An overview of the Geant4 Toolkit

Third African School of Physics
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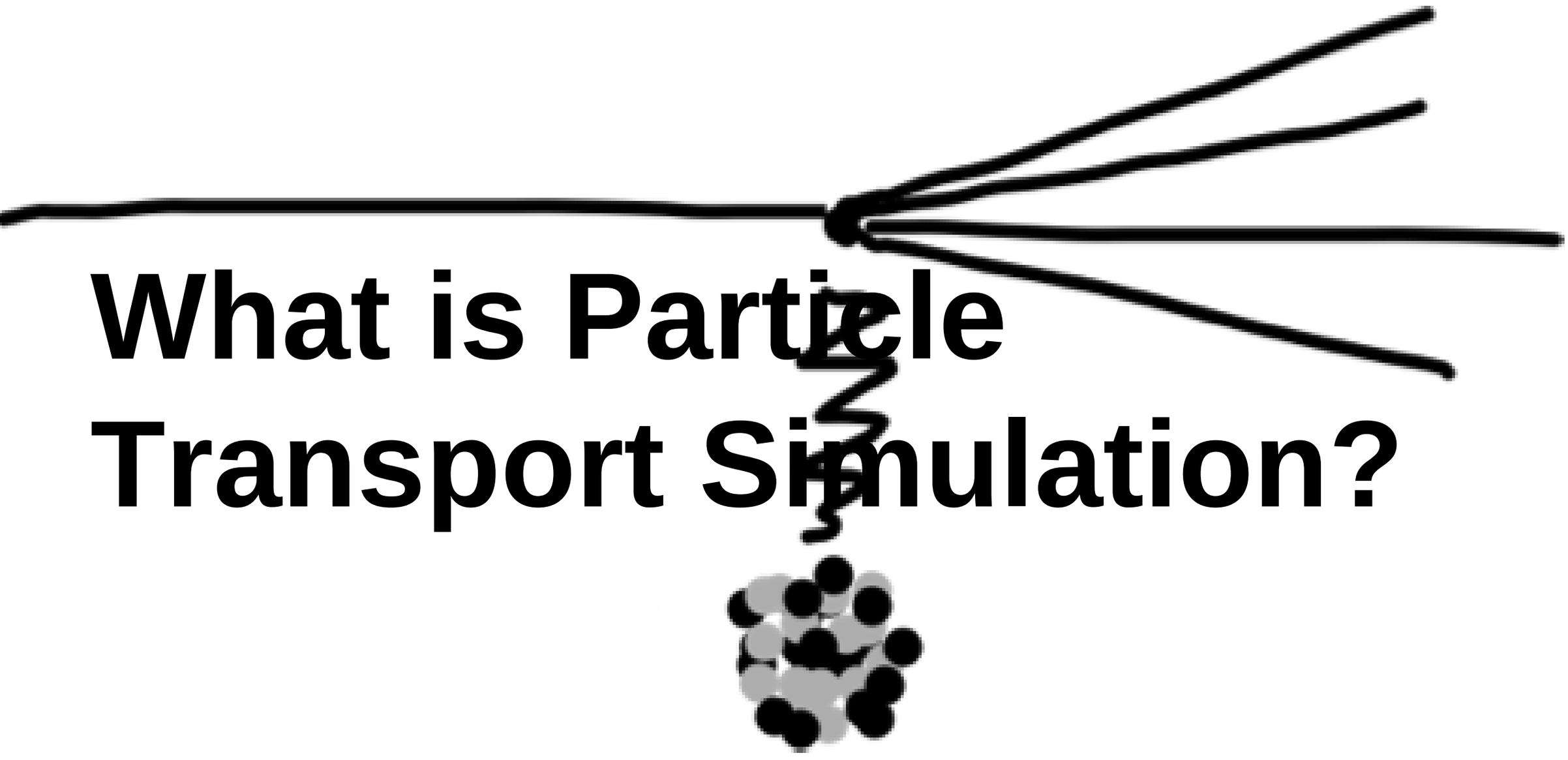
Adapted from talk by **Andrea Dotti** (SLAC- formely CERN)
at the Second African School of Physics, August 2012

Overview

- Introduction
- Geometry and visualization
- Physics processes:
  - Electromagnetic Physics
  - Hadronic Physics and the Physics Lists
- Application Domains:
  - High Energy and Nuclear Physics
  - Medical Physics
  - Space and Satellite Physics
- Future Challenges

What is Particle Transport Simulation?

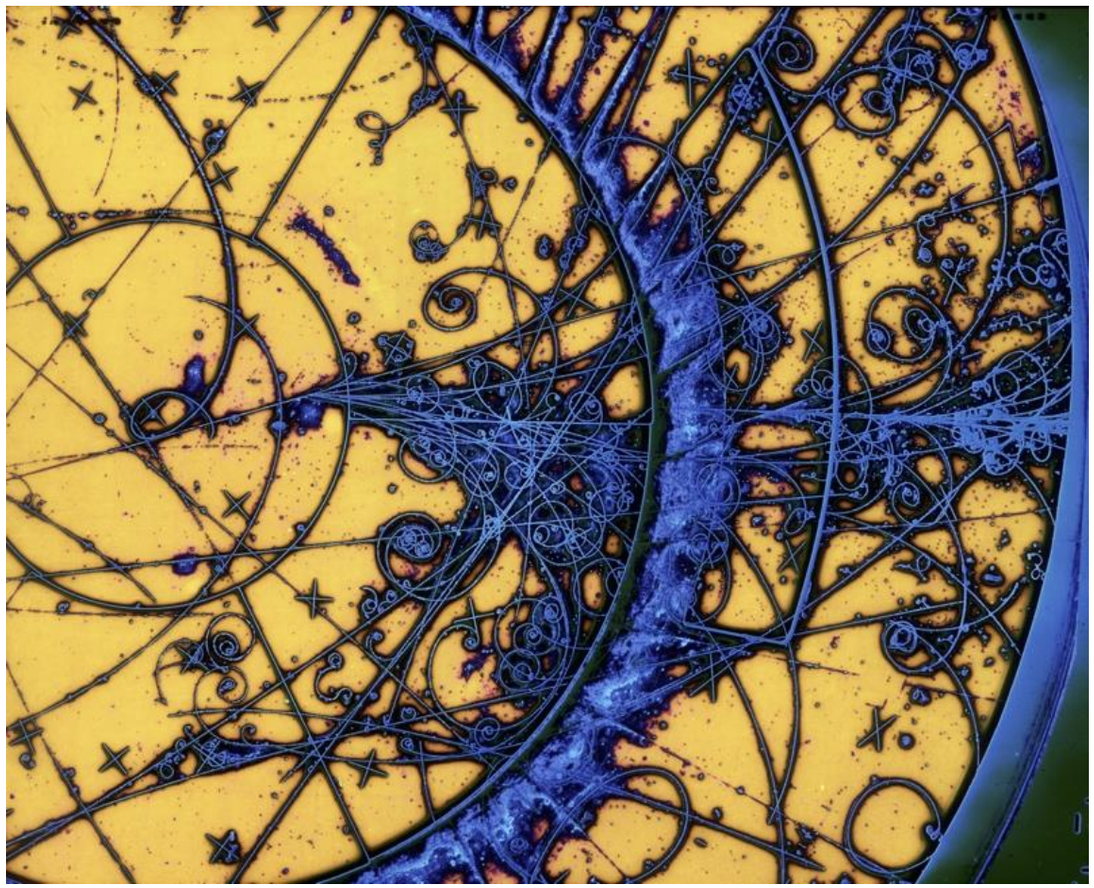


What is Simulation?

- ‘Physical’ system
- Model = equations
- Evolve
- Extract results

Transport: context

- What is transport simulation do?
- What can it do ?

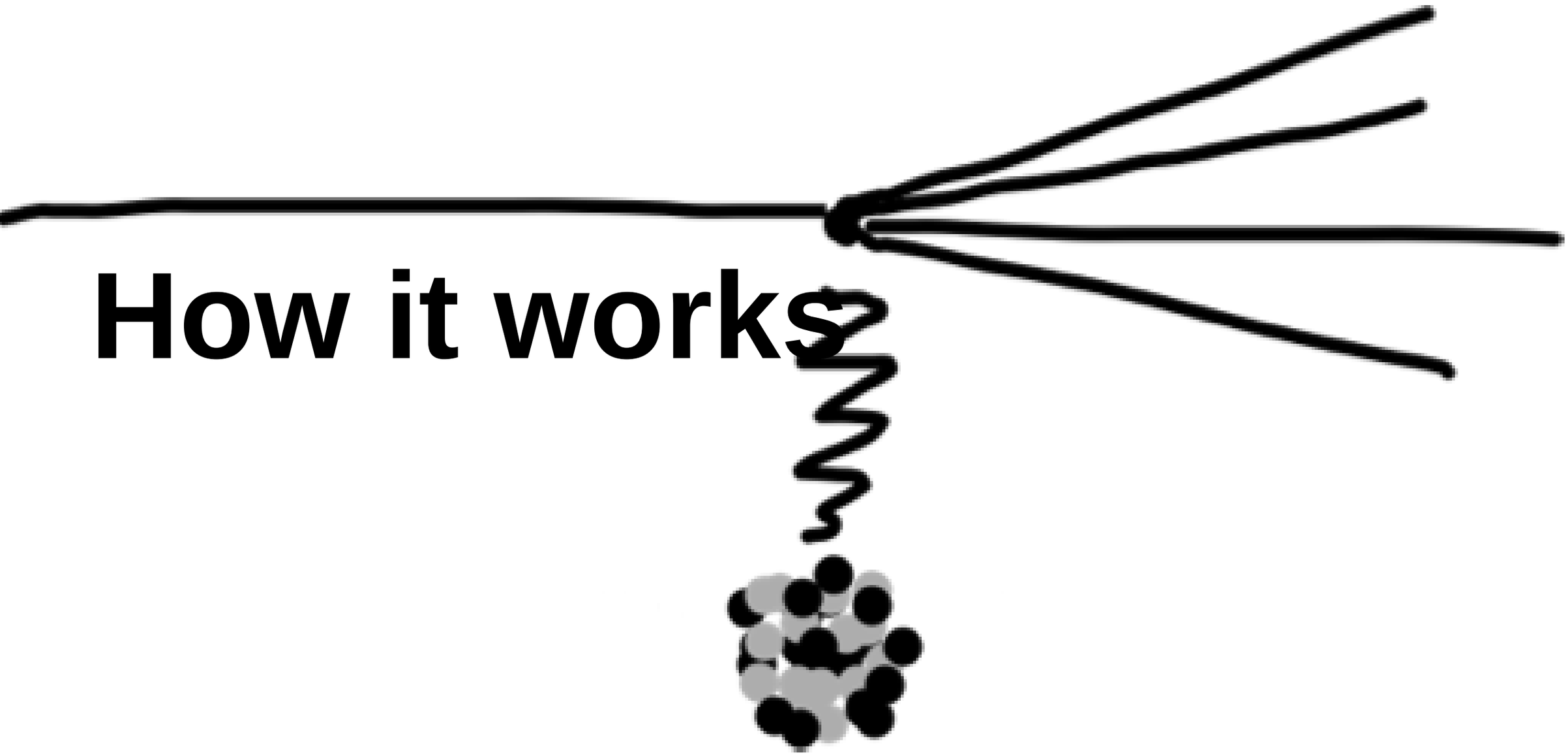


‘Radiation’ Transport

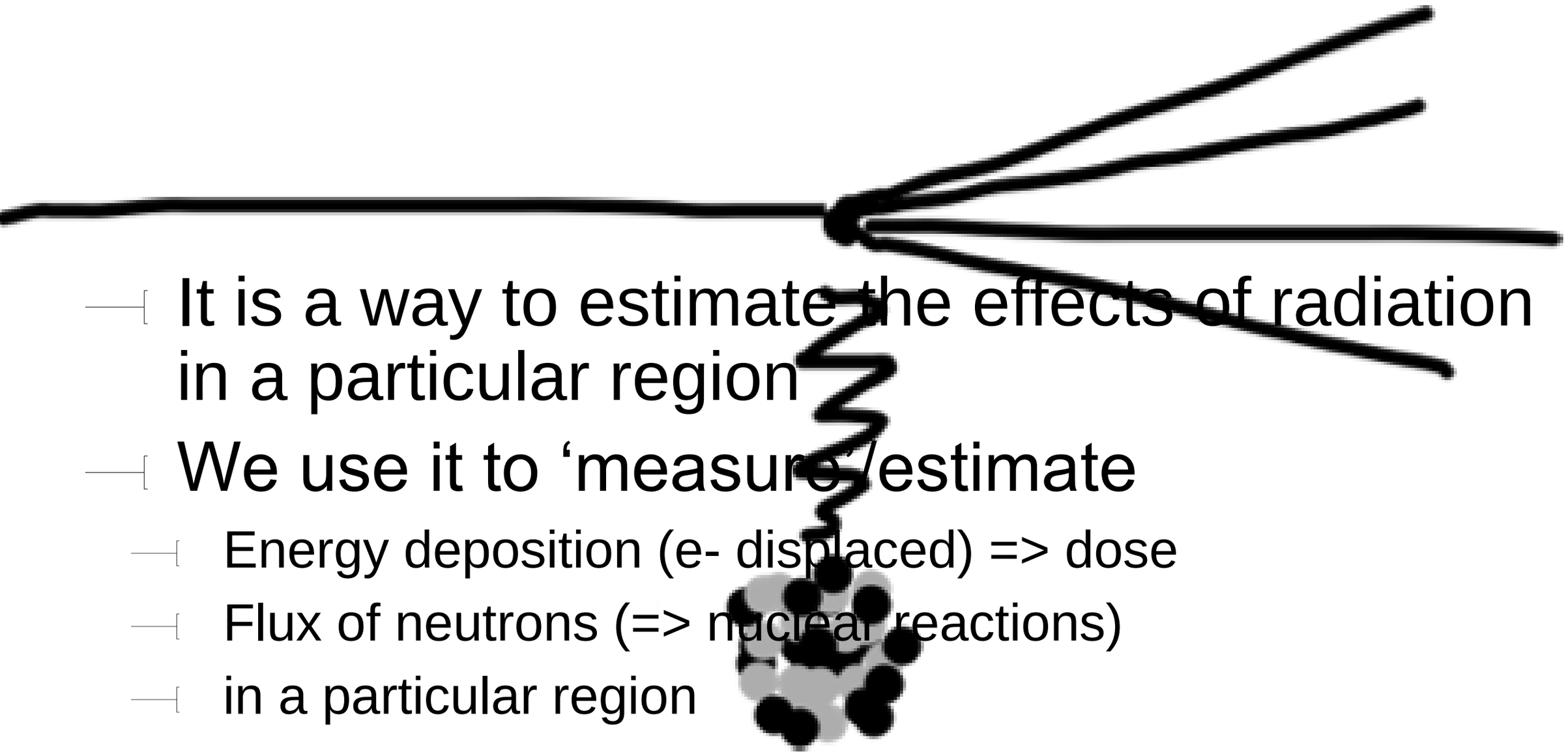
Electromagnetic shower from a 100 MeV electron

red: electrons
blue: gammas

How it works

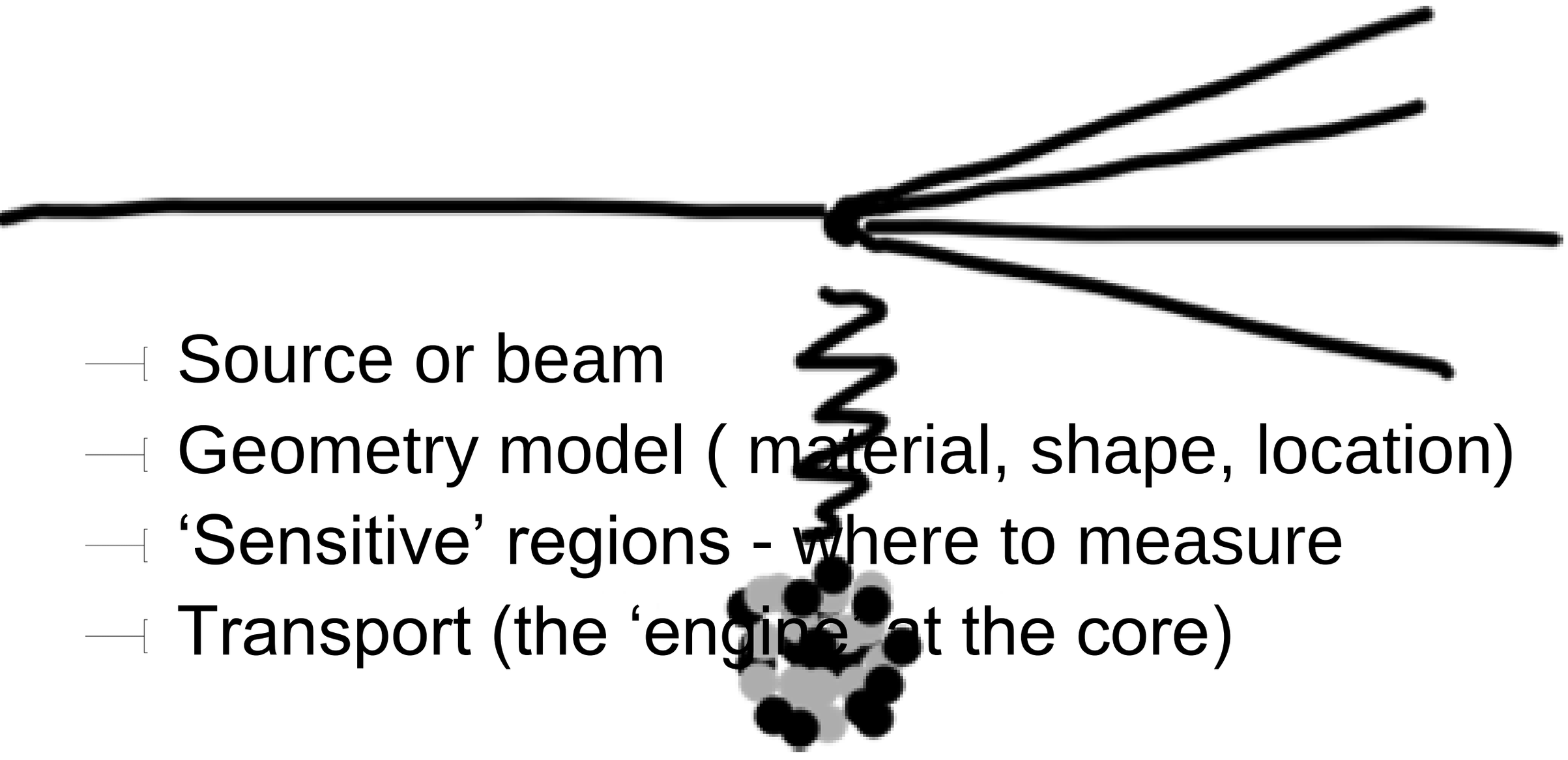


What is it?



- It is a way to estimate the effects of radiation in a particular region
- We use it to ‘measure’/estimate
  - Energy deposition (e- displaced) => dose
  - Flux of neutrons (=> nuclear reactions)
  - in a particular region

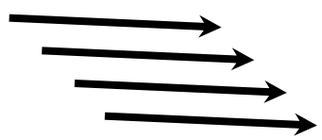
The parts

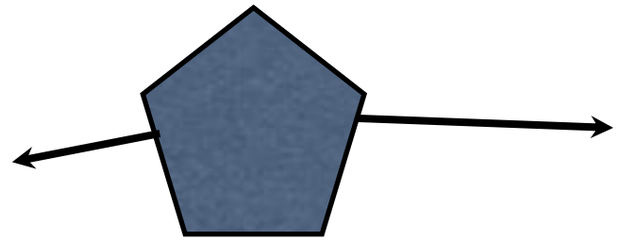


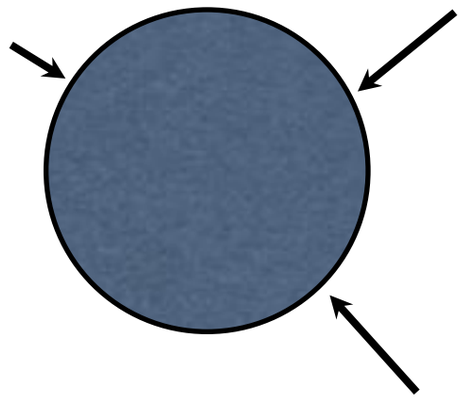
- Source or beam
- Geometry model (material, shape, location)
- ‘Sensitive’ regions - where to measure
- Transport (the ‘engine’ at the core)

1. The particle source

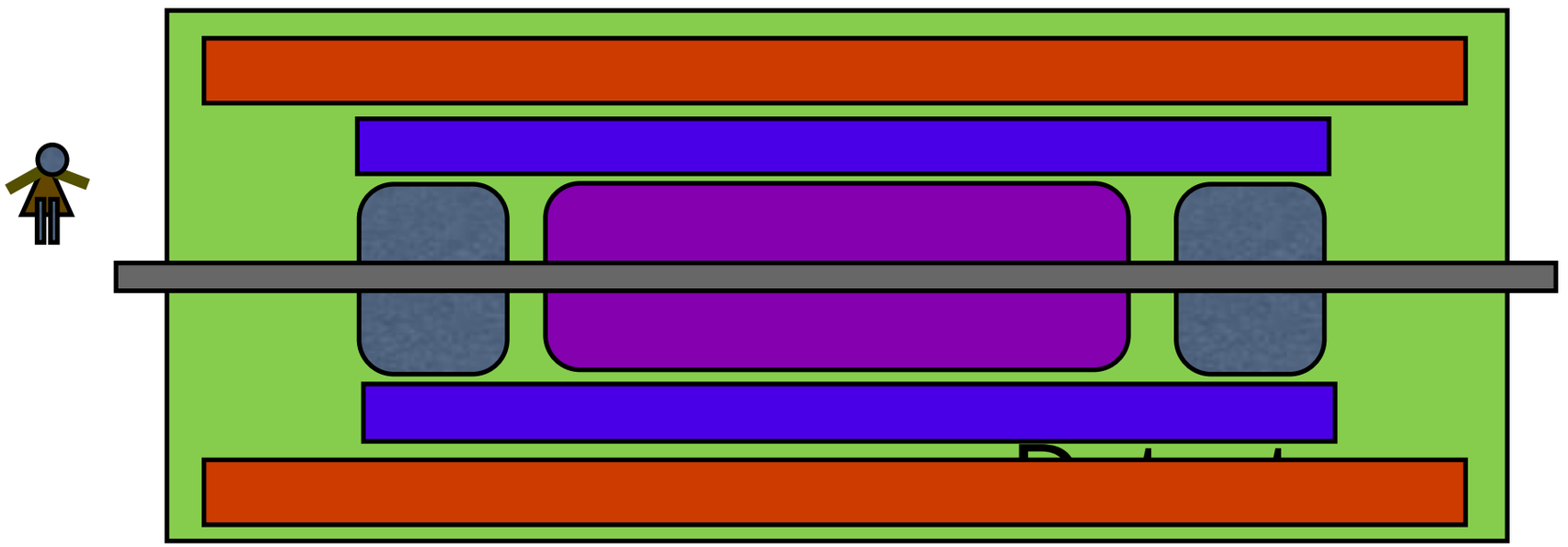
- Beam, ‘source’
- Determines the initial particles
  - type (e.g. e-, proton)
  - momentum
- Distributions or unique

