Geant4 Physics

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Outline:

First Part

- Tracks, Particles, Processes, and Production cuts
- Electromagnetic Physics
- Hadronic Physics

Second Part

- Physics Lists
- Showers, Observables
- Physics Validation

Tracks,

Particles,

Processes,

Production cuts

Introduction

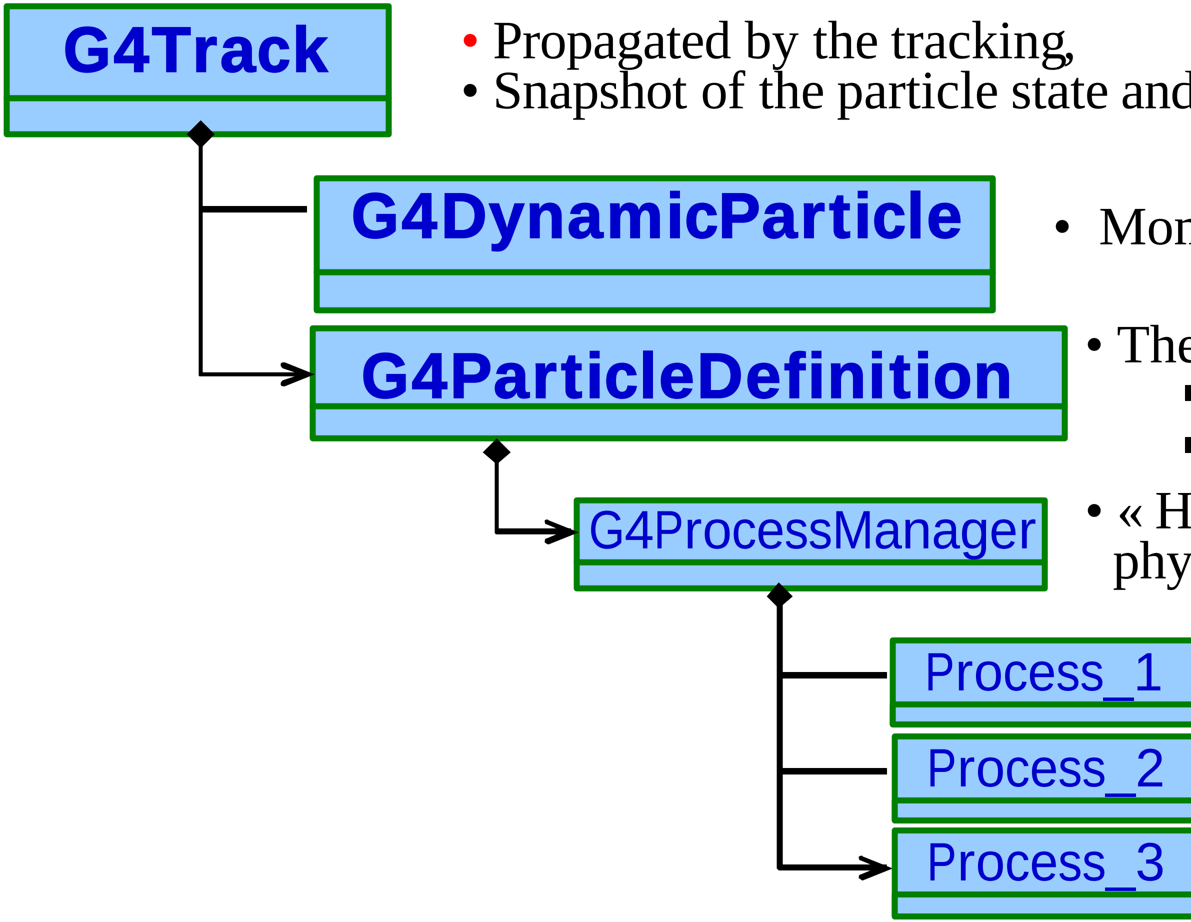
In Geant4, the user has to specify which particles, processes, and production cuts.

This is a ***mandatory*** and ***critical*** user's task.

This allows customization and performance.

Transparency and modularity: e.g. the user can define and use new processes, without knowing the kernel of Geant4.

What is tracked in GEANT4 ?



- Propagated by the tracking,
- Snapshot of the particle state and location.

- Momentum

- The « particle type »
  - G4Electron,
  - G4PionPlus…

- « Hangs » the physics sensitivity;

- The physics processes;

G4Track

- It is created by a process
- It is tracked from its birth until either it exits the world volume or it is killed:
    - by an interaction,
    - or because it comes to rest, and is stable
    - or by a user's action;
- It is not persistent: hits are usually saved.

Processes in Geant4

- Processes describe how particles interact with a material or a volume;
- G4VProcess : abstract interface to

the physics processes;

- processes are associated to particles;
- transportation treated as a process;
- tracking of particles is done in steps:

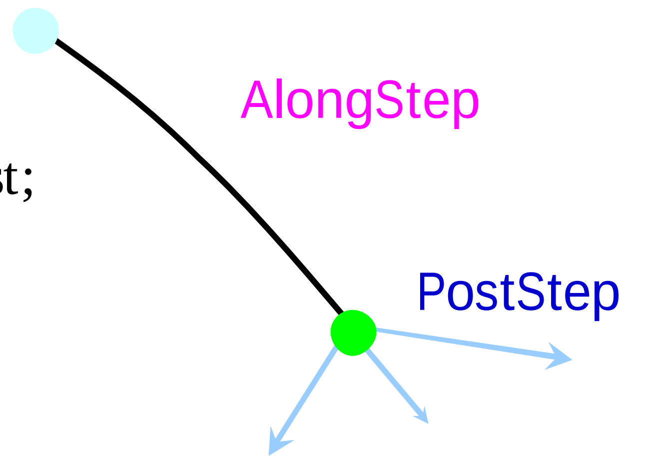
an unbiased procedure must decide the step length and what happens;

- in Geant4, processes and tracking/geometry are well separated and decoupled.

Process actions

There are three situations, where <tracking> may want to ask information from <process>:

- AtRest:
  - Decay, e^+ annihilation, absorption at rest;
- AlongStep
  - To describe 'continuous' interactions, occuring along the path of the particle, like ionization and bremsstrahlung;
- PostStep
  - To describe 'discrete' interactions, in practice **most of the processes**.



The 6 main methods of G4Vprocess

- A process will implement any combination of the 3 actions: AtRest, AlongStep and PostStep;
  Eg: decay = AtRest + PostStep
- Each action defines 2 methods:
  - GetPhysicalInteractionLength():
    Used to ***limit the step size***:
    - because the process « triggers » an interaction, a decay, geometry boundary, a user's limit …
  - DoIt():
    - Implements the ***actual action*** to be applied on the track;
    - Typically final state generation.

G4VProcess & G4ProcessManager

- In practice, the G4ProcessManager has 3 lists of actions:
  - One for the AtRest methods of the particle;
  - One for the AlongStep ones;
  - And one for the PostStep actions.
- Those lists are set up in the Physics List and then used by the Tracking.

Stepping algorithm

Processes have to cooperate in their AlongStep actions; compete for PostStep and AtRest actions.

1. Determine the step length, as the smallest proposed length of all GPILs of all processes associated with the G4Track;
2. Apply all AlongStepDoIt() actions;
3. Apply PostStepDoIt() of the process who won the race for the step length (and also of special “forced” actions);

NB) For AtRest the step length is actually a time.

Ordering of the processes

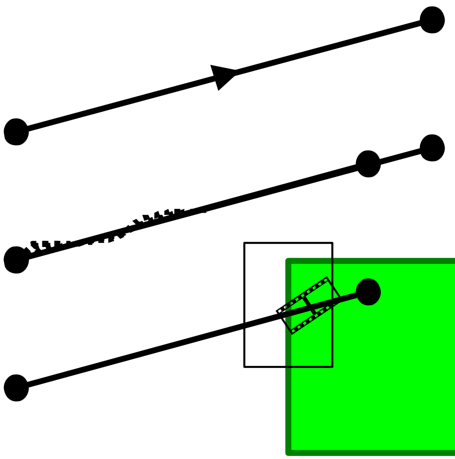
- Ordering of following processes is critical:
  - Assuming n processes, the ordering of the AlongStepGetPhysicalInteractionLength of the last processes should be:

    [n-2] …

    [n-1] multiple scattering

    [n] transportation

- Why ?
  - Processes return a « true path length »;
  - The multiple scattering « virtually folds up » this true path length into a ***shorter*** « geometrical » path length;
  - Based on this new length, the transportation can geometrically limits the step.



- For other processes ordering does not matter.

How to create a new process?

- Inherit from one of the following 7 classes:

  ContinuousProcess, ContinuousDiscreteProcess, DiscreteProcess, RestContinuousDiscreteProcess, RestContinuousProcess, RestDiscreteProcess, RestProcess

- Implement the cross-section of the process

  in: GetPhysicalInteractionLength

- Implement the final-state of the process

  in: DoIt . Get familiar with classes:

  G4Step and G4VParticleChange.

- Learn by looking at some of Geant4 processes (but **not G4MultipleScattering** and **G4Transportation**: they are special!).

The Production Cuts

- In Geant4 there is no tracking cut: particles are tracked down to a zero range/Ekin.
- Only production cuts exist, i.e. cuts allowing a particle to be born or not.
- Why are production cuts needed?

Two electromagnetic processes, δ-rays production and bremsstrahlung, have an infrared divergence; in practice, below the production cut, these processes are treated as continuous effect (AlongStep action).

- For other processes (and particles), production cuts can be an option to speed-up the simulation.

Range vs. Energy production cuts

- In Geant4, users specify production cuts in range, and then internally this is converted into kinetic energy.
- The production of a secondary particle is relevant if it can be “visible” in the detector: range cut allows to easily define such visibility.
- A cut of the same energy would lead to very different ranges: for the same particle type, depending on the material; for the same material, depending on particle type.
- Different range cuts can be chosen per region.

G4UserLimit

This class allows to define the following limits (in a given G4LogicalVolume):

- Maximum step size;
- Maximum track length;
- Maximum track time;
- Minimum kinetic energy (tracking cut).

The user can inherit from G4UserLimit, or can instantiate the default implementation.

These limits are unphysical "tricks" that can improve either the CPU performance of the simulation, or (in the case of the maximum step only) the precision of the simulation.

Electromagnetic Physics

Electromagnetic Physics in G4

- The projectile is assumed to have a kinetic energy between 1 keV and 100 GeV

  (this is the Standard EM: there is a low-energy extension, down to 250 eV, and a high-energy ones, especially for muons, up to several hundred GeV);
- The atomic electrons are quasi-free: their binding energy is neglected (except for the photoelectric effect);
- The atomic nucleus is fixed: the recoil momentum is neglected;
- The matter is described as homogeneous, isotropic, amorphous.
- Single interactions are precisely described by QED, but there are medium-effects that complicate things…
- It must be very CPU performant!

EM processes

Common to all charged particles:

- Ionization
- Coulomb scattering from nuclei
- Scintillation
- Cerenkov effect
- Transition radiation

Electrons and Positrons:

- Bremsstrahlung
- e+ annihilation

Muons

- e+/e- pair production
- Bremsstrahlung
- Nuclear interaction

EM processes (cont.)

Photons:

- conversion
- Compton (incoherent) scattering
- Photo-electric effect

Optical photons:

- Rayleigh (coherent) scattering
- Reflection and refraction
- Absorption

NB) Clear distinction between **G4Gamma** and **G4OpticalPhoton**
(>> atomic scale) for CPU performance reasons.

There are also other processes:

- Synchrotron radiation
- Fluorescence
- Auger effect
- Gamma-nuclear, electron-nuclear

And also weak physics processes: - capture

Energy loss I : ionization

Below the electron production cut, the ionization process: q + atom -> q' + atom+ + e-

is described macroscopically (AlongStep)

as the result of many collisions:

- Bethe-Bloch energy loss is the average.

  Different formulas are used for electrons and positrons, and for low energy.
- Landau distribution describes the fluctuations of energy loss, for thin layers.

  Different models are used for other cases.
- Barkas effect (difference in energy loss between q+ and q- at low energy) is included.

Energy loss II : bremsstrahlung

Below the photon production cut, the bremsstrahlung process:

q + atom -> q' + atom + ■

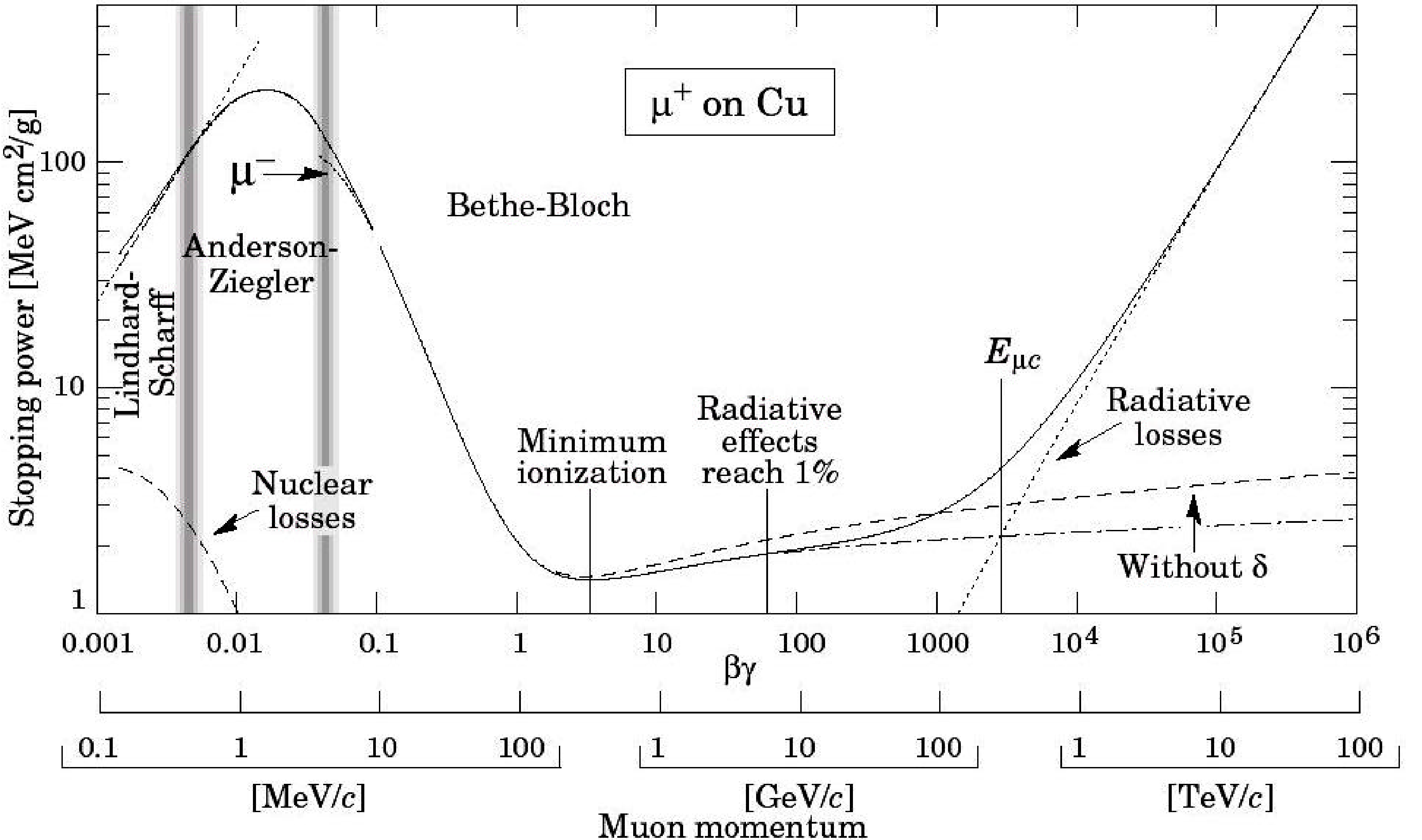
is described macroscopically (AlongStep) as the result of many soft emissions.

