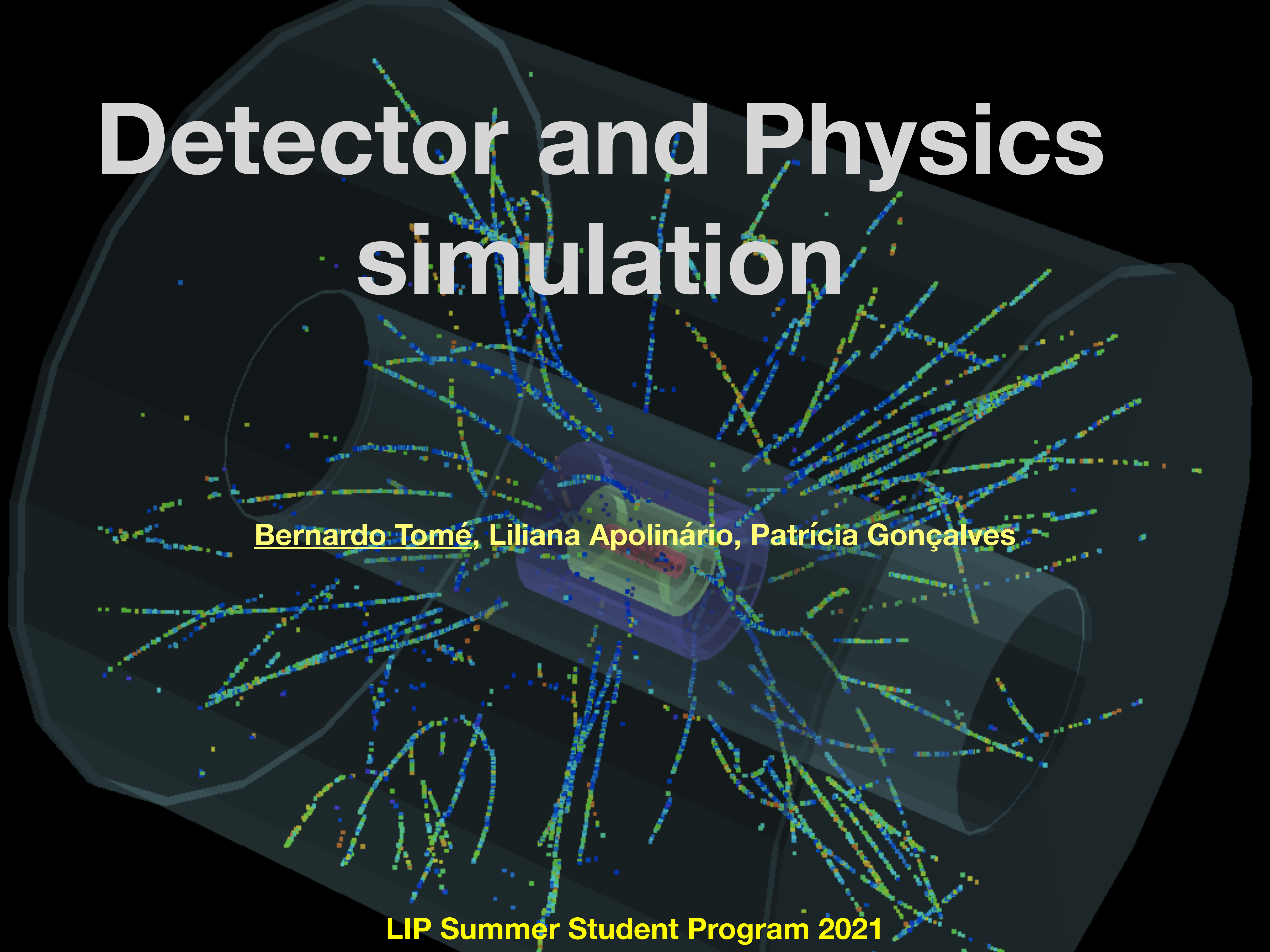
Detector and Physics simulation



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LIP Summer Student Program 2021

Why we need simulations ?

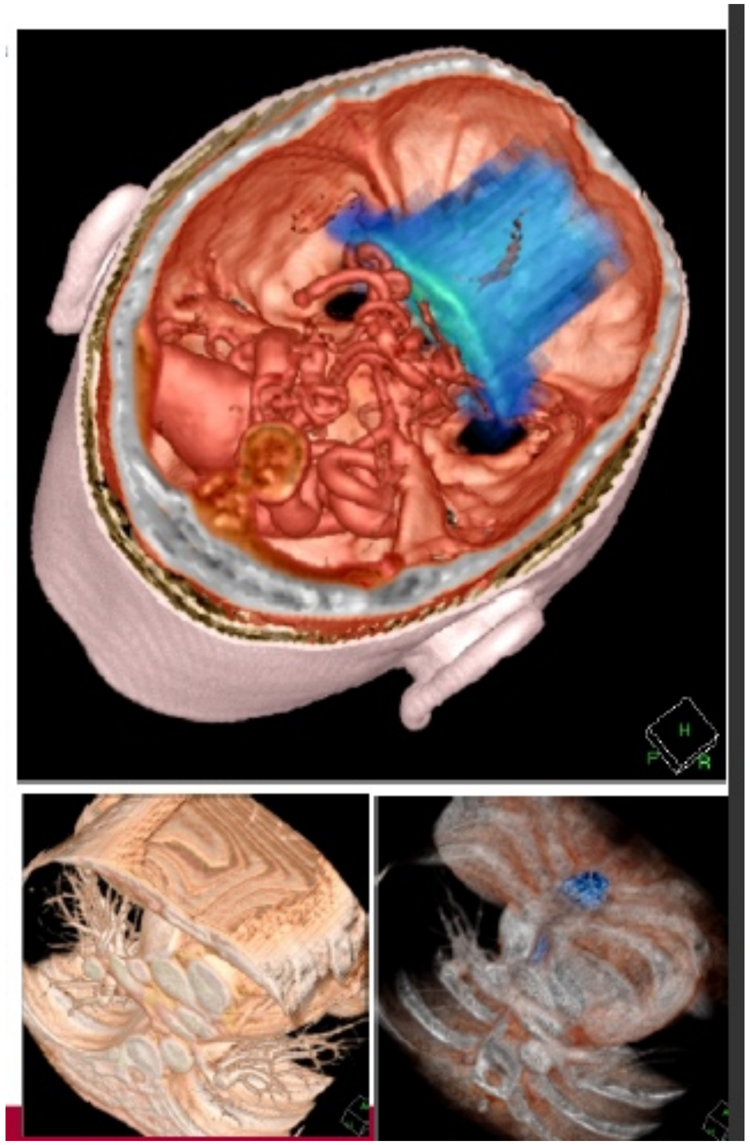
- Simulation is a modern, essential tool to :
  - Design a new experiment, allowing to predict very realistically the performance of the future apparatus;
  - Analyse and understand the data of ongoing experiments;
  - Develop new data analysis methods, train neural networks, etc.
  - Simulate new physics models, understanding how a particular detector design could detect it;
- 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

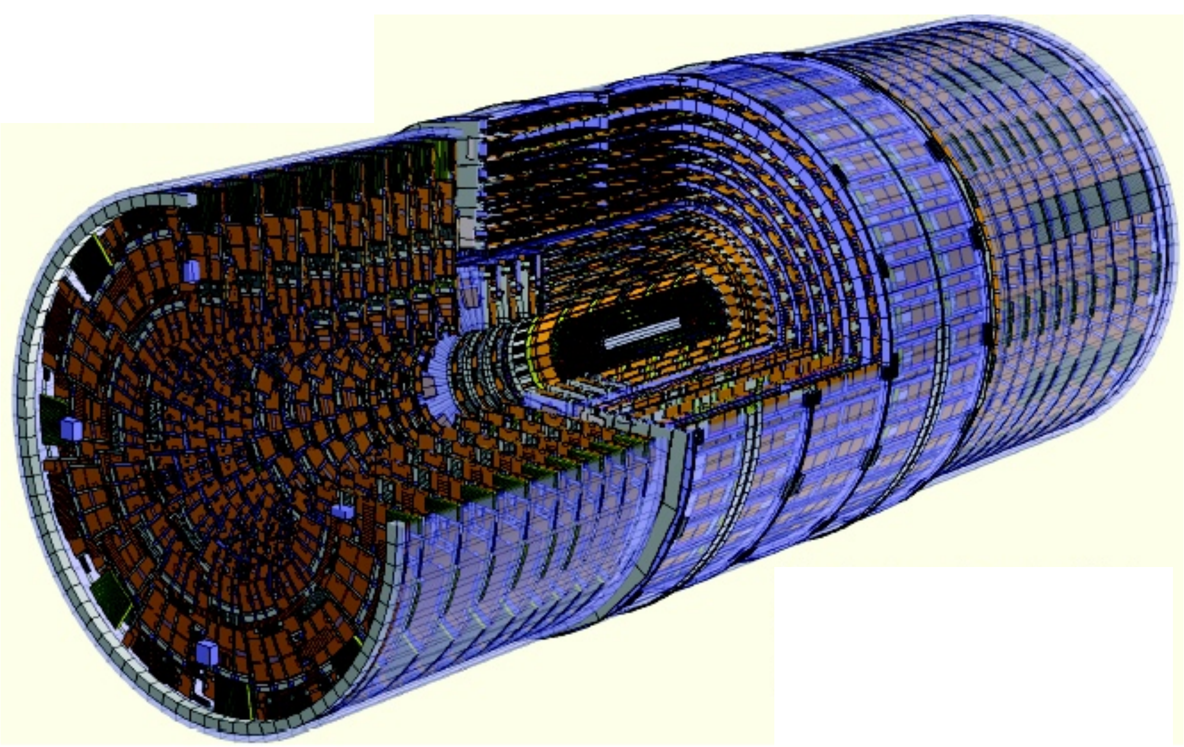
- Monte Carlo radiation transportation tools are non-deterministic (e.g. do not solve equations);
- Physics processes underlying particle detection are governed by the laws of Quantum Mechanics;
- This intrinsic randomness can be approached by using computers and the possibility to generate (pseudo)-random numbers;

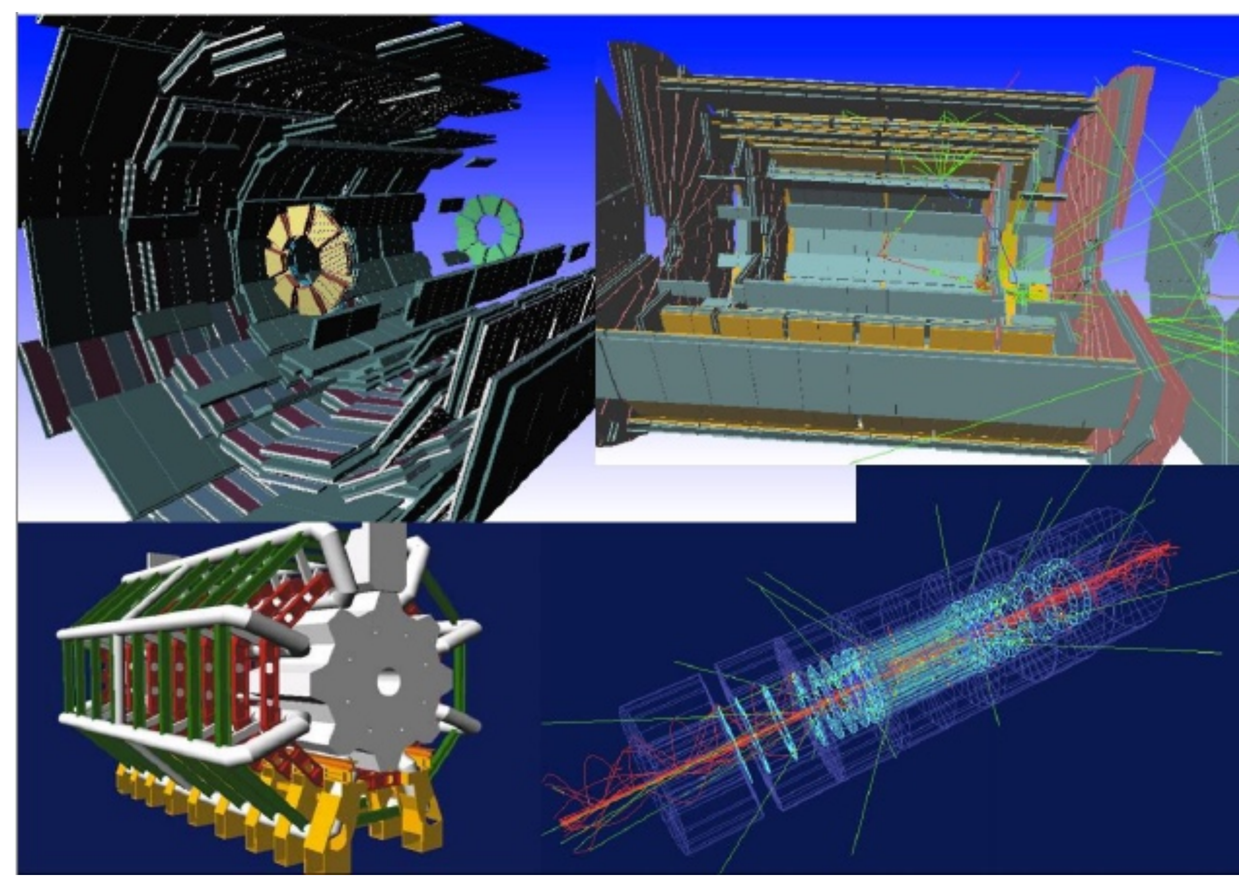
Monte Carlo methods are the tool to simulate random physics processes using a computer



"Detector" simulation is a **multi-disciplinary** field!

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



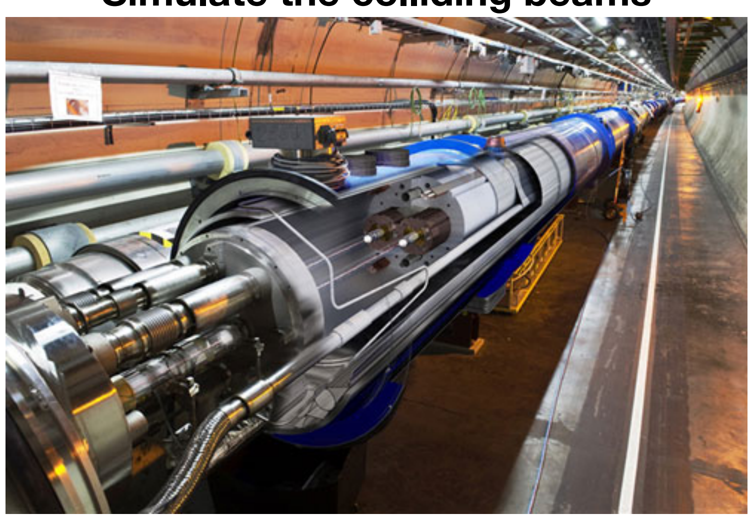


Simulating a High Energy Physics experiment

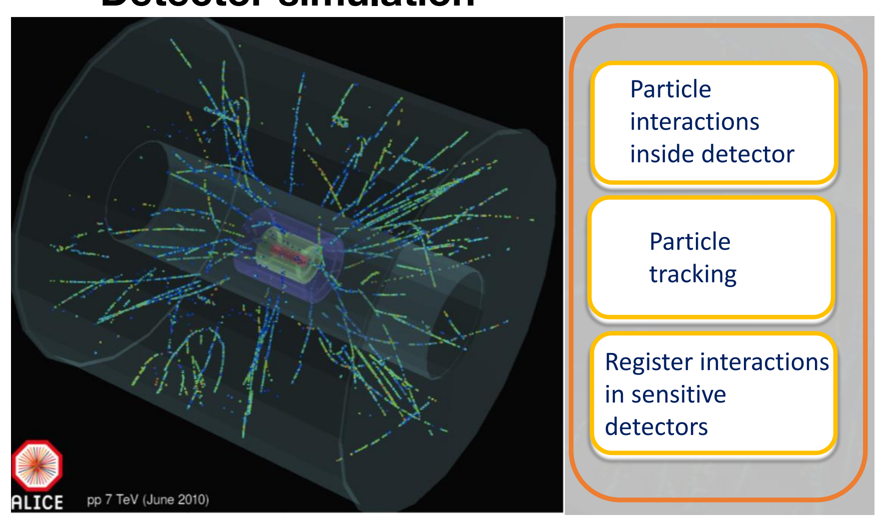
The simulation is usually made of two distinct steps :

- Simulate the colliding beams - Monte Carlo event generator, describing the fundamental 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”