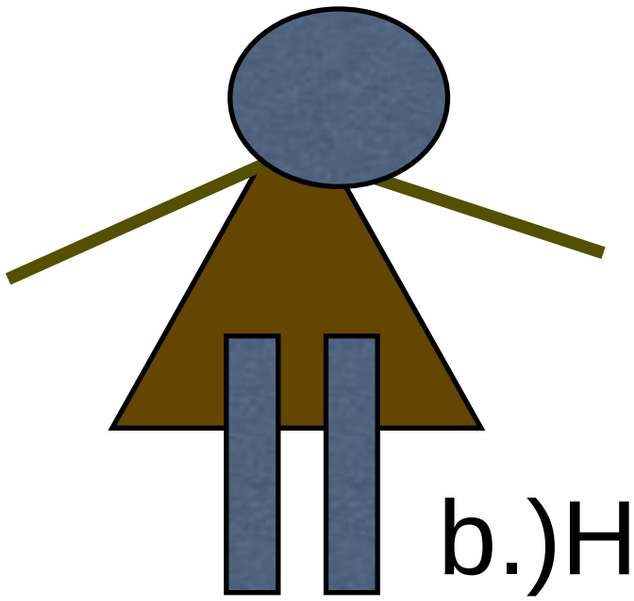




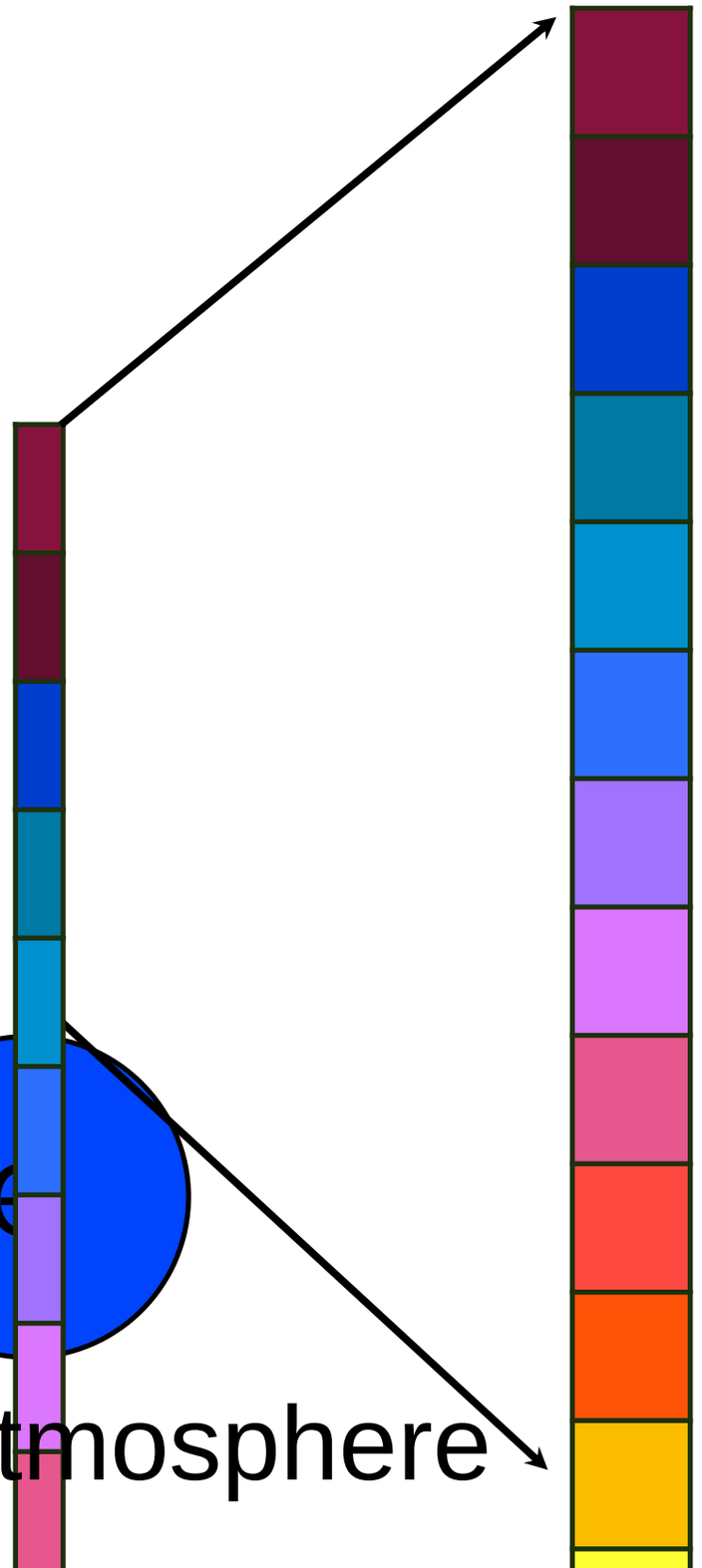


2. The geometry model



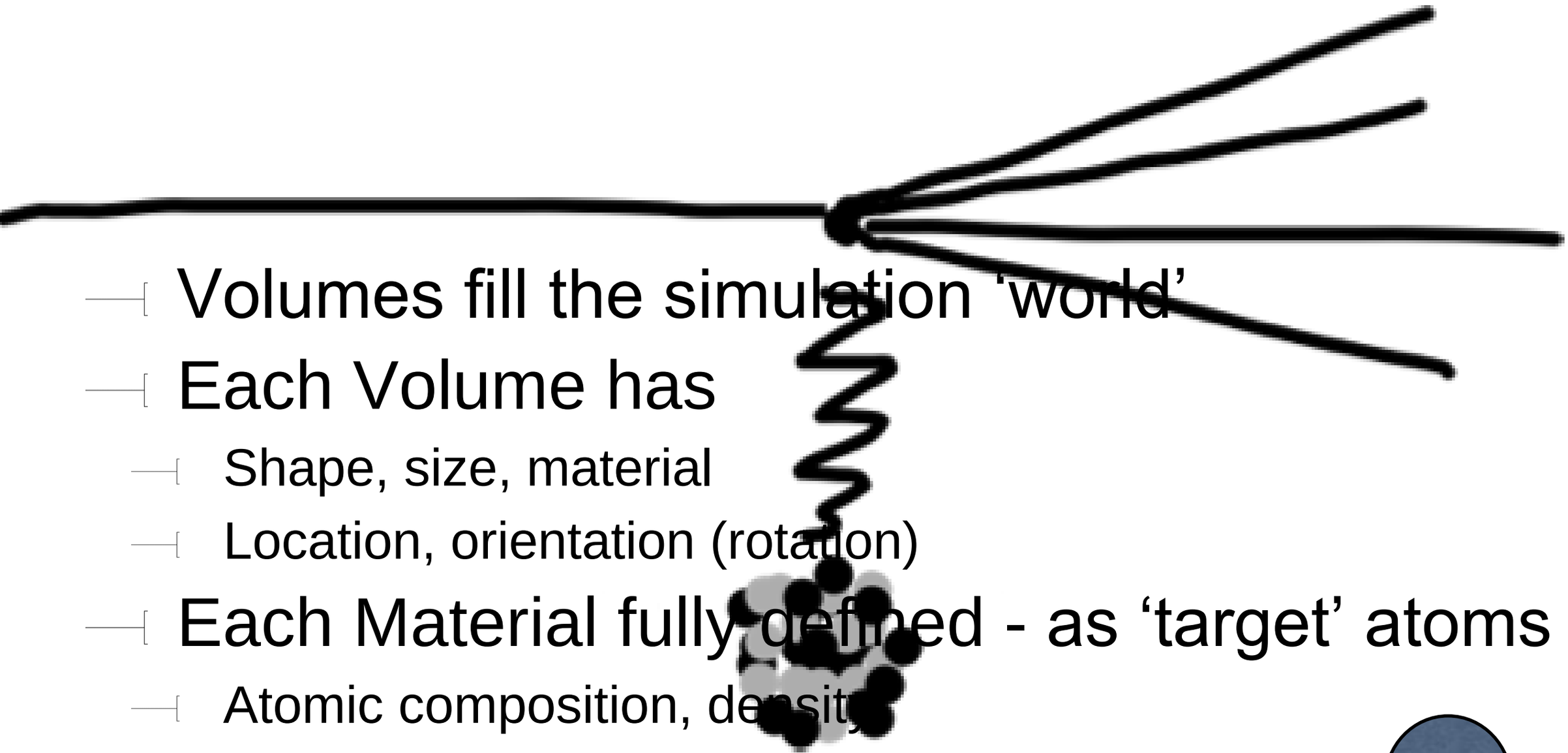


b.)Human

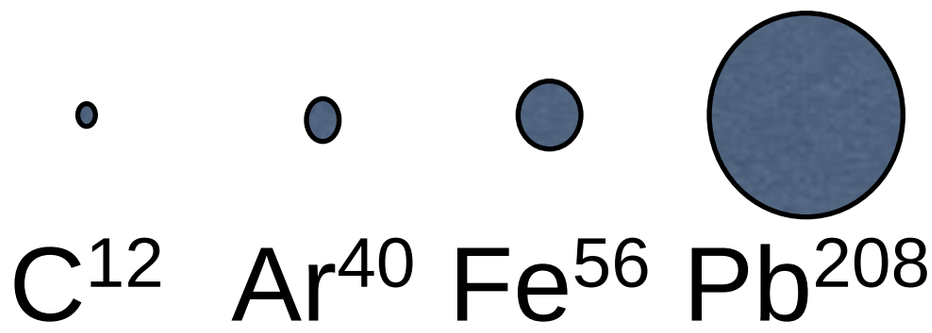


c.) Atmosphere

Geometry/material

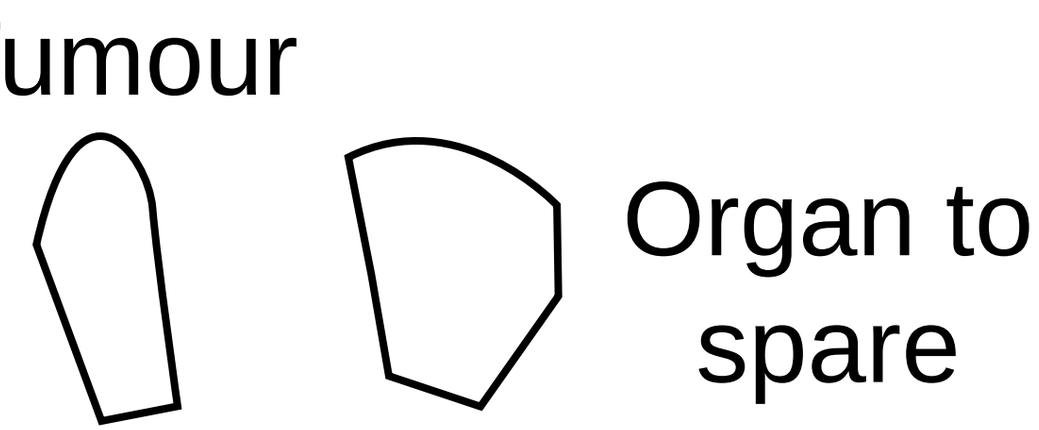


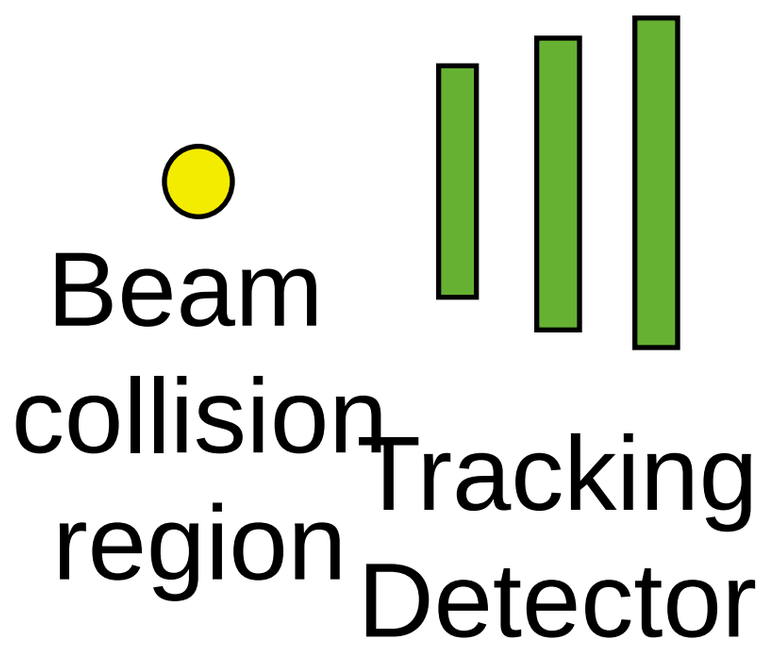
- Volumes fill the simulation ‘world’
- Each Volume has
  - Shape, size, material
  - Location, orientation (rotation)
- Each Material fully defined - as ‘target’ atoms
  - Atomic composition, density



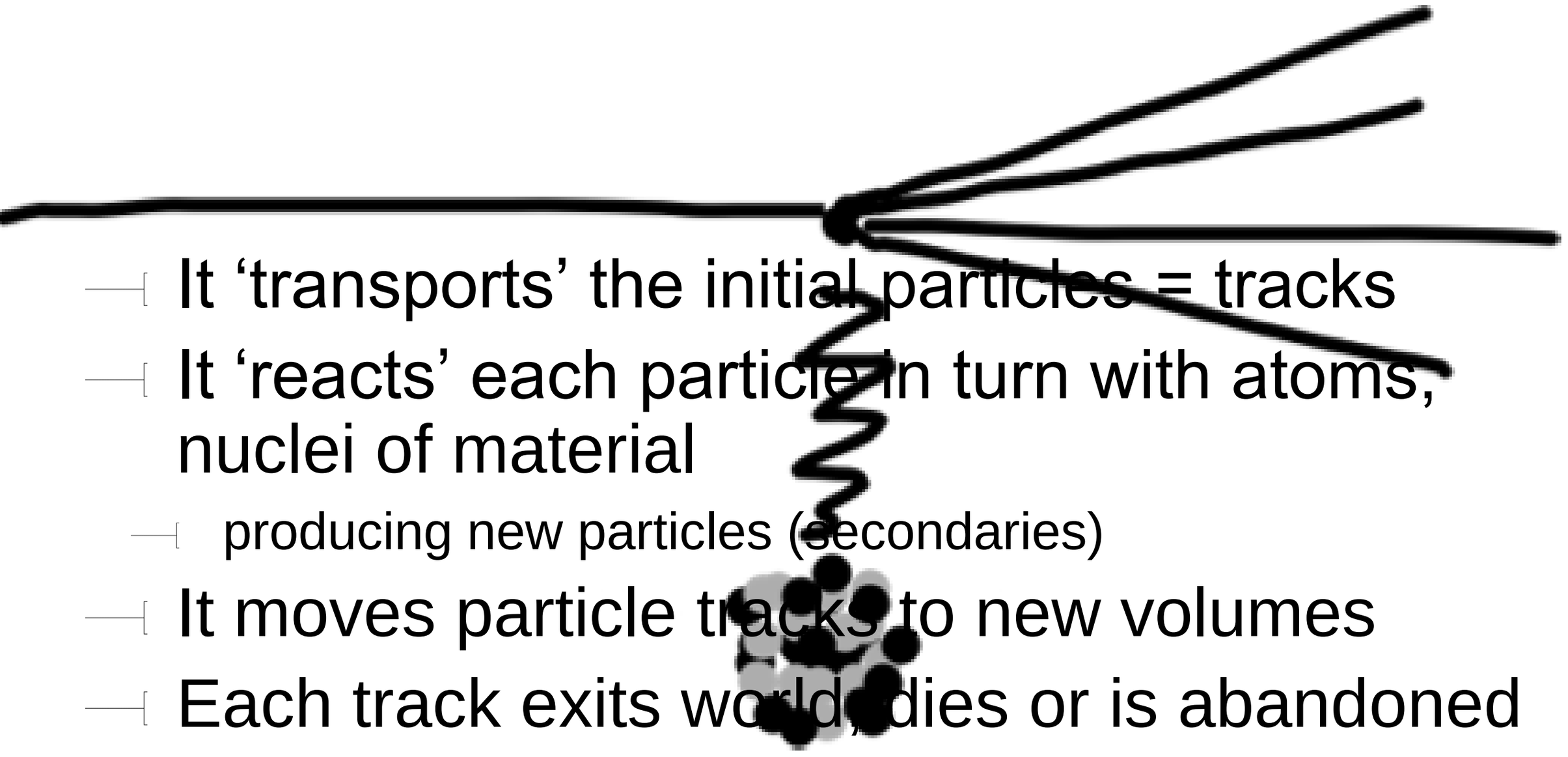
3. Sensitive Volume/Region

- It is a Geometry volume
- It records attribute(s) of each passing particles
  - E, p (momentum)
  - Particle type
  - ΔE, Energy deposition





4. Transport ‘engine’

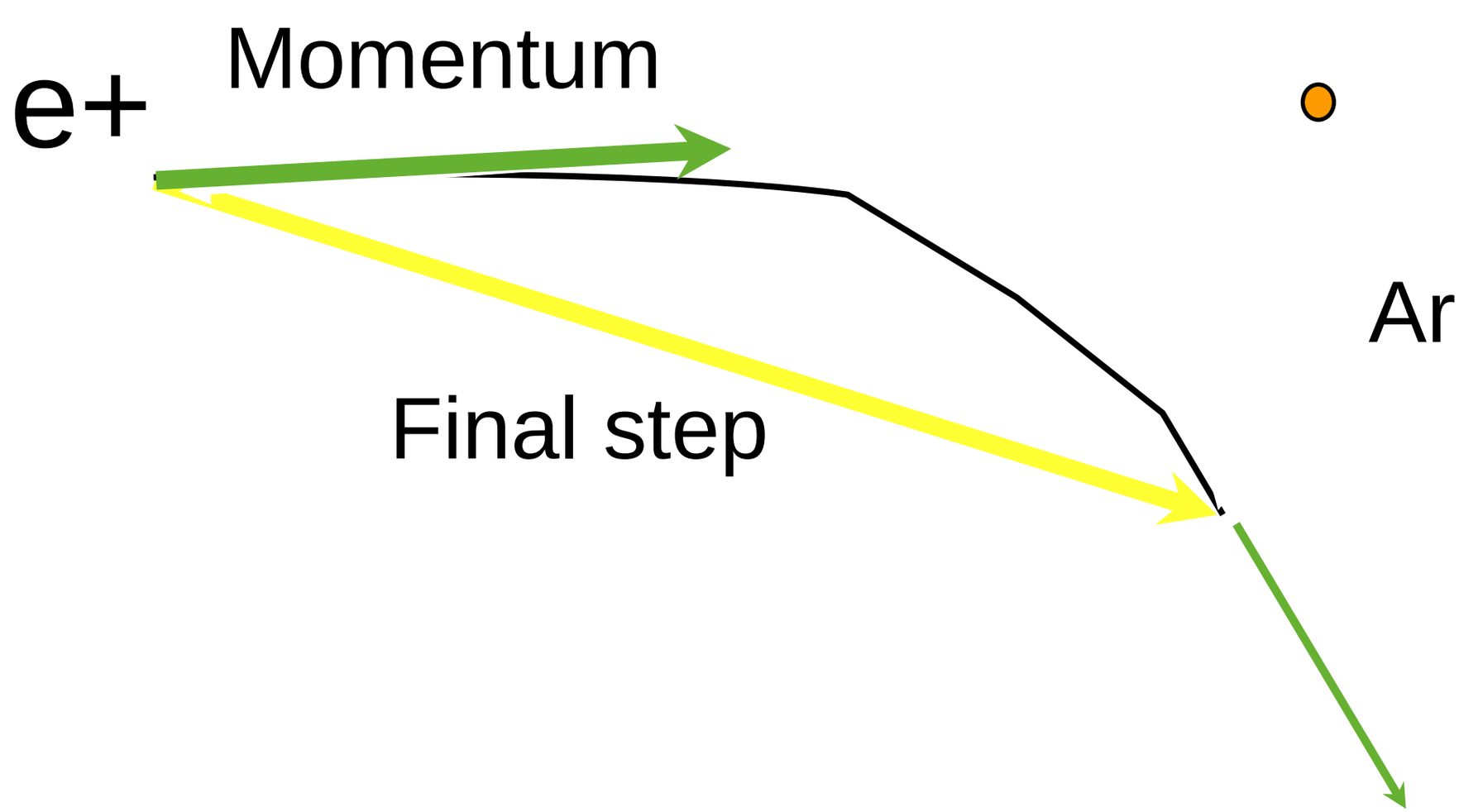


- It ‘transports’ the initial particles = tracks
- It ‘reacts’ each particle in turn with atoms, nuclei of material
  - producing new particles (secondaries)
- It moves particle tracks to new volumes
- Each track exits world, dies or is abandoned

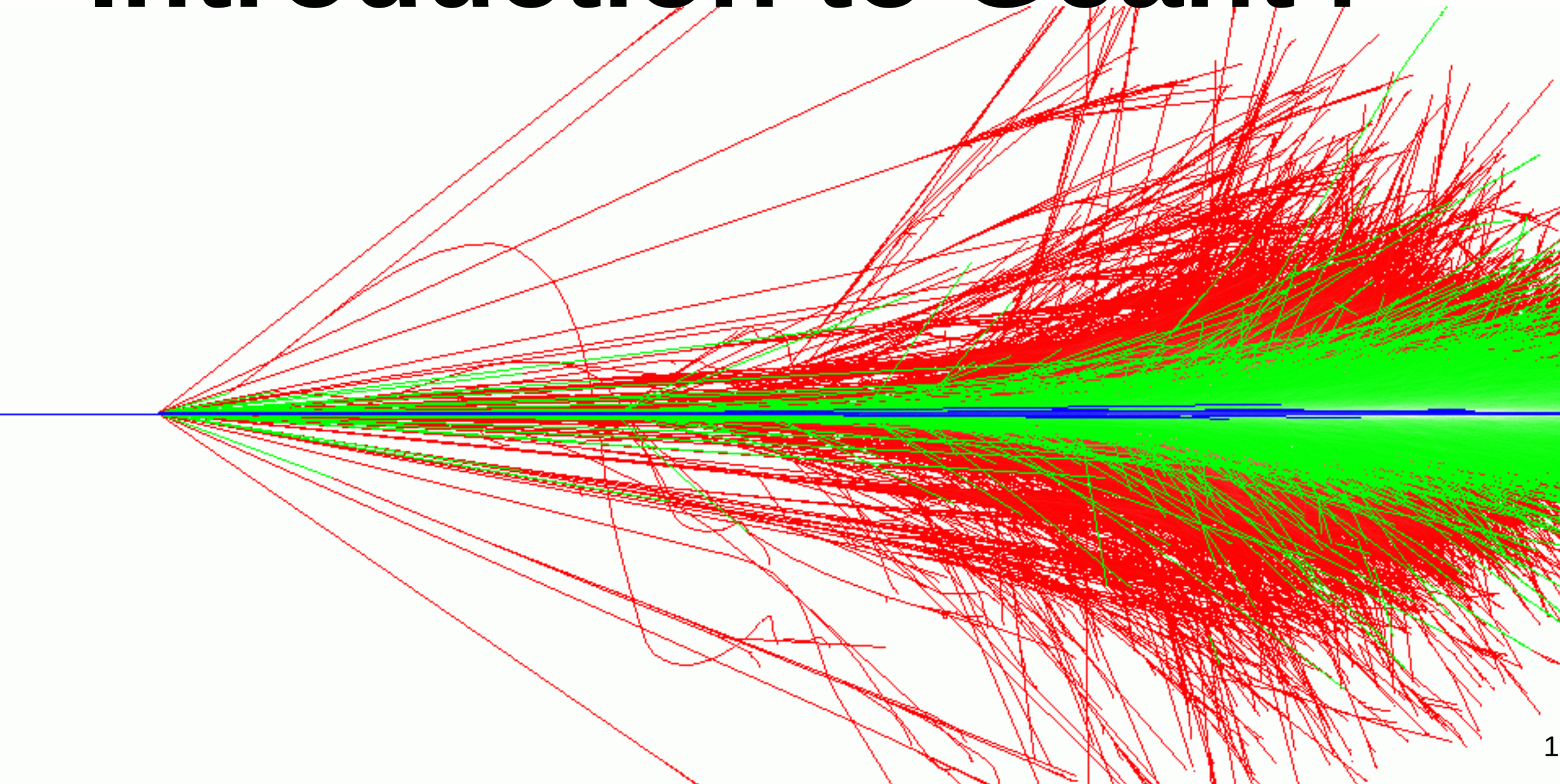
One step at a time

Step size - ‘physics length’

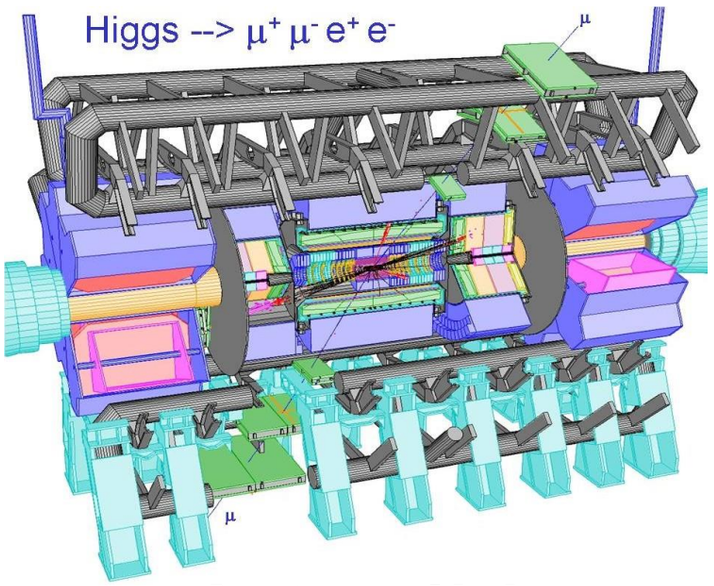
‘Geometry length’ - reduced by Multiple scatter



Introduction to Geant4



What is Geant4?



"Geant4 is a toolkit for the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science"

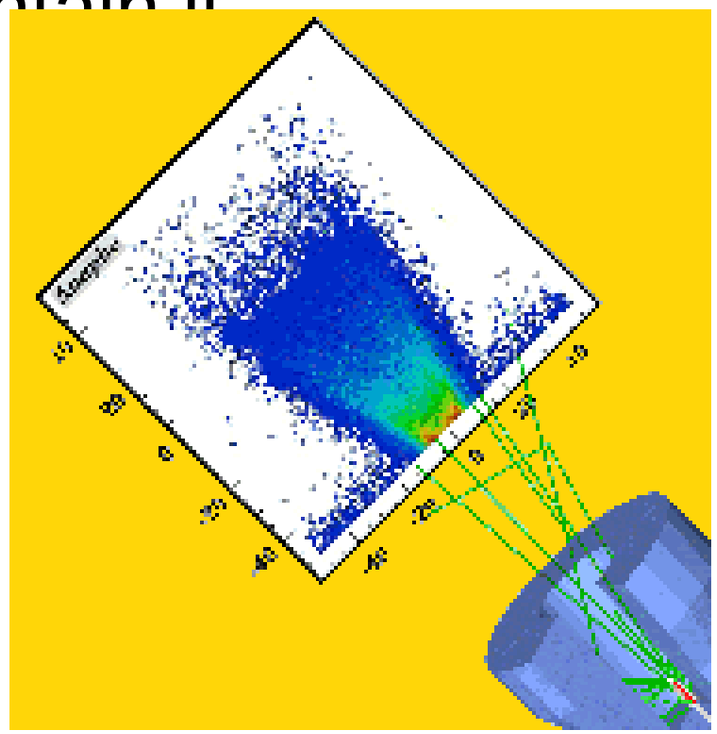
http://www.cern.ch/geant4

Geant4: GEometry ANd Tracking

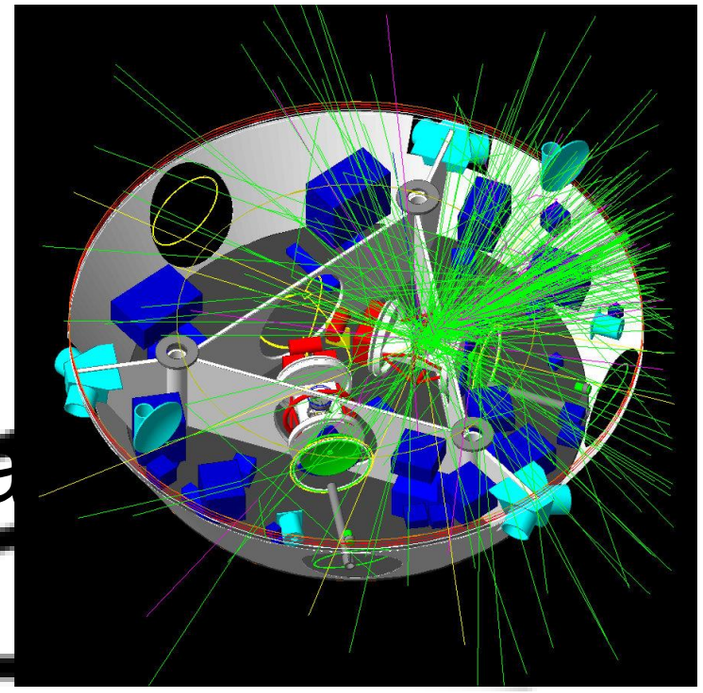
- A toolkit provides "general" tools to undertake (some or all) of the tasks:
  - tracking and geometrical propagation
  - modelling of physics interactions
  - visualization, persistency
- A toolkit enables you to describe your setup:
  - detector geometry
  - radiation source
  - details of sensitive regions

Geant4

- Detector simulation tool-kit from HEP
  - full functionality: geometry, tracking, physics, I/O
  - offers alternatives, allows for tailoring
- Software Engineering and OO technology (C++)
  - provide the architecture & methods to maintain it
- Requirements from:
  - current and future HEP experiments
  - medical and space science applications
- World-wide collaboration



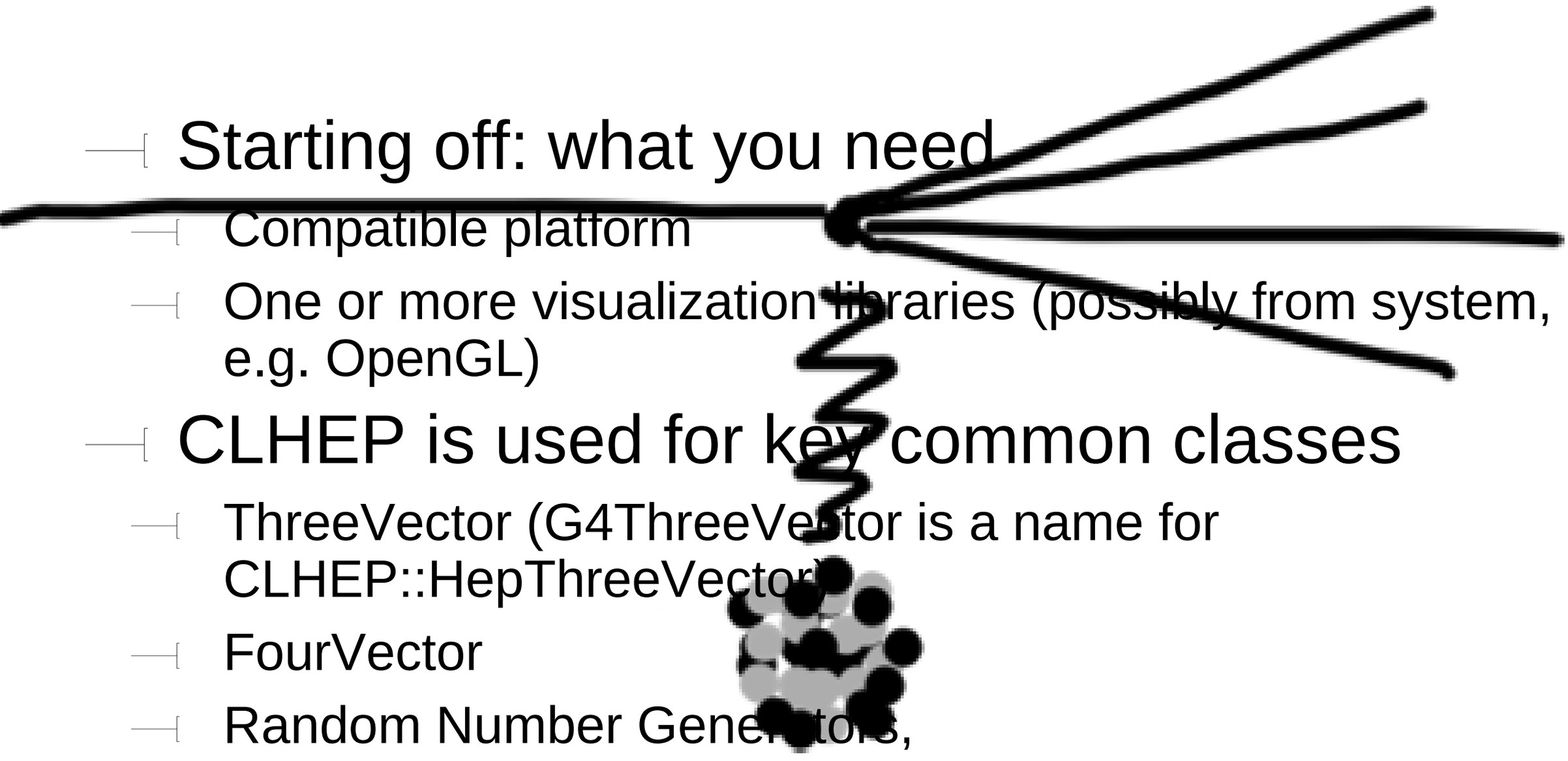
Key capabilities



- ‘Kernel’: create, manage, move tra
  - tracking, stacks, geometry, hits, …
  - Extensible, flexible
- Physics Processes: cross-section, final-state
  - models for electromagnetic, hadronic, …
  - Can be ‘assembled’ for use in an application area
- Tools for faster simulation
  - ‘Cuts’, framework shower parametrisation
  - Event biasing, variance reduction.
- Open interfaces for input/output
  - User commands, visualization, persistency

