

Detector Simulation Introduction

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Content

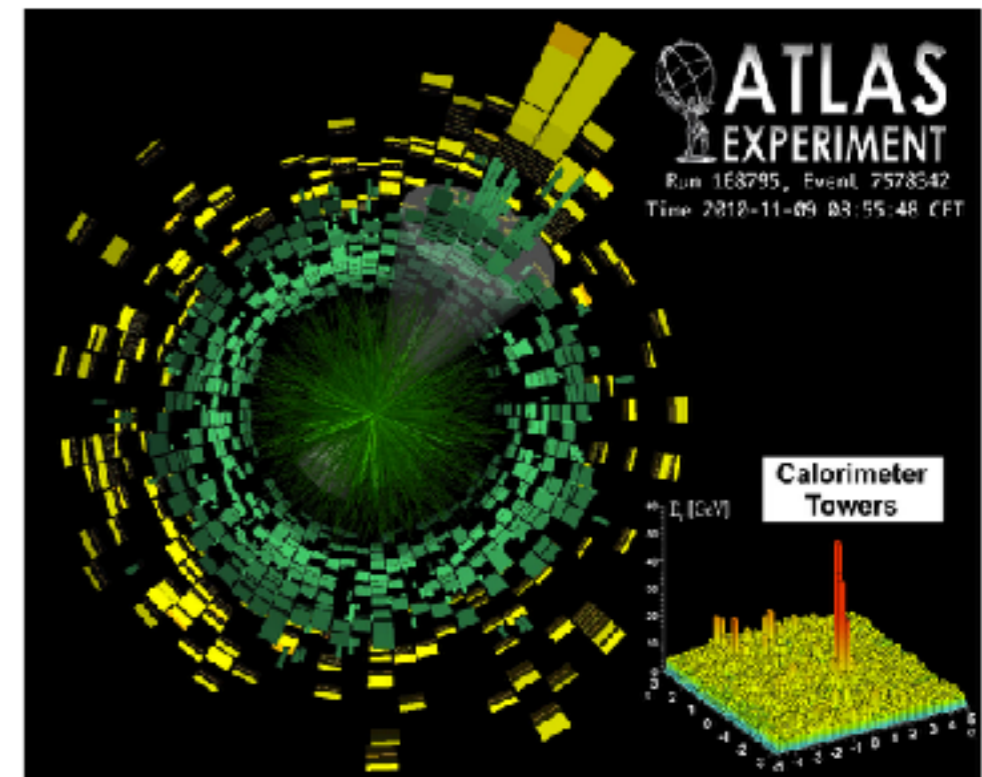
- Introduction to Monte Carlo methods and to Geant4 toolkit
- Geant4 toolkit architecture and physics
- Building a concrete Geant4 application

Introduction to Monte Carlo methods

- What problems do we face?
- What is simulation?
- Why do we need Monte Carlo?

Problems

- to design the apparatus (detector) to fulfil its role
- to run it according to our needs
- to understand the results
- to observe new phenomena



Solution

- SIMULATION
 - we need to simulate the detector before we build it
 - we need to simulate it when we run it
 - we need to simulate it when we analyse results

What is simulation

- simulation = doing 'virtual' experiment
- take all the known physics
- start from your 'initial condition' (two protons colliding)
- calculate the 'final state' of your detector to get the 'experimental' results
 - solve equations of motion, etc
- **IMPOSSIBLE** to be done analytically

Way to do it: Monte Carlo

- analytical solutions impossible due to
 - complexity of the problem
 - number of particles, etc
 - lack of analytical description
 - need of randomness like in nature
 - to pick among possible choices
 - quantum mechanics, fluctuations
 - ... because Einstein was wrong: God does throw dice!
 - Quantum mechanics amplitudes = probabilities. Anything that possibly can happen, will. (but more or less often)



Monte Carlo method

- repeated random sampling to find the result
- used for
 - numerical integration, calculation
 - generation of samples from probability distribution
 - optimisation
 - etc
- applications
 - Particle physics
 - Quantum field theory
 - Astrophysics
 - Molecular modelling
 - Semiconductor devices
 - Light transport calculations
 - Traffic flow simulations
 - Environmental sciences
 - Financial market simulations
 - Optimisation problems
 - ...



Buffon's Needle

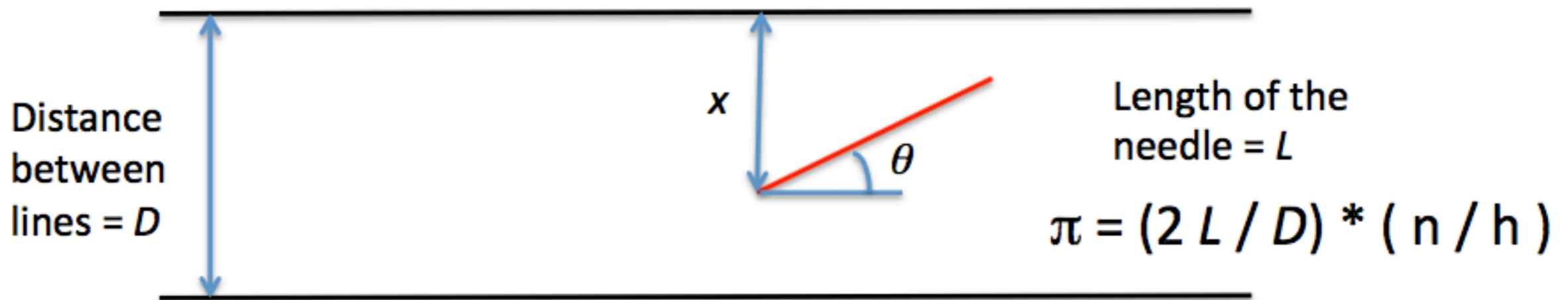
- One of the oldest problems in the field of geometrical probability, first stated in 1777.
- Drop a needle on a lined sheet of paper and determine the probability of the needle crossing one of the lines
- Remarkable result: probability is directly related to the value of π
- The needle will cross the line if $x \leq L \sin(\vartheta)$. Assuming $L \leq D$, how often will this occur?



$$P_{cut} = \int_0^\pi P_{cut}(\theta) \frac{d\theta}{\pi} = \int_0^\pi \frac{L \sin \theta}{D} \frac{d\theta}{\pi} = \frac{L}{\pi D} \int_0^\pi \sin \theta d\theta = \frac{2L}{\pi D}$$

- By sampling P_{cut} one can estimate π .

we drop n needles and find that h of those needles are crossing lines



Laplace's method of calculating π (1886)

- Area of the square = 4
- Area of the circle = π
- Probability of random points inside the circle = $\pi / 4$

- Random points : N
- Random points inside circle : N_c

$$\pi \sim 4 N_c / N$$



- Fermi (1930): random method to calculate the properties of the newly discovered neutron
- Manhattan project (40's): simulations during the initial development of thermonuclear weapons. von Neumann and Ulam coined the term "Monte Carlo"
- Metropolis (1948) first actual Monte Carlo calculations using a computer (ENIAC)
- Berger (1963): first complete coupled electron-photon transport code that became known as ETRAN
- Exponential growth since the 1980's with the availability of digital computers

Geant 4

Basics of Monte Carlo method

- A variable is considered **random** (also called **stochastic**) if its value cannot be specified in advance of observing it.
 - Let x be a single continuous random variable defined over some interval. The interval can be finite or infinite
- The value of x on any observation cannot be specified in advance, but it is possible to talk in terms of probabilities
 - $\text{Prob}\{x_i \leq X\}$ represents the probability that an observed value x_i will be less than or equal to some specified value X . More generally, $\text{Prob}\{E\}$ is used to represent the probability of an event E
- A **Probability Density Function** (PDF) of a single stochastic variable is a function that has the following three properties:
 - 1) it is defined on an interval $[a, b]$
 - 2) it is non-negative on that interval
 - 3) it is normalized such that $\int_a^b f(x) dx = 1$ and a and b are real numbers with $a \rightarrow -\infty$ and/or $b \rightarrow \infty$

- A PDF $f(x)$ is a density function, i.e., it specifies the probability per unit of x , so that $f(x)$ has units that are the inverse of the units of x
- For a continuous random variable, $f(x)$ is not the probability of obtaining x
 - there are infinitely many values that x can assume and the probability of obtaining a single specific value is zero
- Rather, the quantity $f(x) dx$ is the probability that a random sample x_i will assume a value within x and $x+dx$
 - often, this is stated in the form
$$f(x) = \text{Prob}\{ x \leq x_i < x+dx \}$$

- The integral defined by

$$F(x) \equiv \int_a^x f(x') dx'$$

where $f(x)$ is a PDF over the interval $[a, b]$, is called the **Cumulative Distribution Function** (CDF) of f .

- A CDF has the following properties:

- 1) $F(a) = 0.$, $F(b) = 1.$

- 2) $F(x)$ is monotonic increasing, as $f(x)$ is always non-negative

- The CDF is a direct measure of probability. The value $F(x_i)$ represents the probability that a random sample of the stochastic variable x will assume a value between a and x_i , i.e., $\text{Prob}\{a \leq x \leq x_i\} = F(x_i)$.
- More generally,

$$\text{Prob}\{x_1 \leq x \leq x_2\} = \int_{x_1}^{x_2} f(x) dx = F(x_2) - F(x_1).$$

Geant 4

Two Monte Carlo Particle Transport Examples

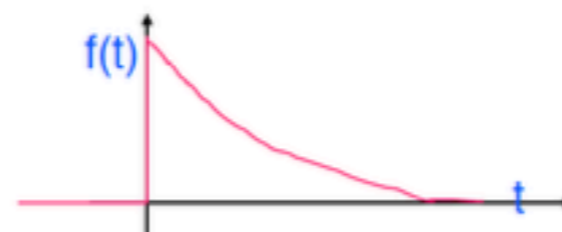


Simplest case – decay in flight (1)

- Suppose an unstable particle of life time t has initial momentum p (\rightarrow velocity v).
 - Distance to travel before decay : $d = t v$
- The decay time t is a random value with probability density function

$$f(t) = \frac{1}{\tau} \exp\left(-\frac{t}{\tau}\right) \quad t \geq 0$$

τ is the mean life of the particle



- the probability that the particle decays at time t is given by the cumulative distribution function F which is itself is a random variable with uniform probability on $[0,1]$

$$r = F(t) = \int_{-\infty}^t f(u) du$$

- Thus, having a uniformly distributed random number r on $[0,1]$, one can sample the value t with the probability density function $f(t)$.

$$t = F^{-1}(r) = -\tau \ln(1 - r) \quad 0 \leq r < 1$$

Simplest case – decay in flight (2)

- When the particle has traveled the $d = t v$, it decays.
- Decay of an unstable particle itself is a random process → Branching ratio

– For example:

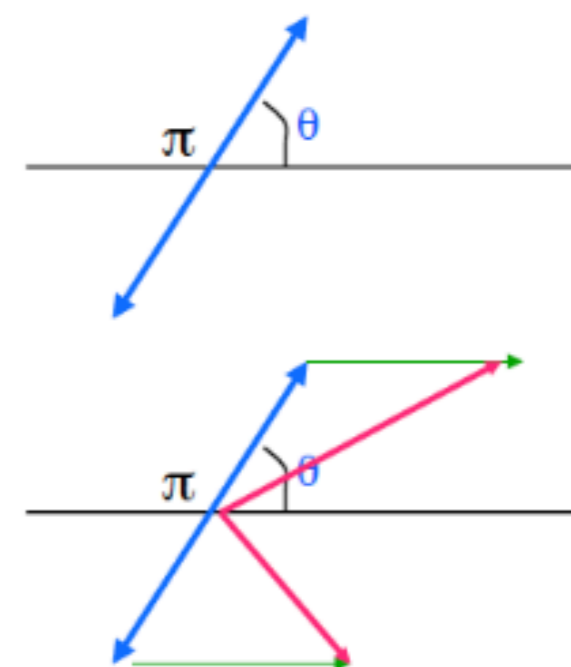
$\pi^+ \rightarrow \mu^+ \nu_\mu$	(99.9877 %)
$\pi^+ \rightarrow \mu^+ \nu_\mu \gamma$	(2.00×10^{-4} %)
$\pi^+ \rightarrow e^+ \nu_e$	(1.23×10^{-4} %)
$\pi^+ \rightarrow e^+ \nu_e \gamma$	(7.39×10^{-7} %)
$\pi^+ \rightarrow e^+ \nu_e \pi^0$	(1.036×10^{-8} %)
$\pi^+ \rightarrow e^+ \nu_e e^+ e^-$	(3.2×10^{-9} %)

- Select a decay channel by shooting a random number
- In the rest frame of the parent particle, rotate decay products in $\theta [0, \pi)$ and $\phi [0, 2\pi)$ by shooting a pair of random numbers

$$d\Omega = \sin\theta d\theta d\phi$$

$$\theta = \cos^{-1}(r_1), \quad \phi = 2\pi \times r_2 \quad 0 \leq r_1, r_2 < 1$$

- Finally, Lorentz-boost the decay products
- You need at least 4 random numbers to simulate one decay in flight



Compton scattering (1)

- Compton scattering

$$e^- \gamma \rightarrow e^- \gamma$$

- Distance traveled before Compton scattering, l , is a random value

Cross section per atom : $\sigma(E, z)$

Number of atoms per volume : $n = \rho N_A / A$

ρ : density, N_A : Avogadro number, A : atomic mass

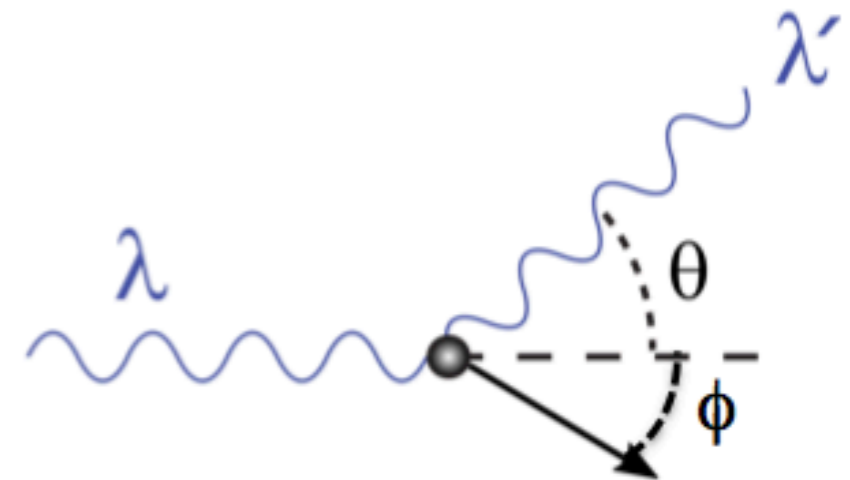
Cross section per volume : $\eta(E, \rho) = n \sigma$

- η is the probability of Compton interaction per unit length. $\lambda(E, \rho) = \eta^{-1}$ is the **mean free path** associated with the Compton scattering process.
- The probability density function $f(l)$

$$f(l) = \eta \exp(-\eta l) = \frac{1}{\lambda} \exp\left(-\frac{l}{\lambda}\right)$$

- With a uniformly distributing random number r on $[0,1)$, One can sample the distance l .

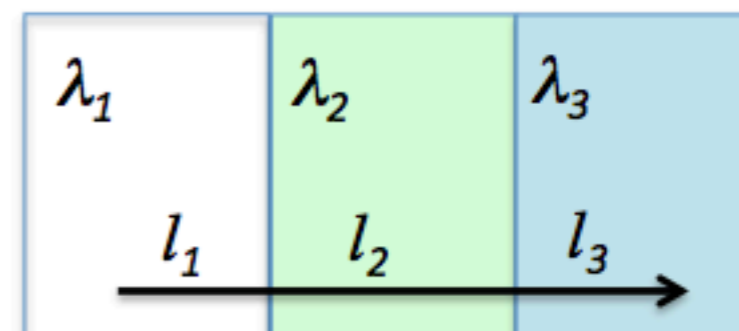
$$l = -\lambda \ln(r) \quad 0 \leq r < 1$$



Compton scattering (2)

- $\lambda(E, \rho)$ and l are material dependent. Distance measured by the unit of mean free path (n_λ) is independent.

$$n_\lambda = \frac{l_1}{\lambda_1} + \frac{l_2}{\lambda_2} + \frac{l_3}{\lambda_3} = \int_0^{end} \frac{dl}{\lambda(l)}$$



- n_λ is independent of the material and a random value with probability density function $f(n_\lambda) = \exp(-n_\lambda)$
 - sample n_λ at the origin of the particle

$$n_\lambda = -\ln(r) \quad 0 \leq r < 1$$

- update elapsed n_λ along the passage of the particle

$$n_\lambda = n_\lambda - l_i / \lambda_i$$

- Compton scattering happens at $n_\lambda = 0$

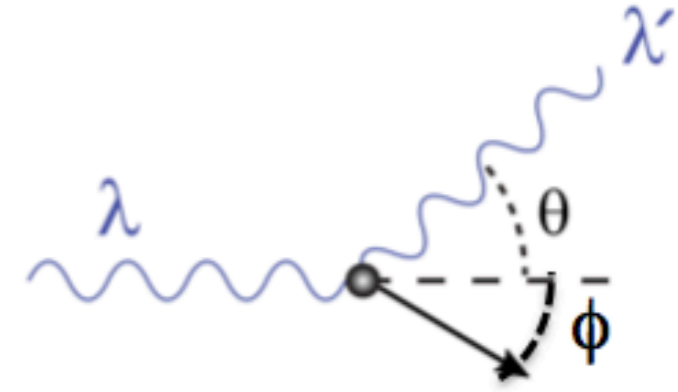
Compton scattering (3)

- The relation between photon deflection (θ) and energy loss for Compton scattering is determined by the conservation of momentum and energy between the photon and recoiled electron.

$$h\nu = \frac{h\nu_0}{1 + \left(\frac{h\nu_0}{m_e c^2}\right) (1 - \cos \theta)},$$

$$E = h\nu_0 - h\nu = m_e c^2 \frac{2(h\nu_0)^2 \cos^2 \phi}{(h\nu_0 + m_e c^2)^2 - (h\nu_0)^2 \cos^2 \phi},$$

$$\tan \phi = \frac{1}{1 + \left(\frac{h\nu_0}{m_e c^2}\right)} \cot \frac{\theta}{2},$$



$h\nu$: energy of incident photon
 $h\nu_0$: energy of scattered photon
 E : energy of recoil electron
 m_e : rest mass of electron
 c : speed of light

