Geant4 Toolkit

Second African School of Physics, 2012

Geant4 ASSOCIATES INTERNATIONAL
Experts in Radiation Simulation
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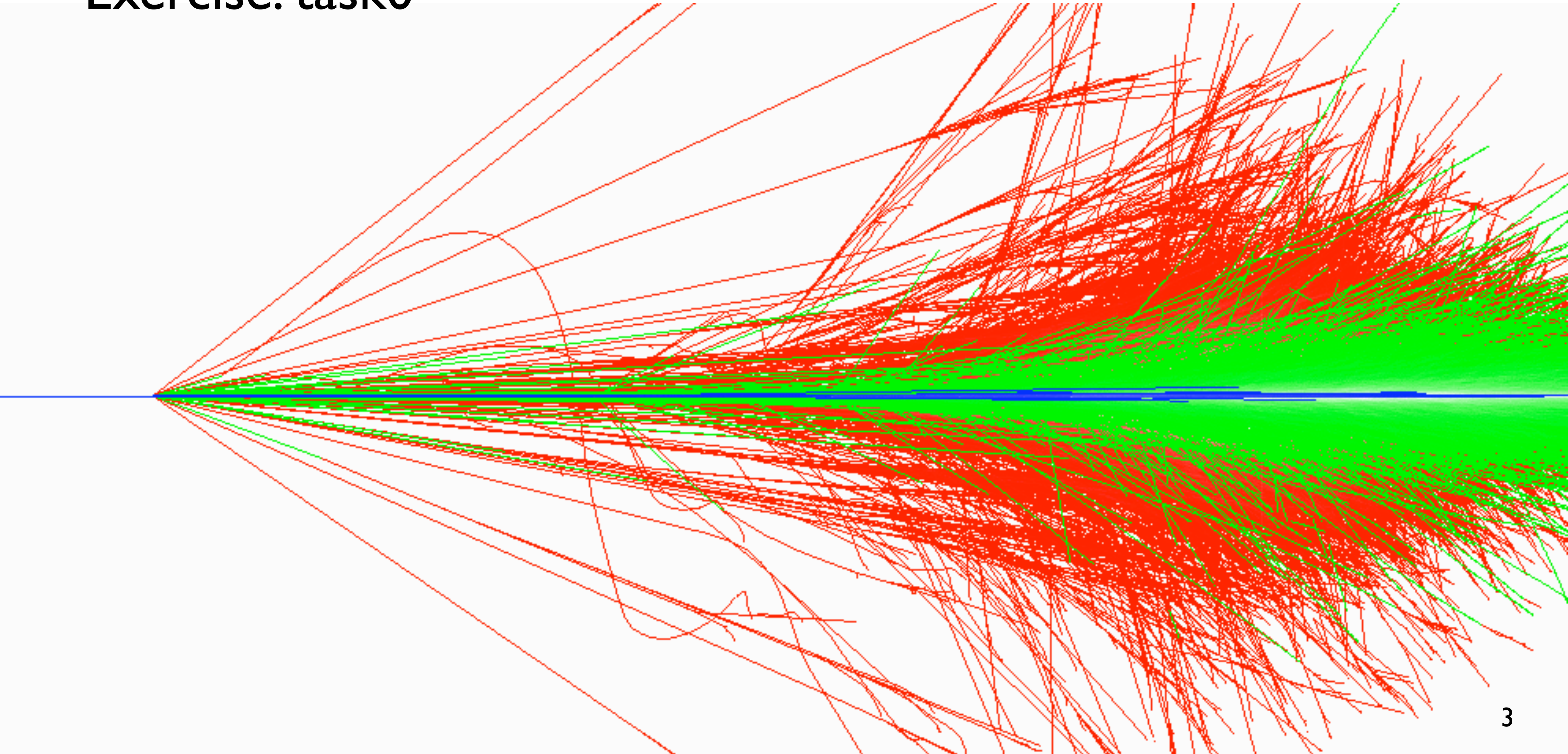
Overview

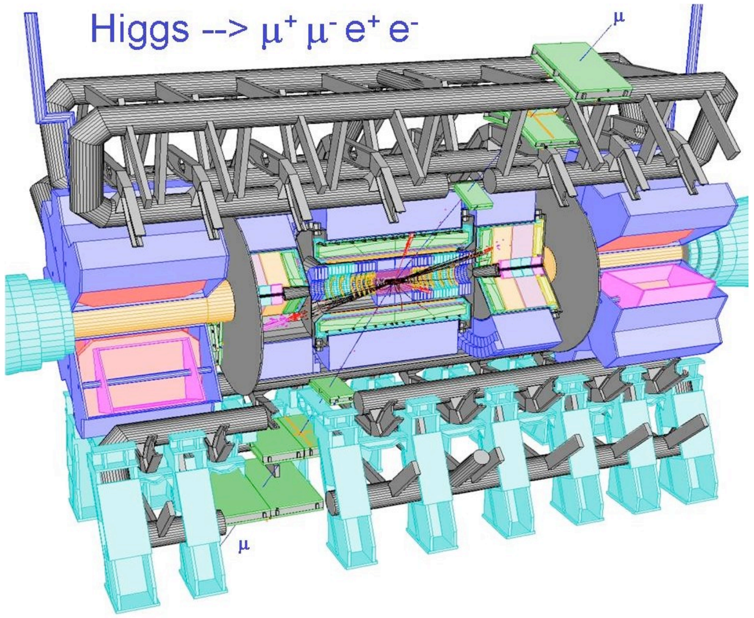
- Introduction
- Geometry and visualization
- Physics processes:
  - Electromagnetic Physics
  - Hadronic Physics and the Physics Lists
- Application Domains:
  - High Energy and Nuclear Physics
  - Medical Physics
  - Space and Satellite Physics
- Future Challenges

Introduction

Exercise: task0



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"

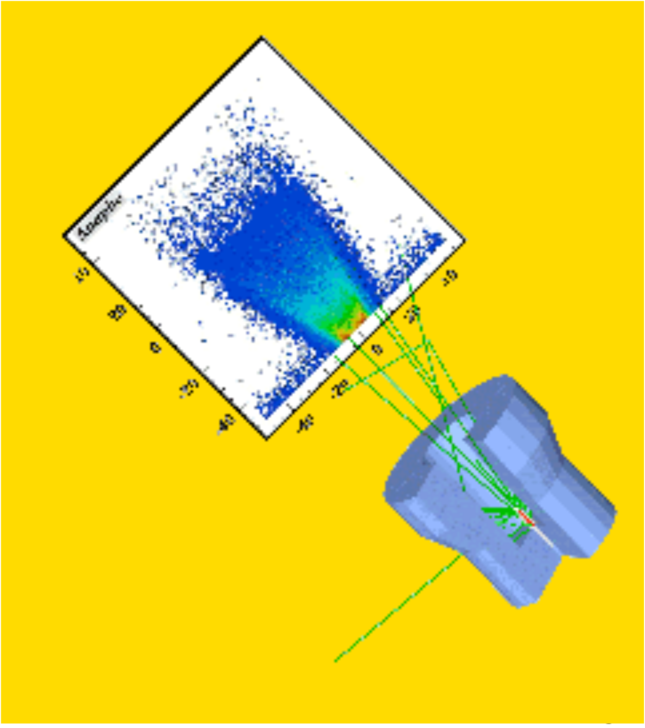
http://www.cern.ch/geant4

Geant4: GEometry ANd Tracking

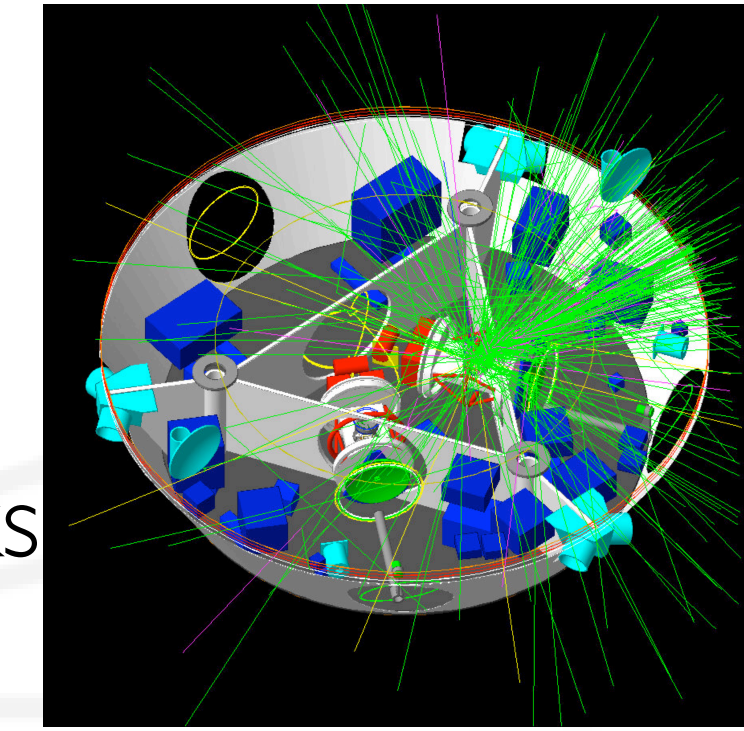
- A toolkit provides "general" tools to undertake (some or all) of the tasks:
  - tracking and geometrical propagation
  - modeling of physics interactions
  - visualization, persistency
- A toolkit enables you to describe your setup:
  - detector geometry
  - radiation source
  - details of sensitive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

Geant4

- Detector simulation tool-kit from HEP
- **full functionality**: geometry, tracking, physics
  - offers alternatives, allows for tailoring
- Software Engineering and OO technology (C++)
- Requirements from:
  - current and future HEP experiments
  - medical and space science applications



Key capabilities

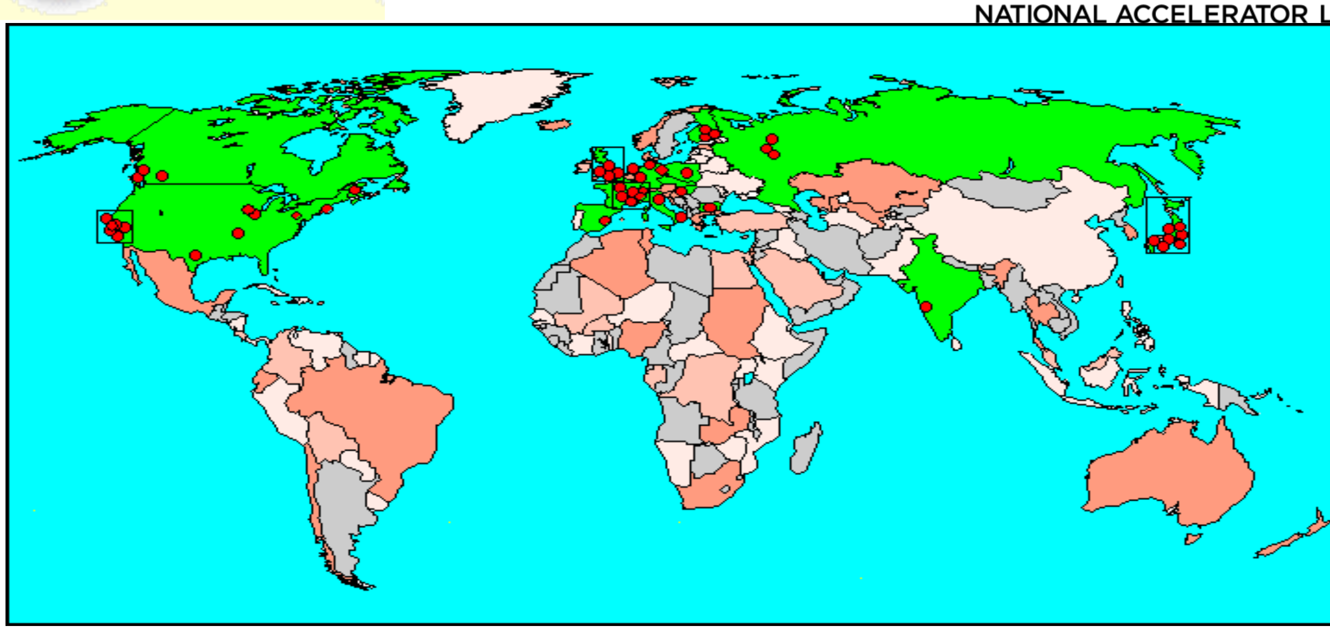


- ‘**Kernel**’: create, manage, move tracks
  - tracking, stacks, geometry, hits, …
  - Extensible, flexible
- **Physics Processes**: cross-section, final-state
  - models for electromagnetic, hadronic, …
  - Can be ‘assembled’ for use in an application area
- Tools for faster simulation
  - ‘Cuts’,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

Worldwide collaboration

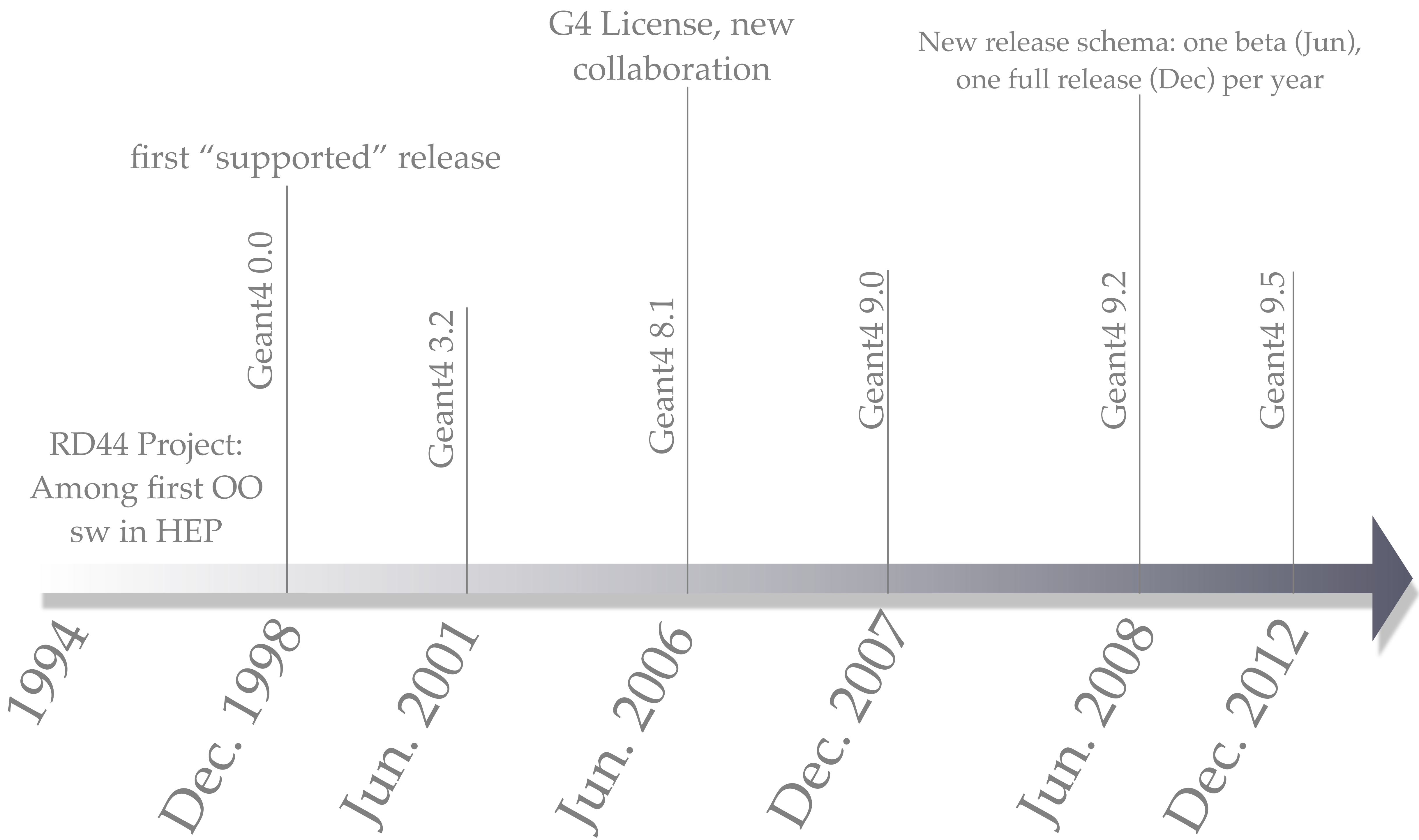
TRIUMF

Lebedev



Collaborators also from non-member institutions, including
IHEP
MEPHI Moscow
Jefferson Laboratory

A bit of history...



Practical Considerations

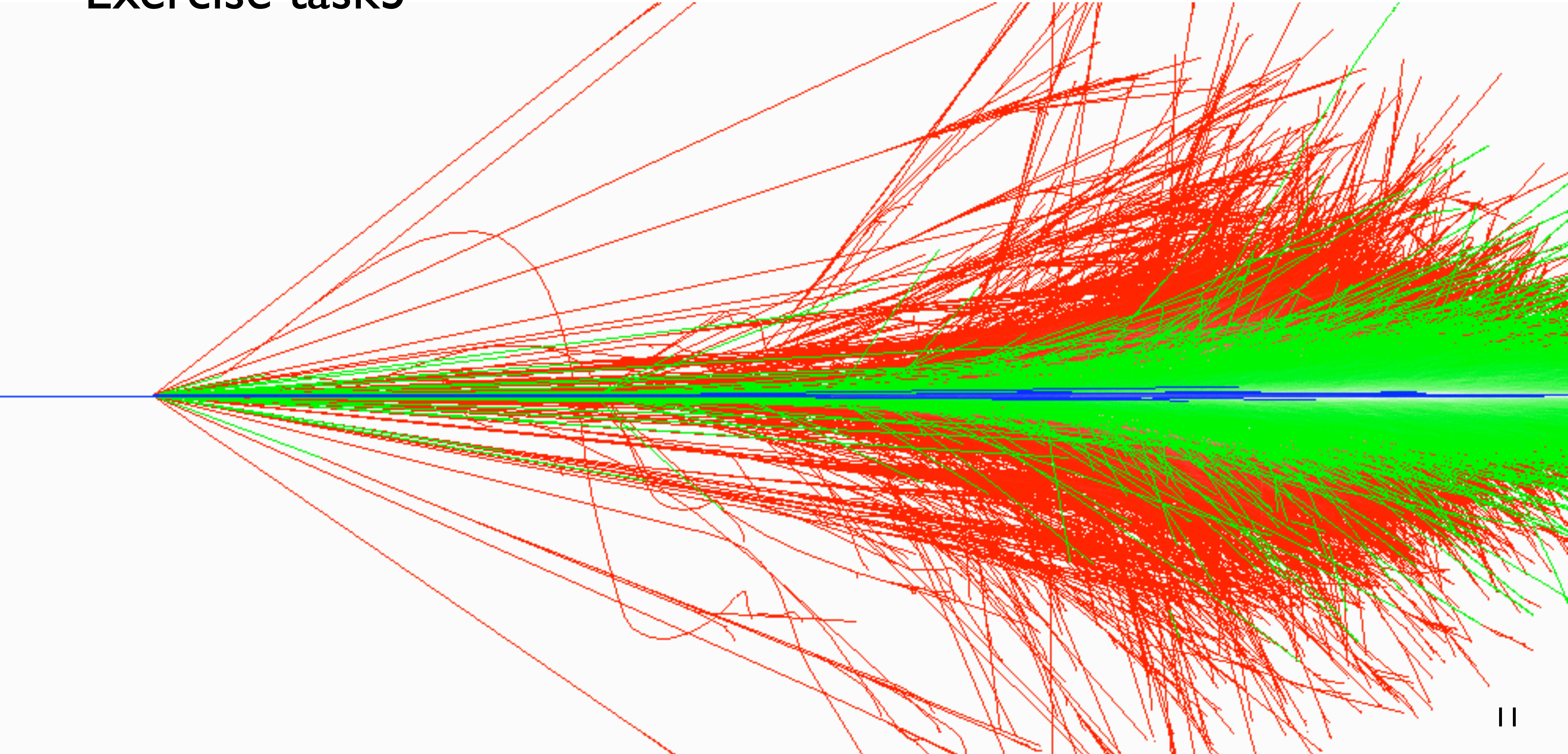
- **Starting: what you need**
  - Compatible platform
  - One or more visualization libraries
- CLHEP is used for key common classes
  - ThreeVector (G4ThreeVector is a name for CLHEP::HepThreeVector)
  - FourVector
  - Random Number Generators,
  - **Starting from version 9.5 (Dec 2011) CLHEP included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

Platforms

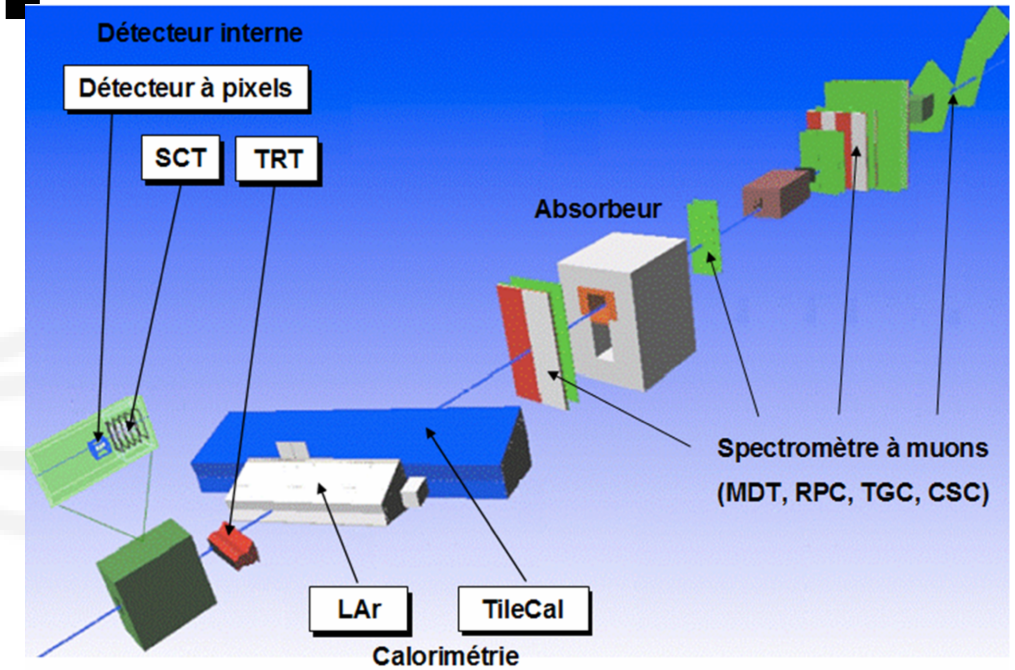
- What works 'best' (used by developers, main testing)
  - Scientific Linux 5 and gcc 4.3 (HEP production)
  - MacOS 10.7
  - Windows 7 (w/ VC++ 10.0)
- What we expect to work
  - Other Linux flavors with gcc 4.1 and 4.3, 4.6, 4.7; icc 12
  - Possibly with fewer options, eg missing some visualization
  - Future will be on Scientific Linux 6 (what you are using now)

Geometry And visualization

Exercise task3



Building G4 Applications



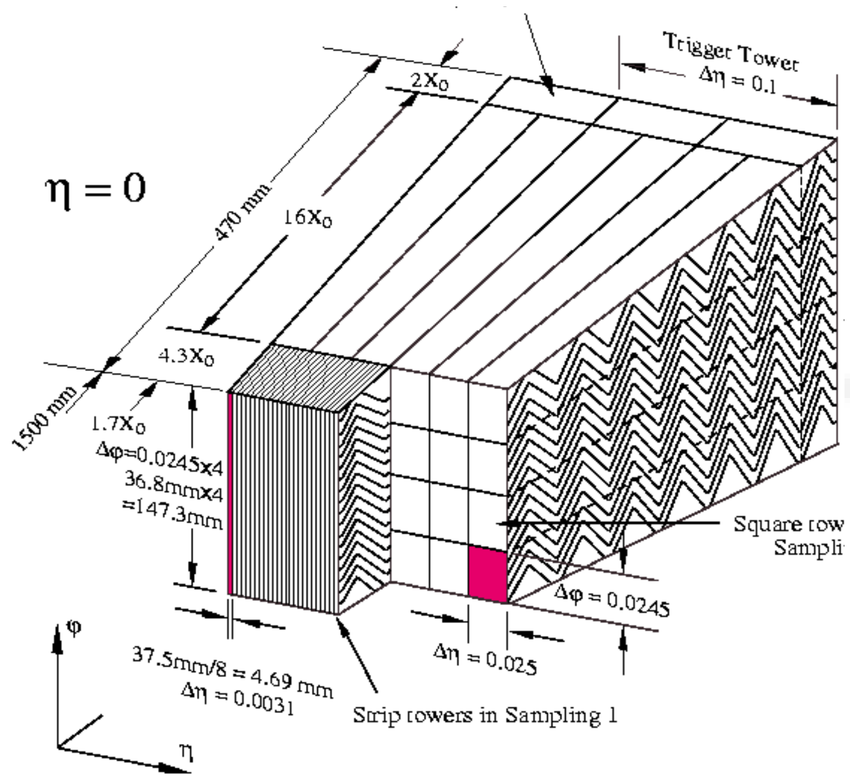
ATLAS Test-beam setup 2004

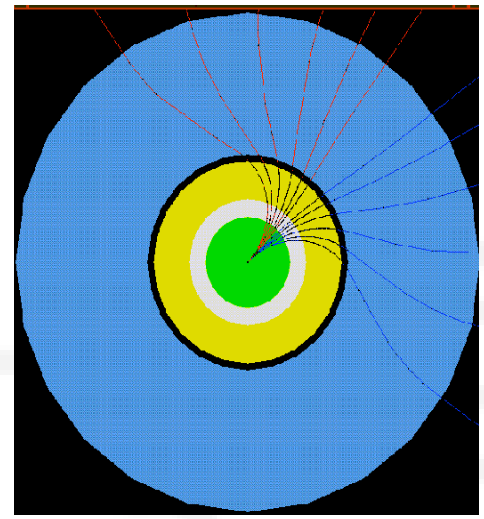
- How do you create a Geant4 simulation ?
  - Get a ready-made application, or
  - Modify a similar, existing, application, or
  - Piece together a custom application

- What are the key steps for creating an application
  - **Describing the setup**: geometry, material, ..
  - Description of the primaries
  - **Choosing the physics to use**
  - Designating the "sensitive" volumes
  - And collecting physics observables

Often the more "coding" intensive steps: build your own detector/device

geometry: what G4 does

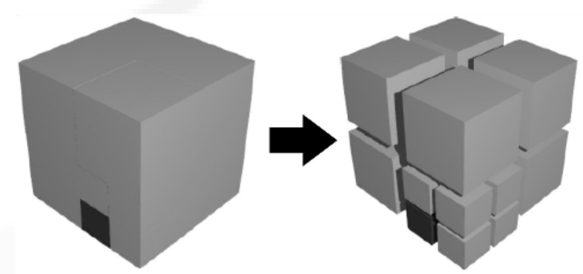




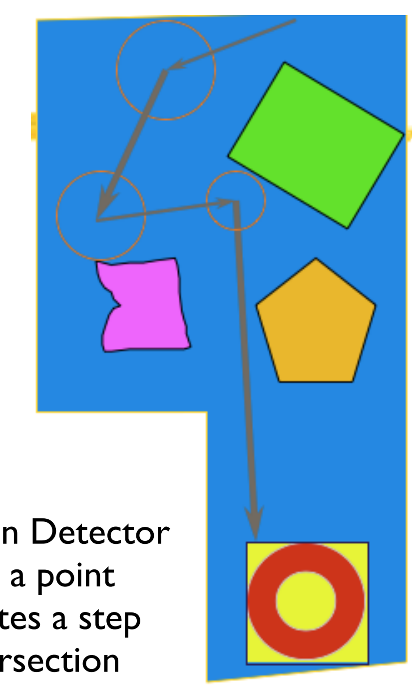
All charged particles ‘feel’ the effect of **EM fields**