For the discrete (PostStep) part (i.e. above the production cut), Bethe-Heitler formula is used, with the following corrections:

- screening of the field of the nucleus
- correction to the Born approximation
- polarization of the medium
- Landau-Pomeranchuk-Migdal (LPM) suppression:

  destructive interference between different photon emission amplitudes.

Example: energy loss of μ+ on Cu

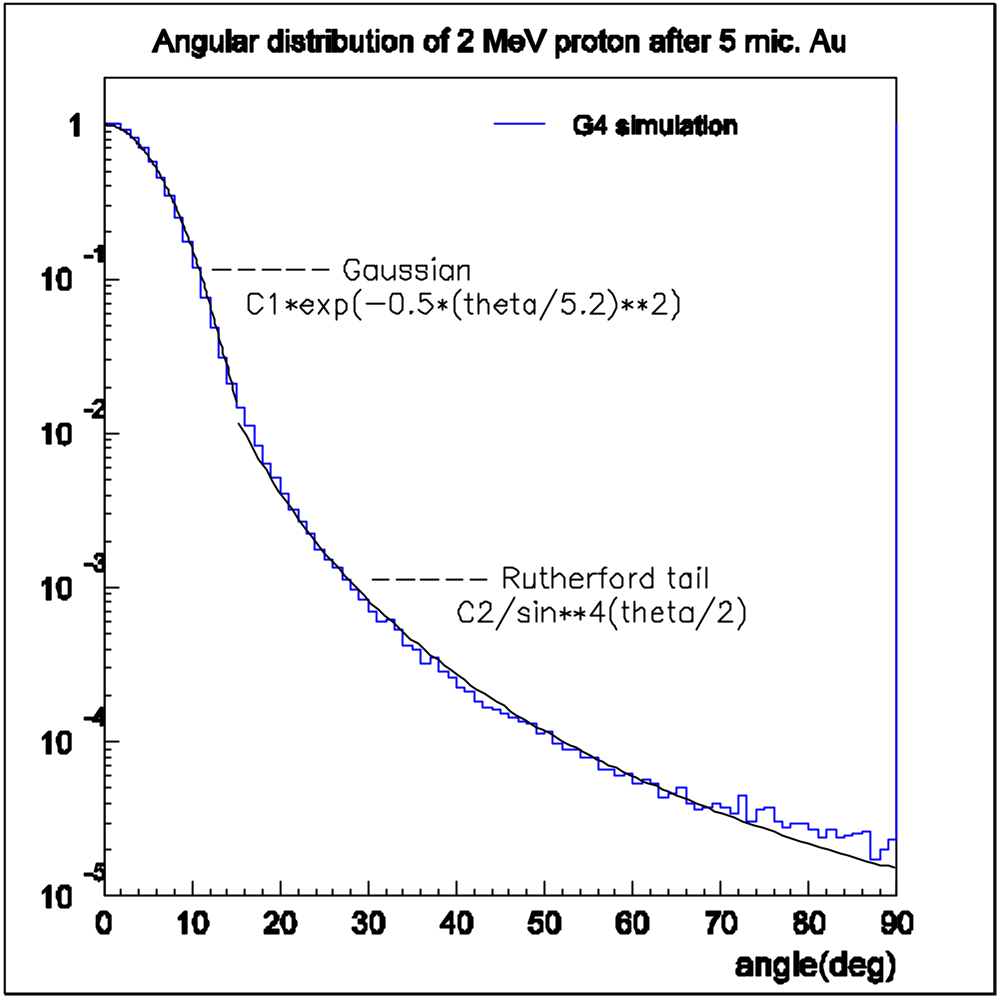


Multiple scattering

A detailed, microscopic simulation of Coulomb scattering with each nucleus would be too time consuming. A condensed approach is used instead in Geant4: the global effects of many collisions after a macroscopic step are simulated, using approximated formulas. The cumulative effect of small angle scatterings results into a gaussian distribution at small angles, whereas for large angles, dominated by single elastic scatterings, the Rutherford distribution is observed.

It is difficult to describe correctly multiple scattering, especially in a wide energy range!

Multiple scattering: angular distribution



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Hadronic Physics

Hadronic physics in G4

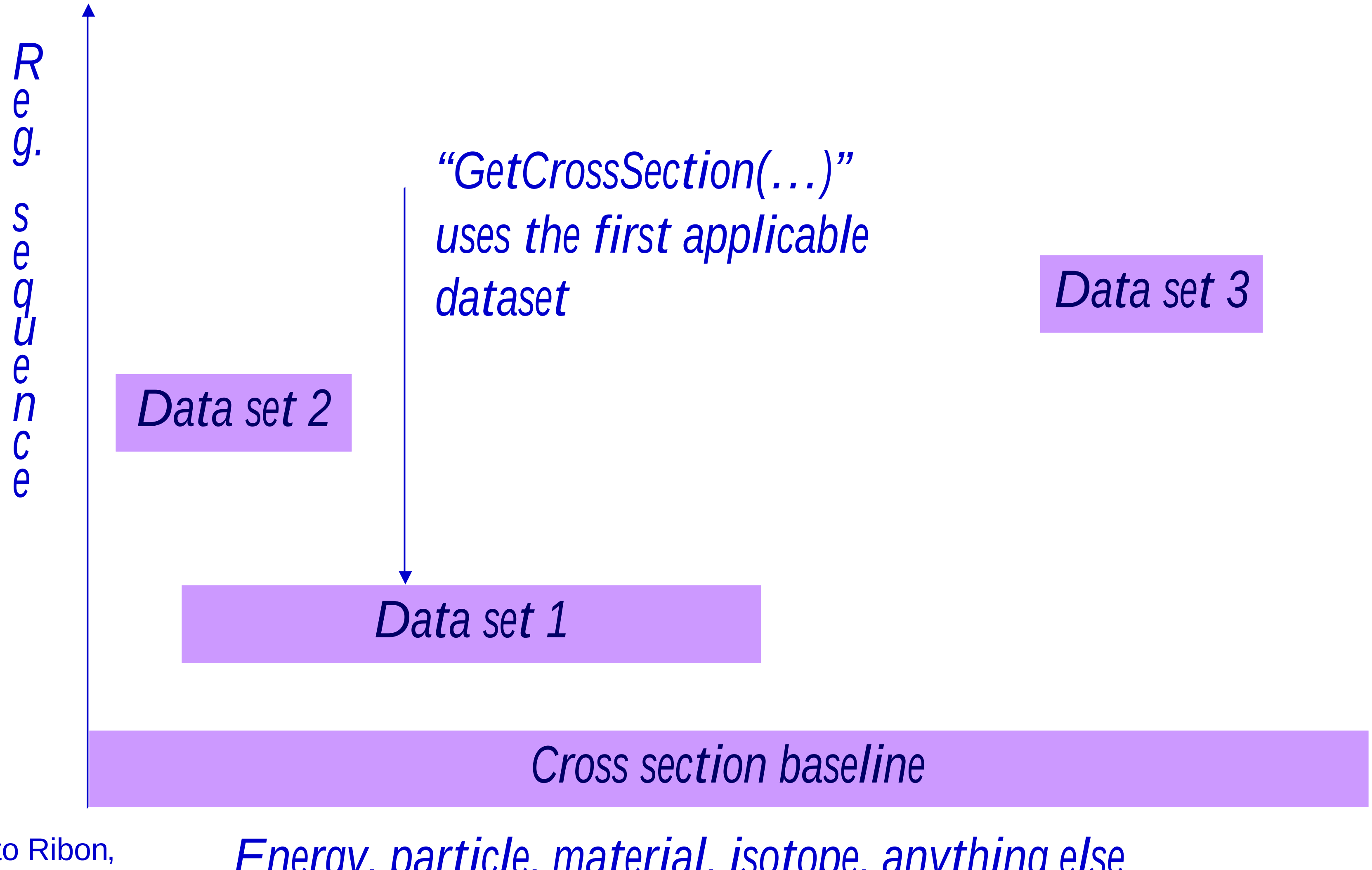
- 15 orders of magnitude in energy:
  from thermal ~10^{-2} eV ÷ 10 TeV (LHC)
- Three main variables:
  1. Beam energy
  2. Particle type
  3. Target isotope

  plus the precision we would like to achieve.
- Non-perturbative QCD regime: no way to do perturbative calculations, so different approximated models are used.
- Hadronic physics is a complex and wide area, but it is usually not CPU critical (unless electromagnetic physics is parameterized).

Had vs. em processes

- In electromagnetic physics (mostly):
  - 1 process = 1 model and 1 cross-section.
- In hadronic physics (mostly):
  - Clear distinction between process, cross-section, and model (i.e. final state of the interaction).
  - 1 process = an assembly and selection of many cross-sections data-sets, models, production codes, model components, sub-assemblies, options.
  - Default cross-sections are provided for each process.
  - You decide in the physics list what exactly you use.
  - Mix, match, assemble.

Cross section logic: “AddDataSet(…)” fills a FILO stack



Cross section implementations

Different kinds of cross-sections:

- Default for all possible situations from Geant 3.21
- Some are theory
- Some are parameterizations
- Some are data from large databases:
  - Low energy neutrons (below 20 MeV): ENDF/B, JENDL, FENDL, CENDL, Brond, Jef, MENDL, MENDL-P, EFF, etc.
  - isotope production: from MENDL-2, MENDL-2P.
  - Proton and neutron reaction cross-sections up to 20 GeV
  - etc.

Final state generators

Three categories of modeling approaches:

- Data driven modeling

  when data is available with sufficient coverage, this approach is the preferred way of modeling;
- Parameterization driven modeling

  widely used, especially for calorimeter simulations, based on experimental inclusive distributions (no correlations), provides good CPU performance;
- Theory driven modeling

  is the safest extrapolation of results toward energies beyond the test-beam region.

NB) The border between these three approaches is fuzzy.

Data driven models

- Low energy neutron transport (neutron_hp)
- Radioactive decay
- photon evaporation
- elastic scattering
- internal conversion
- etc.

Parameterization driven models

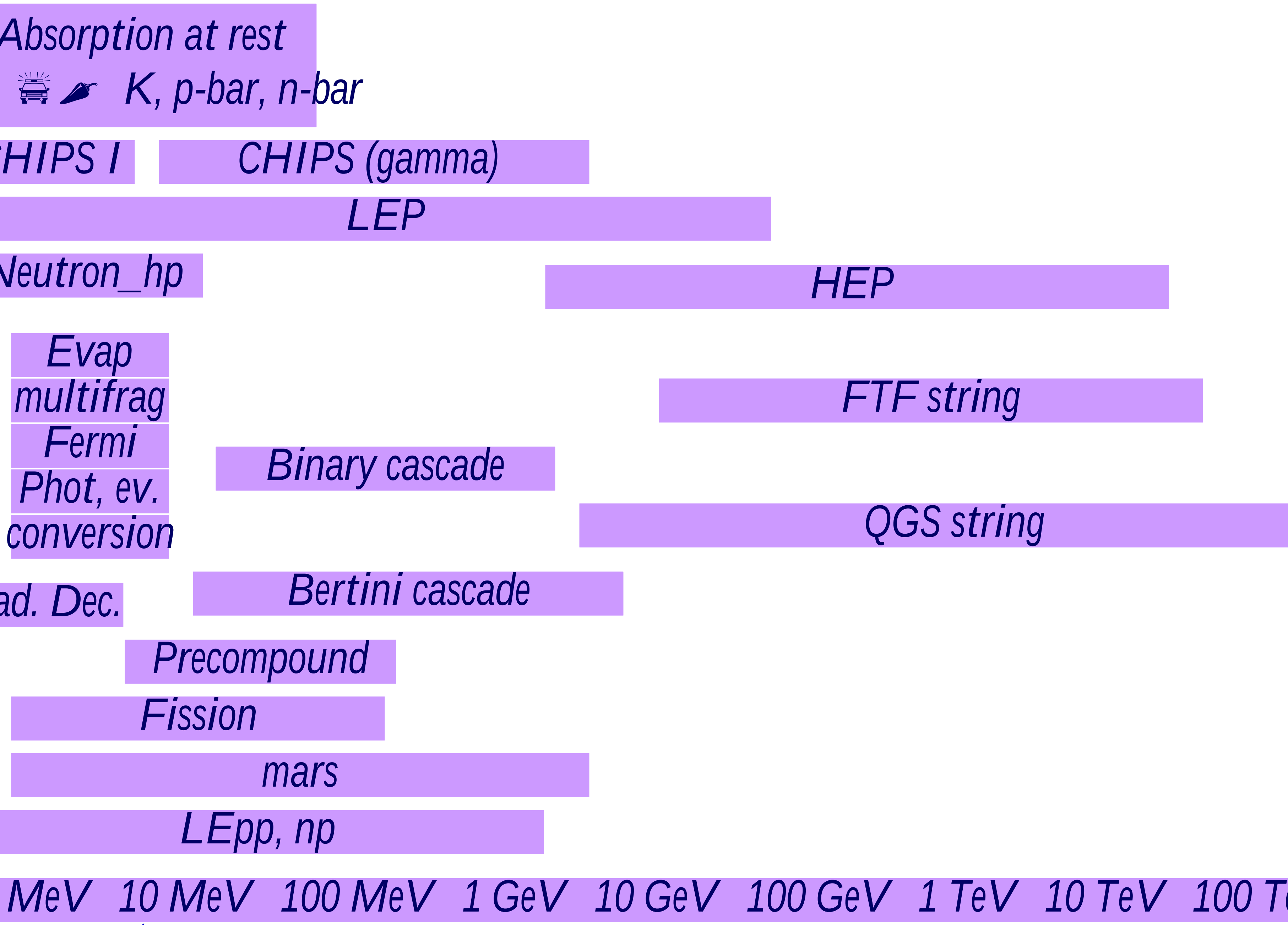
- Two domains:
  - high energy inelastic
  - low energy inelastic, elastic, fission, capture

- Stopping particles
  - base line
  - mu-
  - pi-
  - K-
  - anti-protons
  - Electromagnetic transitions of the exotic atom prior to capture; effects of atomic binding.

