# GEANT4 TOOLKIT

African School of Physics -August 2010

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PH-SFT Group


# 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

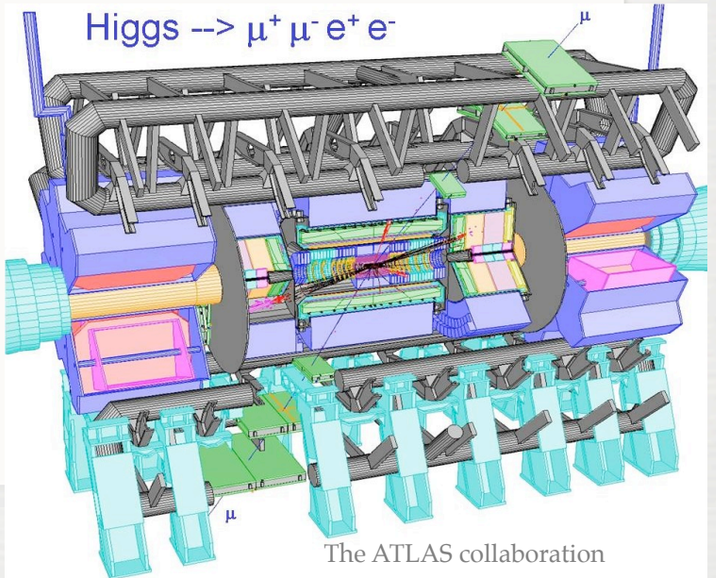
# INTRODUCTION

Geant4: GEometry ANd Tracking

# 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

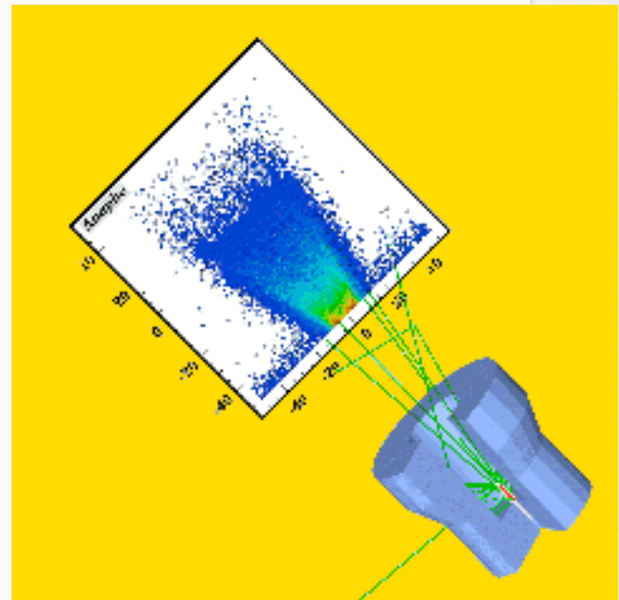
- A toolkit provides "general" tools to undertake (some or all) of the tasks:
  - tracking and geometrical propagation
  - modelling of physics interactions
  - visualization, persistency
- A toolkit enables you to describe your setup:
  - detector geometry
  - radiation source
  - details of sensitive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



The ATLAS collaboration

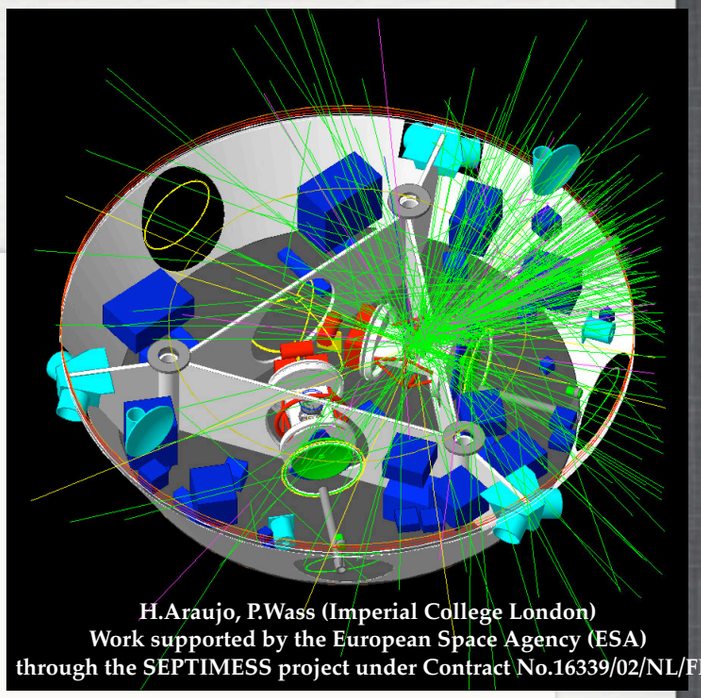
# Geant4

- 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 for maintaining it
- Requirements from:
  - current and future HEP experiments
  - medical and space science applications
- World-wide collaboration



National Institute for Cancer Research, Genova & INFN Genova

# Key Capabilities

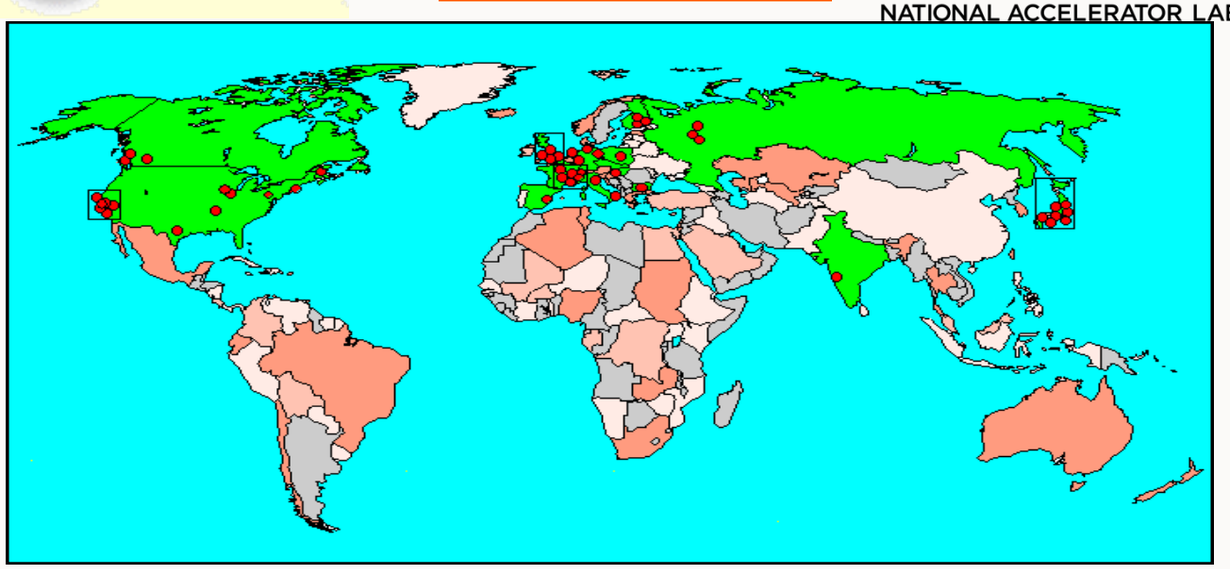



- 'Kernel': create, manage, move tracks
  - tracking, stacks, geometry, hits, …

    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

# World-wide Collaboration

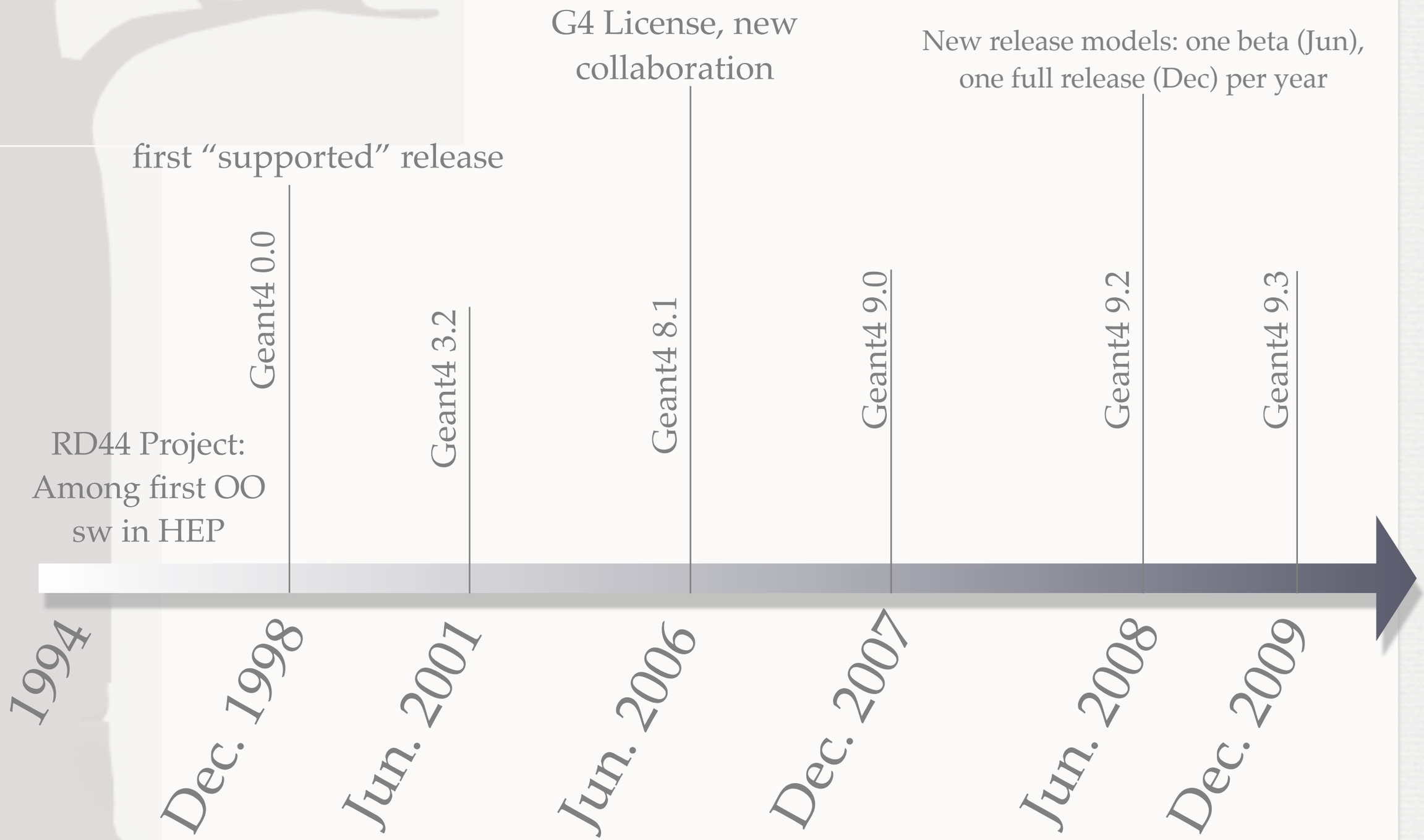


TRIUMF

Lebedev

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

# Geant4: 1994-2009



# PRACTICAL CONSIDERATIONS

- Starting off: what you need
  - Compatible platform
  - Need CLHEP foundation class library
  - One or more visualisation 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, ..
- Coding is needed – except if someone did it for you.
  - Modify existing C++ 'code' to describe your setup
  - Create you own class to describe eg a magnetic field.

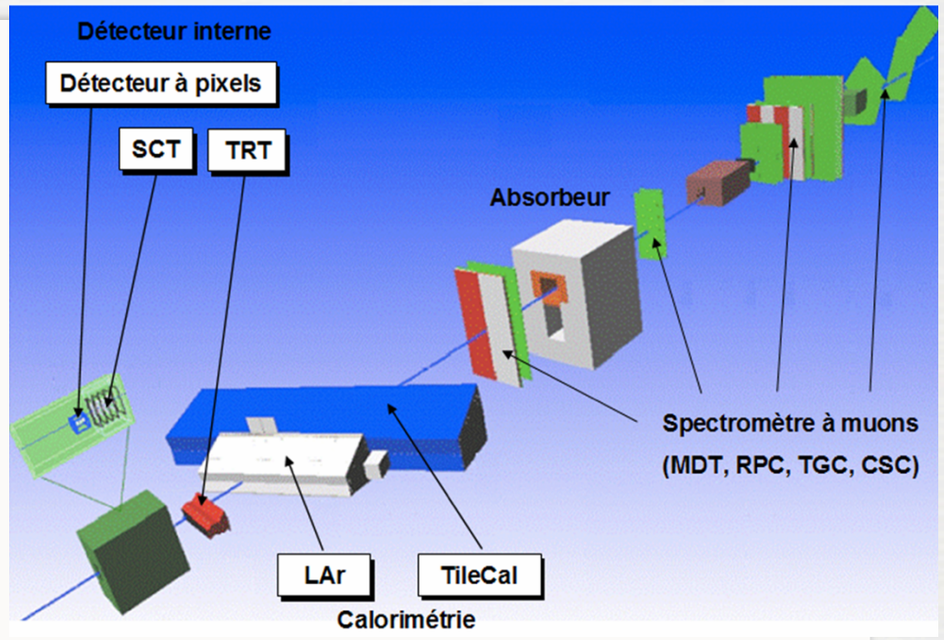
# PLATFORMS

- What works 'best' (used by developers, main testing)
  - Scientific Linux 4 or 5 and gcc 4.3 (HEP production)
  - MacOS 10.5 Leopard
- What we also support (tested + numerous users)
  - Windows (XP) & Visual C++
  - numerous users
- What we expect to work
  - Other Linux flavours with gcc 4.1 and 4.3
    - Possibly with fewer options, eg missing some visualisation
- What others 'ported' and check
  - Sun Solaris

# GEOMETRY AND VISUALIZATION

# Building G4 Applications

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

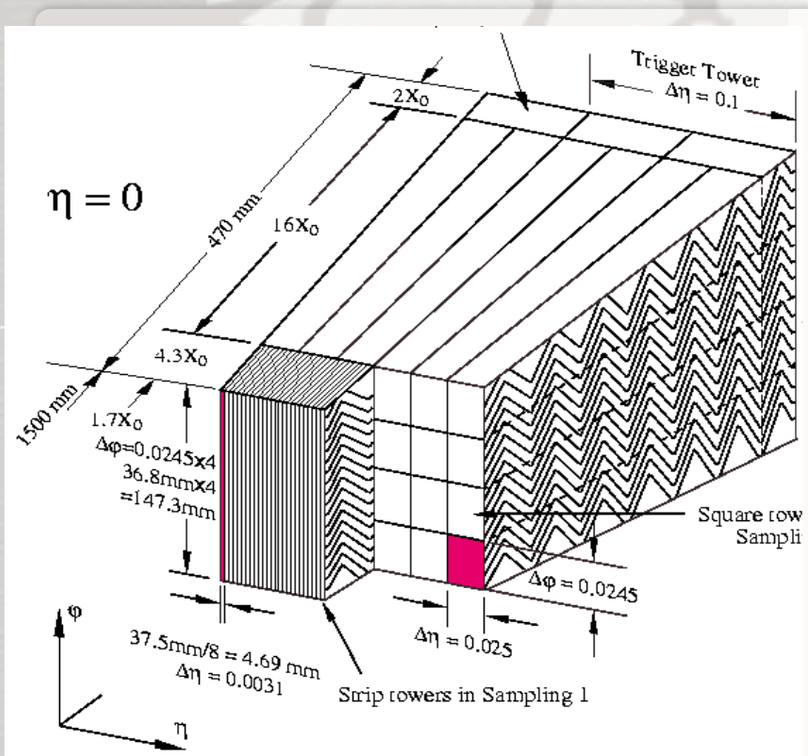


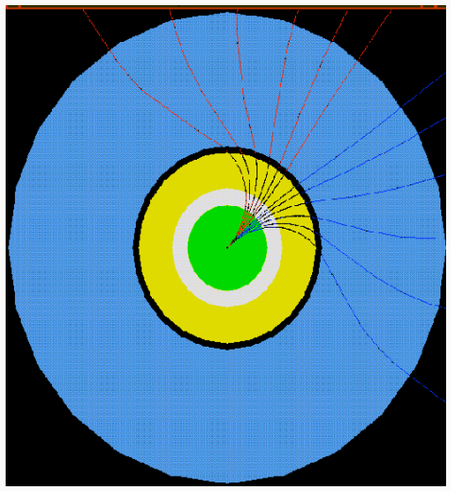

ATLAS Test-beam setup 2004

- 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

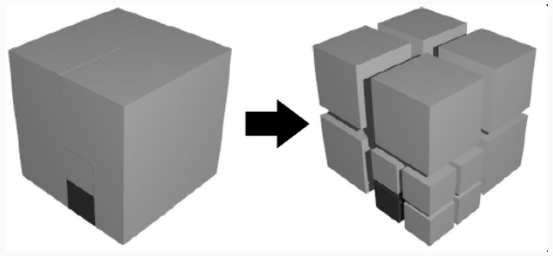


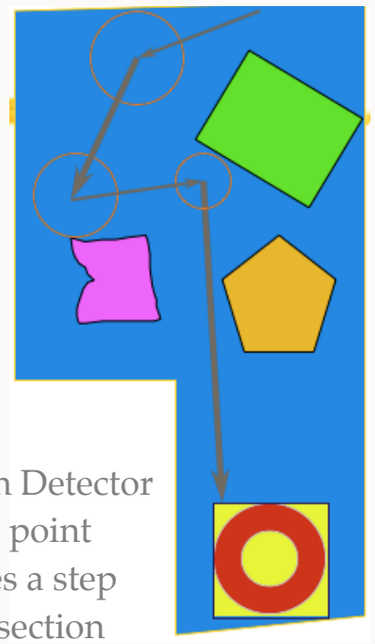
- All charged particles 'feel' the effect of EM fields

  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



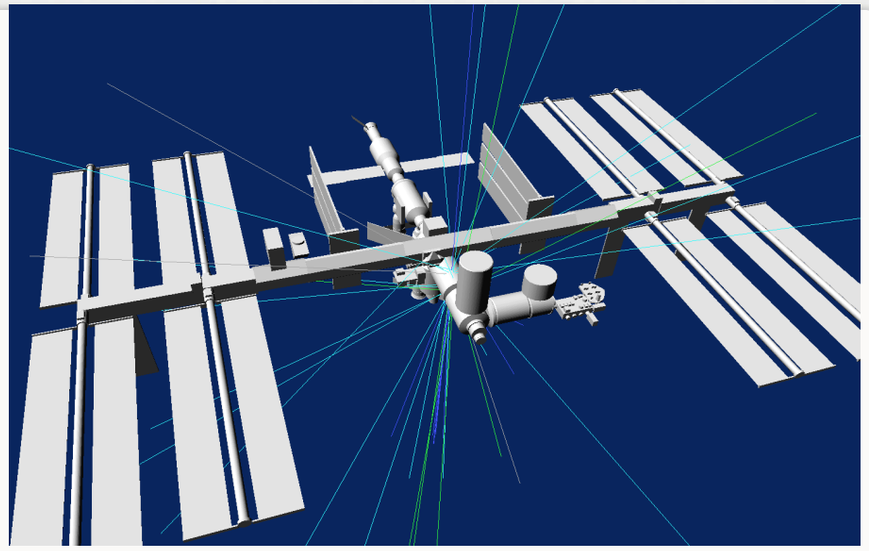
Automatic optimization of complex geometries (voxelization): efficient tracking



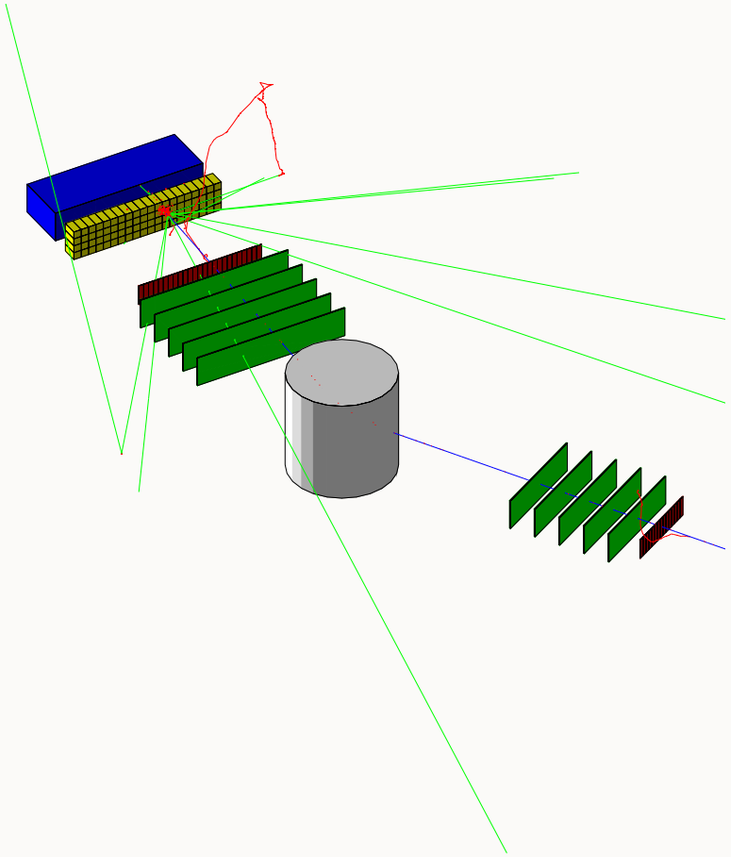
Navigates in Detector
☑ Locates a point
☑ Computes a step
Linear intersection