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



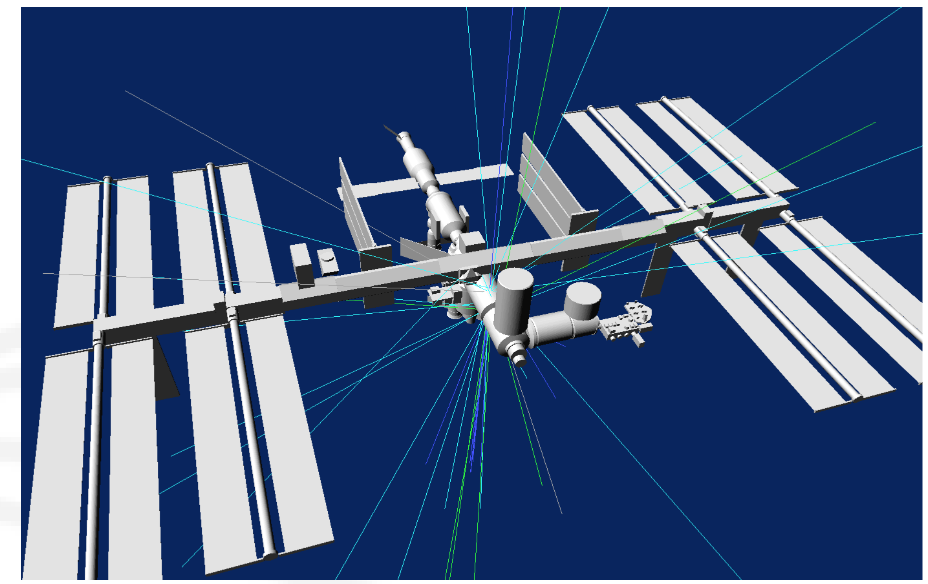
Automatic optimization of complex geometries (voxelization): **efficient tracking**



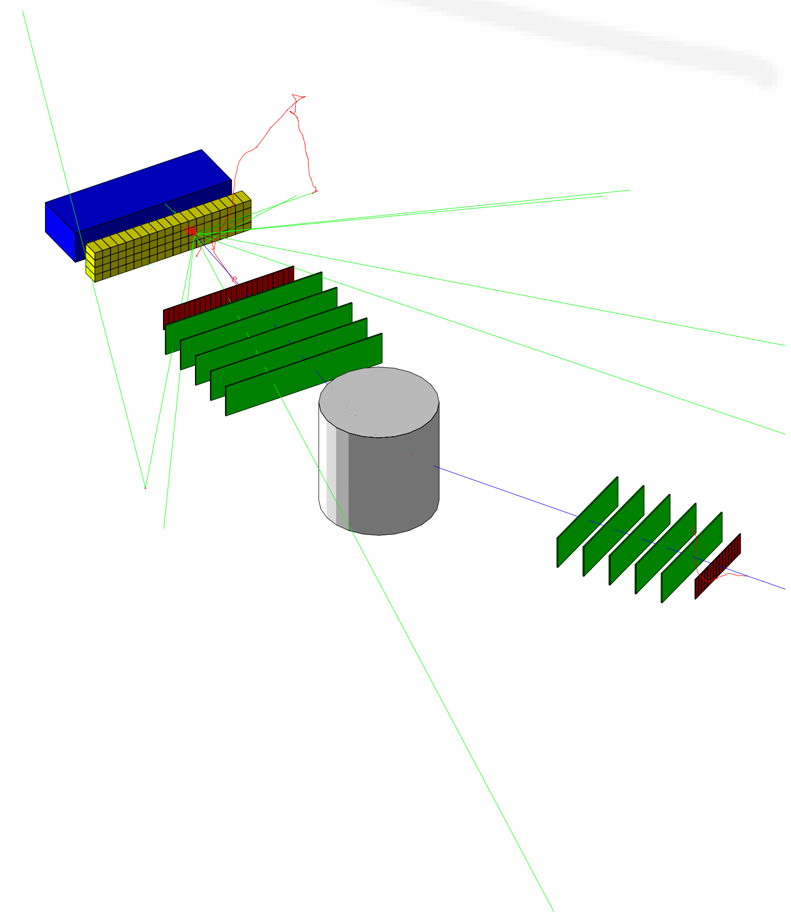
Navigates in Detector
☑ Locates a point
☑ Computes a step
Linear intersection

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**)



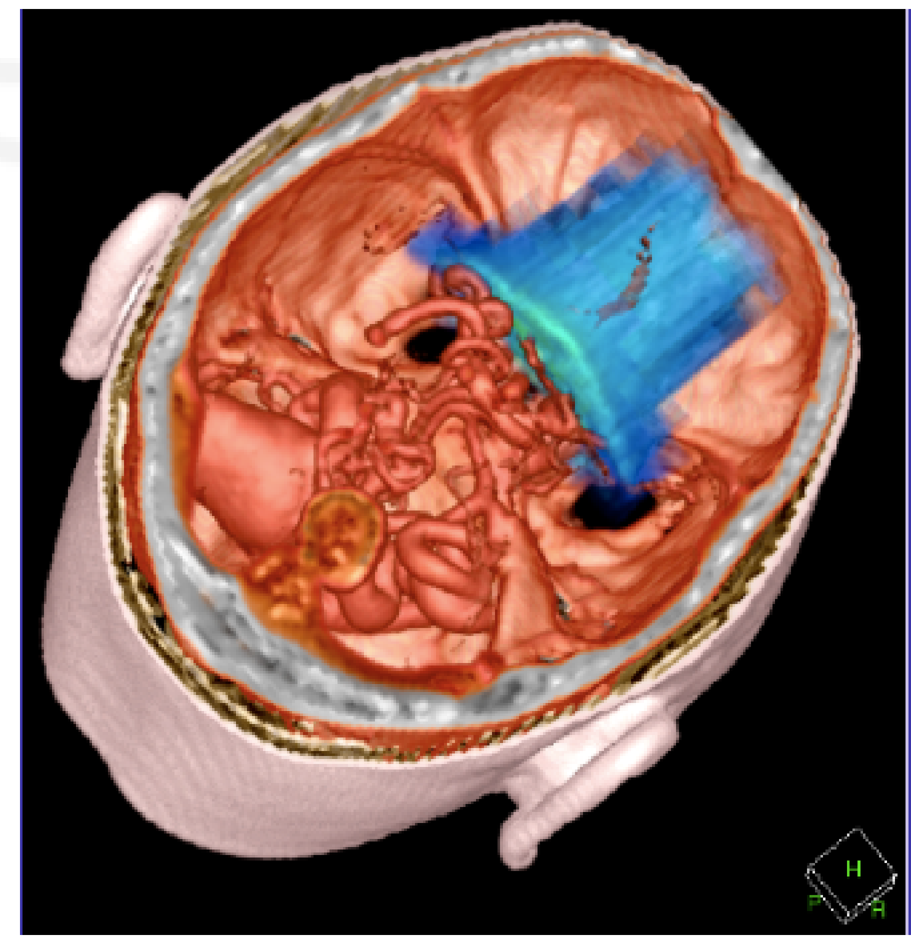
OpenGL driver



DAWN driver

An advanced Tool: gMocren

- From 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 will likely happen soon
  - Based on a commercial package but offered freely to all Geant4 users
- http://geant4.kek.jp/gMocren



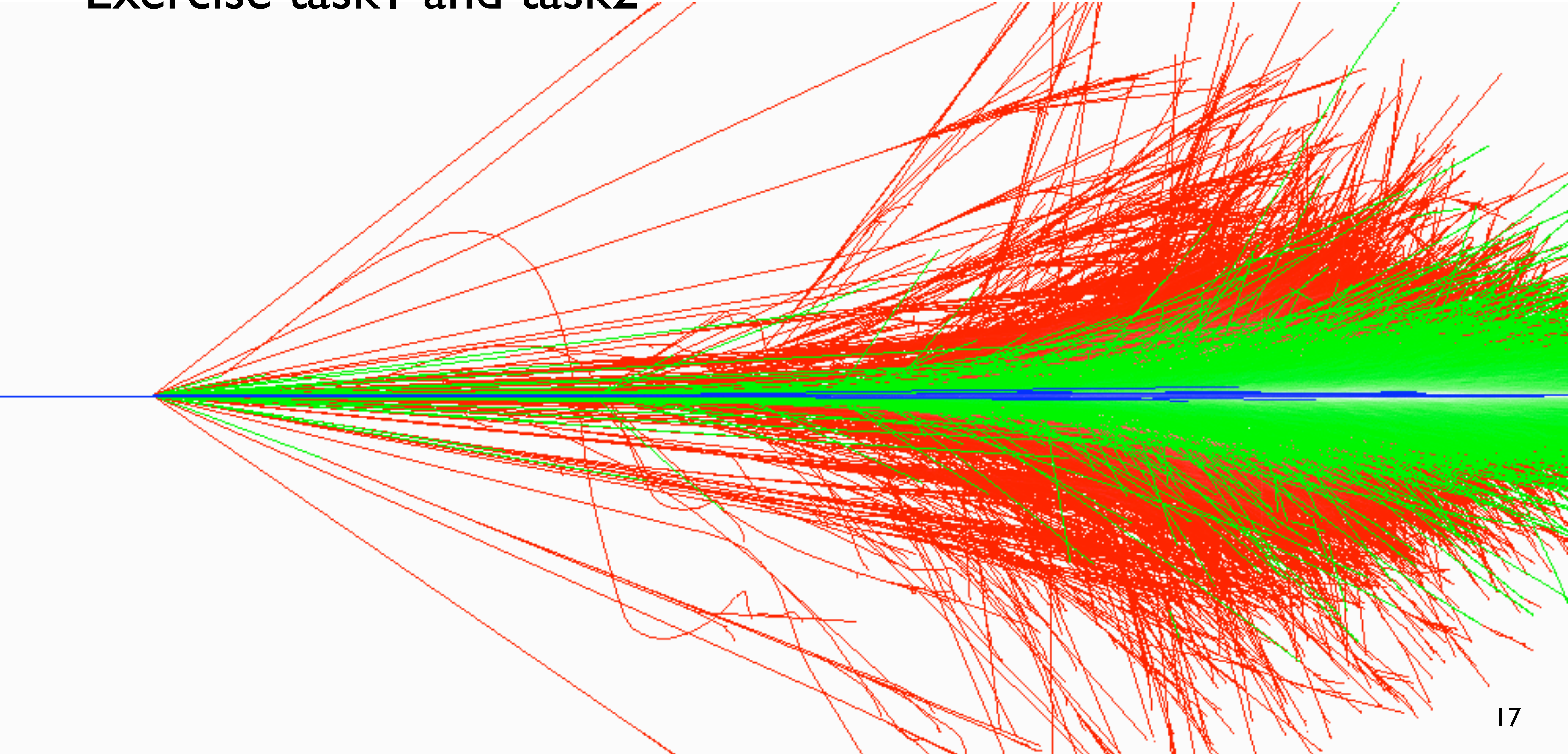
Building the geometry

- Done in three steps

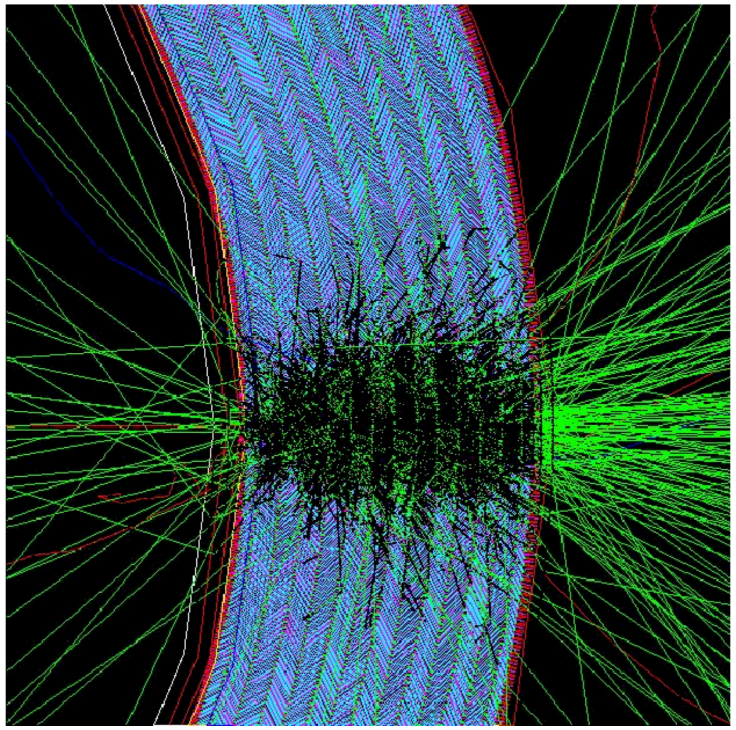
1. Define the **solid volume** (i.e. its shape: a box, a cylinder, etc)
   - Possibilities to read geometry from external files exists (GDML format)
2. Define a **logical volume** (i.e. associate to the solid volume a material)
3. Define a **physical volume** (i.e. where in space the piece of detector goes: define a rotation and translation
   - Geant4 defines hierarchy: start from **world** place one or more **phys volume(s)** inside the world, build a tree
   - Geometry is defined by **mother-daughter** relationship

EM Physics

Exercise task1 and task2

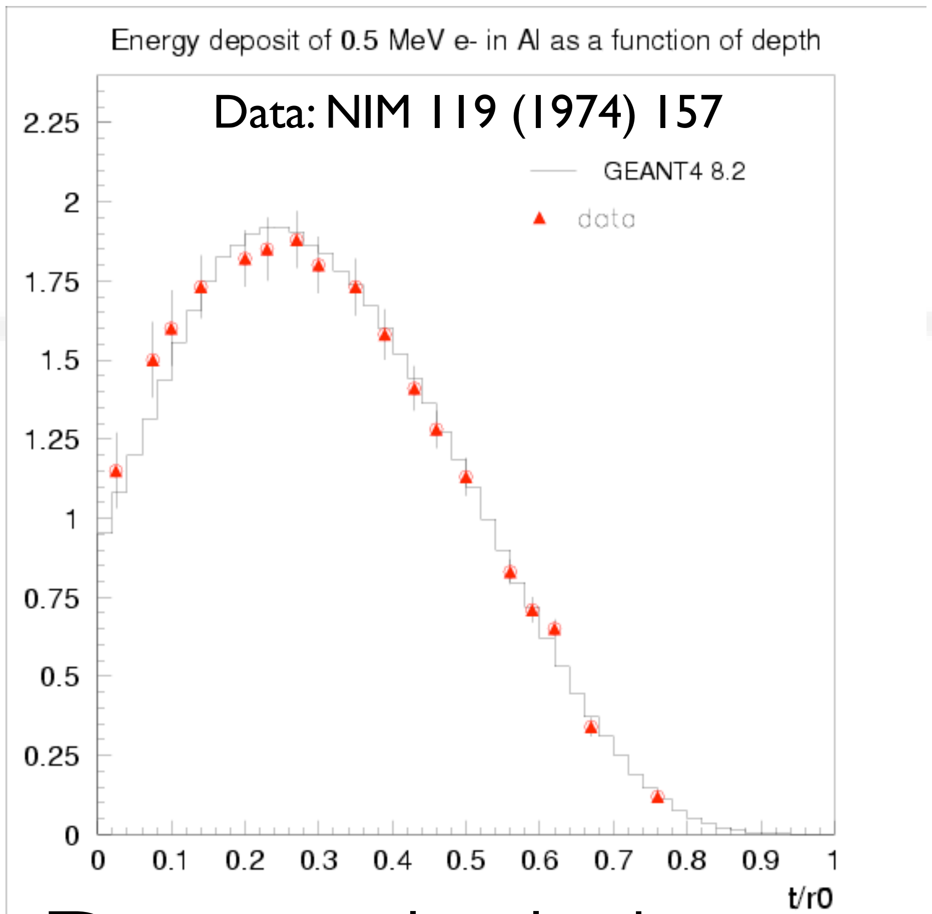


Processes

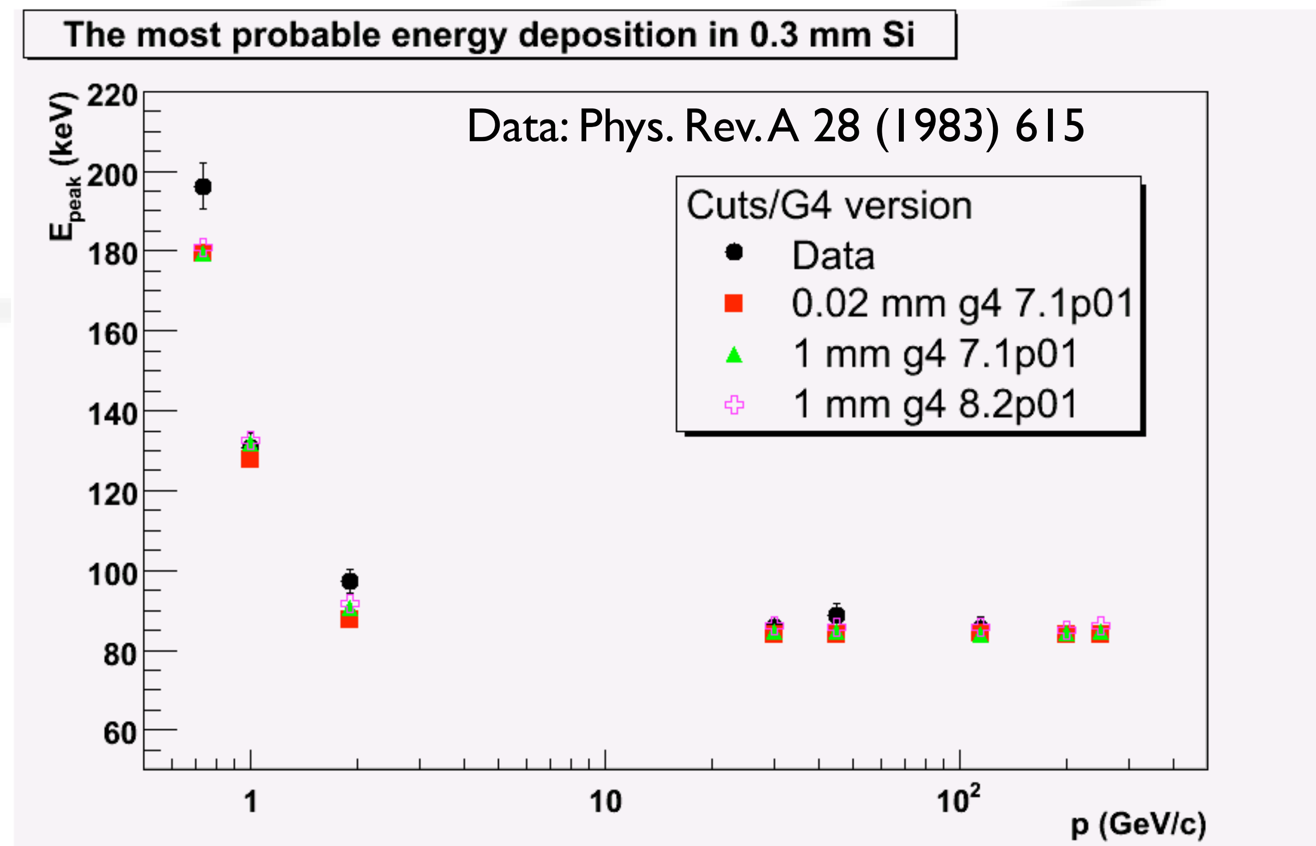


- **Gammas**:
  - Gamma-conversion, Compton scattering, Photo-electric effect
- **Leptons(e, μ), charged hadrons, ions**
  - Energy loss (Ionisation, Bremsstrahlung), Multiple scattering, Transition radiation, Synchrotron radiation, e+ annihilation.
- **Photons:**
  - Cherenkov, Rayleigh, Reflection, 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



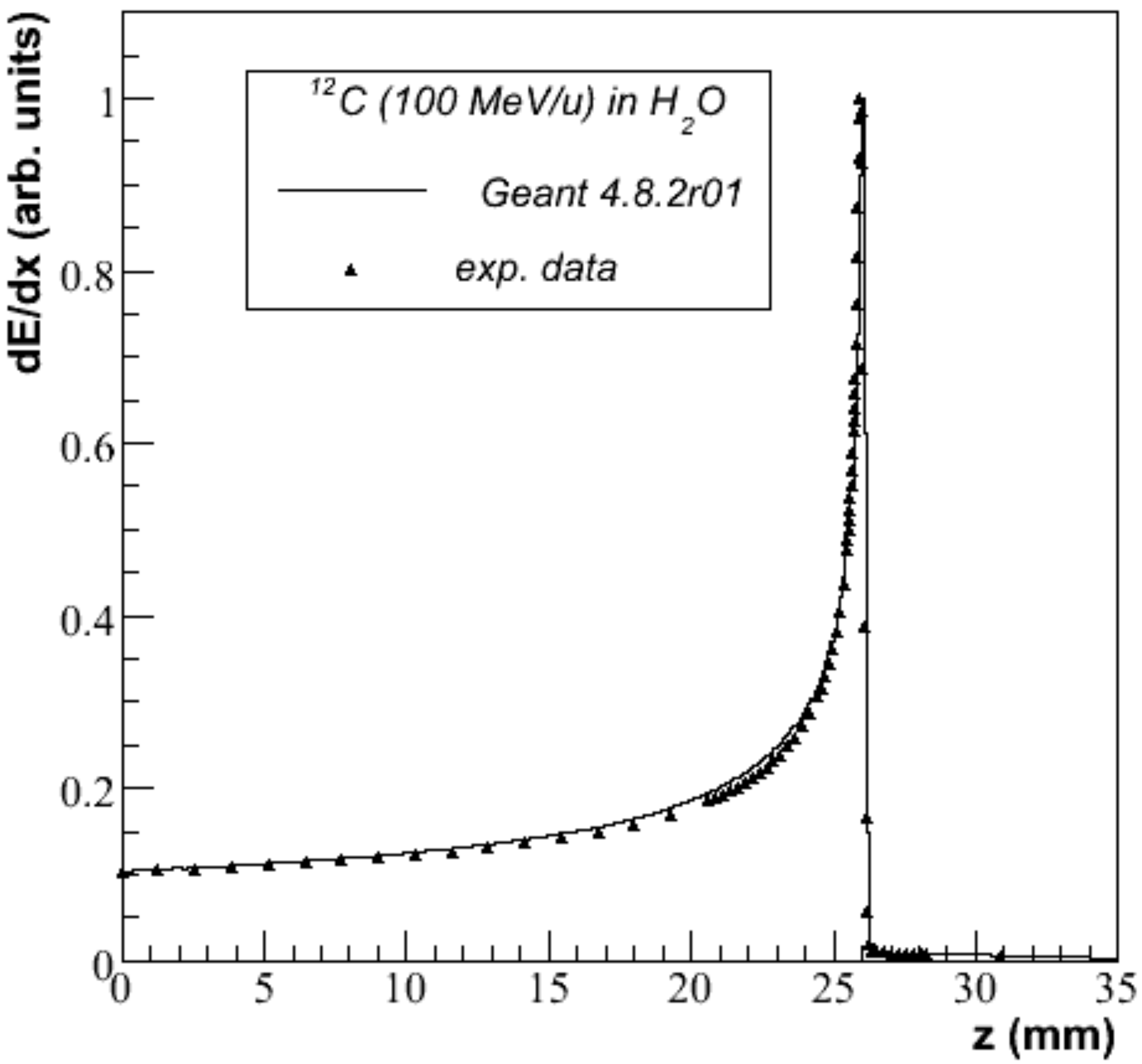
Dose calculation



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

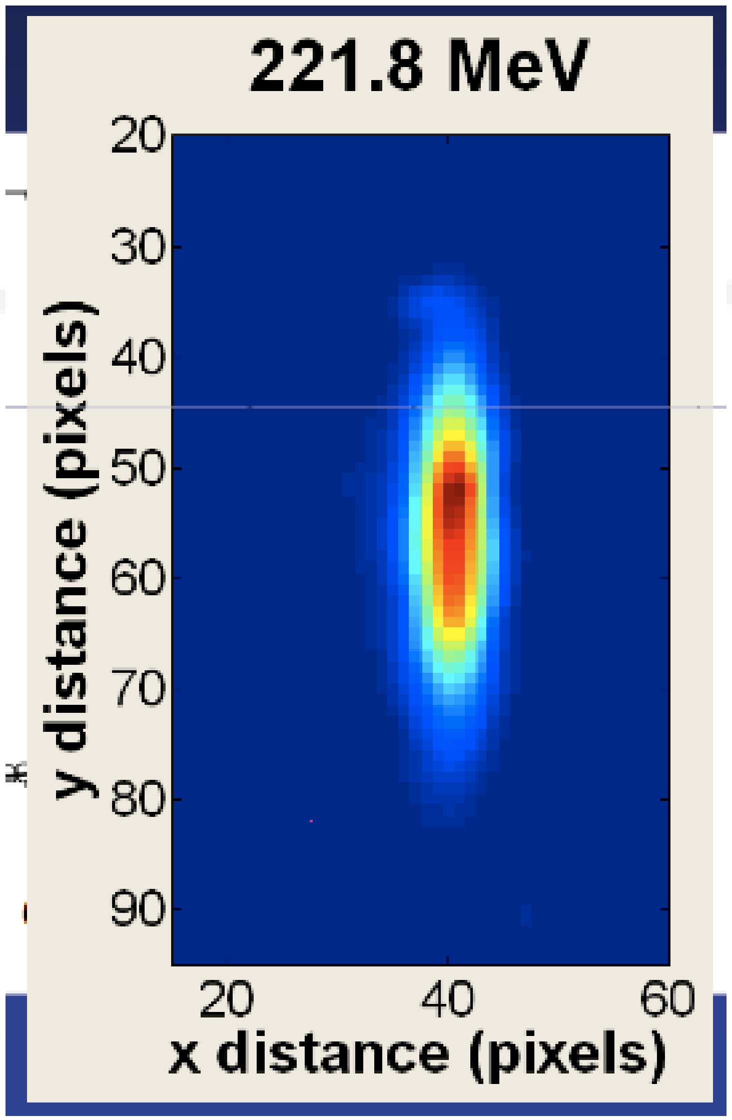


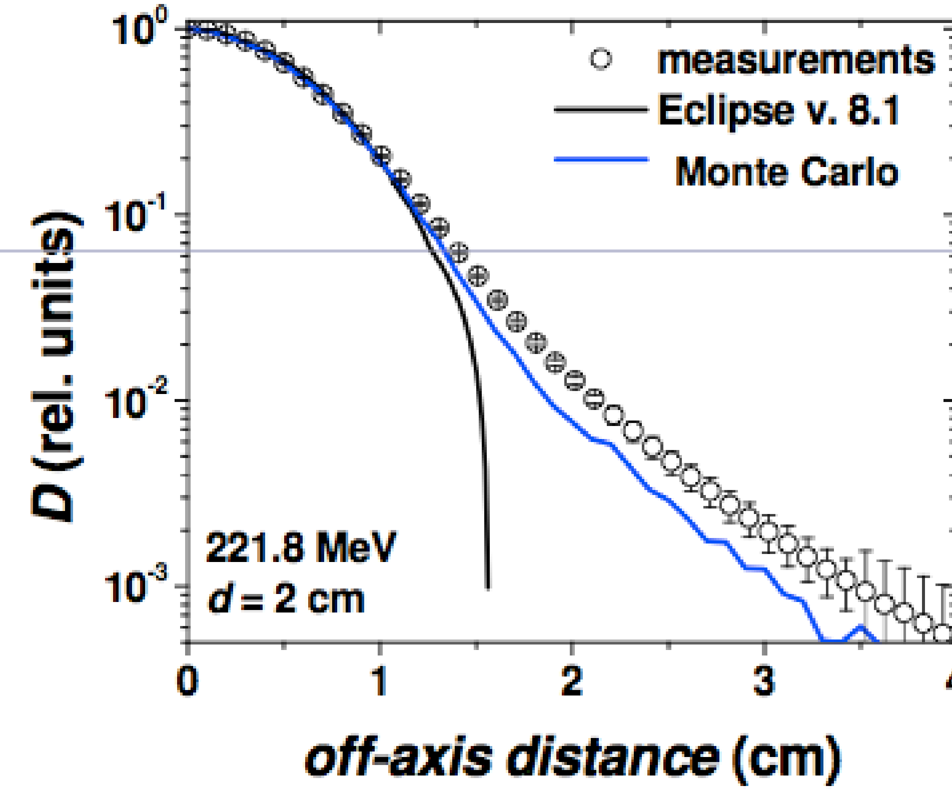
Bragg Peak in water for a 100MeV/u ^{12}C beam

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

But...