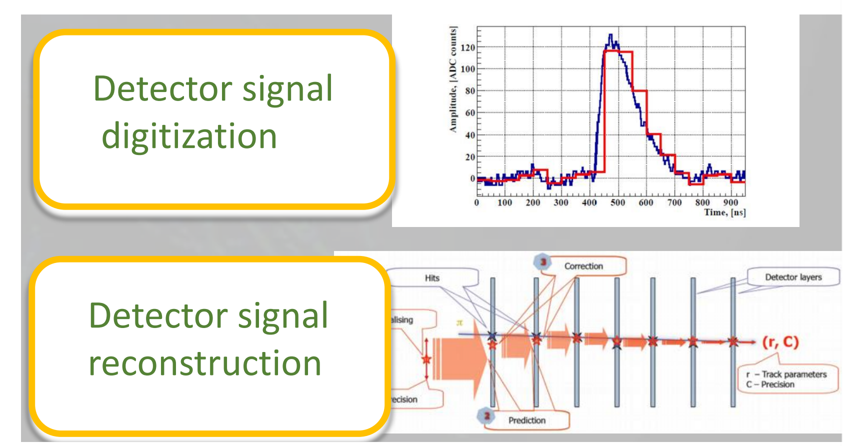
Simulate the colliding beams



Detector simulation

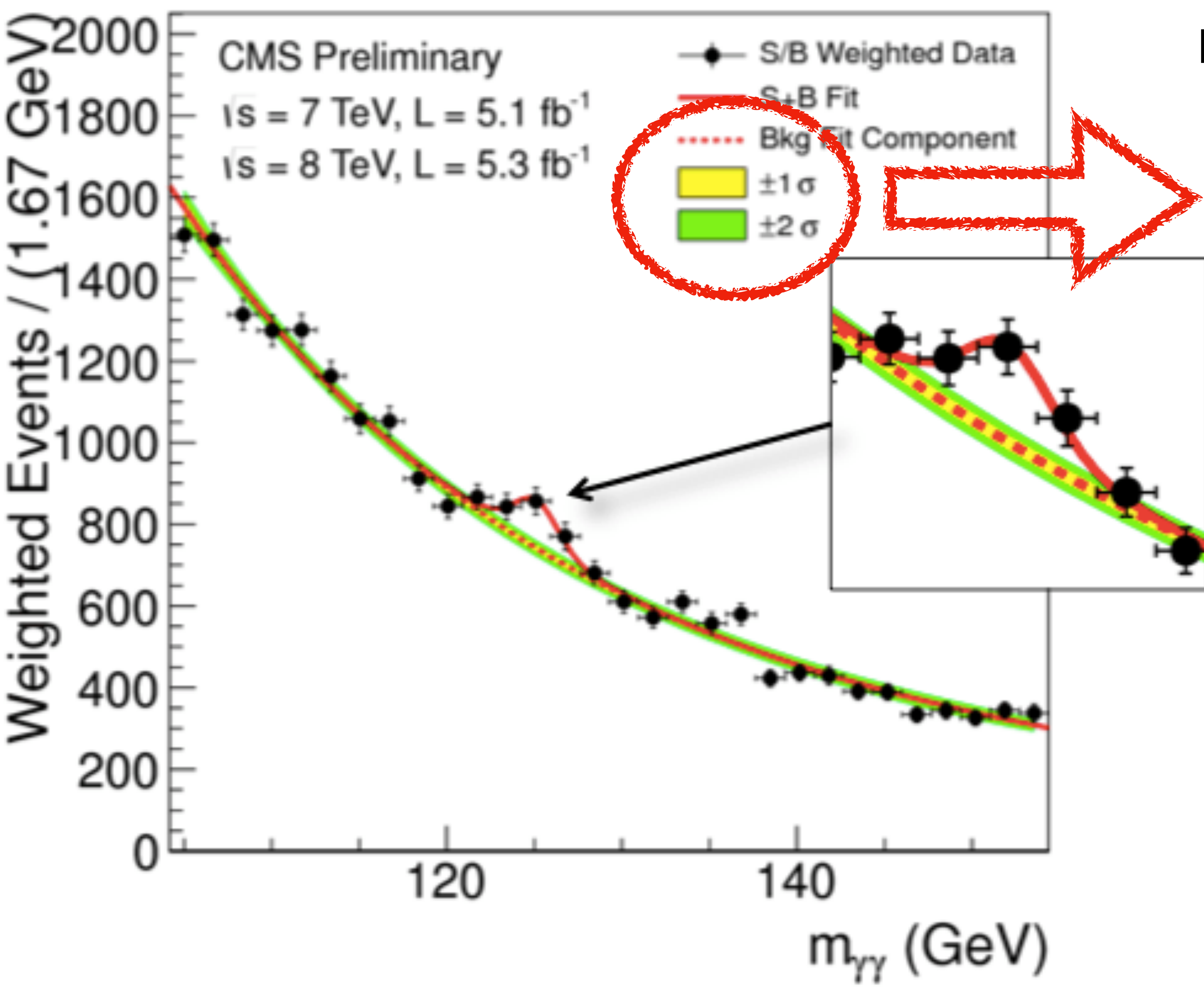


Signal from readout - digitisation



Similar approach can be found in different types of experiments

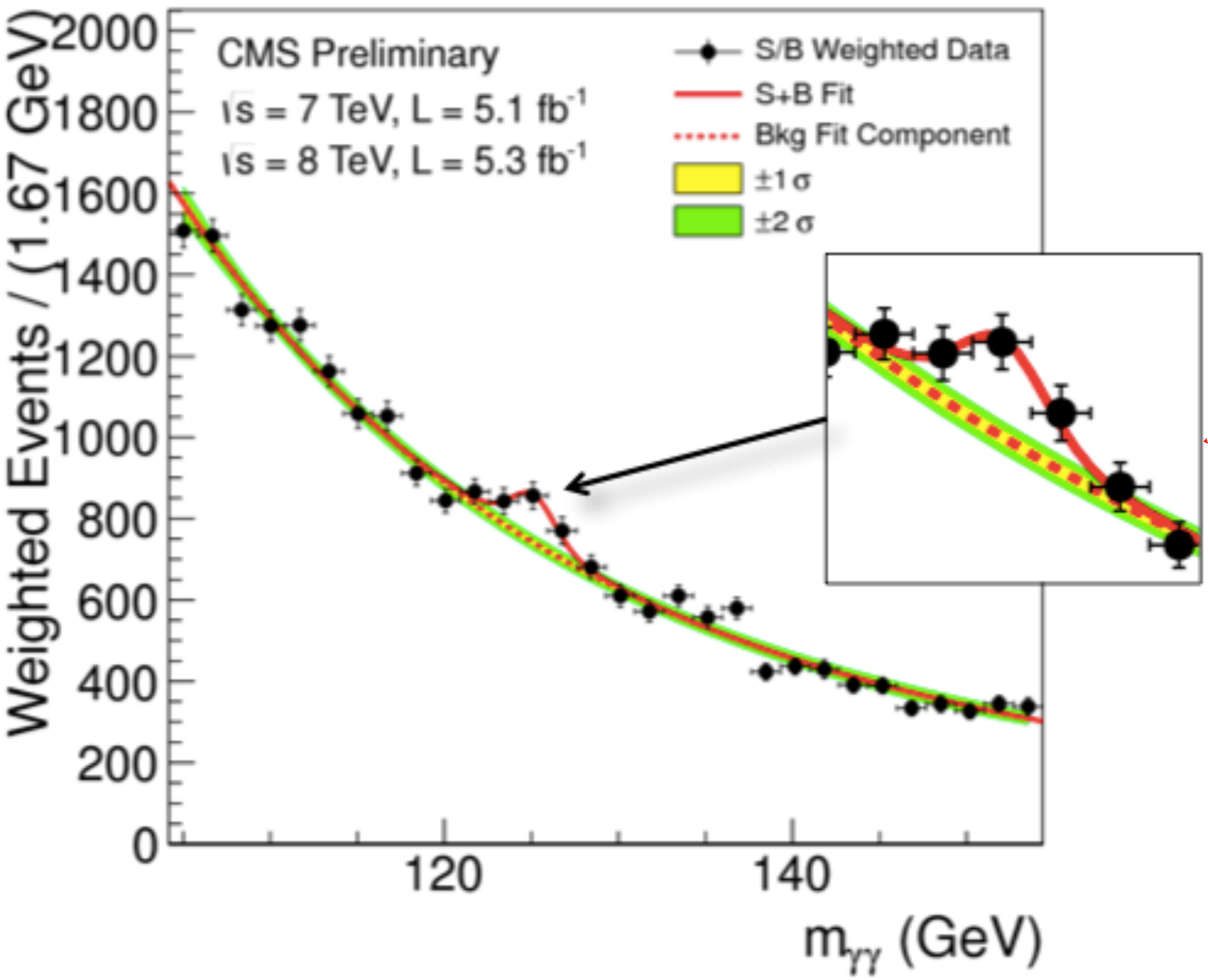
The importance of simulations…



Precisely simulated background :

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

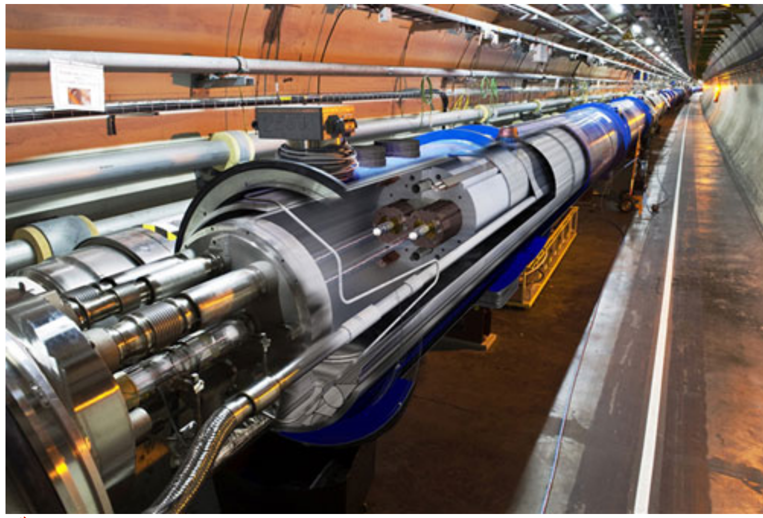
The importance of simulations…



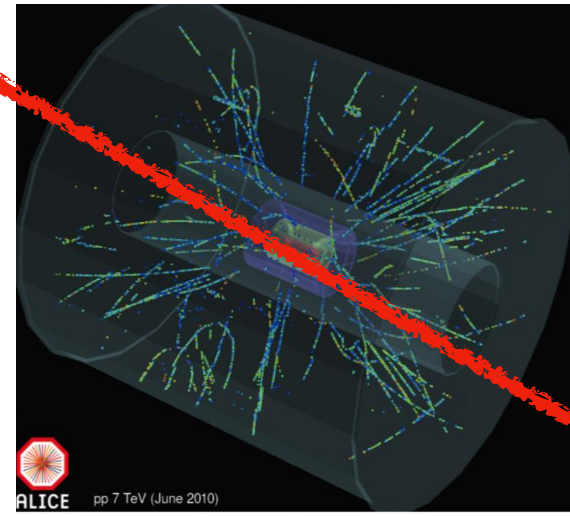
Discovery of the Higgs boson !

Simulating a High Energy Physics experiment

Simulate the colliding beams



Detector simulation



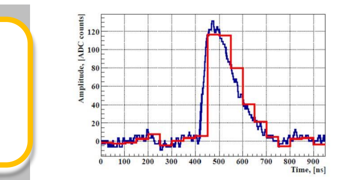
Particle interactions inside detector

Particle tracking

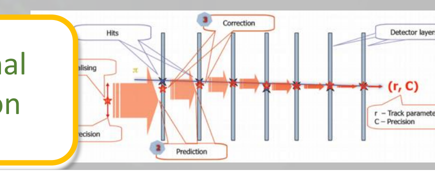
Register interactions in sensitive detectors

