Geant4 Simulation Toolkit

An Introduction

Witek Pokorski

31.05.2013

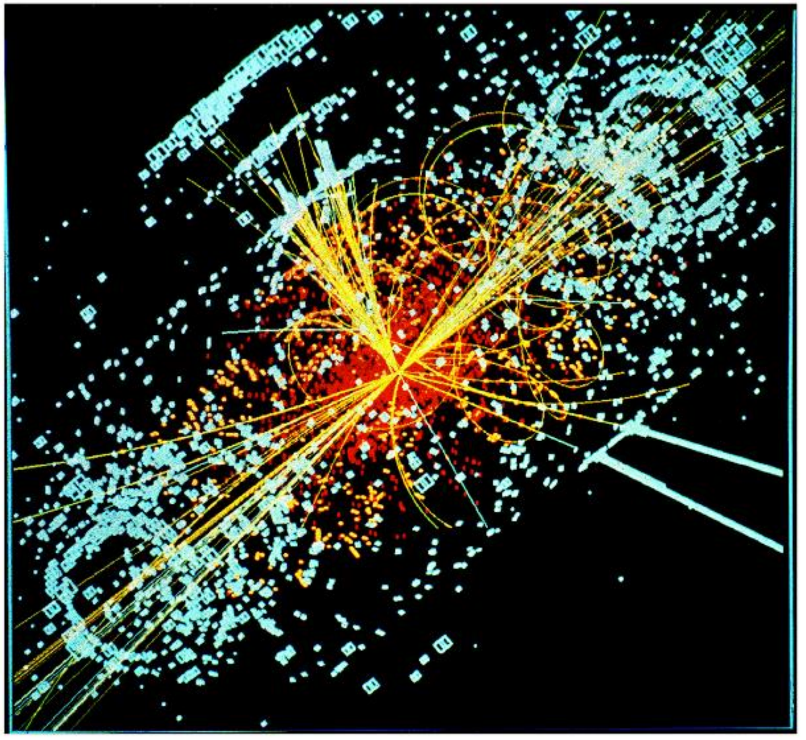
Content

- General Introduction
  - What is it, why do we need it?
- Toolkit architecture
  - What does it consist of?
  - How does it work?
- Geant4 application cookbook
  - Recipe for your first Geant4 application
- Conclusion

INTRODUCTION

What is Geant4?

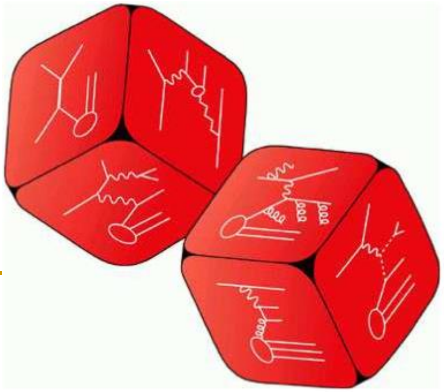
- A software (C++) toolkit for the Monte Carlo simulation of the passage of particles through matter
  - ‘propagates’ particles through geometrical structures of materials, including magnetic field
  - simulates processes the particles undergo
    - creates secondary particles
    - decays particles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



Simulated Higgs event in CMS

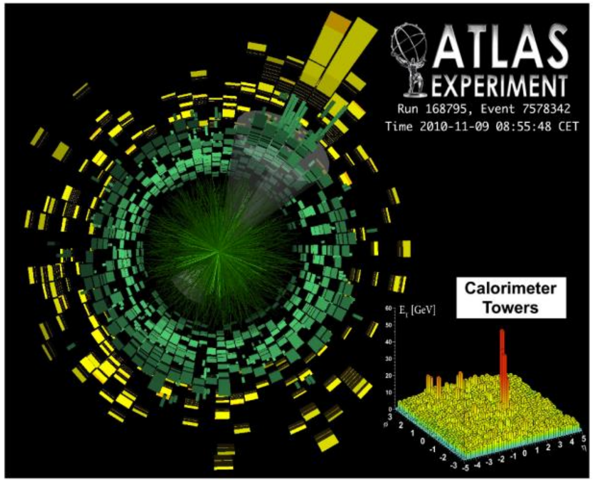
Monte Carlo simulation

- What is Monte Carlo
  - throwing randon numbers
    - to calculate integrals
    - to pick among possible choices
- Why Monte Carlo
  - because Einstein was wrong: God does throw dice! Quantum mechanics: amplitudes => probabilities
    - Anything that possibly can happen, will! (but more or less often)
  - Want to generate events in as much detail as Mother Nature
    - get average and fluctutations right
    - make random choices,~as in nature



Why do we need it?

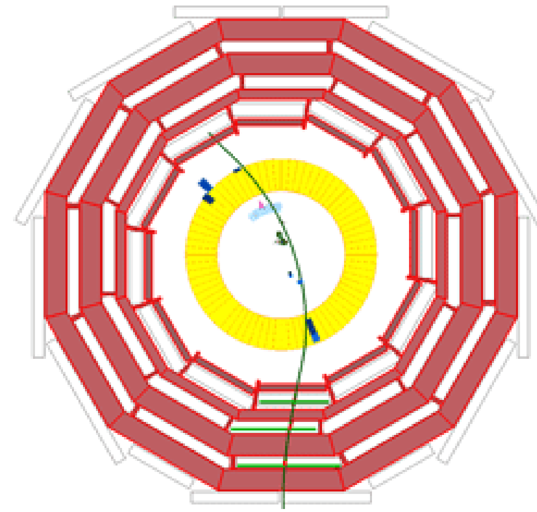
- to design and to construct the devices
  - to get what we are looking for
    - to be able to see the relevant 'events'
  - not to get what we do not want
    - radiation damage, etc
- to operate the devices
  - to adjust and to tune the aparatus
    - medical physics: dose calculation, etc
- to understand the experimental results
  - to compare to the existing theories and models
  - to make discoveries



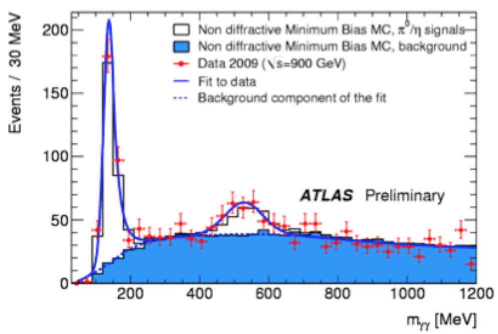
Geant4 has been successfully employed for

- Detector design
- Calibration / alignment
- First analyses

T. LeCompte (ANL)



GEANT4 Comparisons with the Calorimeters



Invariant mass of pairs of well-isolated electromagnetic clusters.

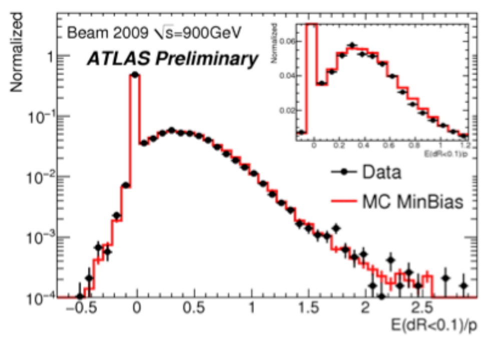
The π^0 mass is within 0.8 ± 0.6% of expectations.

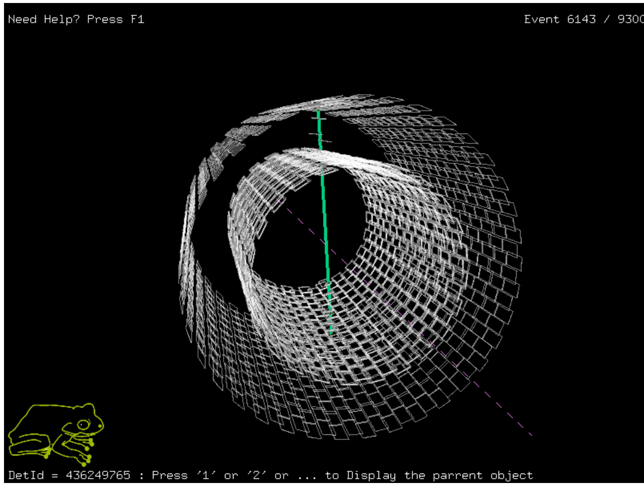
The η^0 mass is within 3 ± 2% of expectations.

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.)