Challenges: An example from Medical Physics



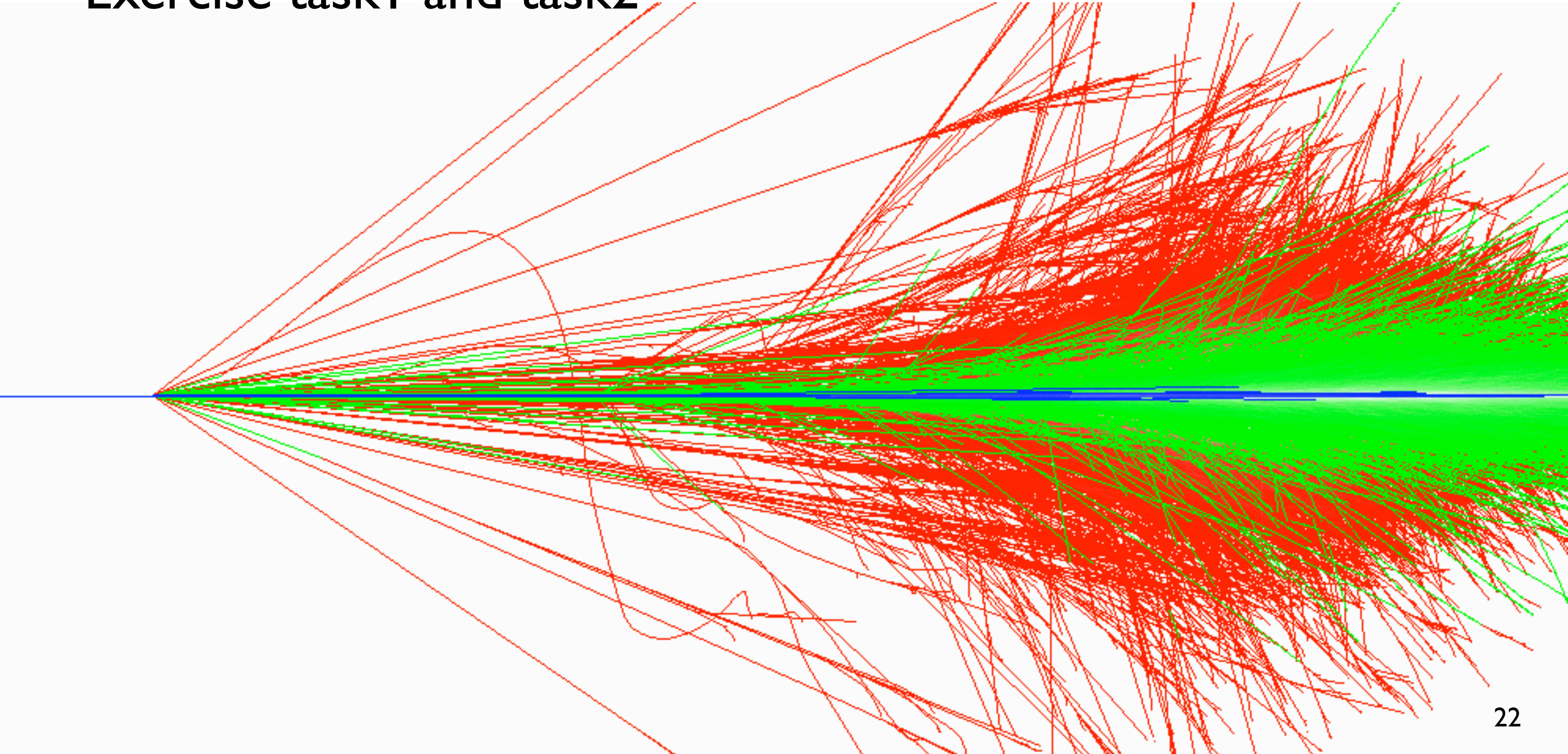


Use a beam for patient treatment:
send thousands/millions of particles (protons, C)

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

Hadronic Physics

Exercise task1 and task2



Processes

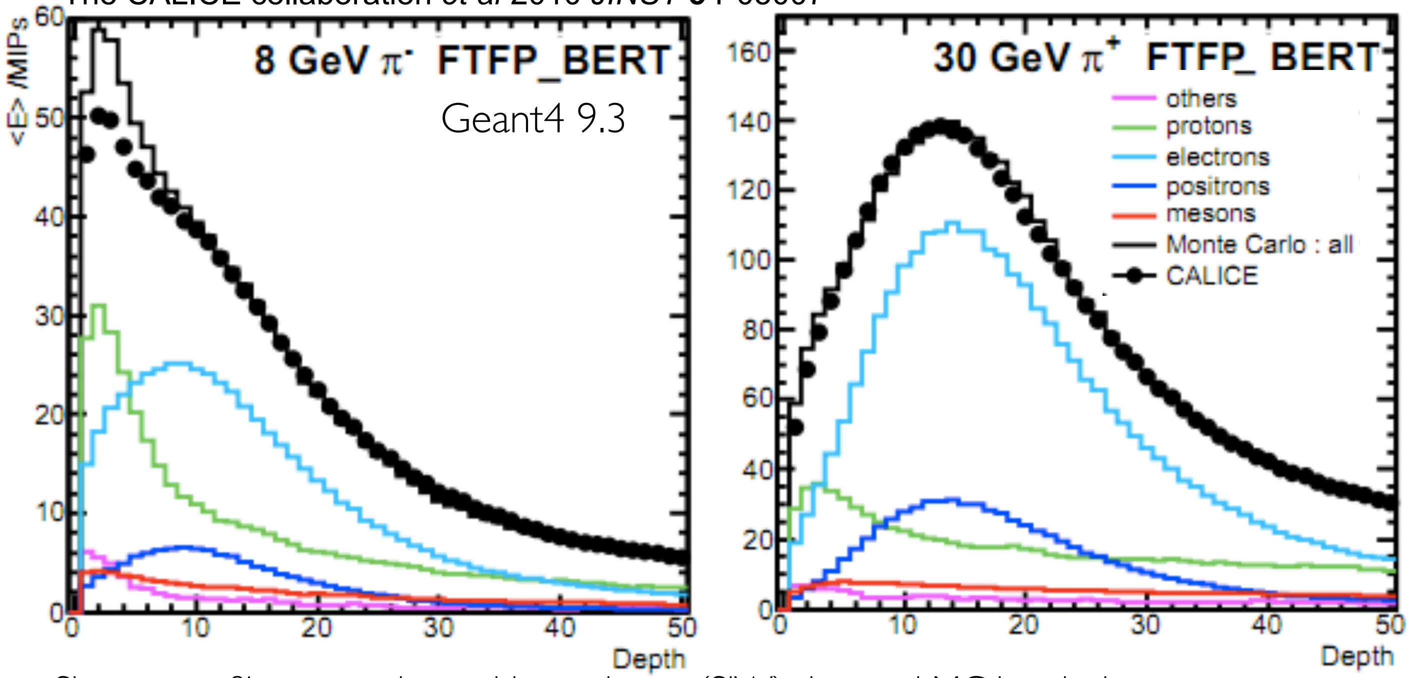
- Hadronic physics is included in Geant4
  - a powerful and **flexible framework** and
  - implementations of **cross-sections & models**.
- **A variety of models and cross-sections**
  - for each energy regime, particle type, material
  - alternatives with different strengths and computing resource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

Models Summary

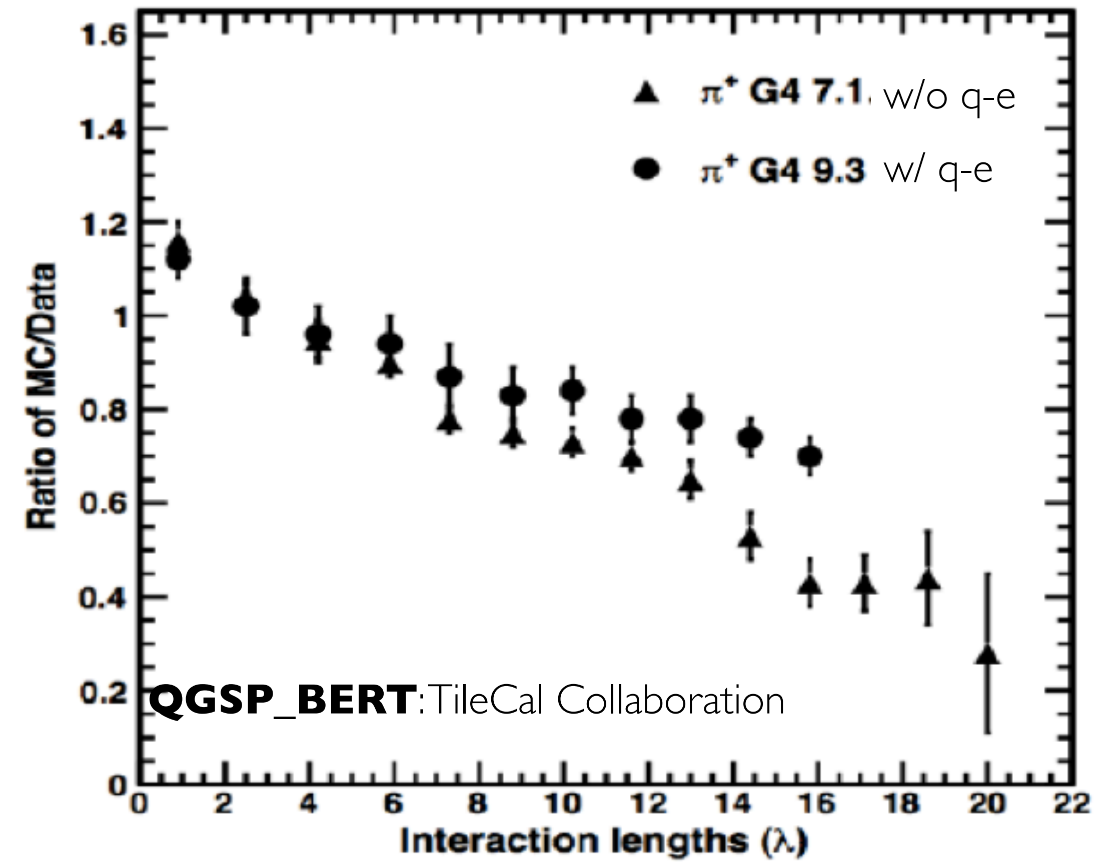
- **Parameterized models** (1997): all E and particles - data driven
- Fritjof, **"FTF"** (new developments): p,n,k,π of high energy (E_{kin}>10 GeV) **Nucl. Phys. 281 289 (1987)**
- Quark-Gluon-String, **"QGS"**: p,n,k,π of high energy (E_{kin}>20 GeV) **See Sec. IV, Chap. 22 of Geant4 Physics Reference 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. 25 of Geant4 Physics Reference Manual and bibliography within**

Longitudinal Shower Shape

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



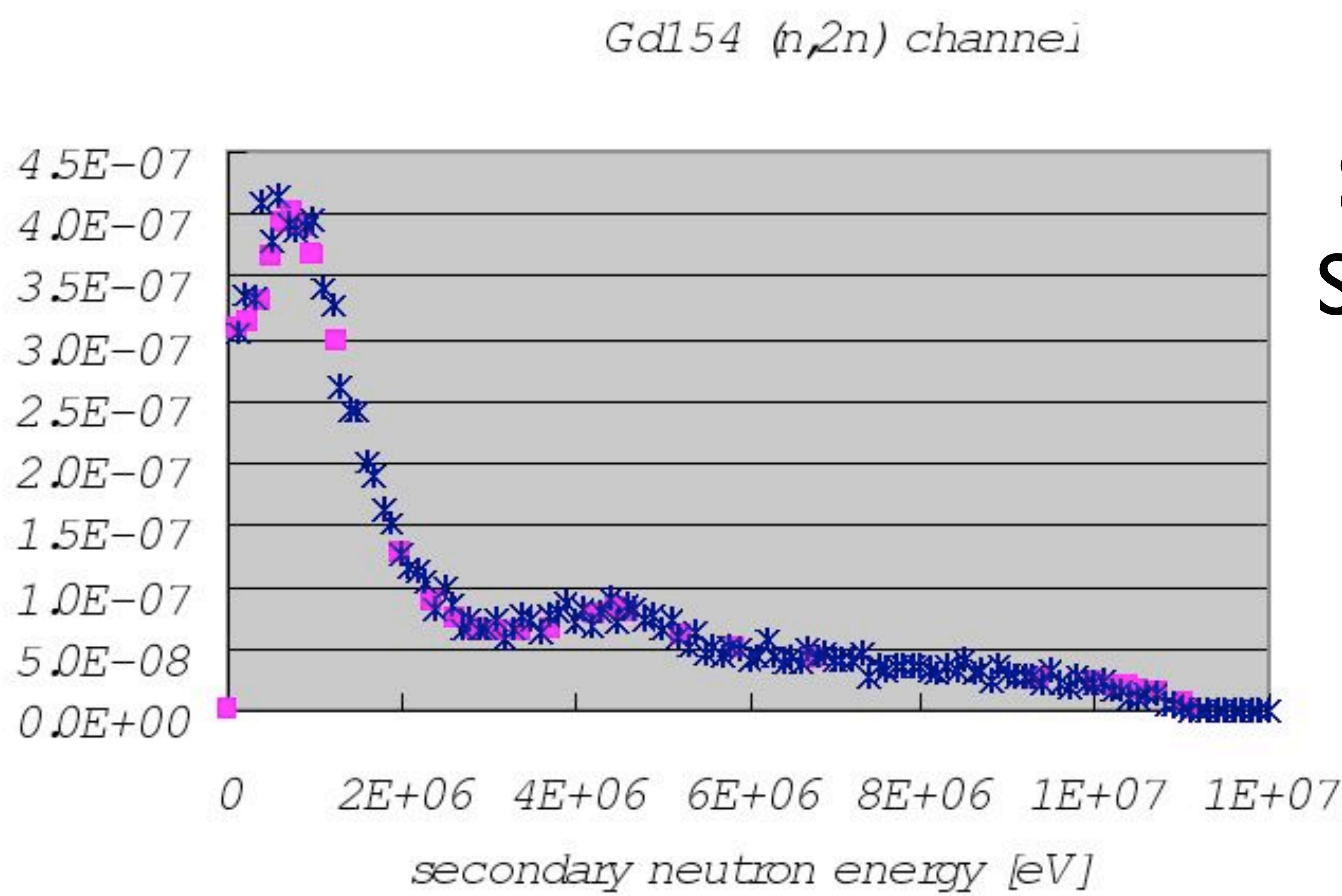
Shower profile: comparison with test-beam (SiW) data and MC break-down



- 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

Thermal neutrons

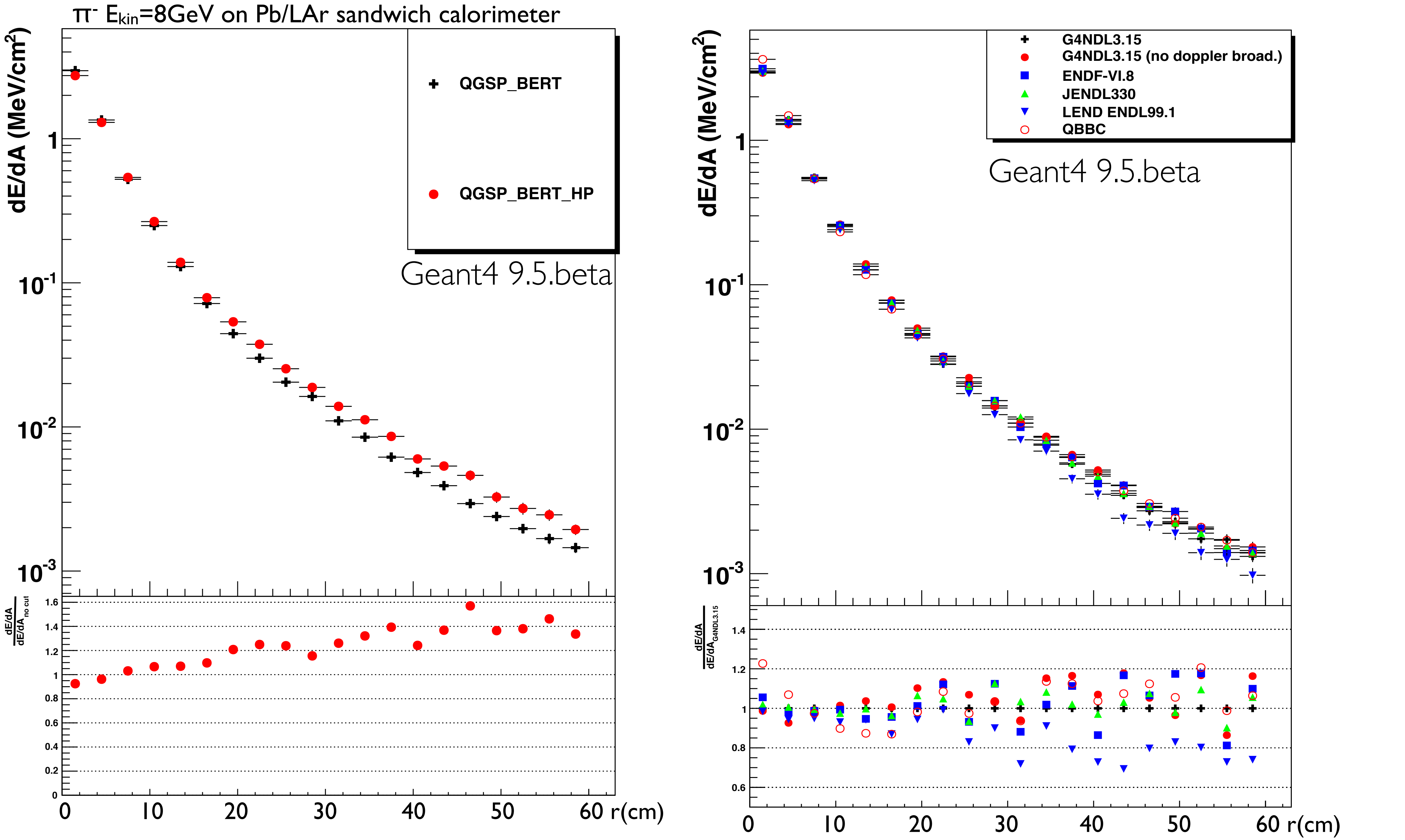
HP (High Precision) extension is needed when interested in thermal neutrons. Expect up to x10 slower simulation!



Squares: NDF data
Stars: G4 HP Model

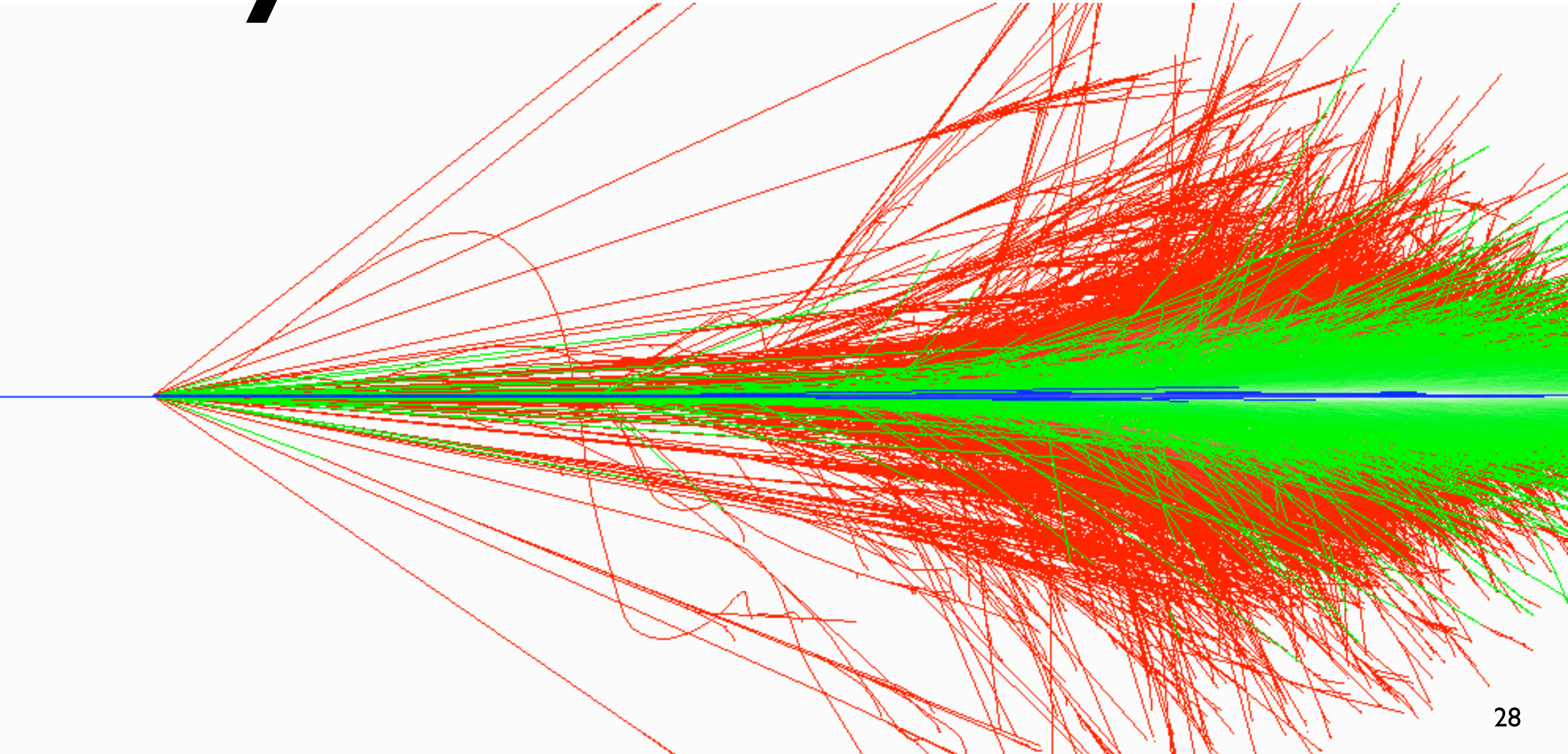
Warning: this is a little bit a tautology, since HP is based on NDF data....