Theory driven models

- Ultra-high energy models
  - Parton transport model
- High energy models
  - 'Fritjof' type string model
  - Quark Gluon String
  - Pythia7 interface
- Intra-nuclear transport models (or replacements)
  - Hadronic cascade+pre-equilibrium
  - Binary and Bertini cascades
  - QMD type models
  - Chiral invariant phase-space decay
  - Partial Mars rewrite
- De-excitation
  - Evaporation, fission, multi-fragmentation, Fermi-break-up

An incomplete hadronic model summary



Physics Lists

Physics List

- As for the geometry and the materials, also the list of particles and processes (physics list) must be specified by the user: there are no defaults in Geant4!
- Whereas the electromagnetic part of the physics list is relatively simple and standard, the hadronic part is complex, and depends on the particular application domain the user is interested in.
- To simplify this task, some physics lists are already prepared for some application domains: in most cases, the user can use one of them.

Examples of Physics Lists

- LHEP, QGSP, QGSC, FTFP, FTFC : "LHEP" : parameterized; "QGS" : Quark Gluon String; "FTF": Fritjof; "P": Pre-equilibrium; "C": CHIPS.
- xxxx_BERT, xxxx_BIC : intra-nuclear transport models, Bertini and binary cascade.
- xxxx_GN : photon-nuclear reactions
- xxxx_HP : high precision low-energy neutron transportation
- xxxx_LEAD : leading-particle biasing.
- Default range production cut: 0.7 mm .
- All with the same standard EM physics.
- Example of how to include a Physics List, e.g. QGSP:

  #include "QGSP.hh"

  …runManager->SetUserInitialization(new QGSP);

Showers, Observables

Showers

- e^-, e^+, ■ impinging on matter, at energies above a certain threshold, produce an electromagnetic shower, i.e. a cascade of ■, produced by bremsstrahlung e -> e + ■

  and e^+ e^- pairs, produced by conversions ■ -> e^- + e^+ .

- hadrons (p, n, 🚔$^{+/-}$, $K^{+/-}$, etc.) impinging on matter, at relatively high energies, can produce an hadronic shower, i.e some hadrons are produced by a nuclear inelastic interaction and these in turn can produce other hadrons…

  An electromagnetic component is present as well, mainly due to 🚔^{0}, which promptly decay into ■ + ■ , and these can start an electromagnetic shower.

- Electromagnetic showers are much shorter, compact, and denser than hadronic showers.

  Few charged particles are produced in hadronic showers, while most of the hadrons produced are neutrons.

Calorimeters

- A calorimeter is a device that allows to measure the energy of a particle, neutral or charged.
- A calorimeter is a block of matter in which the particle to be measured interacts and transforms (part of) its energy into a measurable quantity. The resulting signal may be electrical, optical, thermal or acoustical.
- A calorimeter can be homogeneous (e.g. PbWO4 crystal), or a sampling calorimeter (e.g. Pb-LAr, Fe-Scintillator), in which thick layers of absorber are separated by thin layers of active (sensitive) material.
- A calorimeter is usually made of two parts: the first, more compact one, is the electromagnetic calorimeter;

  the second, larger one, is the hadronic calorimeter.
- Observables of a calorimeter are: the energy resolution s_E/E , ratio e/ , shower shapes (longitudinal and transverse) : all these vs beam energy.

Physics Validation

Physics Validation

Test electromagnetic physics first, then hadronic physics, because hadronic showers have an electromagnetic component.

As for the choice of the Physics List, also the validation should be targeted to each considered application domain: e.g. for high-energy physics one should consider different observables than, for instance, medical physics.

Simulations are always approximations: there are not simulations which are perfect, or very good, in all situations!

Even the criteria to consider a simulation "good" or "bad" shoul be based on the particular application: e.g., for LHC experiments, the main requirement is that the dominant systematic uncertainties for all physics analyses should not be due to the imperfect simulation.

Validation setups

Two main types of test-beam setups:

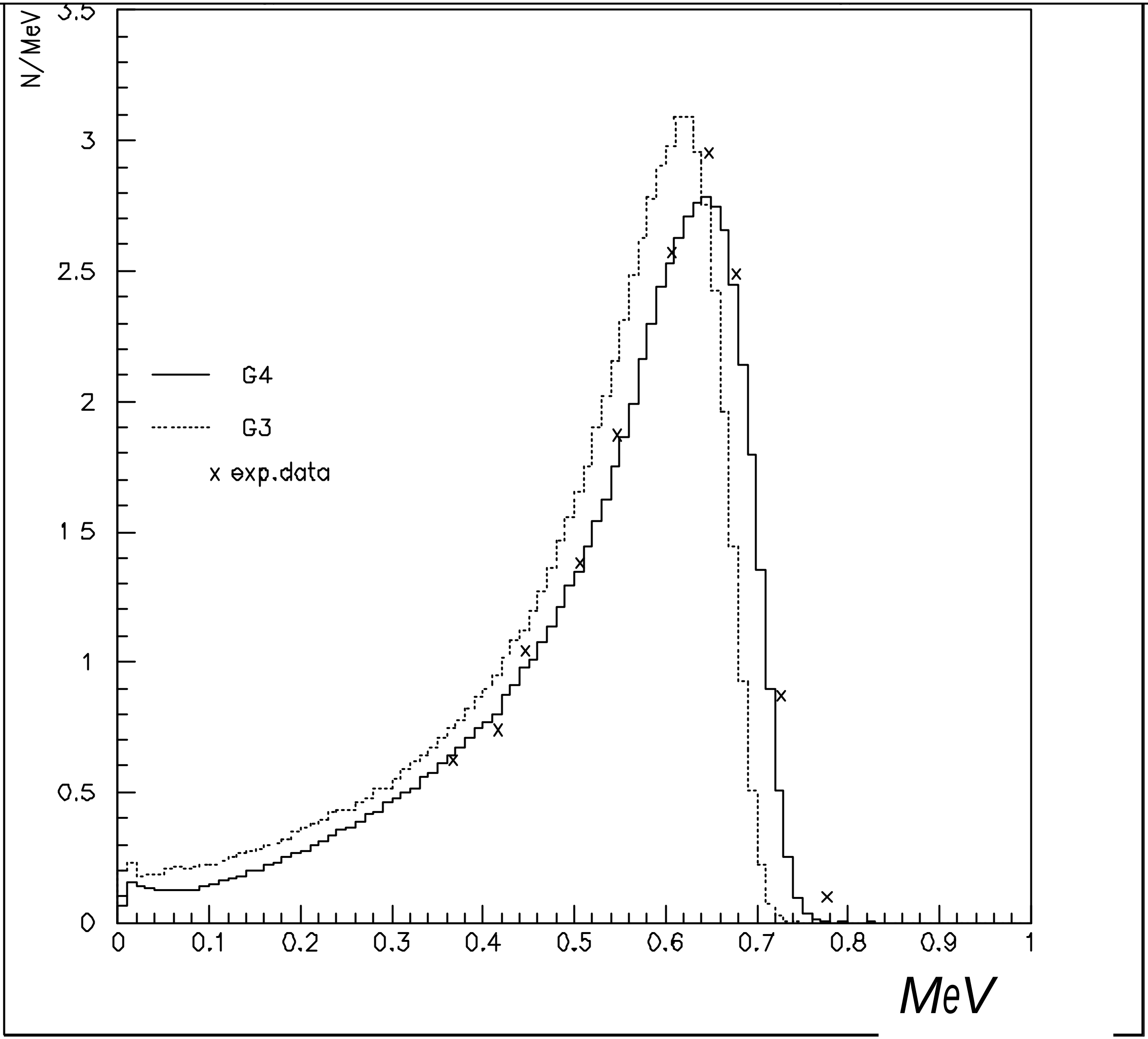
1. Calorimeters: the typical test-beams (made for detector purposes, not for validation).
   The observables are the convolution of many effects and interactions. In other words, one gets a macroscopic test.

2. Simple benchmarks: typical thin-target setups with simple geometry (made, very often, for validation purposes).
   It is possible to test at microscopic level a single interaction or effect.

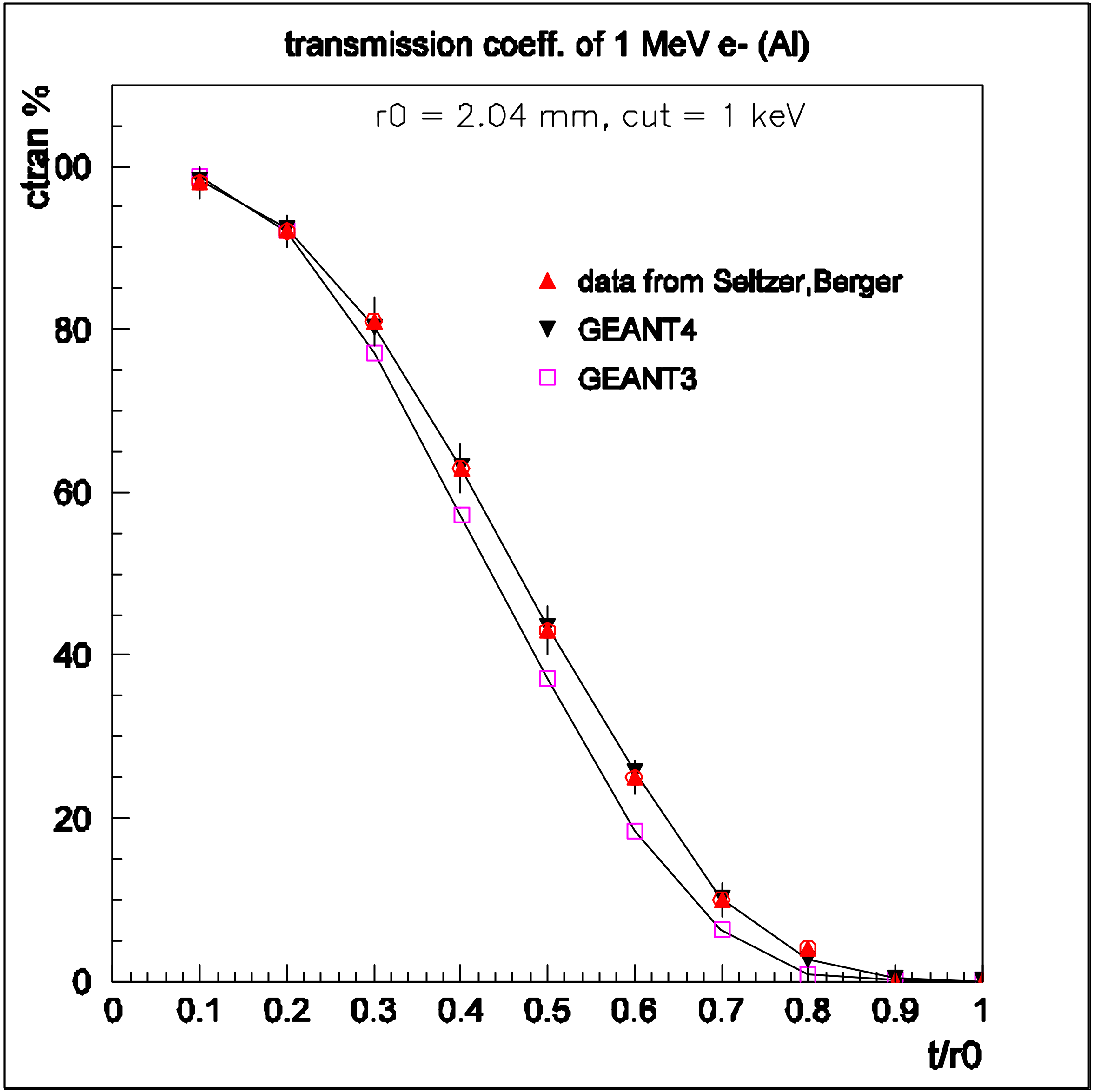
➔ These two kinds of setup provide **complementary** information