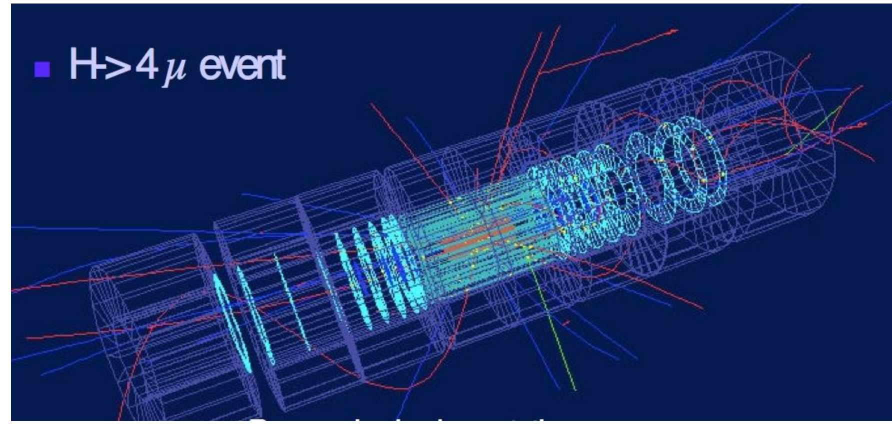


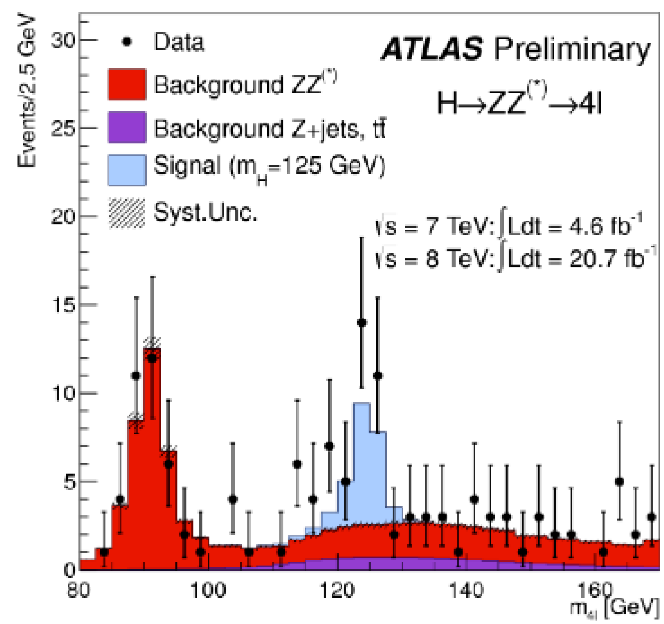


Figures from CMS

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

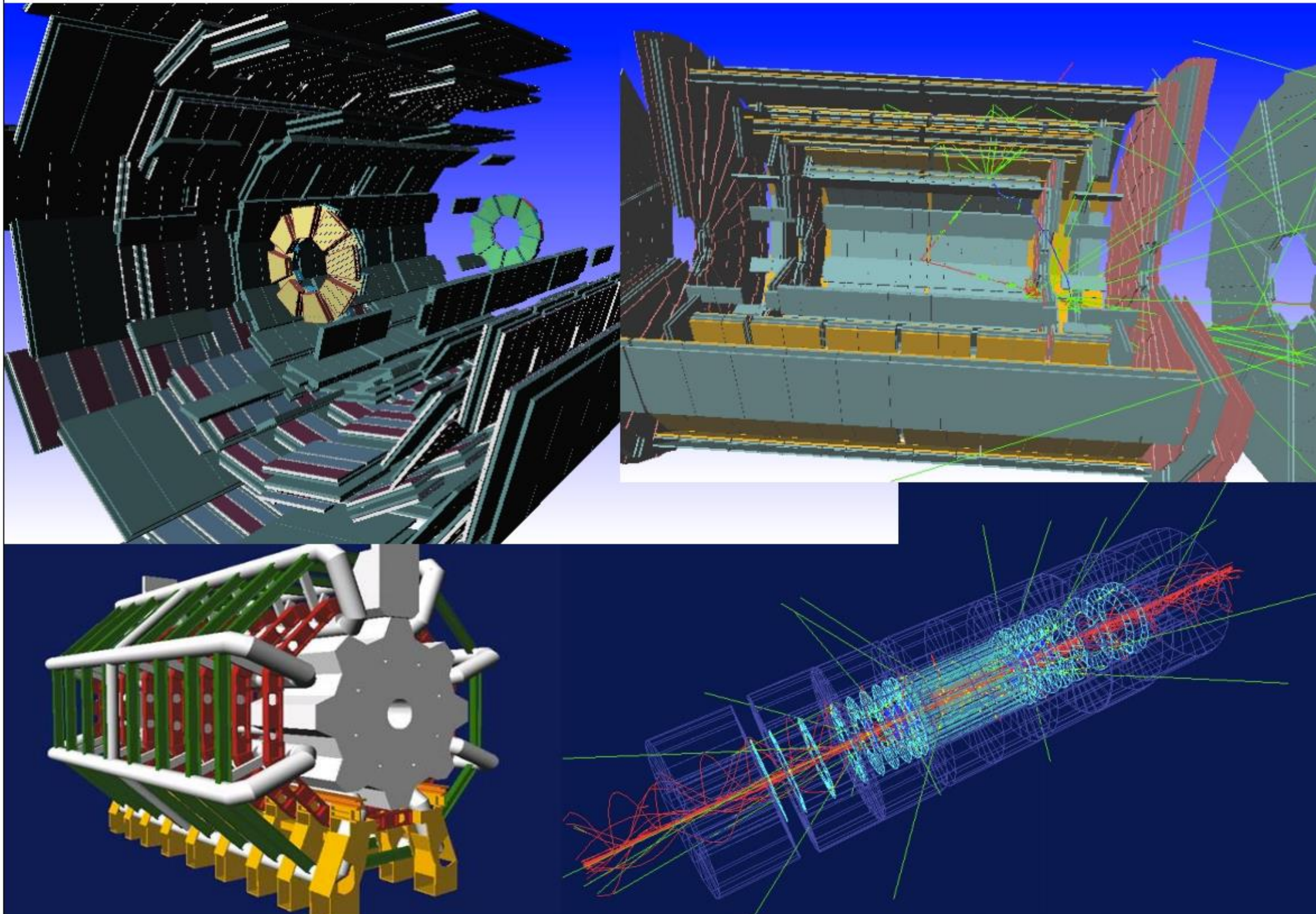


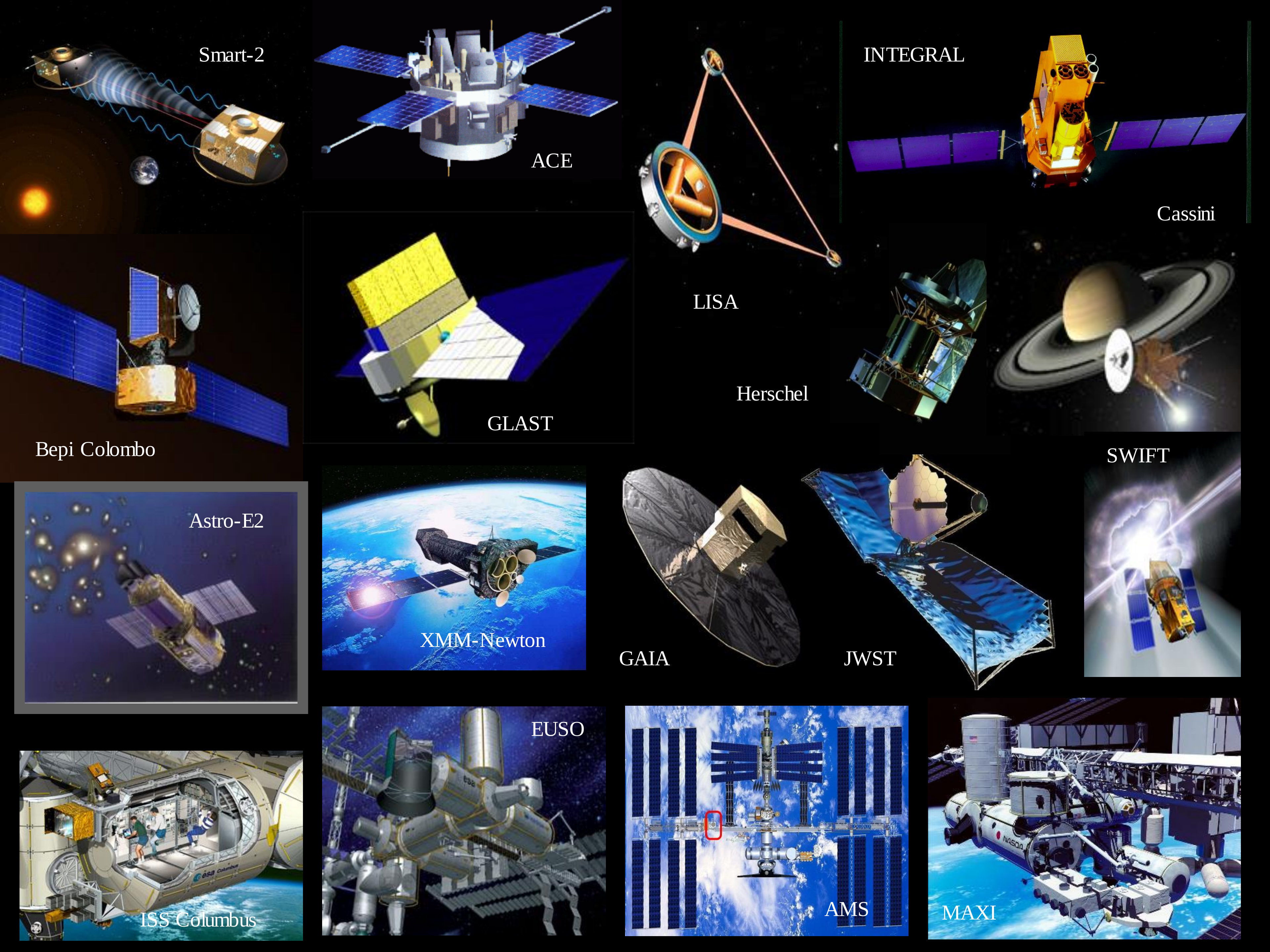


Many applications...

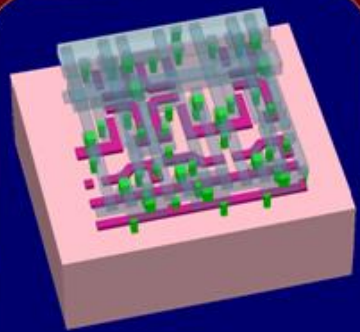
- High Energy Physics
- Astrophysics
- Space Research
- Medical Physics
- Biology
- other fields…

Geant4 in High Energy Physics (ATLAS at LHC)

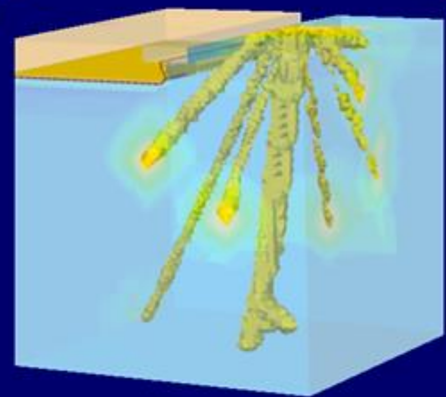



Smart-2
ACE
LISA
INTEGRAL
Cassini
Bepi Colombo
GLAST
Herschel
SWIFT
Astro-E2
XMM-Newton
GAIA
JWST
EUSO
ISS Columbus
AMS
MAXI

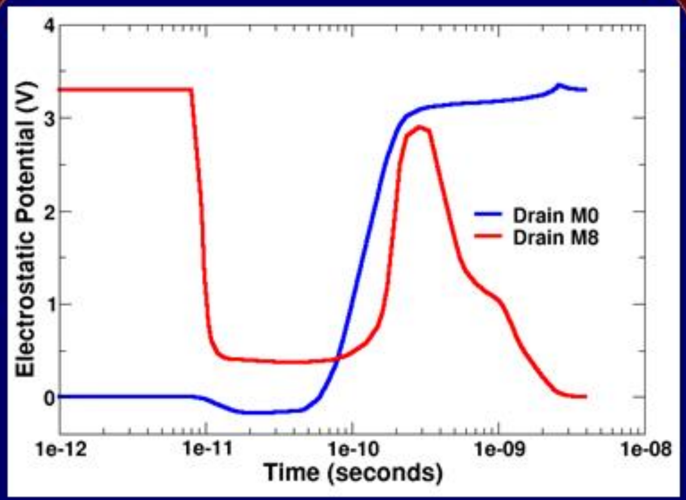
RADSAFE on SEE in SRAMs



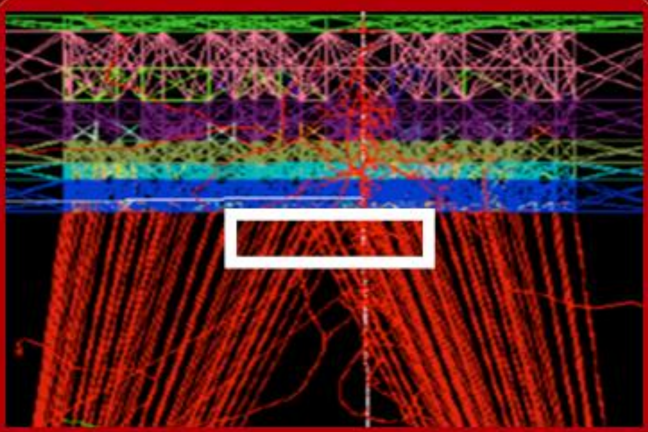
TCAD Cell Structure: SRAM Cell



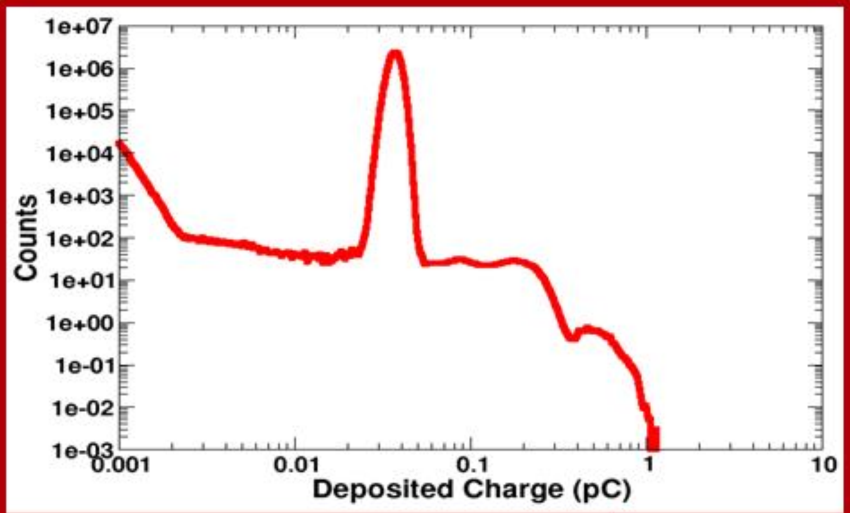
Single Charge Deposition in TCAD: Ne+W Event