Role of neutrons: example



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

Physics Lists



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
  - Since Geant4 9.5 simple to select variants of a physics list:
    - e.g. FTP_BERT_XX
    - XX∈{EMX,EMY, EMX, LIV, PEN, HP}

How well Geant4 performs

Based on LHC feedback: π beams

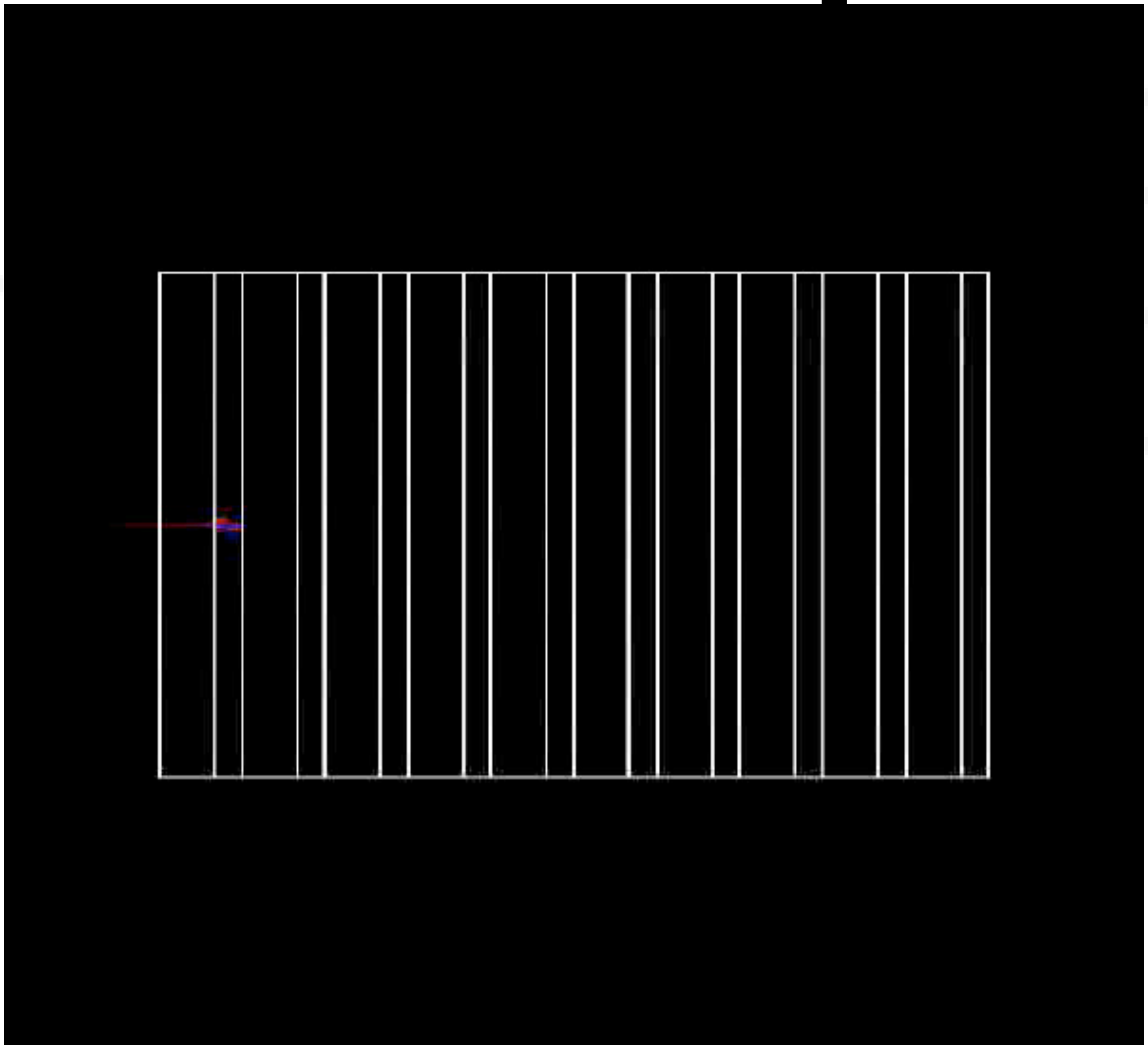
	Response	**Resolution**	**Smoothness**	**Lateral Shape**	**Longitudinal Shape @10λ**	**Peculiarities, comments**
QGSP_BERT	+(1-3)%	-(5-10)%	Δ~5%@10GeV	π,p: -(10-20)%	π: -10% p: -20%	Extensive use of LHEP
FTFP_BERT **QGSP_FTFP_BERT**	**+(0-5)%** **(***)**	**-(3-7)%**	**Δ~0**	**π: -(10-20)%** **p: -(3-10)%**	**π: +10%** **p: +(10-20)%**	**anti-nucleons, hyperons via CHIPS(*), no LHEP**
CHIPS	+(5-10)%	-(10-20)%	Δ~0	π: -(3-10)% p: -(10-20)%	π: -10% p: -20%	anti-nucleons, hyperons, single model
FTF_BIC(**)	+(3-5)%	-(2-6)%	Several irregularities	-	π: +10%	Implements re-scattering at high E, Extensive use of LHEP

(*): Native FTF model under testing

(**): Much less tested at LHC

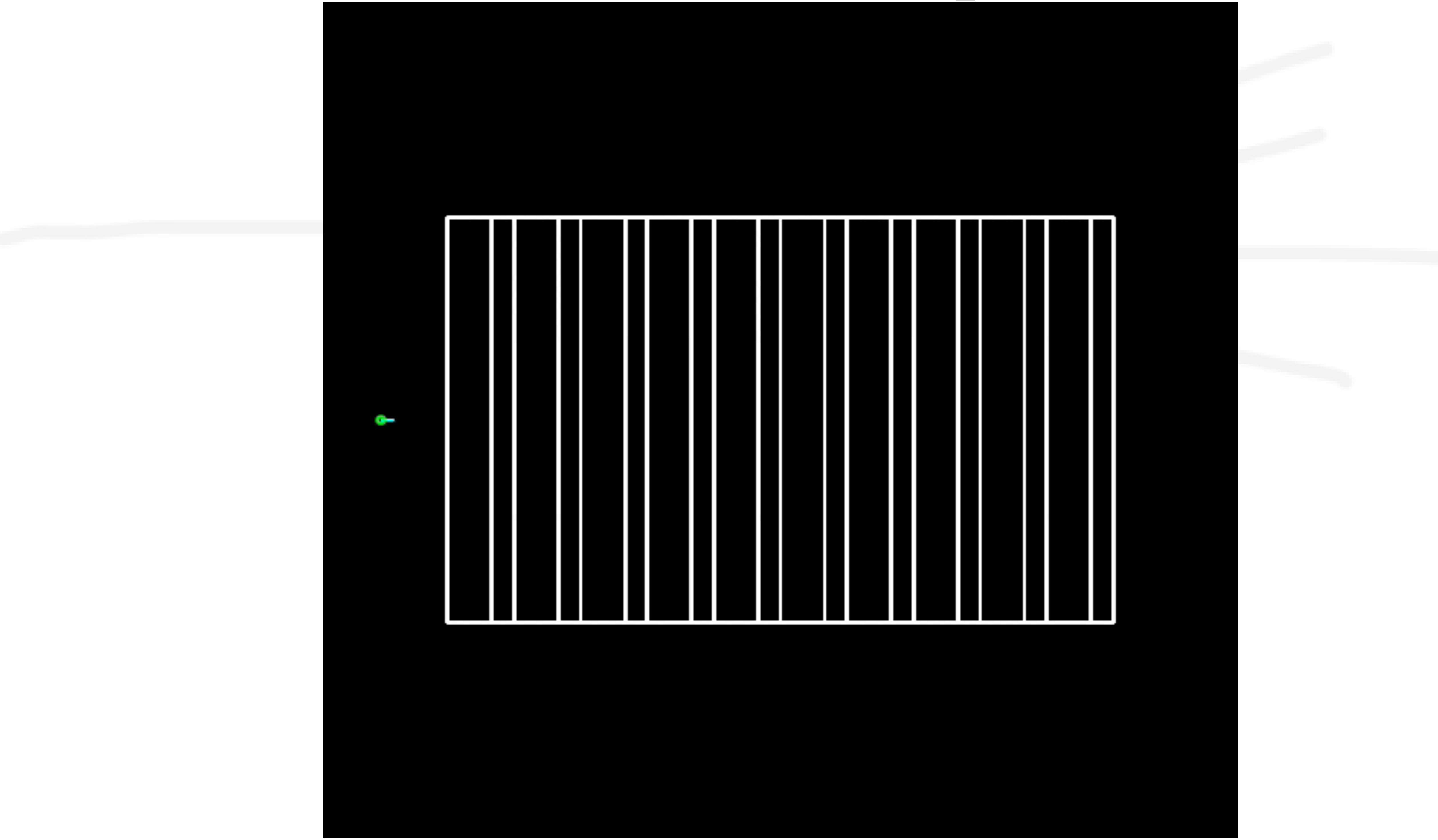
(***): Lower limit: CMS; Upper limit ATLAS

Concrete Example: EM



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

Concrete example: HAD

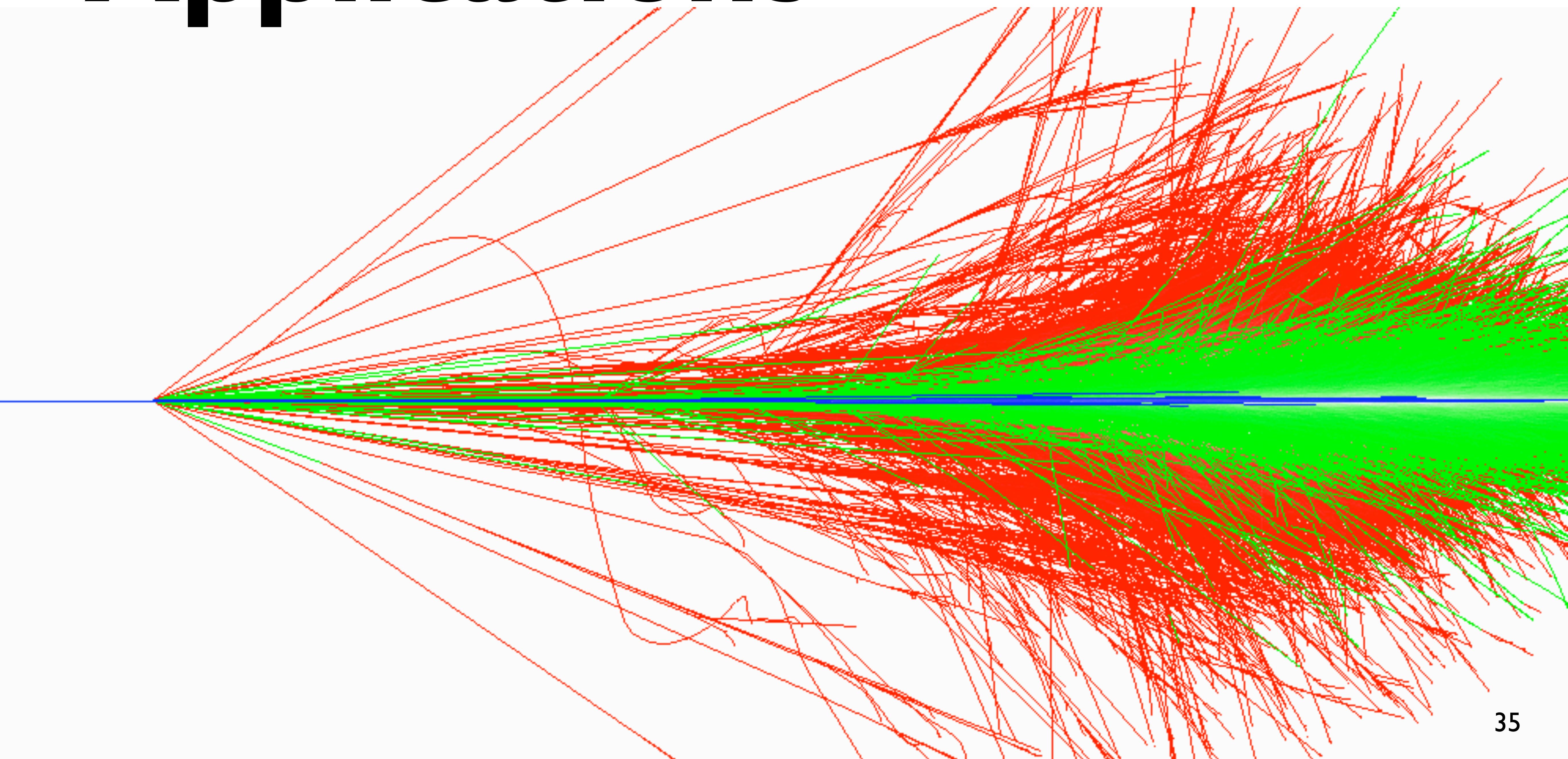


More examples at: http://www.hep.man.ac.uk/u/johna/pub/Geant4/Movies

A concrete Example: what you have seen

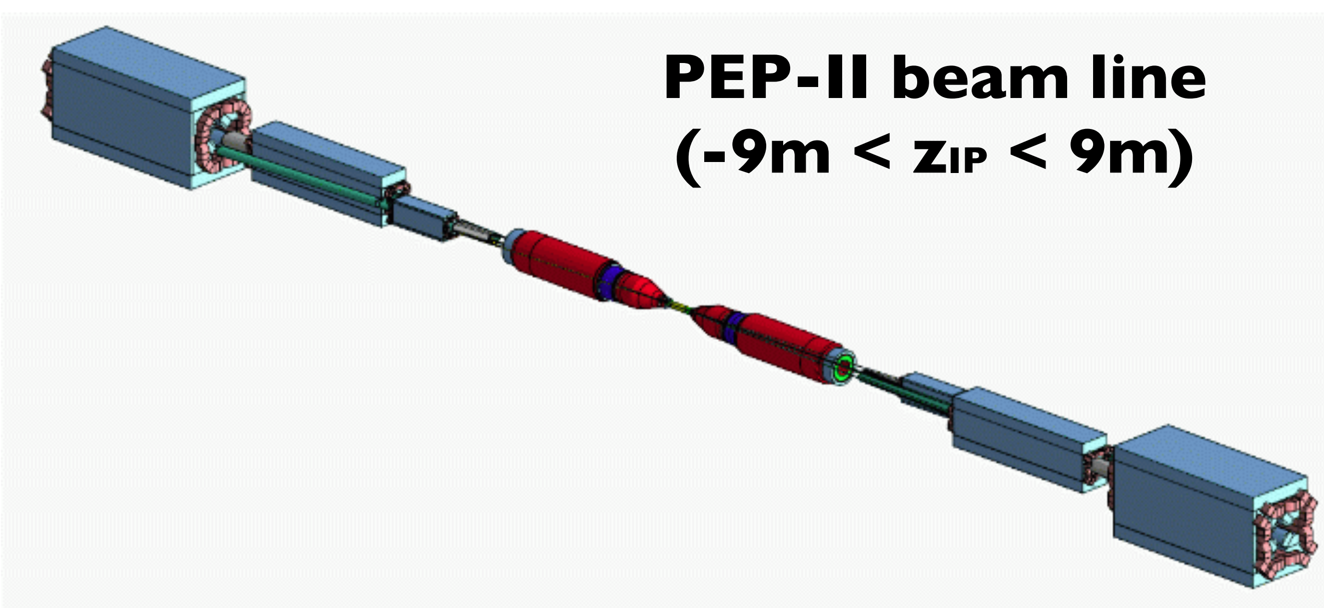
- 10 GeV/c pi- on lead (in a lead-liquid-argon calorimeter, exampleN03 with QGSP physics)
- A plethora of slow pions, protons and neutrons
  - Three fast pi- and one fast pi+ that subsequently interacts again
  - Neutrons (yellow) hang around for several ns
- Green circle is expanding at the speed of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

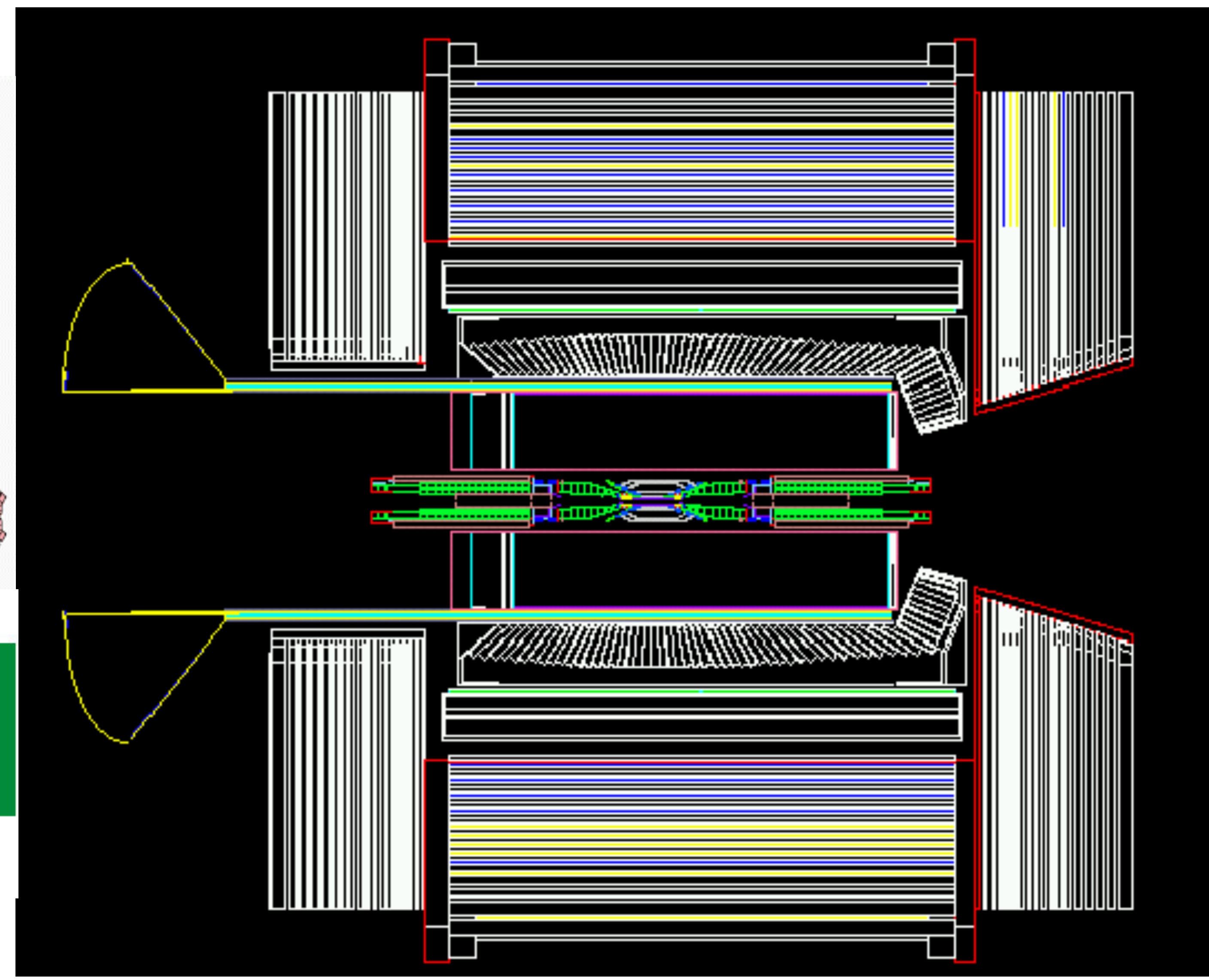
Applications



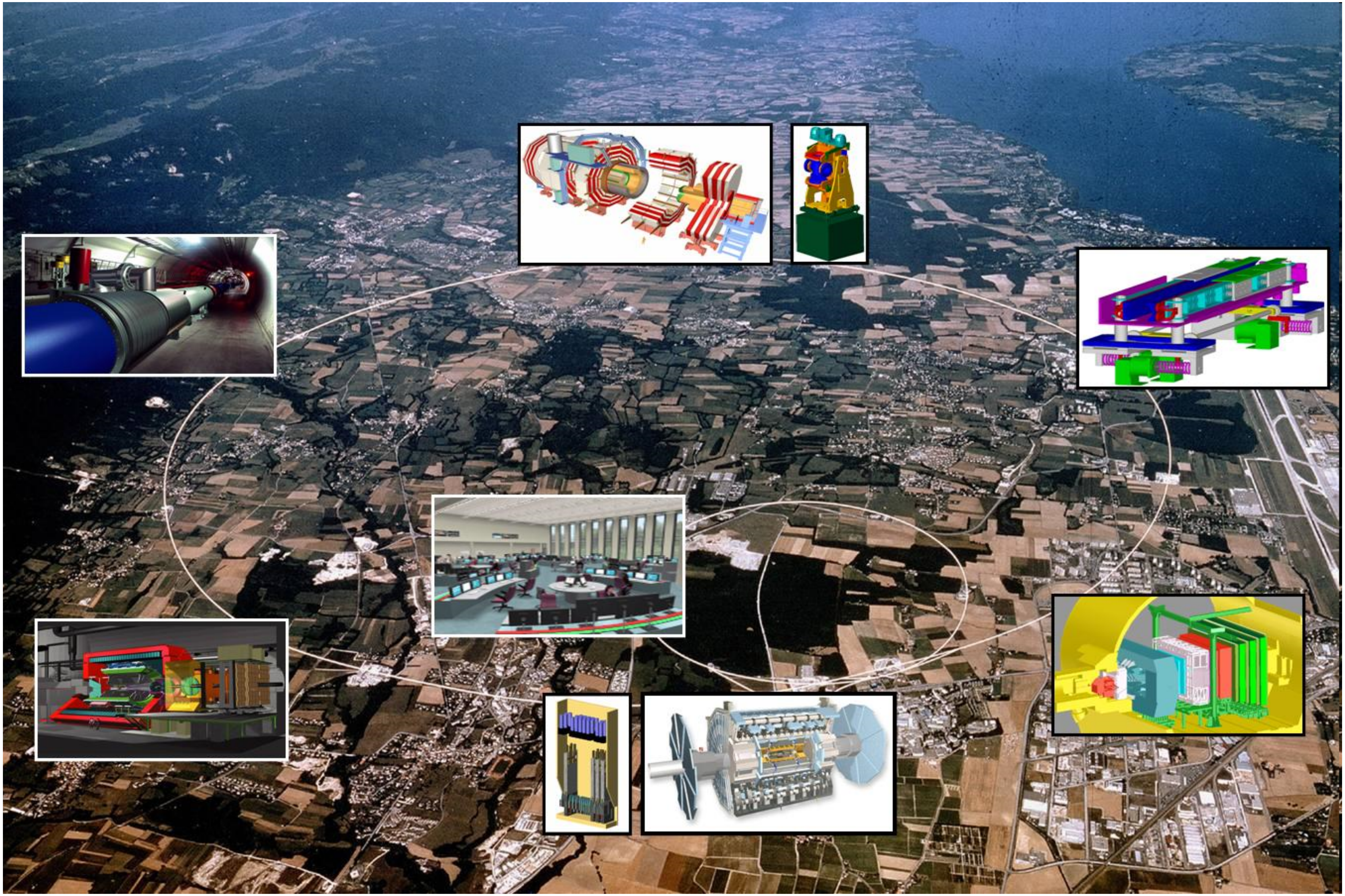
BaBar and Geant4

- 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.