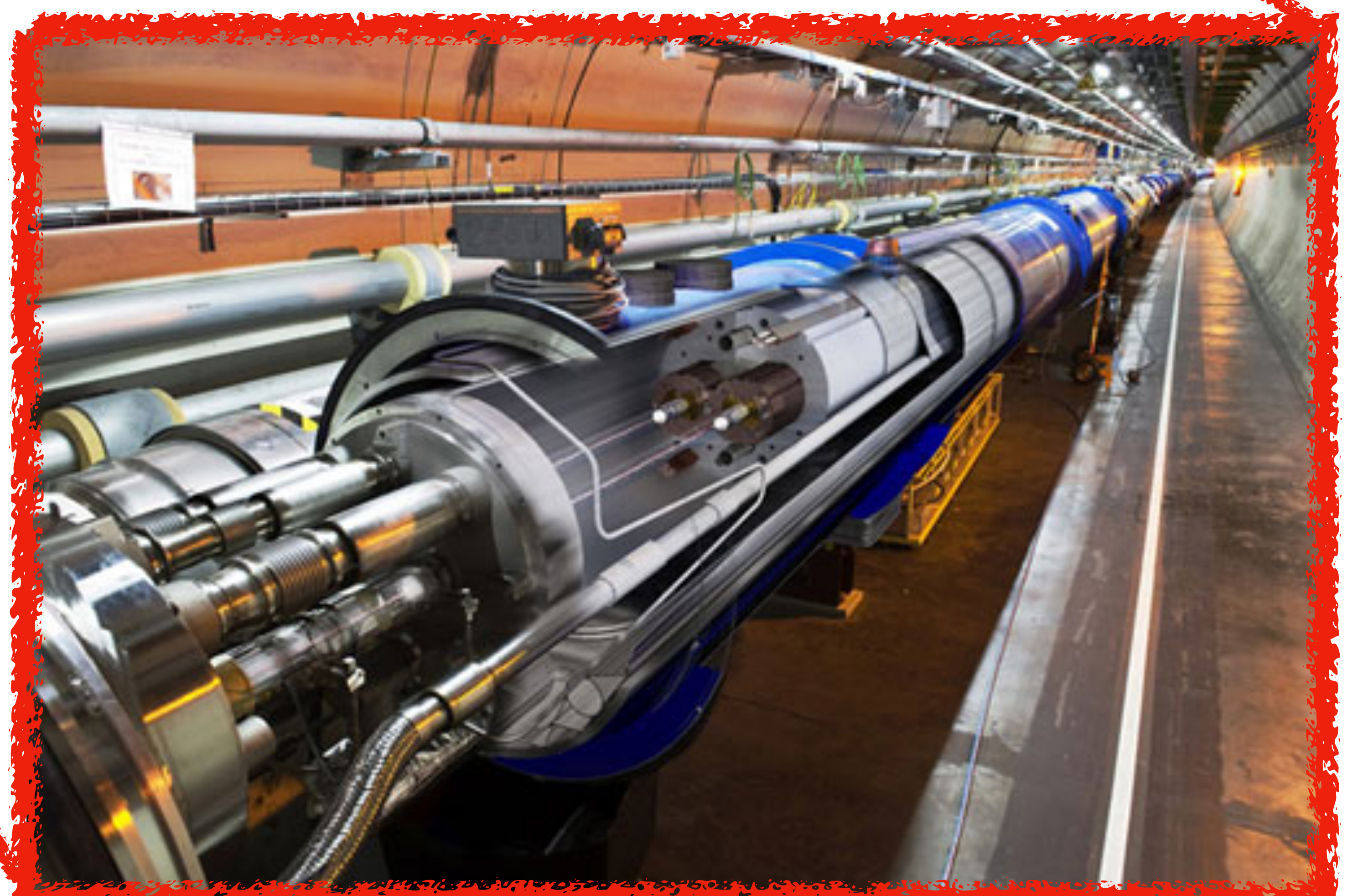
Signal from readout - digitisation

Detector signal digitization

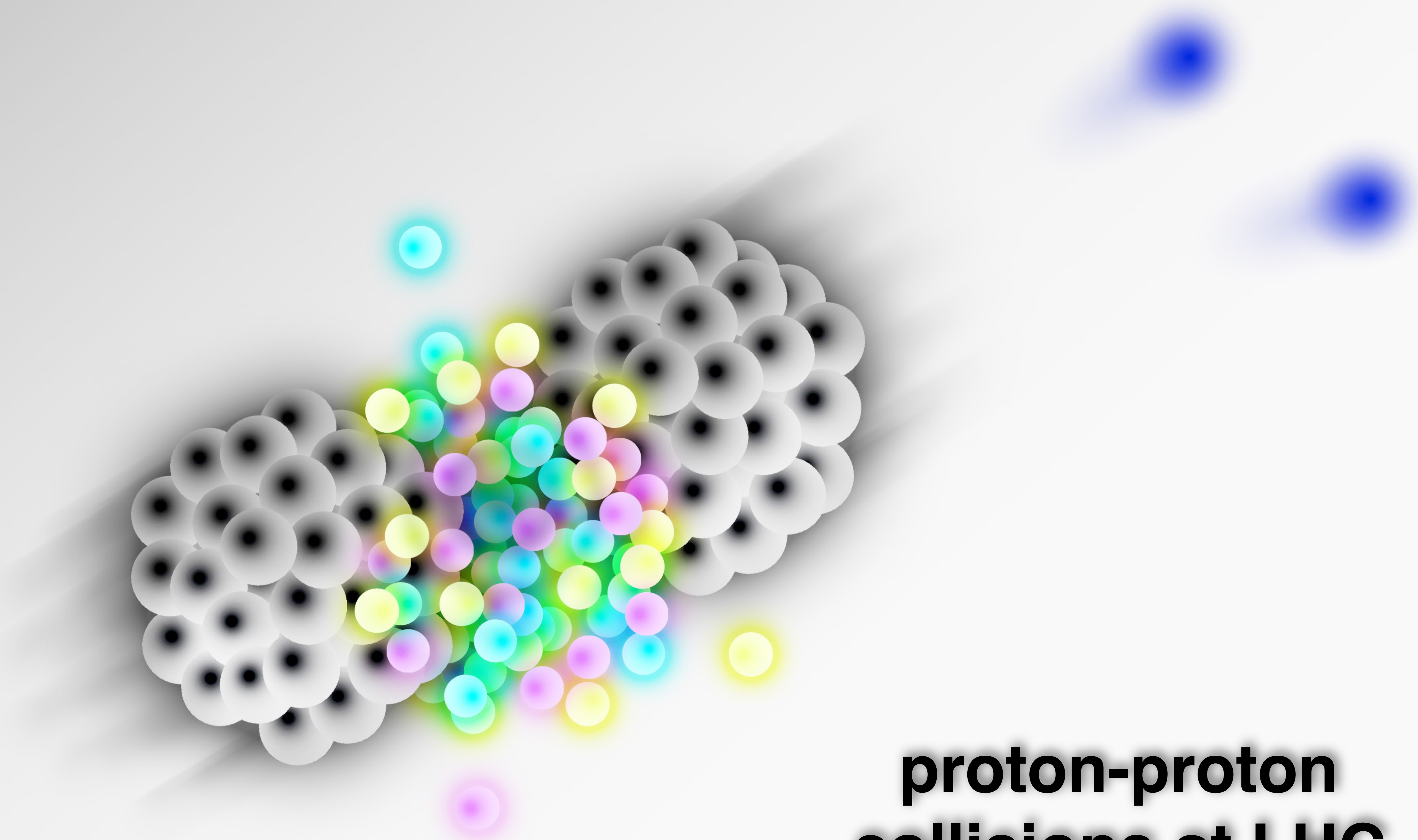


Detector signal reconstruction





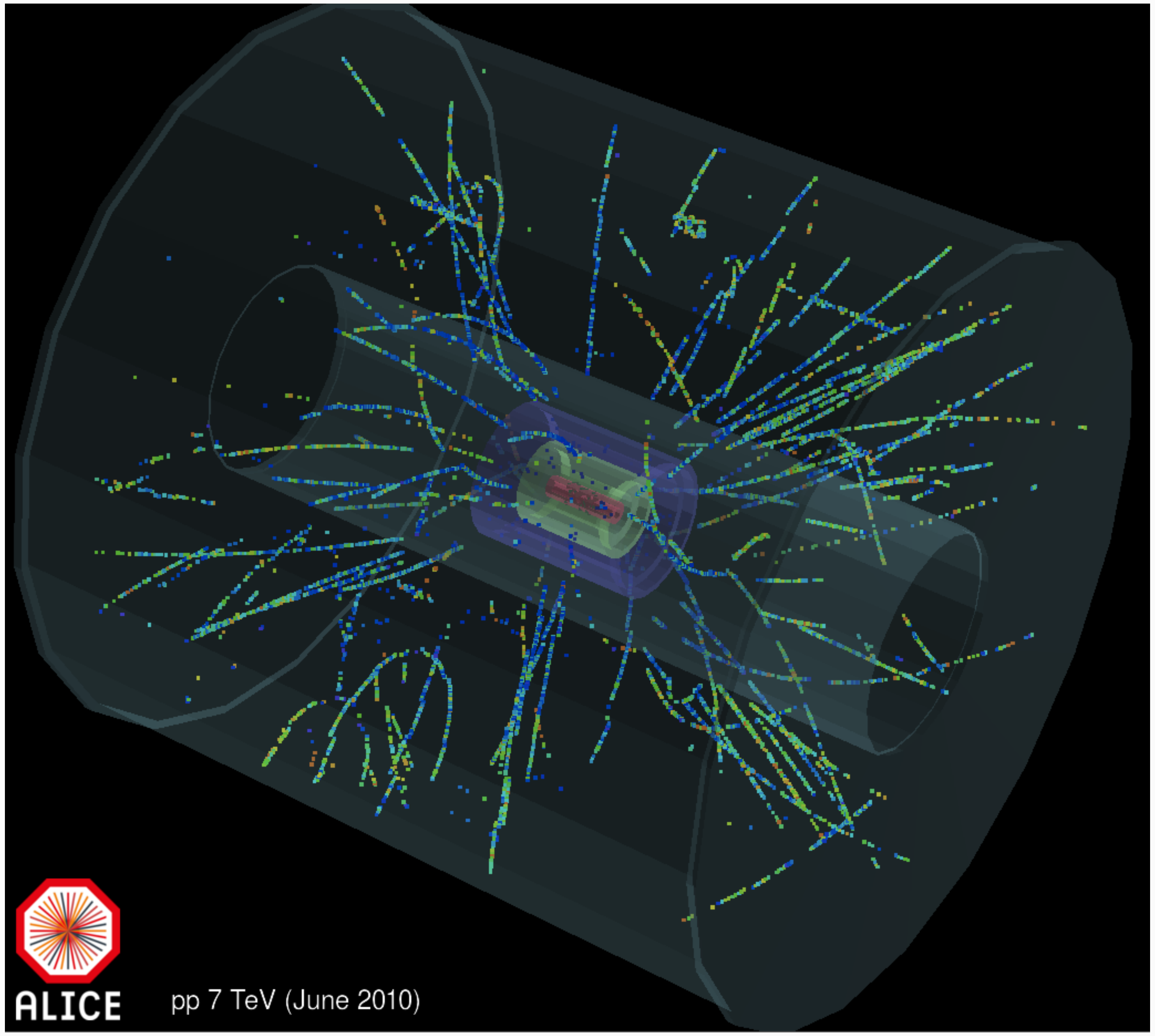
Simulation Physics



proton-proton collisions at LHC

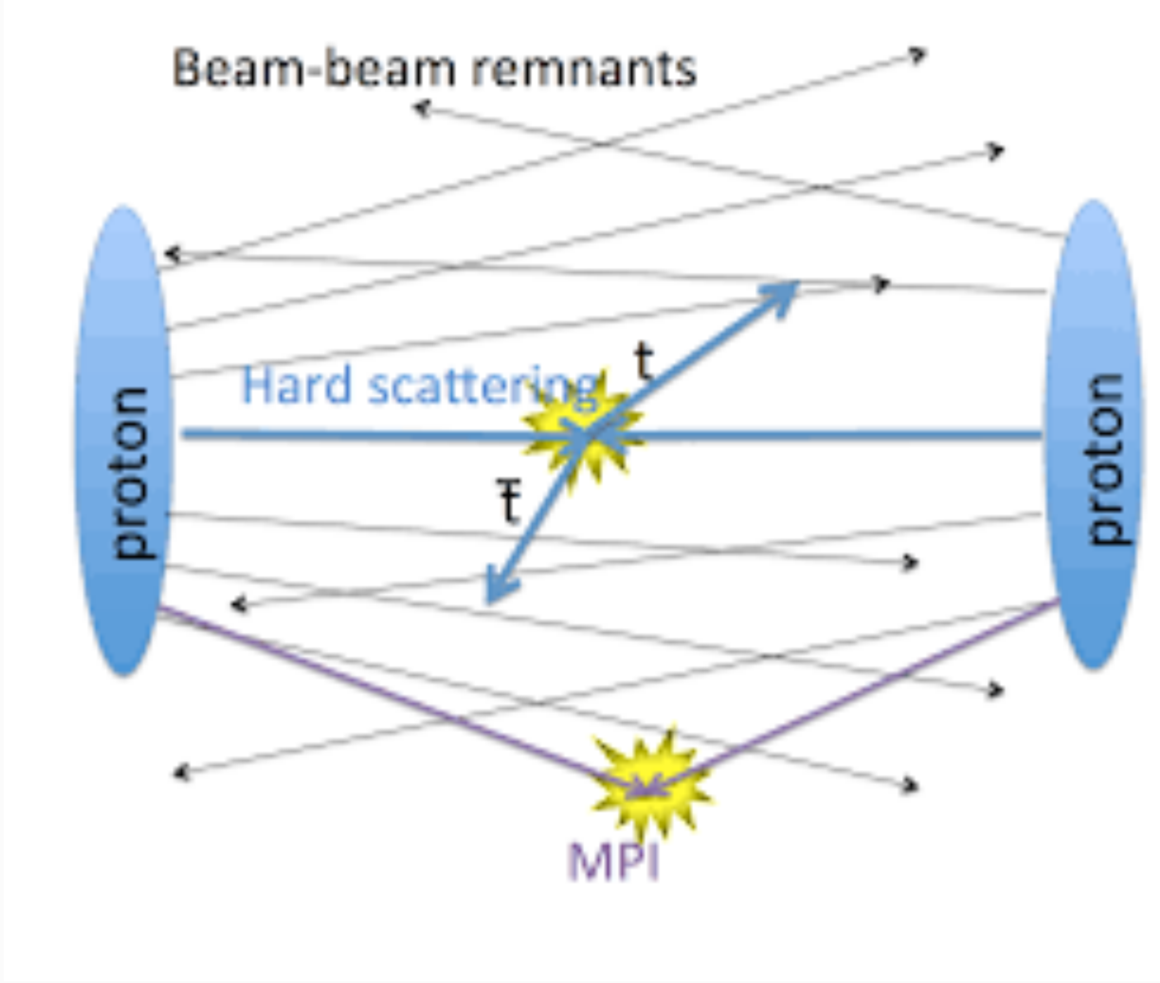
Proton-proton collisions

- What happens when we collide 2 protons?



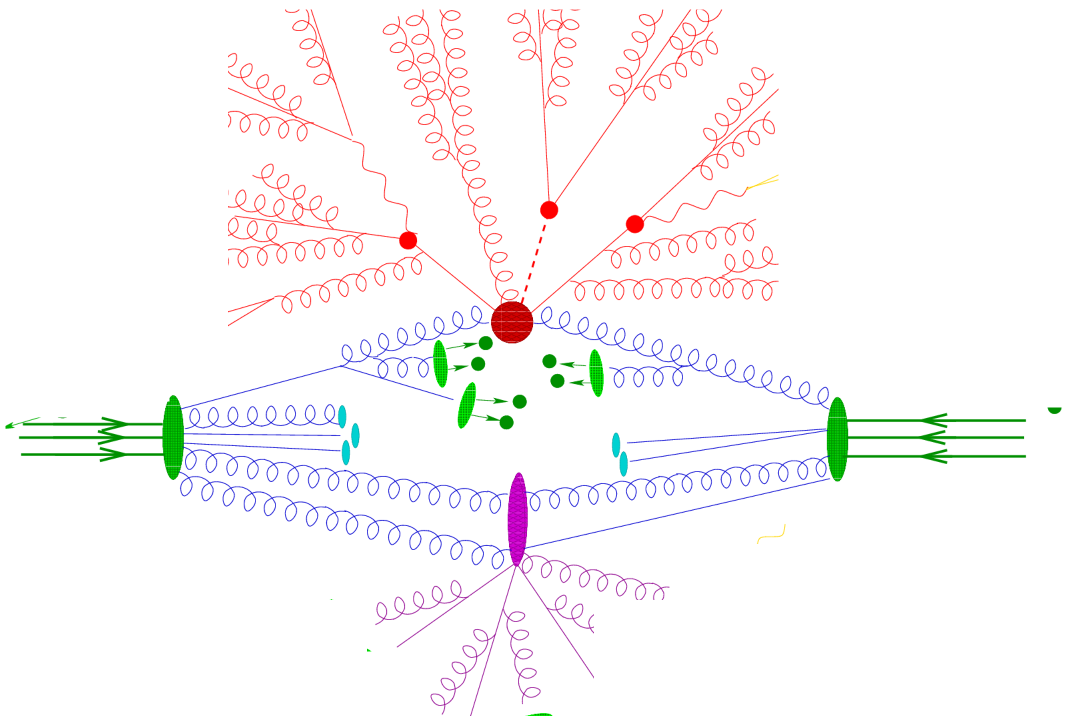
From Collision to Detector

- Need to simulate the full event (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



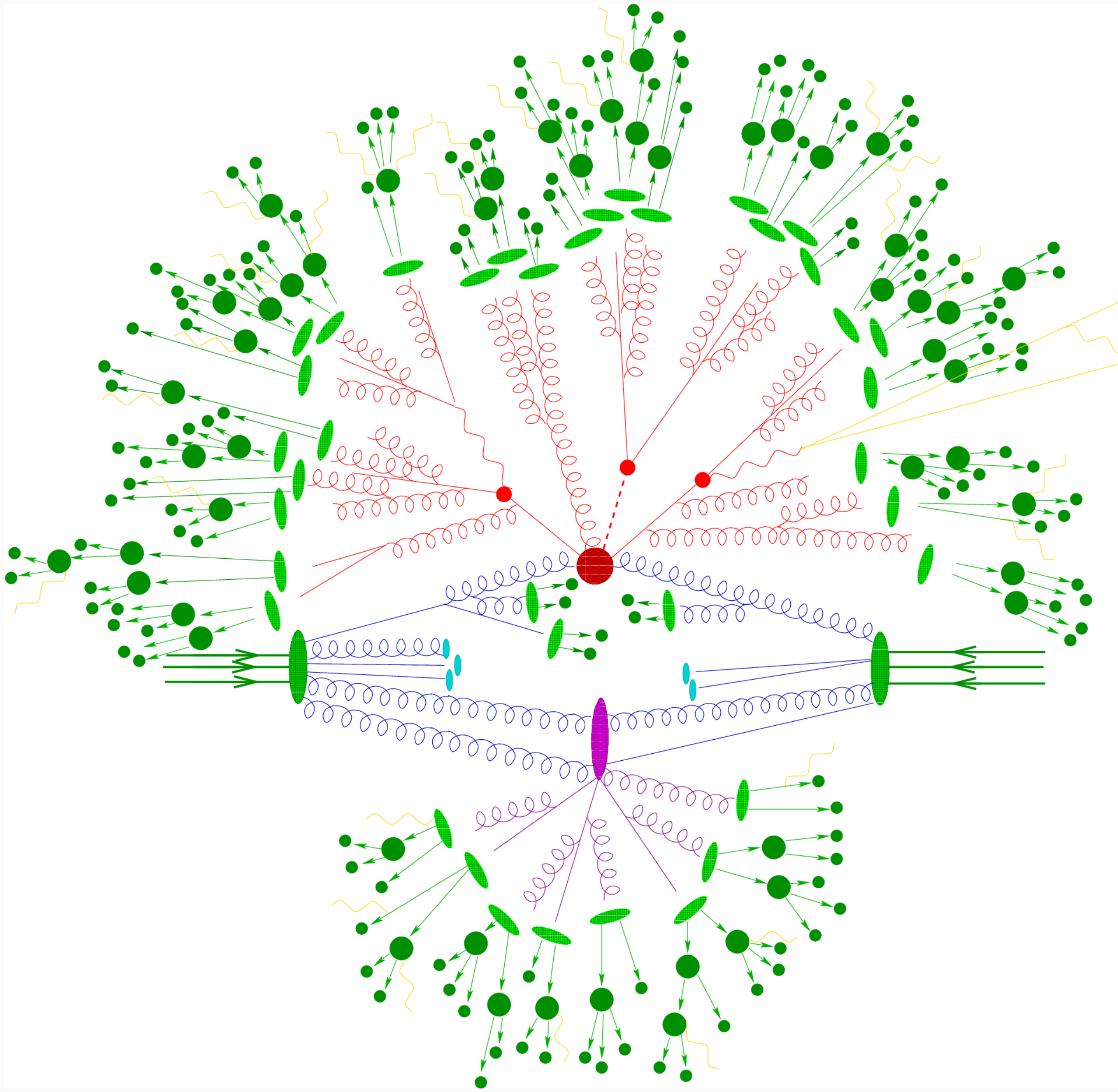
From Collision to Detector

- Need to simulate the full event (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

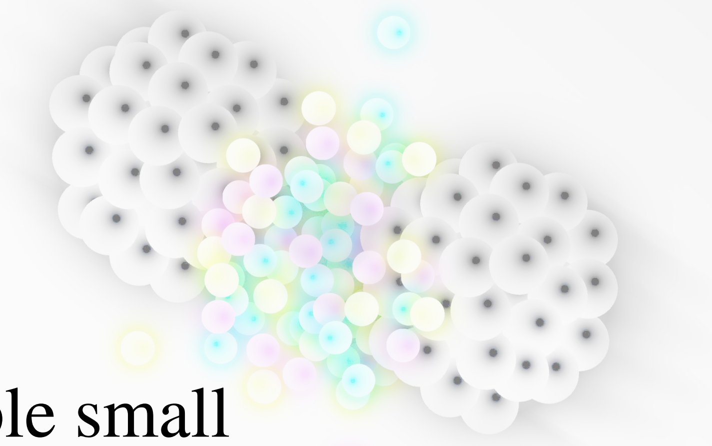
- Need to simulate the full event (before reaching the detector)
  - Monte Carlo codes specialised in simulating hadronic collisions: PYTHIA, HERWIG, …
  - What do they simulate?
    - After the collision (whole event):
      - We don't see coloured particles;
      - Quarks and gluons have to re-arrange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



Event Generator

- Hadronic event generators address a big problem into multiple small problems:

Event Generator



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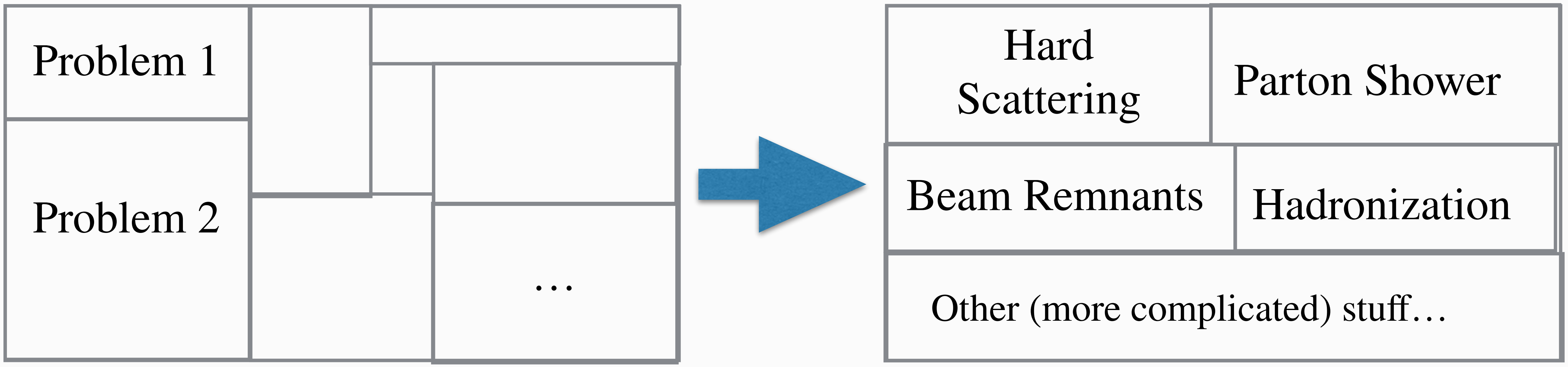
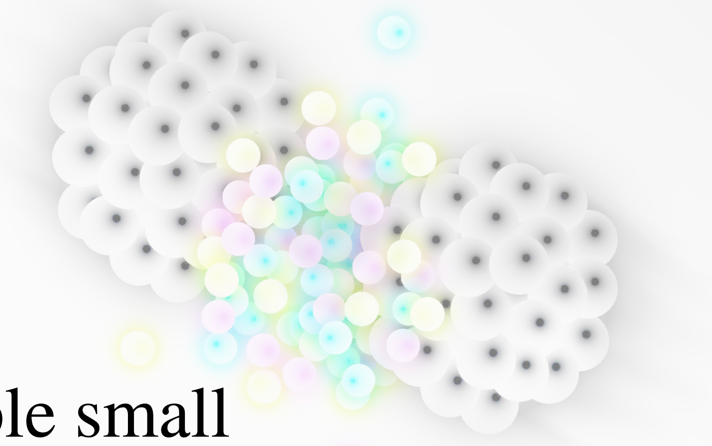


Event Generator



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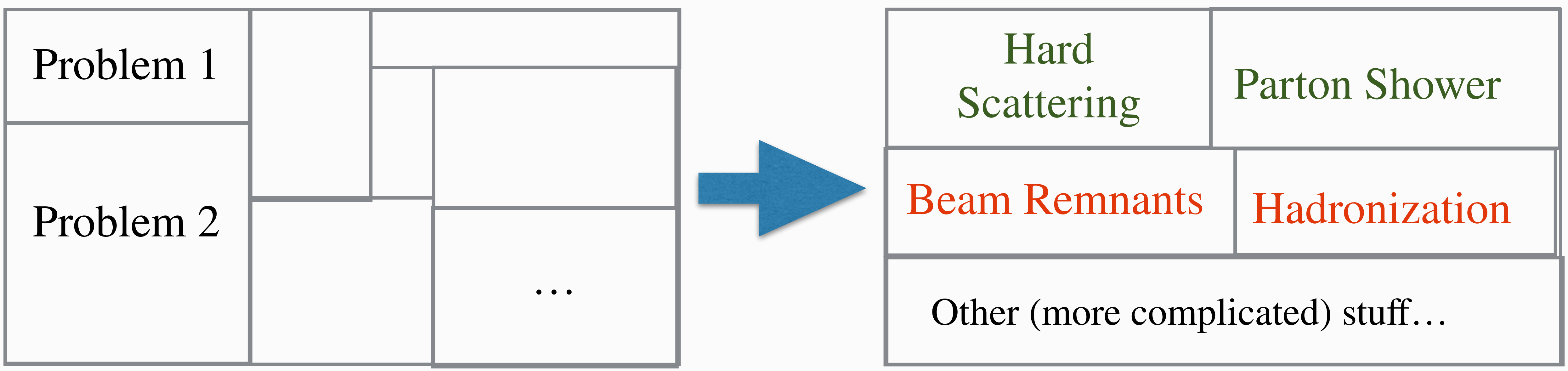
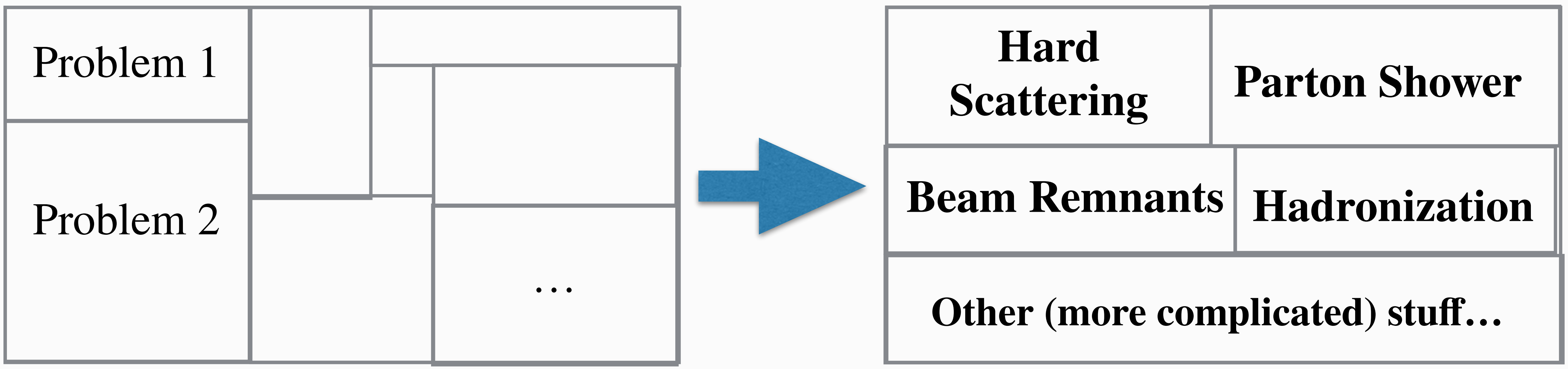


Some heavily based on theory

Others more data-driven

Event Generator

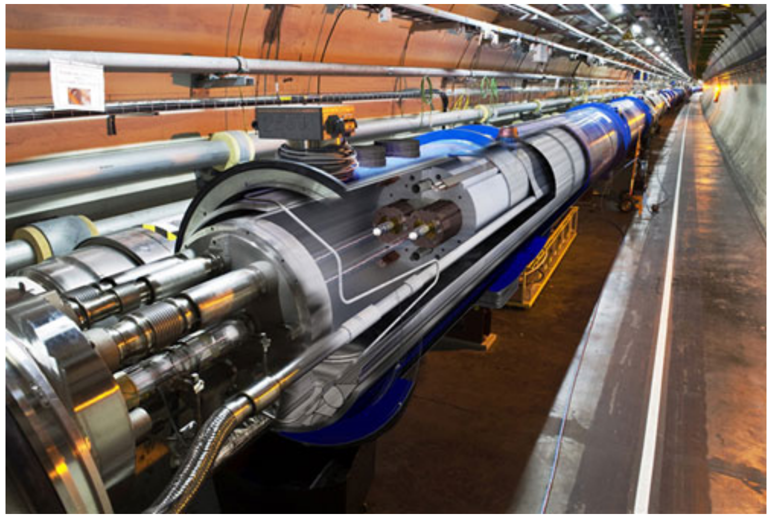
- Hadronic event generators address a big problem into multiple small problems:



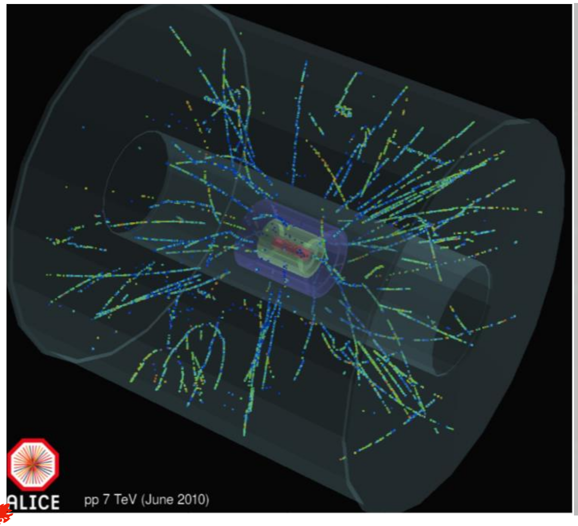
All validated with experimental data

Simulating a High Energy Physics experiment

Simulate the colliding beams



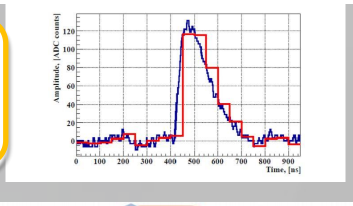
Detector simulation



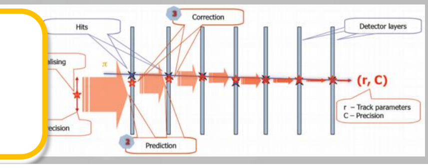
- Particle interactions inside detector
- Particle tracking
- Register interactions in sensitive detectors

