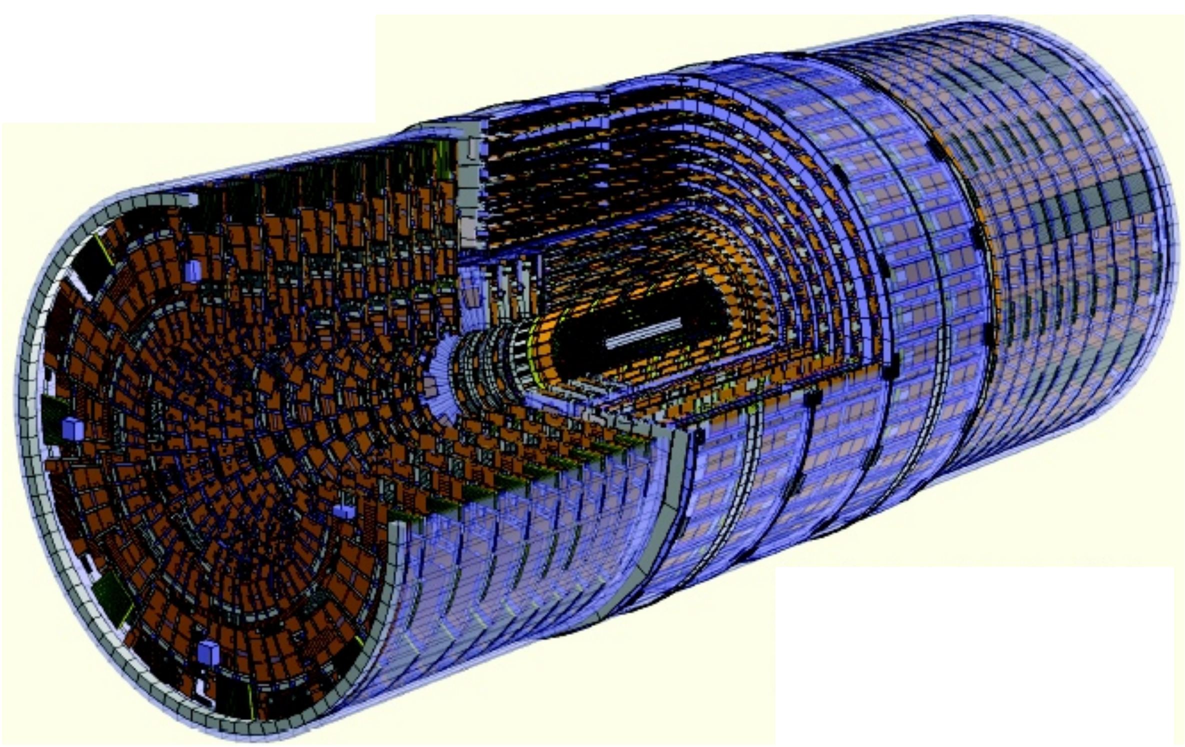
- Monte Carlo radiation transportation tools are non-deterministic
- Physics processes underlying particle detection are governed by the laws of Quantum Mechanics;
- This intrinsic randomness can be emulated by using computers and the possibility to generate (pseudo)-random numbers;

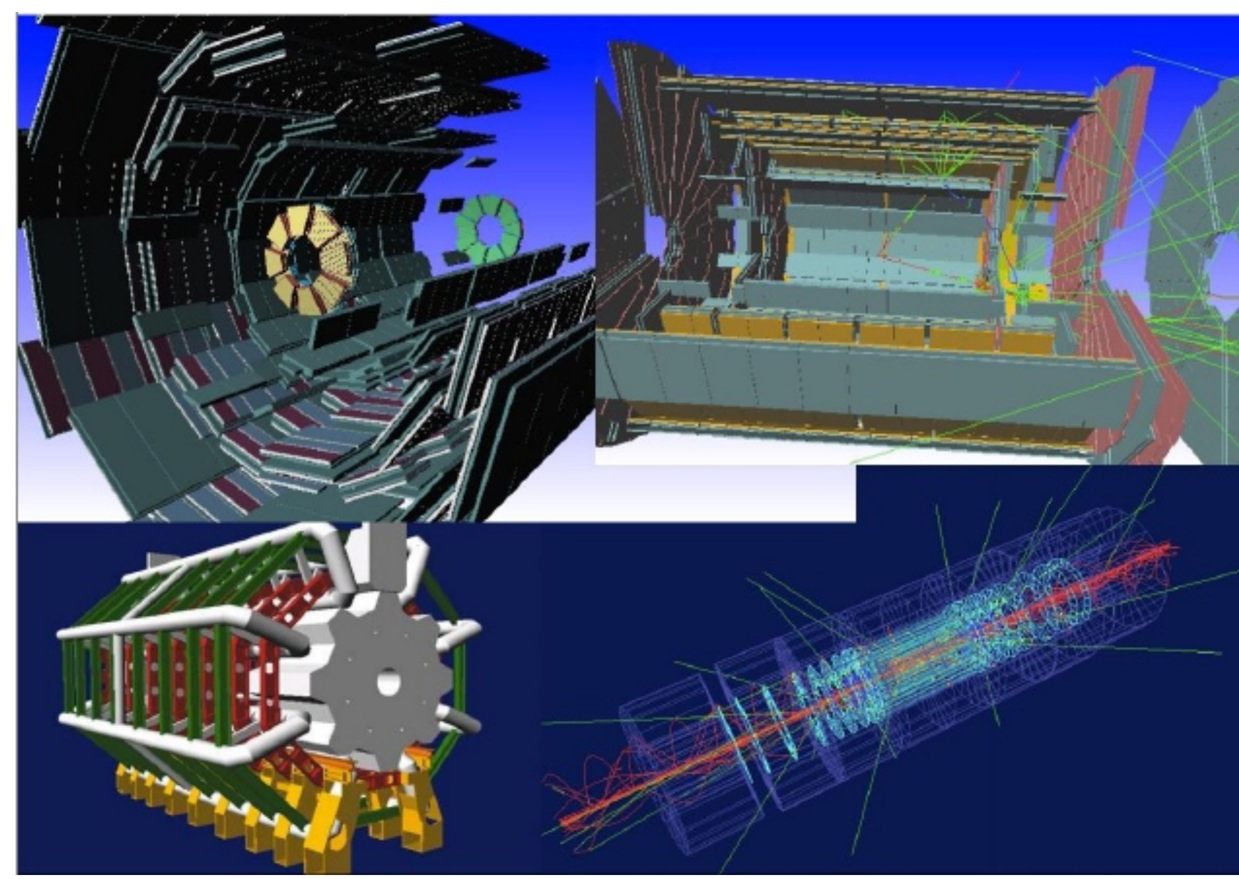
Monte Carlo methods are the tool to simulate random physics processes in a computer



“Detector” simulation is a multi-disciplinary field!

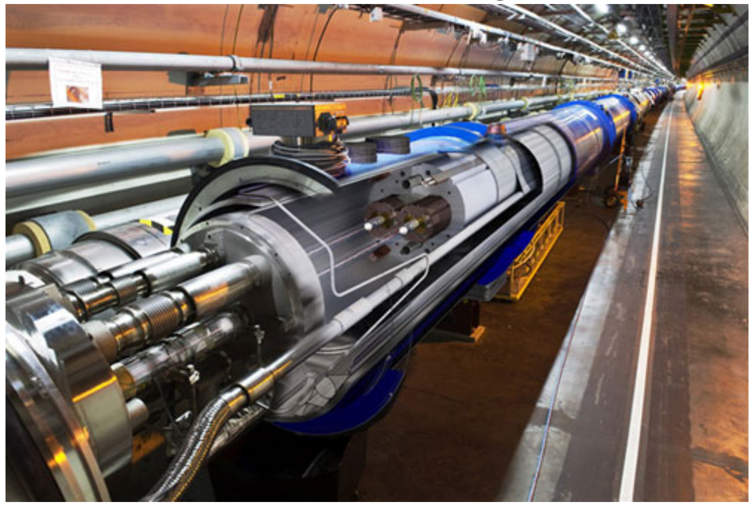
- Nuclear physics
- High-energy physics
- Astrophysics
- Space engineering
- Radiation damage
- Medical physics
- Industrial applications



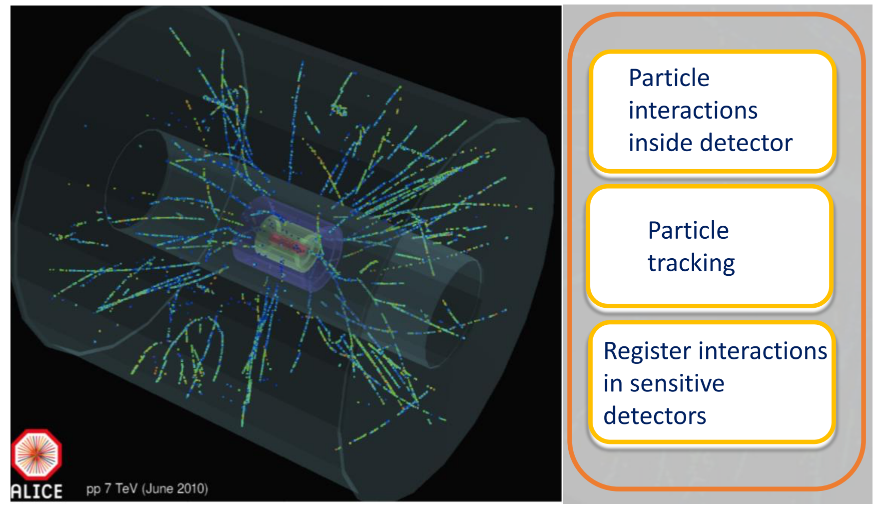


Simulating a High Energy Physics experiment

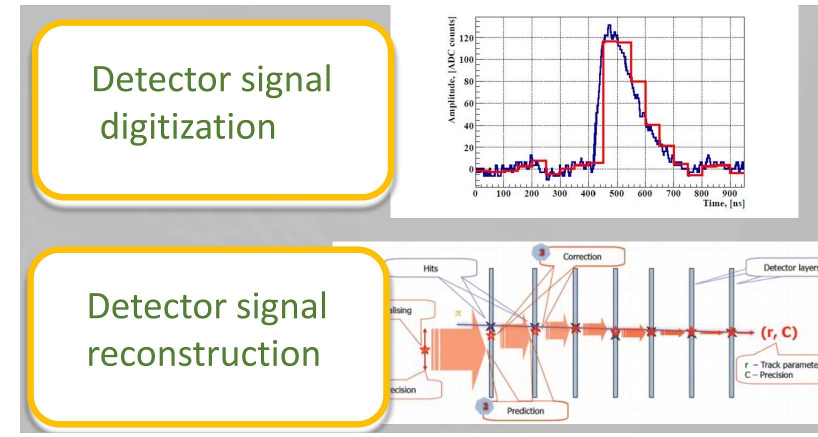
Simulate the colliding beams



Detector simulation



Signal from readout - digitisation



The simulation is usually made in several steps :

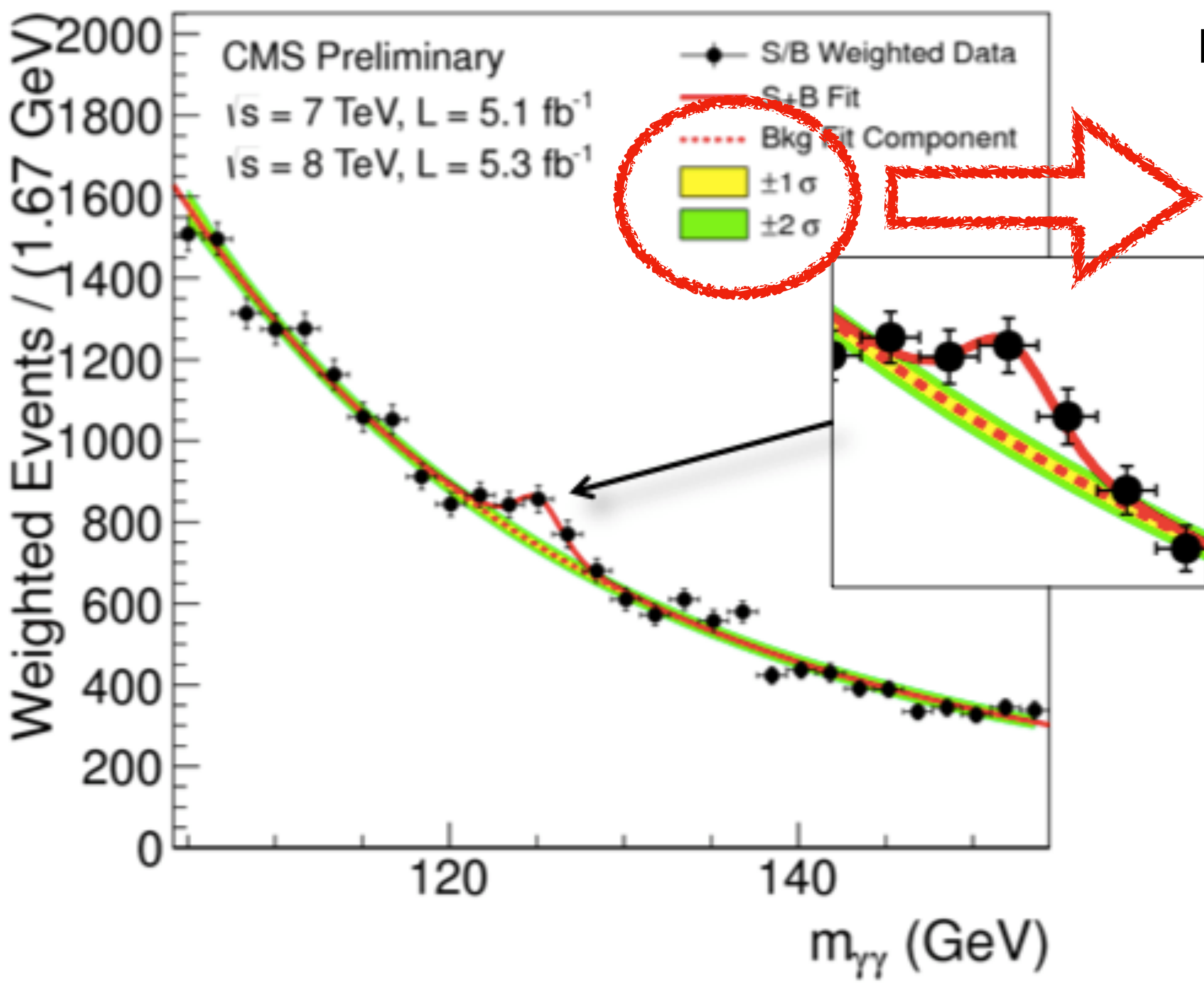
- Simulate the colliding beams - Monte Carlo event generators, describing the physics of the high-energy interactions;

- Simulate the passage of the particles produced in the collisions through the detector - Monte Carlo radiation transportation or simply “detector simulation”;

- Simulate the signals produced in the various active components of the detector.

