

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 how to use 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 ~1M lines of code?

Introduction

Introduction

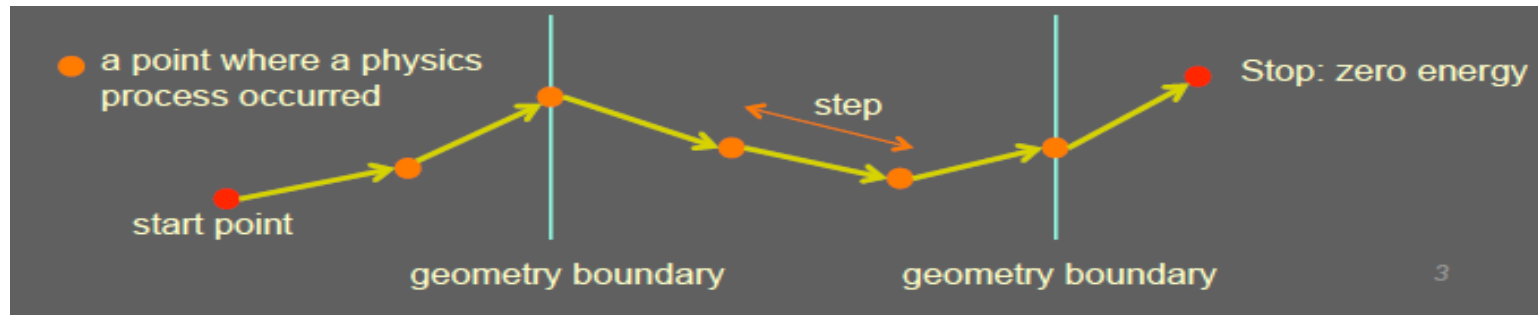
- Simulation is a very useful, essential tool in modern particle physics for:
 - **designing** an experiment (e.g. now ILC/CLIC)
 - **analysing** the data (e.g. now ATLAS, CMS, LHCb)
- For the LHC experiments, the simulation is made of two distinct steps:
 - 1. Simulation of the p-p collision**
 - Monte 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

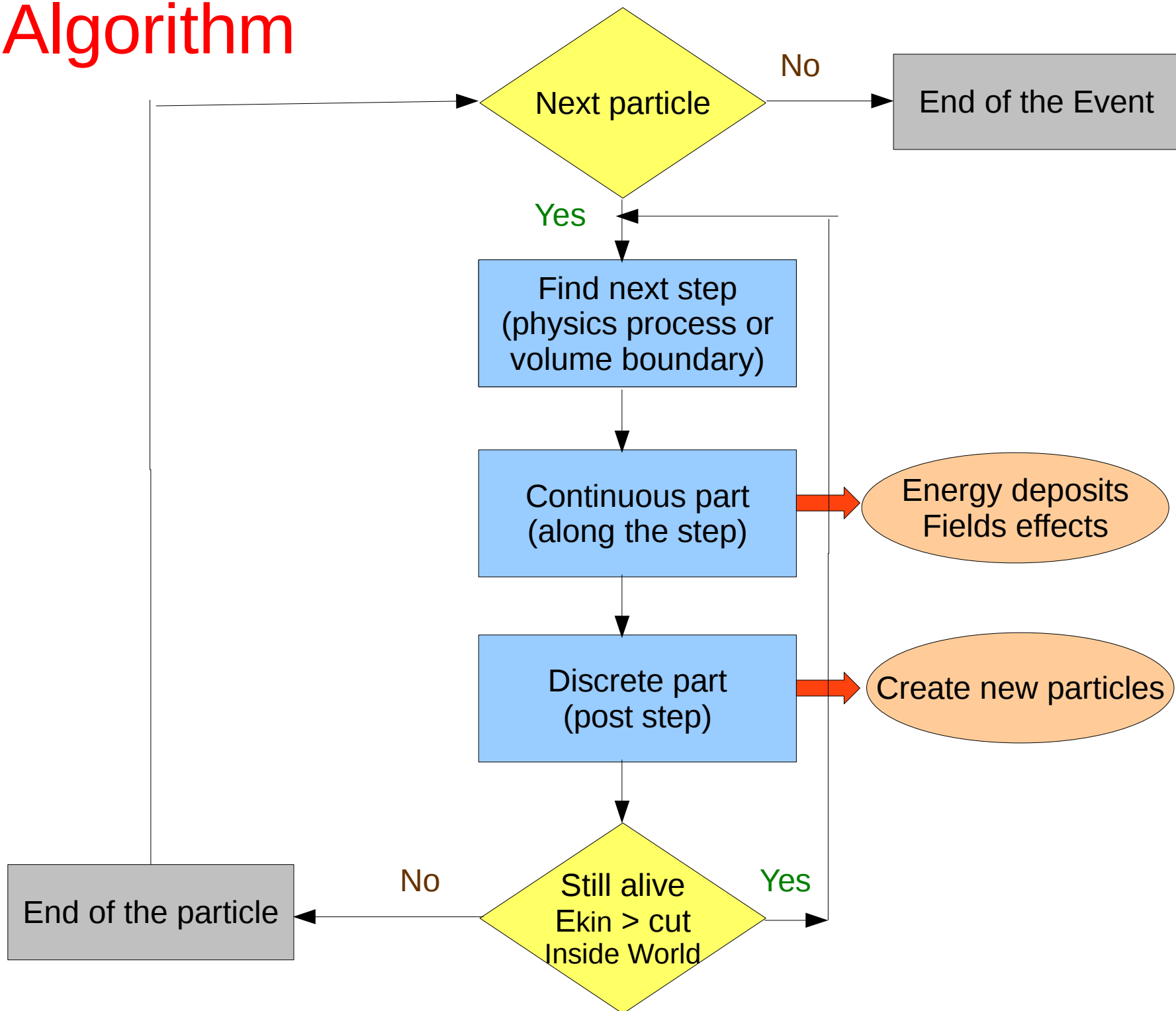
How does it work?

- 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



“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 it would happen in the real experiment
 - The same reconstruction chain can be applied for both real and simulated data
- The general radiation transportation codes provide **energy deposits** in the whole detector; from these, the “digitization” simulates the **electrical signals** induced in the **sensitive parts** of the detector

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
 - To very fast, fully parametrized detector simulations

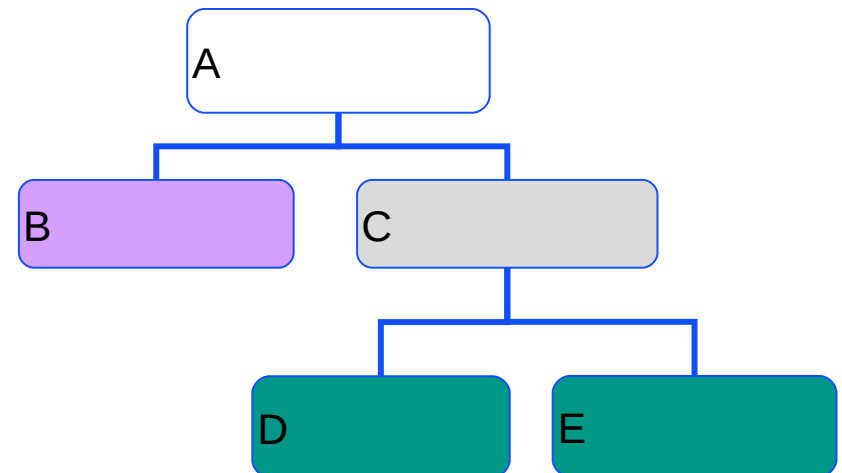
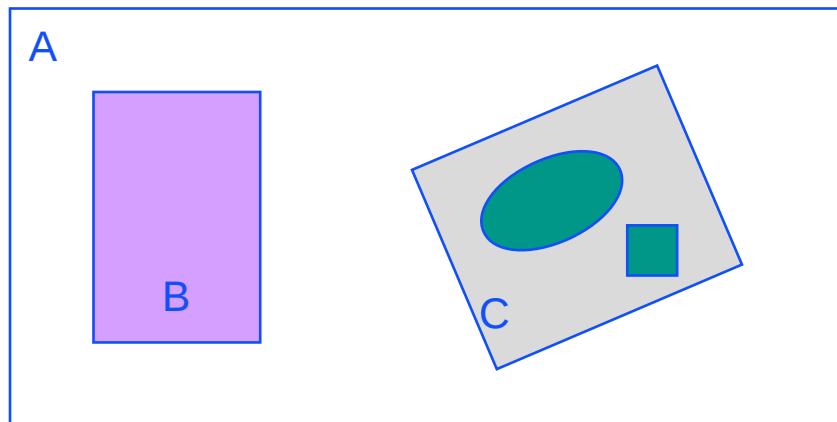
Application domains

- 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!

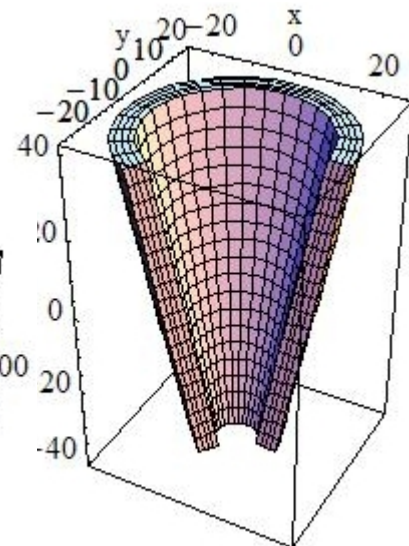
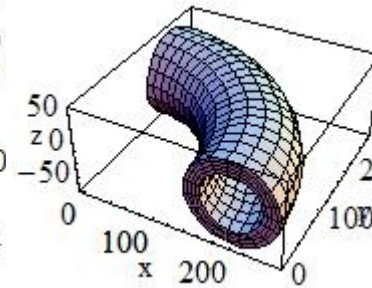
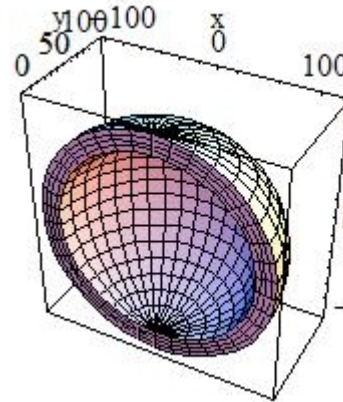
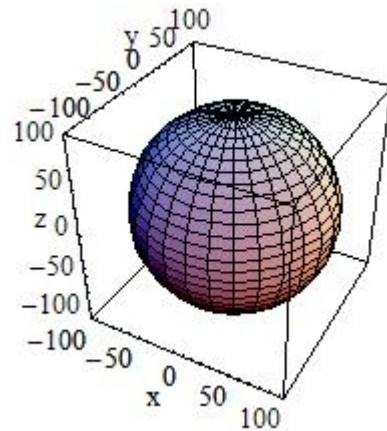
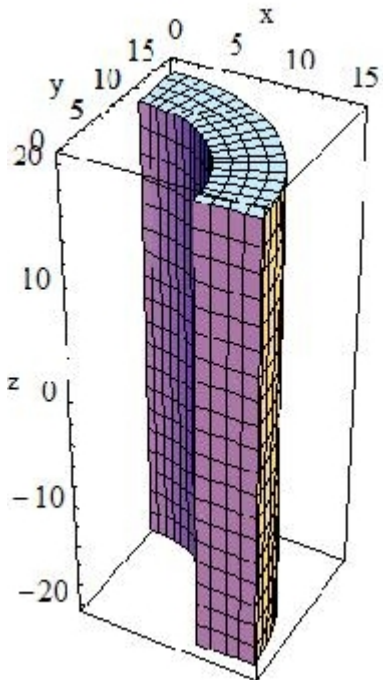
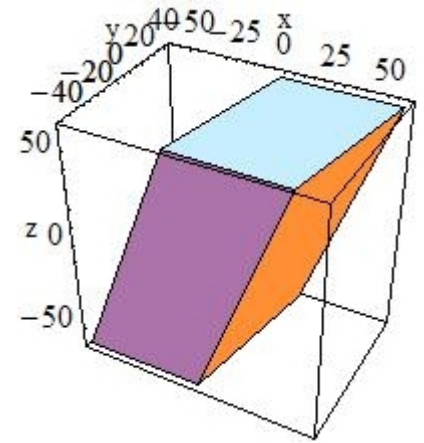
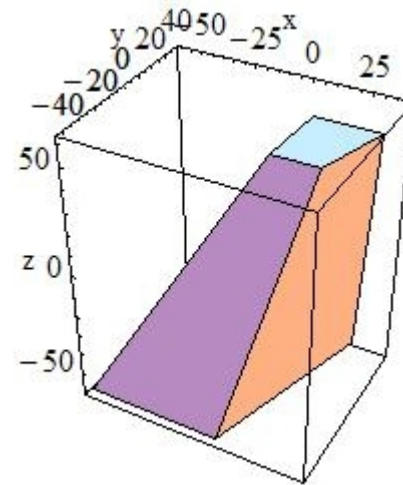
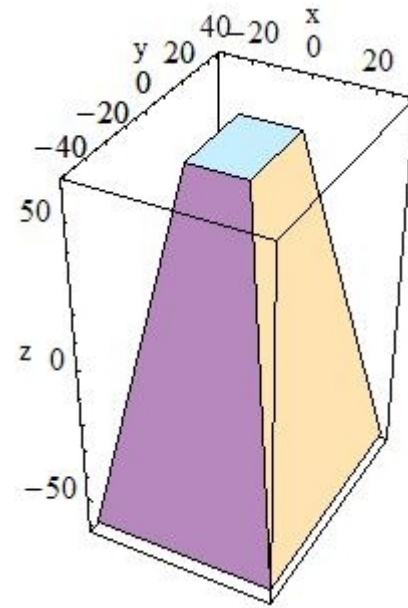
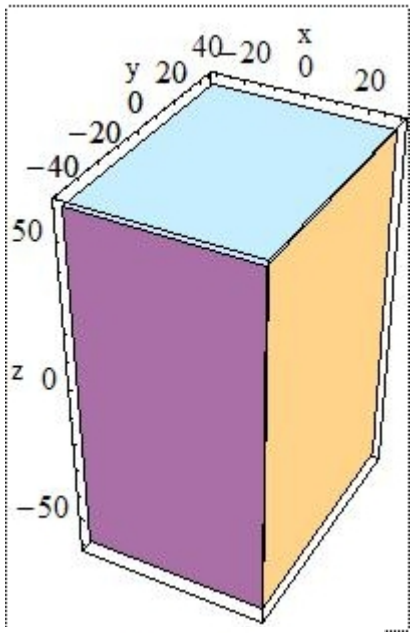
Geometry

Geometry

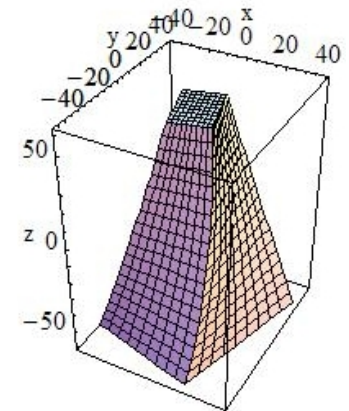
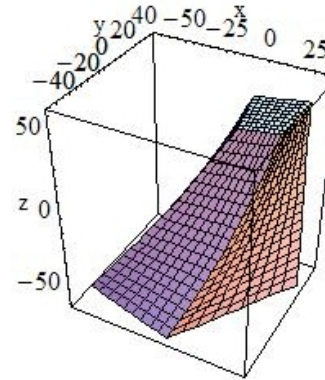
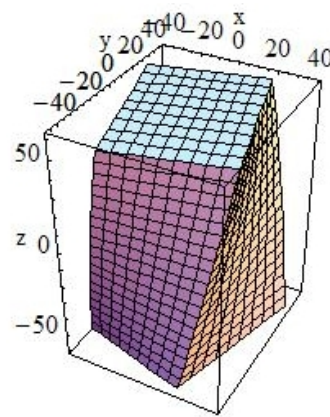
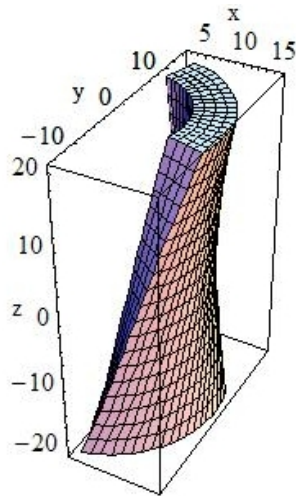
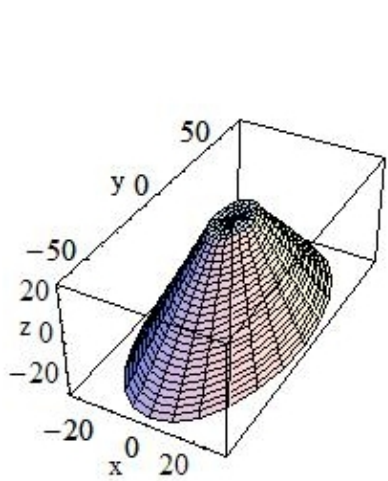
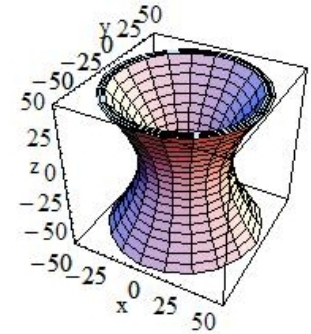
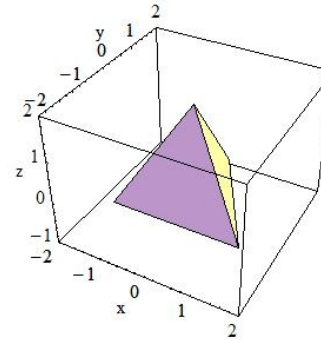
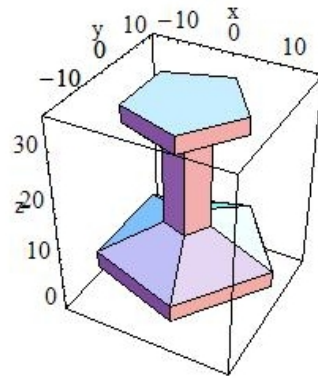
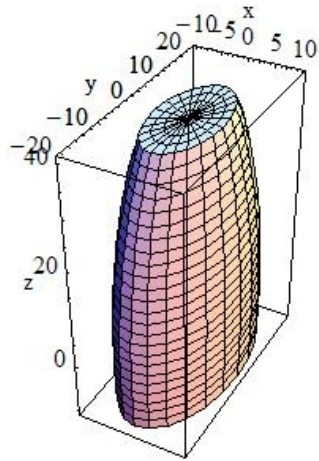
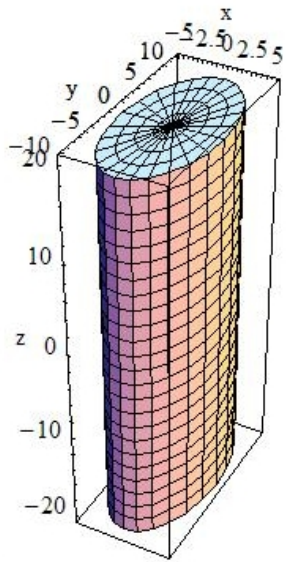
- The way to describe the geometry varies widely between the different simulation engines
 - In Geant4, you need to write some C++ code
 - Geometry objects are instances of classes
 - Geometry parameters (e.g. dimensions) are arguments of the constructors
- The geometry can be “flat” or “hierarchical”
 - 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