Practical Considerations

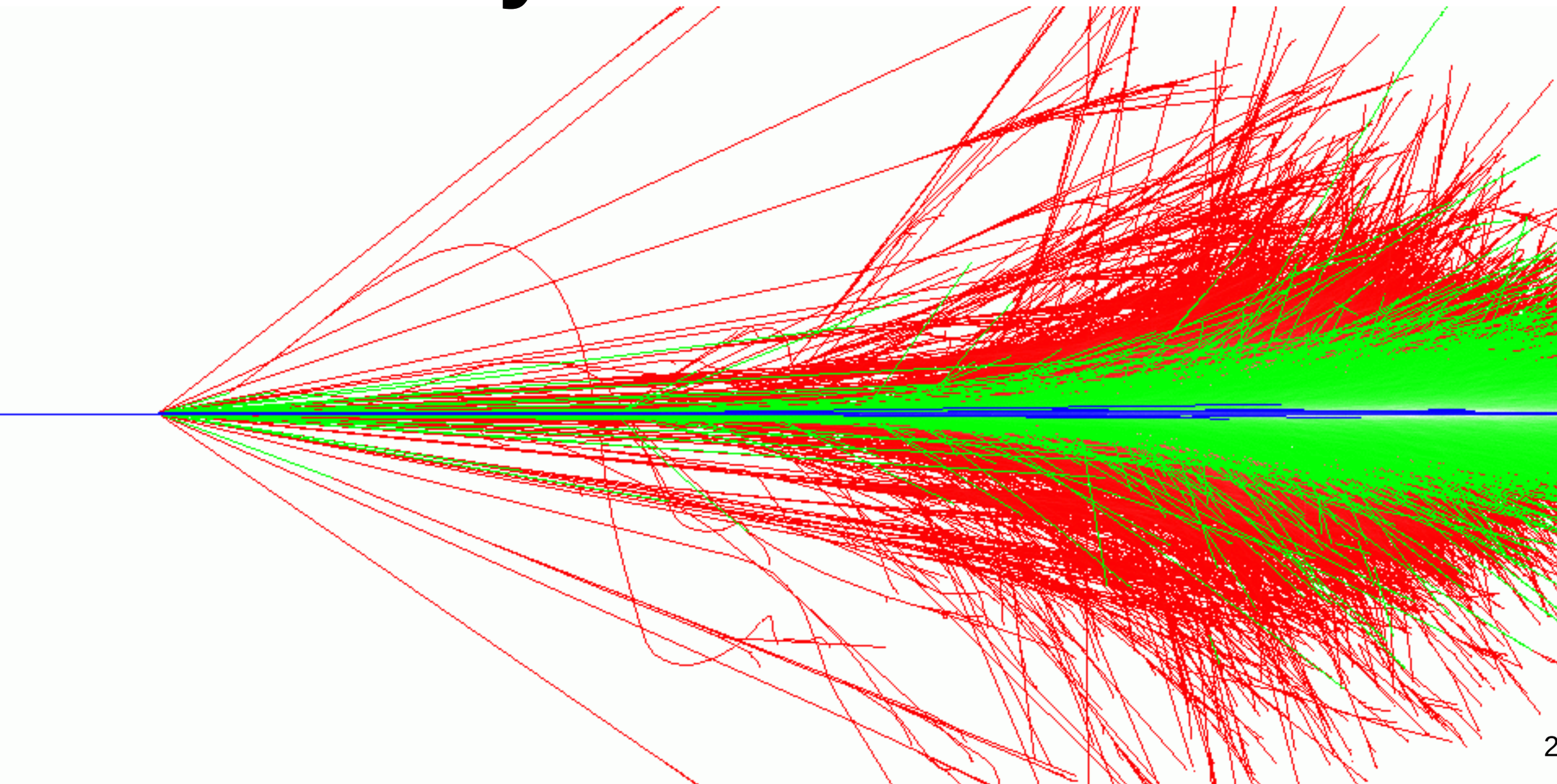
- Starting off: what you need
  - Compatible platform
  - One or more visualization libraries (possibly from system, e.g. OpenGL)
- CLHEP is used for key common classes
  - ThreeVector (G4ThreeVector is a name for CLHEP::HepThreeVector)
  - FourVector
  - Random Number Generators,
  - Starting from version 9.5 (Dec 2011) CLHEP included in G4



Platforms

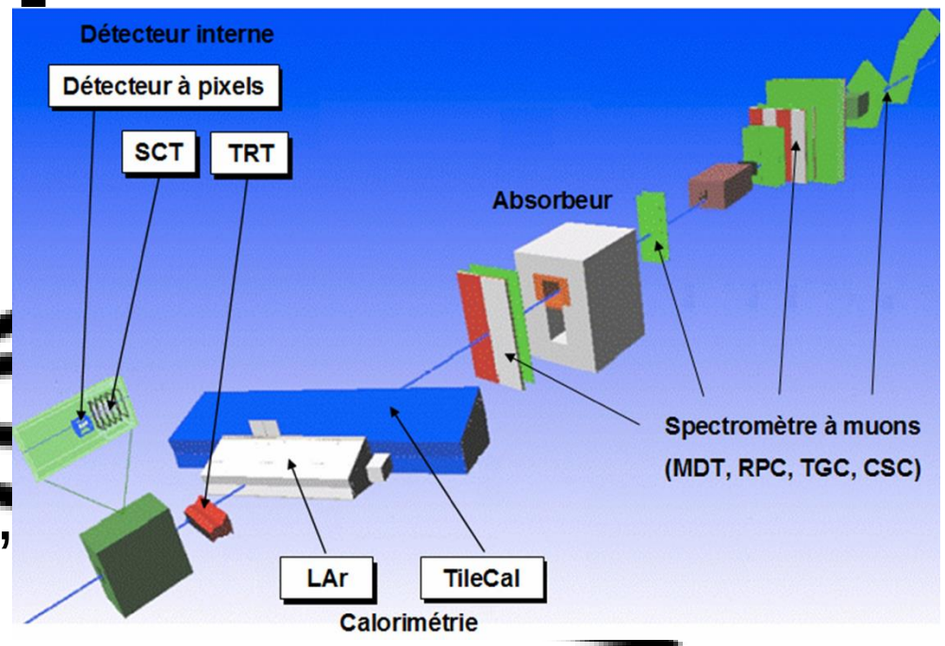
- What works ‘best’ (used by developers, main testing)
  - Linux (Scientific Linux 6) gcc 4.7/4.8 (FIEP production)
  - MacOS 10.8 or 10.9
  - Windows 7/8 (w/ VC++ 10 or 11)
- What is known and/or expected to work
  - Other Linux flavours with gcc 4.x (x>2); icc 12+
  - Possibly fewer options (visualization choices depend on libraries.)
- Likely to work
  - Other Unix/similar systems with gcc or other C++ compiler
  - Expect fewer options to work, especially visualization.

Geometry And visualization



Building a G4 Application

- How do you create a Geant4 simulation
  - Get a ready-made application, or
  - Modify a similar, existing, application,
  - Piece together a custom application

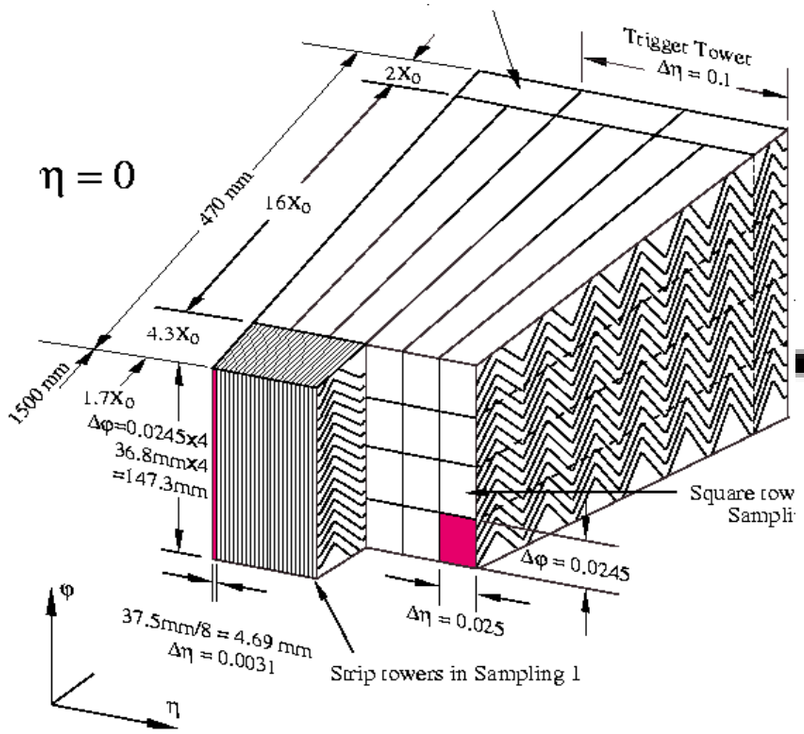


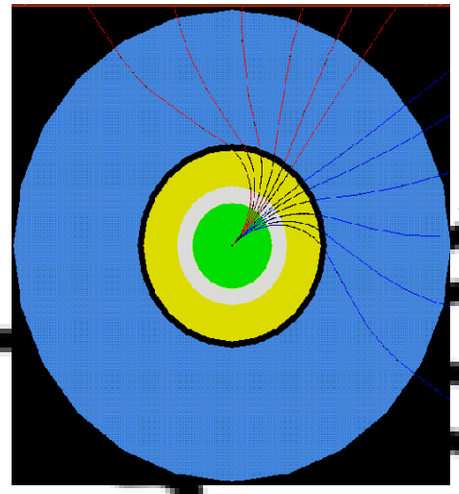
ATLAS Test-beam setup 2004

- What are the key steps for creating an application
  - **Describing the setup**: geometry, material, ..
  - Creating the primary tracks
  - Choosing the *physics* to use
  - **Designating** the “sensitive” volumes
  - And collecting physics observables.

Often the most
“coding” intensive steps:
build your own detector/device

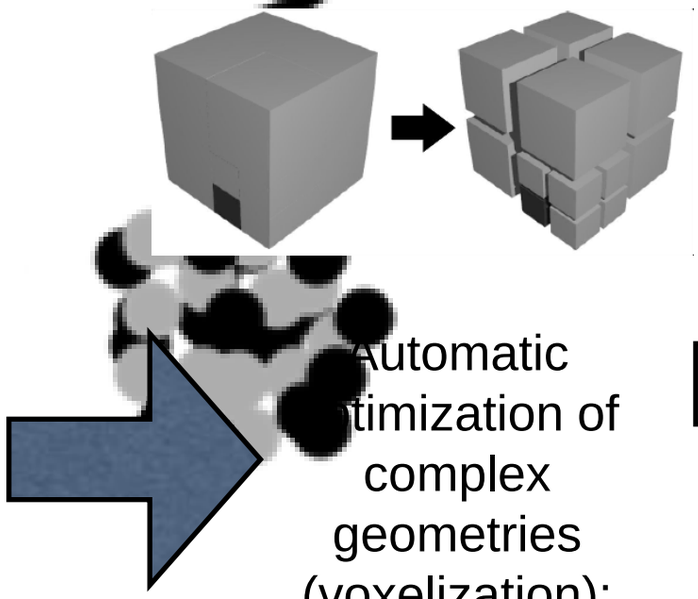
geometry: what G4 does





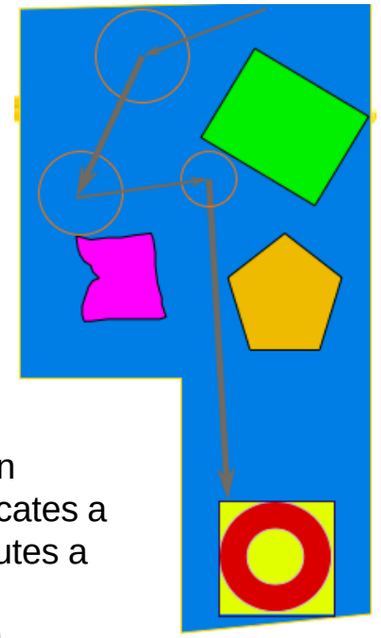
All charged particles 'feel' the effect of **EM fields**Automatically following paths that approximate their curved trajectories

- **User must describes a Setup**
  - Hierarchy of volumes
  - Materials
- **Up to hundreds of thousands of volumes**
- Importing solids from CAD systems



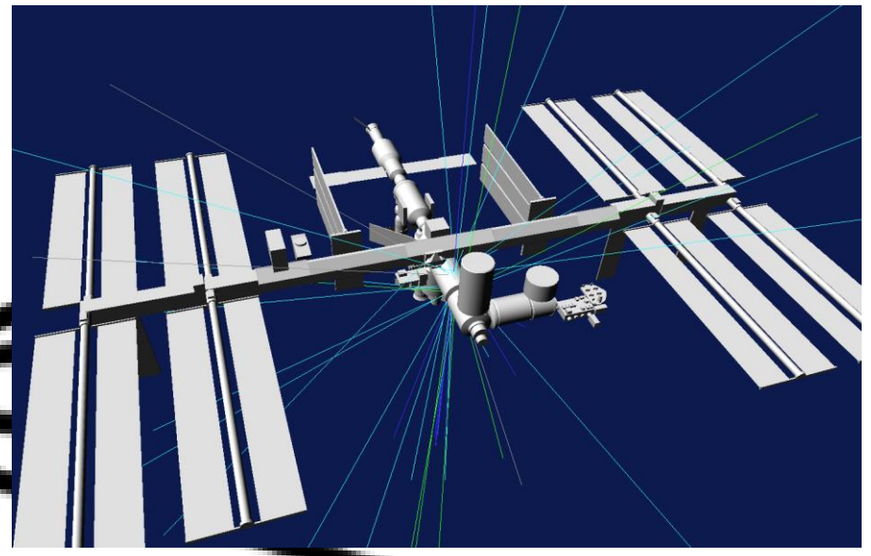
Automatic optimization of complex geometries (voxelization): **efficient tracking**

Navigates in DetectorLocates a pointComputes a stepLinear intersection

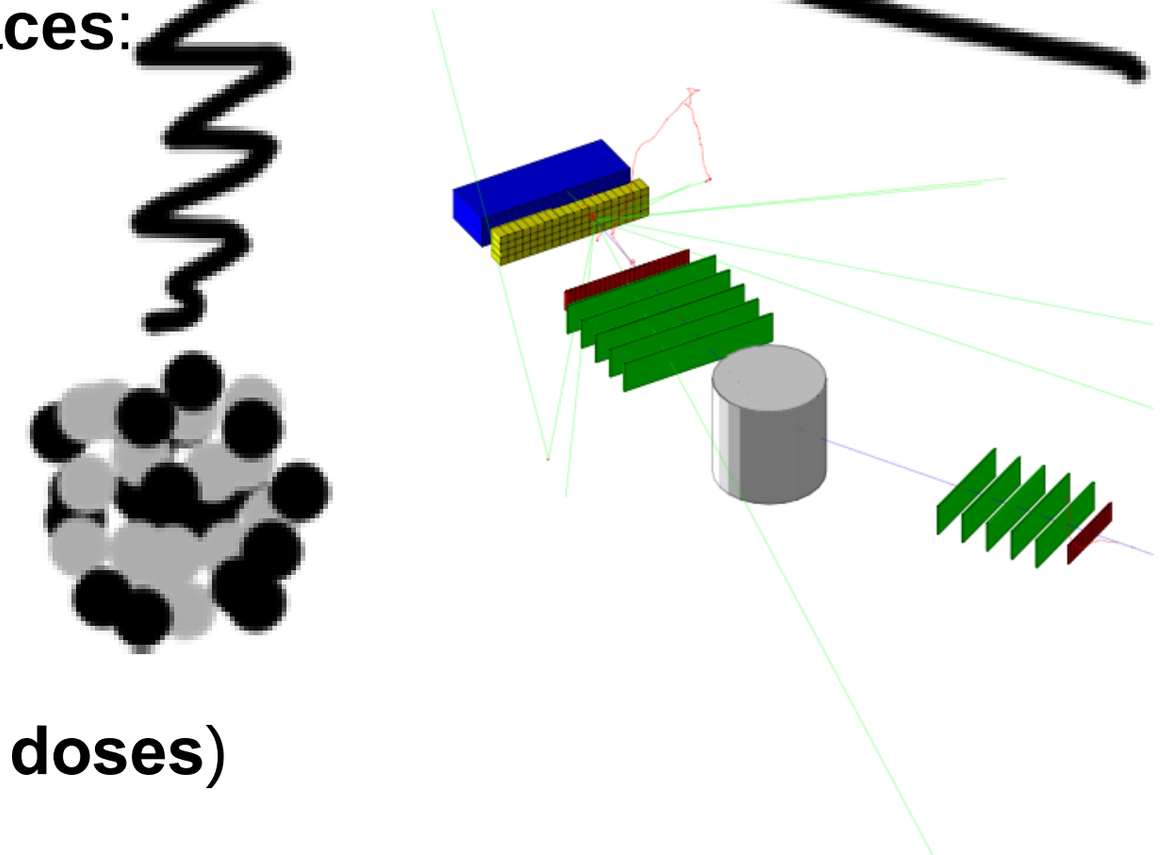


Visualization

- Much functionality is implemented
- Several **drivers**:
  - OpenGL, VRML, Open Inventor,
    DAWN renderer (G4),...
- Also choice of **User Interfaces**:
  - Terminal (text) or
  - GUI
- Editors for geometry
- Visualization of:
  - Volumes
  - **Tracks**
  - Energy deposits (**“hits”, doses**)



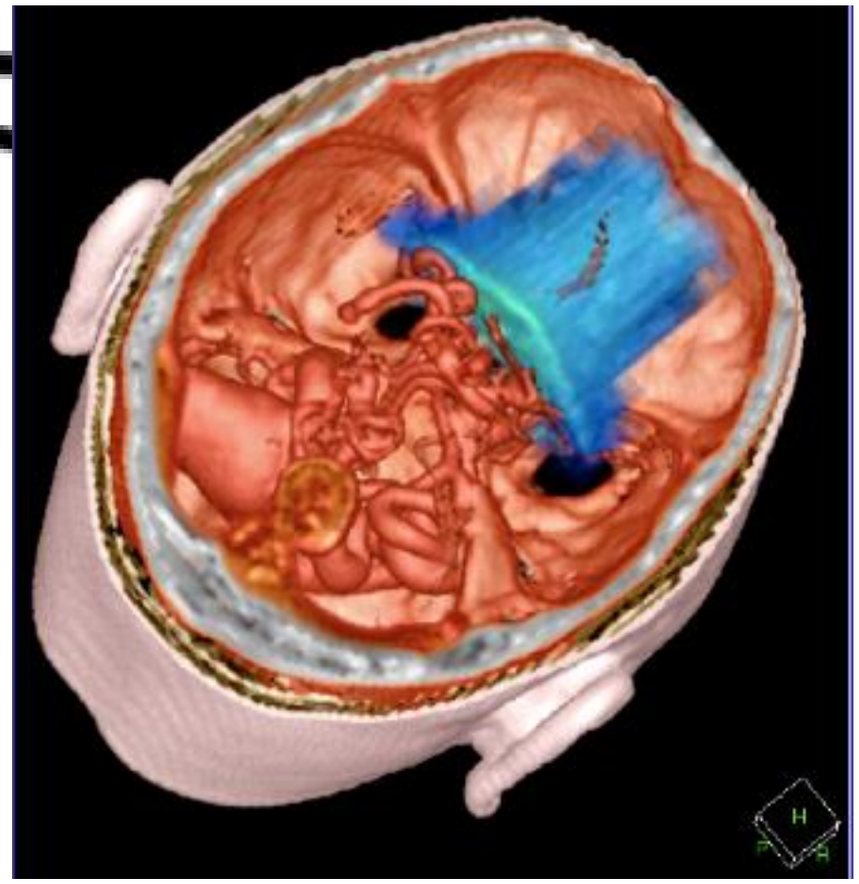
OpenGL driver



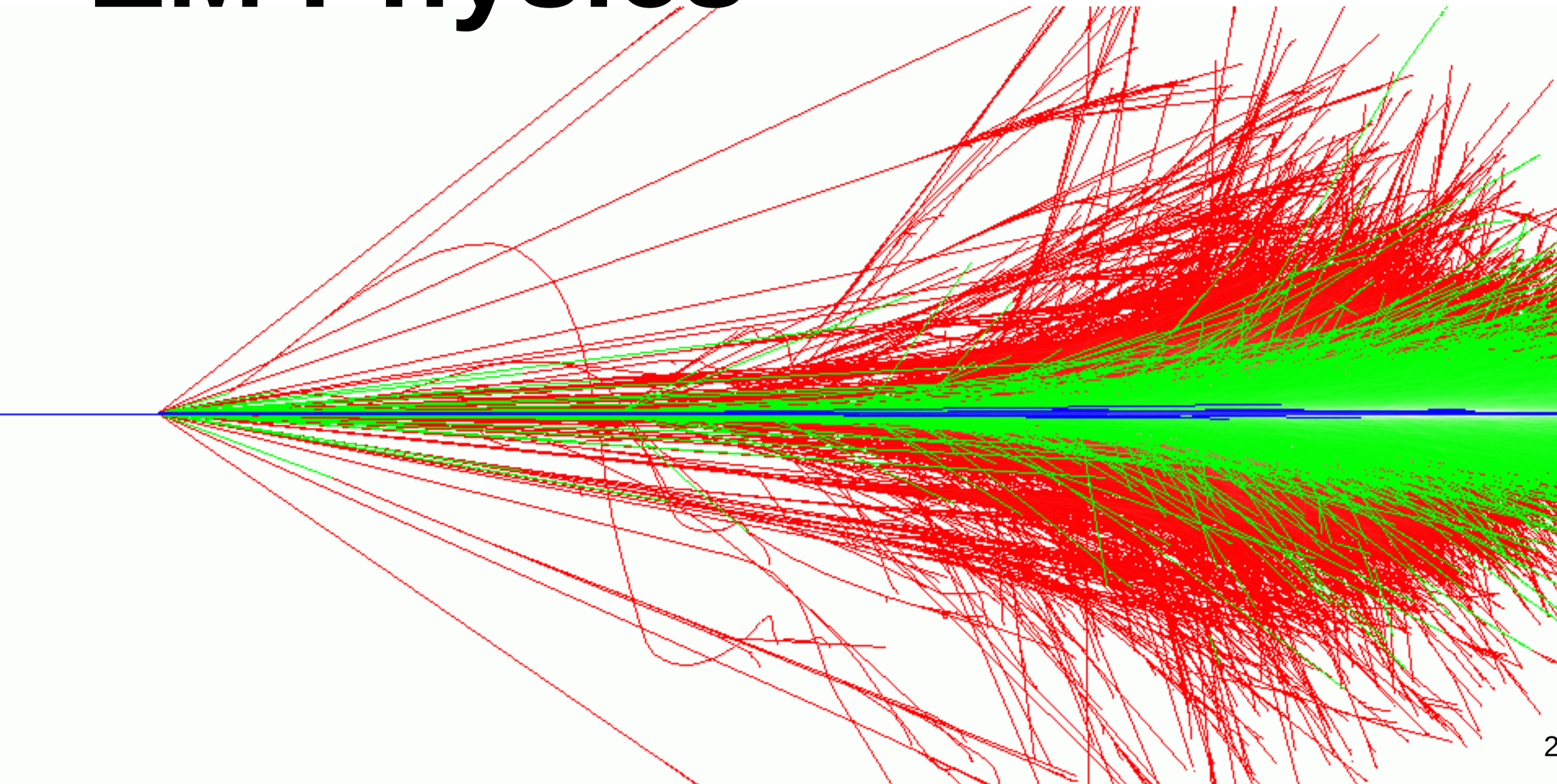
DAWN driver

An advanced Tool: gMocren

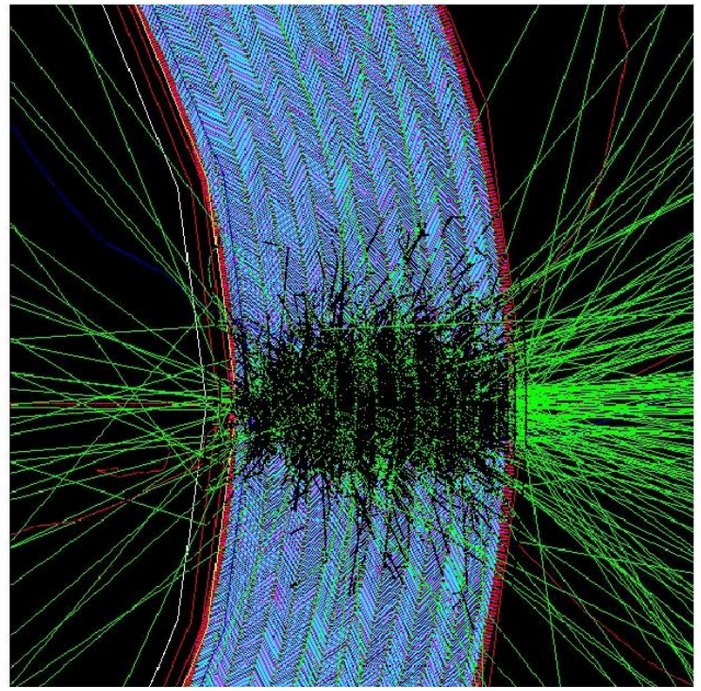
- Created by the JST/CREST project (Japan) to improve Geant4 for medical physics
- Able to visualize:
  - Volume data (including overlay of more than one set)
  - Trajectories
  - Geometry
- Runs on:
  - Windows and Linux
  - Mac - future ?
  - Based on a commercial package but offered freely to all Geant4 users
- http://geant4.kek.jp/gMocren