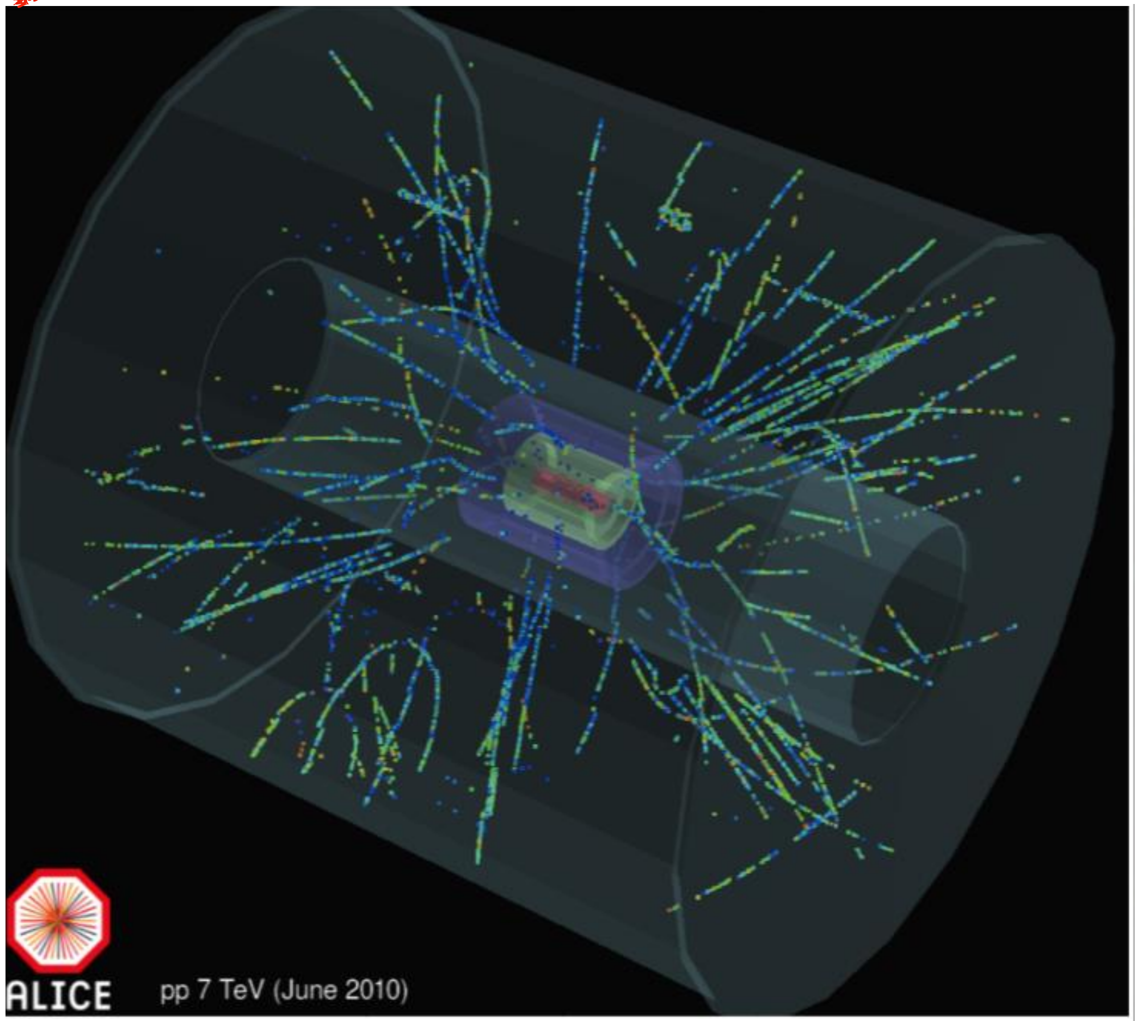
Signal from readout - digitisation

- Detector signal digitization



- Detector signal reconstruction





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

Creating a virtual detector

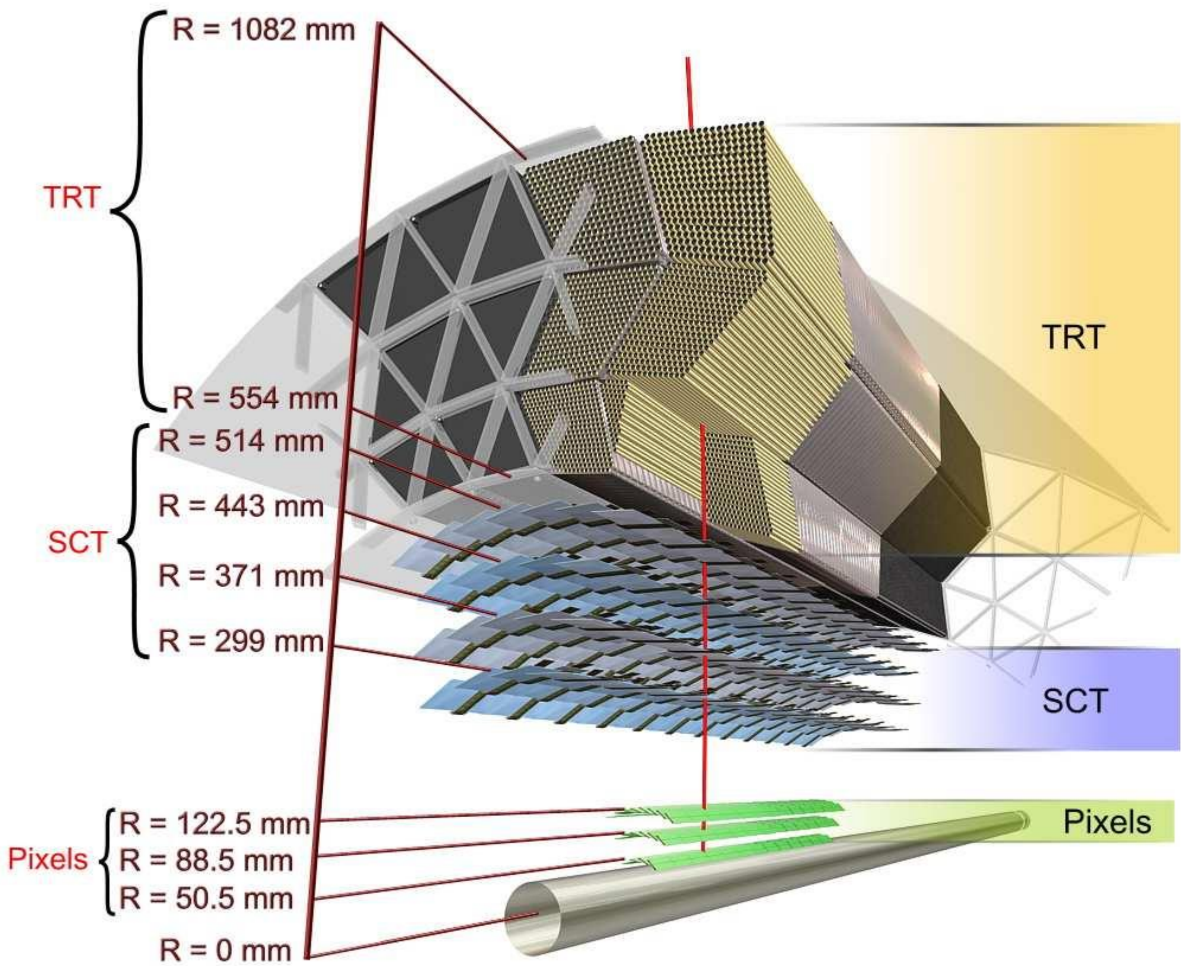
Detector geometry and materials

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

The detector definition requires the representation of its geometrical elements, their 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 possible or not needed…

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

What do we need to simulate ?

Electromagnetic physics 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

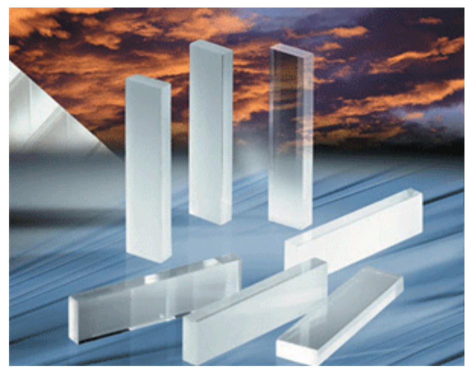
Hadronic interactions

- 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:

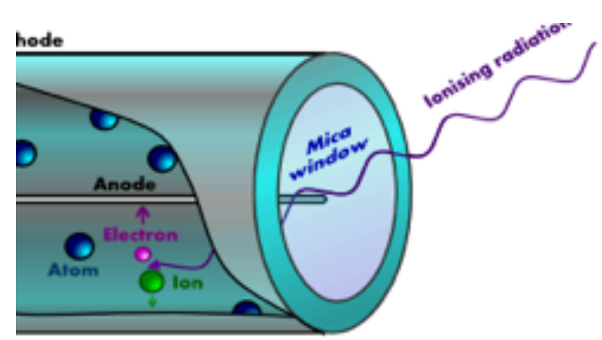


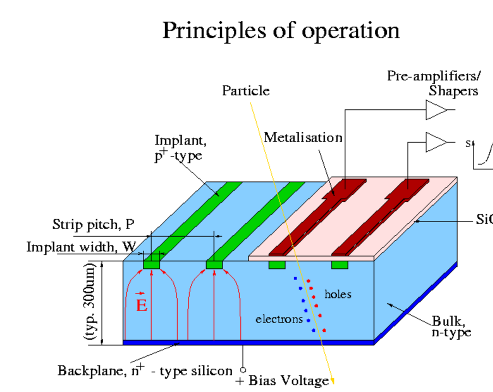
- Cerenkov Radiation
- Scintillation
- Wavelenght shifting
- Absorption

- Rayleigh and Mie Scattering
- Light detection
- ...

Charge production in gaseous and solid state detectors:

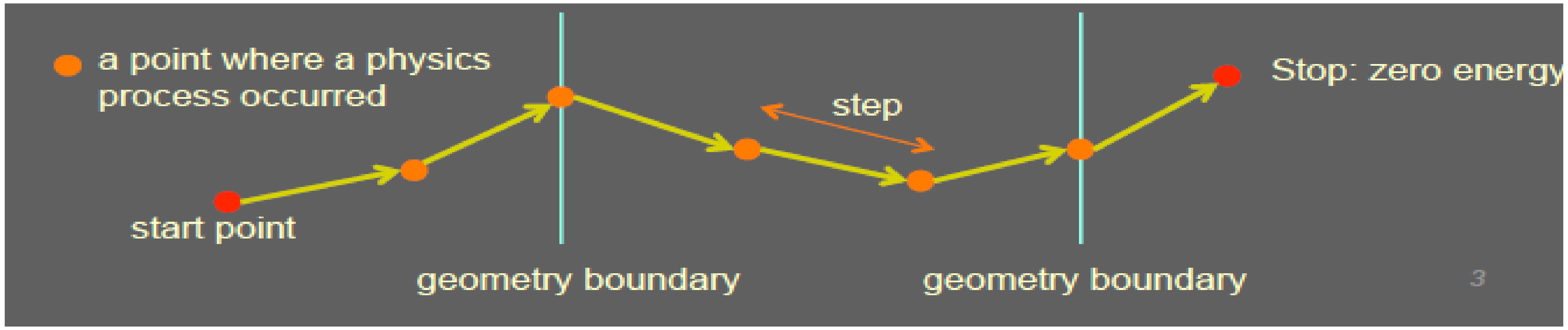
- Avalanche development
- Charge drift
- Induced signals / charge collection
- ...





Monte Carlo radiation transportation codes
General strategy

- 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)

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CERN PH/SFT

Accuracy *vs.* Speed

- Huge samples (billions) of simulated events are needed by the experiments for their physics analyses
- The number of simulated events is limited by CPU
- The simulation time is dominated by the detector simulation
- Tradeoff between **accuracy** and **speed** of the detector simulation
  - More precise physics models are slower and, more importantly, create more secondaries and/or steps
  - Smaller geometrical details slow down the simulation
    - Never model explicitly screws, bolts, cables, etc
  - Continuous spectrum of types of detector simulations
    - From full, detailed detector simulations
    - To very fast, fully parametrized detector simulations

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CERN PH/SFT

“Digitisation”

- The general radiation transportation code provides **energy deposits** in the detector;

- From here one must simulate the generation of the signal to be detected :
    - 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;

"Digitisation"

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  - some codes allow part of this task in the same simulation;

- **"Digitization"** is a detector-specific aspect of the simulation:
  - simulate the detector response in terms of measurable signals in the DAQ 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 **simulated data as in real data**;

Validation

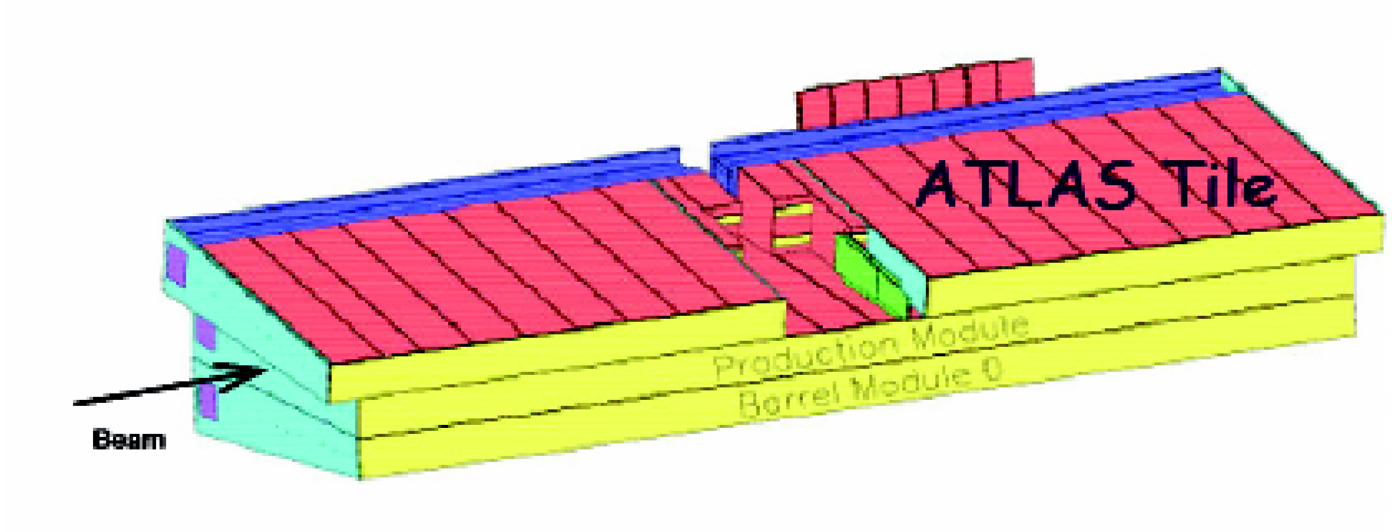
- Validation is a very important issue in the implementation of a Monte Carlo simulation code;

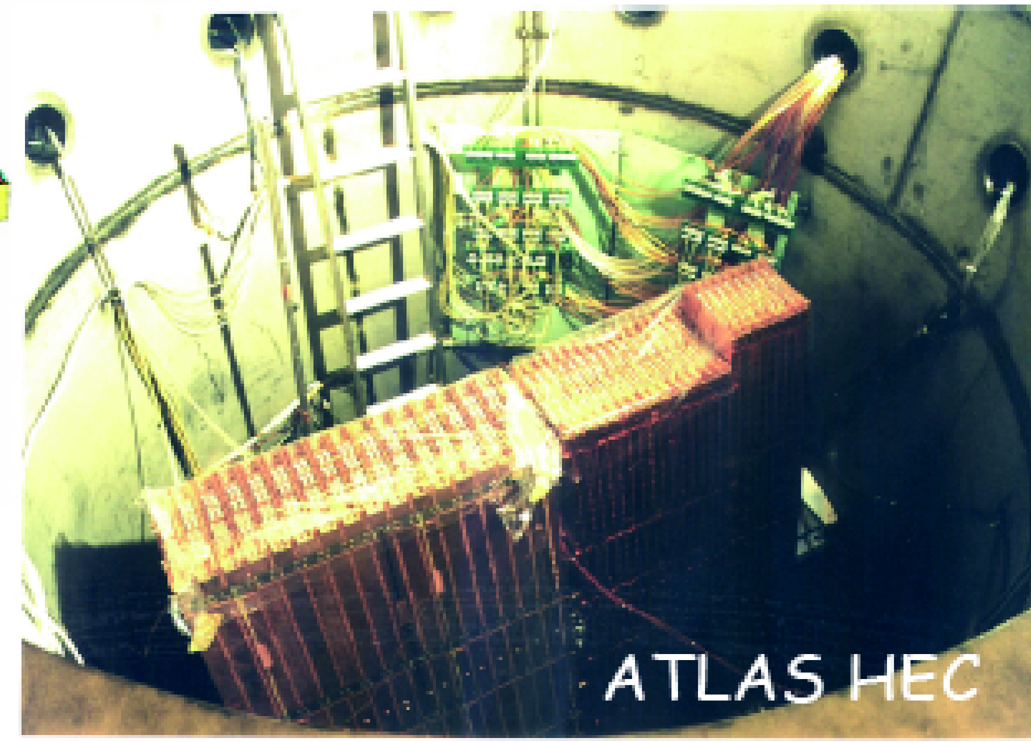
- It encompasses the physics models used and the code implementation;

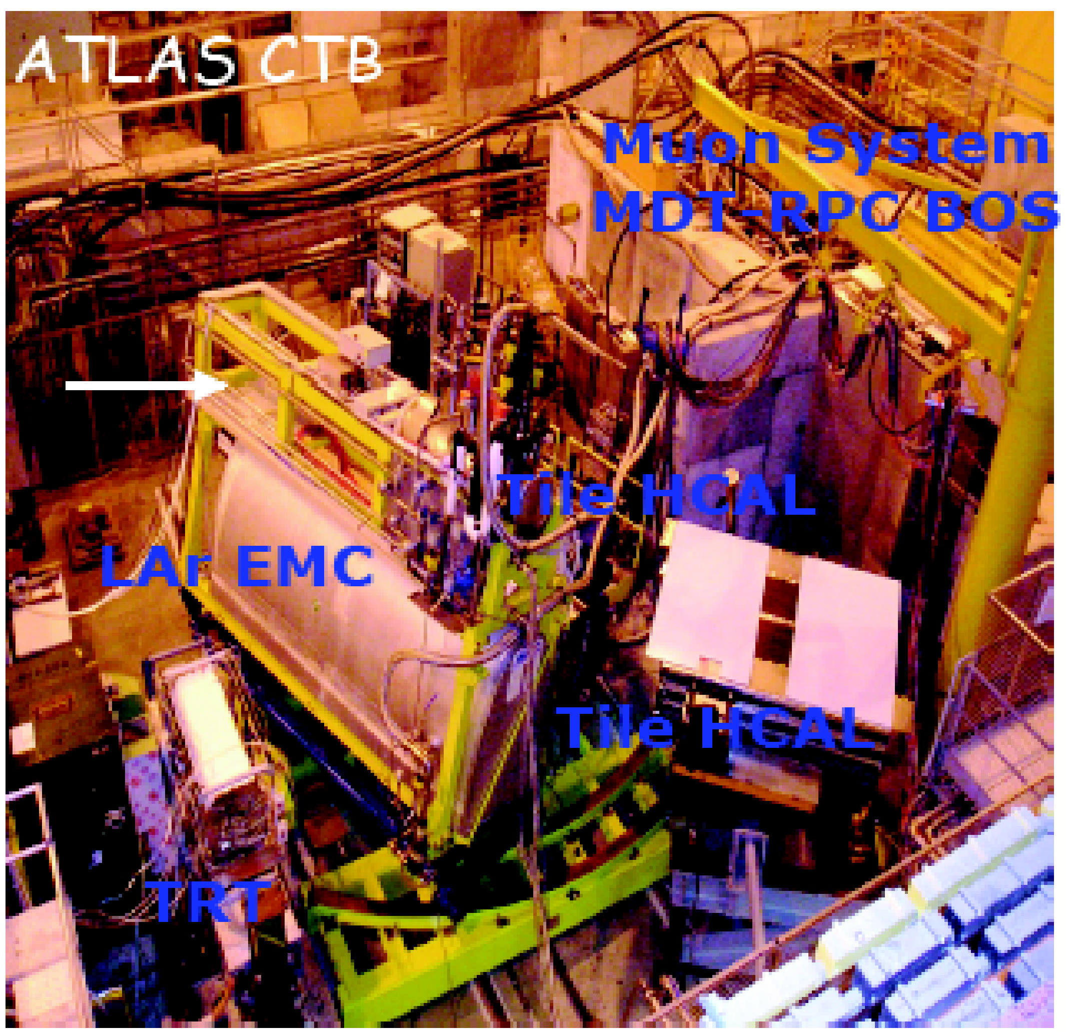
- How can we trust several million lines of code?