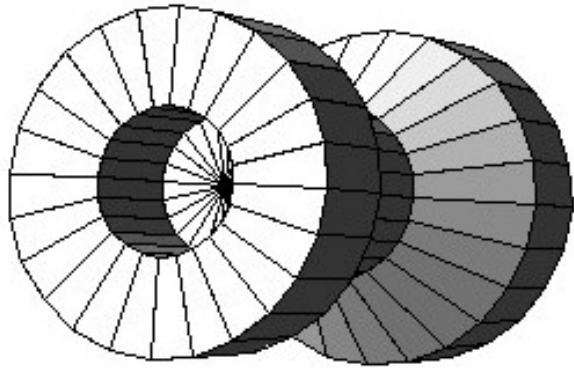
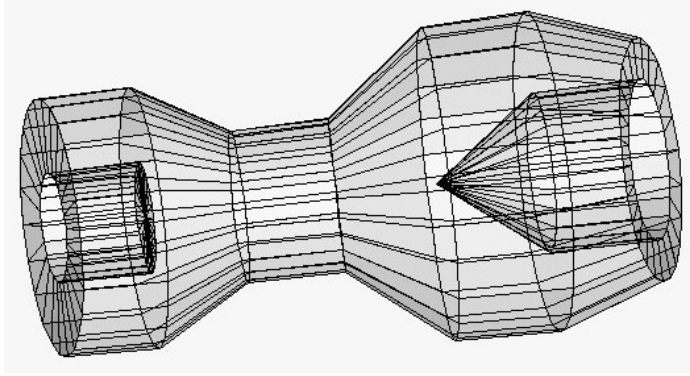
CGS (Constructed Geometry) Solids



Other CGS solids

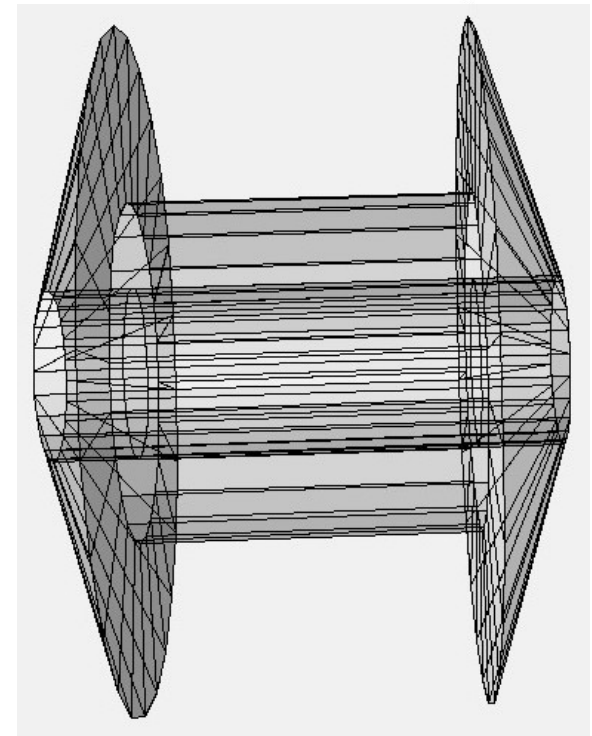
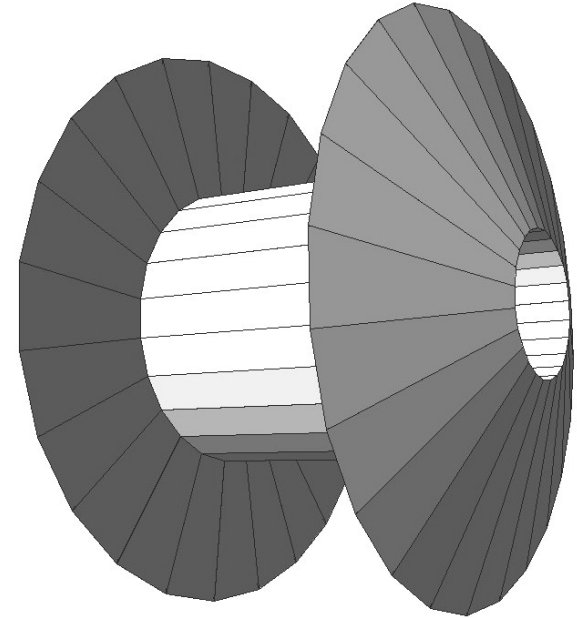


Polycone

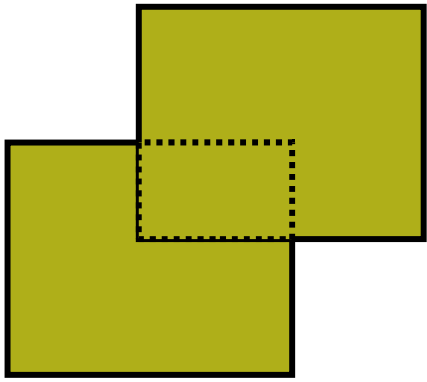


BREP

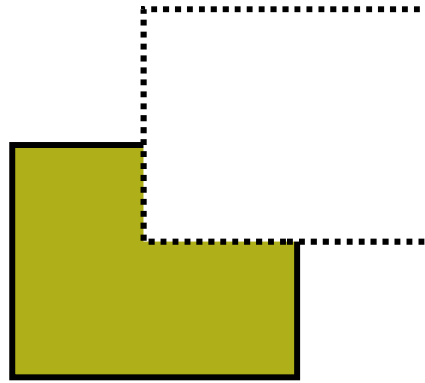
(Boundary REPresented Solid)



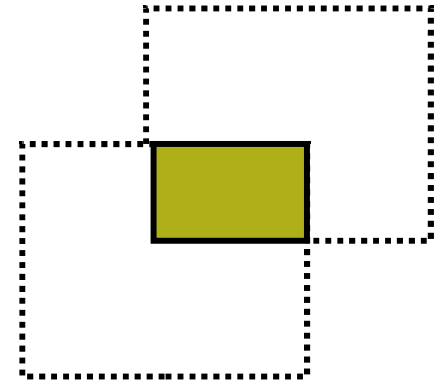
Boolean solids



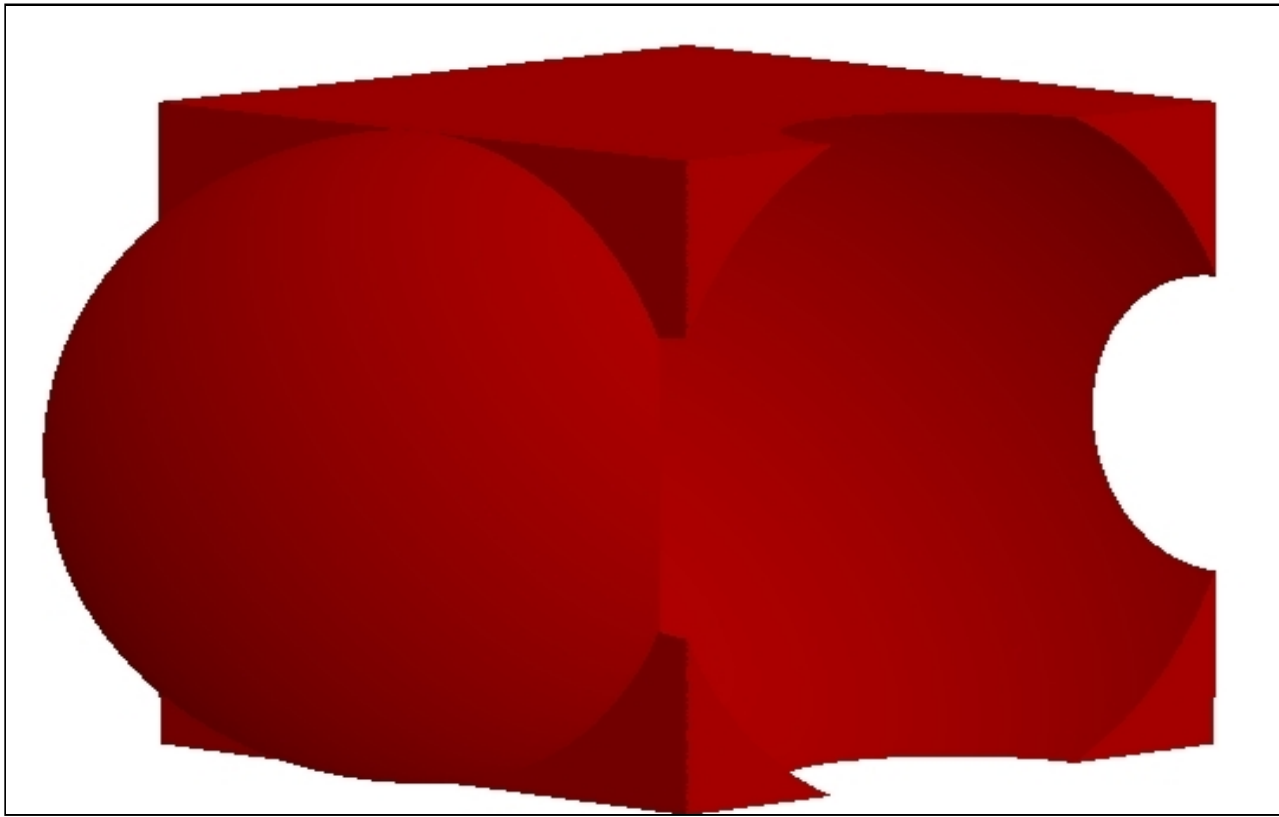
Union



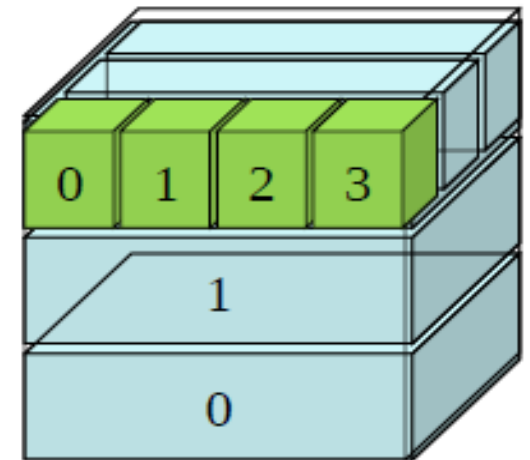
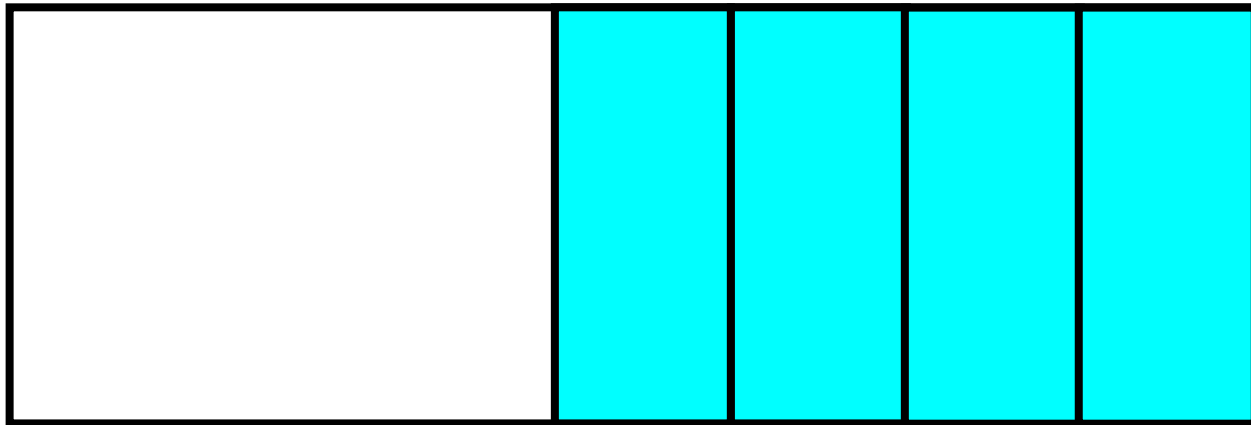
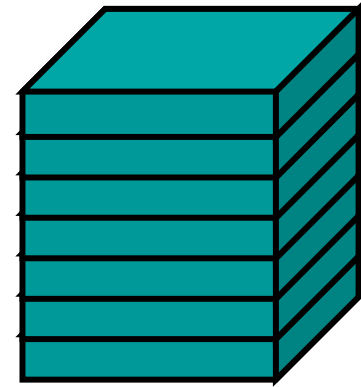
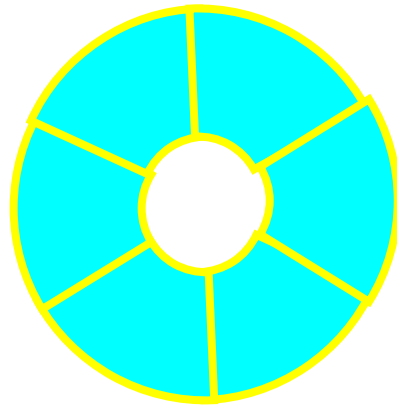
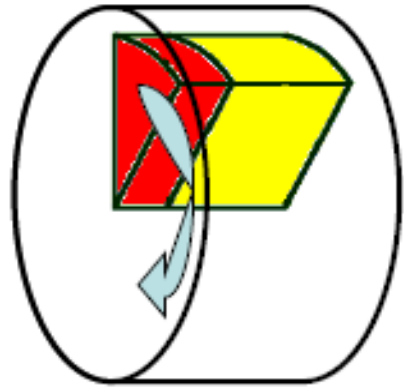
Subtraction