- For unpolarized photon, the Klein-Nishina angular distribution function per steradian of solid angle Ω

$$\frac{d\sigma_c^{KN}}{d\Omega}(\theta) = r_0^2 \frac{1 + \cos^2 \theta}{2} \frac{1}{[1 + h\nu(1 - \cos \theta)]^2} \left\{ 1 + \frac{h\nu^2(1 - \cos \theta)^2}{(1 + \cos^2 \theta)[1 + h\nu(1 - \cos \theta)]} \right\}$$

$$= \frac{1}{2} r_0^2 \left(\frac{k}{k_0}\right)^2 \left(\frac{k}{k_0} + \frac{k_0}{k} - \sin^2 \theta\right) \quad (cm^2 sr^{-1} electron^{-1}),$$

- One can use acceptance-rejection method to sample the distribution.

$$k_0 = \frac{h\nu_0}{m_e c^2}, \quad k = \frac{h\nu}{m_e c^2}$$

Monte Carlo in HEP

- Simulation is an essential tool in modern particle physics for:

- prediction event rates and topologies

- can estimate feasibility

- evaluation of possible backgrounds

- can devise analysis strategies

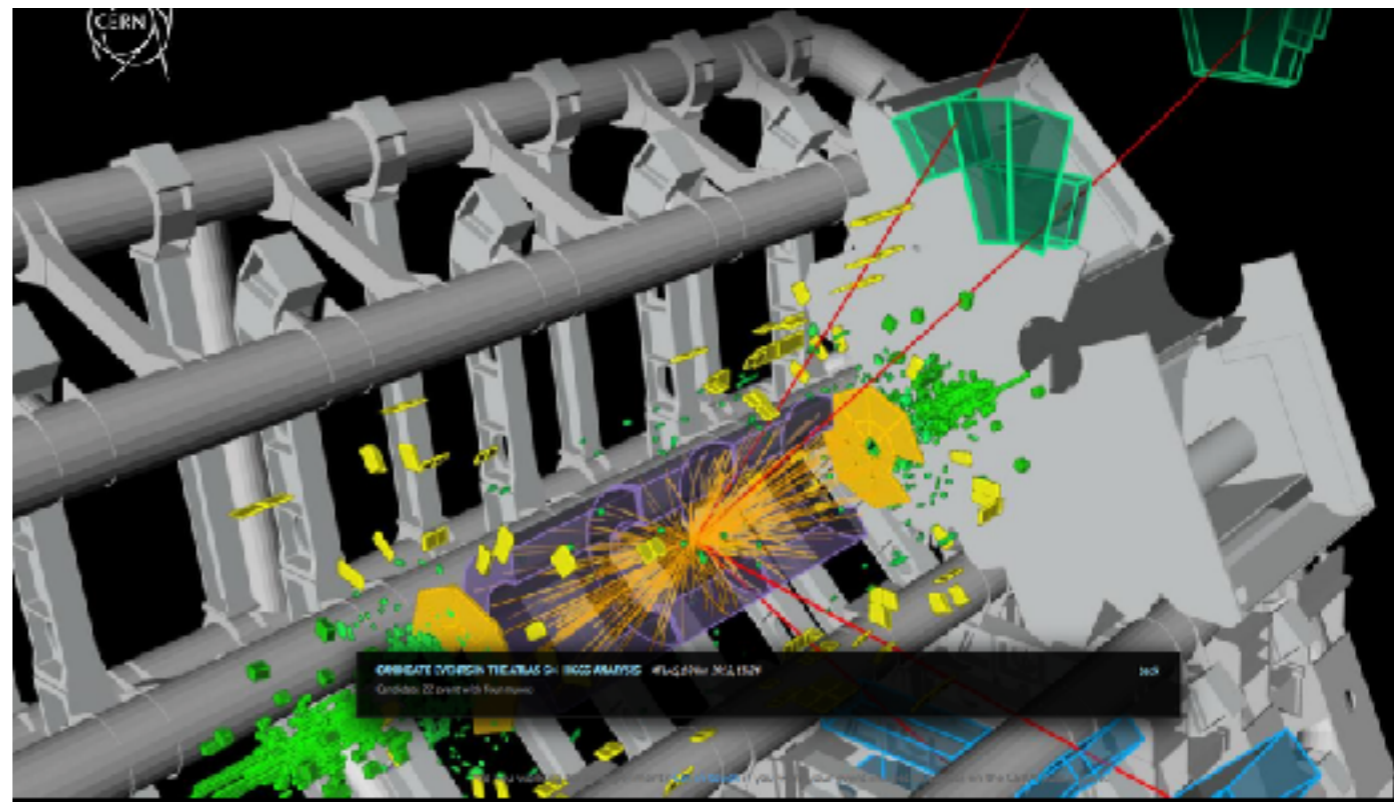
- study detector requirements

- optimisation detector/trigger design

- studying detector imperfections

- can evaluate acceptance corrections

- analysing the data



Monte Carlo in LHC experiments

- For the LHC experiments, the simulation is made of two distinct steps:

1. Simulation of the p-p collision

- Monte Carlo event generators

2. Simulation of the passage of the produced particles through the experimental apparatus

- Monte Carlo radiation transportation, or simply “detector simulation”

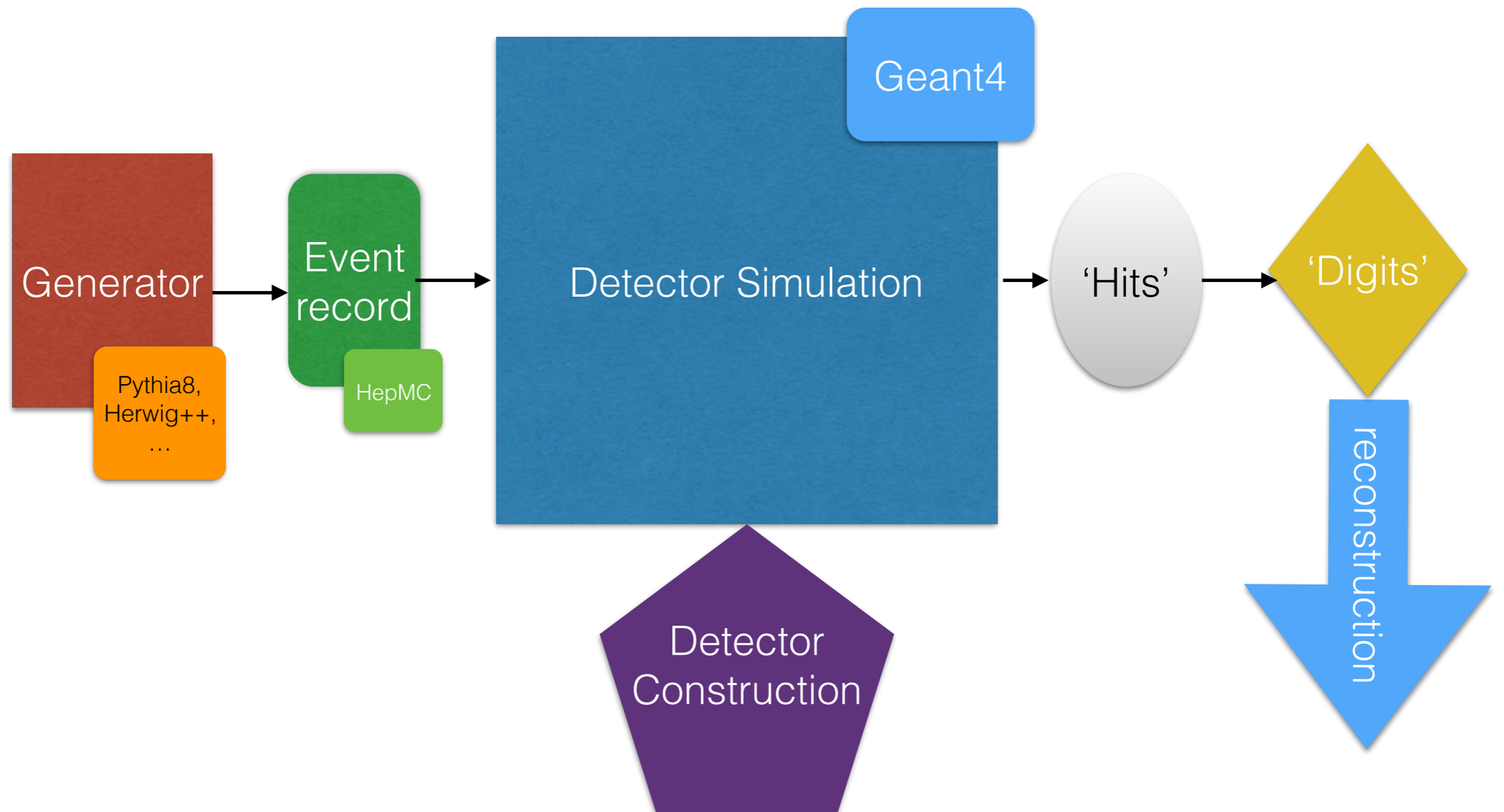
- The output of 1. is the input of 2.



Monte Carlo radiation transportation codes

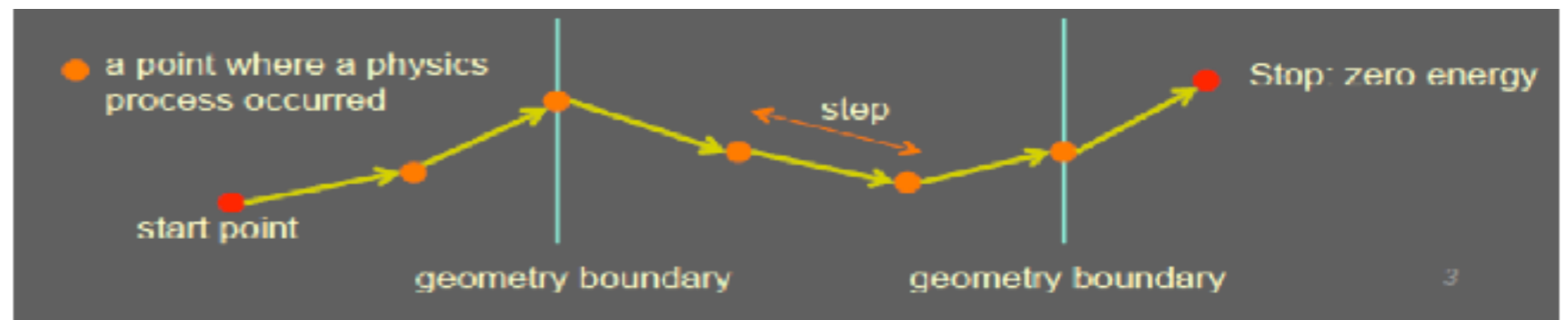
- The simulation of the p-p collision is the same for different experiments at the same collider, e.g. ATLAS and CMS
- The detector simulation is different for each experiment. However, [general codes exist that can be used for simulating any detector](#)
 - An experimental apparatus can be modelled in terms of [elementary geometrical objects](#)
 - The [physics processes](#) are detector independent
- These general codes, e.g. Geant4, are called “[Monte Carlo radiation transportation codes](#)”
 - Non-deterministic (e.g. do not solve equations); use random numbers to reproduce distributions
 - Transport particles through matter

Simulation chain for HEP experiment



How does detector simulation work?

- 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)

Digitization

- Besides the geometry, another experiment-specific aspect of the detector simulation is the “digitization”
 - It is not part of the general radiation transportation codes
- It consists of producing the detector response in terms of **electric current & voltage signals**, as it would happen in the real experiment
 - The same reconstruction chain can be applied for both real and simulated data
- The general radiation transportation code provides **energy deposits** in the whole detector; from these, the “digitization” simulates the **electrical signals** induced in the **sensitive parts** of the detector

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

Application domains

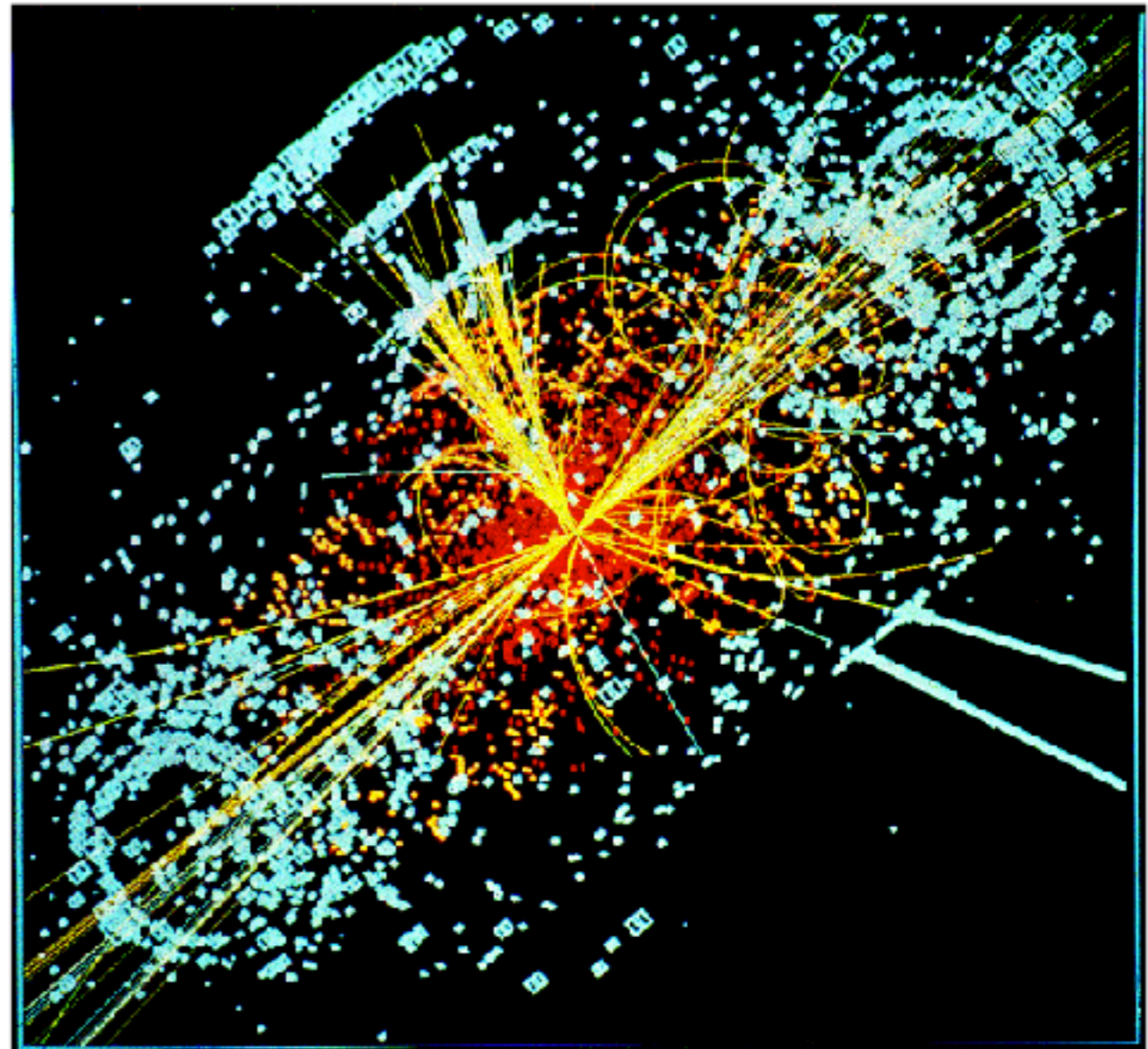
- We are considering here mainly high-energy physics, but... There are other domains where the same radiation transportation codes are successfully used:
 - Nuclear physics
 - Accelerator science
 - Astrophysics
 - Space engineering
 - Radiation damage
 - Medical physics
 - Industrial applications
- So, detector simulation is a multi-disciplinary field!

Monte Carlo toolkits

- Geant4 (Geant3)
- FLUKA
- MCNP, MCNPX
- MARS
- GeantV - ongoing effort to explore parallelism and vectorisation

What is Geant4?

- A software (C++) toolkit for the Monte Carlo simulation of the passage of particles through matter
 - 'propagates' particles through geometrical structures of materials, including magnetic field
 - simulates processes the particles undergo
 - creates secondary particles
 - decays particles
 - calculates the deposited energy along the trajectories and allows to store the information for further processing ('hits')

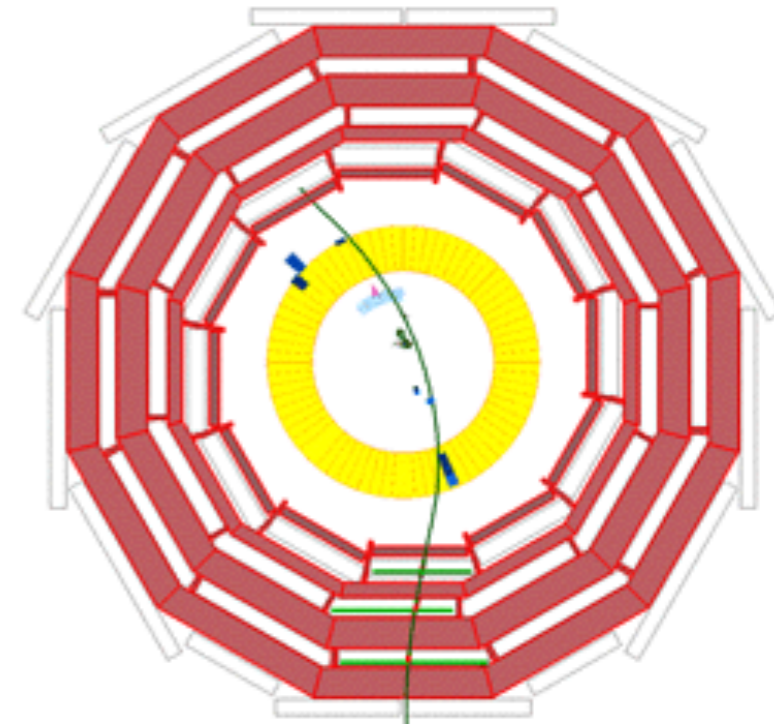


Simulated Higgs event in CMS

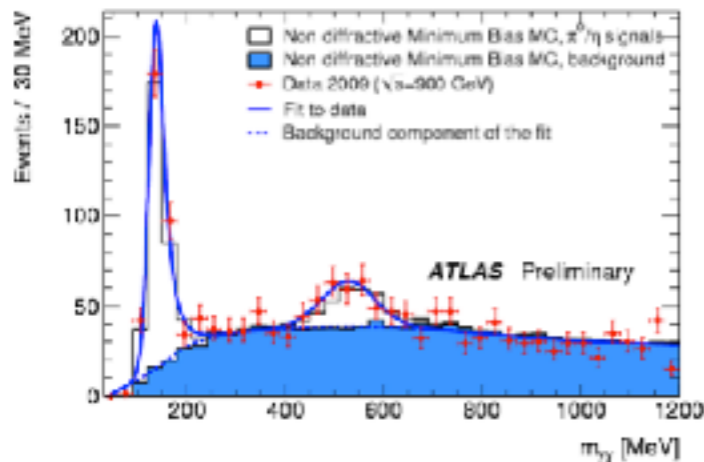
Geant4 has been successfully employed for

- Detector design
- Calibration / alignment
- First analyses

T. LeCompte (ANL)



GEANT4 Comparisons with the Calorimeters



Invariant mass of pairs of well-isolated electromagnetic clusters.