SRAM Cell Upset

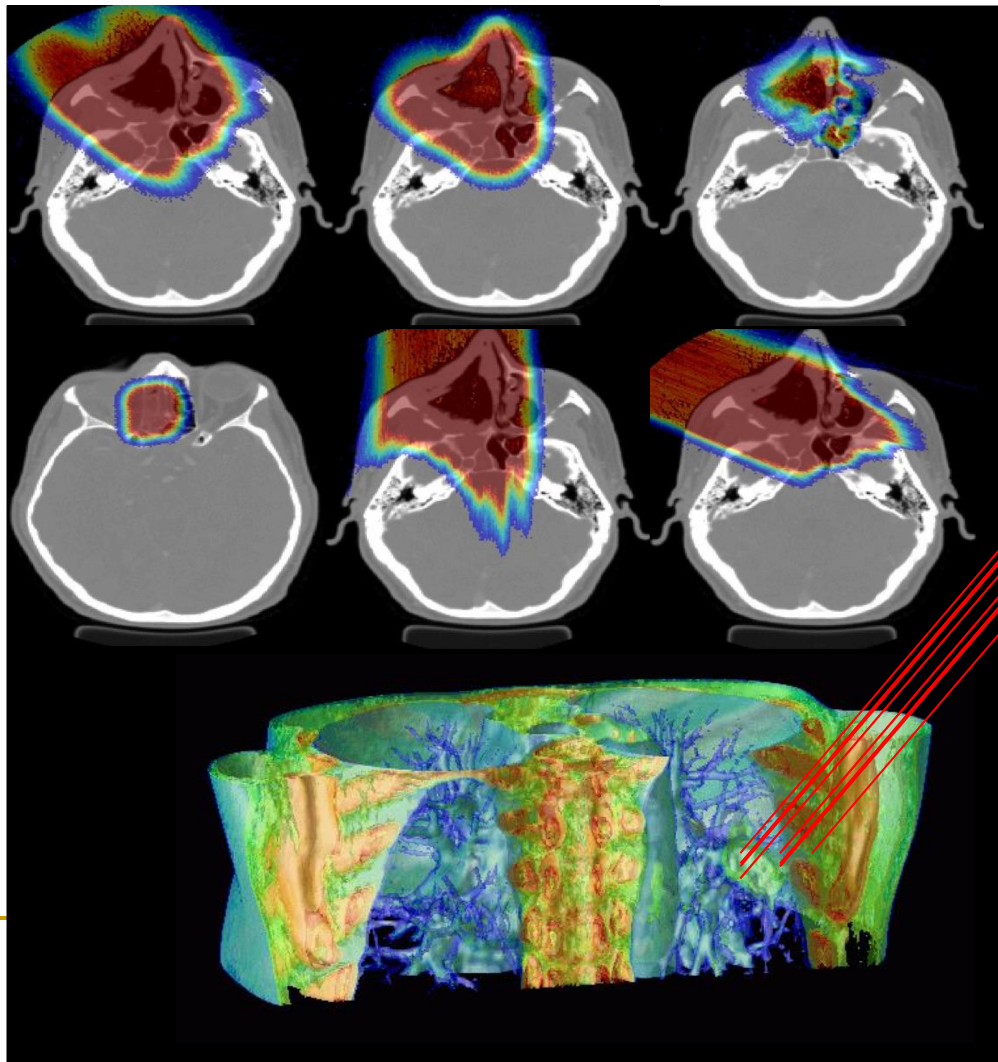


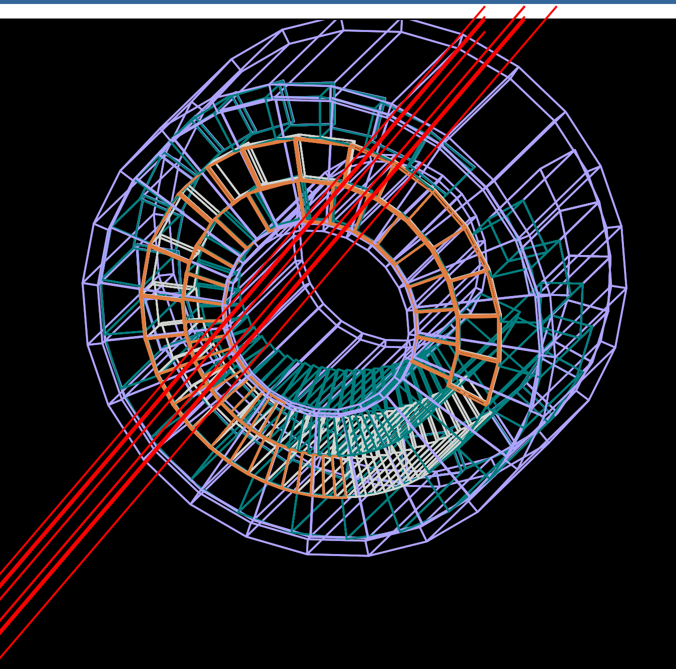
Geant4 Geometry and 523 MeV Neon Event



MRED Energy Deposition for 10^8 Events

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





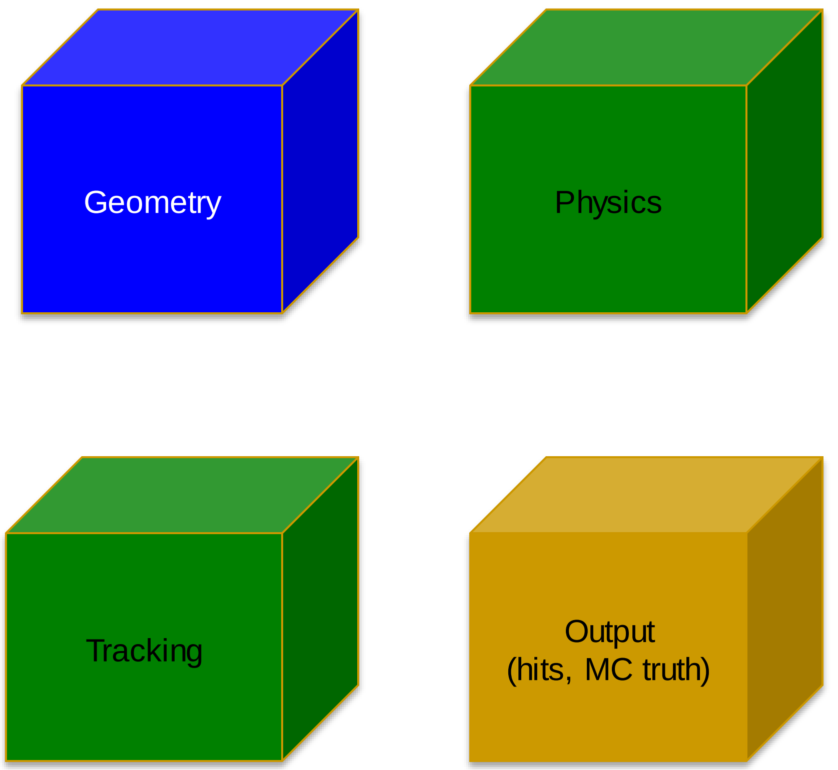
Harald Paganetti

MASSACHUSETTS GENERAL HOSPITAL

HARVARD MEDICAL SCHOOL

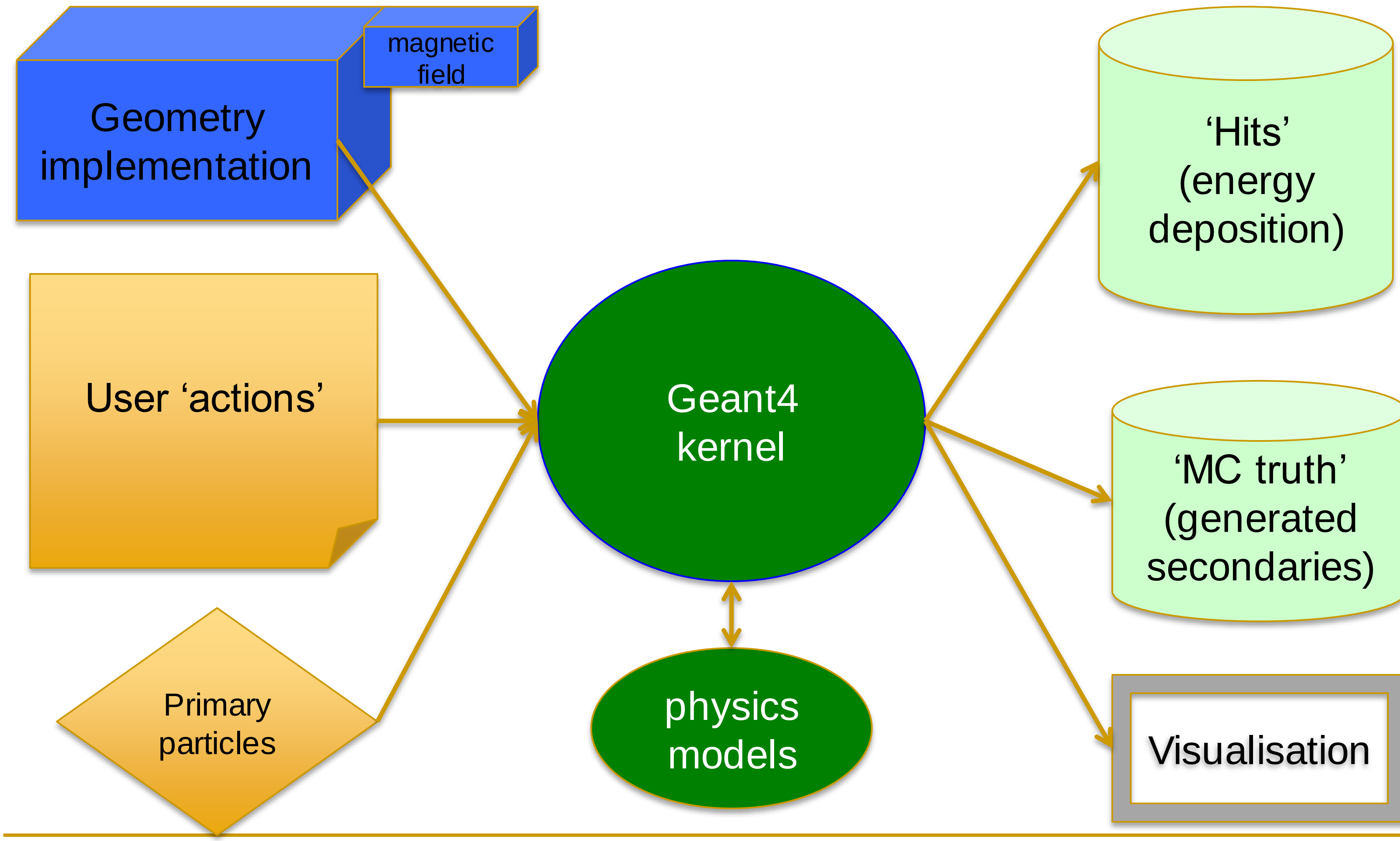
TOOLKIT ARCHITECTURE

Geant4 Components



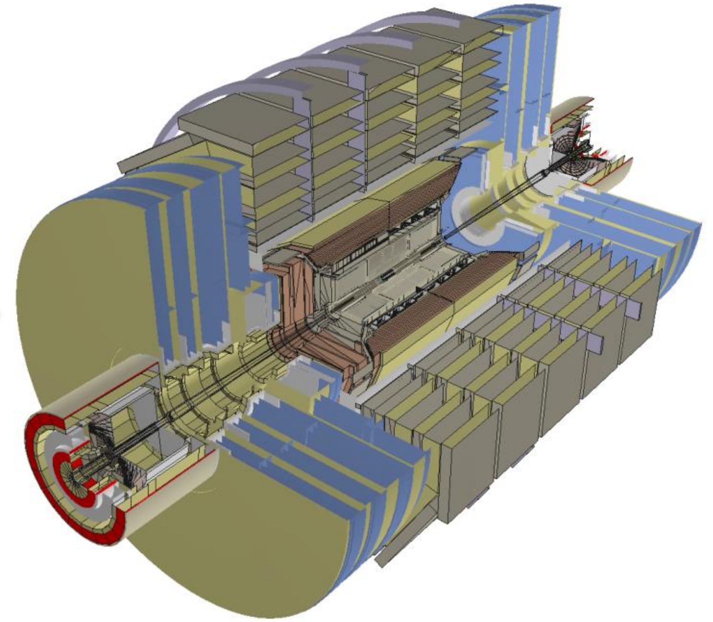
- 'kernel', internals of the engine, no direct interaction with the user code
- 'user interface'
  - classes directly instantiated by the users with specific parameters
    - box of dimension x, y, z
  - base classes for concrete users implementations
    - 'user actions', sensitive detectors