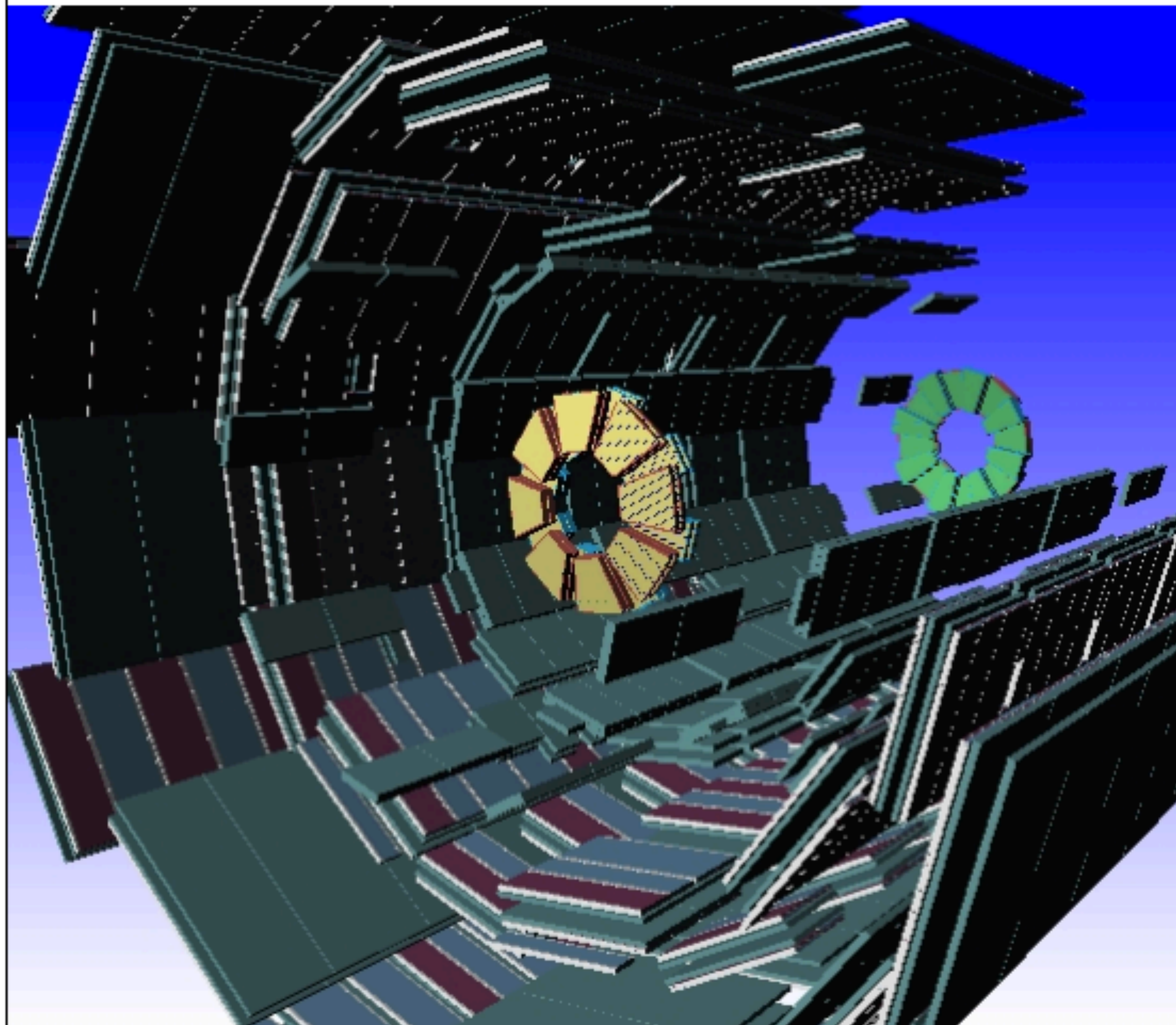


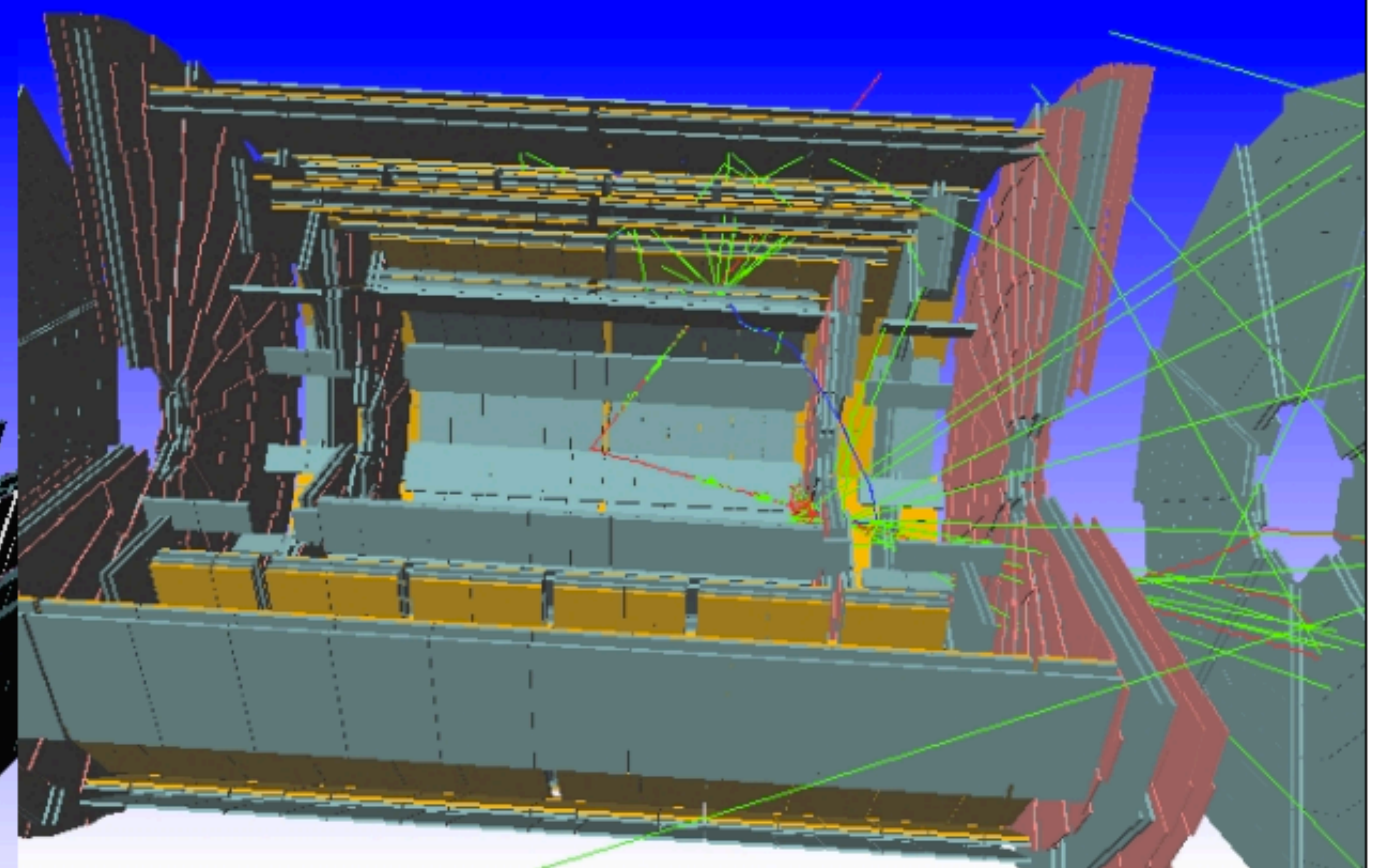


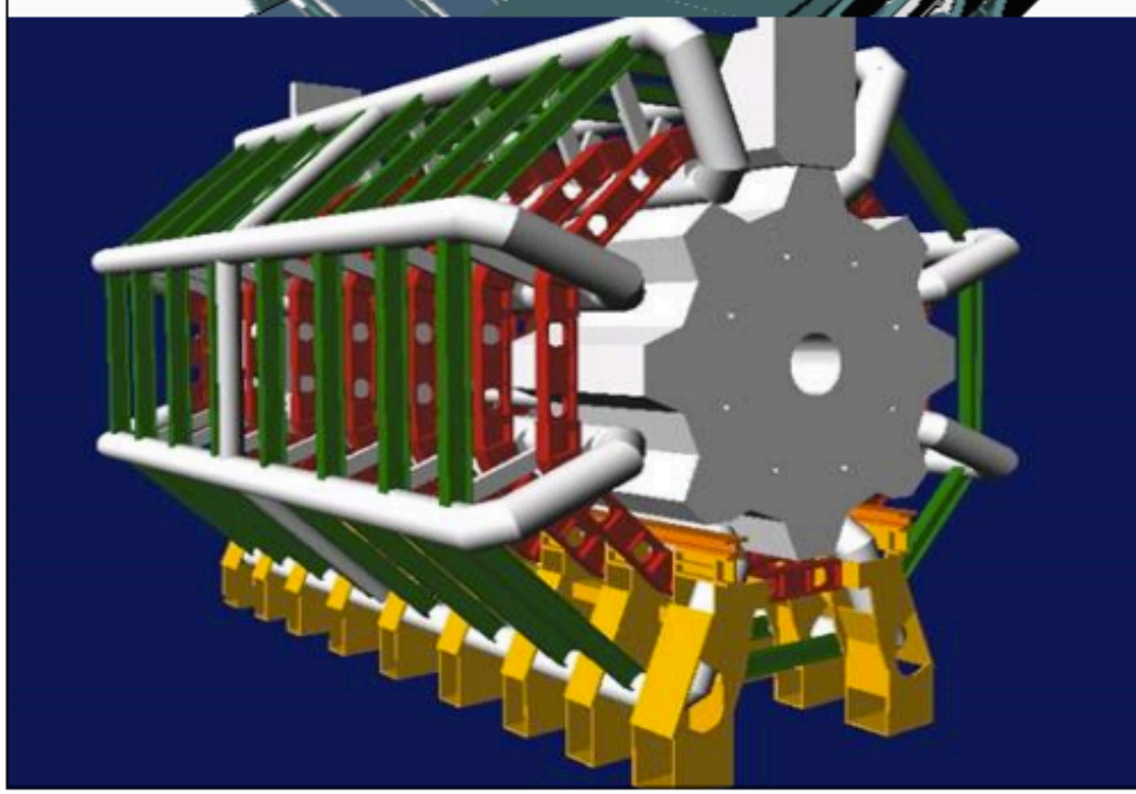
Large Hadron Collider (LHC) @ CERN

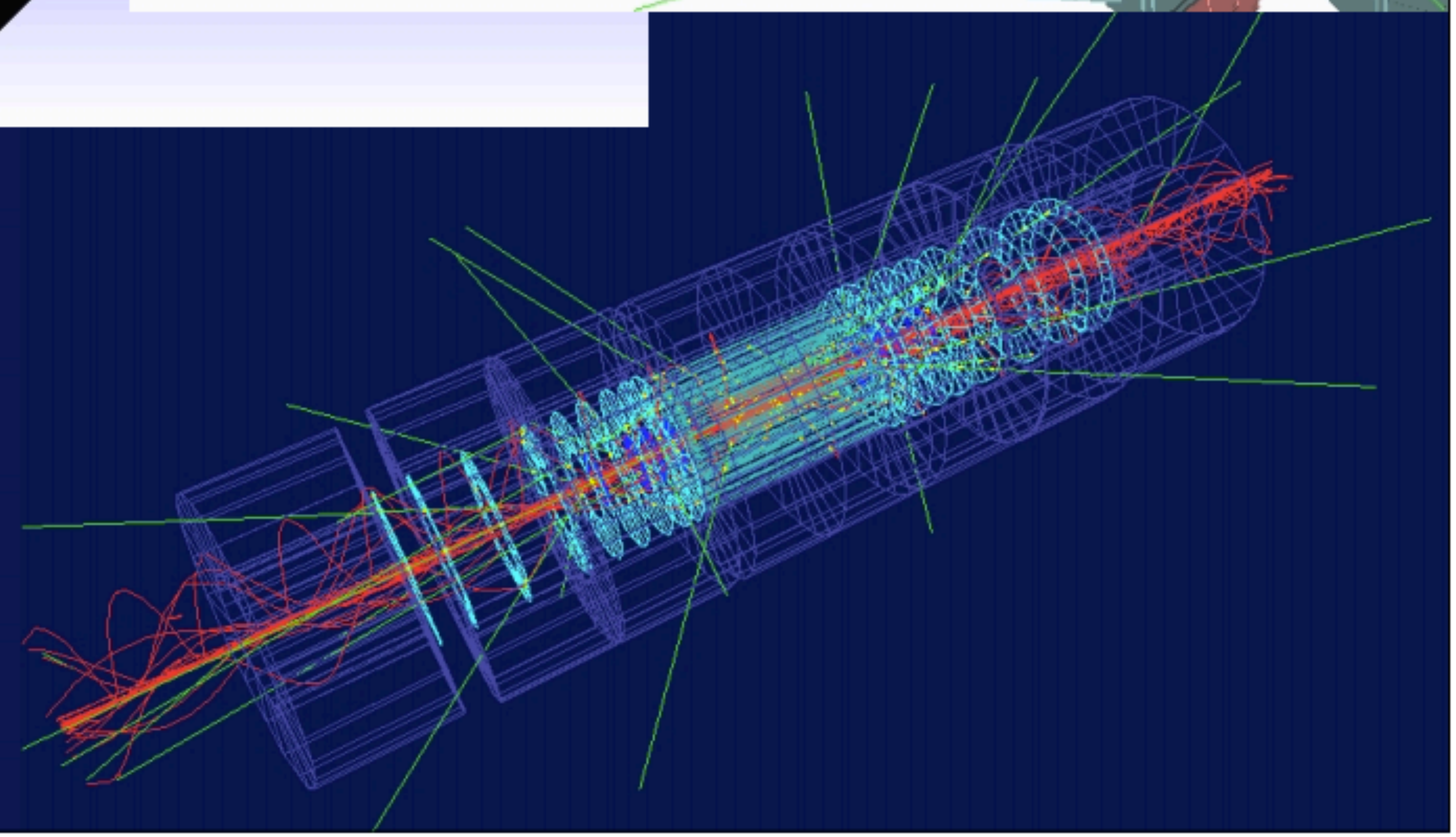


Geant4 in High Energy Physics (ATLAS at LHC)





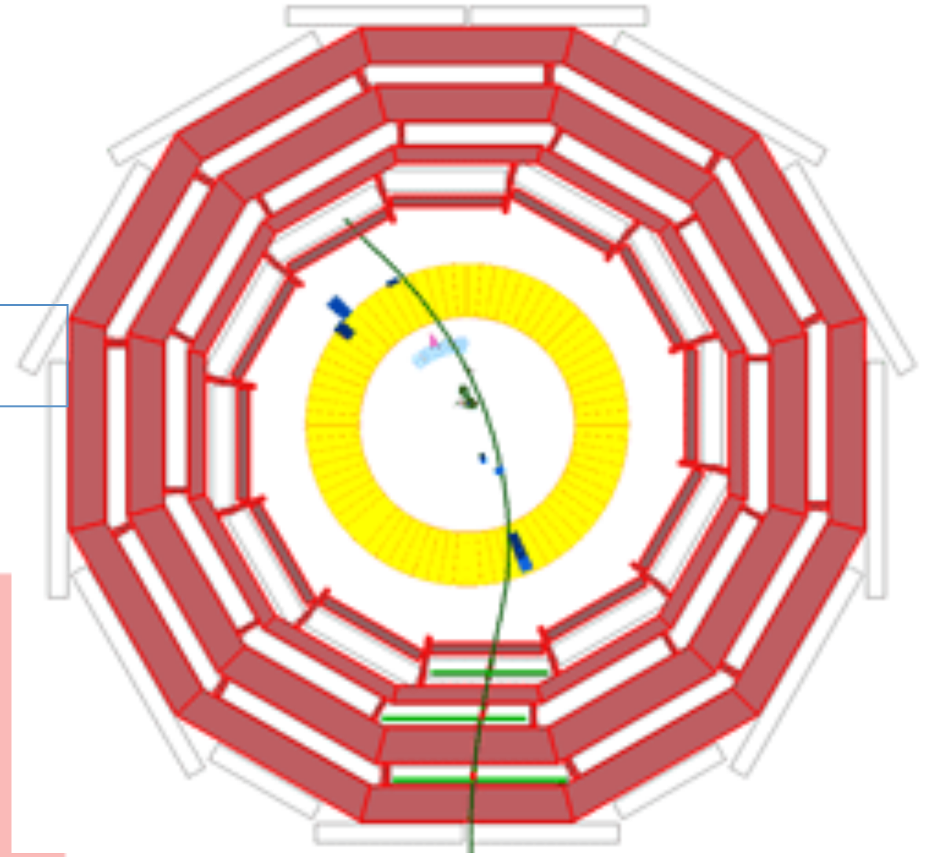




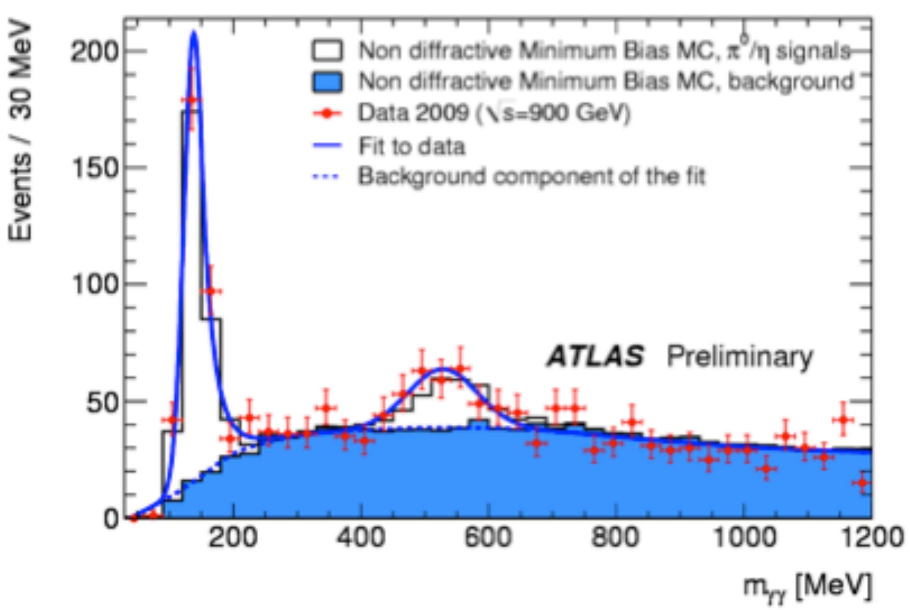
Geant4 has been successfully employed for

- Detector design
- Calibration / alignment
- First analyses

T. LeCompte (ANL)



GEANT4 Comparisons with the Calorimeters



Invariant mass of pairs of well-isolated electromagnetic clusters.

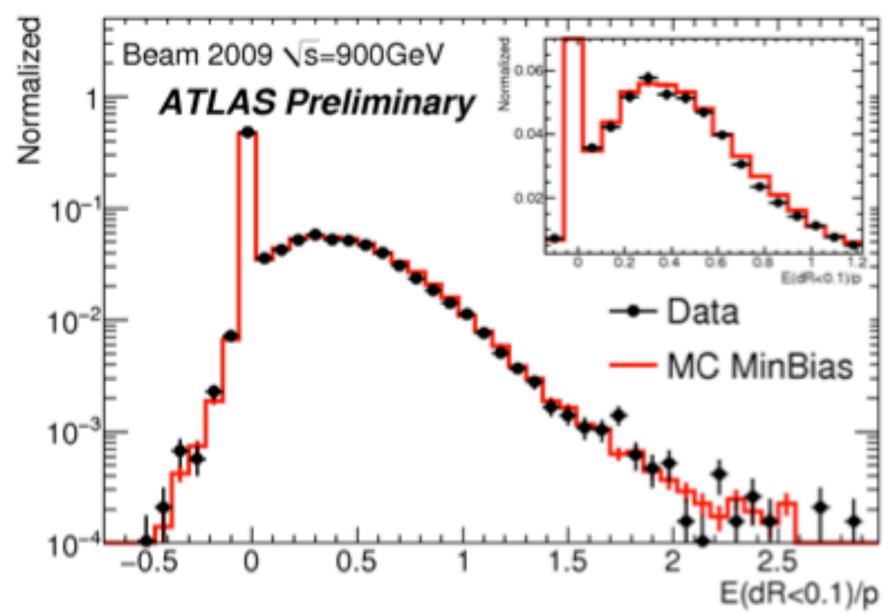
The π^0 mass is within 0.8 ± 0.6% of expectations.

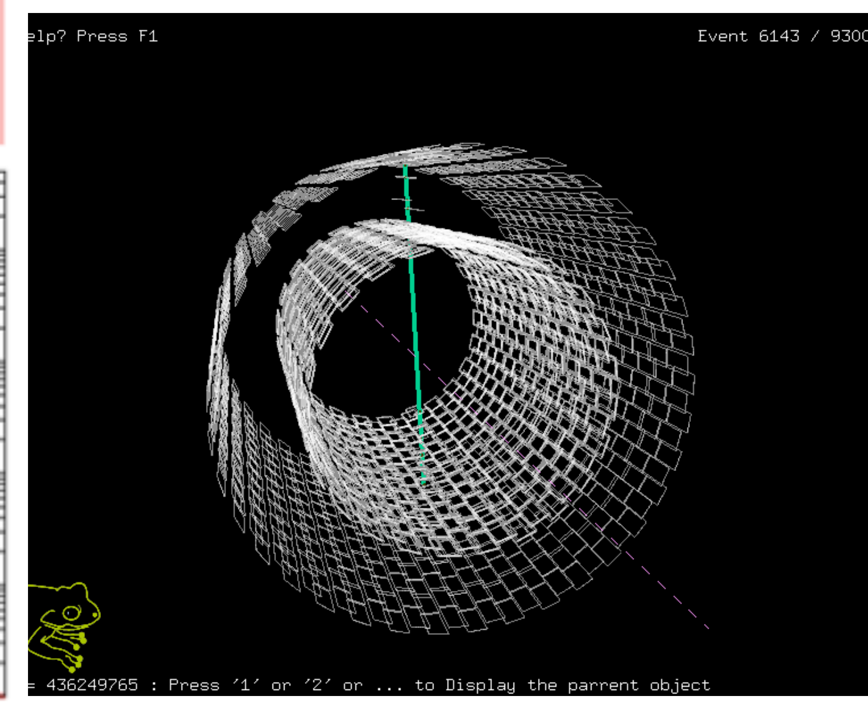
The η^0 mass is within 3 ± 2% of expectations.

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.

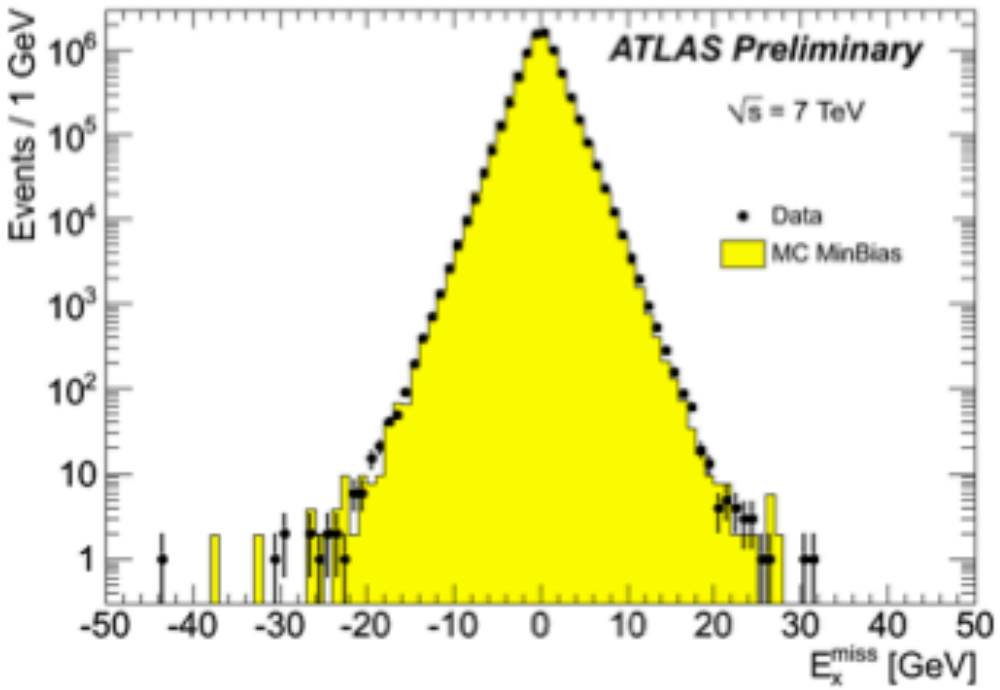
This plot agreed better than we ever expected. (I sent the student who made it back to make sure that they didn't accidentally compare G4 with G4.

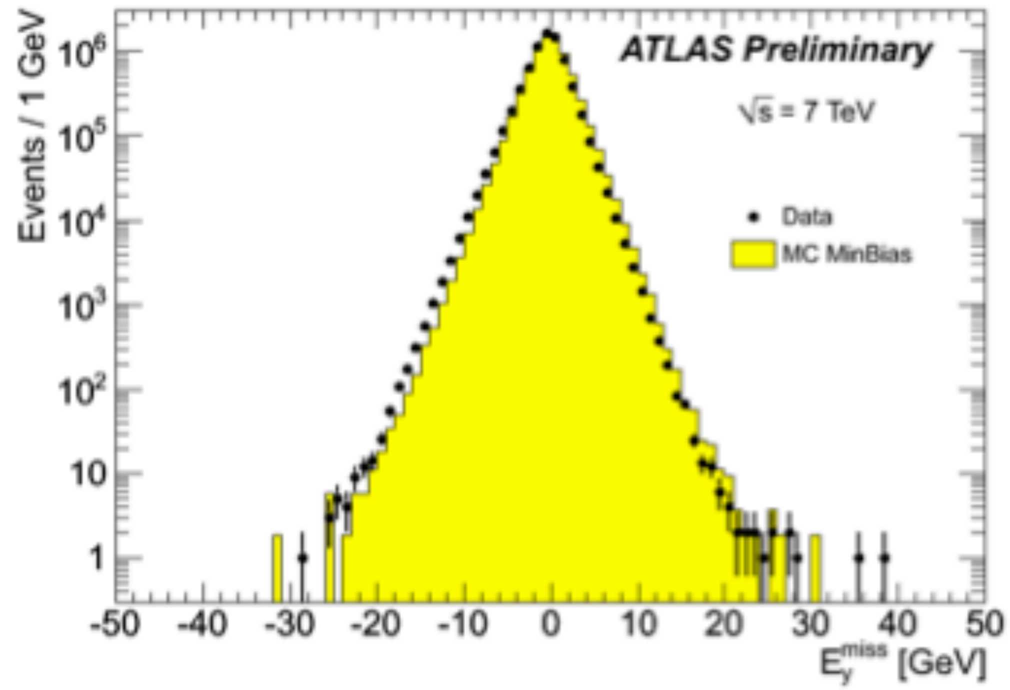




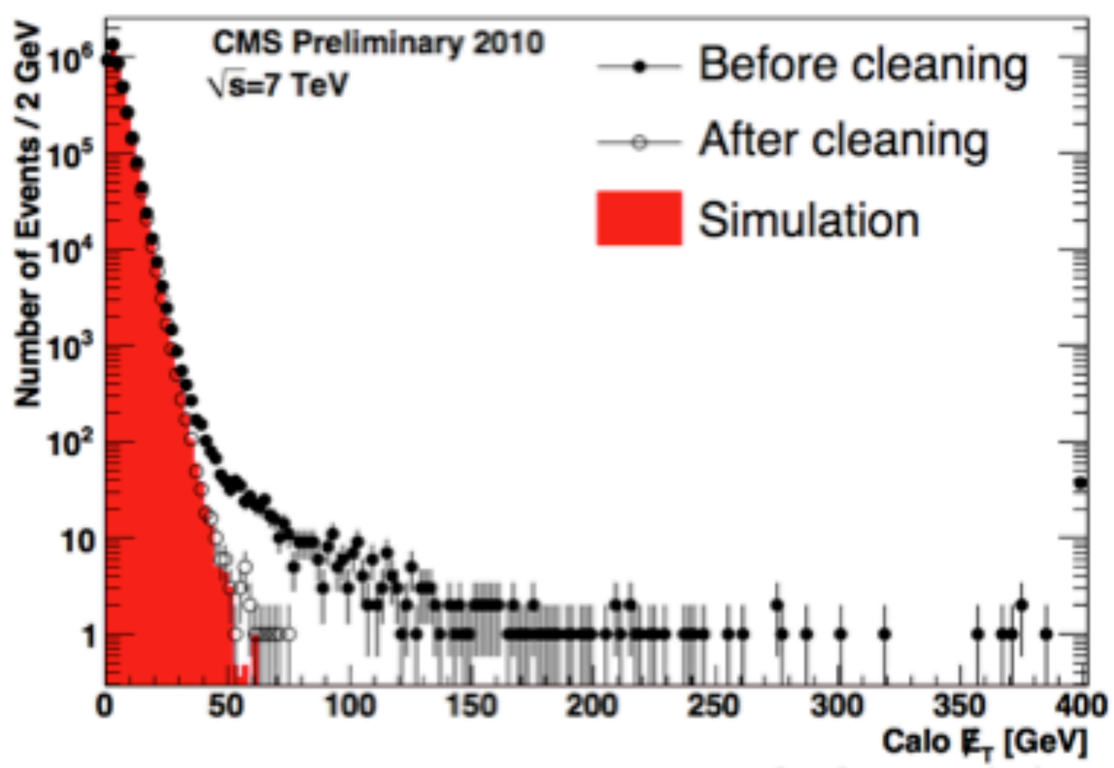
Figures from CMS

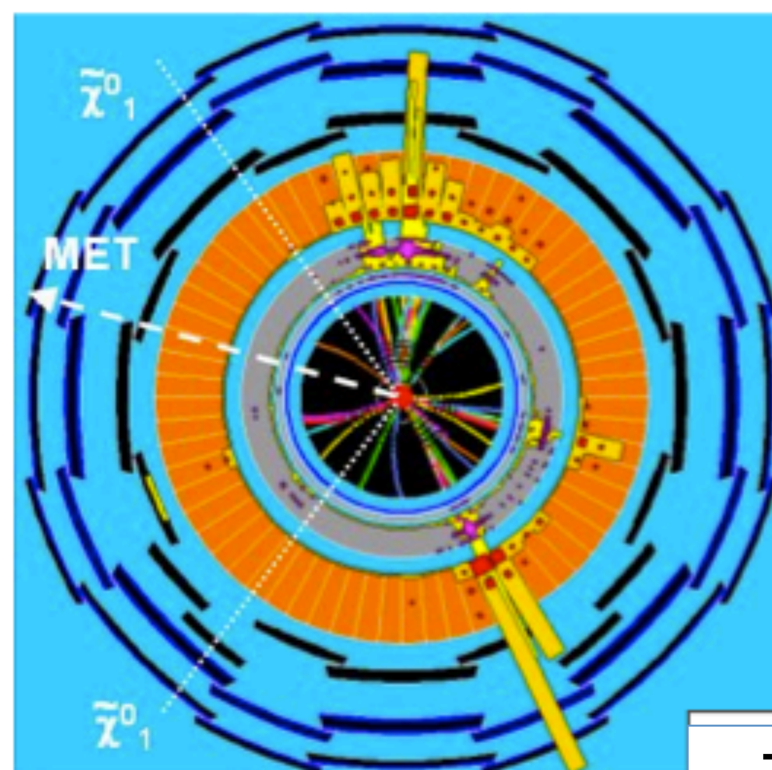
Missing E_T





This is one of the hardest things to get right. MET incorporates everything measured in the detector and attempts to identify non-interacting particles, such as neutrinos or dark matter.





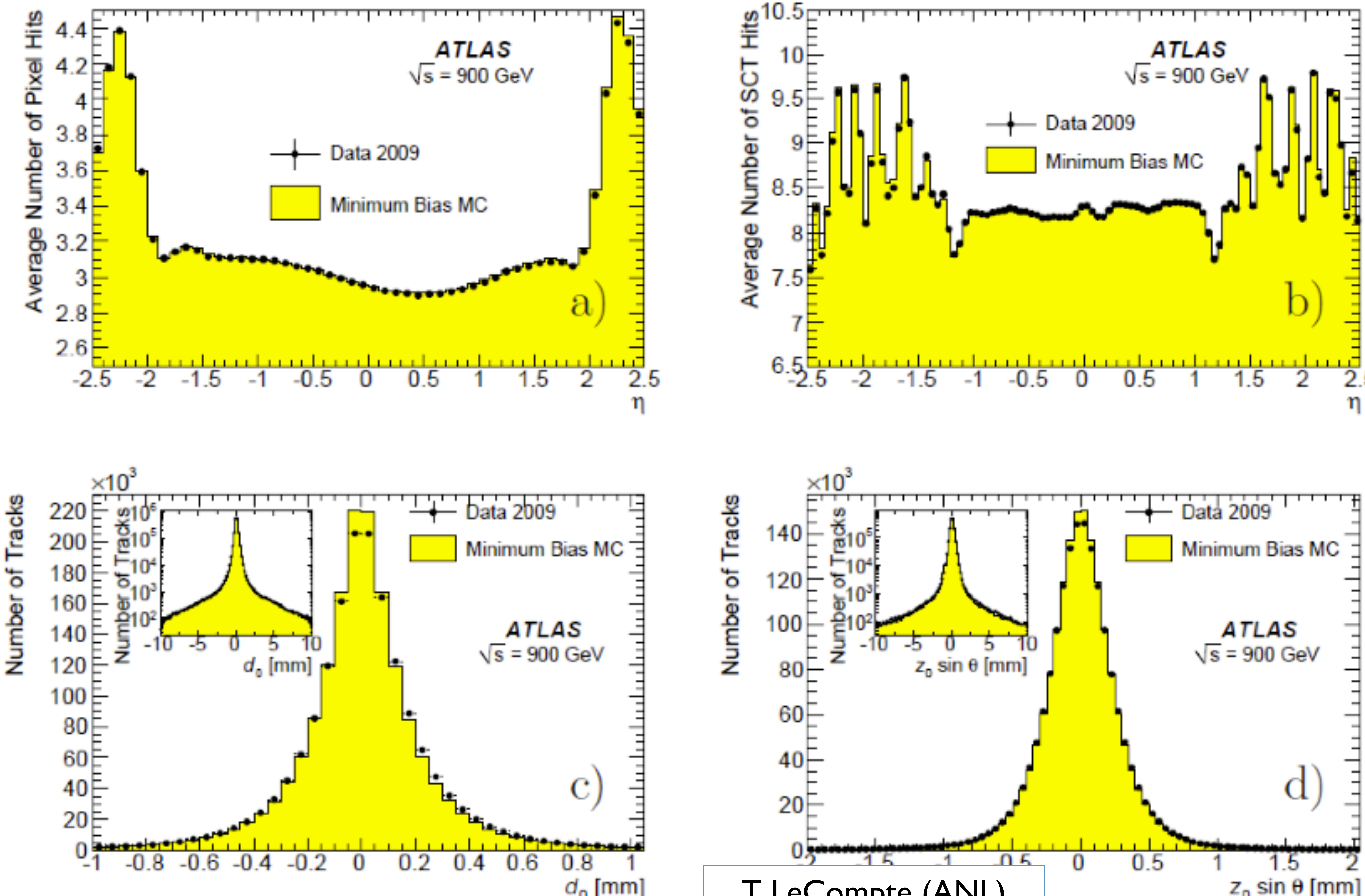
Agreement is astounding.

