

Introduction to Geant4

Matteo Negrini
INFN-Bologna



Istituto Nazionale di Fisica Nucleare

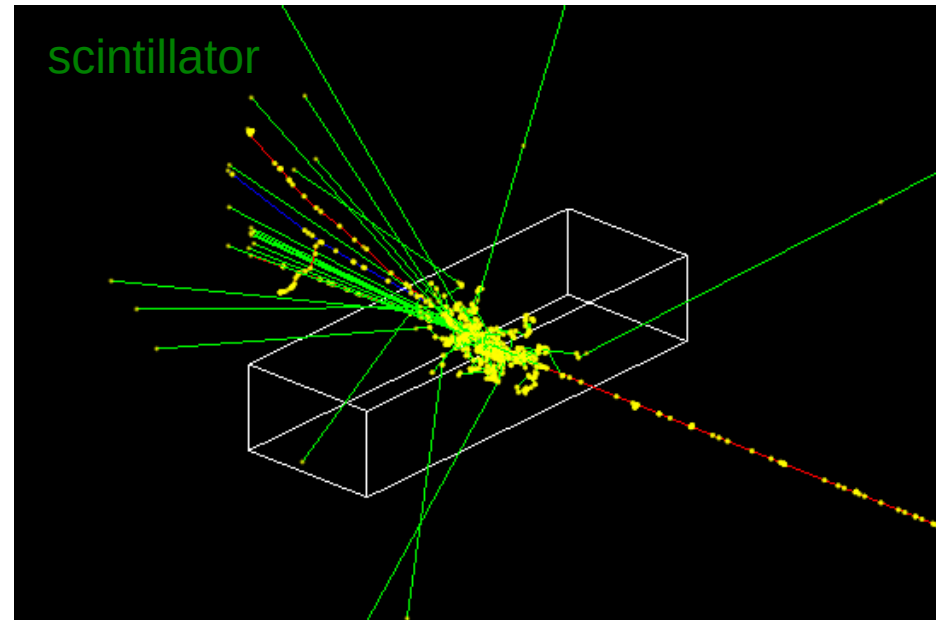
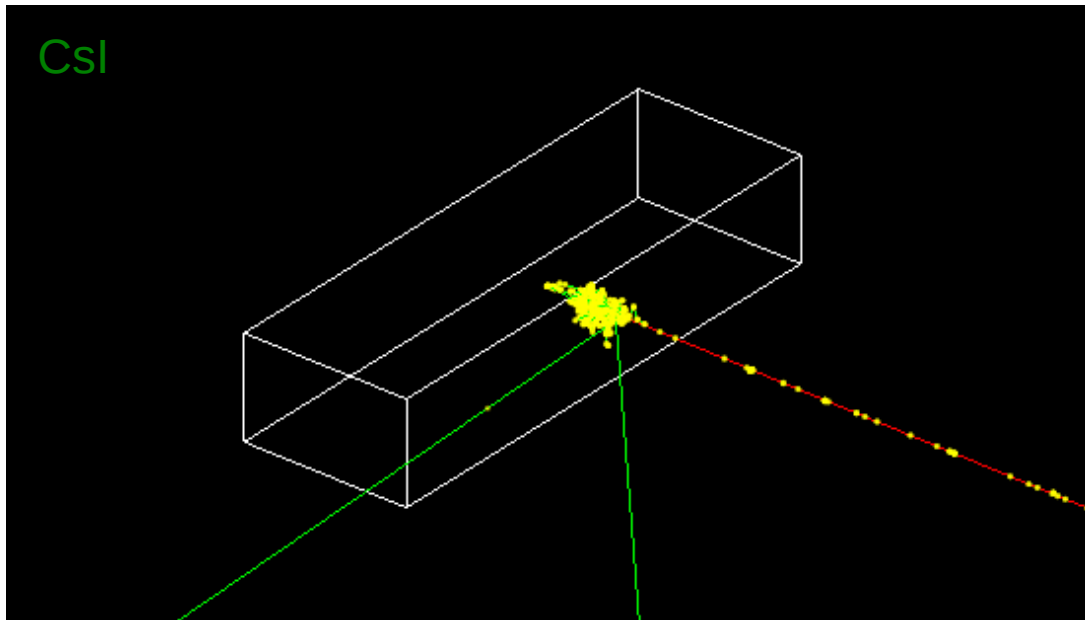


What is Geant4?

- Geant4 website: <http://geant4.cern.ch/>
- According to the website: “Geant4 is a toolkit for the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science.”
- Open source, object oriented, coded in C++
- Several examples available (provide useful guidance in developing applications)
- Applications:
 - detector design (geometry/material optimization, backgrounds, ...)
 - detector response to particles (signal amplitudes, energy spectra, resolutions, efficiencies, ...)

What is Geant4?

Simulations of an electron impacting on a block of CsI or scintillator



Images from SLAC Geant4 tutorial: <http://geant4.slac.stanford.edu/SLACTutorial14/HandsOn2/>

Before we start...

- Download code from the Geant4 website
- Follow installation guide:
<http://geant4.web.cern.ch/geant4/UserDocumentation/UsersGuides/InstallationGuide/html/index.html>
- Before to proceed, you should have / install:
 - C++11 compiler
 - cmake 3.3 (or higher)
 - CLHEP library (an internal version is supplied with the Geant4 source)
 - Additional packages are needed for optional features, such as geometry visualization
- Run the geant4 setup script **each time you login** (linux tip: execute the script in .bashrc)
- Compile and run one example

Goal: the exercise

- The exercise is the simulation of a sampling calorimeter to test its performance on given particles
- A particle gun event generator is used Particle gun shoots one particle
- It is derived from the standard Example B4c
 - You should: define the detector geometry, customize the primary generator, collect hits at each event, extend hit information for the analysis
 - The meaning of all these steps will be discussed in these lectures
- The example B4c can be copied in a clean dir and compiled in the same way as all Geant4 examples
 - Make a new directory where the example is run
 - From this dir (*cmake* only the 1st time, *make* every time something is changed):
 - > `cmake -DGeant4_DIR=<Geant4InstallationDir> ../<dirWithB4cExample>`
 - > `make`

Some useful links

- Getting started:

<http://geant4.cern.ch/support/gettingstarted.shtml>

- In particular: user's guide for application developers:

<http://geant4.web.cern.ch/geant4/UserDocumentation/UsersGuides/ForApplicationDeveloper/html/index.html>

- Online code browser:

<http://www-geant4.kek.jp/Reference/>

- Slides of these lectures:

<http://www.bo.infn.it/~negrini/MonteCarloIntro.pdf>

<http://www.bo.infn.it/~negrini/Geant4.pdf>

Geant4 Workflow overview

- **Your tasks:**
 - provide geometrical and material description of apparatus^{with a class}
 - provide event generator done in the example, understand how to use it
 - choose an appropriate physics list and production cuts
- **Geant4 tasks:** more explanation later but basically I decide according to my problem to turn off some processes
 - propagate each particle in the materials
 - simulate interactions and produce secondary particles
 - compute energy release in the materials
 - iterate on the desired number of events

