# Detector Simulation

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# Foreword

This lecture is aimed to offer a **simple and general introduction** to detector simulation.

**Geant4** will be considered as a concrete example (because it is used by the LHC experiments) but only to illustrate general aspects of detector simulation.

This lecture is **not** a tutorial on Geant4 !

*(The best way to learn how to use any simulation package is by starting with an example)*

# Outline

## 1. Introduction

- Why do we need to simulate a detector?
- How does it work?

## 2. Geometry

- How do we describe an experimental apparatus?

## 3. Physics

- What is available and what to use?
- What are the challenges?

## 4. Validation

- How can we trust a few million lines of code?

# Introduction

# Introduction

- Simulation is a very useful, essential tool in modern particle physics for:

  - **designing** an experiment (e.g. now ILC/CLIC, FCC)

  - **analysing** the data (e.g. now LHC experiments)

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

  1. Simulation of the p-p collision

     - Monte Carlo event generators

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

     - Monte Carlo radiation transportation, or simply "detector simulation"
     - From the beam pipe to the end of the cavern
     - The output of 1. is the input of 2.

# Monte Carlo radiation transportation codes

- The simulation of the p-p collision is the same for different experiments at the same collider, e.g. ATLAS and CMS

- The detector simulation is different for each experiment. However, general codes exist that can be used for simulating any detector

  - An experimental apparatus can be modeled in terms of elementary geometrical objects

  - The physics processes are detector independent

- These general codes, e.g. Geant4, are called "**Monte Carlo radiation transportation codes**"

  - Non-deterministic (e.g. do not solve equations); use random numbers to reproduce distributions

  - Transport particles through matter

# How does it work?

- Treat one particle at the time

- Treat a particle in **steps**
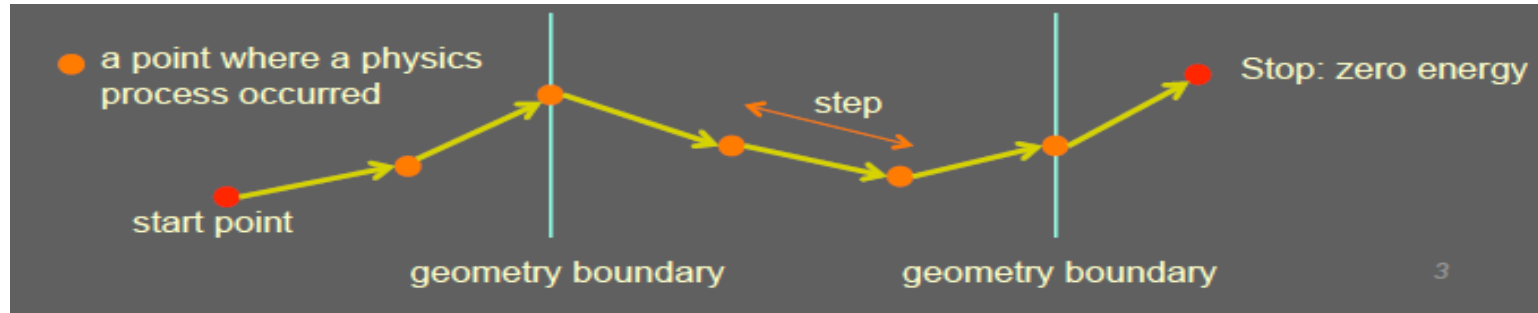


- For each step

  - the step length is determined by the cross sections of the physics processes and the geometrical boundaries; if new particles are created, add them to the list of particles to be transported;

  - local energy deposit; effect of magnetic and electric fields;

  - if the particle is destroyed by the interaction, or it reaches the end of the apparatus, or its energy is below a (tracking) threshold, then the simulation of this particle is over;
    else continue with another step.

- Output  -  new particles created (indirect)
              -  local **energy deposits** throughout the detector (direct)

# Algorithm



**Next particle** — No → End of the Event

Yes ↓

**Find next step** (physics process or volume boundary)

↓

**Continuous part** (along the step) → Energy deposits / Fields effects

↓

**Discrete part** (post step) → Create new particles

↓

**Still alive Ekin > cut Inside World** — No → End of the particle / Yes →

End of the particle

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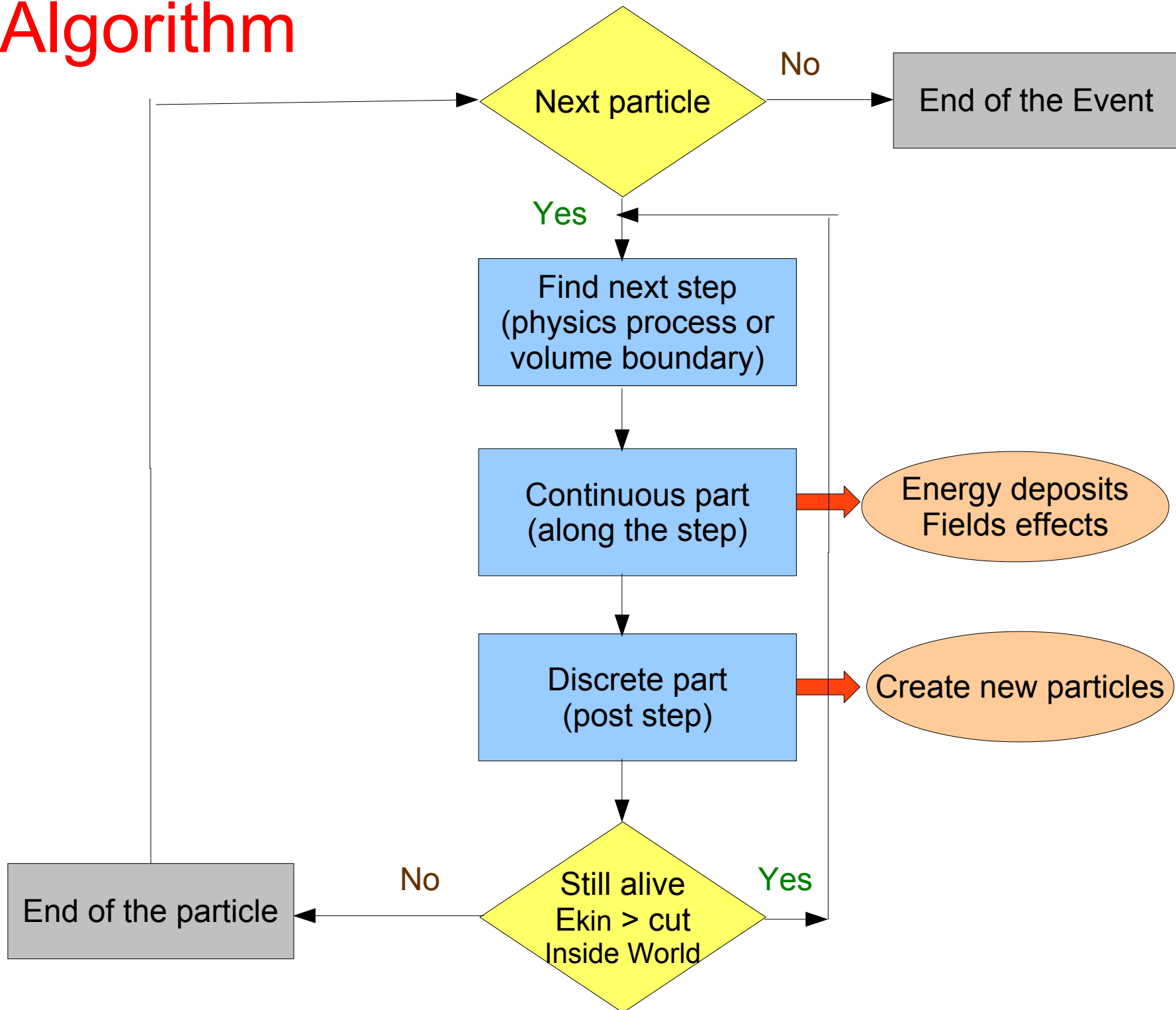
# "Digitization"

- Besides the geometry, another experiment-specific aspect of the detector simulation is the "digitization"

  - It is not part of the general radiation transportation codes

- It consists of producing the detector response in terms of electric current & voltage signals, as in the real experiment

  - The same reconstruction chain can be applied for both real and simulated data

- The general radiation transportation code provides energy deposits in the whole detector; from these, the "digitization" simulates the electrical signals induced in the sensitive parts of the detector

- Another detector-specific aspect is the "pile-up" ...

# Accuracy *vs.* Speed

- Huge samples (billions) of simulated events are needed by the experiments for their physics analyses

- The number of simulated events is limited by CPU

- The simulation time is dominated by the detector simulation

- Tradeoff between **accuracy** and **speed** of the detector simulation

  - More precise physics models are slower and, more importantly, create more secondaries and/or steps

  - Smaller geometrical details slow down the simulation
    - Never model explicitly screws, bolts, cables, etc.

  - Continuous spectrum of types of detector simulations
    - From full, detailed detector simulations (covered in this lecture)
    - To very fast, fully parametrized detector simulations (not covered here!)

- *On-going effort to exploit the latest CPU features*

  - *Multi-threading (e.g. G4 10 ) ; Vectorization (e.g. Geant-V )*

# Application domains

- We are considering here mainly high-energy physics, but...

- There are other domains where the same radiation transportation codes are successfully used:

  - Nuclear physics

  - Accelerator science

  - Astrophysics

  - Space engineering

  - Radiation damage

  - Medical physics

  - Industrial applications

- So, detector simulation is a multi-disciplinary field!

# Geometry

# Geometry

- The way to describe the geometry varies widely between the different simulation engines

  - In Geant4, you need to write some C++ code

    – Geometry objects are instances of classes

    – Geometry parameters (e.g. dimensions) are arguments of the constructors

- The geometry can be "flat" or "hierarchical"

  - In Geant4, it is hierarchical: a volume is placed in its mother volume; there are mother-daughter relationships

- A **material** should be assigned to each volume

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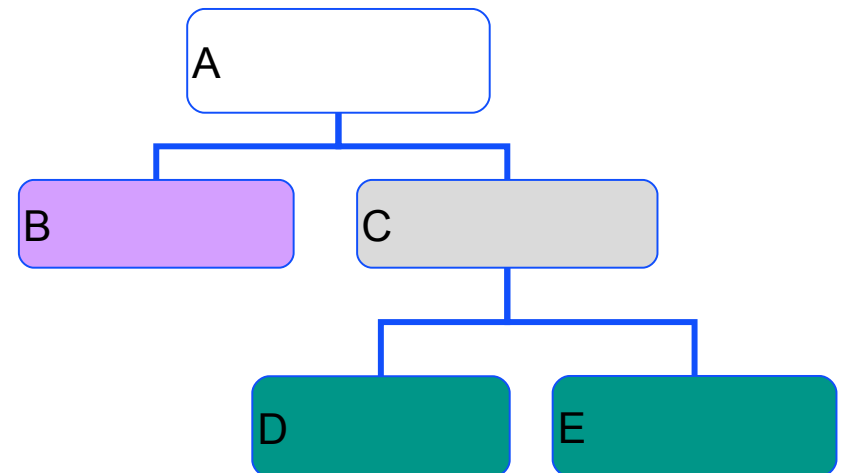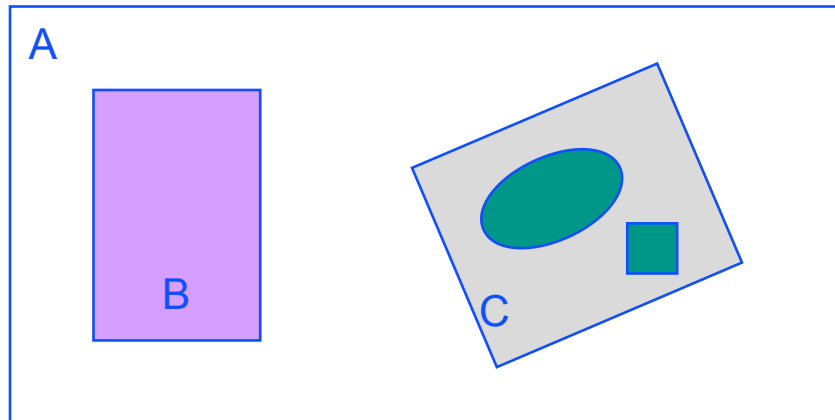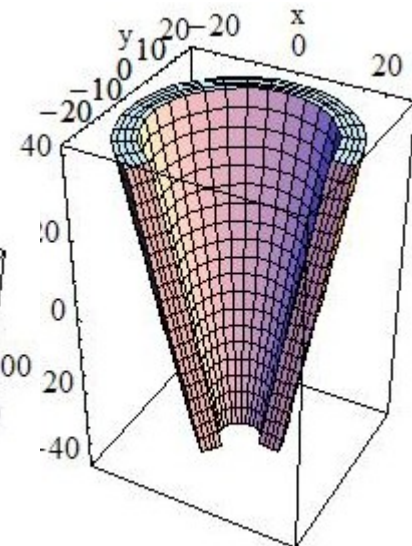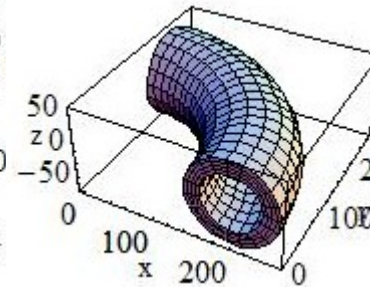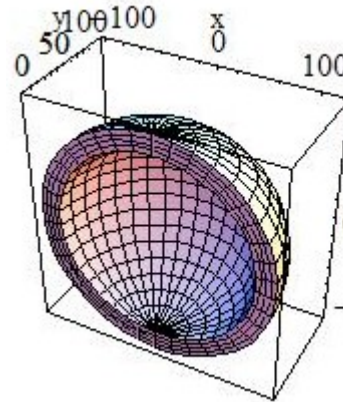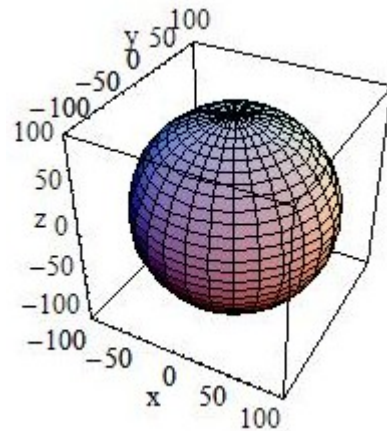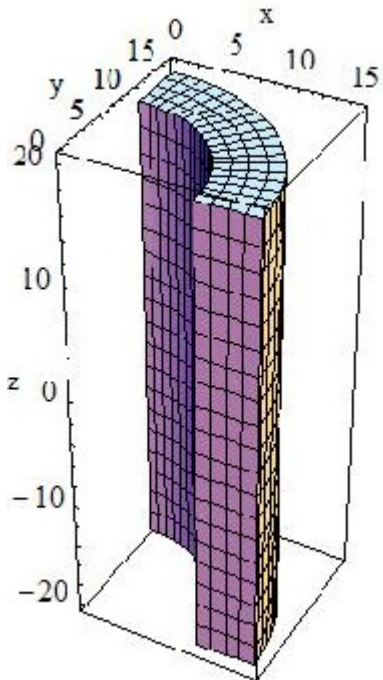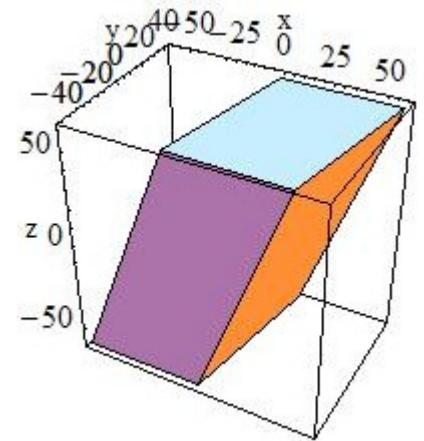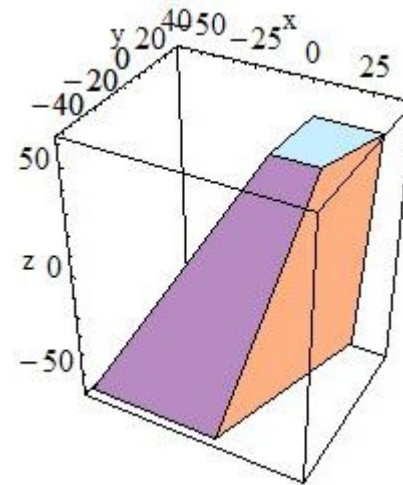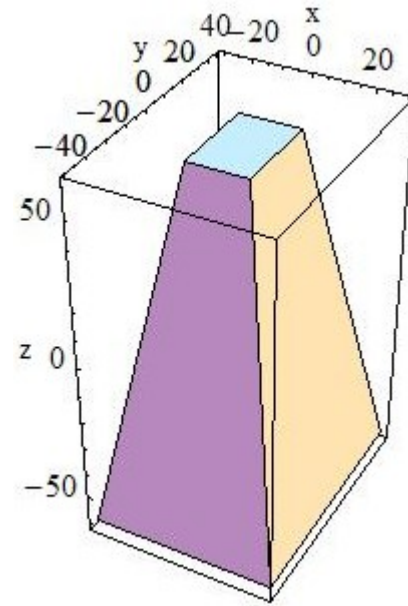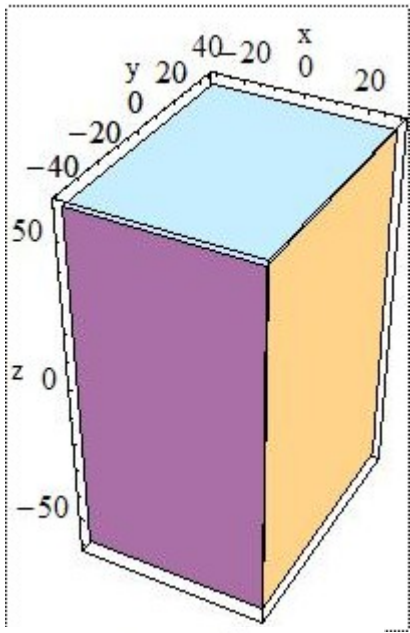
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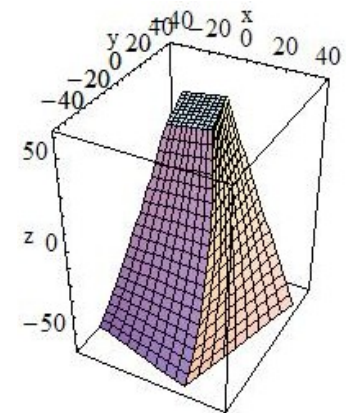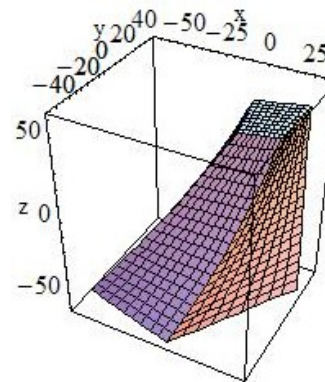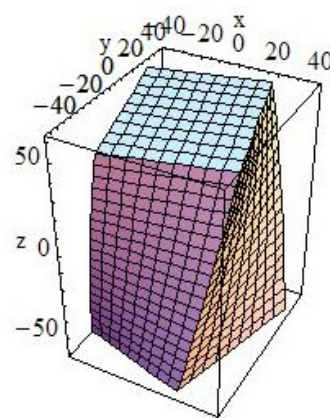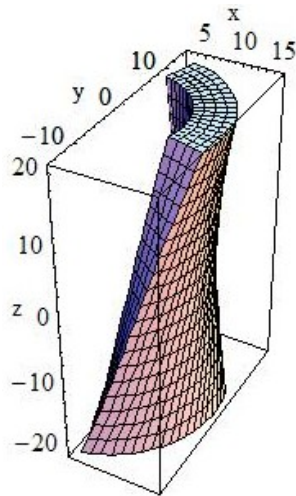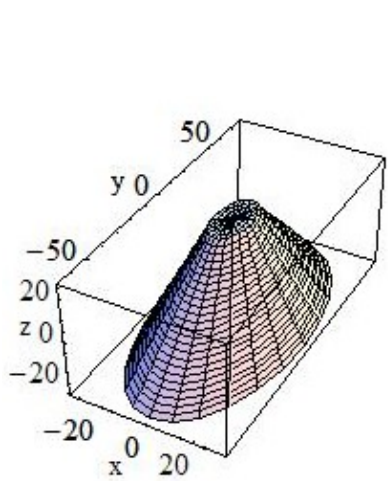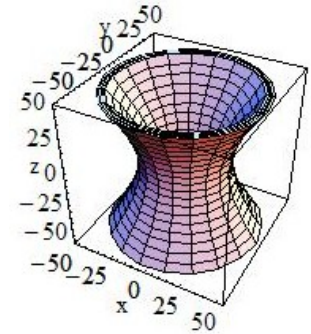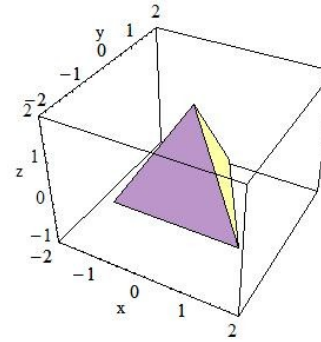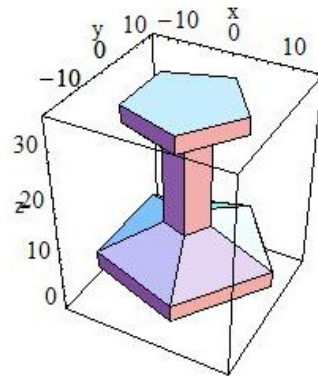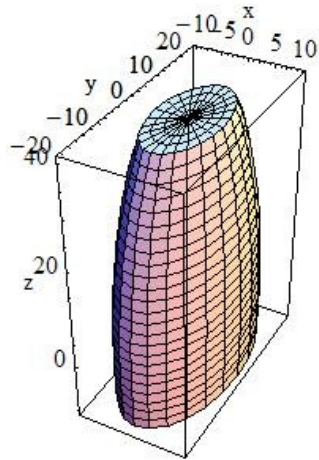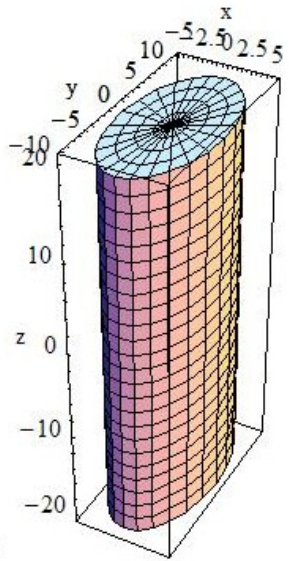
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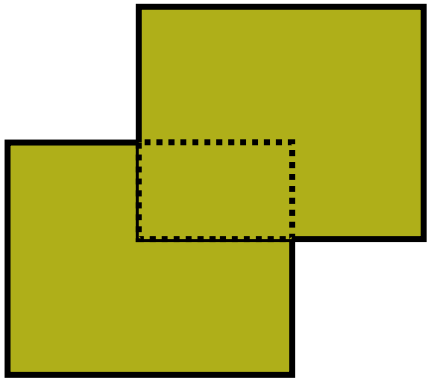