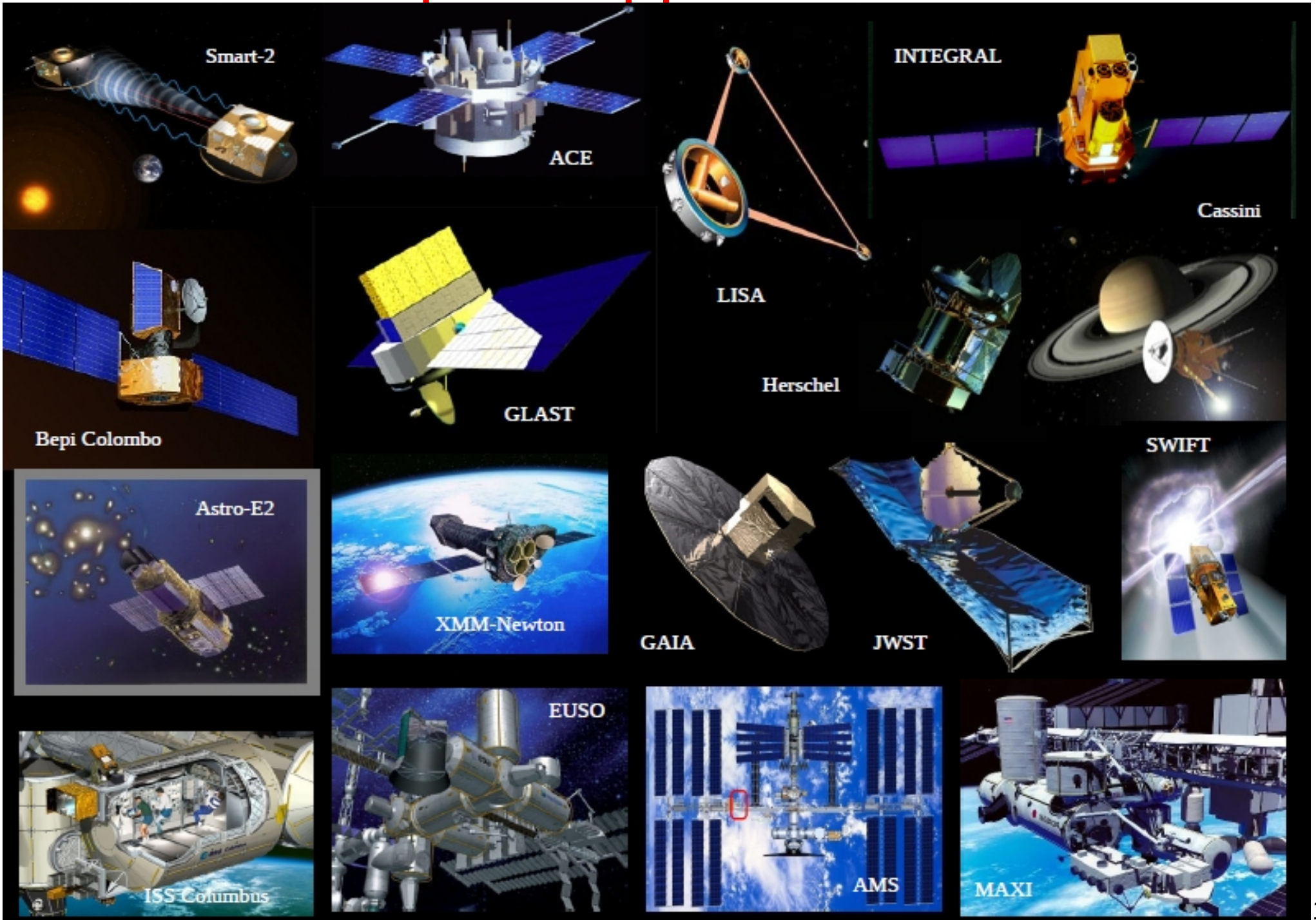
Intersection



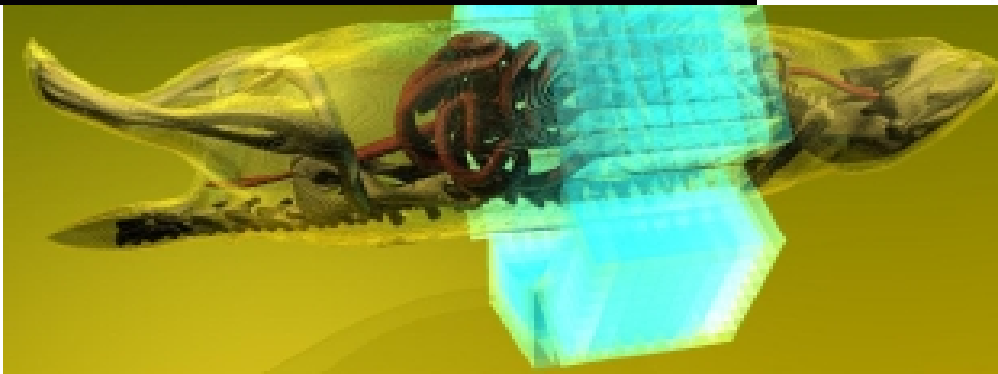
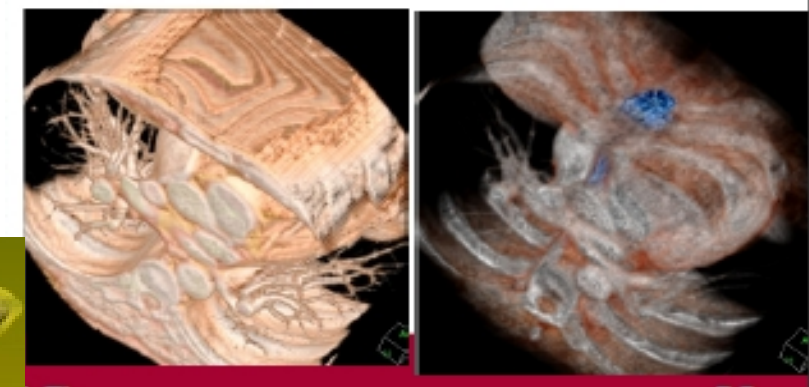
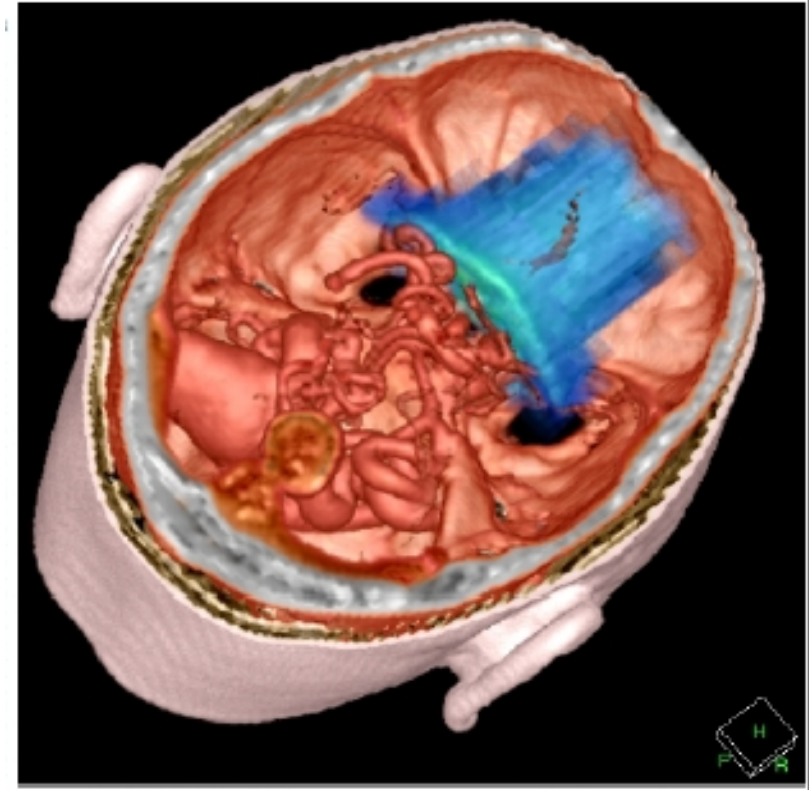
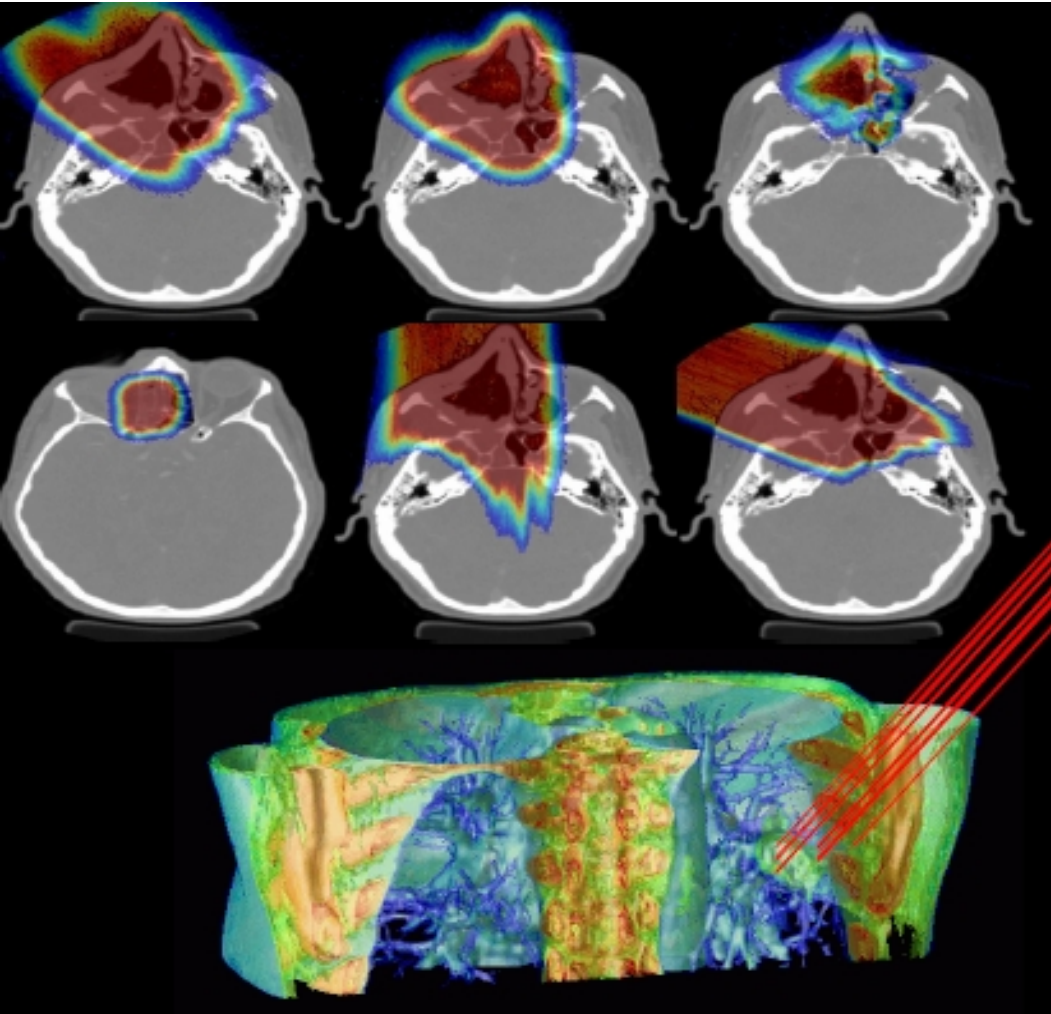
Geometrical symmetries



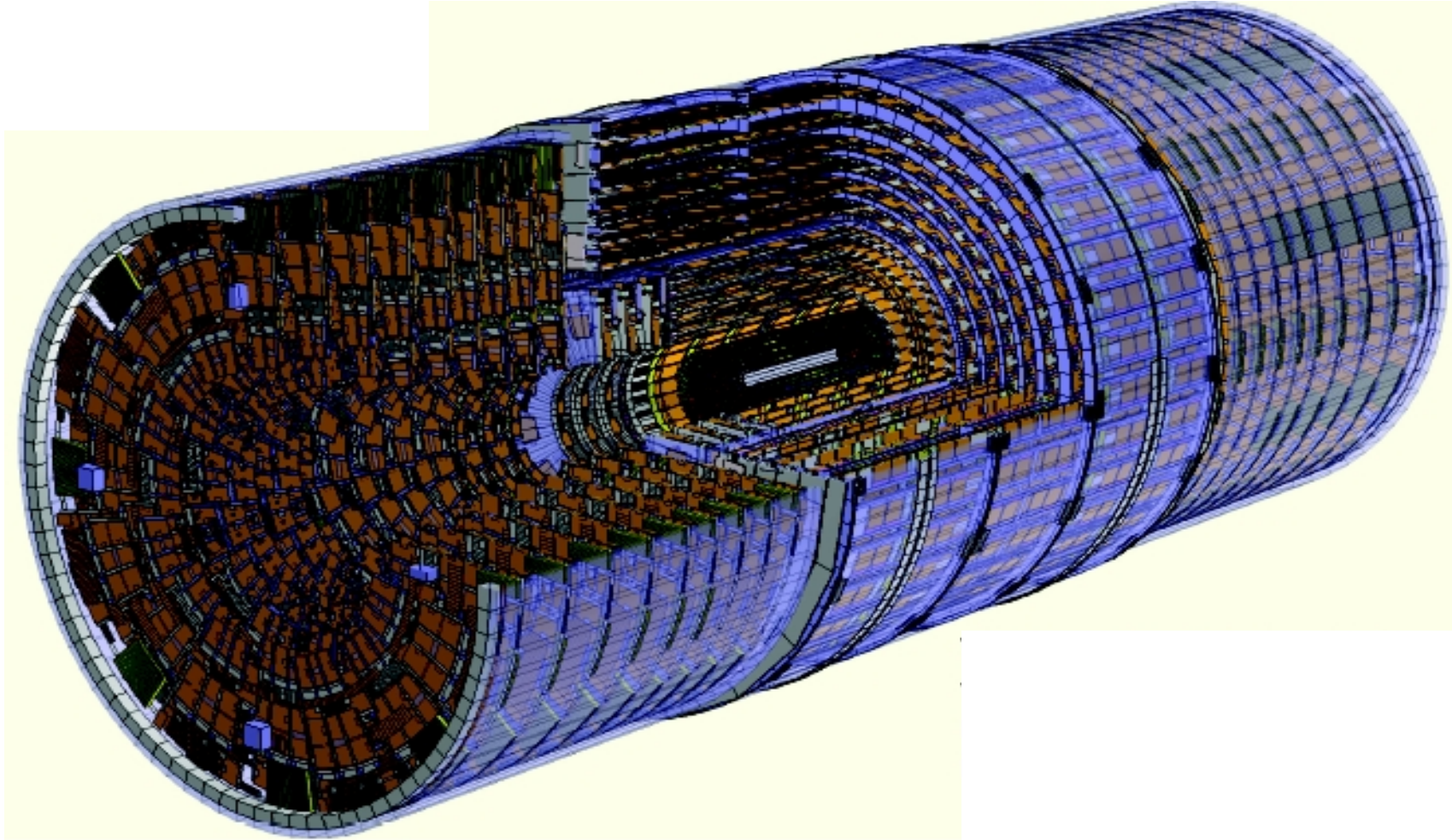
Space applications



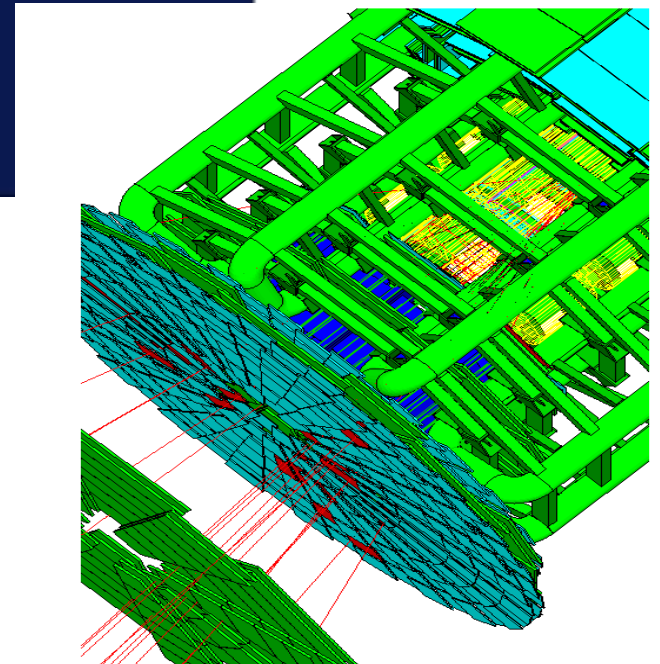
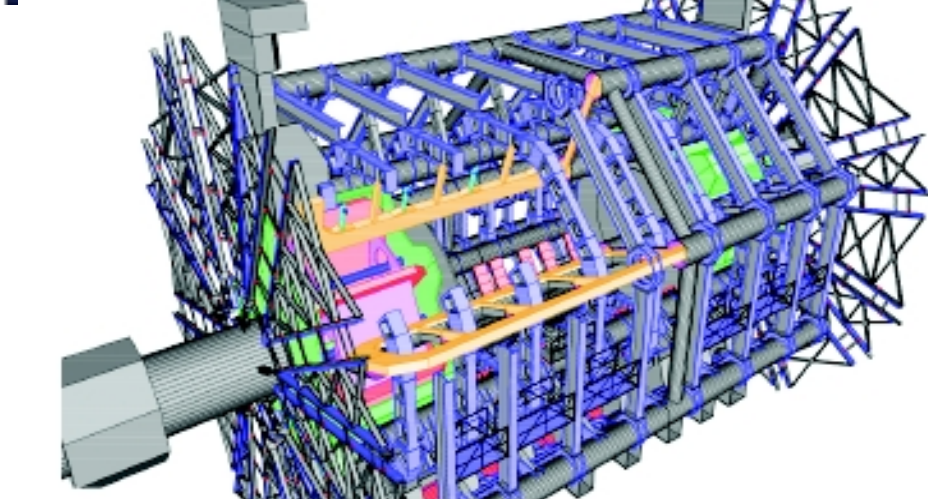
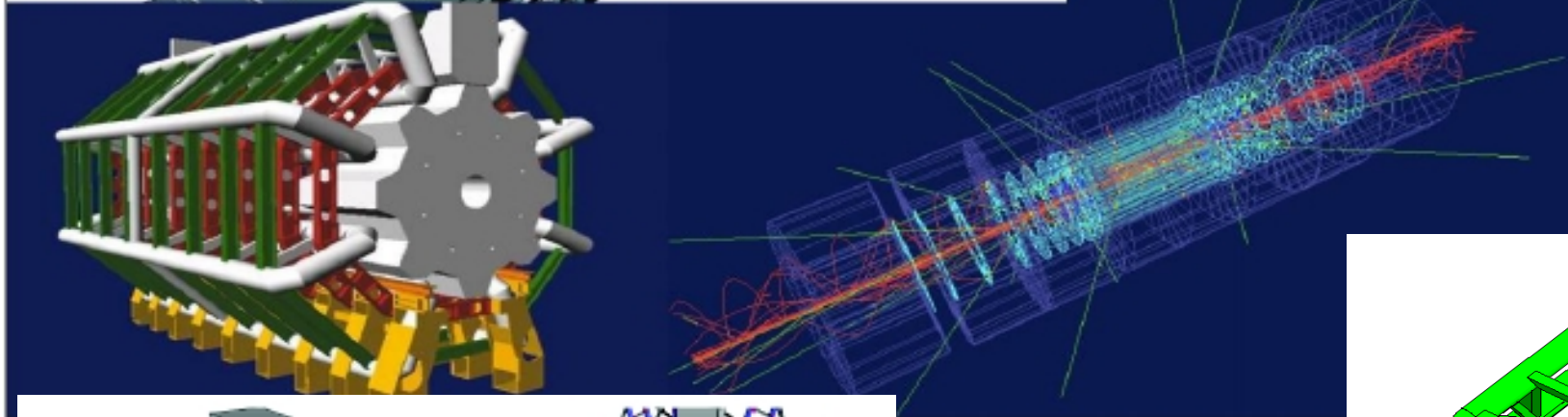
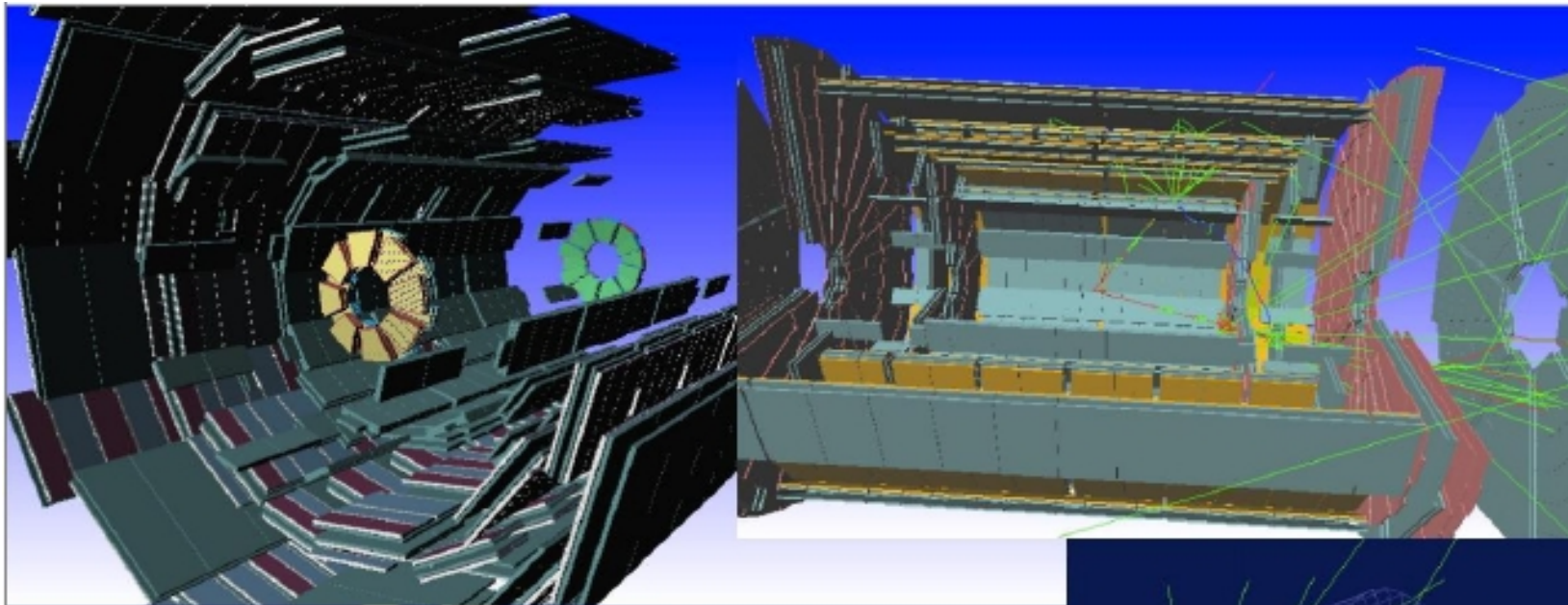
Medical applications