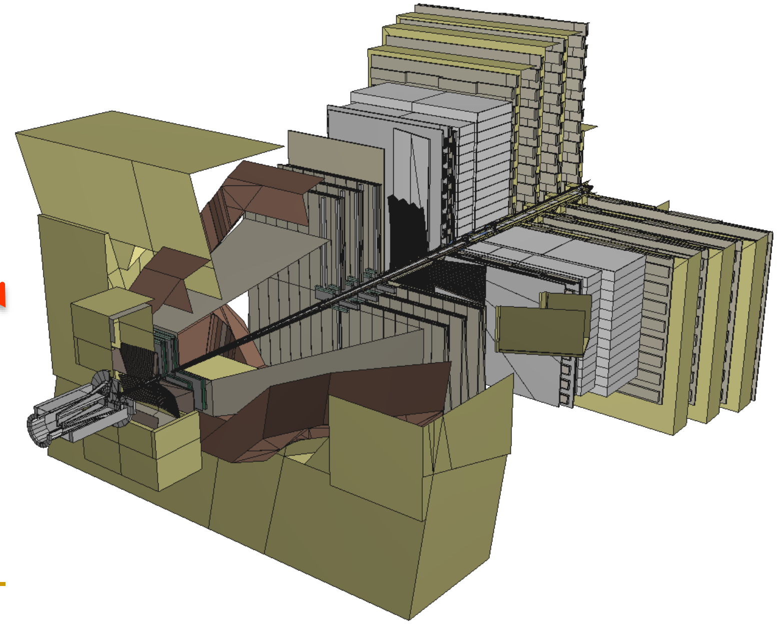
Geant4 application



Geometry

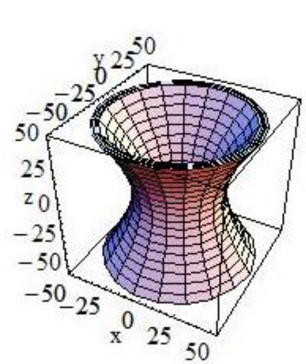
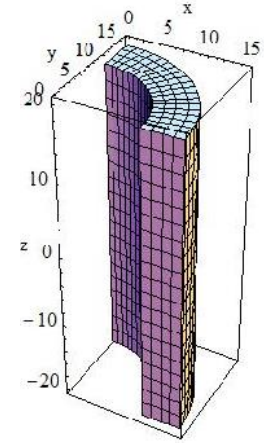
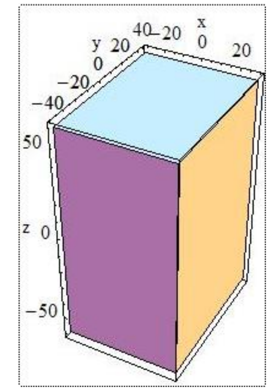
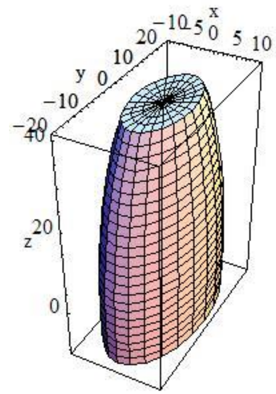
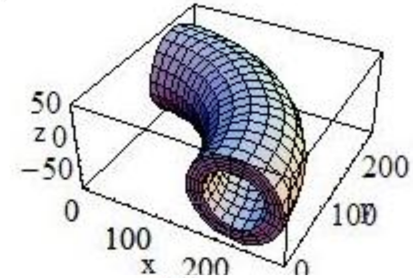
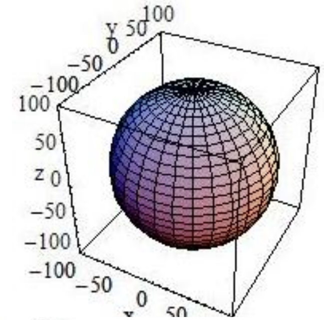
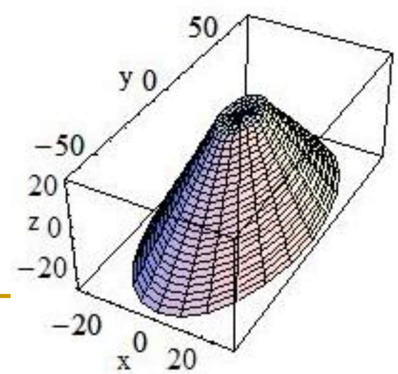
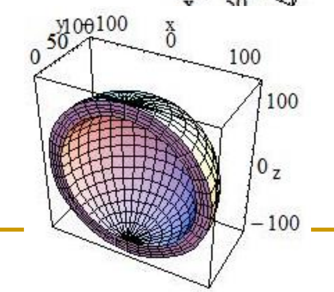
- how to implement (efficiently) this in your computer program?
  - you need ‘bricks’
    - ‘solids’, ‘shapes’
    - you need to position them
    - you want to ‘reuse’ as much as possible the same ‘templates’



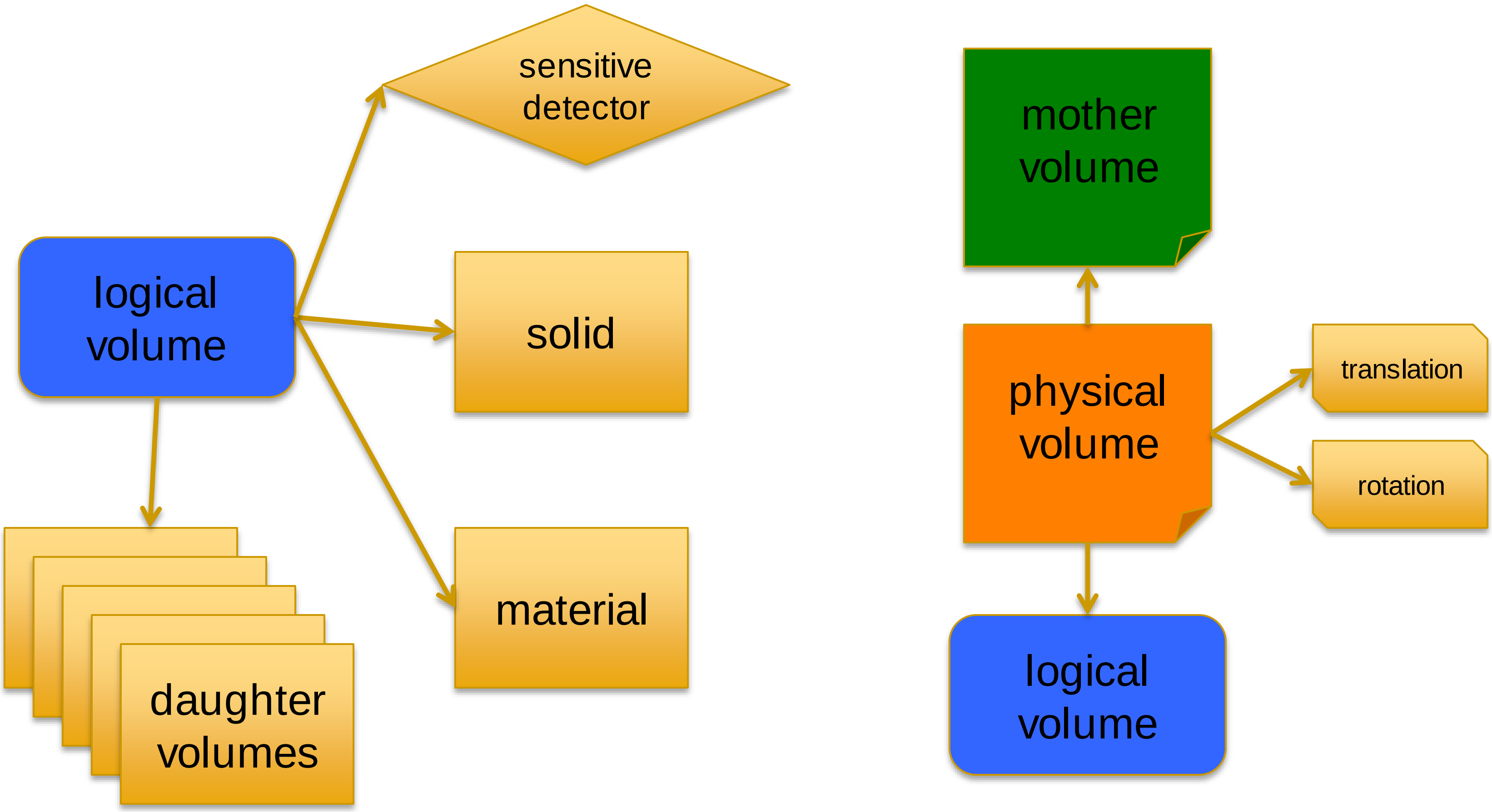


Geometry (1/3)

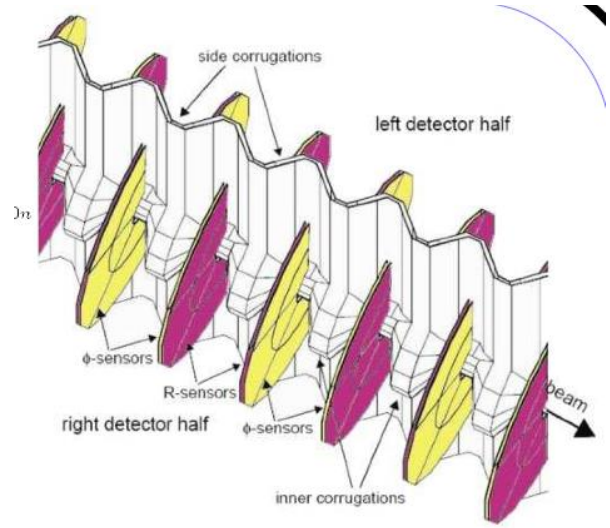
- set of solids (shapes) classes
  - box, sphere, tube, etc, etc…
  - boolean operations on solids
- logical volumes
  - unpositioned volumes with associated materials and possibly with 'daughter' volumes
    - unpositioned hierarchies of volumes
- physical volumes
  - concrete 'placements' of logical volumes
  - can reuse the same logical volume several times

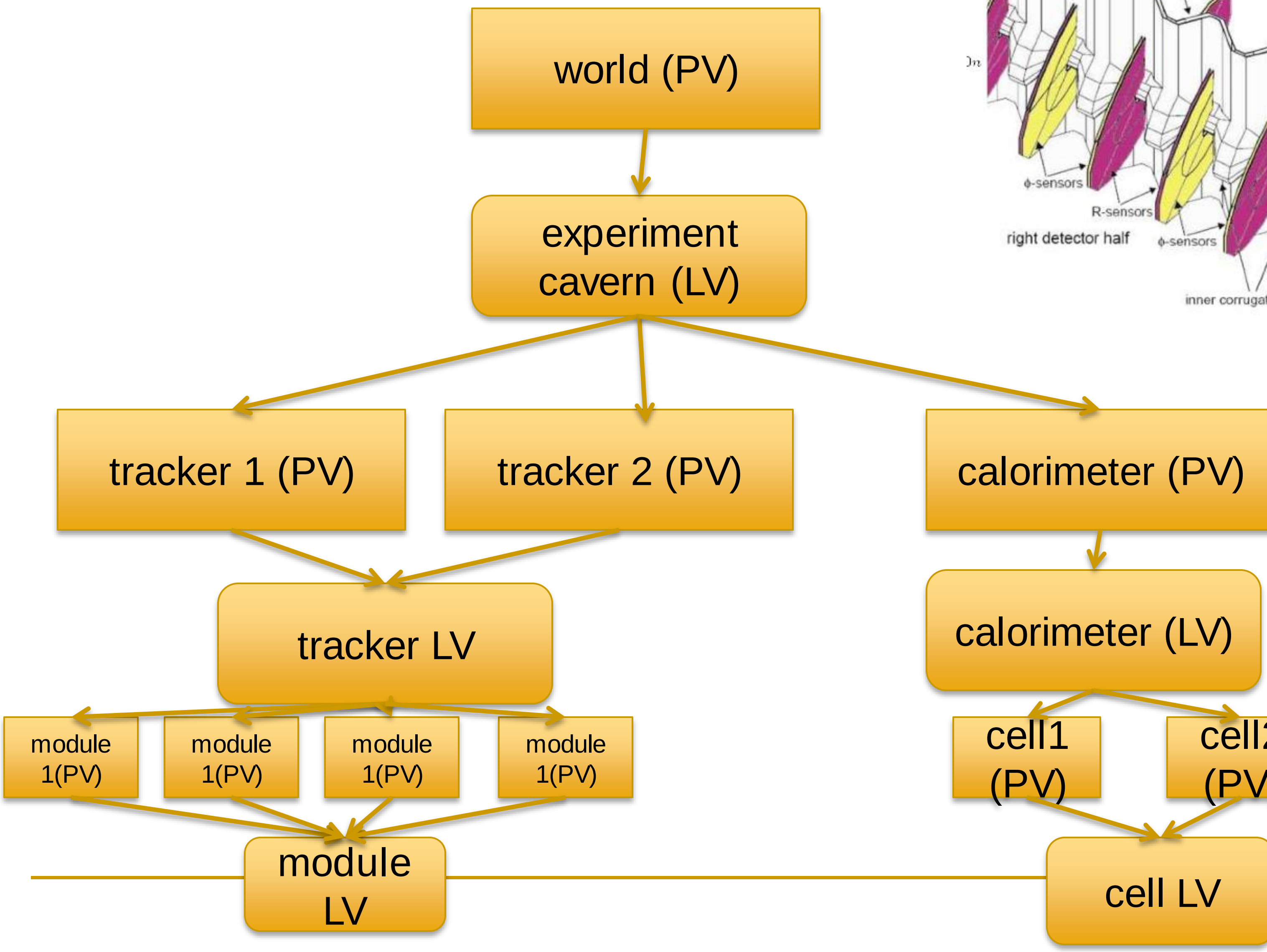









Geometry (2/3)


sensitive detector
logical volume
solid
material
daughter volumes
mother volume
physical volume
translation
rotation
logical volume