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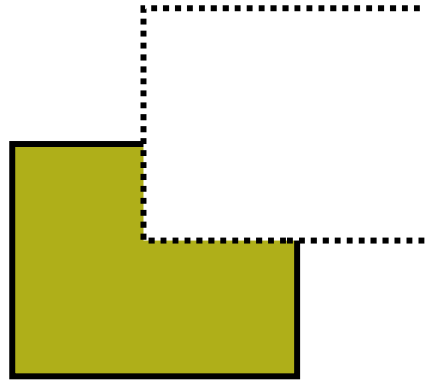
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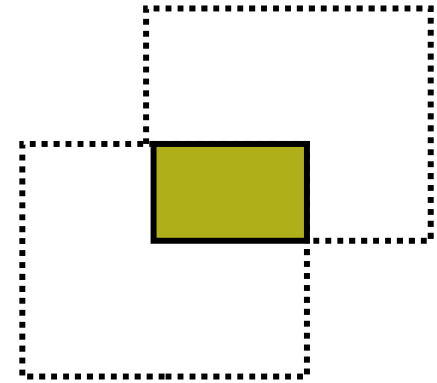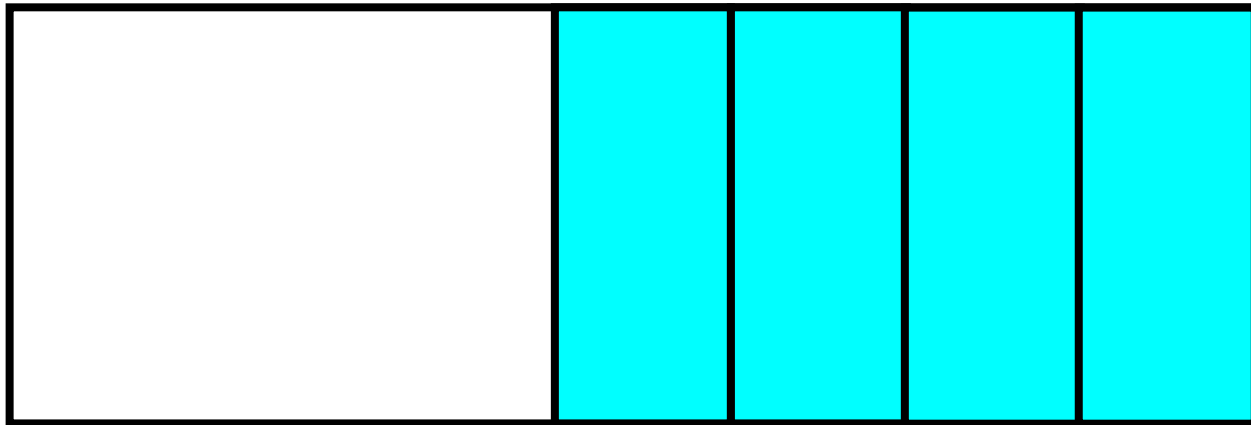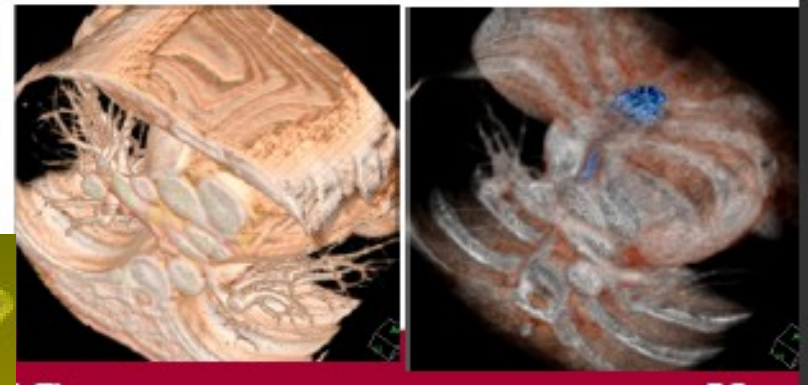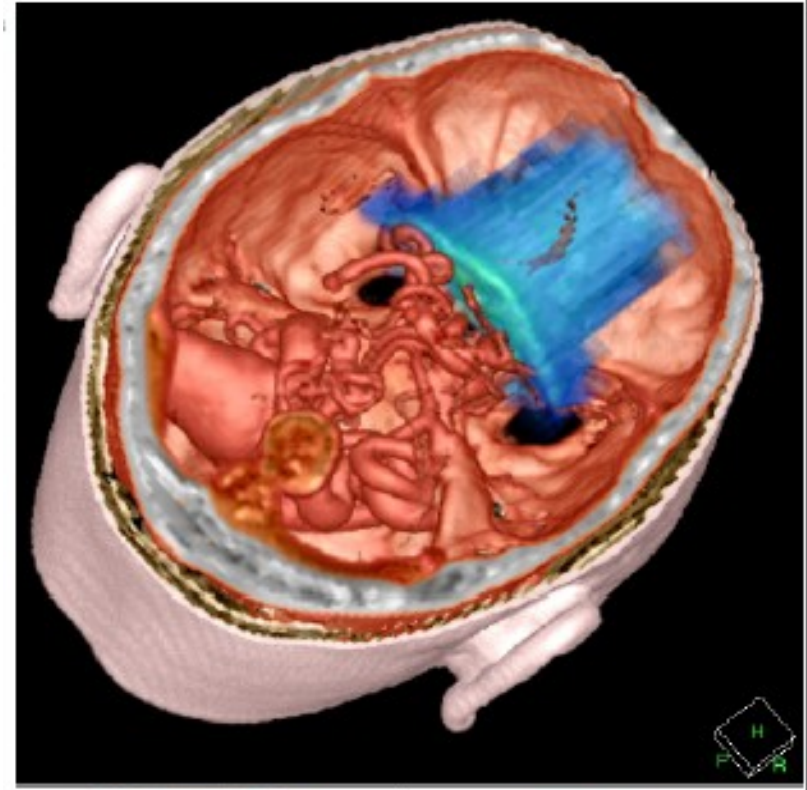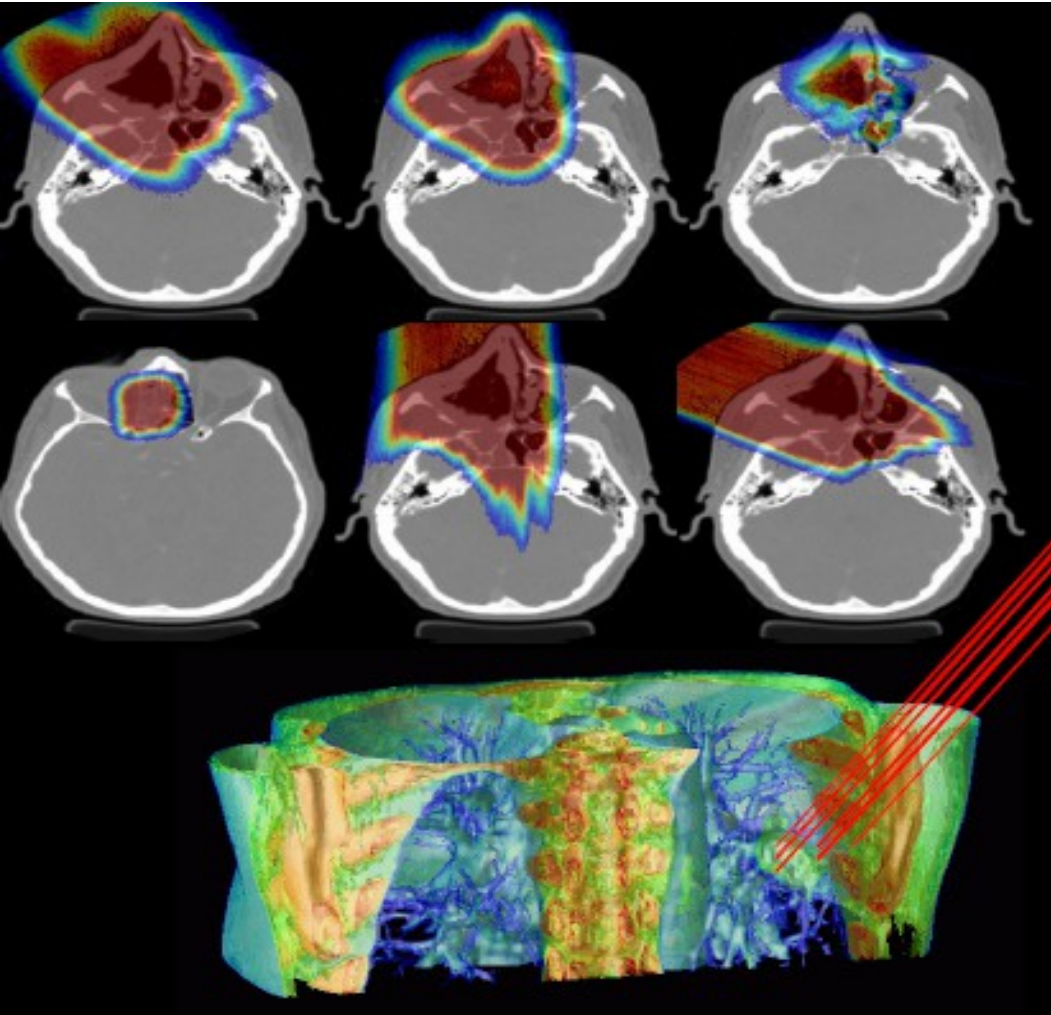
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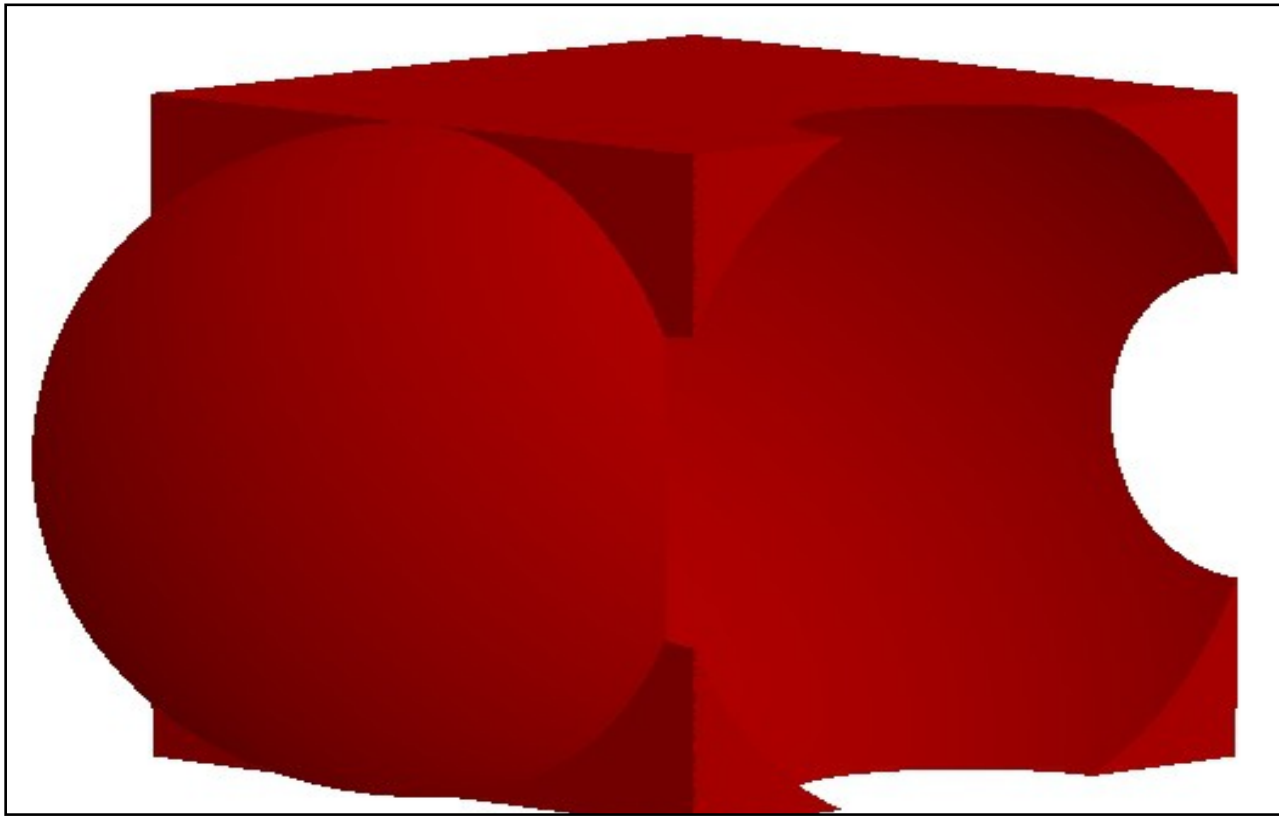
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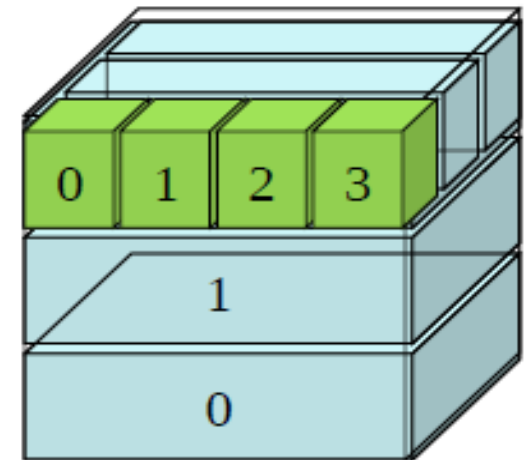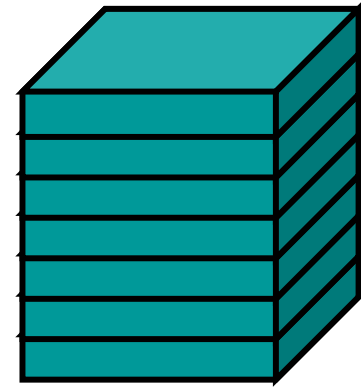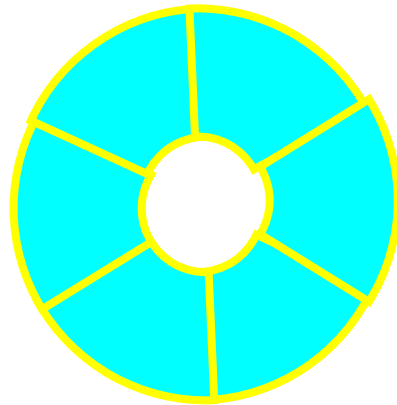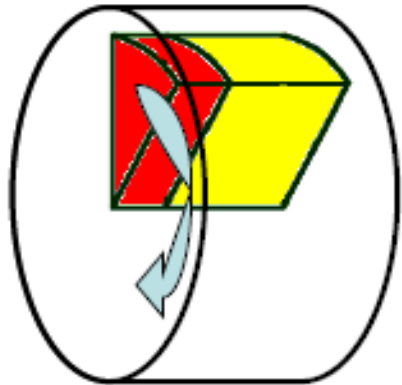
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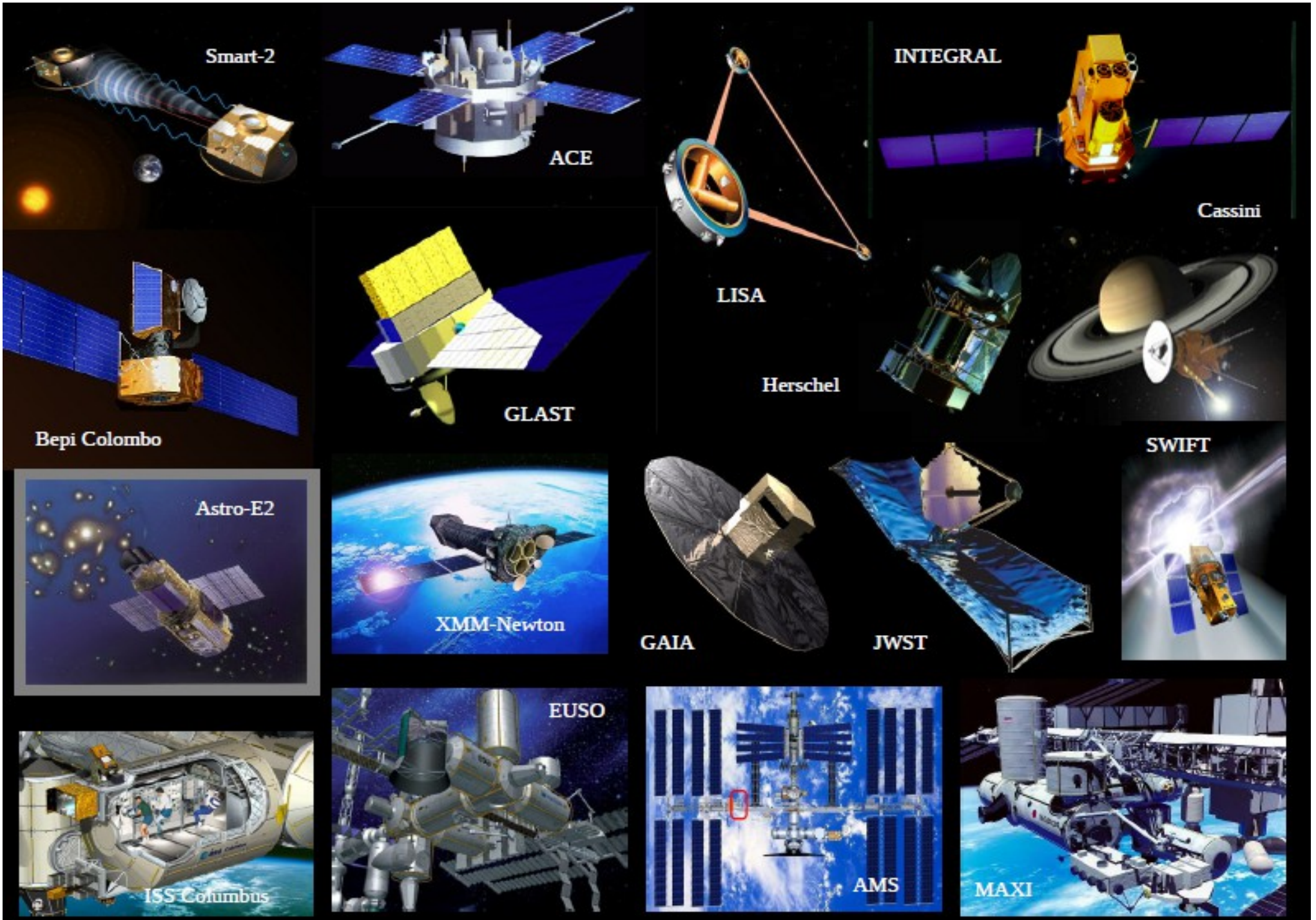
# Medical applications