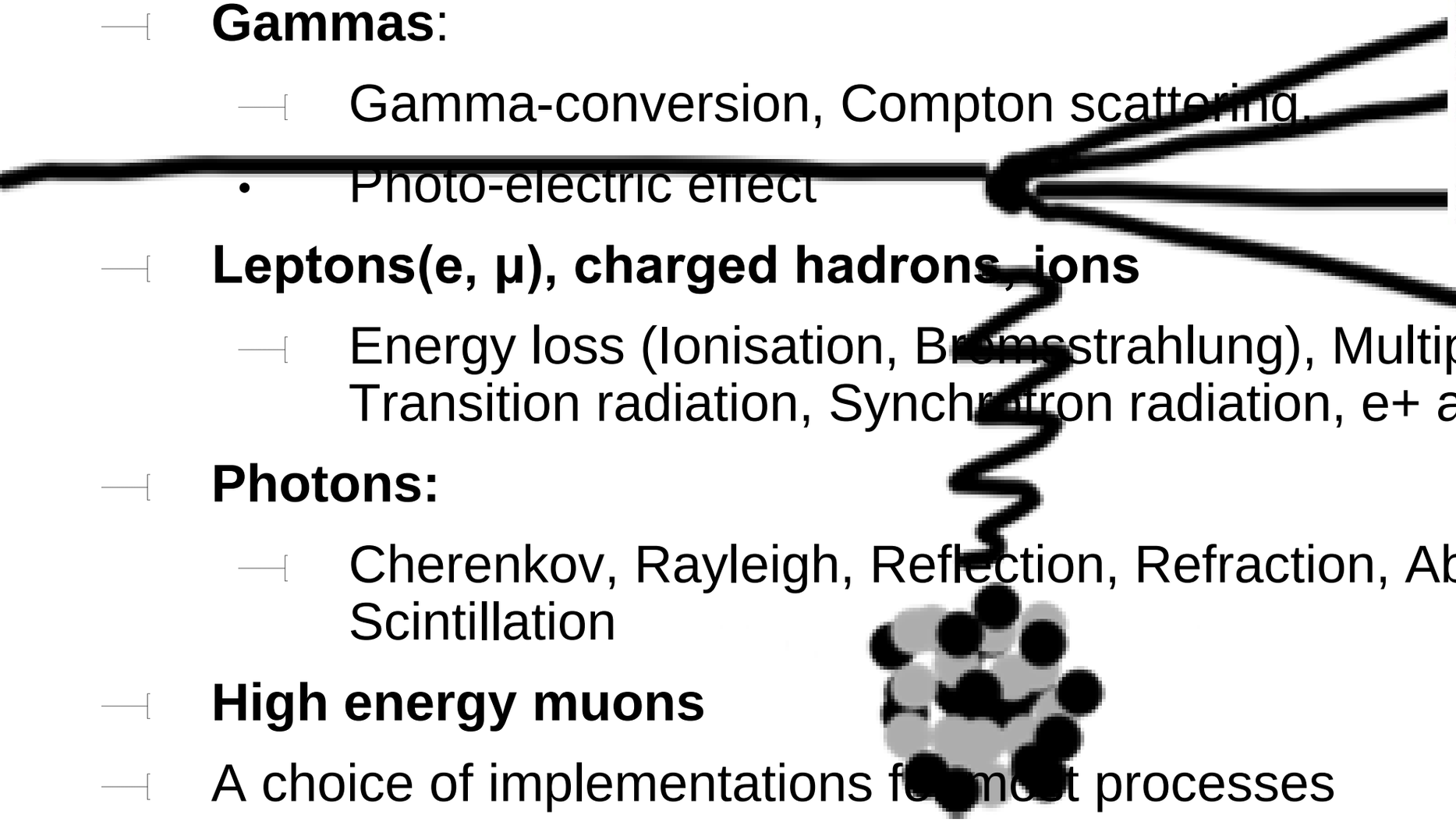
EM Physics



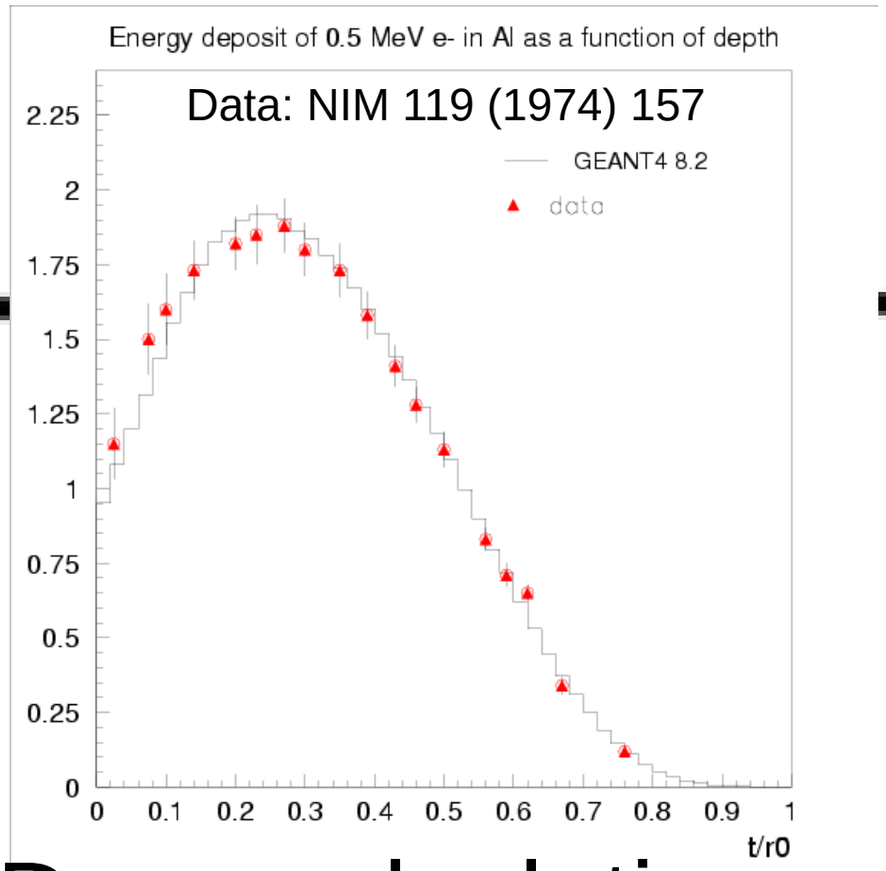
Processes

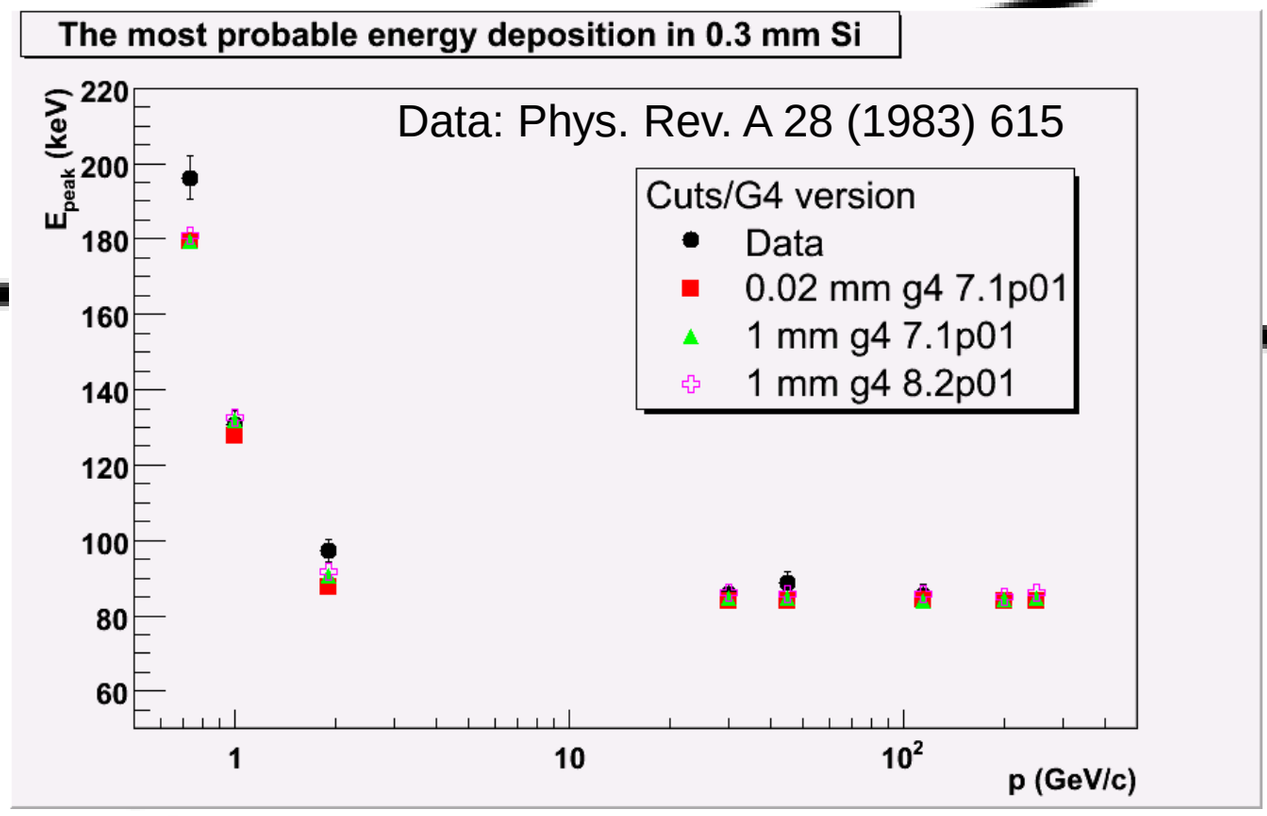


- **Gammas**:
  - Gamma-conversion, Compton scattering.
  - Photo-electric effect
- **Leptons(e, μ), charged hadrons, ions**
  - Energy loss (Ionisation, Bremsstrahlung), Multiple scattering, Transition radiation, Synchrotron radiation, e+ annihilation.
- **Photons:**
  - Cherenkov, Rayleigh, Reflection,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



Validation: examples



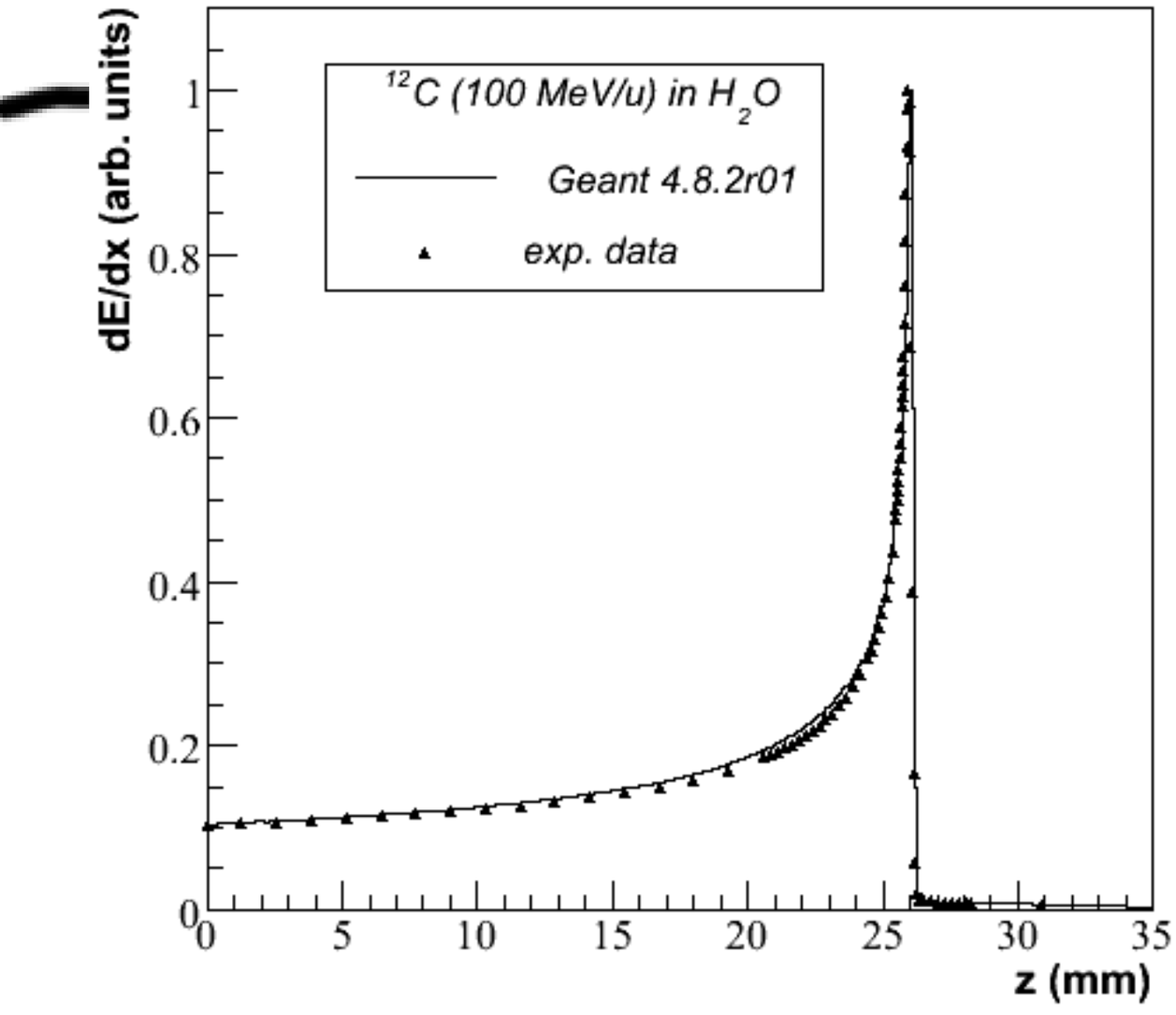


Dose calculation

Ionisation in thin layers

- Very good level of agreement reached from **keV to TeV** of kinetic energy range
- Results available at: http://geant4.web.cern.ch/geant4/collaboration/working_groups/electromagnetic/tests.shtml

Validation: Medical physics

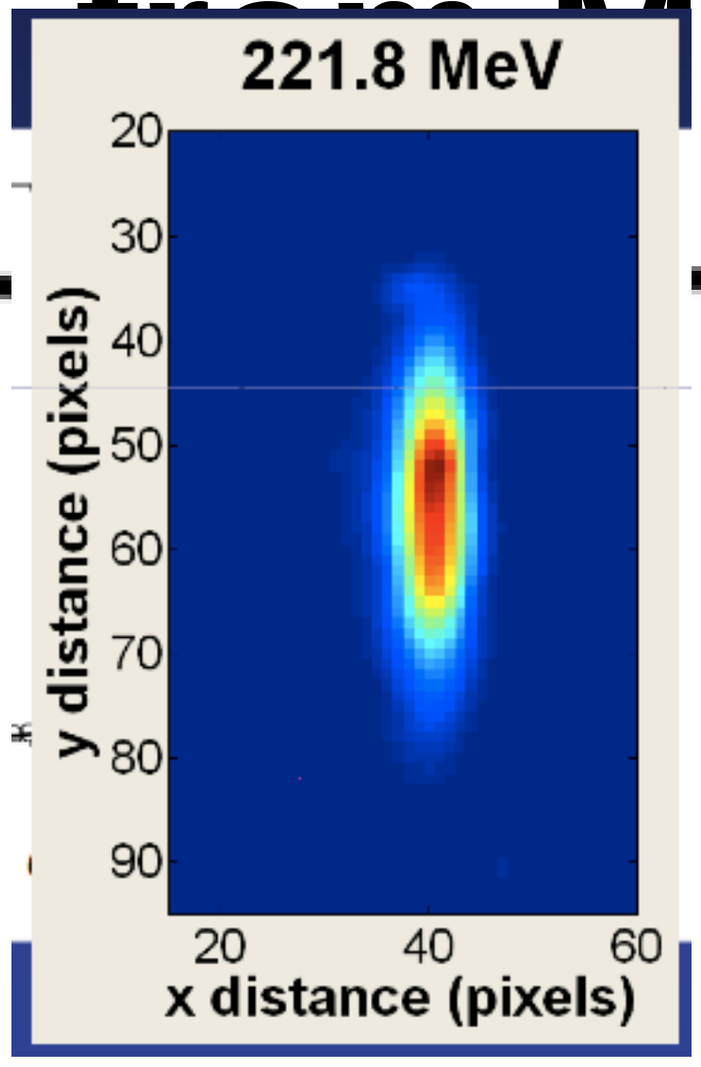


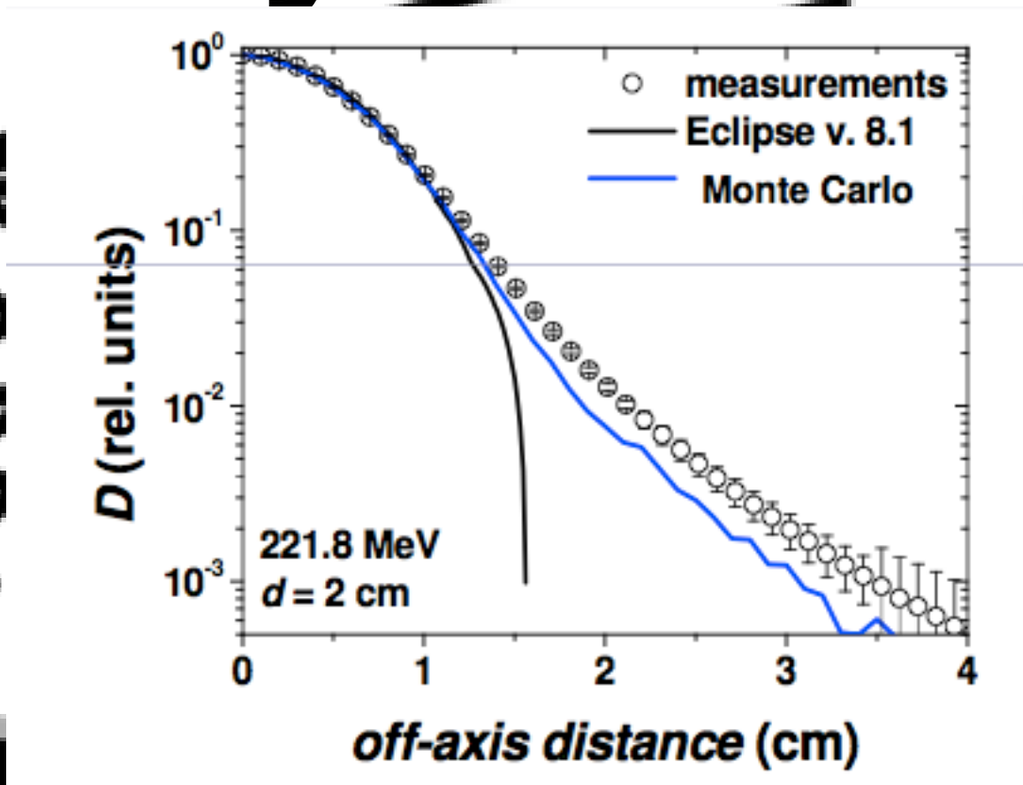
- Bragg Peak in water for a 100MeV/u ^{12}C beam

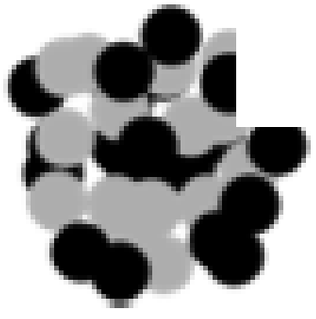
- Precision of the position of the peak is the key observable to judge simulation quality

But...

Challenges: An example from Medical Physics



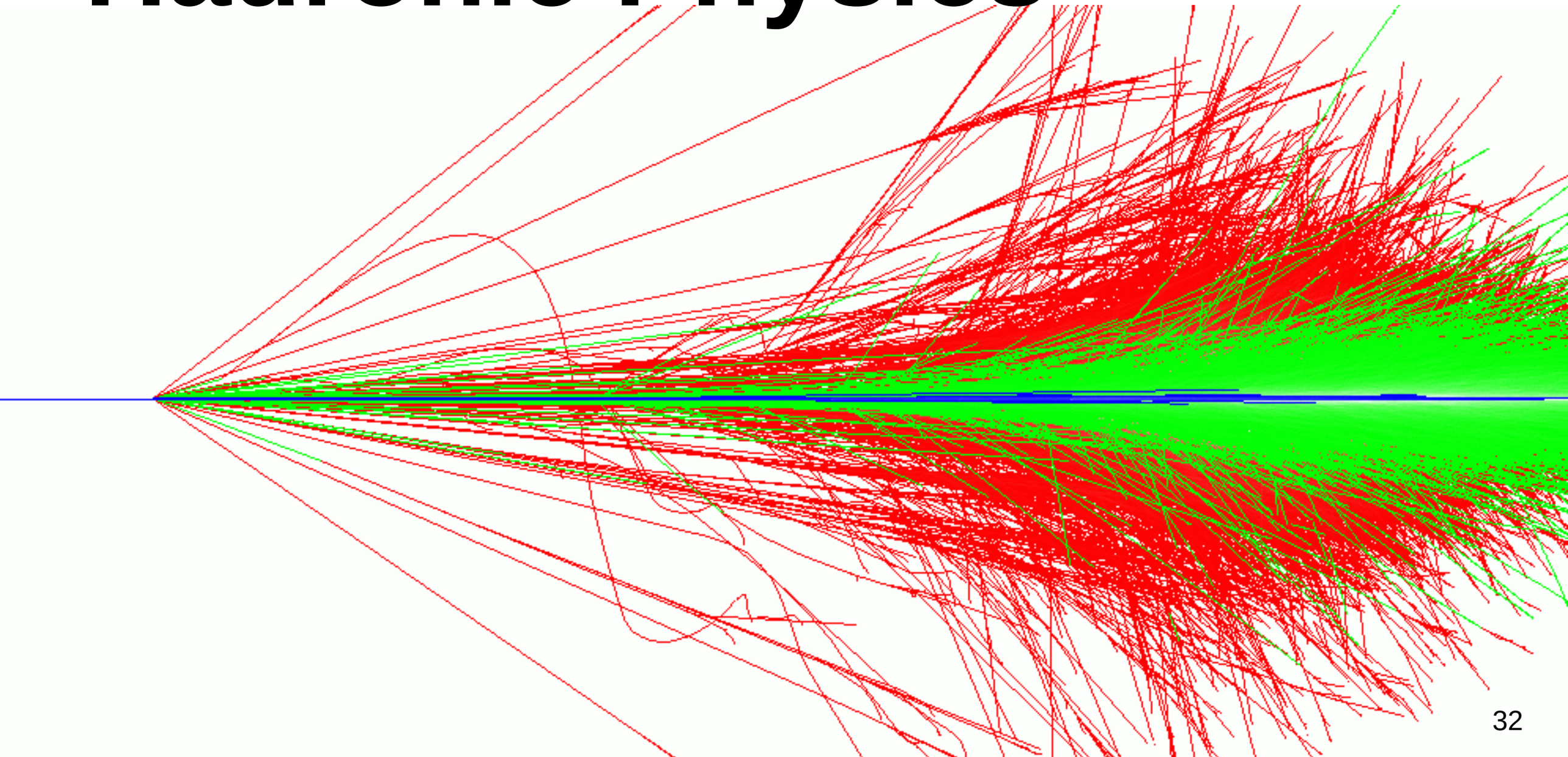




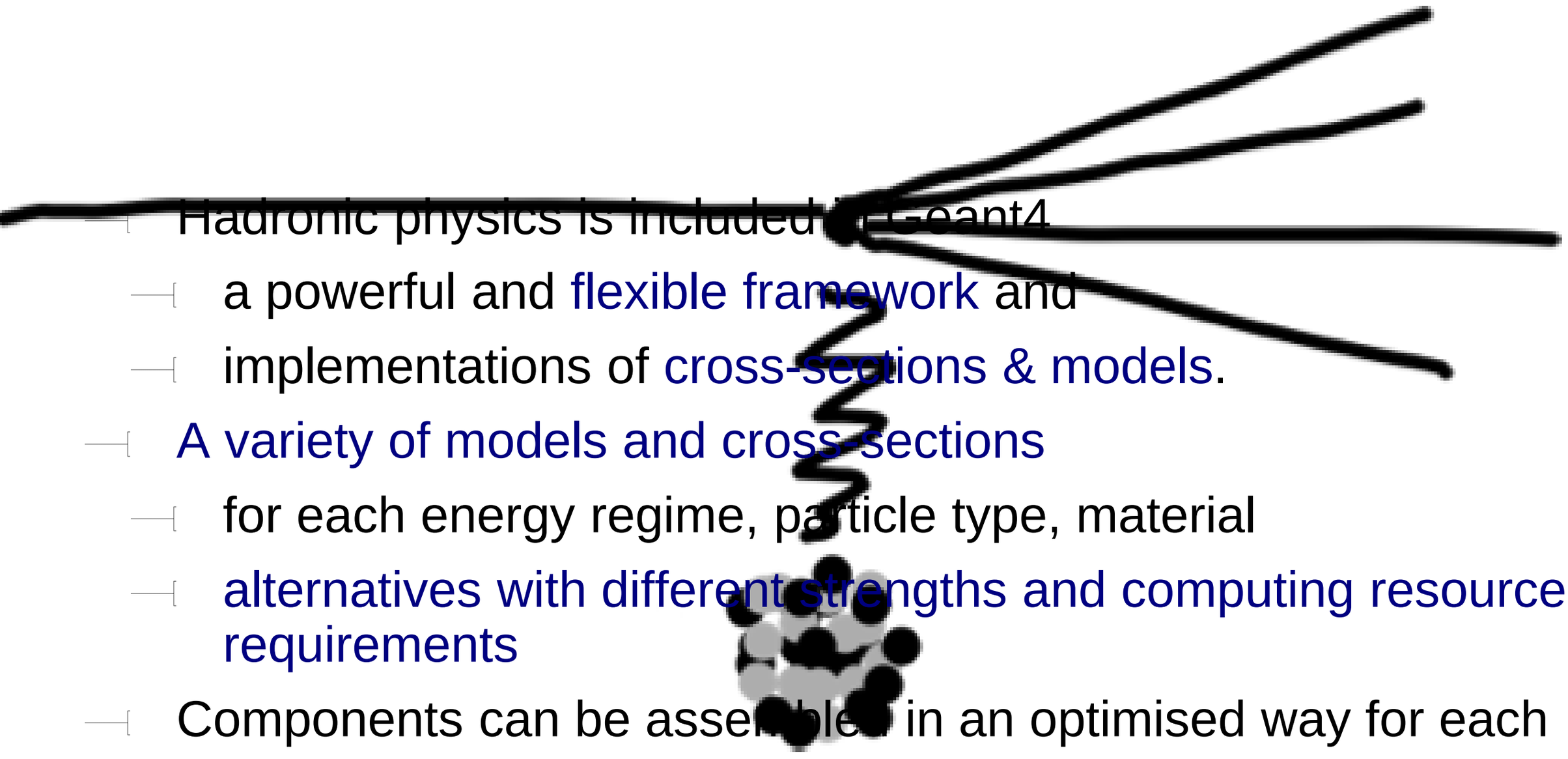
Use a beam for patient treatment:
send thousands/millions of particles (protons, C)

Tails become important:
1 spot, difference <0.1% (perfectly ok for ATLAS, CMS, ...)
10000 spots, difference > 5%

Hadronic Physics



Processes



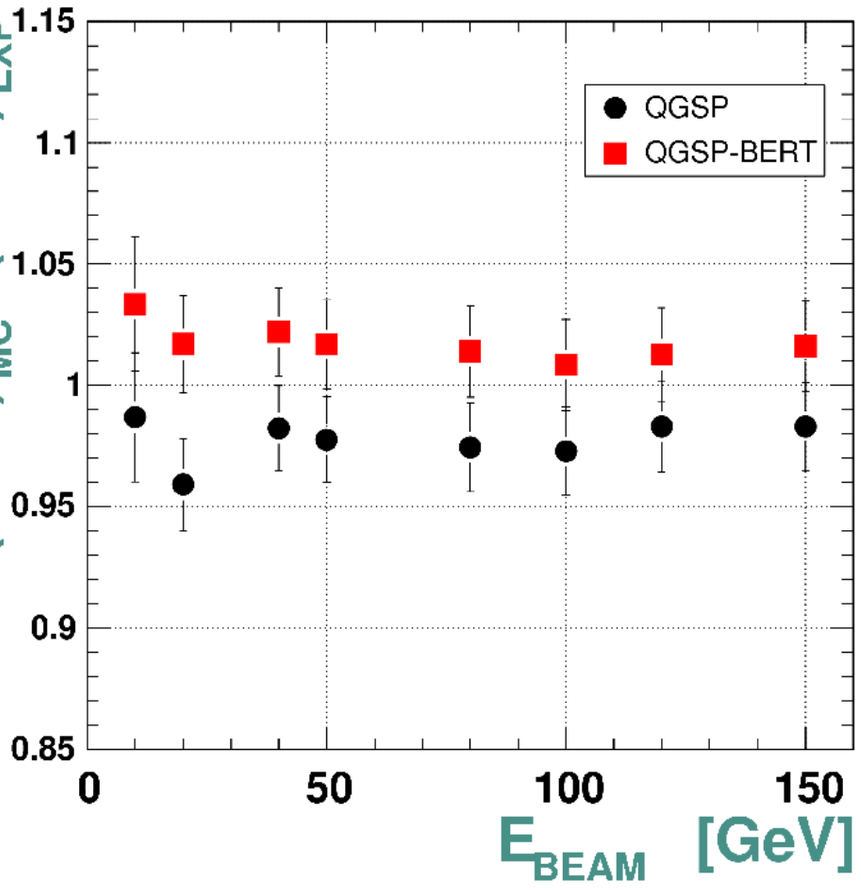
- Hadronic physics is included in Geant4
  - a powerful and flexible framework and
  - implementations of cross-sections & models.
- A variety of models and cross-sections
  - for each energy regime, particle type, material
  - alternatives with different strengths and computing resource requirements
- Components can be assembled in an optimised way for each use case.