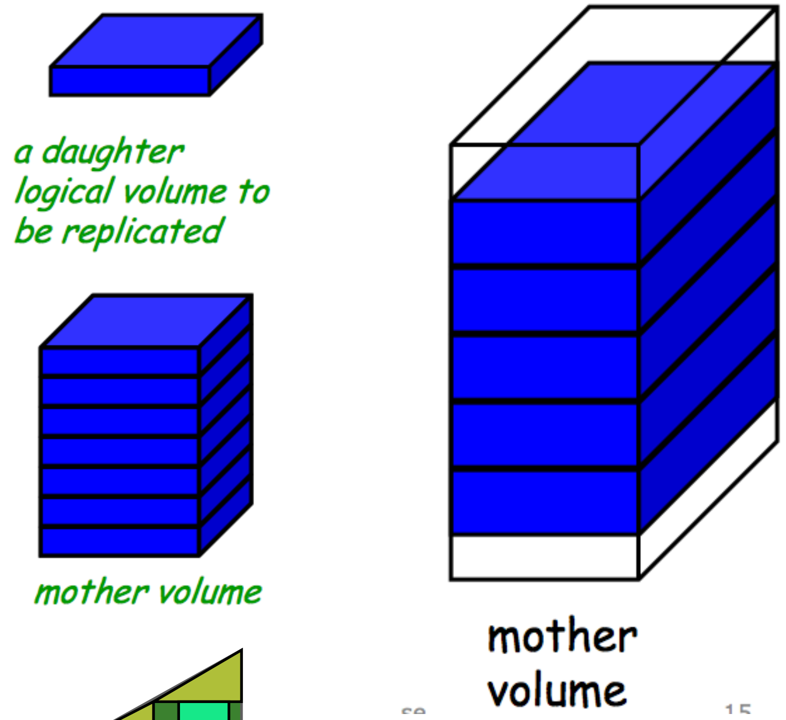
Geometry (3/3)

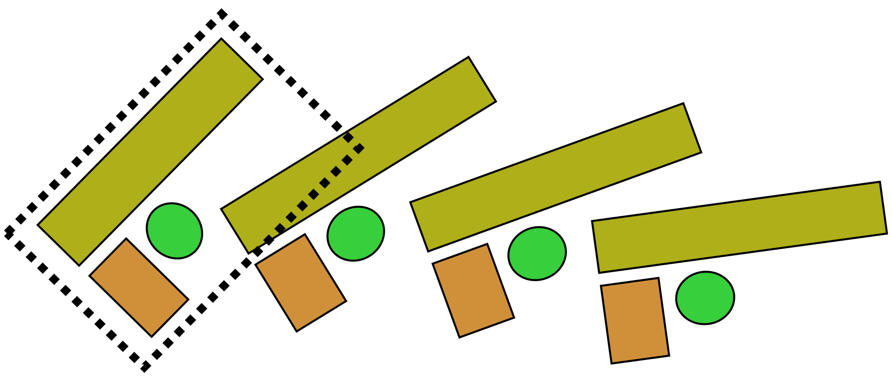

side corrugations
left detector half
ϕ-sensors
R-sensors
right detector half
ϕ-sensors
inner corrugations
beam

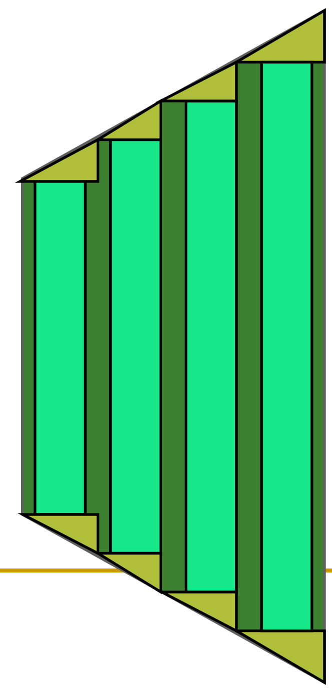

world (PV)
experiment cavern (LV)
tracker 1 (PV)
tracker 2 (PV)
calorimeter (PV)
tracker LV
calorimeter (LV)
module 1(PV)
module 1(PV)
module 1(PV)
module 1(PV)
cell1 (PV)
cell2 (PV)
module LV
cell LV

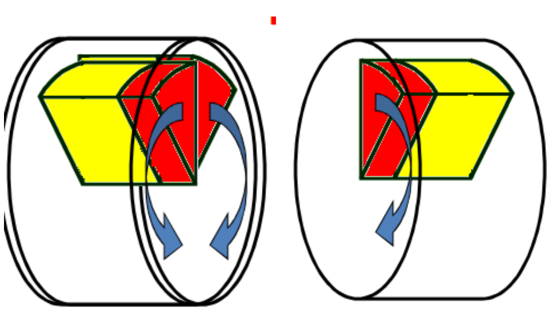
Advance geometry

- replicas
- divisions
- reflections
- assemblies
- parameterizations









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

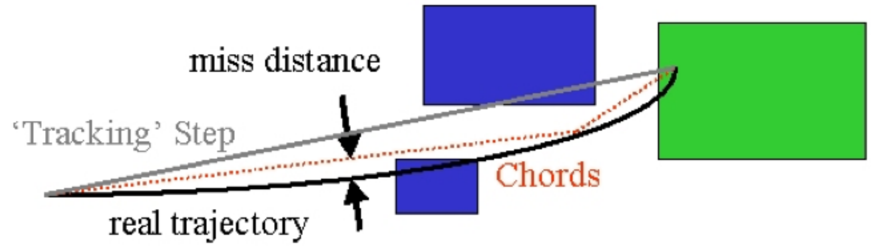
Navigation and tracking

- ‘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’

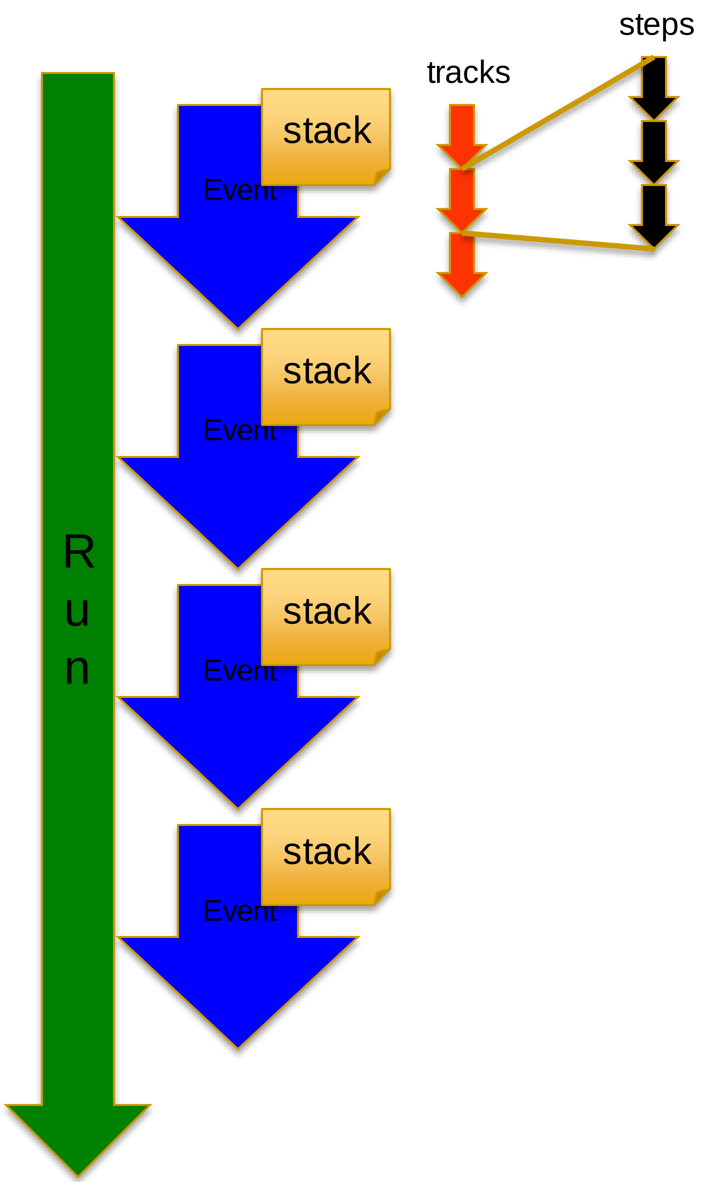
Magnetic field

- 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



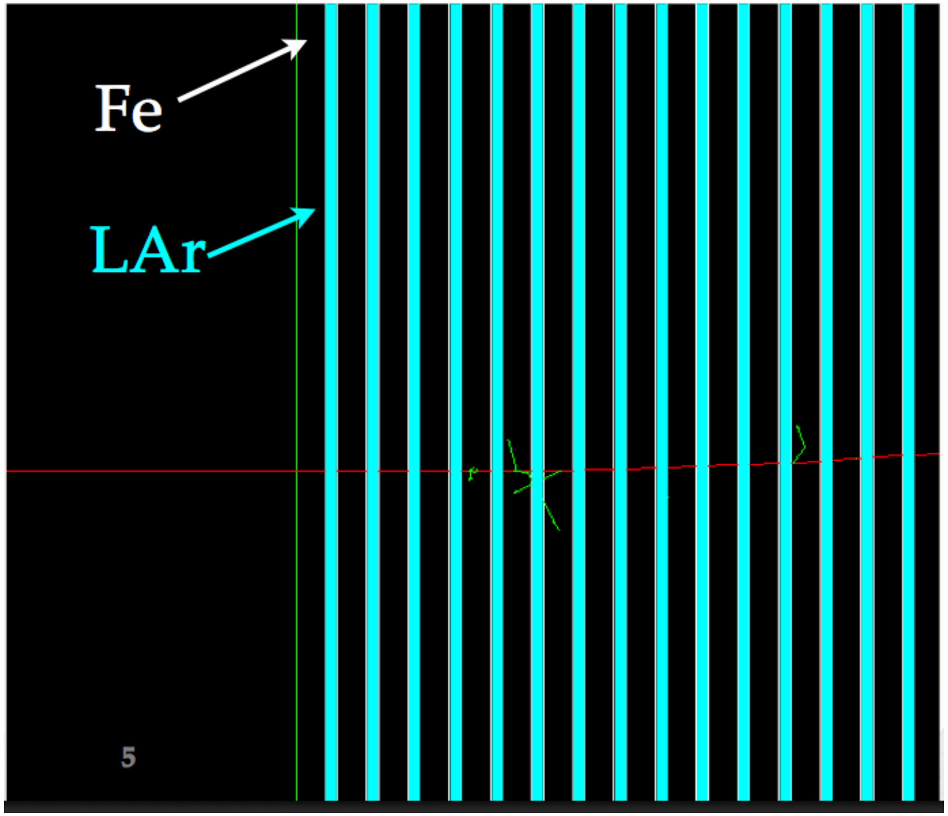
User actions

- how to control your simulation?
  - G4UserRunAction
    - BeginOfRunAction, EndOfRunAction
  - G4UserEventAction
    - BeginOfEventAction, EndOfEventAction
  - G4UserStackingAction
    - ClassifyNewTrack, NewStage, PrepareNewEvent
  - G4UserTrackingAction
    - PreUserTrackingAction, PostUserTrackingAction
  - G4UserSteppingAction
    - BeginOfStepAction, EndOfStepAction
- 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