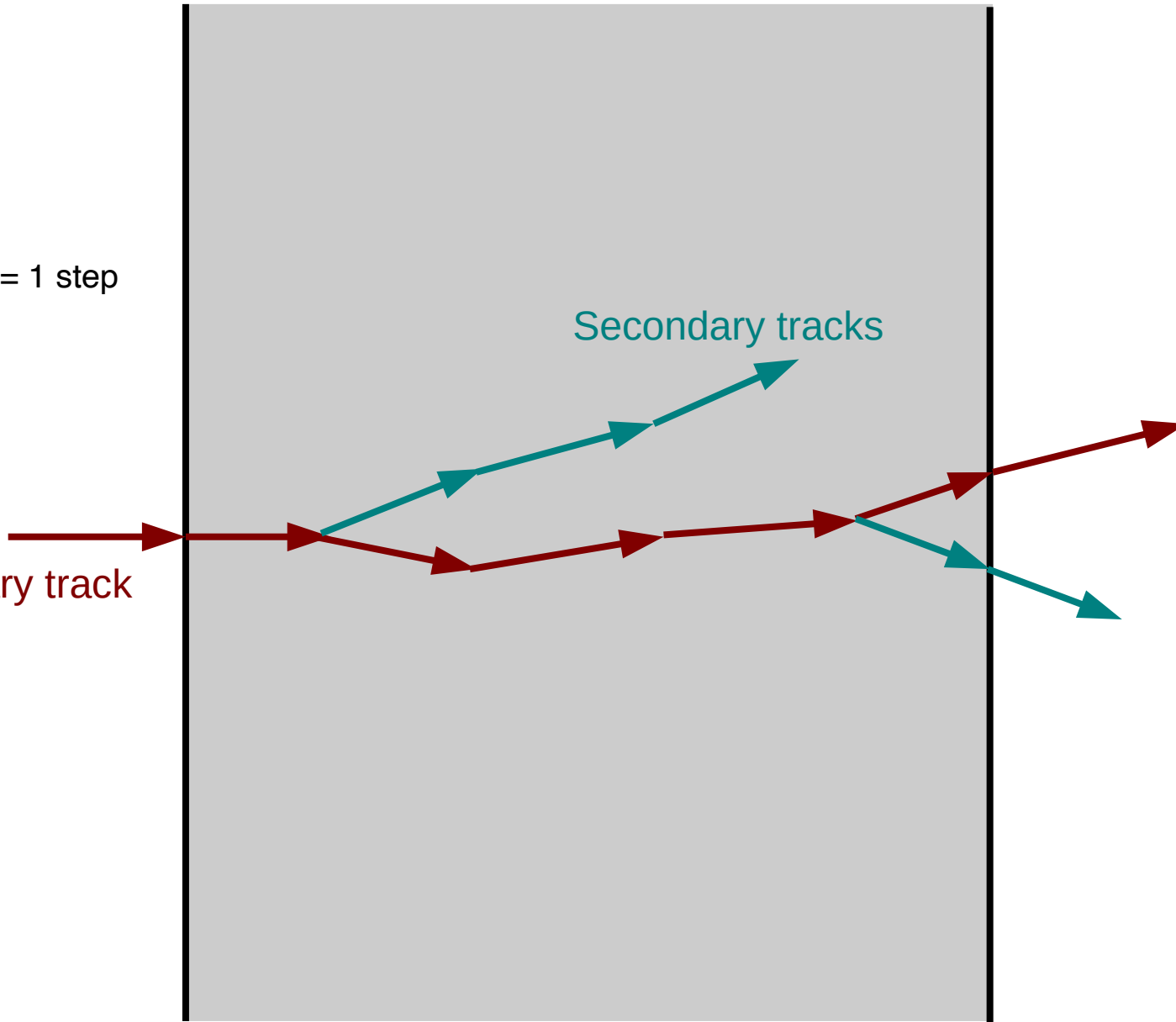
Terminology

- **Run:** a collection of events in the same detector conditions and settings of physics processes
- **Event:** each event starts with the generation of primary particles. Particles are added/removed from a stack when they are generated/disappear. When the stack is empty the event is finished.
- **Track:** is the snapshot of a particle. It is deleted if: it goes outside the world volume, it disappears (interaction), it comes to rest (0 kin. energy), the user decides to kill it
- **Step:** is the smallest unit of propagation of each particle. It has an initial and final point, time-of-flight, energy deposition, ...

1 arrow = 1 step

Primary track

Secondary tracks



User application

- Geant4 is a toolkit, the main() file to build the application must be provided by the user
- In the main file the user must:
 - construct the G4RunManager
 - notify the G4RunManager the existence of user-defined classes
 - initialize optional features, like the visualization manager

Overview of some user classes

- **G4VUserDetectorConstruction**: defines the detector setup (mandatory)
- **G4VUserPhysicsList**: defines the active physics processes (mandatory)
- **G4VUserPrimaryGeneratorAction**: defines the event generator (mandatory)
- **G4VUserActionInitialization**: to initialize user's actions
- **G4VUserRunAction**: to define actions to be performed at the beginning/and of the run
- **G4VUserEventAction**: to define actions to be performed at the beginning/and of the event
- **G4VUserSteppingAction**: to define actions to be performed at the beginning/and of the step

Simple example of main

Example from the Geant4 user's guide

```
#include "G4RunManager.hh"
#include "G4UImanager.hh"

#include "ExG4DetectorConstruction01.hh"
#include "ExG4PhysicsList00.hh"
#include "ExG4ActionInitialization01.hh"

int main()
{
    // construct the default run manager
    G4RunManager* runManager = new G4RunManager;

    // set mandatory initialization classes
    runManager->SetUserInitialization(new ExG4DetectorConstruction01);
    runManager->SetUserInitialization(new ExG4PhysicsList00);
    runManager->SetUserInitialization(new ExG4ActionInitialization01);

    // initialize G4 kernel
    runManager->Initialize();

    // get the pointer to the UI manager and set verbosity
    G4UImanager* UI = G4UImanager::GetUIpointer();
    UI->ApplyCommand("/run/verbose 1");
    UI->ApplyCommand("/event/verbose 1");
    UI->ApplyCommand("/tracking/verbose 1");

    // start a run
    int numberOfEvent = 3;
    runManager->BeamOn(numberOfEvent);

    // job termination
    delete runManager;
    return 0;
}
```

Some examples of user action classes

- **G4UserRunAction**
 - Define parameters or define custom additional information
 - Book variables / histograms / analysis tools, ... to collect information for the run
- **G4UserEventAction**
 - Event selection and analysis
 - Hit collection
- **G4UserSteppingAction**
 - Control particle propagation
 - Collect specific information on interactions

1. Geometry and materials

System of units

- Units defined in: `G4SystemOfUnits.hh`
- Always include units when defining input parameters

```
G4double block_size = 10.0 *cm;  
G4double pmma_density = 1.18*g/cm3;
```

- Retrieve output specifying the unit (otherwise internal units used)

```
G4cout << KineticEnergy/keV << " keV";
```

Geant4 internal system of units:

millimeter	(mm)
nanosecond	(ns)
Mega electron Volt	(MeV)
positron charge	(eplus)
degree Kelvin	(kelvin)
the amount of substance	(mole)
luminous intensity	(candela)
radian	(radian)
steradian	(steradian)

Materials

Materials are made of **elements**, which are made of **isotopes**. These concepts are represented in **3 classes** in Geant4:

- **G4Isotope**: properties of atoms: atomic number, number of nucleons, mass per mole, etc
- **G4Element**: properties of elements: effective atomic number, effective number of nucleons, effective mass per mole, number of isotopes, shell energy, cross section per atom, ...
- **G4Material**: macroscopic properties of matter: density, state, temperature, pressure, radiation length, mean free path, dE/dx , ...