# 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)



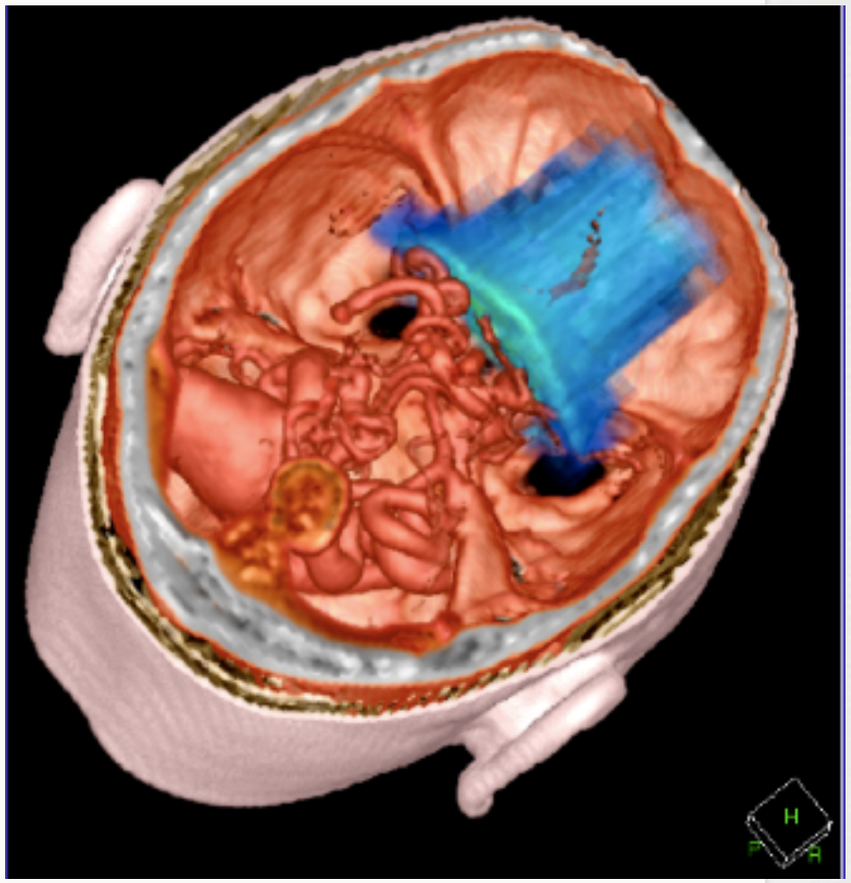
OpenGL driver



DAWN driver

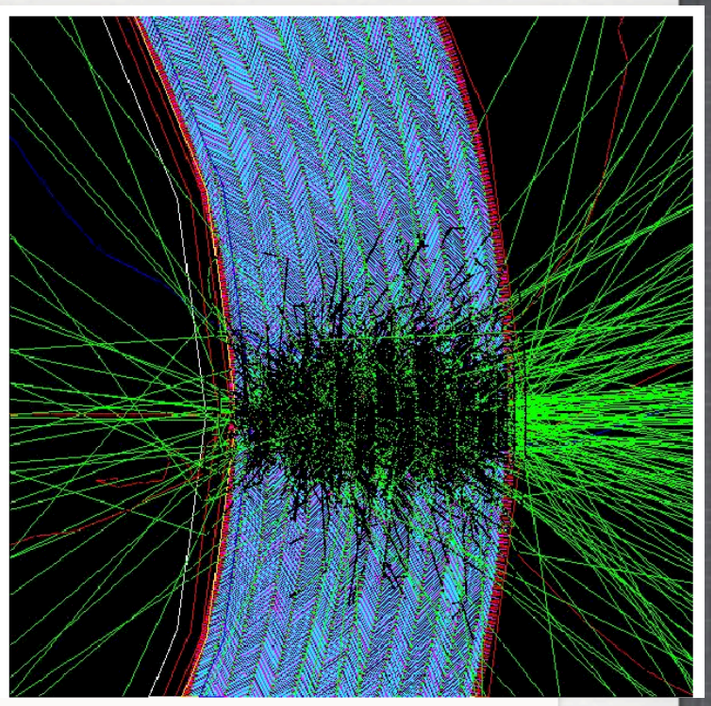
# An Advanced Tool: gMocren

- 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



# EM PHYSICS

# Processes

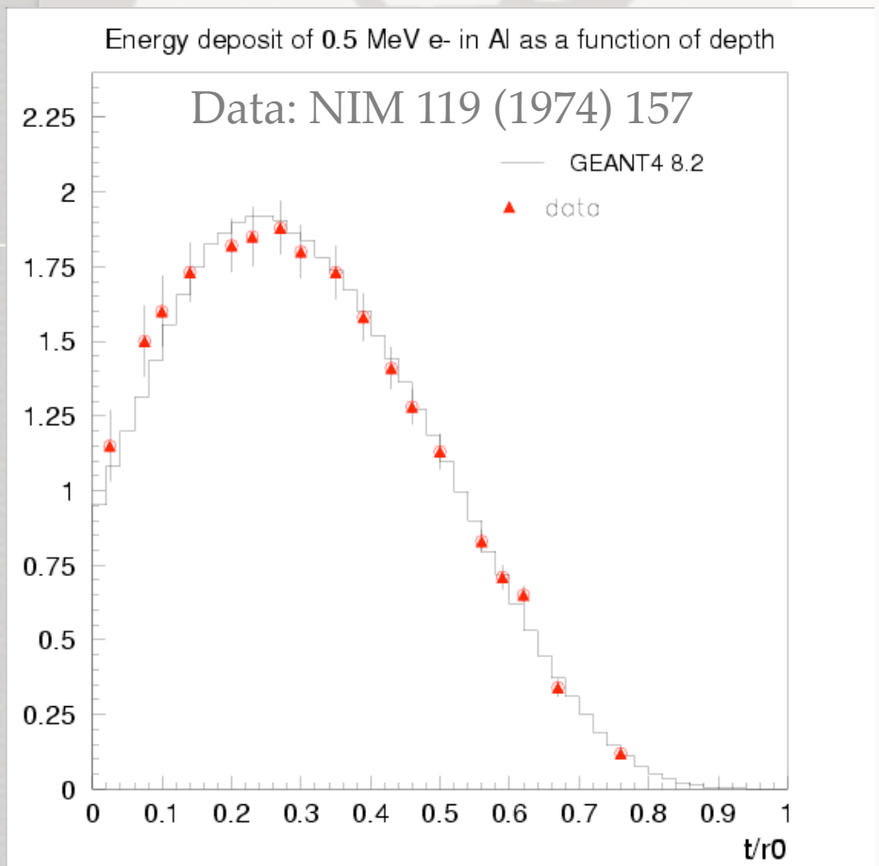


- Gammas:
  - Gamma-conversion, Compton scattering,

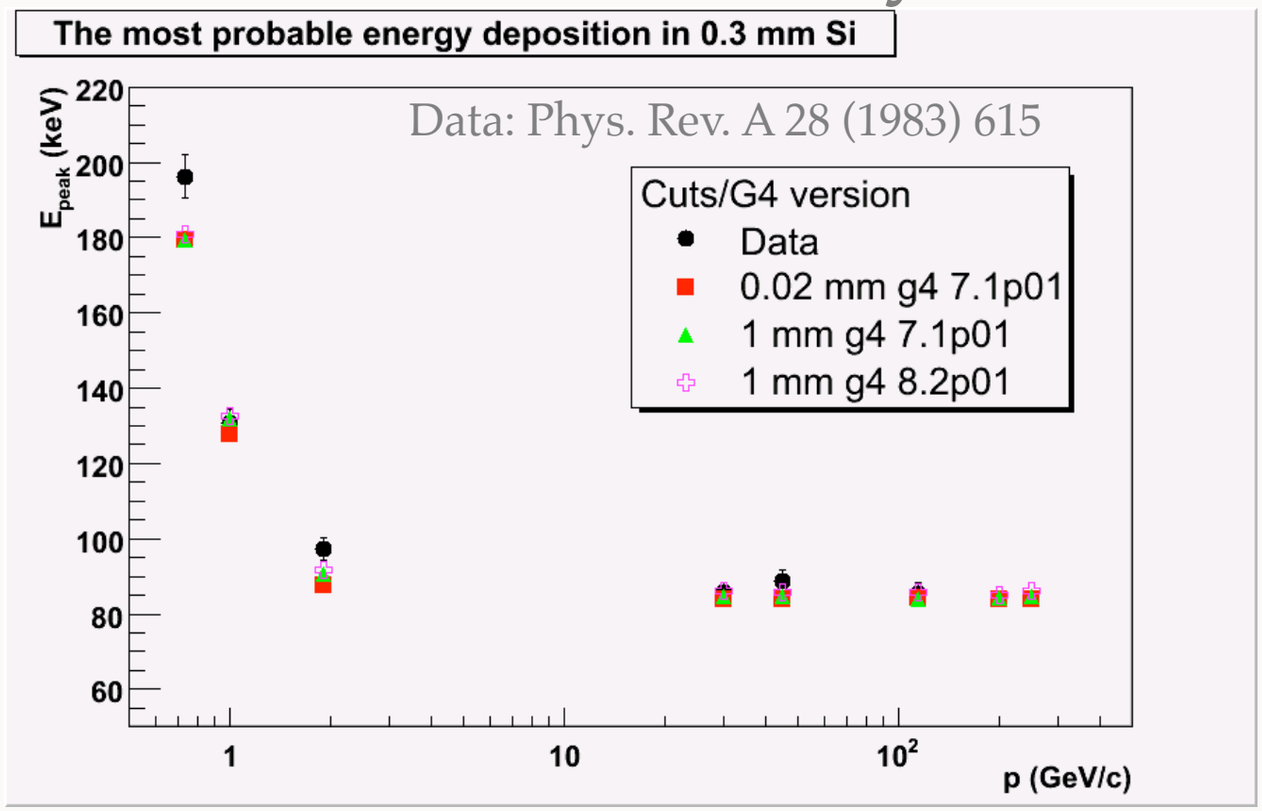
    Photo-electric effect
- Leptons(e, μ), charged hadrons, ions
  - Energy loss (Ionisation, Bremsstrahlung), Multiple scattering, Transition radiation, Synchrotron radiation, e+ annihilation.
- Photons:
  - Cherenkov, Rayleigh, Reflection, Refraction, Absorption, Scintillation
- High energy muons
- A choice 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

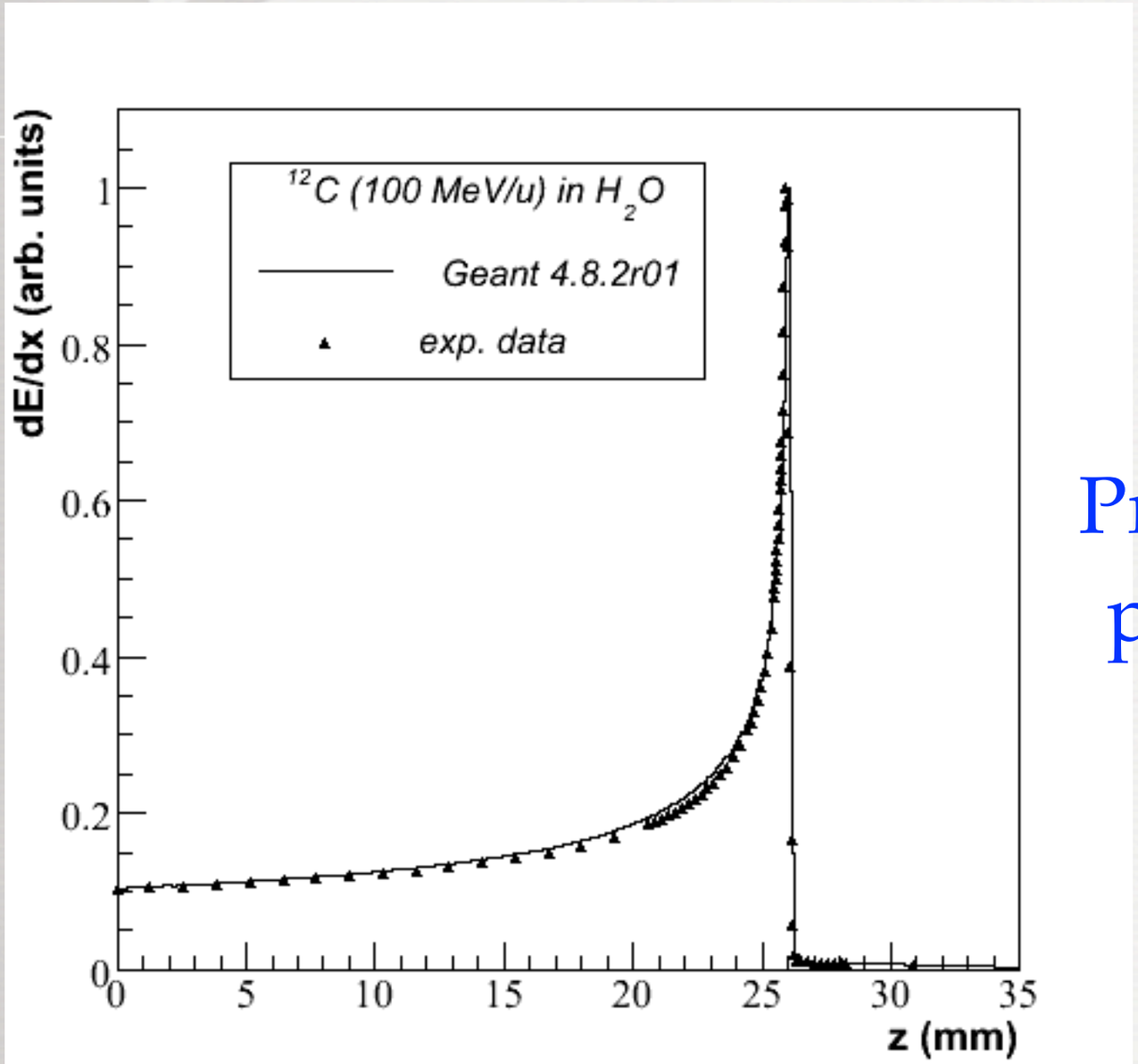



## Ionisation in thin layers




- 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

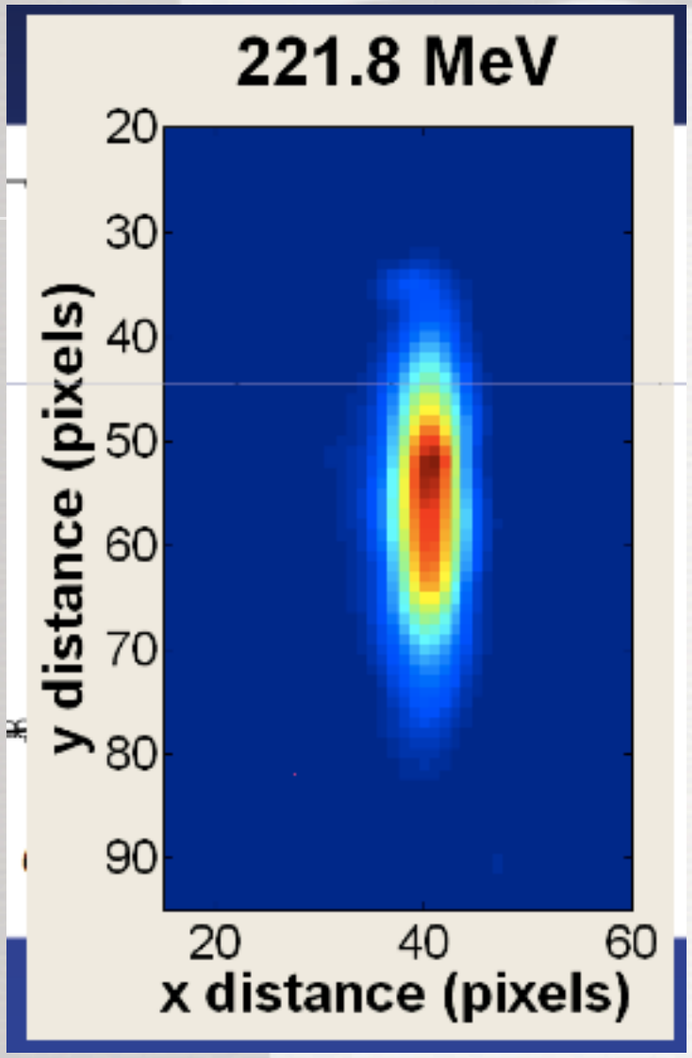
# Validation: Medical Physics

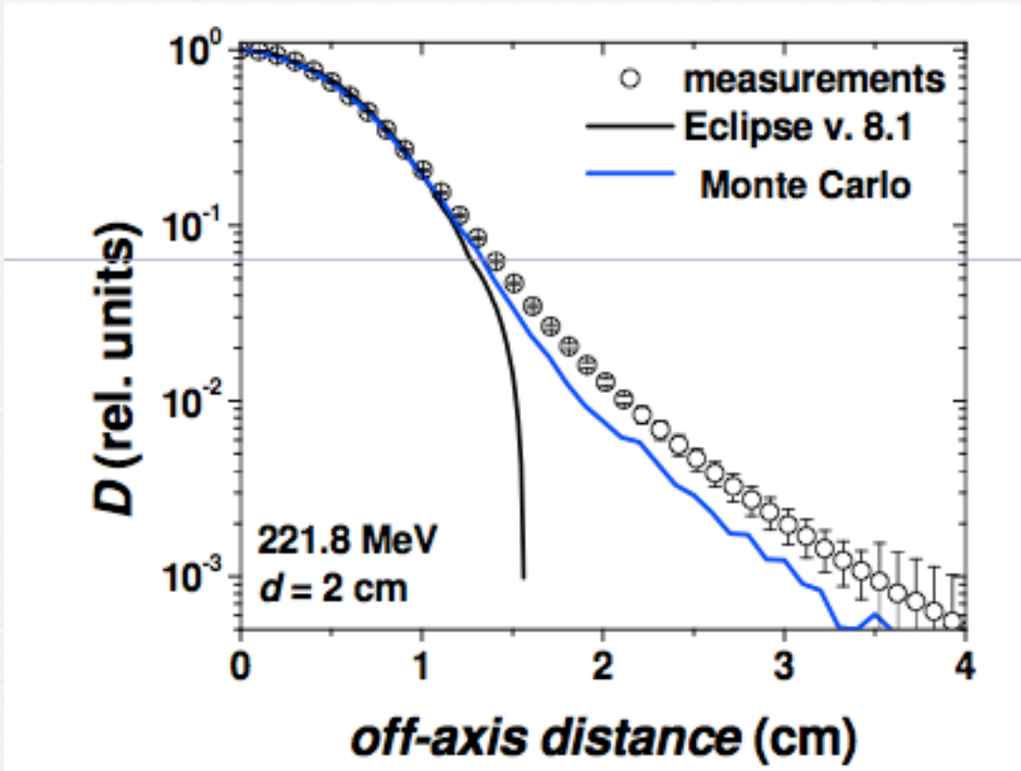



Bragg Peak in water
for a 100MeV/u $^{12}C$ beam
Precision of the position of the peak is the key observable to judge simulation quality

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

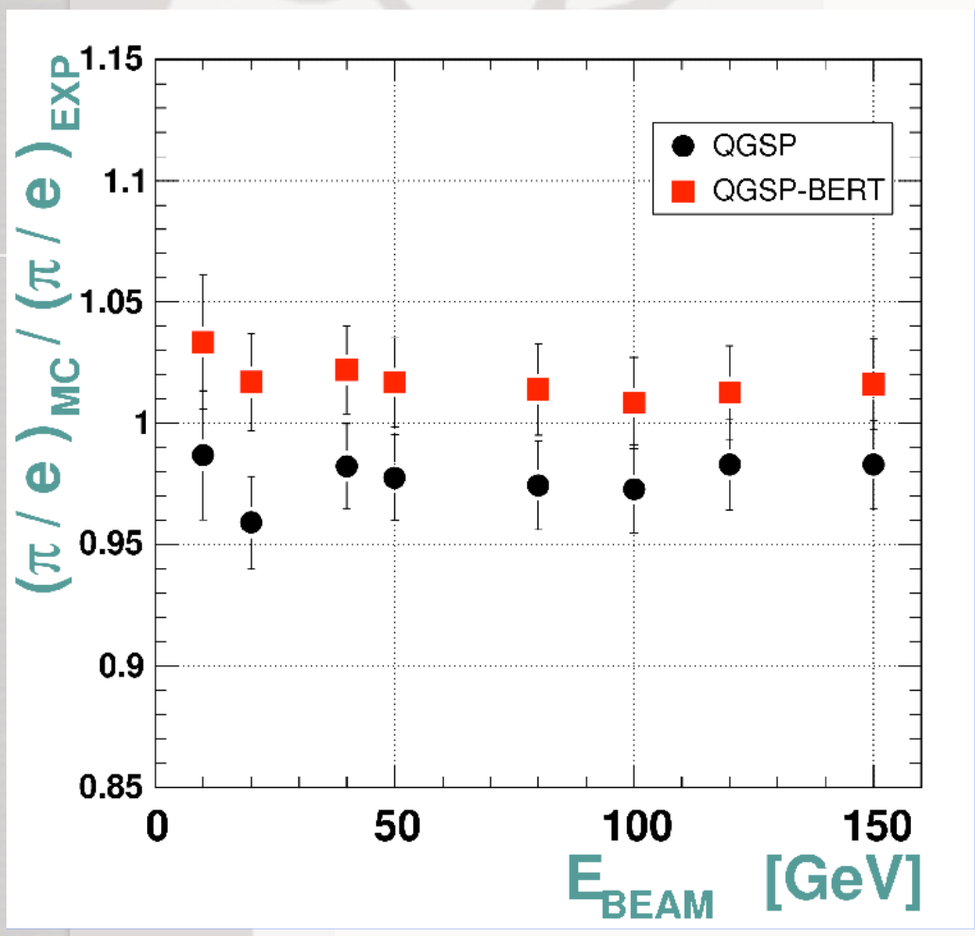
- Hadronic physics is included in Geant4
  - a powerful and flexible framework and
  - implementations of cross-sections & models.
- A variety of models and cross-sections
  - for each energy regime, particle type, material
  - alternatives with different strengths and computing resource requirements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

# Models Summary

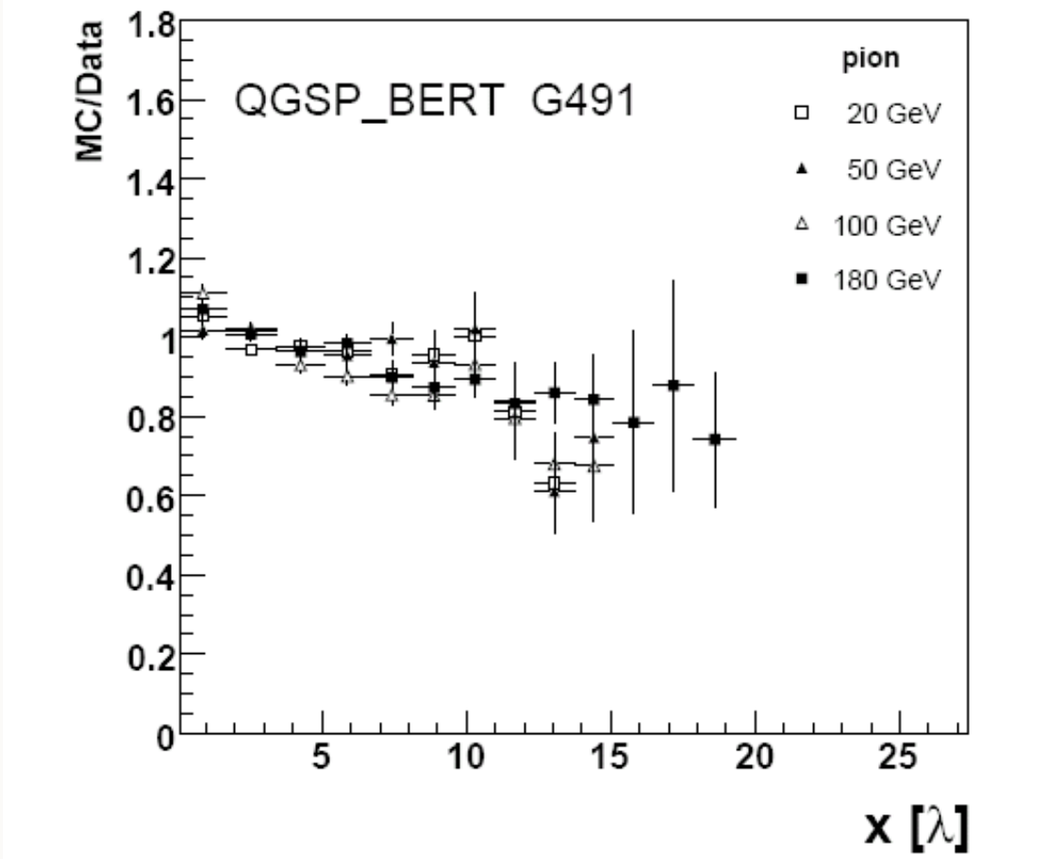
- Parameterized models (1997): all E and particles - data driven
- Quark-Gluon-String, "QGS": p,n,k,π of high energy ($E_{kin}$>20 GeV) See Sec. IV, Chap. 22 of Geant4 Physics Reference Manual and bibliography within
- Fritjof, "FTF" (new developments): p,n,k,π of high energy ($E_{kin}$>10 GeV) Nucl. Phys. 281 289 (1987)
- 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
- Chiral Invariant Phase Space Decay,"CHIPS" (new developments): all E and particles. Eur. Phys. J. A 8, 217-222 (2000) ; Eur. Phys. J. A 9, (2001) ; Eur. Phys. J. A 9, (2001)