Similar approach can be found in other types of experiments

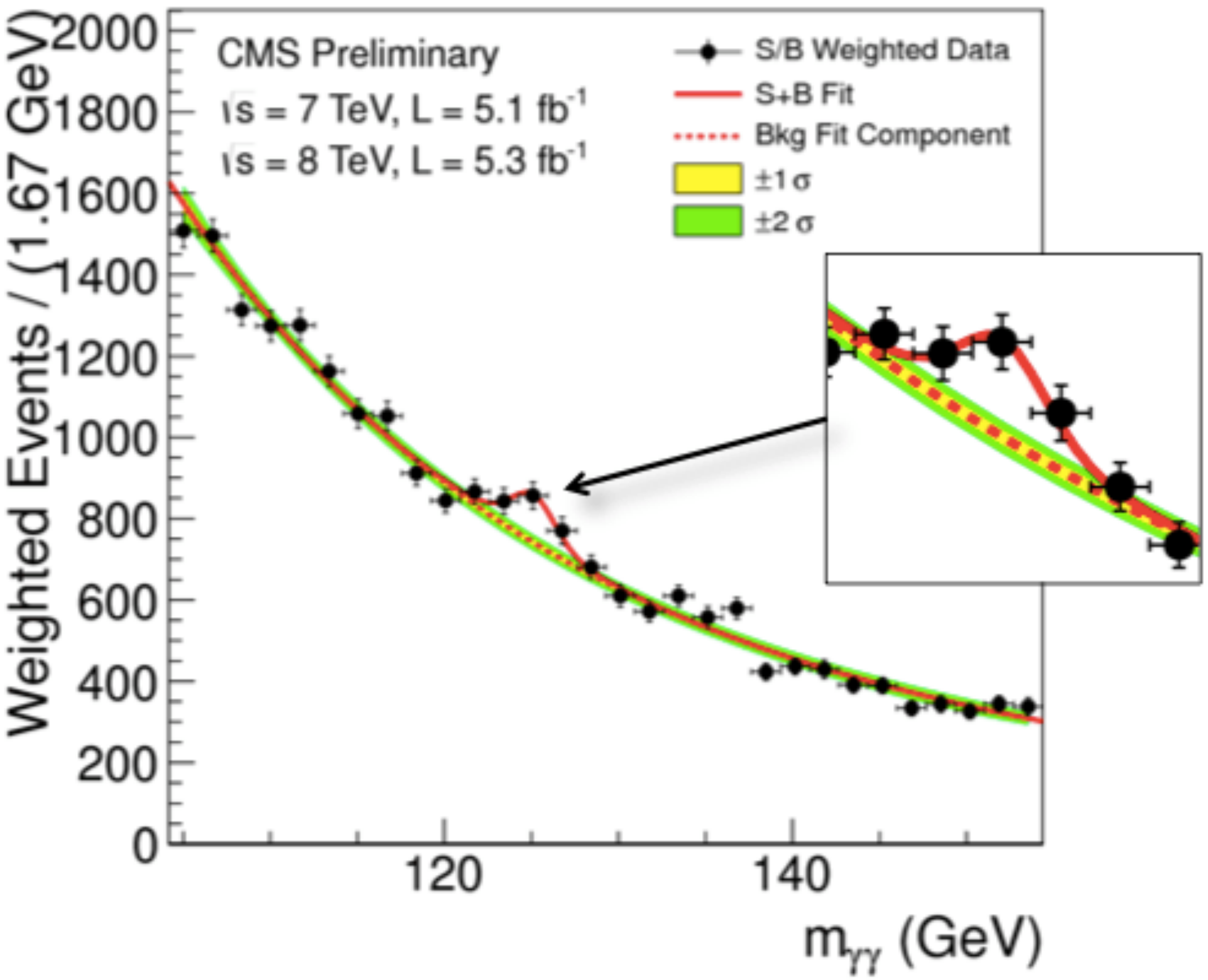
The importance of simulations…



Precisely simulated background :

- **Simulation of pp collisions;**
- **Simulation of detector response;**

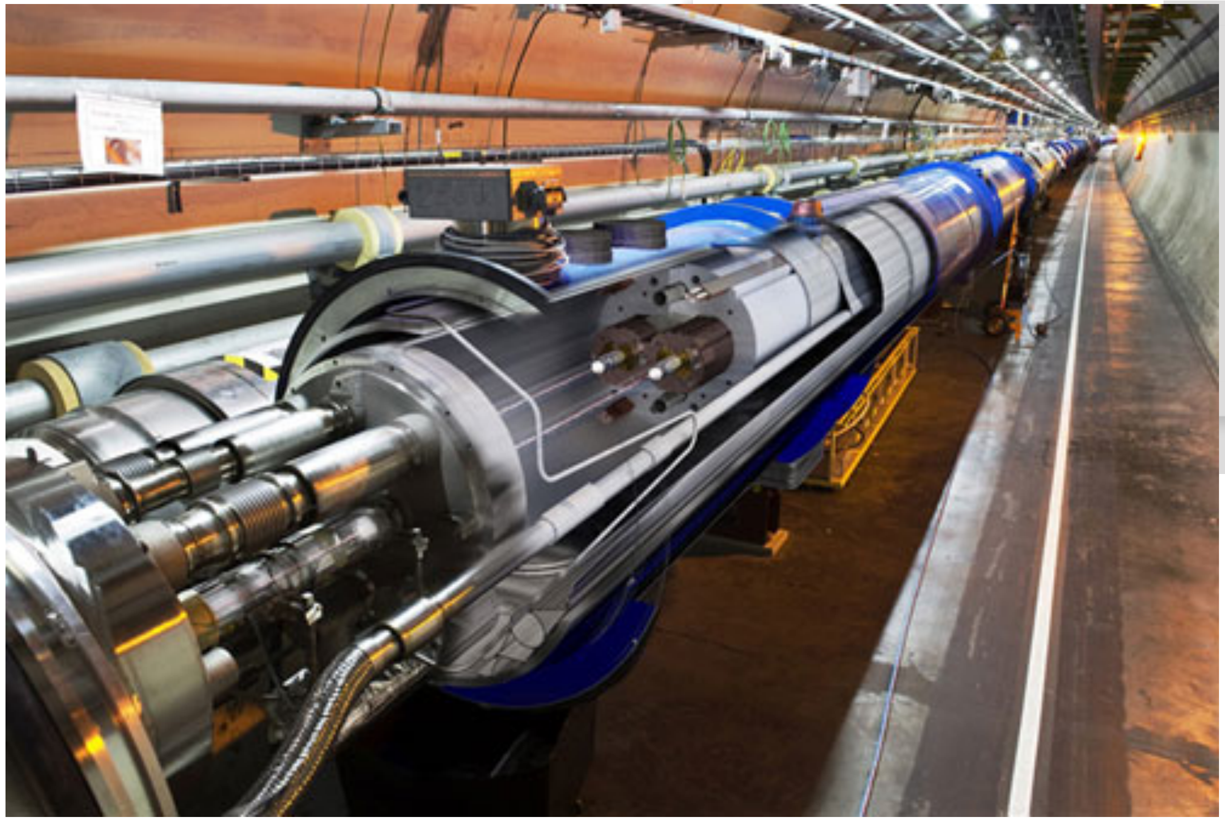
The importance of simulations…

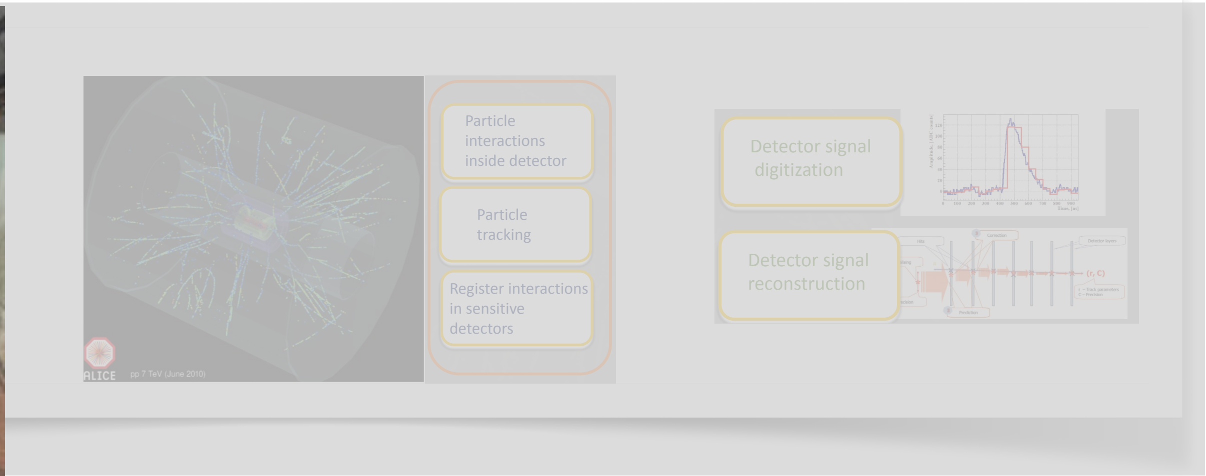


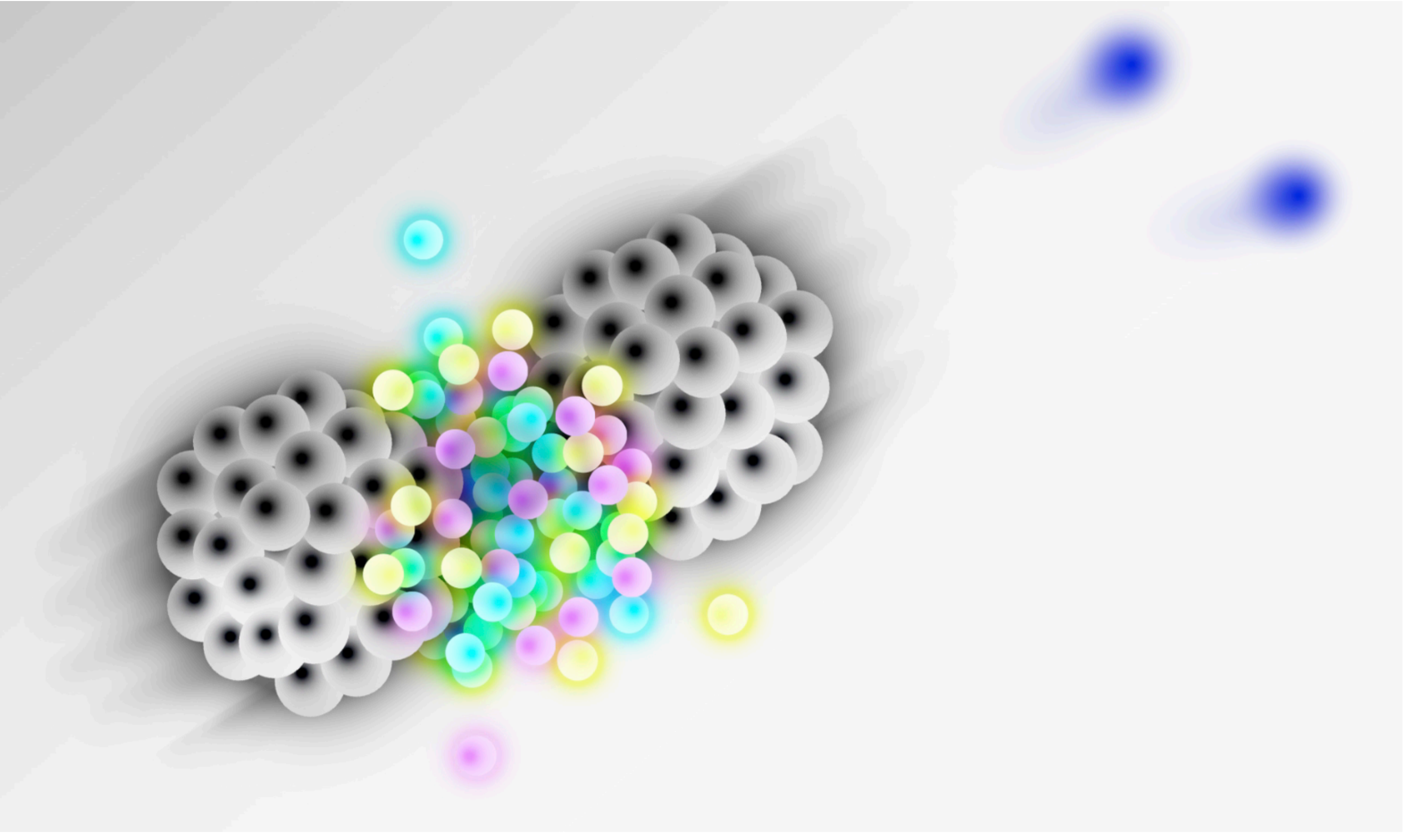
Discovery of the Higgs boson !

Simulating a High Energy Physics experiment

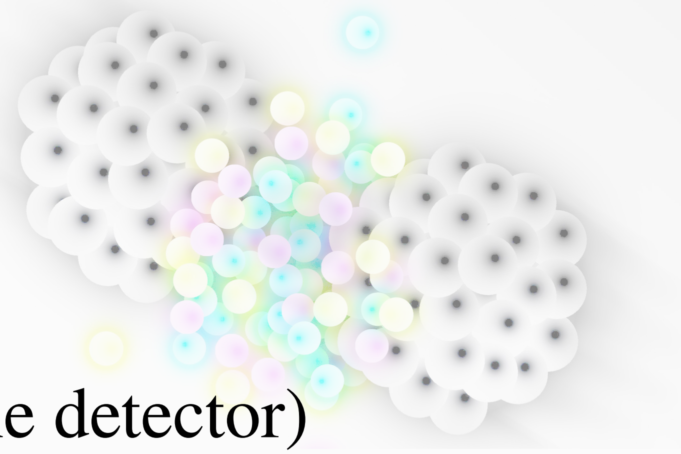
Simulate the colliding beams



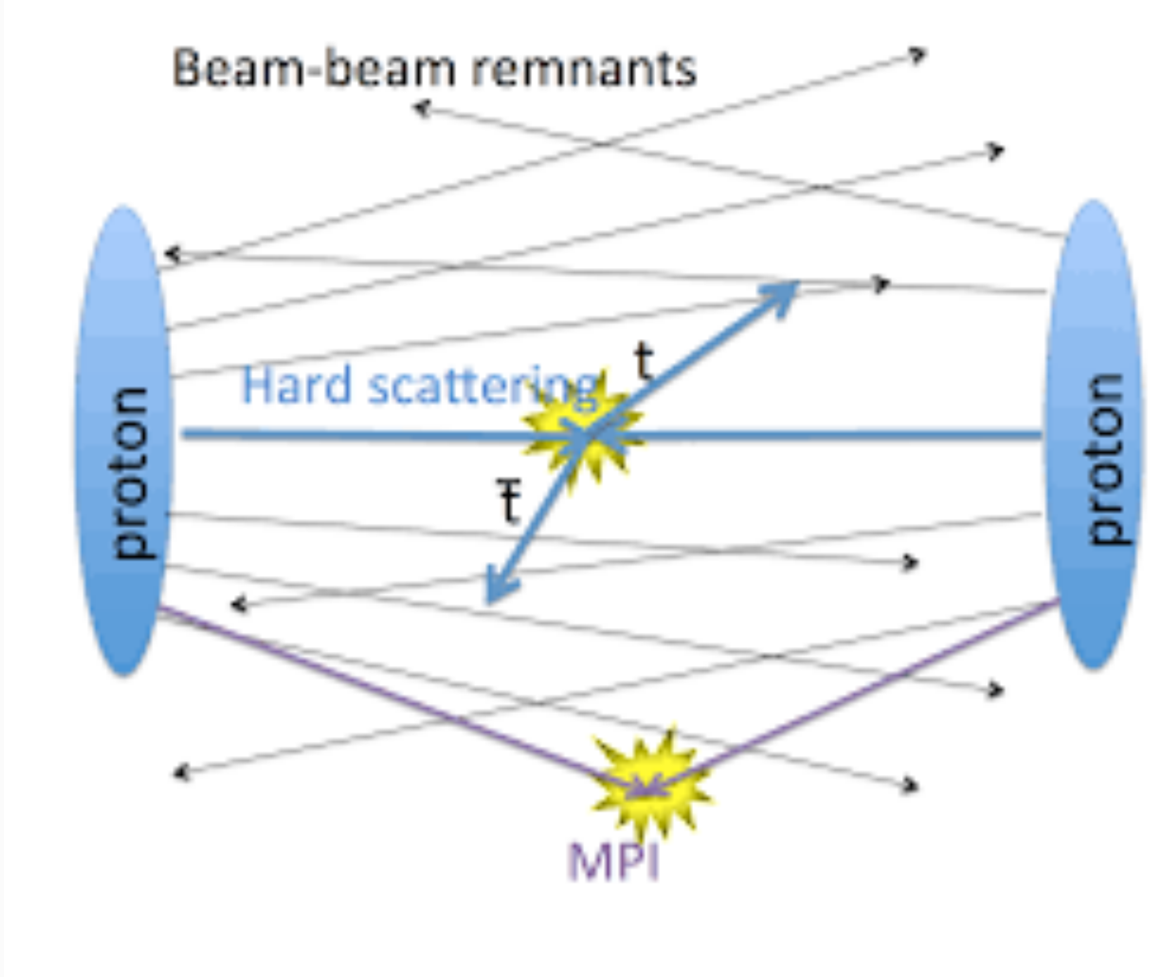




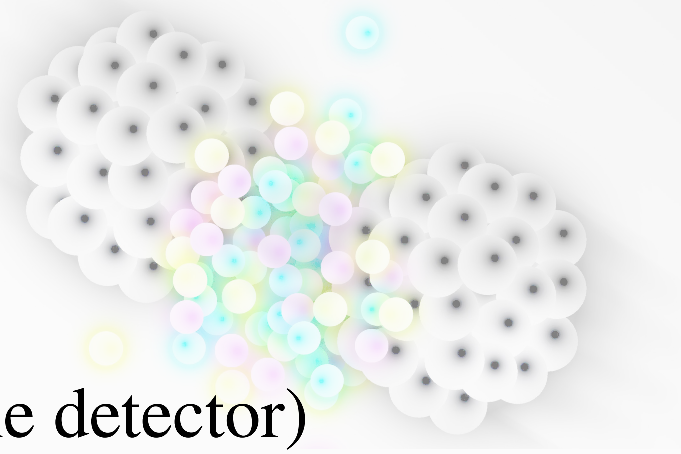
From Collision to Detector



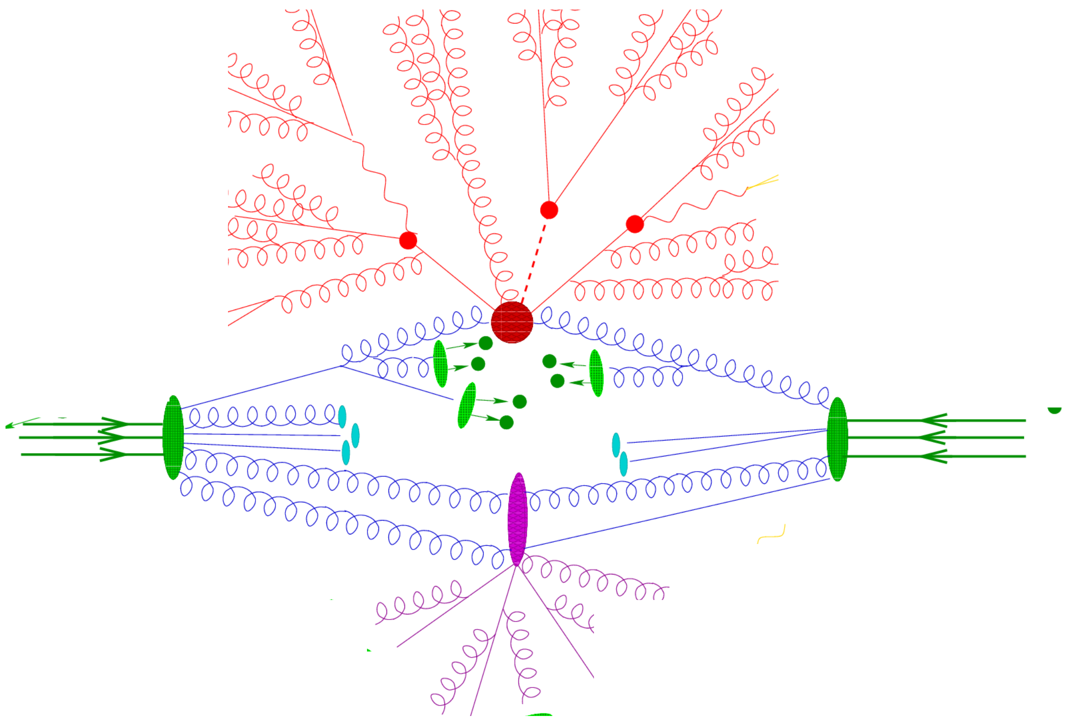
- Need to simulate the full event/interaction (before reaching the detector)
  - Monte Carlo codes specialised in simulating hadronic collisions: PYTHIA, HERWIG, …
  - What do they simulate?
    - Moment of the collision:
      - Hard Scattering: head-on collisions between particles of each proton
      - Beam remnants: mild interaction between particles of each proton