Geant4 contains **tables of elements and common materials**, derived from the **NIST databases** of elements and materials, that can be retrieved

```
G4NistManager* nist = G4NistManager::Instance();  
G4Element* el_H = nist->FindOrBuildElement("H");  
G4Material* mat_air = nist->FindOrBuildMaterial("G4_AIR");
```


User defined materials

- Materials not included in the list can be defined by the user, specifying the **composition** and the **density**

```
// define a material from elements.   case 1: chemical molecule
density = 8.280*g/cm3;
G4Material* PbW04= new G4Material(name="PbW04", density, ncomponents=3);
PbW04->AddElement(elO , natoms=4);
PbW04->AddElement(elW , natoms=1);
PbW04->AddElement(elPb, natoms=1);

// define a material from elements.   case 2: mixture by fractional mass
density = 1.290*mg/cm3;
G4Material* Air = new G4Material(name="Air  " , density, ncomponents=2);
Air->AddElement(elN, fractionmass=0.7);
Air->AddElement(elO, fractionmass=0.3);
```

Detector construction

- Implement a class describing the detector geometry, inheriting from the abstract G4VUserDetectorConstruction

```
class B1DetectorConstruction : public G4VUserDetectorConstruction
{
public:
    ...
    virtual G4VPhysicalVolume* Construct(); ← Contains the
    ...                                     geometrical
};                                         description
```

- **The Construct method must be implemented**
 - contains all the geometry (volumes and solids) and material information
 - returns the pointer to the “world” volume

Geometry structure

The detector geometry is defined using 3 different concepts, associated to different objects:

- **Solid**: information on shape and size of a detector component forma
- **Logical Volume**: information associated with detector elements represented by a given Solid and Material, independently from its physical position in the detector di cosa è fatto
- **Physical Volume**: represent the spatial positioning of the volumes describing the detector elements. Can be simple placement of a single copy or repeated positioning. dove è

All the volumes are contained in the “**world**” volume, that **must** be defined by the user

Basic strategy:

1. create a solid
2. associate properties to the solid through a logical volume
3. place the volume in the world

```
G4Tubs* pipe = new G4Tubs("Pipe", rint, rext, 0.5*len, 0*deg, 360*deg);
```

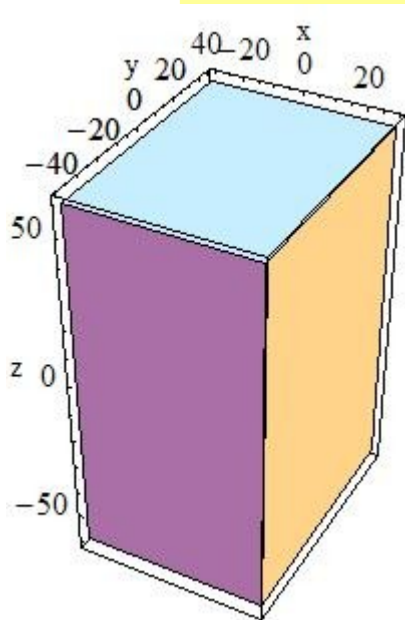
```
G4LogicalVolume* logicPipe = new G4LogicalVolume(pipe, pipe_mat, "Pipe");
```

```
G4ThreeVector pospipe = G4ThreeVector(0*cm, 0*cm, 10*cm);  
new G4PVPlacement(rotpipe, pospipe, logicPipe, "Pipe",  
logicMotherVol, false, 0, checkOverlaps);
```

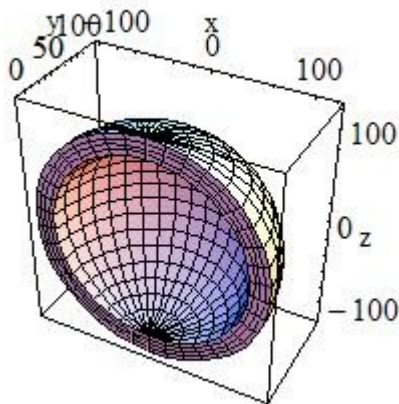
since we are building a sampling cal we will just need the box

Solids

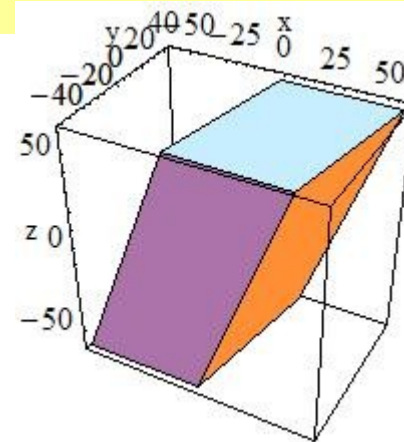
```
G4Box(const G4String& pName,
        G4double pX,
        G4double pY,
        G4double pZ)
```



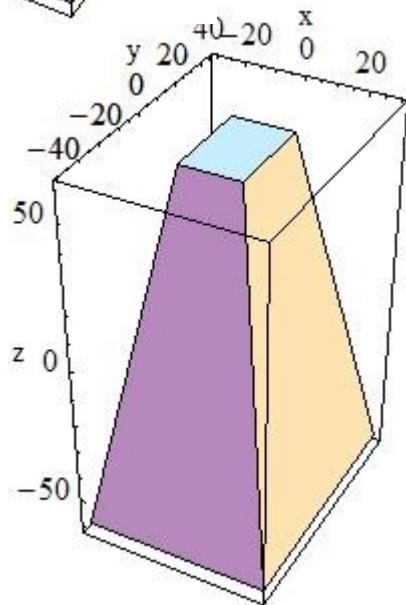
```
G4Sphere(const G4String& pName,
          G4double pRmin,
          G4double pRmax,
          G4double pSPhi,
          G4double pDPhi,
          G4double pSTheta,
          G4double pDTheta)
```