- Validation of complete physics configurations is performed mostly via measurements in test-beam setups;

LHC calorimeter test-beams

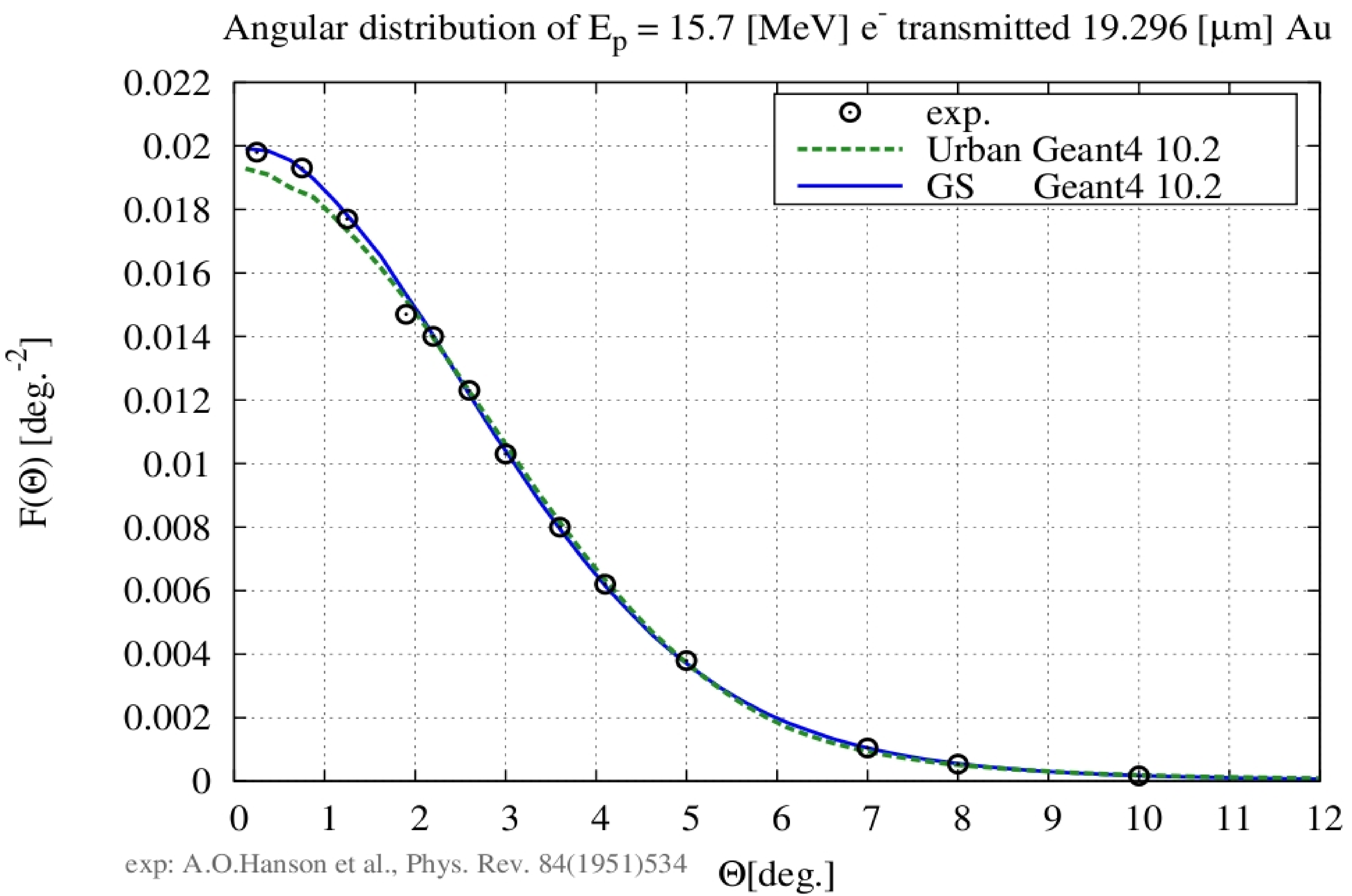






Electromagnetic validation

Multiple Coulomb scattering of electrons



exp: A.O.Hanson et al., Phys. Rev. 84(1951)534

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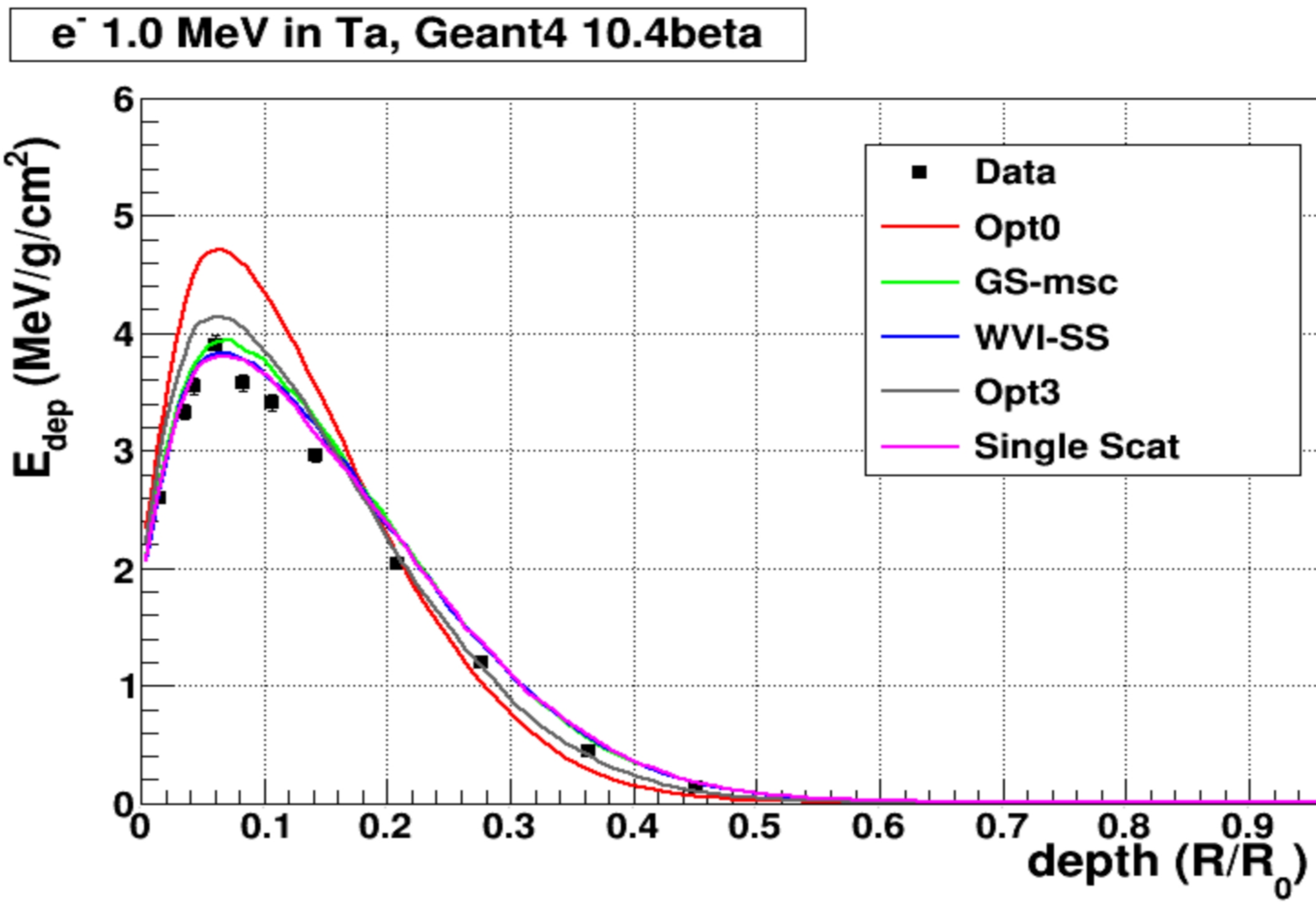
Electromagnetic validation

Electron energy deposit in thick target



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The Geant4 toolkit

in a nutshell

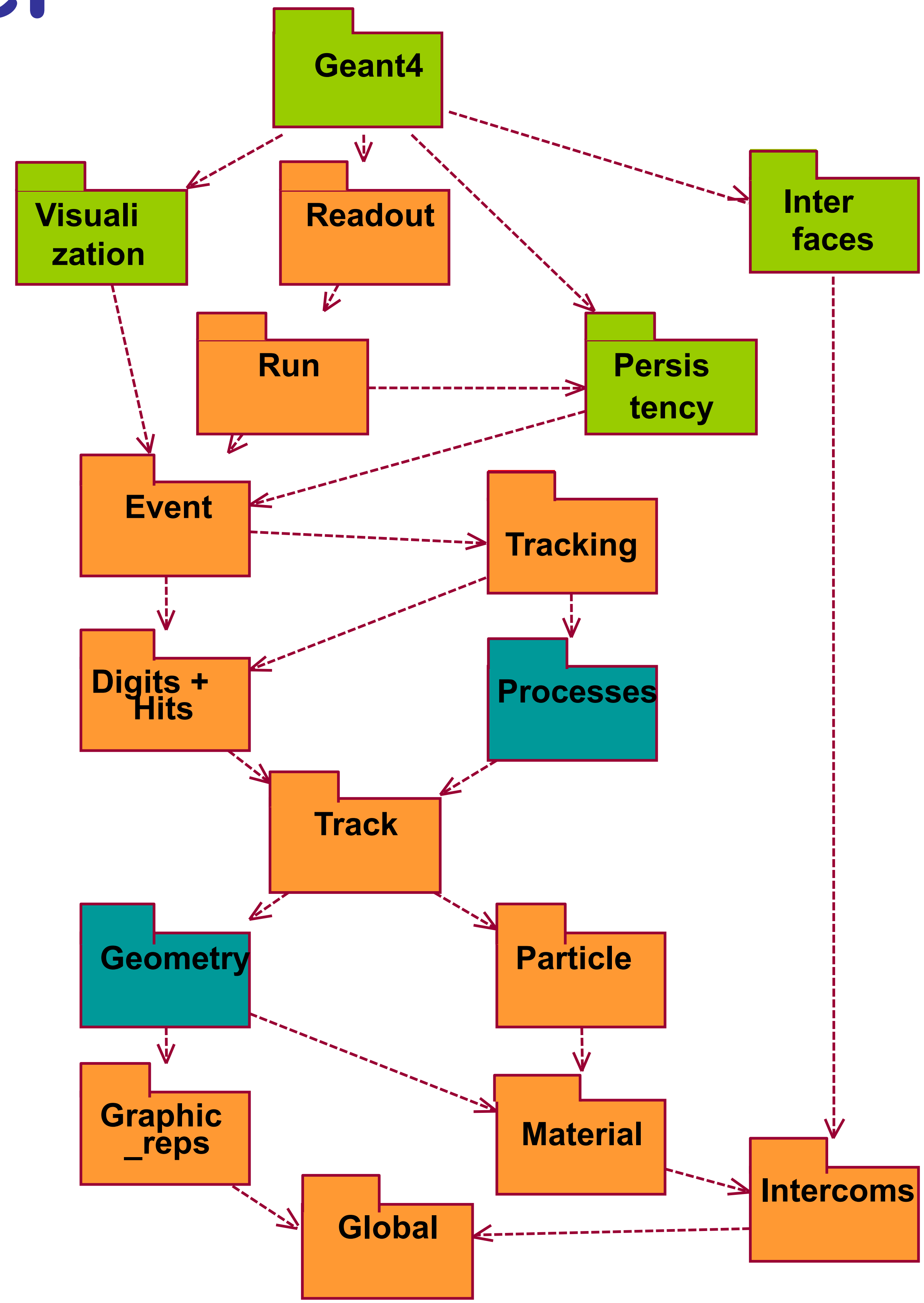
GEANT4
A SIMULATION TOOLKIT

Geant4 in a nutshell

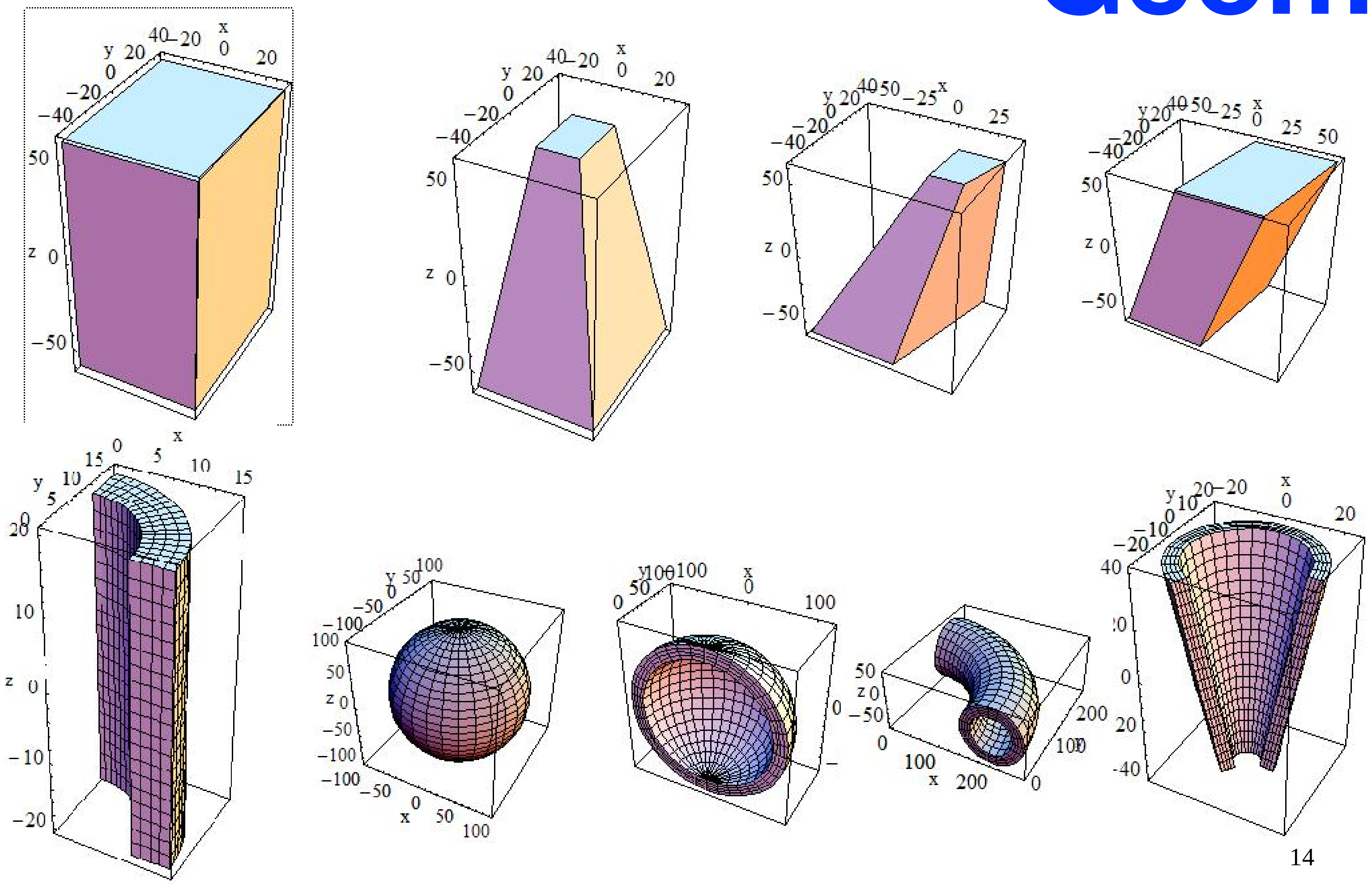
- Geant4 is a general purpose **C++ toolkit** for tracking particles through matter, breaking the particle motion into small segments, applying appropriate physical processes and probabilities at each .
- It provides a **complete set of tools for all domains of radiation transport**:
  - Definition of 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;
- 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.

Geant4 kernel

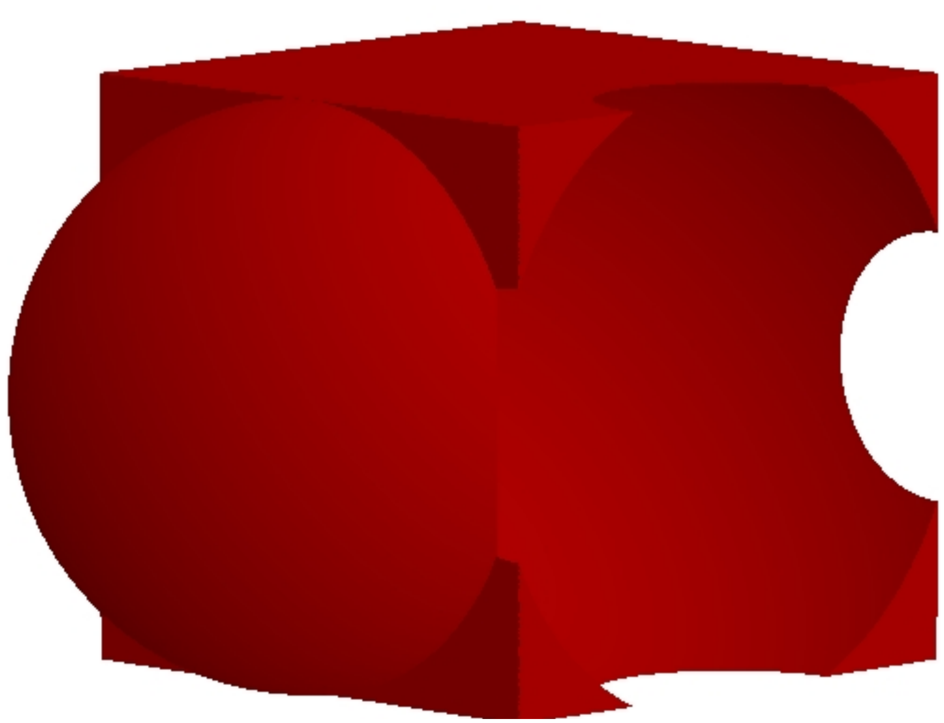
- Geant4 consists of 17 categories.
  - Independently developed and maintained by WG(s) responsible to each category.
  - Interfaces between categories (e.g. top level design) are maintained by the global architecture WG.
- Geant4 Kernel
  - Handles run, event, track, step, hit, trajectory.
  - Provides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