# Validation: Examples

Response to pions: ATLAS HEC



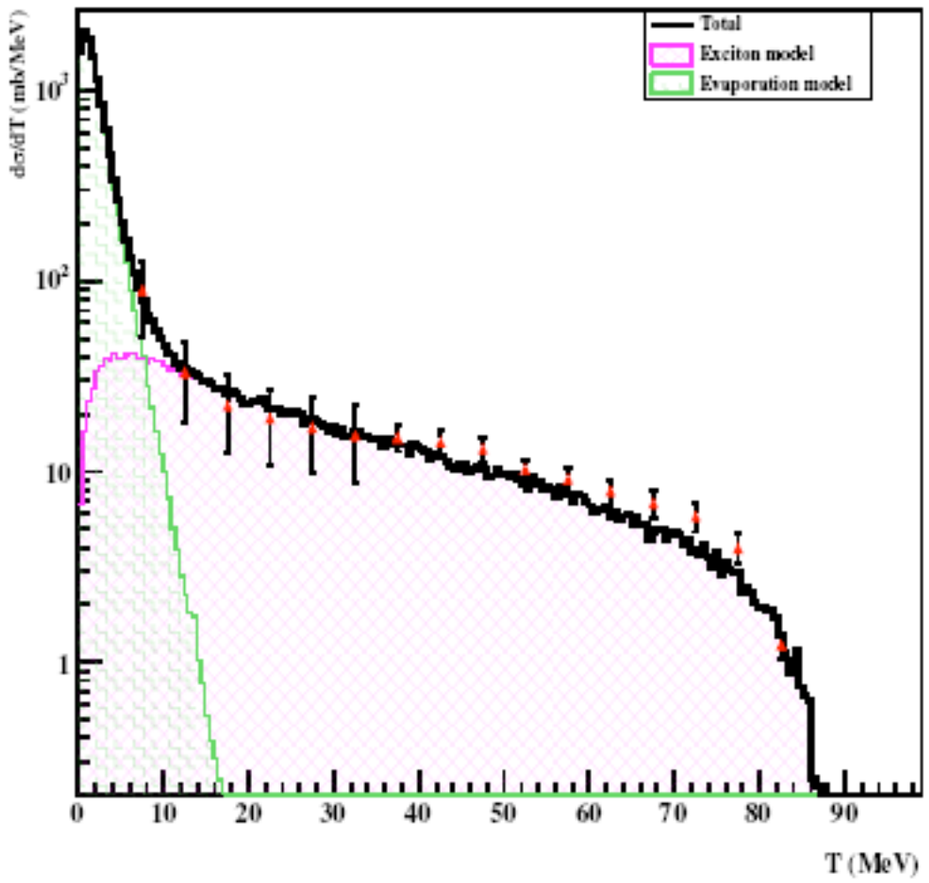

Longitudinal Shower shape: ATLAT TileCal




- 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

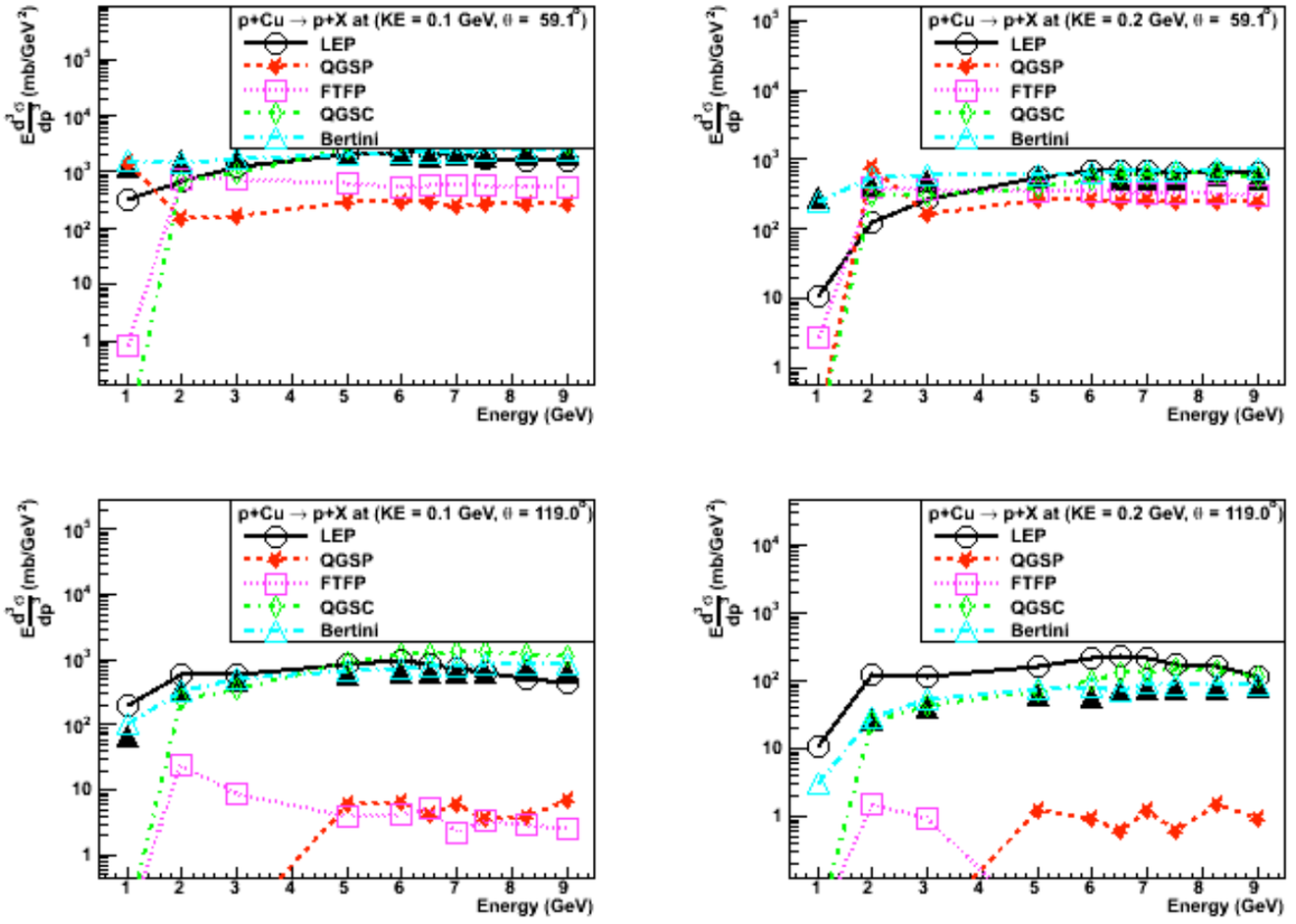
# More Validation Examples

Neutron cross section




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

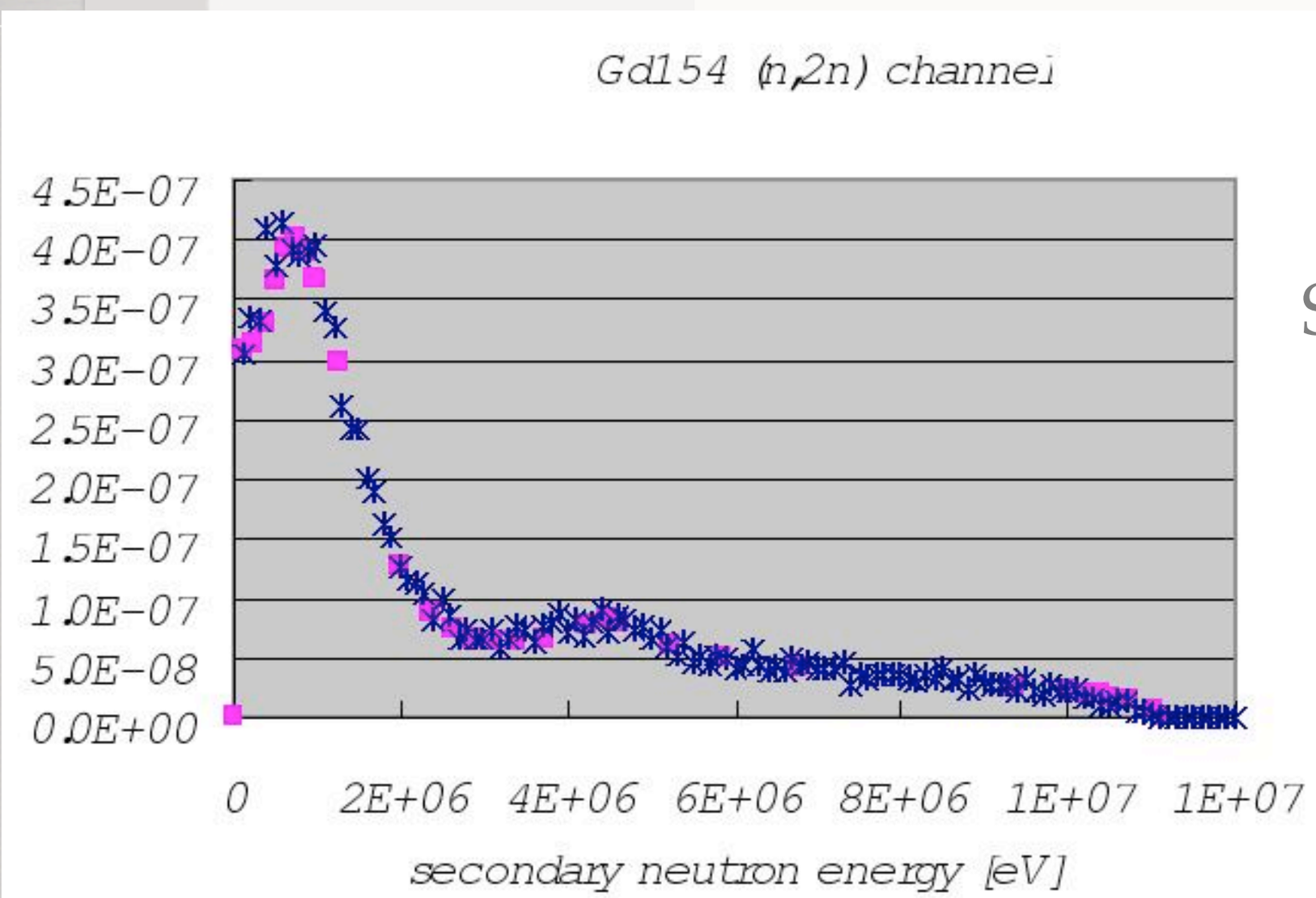
p cross-sections for various models at different angles




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....

# 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

# Physics Lists: Some Examples

- LHEP is the fastest for CPU
  - uses the LEP and HEP parameterized models for inelastic scattering
  - Started from GHEISHA
- QGSP refines high energy:
  - used theory-driven modeling for reactions of πs, Ks, and nucleons above ~ 15 GeV.
  - Quark Gluon String Model

    for the 'punch-through' interactions of the projectile
  - A Pre-equilibrium decay model

    with an extensive evaporation phase to model the nucleus 'after the punch'.
- QGSC
  - similar to QGSP, but using CHIPS for fragmentation
- QGSP_BERT
  - Adds Bertini cascade

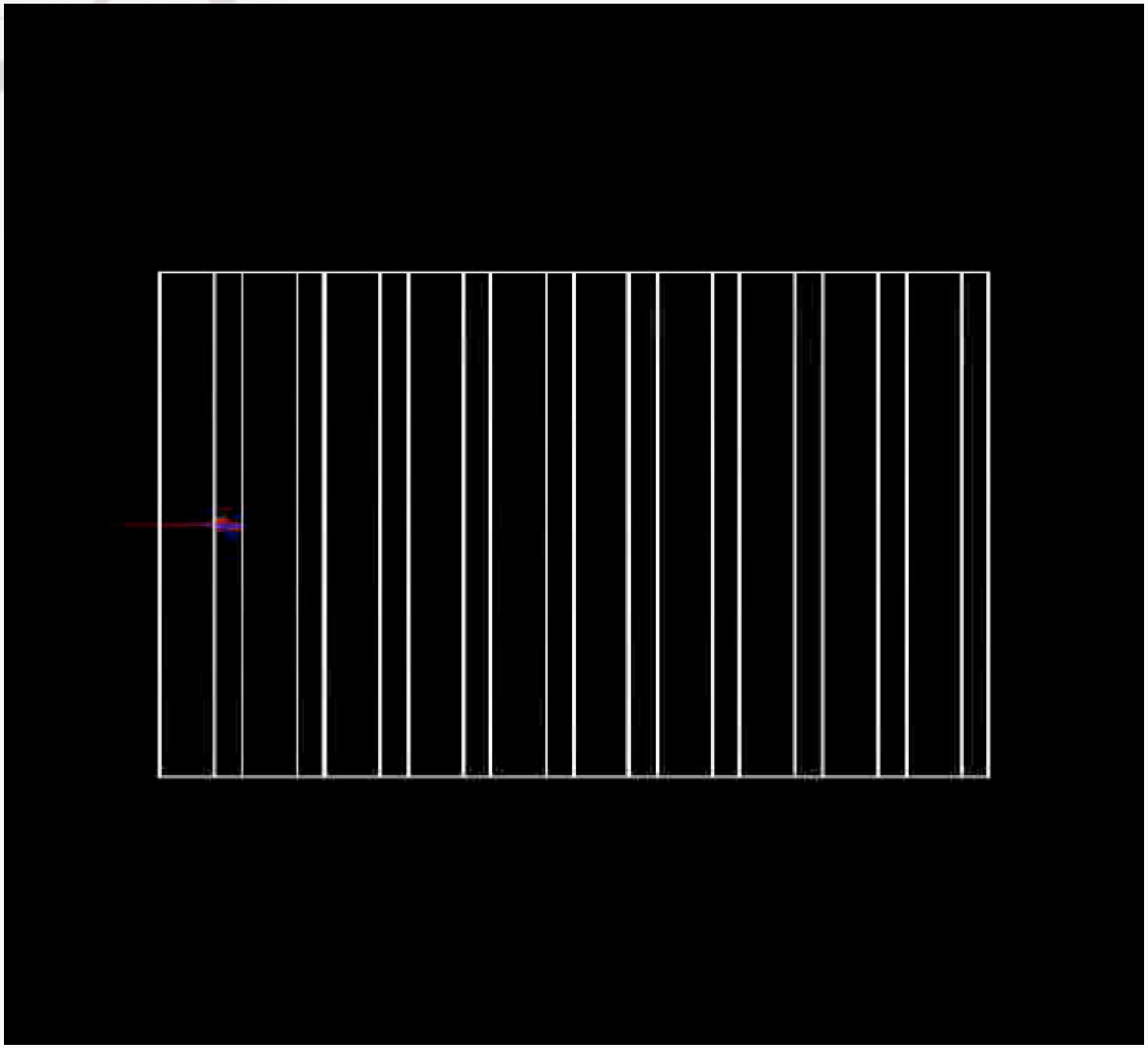
    for p, n, & π interactions at Ekin < ~ 9.5 GeV
  - In production in the LHC experiments
- FTFP varies the string interaction
  - starts with QGSP and replaces instead the string with a diffractive string excitation

    similar to that in FRITJOF, and the Lund fragmentation functions.

# Concrete Examples: EM

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

# Concrete Examples: EM



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# Concrete Examples: HAD

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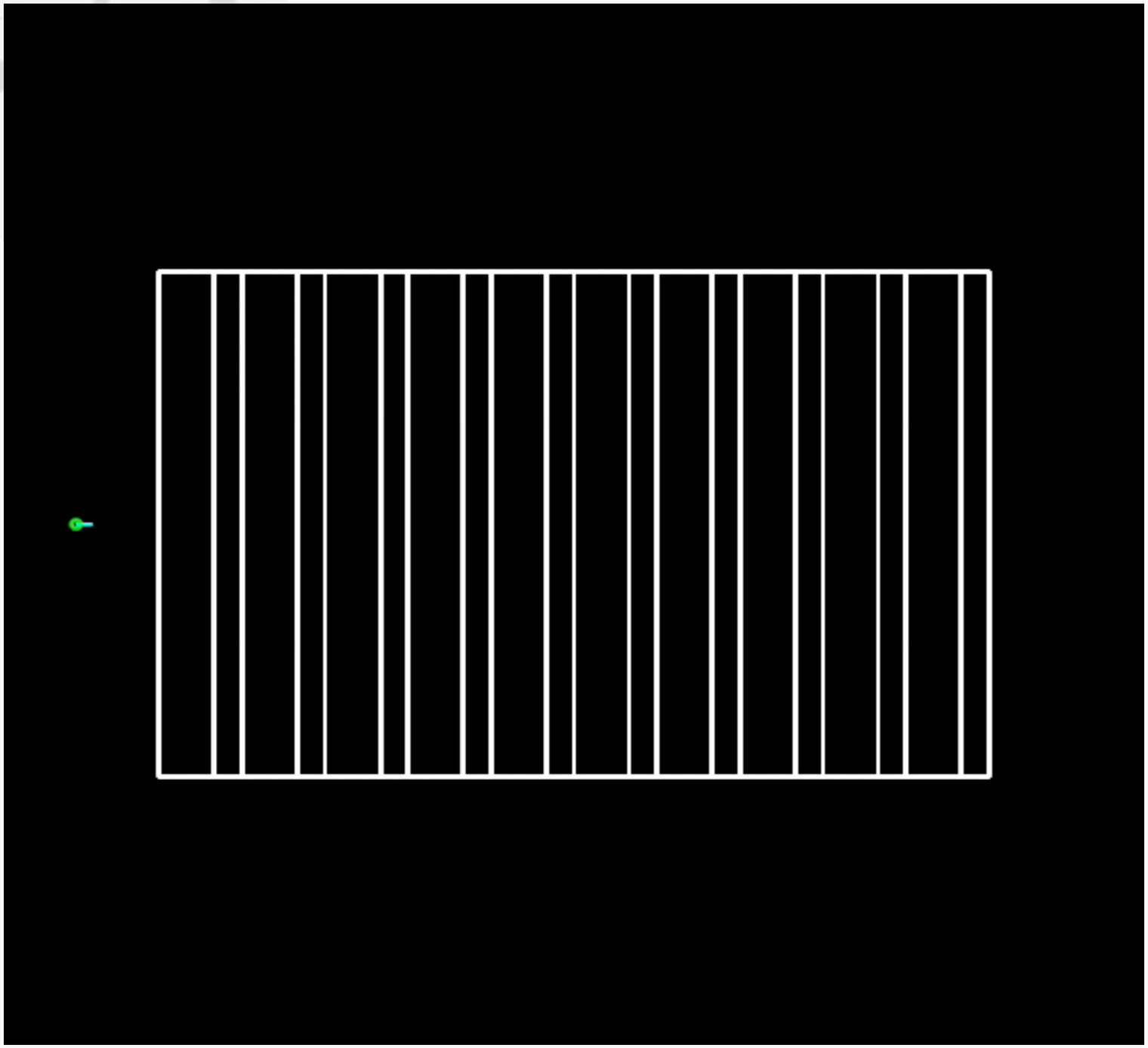

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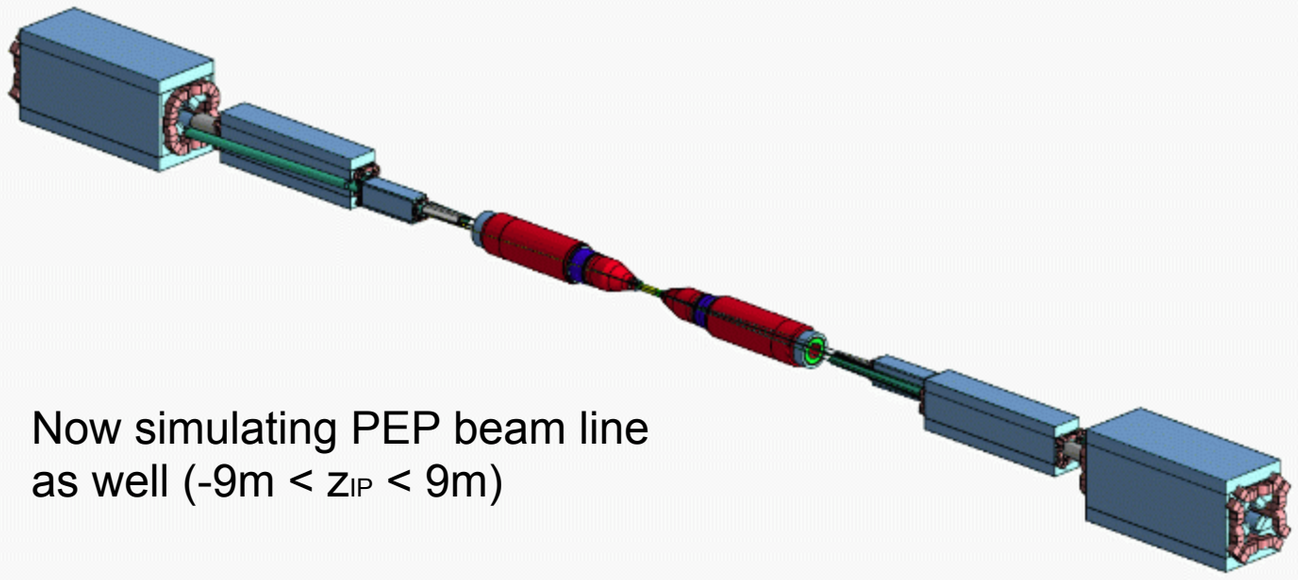
# A Concrete Example: What You Have Seen