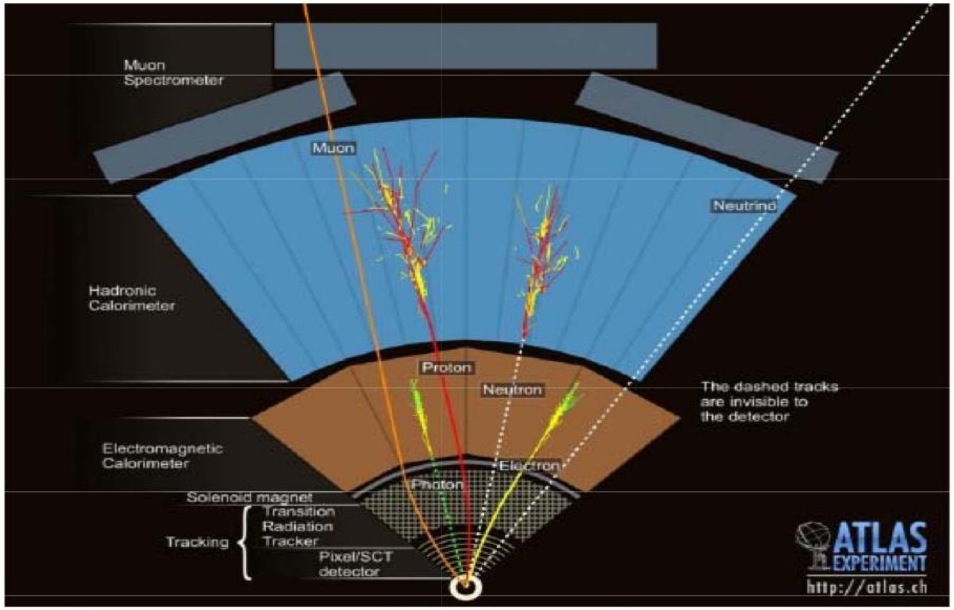
Users actions – sensitive detectors

- 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
  - Initialize – called at the beginning of each event
  - EndOfEvent – called at the end of each event
- they simulate detector response to the particles passing through the sensors

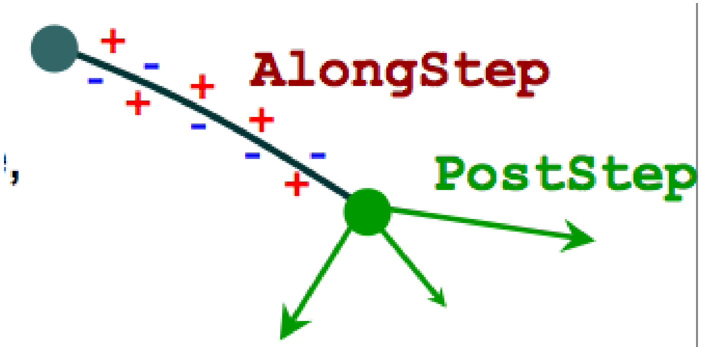


Physics…

- what happens to a particles in matter?
- we need to implement the physics we know



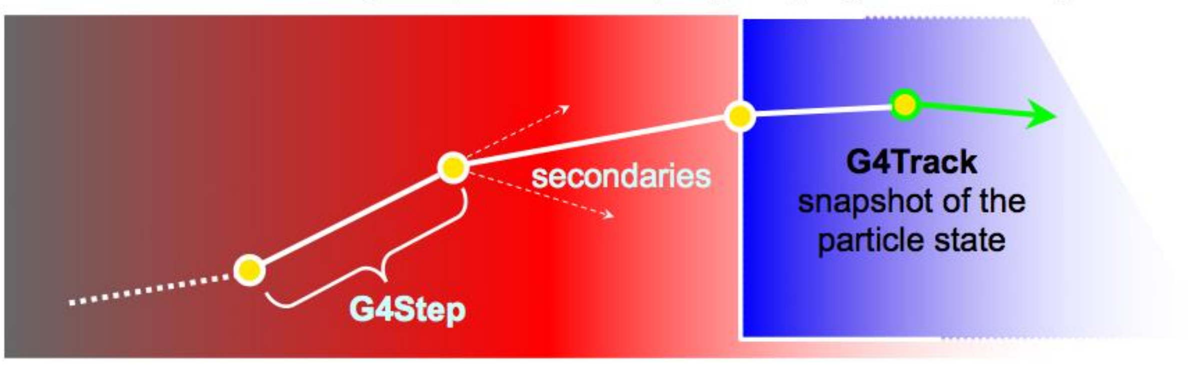
Physics processes (1/2)



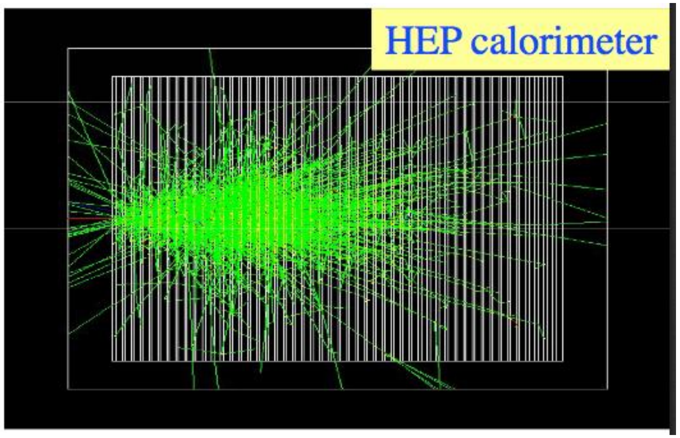
- each process provides
  - GetPhysicalInteractionLength method
    - calculates probability of interactions from the cross-section
  - *DoIt methods
    - AlongStepDoIt – always invoked for all the processes defined for a given particle
    - PostStepDoIt – invoked at the end of the step if the given process provided the smallest Physical Interaction Lenght.
    - AtRestDoIt – like PostStepDoIt but for stopped particles

Physics processes (2/2)

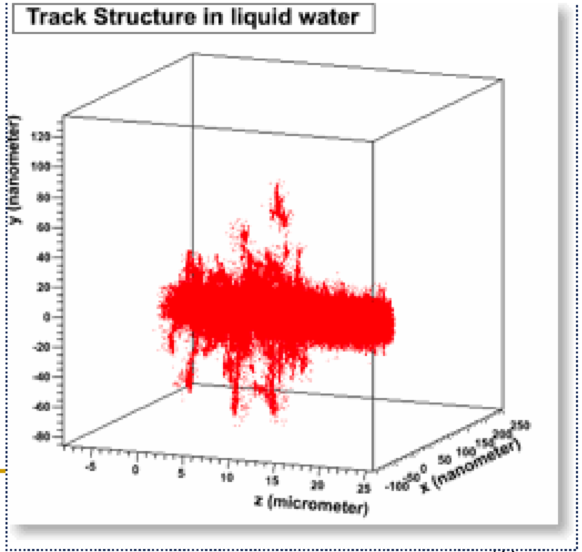
- Physical interaction lengths and distance to the next boundary (eventually recalculated) are compared
  - the smallest value wins
- along step called for all processes and resulting change of the track accumulated in G4Step
- particle change object stores the final state information including secondary tracks generated by DoIt methods



Electromagnetic (1/2)

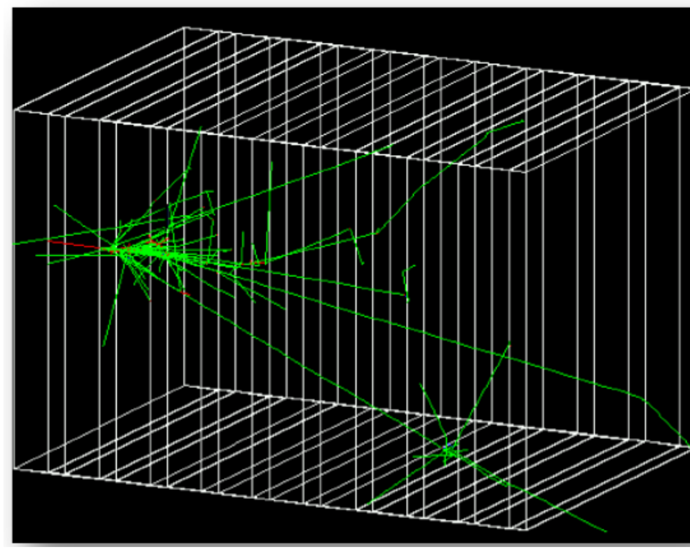


- simulation of electromagnetic interactions of charged particles, gammas and optical photons
  - standard electromagnetic physics
    - optimized for high and medium energy applications
      - energy range from 1keV to 1PeV
  - low energy electromagnetic physics
    - down to eV
      - medical and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



Electromagnetic (2/2)

- Gammas:
  - Gamma-conversion, Compton scattering, Photo-electric effect
- Leptons(e, ⌠), 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

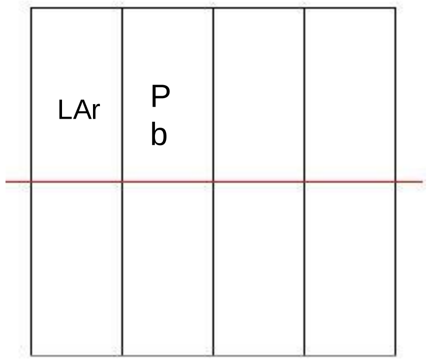
Why cut in range

- 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 also 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

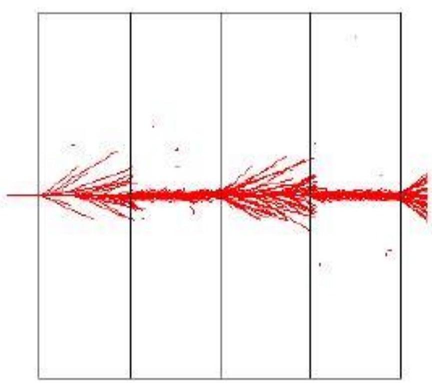
Cut in range (production threshold) vs. energy cut

Example: 500 MeV p in LAr-Pb Sampling Calorimeter

Geant3 (and others)