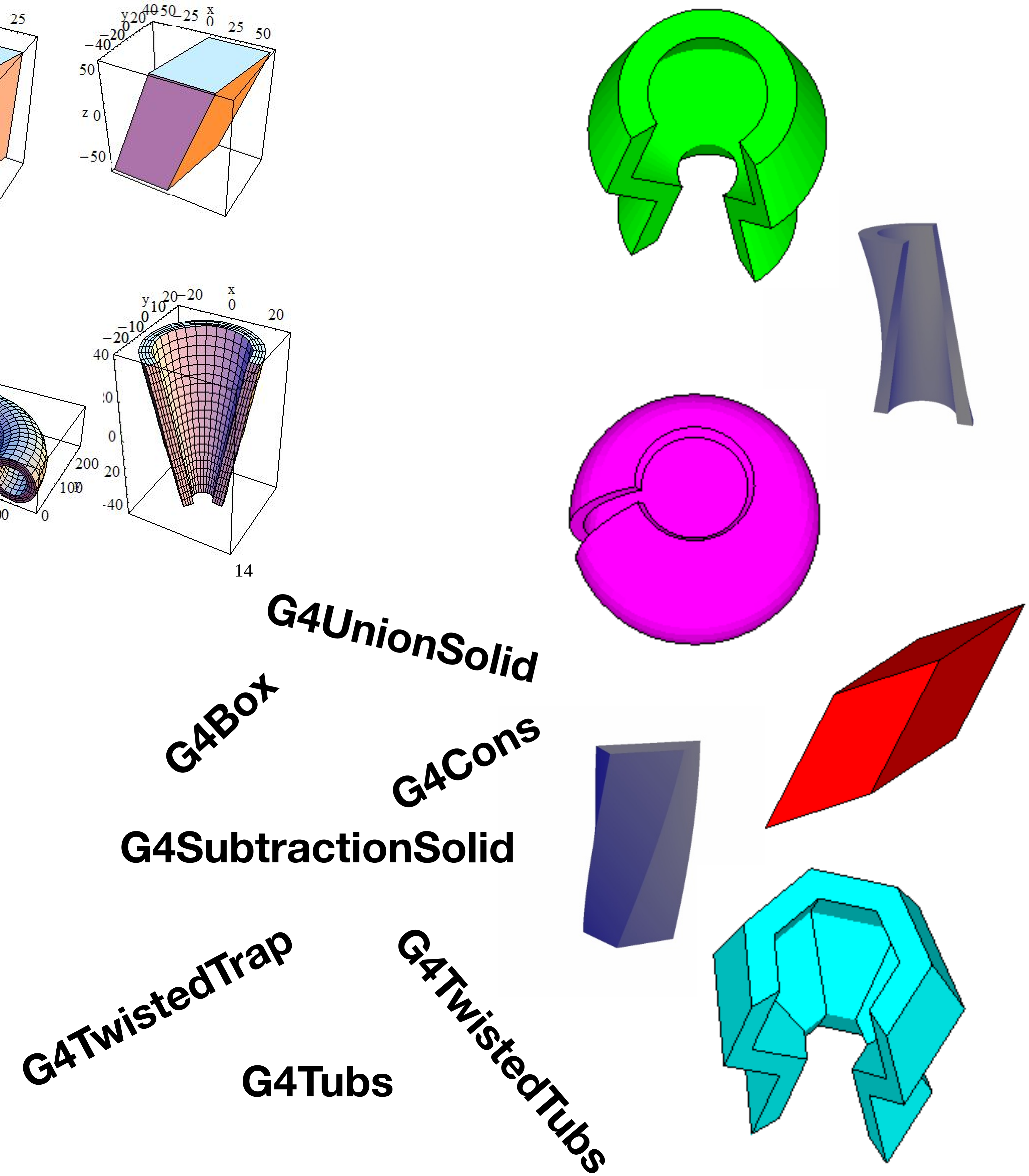


Geometries in Geant4



Boolean solid

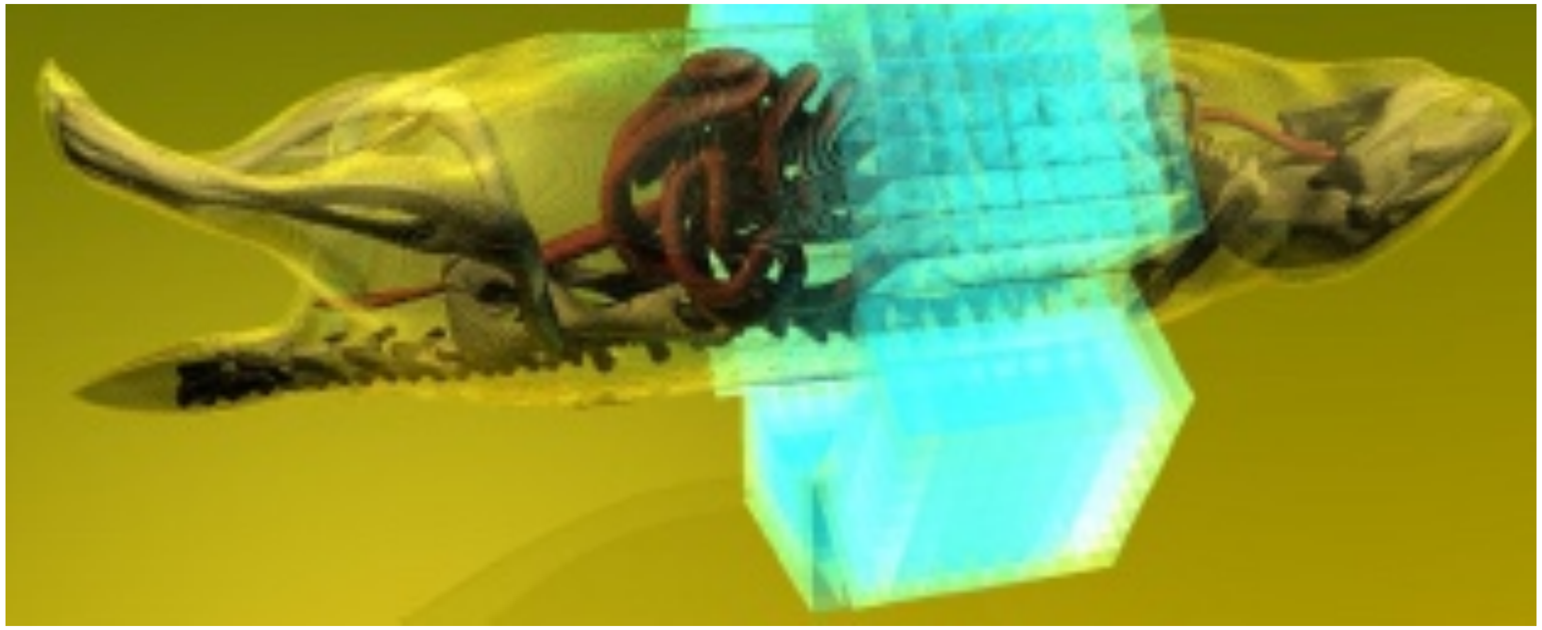




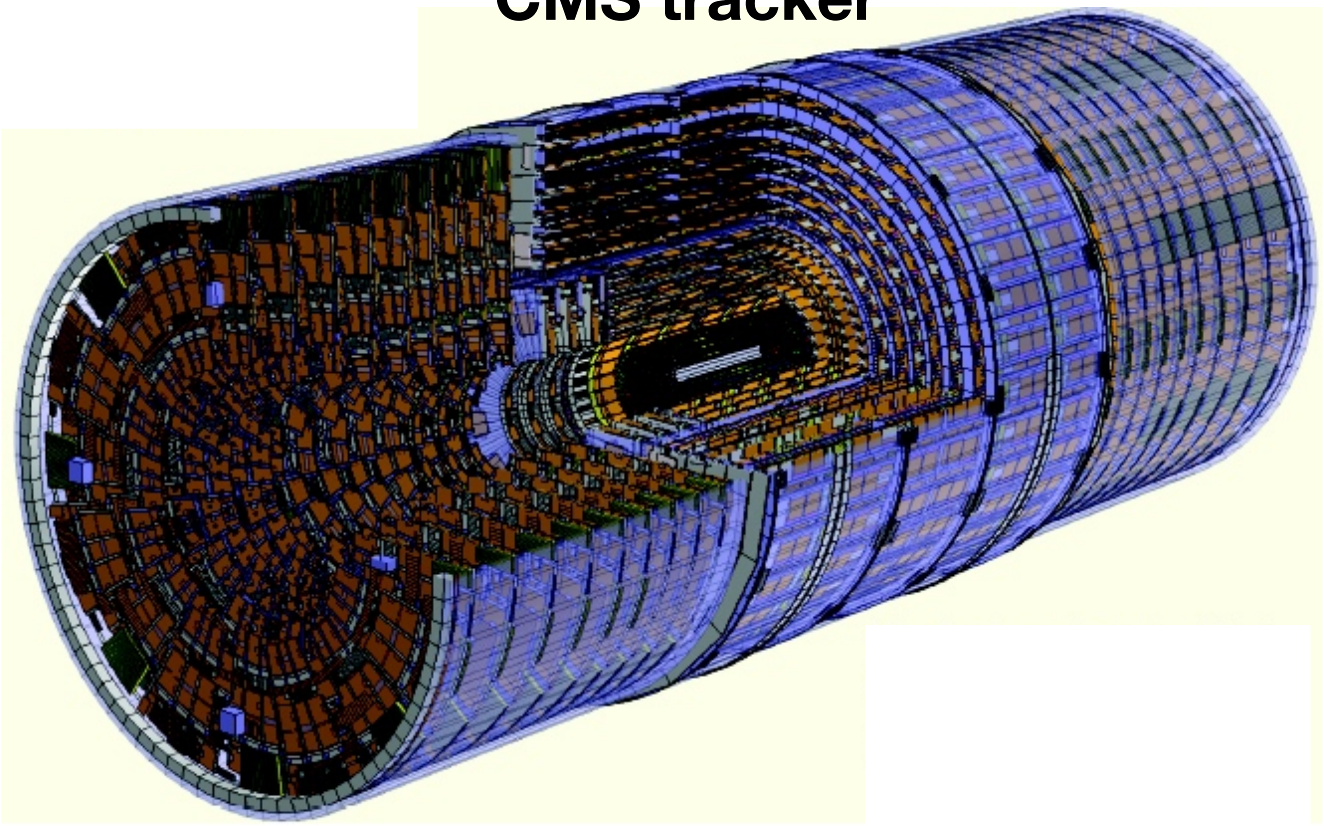
Volkswagen camper van built from 400 000 Lego bricks !

Defining complex geometries with Geant4...

Medical phantoms - animal PET



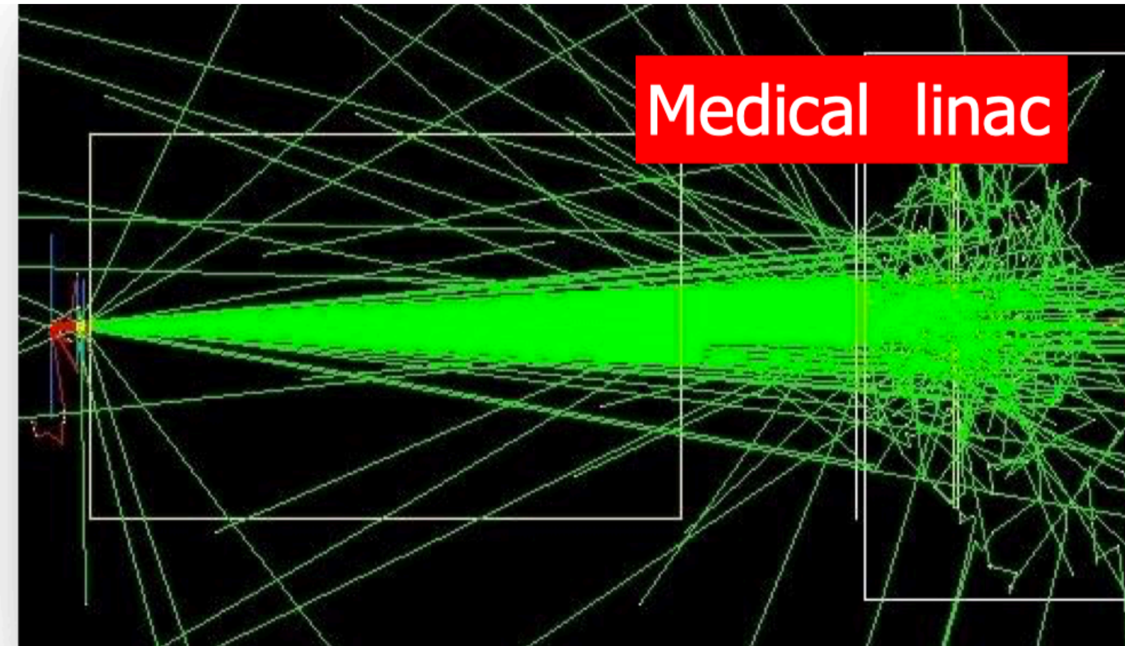
CMS tracker

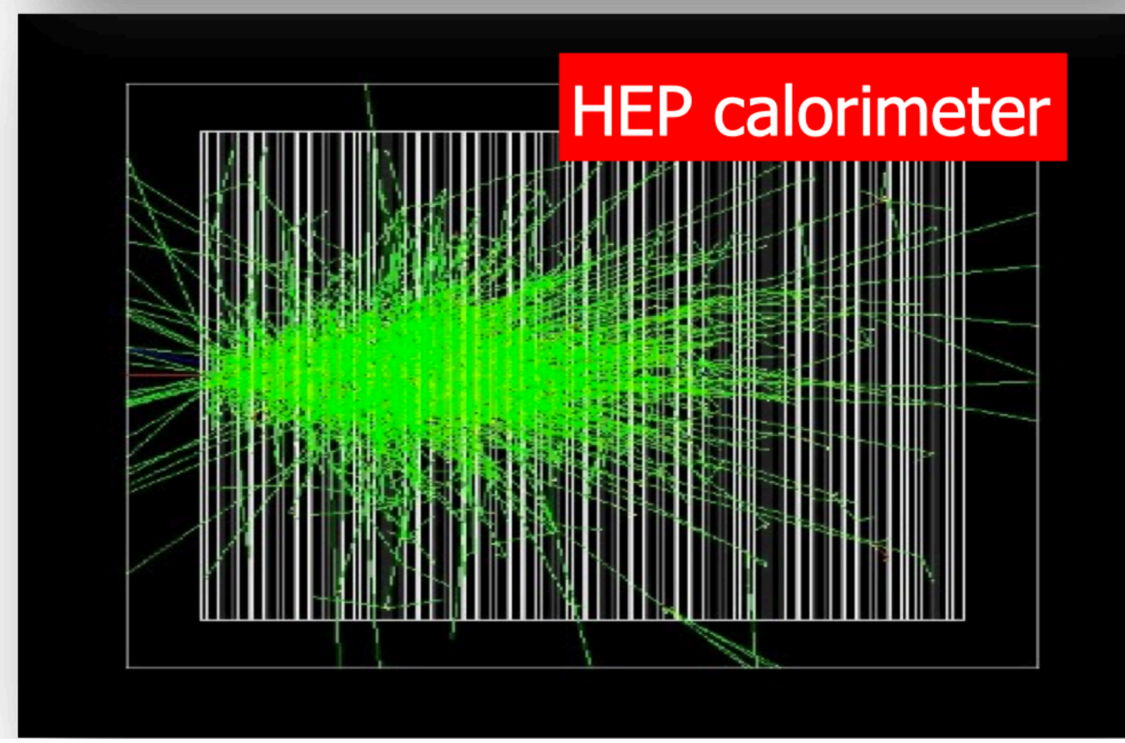


Simplified (!) version of the geometry

Processes for Gamma and Electron

- 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

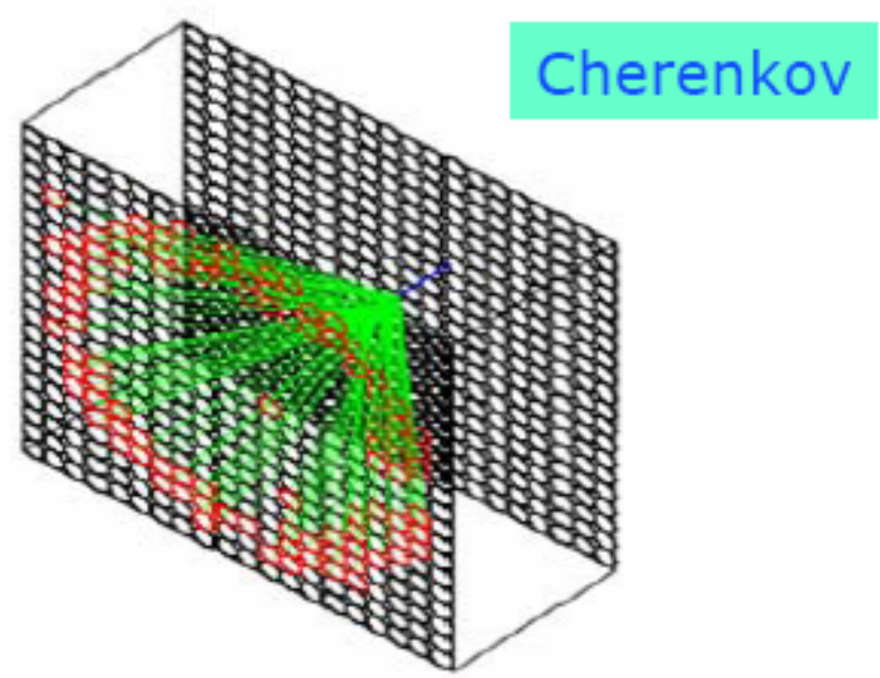


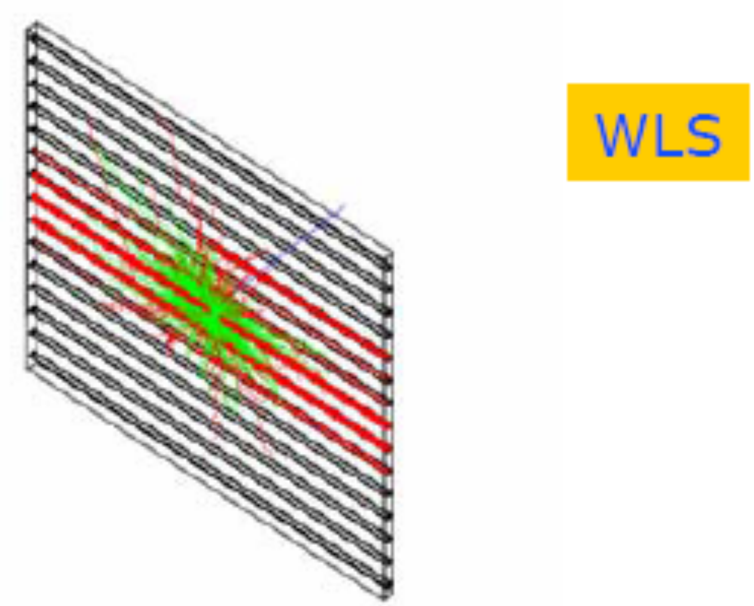


also all relevant processes for hadrons **(elastic, inelastic, capture, fission, radioactive decay, photo-nuclear, lepton-nuclear,…)**

X-ray and optical photon simulation

- Standard packages:
  - Cherenkov radiation
  - Synchrotron radiation
  - Transition radiation
  - Scintillation
- Low-energy EM package:
  - Atomic relaxations – fluorescence and Auger transitions
- Optical
  - Reflection
  - Refraction
  - Absorption
  - Rayleigh scattering