# HEP : CMS tracker
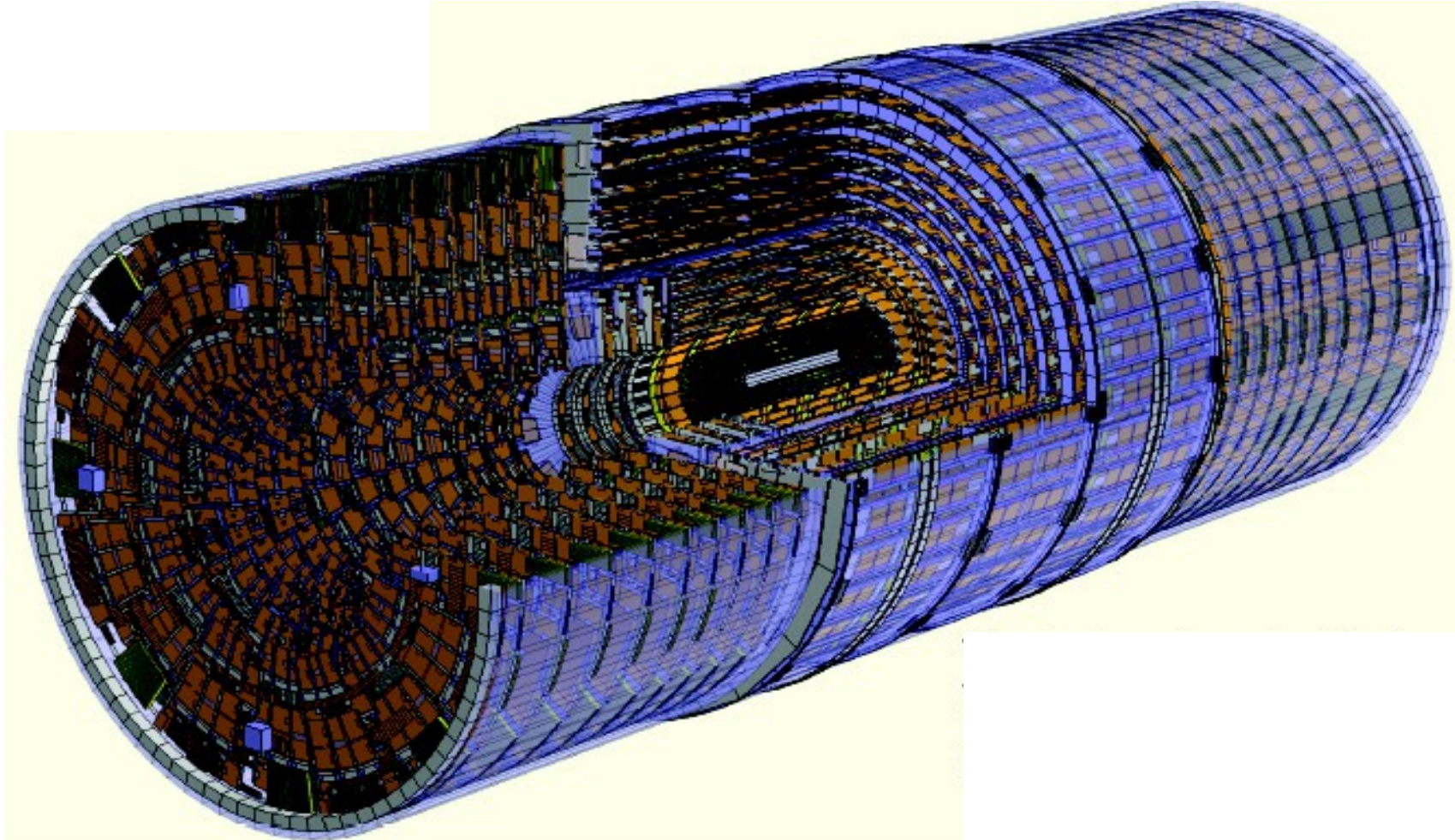
HEP :
ATLAS

# Physics

# Particle interactions

Each particle type has its own set of physics processes.
Only electromagnetic effects are directly measurable
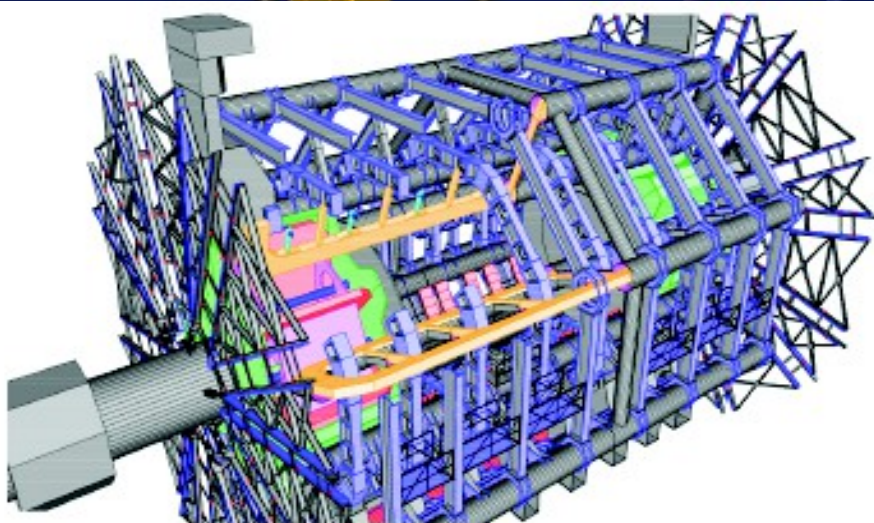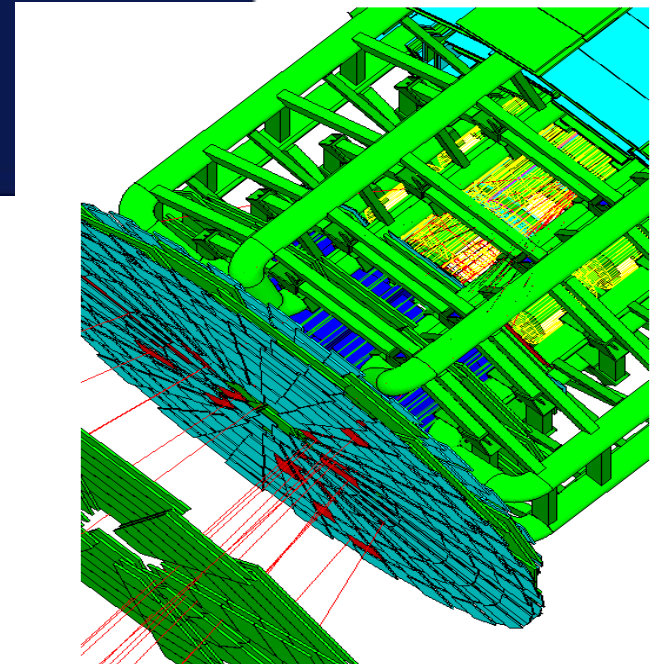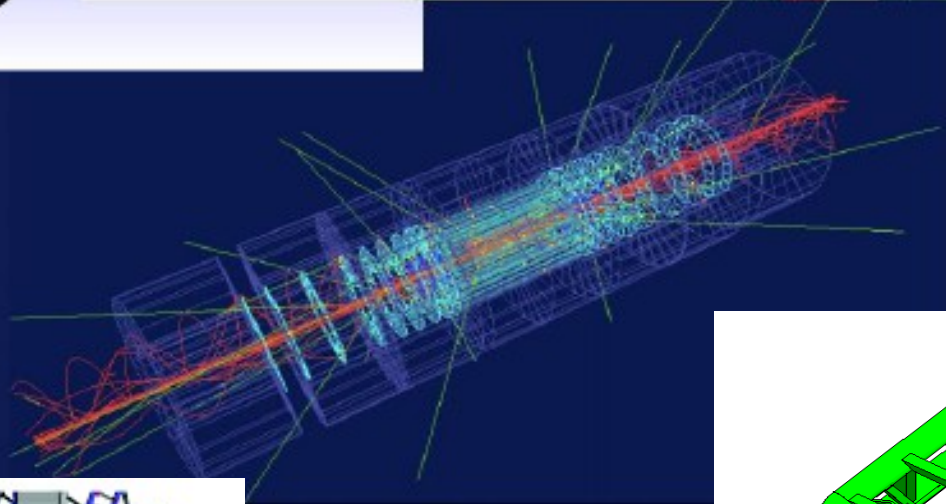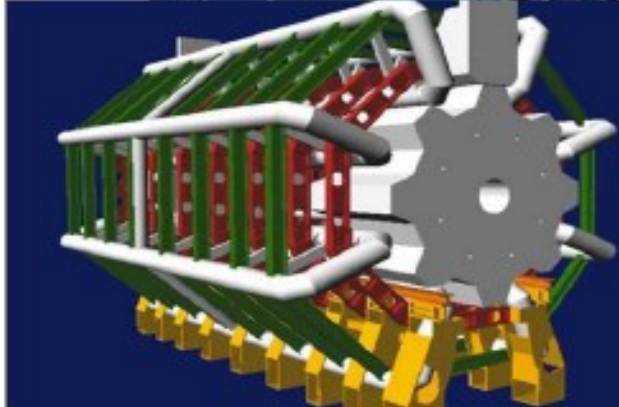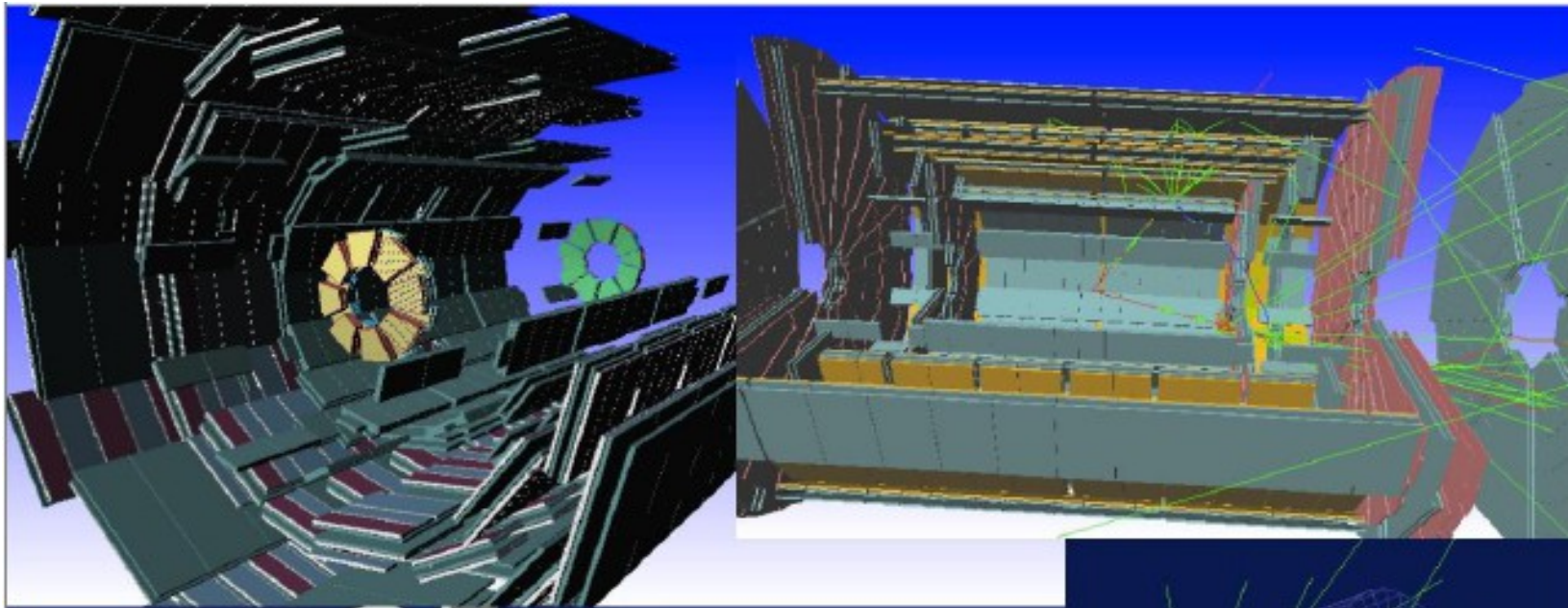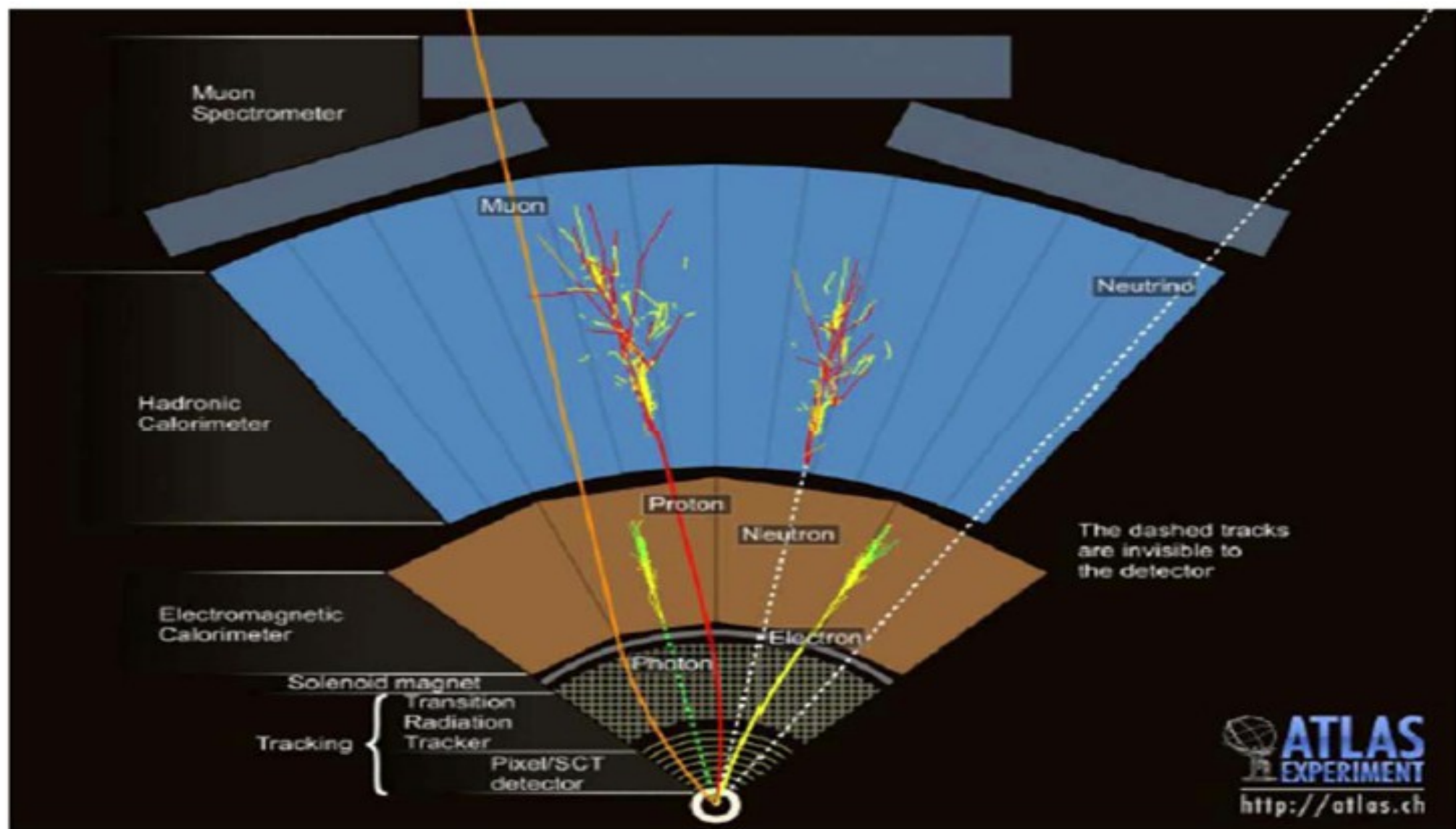
# Main electromagnetic processes