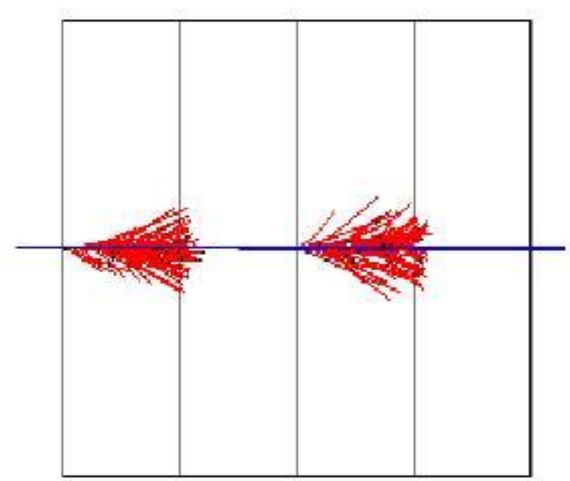


Cut = 2 MeV



Cut = 450 keV

Geant4

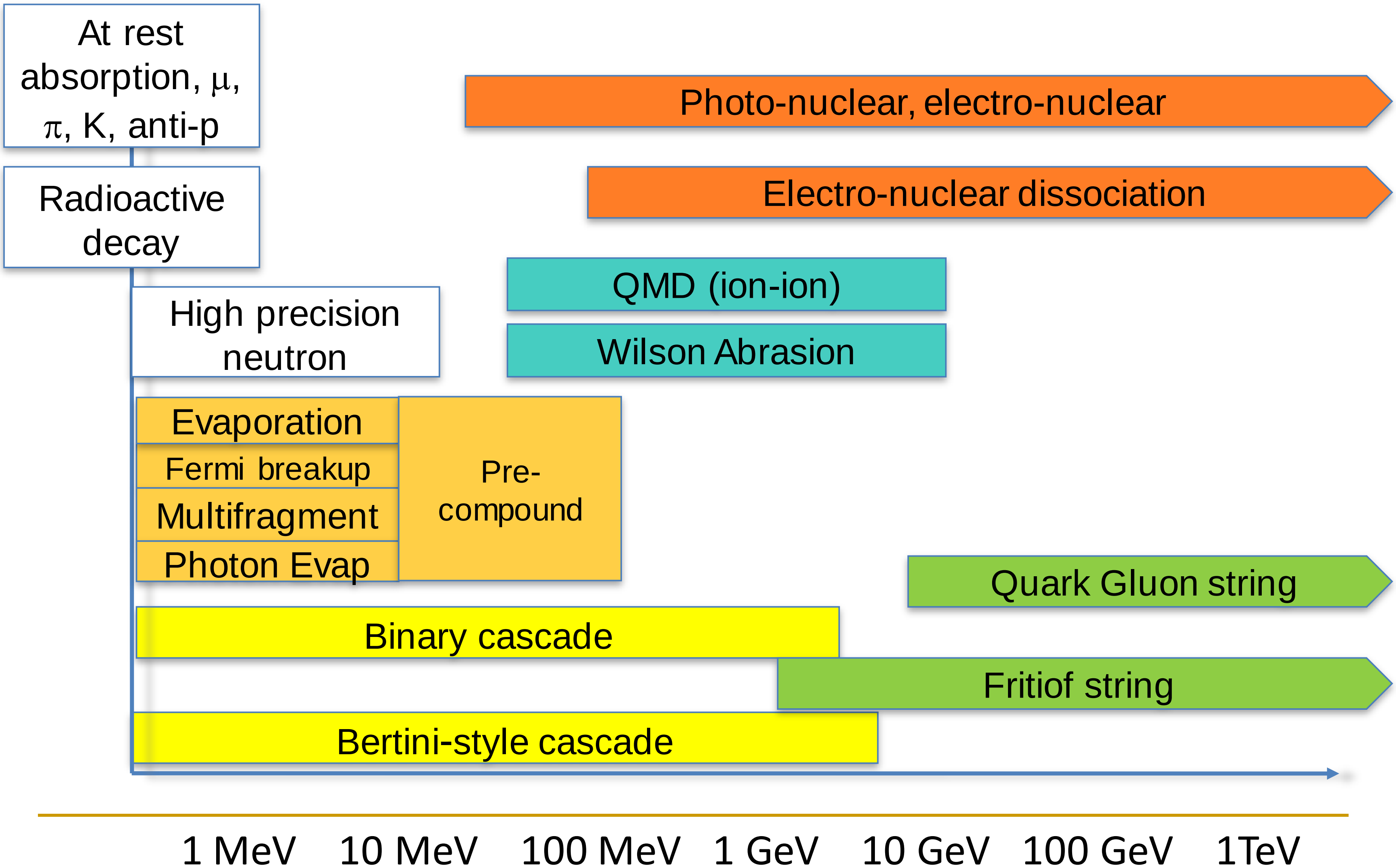


Production range = 1.5 mm

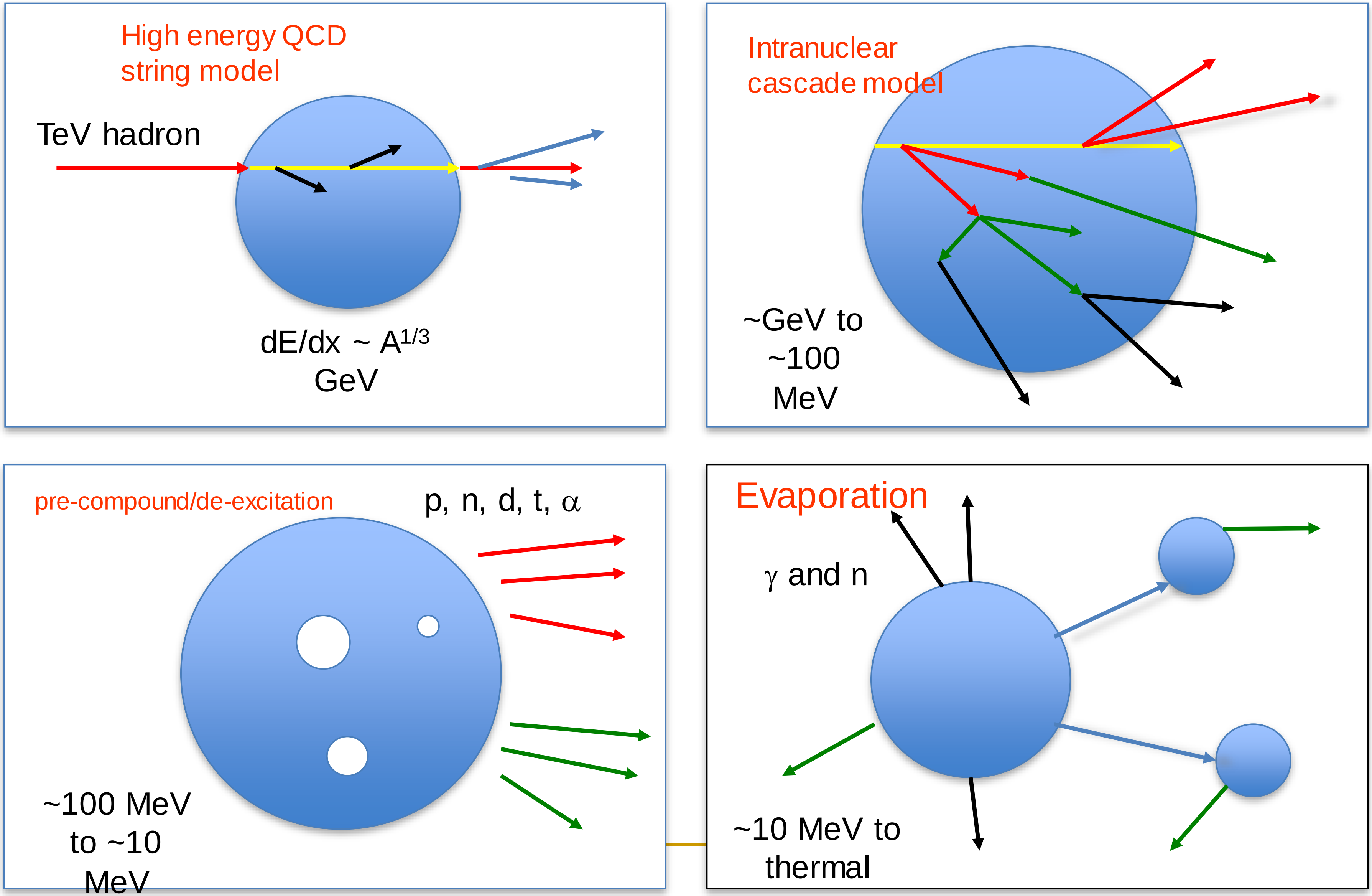
Hadronic

- hadrons at rest
  - π, K absorption
  - neutron capture
  - anti-proton, anti-neutron annihilation
  - μ- capture
- hadrons in flight
  - inelastic scattering
  - elastic scattering
  - fission
  - neutron, anti-neutron capture

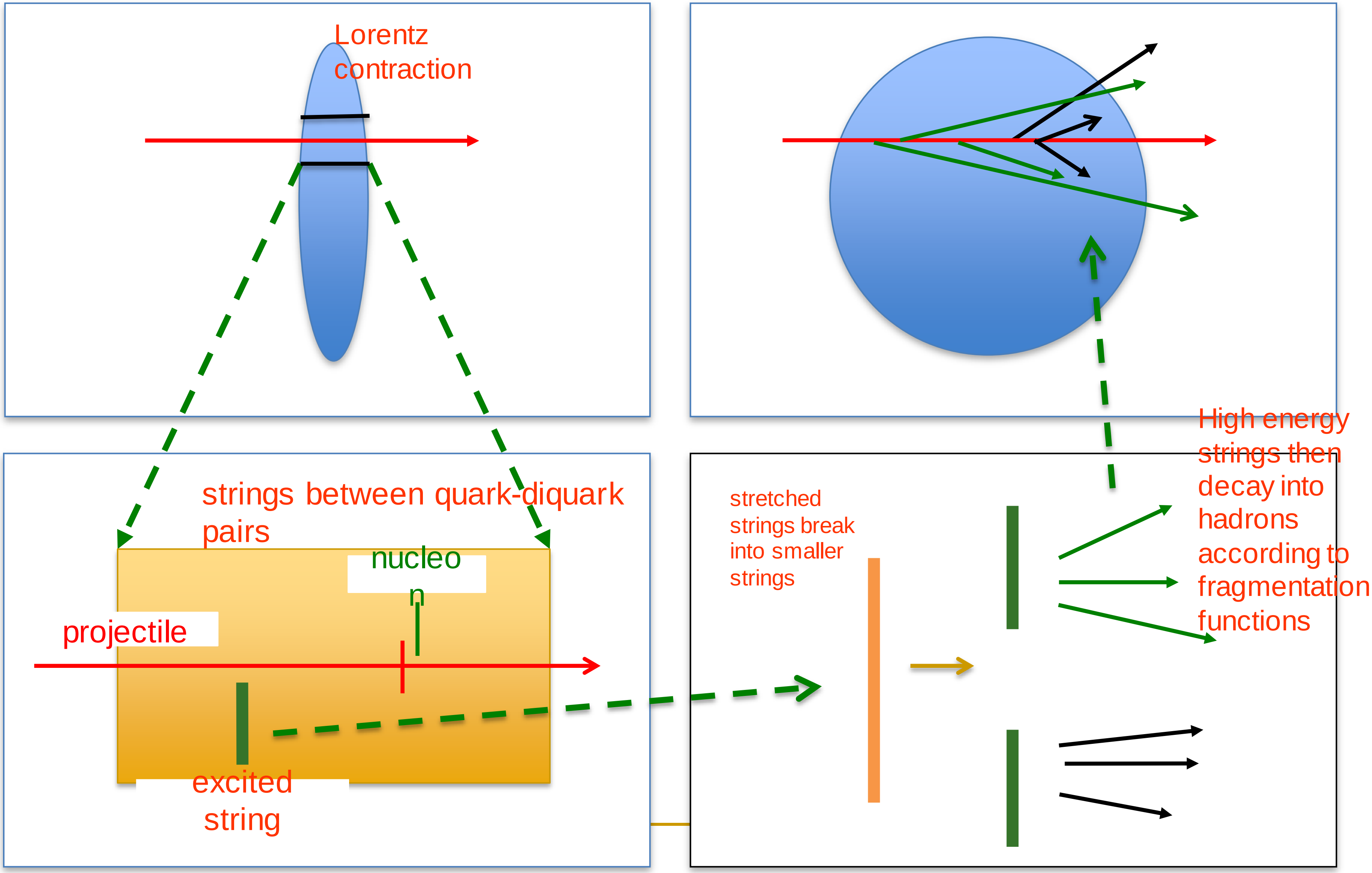
Partial hadronic model inventory



Hadronic Interactions from TeV to meV



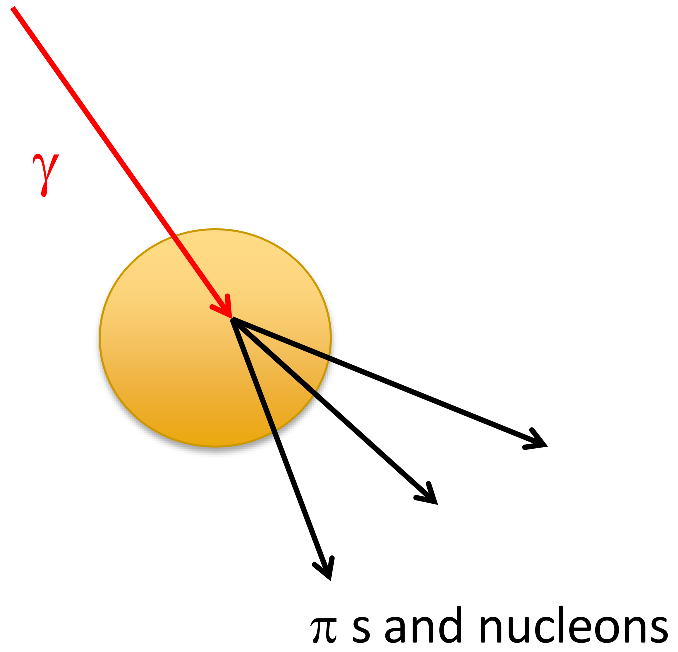
High Energy Nuclear Interaction



Gamma- and Lepto-nuclear Models (1/2)