- 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 the light front

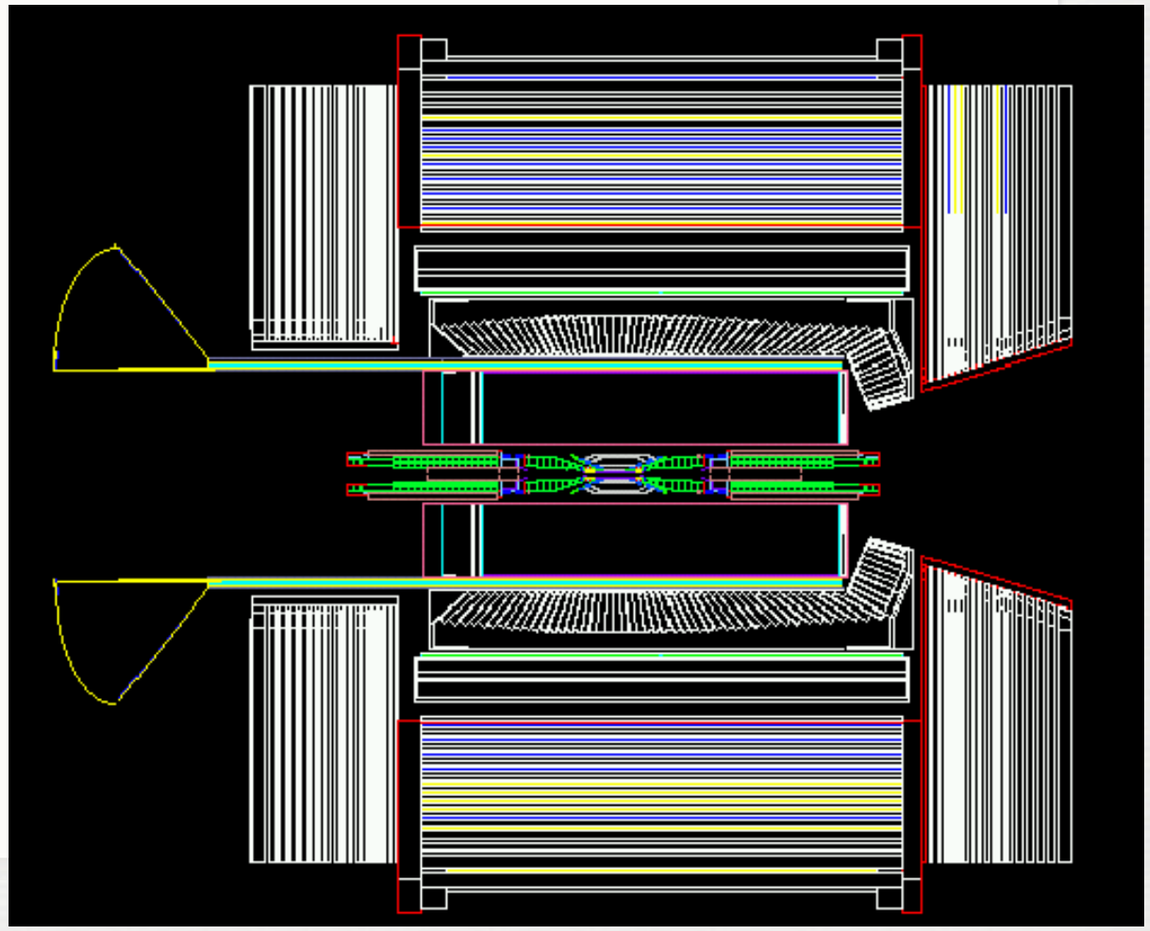
# HEP APPLICATIONS

# The Past: BaBar (@ SLAC)

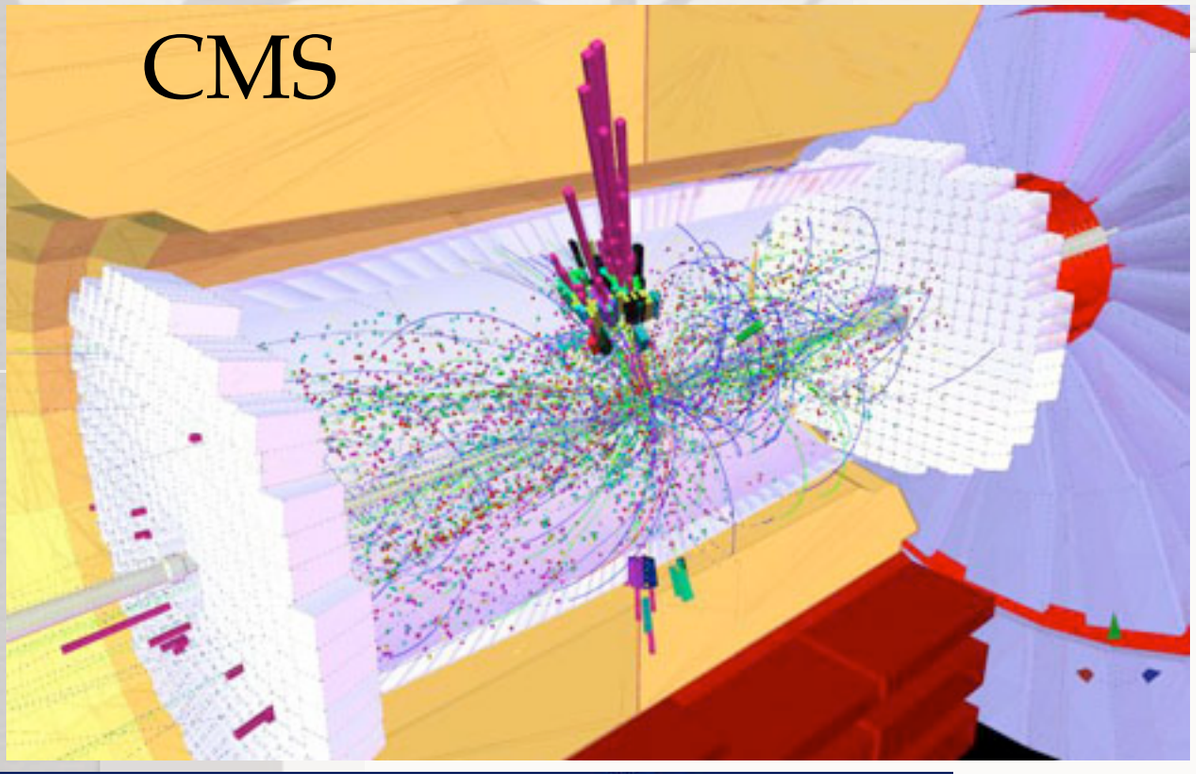


Now simulating PEP beam line as well ($-9m < z_{IP} < 9m$)

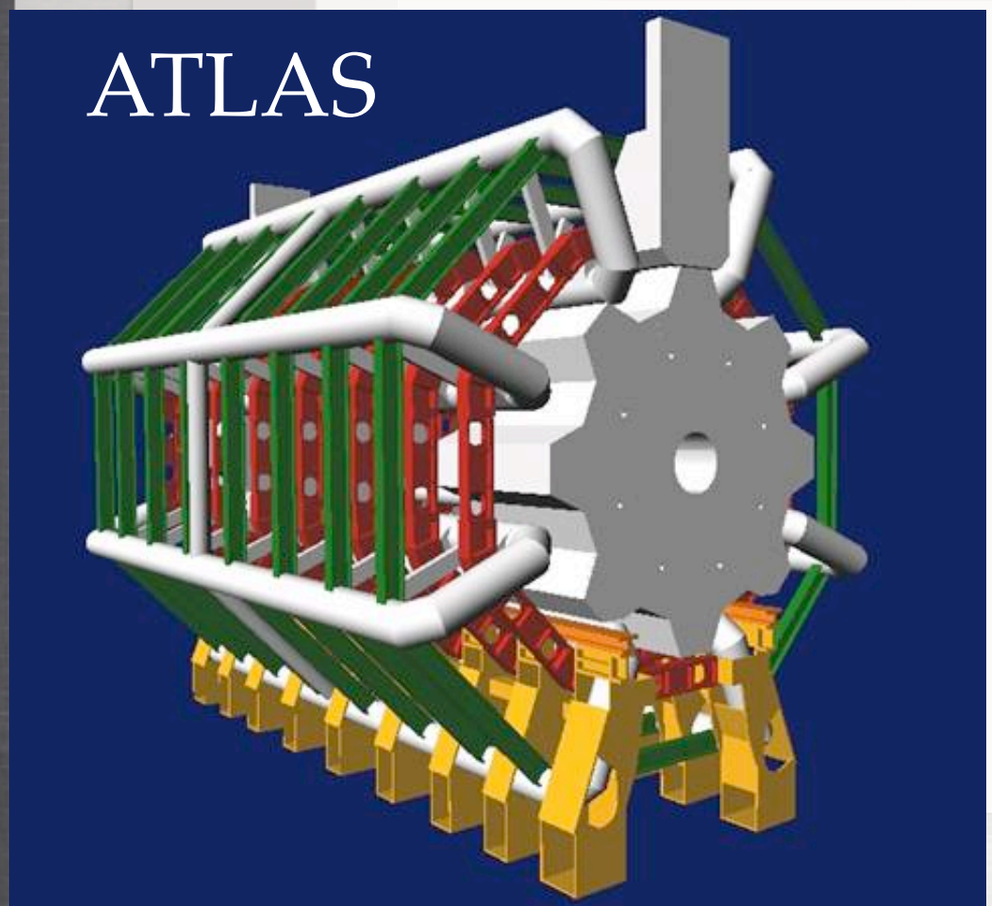
- Pioneer experiment in HEP to use G4
- Started in 2000
- Simulated more than $2x10^{10}$ events

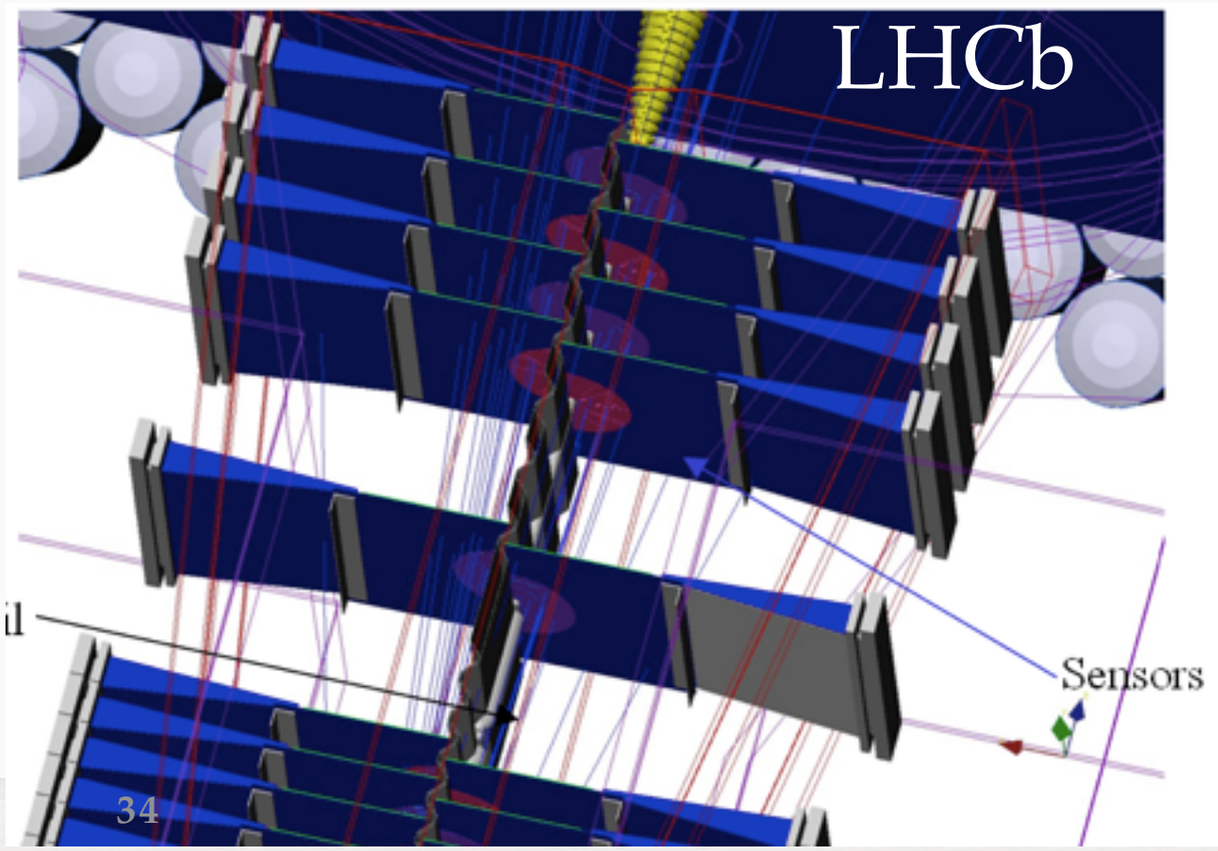


# The Present: LHC (@CERN)

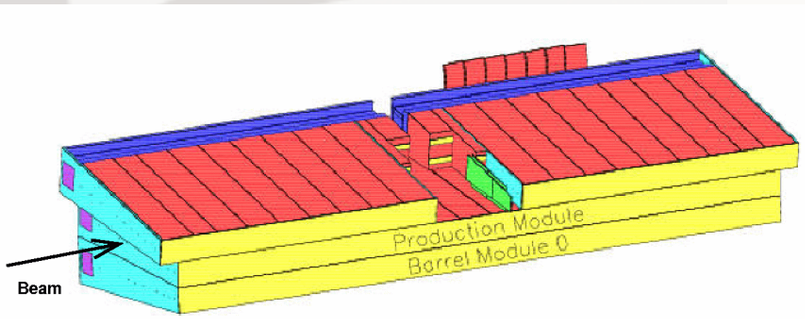


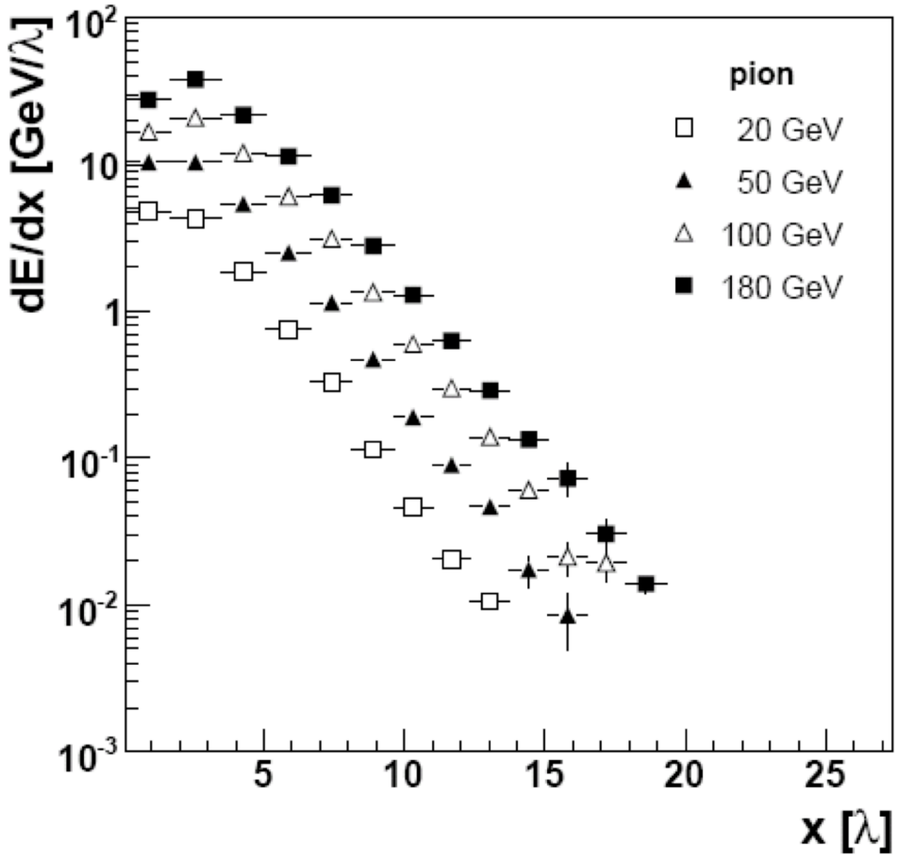

- Massive production on the GRID (distributed computing)
- More than two billions events generated
- Geant4 for used to: develop analysis, calculate background/acceptance corrections, (ATLAS) extract calibration constants for hadrons