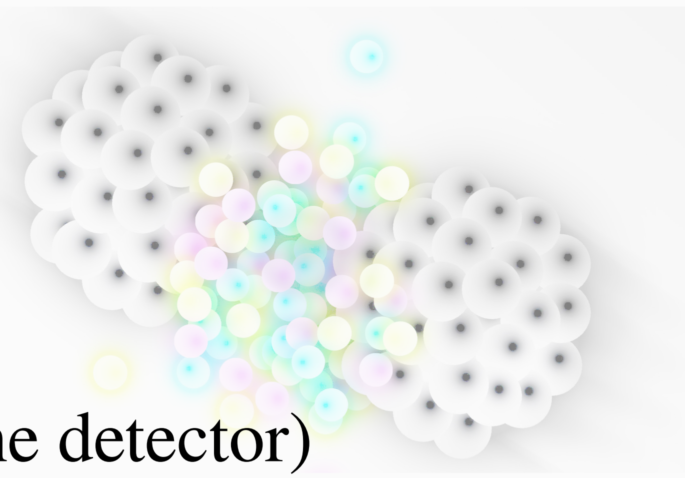
From Collision to Detector



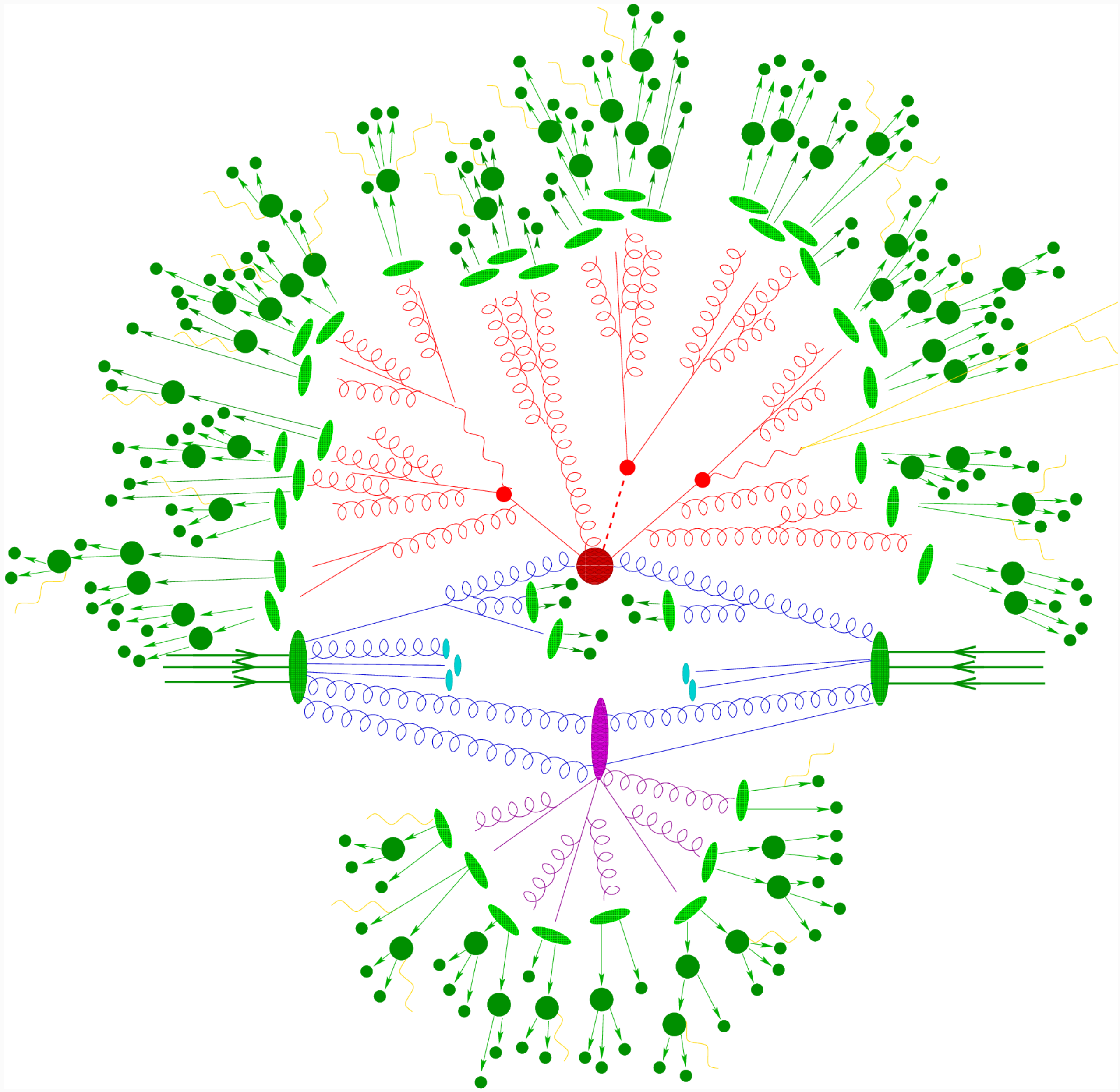
- Need to simulate the full event/interaction (before reaching the detector)
  - Monte Carlo codes specialised in simulating hadronic collisions: PYTHIA, HERWIG, …
  - What do they simulate?
    - After the collision (hard scattering):
      - Particles from hard scattering (quarks and gluons) have lots of energy!
      - They want to radiate to go to the *fundamental state*: **parton shower**



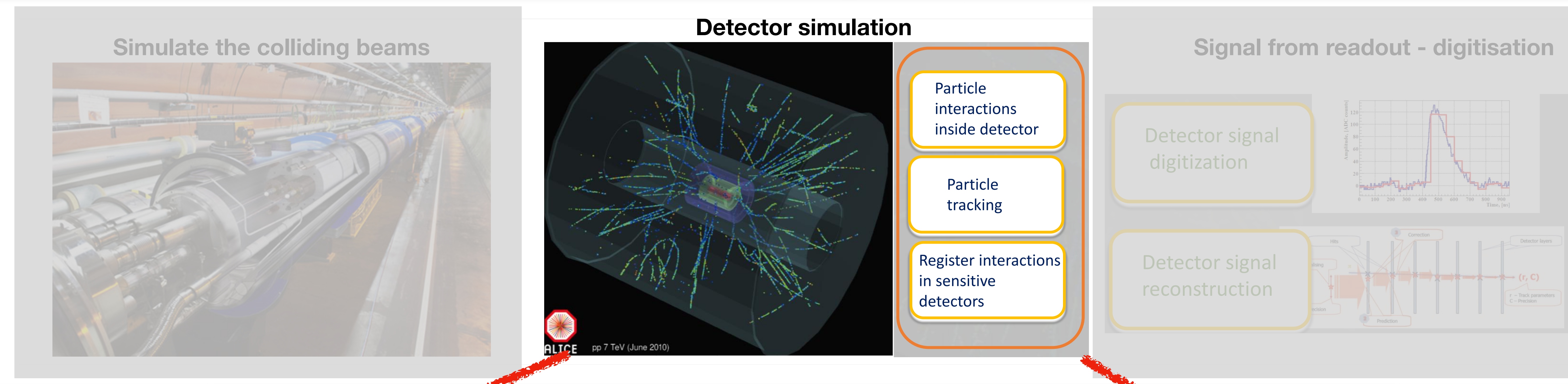
From Collision to Detector

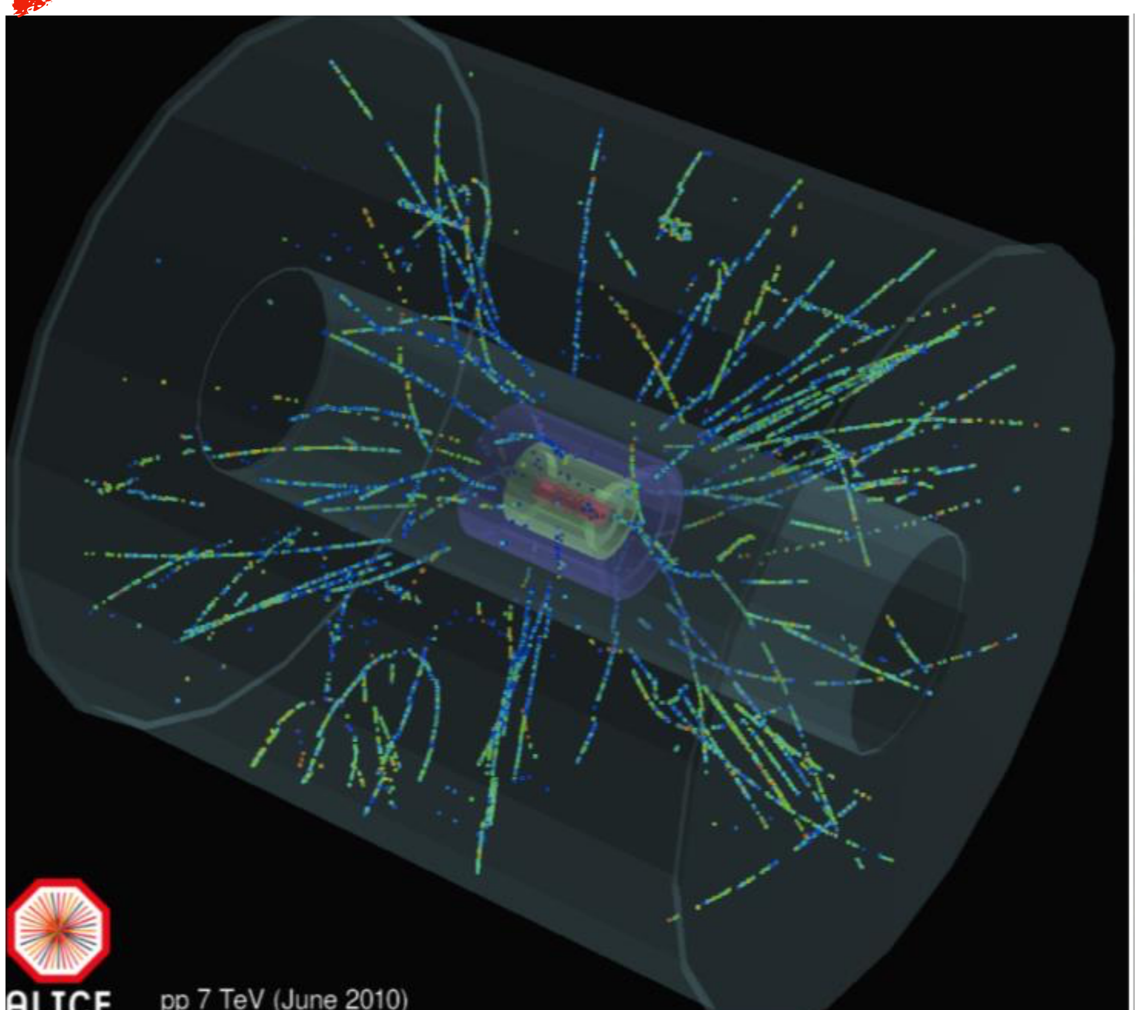


- Need to simulate the full event/interaction (before reaching the detector)
  - Monte Carlo codes specialised in simulating hadronic collisions: PYTHIA, HERWIG, …
  - What do they simulate?
    - After the collision (whole event):
      - We don't see coloured particles;
      - Quarks and gluons have to re-arrange into composite particles (new hadrons): **hadronization**



Simulating a High Energy Physics experiment





Particle interactions inside detector

Particle tracking

Register interactions in sensitive detectors

Creating a virtual detector

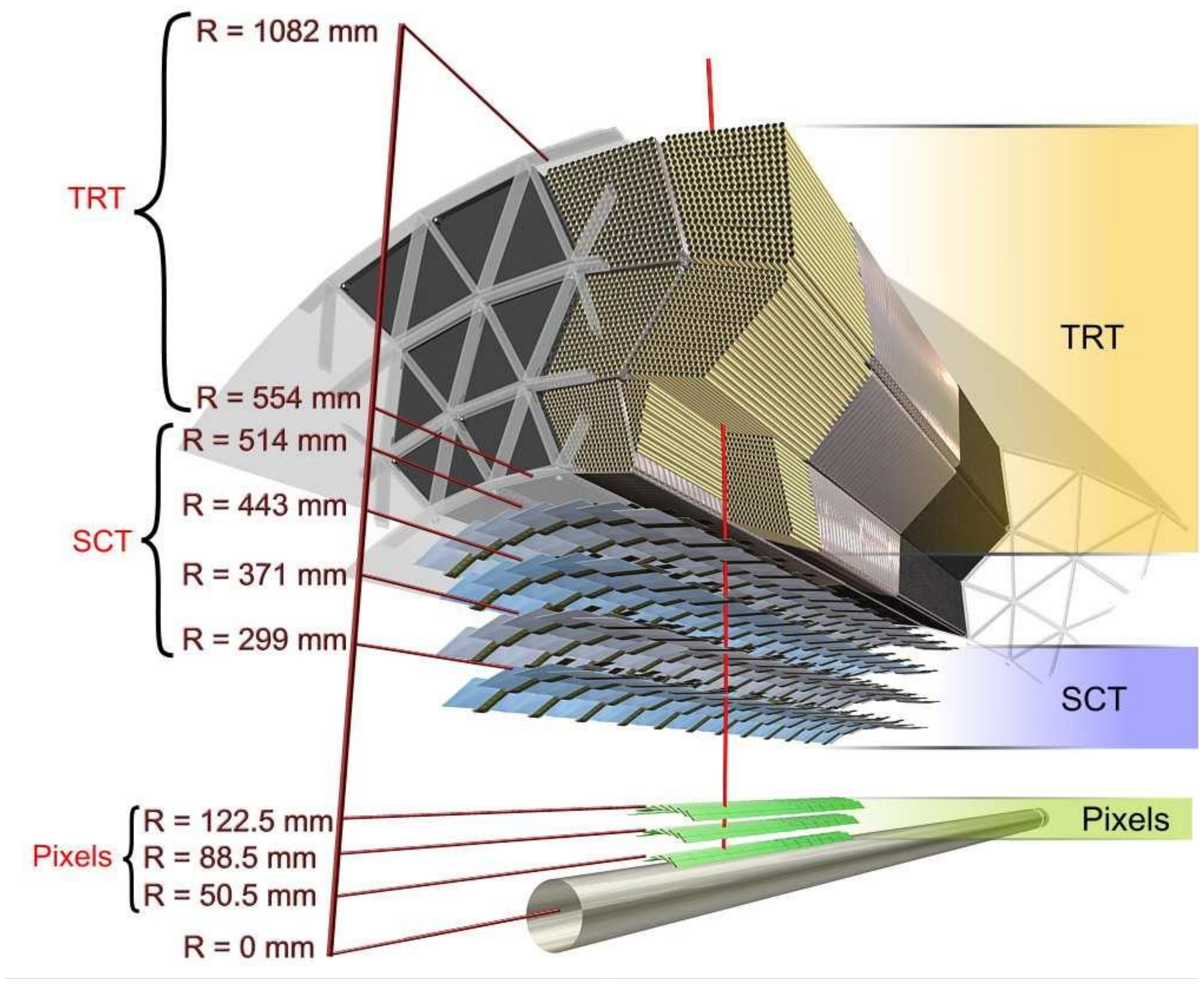
Detector geometry and materials

For detector simulation, an accurate (enough) description of the detector is needed.

The detector definition requires the representation of its geometrical elements, materials and electronics properties.