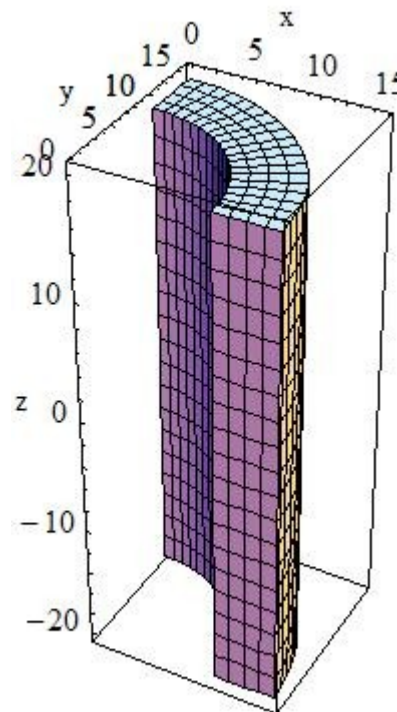
```
G4Para(const G4String& pName,
        G4double dx,
        G4double dy,
        G4double dz,
        G4double alpha,
        G4double theta,
        G4double phi)
```



```
G4Trd(const G4String& pName,
       G4double dx1,
       G4double dx2,
       G4double dy1,
       G4double dy2,
       G4double dz)
```



```
G4Tubs(const G4String& pName,
        G4double pRmin,
        G4double pRmax,
        G4double pDz,
        G4double pSPhi,
        G4double pDPhi)
```



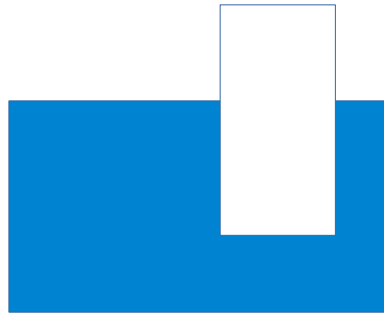
Boolean solids

- Simple solids can be combined in using boolean operations, requiring:
 - two solids
 - an operation: union, subtraction, intersection
 - an optional transformation for the second solid
- The result of the operation is a solid
- Examples: hole on a sphere, cylinder ending with a cone

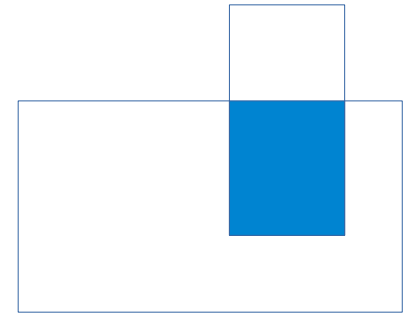
G4UnionSolid



G4SubtractionSolid



G4IntersectionSolid



Logical Volume

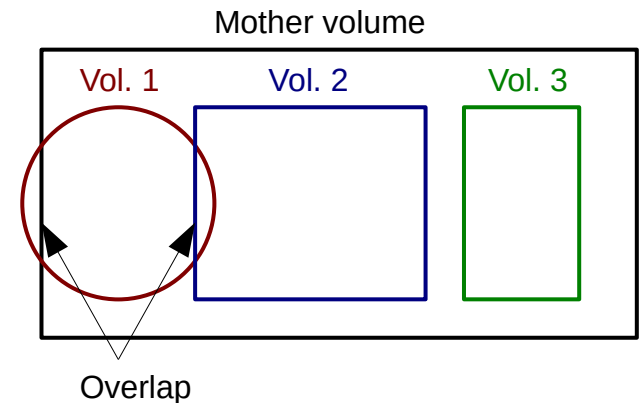
- The Logical Volume manages the information associated with detector elements represented by a given **Solid** and **Material**, independently from its physical position in the detector.
- A Logical Volume knows **which physical volumes are contained** within it. **A Logical Volume thus represents a hierarchy of unpositioned volumes whose positions relative to one another are well defined.**
- By creating **Physical Volumes**, which are **placed instances of a Logical Volume**, this hierarchy or tree can be repeated.
- A Logical Volume also manages the information relative to the Visualization attributes and user-defined parameters related to tracking, electro-magnetic field or cuts.

Physical Volume

- Physical volumes represent the spatial positioning of the volumes describing the detector elements.
- G4PVPlacement**: The simple placement involves the definition of a transformation matrix for the volume to be positioned.
placement basic method, but we will use the replica
- G4PVReplica**: Repeated positioning is defined using the number of times a volume should be replicated at a given distance along a given direction.
 - G4PVParameterised** for more complex positioning

Overlaps are not allowed:

- volumes intersecting each other
- volumes extending beyond the boundaries of their mother volumes



2. Physics model

Physics processes

- **Physics processes** define how particles can interact with the materials
Turning on all processes at the same time is a waste of cpu time
- The process:
 - defines if a given interaction occurs during the step, based on the cross-section
 - changes momentum of the particle
 - generates secondary particles
- Examples: ionization, photoelectric effect, positron annihilation, hadronic interaction, ...
- All details in the Geant4 physics reference manual:

geant4.web.cern.ch/geant4/UserDocumentation/UsersGuides/PhysicsReferenceManual/fo/PhysicsReferenceManual.pdf

Physics lists

- Geant4 provides a flexible framework that allow the implementation of any user-defined model to describe physics processes

I need to tell geant which phys list to use

- The definition of a physics list is mandatory

```
class MyPhysicsList: public G4VUserPhysicsList
{
public:
    MyPhysicsList();
    ~MyPhysicsList();
    void ConstructParticle();
    void ConstructProcess();
    void SetCuts();
}
```

I will not need to build it, already done in initialization

- **Modular** physics lists can be constructed from basic blocks
- **Reference** physics lists are complete lists with realistic physics models that can be chosen according to the use case

Reference physics lists

- Reference physics lists are listed at http://geant4.cern.ch/support/proc_mod_catalog/physics_lists/referencePL.shtml
- How to initialize a reference physics list:

```
#include "QGSP_BIC_HP.hh" This is a phy list that can be used also for hadronic int  
                           see slide 34 for more info on the header  
  
int main(int argc, char** argv)  
{  
    ...  
    G4RunManager* runManager = new G4RunManager;  
  
    // Physics list  
    G4VModularPhysicsList* physicsList = new QGSP_BIC_HP;  
    runManager->SetUserInitialization(physicsList);  
  
    ...  
    runManager->Initialize();  
    ...  
}
```

Production cuts

- Particles are produced above defined thresholds
- Cuts are only at the production stage, no tracking cut is applied
 - Cuts are used to limit the generation of secondary particles
 - After production a particle is tracked until it stops or disappears
 - Cuts are expressed in ^{spacial range} range, corresponding to a different energy for each material
- It is possible to apply cuts to specific volumes

Electromagnetic physics - basic concepts

- The same **physics interaction** or **process** can be described by different models
 - they may be different / complementary / suggested in some energy ranges
- Example: available **Compton scattering** models inGeant4
 - **Klein-Nishina**
 - **Livermore** (for low E, based on Livermore database)
 - **Penelope** (for low E, based on Penelope model)
 - **LowEP** (Monash Univ. model, 3D fully relativistic treatment)
 - **Polarized** (add polarization to Klein-Nishina or Livermore)
- EM physics list constructors:
http://geant4.cern.ch/collaboration/working_groups/electromagnetic/physlist10.3.shtml

Standard EM models

- Complete set of models for: γ , e , μ , hadrons, ions
- Designed for high-energy physics applications
 - Less CPU intensive
 - Approximations in the low-energy regime
- Theoretical or phenomenological models (Bethe-Bloch, Klein-Nishina, ...)
- Specific high-energy extensions available (e.g. $\gamma \rightarrow \mu^+\mu^-$)
- Dedicated library for optical photons (Cherenkov)

Livermore EM models

- Based on publicly available data tables from the [Livermore data library](#) for e^- , γ
- Tables go down to ~ 10 eV
- Applications: low-energy EM, medical, underground, rare events, space, ...
- Possible to use polarized models
 - same cross-section calculation
 - describe in detail the interaction of polarized photons

Penelope EM models

- Based on the low-energy models for e^- , e^+ , γ from the **PENELOPE Monte Carlo** code
 - NIM B 2017 (2003) 107
- Mixed approach: analytical, parameterized, database-driven
- Energy range: **100 eV - 1 GeV**
- Applications: similar to Livermore but includes positrons

Low-energy EM models should be adopted for EM physics at the **\sim keV scale**.