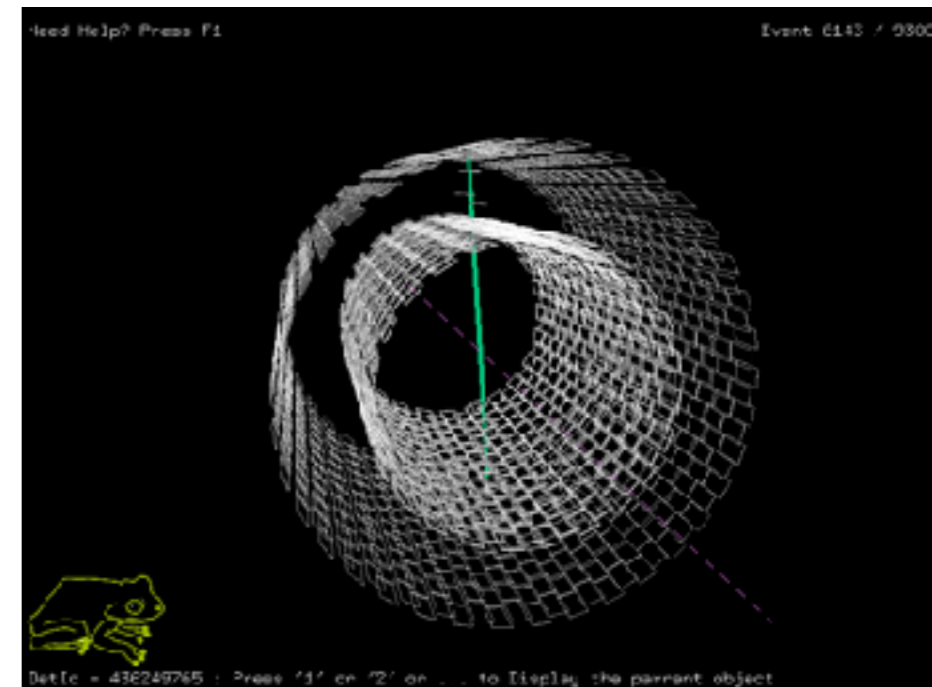
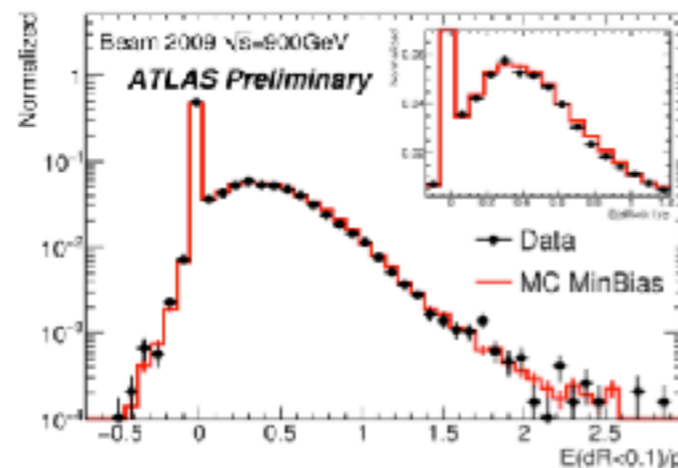
The π^0 mass is within $0.8 \pm 0.6\%$ of expectations.

The η^0 mass is within $3 \pm 2\%$ of expectations.

The detector uniformity is better than 2%.

Response of the calorimeter to single isolated tracks. To reduce the effect of noise, topological clusters are used in summing the energy.

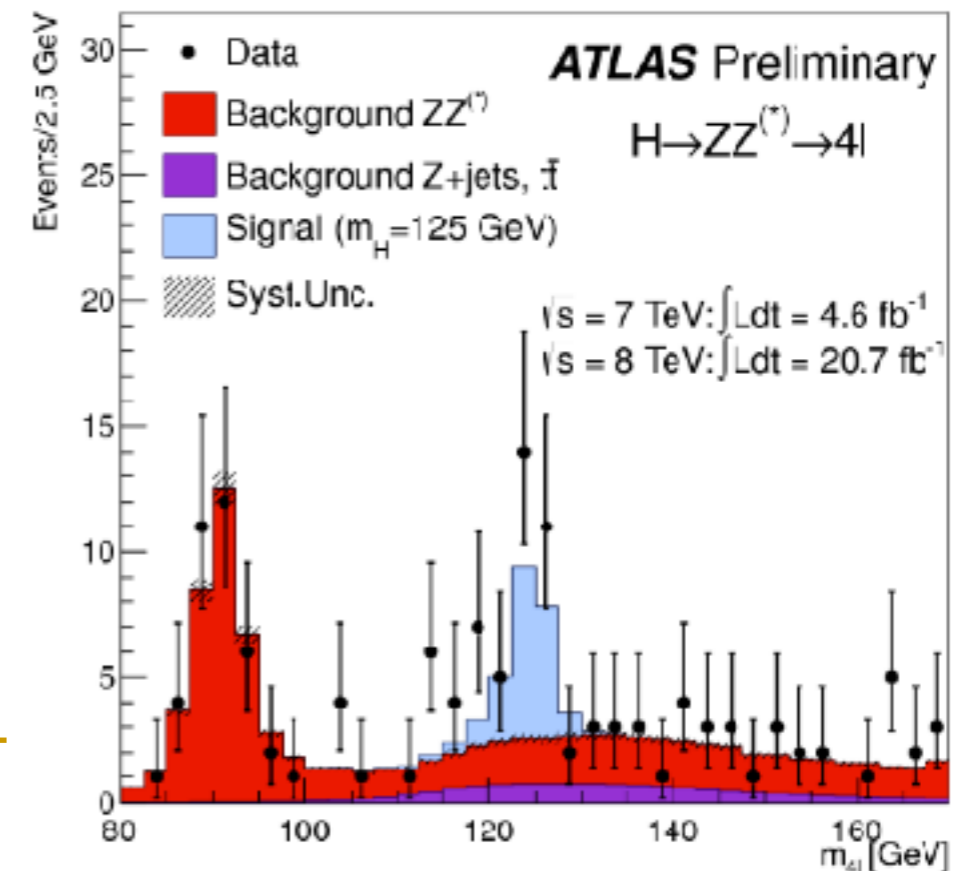
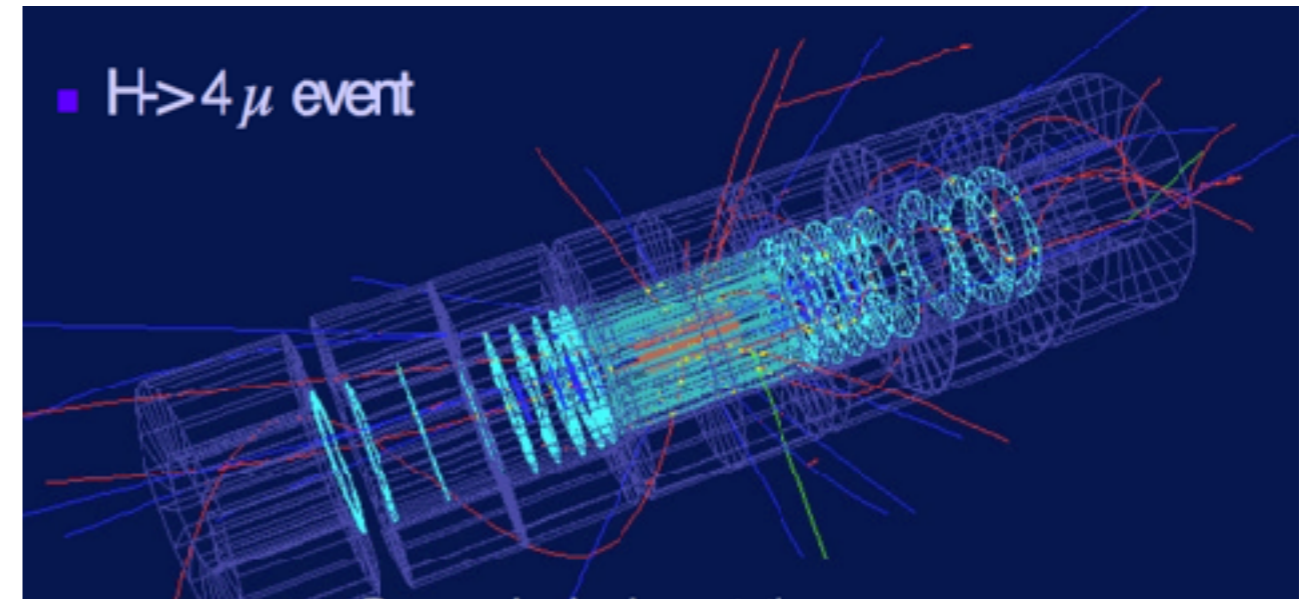
This plot agreed better than we ever expected. (I sent the student who made it back to make sure that they didn't accidentally compare G4 with G4.)



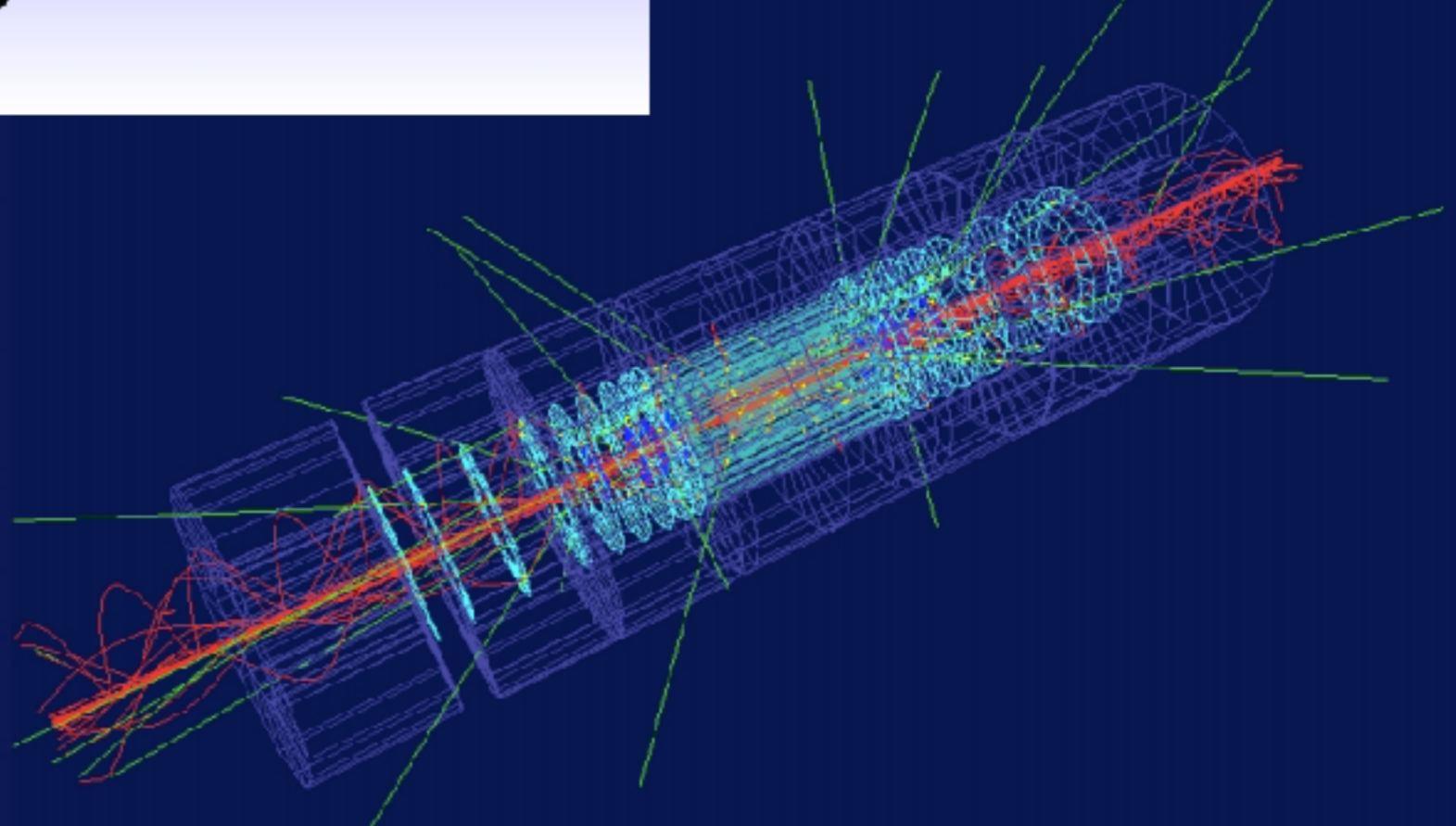
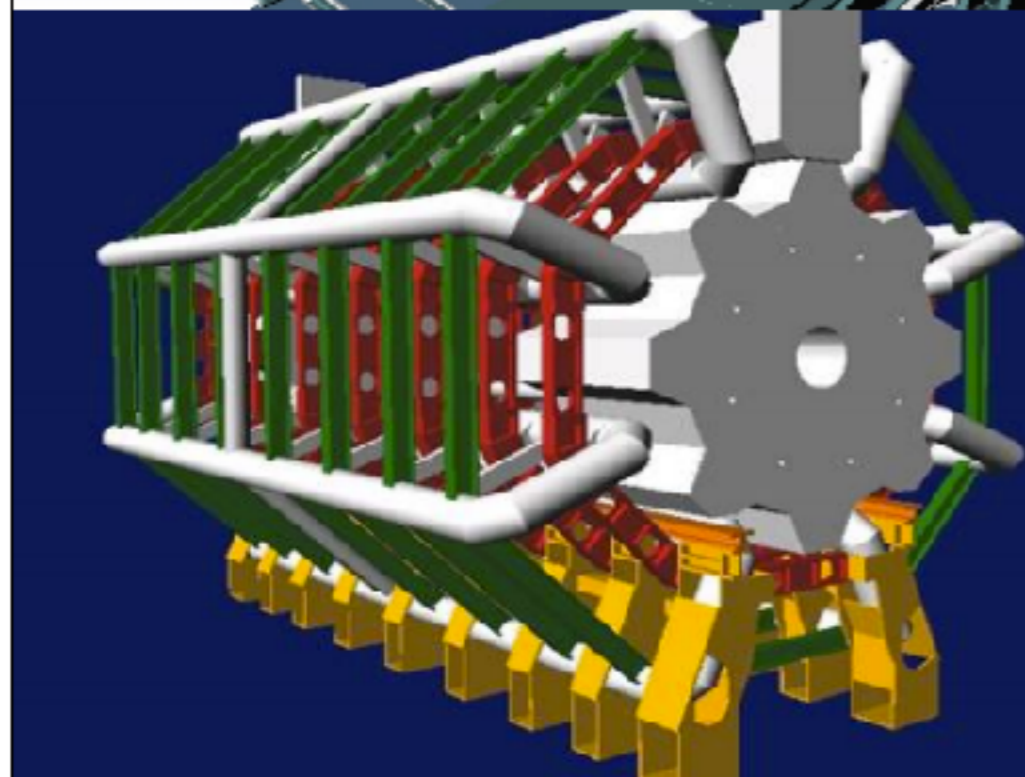
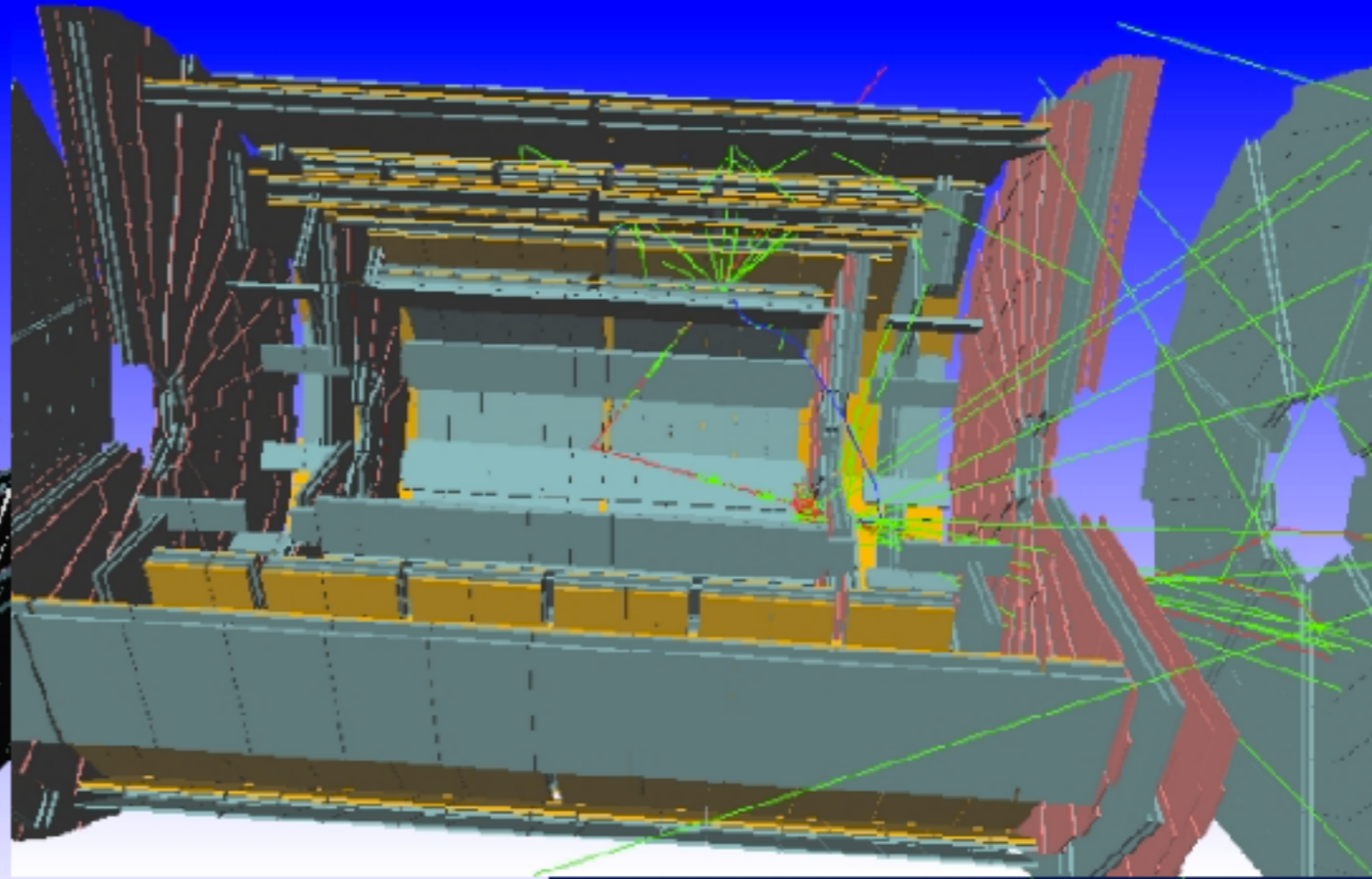
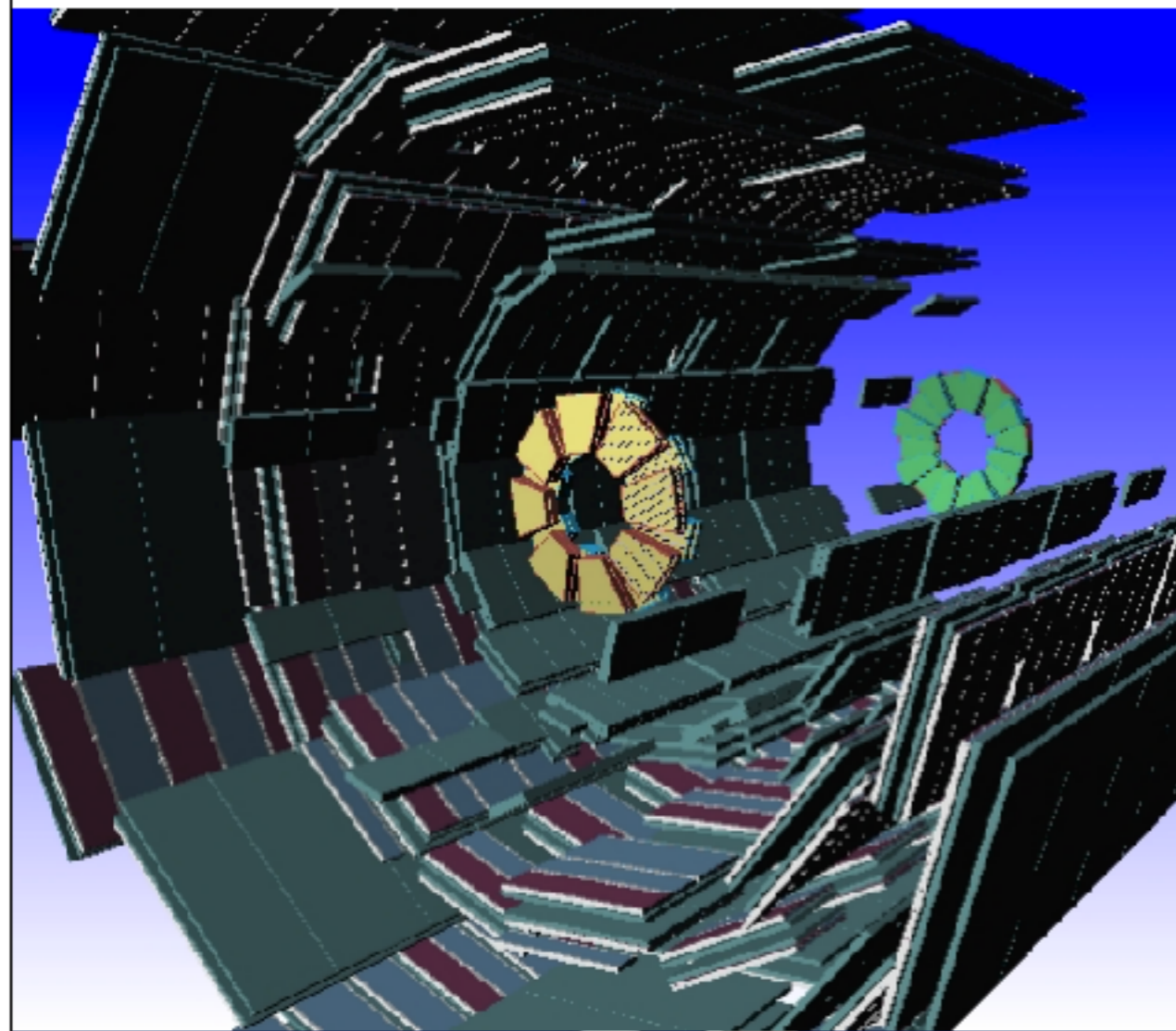
Figures from CMS