HEP : CMS tracker



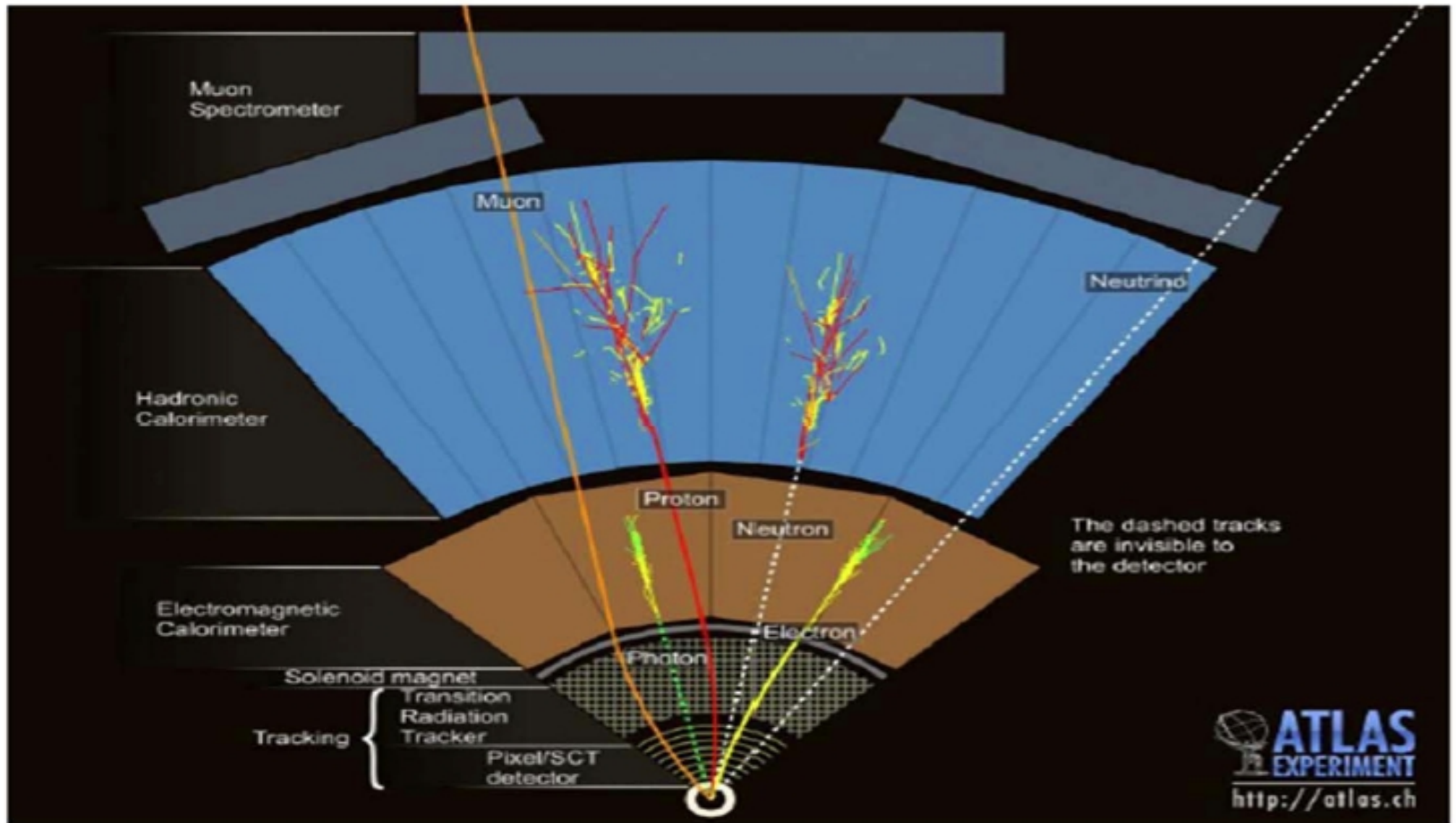
HEP : ATLAS



Physics

Particle interactions

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



Main electromagnetic processes

Gamma

- Conversion :
 $\gamma \rightarrow e^+ e^- , \mu^+ \mu^-$
- Compton scattering :
 $\gamma (\text{atomic})e^- \rightarrow \gamma (\text{free})e^-$
- Photo-electric
 $\gamma \text{ material} \rightarrow (\text{free})e^-$
- Rayleigh scattering
 $\gamma \text{ atom} \rightarrow \gamma \text{ atom}$

Muon

- Pair production
 $\mu^- \text{ atom} \rightarrow \mu^- e^+ e^-$
- Bremsstrahlung
 $\mu^- (\text{atom}) \rightarrow \mu^- \gamma$
- MSC (Coulomb scattering) :
 $\mu^- \text{ atom} \rightarrow \mu^- \text{ atom}$
- Ionization :
 $\mu^- \text{ atom} \rightarrow \mu^- \text{ ion}^+ e^-$

Total cross section:
→ step length

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

Electron, Positron

- Bremsstrahlung
 $e^- (\text{atom}) \rightarrow e^- \gamma$
- MSC (Coulomb scattering):
 $e^- \text{ atom} \rightarrow e^- \text{ atom}$
- Ionization :
 $e^- \text{ atom} \rightarrow e^- \text{ ion}^+ e^-$
- Positron annihilation
 $e^+ e^- \rightarrow \gamma \gamma$

Charged hadron, ion

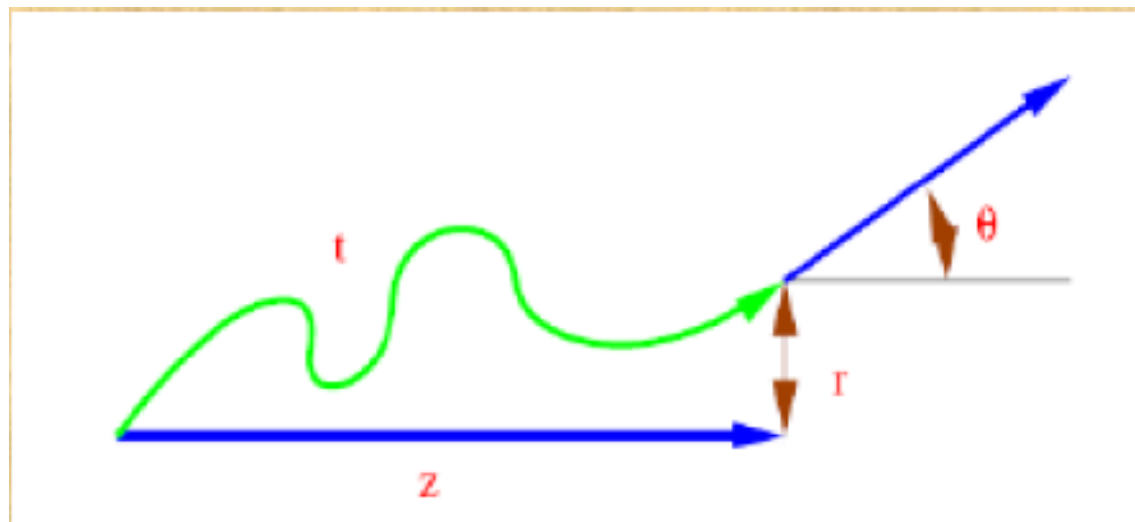
- (Bremsstrahlung
 $h^- (\text{atom}) \rightarrow h^- \gamma$)
- MSC (Coulomb scattering):
 $h^- \text{ atom} \rightarrow h^- \text{ atom}$
- Ionization :
 $h^- \text{ atom} \rightarrow h^- \text{ ion}^+ e^-$

Production and tracking cuts

- **Ionization and 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 **$E_{kin} \sim 1 \text{ keV}$**
 - Either, stop it below a **tracking cut** and deposit its energy locally
 - Or, go down to $E_{kin} \rightarrow 0$ 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



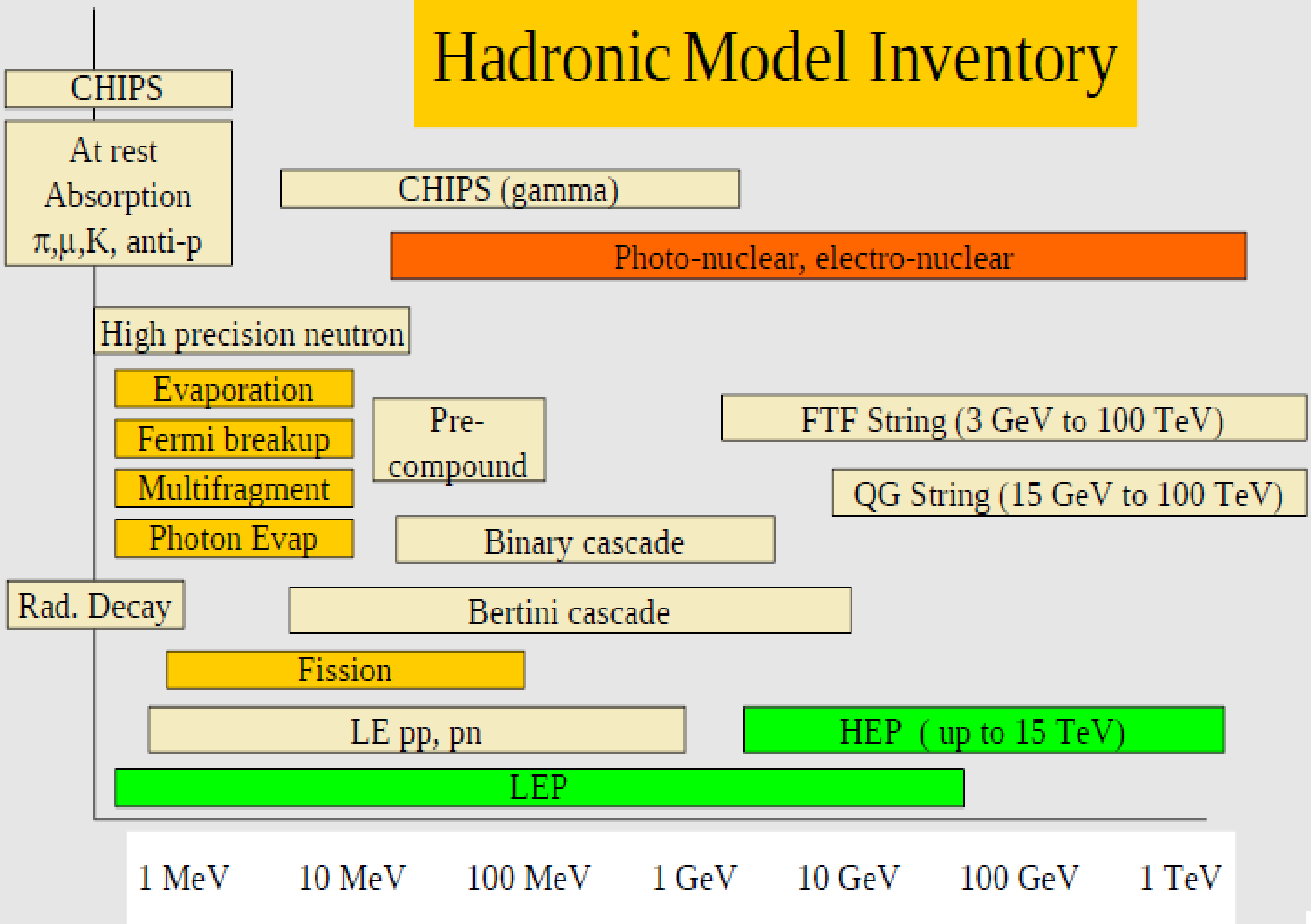
Electromagnetic physics

- 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 $\sim 1\%$
 - 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 interactions

- Hadrons (π^\pm , K^\pm , K^0_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 available only for a tiny phase-space region
 - the hard scattering at high transverse momentumwhereas for the rest, i.e. most of the phase space
 - soft primary scattering, re-scattering, and nucleus de-excitation
only approximate models are available
- **Hadronic models are valid for limited combinations of**
 - **particle type - energy - target material**

Hadronic Model Inventory

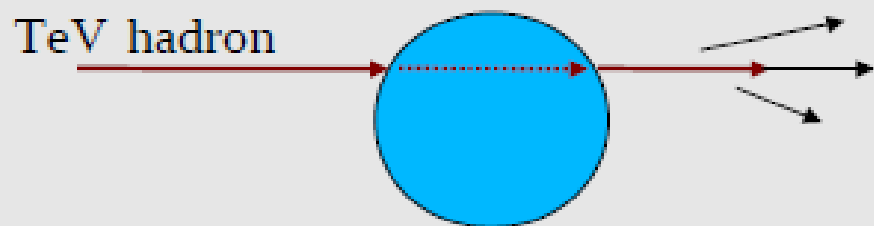


Physics configuration

- 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

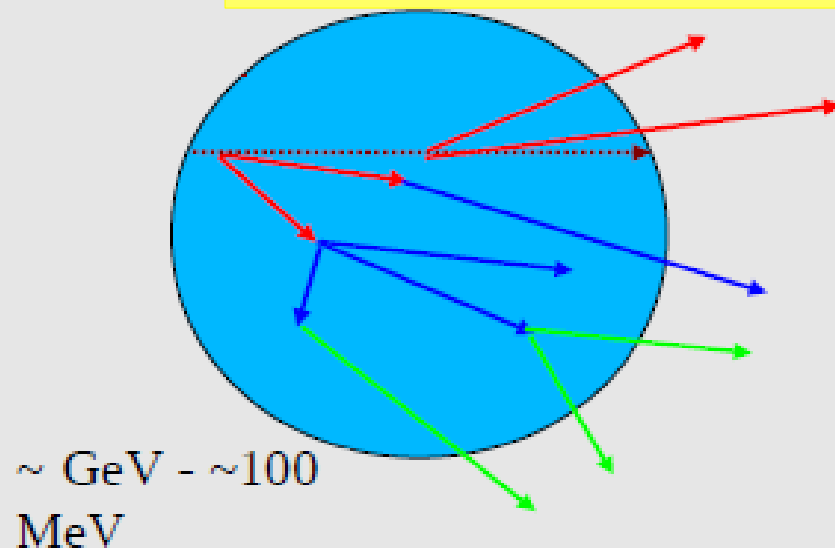
Hadronic Interactions from TeV to meV

String model

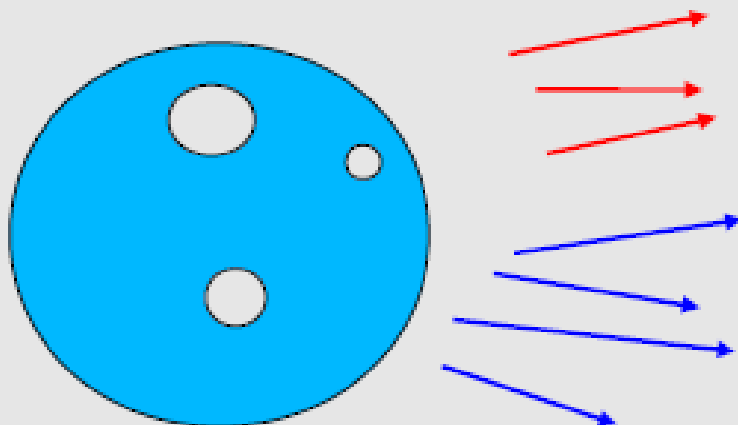


$$dE/dx \sim A^{1/3} \text{ GeV}$$

Intra-nuclear cascade model

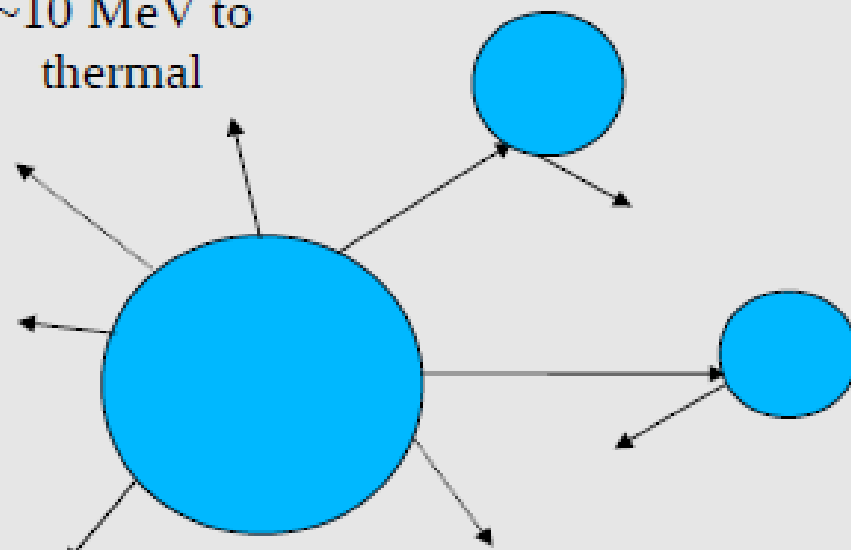


$\sim 100 \text{ MeV} - \sim 10 \text{ MeV}$



Pre-equilibrium (Precompound) model

$\sim 10 \text{ MeV}$ to
thermal



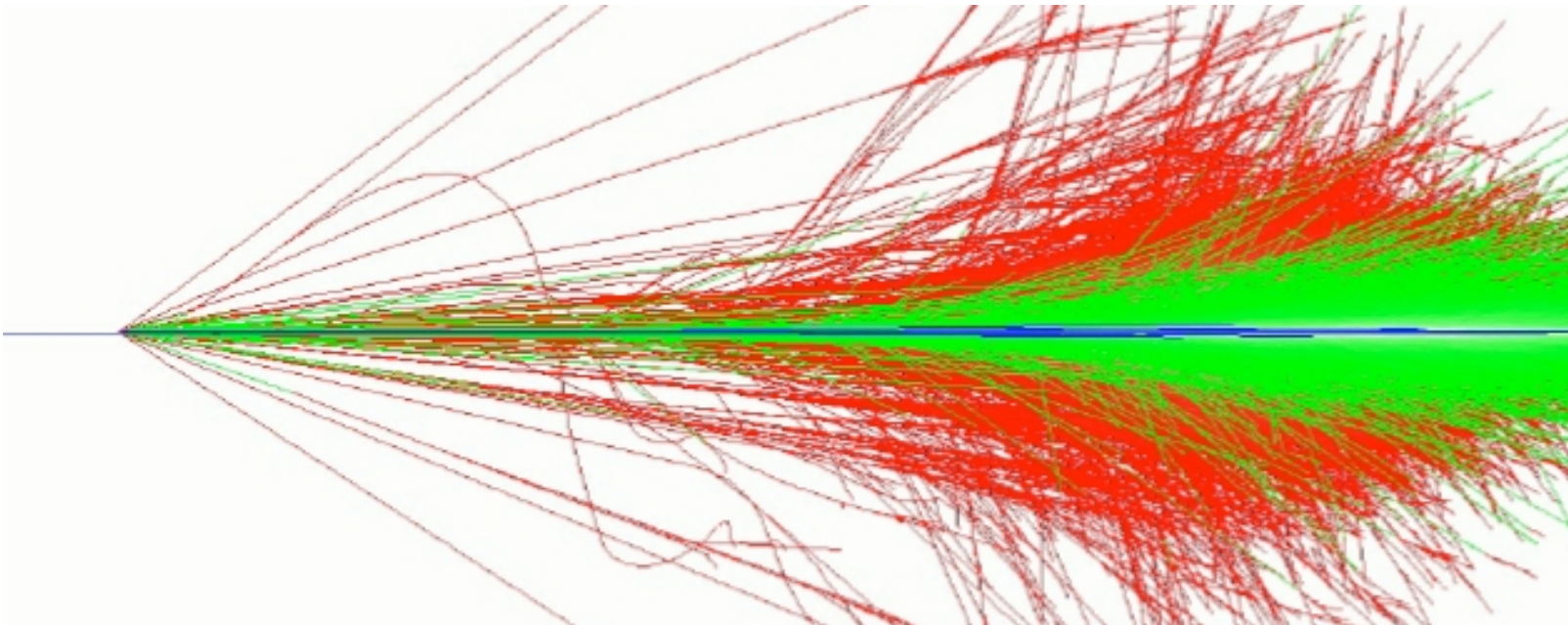
Equilibrium (Evaporation) model

An interesting complication: Neutrons

- Neutrons are abundantly produced, mostly by hadron-nucleus interactions
 - It is typically the 3rd 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 orders of magnitudes 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