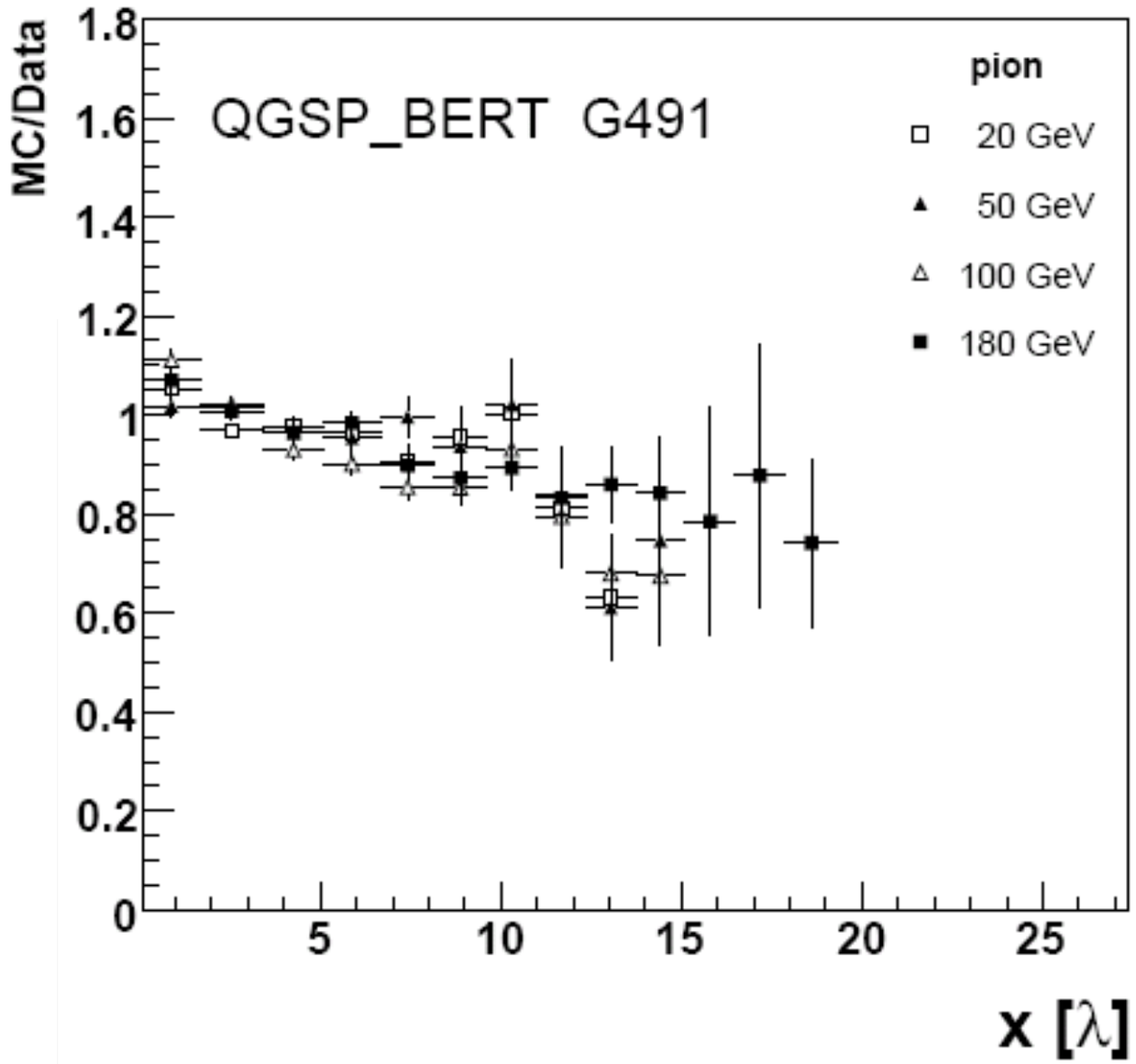


# Pion Longitudinal Shower Profile In Stand-alone ATLAS TileCal Test-beam At 90deg

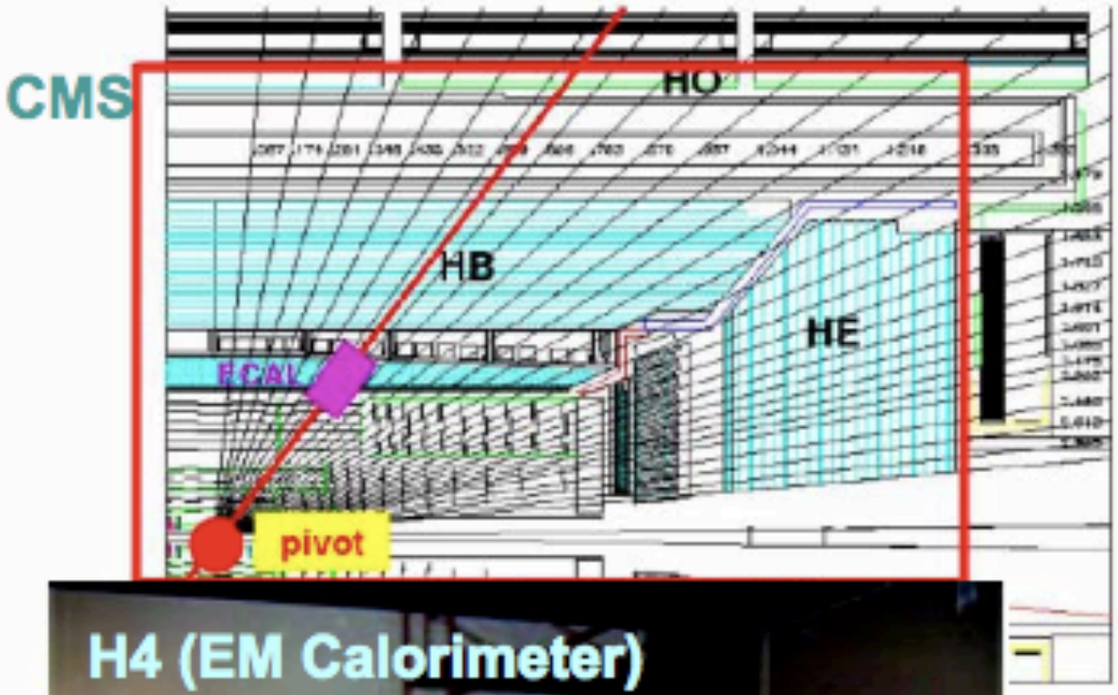


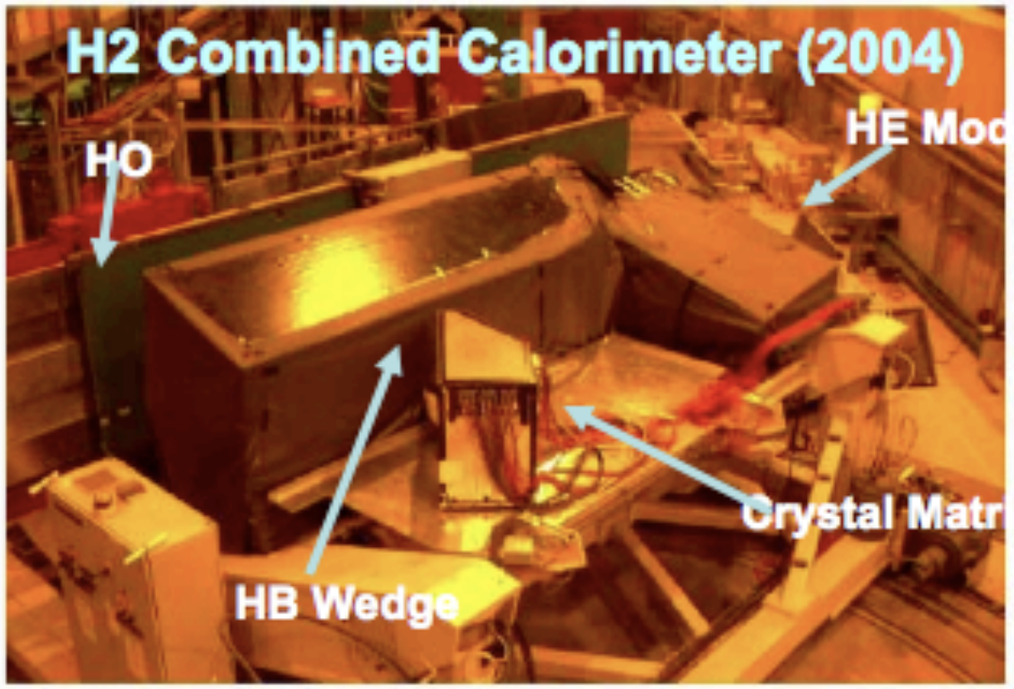



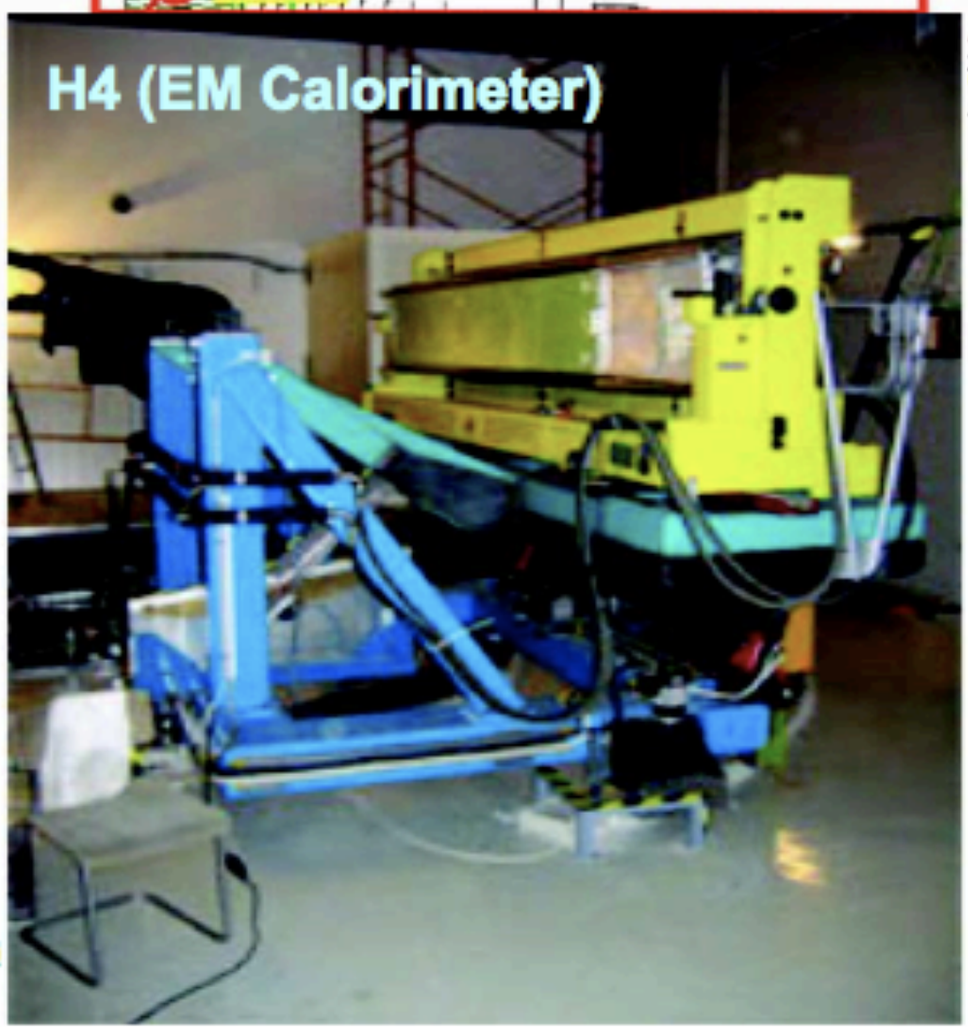



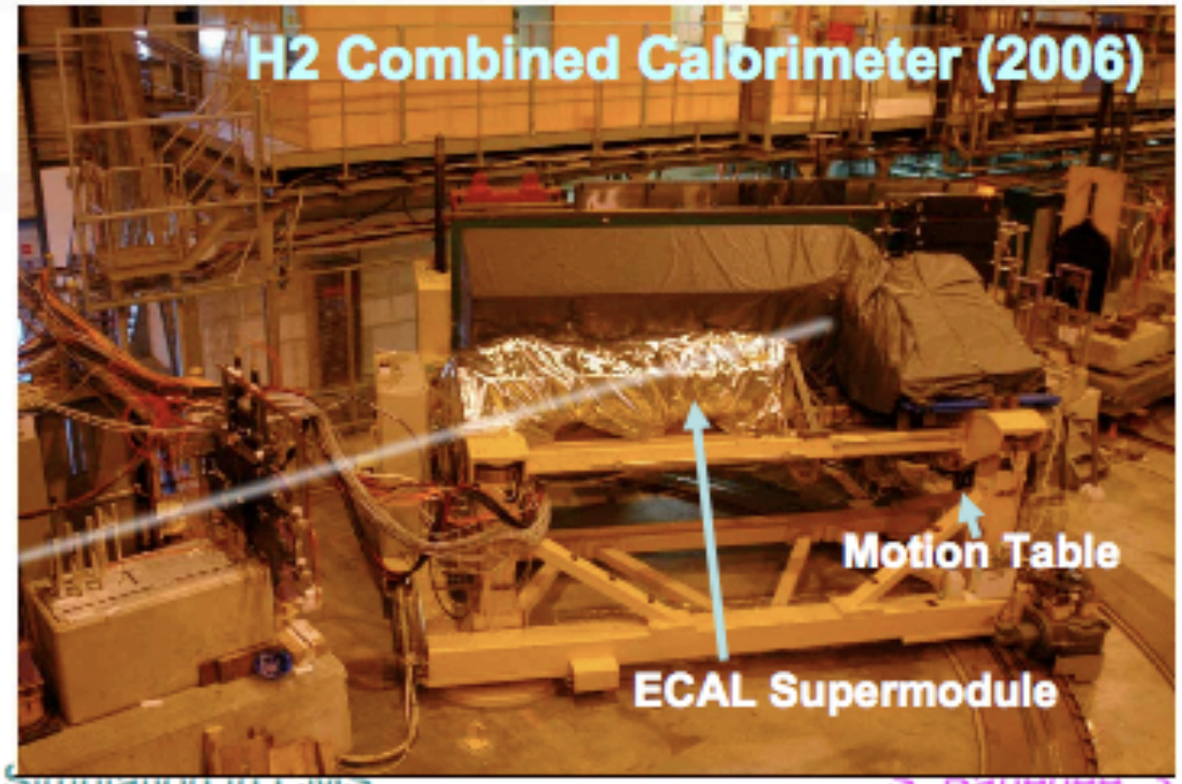

For Protons : -(20%-40%) at 10 λ .

# CMS Test Beam Efforts



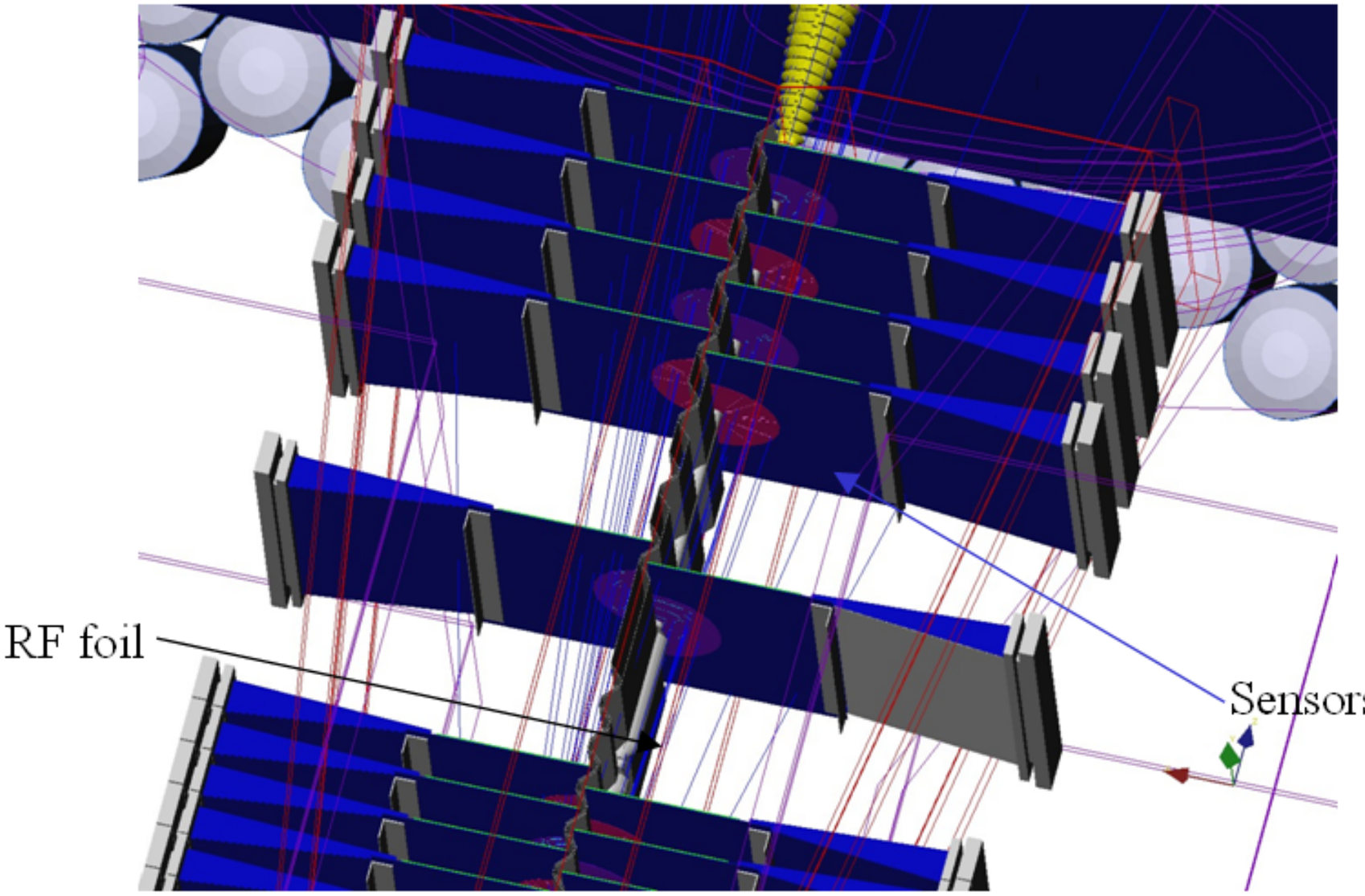



Geant 4

# Geant4 at the LHC Today




Complicated geometry
Details are very important

Geant4 can handle it!!

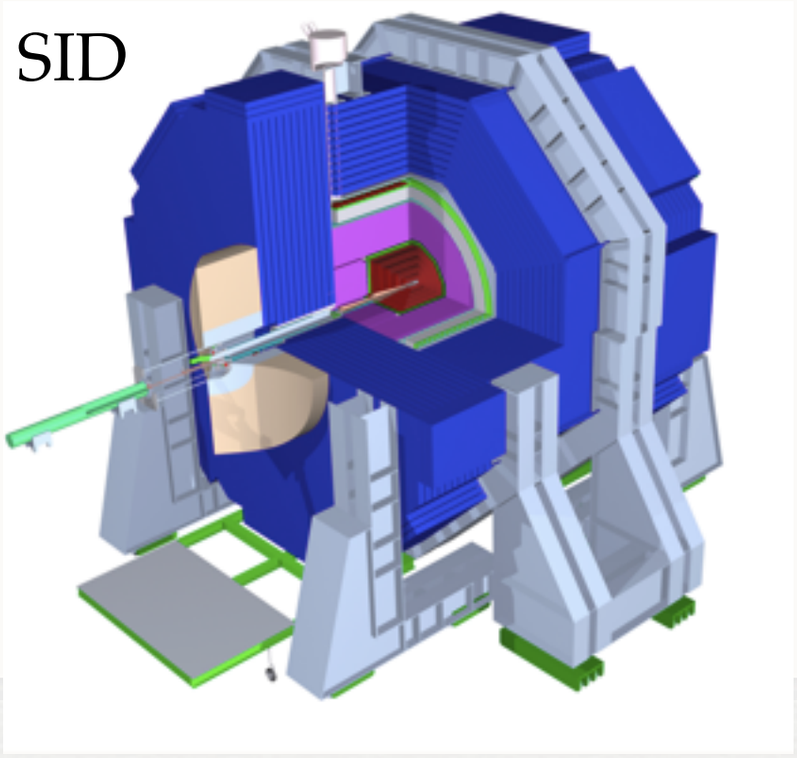
**LHCb Vertex Locator description**

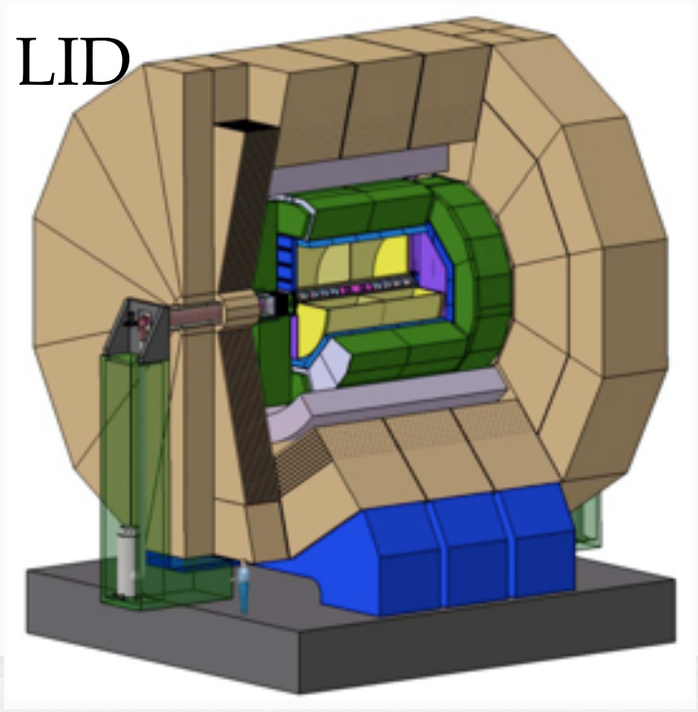
Albert De Roeck (CERN)24

# The Future: ILC

- International Linear Collider: R&D phase, physics program will be driven by LHC discoveries. Need to study different detector technologies and setups

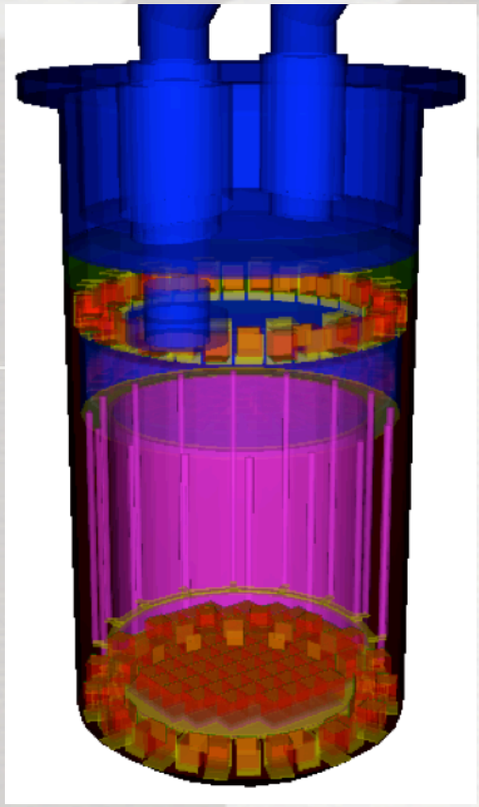
- Geant4 offers flexibility for fast but detailed description of different combinations of materials/ layouts



# NEAR "HEP"

# Underground Experiments



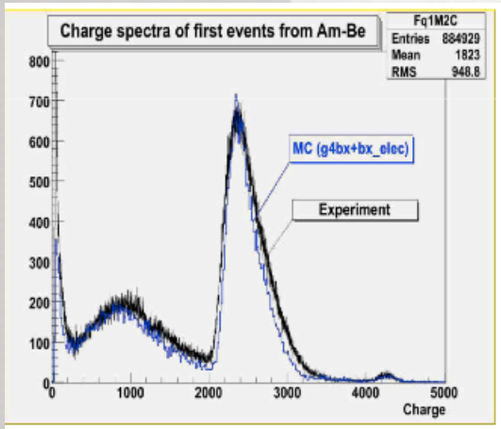
A. Kish (U. Zurich), I. Machulin (Kurchatov Institute)

- G4 Simulation of XENON100 detector (dark matter searches)
- But also: KamLAND, Borexino

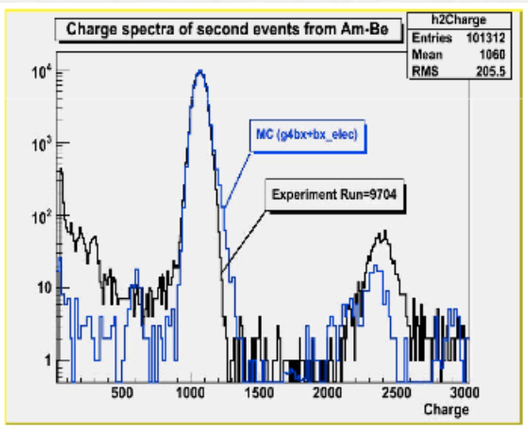
Development with simulation of the position reconstruction algorimths



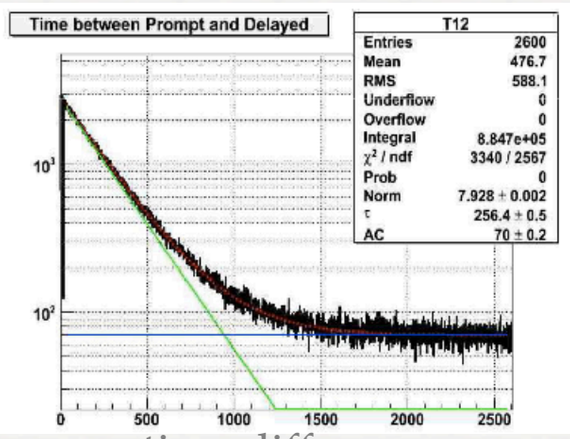

## Borexino results




Prompt signal from Am-Be source

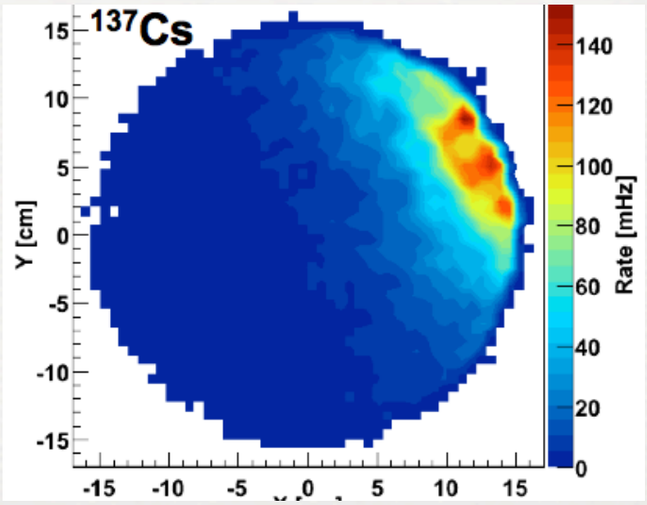



Delayed signal from Am-Be source




time difference:
n lifetime in Borexino scintilaltor

$\tau$(G4)=254.0±0.5 μs
$\tau$(data)=256.4±0.5 μs



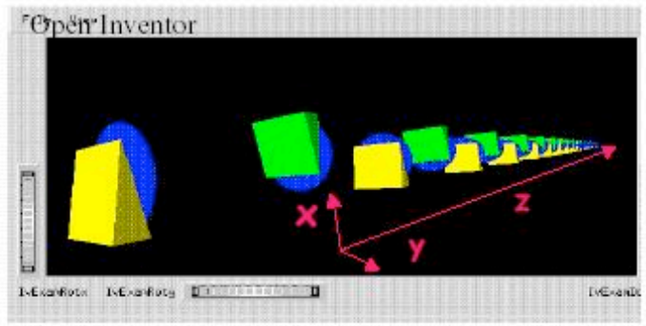
# Geant4 For Beam Transportation

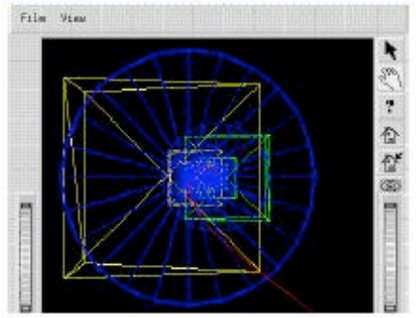
## Example: Helical Channel

Published in proc. of PAC 2001 (Fermilab-Conf-01-182-T)

72 m long solenoidal + dipole field with wedge absorbers and thin cavities

$$B_{xy} = B_T \cos,\sin\left(\frac{2p}{L} z\right) \qquad B_z = B_0$$



**Other simulations:**

- Alternate Solenoid Channel (sFoFo), published in proceedings of PAC2001 and Feasibility Study II for a Neutrino Factory at BNL (2001)
- Bent Solenoid Channel, presented at Emittance Exchange Workshop, BNL 2000
- Low Frequency r.f. Cooling Channel, presented at International Cooling Experiment Workship, CERN 2001
- Cooling Experiment (MICE) Simulation (in progress)

*G4 Users Meeting, February 21st , 2002* *V. Daniel Elvira, Fermilab*

Geant4 extensions for beam transport:

- BeamTools (FNAL, revised to 2003)
- Microbeam studies (Bordeaux)
- BDSIM
- http://flc.pp.rhul.ac.uk/bdsim.html
- G4Beamline
- http://www.muonsinc.com/tiki-index.php?page=G4beamline

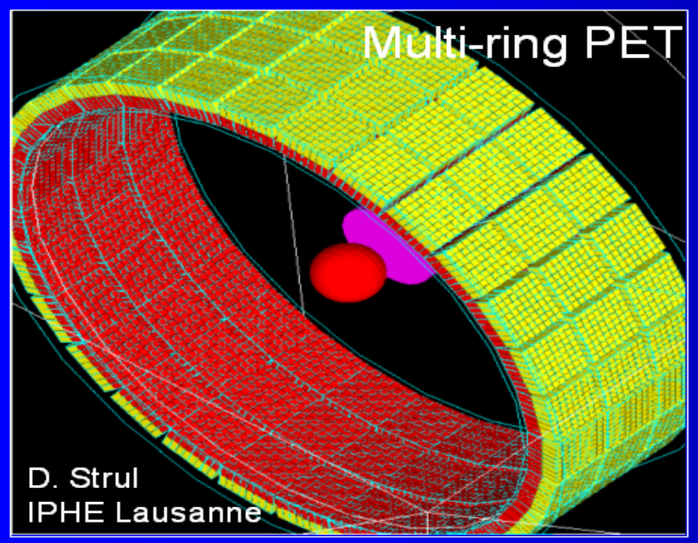
# MEDICAL APPLICATIONS

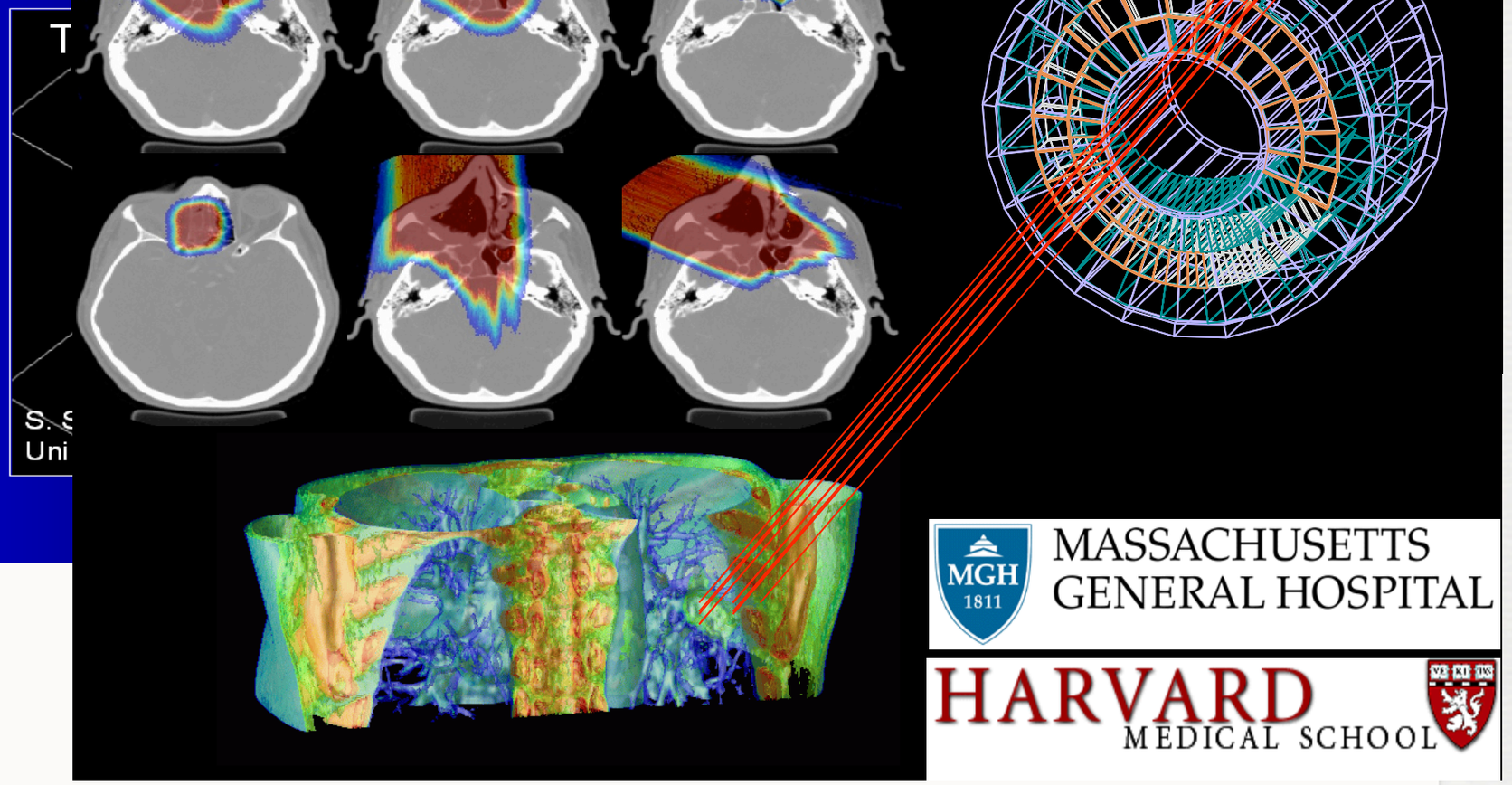
# Medical Physic

- 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)