## Gamma

- Conversion
  γ -> e+ e- , μ+ μ-

- Compton scattering
  γ *(atomic)*e- -> γ *(free)*e-

- Photo-electric
  γ material -> *(free)*e-

- Rayleigh scattering
  γ atom -> γ atom

## Muon

- Pair production
  μ- atom -> μ- e+ e-

- Bremsstrahlung
  μ- atom -> μ- γ

- MSC (Coulomb scattering)
  μ- atom -> μ- atom

- Ionization :
  μ- atom -> μ- ion+ e-

## Electron, Positron

- Bremsstrahlung
  e- atom -> e- γ

- MSC (Coulomb scattering)
  e- atom -> e- atom

- Ionization
  e- atom -> e- ion+ e-

- Positron annihilation
  e+ e- -> γ γ

## Charged hadron, ion

- Bremsstrahlung
  h- atom -> h- γ

- MSC (Coulomb scattering)
  h- atom -> h- atom

- Ionization
  h- atom -> h- ion+ e-

Total cross section:
⇨ step length

Differential & partial cross sections :
⇨ final state
(multiplicity & spectra)

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# Production and tracking cuts

- Ionization & bremsstrahlung processes produce an increasing number of secondaries as the secondary energy decreases, so we need to set a production cut

  - Above the cut, new particles (e-, γ) are created

  - Below the cut, "continuous" energy loss of the primary

- Once a charged particle is created, it can be reliably transported down to $E_{kin} \sim 1$ keV

  - Either, stop it below a tracking cut and deposit its energy locally

  - Or, go down to $E_{kin} \to 0$ using its approximated range

- Production and tracking cuts can be expressed directly as kinetic energy thresholds or indirectly as equivalent range thresholds

# Multiple (Coulomb) scattering (MSC)

- Charged particles traversing a finite thickness of matter suffer a huge number (millions) of elastic Coulomb scatterings

- The cumulative effect of these small angle scatterings is mainly a net deflection from the original particle direction

- In most cases, to save CPU time, these multiple scatterings are not simulated individually, but in a "condensed" form

- Various algorithms exist, and new ones under development. One of the main differences between codes
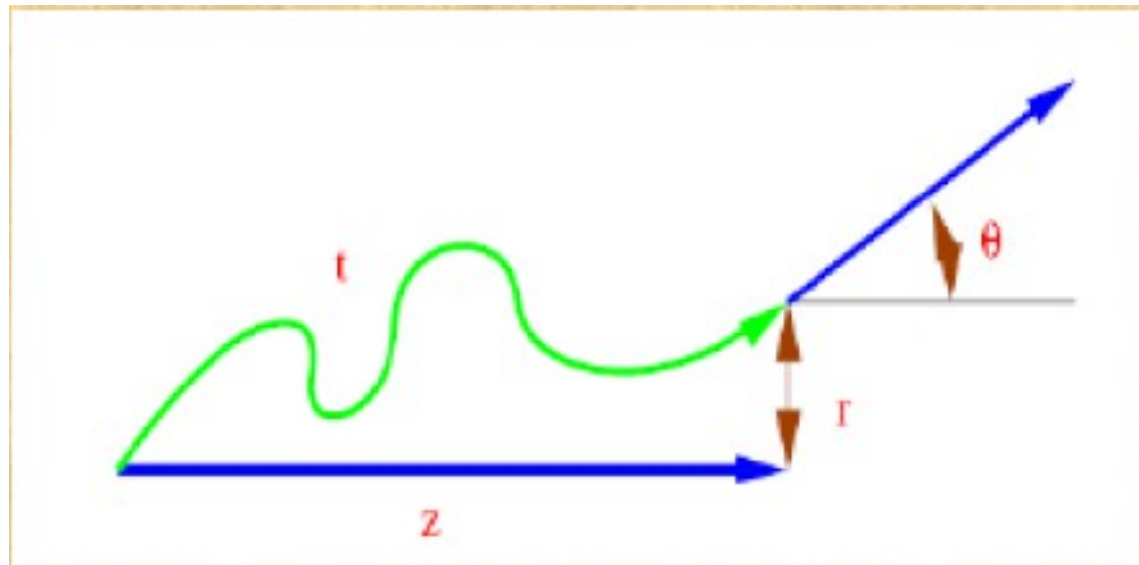
# Electromagnetic physics

- Typical validity of electromagnetic physics **≥ 1 keV** ;
  for a few processes, extensions to lower energies

- CPU performance of electromagnetic physics is critical :
  continuous effort to improve it

- Detailed validation of electromagnetic physics is necessary
  before the validation of hadronic physics

- Typical precision in electromagnetic physics is **~1%**

  - QED is extremely precise for elementary processes,
    but atomic and medium effects, important for detector simulations,
    bring larger uncertainties...

  - Moreover, the "condensed" description of multiple scattering
    introduces further approximations...

  - Continuous effort to improve the models

# Hadronic physics

- Hadrons (π±, K±, K°L , p, n, α, *etc.*), produced in jets and decays, traverse the detectors (H,C,Ar,Si,Al,Fe,Cu,W,Pb...)

- Therefore we need to model hadronic interactions

    **hadron – nucleus  ->  *anything***

  in our detector simulations

- In principle, QCD is the theory that describes all hadronic interactions; in practice, perturbative calculations are applicable only in a tiny (but important!) phase-space region

  - the hard scattering at high transverse momentum

  whereas for the rest, i.e. most of the phase space

  - soft scattering, re-scattering, hadronization, nucleus de-excitation

   only approximate models are available

- Hadronic models are valid for limited combinations of

  - **particle type - energy - target material**

# Hadronic models available in Geant4
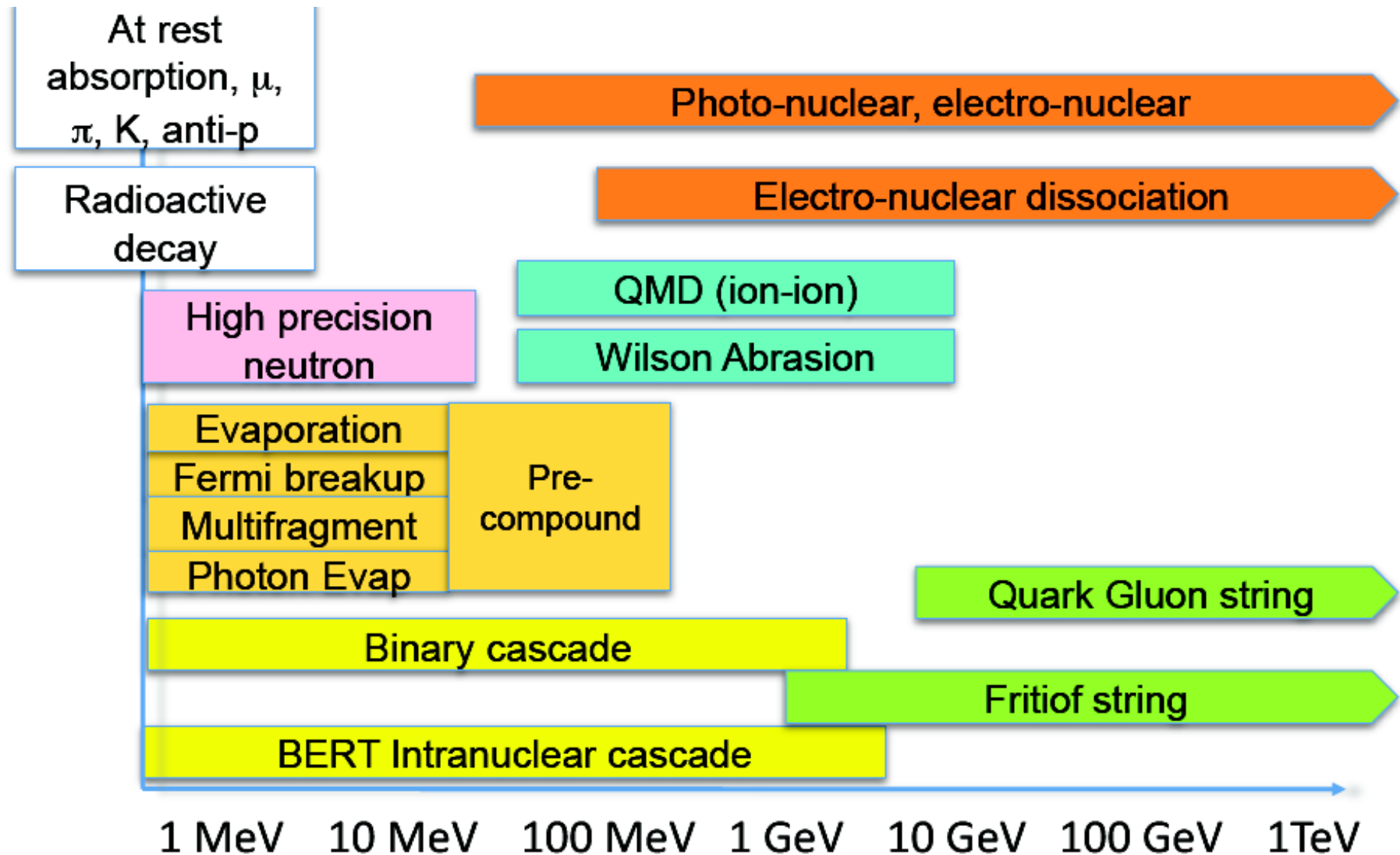
# Physics configuration

- No "unified" hadronic model: need to choose a set of hadronic models able to cover all possible interactions

  - The choice depends on the use-case, because of:
    - The energy scale involved
    - The compromise between accuracy and CPU speed
  - The choice is often done by the developers
    - Options can be proposed according to use-cases

- In the case of Geant4

  - These physics configurations are called "physics lists"
    - The particles to be considered in the simulation are also specified
  - There is no default
  - Ready-to-use "physics lists" exist, for different use-cases
  - Users can also tailor/modify any of these, or write their own

# Hadronic Interactions from TeV to meV



String model

TeV hadron

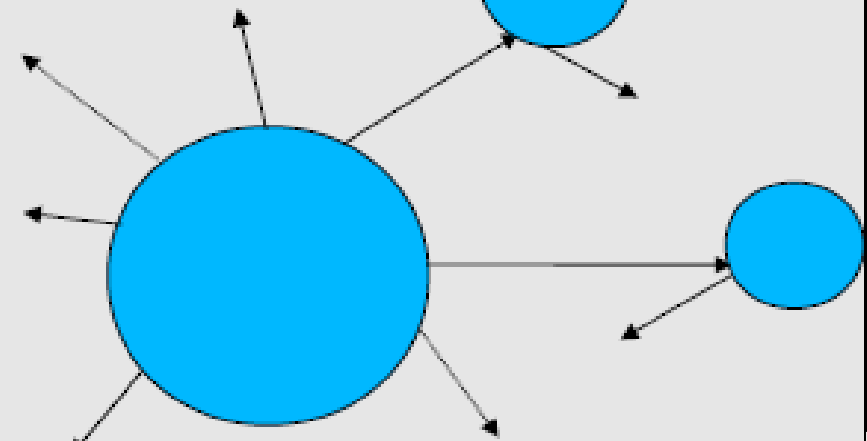$dE/dx \sim A^{1/3}\, GeV$
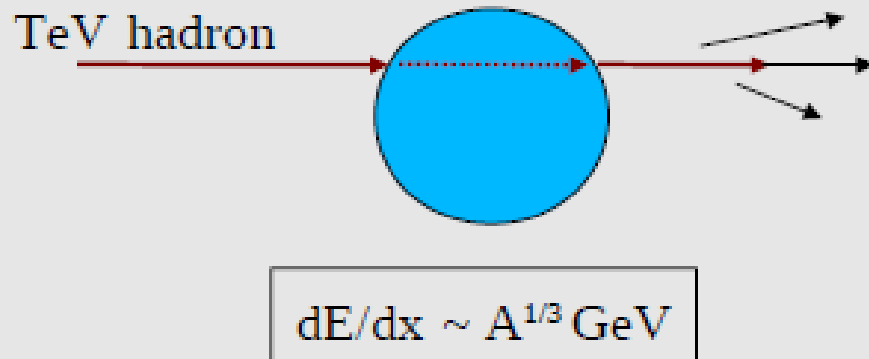
Intra-nuclear cascade model
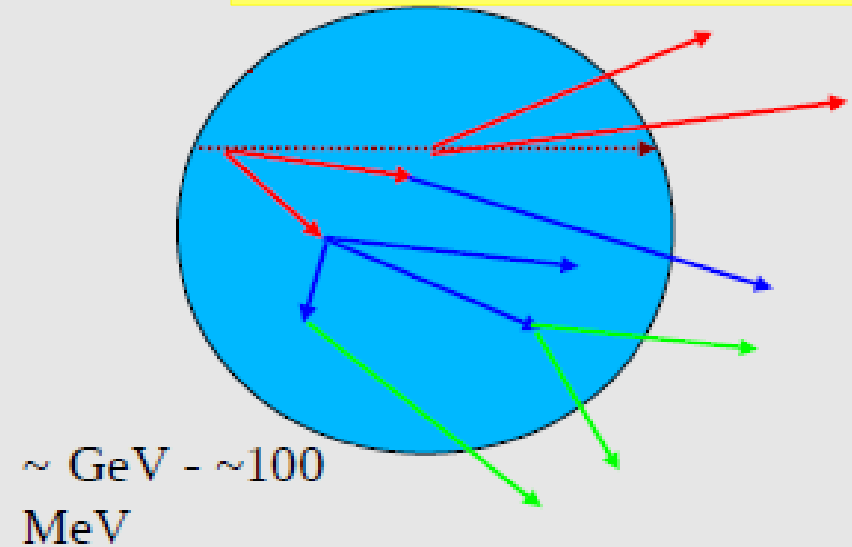
$\sim$ GeV - $\sim$100 MeV

$\sim$100 MeV - $\sim$10 MeV
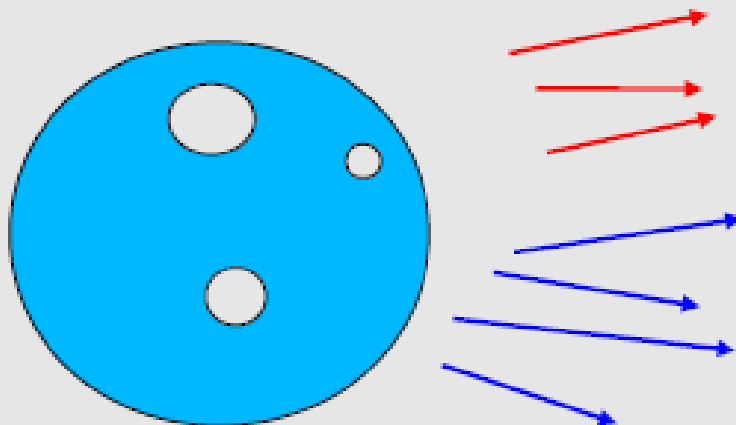
Pre-equilibrium (Precompound) model

$\sim$10 MeV to thermal

Equilibrium (Evaporation) model

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# An interesting complication: Neutrons

- Neutrons are abundantly produced

  - Mostly "soft" neutrons, produced by the de-excitations of nuclei, after hadron-nucleus interactions

  - It is typically the 3$^{rd}$ most produced particle (after e-, γ)

- Before a neutron "disappears" via an inelastic interaction, it can have many elastic scatterings with nuclei, and eventually it can "thermalize" in the environment

- The CPU time of the detector simulation can vary by an order of magnitude according to the physical accuracy of the neutron transportation simulation

  - For typical high-energy applications, a simple treatment is enough (luckily!)