Not to be used for EM physics at the **$>$ MeV scale**: same results as Standard with lower performance

Hadronic physics - basic concepts

- More complex than EM physics
- Involves several process, in different energy regimes
 - < 100 MeV: low-energy
 - 100 MeV - 10 GeV: resonance and cascade region
 - >20 GeV: QCD strings
 - thermal to 20 MeV neutrons
- Several models available in each energy regime, many of them are phenomenological
- Hadronic processes: elastic, inelastic, capture, fission

user will still in any case just shoot a particle

Reference physics lists for hadronic interactions

- String models:
 - **QGSP**: uses the **quark-gluon string model** for high-energy hadronic interactions between, p, n, π , K, nuclei. Low Energy Parameterised (LEP) model applied to all particles.
 - **FTFP**: uses the **FRITIOF model** of string excitation and fragmentation
- Alternative cascade models:
 - **BERT**: Geant4 Bertini cascade model for primary p, n, π and K below ~ 10 GeV, instead of the LEP model. **More secondary neutrons and protons** produces than the LEP model, yielding a better agreement to experimental data.
 - **BIC**: Geant4 Binary cascade for primary protons and neutrons with energies below ~ 10 GeV, instead of the LEP model. Binary cascade **better describes production of secondary particles produced in interactions of protons and neutrons with nuclei.**

In slide 27 ho un QGSP_BIC_HP

HP means High energy Pregigion on low en neutrons (prossima slide)

Neutron HP model

- Dedicated **High-Precision (HP)** model available for **very-low energy neutrons**
- **Cross-sections** and **final state information** based on **tabulated data** (G4LEND)
 - elastic, inelastic scattering, capture, fission, isotope production
- Applied from **thermal energies up to 20 MeV**
 - Very precise but also slow (thermal neutron tracking is CPU intensive)

Particle HP models

- Data driven approach extended to inelastic interactions of p , d , t , ${}^3\text{He}$, α (G4TENDL)
- Recently added to Geant4 (since v 10.2)
- Same energy range of applicability of neutron HP models
- The new package include neutrons
 - NeutronHP \rightarrow ParticleHP

3. Primary event generator

G4VUserPrimaryGeneratorAction

- Mandatory user class, controls the generation of primary particles
 - Constructor:
 - Instantiate primary generator (i.e. G4ParticleGun())
generator that shoots one particle
 - Define default values (i.e. energy)

```
G4ParticleGun* particleGun = new G4ParticleGun(n_particle);  
particleGun -> SetParticleEnergy(1.0*GeV);
```

- GeneratePrimaries():
 - User defined modifications of generator parameters (e.g. energy, vertex position)
 - Ends invoking GeneratePrimaryVertex() of the generator

```
particleGun->GeneratePrimaryVertex(anEvent);
```

G4ParticleGun

- Provided implementation of the primary generator designed to
 - Shoot a single particle
 - From a given point
 - In a given direction
- Use the different Set methods available

```
G4ParticleDefinition* particle = particleTable->FindParticle("gamma");  
particleGun->SetParticleDefinition(particle);  
particleGun->SetParticleEnergy(100*keV);  
particleGun->SetParticlePosition(G4ThreeVector(x0,y0,z0));  
particleGun->SetParticleMomentumDirection(G4ThreeVector(xdir,ydir,zdir));  
  
...  
  
particleGun->GeneratePrimaryVertex(anEvent);
```

particelle prodotte da generatorimontecarlo, tipo pythia, poi possono essere
feeded a geant per studiare la fis

4. Tracking

Particle production and propagation

- Primary particles are produced by the event generator, secondary particles by processes
 - G4ParticleDefinition: particle definition properties (mass, charge, PDGID, name, ...)
 - G4DynamicParticle: dynamic properties (momentum, polarization, ...) all things that do not belong to the part but are part of the kinematics of the part
- G4Track contains the information for tracking the particle inside the detector geometry (position, step, current volume, ...) where the particle is, like tracker or cal...
- The information is updated after each step
- The track is deleted when the particle disappears in an interaction, has 0 kinetic energy, goes outside the world volume, or is manually killed by the user

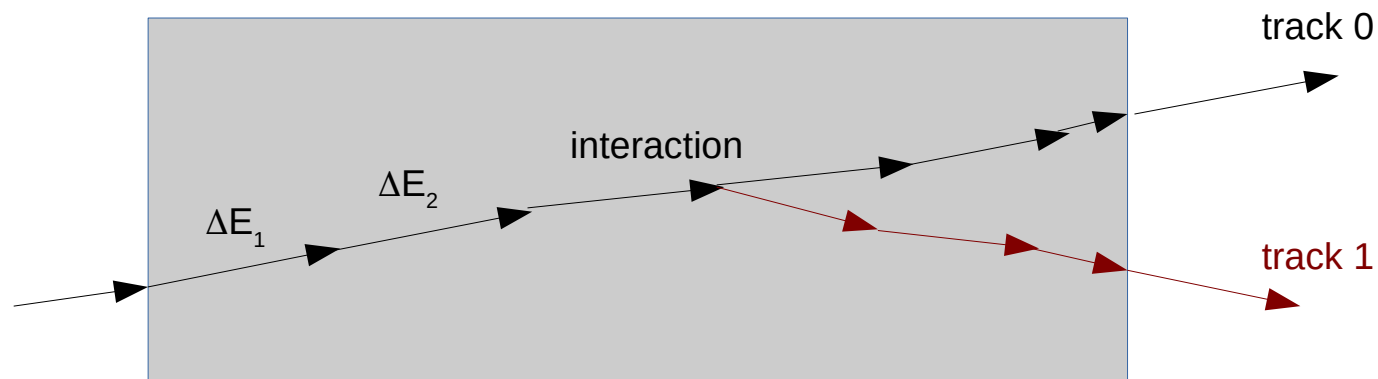
Step

- **G4Step** represents the smaller unit of particle propagation
- The step contains information about the initial and final points, energy depositions in the materials, ...
- **If a boundary between volumes is crossed, the step length is limited to end at the boundary**
I cannot have a step that crosses 2 volumes
Then when I exit the volume another step is needed
- **The user can define limits to the step length, that can assume different values for different volumes**

for ex 1 mm step in air for an e- I have many steps where nothing happens, but in Fe it may be ok

Particle propagation procedure

- A particle is shot
- The geometrical step length is computed, based on the cross-sections of all processes and choosing the smallest one
 - Check if crossing boundaries
- All processes involved are executed
- Post-step procedures are executed (track update, secondaries added to the stack, ...)