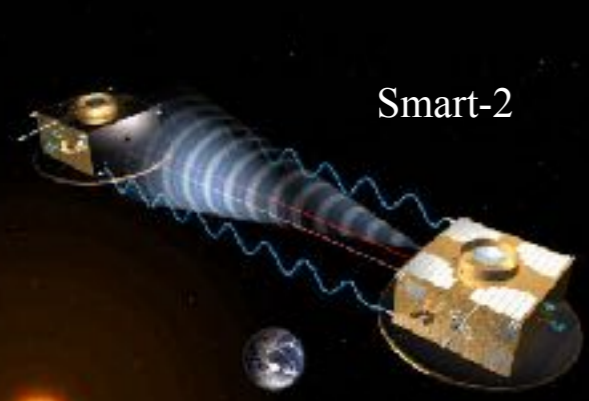
Simulation is needed to make discoveries

- We need to understand the detector to do physics
- We need to know what to expect to
 - verify existing models
 - find new physics

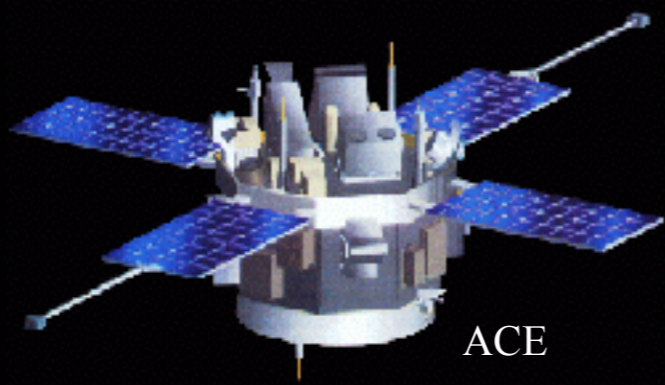


Geant4 in High Energy Physics (ATLAS at LHC)

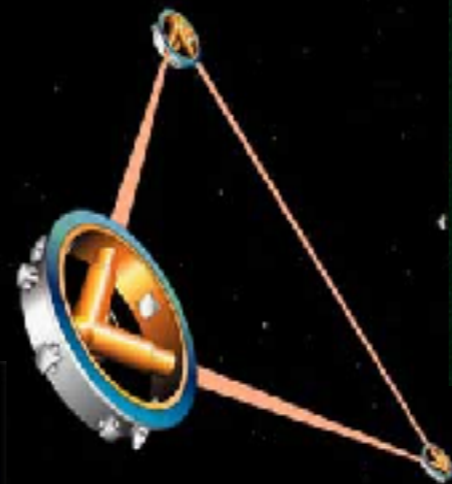




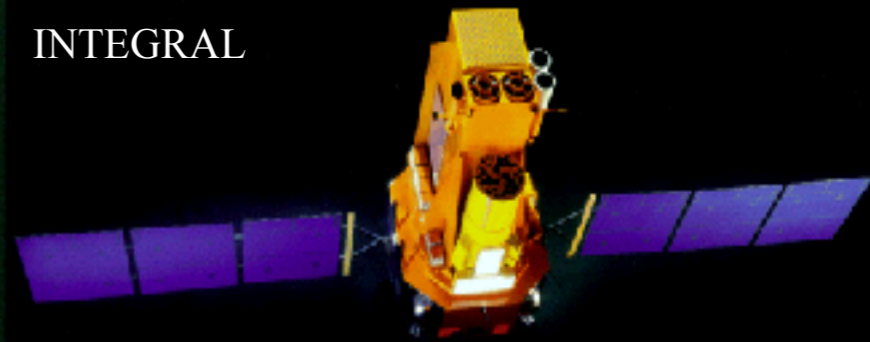
Smart-2



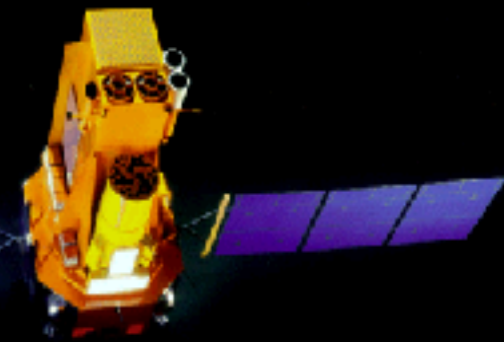
ACE



LISA



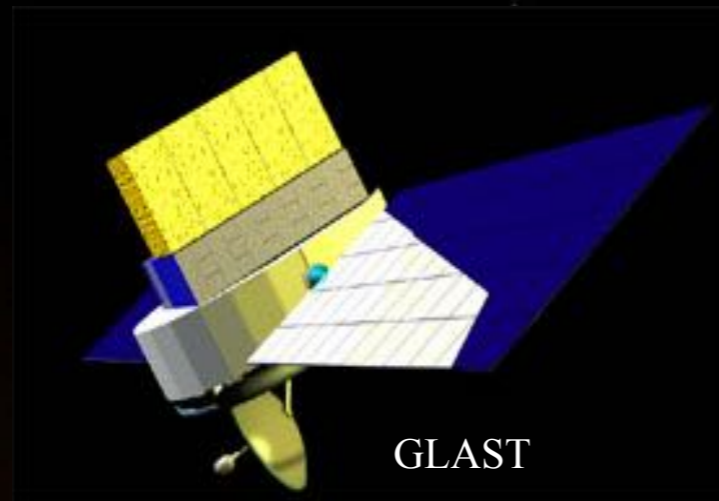
INTEGRAL



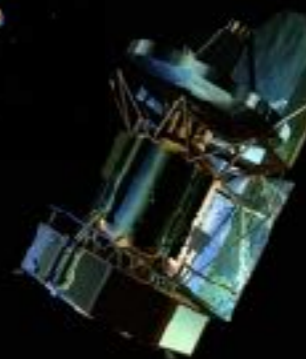
Cassini



Bepi Colombo



GLAST



Herschel



SWIFT



Astro-E2

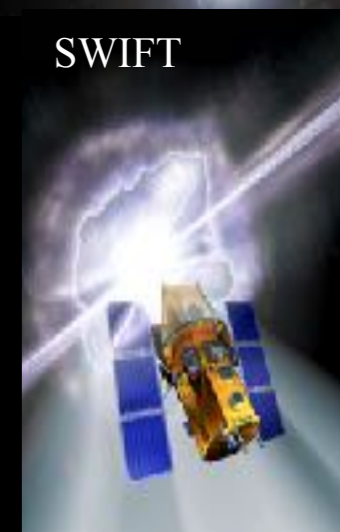


XMM-Newton



GAIA

JWST



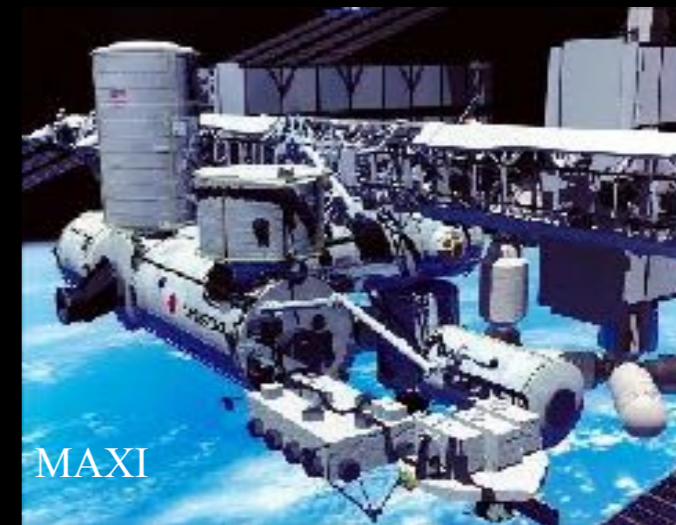
ISS Columbus



EUSO

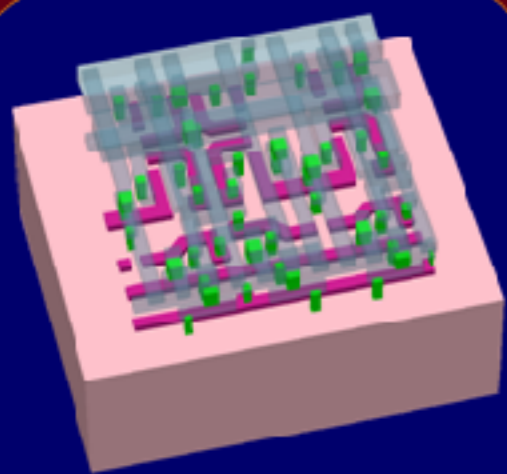


AMS

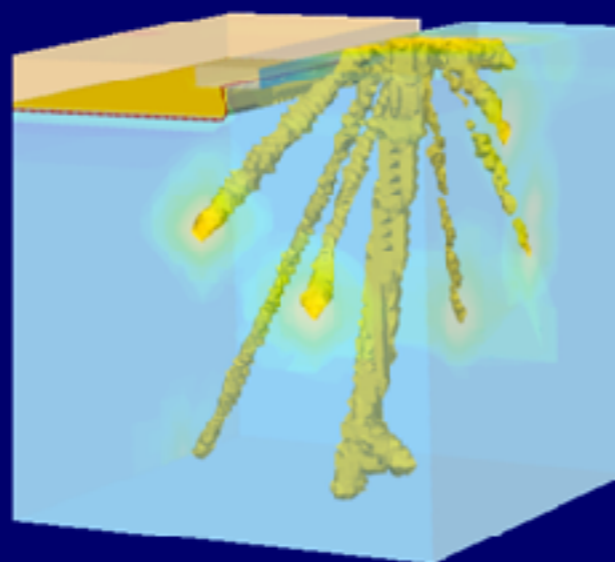


MAXI

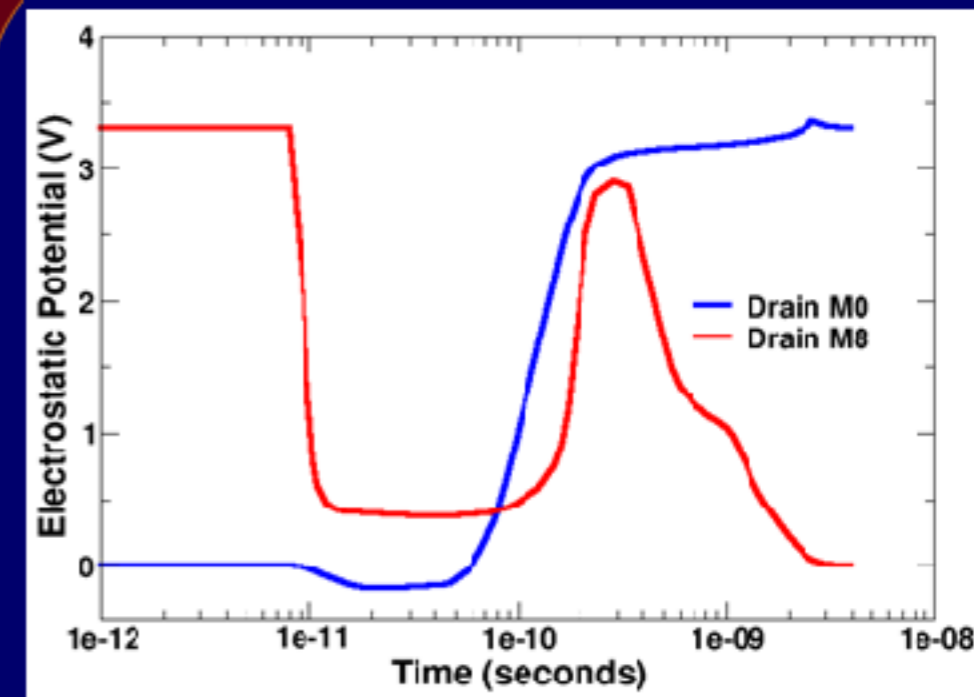
RADSAFE on SEE in SRAMs



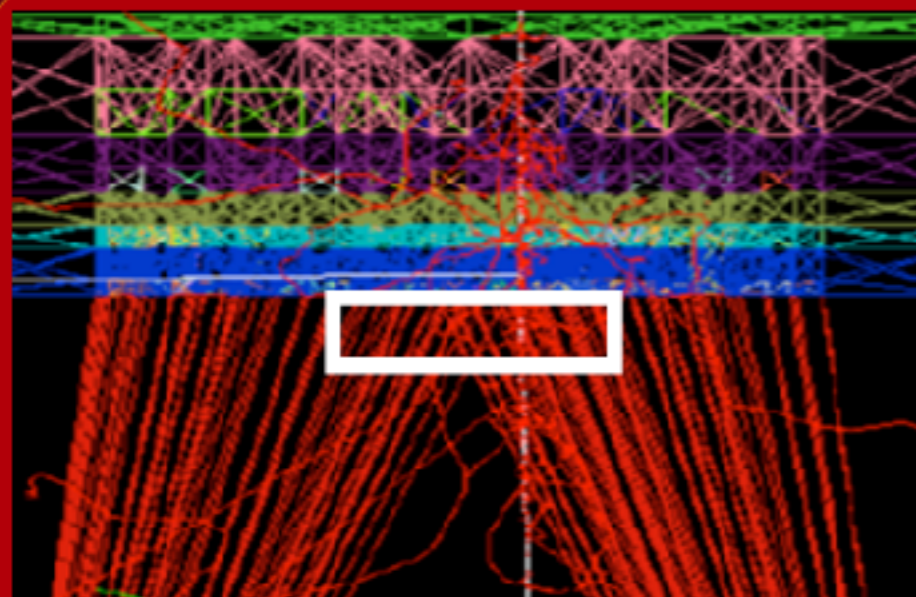
TCAD Cell Structure: SRAM Cell



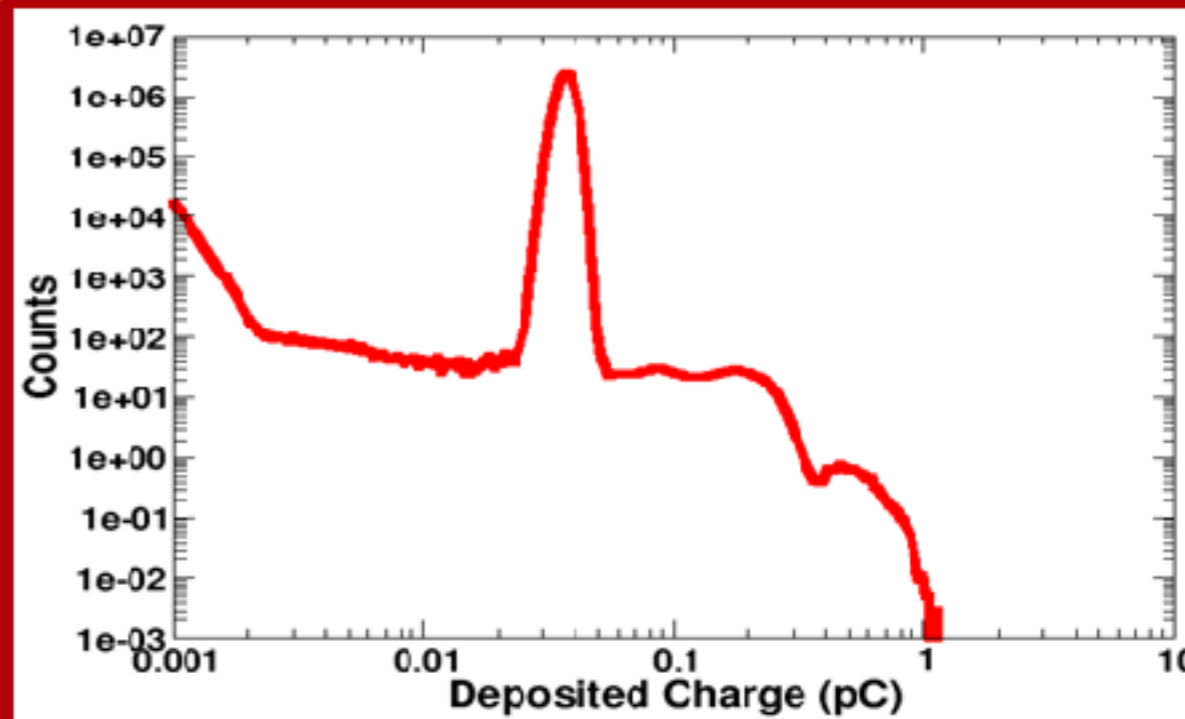
Single Charge Deposition in TCAD: Ne+W Event