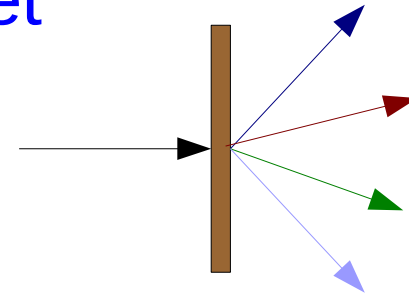
- A single hadron impinging on a large block of matter (e.g. a hadron calorimeter) produces secondary hadrons of lower energies, which in turn can produce other hadrons, and so on: the set of these particles is called a **hadronic shower**
 - $e^-/e^+/\gamma$ (electromagnetic component) are also produced copiously because of $\pi^0 \rightarrow \gamma\gamma$ and ionization of charged particles
- The development of a hadronic shower involves **many energy scales, from hundreds of GeV down to thermal energies**



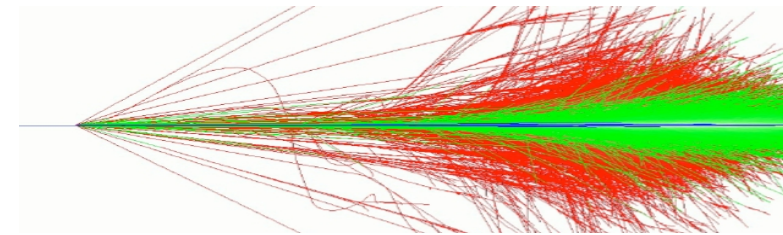
Validation

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



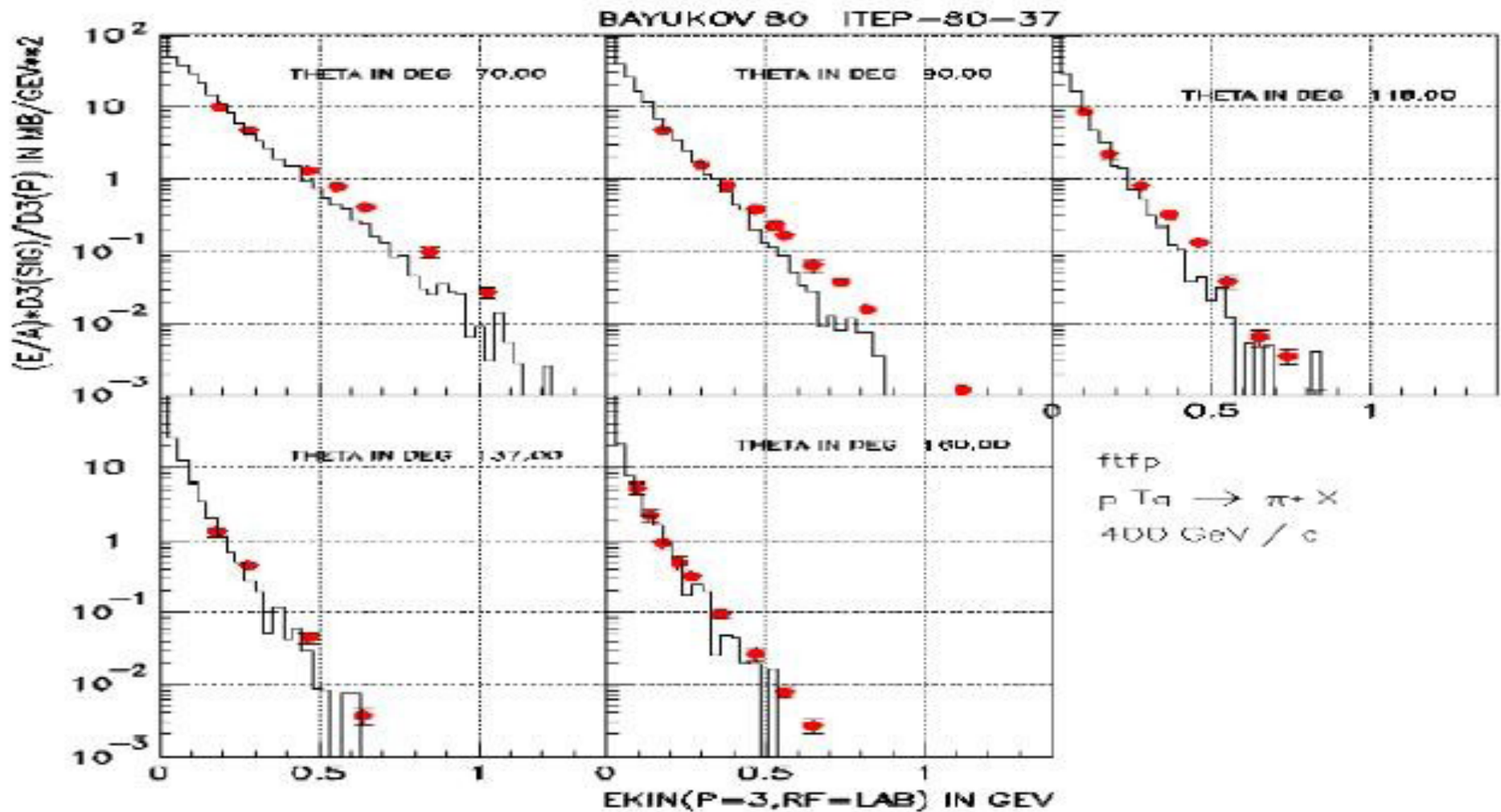
- Validation of complete physics configurations is performed by users mostly via measurements of **hadronic showers in calorimeter test-beam setups (thick targets)**



- 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.