The geometrical representation of detector elements focuses on the definition of solid models and their spatial positioning.

For each component/material one needs to know the relevant physical properties -> compute interaction cross-sections for all the relevant processes;



A detector is here viewed as any passive or active volume where particles may interact

Creating a virtual detector

A universal description is usually not needed, or even not possible …

- Approximations will always have to be made when devising the simulation of a real experiment :
  - Complexity of the geometry to be implemented;
  - Lack of a perfect description of the physical properties of the materials;
  - Limitations in describing the relevant physics processes;
  - Computing time available;
  - …
- But the impact of the approximations must be assessed ! Systematic error of our simulation…

What physics we need to simulate ?

Particle interactions with detector materials :

Electromagnetic processes

Photon processes:

- Compton scattering
- gamma conversion
- photo-electric effect
- muon pair production

Charged particle processesses (electron/ positron, muons, ions ...):

- ionization and delta ray emission
- Bremsstrahlung
- positron annihilation
- Multiple scattering

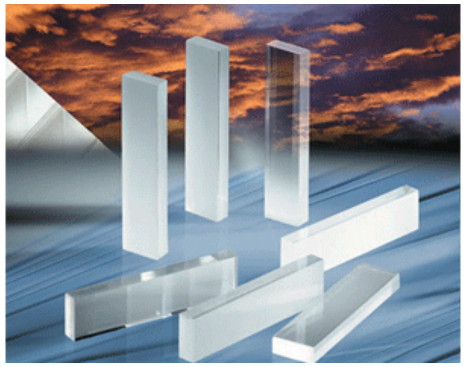
Hadronic interactions

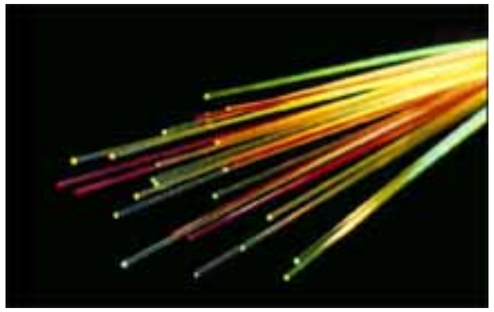
- lepton-hadron interactions
- photonuclear and electronuclear reactions
- nucleus-nucleus reactions
- elastic scattering
- nuclear cascades
- fission, evaporation, break-up models
- low energy neutron interactions
- radioactive decay

What do we need to simulate ?

Secondary processes giving rise to the measured signal :

Optical Photons:

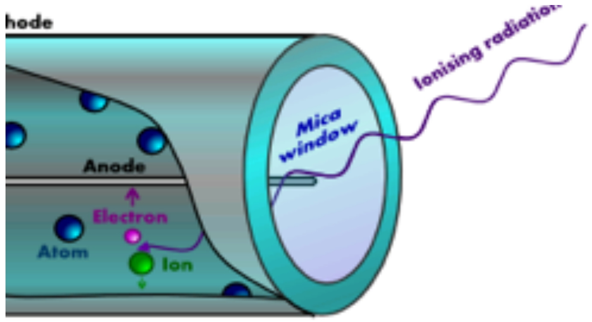


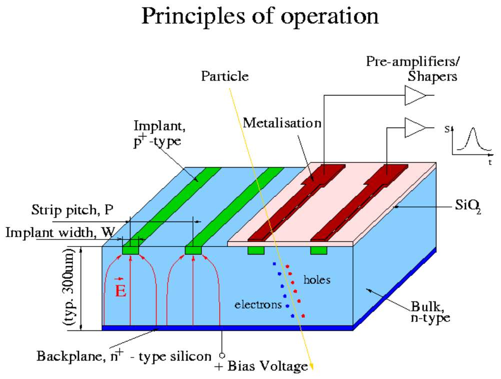


- Cerenkov Radiation
- Scintillation
- Wavelenght shifting
- Absorption
- Rayleigh and Mie Scattering
- Light detection
- …

Charge production in gaseous and solid state detectors:

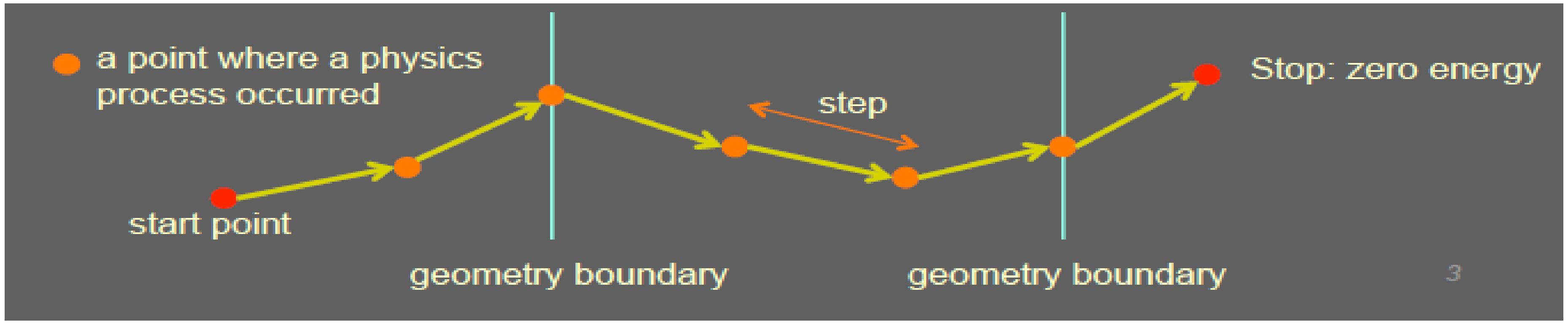
- Avalanche development
- Charge drift
- Induced signals / charge collection
- …





Monte Carlo radiation transportation

- Treat one particle at the time
- Treat a particle in **steps**

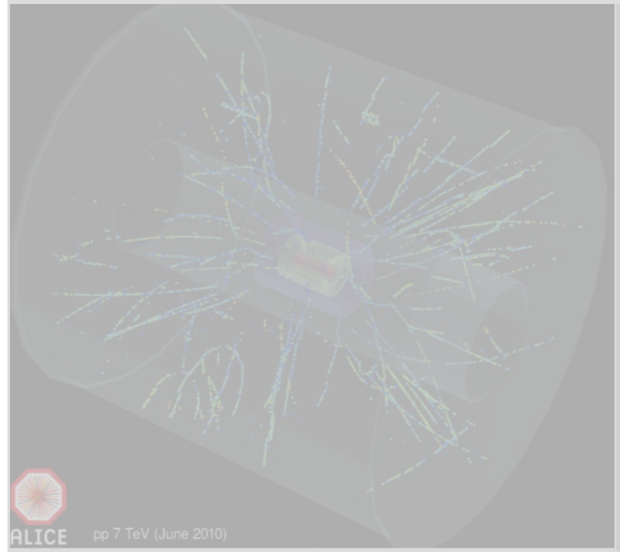


- For each step
  - the step length is determined by the cross sections of the physics processes and the geometrical boundaries; if new particles are created, add them to the list of particles to be transported;
  - local energy deposit; effect of magnetic and electric fields;
  - if the particle is destroyed by the interaction, or it reaches the end of the apparatus, or its energy is below a (tracking) threshold, then the simulation of this particle is over;
    else continue with another step.
- Output - new particles created (indirect)
  - local **energy deposits** throughout the detector (direct)

Simulating a High Energy Physics experiment

Simulate the colliding beams

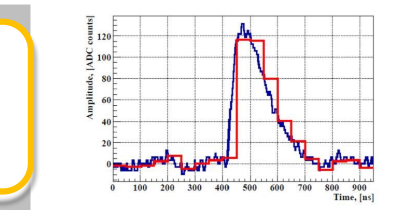
Detector simulation



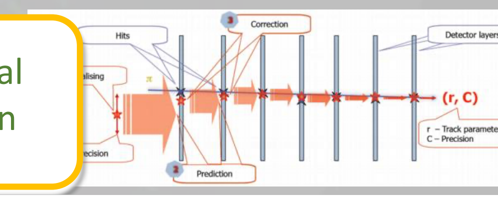
- Particle interactions inside detector
- Particle tracking
- Register interactions in sensitive detectors

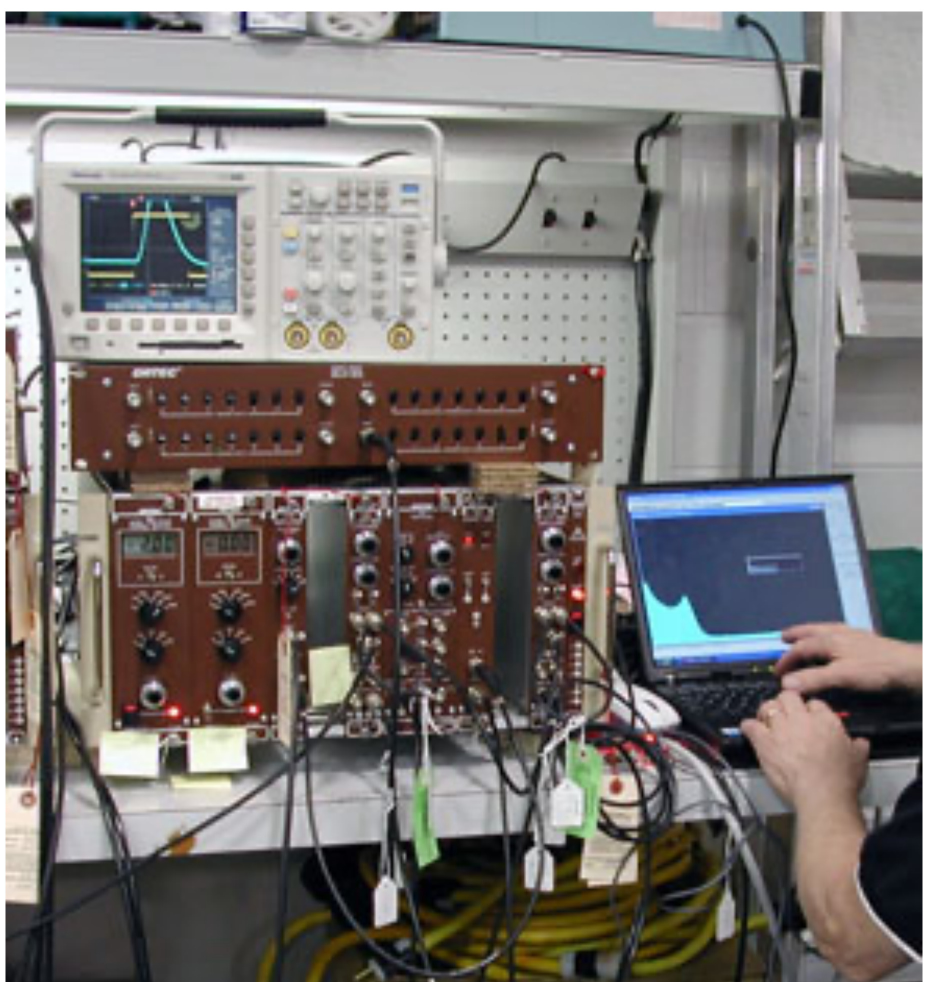
Signal from readout - digitisation

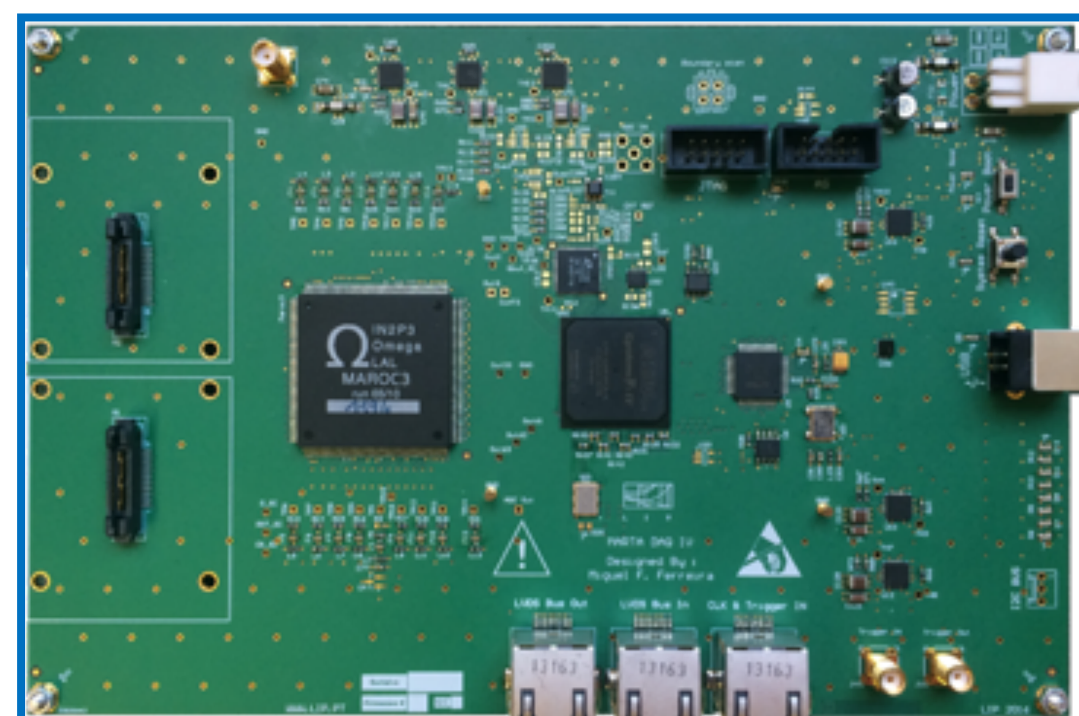
- Detector signal digitization



- Detector signal reconstruction







“Digitisation”

- General radiation transport codes provide energy deposits in the detector.

- From this point, one must simulate the generation of the detectable signal, which includes:
    - emission and propagation of scintillation light in optical materials;
    - charge production, multiplication and collection in gaseous detectors;
    - some codes allow part of this task in the same simulation flow;

“Digitisation”

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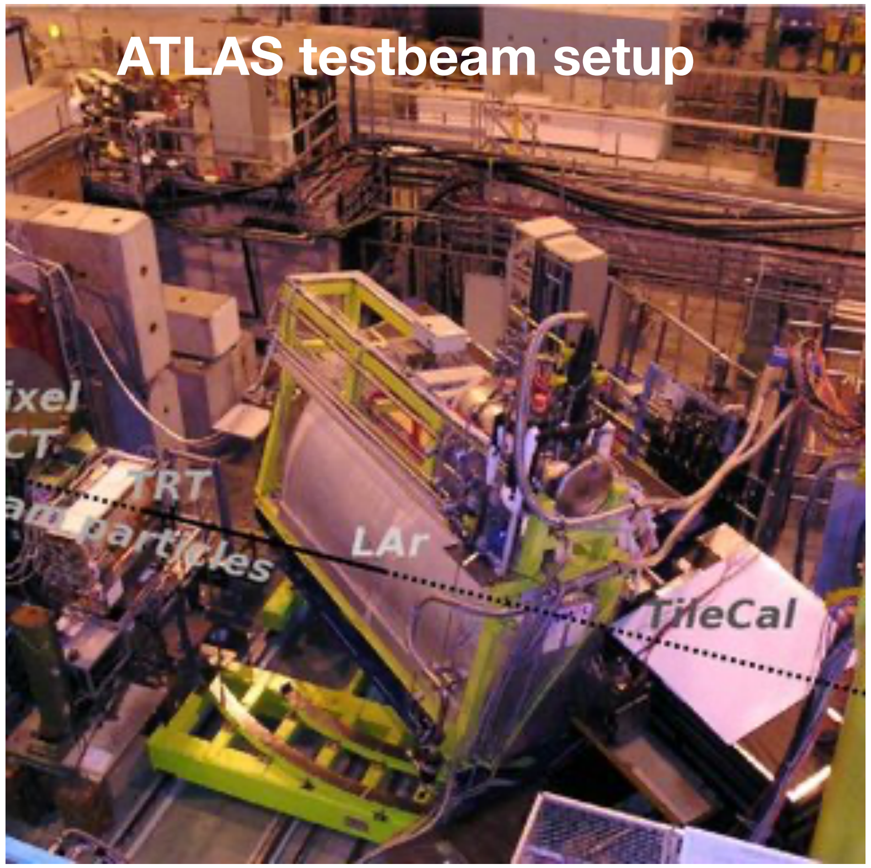
- From this point, one must simulate the generation of the detectable signal, which includes:
    - emission and propagation of scintillation light in optical materials;
    - charge production, multiplication and collection in gaseous detectors;
    - some codes allow part of this in the same simulation flow;