SRAM Cell Upset

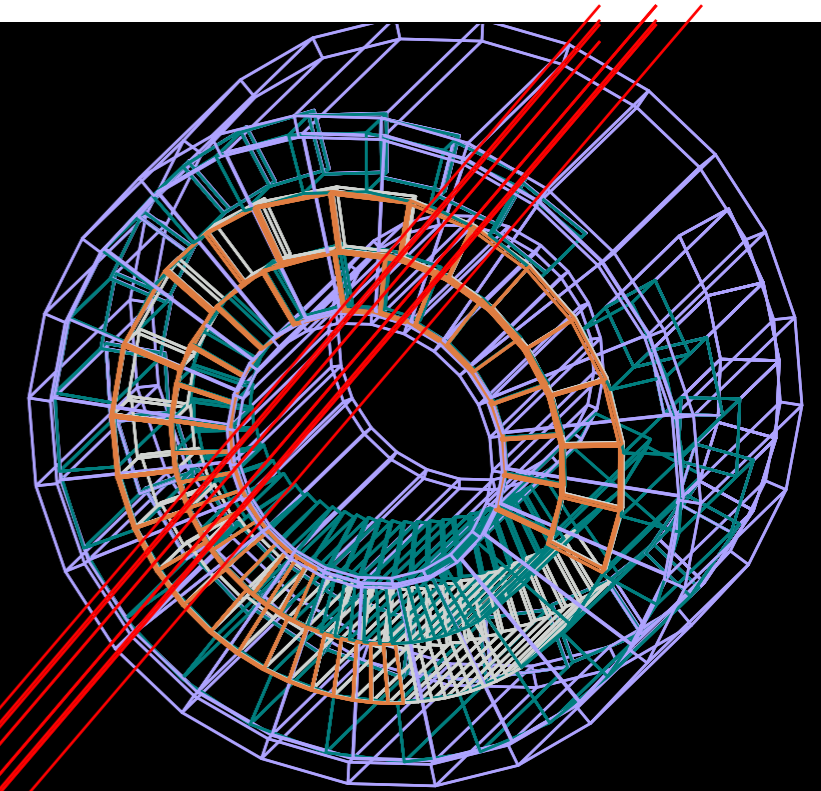
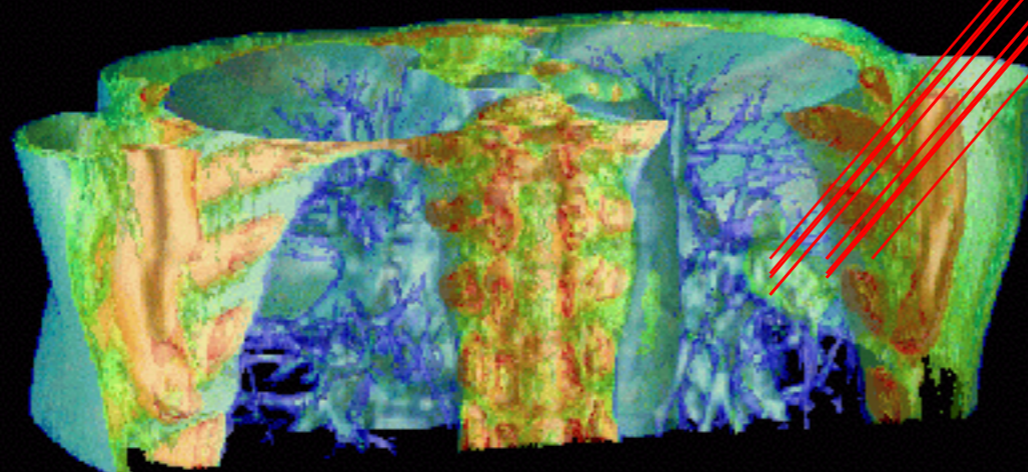
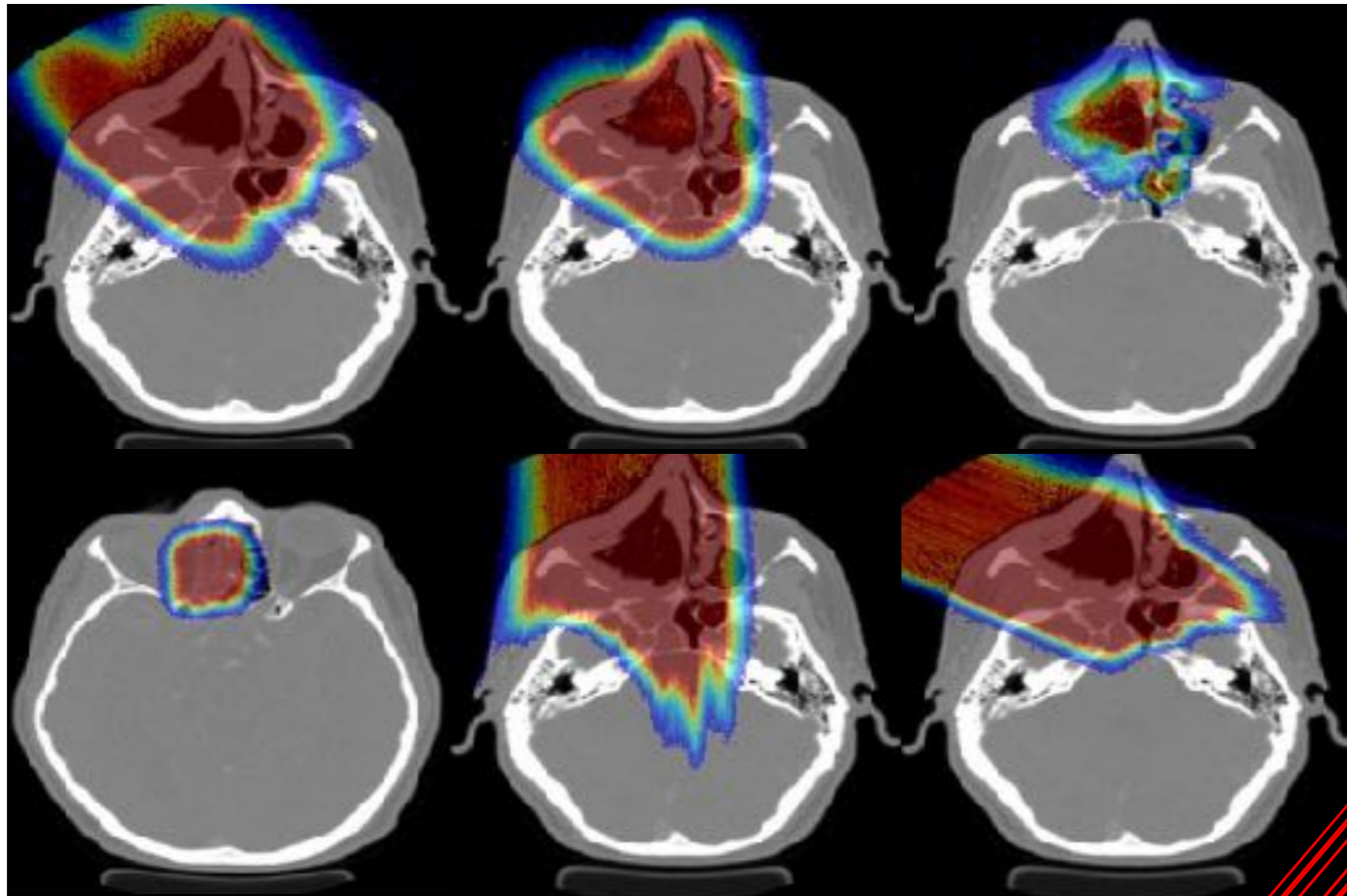


Geant4 Geometry and 523 MeV Neutron Event



MRED Energy Deposition for 10⁸ Events

GEANT4 based proton dose calculation in a clinical environment: technical aspects, strategies and challenges



Harald Paganetti



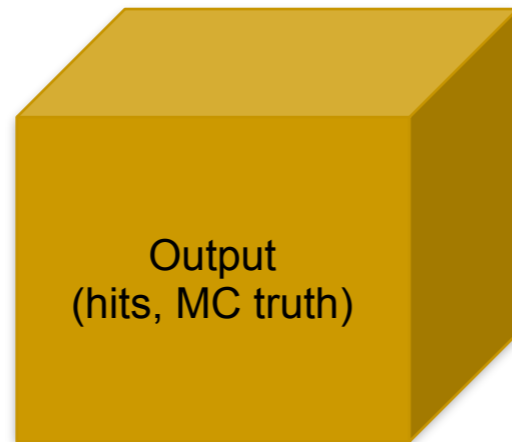
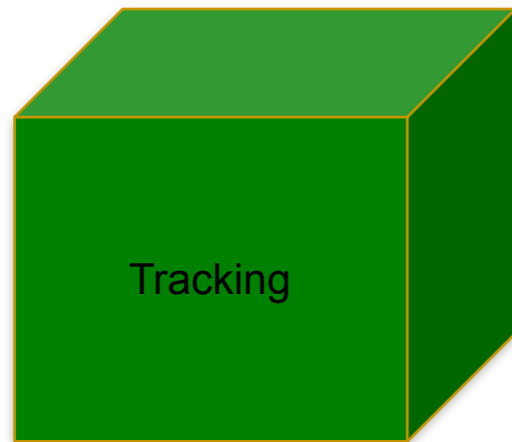
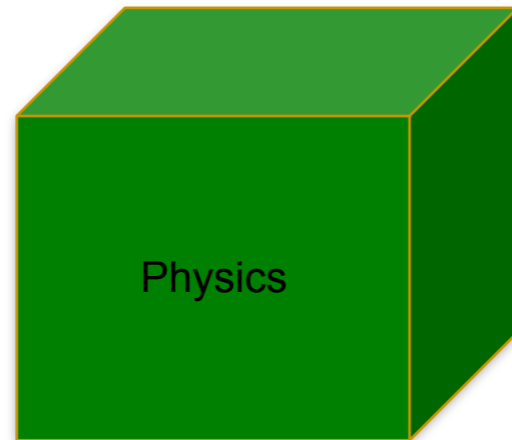
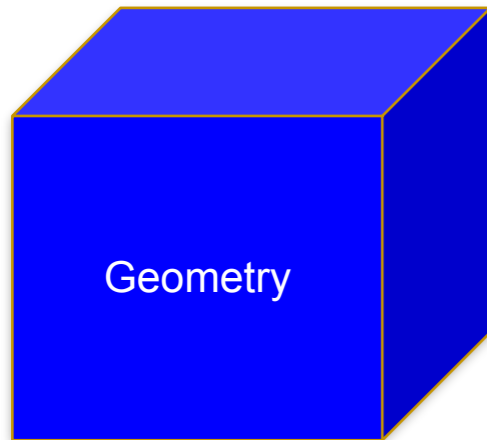
MASSACHUSETTS
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HARVARD
MEDICAL SCHOOL