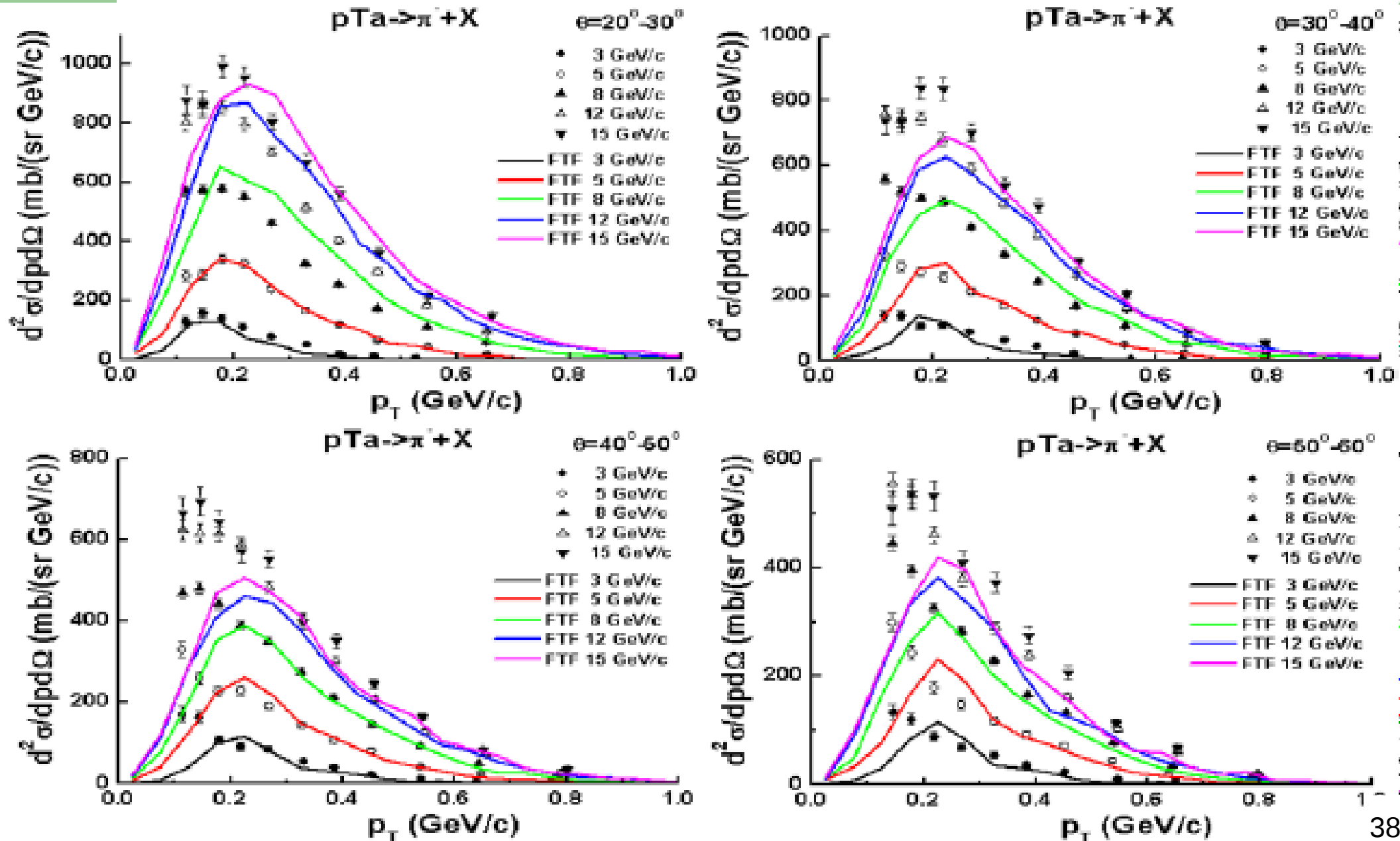
Model-level thin-target test

FTF Results at 400 GeV/c
 $p \text{ Ta} \rightarrow \pi^+ X$



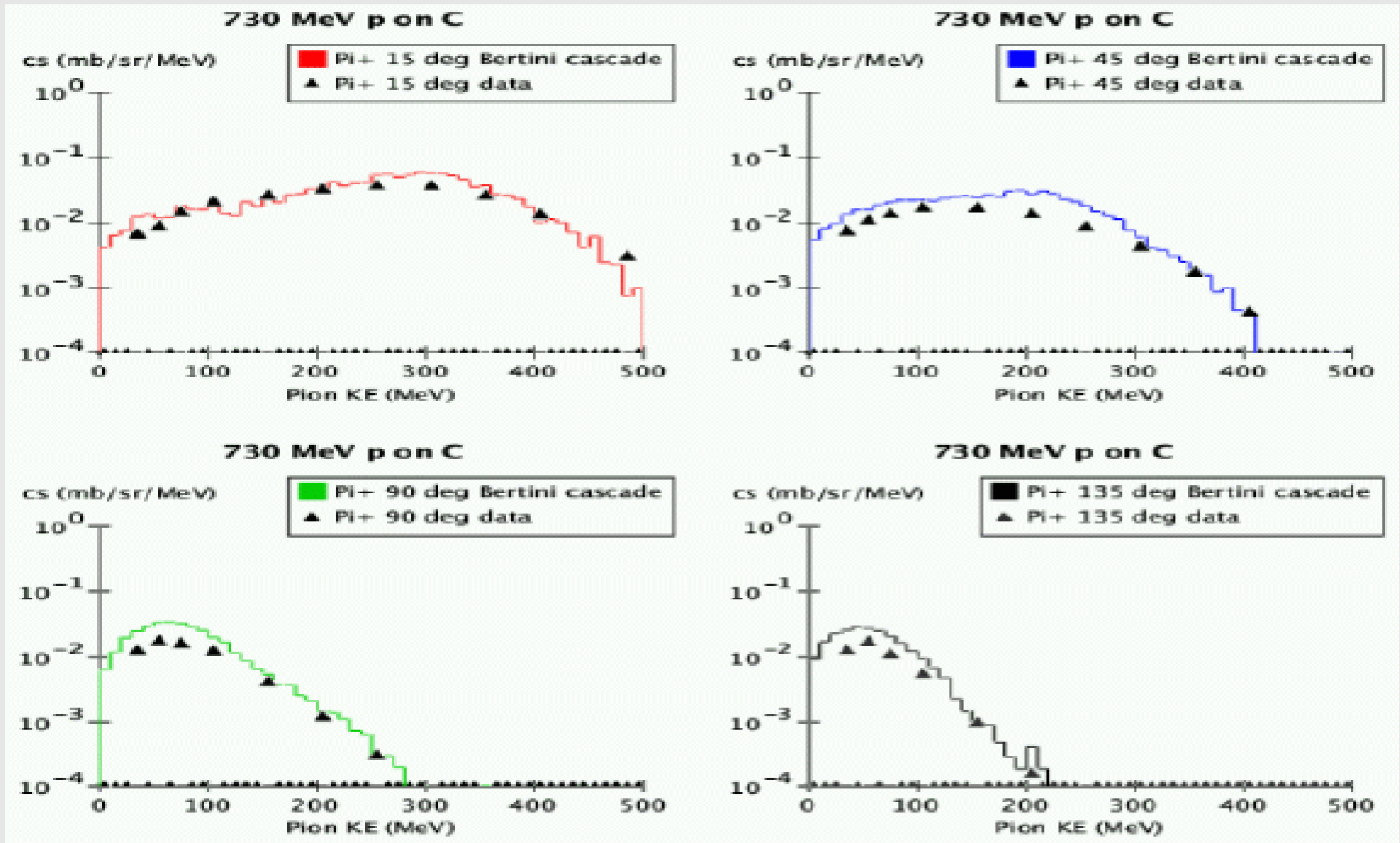
Model-level thin-target test

FTF validation, HARP-CDP data



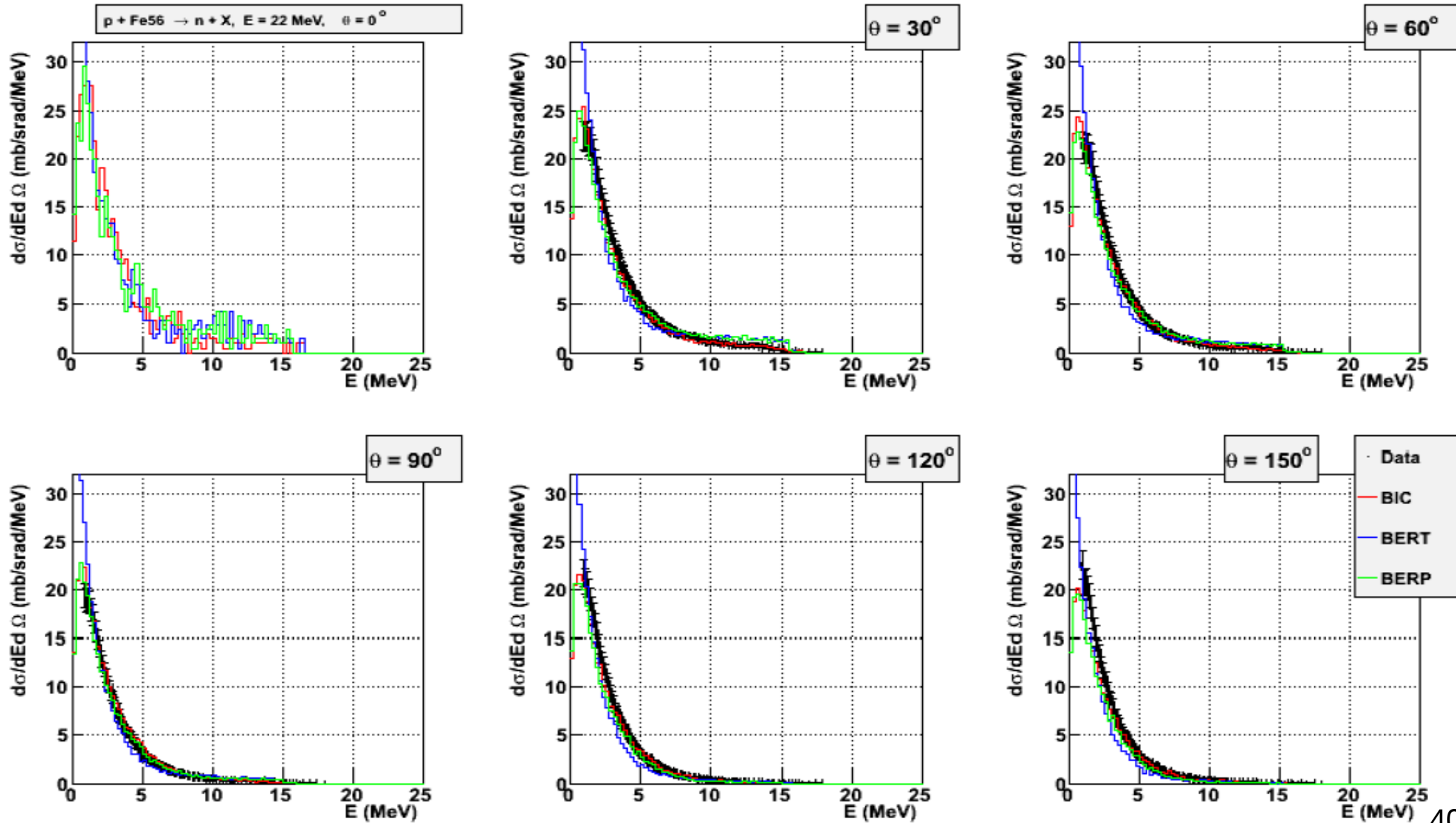
Model-level thin-target test

Validation of the Bertini Cascade

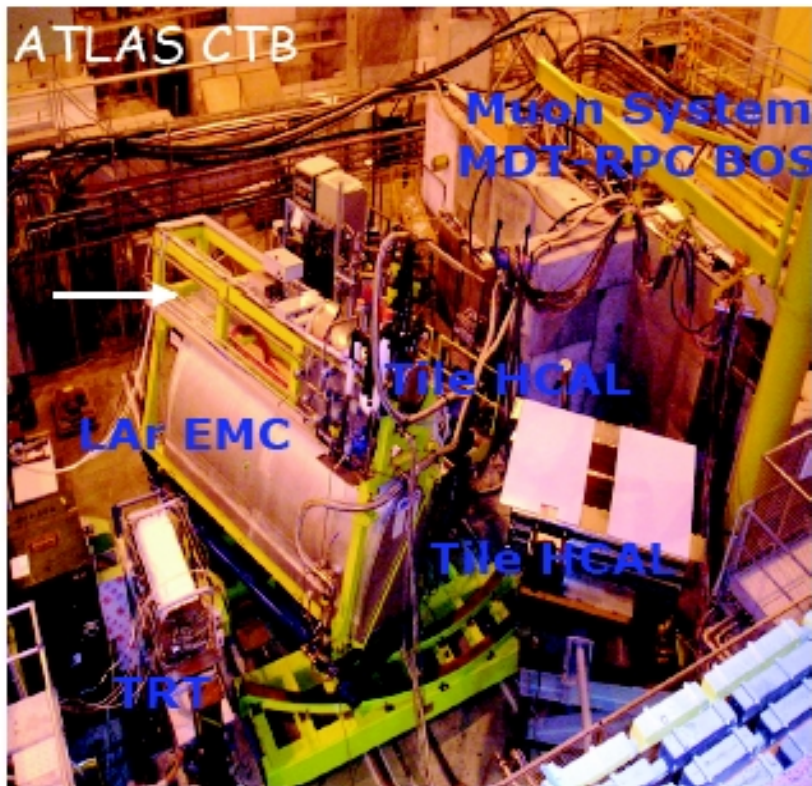
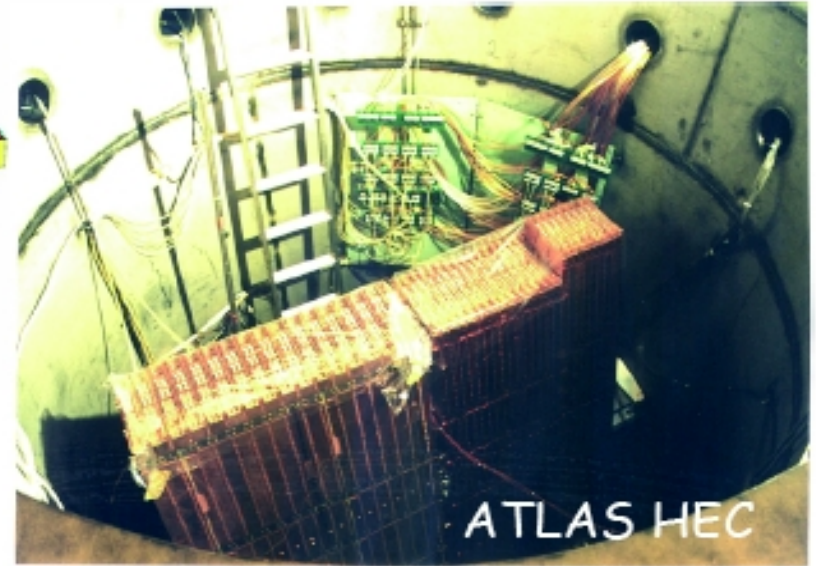
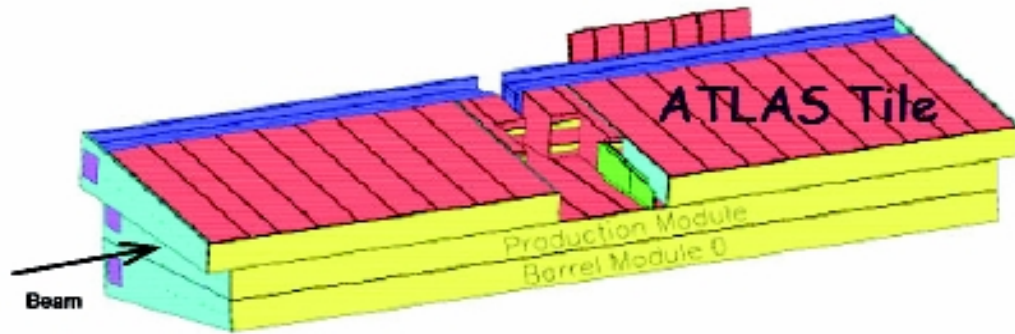


Model-level thin-target test

Preco validation, 22 MeV p – Fe \rightarrow n

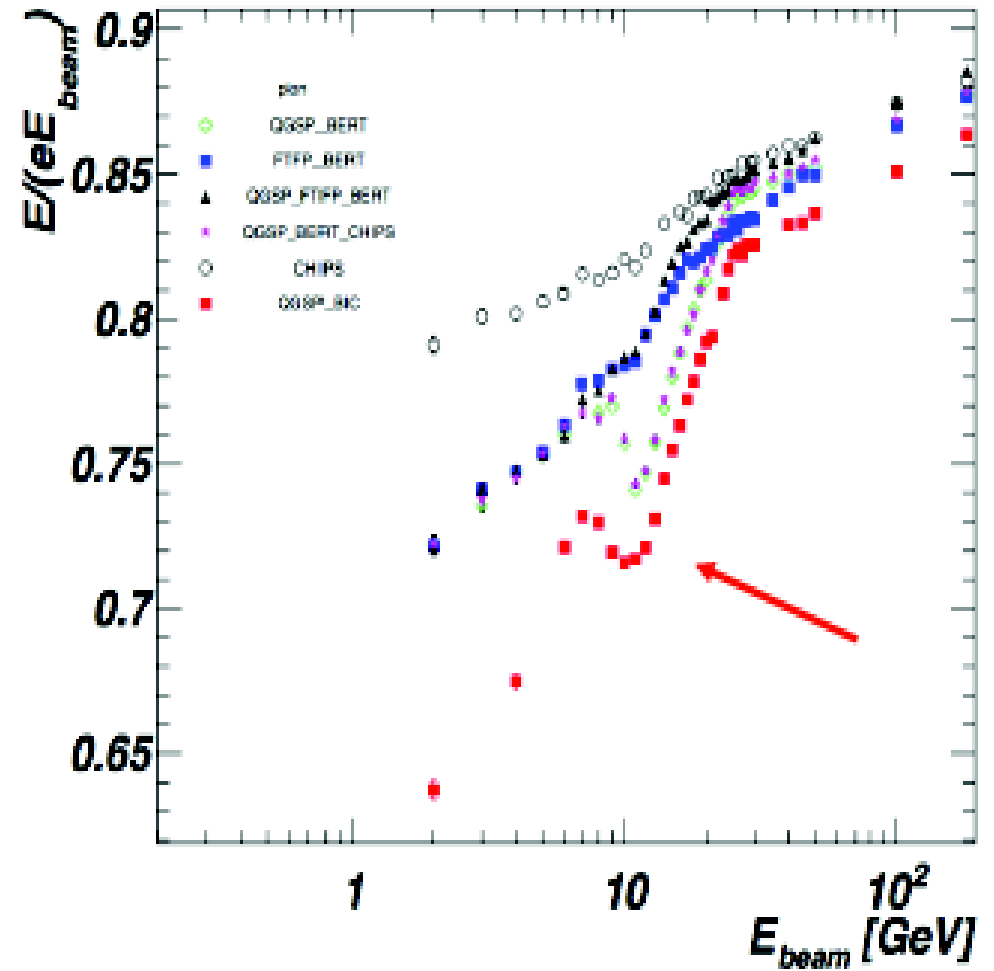
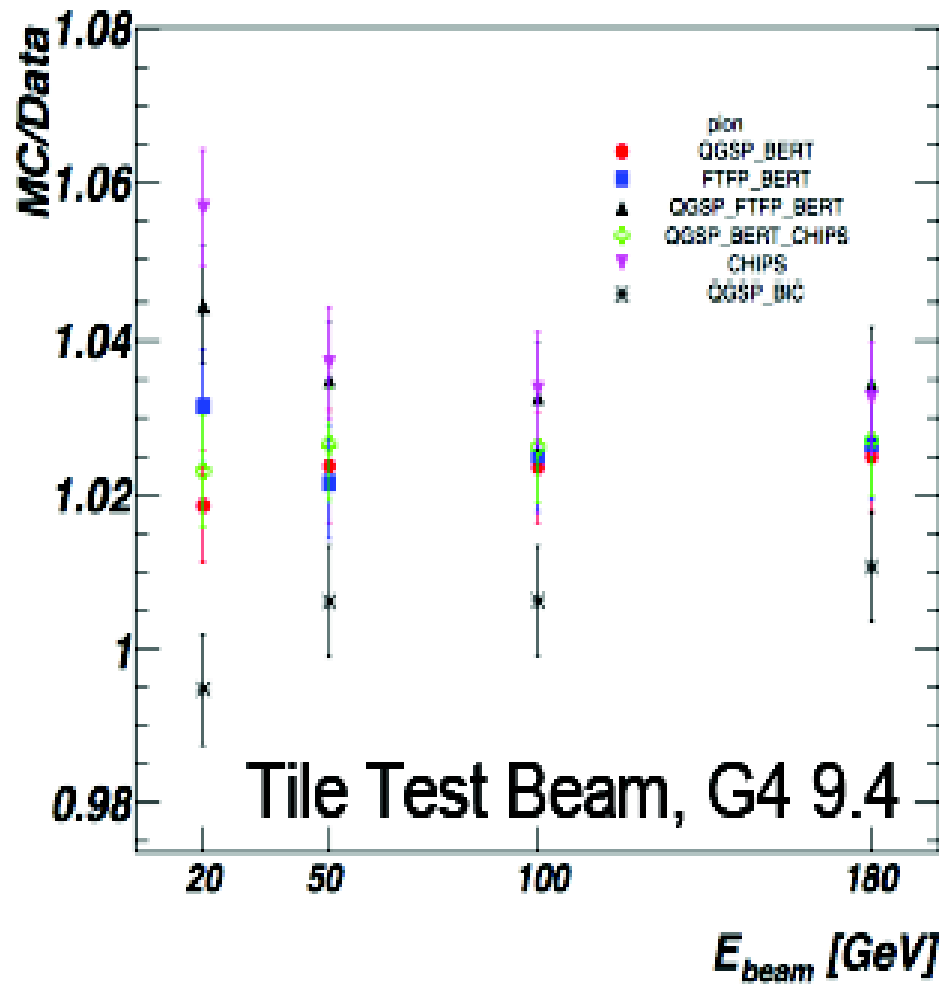


LHC calorimeter test-beams



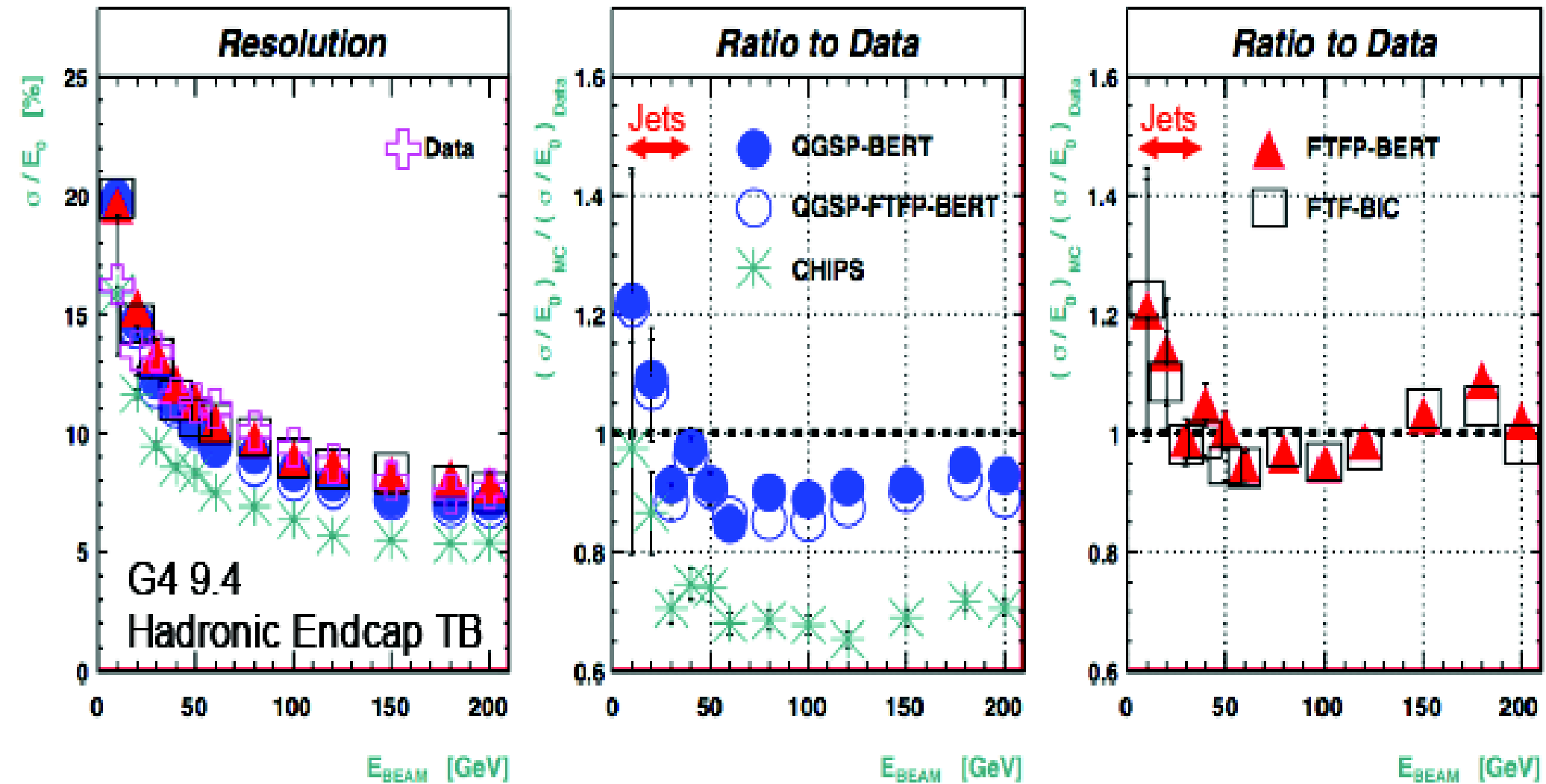
Energy response

ATLAS TileCal test-beam



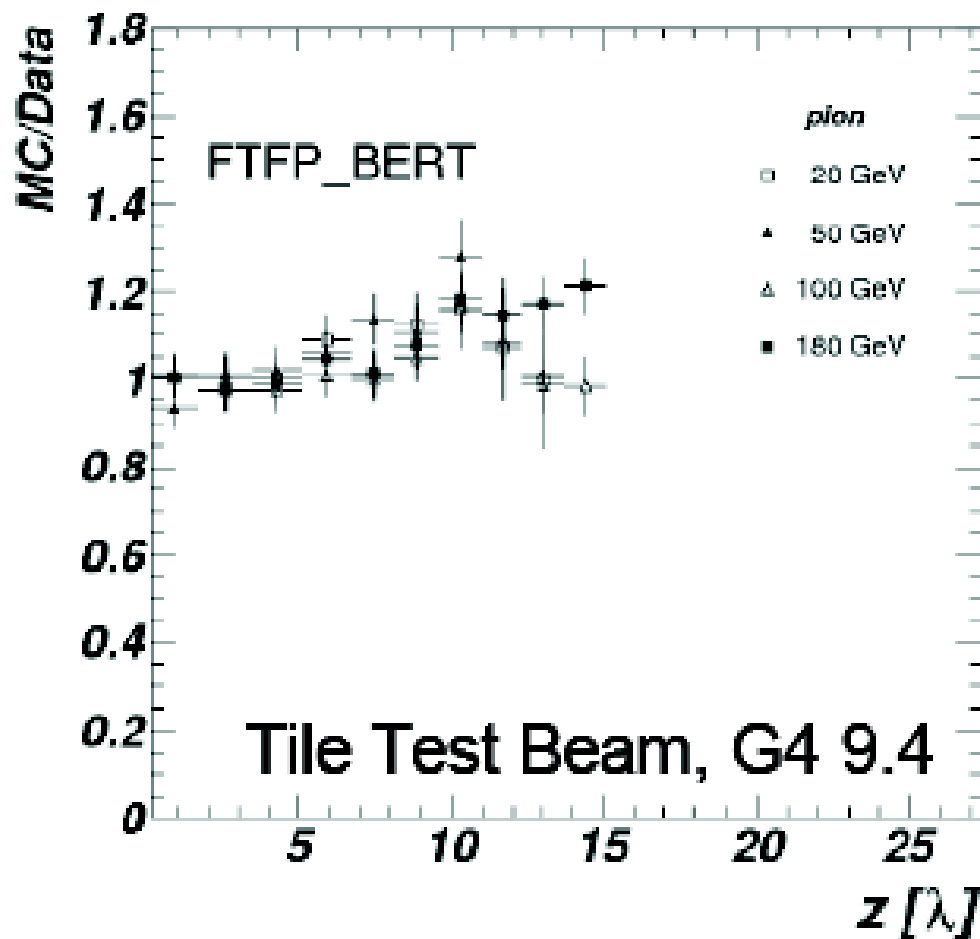
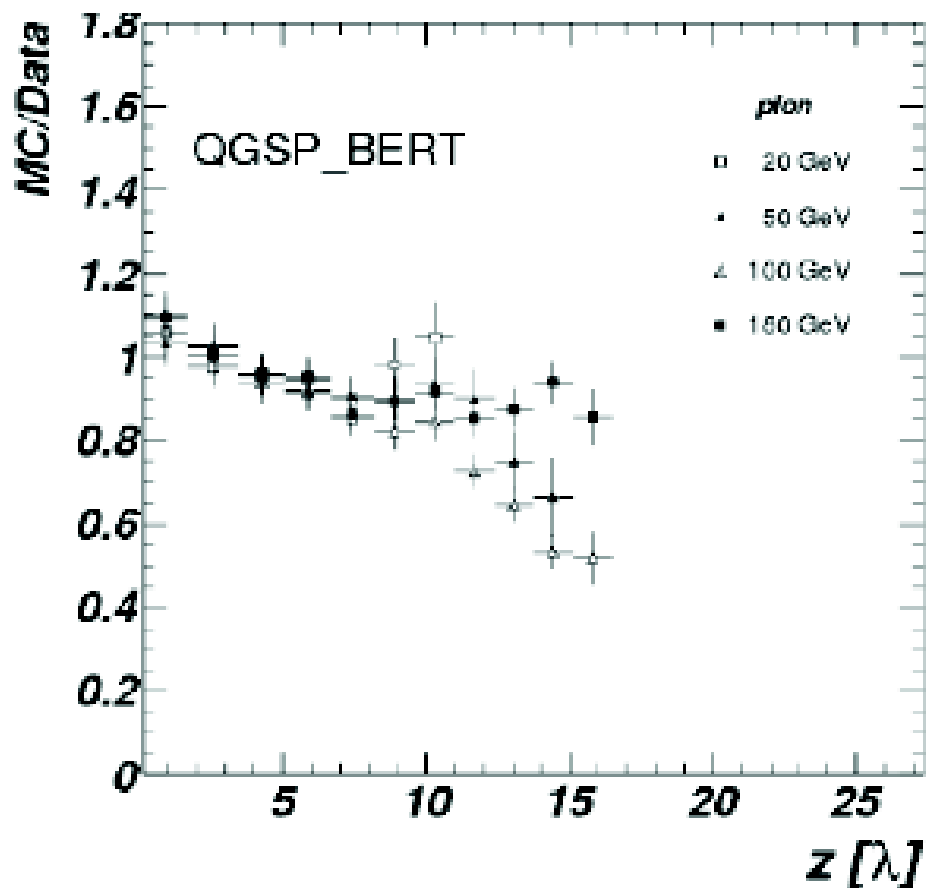
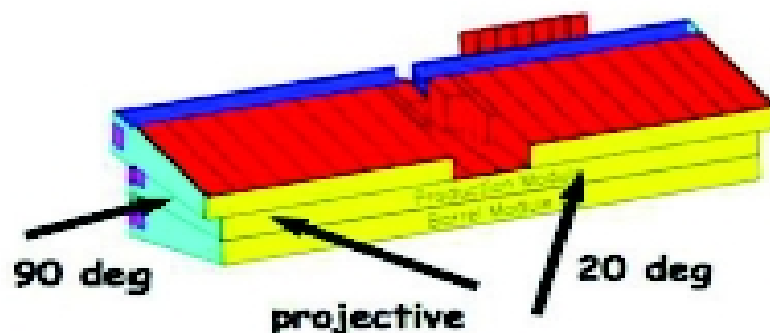
Energy resolution