You can even see that the ATLAS detector is not quite centered – in both data and MC.

T. LeCompte (ANL)

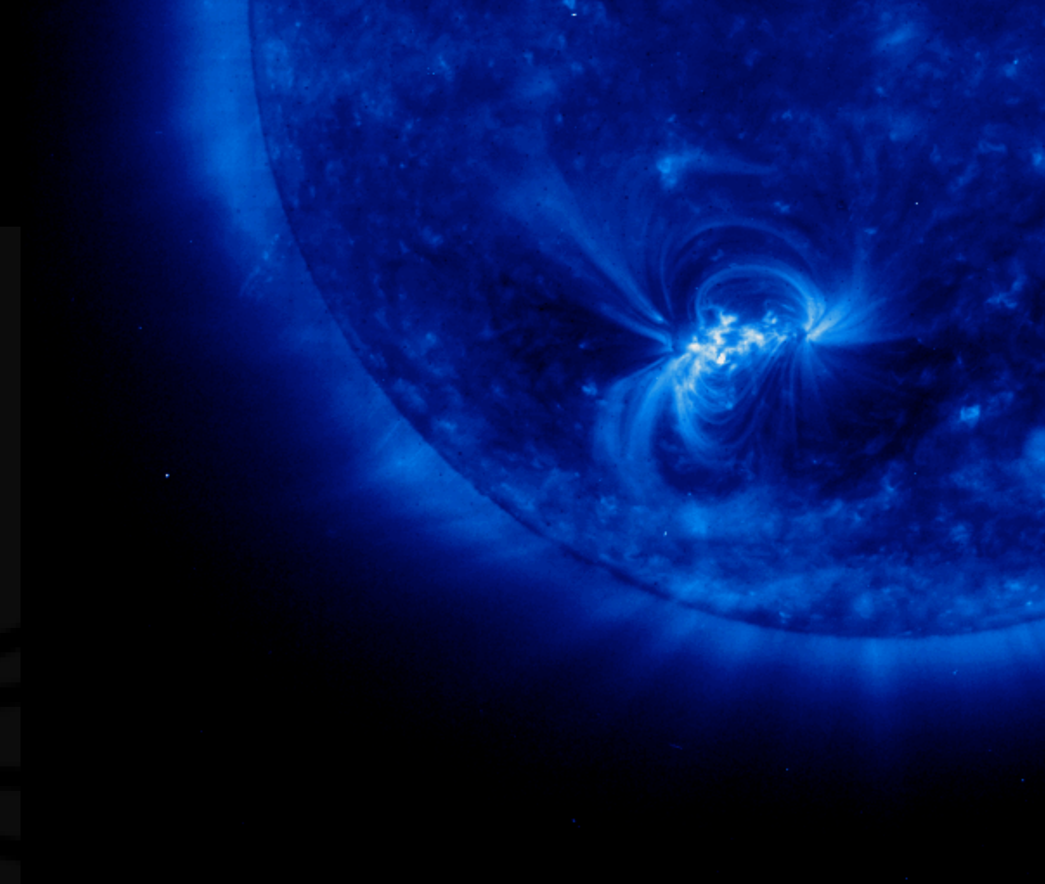
Both ATLAS and CMS plots are made from a tiny piece of the very earliest data.

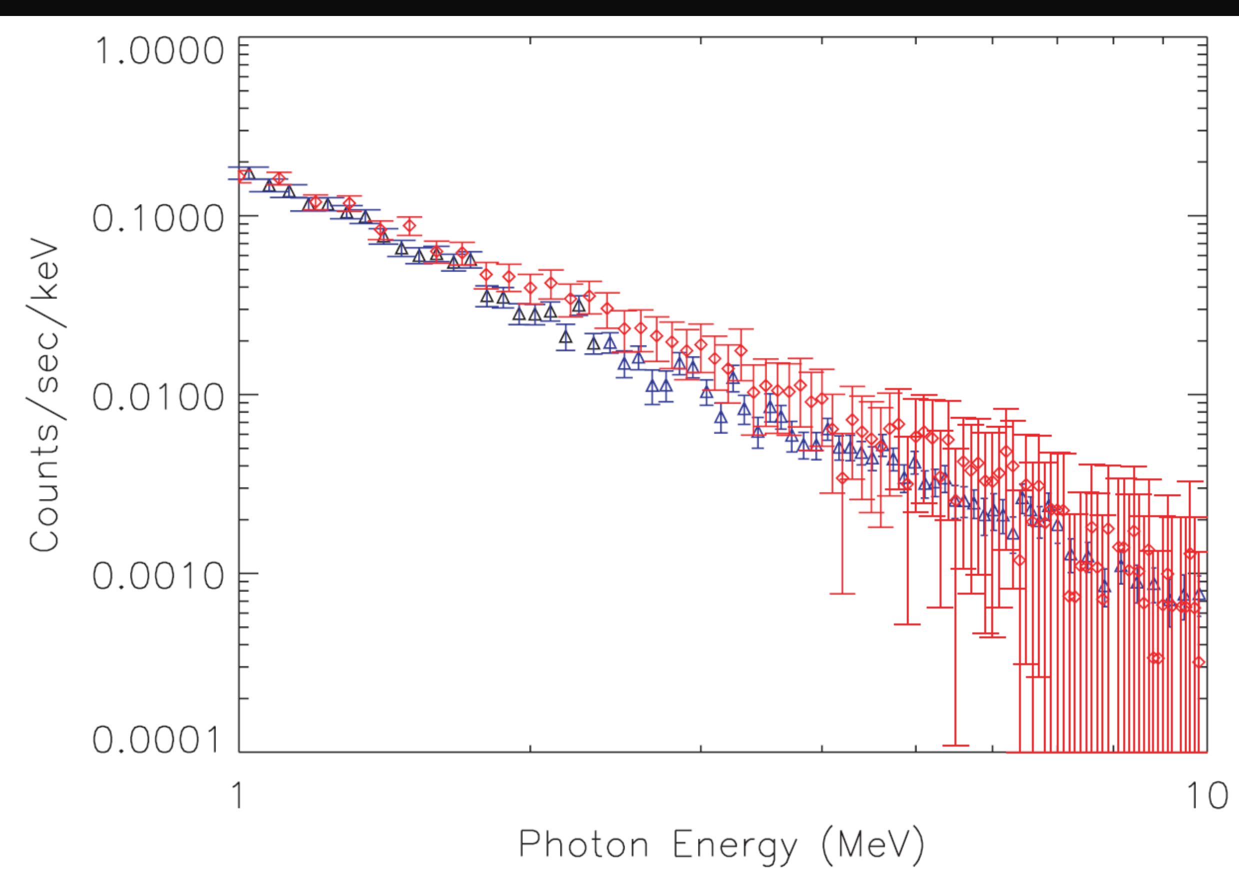
Data and simulation agreements

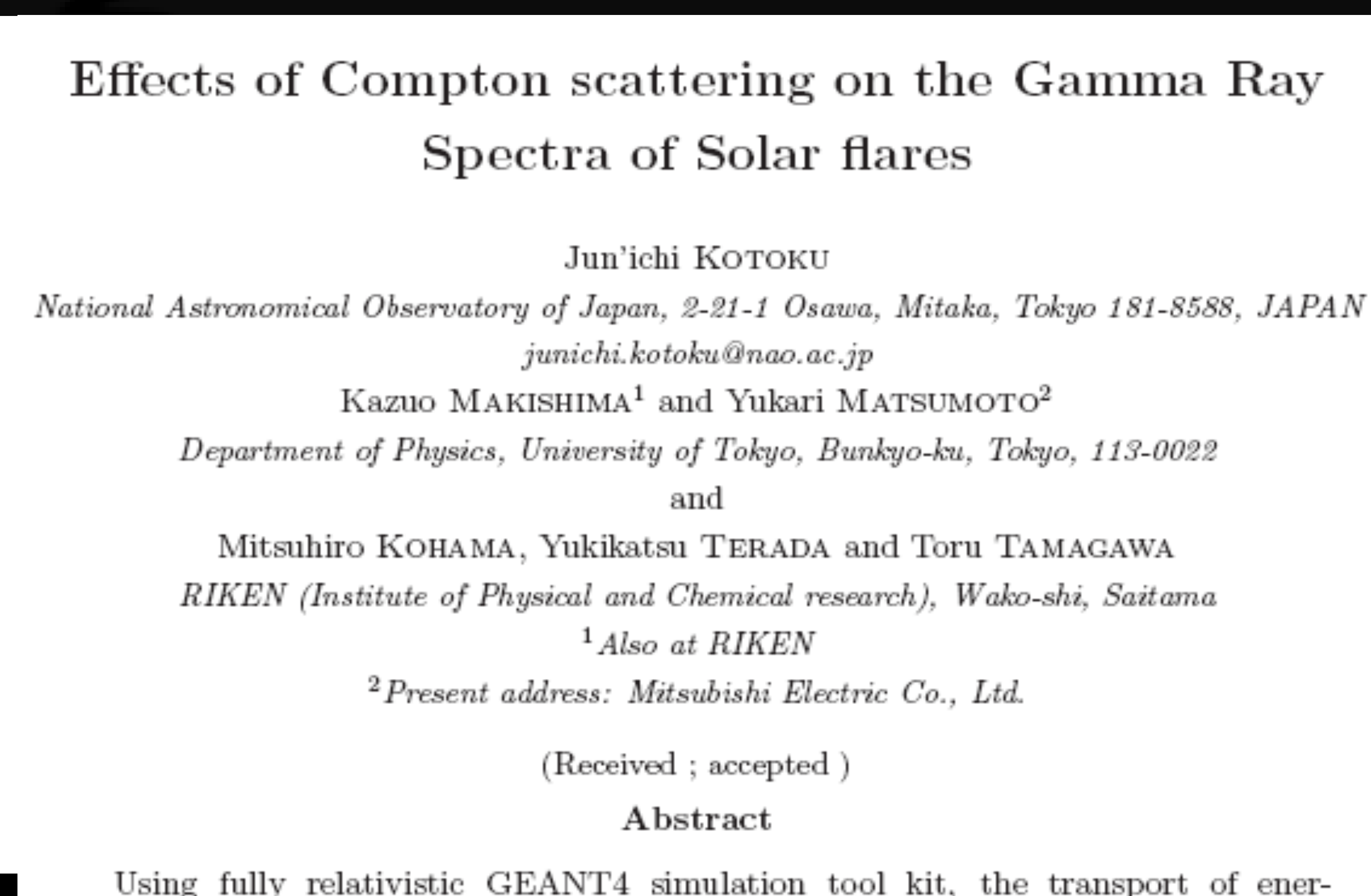


T. LeCompte (ANL)

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







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

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Department of Physics, University of Tokyo, Bunkyo-ku, Tokyo, 113-0022
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Mitsuhiro KOHAMA, Yukikatsu TERADA and Toru TAMAGAWA
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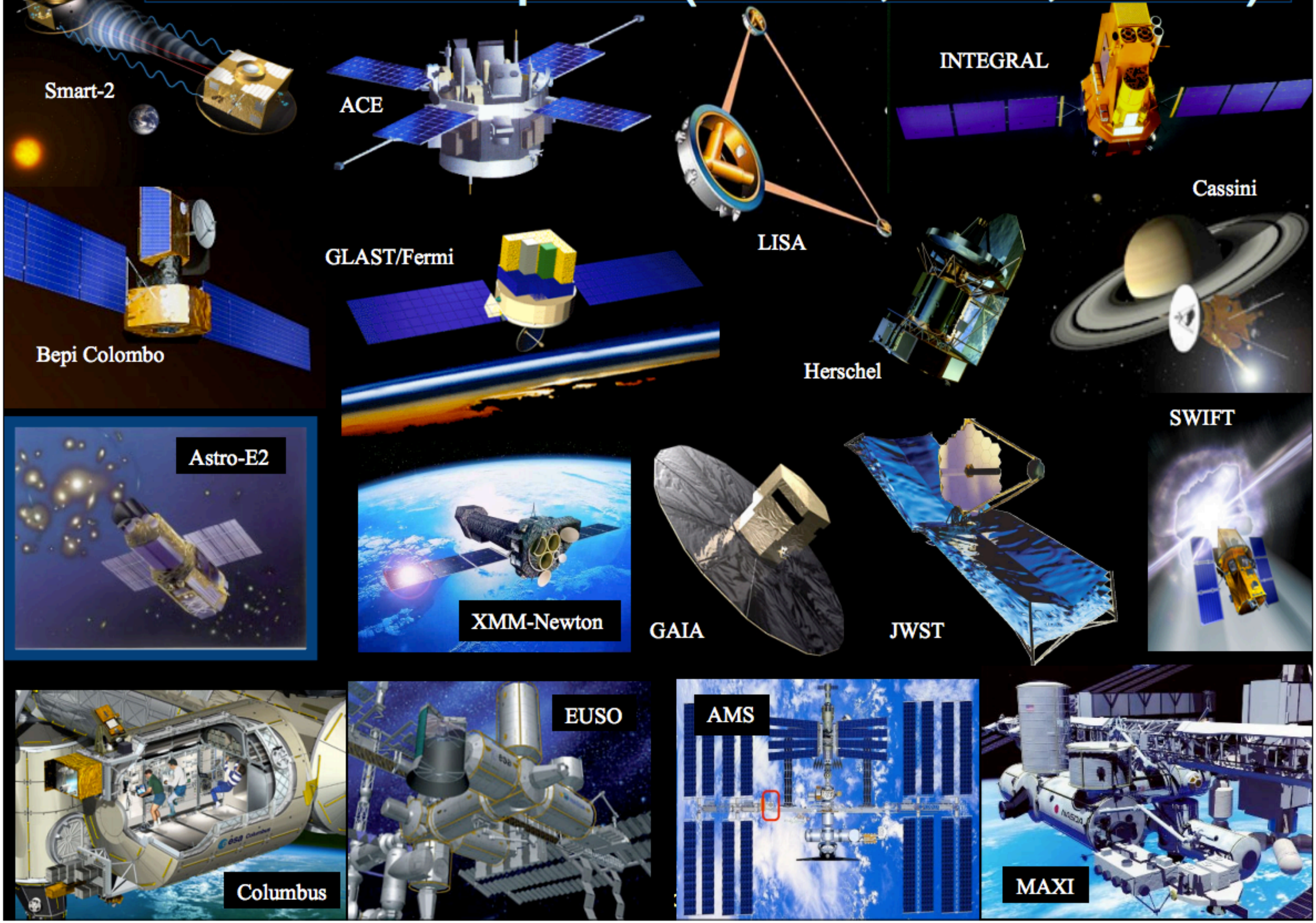
[1] *Also at RIKEN*
[2] *Present address: Mitsubishi Electric Co., Ltd.*

(Received ; accepted)

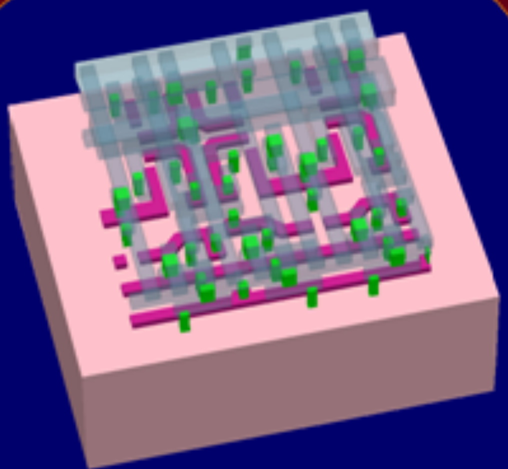
Abstract

Using fully relativistic GEANT4 simulation tool kit, the transport of ener-

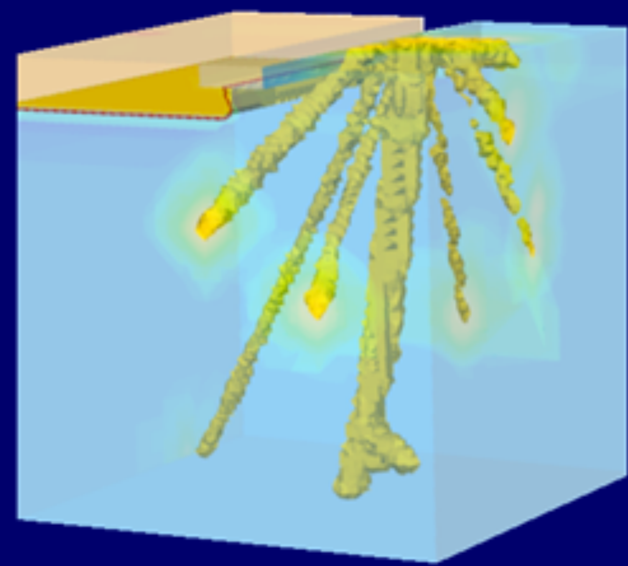
Geant4 in Space (NASA, ESA, JAXA)



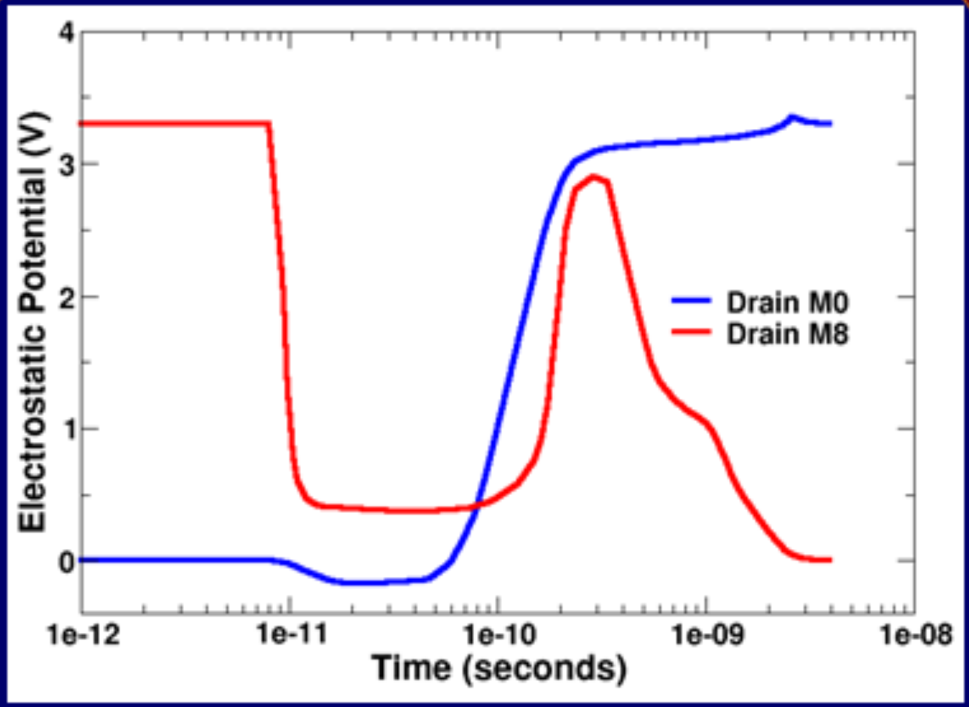
RADSAFE on SEE in SRAMs



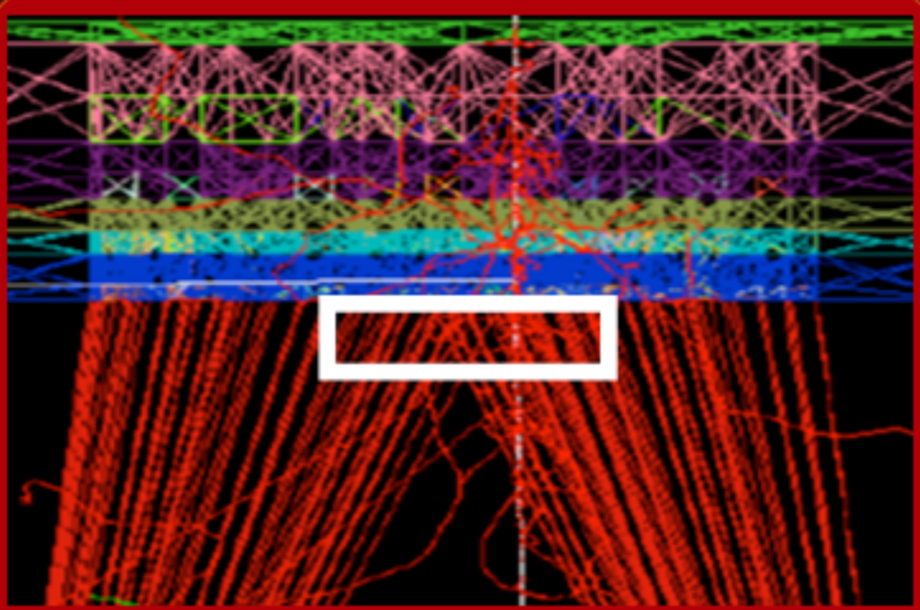
TCAD Cell Structure: SRAM Cell



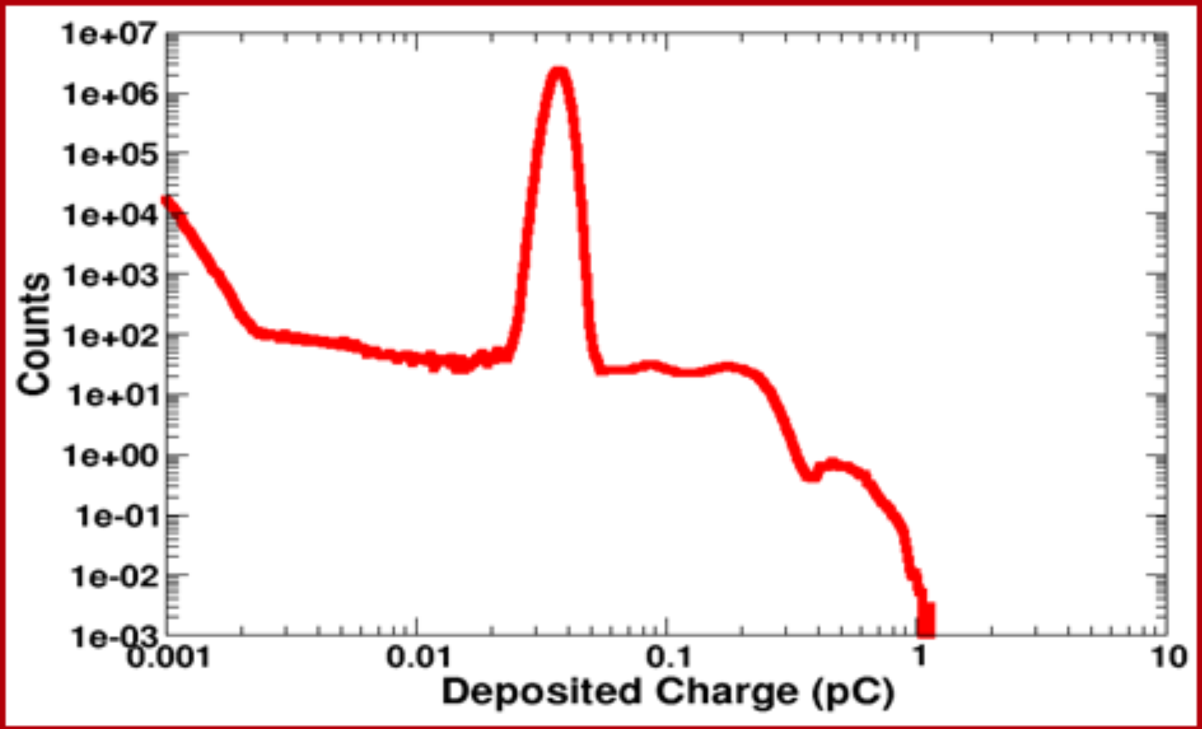
Single Charge Deposition in TCAD: Ne+W Event