Production cuts

- It is unpractical to track all secondary particles of “very low” energy
 - The simulation should balance between accuracy and execution time (performance)
- The user can define **limits on particles that are produced**
 - limits can be **general** or specific **for given regions**
 - Geant4 allows to define a **range limit** (the resulting energy cut depends on the particle and the material)
 - particles that cannot travel for at least the cut value are not produced
- **No tracking cuts exist in Geant4: once a particle is added to the stack it is tracked down to 0 energy (or until it disappears)**

5. Hits

G4Hit

- The definition of a Hit is provided by the user, so various type of information can be stored in a Hit
- Typically a Hit contain the information needed to describe the energy deposition in the detector
 - position, time, energy deposition
 - can also contain additional information associated to the G4Step, such as: particle type and momentum, volume, ...
- Hits are then created and filled by the SensitiveDetector
- Hits are stored in the HitCollection attached to the event and can be read back at the end of the event

Note: an example of the Hit/SD implementation can be found in the example B5

G4Hit

```
class MyCalorimeterHit : public G4VHit
{
public:
    MyCalorimeterHit();
    ~MyCalorimeterHit();
    ...

private:
    G4double edep;
    G4ThreeVector pos;
    ...

public:
    inline void SetEdep(G4double de)
    { edep = de; }
    inline G4double GetEdep() const
    { return edep; }
    inline void SetPos(G4ThreeVector xyz)
    { pos = xyz; }
    inline G4ThreeVector GetPos() const
    { return pos; }
    ...
};

using MyCalorimeterHitsCollection =
    G4THitsCollection<MyCalorimeterHit>;
```

Since a simulation may contain different detectors (e.g. calorimeter and Si tracker), it is possible to create several G4Hit classes storing different information

Sensitive Detector and hit collection

- The definition of the Sensitive Detector (SD) is a powerful and flexible way of extracting information from the simulation
 - Derive concrete classes from `G4VV = virtualSensitiveDetector` and `G4VHit`
- The method `ProcessHit()` of the SD is invoked at each step starting in the SD logical volume. It must create, fill and store the Hit objects
 - `Initialize()` and `EndOfEvent()` methods are invoked at the beginning and at the end of the event
- The Hits are stored in a `HitCollection` (an array of hits)
 - the `G4Event` has an associated `G4HCofThisEvent` object, storing all hit collections created during the event
 - All the hits are accessible in the `EndOfEventAction()` method of the `EventAction`
 - retrieved using `G4Event::GetHCofThisEvent()`

G4SensitiveDetector

```
class MyCalorimeterSD : public G4VSensitiveDetector
{
public:
    MyCalorimeterSD(G4String name);
    virtual ~MyCalorimeterSD();

    virtual void Initialize(G4HCofThisEvent* HCE);
    virtual G4bool ProcessHits(G4Step* aStep, G4TouchableHistory*R0hist);
    virtual void EndOfEvents(G4HCofThisEvent* HCE);

private:
    MyCalorimeterHitsCollection* fHitsCollection;
    G4int fHCID;
};
```

G4SensitiveDetector - Initialize()

```
void MyCalorimeterSD::Initialize(G4HCofThisEvent* hce)
{
    fHitsCollection
        = new MyCalorimeterHitsCollection(SensitiveDetectorName, collectionName);
    fHCID = G4SDManager::GetSDMpointer()->GetCollectionID(fHitsCollection);

    hce->AddHitsCollection(fHCID, fHitsCollection);

    fHitsCollection->insert(new MyCalorimeterHit());
}
```

I construct hit collection and insert it into the hits of my cal

- Constructs all the HitCollections
- Insert them into the G4HCofThisEvent

G4SensitiveDetector - ProcessHits()

```
G4bool MyCalorimeterSD::ProcessHits(G4Step* step, G4TouchableHistory*)
{
    MyCalorimeterHit hit;

    G4double edep = step->GetTotalEnergyDeposit();
    ... // All variables of interest

    hit.SetEnergyDeposit(edep);
    ... // set all hit member variables

    hitCollection.insert(hit);

    return true;
}
```