Energy distribution

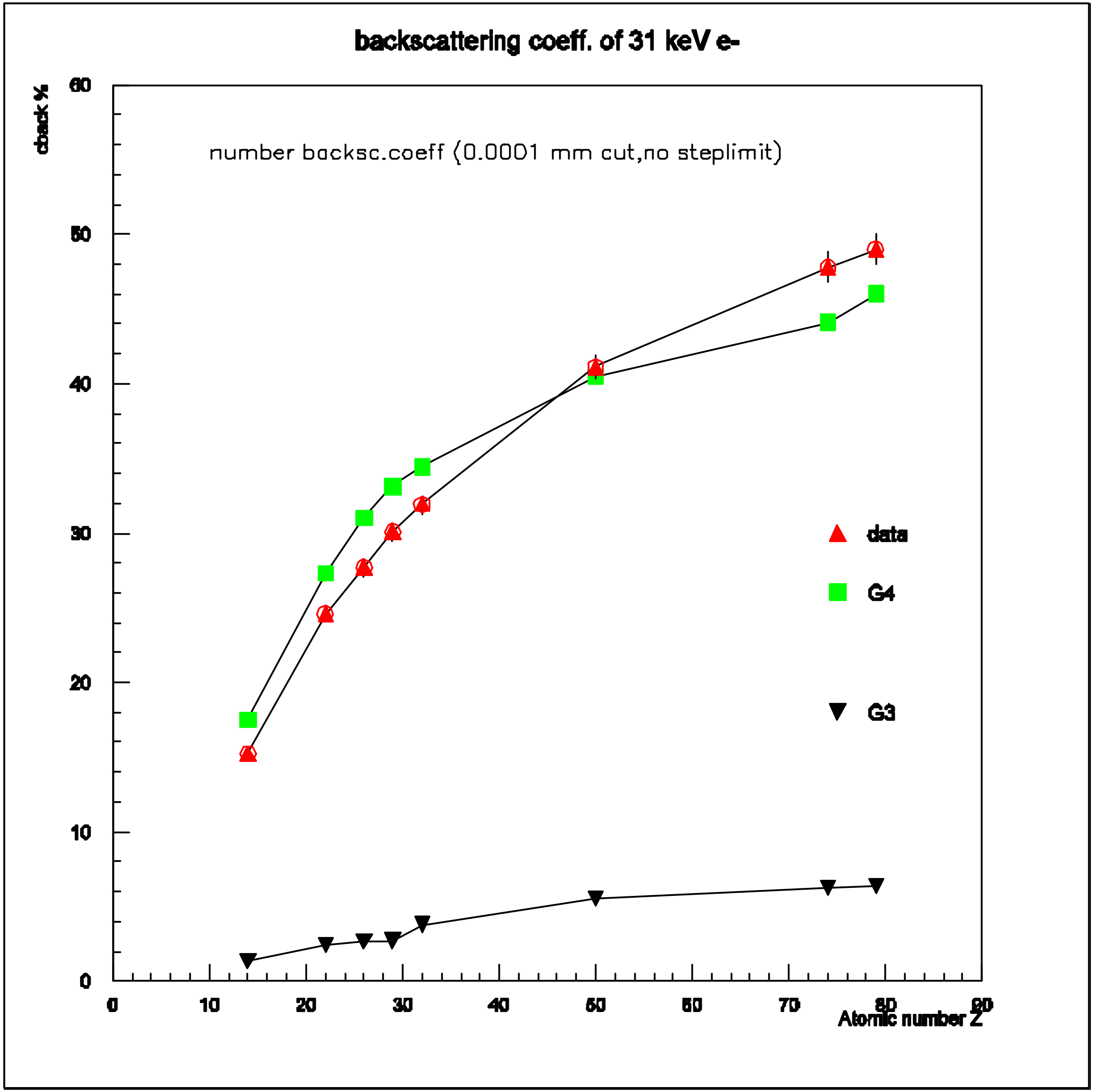
Energy distribution of transmitted 1 MeV e- in Al



Multiple scattering: transmission



Multiple scattering: backscattering



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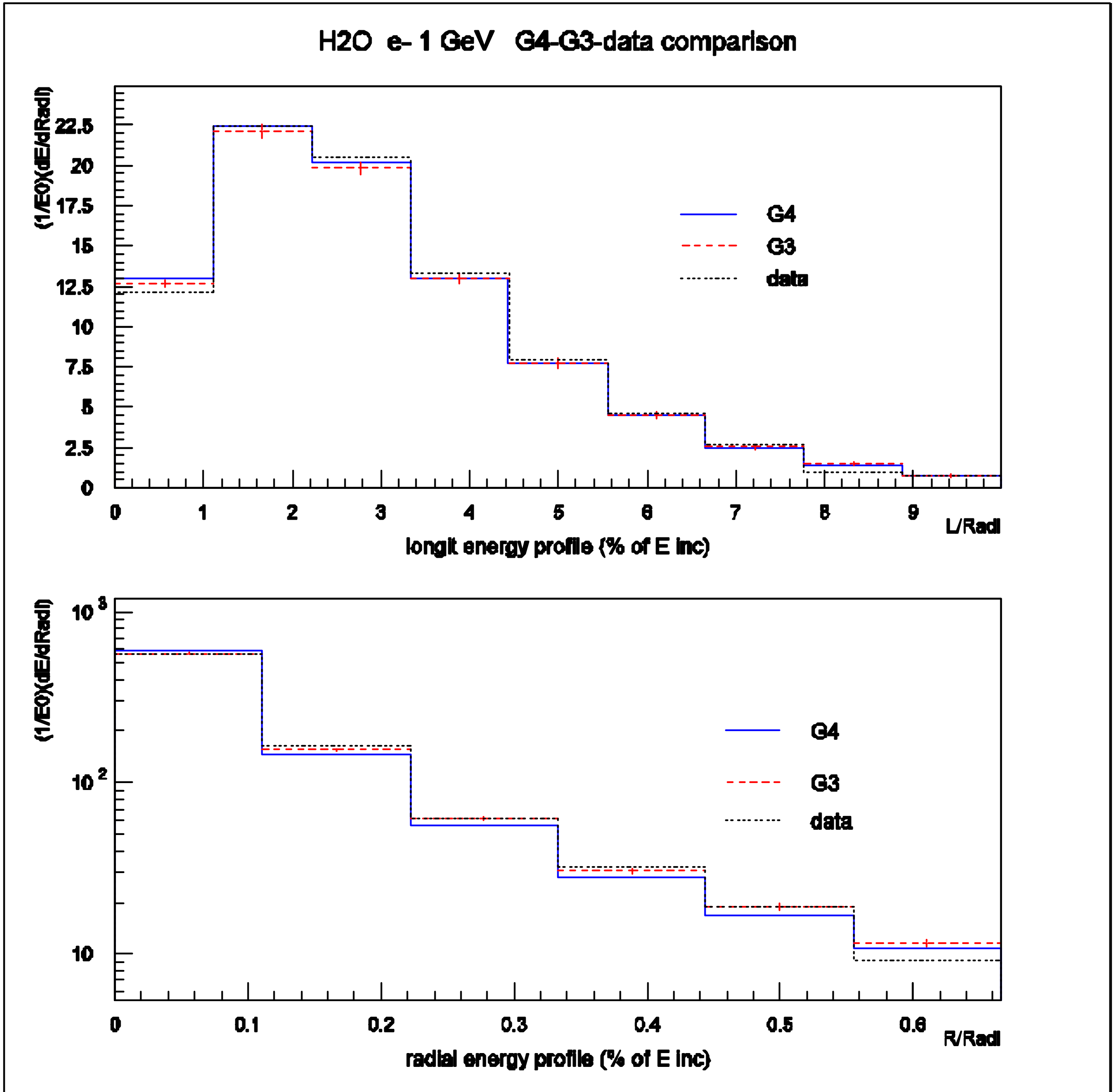
Electromagnetic shower shape



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LHC experiments test beam data

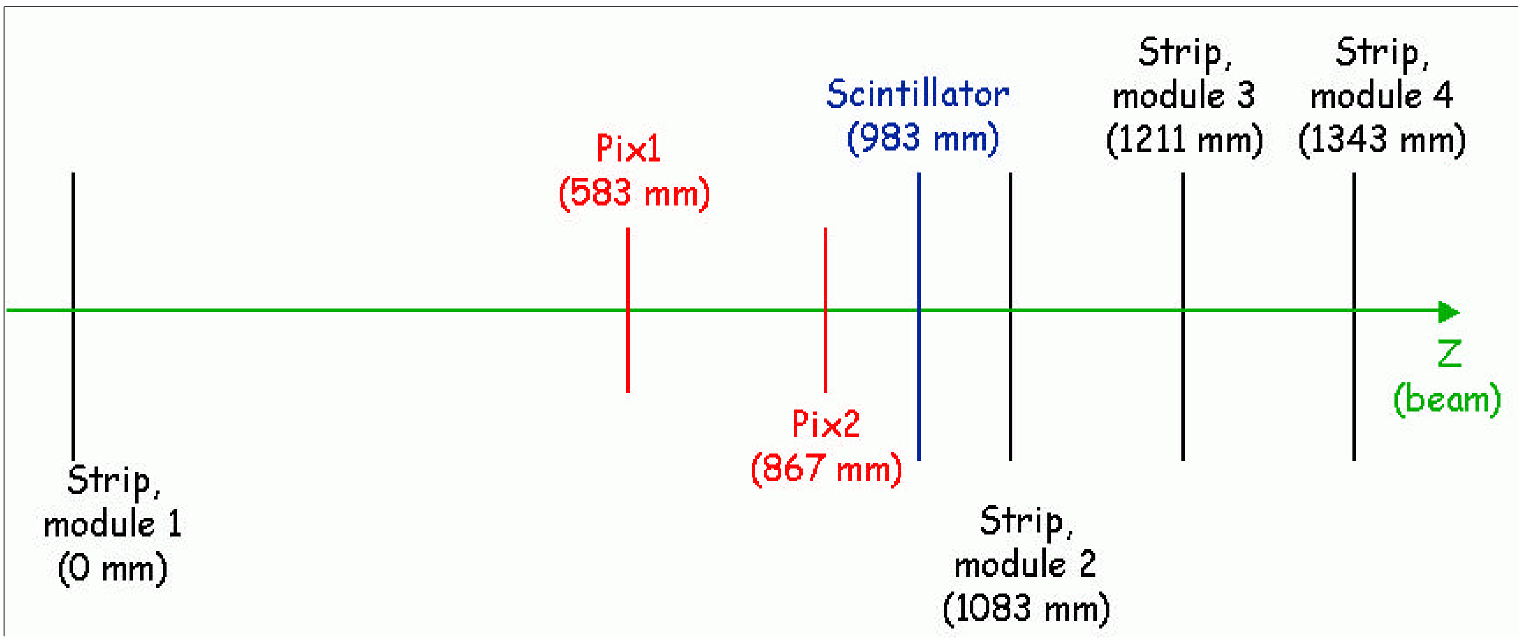
- ATLAS:
  - **Pixel Detector**
  - HEC : copper + LAr
  - Tilecal : iron + scintillator tile
  - FCAL : copper/tungsten + LAr
    (work in progress, not shown here!)
- CMS:
  - ECAL : crystal PbWO4
  - HCAL : copper + scintillator tile
- LHCb:
  - HCAL : iron + scintillator tile
  - ECAL : lead + scintillator
    (work in progress, not shown here!)

Simple benchmarks

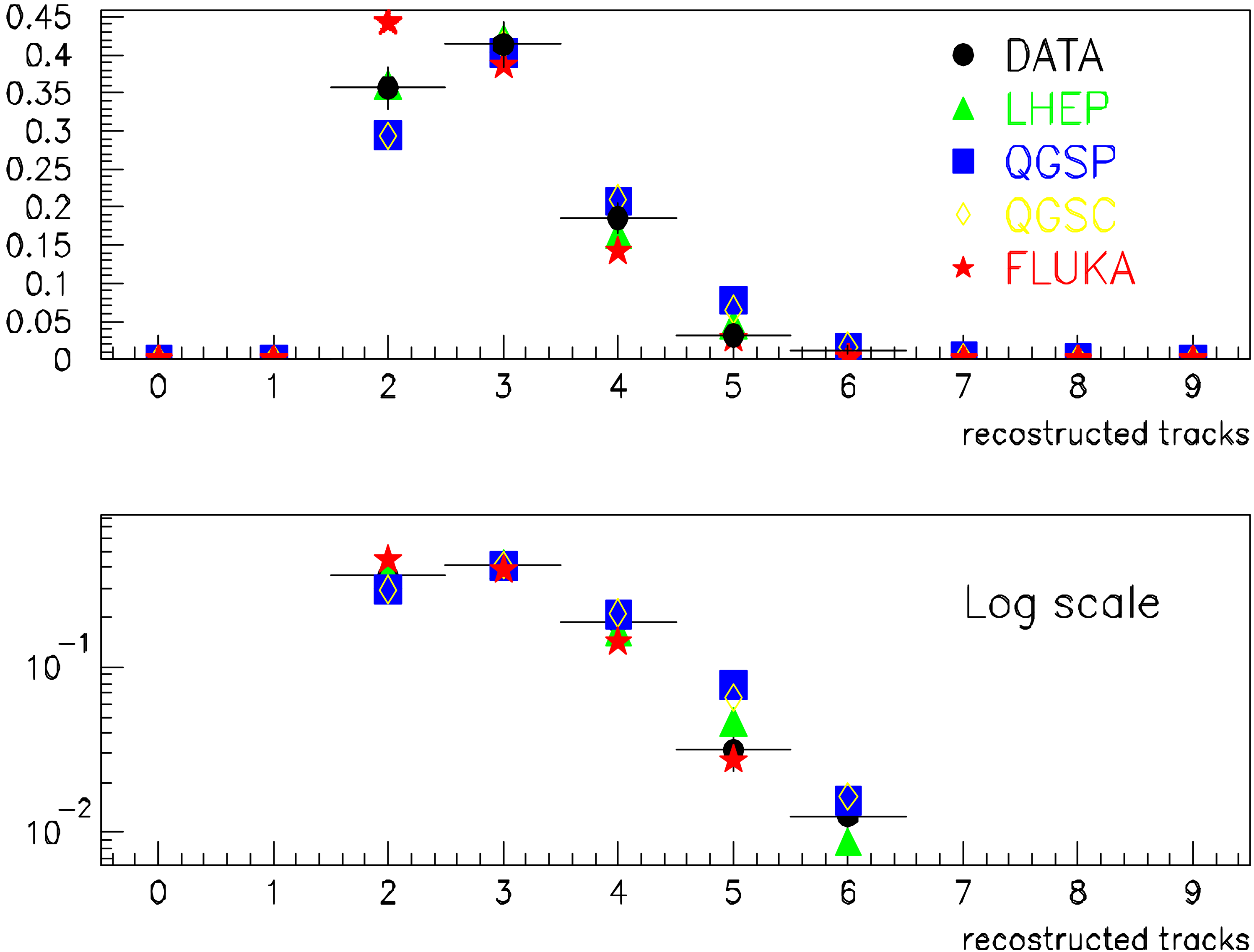
- Double-differential neutron production cross-sections
- Pion absorption in flight: work in progress, not shown here!