SRAM Cell Upset



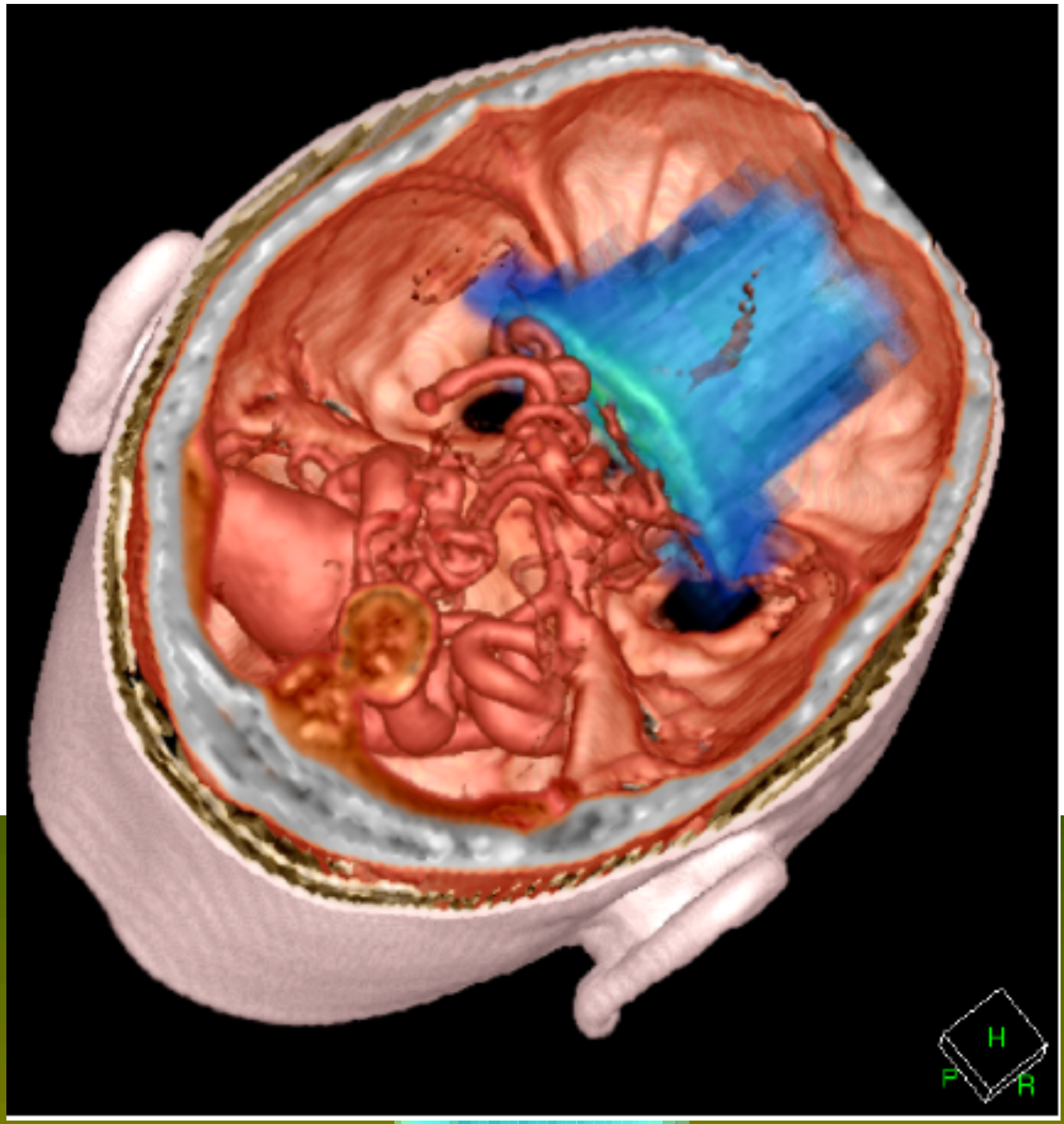
Geant4 Geometry and 523 MeV Neon Event

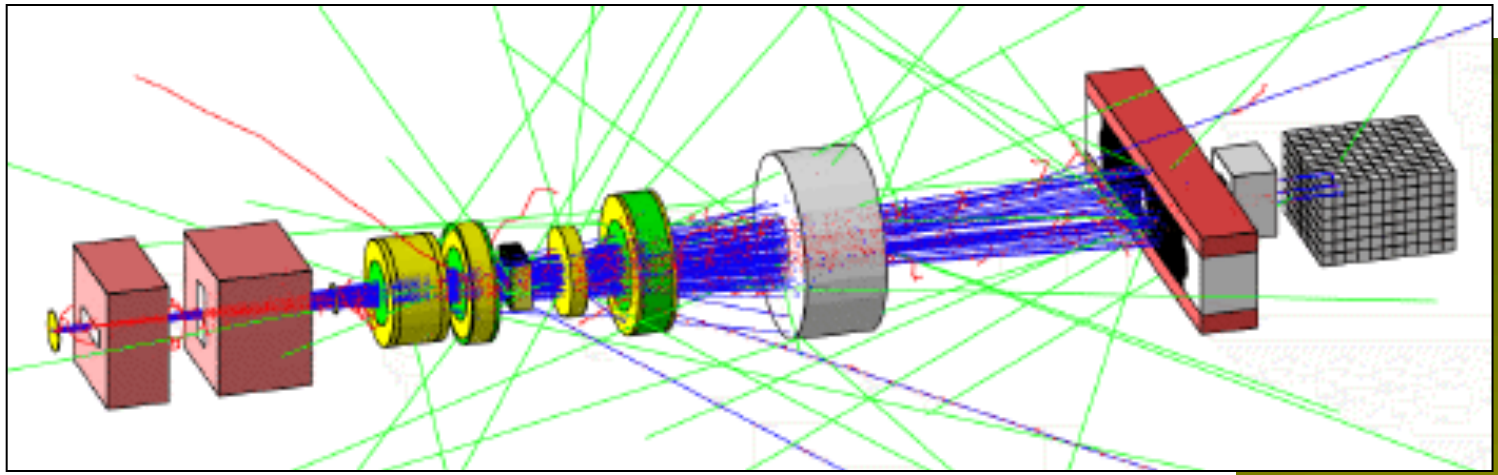


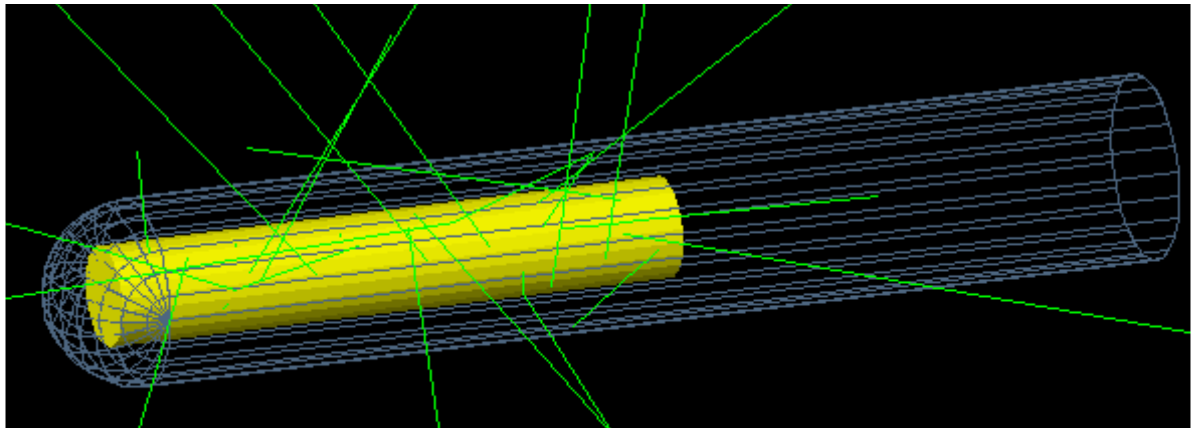
MRED Energy Deposition for 10^8 Events

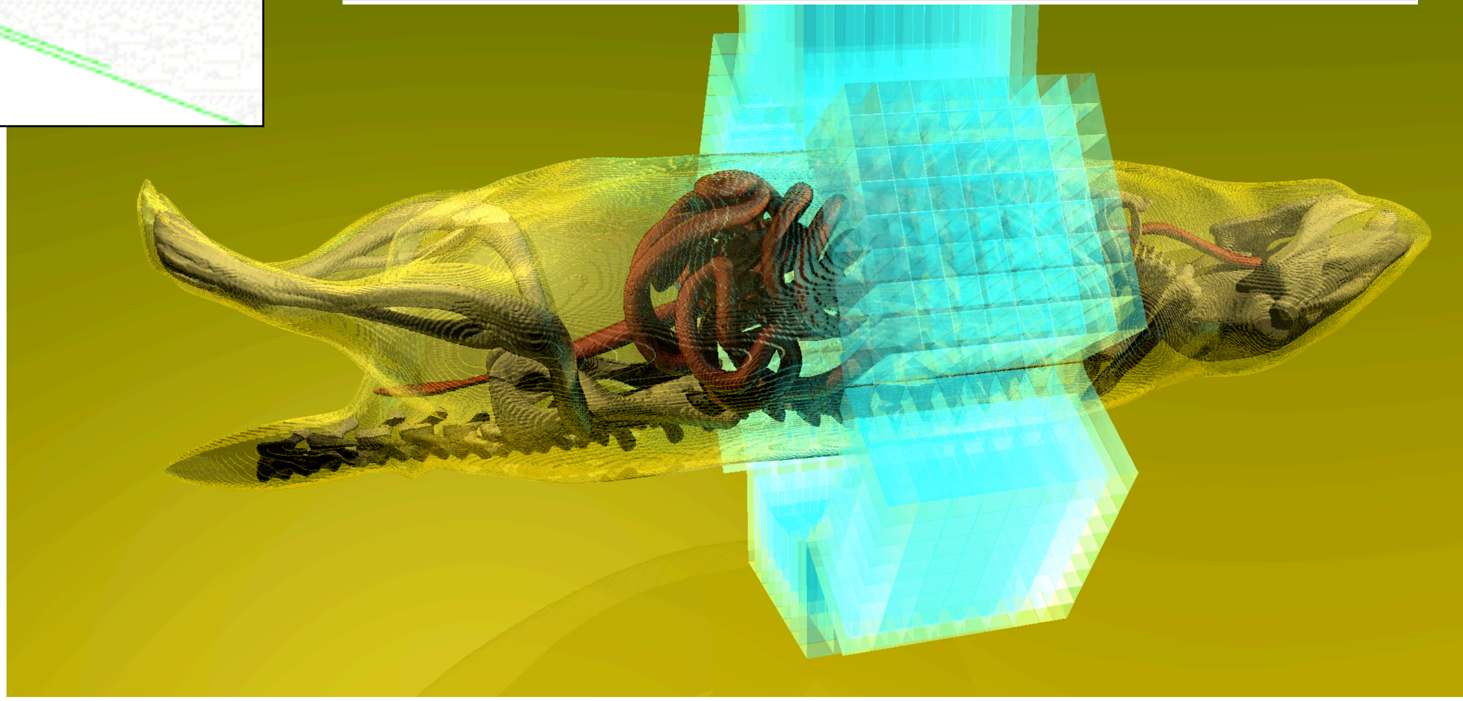
Geant4 @ Medical Science

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









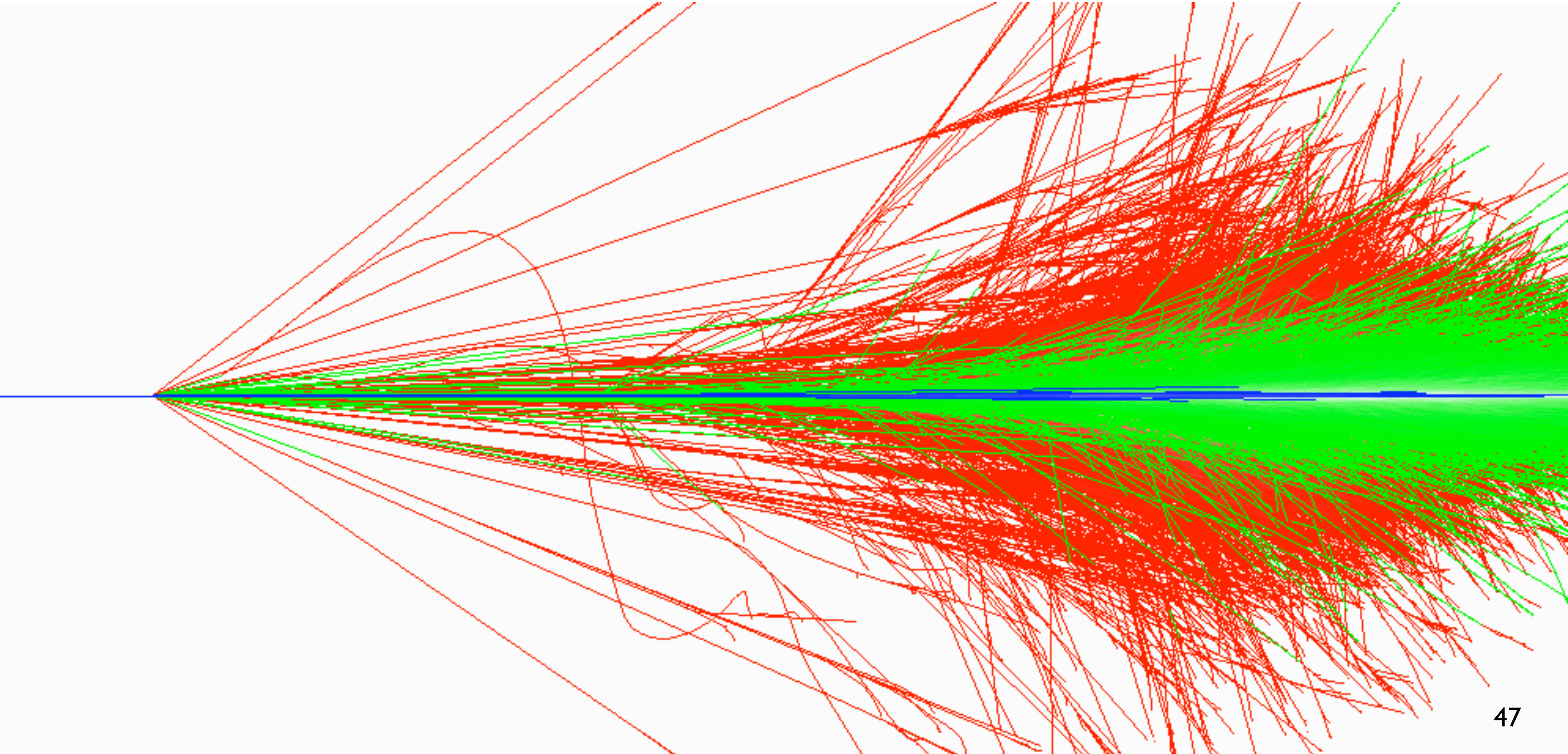
See exercise task4

Medical Physic

- Geant4 is used to calculate **doses**
- but also to design **imaging devices** (PET, gamma cameras): http://www.opengatecollaboration.org/

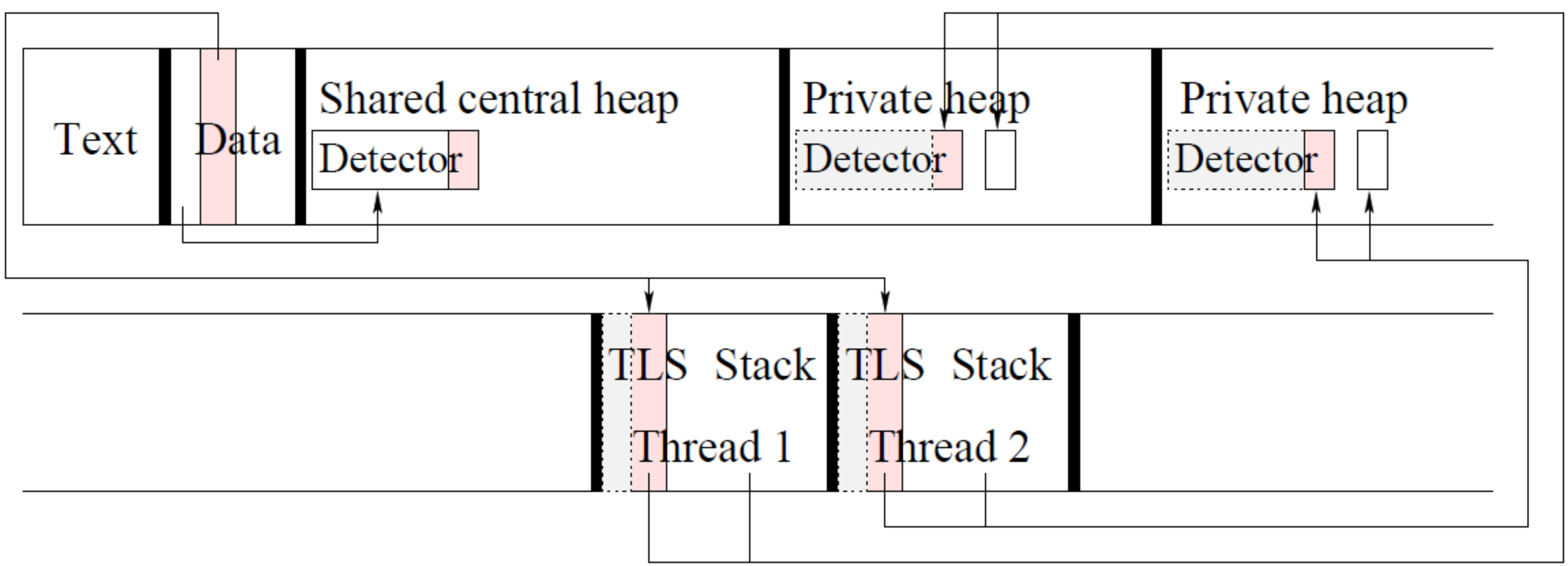
- Need **very precise low energy** (keV-MeV) em physics description (at the opposite of the spectra with compared to HEP)

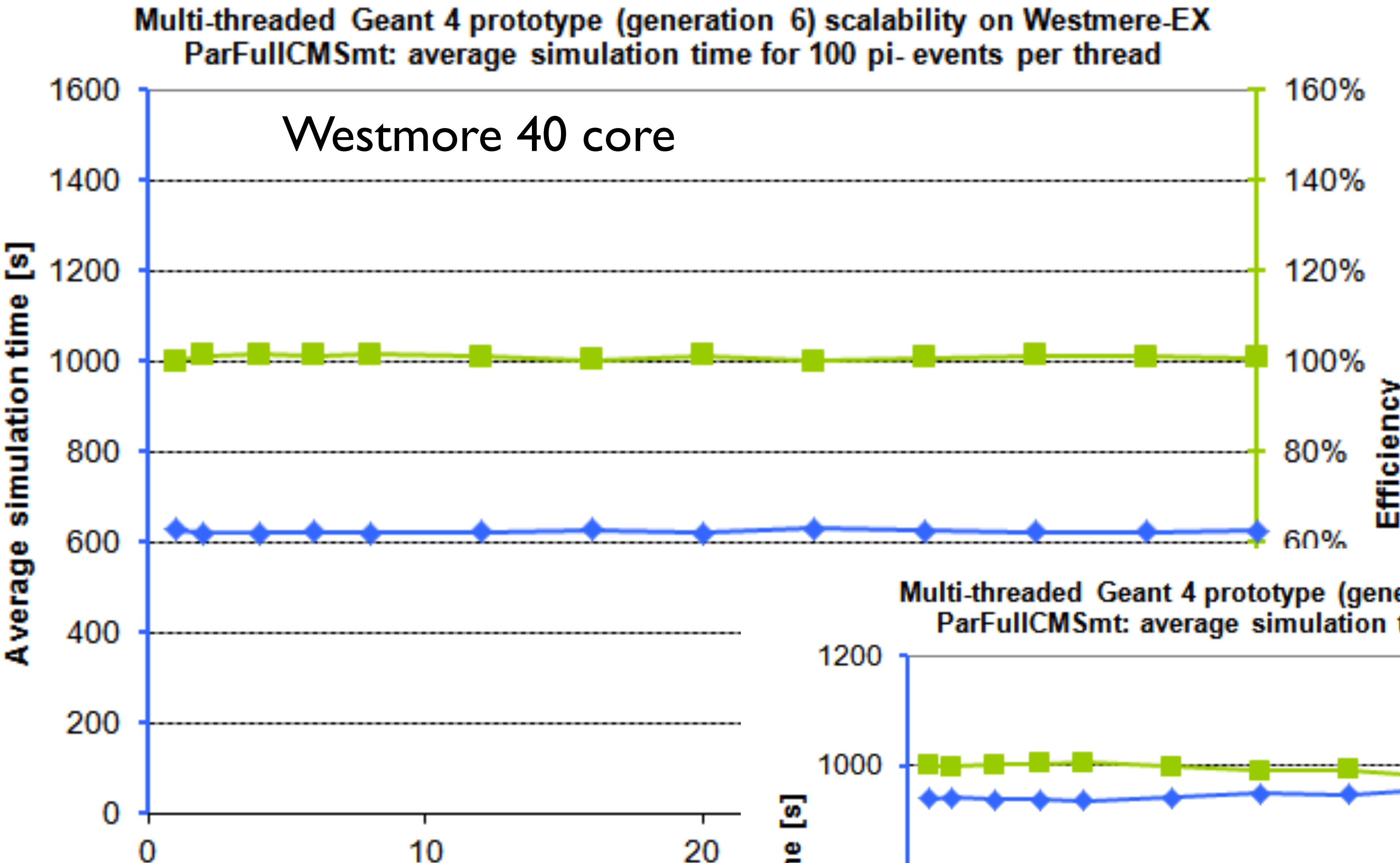
Future directions



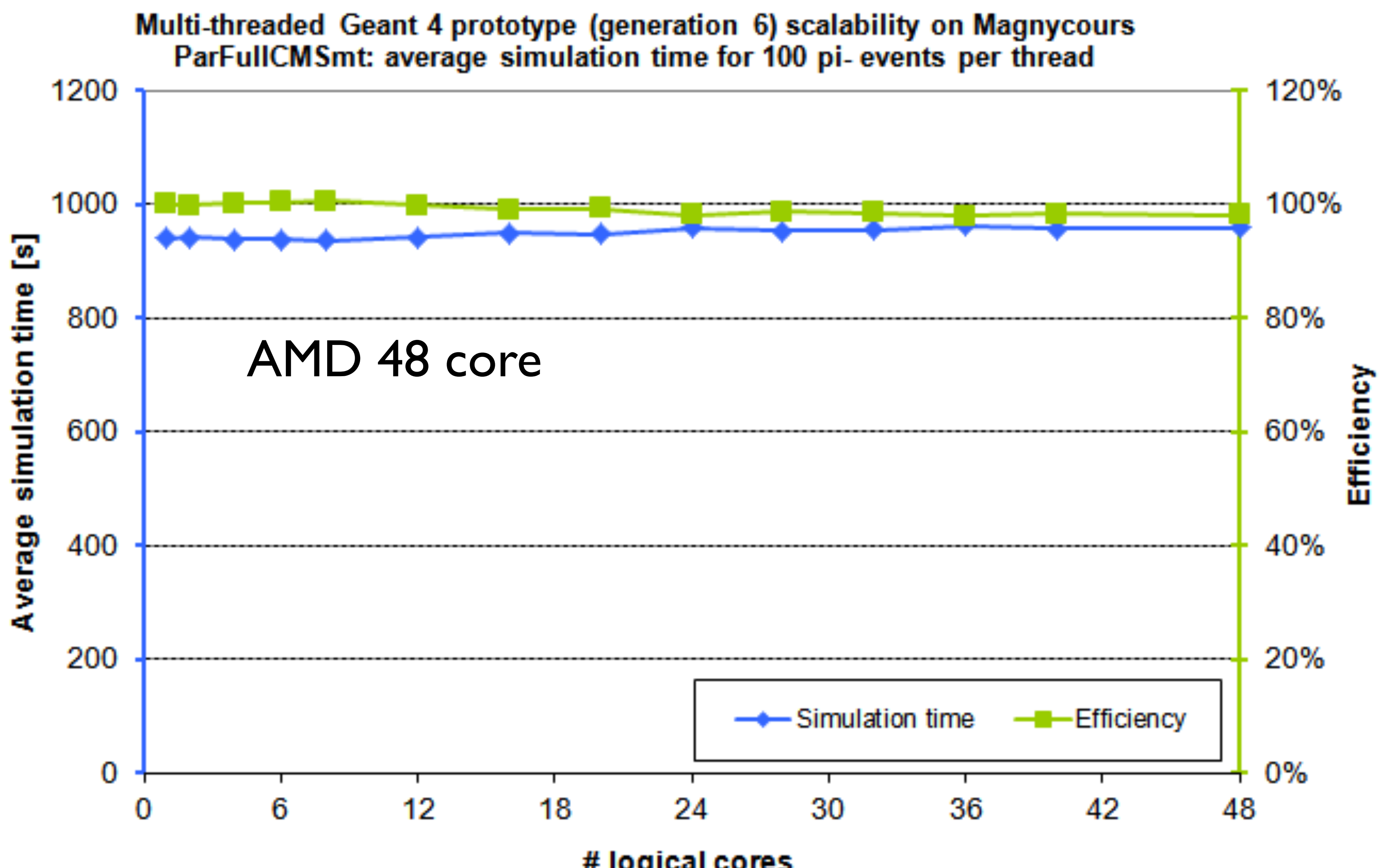
Multi-threaded Geant4

- Offers event-level parallelism within one job with many threads.
- Uses the many-core machine in a memory-efficient scalable manner.
- Shares "relatively read-only data" among threads for memory footprint reduction.
  - Relatively read-only data : data written at initialization phase but kept unchanged during the event loop
- Allocates thread-local heap for transient objects.
  - Full-CMS benchmark showed only 25MB of memory per thread.





Courtesy of Andrzej Nowak (OpenLab)



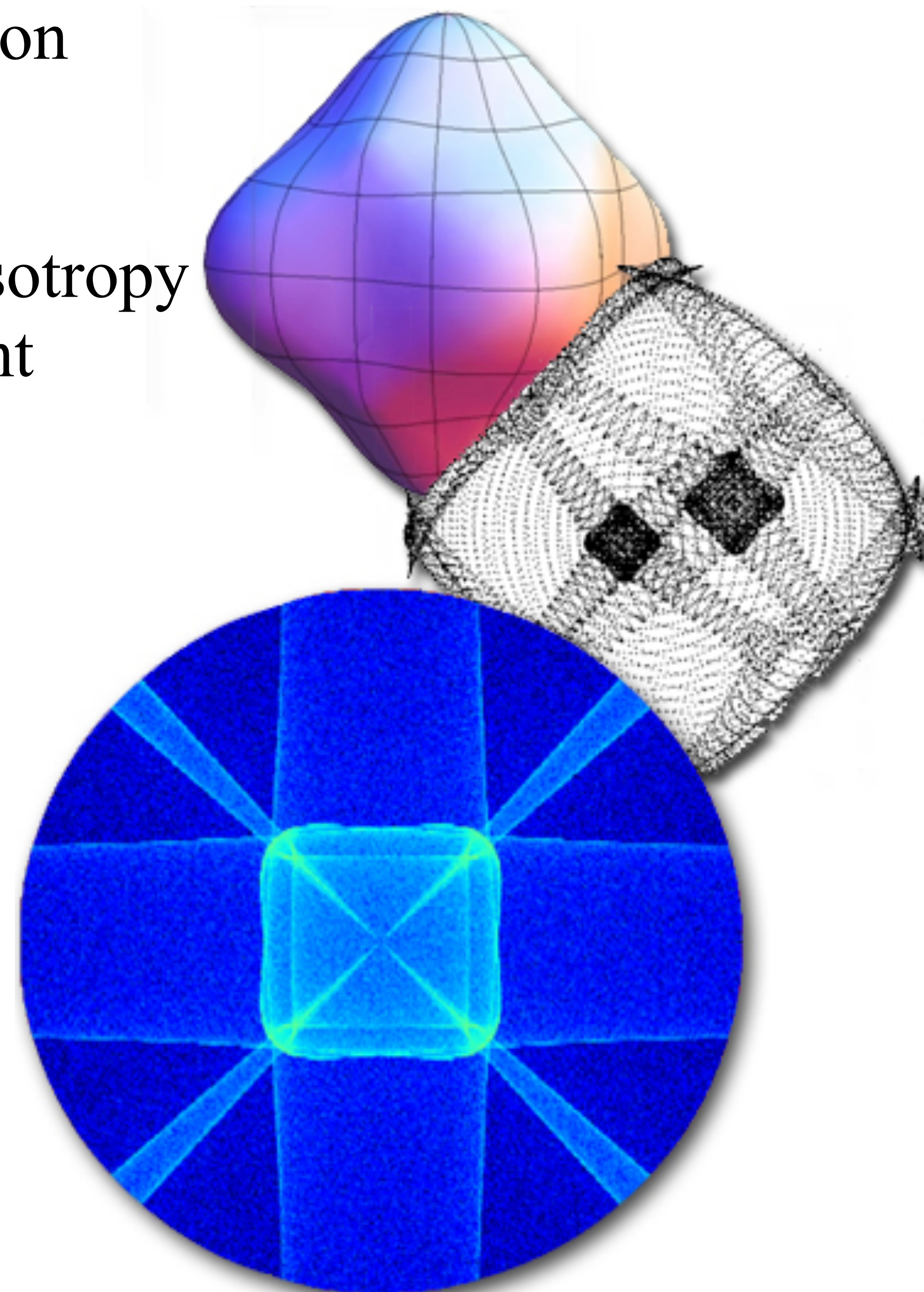
Andrzej Nowak, CERN openlab 2011

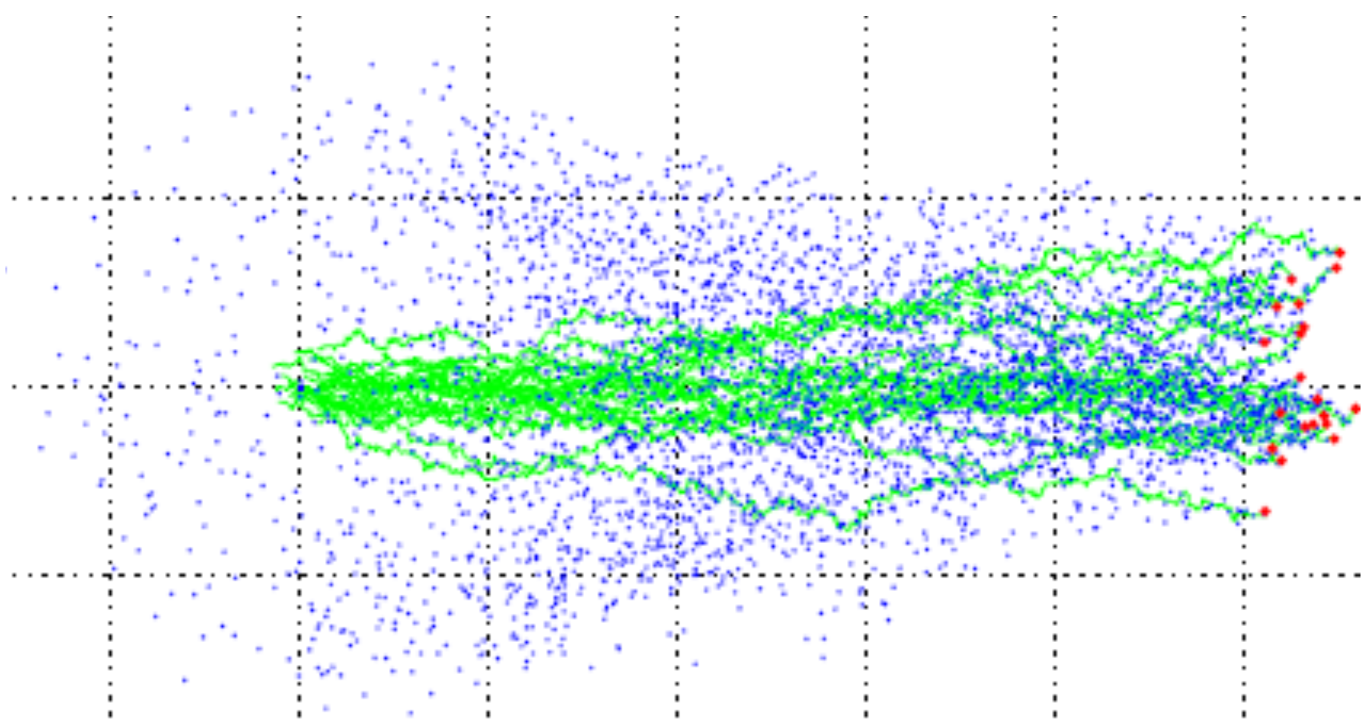
Note: scaling was still perfect with using 80 threads on Westmore (2 threads per core).
Latest news – G4MT showed perfect scalability for Intel MIC prototype as well.