ATLAS HEC test-beam



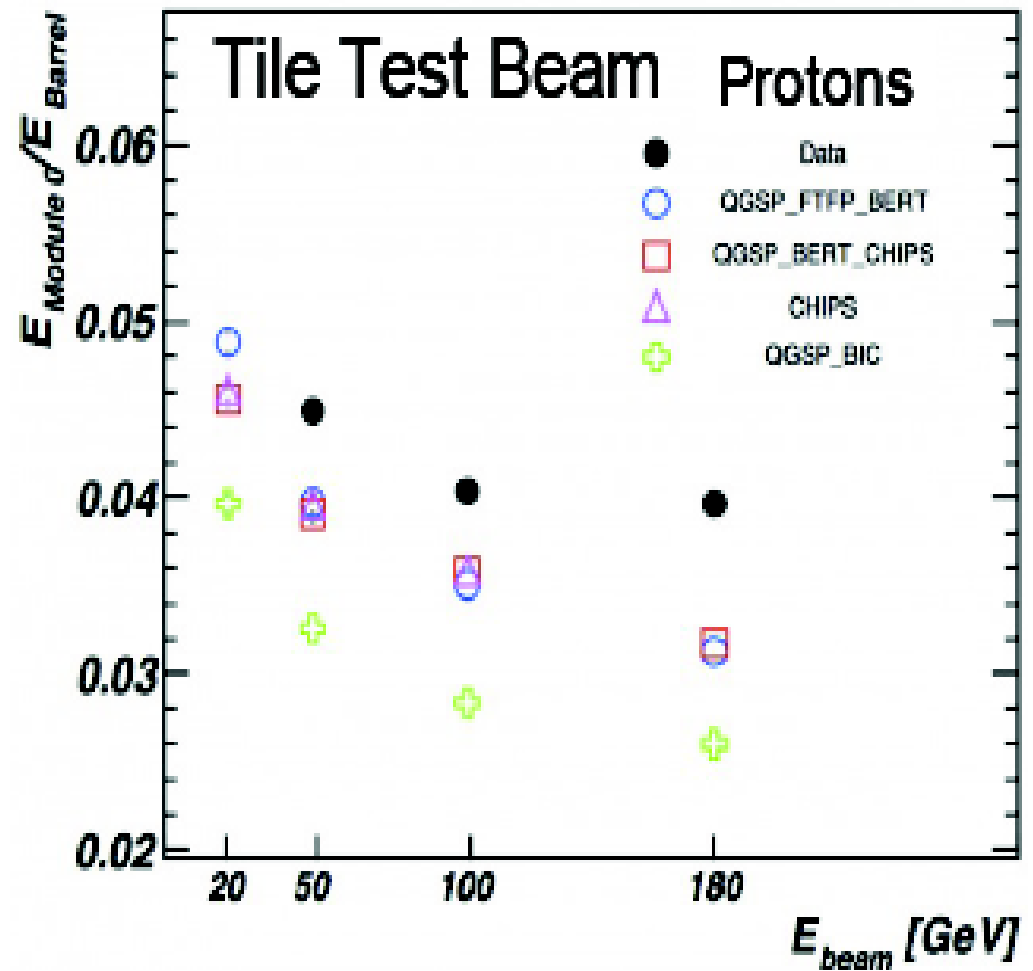
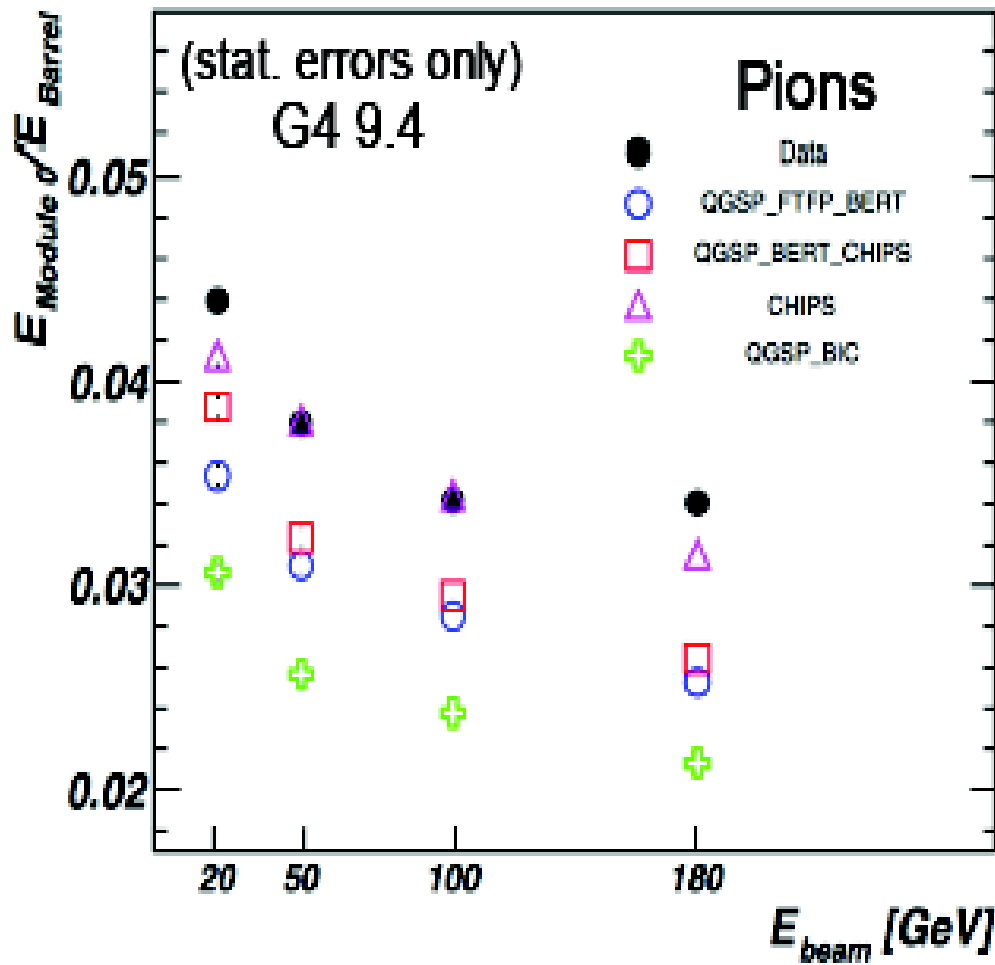
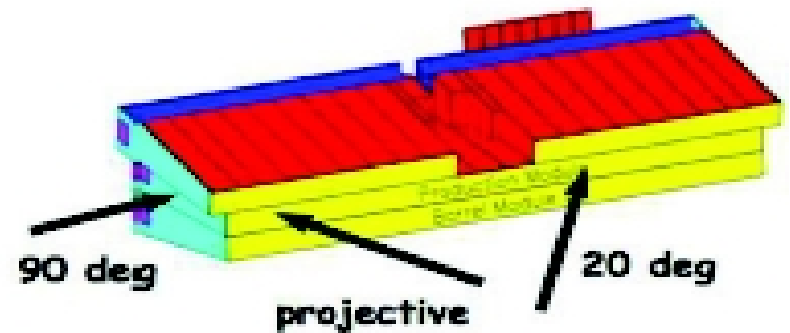
Longitudinal shower shapes

ATLAS TileCal test-beam @90°

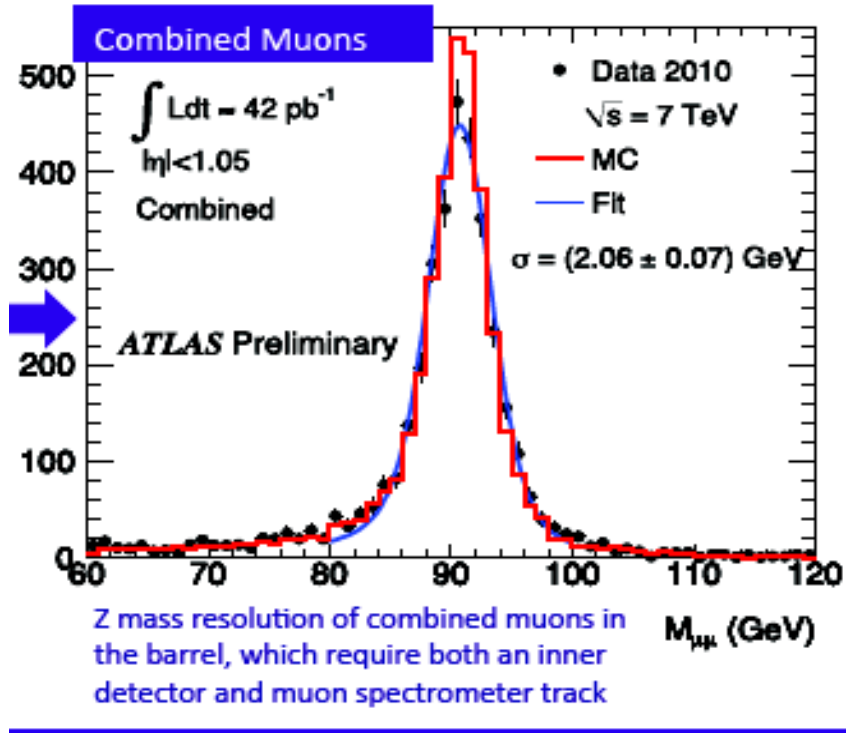


Lateral shower shapes

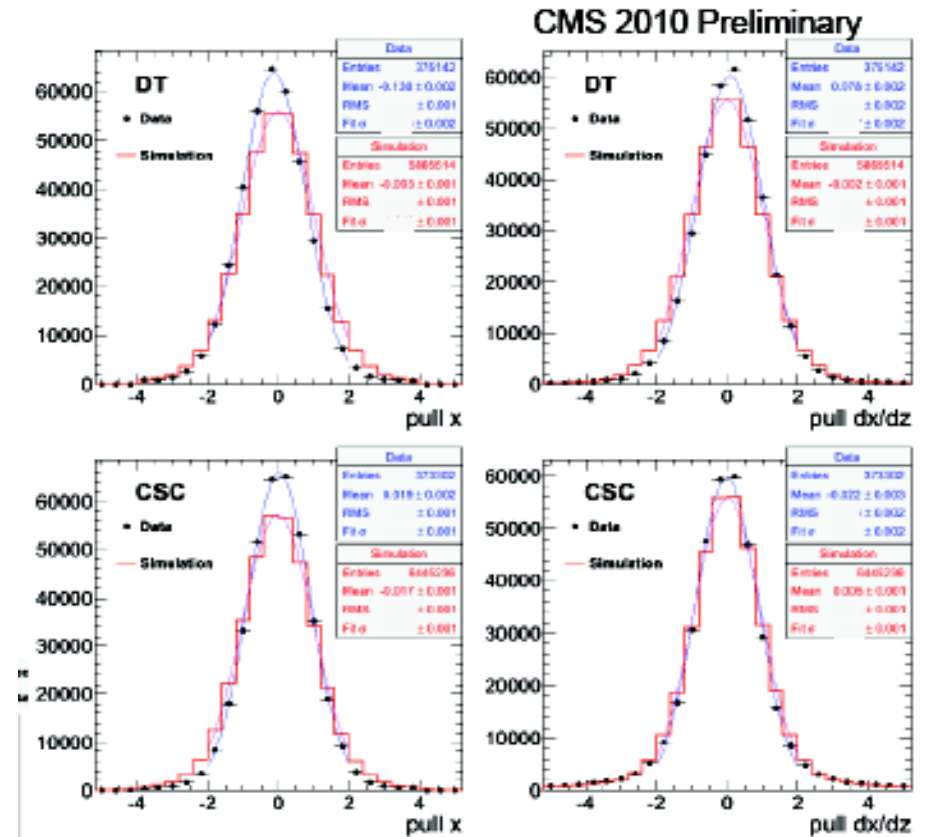
ATLAS TileCal test-beam @90°



Muon simulation vs. p-p collision data



Muon physics in G4 is extensively tested and validated in the energy range 10 GeV – 10 TeV

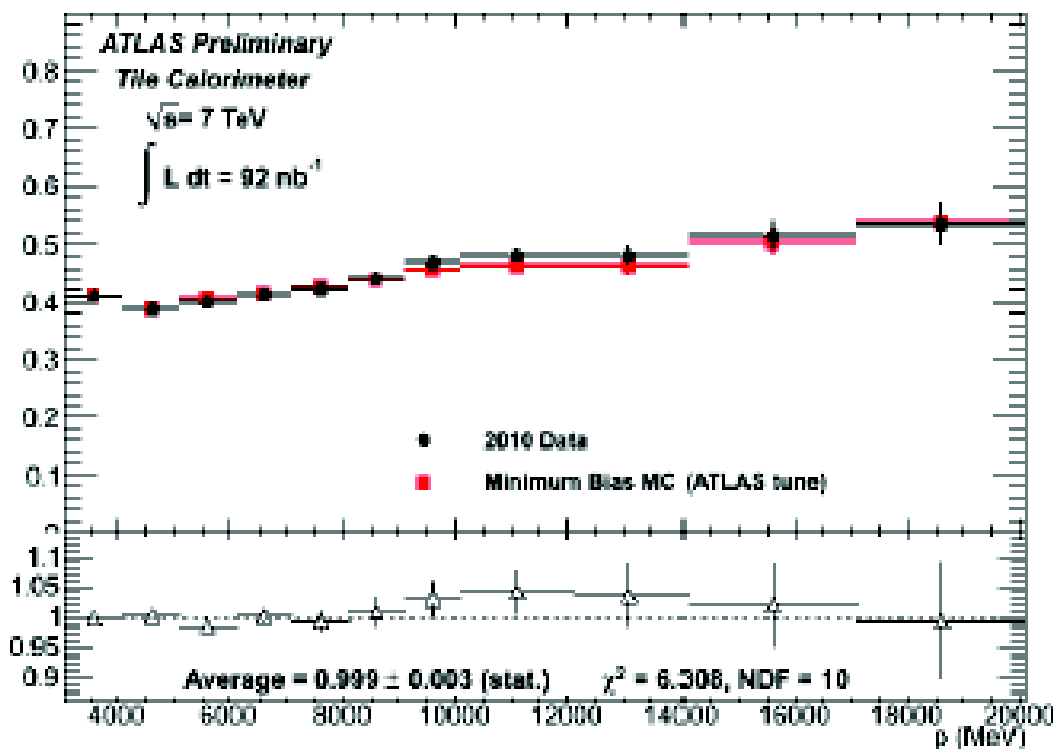
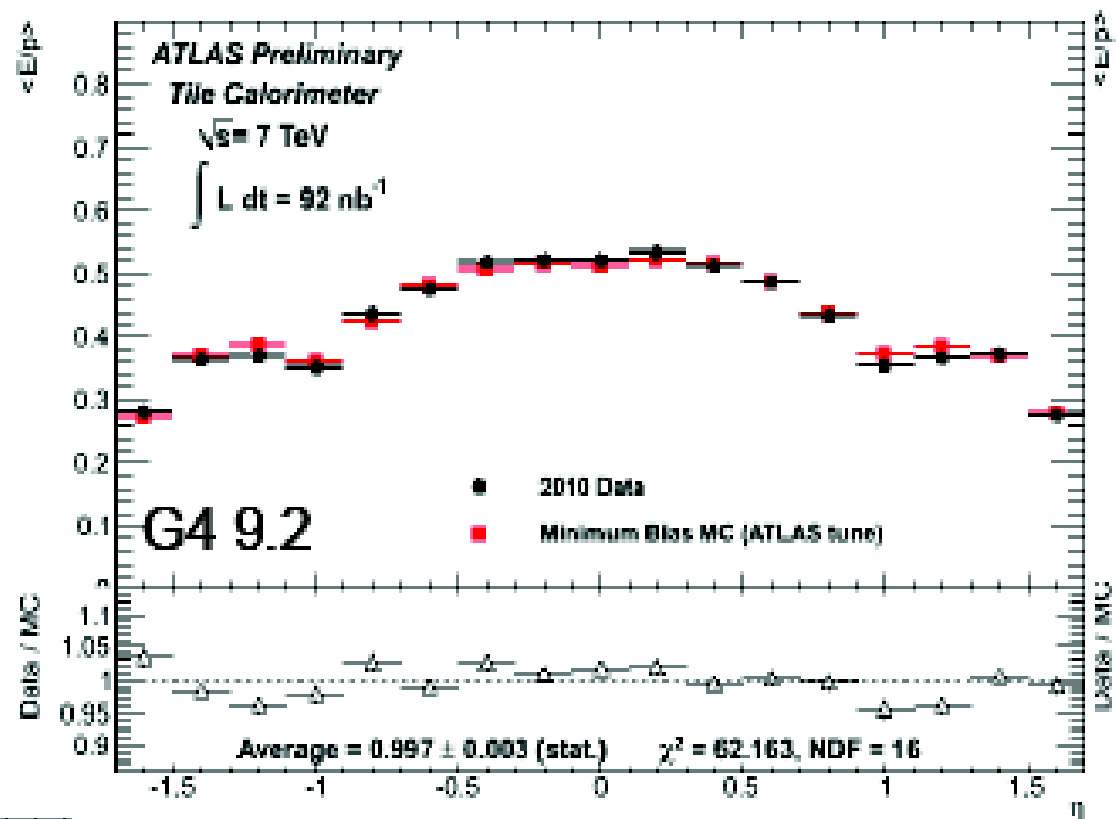