Models Summary

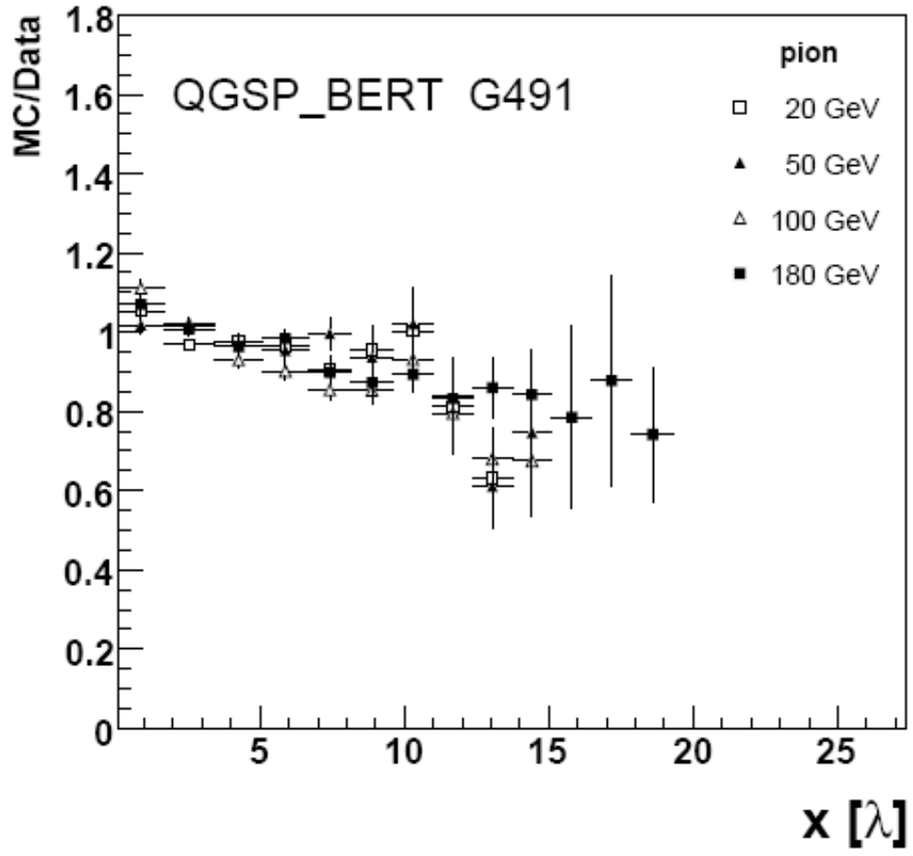
- **Parameterized models** (1997): all E and particles - data driven
- Fritjof, **"FTF"** (new developments): p,n,k,π of high energy (E_{kin}>10 GeV) **Nucl. Phys. 281 289 (1987)**
- Quark-Gluon-String, **"QGS"**: p,n,k,π of high energy (E_{kin}>20 GeV) **See Sec. IV, Chap. 2 of Geant4 Physics Reference Manual and bibliography within**
- **Bertini** cascade: low energy intra-nuclear cascade (E_{kin} < 5 GEV) **Nucl. Instr. Meth, 66, 1968, 29 ; Physical Review Letters 17, (1966), 478-481**
- **Binary** cascade: low energy intra-nuclear cascade (E_{kin} < 5 GEV) **See Sec. IV, Chap. 2 of Geant4 Physics Reference Manual and bibliography within**

Validation: examples

Response to pions: ATLAS HEC



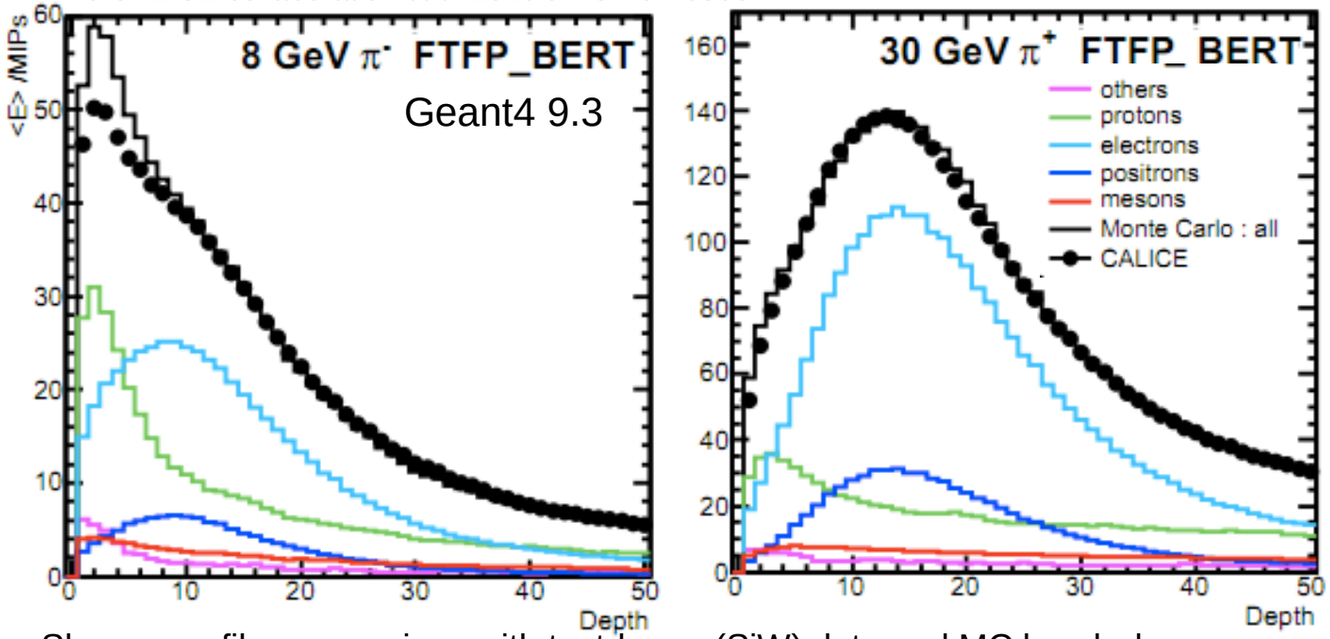
Longitudinal Shower shape: ATLAT TileCal



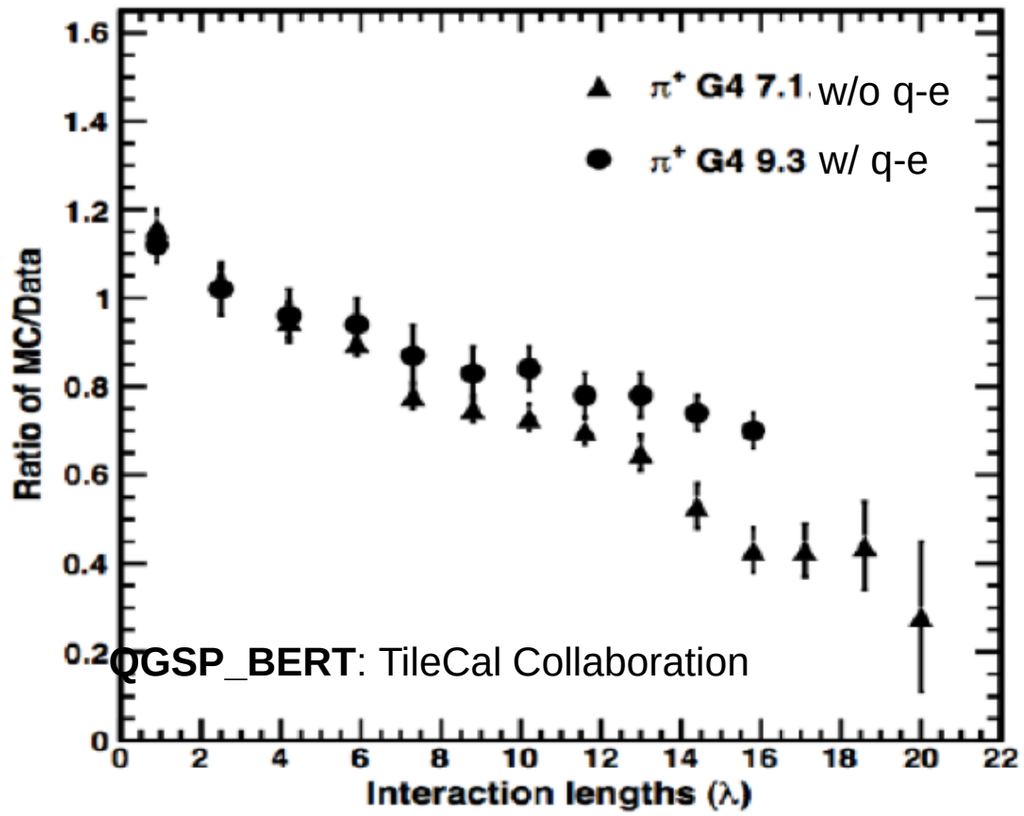
- Hadronic models are of primary interest for LHC experiments: close collaboration
  - Example: ATLAS plans to use extensively G4 to extract “corrections” and “calibration constants” for jet calibration
- Comparison with thin target experiments and LHC test-beams data
- More details: http://geant4.fnal.gov/hadronic_validation/validation_plots.htm

Longitudinal Shower Shape

The CALICE collaboration *et al* 2010 *JINST* **5** P05007



Shower profile: comparison with test-beam (SiW) data and MC break-down

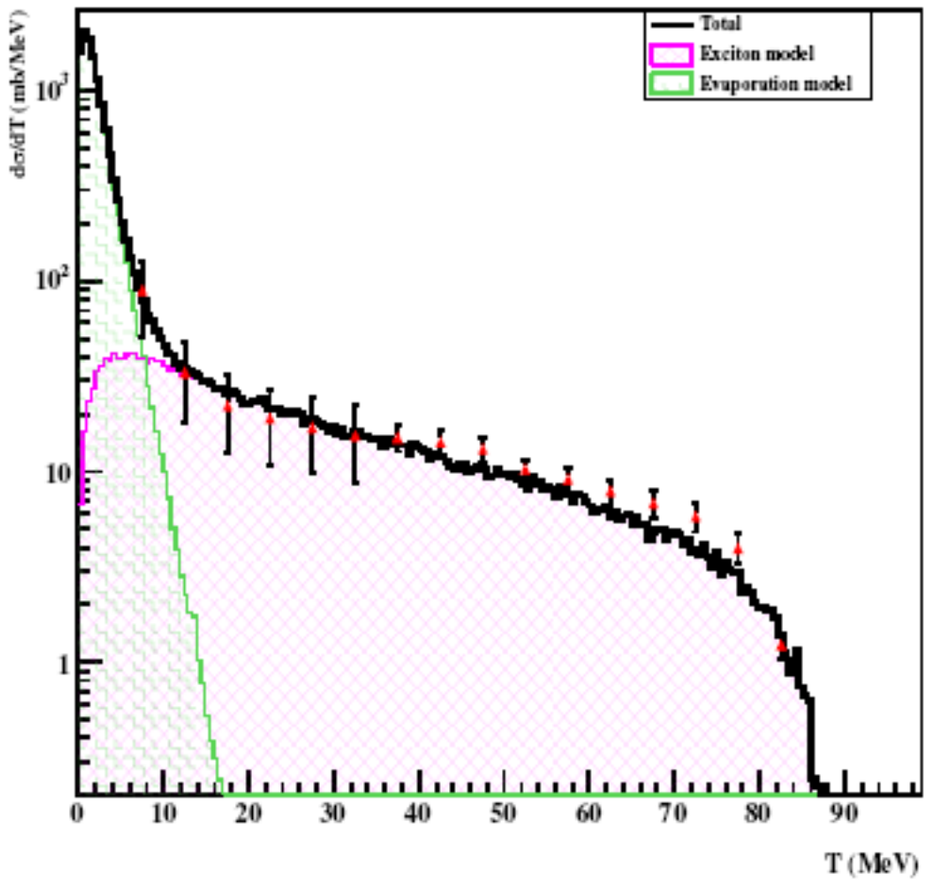


QGSP_BERT: TileCal Collaboration

- CALICE: unprecedented details in shower development
  - High energy: data better described
  - Low energy: too many protons (role of precompound: under investigation)
- LHC experiments showed **"forward physics" processes** (quasi-elastic, diffraction) are needed to describe longitudinal evolution of showers

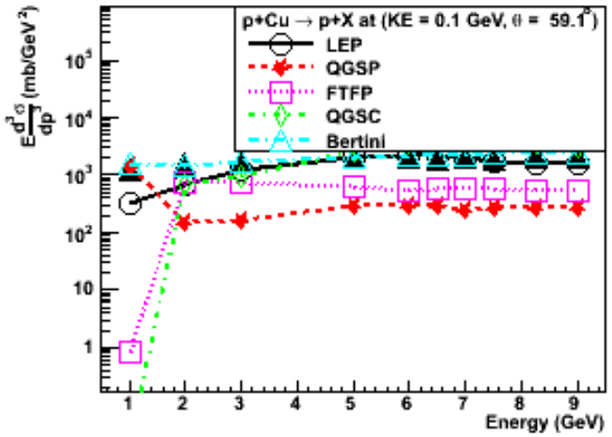
More Validation Examples

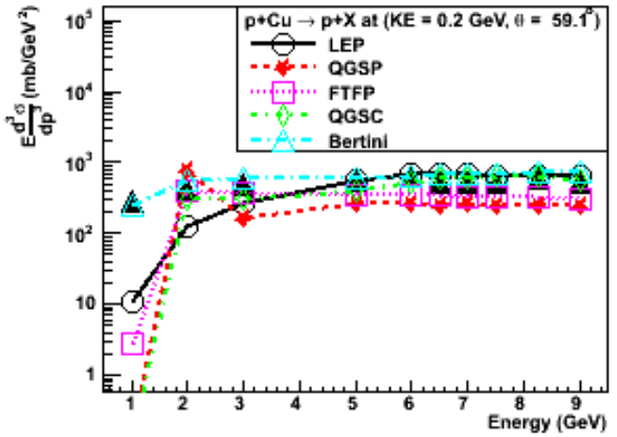
Neutron cross section

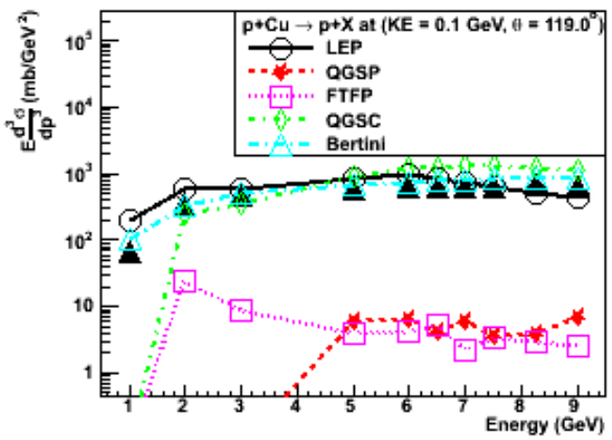


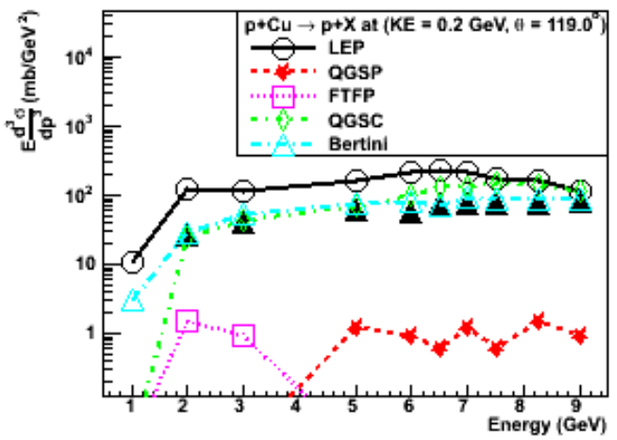
Protons of 90 MeV Bi(p,n) reaction:
Precompound model

p cross-sections for various models at different angles





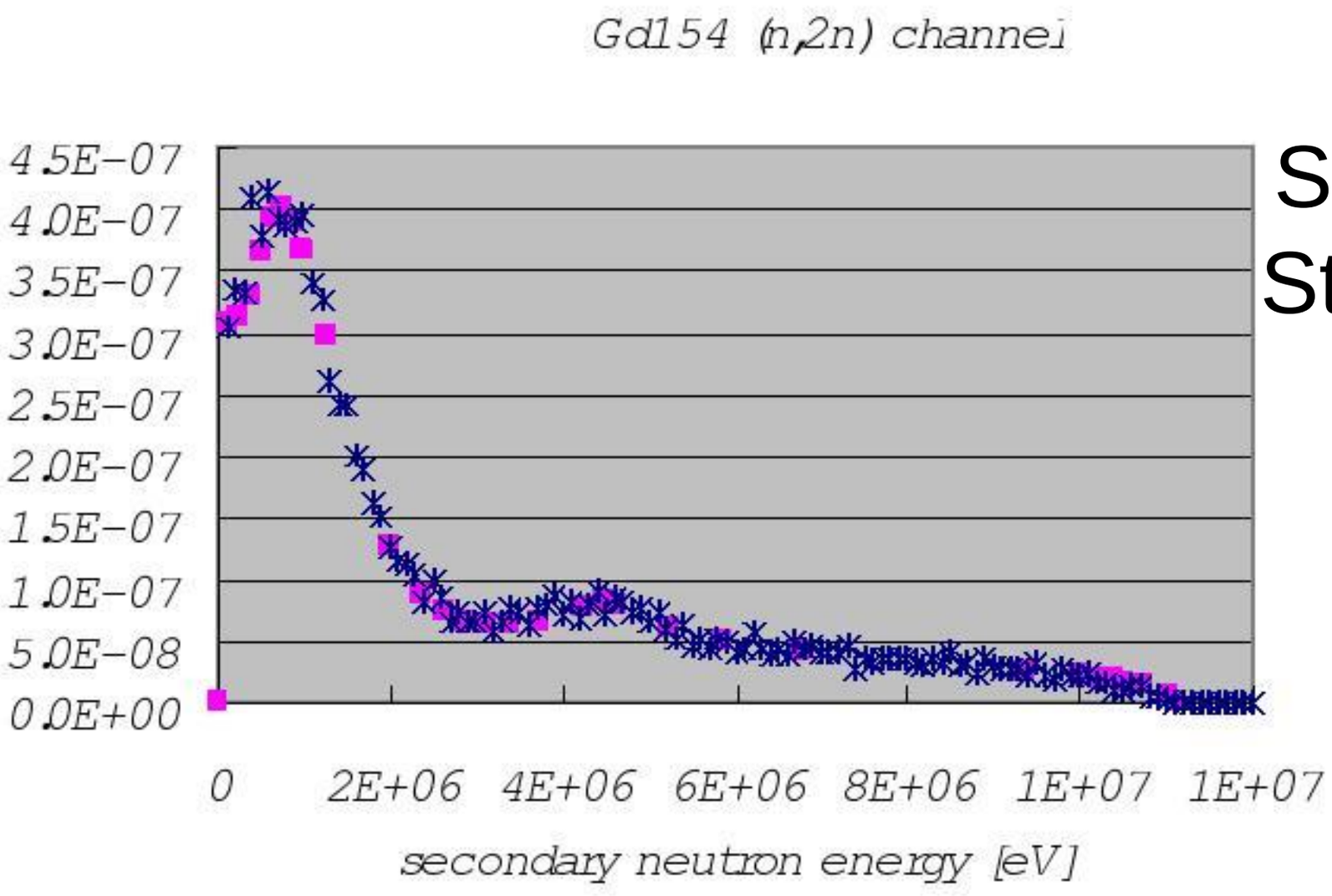




p on Cu with kinetic energy of 0.1/0.2 GeV

Another example: Thermal neutrons

HP (High Precision) extension is needed when interested in thermal neutrons. Expect up to x10 slower simulation!

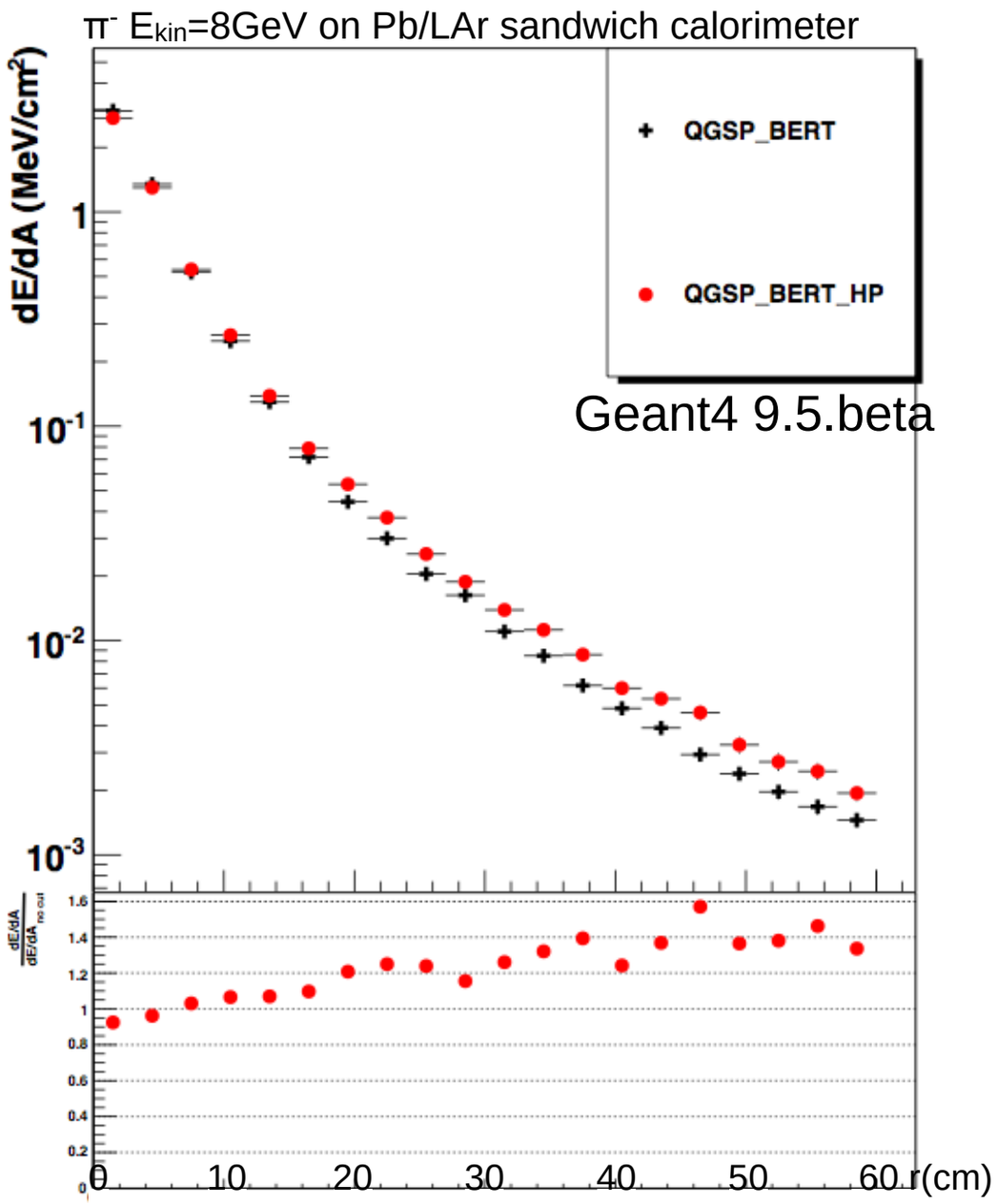


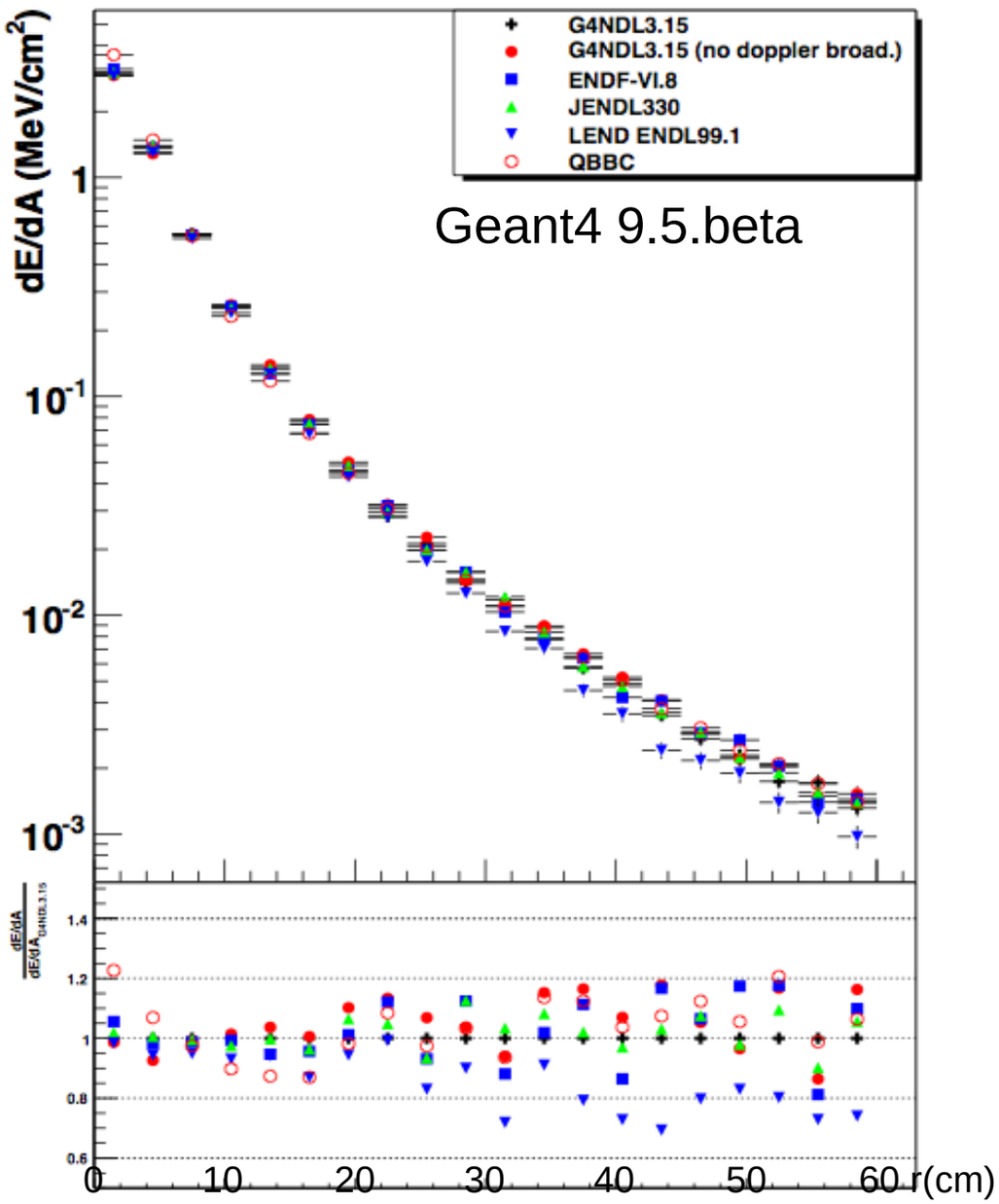
Squares: NDF data

Stars: G4 HP Model

Warning: this is a little bit a tautology, since HP is based on NDF data....

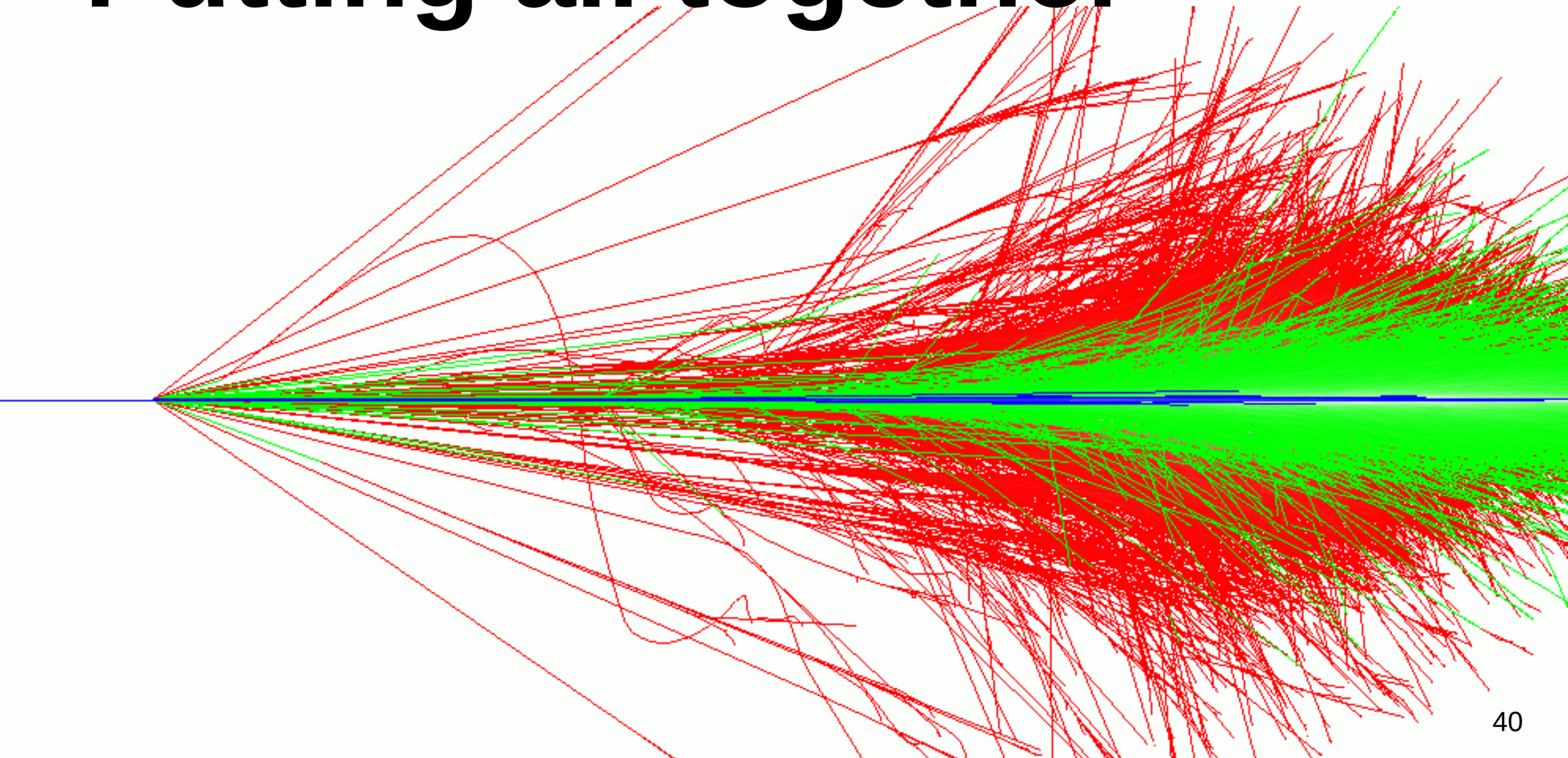
Role of neutrons: example



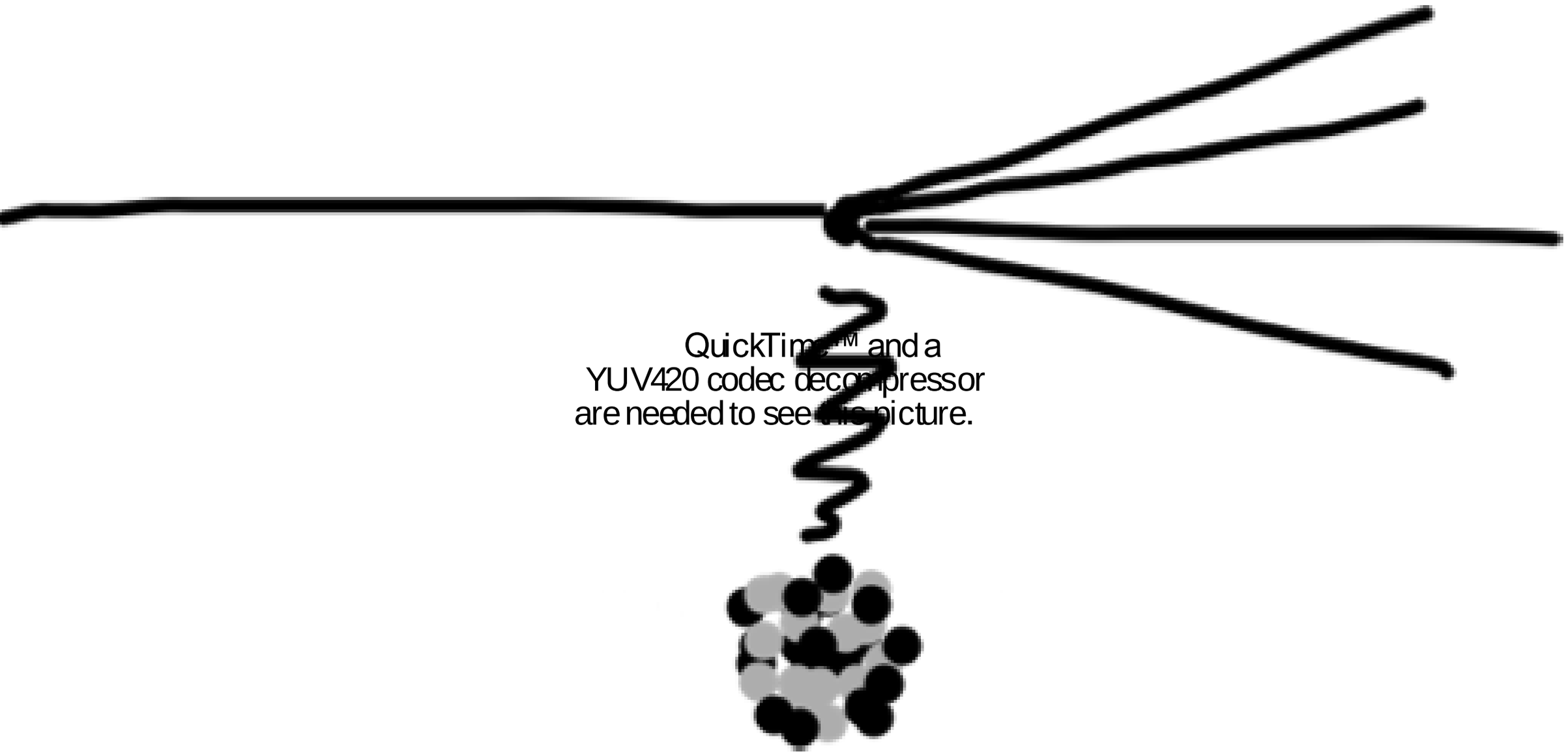


Low-E neutrons play important role for lateral profile
Need high granularity calorimeter for better understanding (CALICE)