# New Trends In Modelling: Imaging In Radiotherapy

## Geometry examples of GATE applications



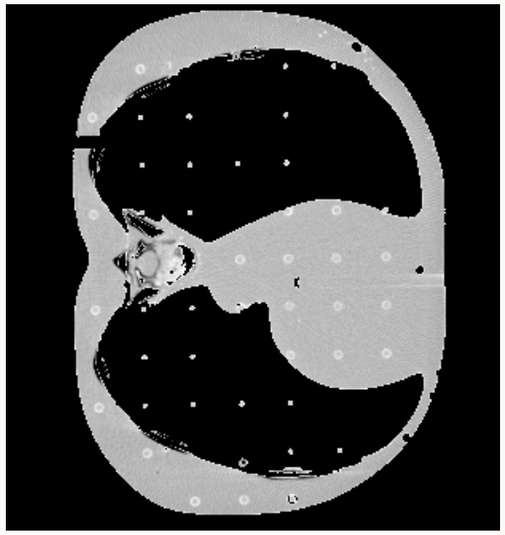

- Application Vs Toolkit: completely functional software built on top of G4, implementing I/O and UI. No need to code any more (very useful for non experts, e.g. doctors)

# Validation Effort

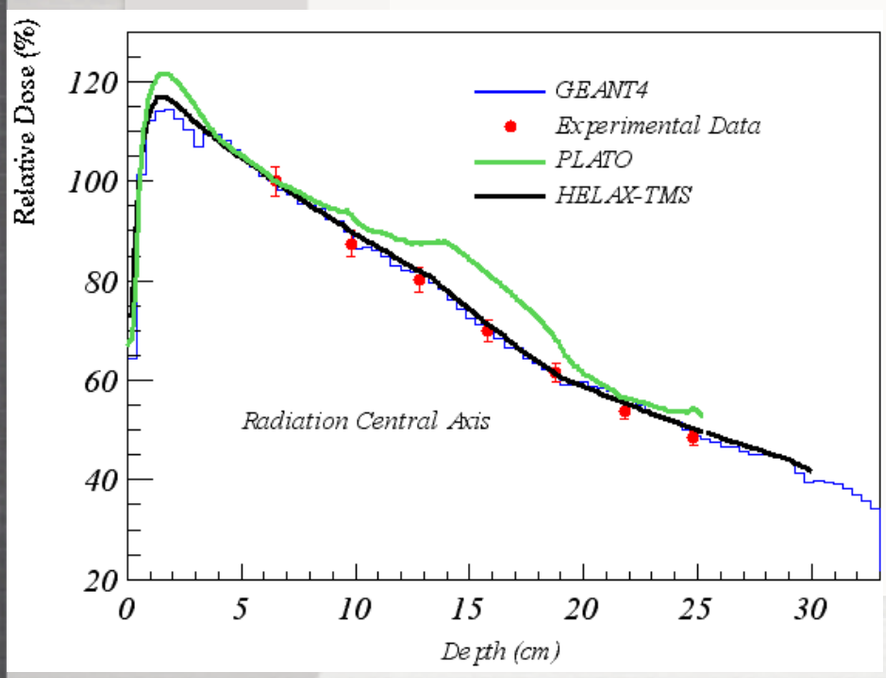
- Detailed validation and comparison with classical treatment planning systems plays a crucial role

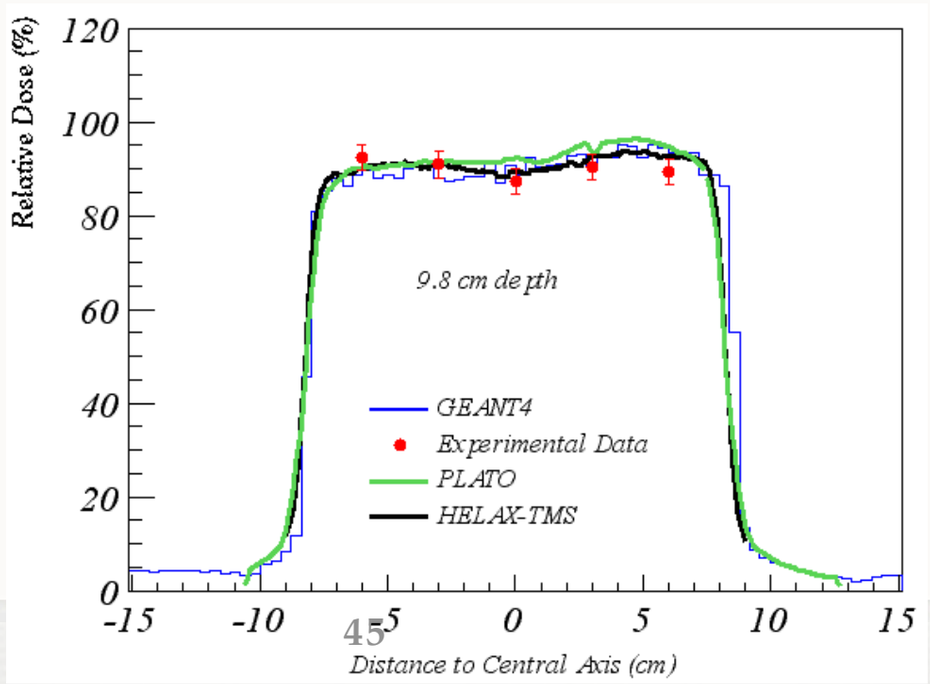
CT images used to define the geometry:

a thorax slice from a Rando anthropomorphic phantom



CT-simulation with a Rando phantom
Experimental data obtained with TLD LiF dosimeter



# SPACE APPLICATIONS

http://geant4.esa.int

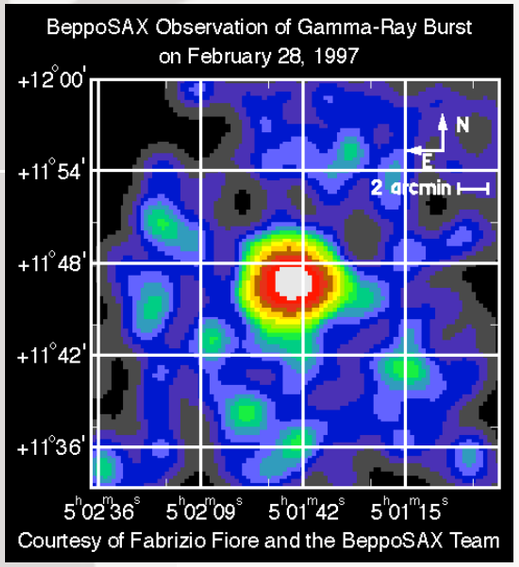
Few examples in the following slides

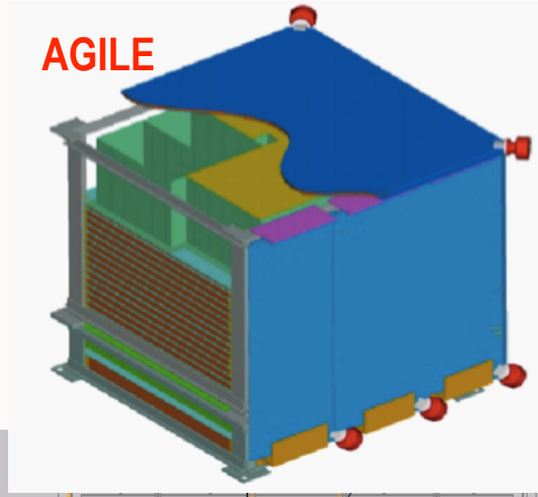

- Geant4 Space Users' web page
- Contacts, publications, news
- Space Users' Workshops (since 2003)
- Hyper-news:
- "Space applications" forum

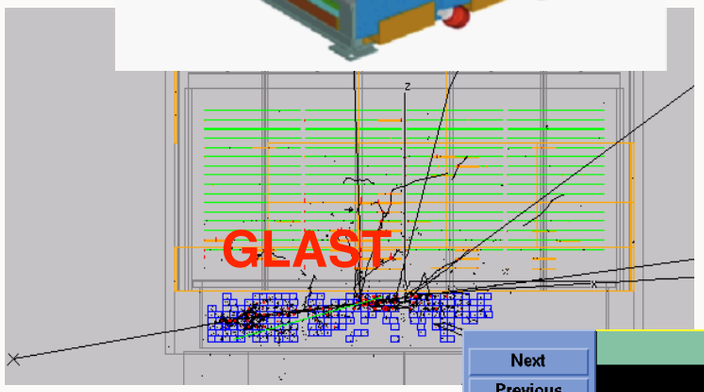
- Design of detectors for gamma and X rays physics
- Study shielding for satellites:
  - Physicists-engineers collaboration
- Single Event Effects (SEE) studies:
  - Effect of (rare) energetic events on spacecraft electronics

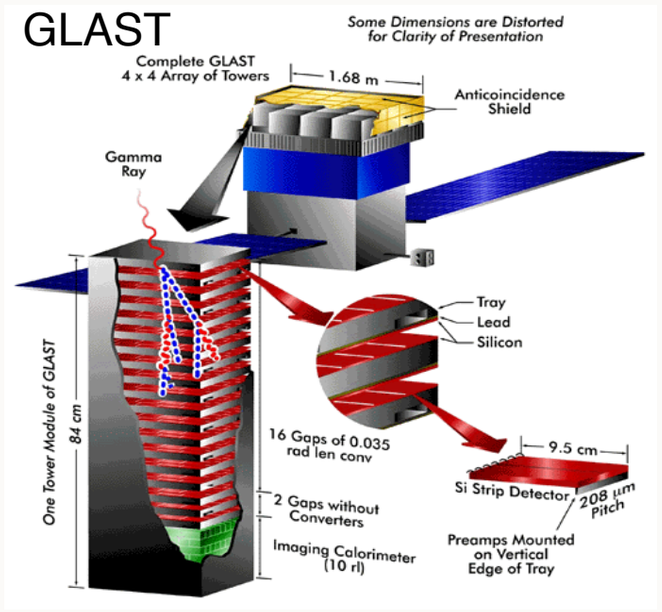
# Gamma Astrophysics

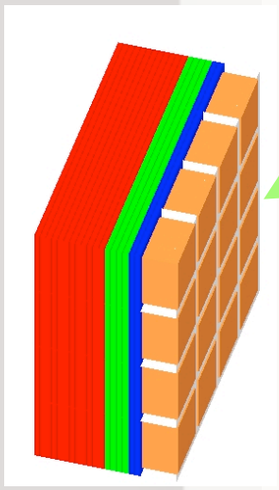
## γ-ray bursts



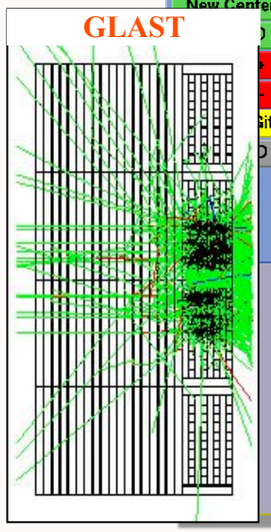



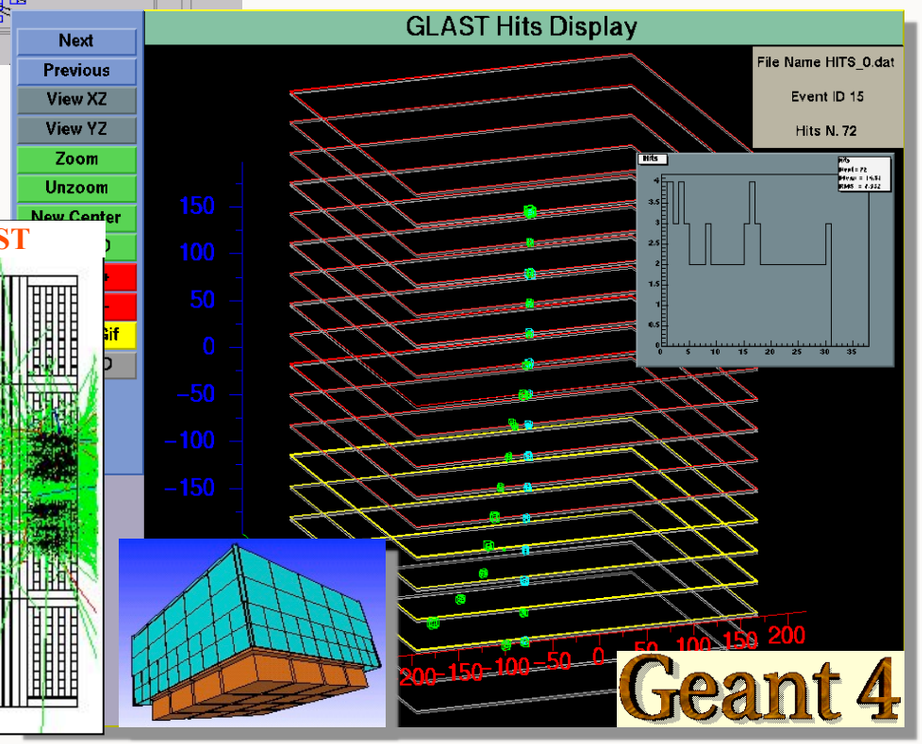



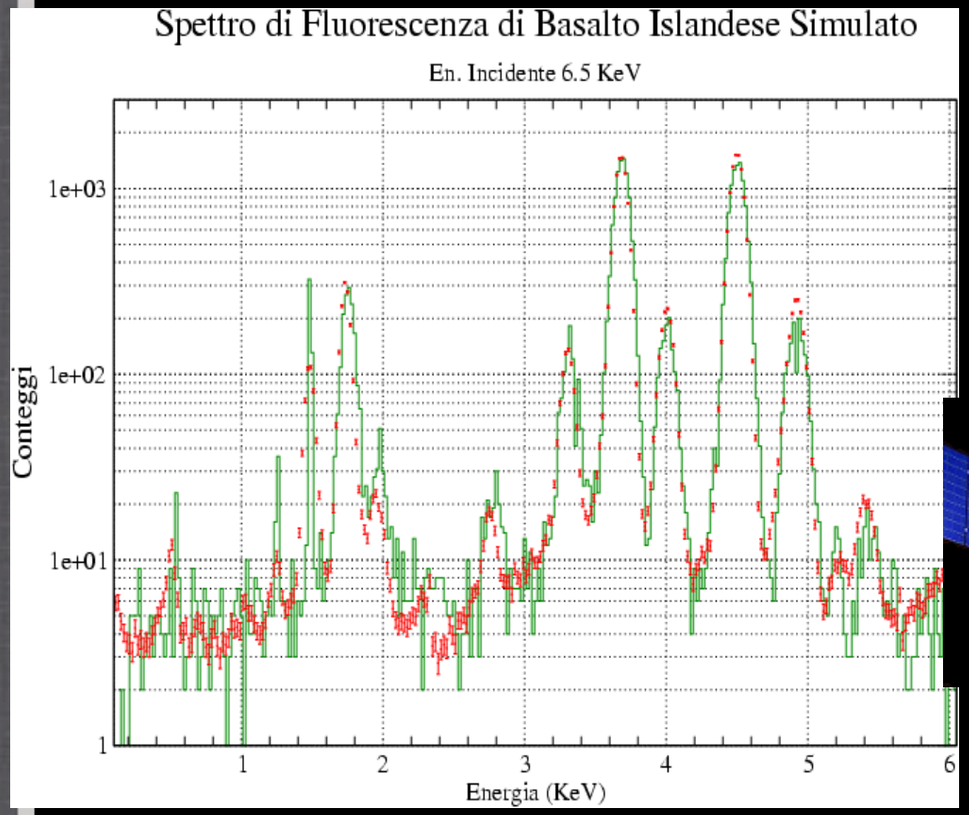
Typical telescope:
*Tracker*
*Calorimeter*
*Anticoincidence*

- γ conversion
- electron interactions
- multiple scattering
- δ-ray production
- charged particle tracking

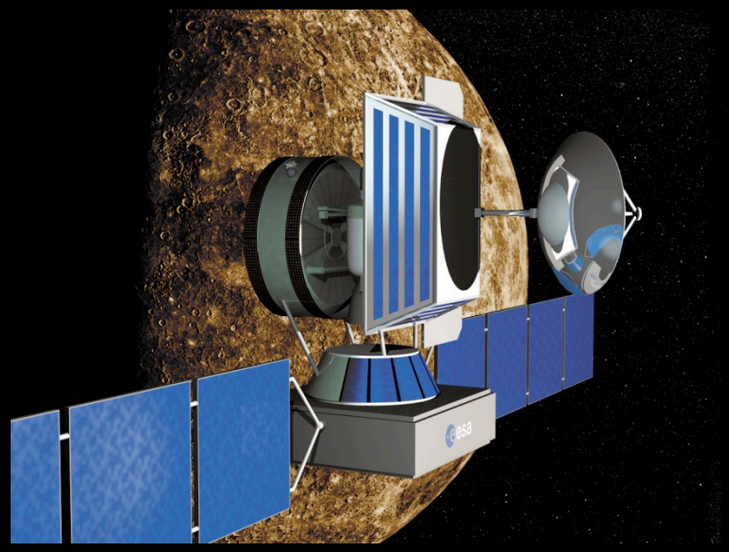


# Bepi Colombo: X-Ray Mineralogical Survey Of Mercury




BepiColombo
ESA cornerstone mission to Mercury

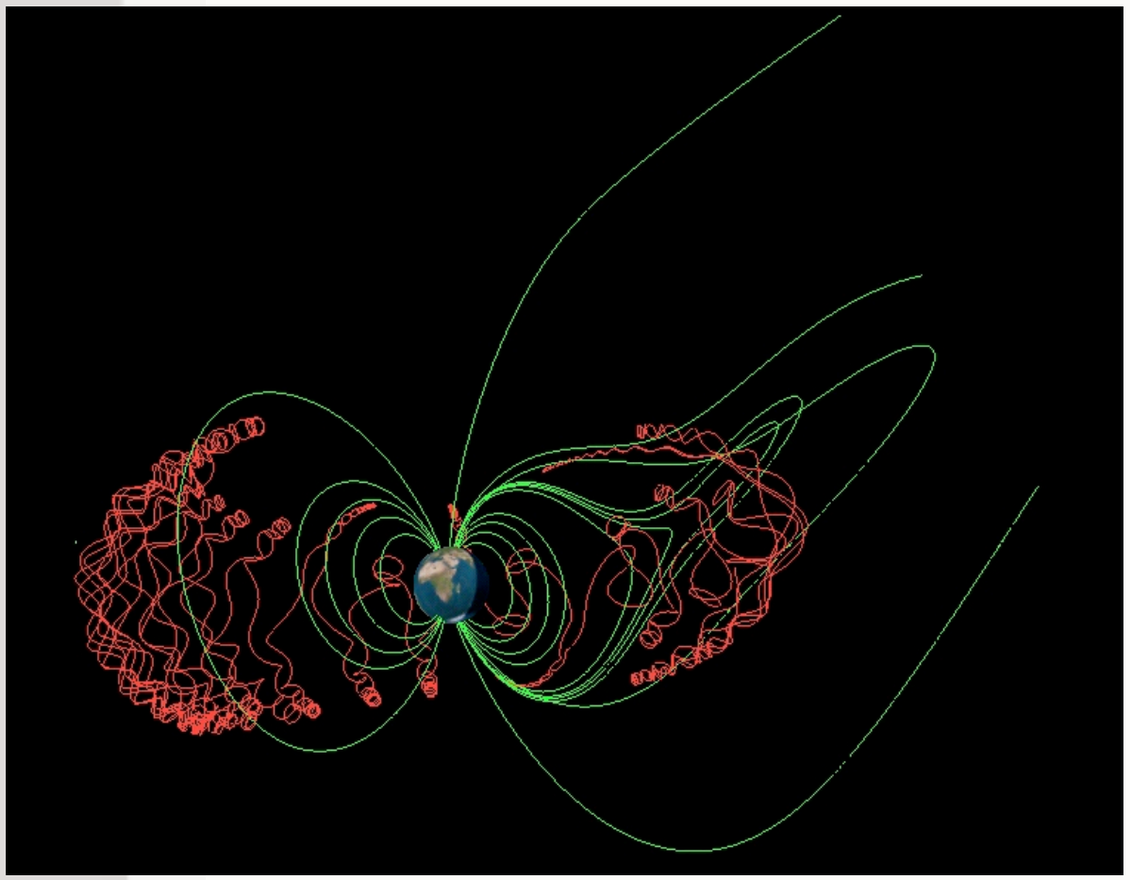


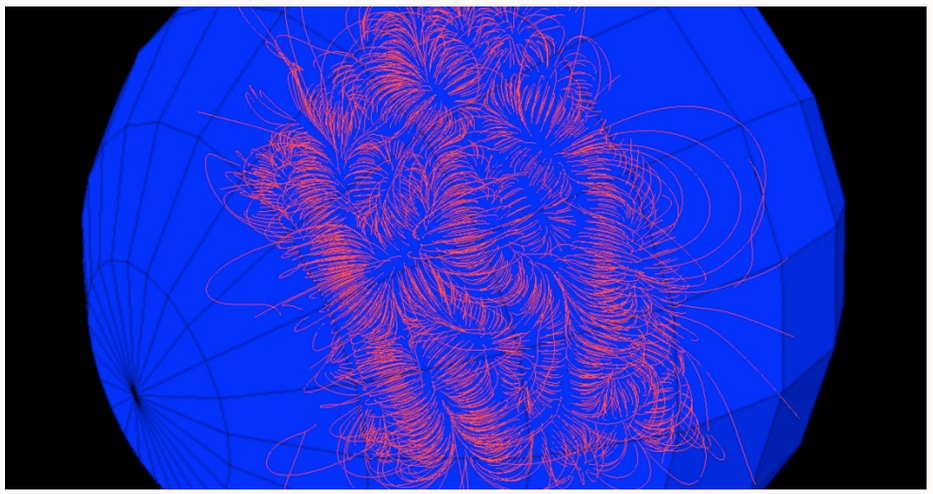
# PlanetoCosmics: Geant4 Simulation Of Cosmic Rays In Planetary Atmo-/ Magneto- Spheres