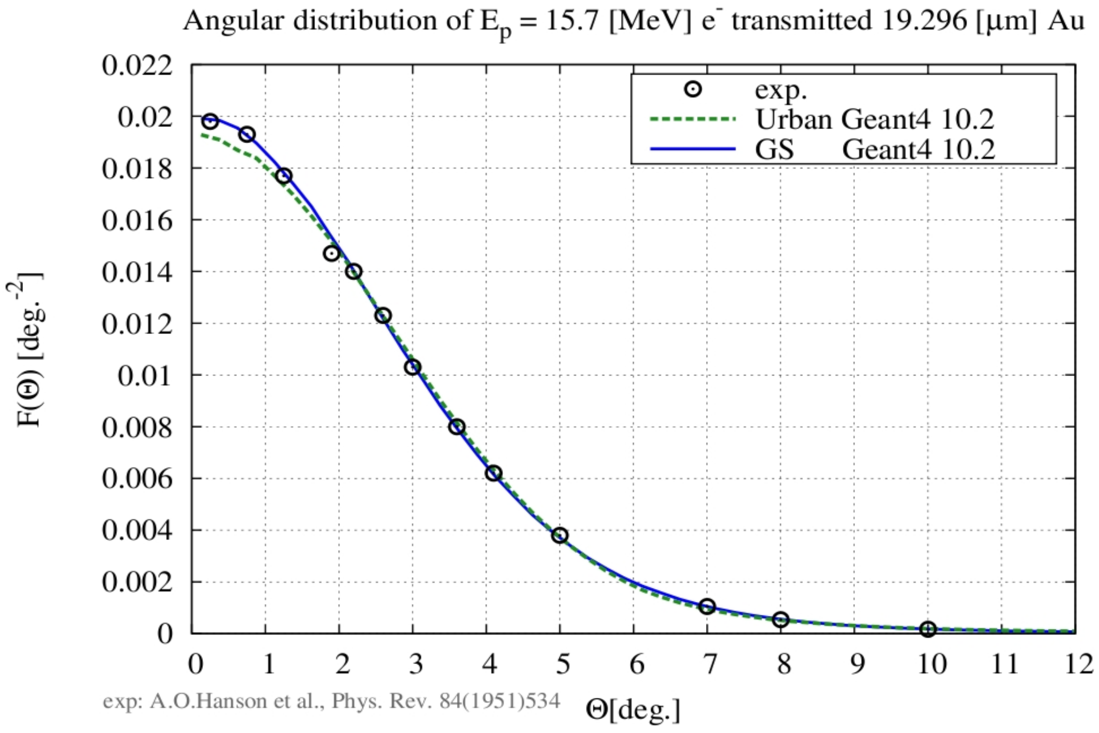
- **“Digitization”** is a detector-specific aspect of the simulation:
    - simulate the detector response in terms of measurable signals from the data acquisition electronics as in the real experiment;
    - simulate the trigger logics, pile-up; generation of raw data;

- From here the calibration procedures, event reconstruction algorithms and data analysis can be applied for the **simulated data as it is done in real data**;

Validation

- Validation is a critical aspect in implementing a Monte Carlo simulation code;
- It covers both the physics models utilized and the code implementation;
- Trusting several million lines of code ?
- Validation of complete physics configurations is primarily conducted through measurements in test-beam setups.





The Geant4 toolkit

GEANT4 A SIMULATION TOOLKIT

About | Download | Documentation | User Forum | Bug Reports | Events | Contact Us

Geant4

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.

Getting started

Get started

Everything you need to get started with Geant4.

I'm ready to start!

Download

Geant4 source code and installers are available for download, with source code under an open source license.

Latest: 11.3.2

Docs

Documentation for Geant4, along with tutorials and guides, are available online.

Read documentation

News

» More

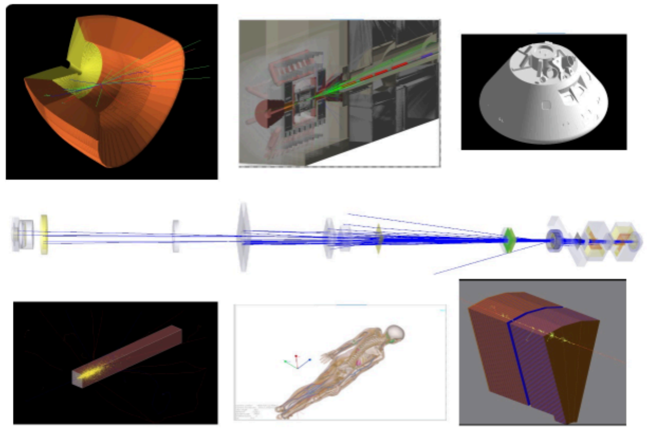
25 Apr 2025
Release 11.3.2

21 Mar 2025
Release 11.3.1

11 Mar 2025
2025 Planned Features

06 Dec 2024
Release 11.3

28 Jun 2024
Release 11.3.beta



About us

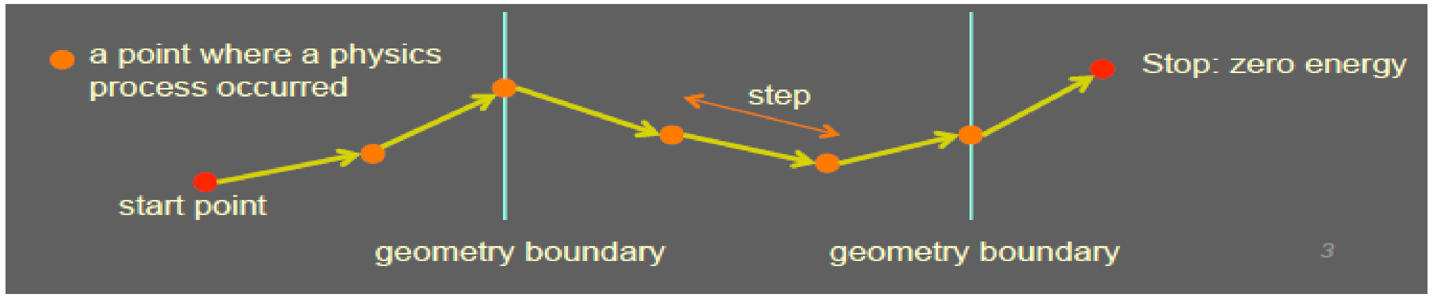
Collaboration

Contribute

https://geant4.web.cern.ch/

Geant4 in a nutshell

- Geant4 is a general purpose Monte Carlo simulation toolkit for tracking particles through matter breaking the particle motion into small segments, applying appropriate physical processes and probabilities at each step.



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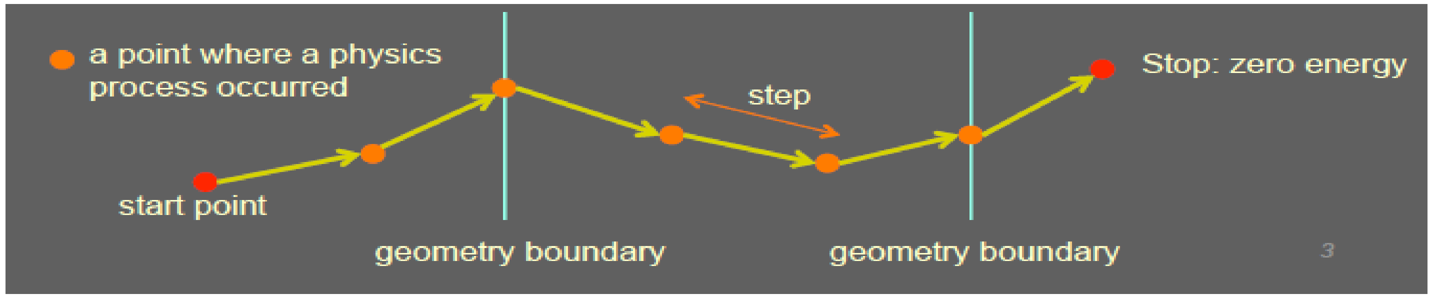
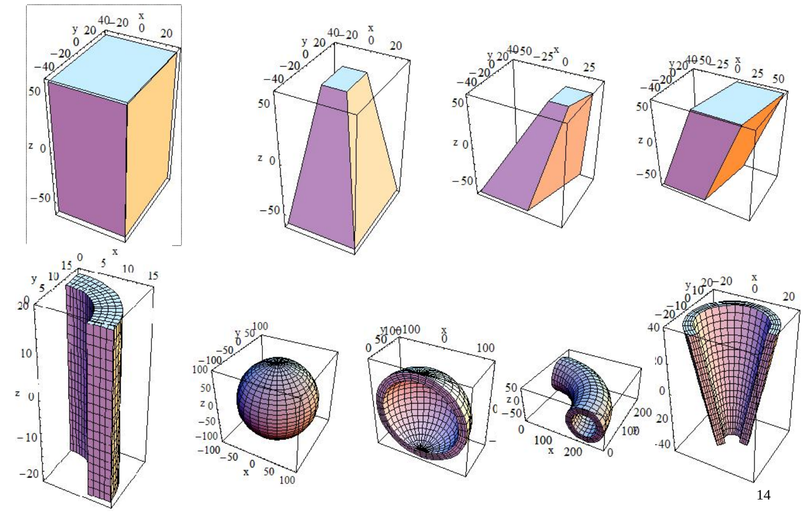
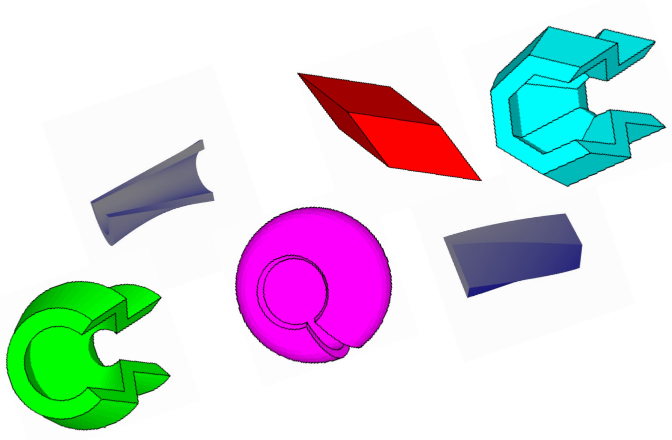


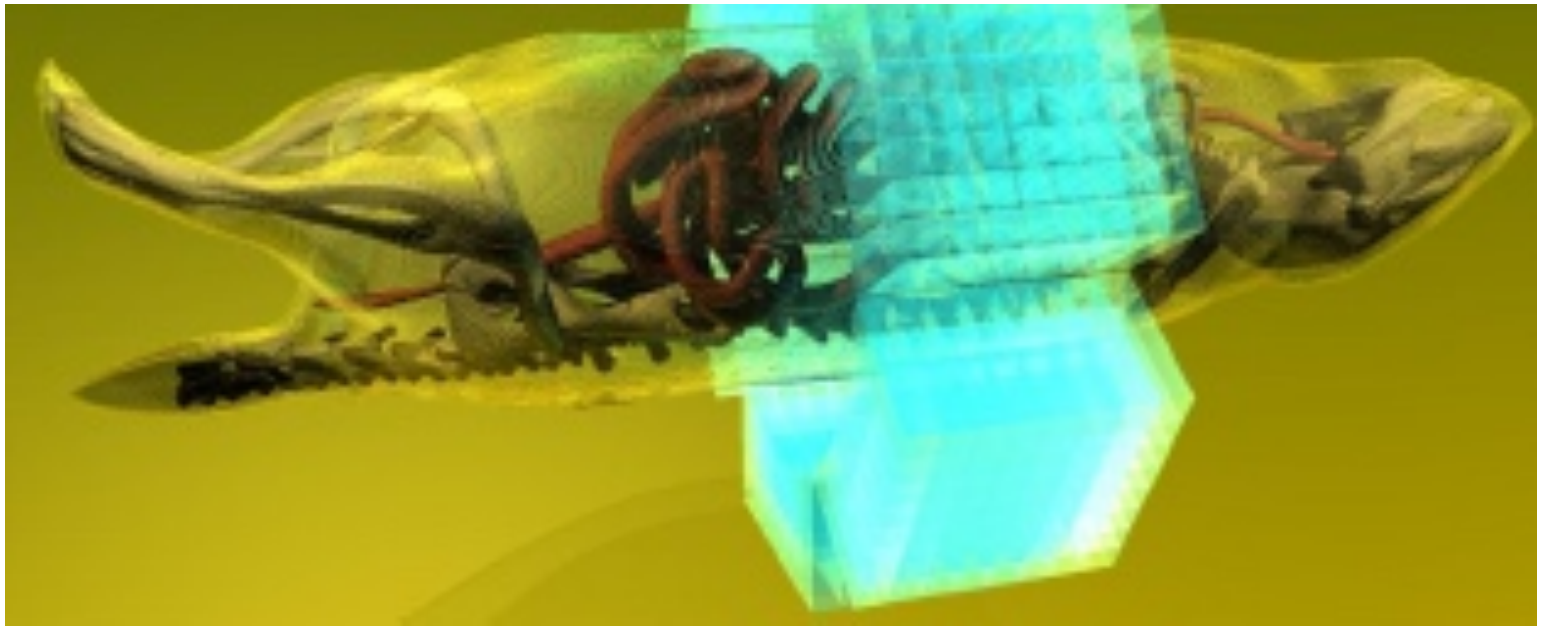
- It provides a **complete set of tools for all domains of radiation transport**:
  - Definition of geometries and materials of almost arbitrary complexity, namely through importing of CAD models;
  - Particle tracking including propagation in electric and magnetic fields;
  - Description of all relevant physics processes;
  - Scoring of particle interactions;
  - Biasing techniques;
  - Graphical and user interfaces;



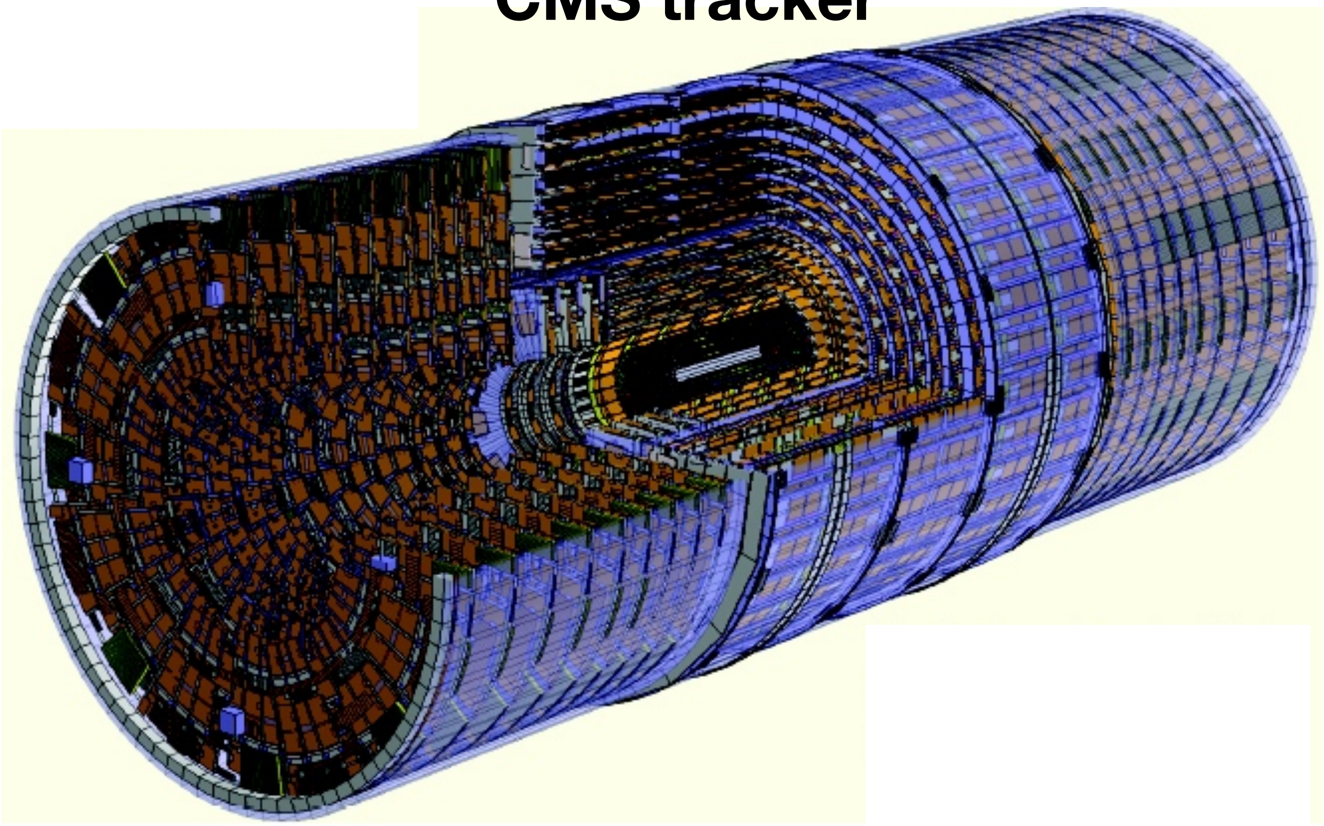


Defining complex geometries with Geant4

Medical phantoms - animal PET



CMS tracker



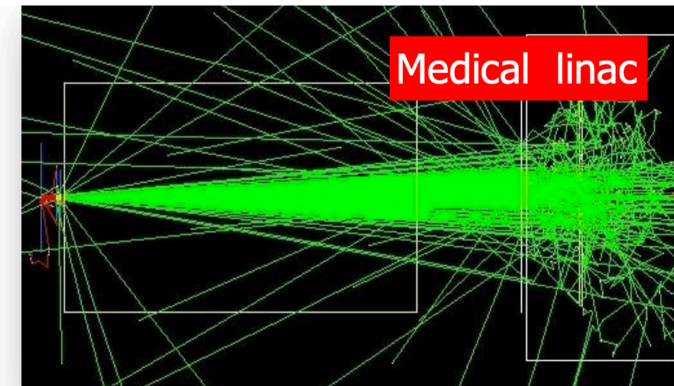
Simplified (!) version of the geometry

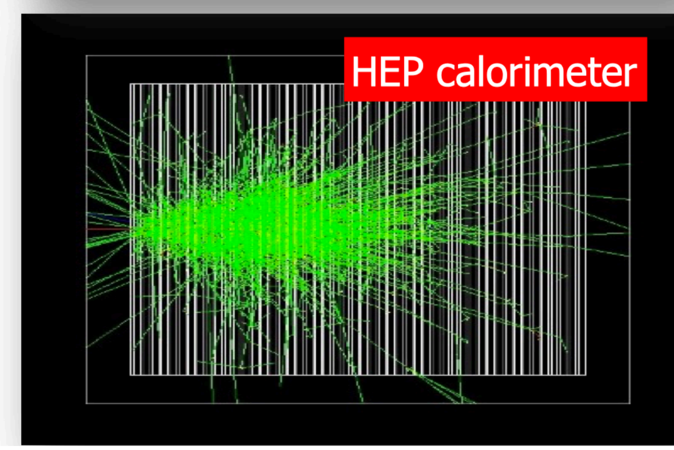
- Photon processes
  - γ conversion into e+e- pair
  - Compton scattering
  - Photoelectric effect
  - Rayleigh scattering
  - *Gamma-nuclear interaction in hadronic sub-package*
- Electron and positron processes
  - Ionisation
  - Coulomb scattering
  - Bremsstrahlung
  - Positron annihilation
  - Production of e+e- pairs
  - *Nuclear interaction in hadronic sub-package*
- Suitable for HEP & many other Geant4 applications with electron and gamma beams

Geant4 in a nutshell

- Geant4 physics processes describe electromagnetic and nuclear interactions of particles with matter, at energies from eV to TeV.