Condensed Matter Physics in Geant4

•Phonon propagation, including focusing based on elasticity tensor (right)

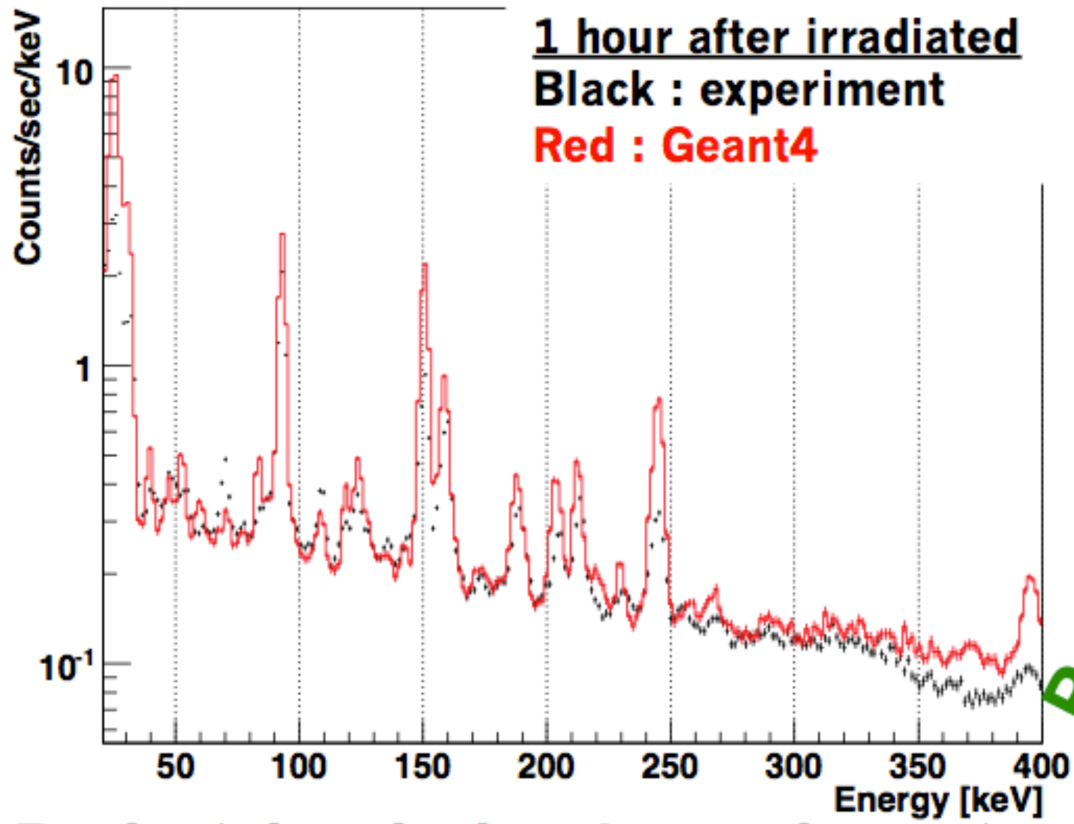
•e-/h+ transport, including conduction band anisotropy and Luke-Neganov emission, under development (below)



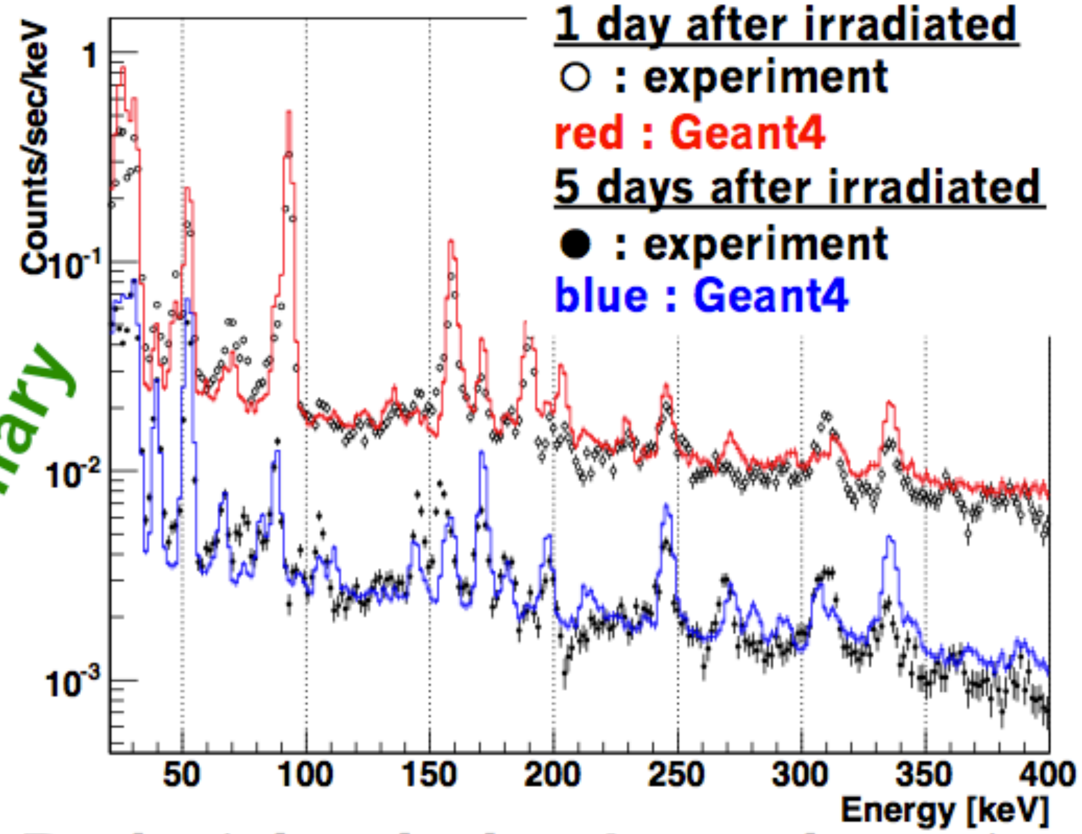


Time evolution of the activation background

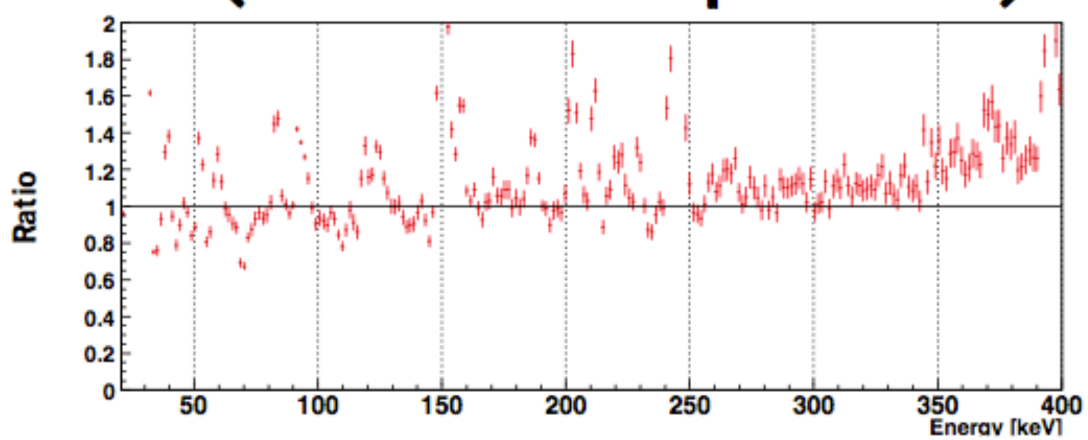
Comparison with Geant4



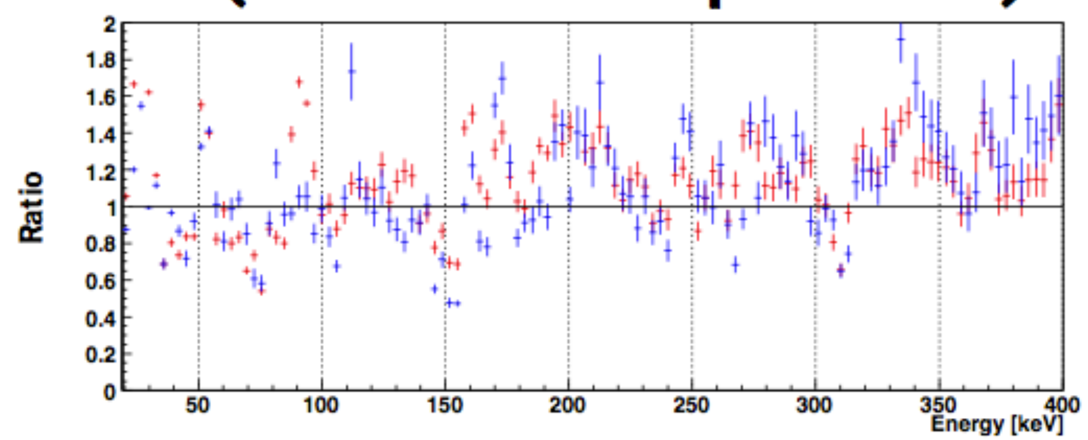
Preliminary



Ratio (simulation/experiment)



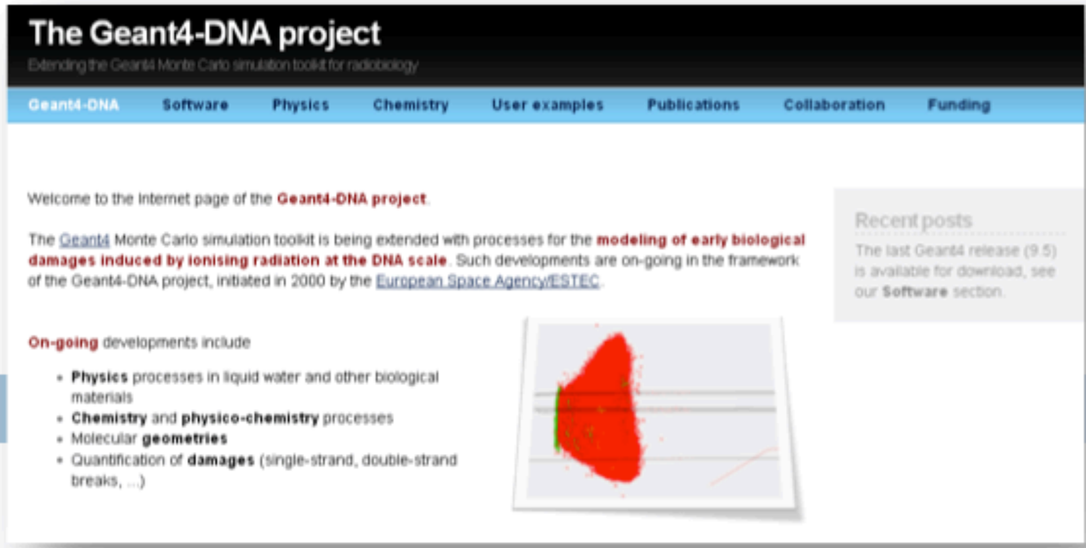
Ratio (simulation/experiment)



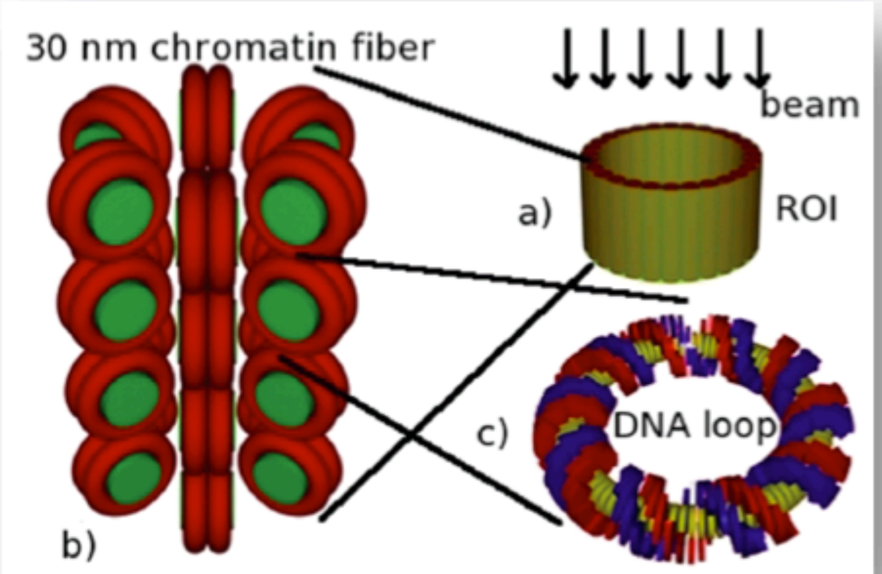
❖ Simulation results agrees with experimental data within a factor of two in terms of the line intensities

The Geant4-DNA project

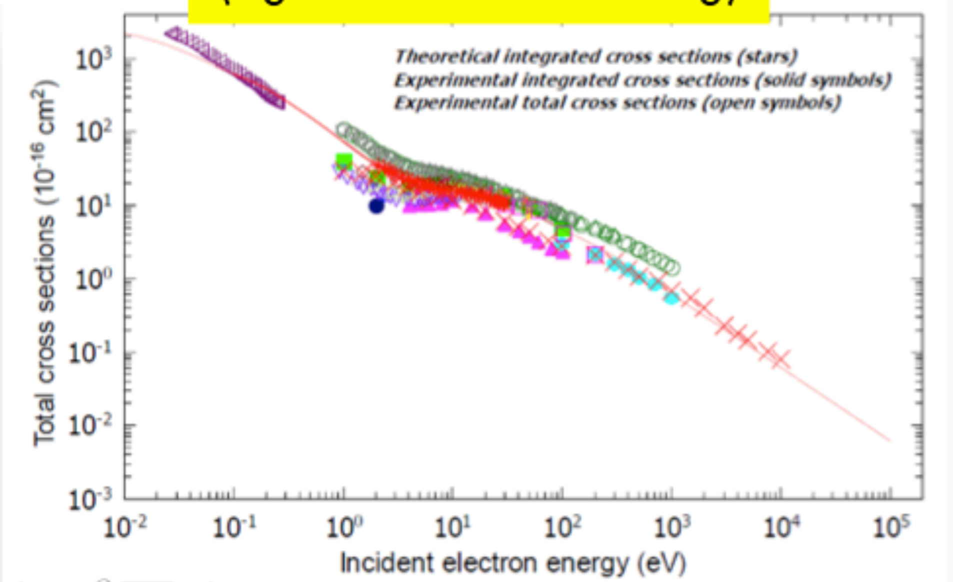
http://geant4-dna.org



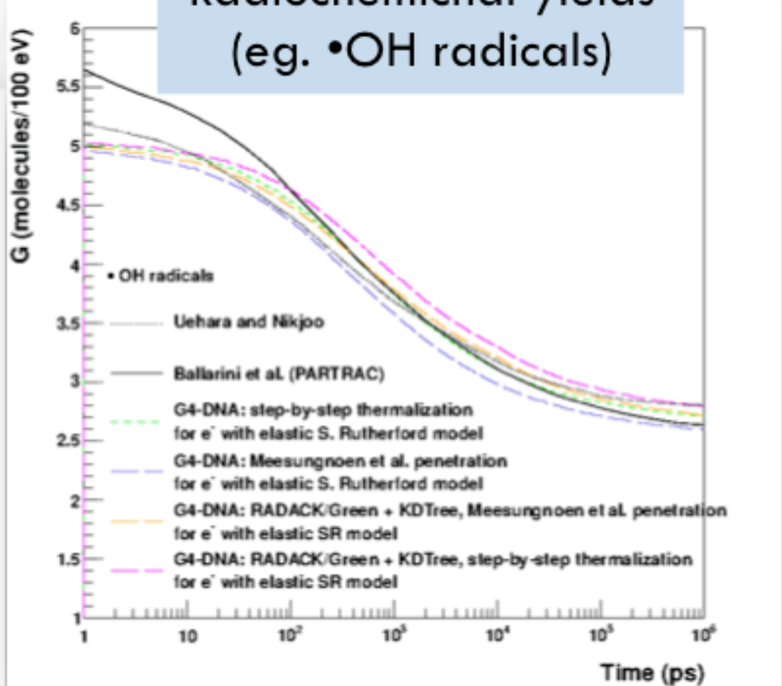
- Initiated in 2001 by the European Space Agency
- Purpose
  - extend Geant4 capabilities for the modelling of early DNA damages from ionising radiation in biological cells
  - including physical and physico-chemistry processes
    - water radiolysis
  - down to the eV and nanometer scales
- Status
  - A full component of the Geant4 toolkit



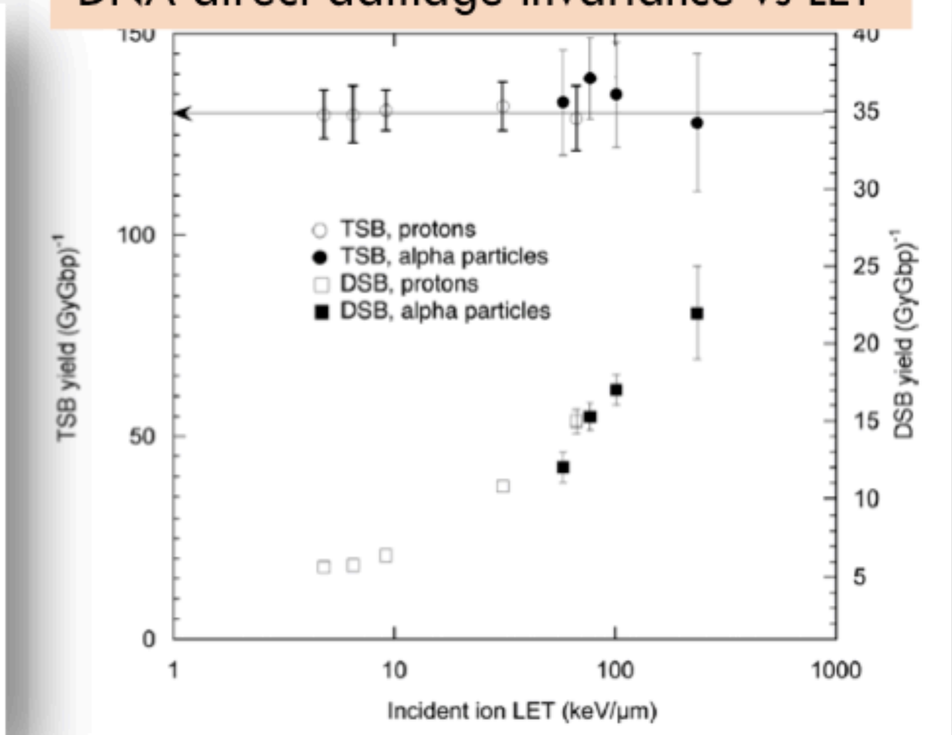
Accurate physics models (eg. e- elastic scattering)



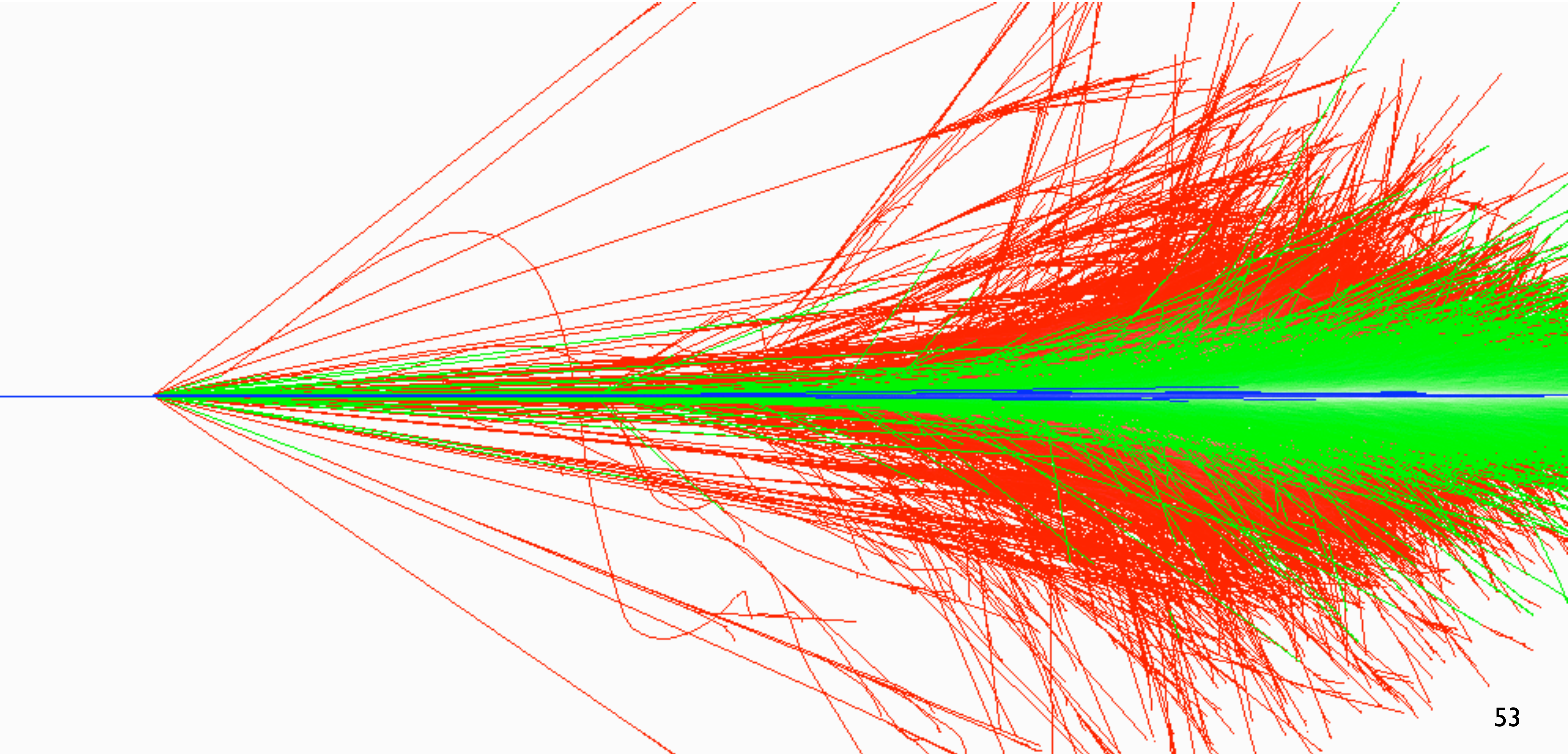
Radiochemichal yields (eg. •OH radicals)



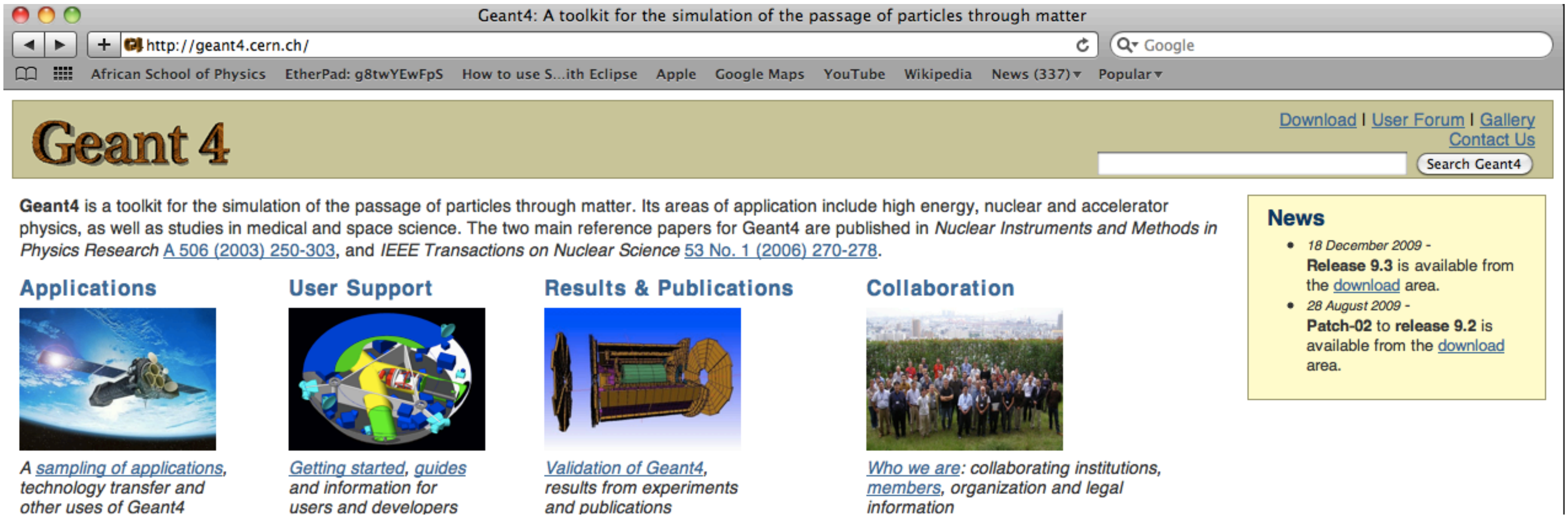
DNA direct damage invariance vs LET



Conclusions



More information...



- Can be found starting from: http://www.geant4.org
- The two main reference papers for Geant4 are published in **Nuclear Instruments and Methods in Physics Research A 506 (2003) 250-303, and IEEE Transactions on Nuclear Science 53 No. 1 (2006) 270-278.**
- Full week courses can be found under the "Events" section

Conclusions

- Geant4 has been developed to **simulate the passage of particle through matter**
- It initiated in the HEP community, but it is rapidly expanding in the fields of:
  - **Medical Physics**: imaging, beam-transportation, treatment planning
  - **Space Physics**: detector optimization, shielding
  - **Industrial applications:** shielding, SEE
- Geant4 is a mature package which results are constantly **validated** agains experimental data and other MC codes
- Open Source License: **everybody can contribute** to improve the code
- Many activities ongoing both to improve the physics description and to cope with technology changes

Acknowledgment

- I would like to thank all my Geant4 colleagues from which I took material for this slide in particular M. Asai (SLAC) for the material on Geant4 future directions