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 x

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

→

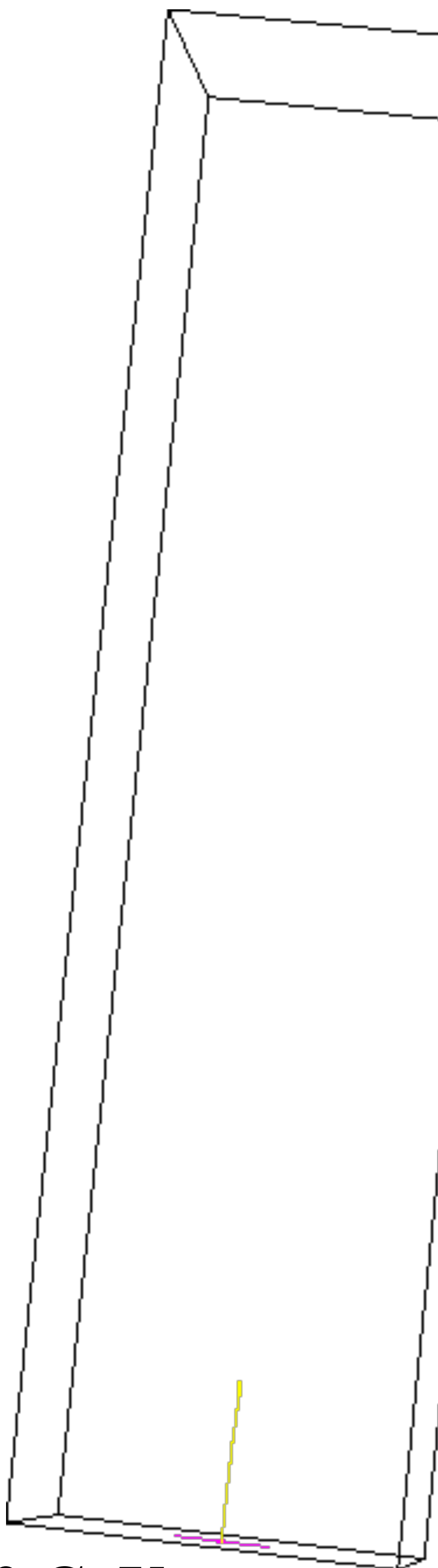
Interaction with detector materials:
Production of secondaries,
Energy deposits
Energy loss
Multiple scattering etc

→

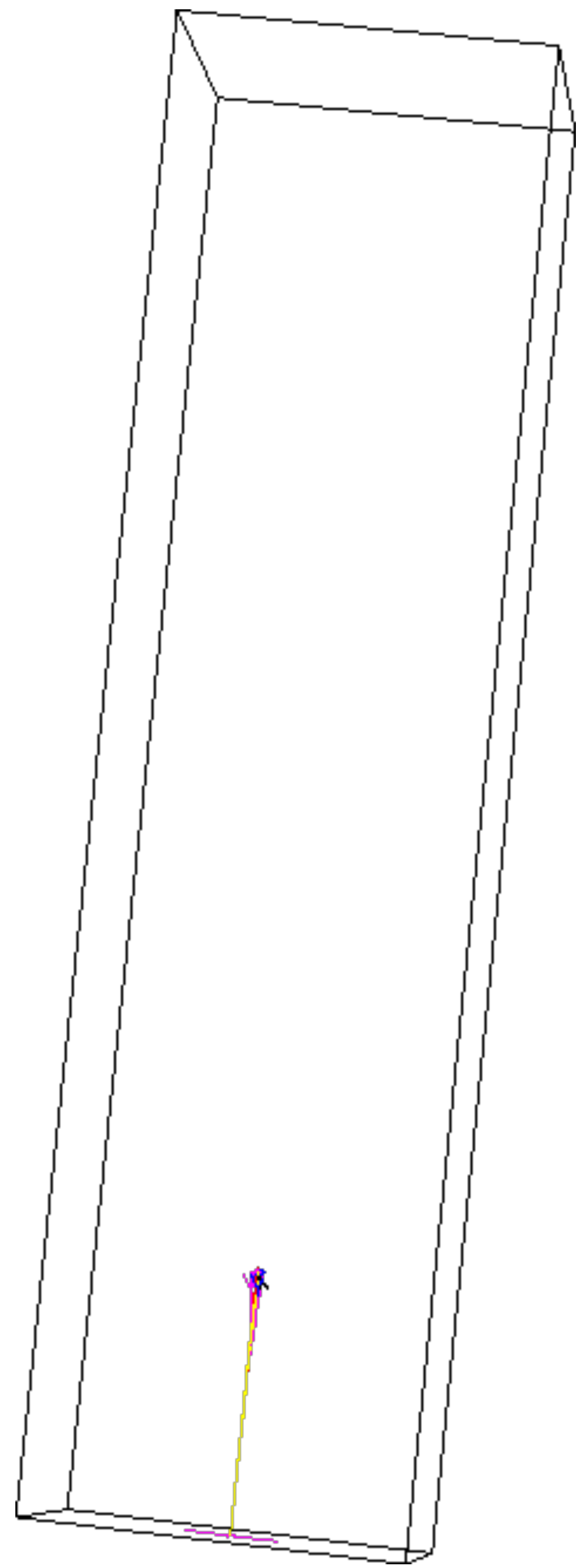
Register signals in sensitive detectors:
Deposited energy
Track momentum
Time
Position
Detector ID
Particle type
Etc

Geant4 simulation of a crystal calorimeter

37 x 10 x 10 cm^3 Lead Glass scintillator

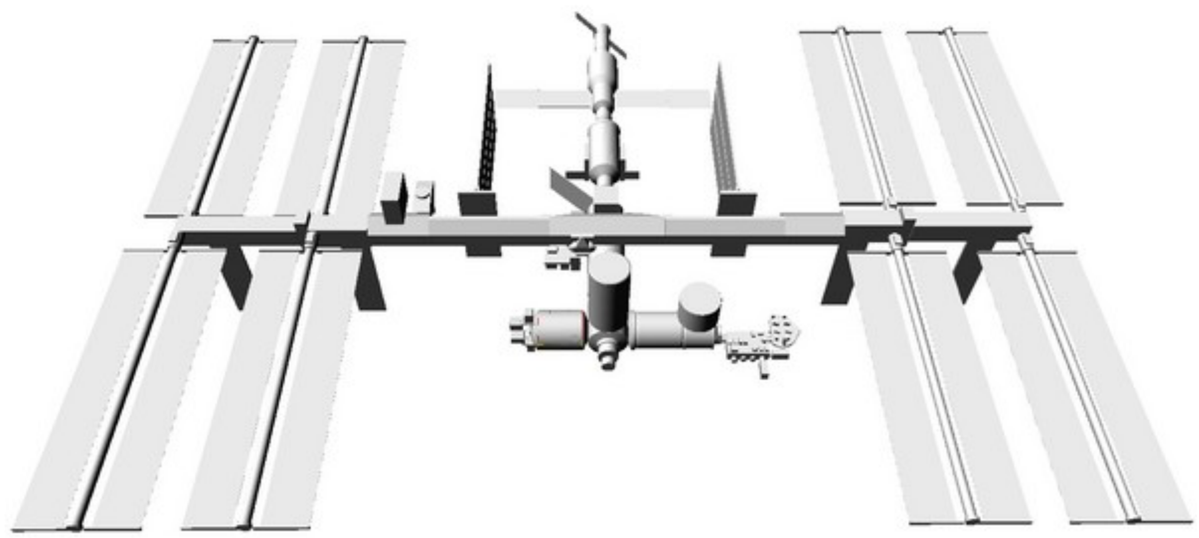


2 GeV e$^-$

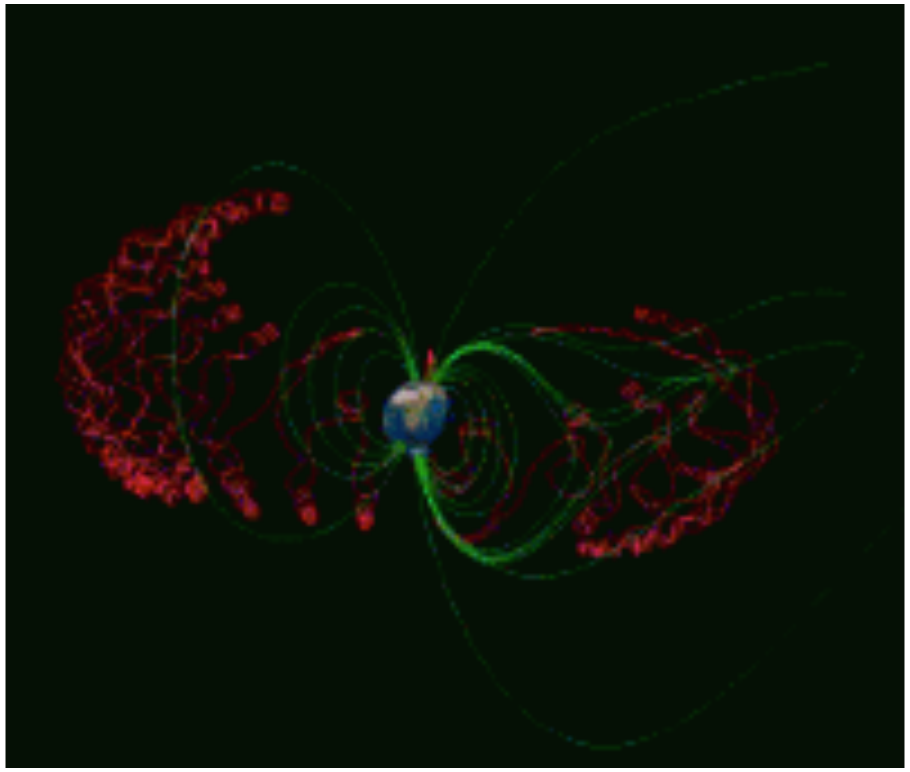


80 GeV e$^-$

Some examples of Geant4 applications

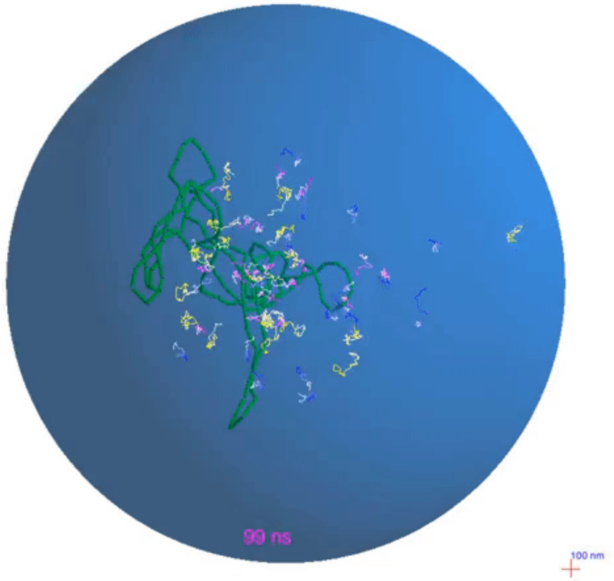


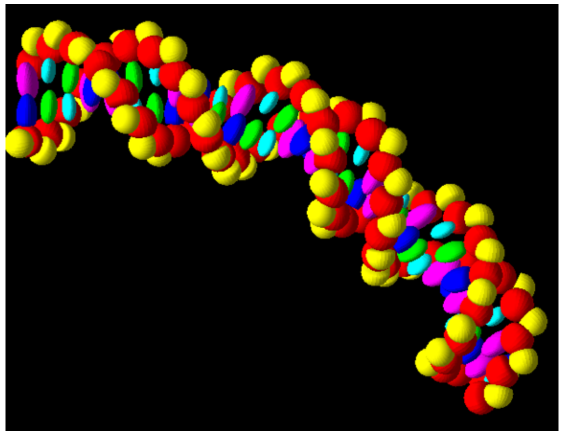
DESIRE - Dose Estimation by Simulation of the ISS Radiation Environment



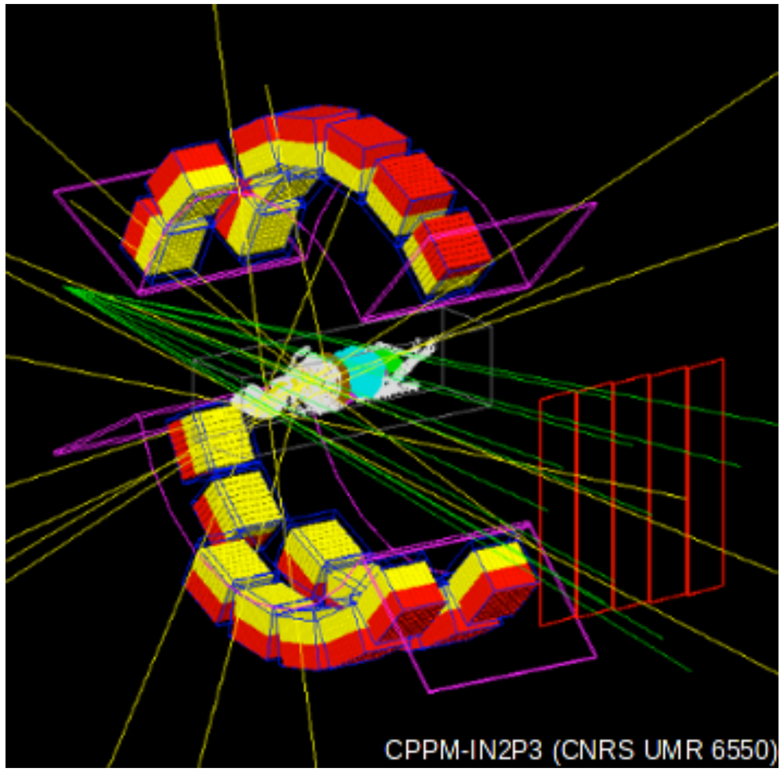
PLANETOCOSMICS - interactions of cosmic rays with planets atmospheres, magnetic field and soil.

GEANT4-DNA : Simulation tools for radiobiology



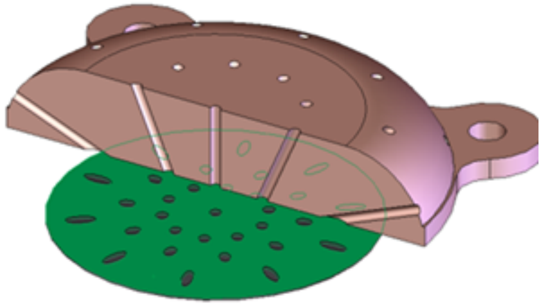


Irradiation of a pBR322 plasmid, including radiolysis
movie courtesy of V. Stepan (NPI-ASCR/CENBG/CNRS/IN2P3/ESA) -

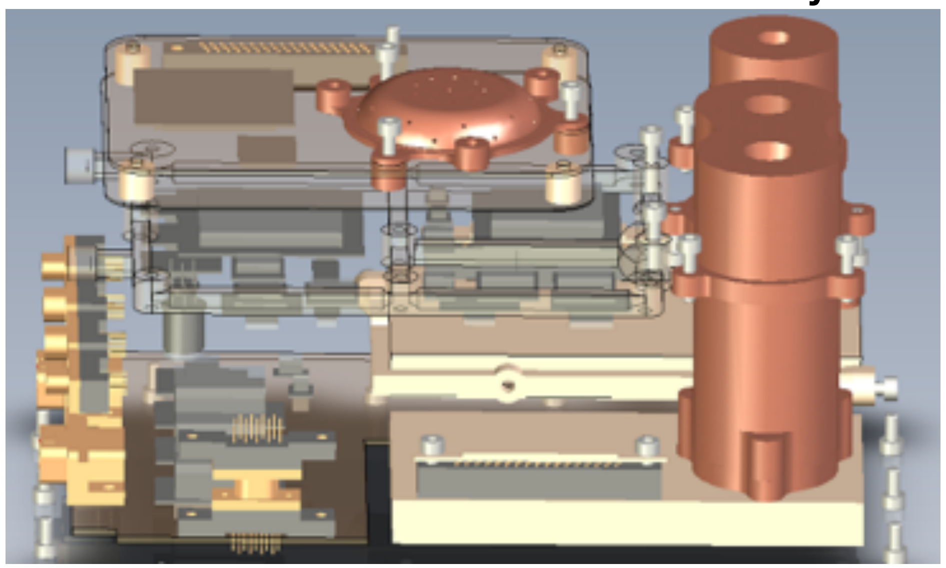


GATE - numerical simulations in medical imaging and radiotherapy. Simulations of Emission Tomography (PET and SPECT), Computed Tomography (CT), Optical Imaging (Bioluminescence and Fluorescence) and Radiotherapy experiments.

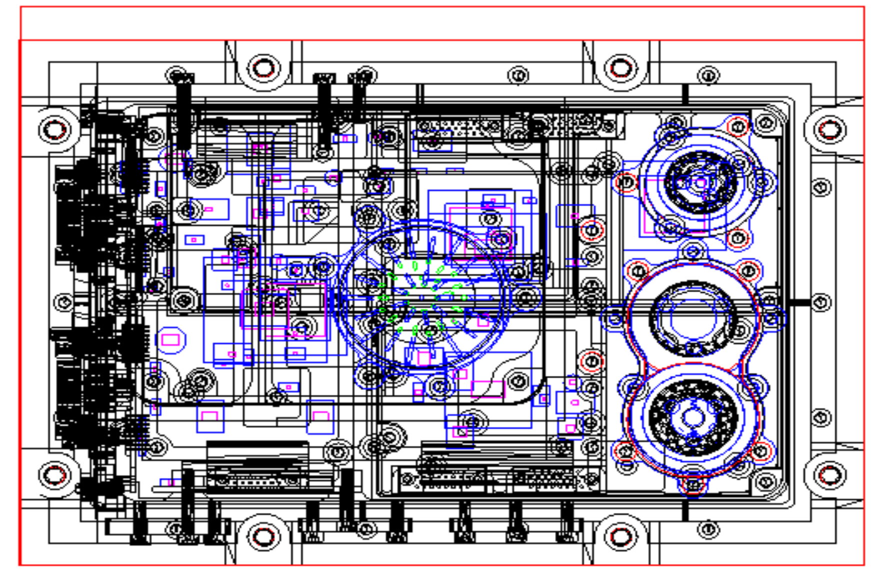
Geant4 @ LIP



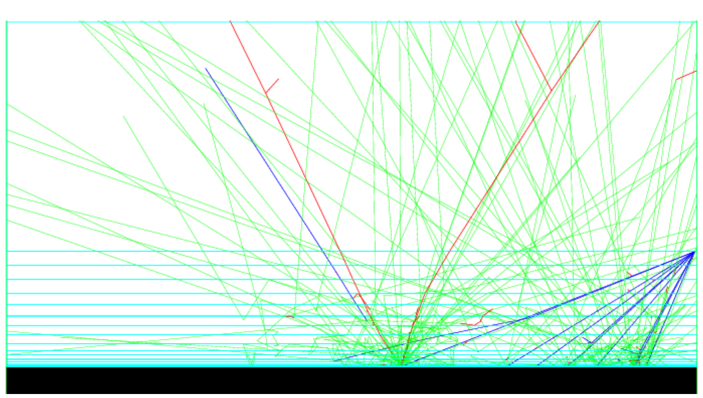
RADEM - Radiation Monitor for the Jovian system