  - For activation and radiation damage studies, a more precise, data-driven and isotope-specific treatment is needed, especially for neutrons of kinetic energy below ~ MeV

# Hadronic showers

- A single hadron impinging on a large block of matter (e.g. a calorimeter) produces secondary hadrons of lower energies, which in turn can produce other hadrons, and so on: the set of these particles is called a **hadronic shower**

  - e-/e+/γ (electromagnetic component) are also produced copiously because of **π° -> γ γ** and ionization of charged particles

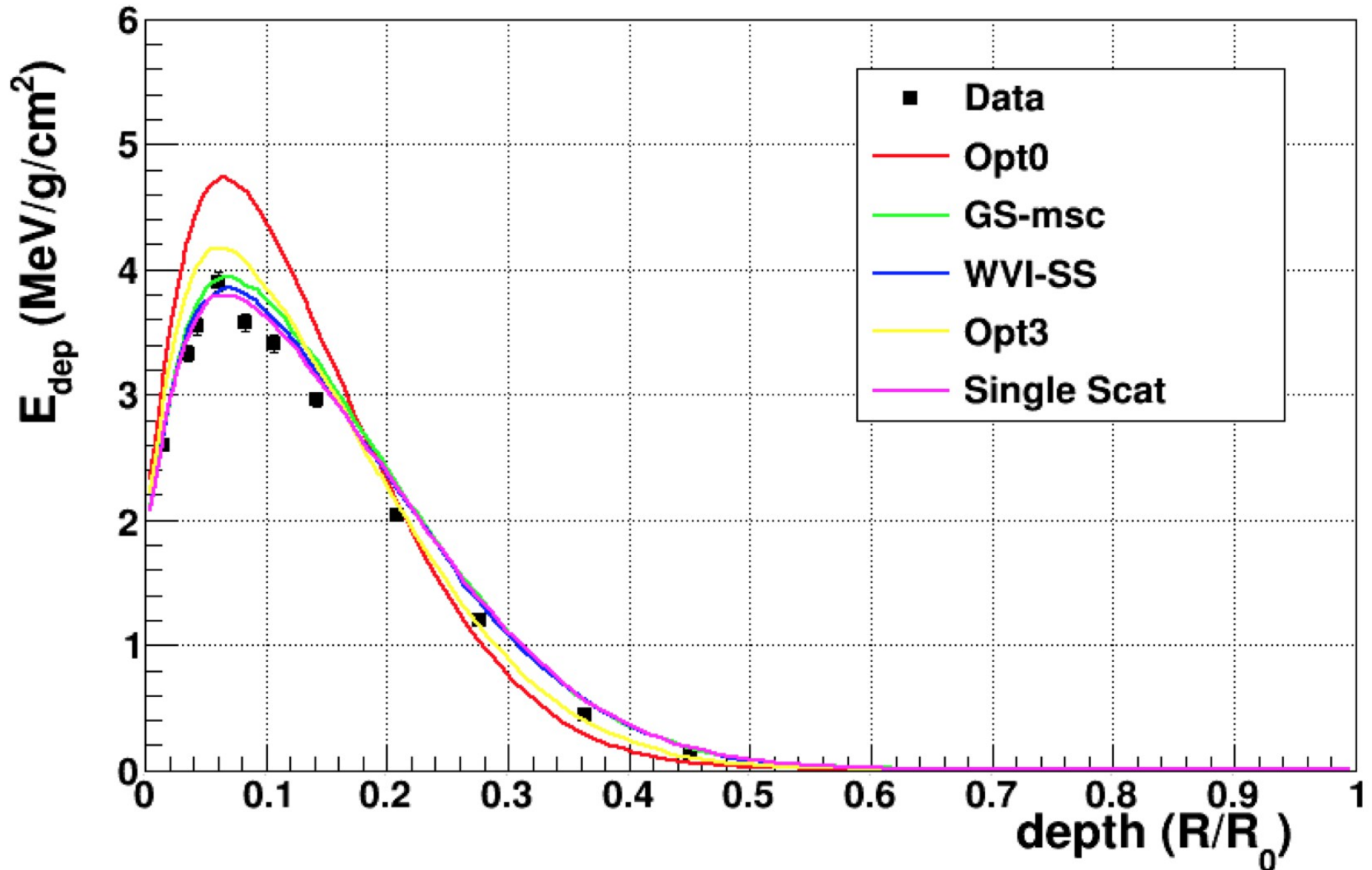- The development of a hadronic shower involves many energy scales, from hundreds of GeV down to thermal energies
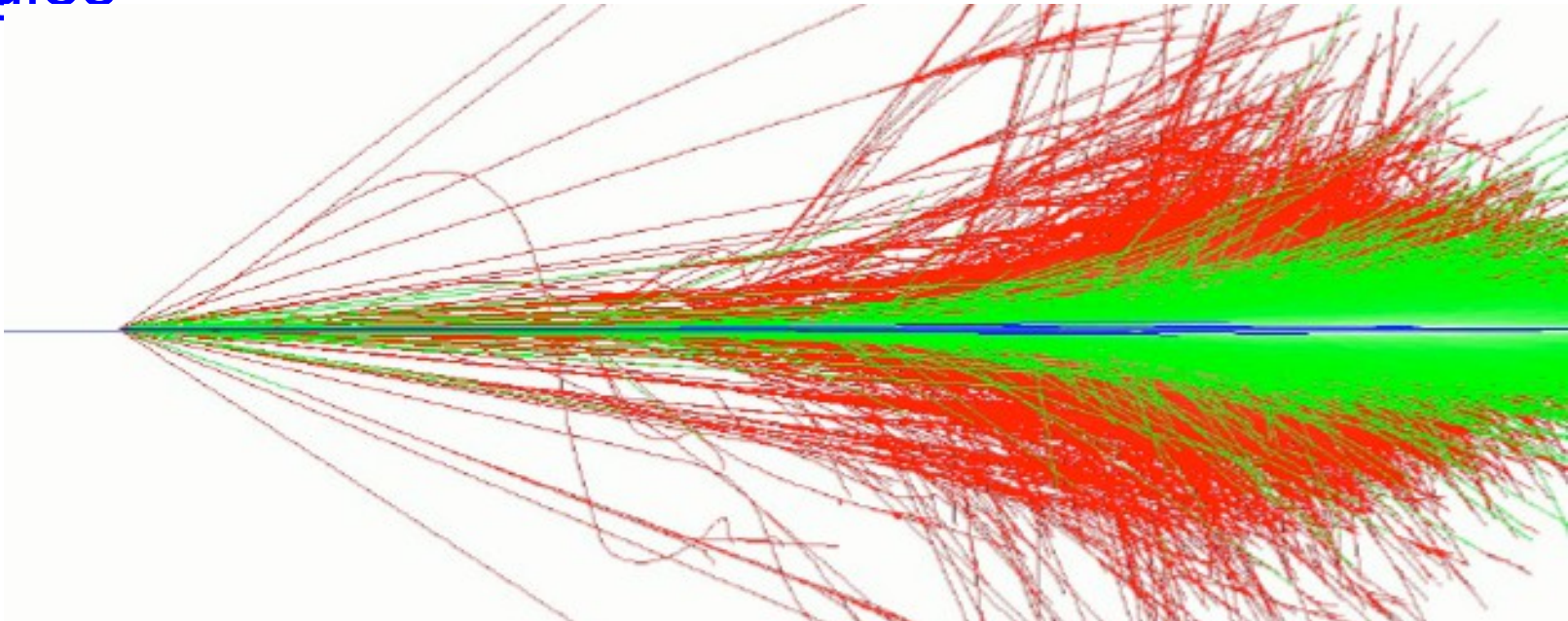
# Validation

# Multiple (Coulomb) scattering of electrons



Angular distribution of $E_p = 15.7$ MeV $e^-$ transmitted Au 19.296 μm

GS -opt0; $R_f = 0.15$
Urban -opt0; $R_f = 0.04$
experiment

$F(\Theta)$ [deg$^{-2}$]

$\Theta$ [deg.]

exp: A.O.Hanson et al., Phys. Rev. 84(1951)534
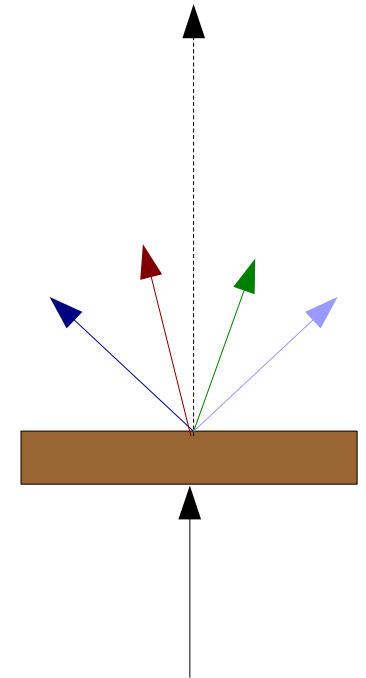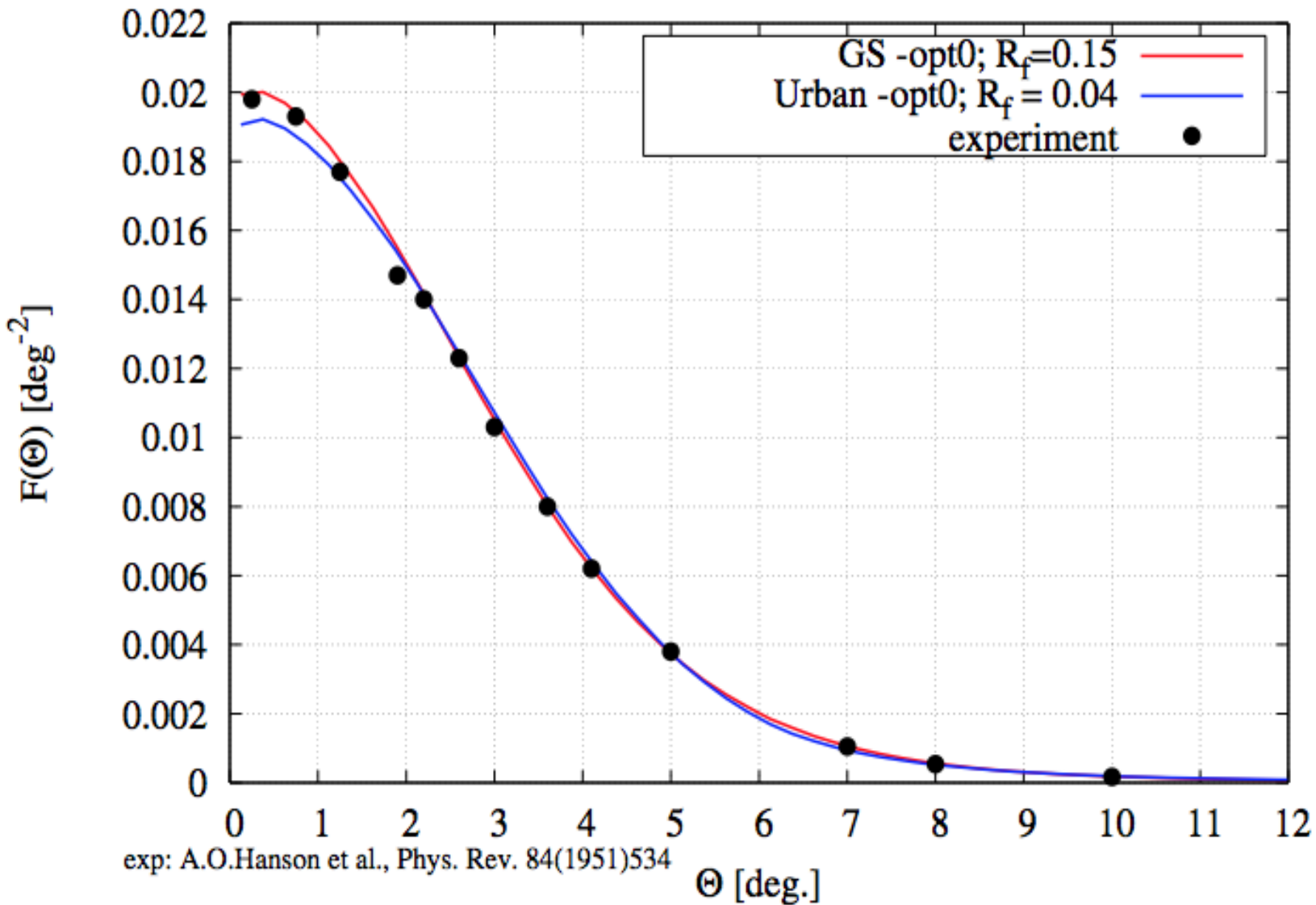
# Electron energy deposit



e⁻ 1.0 MeV in Ta, Geant4 10.2ref05

# Validation & tuning of hadronic models

- The developers of the hadronic models are responsible of the tuning & validation of these models with thin-target (microscopic, single-interaction) measurements
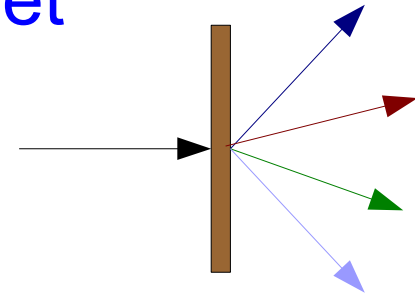
- Validation of complete physics configurations is performed by users mostly via measurements of hadronic showers in calorimeter test-beam setups (thick targets)
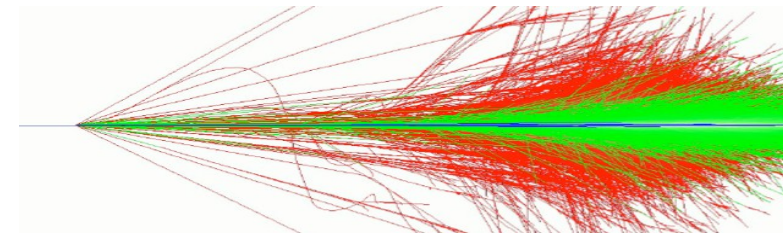
- The most important application of the hadronic models for collider experiments is the **simulation of jets**, which involves

    **1.** the Monte Carlo event generator

    **2.** the convolution of the showers for each constituent hadron

    **3.** experiment specific: geometry & materials, digitization, etc.

# Model-level thin-target tests



FTF Results at 400 GeV/c
p Ta -> pi+ X
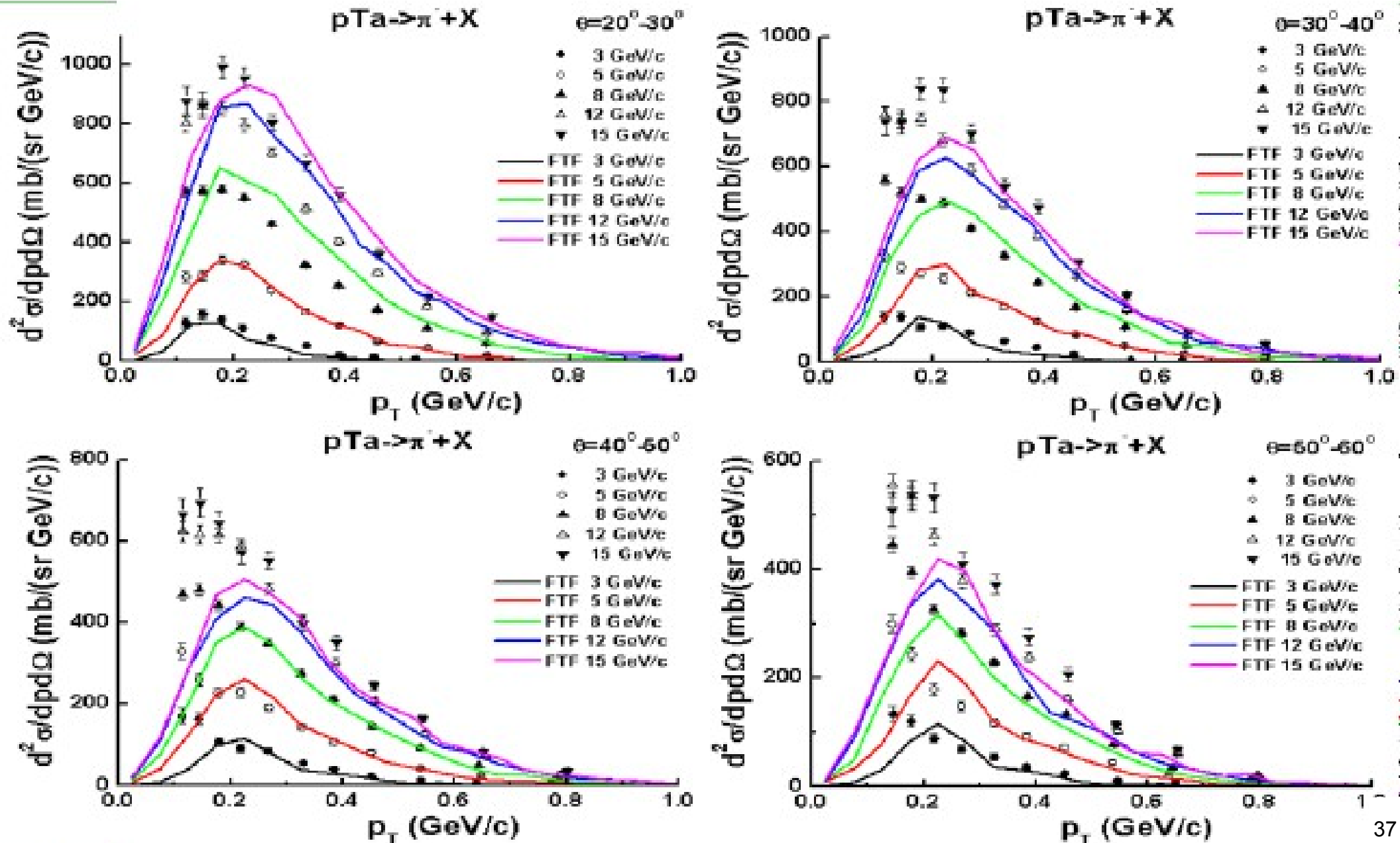
# Model-level thin-target tests