Putting all together

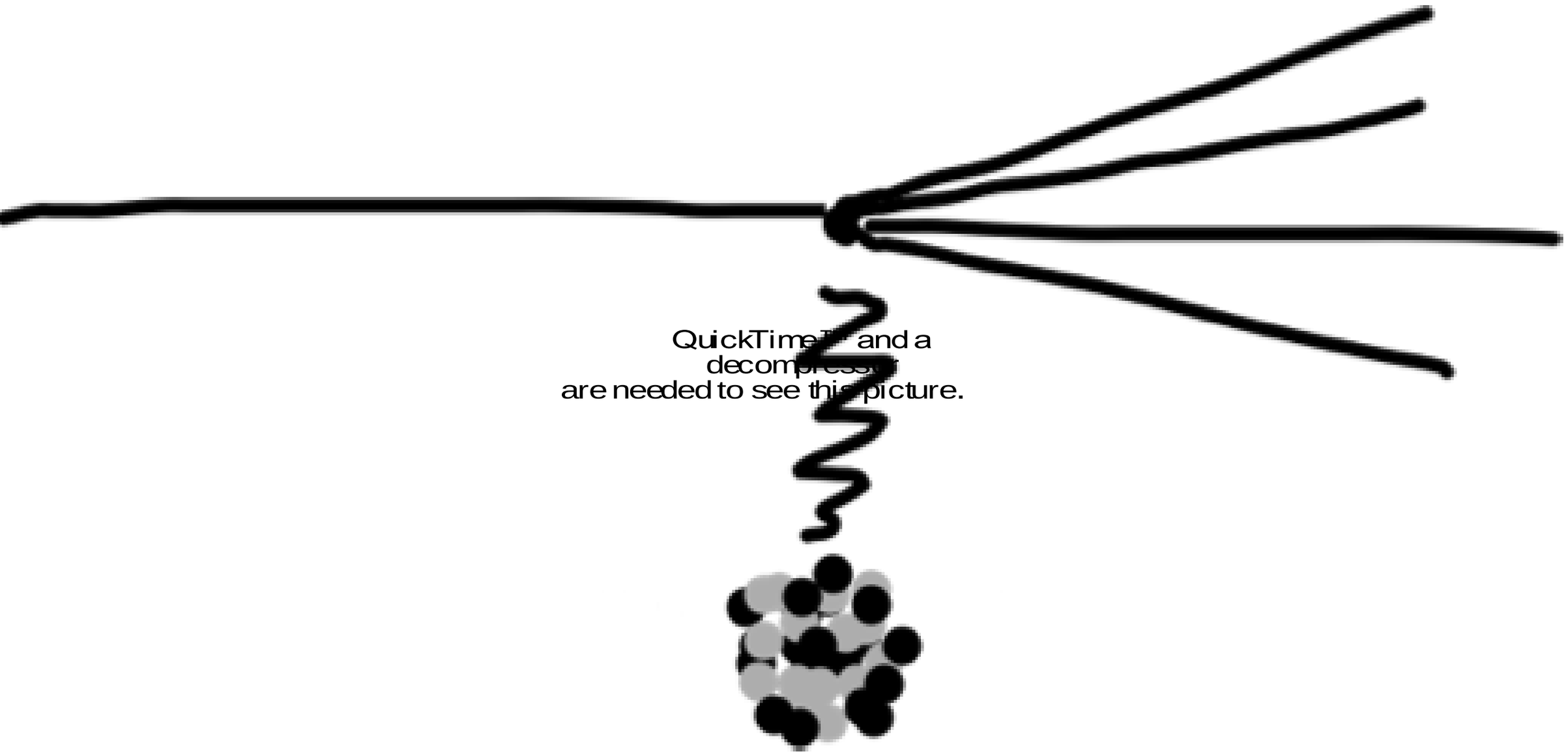


Electron/gamma shower



- More examples at: http://www.hep.man.ac.uk/u/johna/pub/Geant4/Movies

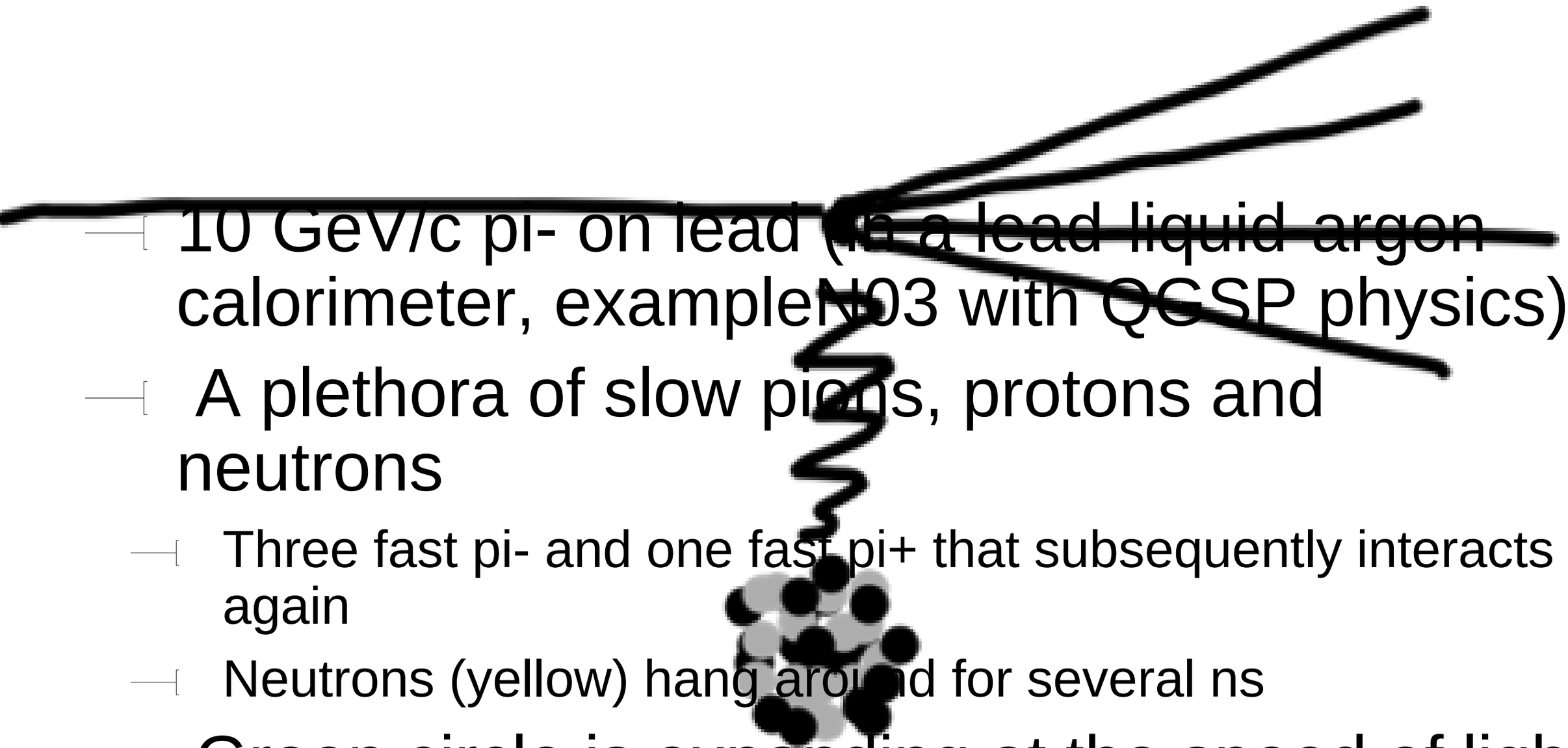
Hadronic Shower



- More examples at: http://www.hep.man.ac.uk/u/johna/pub/Geant4/Movies

A concrete Example: what you have seen

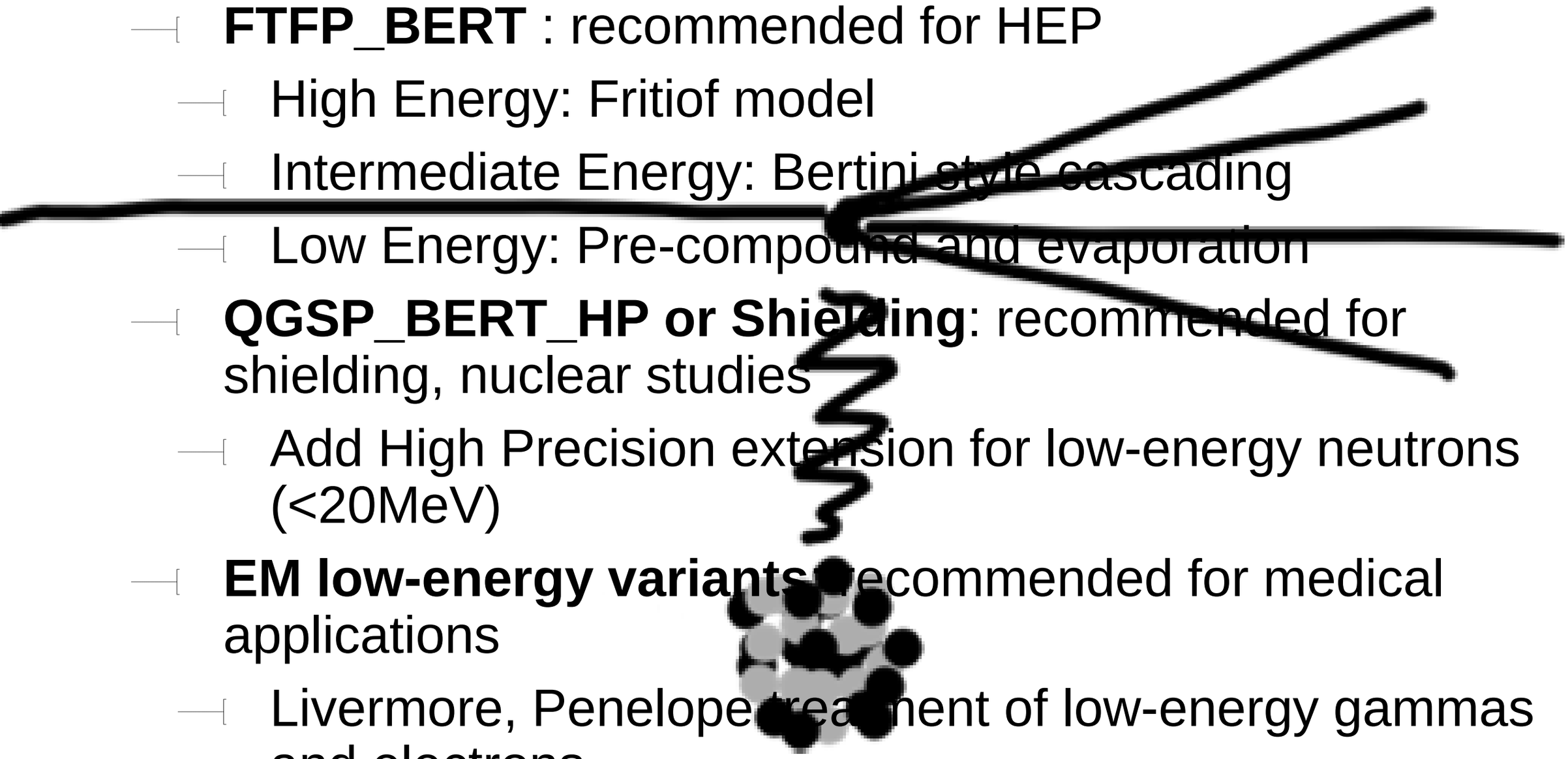
- 10 GeV/c pi- on lead (in a lead liquid argon calorimeter, exampleN03 with QGSP physics)
- A plethora of slow pions, protons and neutrons
  - Three fast pi- and one fast pi+ that subsequently interacts again
  - Neutrons (yellow) hang around for several ns
- Green circle is expanding at the speed of light



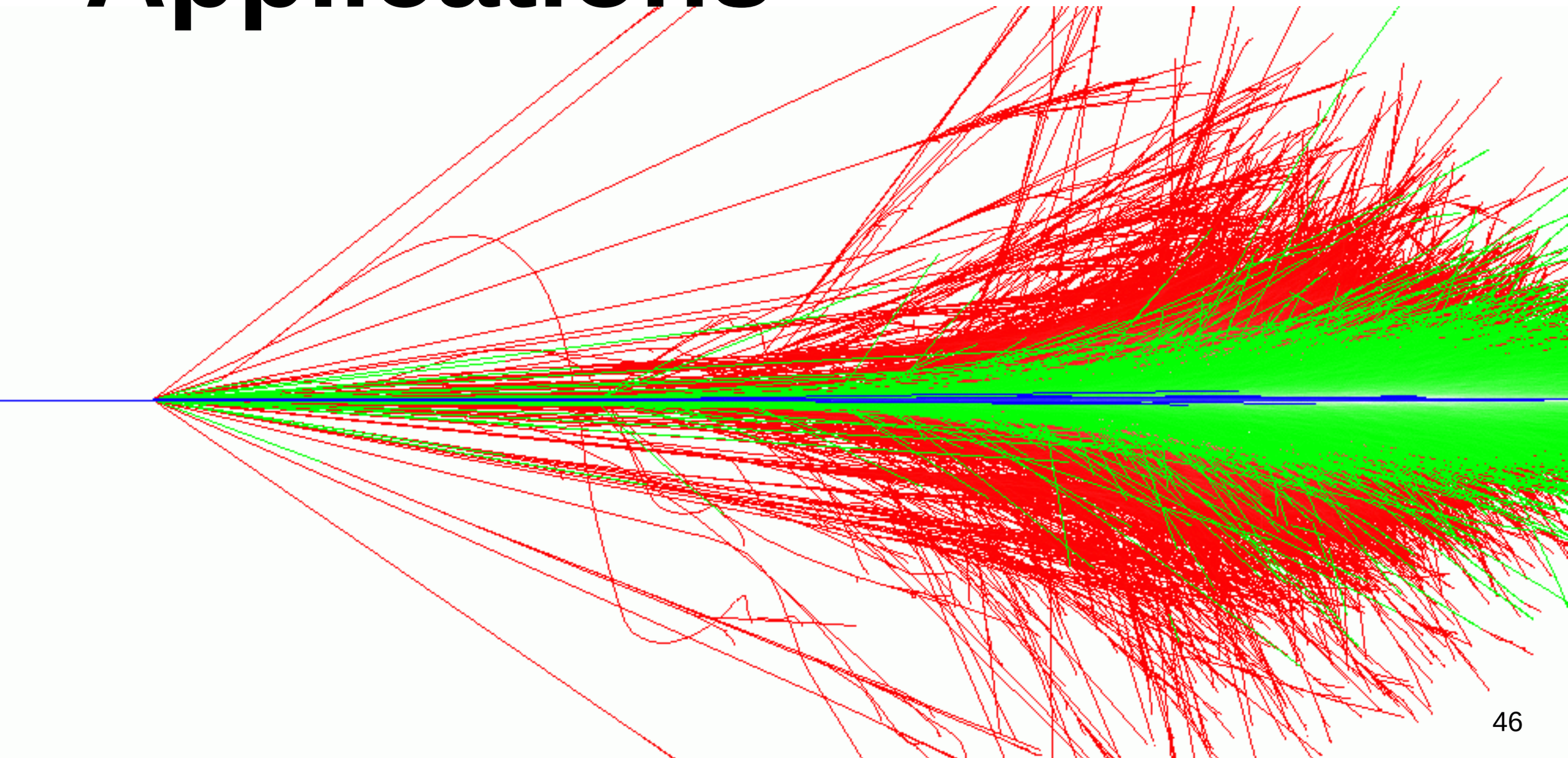
Physics Lists

- Since different (hadronic) models exists with **different performances** (quality of results and computing requirements) at different energy ranges, multiple choices are available:
  - Models are assembled in “physics lists”
- **Can be built from scratch or use one of the provided “educated” physics lists** for applications in:
  - HEP calorimetry, tracking, low-E dosimeter with neutrons, shielding, medical applications, air shower applications, low background experiments, space applications

- Currently suggested physics lists:
  - **FTFP_BERT** : recommended for HEP
    - High Energy: Fritiof model
    - Intermediate Energy: Bertini style cascading
    - Low Energy: Pre-compound and evaporation
  - **QGSP_BERT_HP or Shielding**: recommended for shielding, nuclear studies
    - Add High Precision extension for low-energy neutrons (<20MeV)
  - **EM low-energy variants**: recommended for medical applications
    - Livermore, Penelope: treatment of low-energy gammas and electrons
    - Under-development: G4-DNA, simulate also physio-chemical step of DNA damage

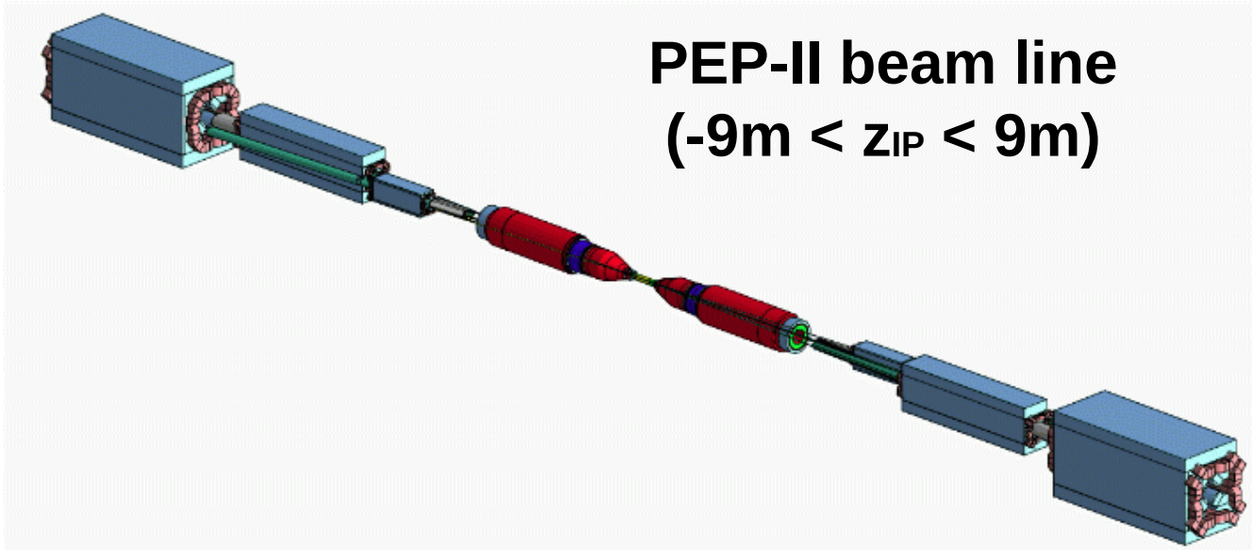


Applications

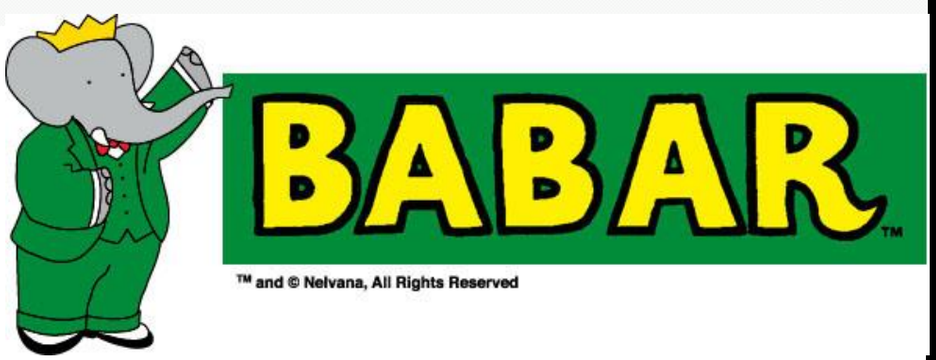


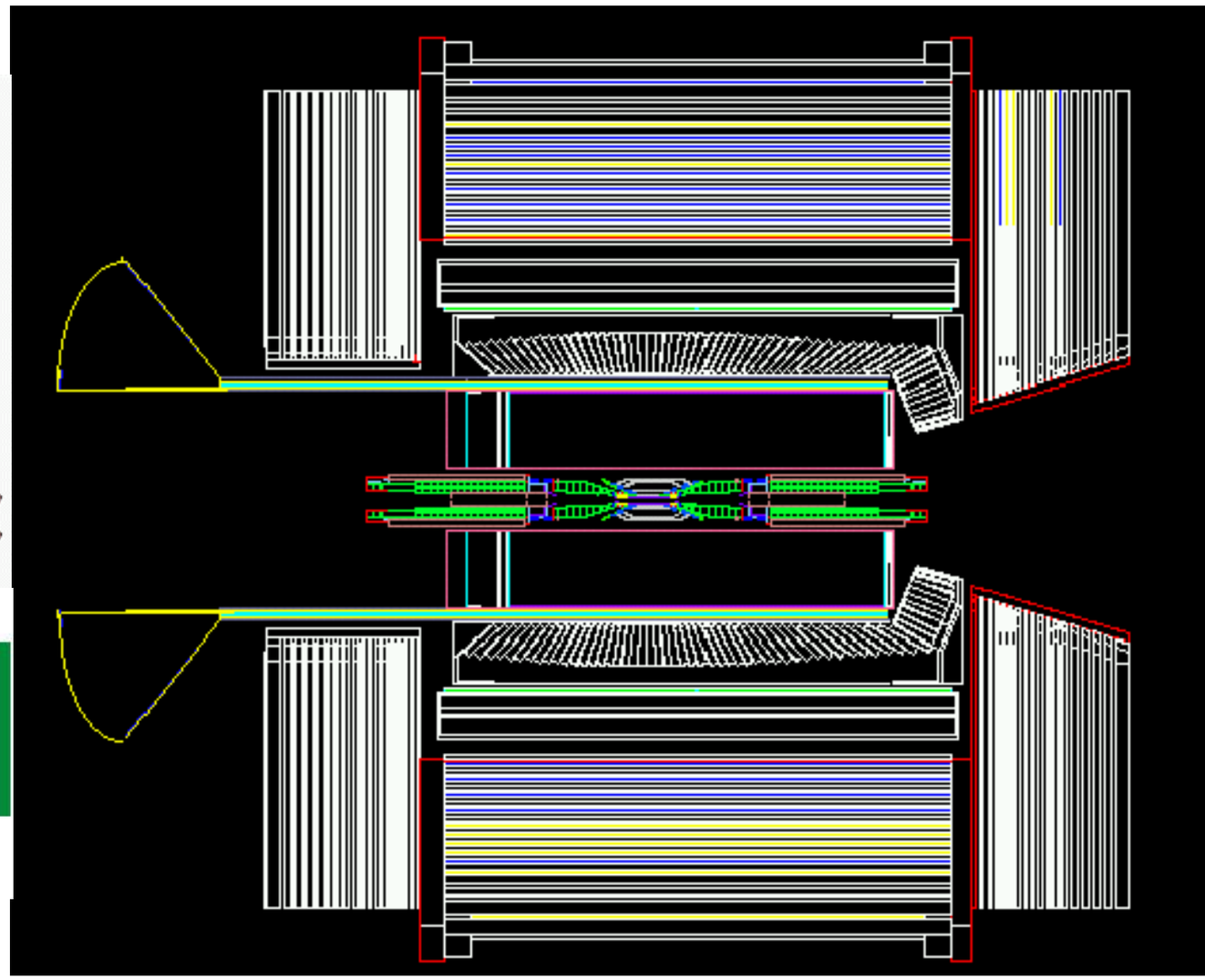
BaBar and Geant4

- BaBar is the pioneer HEP experiment in use of OO technology, and the first customer of Geant4.
  - During the R&D phase of Geant4, we acknowledge lots of valuable feedbacks were provided by BaBar.
- BaBar started its simulation production in 2000 and had produced more than 10 billion events at more than 20 sites in Europe and North America.