- A choice of physics models exists for many processes, providing options for applications with different accuracy and time requirements.





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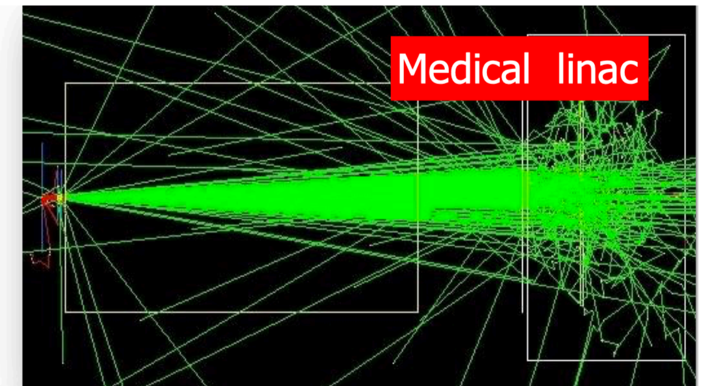
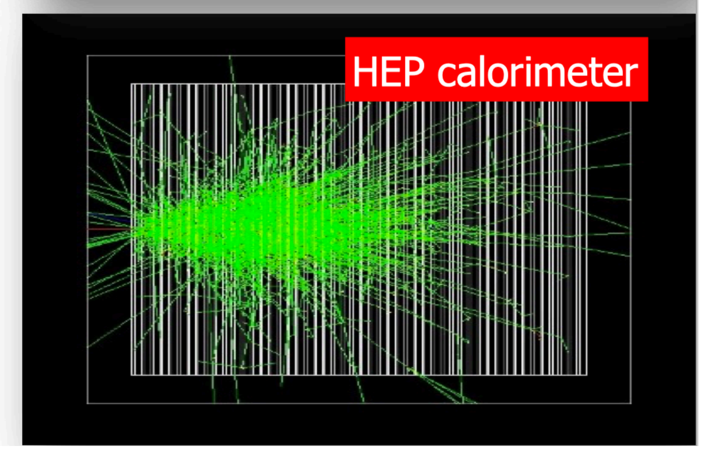
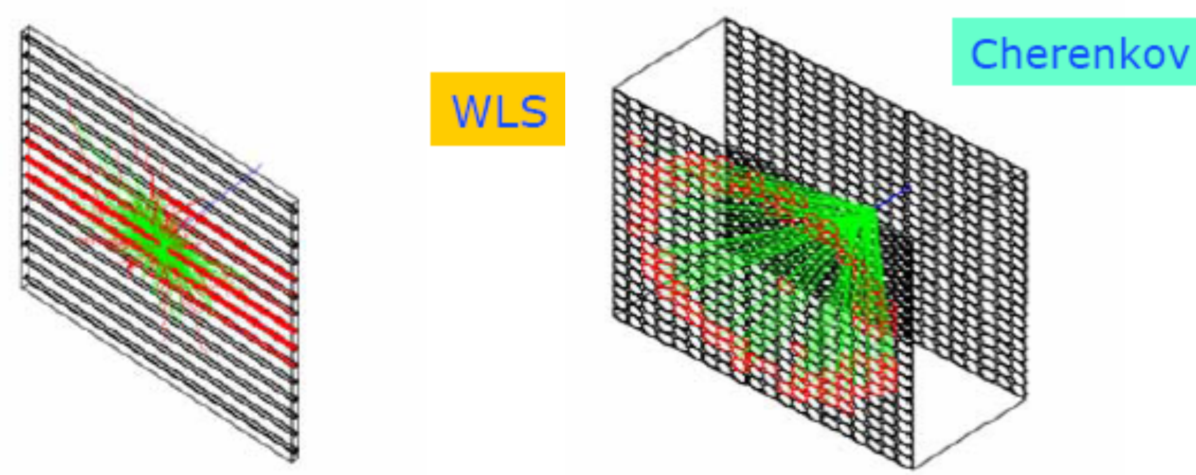




- Geant4 physics processes describe electromagnetic and nuclear interactions of particles with matter, at energies from eV to TeV.

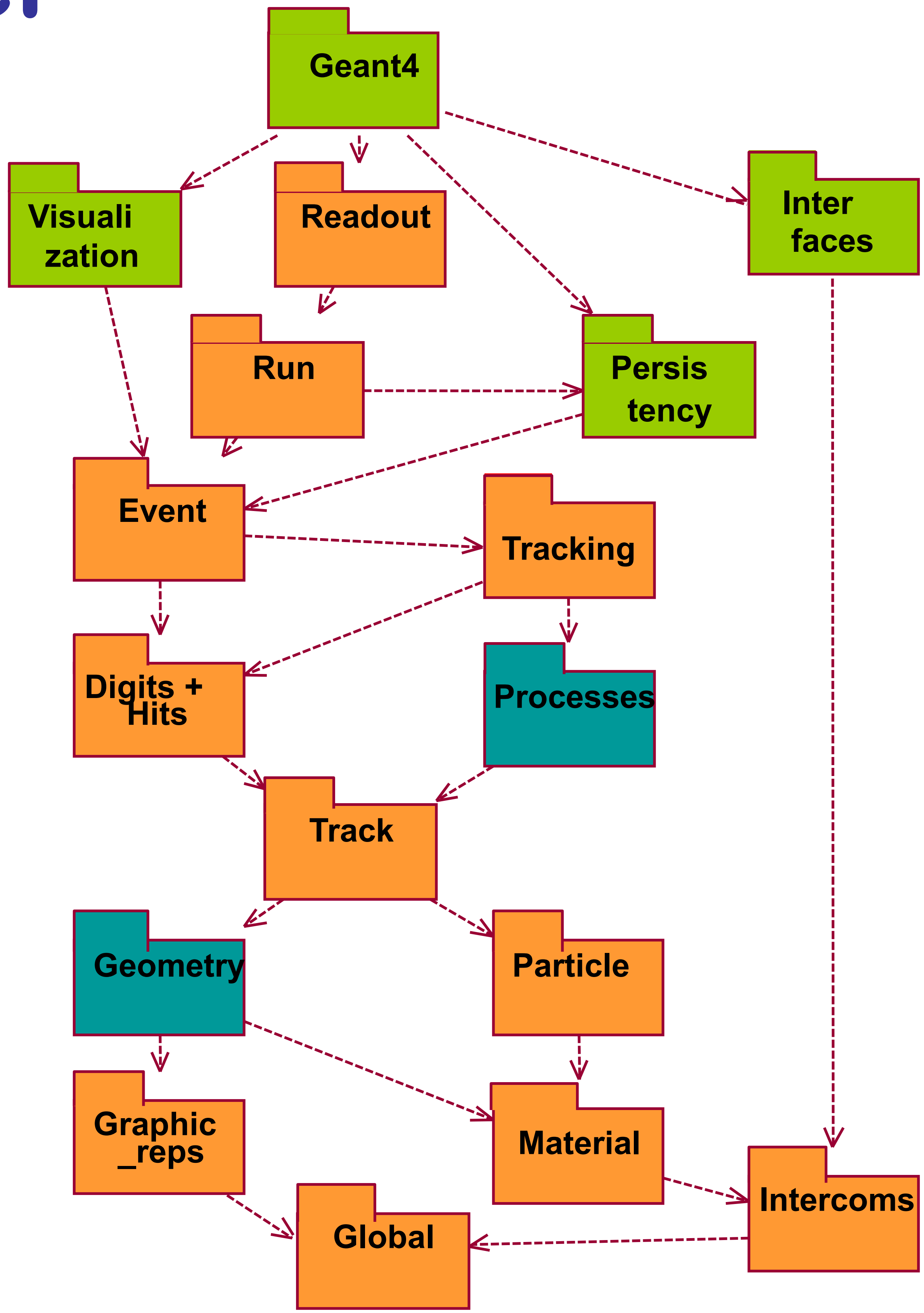
- A choice of physics models exists for many processes, providing options for applications with different accuracy and time requirements.

- Simulation of secondary processes :
  - Cherenkov and scintillation light;
  - Synchrotron and transition radiation;
  - Propagation of light in dielectric media



Geant4 kernel

- Geant4 consists of 17 categories.
  - Independently developed and maintained by WG(s) responsible to each category.
  - Interfaces between categories (e.g. top level design) are maintained by the global architecture WG.
- Geant4 Kernel
  - Handles run, event, track, step, hit, trajectory.
  - Provides frameworks of geometrical representation and physics processes.



Workflow of a Geant4 simulation

Pre-Initialization

Detector construction:
Geometry
Materials
EM Fields
Sensitivity

Physics List choice:
electromagnetic,
Hadronic high precison
neutrons…
+
Particle production cuts

Run-time

N events

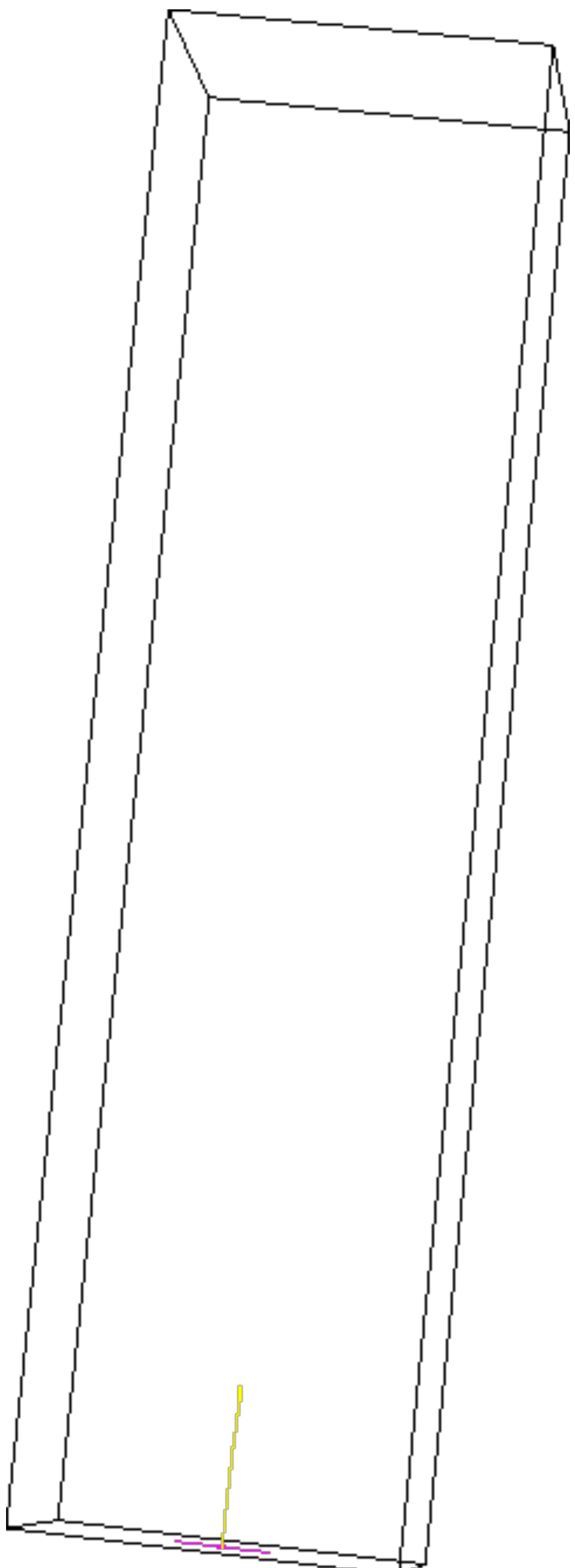
Primary vertex generation (from Event Generator):
Position
Direction
Energy
Particle type

Interaction with detector materials:
Production of secondaries,
Energy deposits
Energy loss
Multiple scattering, etc

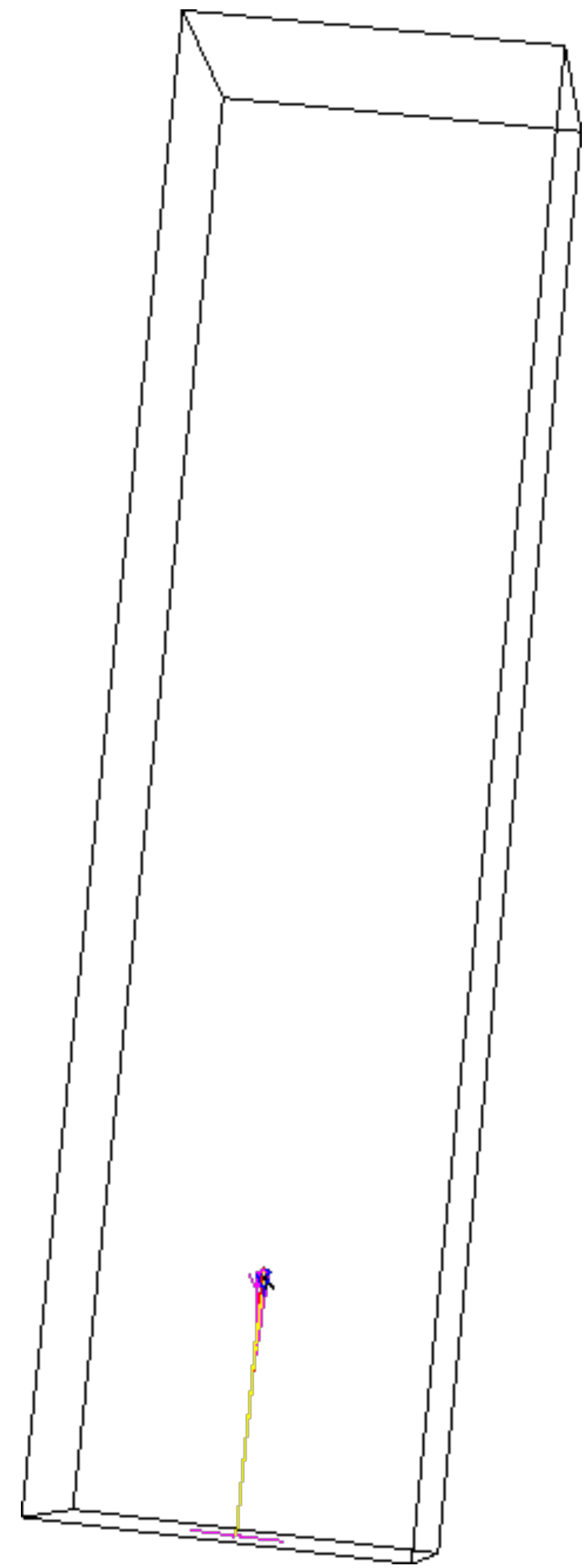
Register signals in sensitive detectors:
Deposited energy
Track momentum
Time
Position
Detector ID
Particle type
Etc