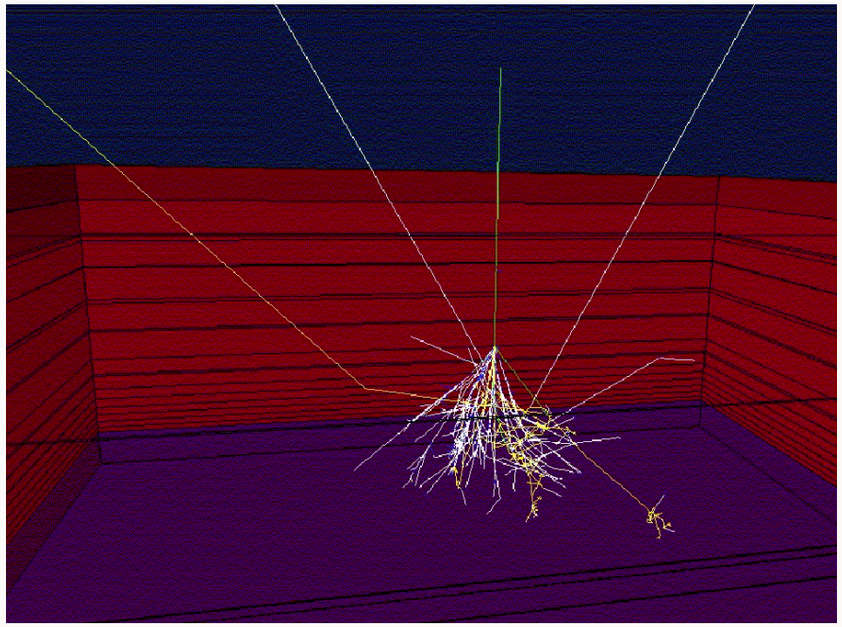


**Geant4 Simulation of the Propagation of Cosmic Rays through the Earth's Atmosphere**

L. Desorgher, E. O. Flückiger, M. R. Moser, and R. Bütikofer
*Physikalisches Institut, University of Bern, CH-3012 Bern, Switzerland*



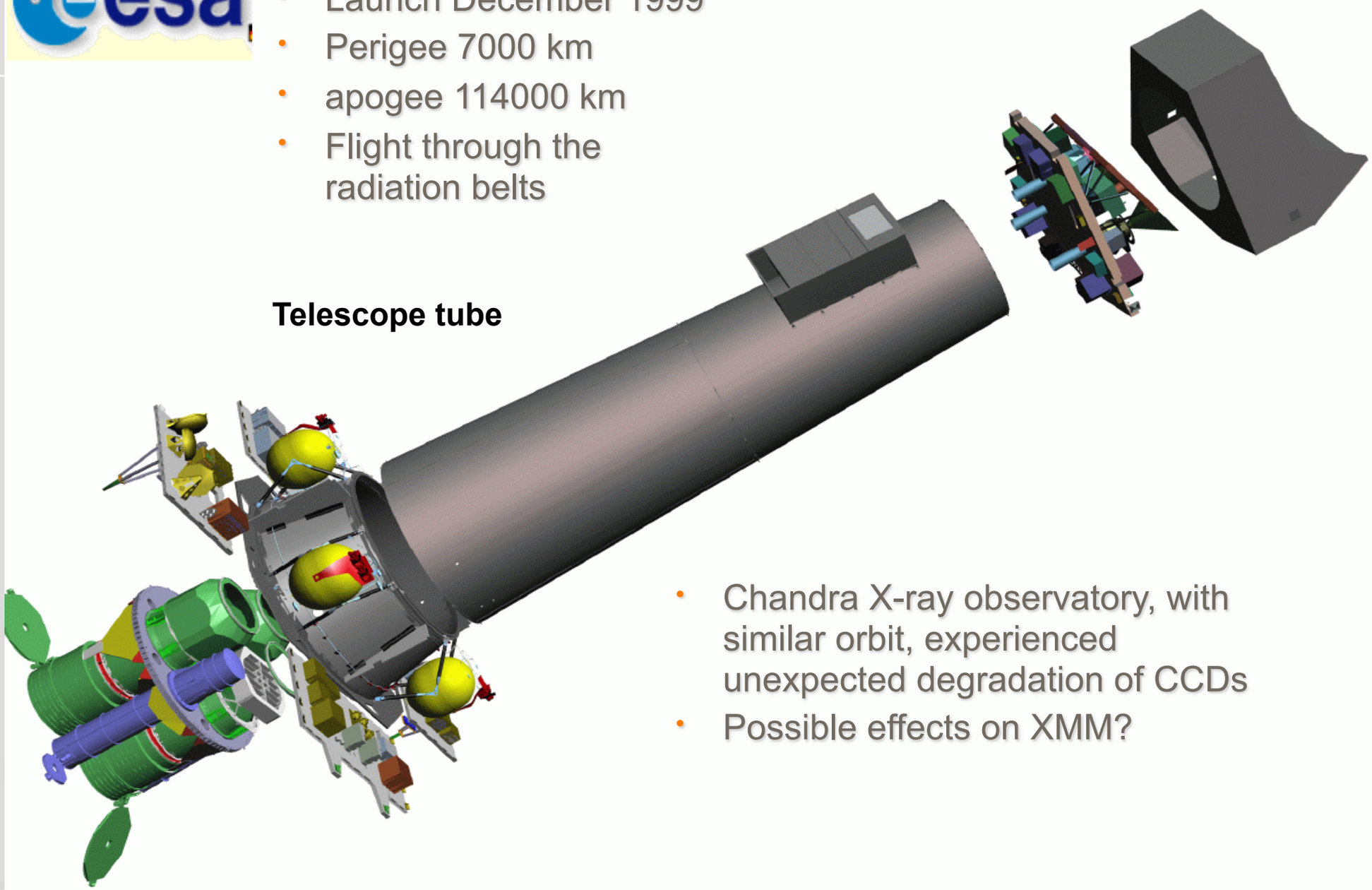




# Example Of Dosimetry/Shielding Studies

## XMM Mission

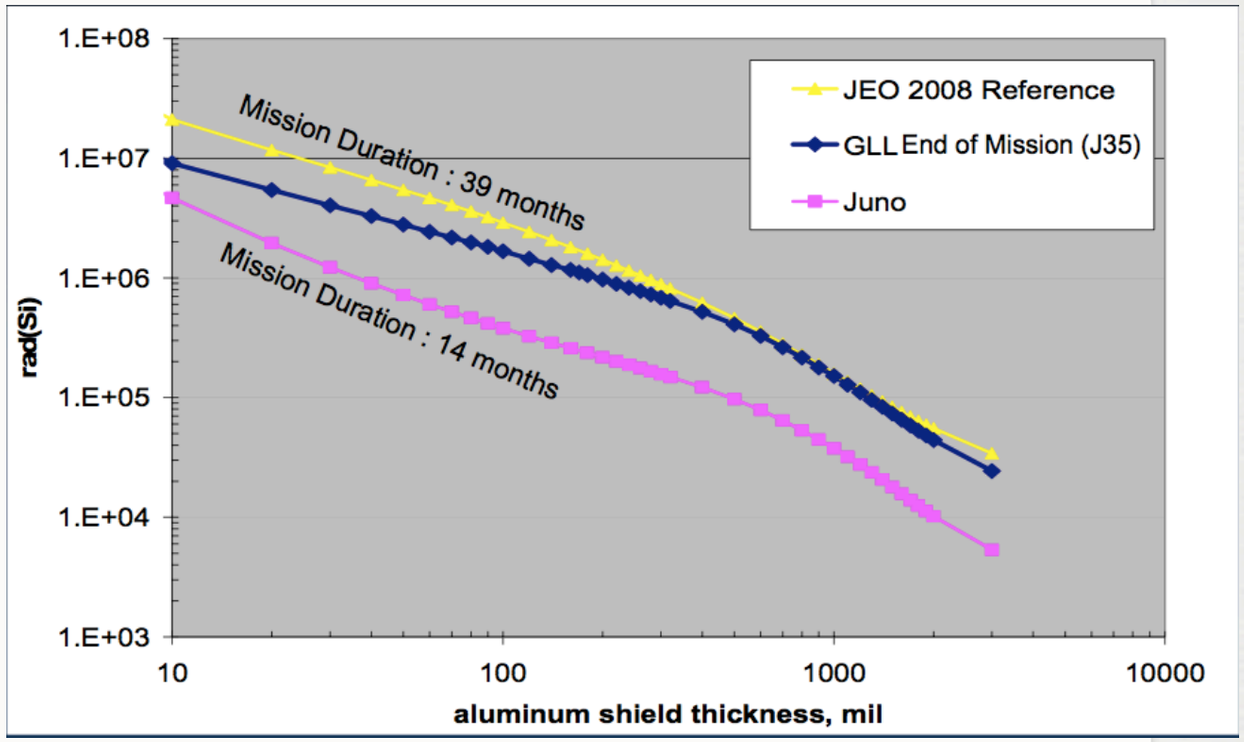
- Launch December 1999
- Perigee 7000 km
- apogee 114000 km
- Flight through the radiation belts

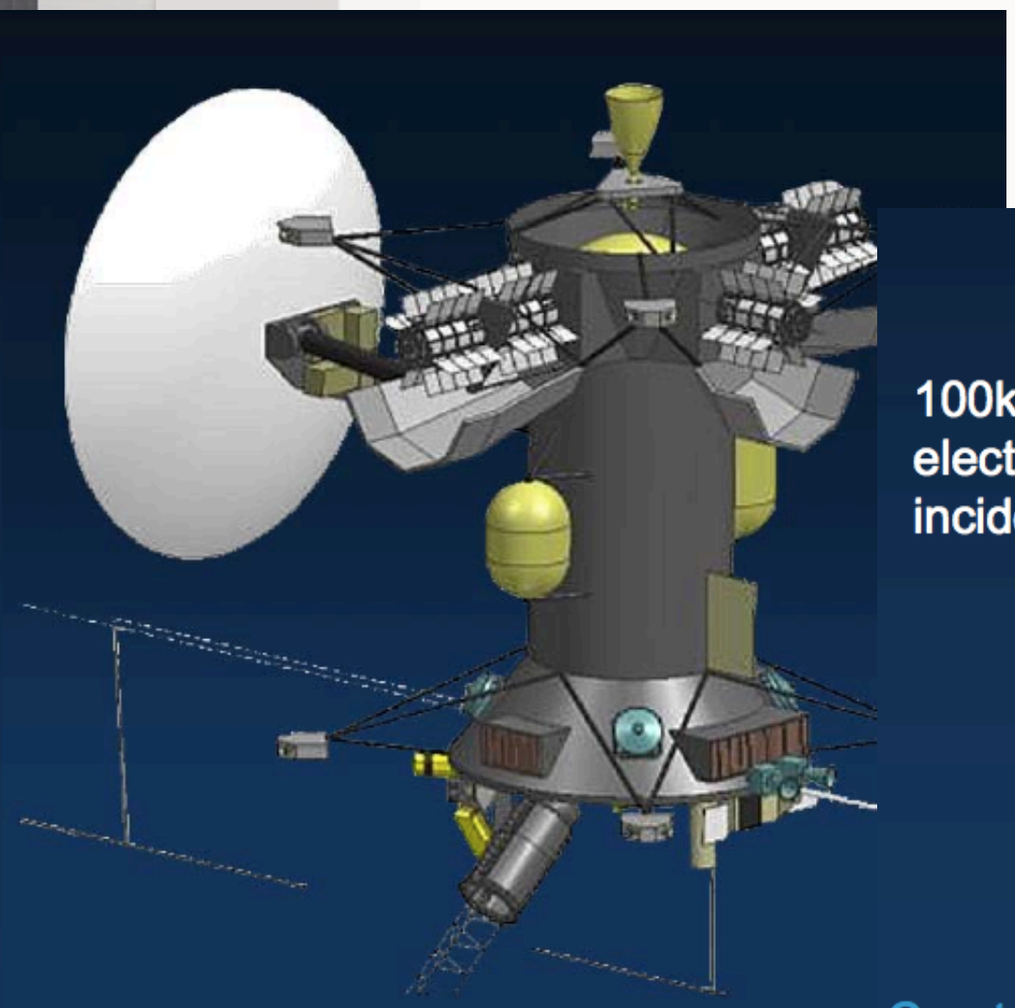



- Chandra X-ray observatory, with similar orbit, experienced unexpected degradation of CCDs
- Possible effects on XMM?

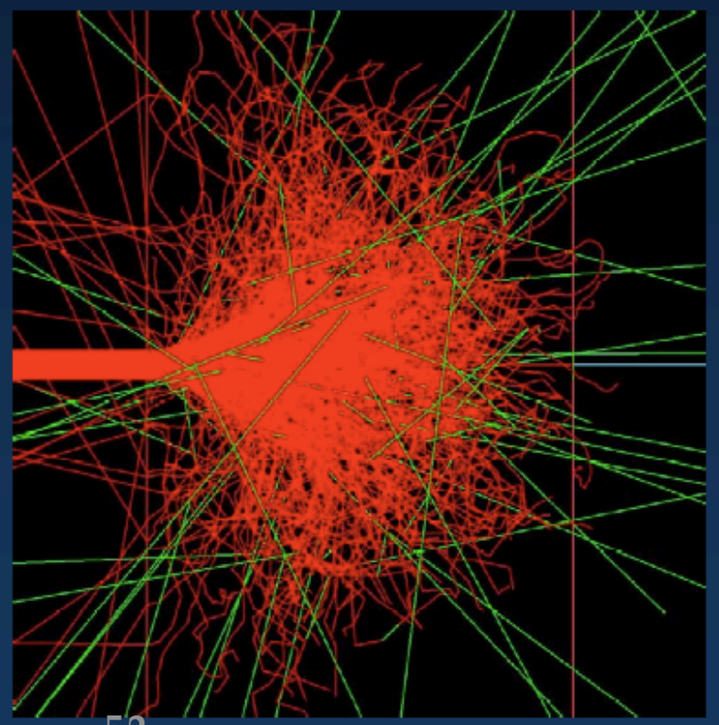
# Jupiter System Exploration (2020-2029)

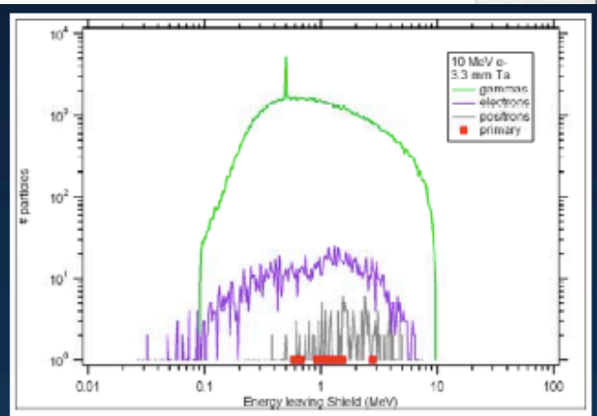
- EJSM (Europa Jupiter System Mission) detailed study of Jupiter moons. Joint NASA-ESA mission.
- JEO: Jupiter-Europa-Orbiter, NASA spacecraft of the Mission
- Geant4 used to study shielding and optimization of signal/noise ratio in detectors

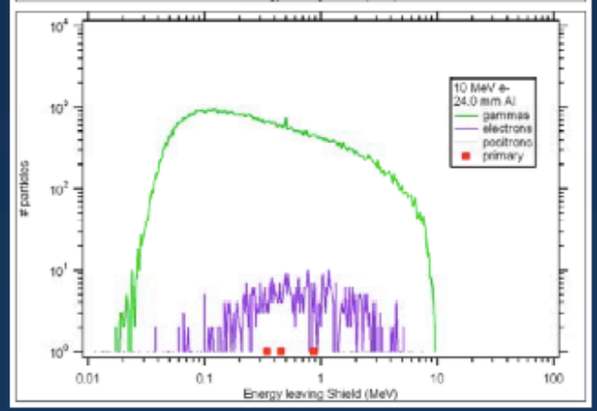


100k electrons incident



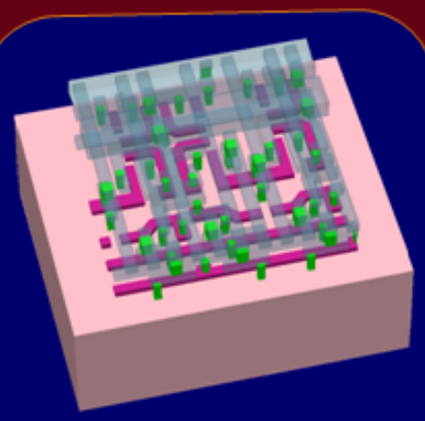


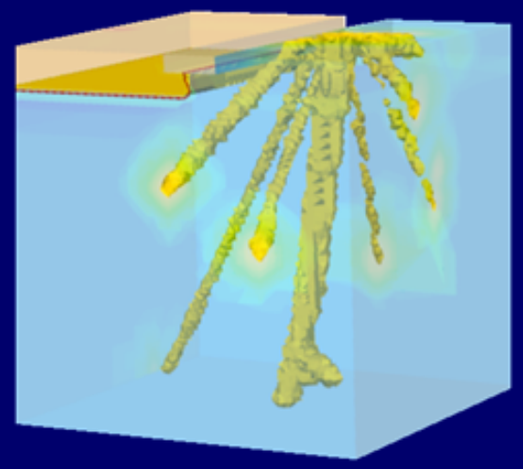

Courtesy of D. Haggerty (APL)

# SEE Studies

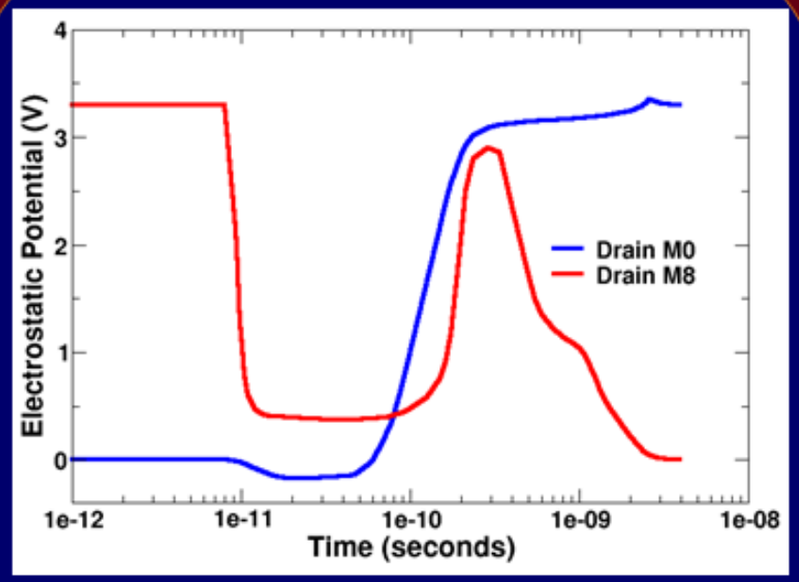
## RADSAFE on SEE in SRAMs



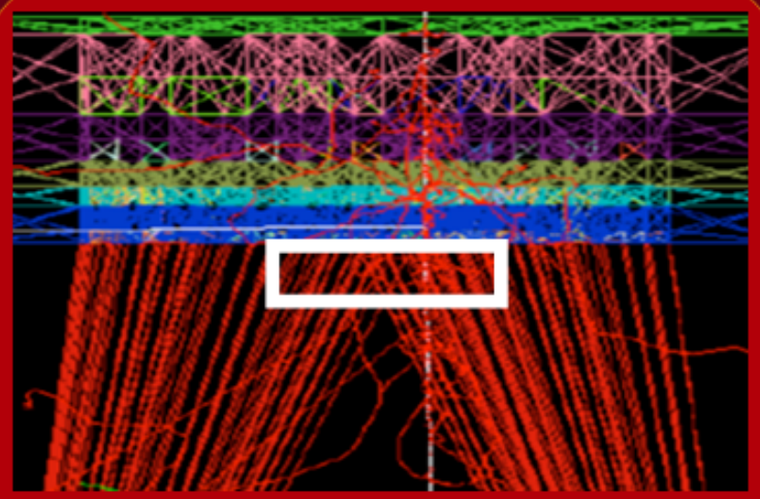
TCAD Cell Structure: SRAM Cell



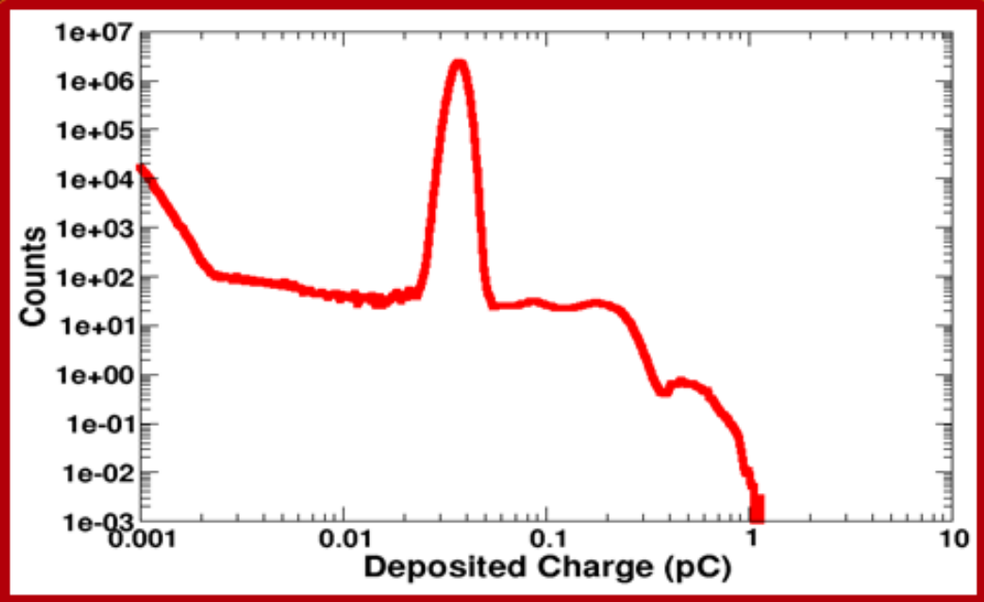
Single Charge Deposition in TCAD: Ne+W Event