Hadronic interactions in ATLAS pixel test-beam

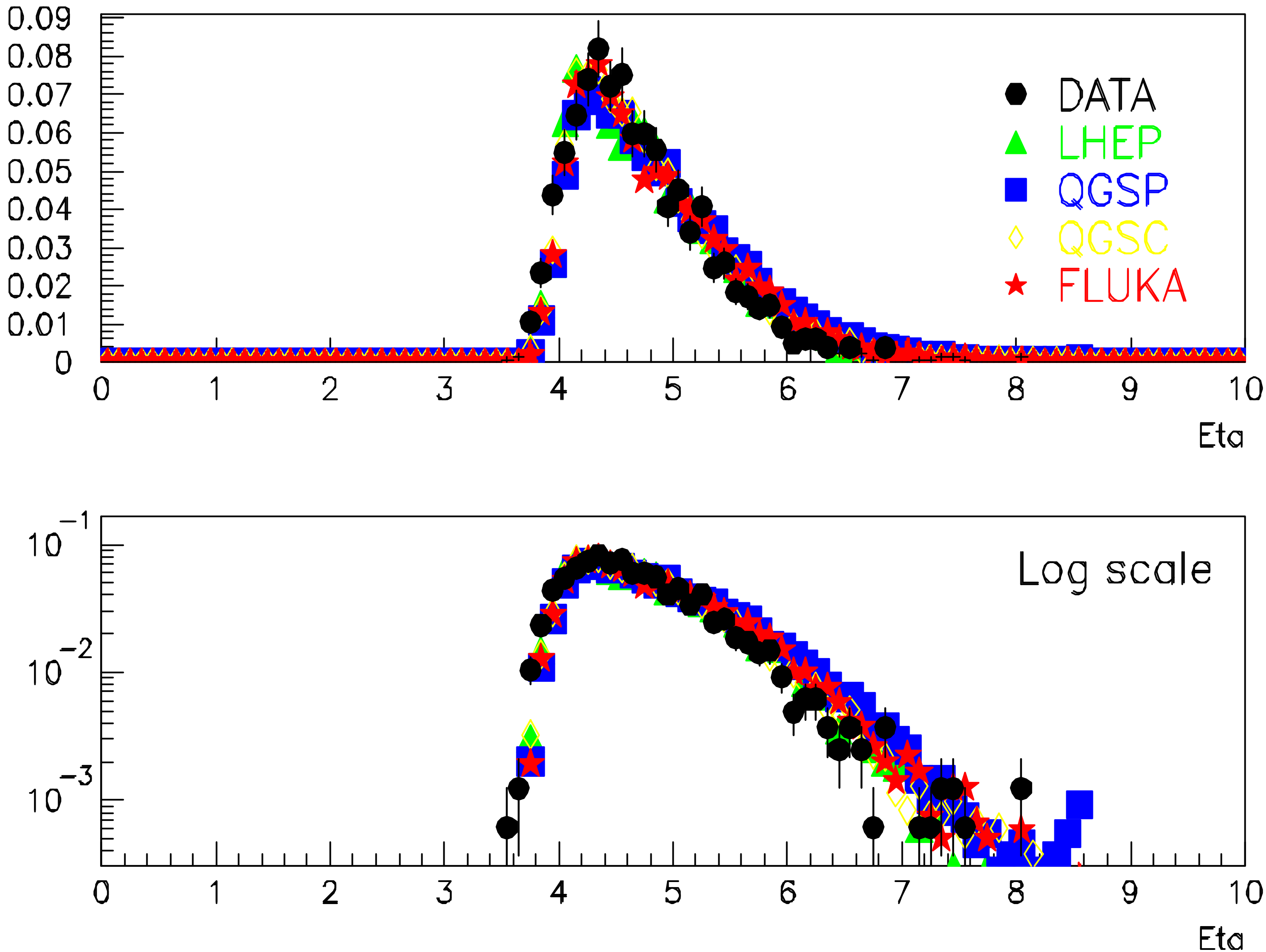
180 GeV/c nominal 🚔+ beam



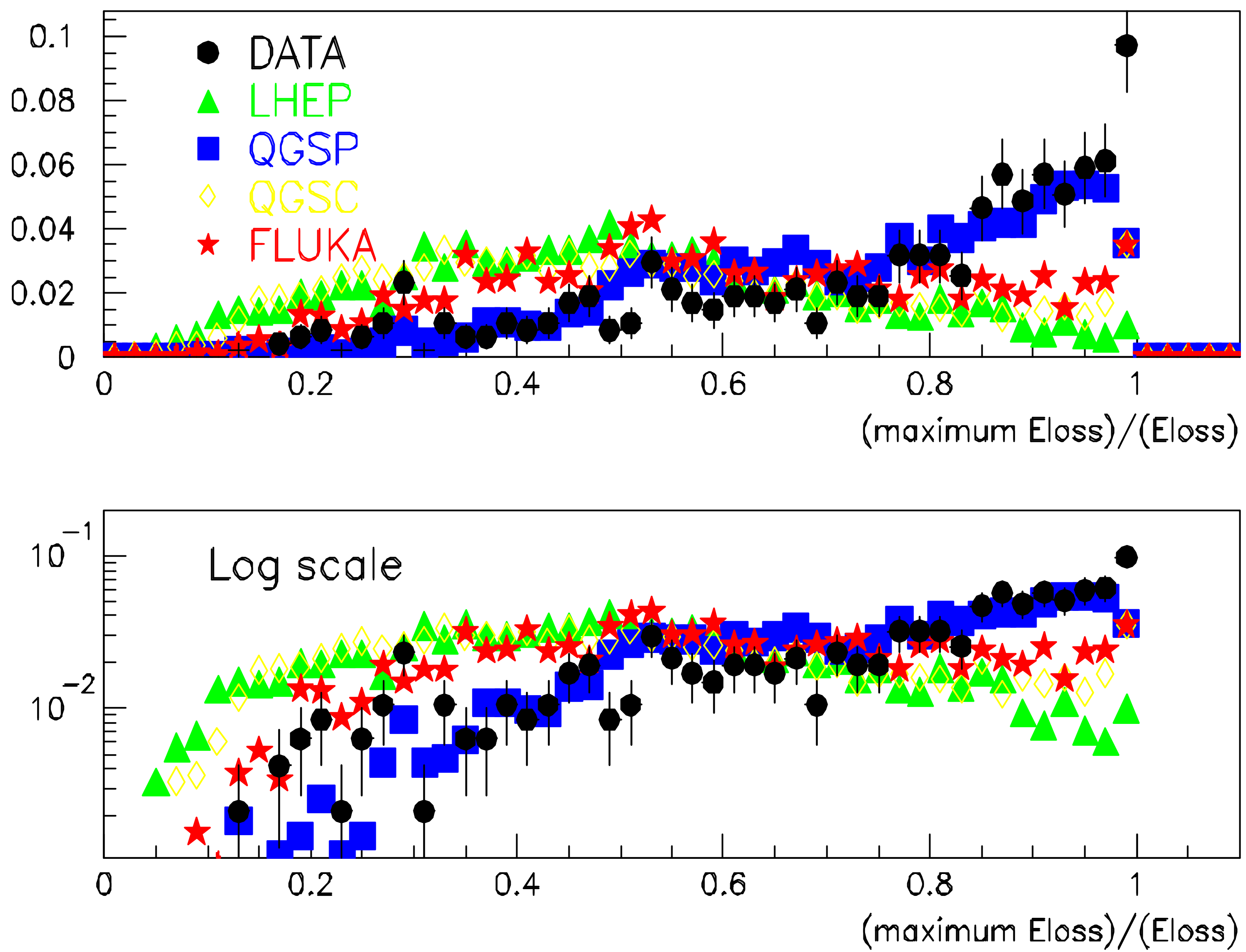
Number of reconstructed tracks



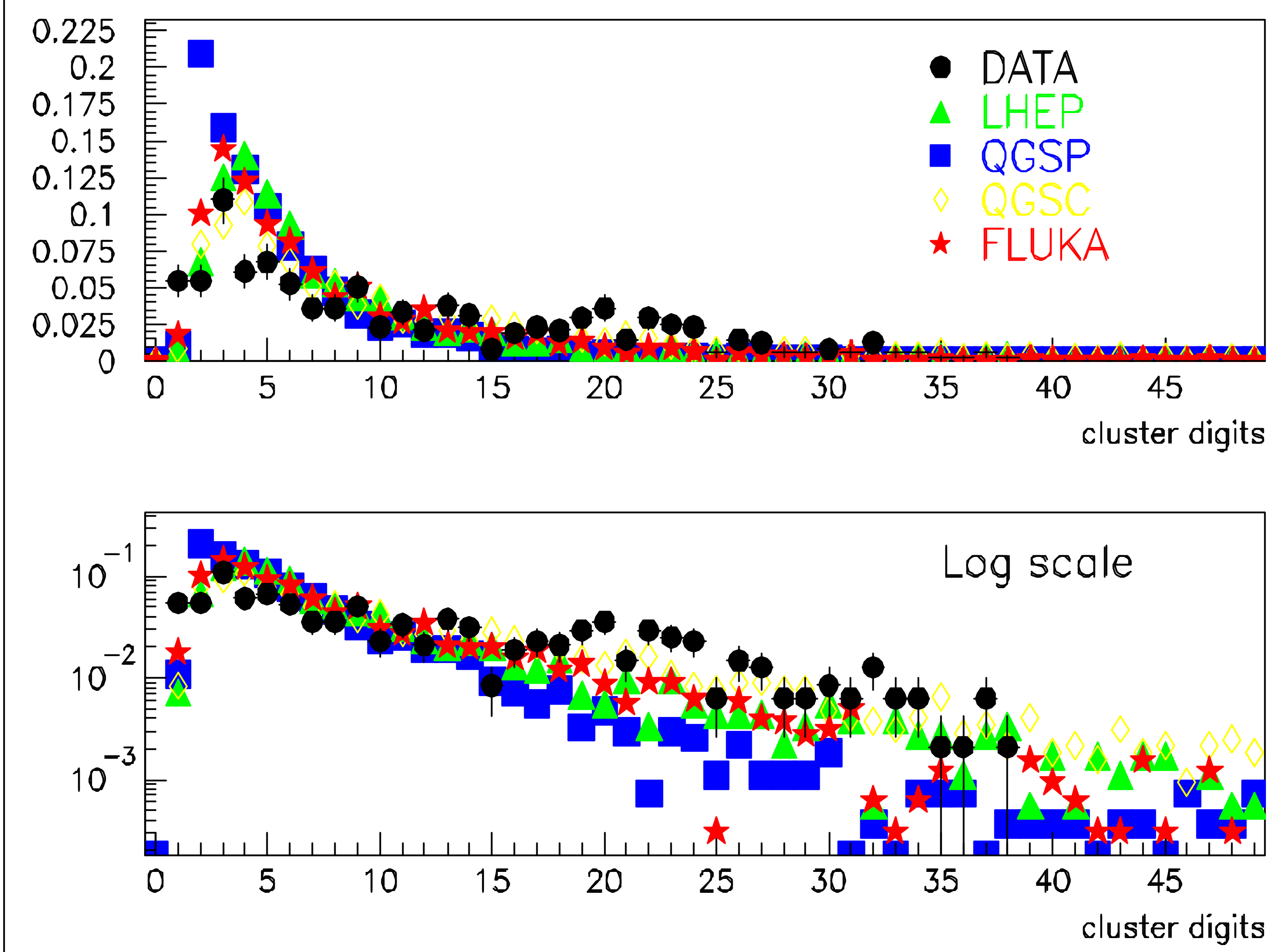
Pseudorapidity distribution



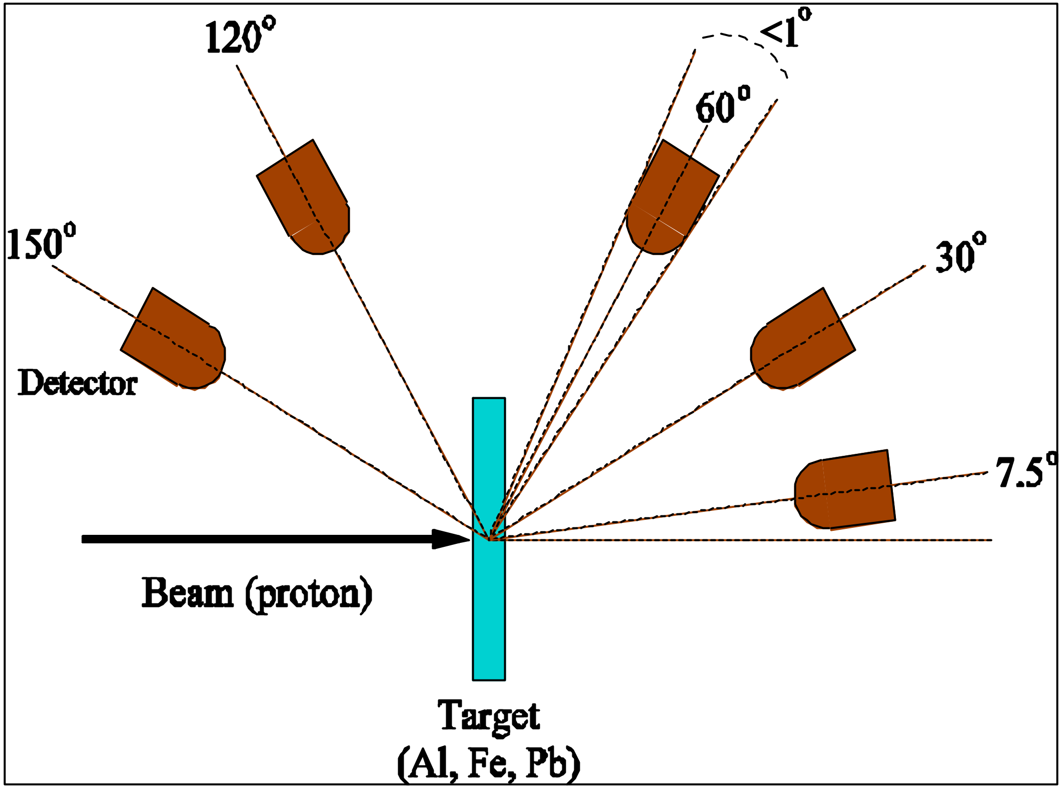
Ratio max Eloss / total Eloss



Cluster size



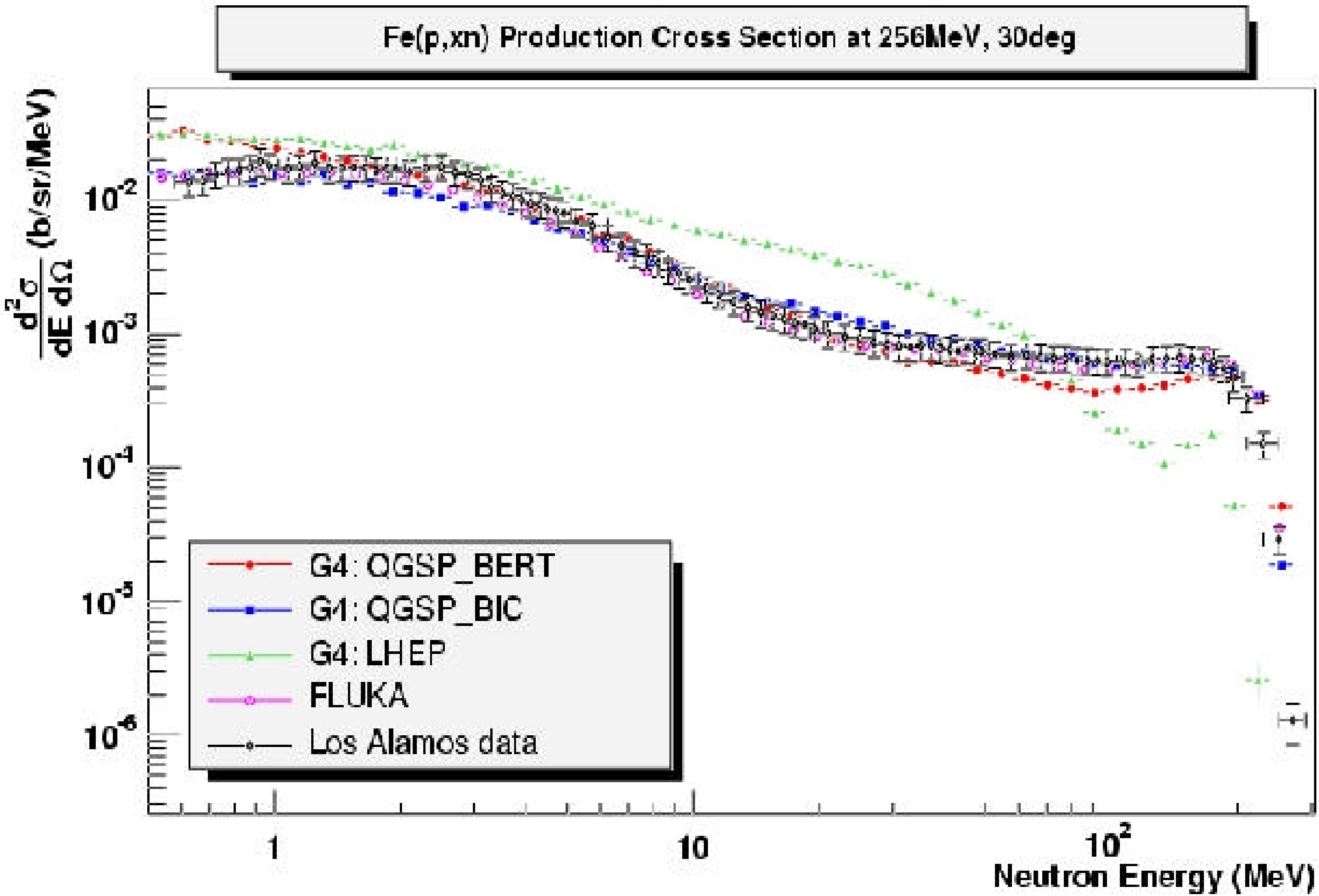
Double-differential neutron production (p,xn)



Proton beam energies: 113, 256, 597, 800 MeV

Neutron detectors (TOF, scintillators) at 5 angles