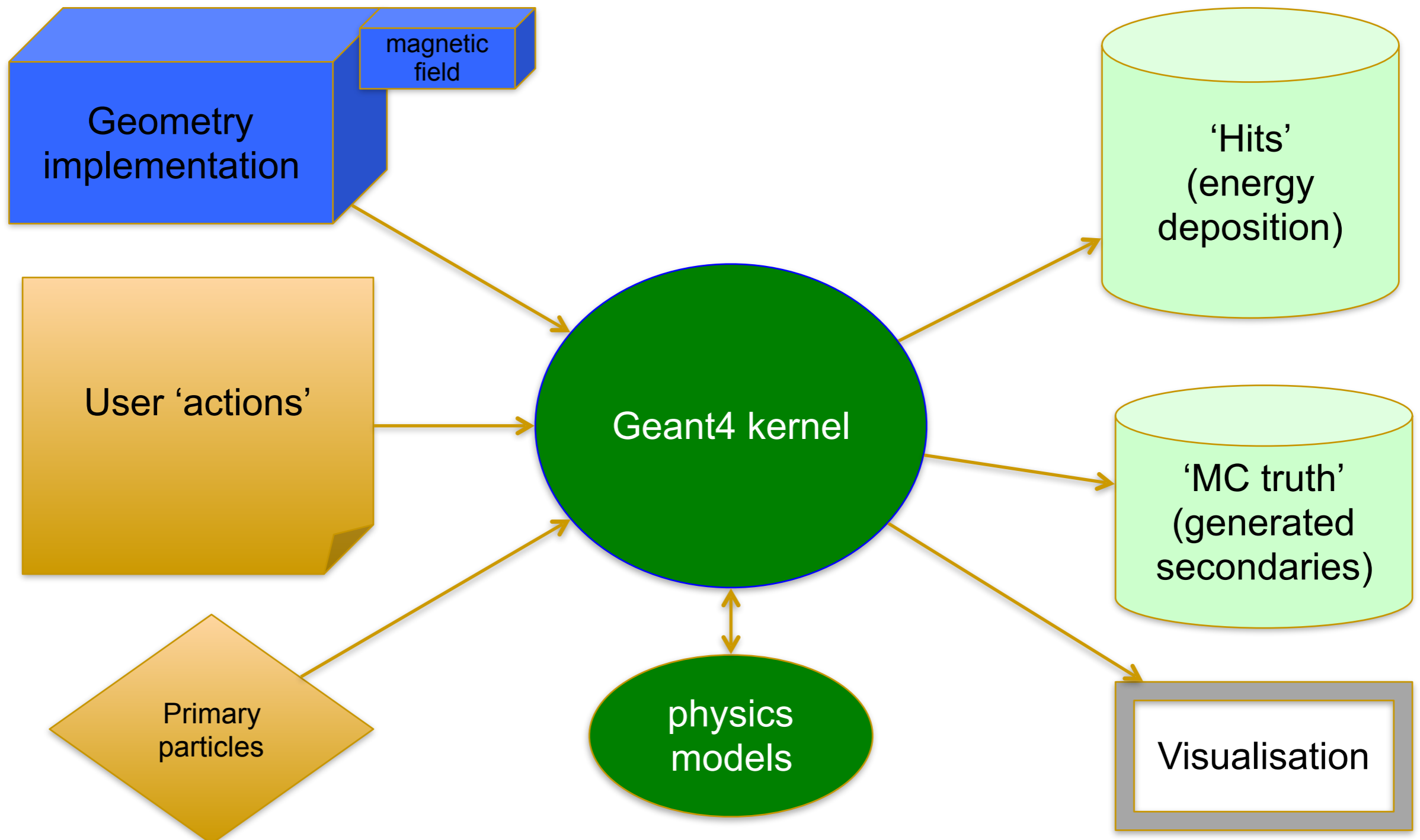
TOOLKIT ARCHITECTURE

Geant4 Components



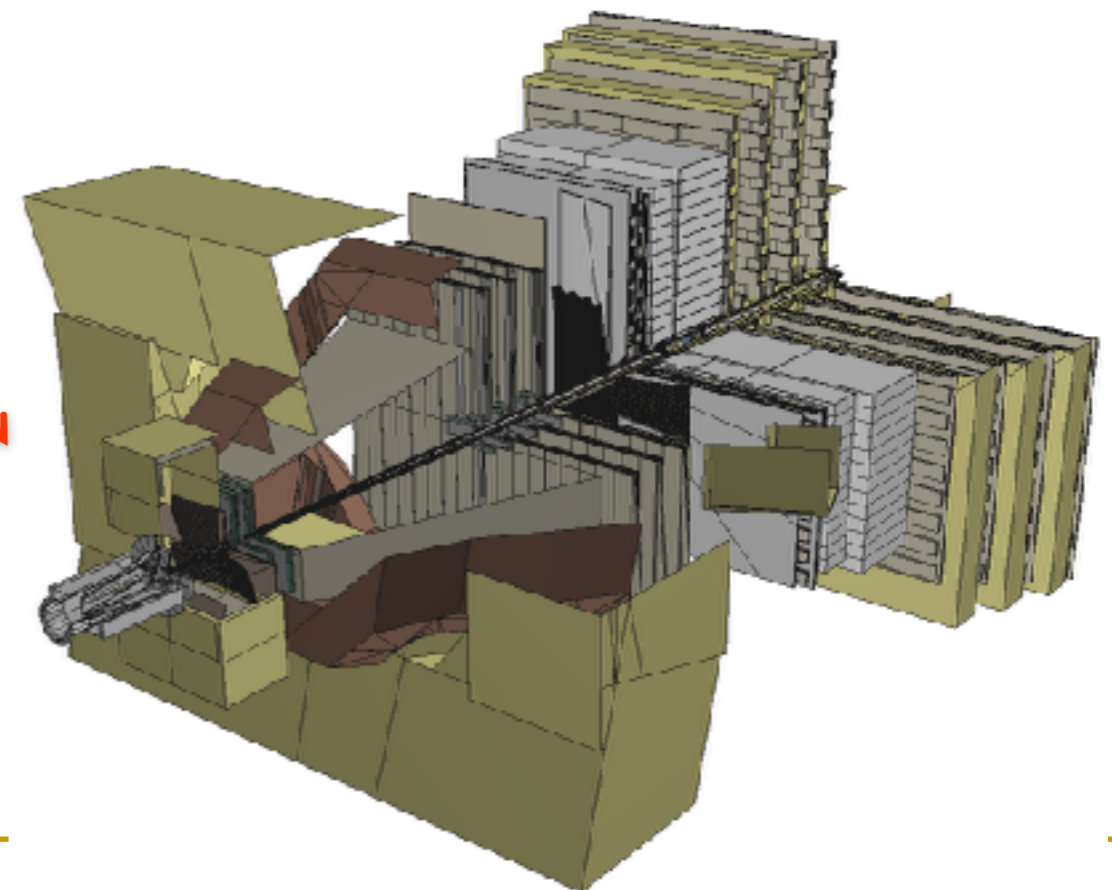
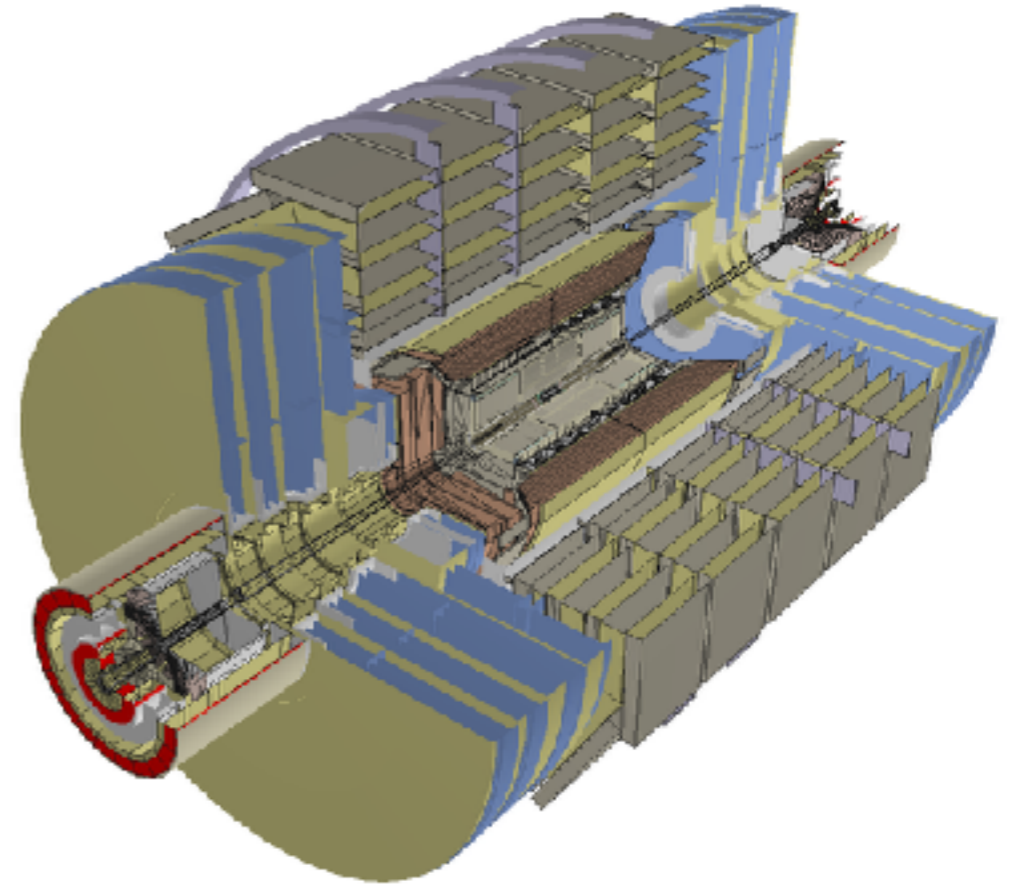
- 'kernel', internals of the engine, no direct interaction with the user code
- 'user interface'
 - classes directly instantiated by the users with specific parameters
 - box of dimension x, y, z
 - base classes for concrete users implementations
 - 'user actions', sensitive detectors

Geant4 application

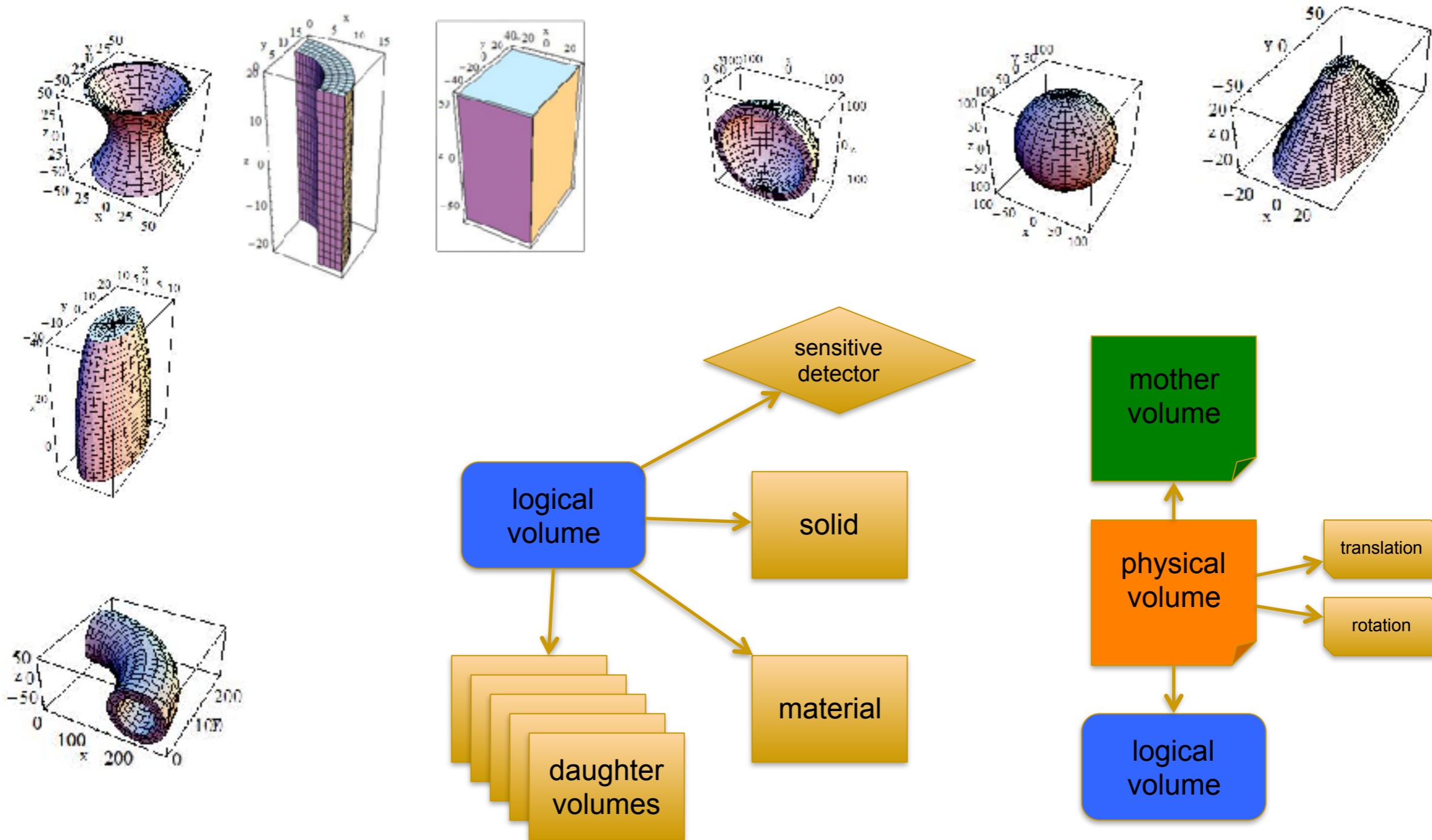


Geometry

- how to implement (efficiently) this in your computer program?
 - you need 'bricks'
 - 'solids', 'shapes'
 - you need to position them
 - you want to 'reuse' as much as possible the same 'templates'



Geometry construction

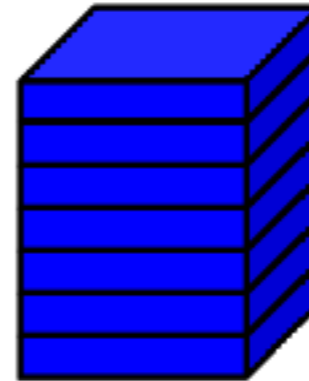


Advance geometry

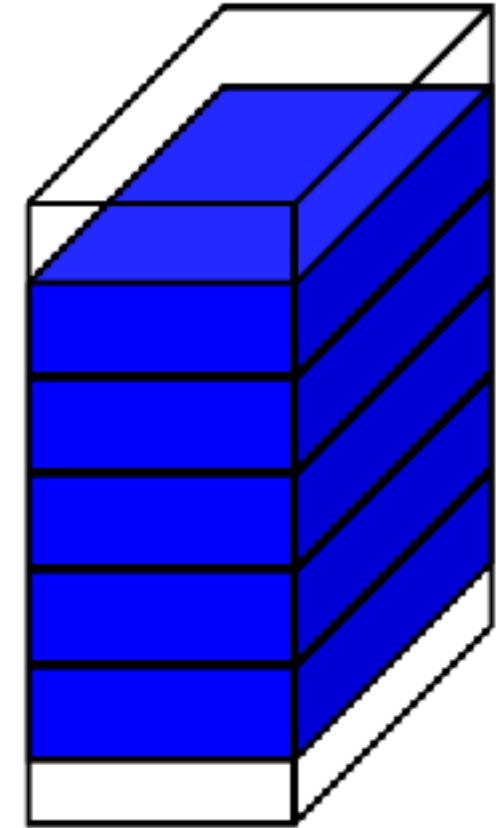
- replicas
- divisions
- reflections
- assemblies
- parameterizations



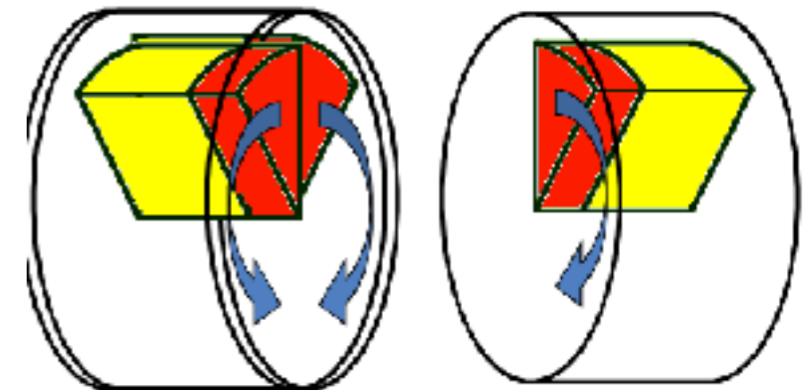
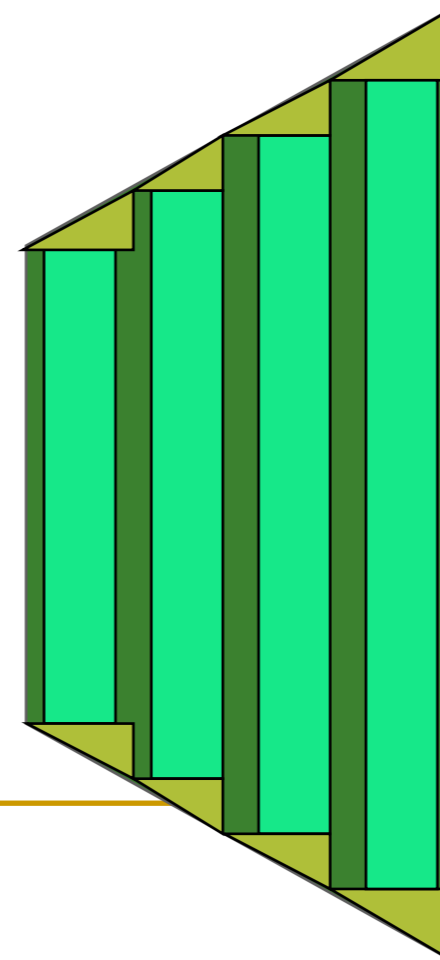
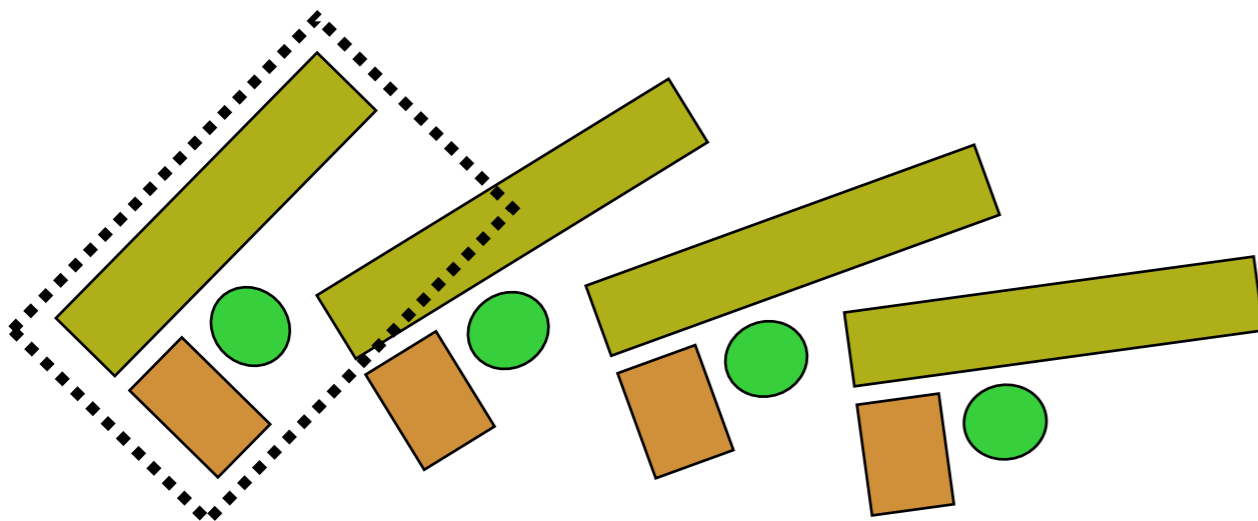
*a daughter
logical volume to
be replicated*



mother volume



mother
volume



Materials

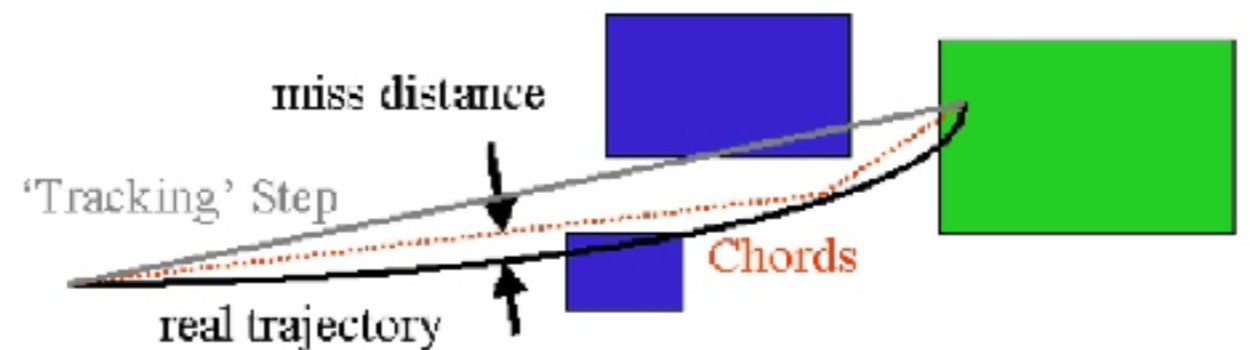
- In nature, materials (chemical compounds, mixtures) are made of elements, and elements are made of isotopes
- In Geant4: G4Isotope, G4Element, G4Material
 - users can 'build' their materials, instantiating elements and adding them with the right fractions
- Geant4 contains also National Institute of Standards (**NIST**) database of materials
 - materials can be instantiated directly from it
 - strongly recommended to be used

Navigation and tracking

- ‘navigator’ role is to provide geometry information to tracking mechanism
 - locates the point in the geometry structure
 - which volume I am in?
 - calculates the distances to the boundaries (along specified direction)
- non-trivial problem of simulation ‘continuous’ physics (space-time) with discrete steps
 - steps cannot be infinitely small
- steps need to be limited by crossing geometrical boundaries, physics or kinetic energy going to 0
- accuracy of tracking on the surfaces defined by geometrical ‘tolerance’