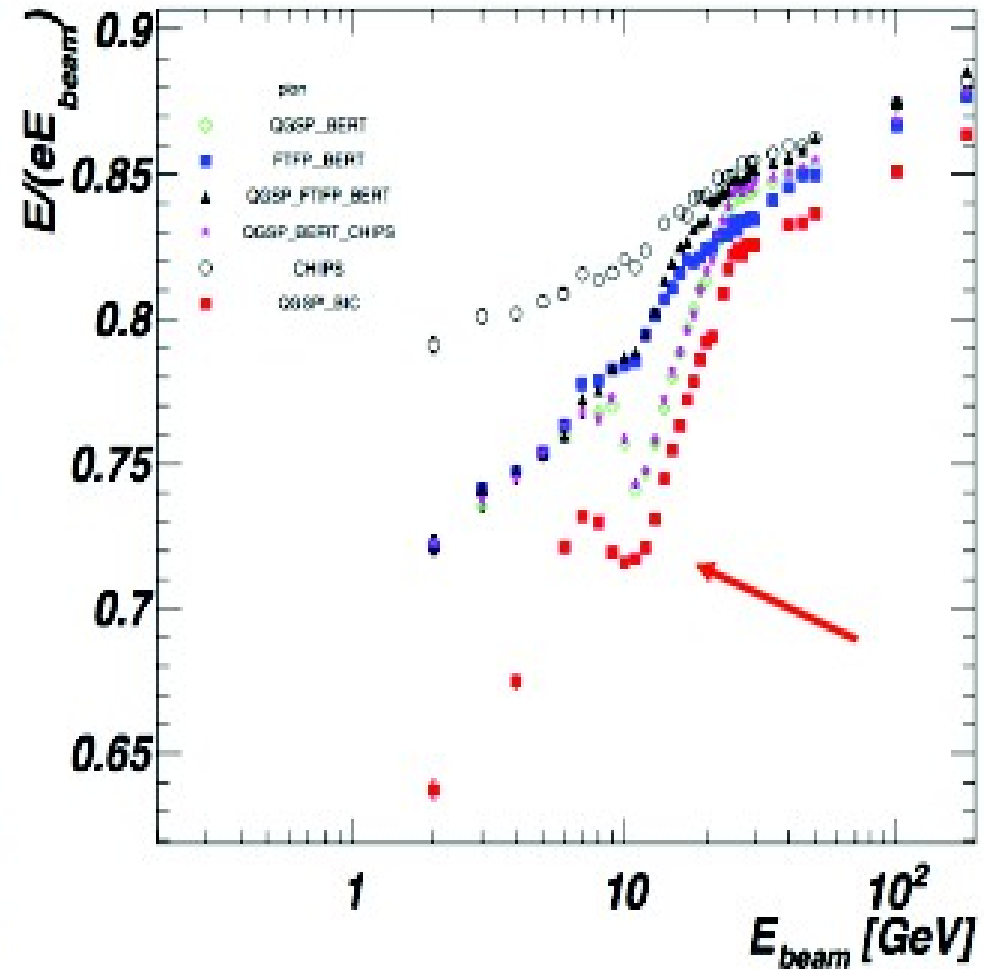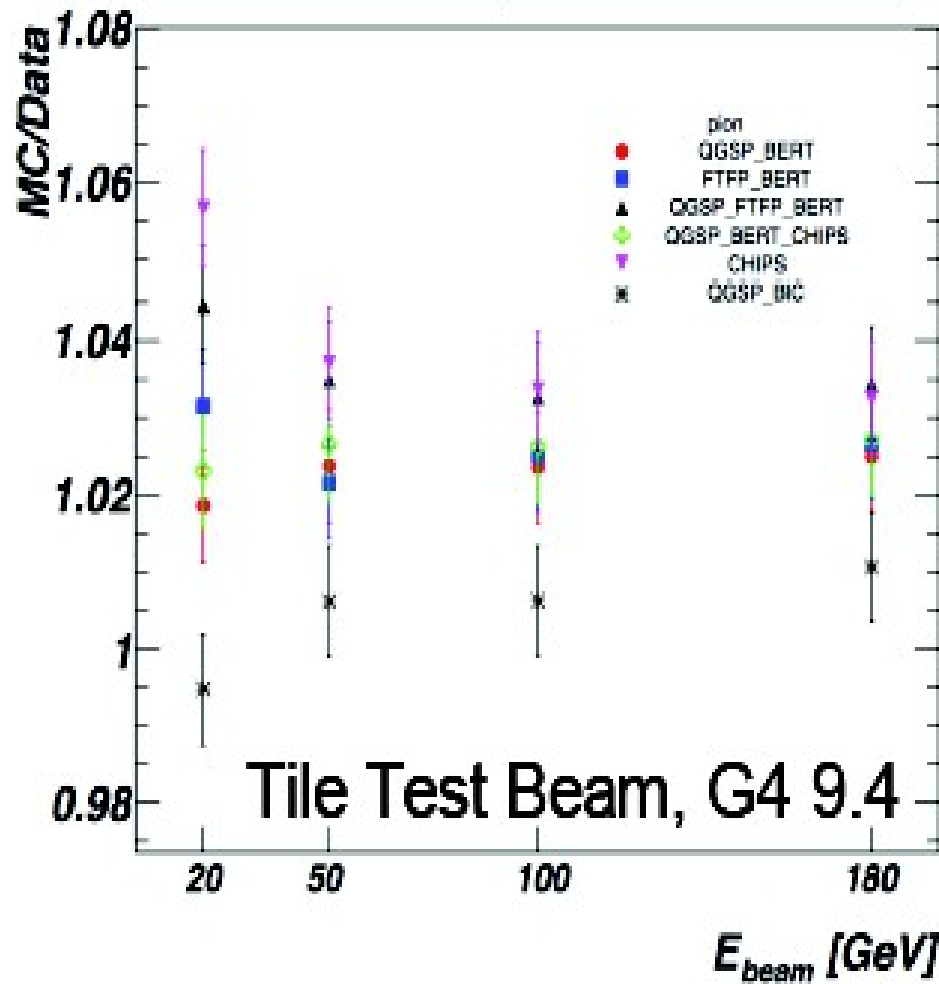# Validation of the Bertini Cascade
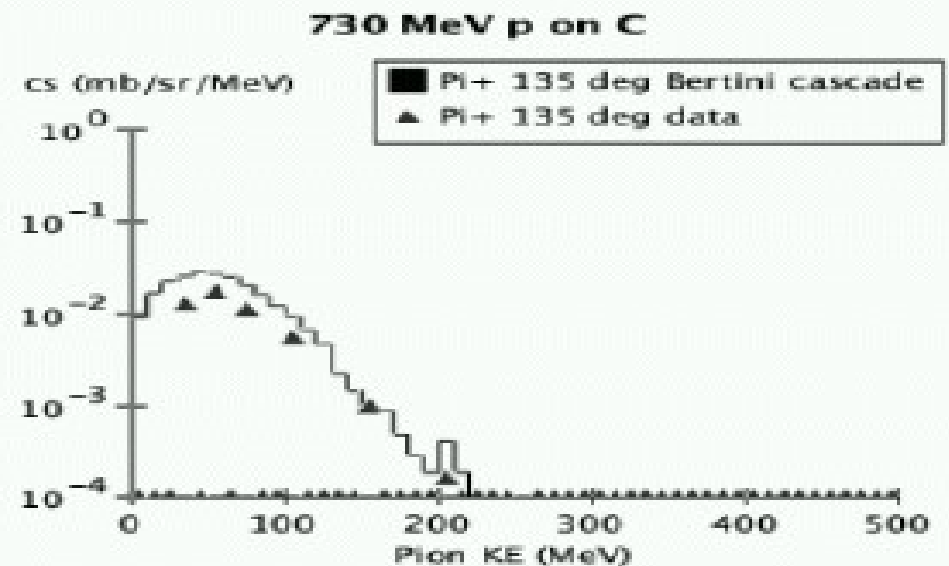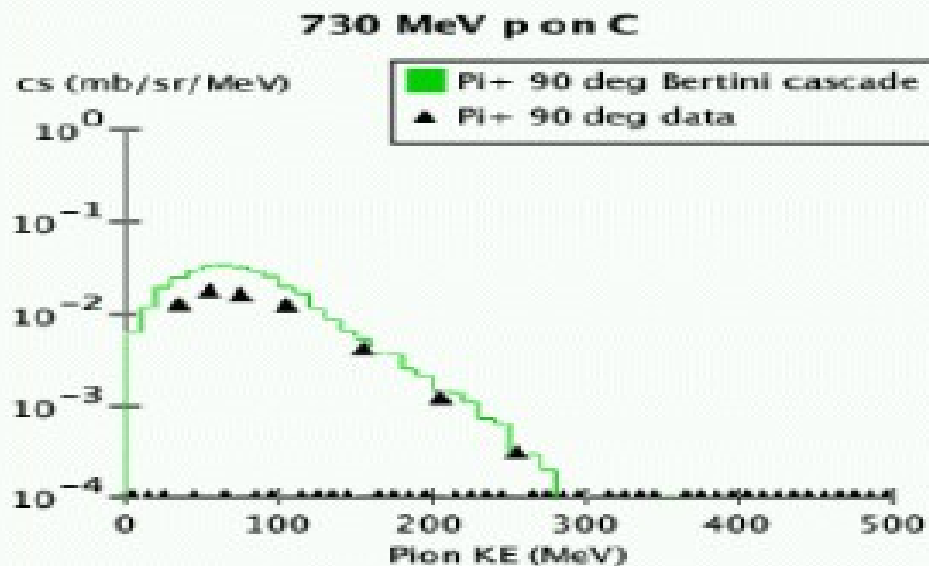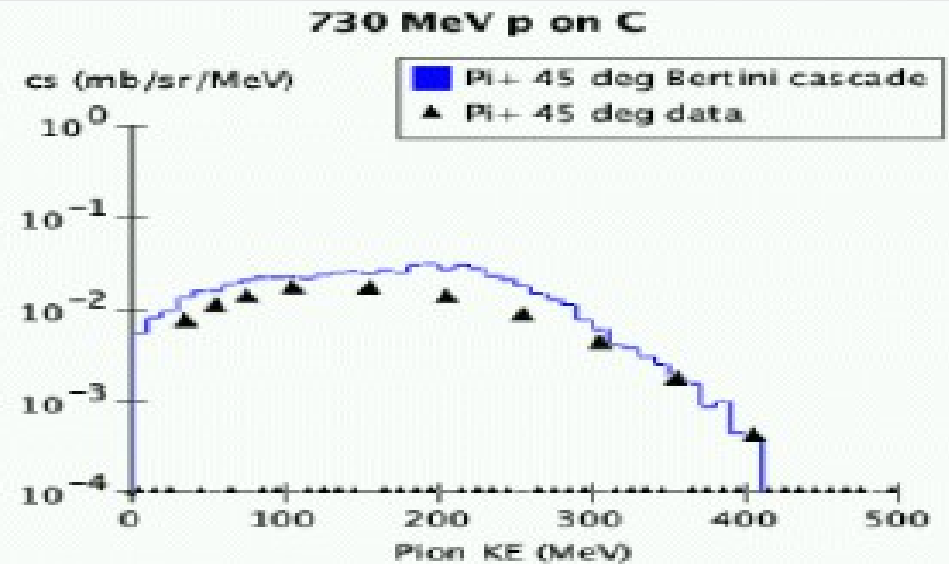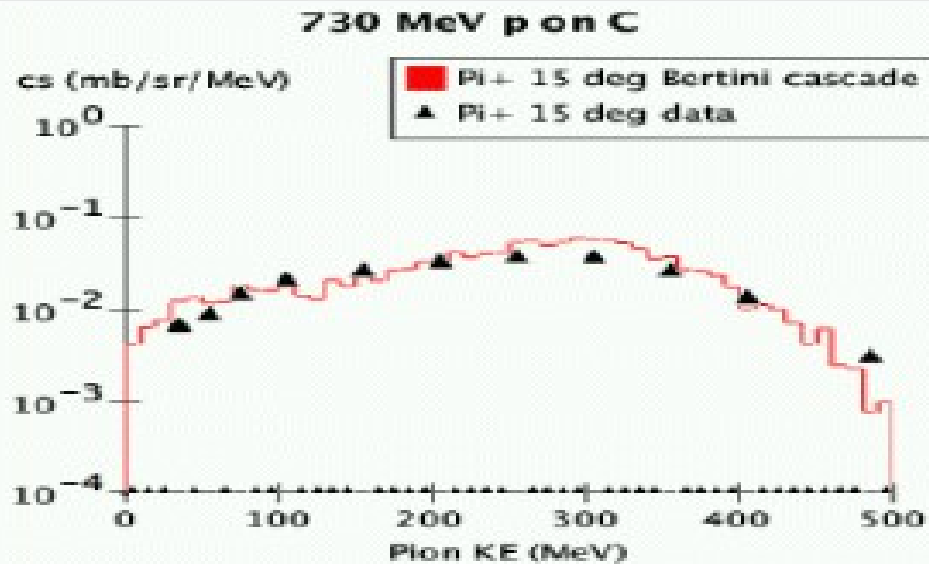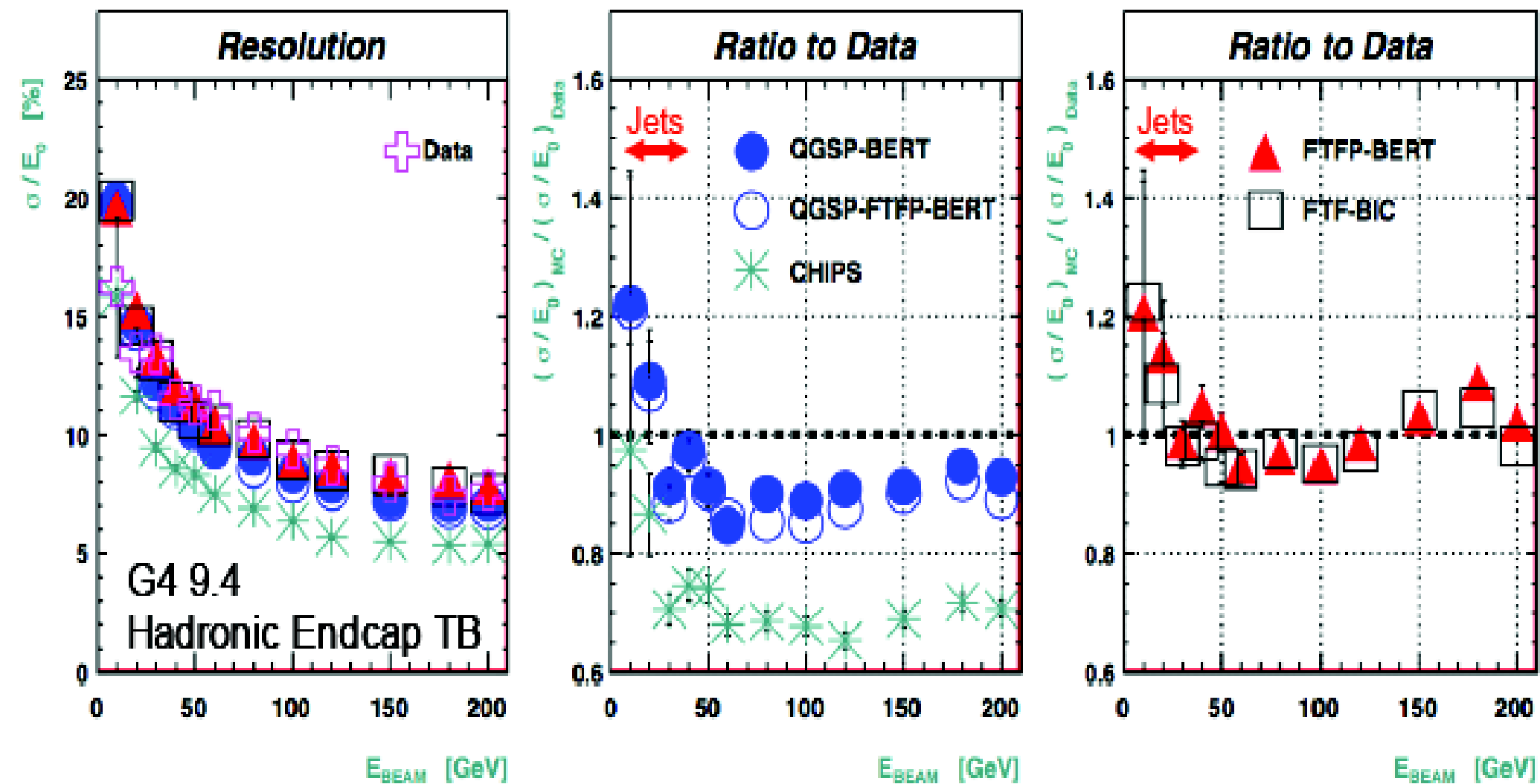
# Model-level thin-target tests
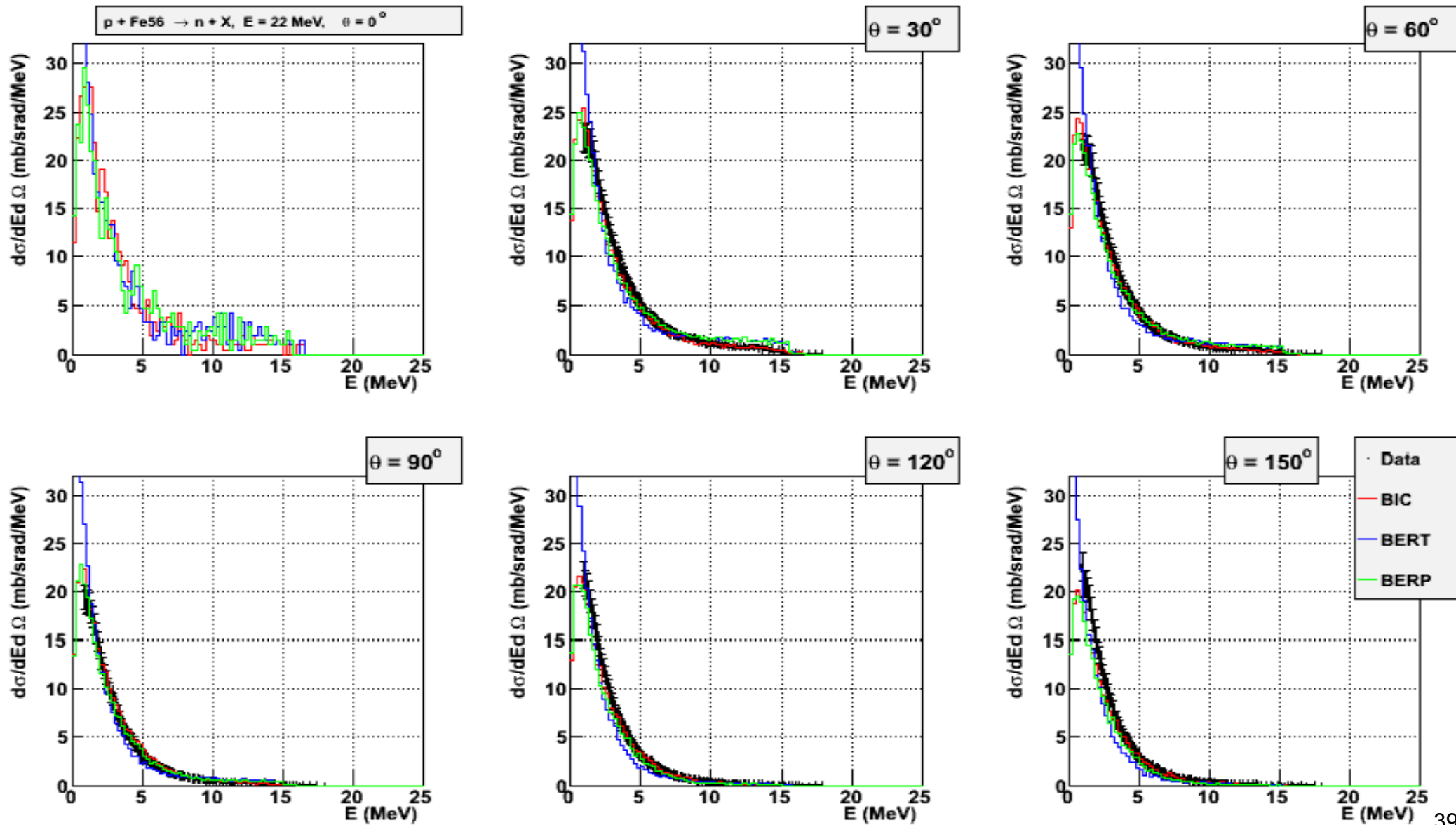
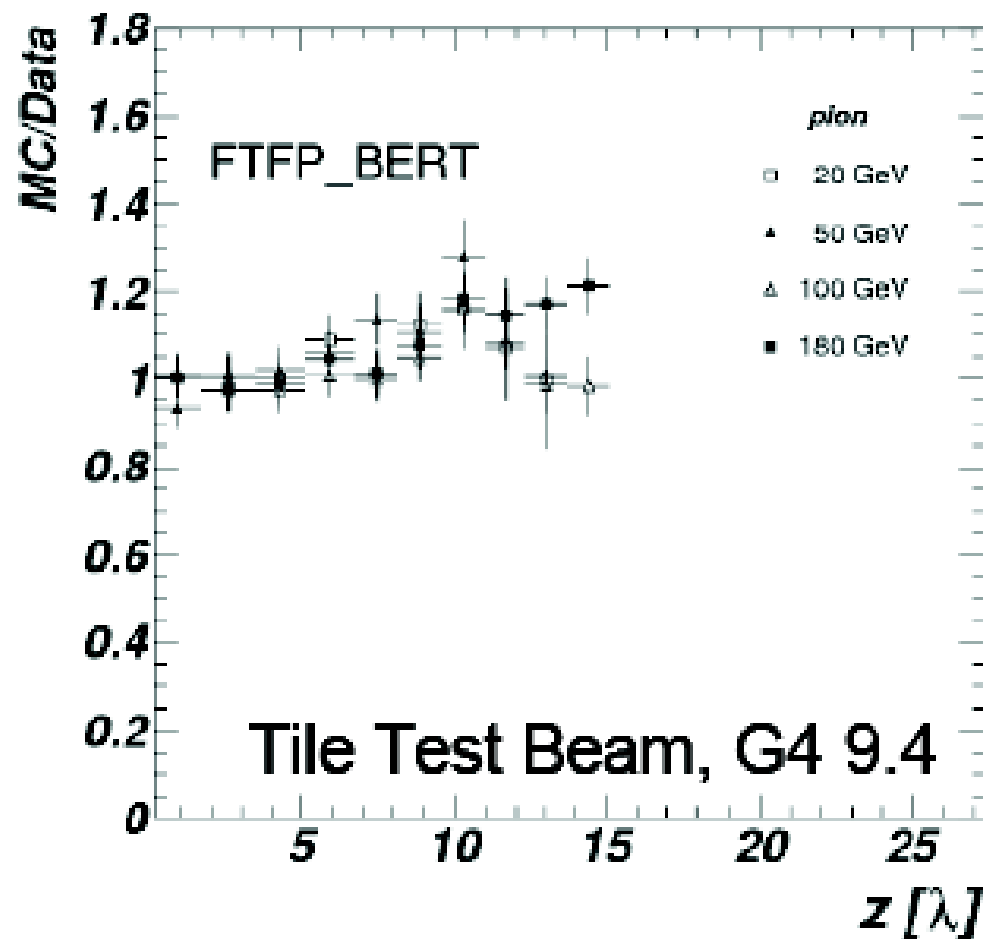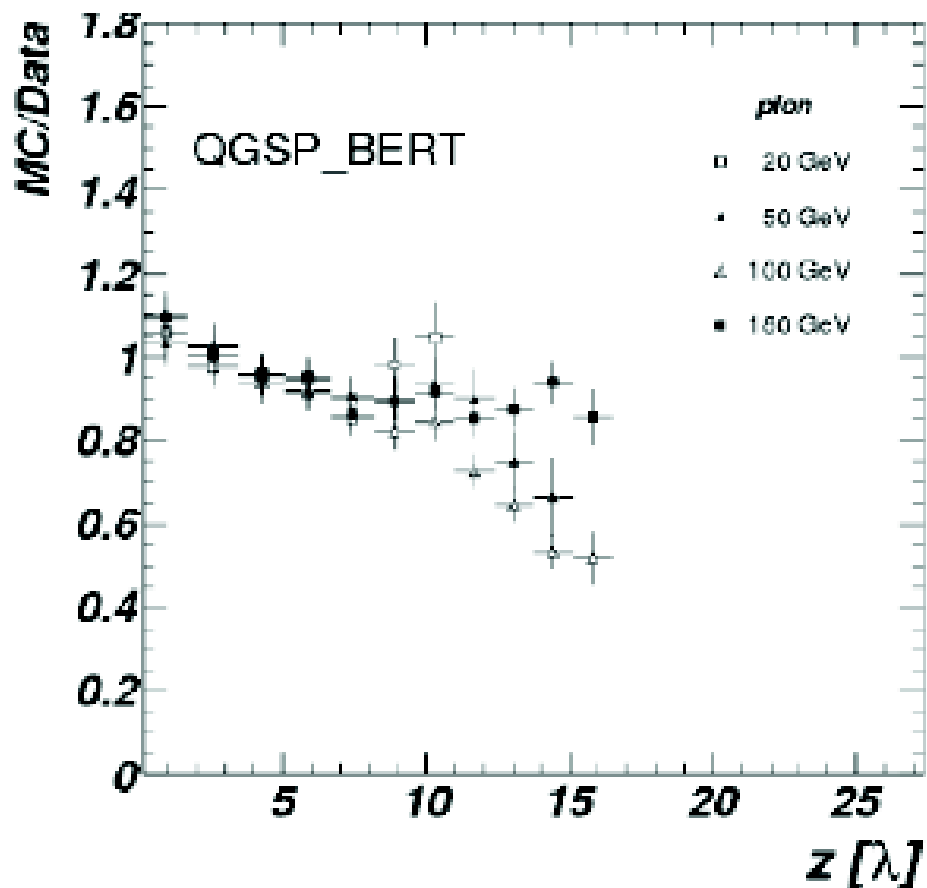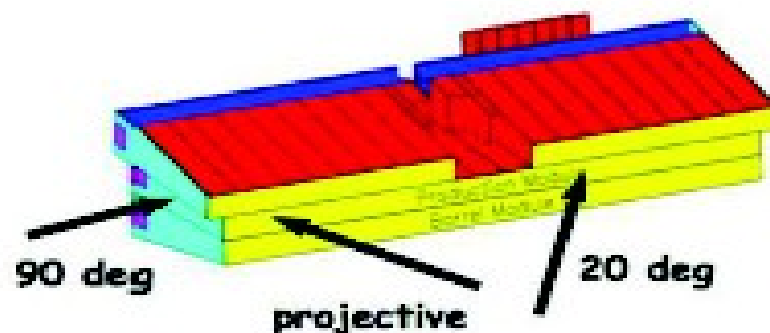# LHC calorimeter test-beams
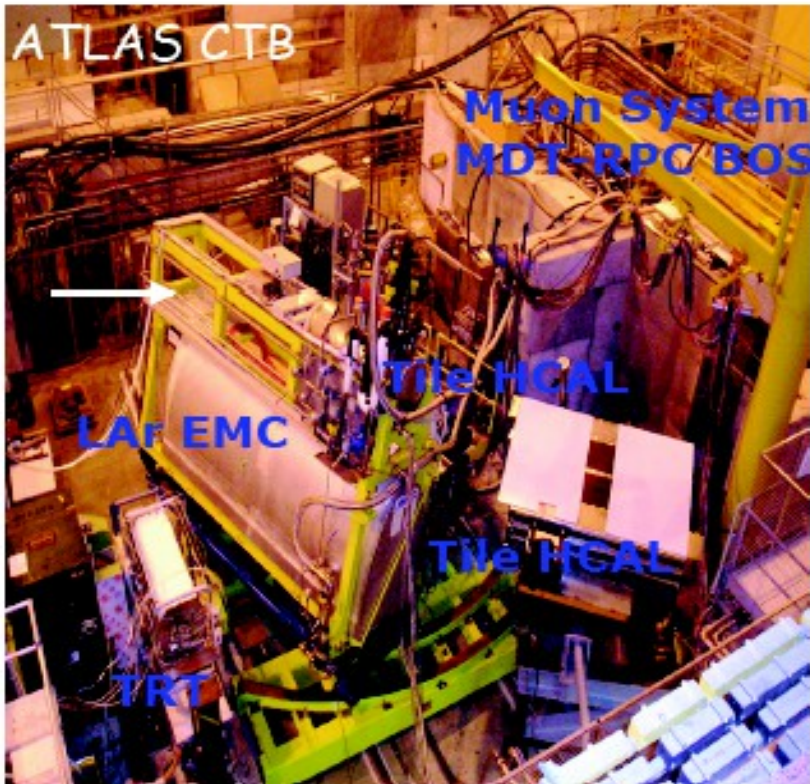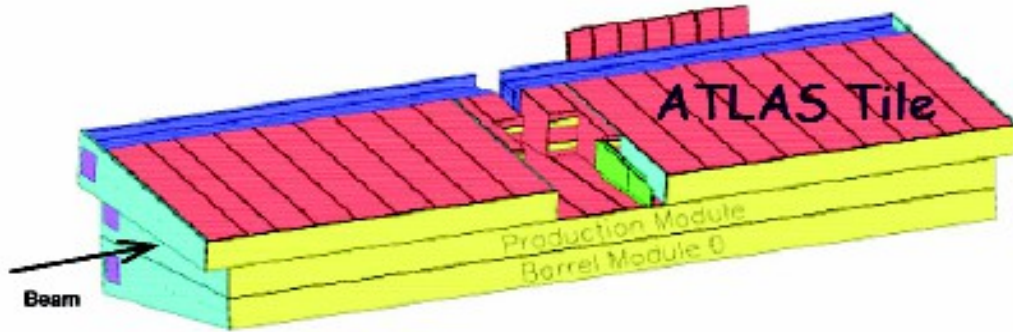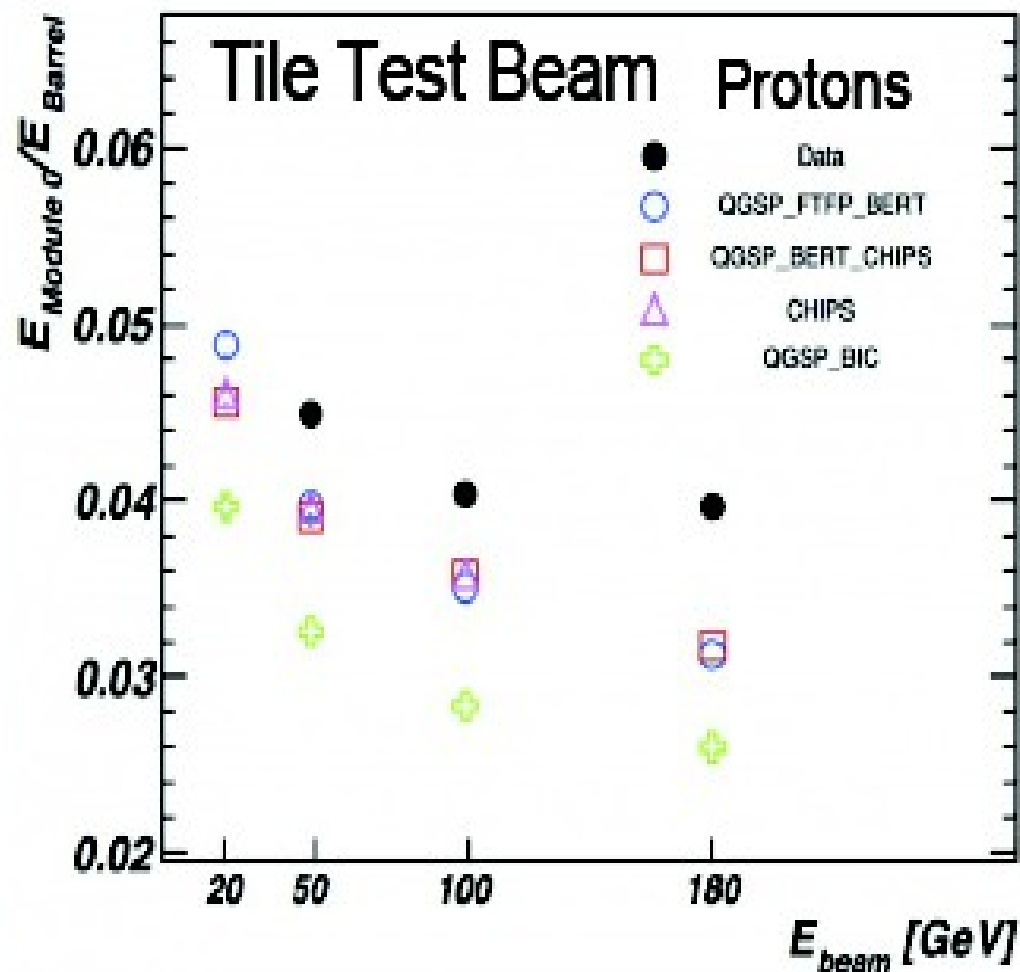
# Energy response