Study of the neutron production spectrum (kinetic energy) at fixed angles.



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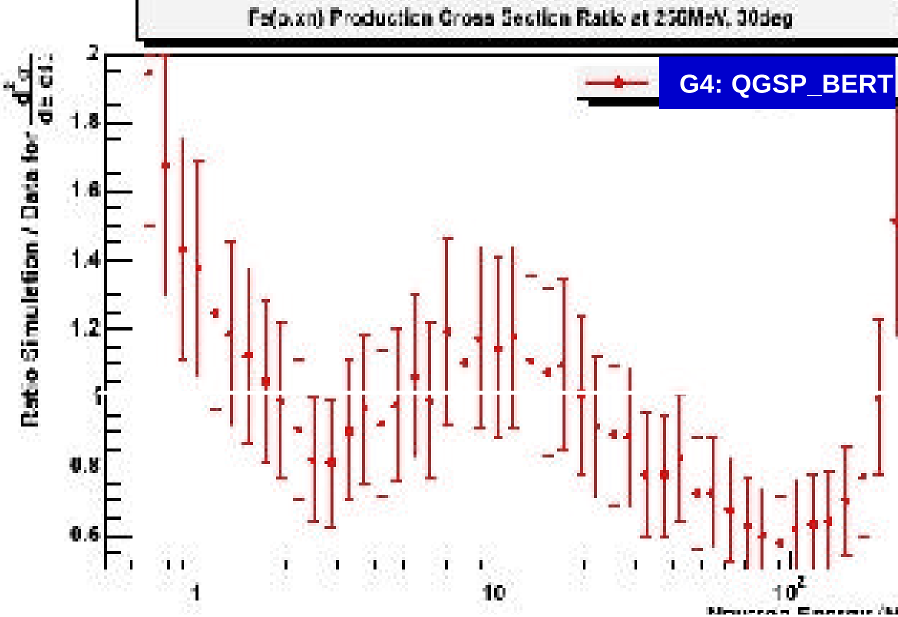
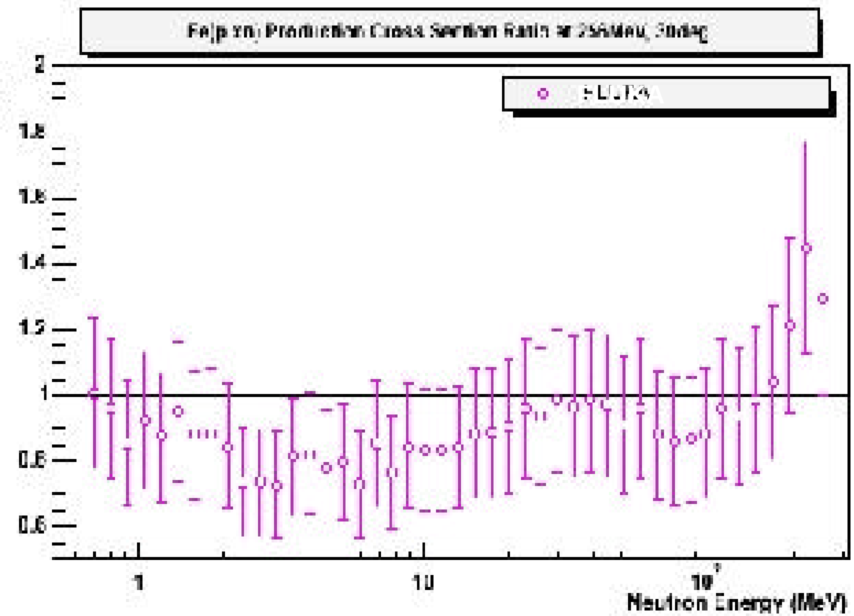
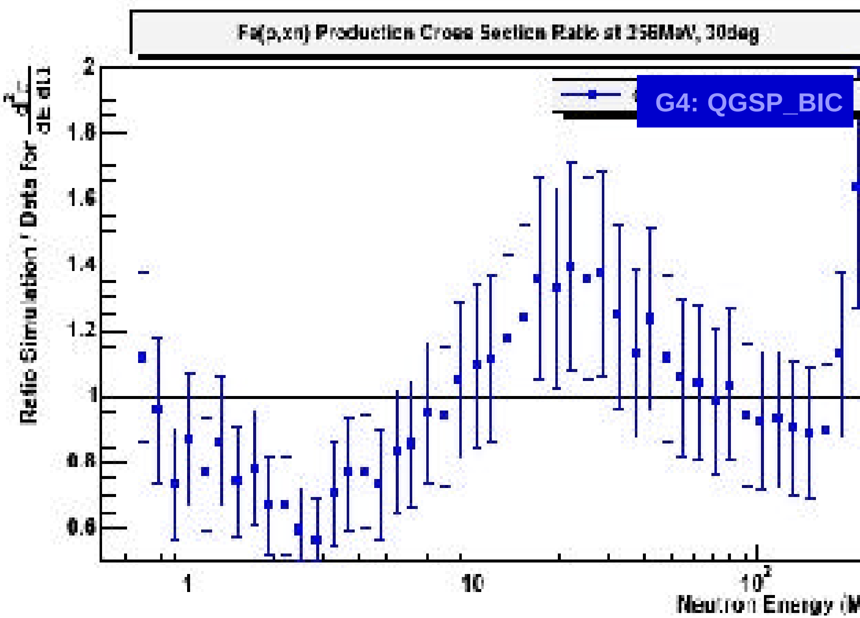
enchmark studies

- ratio simulated / experimental data
  for data shown on previous slide
- error bars include errors from
  experimental data (stat+syst) and from
  simulation (stat)
  - dominated by experimental syst. errors

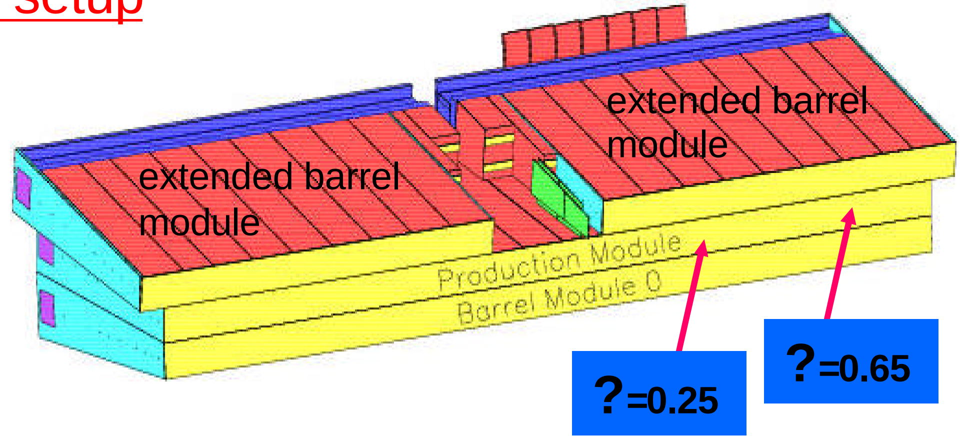
- typical agreement at level of 1 s to 2s