Geant4 simulation of a crystal calorimeter

37 x 10 x 10 cm^3 Lead Glass scintillator

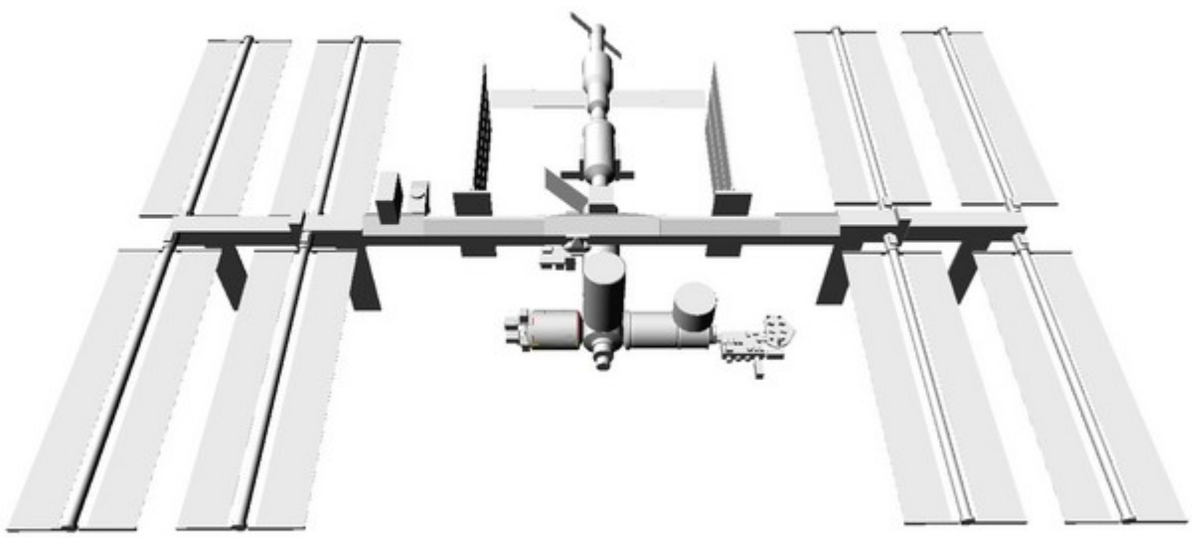


2 GeV e$^-$

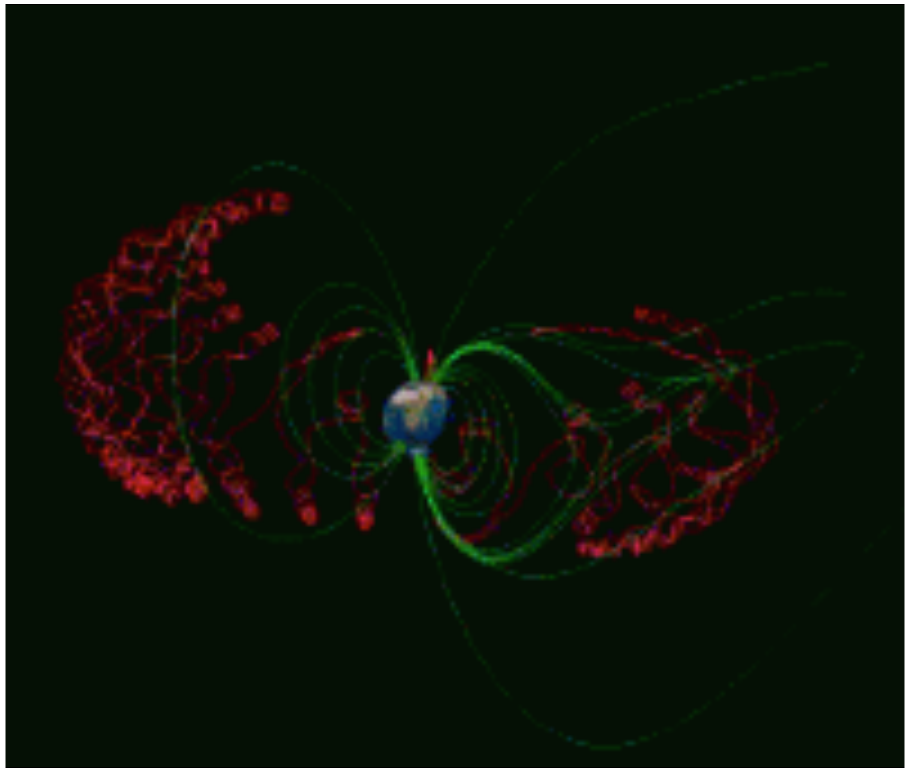


80 GeV e$^-$

Examples of Geant4 applications

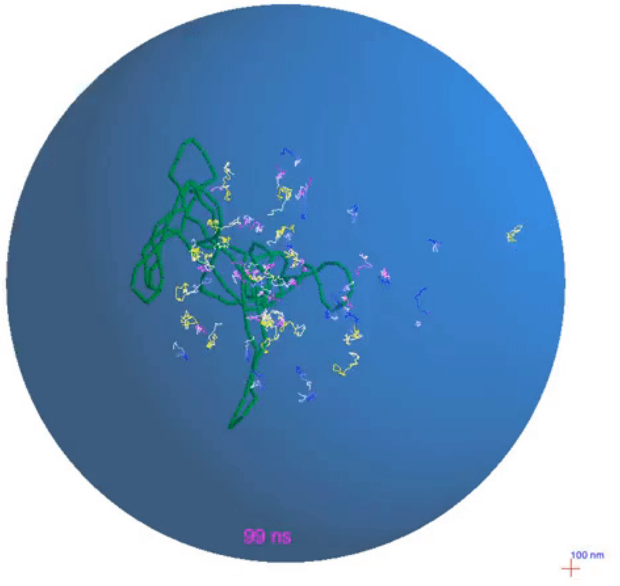


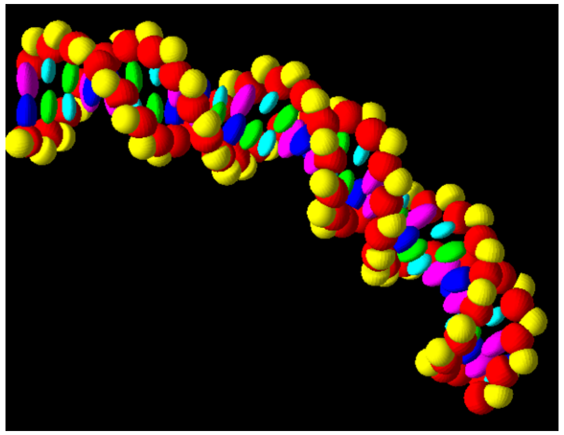
DESIRE - Dose Estimation by Simulation of the ISS Radiation Environment



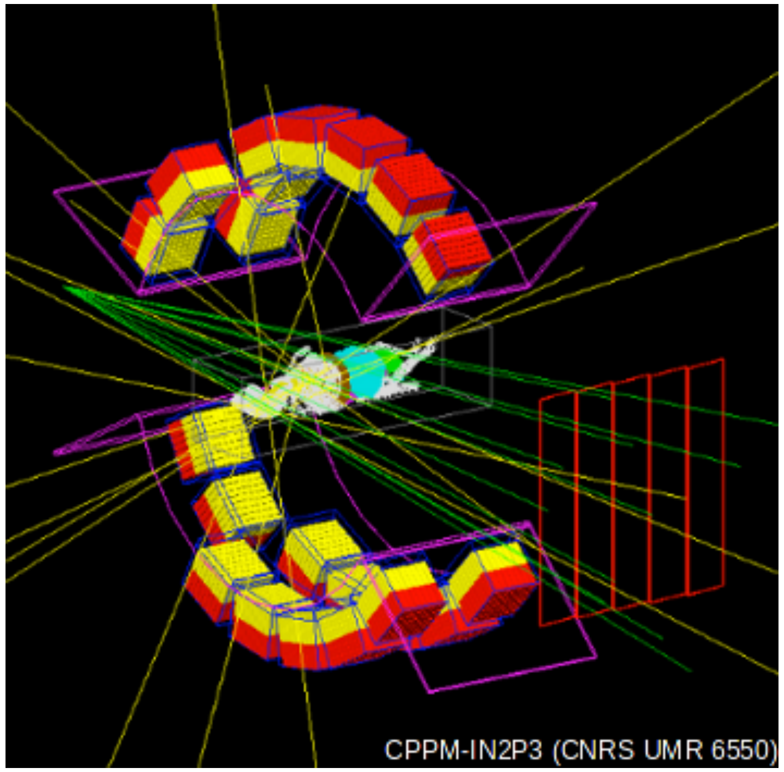
PLANETOCOSMICS - interactions of cosmic rays with planets atmospheres, magnetic field and soil.

GEANT4-DNA : Simulation tools for radiobiology





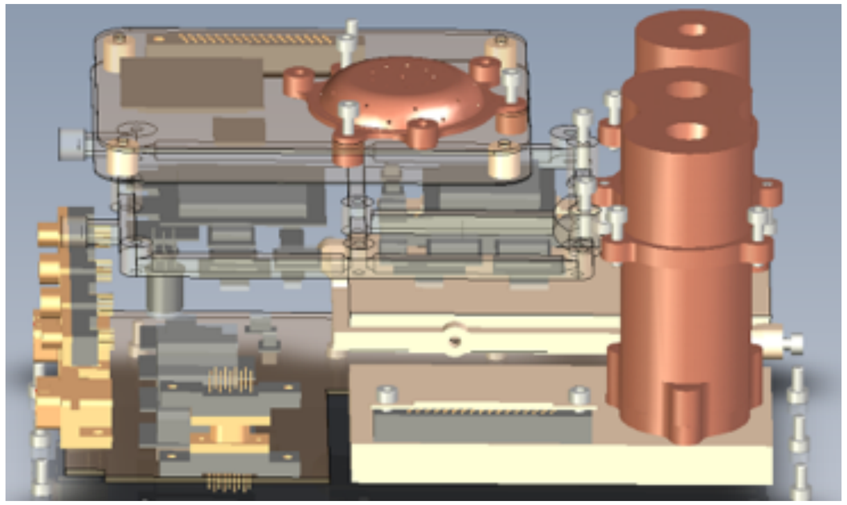
Irradiation of a pBR322 plasmid, including radiolysis
movie courtesy of V. Stepan (NPI-ASCR/CENBG/CNRS/IN2P3/ESA) -

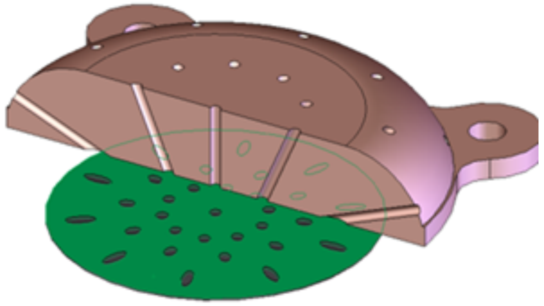


GATE - numerical simulations in medical imaging and radiotherapy. Simulations of Emission Tomography (PET and SPECT), Computed Tomography (CT), Optical Imaging (Bioluminescence and Fluorescence) and Radiotherapy experiments.