SRAM Cell Upset



Geant4 Geometry and 523 MeV Neon Event



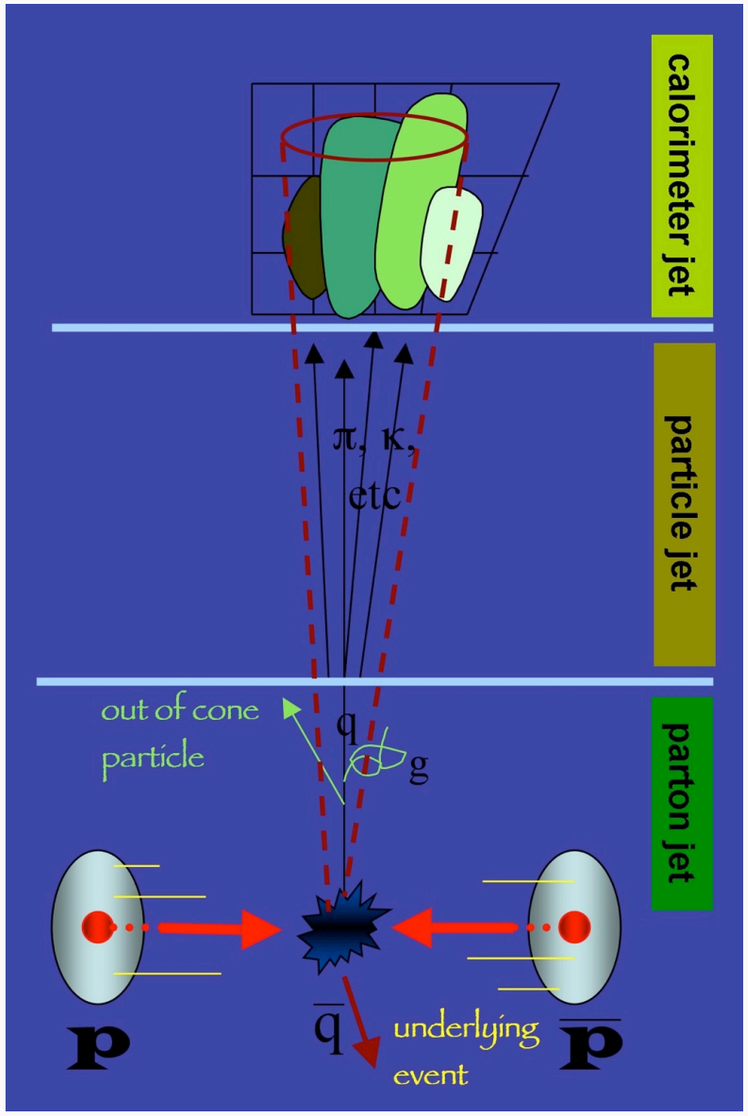

MRED Energy Deposition for $10^8$ Events

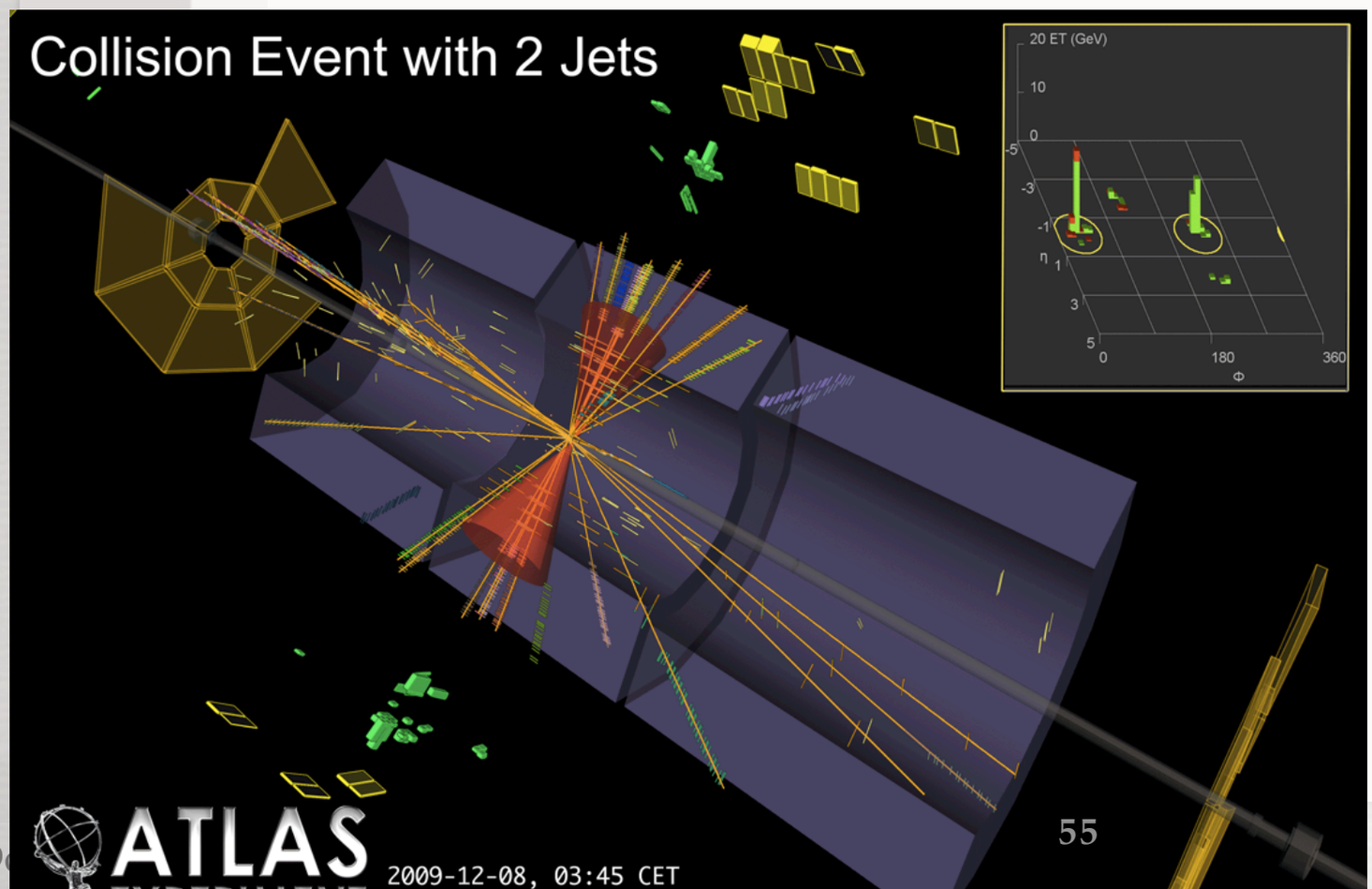
# FUTURE CHALLENGES

# Hadronic Physics Challenges

- Hadronic interactions are the most difficult to simulate

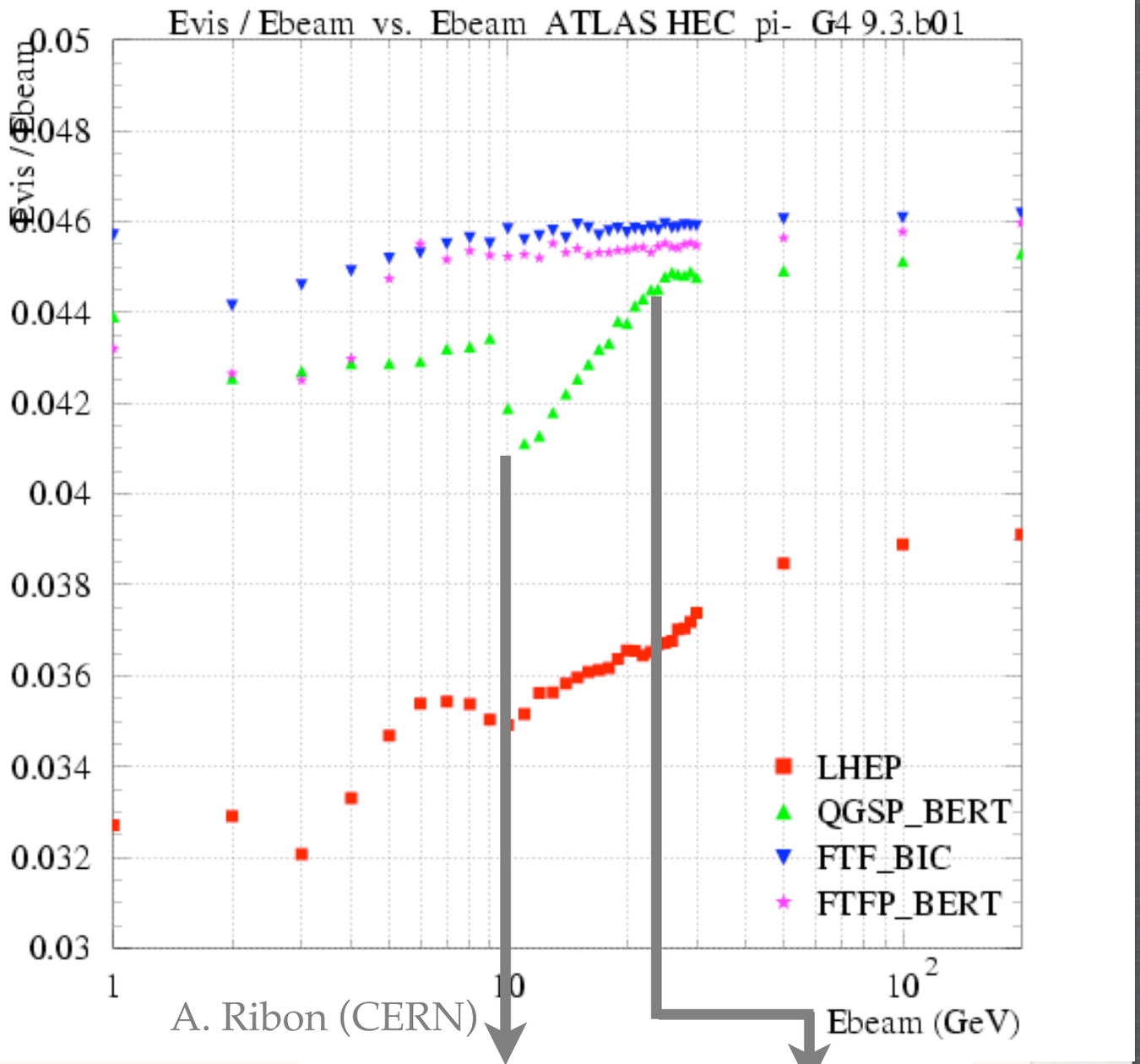
- Much attention has been put in the past to provide LHC experiments a detailed and reliable simulation. Most stringent requirements come from jet studies. At LHC: measurement of top quark mass



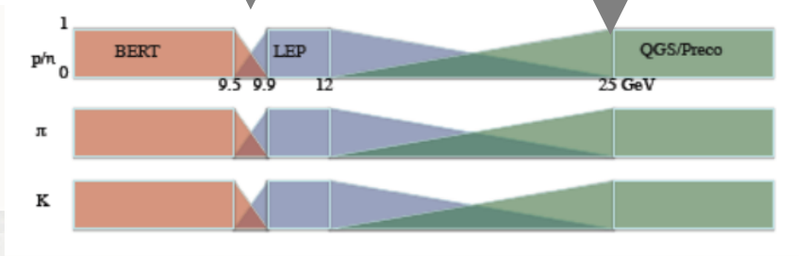



# Feedback From LHC Calos

- Non smooth transition between different models used in physics lists
  - Caused by the use of parametrized models (LHEP) at intermediate energies
  - Detailed studies carried out: cause identified
- Different possibilities to solve this issue are at the moment under study and validation (in parallel):
  - Change transition regions between models in existing physics lists
  - Creating new mixtures of models in new physics lists
  - Improve the hadronic models themselves



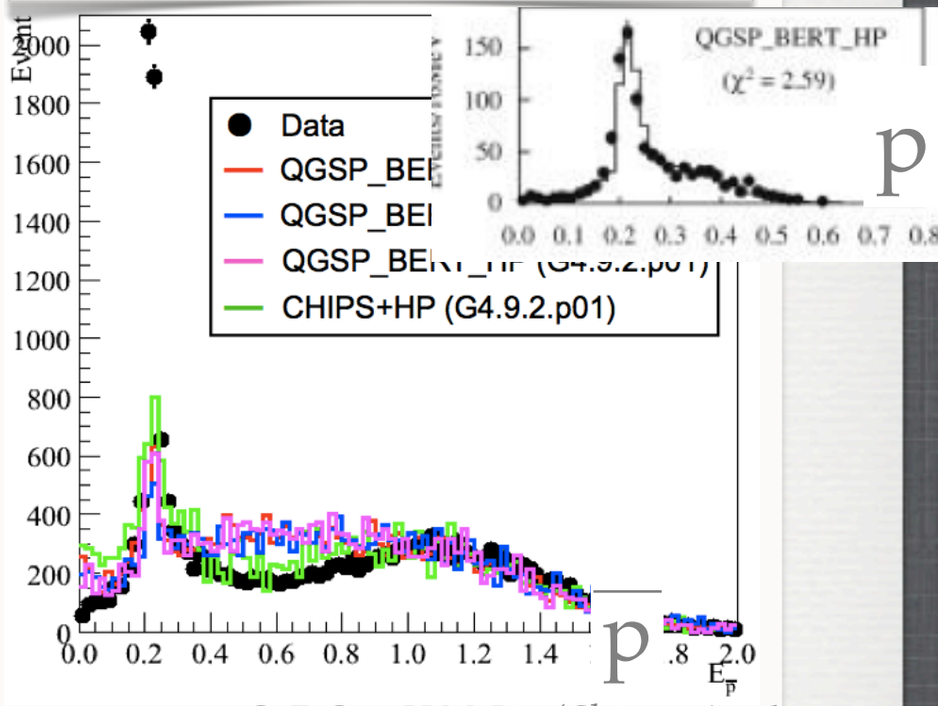

A. Ribon (CERN)



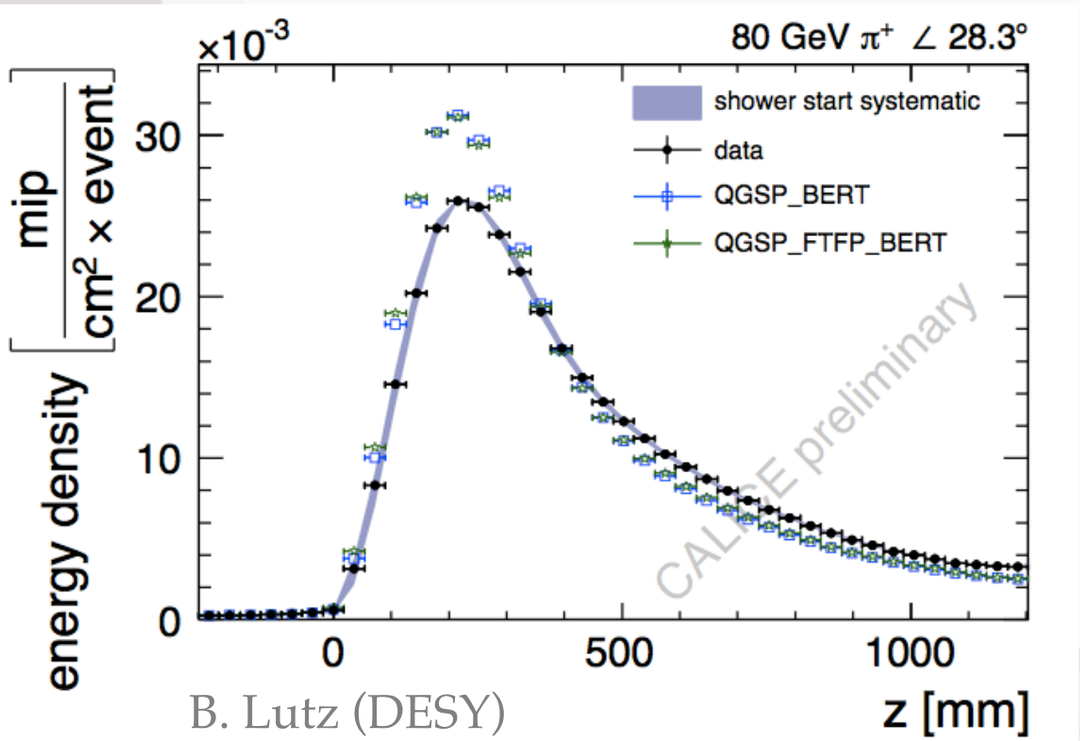
# Not Only LHC

- BESIII: pure anti-proton sample
  - Comparing energy released in calorimeter with different physics lists
  - Feedback on a particle type not studied at LHC test-beams
- CALICE Collaboration
  - Extreme segmentation: verify shower shapes at a level beyond LHC possibilities
  - Future challenge for G4: describe shower shape for ILC calorimeters!

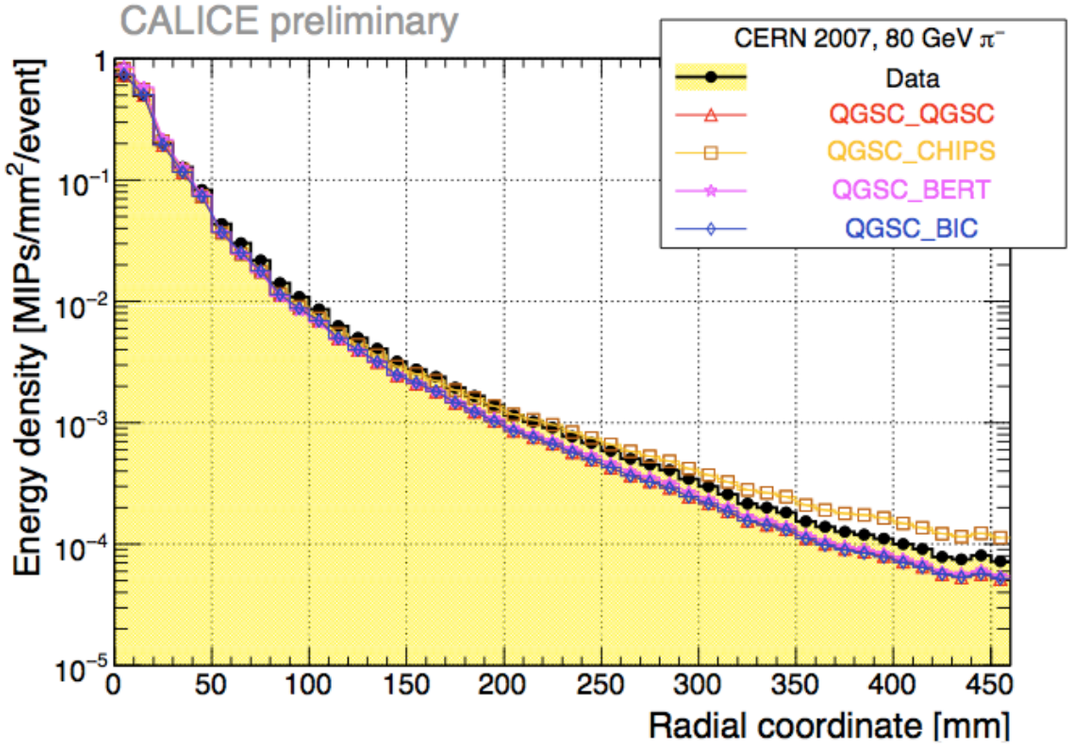
BESIII @ Beijing Electron Positron Collideer




G. F. Cao, H.M. Liu (Chinese Academy of Science)

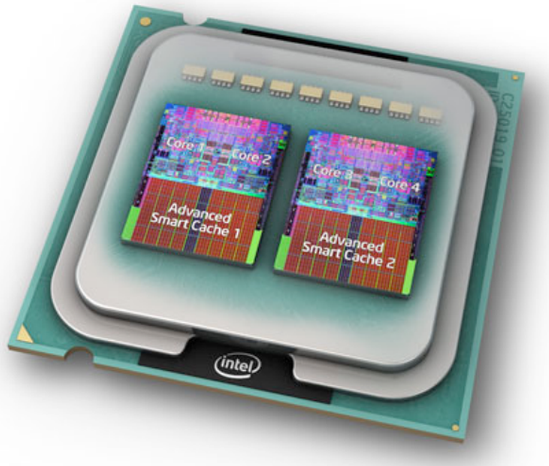


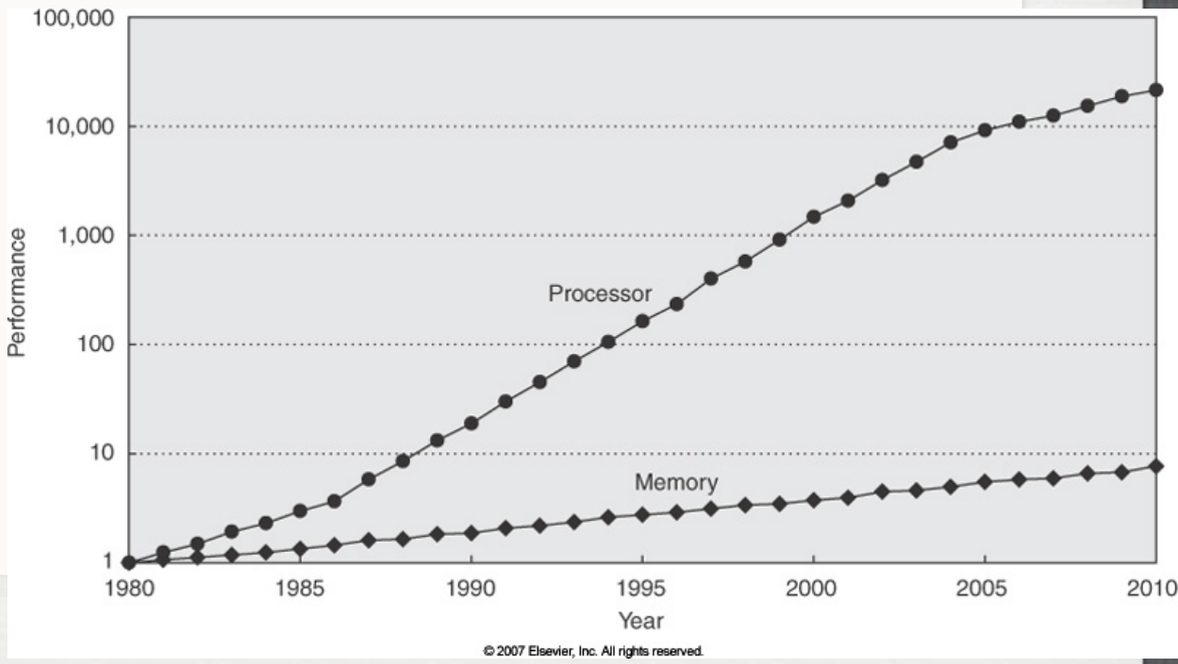

B. Lutz (DESY)



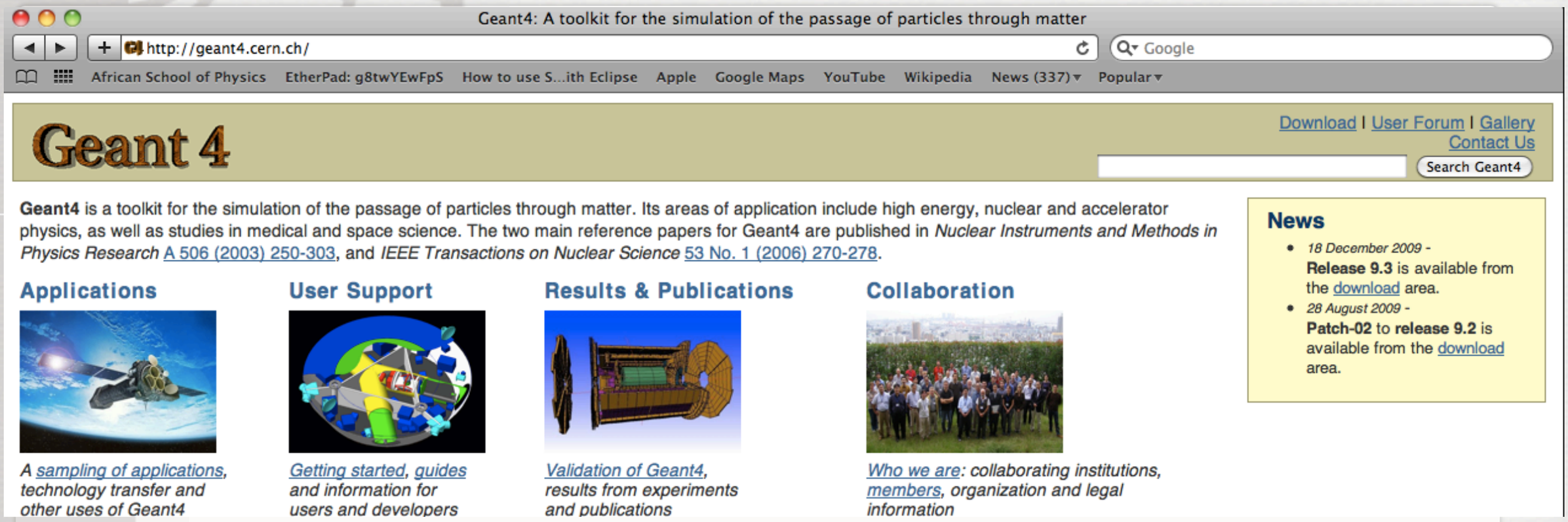
# Trends In Computing Technology

- Computer Industry introduced multi/many core processors
- Typical (server, Geant4 on the GRID for LHC) machine has 2 CPU x 2 Cores. With hw-threds, GPUs, parallelism will explode: expect O(100) cores in the (near) future!
- Typical physics simulation: parallelism often only at the level of a run: clone a process N times
- CPU power grows much faster than RAM performances: expect LESS memory per proc. unit in the (near) future!
- Need to push parallelism (at least) at the level of event: advanced techniques to reduce memory footprint (Geant4MT)



# More Information...




- Can be found starting from: http://www.cern.ch/geant4
- 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.

# Conclusions

- Geant4 has been developed to simulate the passage of particle through matter
- As a toolkit provides enough flexibility to design an application tailored on the user needs:
  - High Energy Domain: LHC experiments, but also ILC, underground experiments
  - Medical Physics: imaging, beam-transportation, treatment planning
  - Space Physics: detector optimization, shielding
- Geant4 is a mature package which results are constantly validated agains experimental data
- Open Source License: everybody can contribute to improve the code
- Many activities are ongoing both to improve the physics description and to cope with technology changes