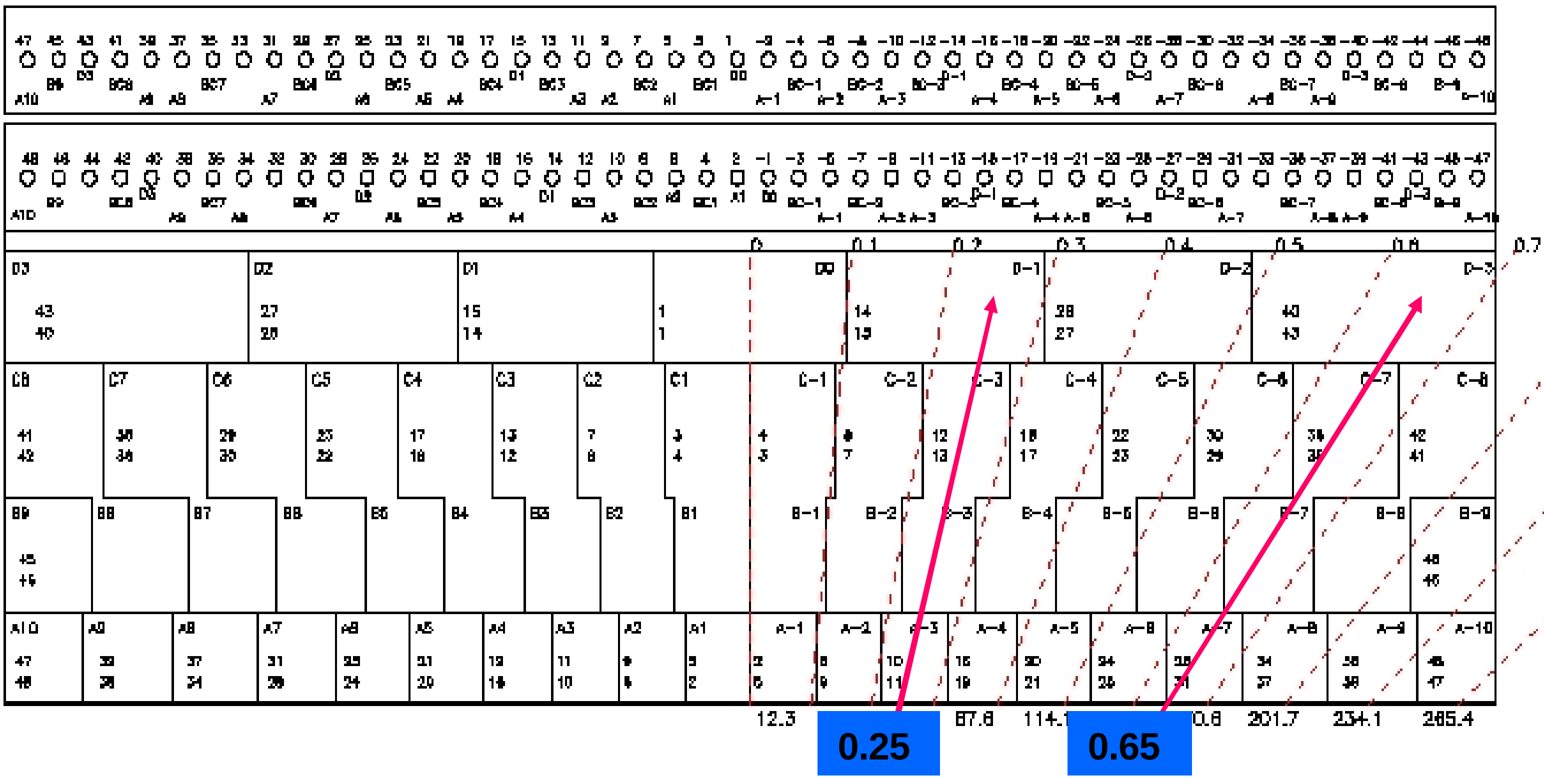


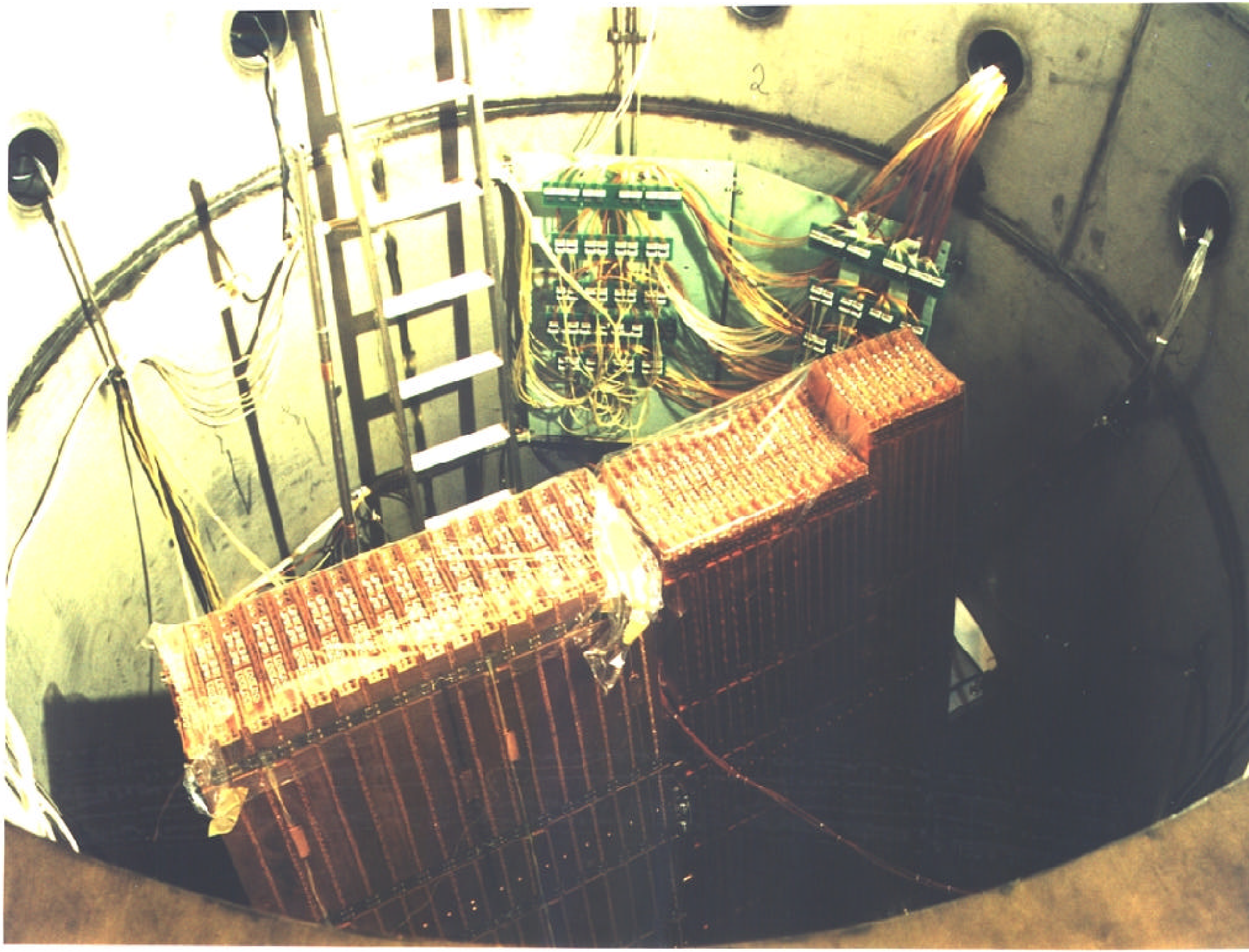




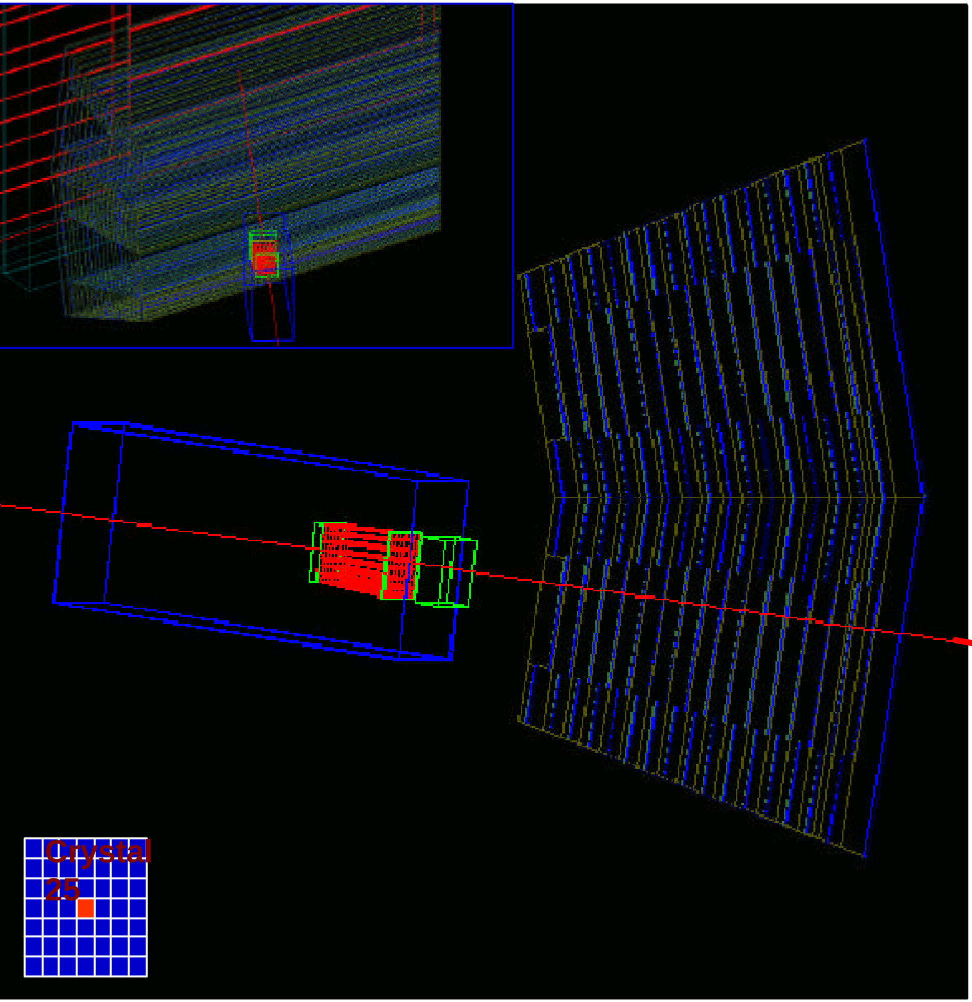
ATLAS Tilecal test beam setup

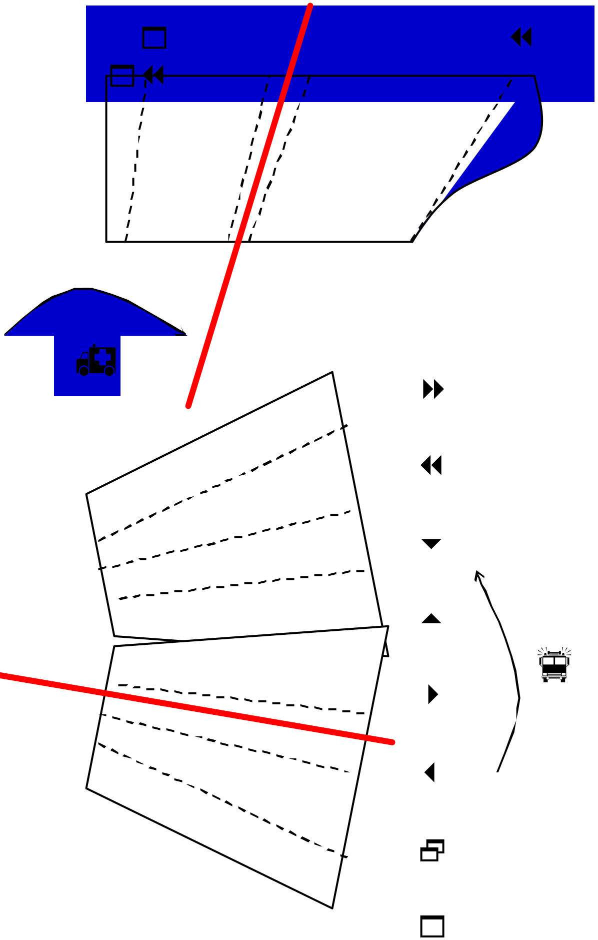




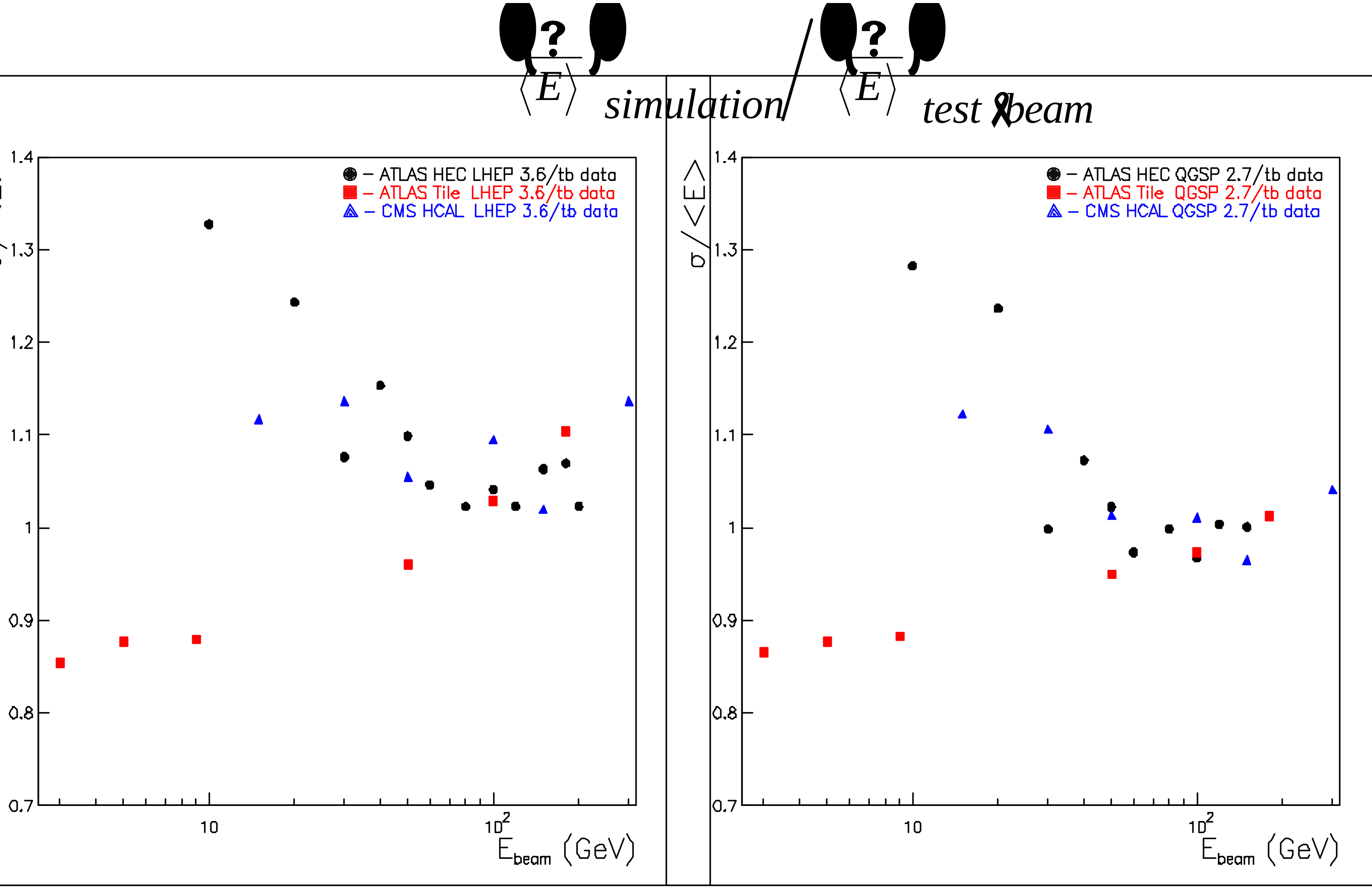


CMS HCAL & ECAL test beam setup





nergy resolution of pions



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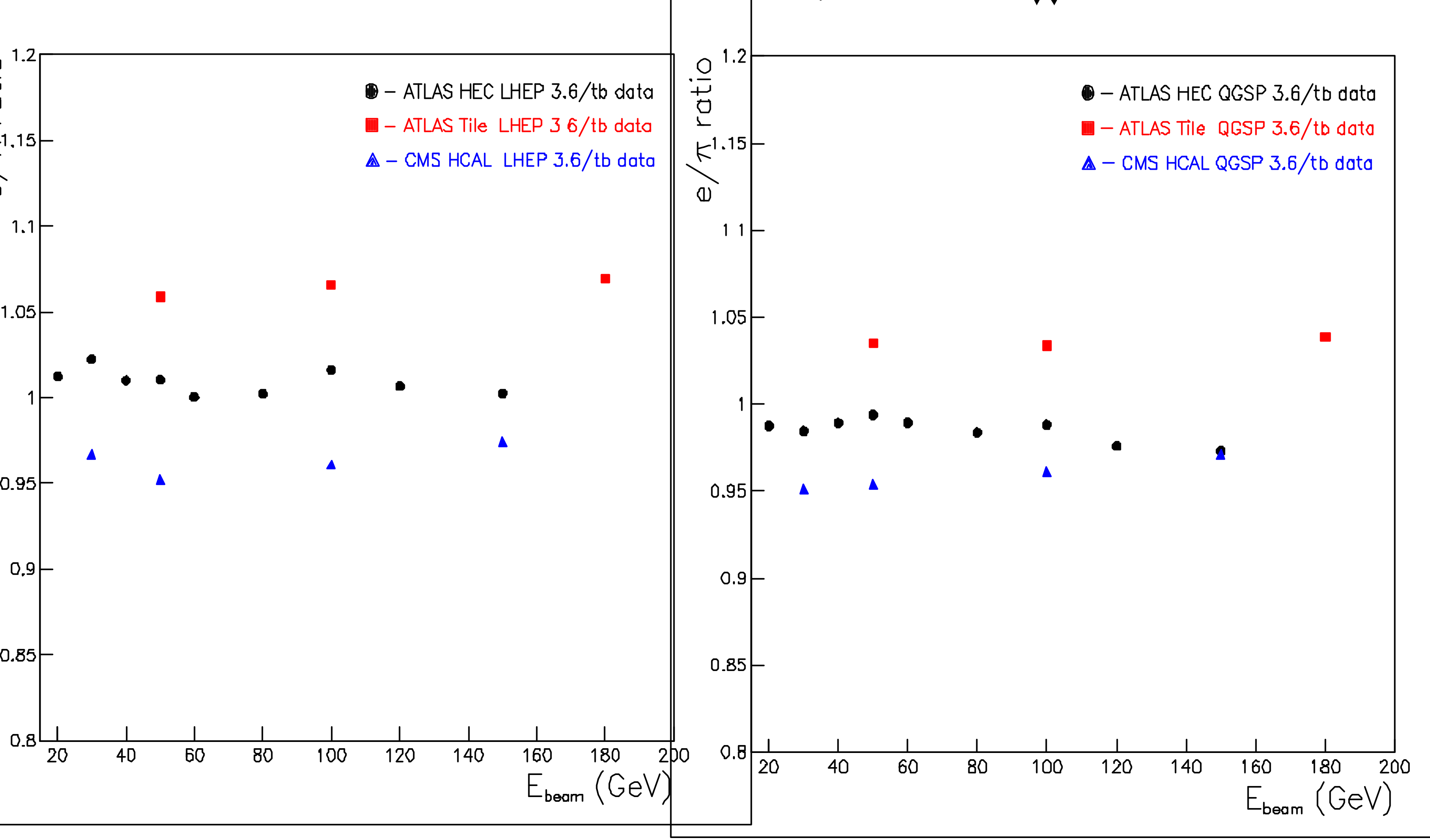
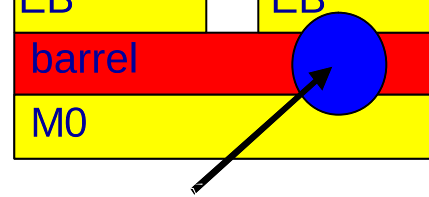
/p ratio