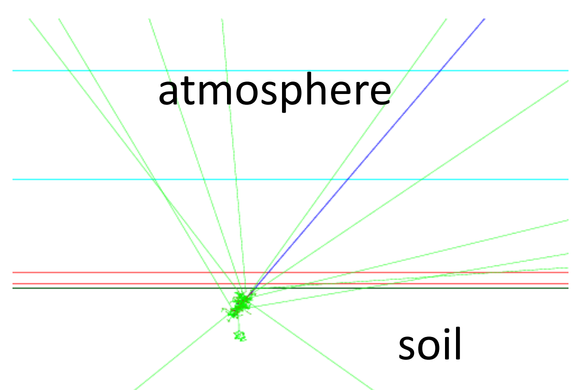


CAD model of RADEM

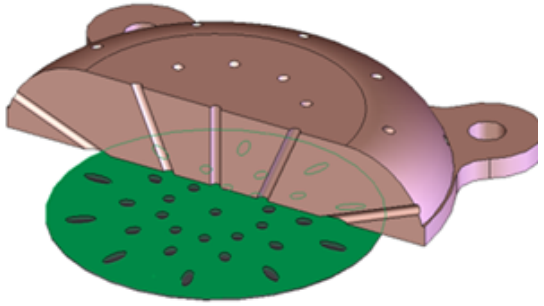


detailed Martian Energetic Radiation Environment Model

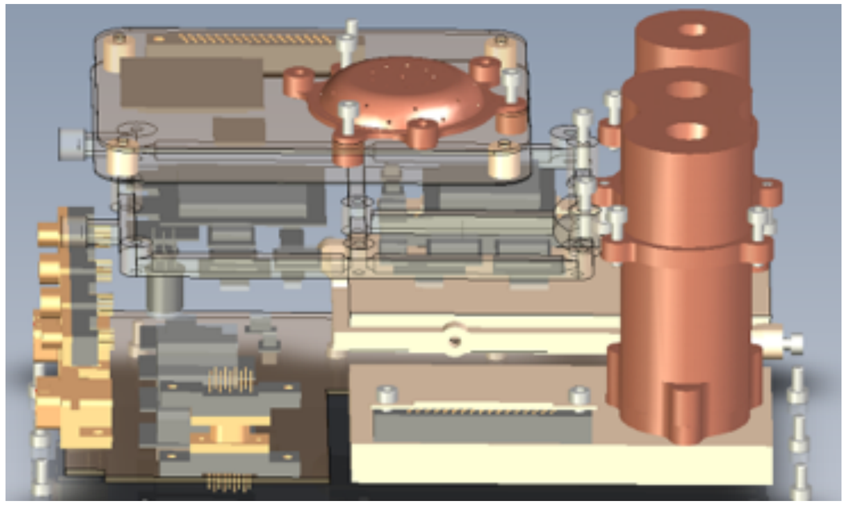




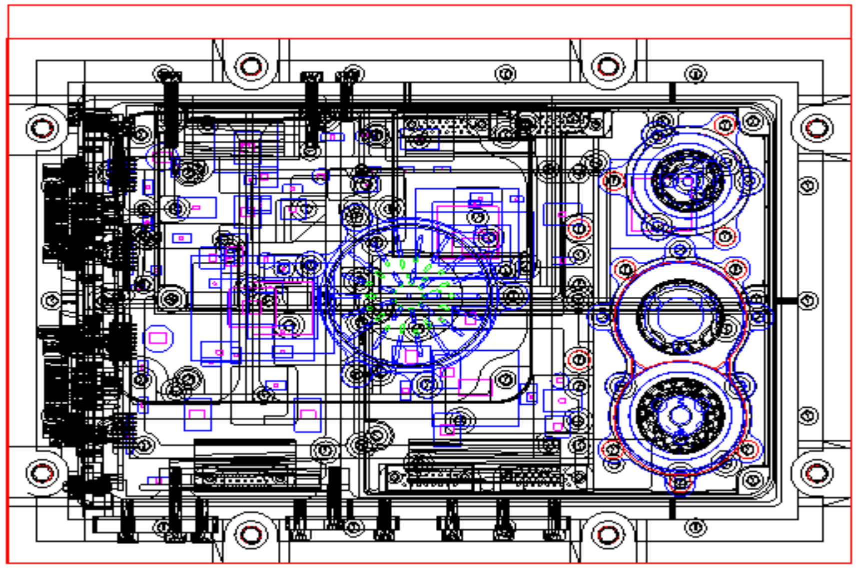
Geant4 @ LIP



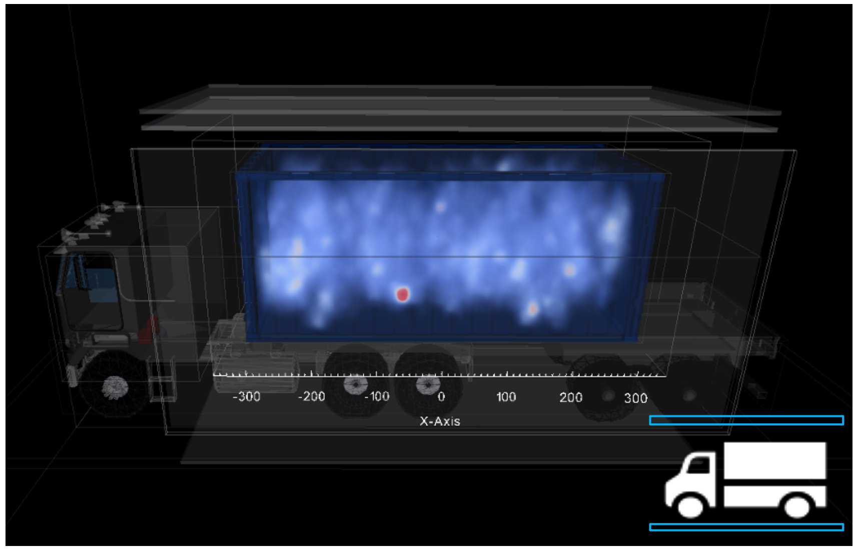
RADEM - Radiation Monitor for the Jovian system



CAD model of RADEM

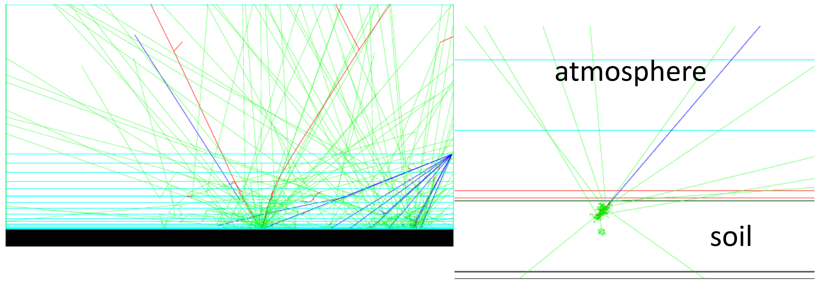


Muon tomography



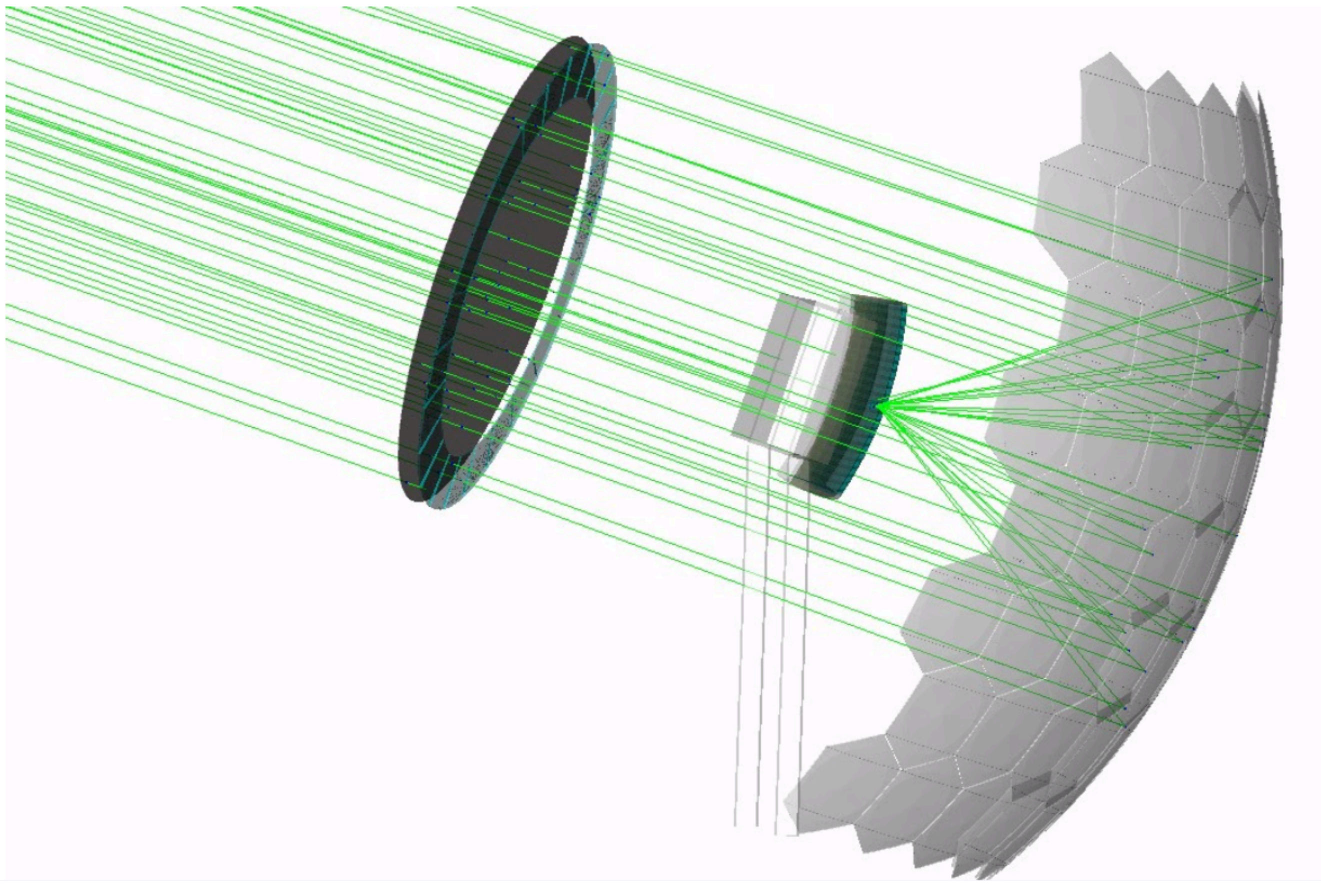
Simulation of particles interacting in the Martian atmosphere and soil

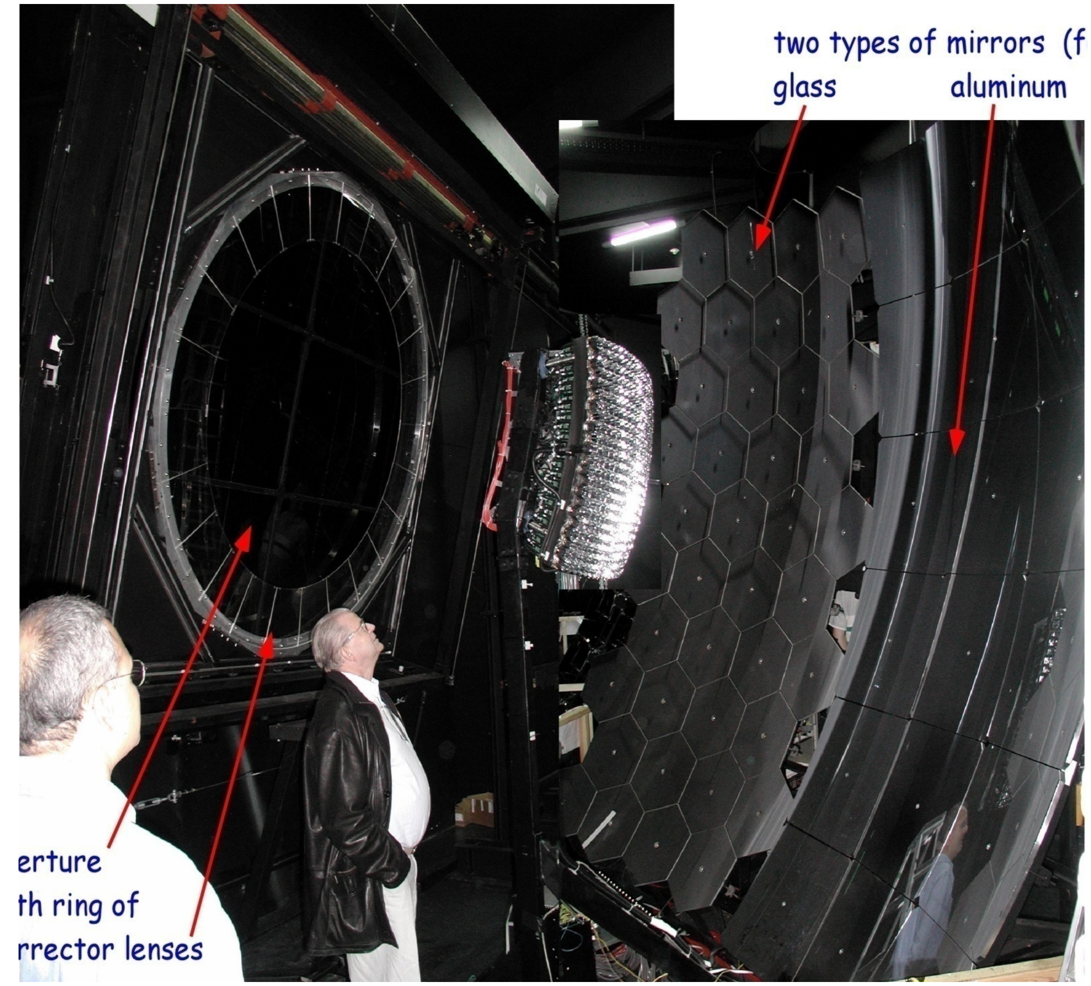
detailed Martian Energetic Radiation Environment Model

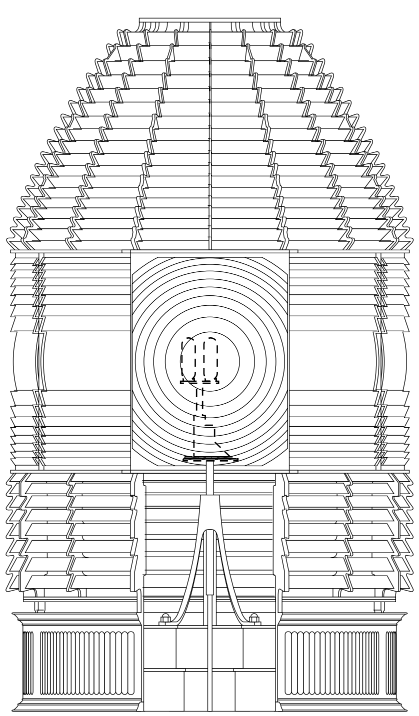


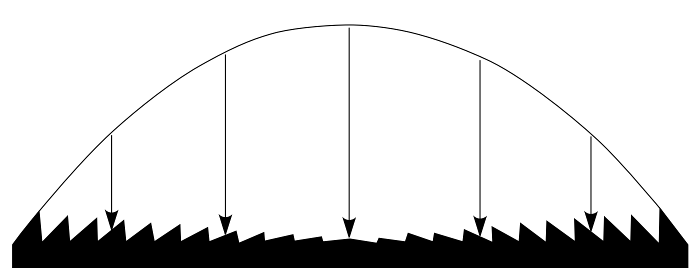
Geant4 @ LIP - Optics simulations

Fluorescence Detector of the Pierre Auger Observatory

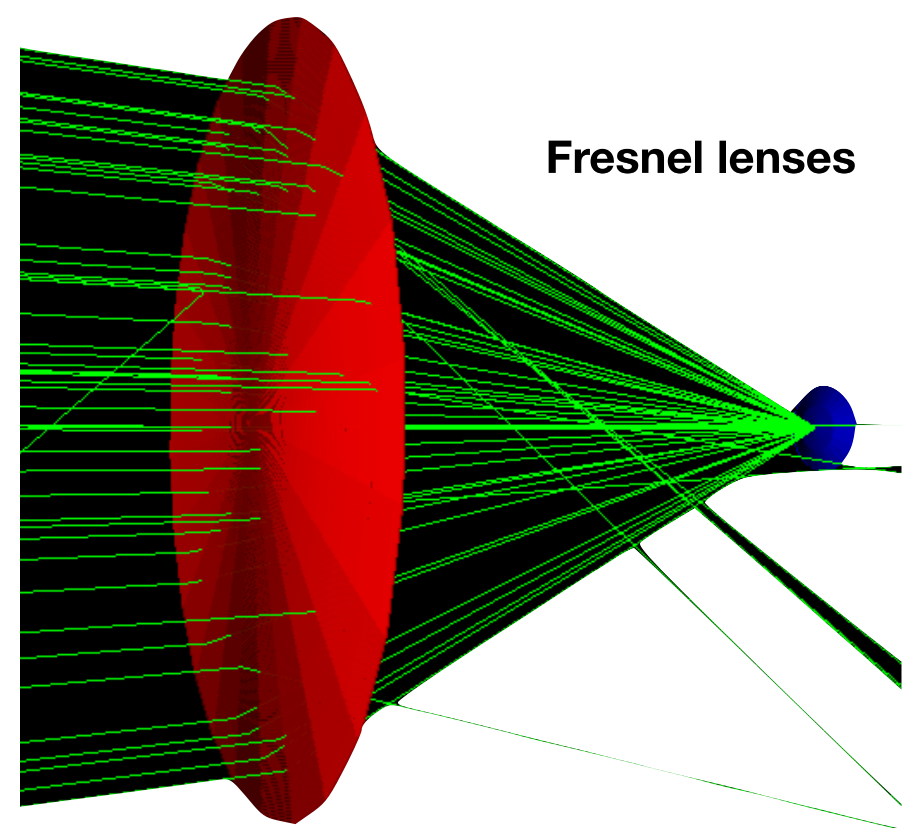






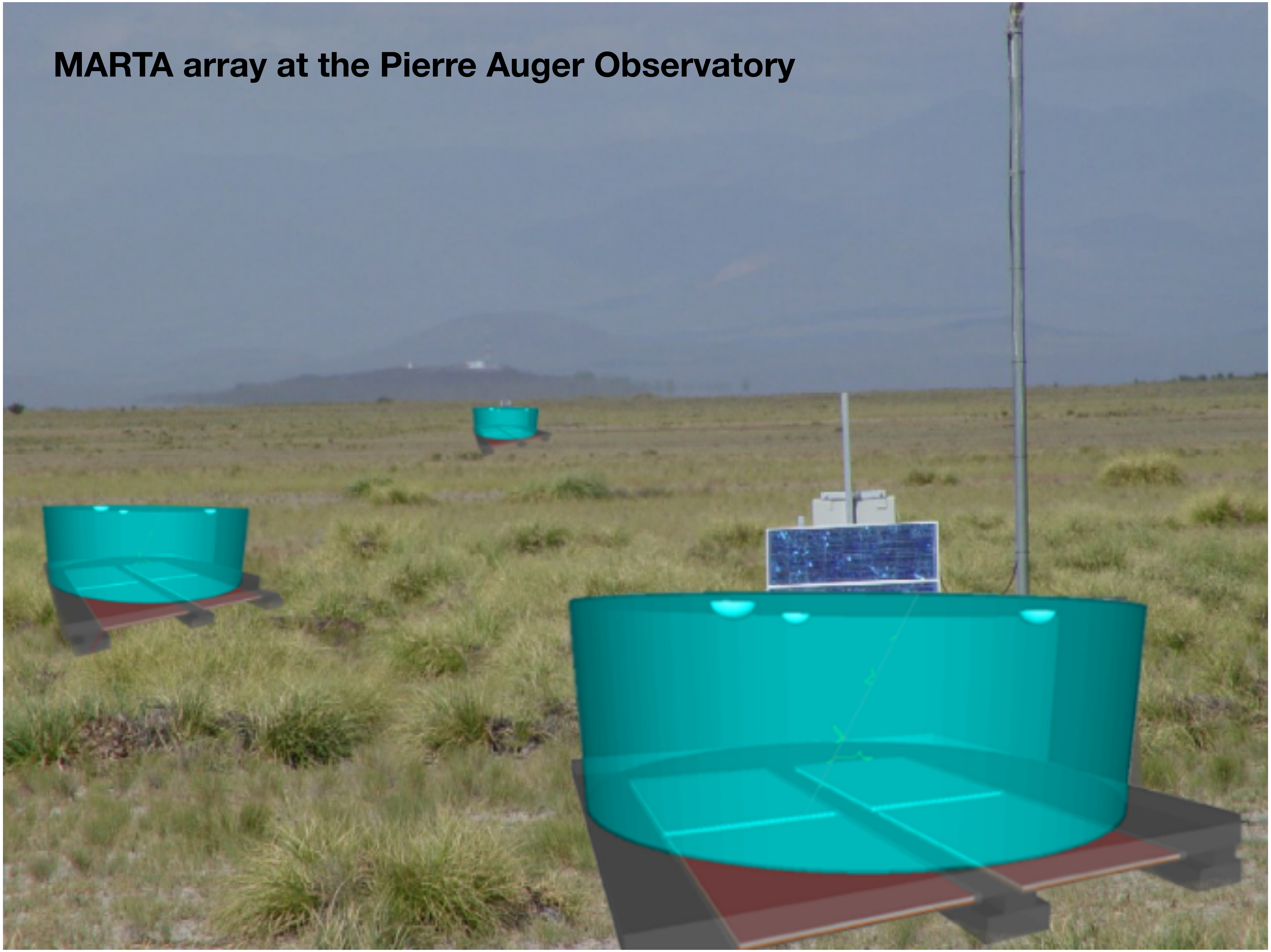


Fresnel lenses in the St. Augustine (Florida) lighthouse



Fresnel lenses

Simulations of full cosmic ray detectors



SWGO

Southern Wide-field Gamma-ray Observatory

Energy range 100 GeV – 100 TeV (hopefully up to tens of PeV !)
High altitude in South America
Based on Water Cherenkov Detectors (WCD)