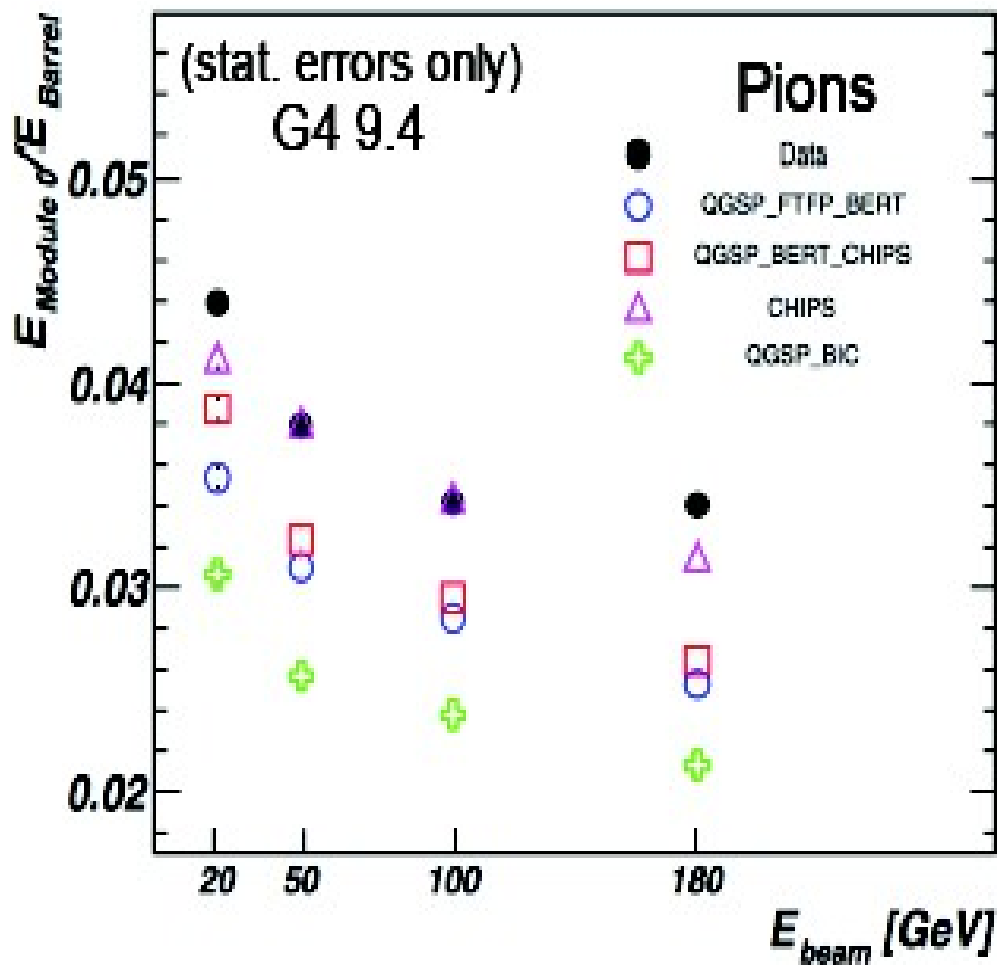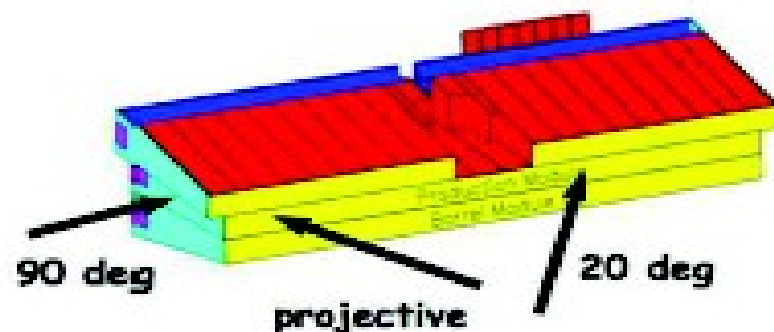ATLAS TileCal test-beam