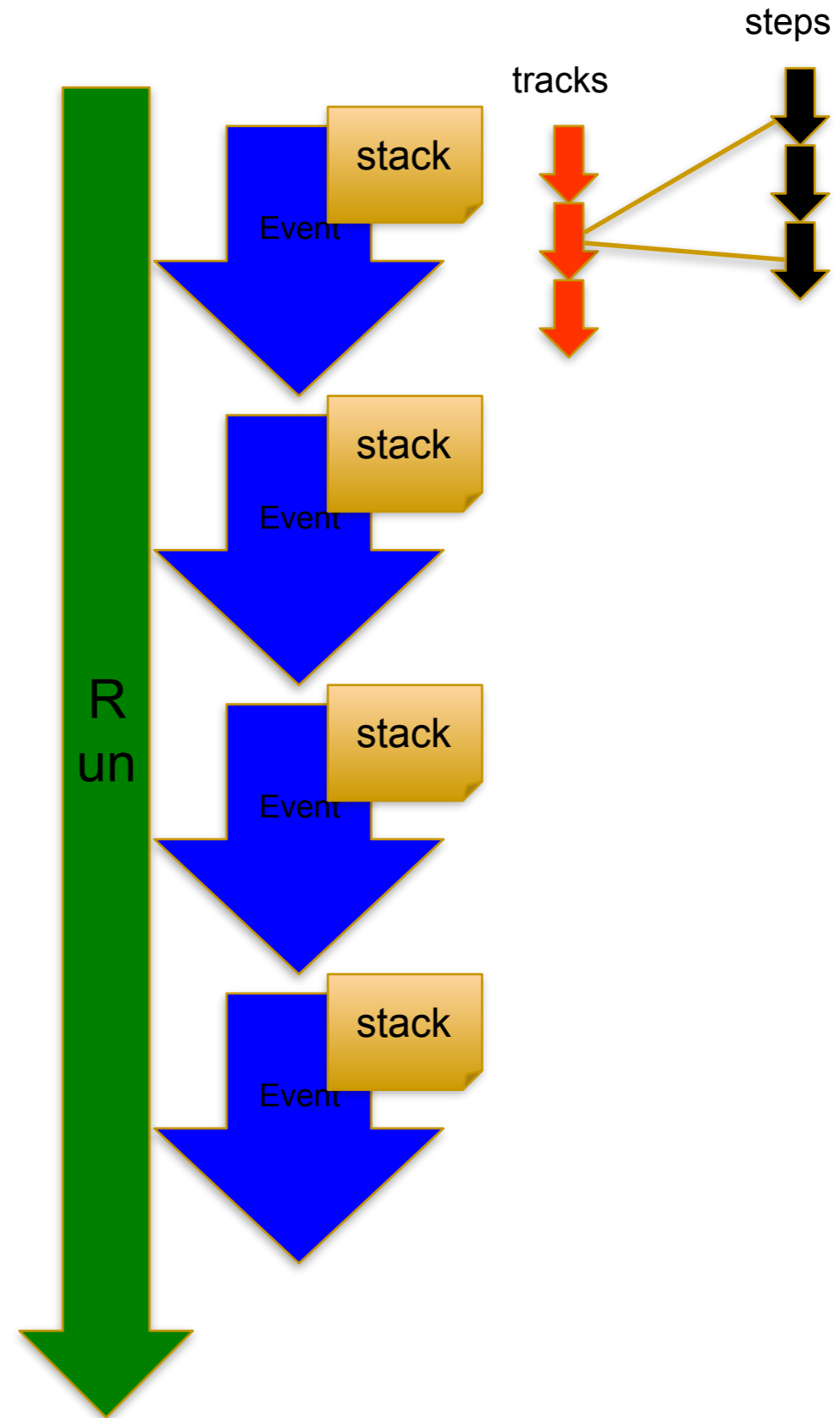
Magnetic field

- Geant4 can propagate in magnetic fields, electric fields, electromagnetic fields, and gravity fields, uniform or non-uniform
- the equation of motion of the particle in the field is integrated using Runge-Kutta method
 - in particular cases analytical solutions can be used
- curved trajectory broken up in linear cord segments
- parameter 'miss distance' sets how closely the curved path is approximated
- non trivial problem to avoid qualitatively wrong results



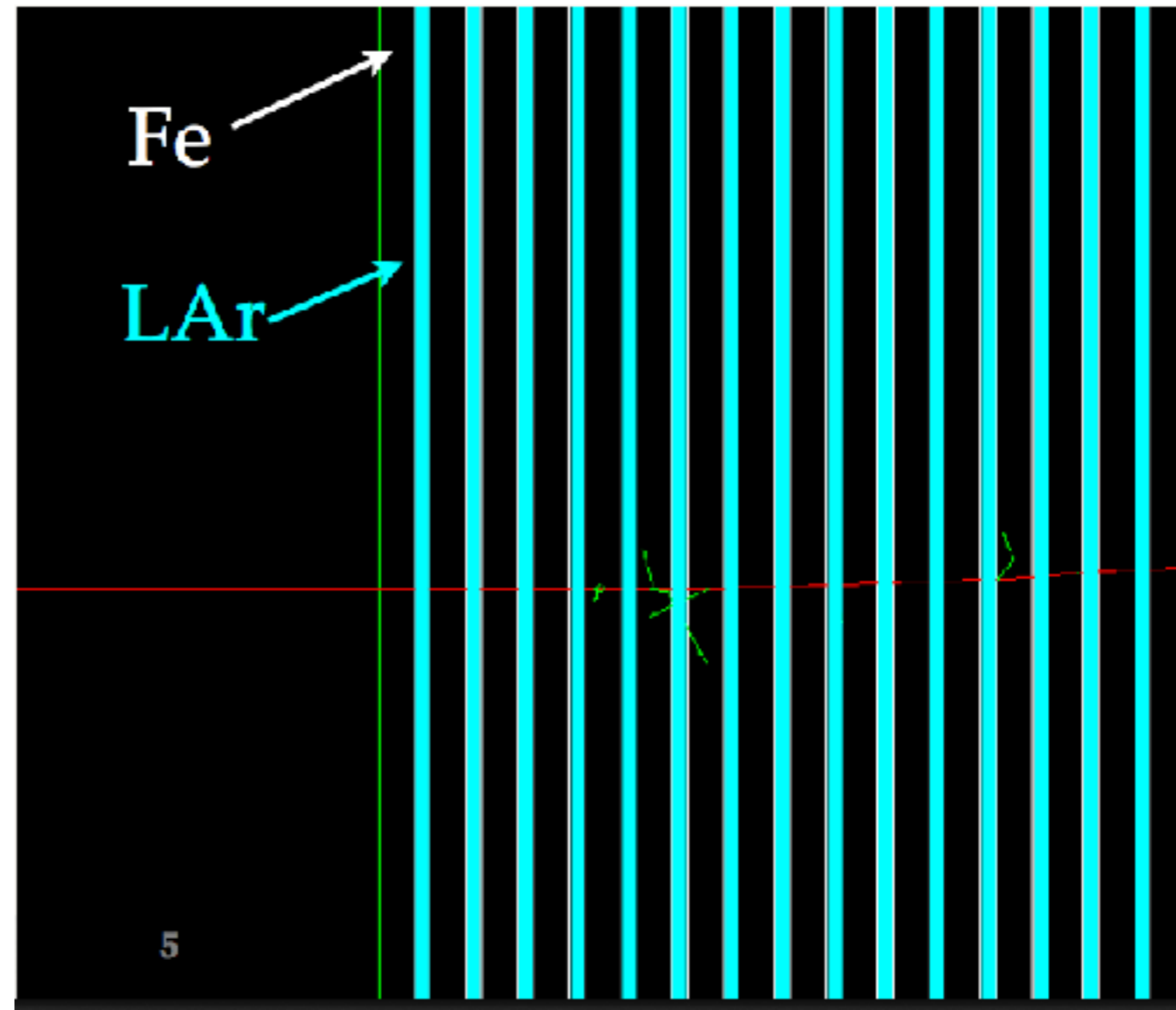
User actions

- how to control your simulation?
 - ‘user actions’
 - G4UserRunAction
 - G4UserEventAction
 - G4UserStackingAction
 - G4UserTrackingAction
 - G4UserSteppingAction
 - fully customizable (empty by default)
 - allow user to take actions depending on his specific case
 - simulated only relevant particles
 - save specific information, fill histograms
 - speed-up simulation by applying different limits



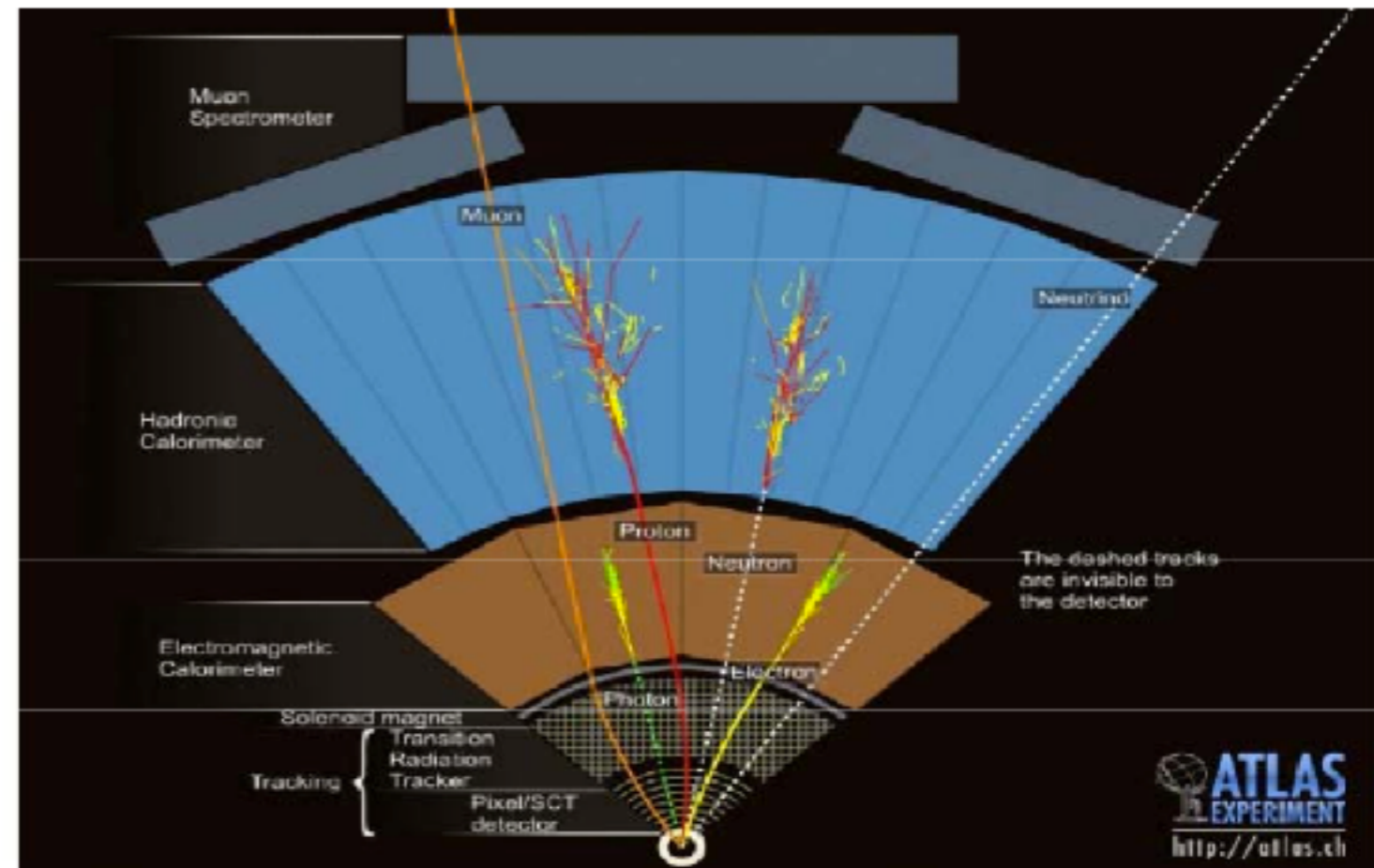
Users actions – sensitive detectors

- sensitive detectors are user actions attached to specific volumes
 - ProcessHits – invoked when a particle enters the ‘sensitive’ volume
 - allows to create ‘hits’
 - energy deposition, x, y, z coordinates, etc
- they simulate detector response to the particles passing through the sensors

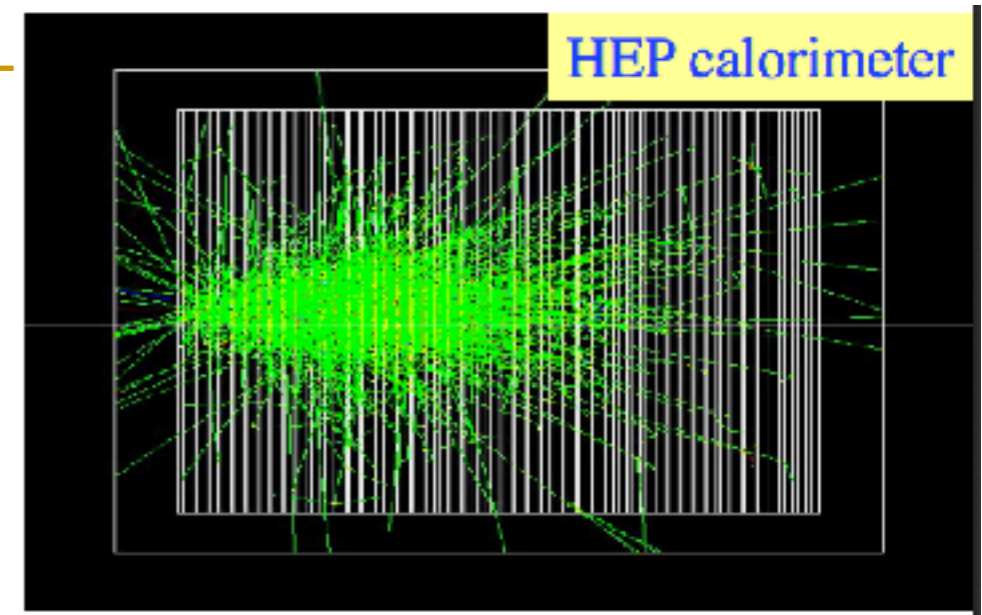


Physics...

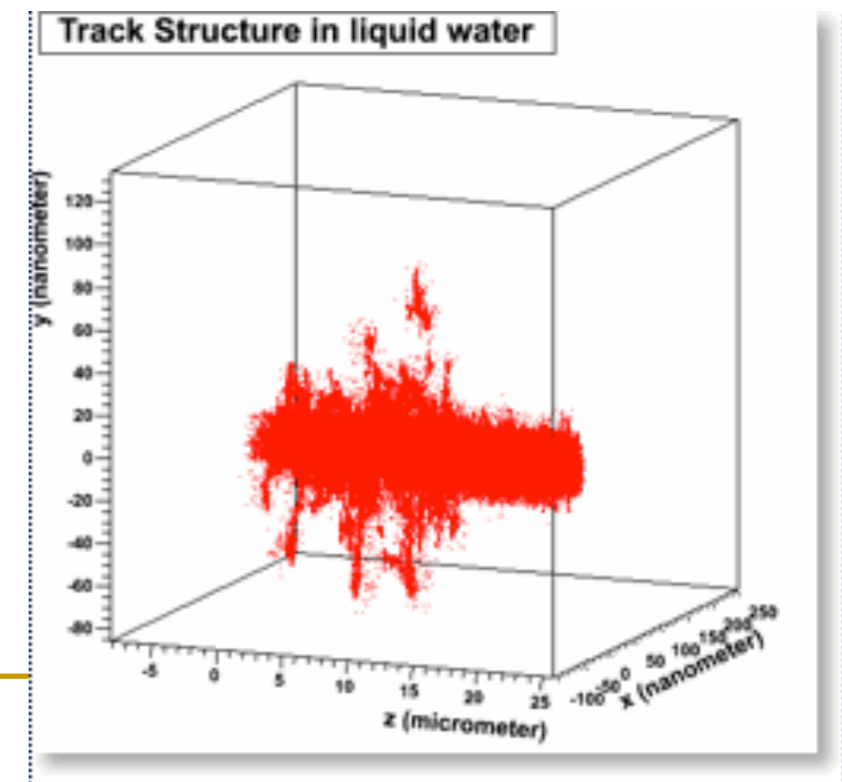
- what happens to when a particle traverses some material?
- we need to implement the physics we know



Electromagnetic (1/2)

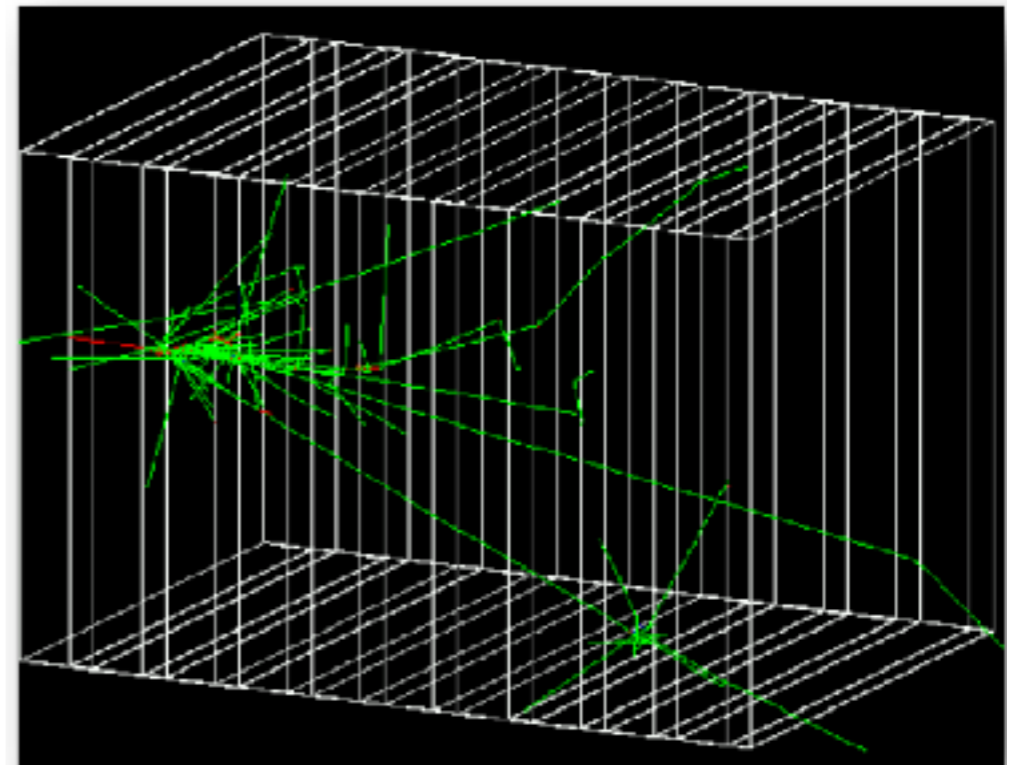


- simulation of electromagnetic interactions of charged particles, gammas and optical photons
 - standard electromagnetic physics
 - optimized for high and medium energy applications
 - energy range from 1keV to 1PeV
 - low energy electromagnetic physics
 - down to eV
 - medical and biological application
 - Geant4-DNA project



Electromagnetic (2/2)

- **Gammas:**
 - Gamma-conversion, Compton scattering, Photoelectric effect
- **Leptons(e, μ), charged hadrons, ions**
 - Energy loss (Ionisation, Bremstrahlung), Multiple scattering, Transition radiation, Synchrotron radiation, e^+ annihilation.
- **Photons:**
 - Cerenkov, Rayleigh, Reflection, Refraction, Absorption, Scintillation
- High energy muons
- **A choice of implementations for most processes**
 - “Standard”: performant, where relevant physics above 1 KeV
 - “Low Energy”: Extra accuracy, for application delving below 1 KeV



50 MeV e^- entering
LAr-Pb calorimeter

Need for production cuts

- some electromagnetic processes have infrared divergences
 - threshold needed below which no secondaries are generated
 - production threshold for gammas, electrons and positrons
- ‘cuts’ can be defined per region of the geometry
 - detailed simulation of the EM shower in the sensitive part, but no details needed in some ‘dead’ materials (support, etc)
- Geant4 uses ‘cut in **range**’
 - converted to energy for each material
 - assures better coherency of the simulation that a cut in energy would do