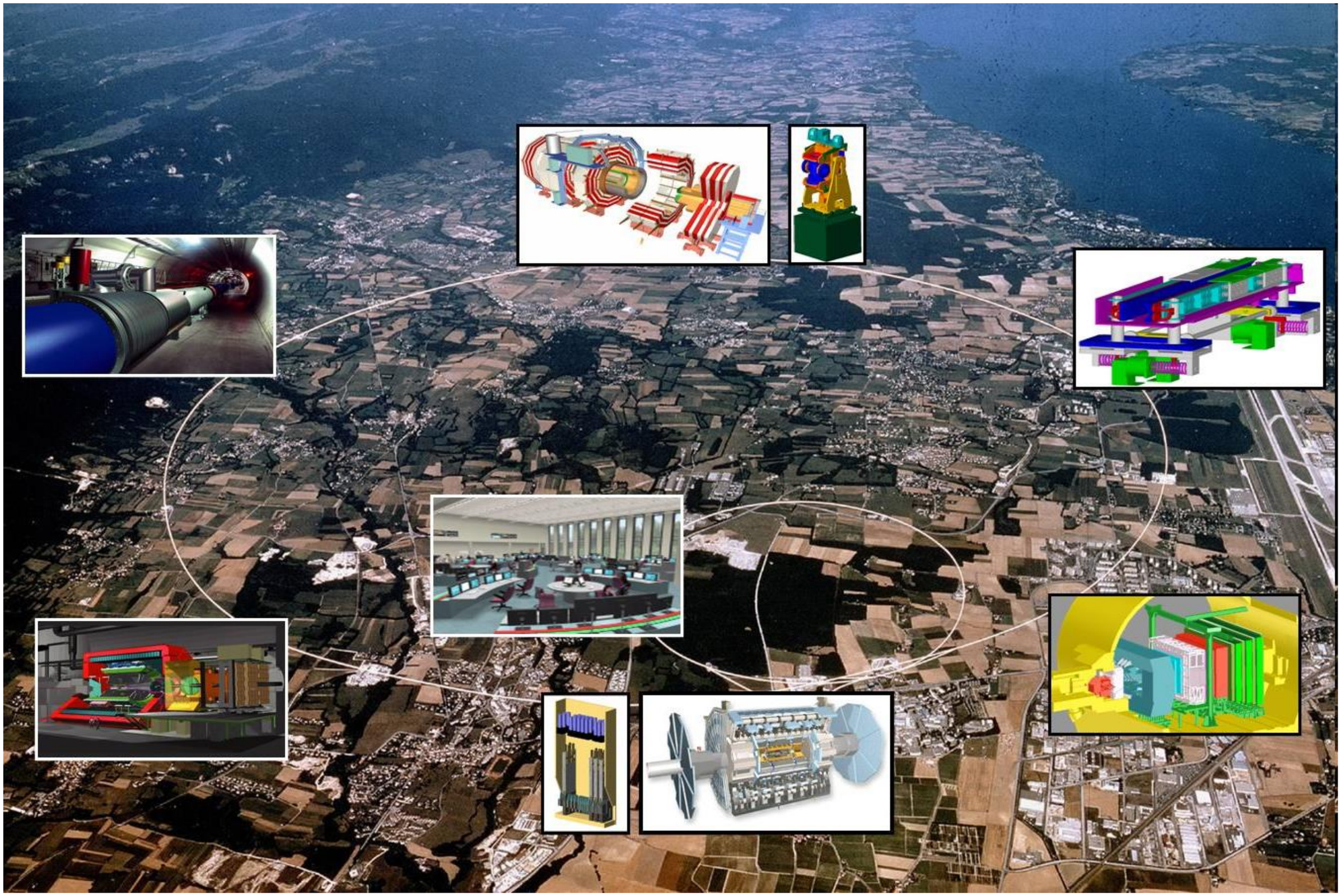


PEP-II beam line
(-9m < z_{IP} < 9m)

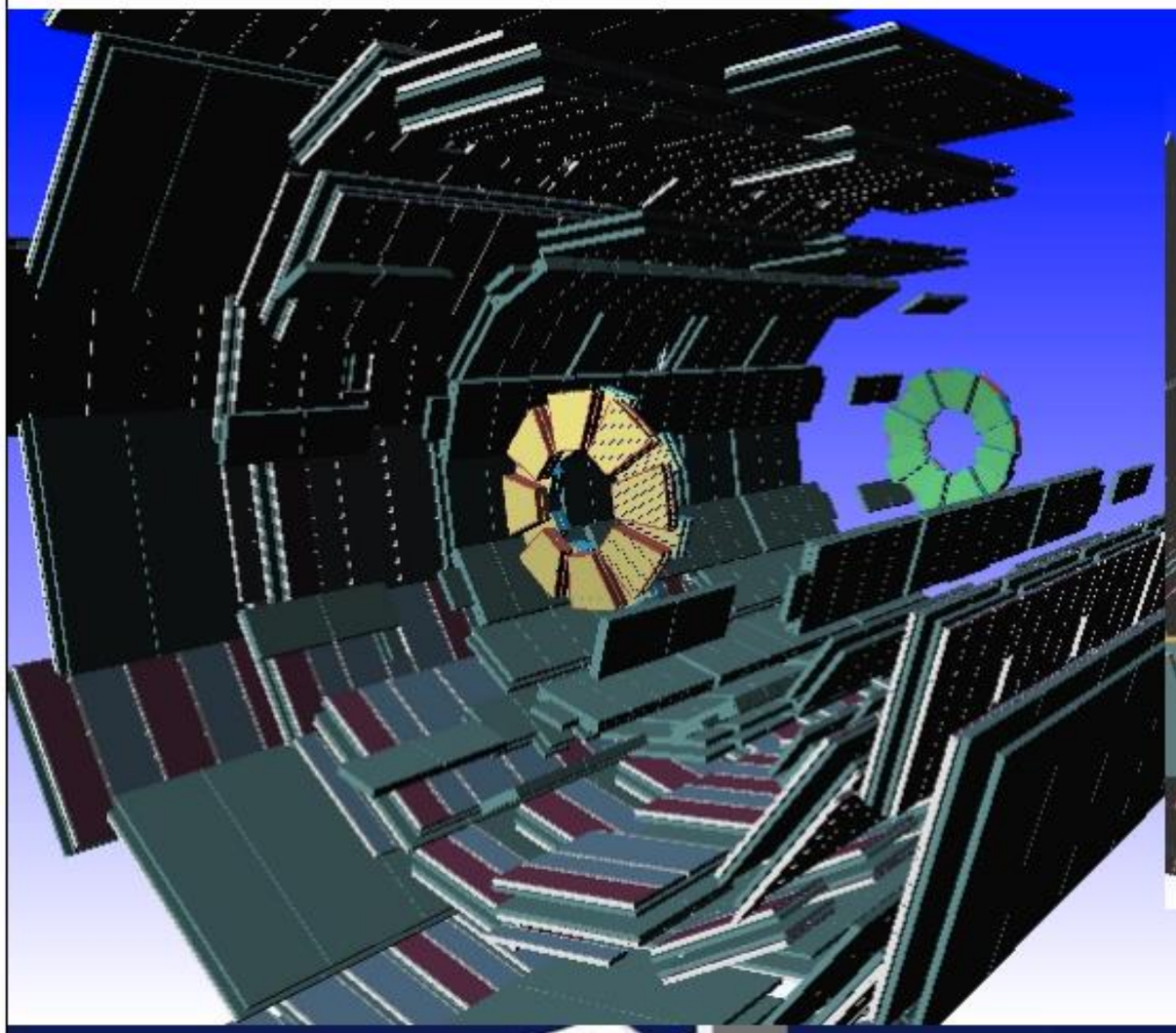


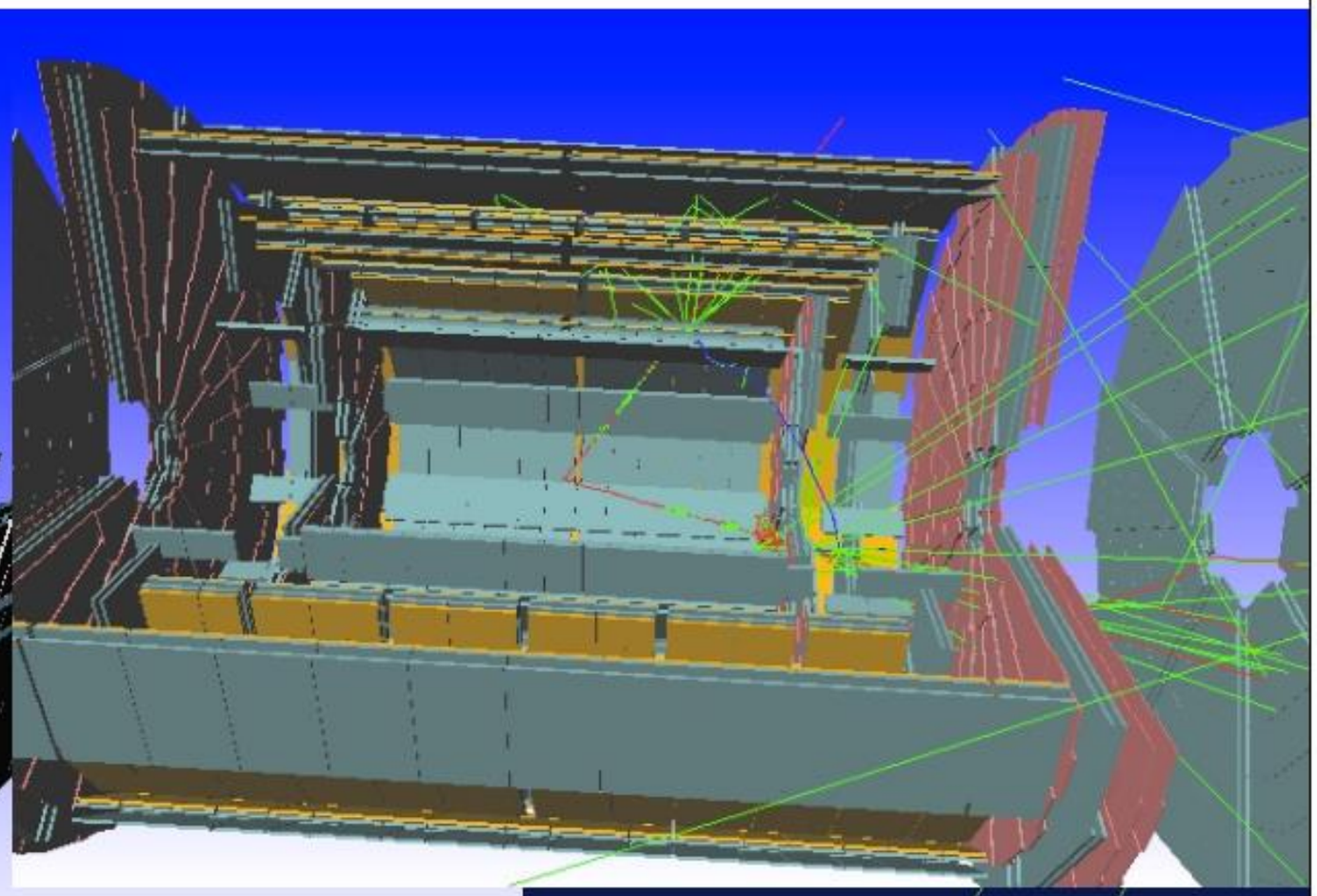


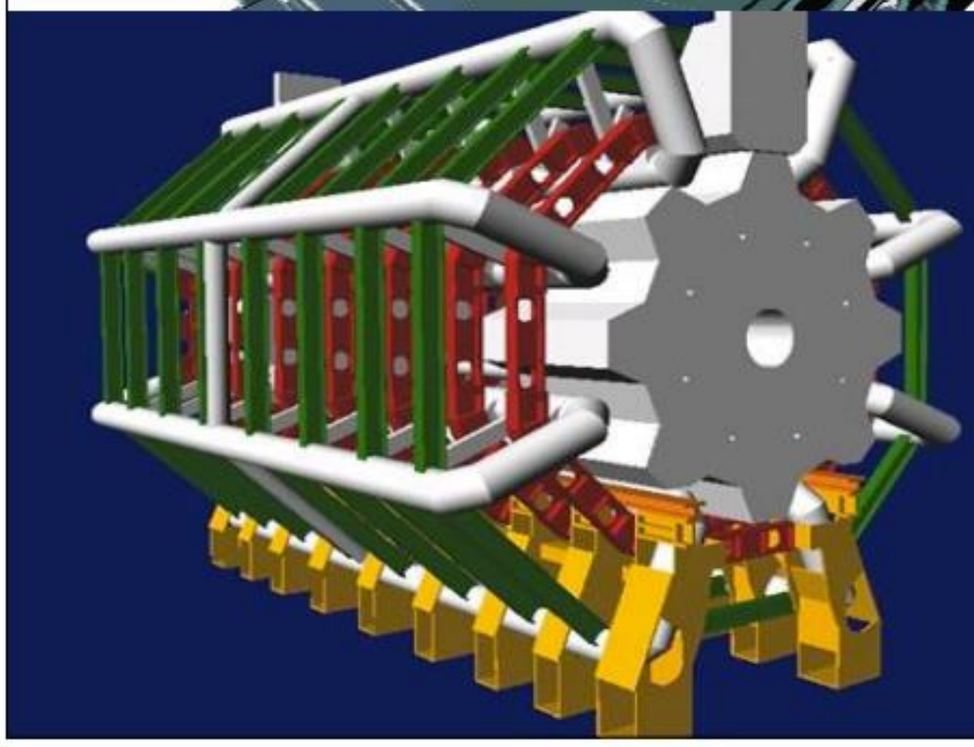
Large Hadron Collider (LHC) @ CERN

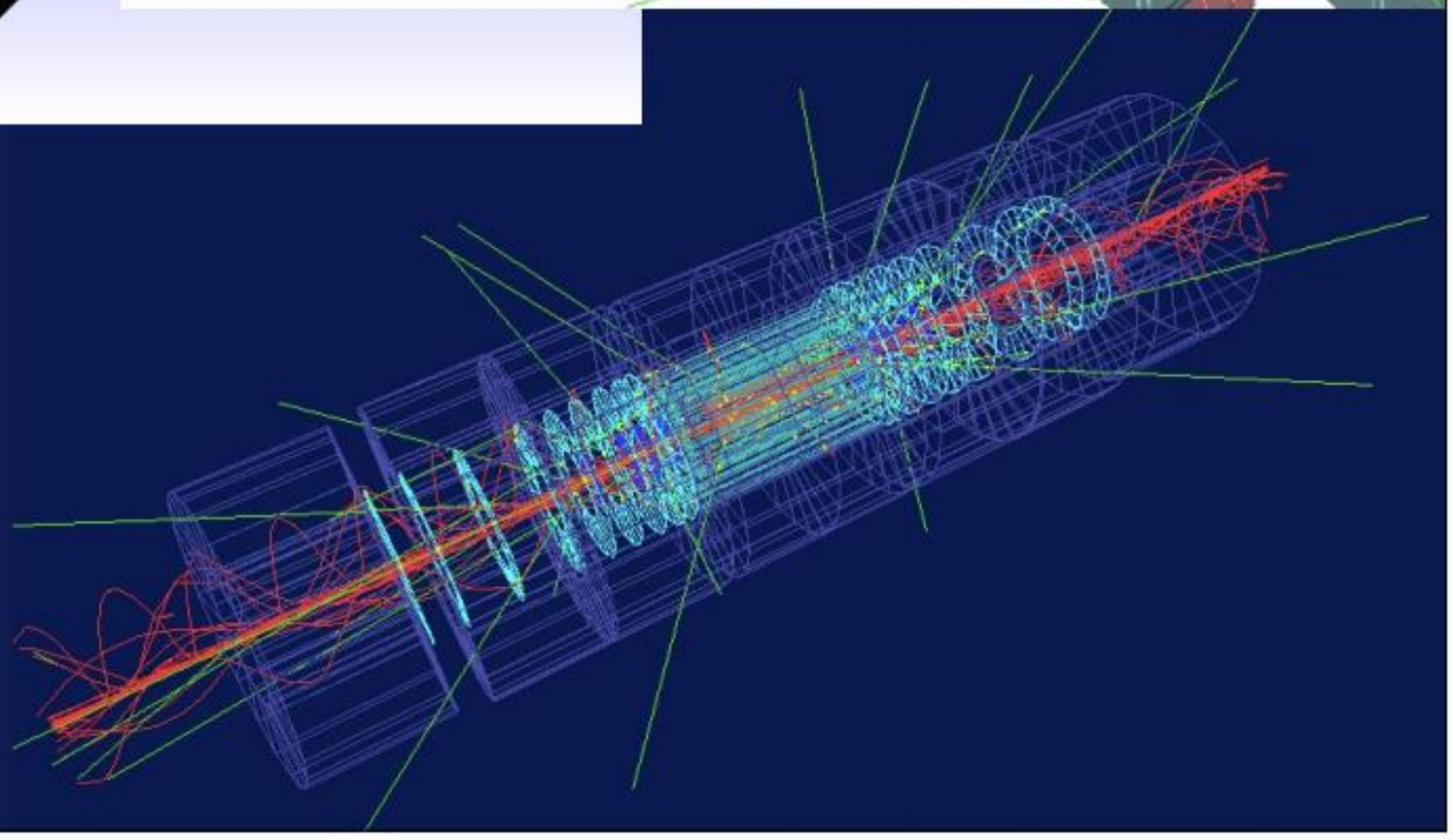


Geant4 in High Energy Physics (ATLAS at LHC)





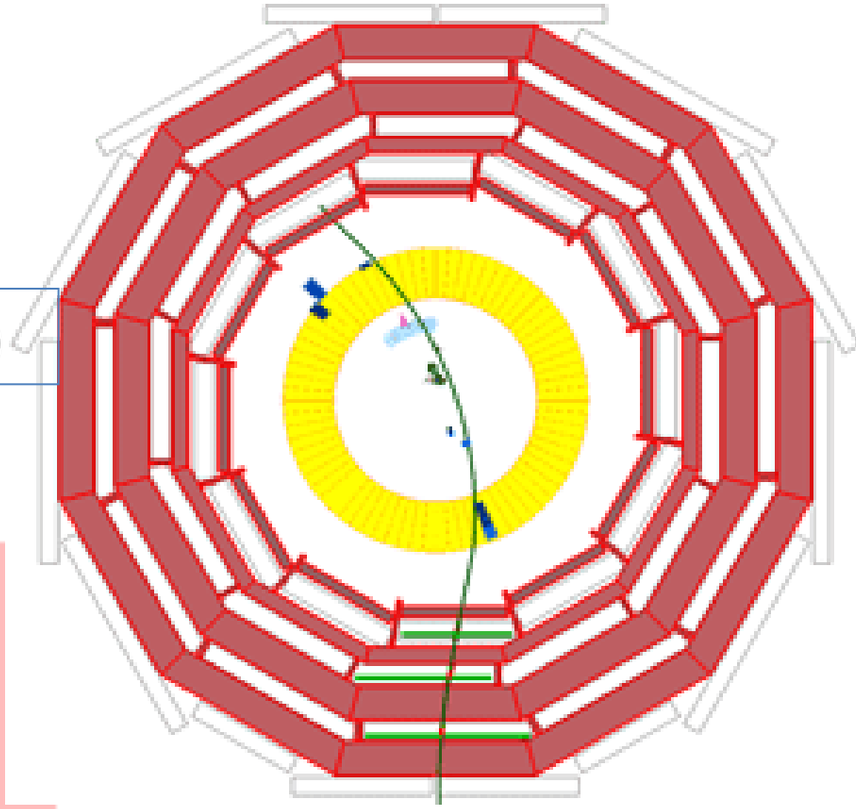




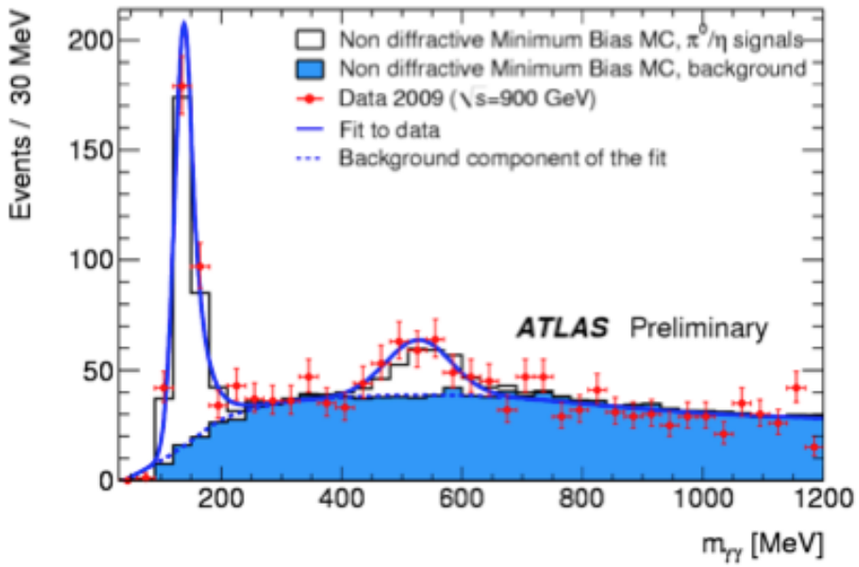
Geant4 has been successfully employed for

- Detector design
- Calibration / alignment
- First analyses

T. LeCompte (ANL)



GEANT4 Comparisons with the Calorimeters



Invariant mass of pairs of well-isolated electromagnetic clusters.

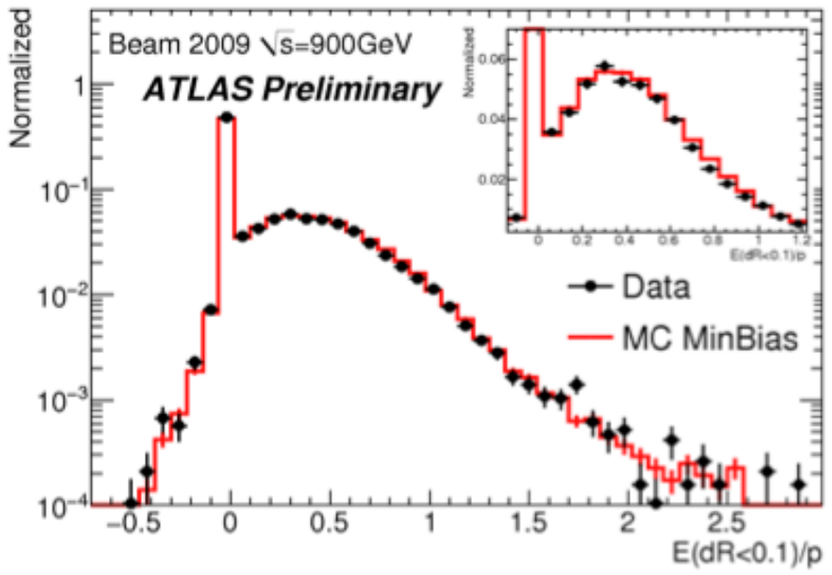
The π^0 mass is within 0.8 ± 0.6% of expectations.

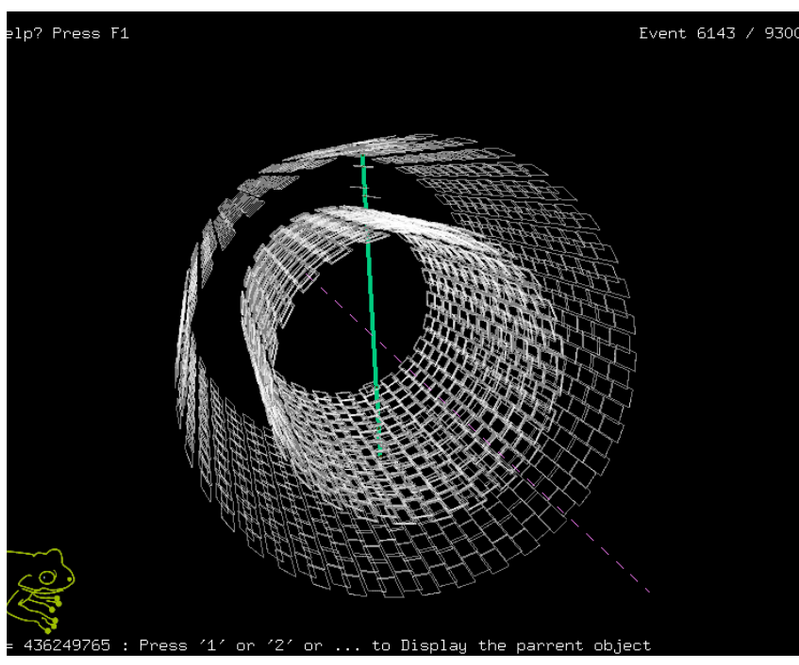
The η^0 mass is within 3 ± 2% of expectations.

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.

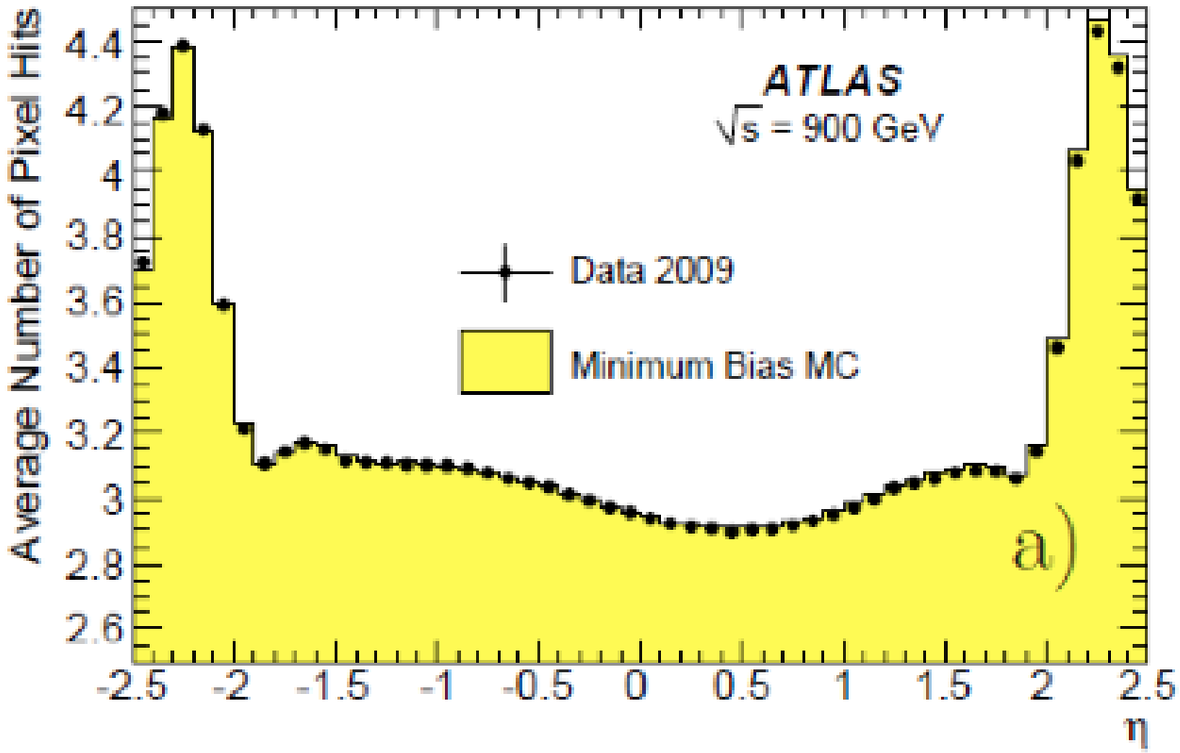
This plot agreed better than we ever expected. (I sent the student who made it back to make sure that they didn't accidentally compare G4 with G4.