# Energy resolution

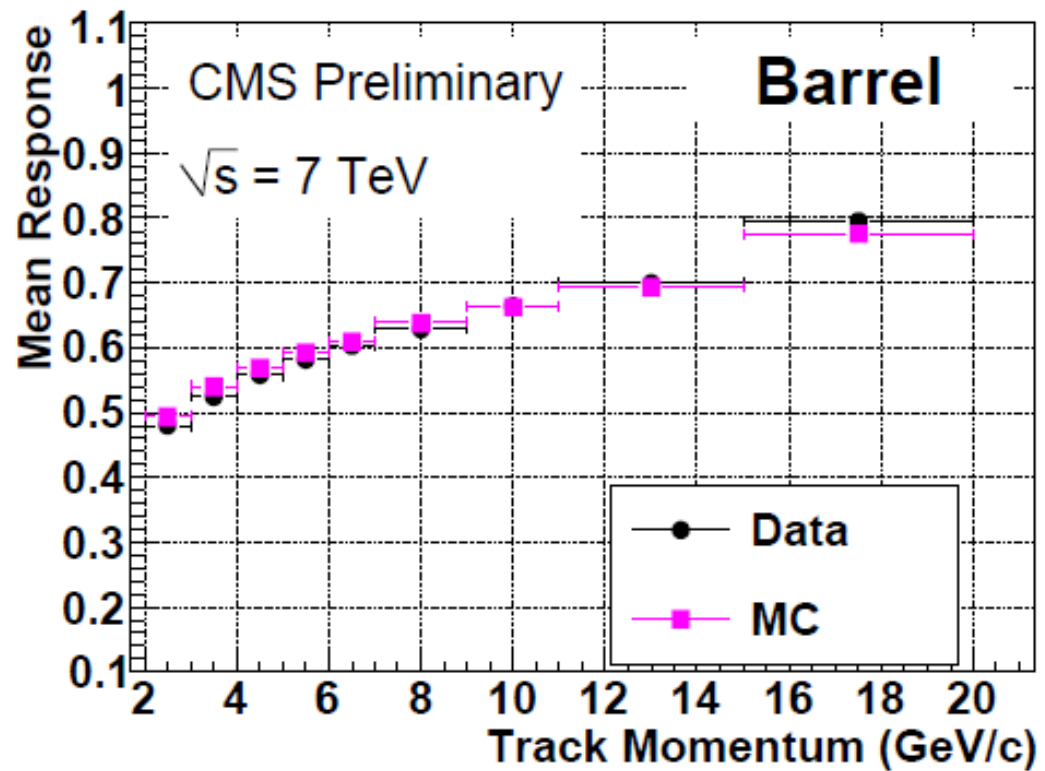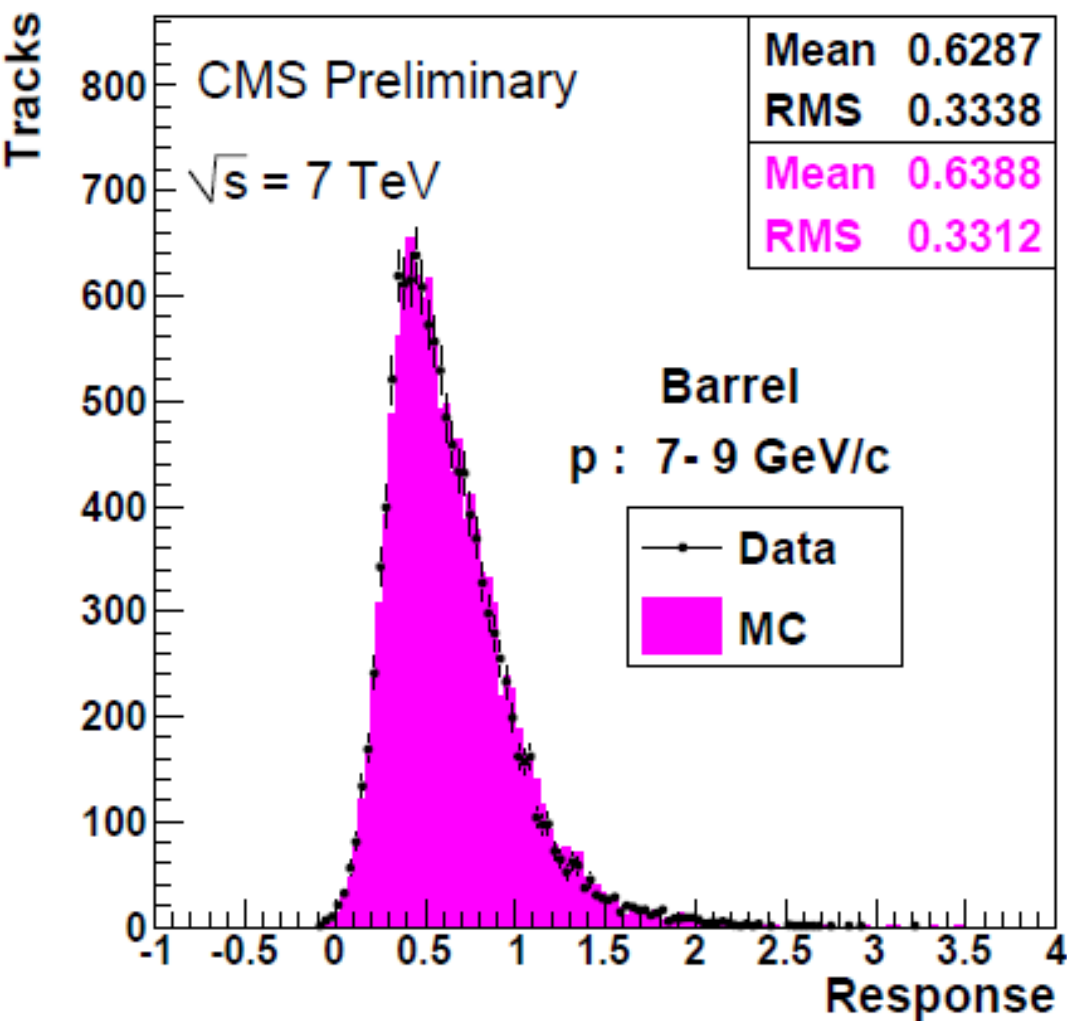# Longitudinal shower shape

ATLAS TileCal test-beam @90°

# Lateral shower shape



ATLAS TileCal test-beam @90°

# Isolated single hadron response: simulation *vs.* CMS p-p data

## Agreement is better than ±3% between 2-20 GeV/c

# Di-jet invariant mass: simulation *vs.* CMS p-p data
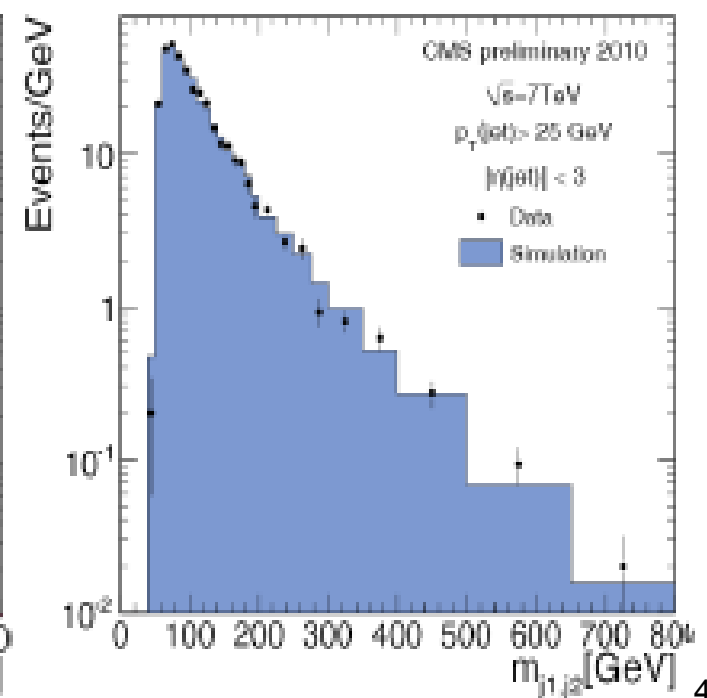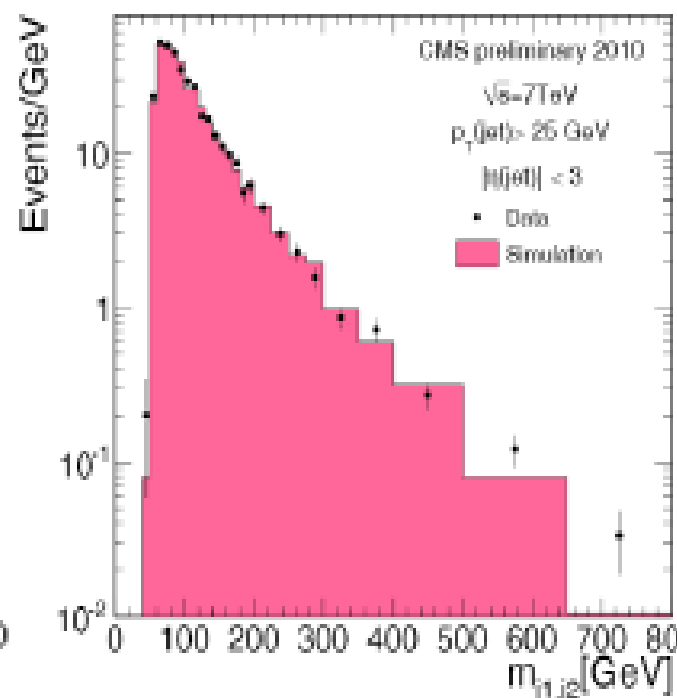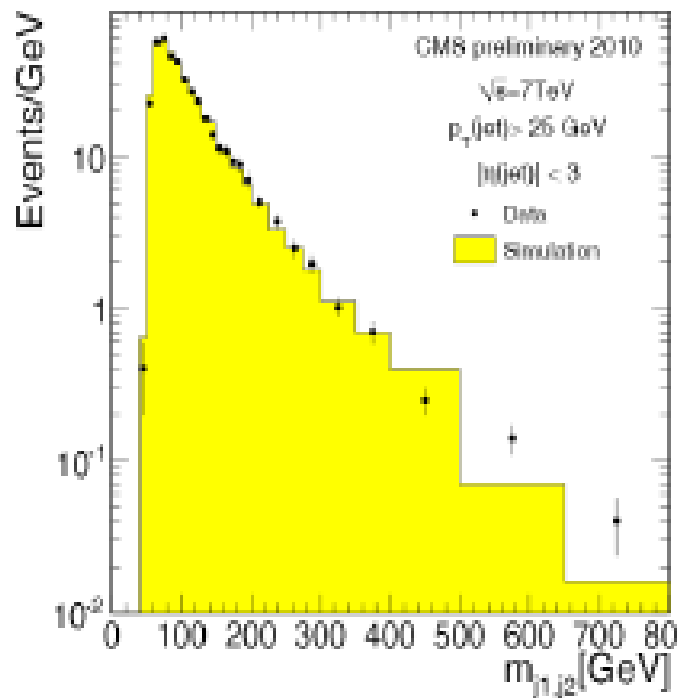
Very good agreement between simulation and collision data!

Three ingredients are convoluted in the simulation:
- Monte Carlo event generator: Pythia
- Detector simulation engine: Geant4
- Experiment-specific aspects: geometry/materials, digitization, calibration, rec.
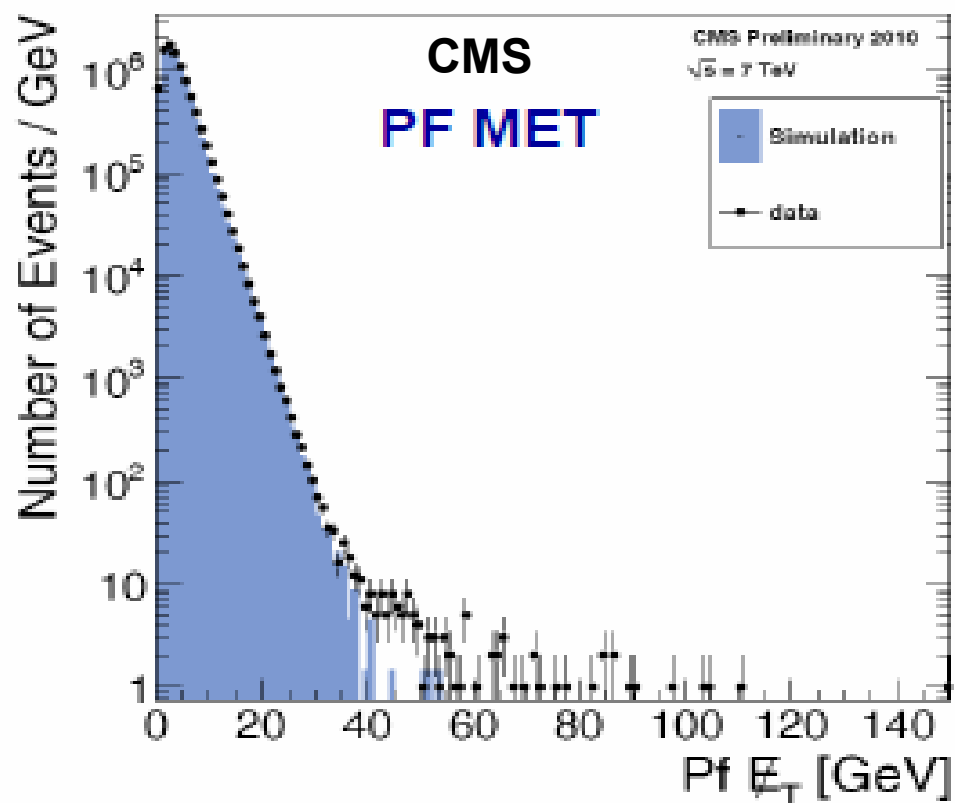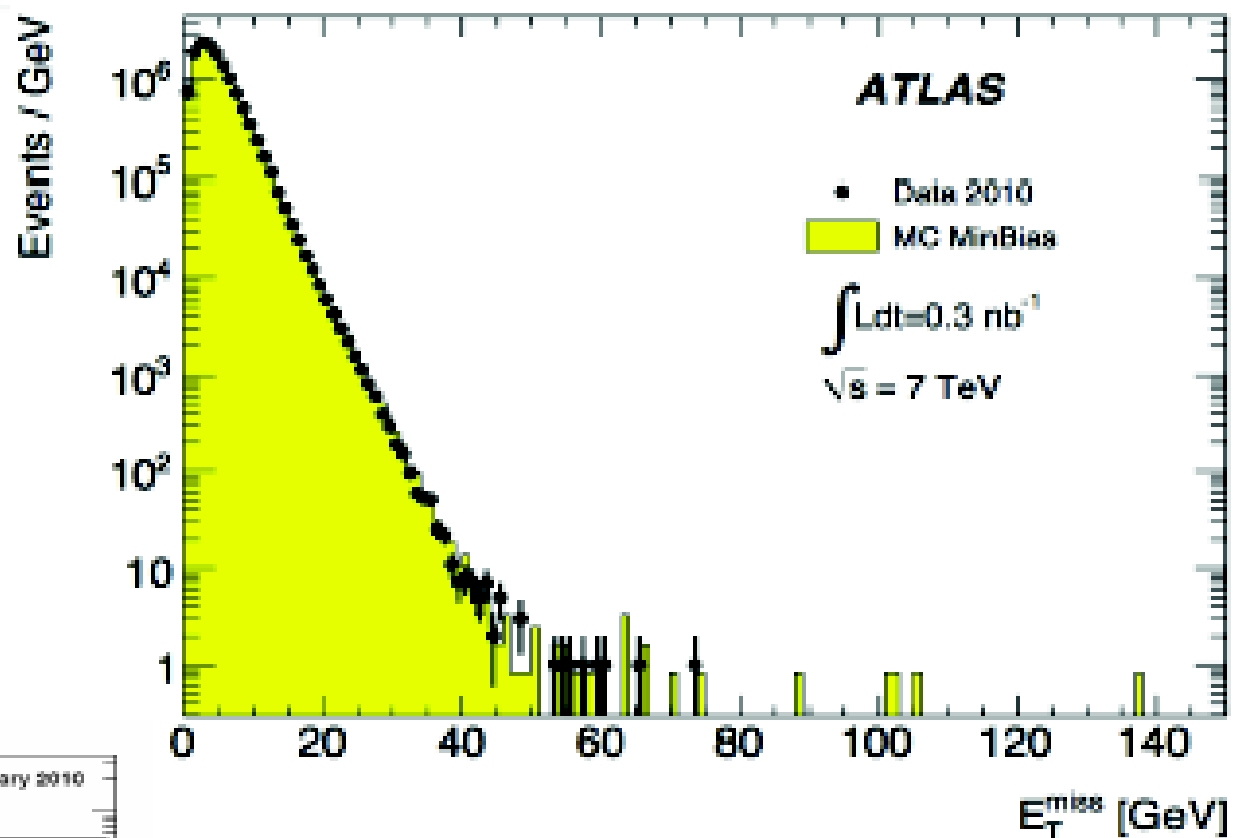
**Calo jets**　　　　　**JPT jets**　　　　　**PF jets**

# Missing E_T : simulation vs. collision data



Missing ET is a very complex (global) variable

Good agreement over 6 orders of magnitudes!

# Summary

- Detector simulation is one of the main tools of modern high-energy physics

- The main challenges of detector simulation are:

  - Physics accuracy

  - CPU performance

  - Validation


- *Suggestions for you:*

  - *Learn by studying and playing with existing examples*

  - *Be critical and pragmatic when using simulations*

  - *Contribute to the validation and provide feedback*

# Other codes

- General
  - **Fluka**
  - Geant3
  - MARS
  - **MCNP / MCNPX**

- Dedicated to electromagnetic physics
  - EGS4
  - EGS5
  - EGSnrc
  - ETRAN
  - Penelope

# Acknowledgment

Thanks to:

- Katsuya Amako

- Makoto Asai

- Andrea Dotti

- Michel Maire

- Dennis Wright

- Alberto Ribon

for some of the figures used in this lecture