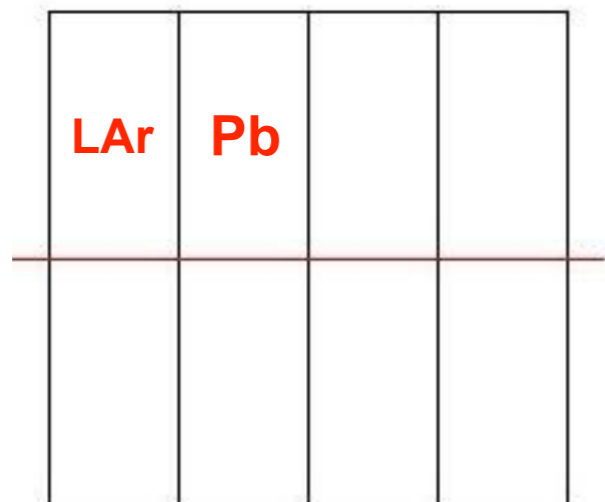
Why cut in range

- traditionally Monte Carlo simulations impose absolute cutoff in energy
 - particle are stopped when this energy is reached
 - remaining energy is dumped at that point
- this can lead to imprecise stopping location and deposition of energy
- there is a particle dependence
 - range of a 10 keV γ in Si is a few cm
 - range of a 10 keV e- in Si is a few microns
- and a material dependence
 - suppose you have a detector made of alternating sheets of Pb and plastic scintillator
 - if the cutoff is OK for Pb it will likely be wrong for the scintillator which does the actual energy measurement

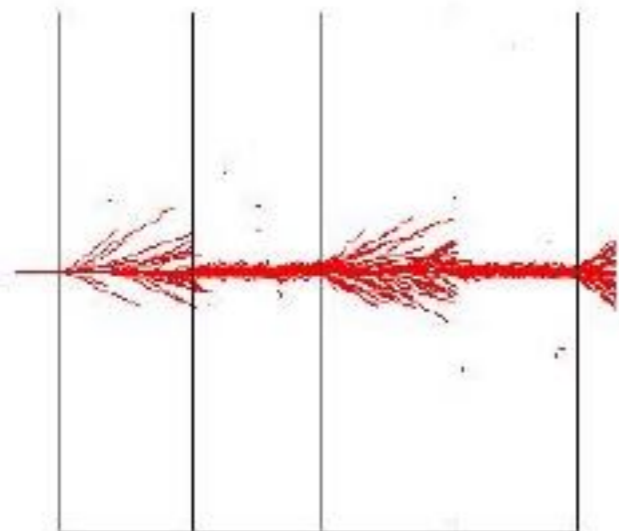
Cut in range (production threshold) vs. energy cut

Example: 500 MeV p in LAr-Pb Sampling Calorimeter

Geant3 (and others)

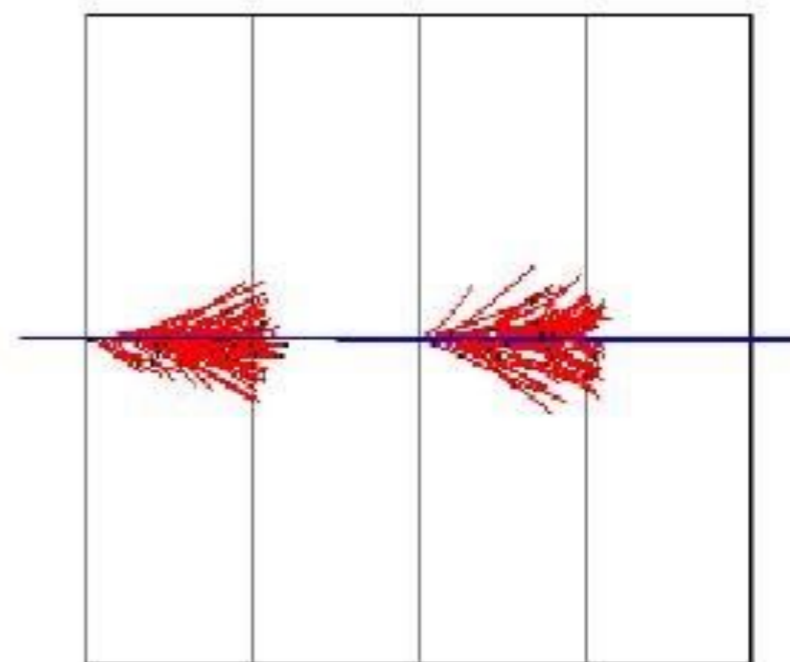


Cut = 2 MeV



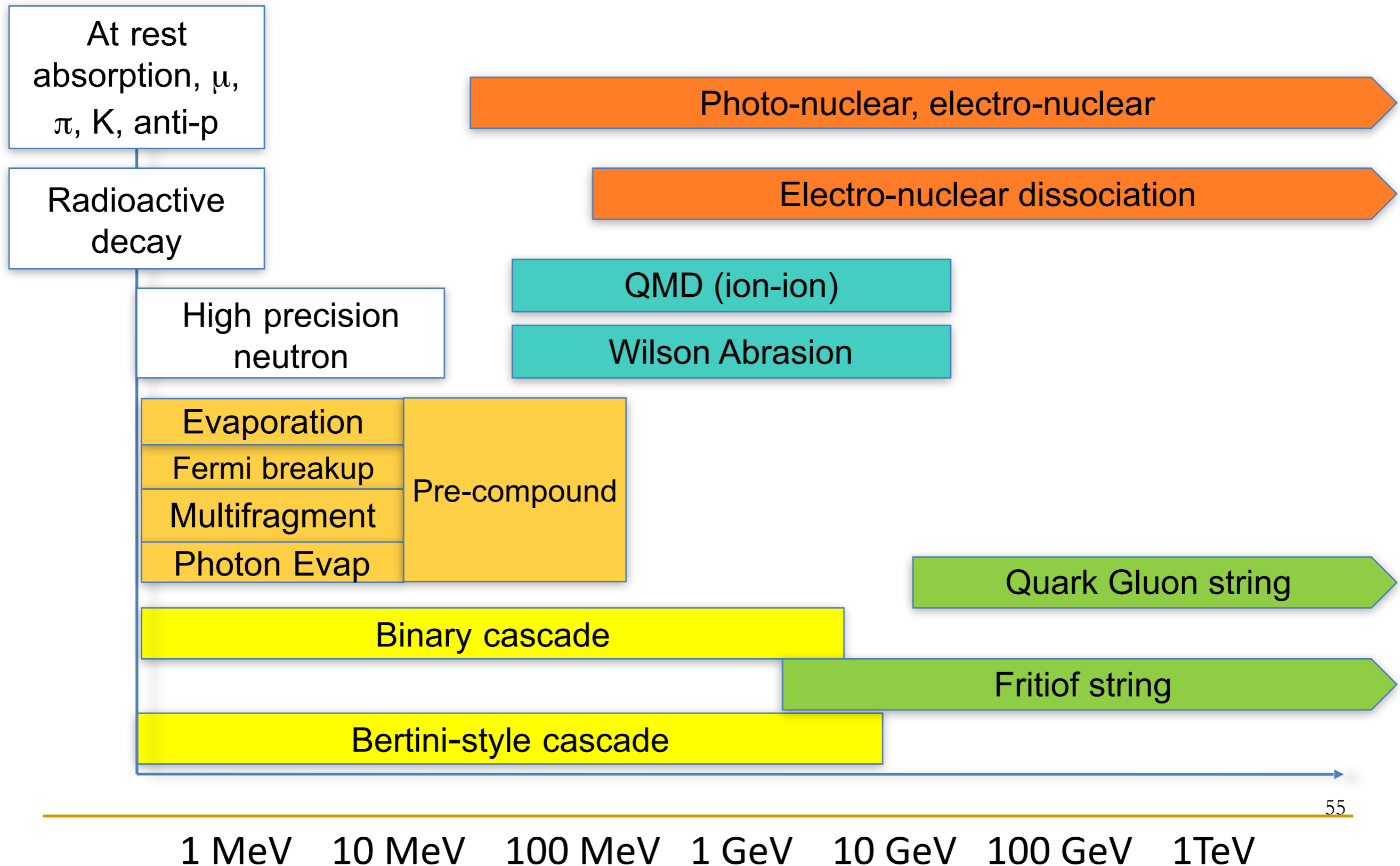
Cut = 450 keV

Geant4



Production range = 1.5 mm

Partial hadronic model inventory

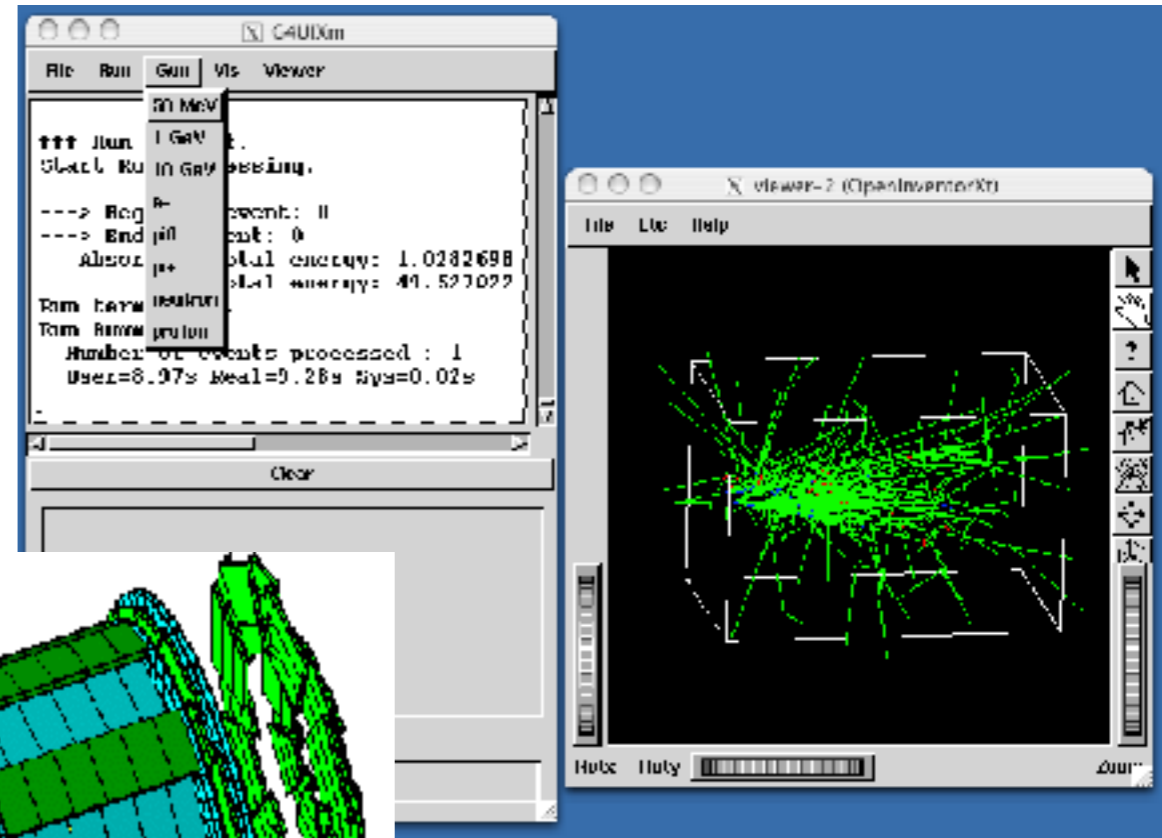
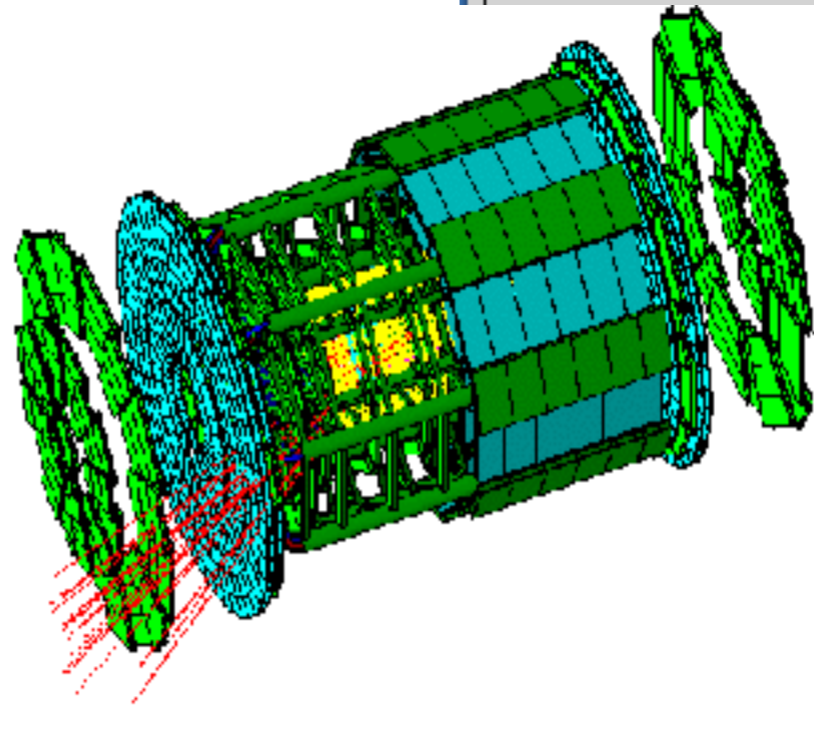


Geant4 'Physics Lists'

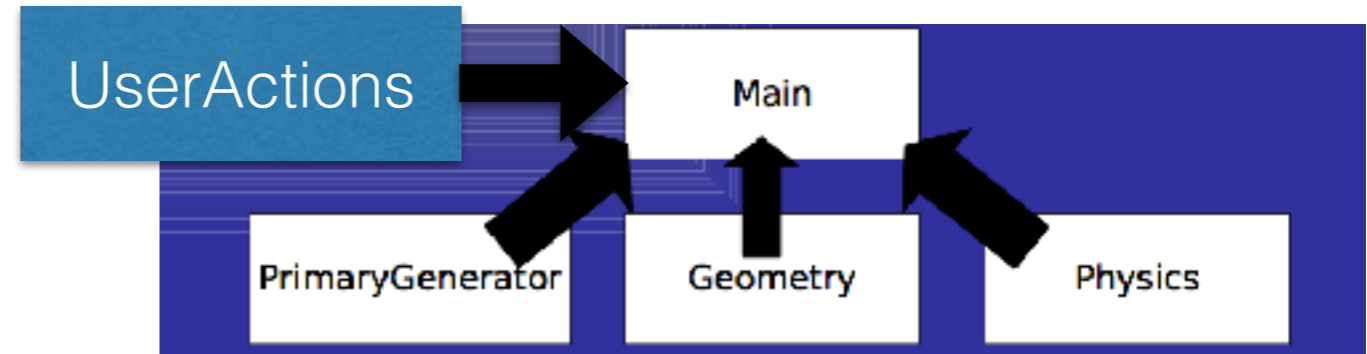
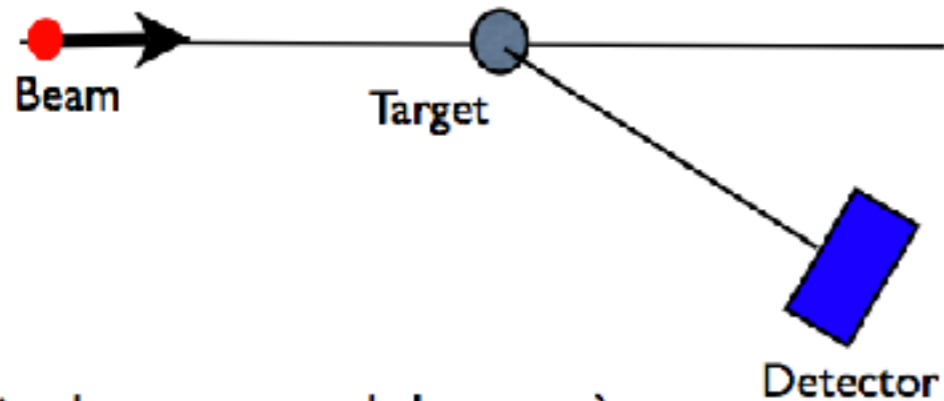
- set of physics models covering all the needed processes for the relevant particles and cross sections for them
- predefined physics lists for specific applications
 - general high energy physics
 - high precision high energy physics (detailed tracking of neutrons)
 - low energy
 - etc

Visualisation

- visualize
 - geometry
 - tracks
 - hits
- available visualization drivers
 - OpenGL
 - OpenInventor
 - HepRep
 - DAWN
 - VRML
 - RayTracer
 - gMocren
 - ASCIITree



What you need to make simulation?



and to get something out of it...



Conclusion

- Geant4 is a Monte Carlo simulation toolkit used in different domains like High Energy Physics, astrophysics, space research, medical physics, biology, etc
 - it allows you to simulate the passage of the particle through the matter, the process they undergo and the energy deposition they make
- the use of such a simulation is essential to build, understand and use your devices

Resources for more information

- Geant4 web site
 - <http://cern.ch/geant4/>
- Geant4 Training Page
 - Material form several training courses
 - <http://cern.ch/geant4/support/> “Training” link, or directly
 - <http://geant4.web.cern.ch/geant4/support/training.shtml>
- Geant4 Tutorials, Users Workshops and workshop presentations
 - 2011 Tutorial, CENBG Bordeaux
 - 2009 Users Wrkshp **Catania** (October 09)
 - <http://www.lns.infn.it/geant4/geant4ws2009/>
 - Look for [Timetable](#)
 - 2008 [Kobe](#), 2007 [UK](#), 2006 [Lisbon](#)
 - 2005 **Bordeaux** – several sessions focus on Medical applications
 - <http://geant4.in2p3.fr/2005/>
 - Workshops and Users Workshops links at
 - <http://geant4.web.cern.ch/geant4/collaboration/workshops.shtml>
- Geant4 [Physics Validation](#)
 - | [EM https://twiki.cern.ch/twiki/bin/view/Geant4/EMValidation](https://twiki.cern.ch/twiki/bin/view/Geant4/EMValidation)
 - | [Hadronic http://geant4.fnal.gov/hadronic_validation/validation_plots.htm](http://geant4.fnal.gov/hadronic_validation/validation_plots.htm)
- [Working Group web sites](#)
 - | [Electromagnetic: Standard & Low-Energy, Hadronic](#), at
 - | http://cern.ch/geant4/organisation/working_groups.html
- Many papers on [Geant4](#) and its validation
- Latest reference paper
 - *Nuclear Instruments and Methods in Physics Research* [A 835](#) (2016) 186-225