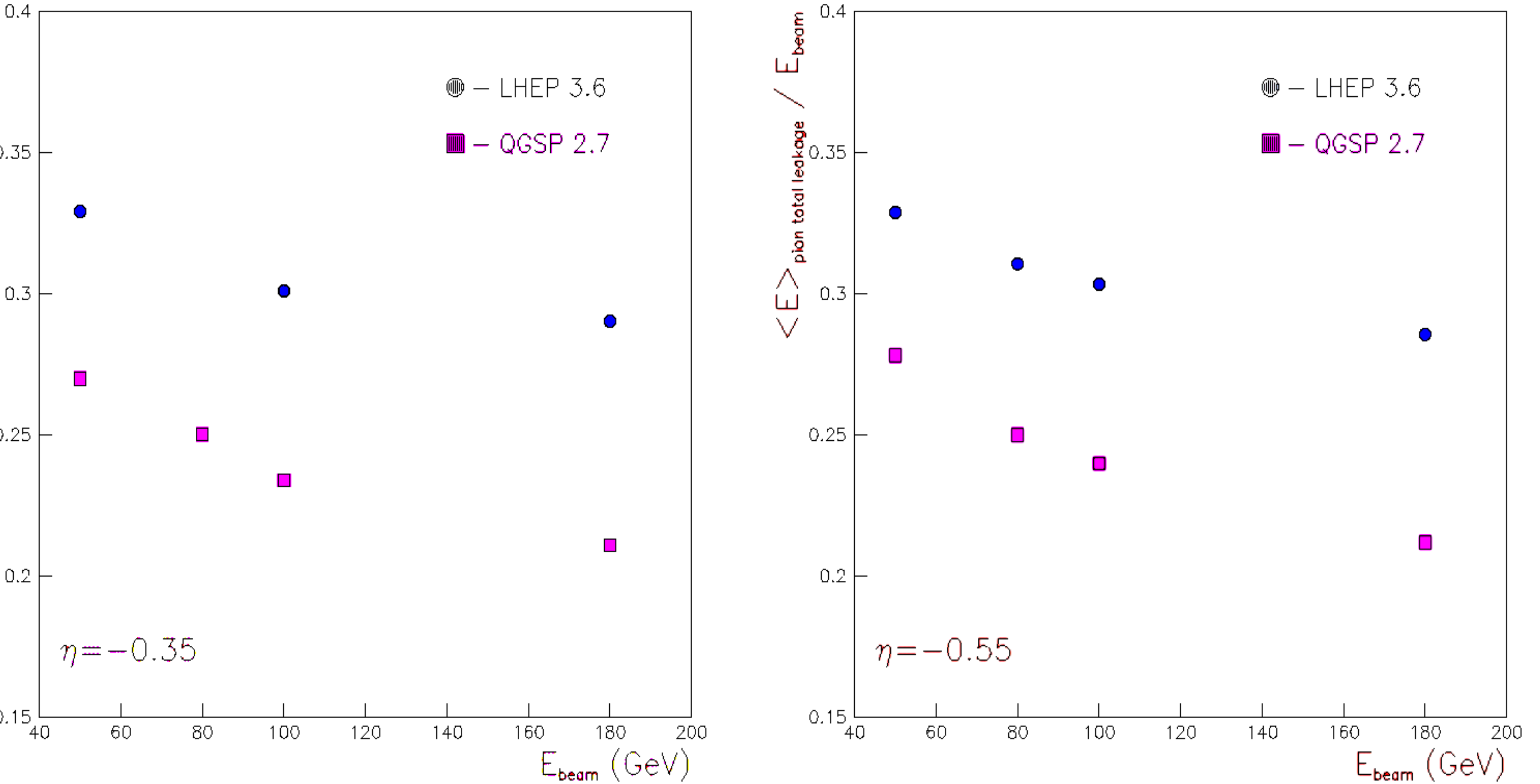
$$\left(\frac{e}{\pi}\right)_{simulation} \Big/ \left(\frac{e}{\pi}\right)_{test\ beam}$$



ATLAS Tile: p leakage

- p energy outside barrel module / total energy
- QGSP shower is more compact than LHEP





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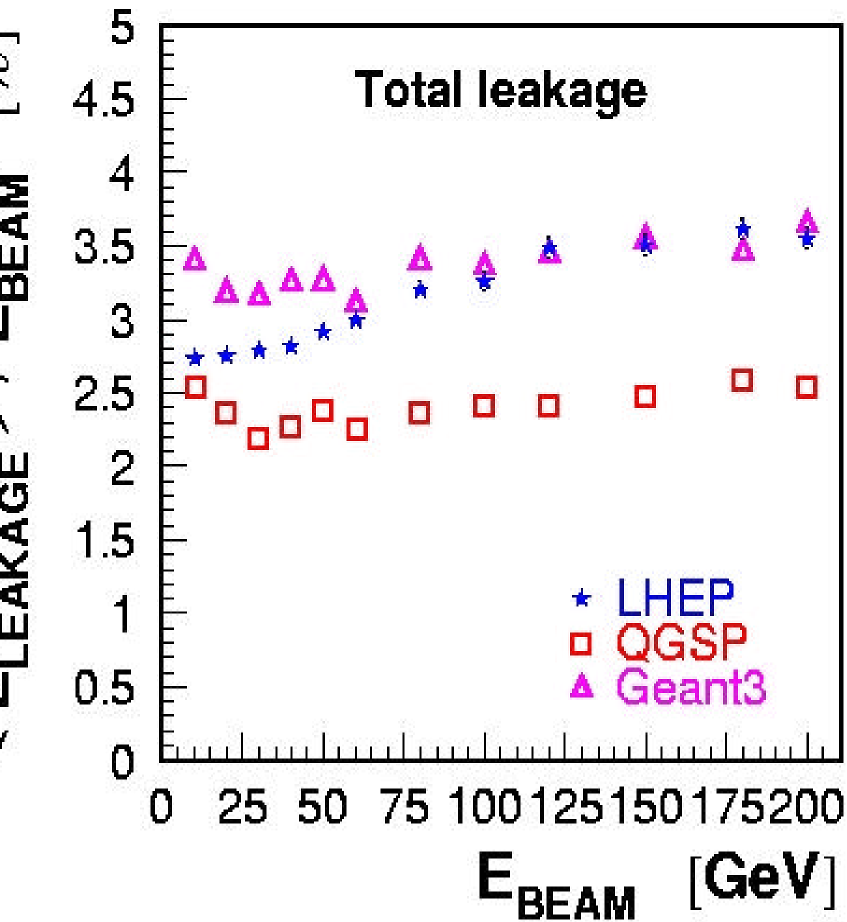
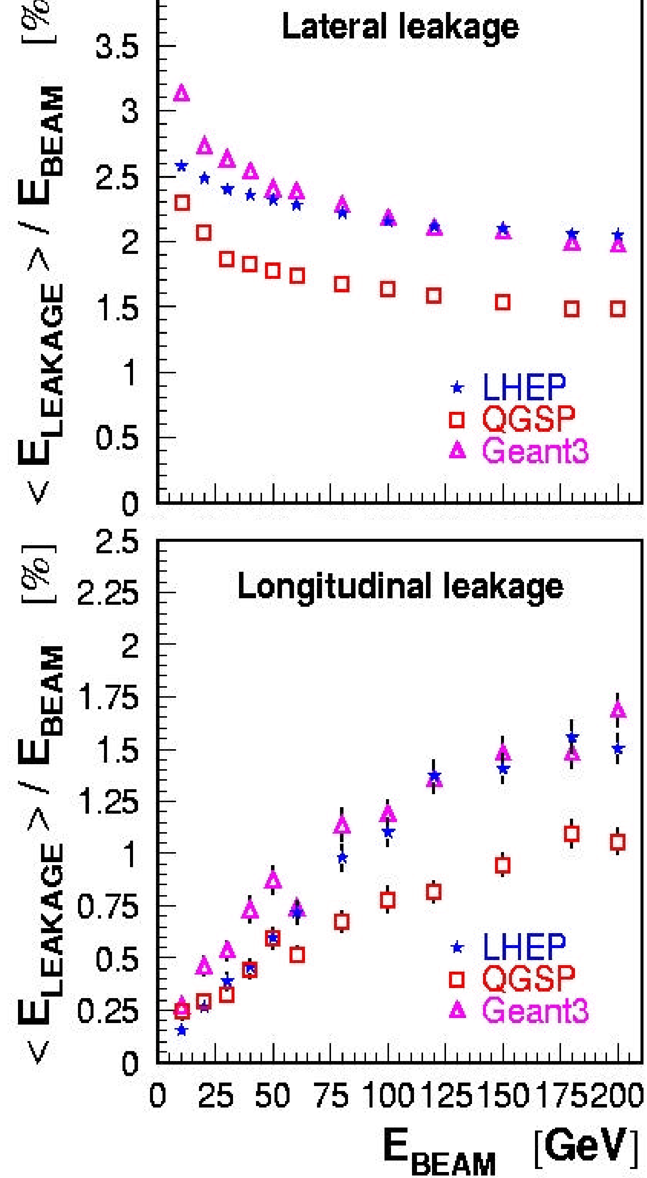
ATLAS HEC: leakage

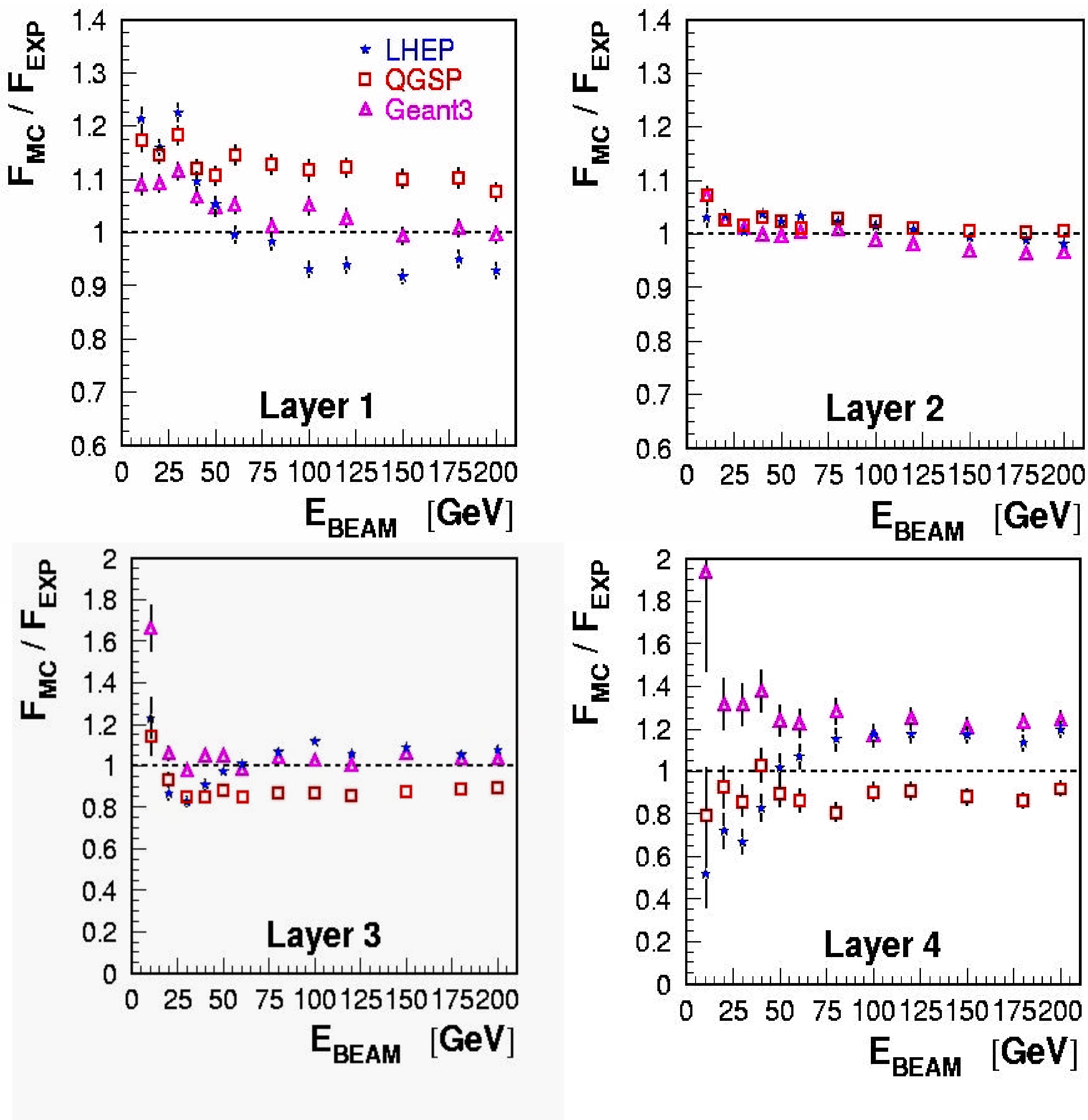




ATLAS HEC: energy deposition

There are 4 longitudinal segments: 2 in HEC1 and 2 in HEC2.

F is the fraction of the total energy deposition in each layer.



Summary

Geant4 is quite versatile even in the physics customization, i.e. in the specification of which particles to be considered and which are their physics processes.

Geant4, however, offers a set of Physics Lists which covers major application domains, especially in high-energy physics.

Geant4 physics has been already tested in several different setups, with good results.

BaBar experiment, and three LHC experiments, ATLAS, CMS, LHCb, are using Geant4 in production.

Geant4 describes well the calorimeter energy resolution, s/E, and the ratio e/ .

The shape of hadronic showers (and perhaps some tracker observables) still need further improvements.

How to get more information (and references)?

Go to the main Geant4 web page:

www.cern.ch/geant4

then click on:

Documentation

then click on:

Physics Reference Manual