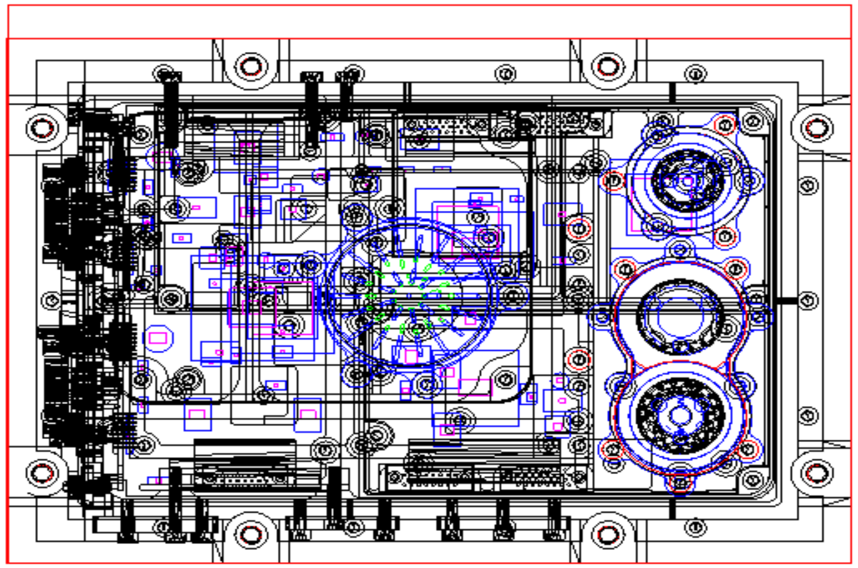
Geant4 @ LIP

RADEM - Radiation Monitor for the Jovian system

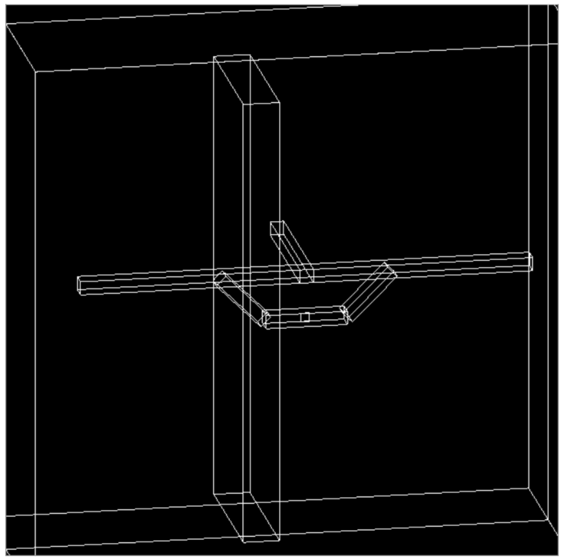


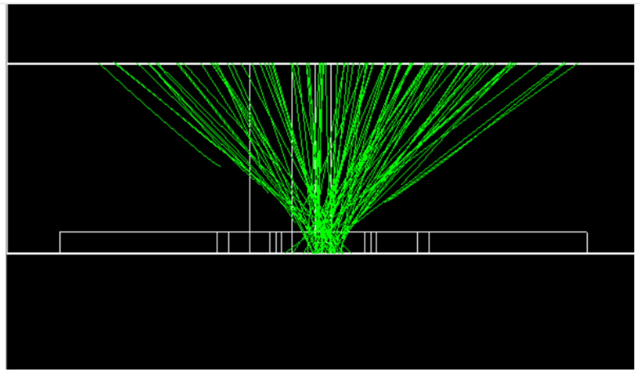


CAD model of RADEM

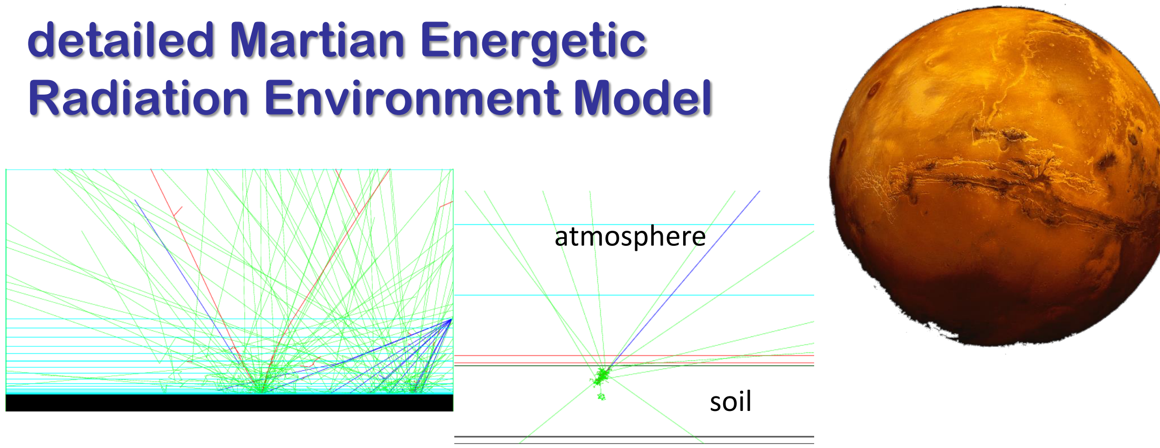


Muon tomography in Lousal mine



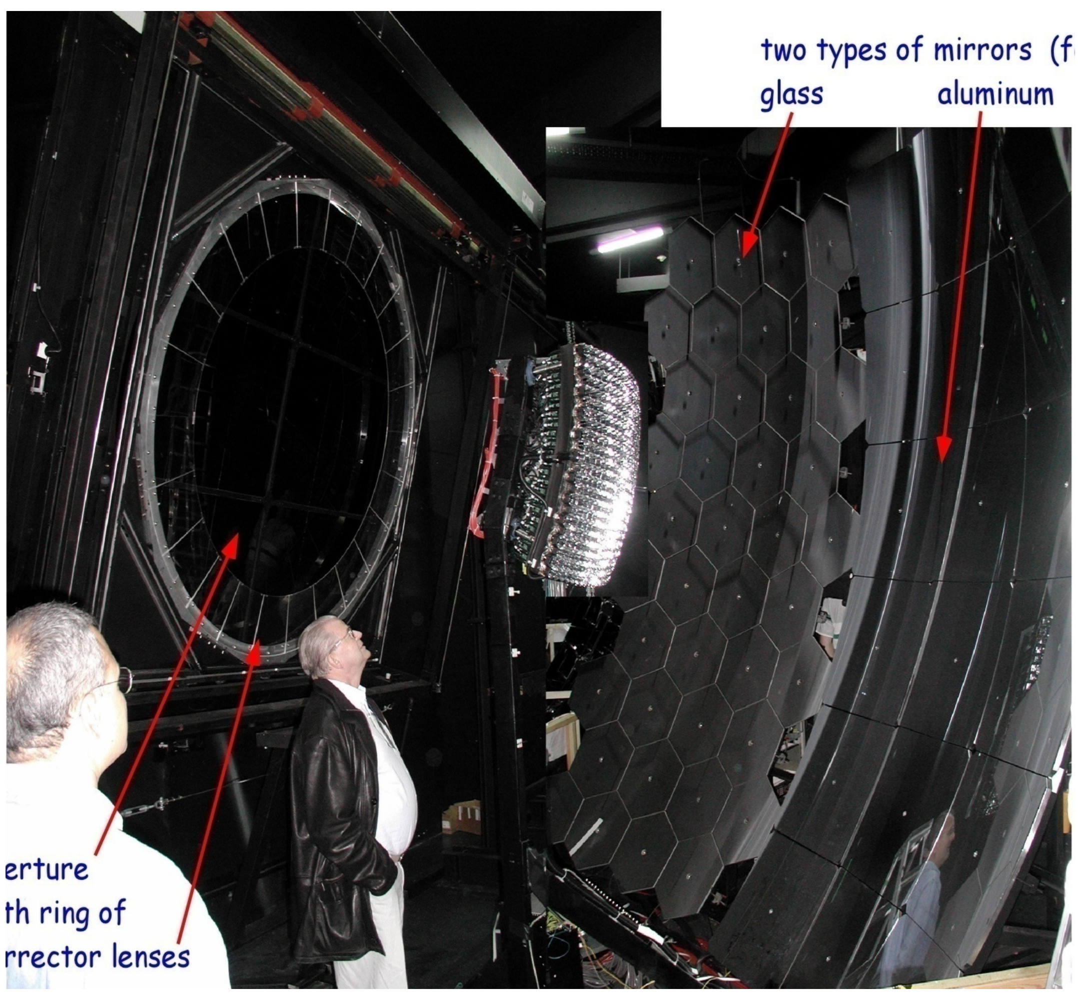


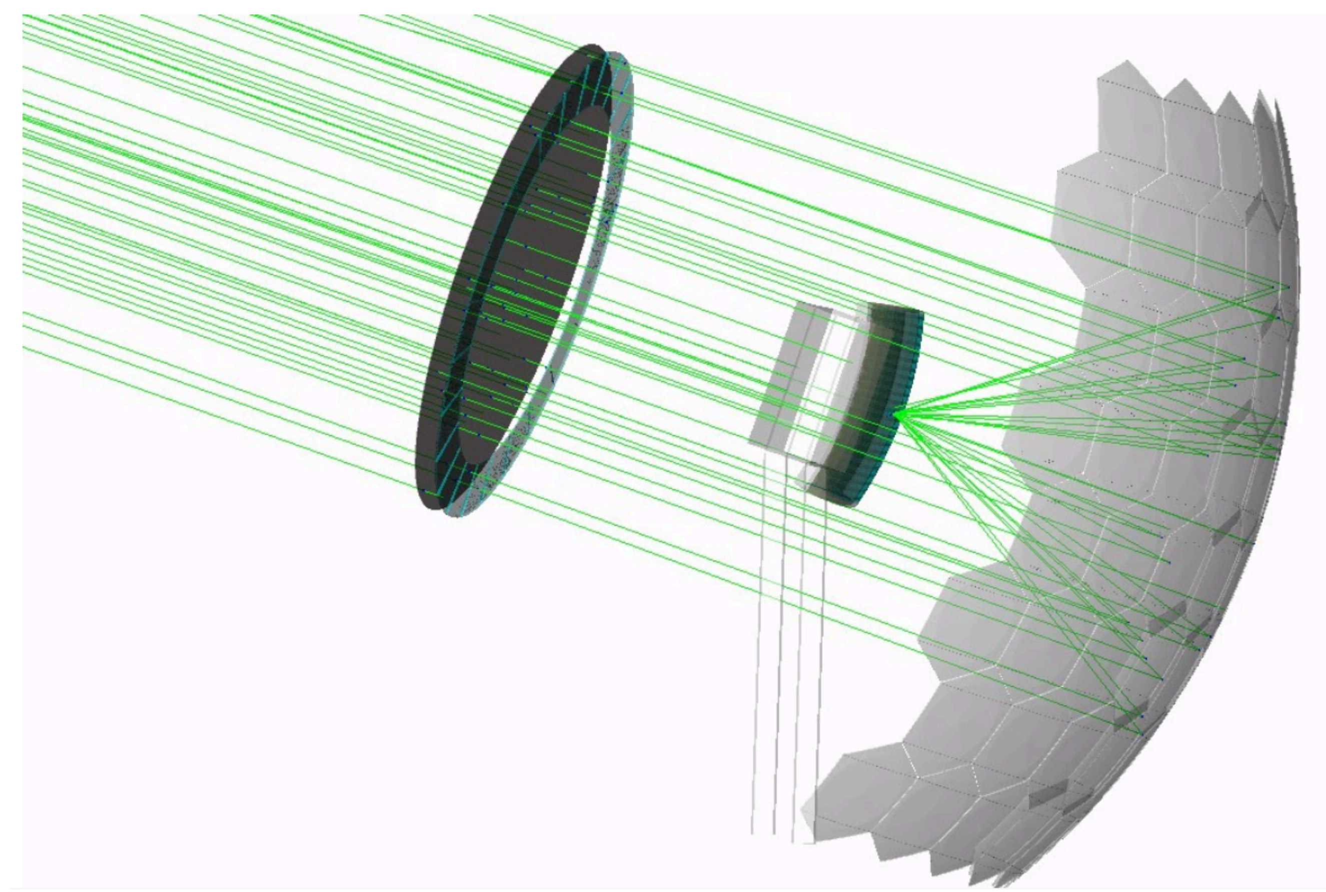
Simulation of particles interacting in the Martian atmosphere and soil



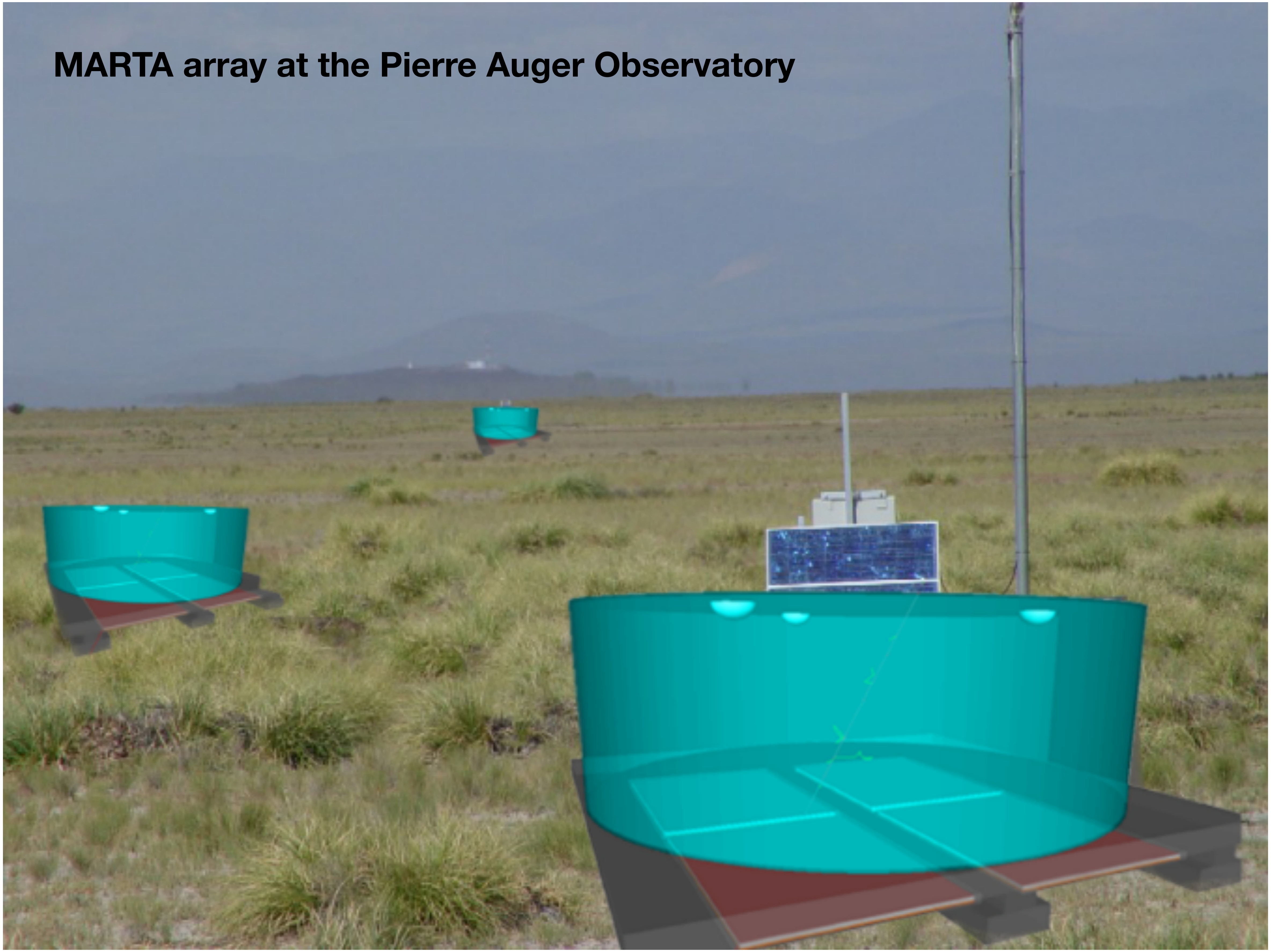
Geant4 @ LIP - Optics simulations

Fluorescence Detector of the Pierre Auger Observatory

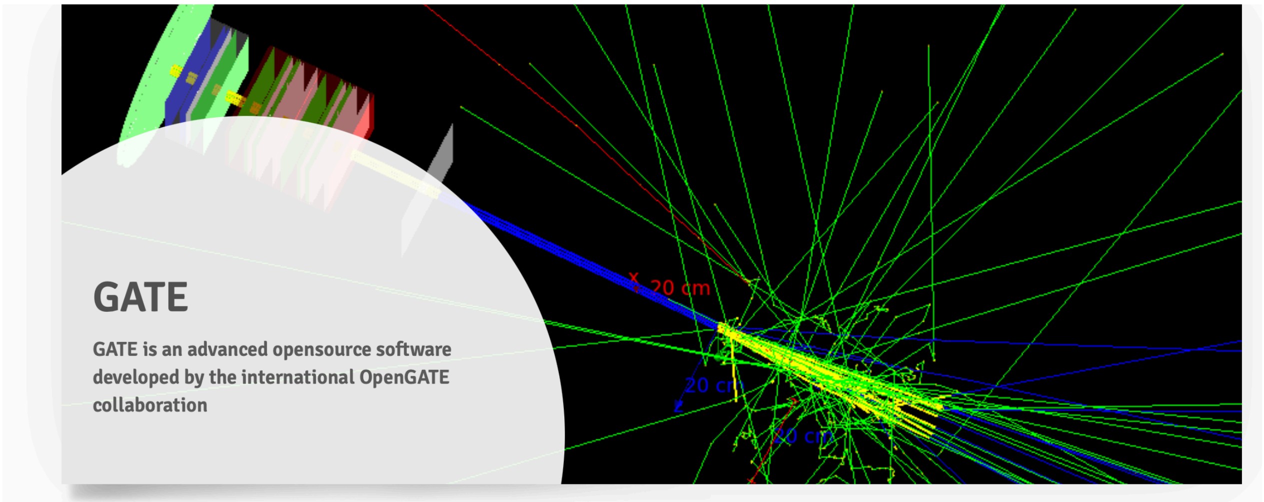


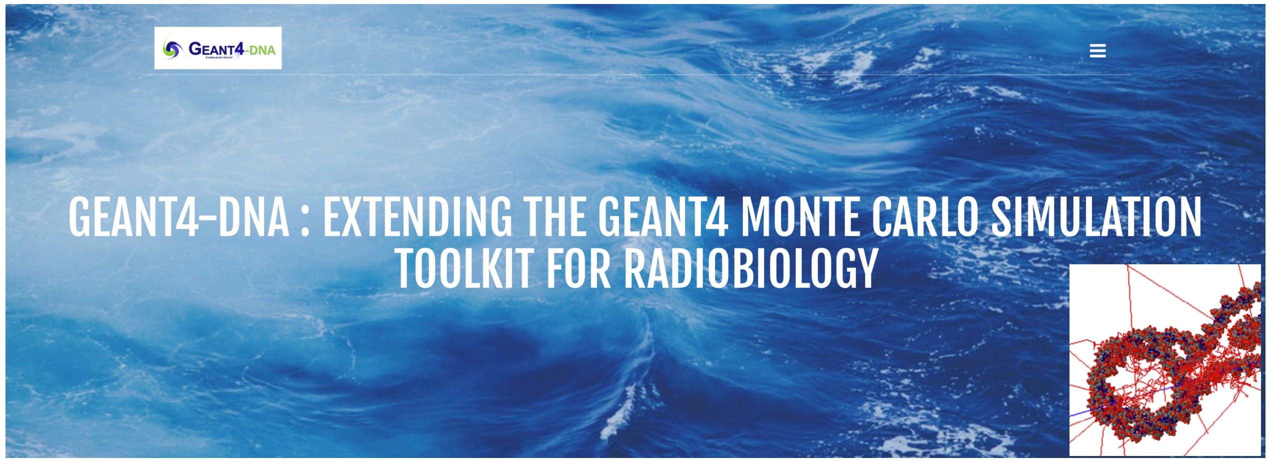


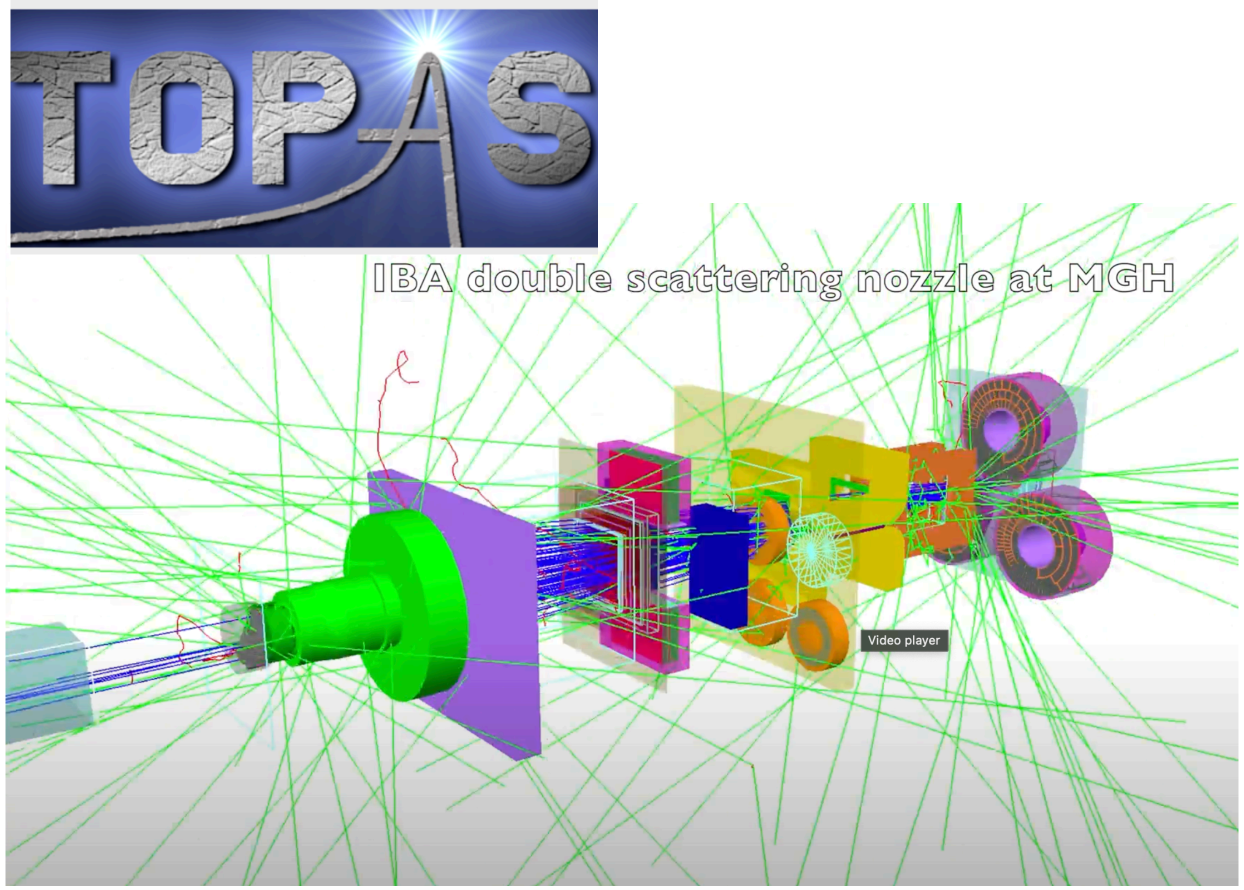
Simulations of full cosmic ray detectors



Geant4 based simulation tools







Tutorial on TOPAS, July 2nd

by Joana Antunes