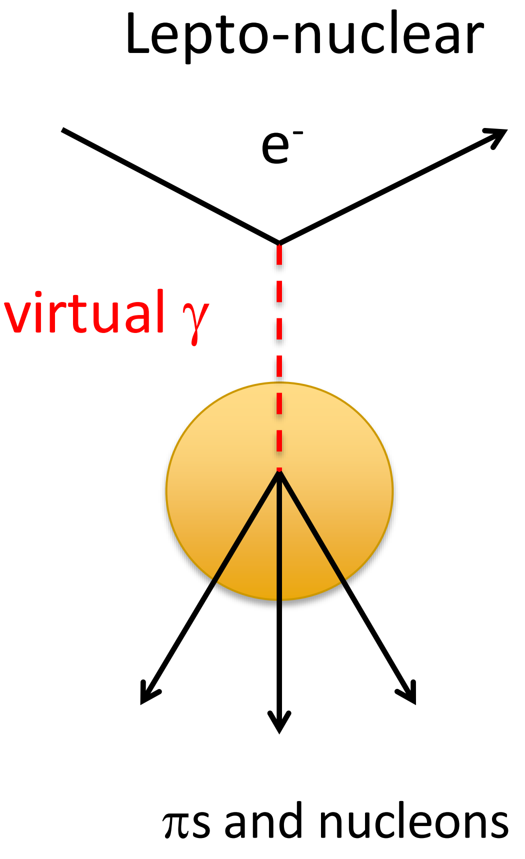
- Gammas interact directly with the nucleus
  - at low energies they are absorbed and excite the nucleus as a whole
  - at high energies they act like hadrons (pion, rho, etc.) and form resonances with protons and neutrons

Gamma-nuclear



Gamma- and Lepto-nuclear Models (2/2)

- Electrons and muons cannot interact hadronically, except through virtual photons
  - electron or muon passes by a nucleus and exchanges virtual photon
  - virtual photon then interacts directly with nucleus (or nucleons within nucleus)

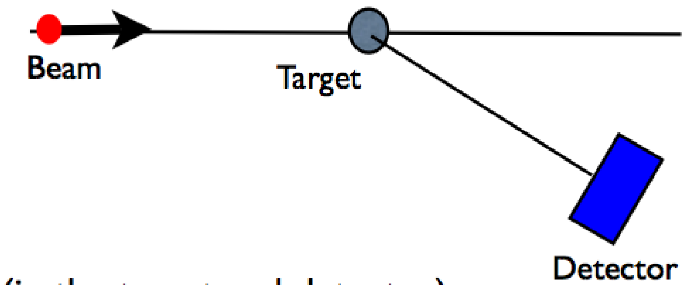


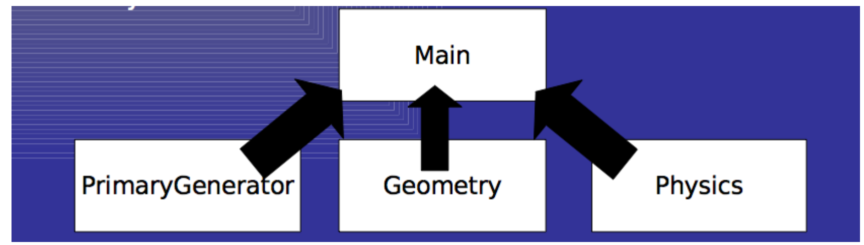
Geant4 ‘Physics Lists’

- 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

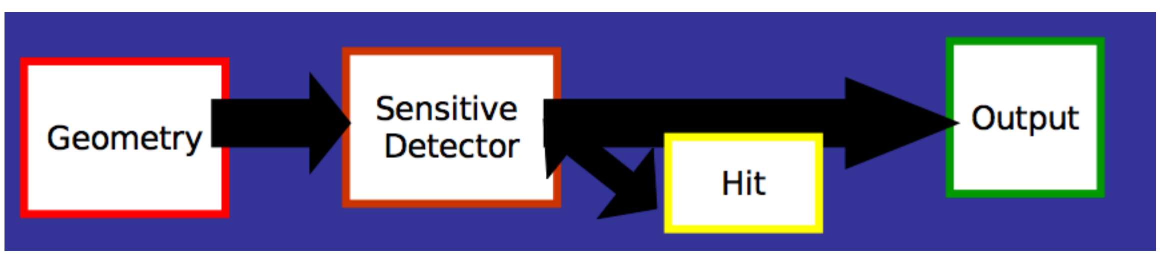
GEANT4 APPLICATION COOKBOOK

What you need to make simulation?





and to get something out of it…



Your first Geant4 application recipe

- geometry
- primary generator
- user actions
- give commands to UI manager

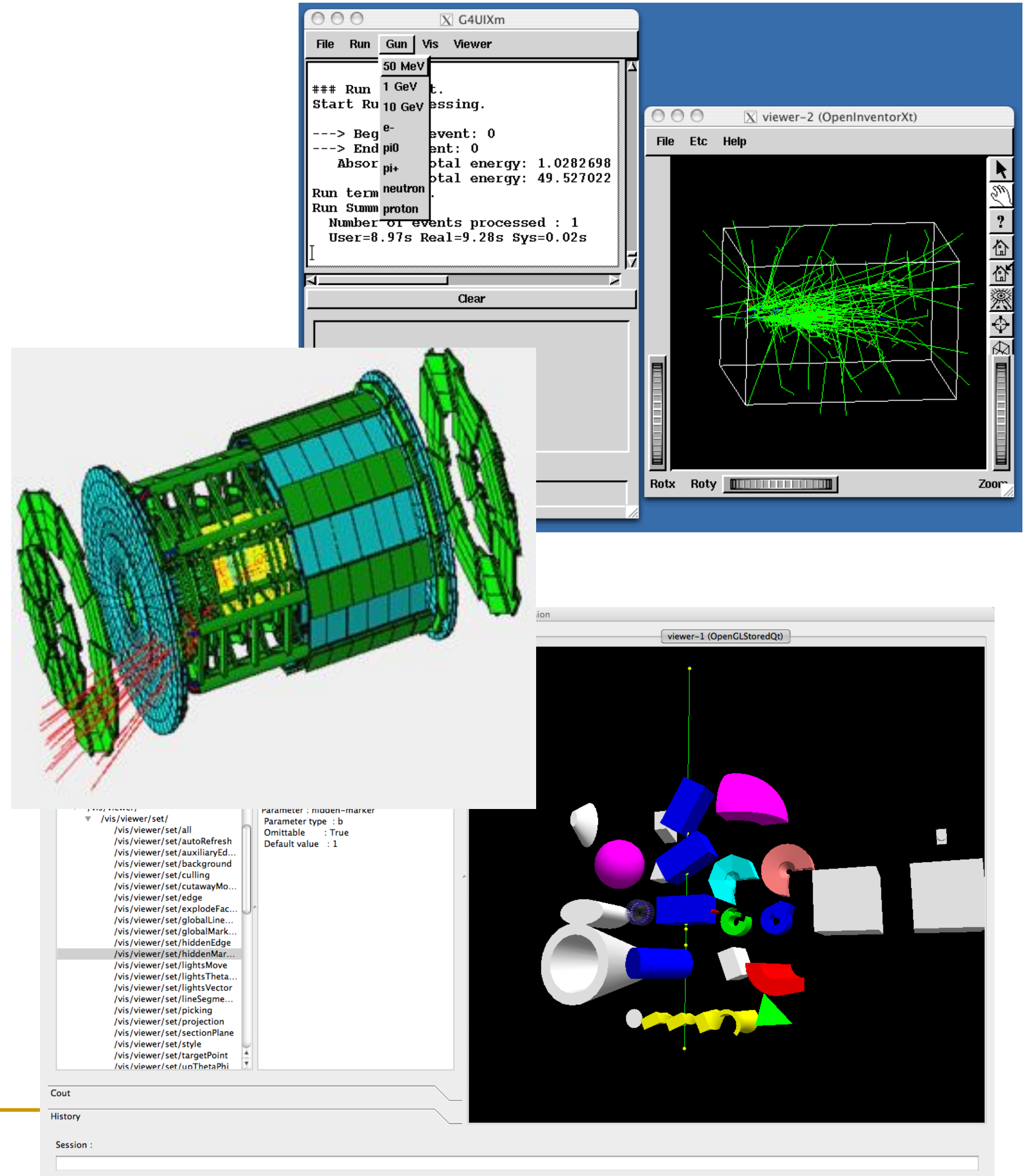
```
# e+ 200MeV
/gun/energy 200 MeV
/gun/particle e+
/run/beamOn 1
```

```
int main(int argc,char** argv)
{
  // Construct the default run manager

  G4RunManager * runManager = new G4RunManager;

  // Set mandatory initialization classes

  runManager->SetUserInitialization(new B2aDetectorConstruction());

  G4VModularPhysicsList* physicsList = new FTFP_BERT;

  runManager->SetUserInitialization(physicsList);

  // Set user action classes

  runManager->SetUserAction(new B2PrimaryGeneratorAction());
  runManager->SetUserAction(new B2RunAction());
  runManager->SetUserAction(new B2EventAction());

  // Initialize G4 kernel

  runManager->Initialize();

  // Get the pointer to the User Interface manager
  G4UImanager* UImanager = G4UImanager::GetUIpointer();

  G4UIExecutive* ui = new G4UIExecutive(argc, argv);

  return 0;
}

//....oooOO0OOooo........oooOO0OOooo........oooOO0OOooo........oooOO0OOooo.....
```

- look into Geant4 basic examples
  - in the examples directory

Visualisation

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



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 their undergo and the energy deposition they make
- the use of such a simulation is essential to build, understand and use your devices

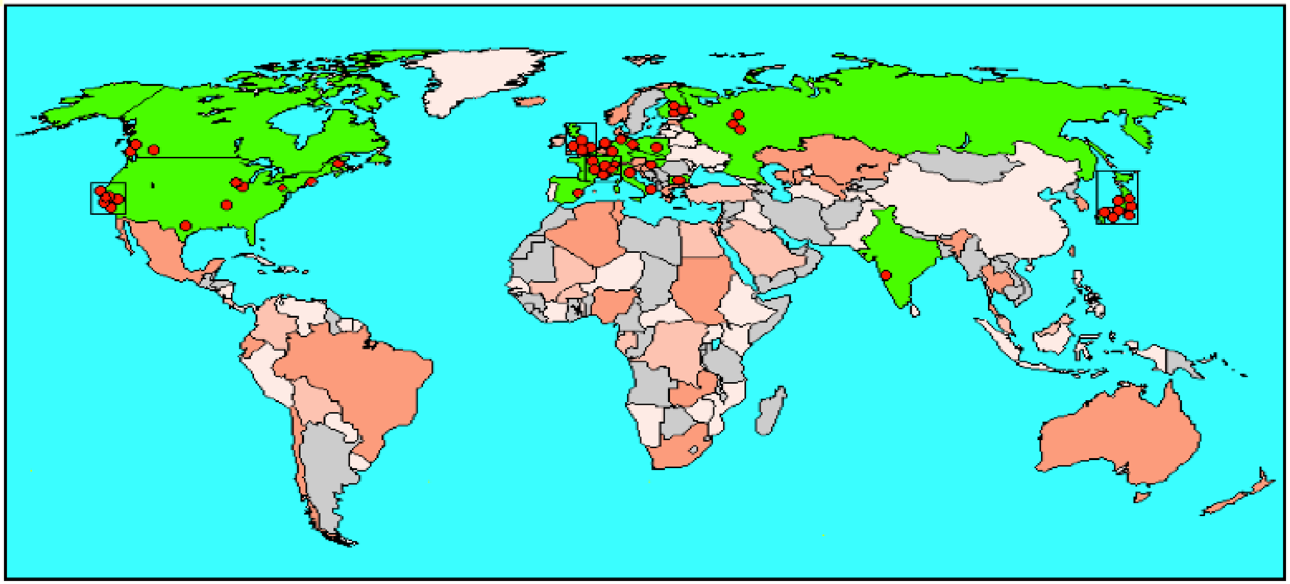
Resources for more information

- 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.w eb.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
  - Hadronic 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
- First 'reference' paper
  - "Geant4: a simulation toolkit", Nucl. Instr. and Methods **A** 506 (2003), 250-303.

Geant4 is an International Collaboration

SLAC
NATIONAL ACCELERATOR LABORATORY



TRIUMF

Lebedev

J.W.Goethe Universität

Fermilab

UNIVERSITAT DE BARCELONA

Collaborators also from non-member institutions, including
Budker Inst. of Physics
IHEP Protvino
MEPHI Moscow
Pittsburg University