- Resolutions of extrapolations from central tracker to muon segments ↗
- checks proper implementation of material, multiple scattering through solenoid, absorber

Isolated single hadron response: simulation vs. ATLAS p-p data

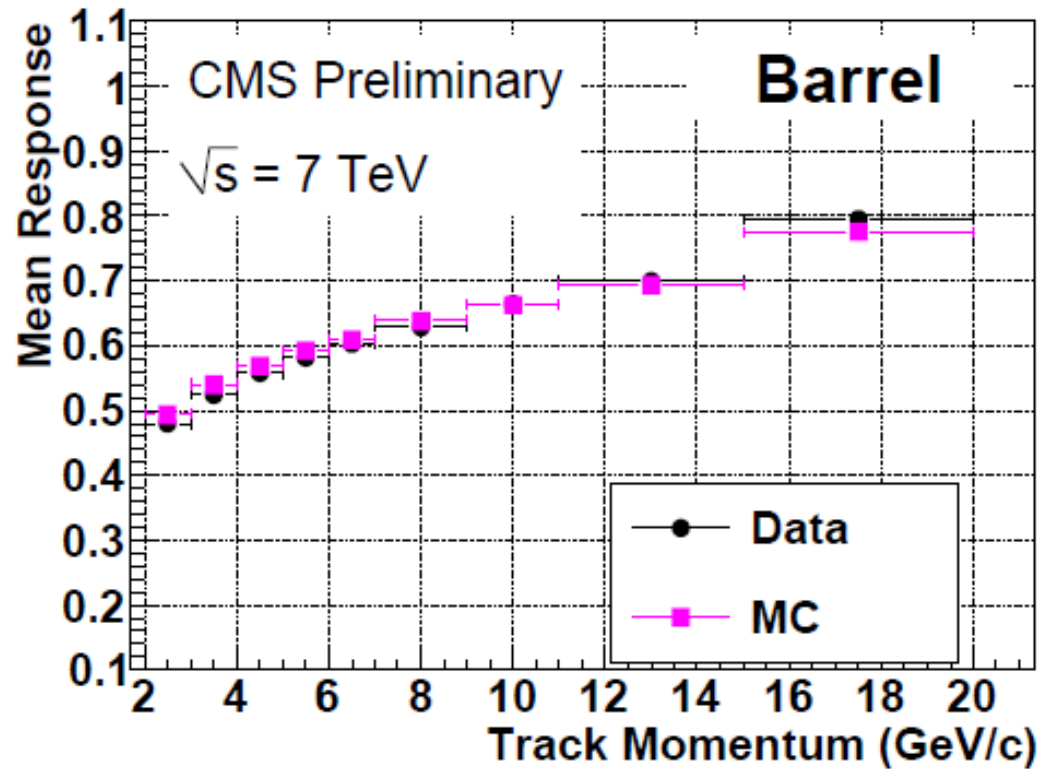
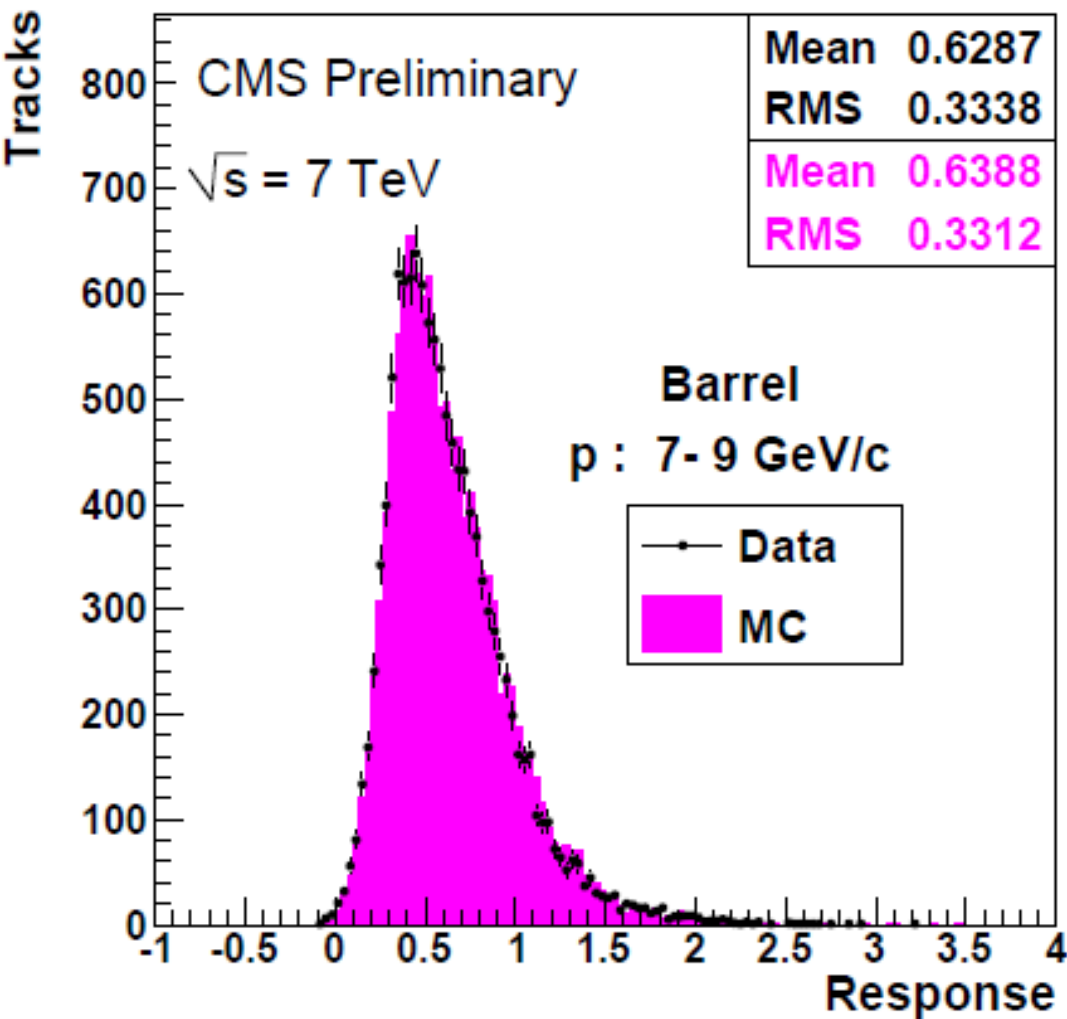
E/p vs η

E/p vs p



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

Agreement is better than $\pm 3\%$ between 2-20 GeV/c



Di-jet invariant mass: simulation vs. CMS p-p data

Very good agreement between simulation and collision data!

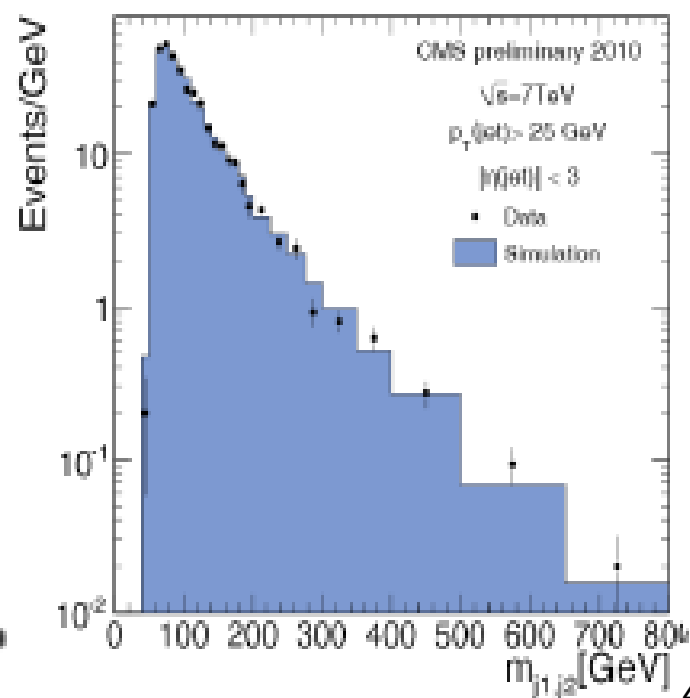
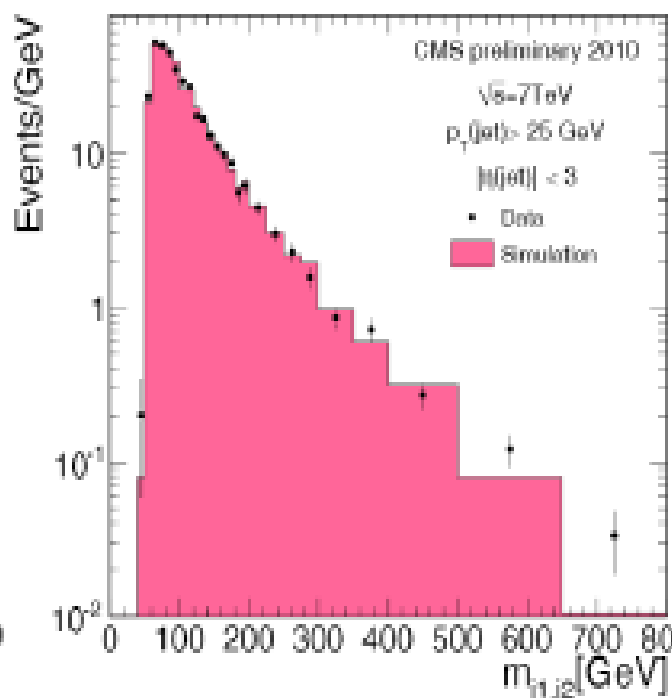
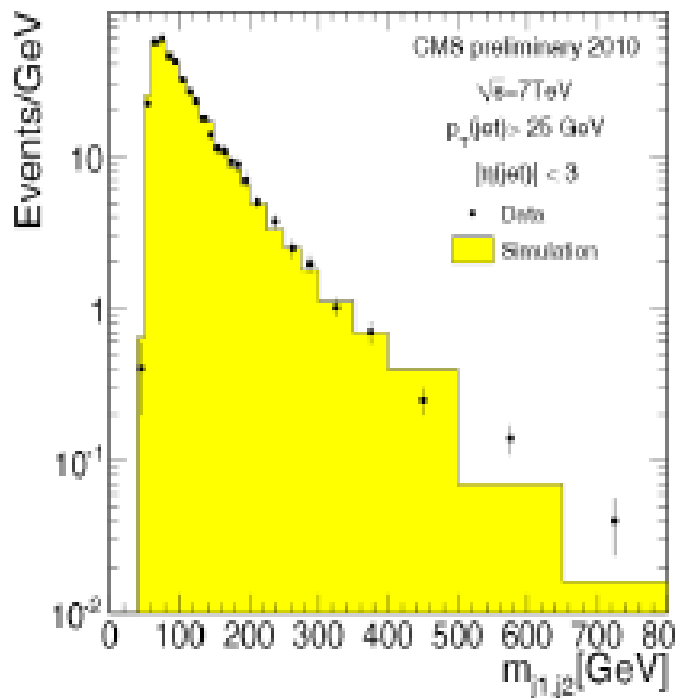
Three ingredients are convoluted in the simulation:

- Monte Carlo event generator: Pythia
- Detector simulation engine: Geant4
- Experiment-specific aspects: geometry/materials, digitization, calibration, rec.

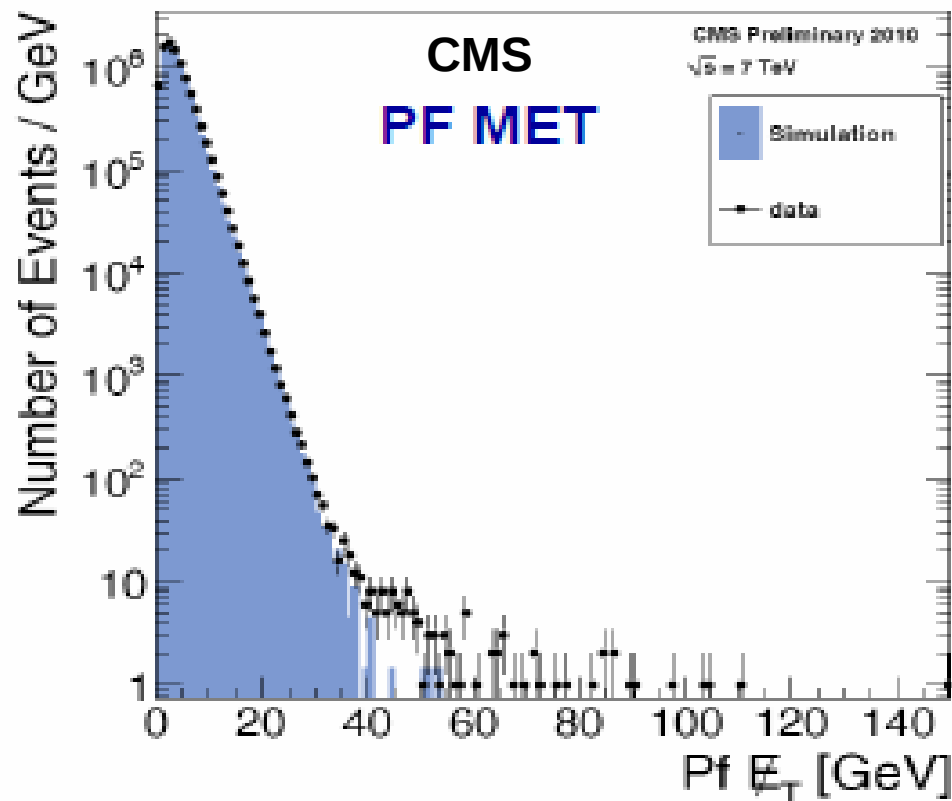
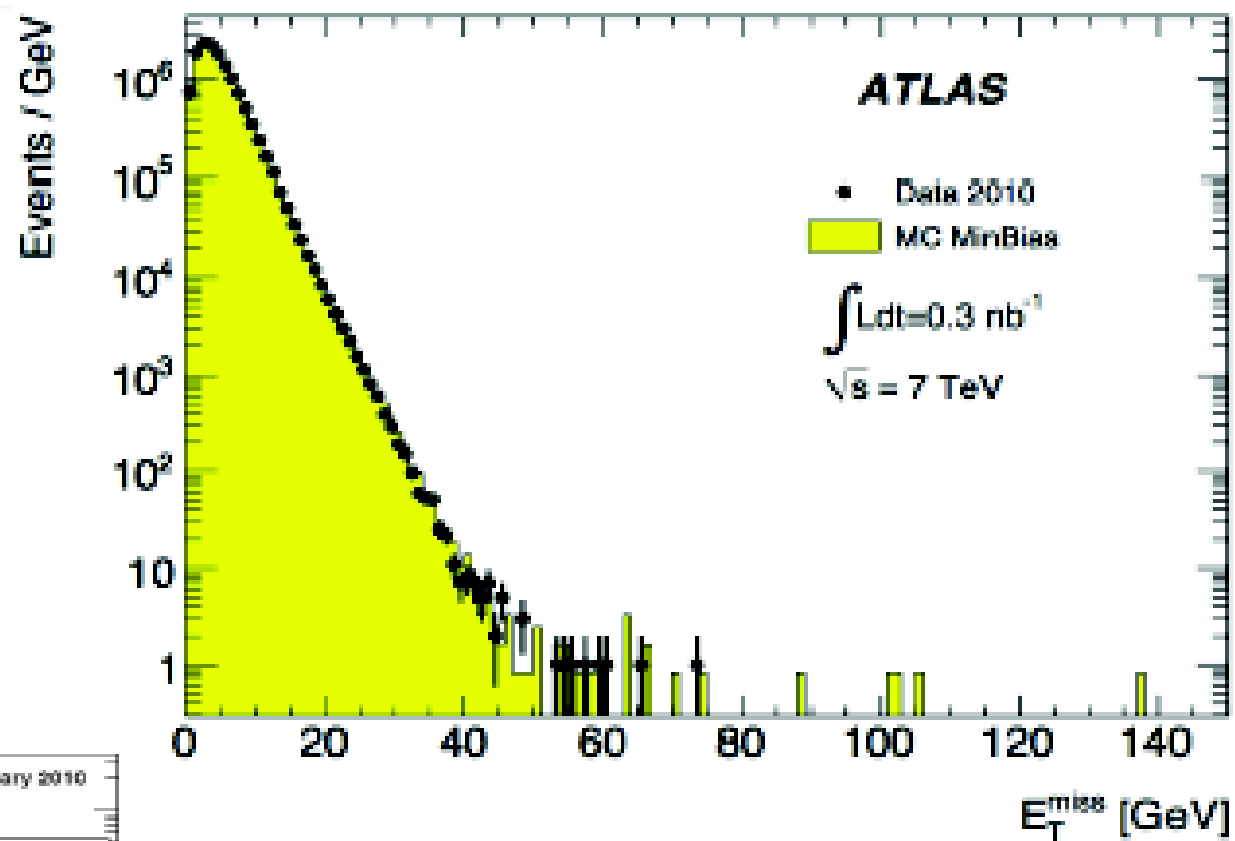
Calo jets

JPT jets

PF jets



Missing E_T : simulation vs. collision data



Missing E_T 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
 - ETRAN
 - EGS4
 - EGS5
 - EGSnrc
 - Penelope

Acknowledgment

Thanks to:

- Katsuya Amako
- Makoto Asai
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- Michel Maire
- Dennis Wright

for some of the figures used in this lecture