- Invoked at every step
- Generates and stores hits

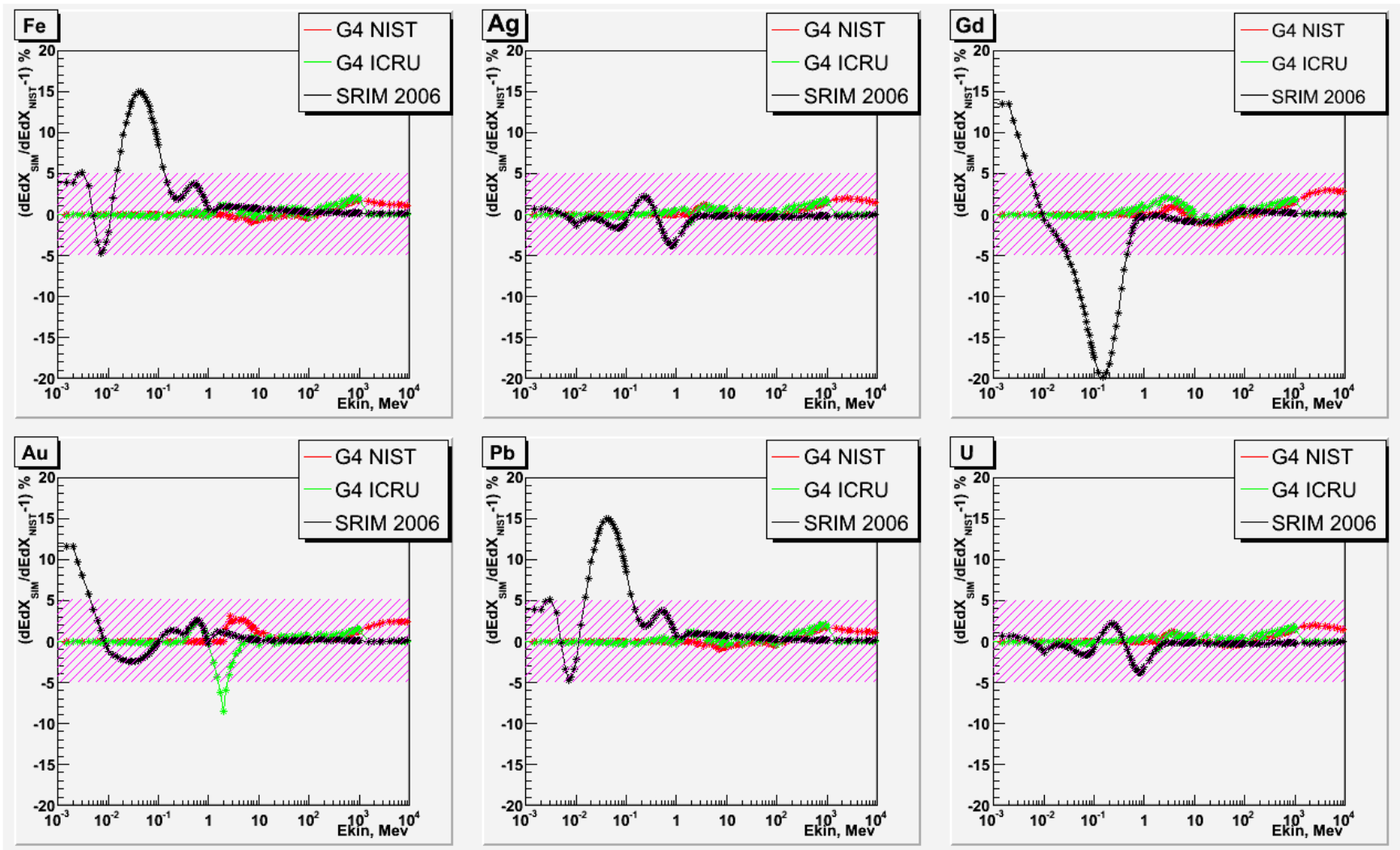
6. Performance and Validation

Geant4 performance and validation

- **Performance** (CPU and memory) and **validation tests** regularly performed by the Geant4 collaboration
- New releases tested against
 - experimental data
 - previous releases
- Collected in <http://geant4.cern.ch/results/results.shtml>
- Some examples in the following

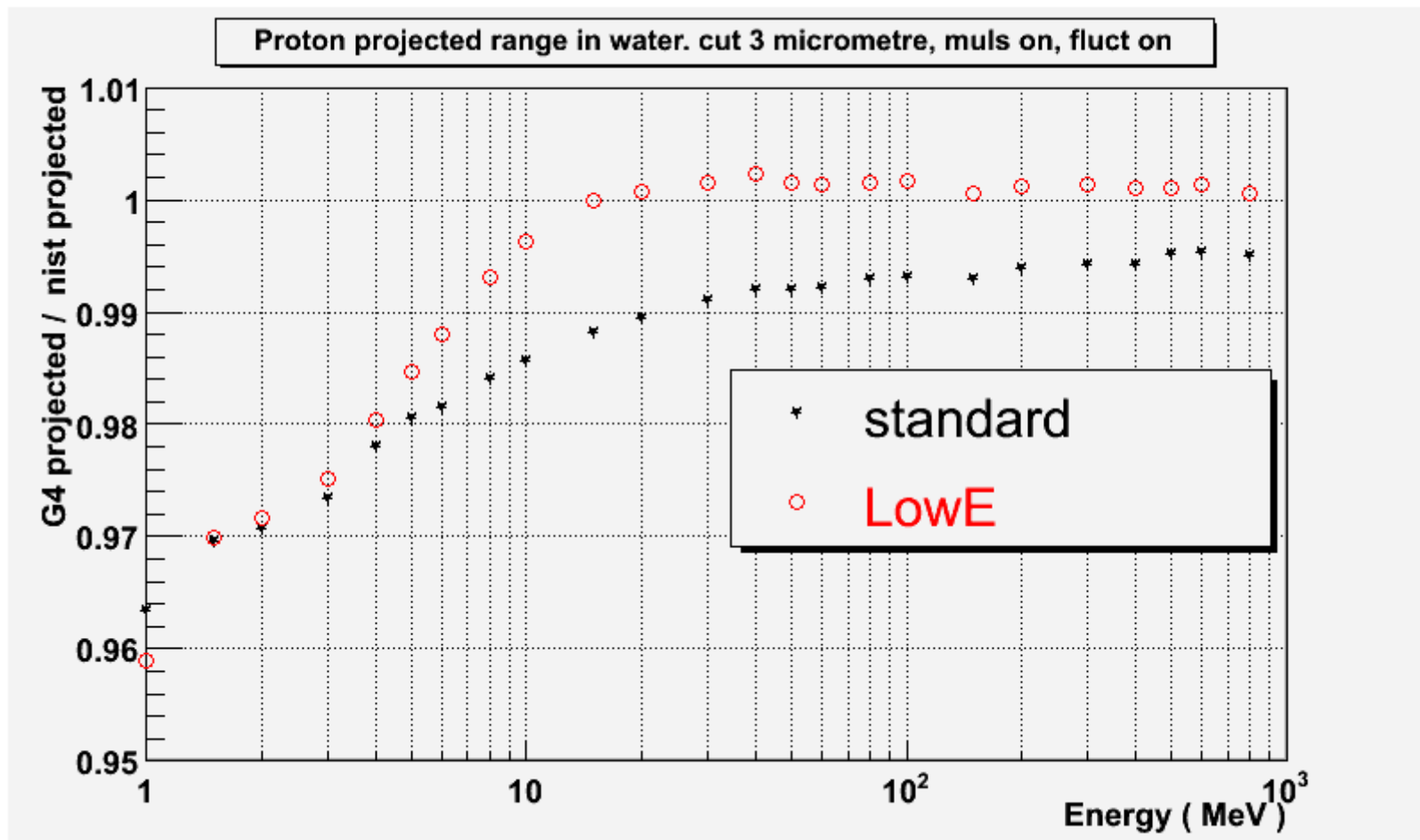
EM physics validation - 1

Proton stopping power compared with NIST data - Data accuracy $\sim 2\%$ for $E > 1\text{MeV}$