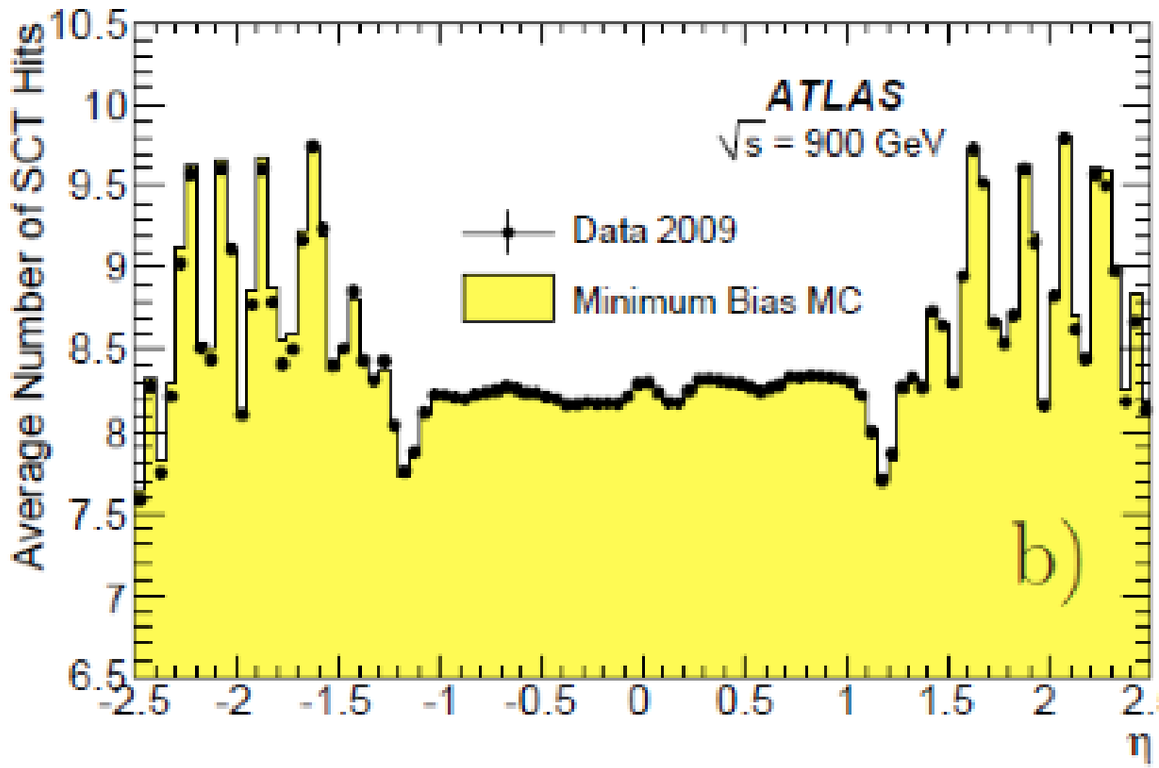


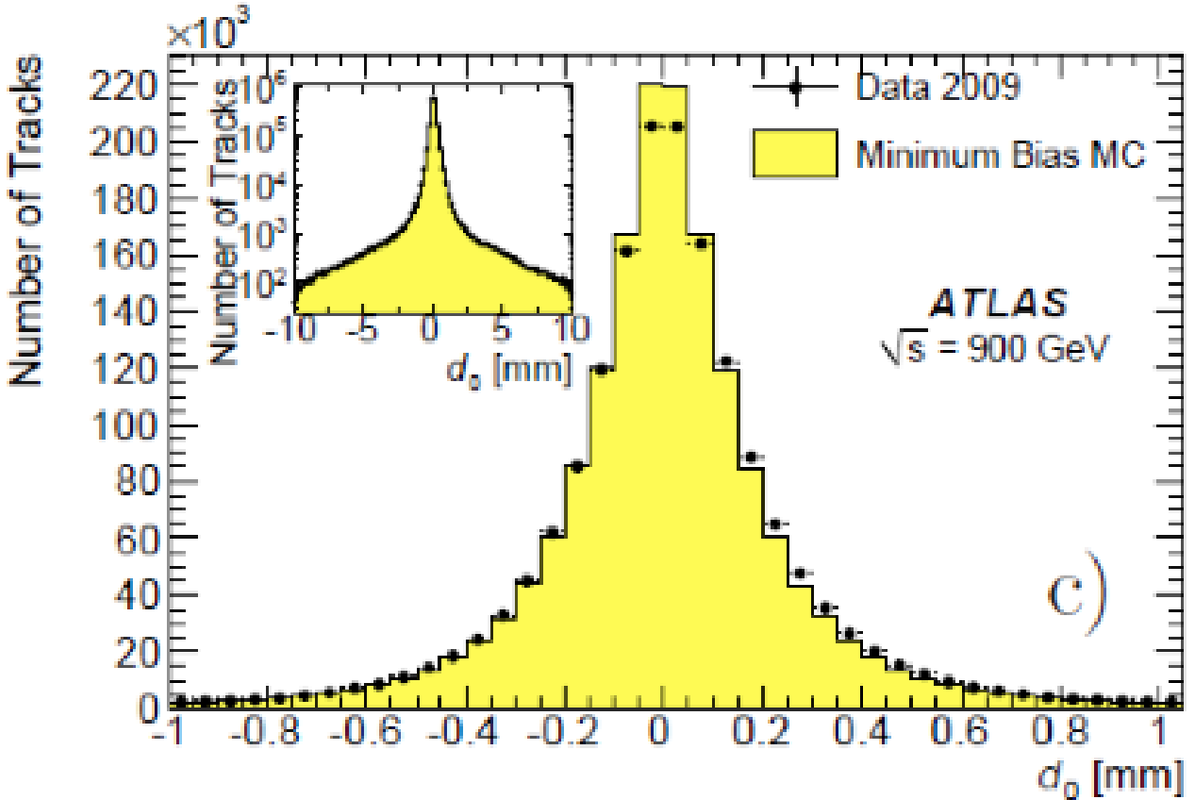


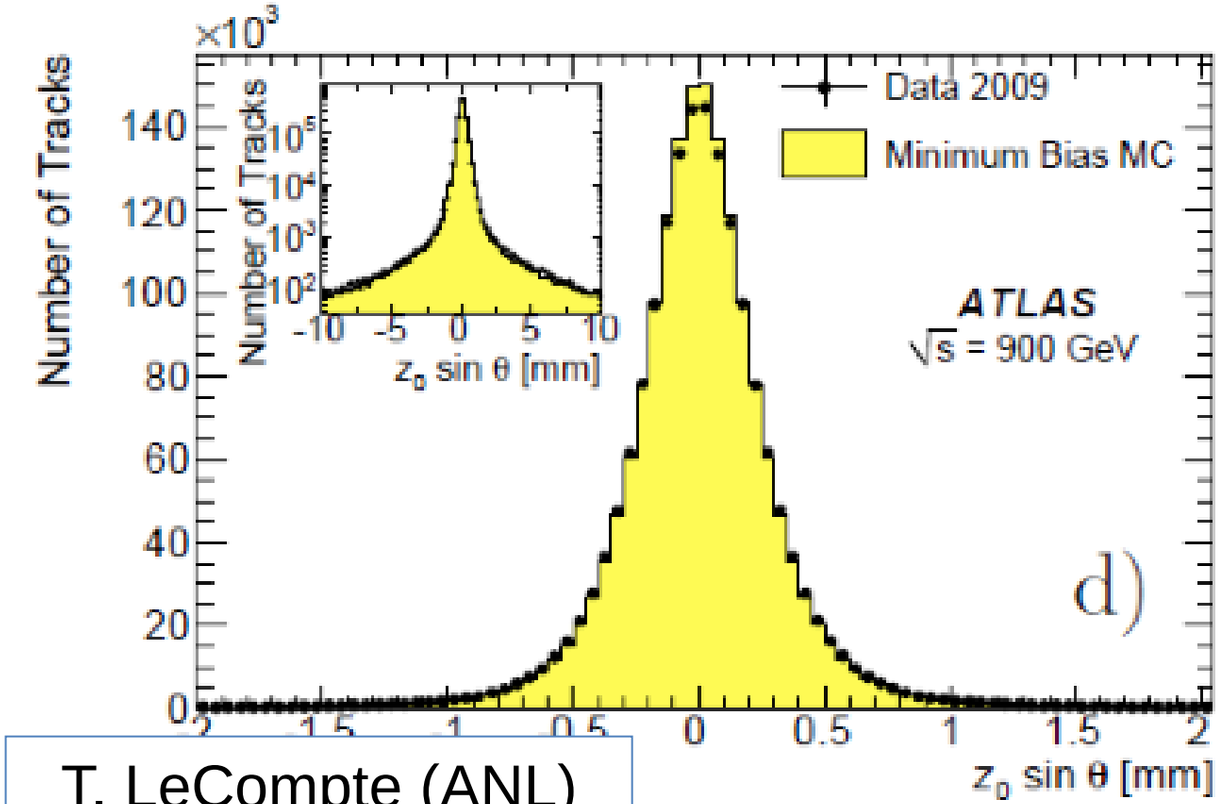
Figures from CMS

Data and simulation agreements





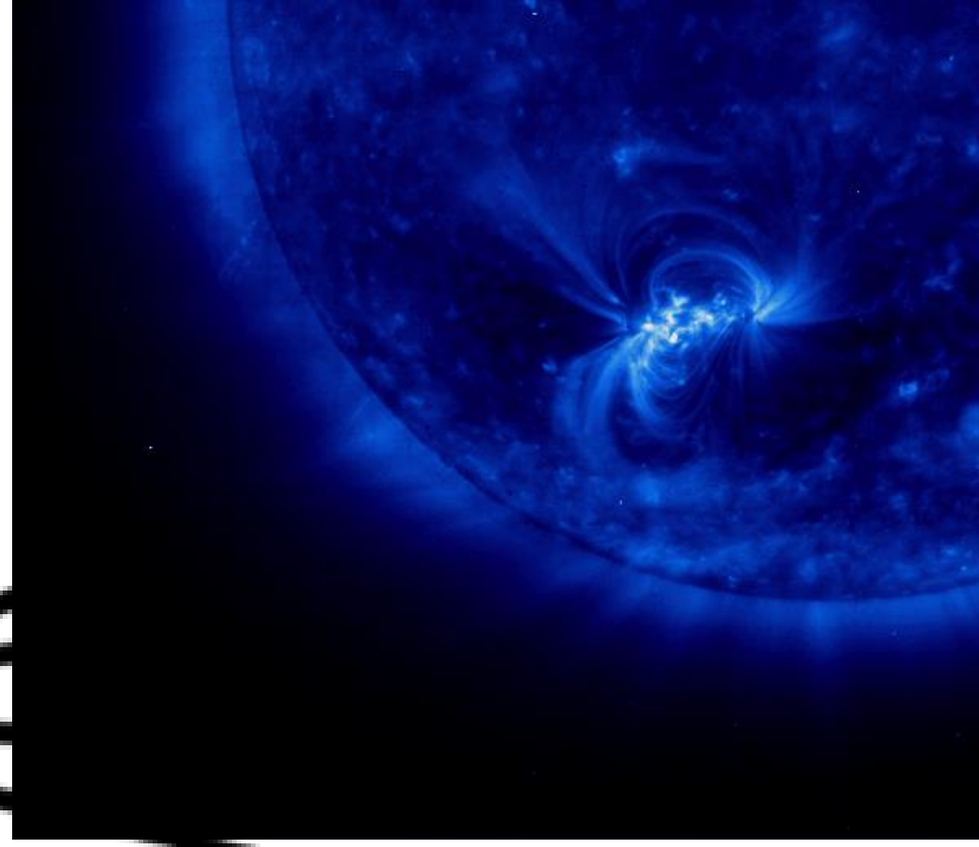


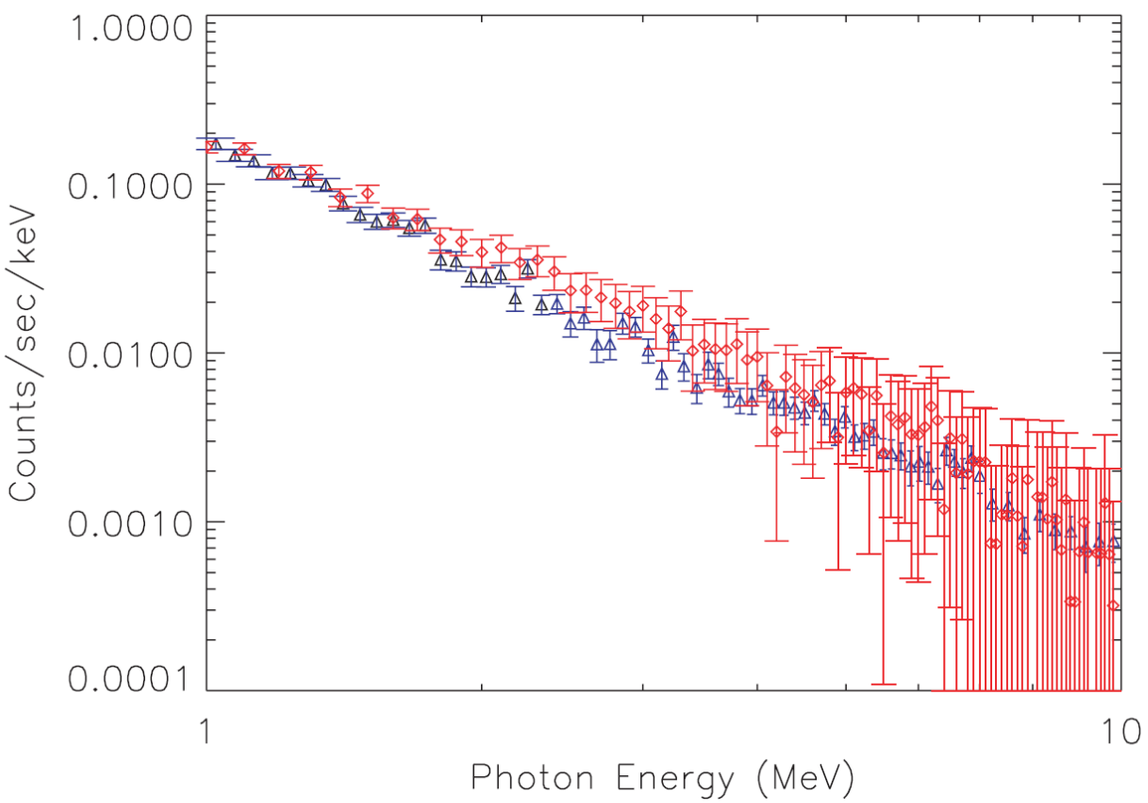


T. LeCompte (ANL)

Solar event gamma-rays

- Electron Bremsstrahlung – induced gammas in solar flares
- Compton back-scattering
- → observable gamma-ray spectrum
- much softer than predic simple





Effects of Compton scattering on the Gamma Ray Spectra of Solar flares

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(Received ; accepted)

Abstract

Using fully relativistic GEANT4 simulation tool kit, the transport of energetic electrons generated in solar flares was Monte-Carlo simulated, and resultant bremsstrahlung gamma-ray spectra were calculated. The solar atmosphere was ap-

Geant4 in Space (NASA, ESA, JAXA)

Smart-2

ACE

LISA

INTEGRAL

Cassini

Bepi Colombo

GLAST/Fermi

Herschel

SWIFT

Astro-E2

XMM-Newton

GAIA

JWST

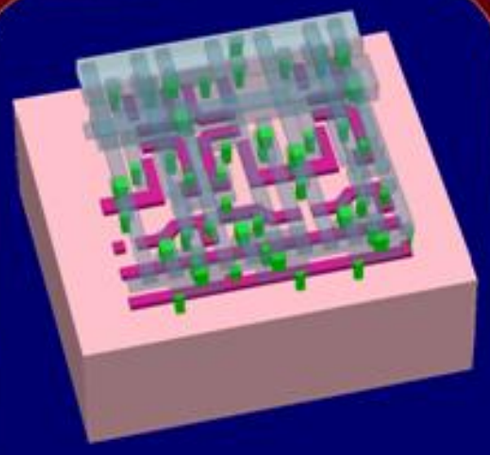
Columbus

EUSO

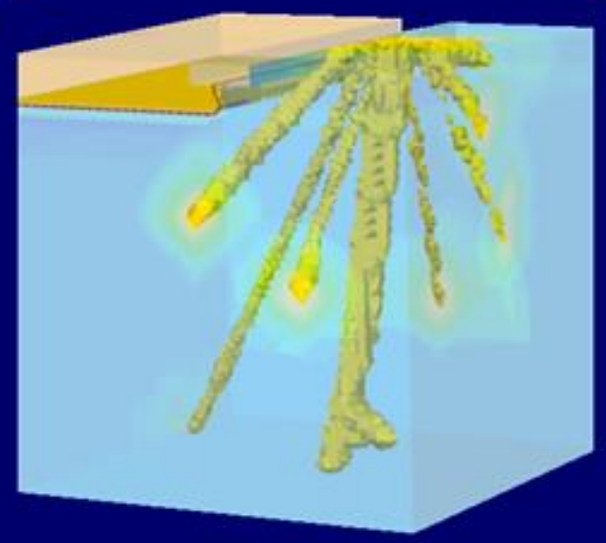
AMS

MAXI

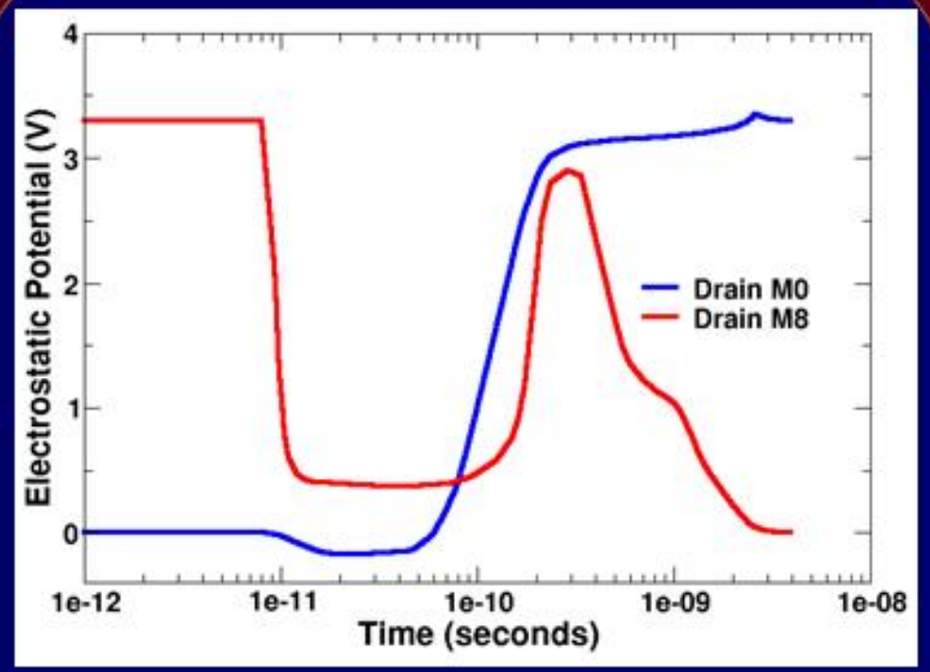
RADSAFE on SEE in SRAMs



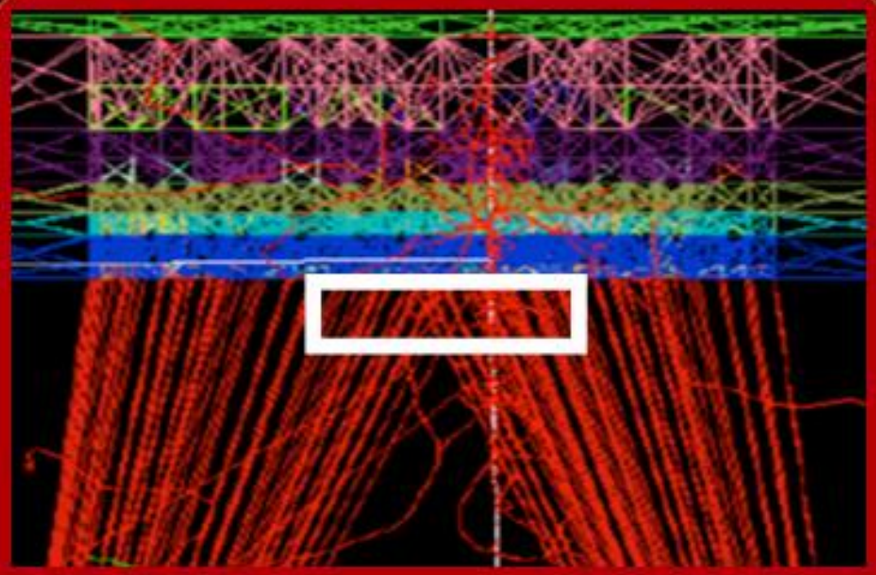
TCAD Cell Structure: SRAM Cell



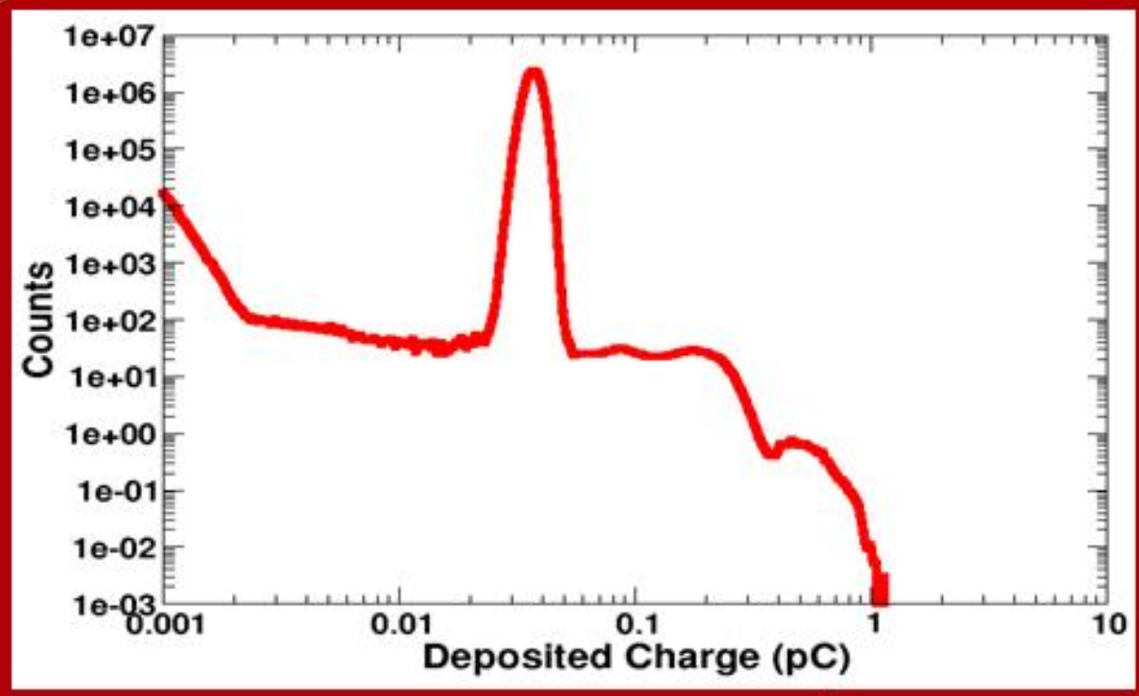
Single Charge Deposition in TCAD: Ne+W Event



SRAM Cell Upset



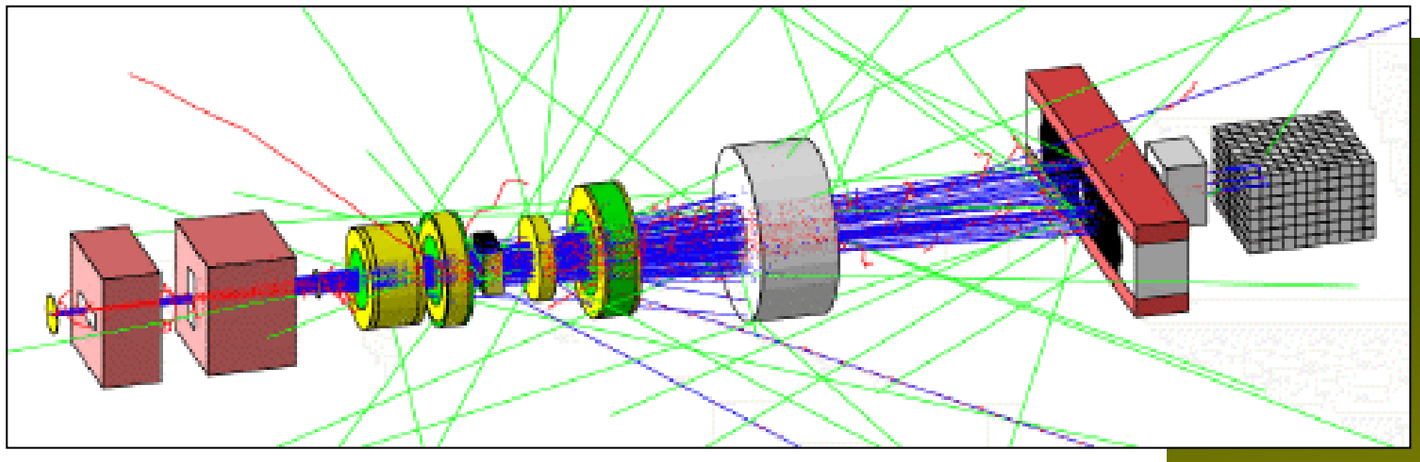
Geant4 Geometry and 523 MeV Neon Event

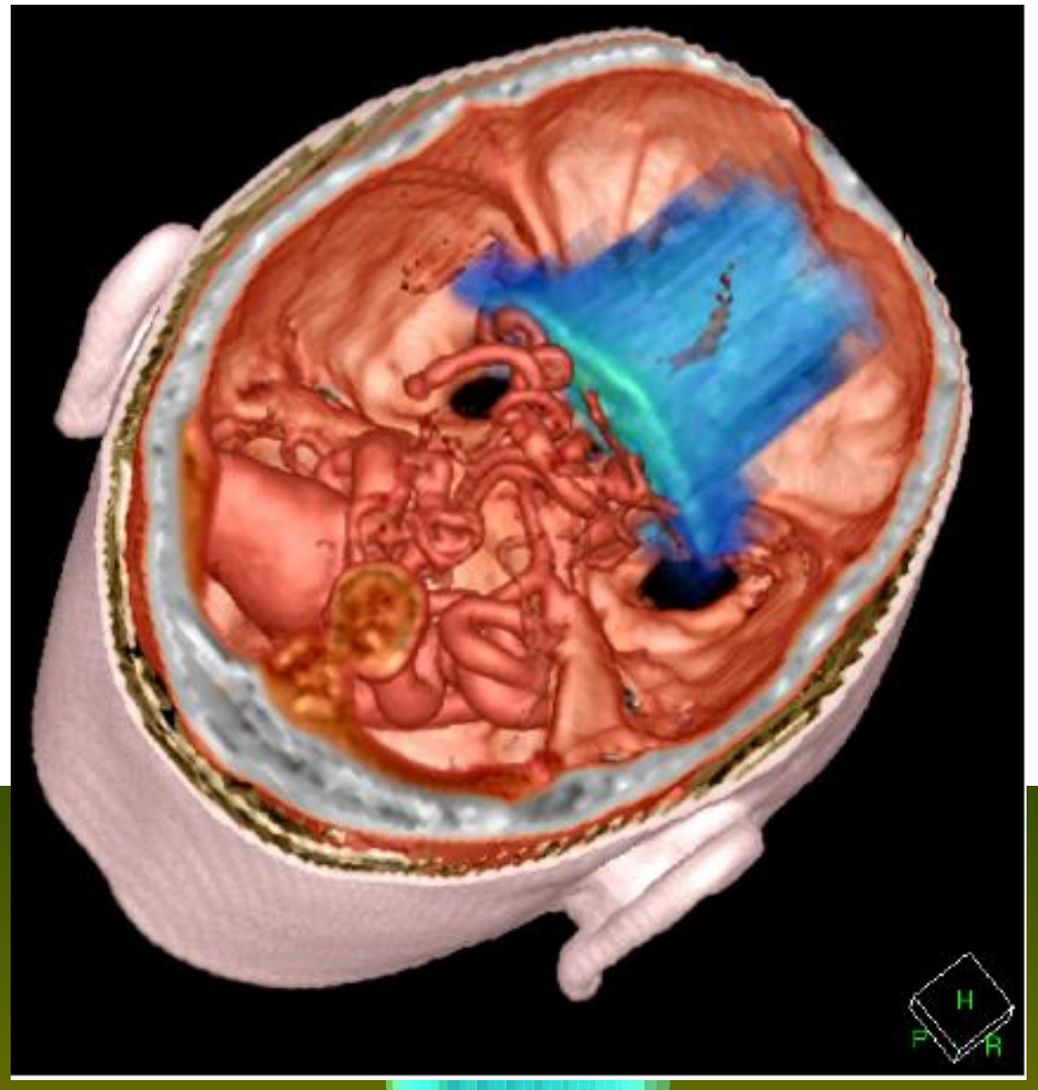


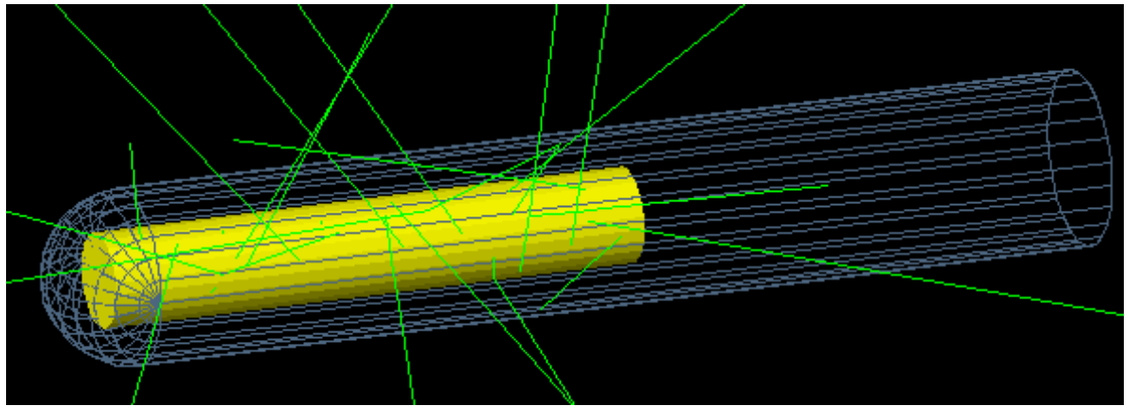
MRED Energy Deposition for 10^8 Events

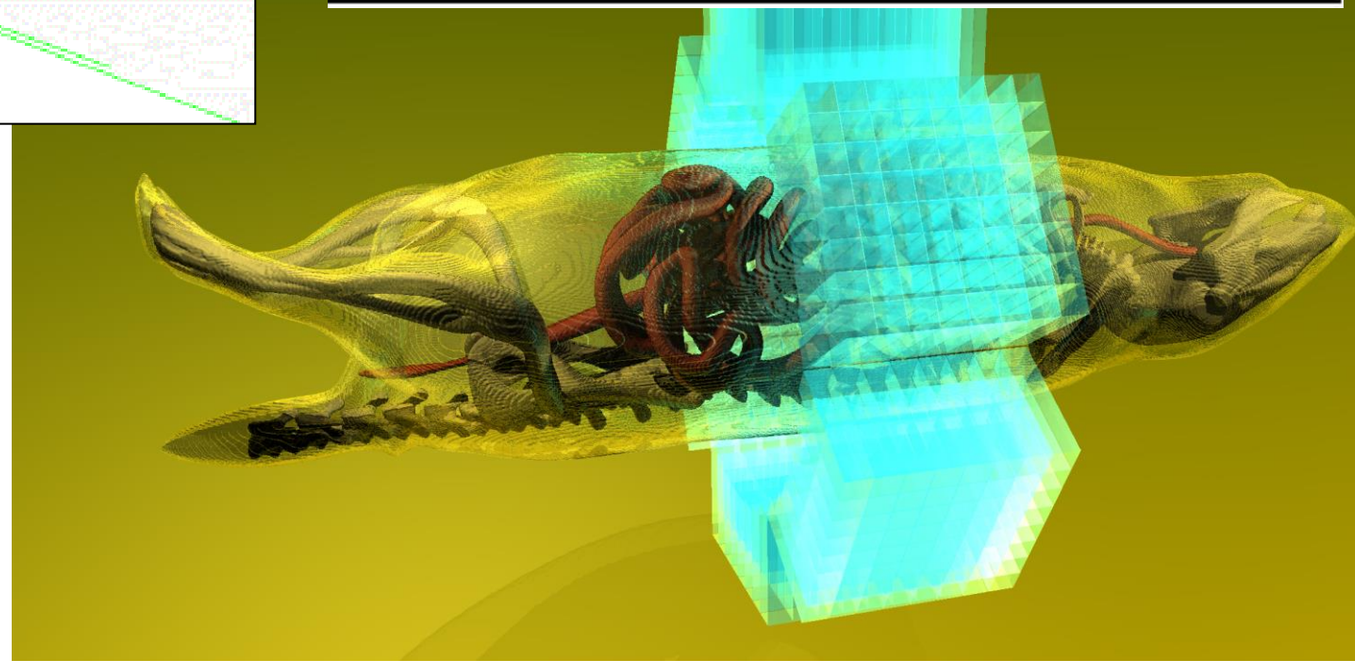
Geant4 @ Medical Science

- Four major use cases
  - Beam therapy
  - Brachytherapy
  - Imaging









Medical Physic

- Geant4 is used to calculate **doses**
- but also to design **imaging devices** (PET, gamma cameras)
- Geant4 is used to **validate results** obtained with software (fast calculations) to plan therapies
  - Interesting future direction: hadron beams for cancer therapy (C^{12}, p beams)
- Need **very precise low energy** (keV-MeV) em physics description (at the opposite of the spectra with compared to HEP)