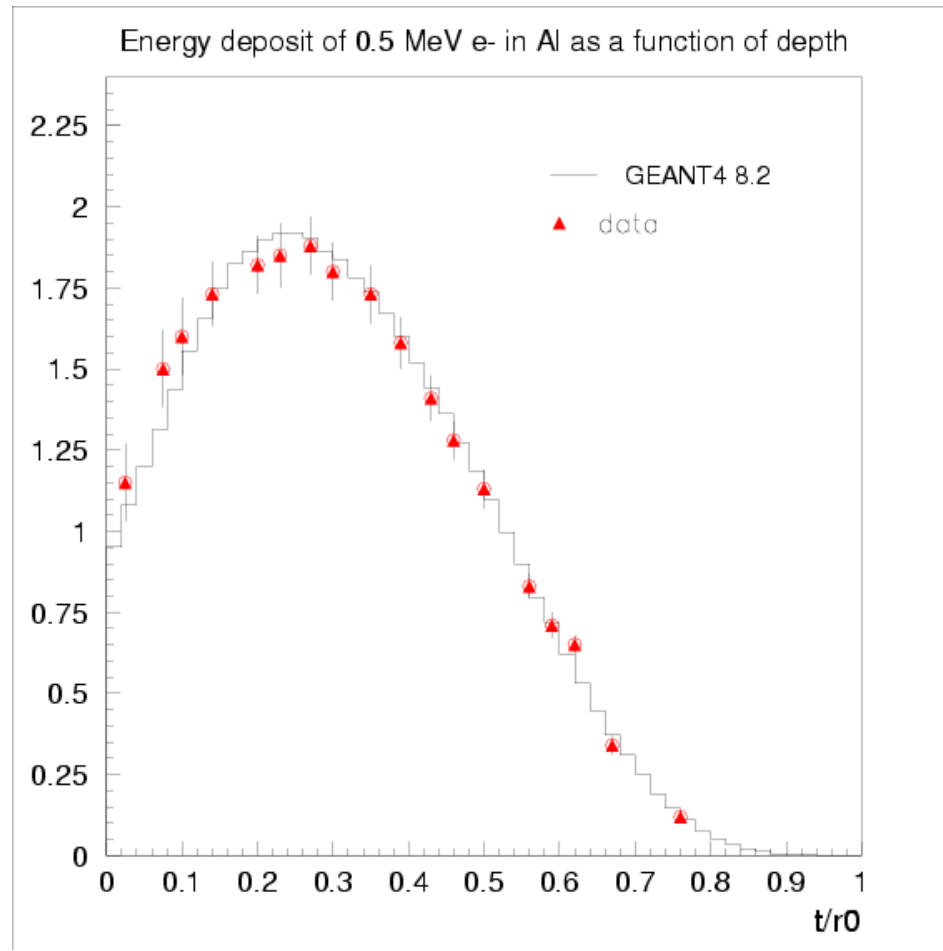
EM physics validation - 2

Proton range compared with NIST data - Data accuracy $\sim 2\%$ for $E > 1\text{MeV}$



EM physics validation - 3

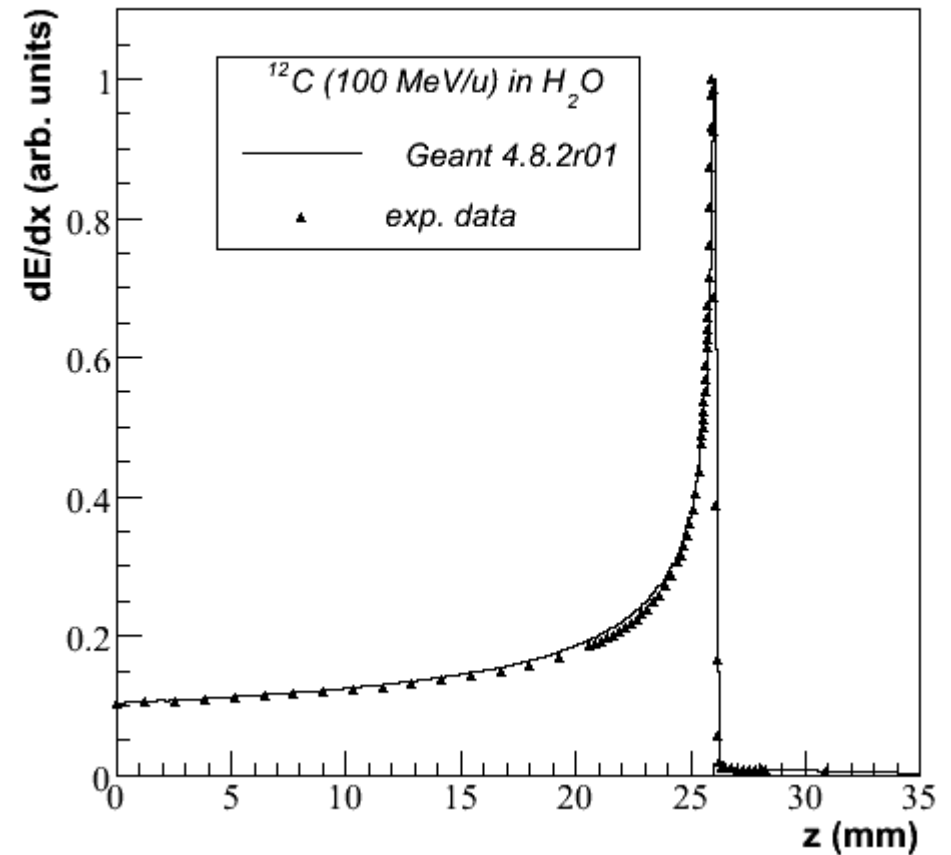
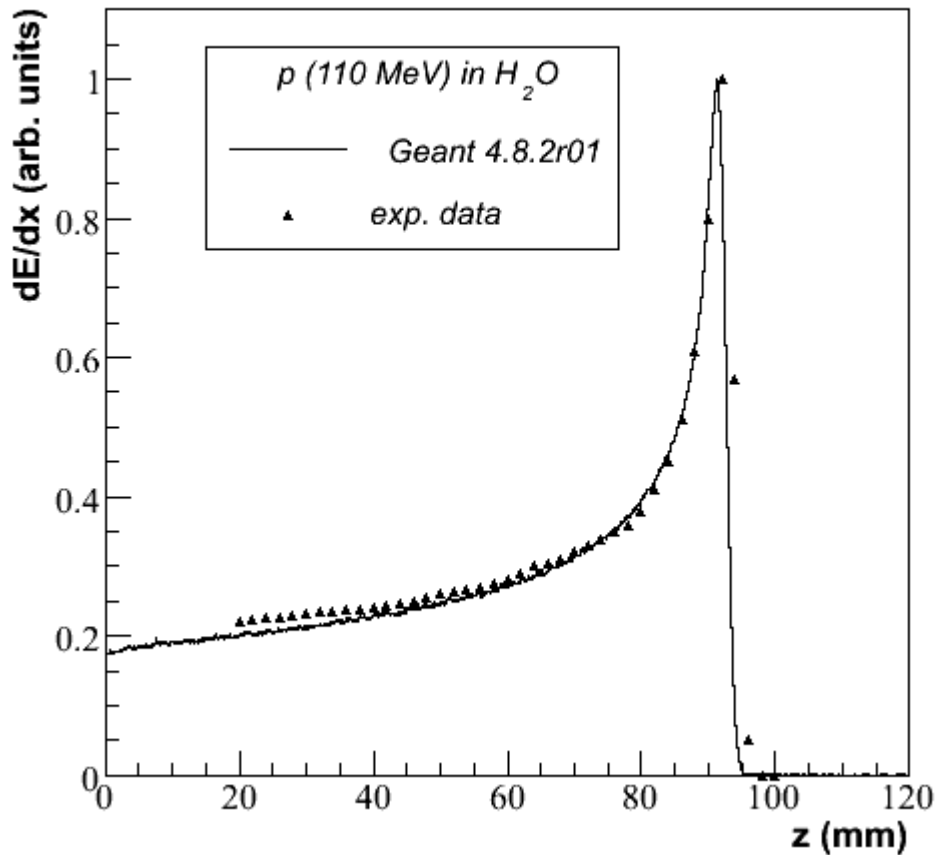
Energy deposition profile of 0.5 MeV e^- in Al



EM physics validation - 4

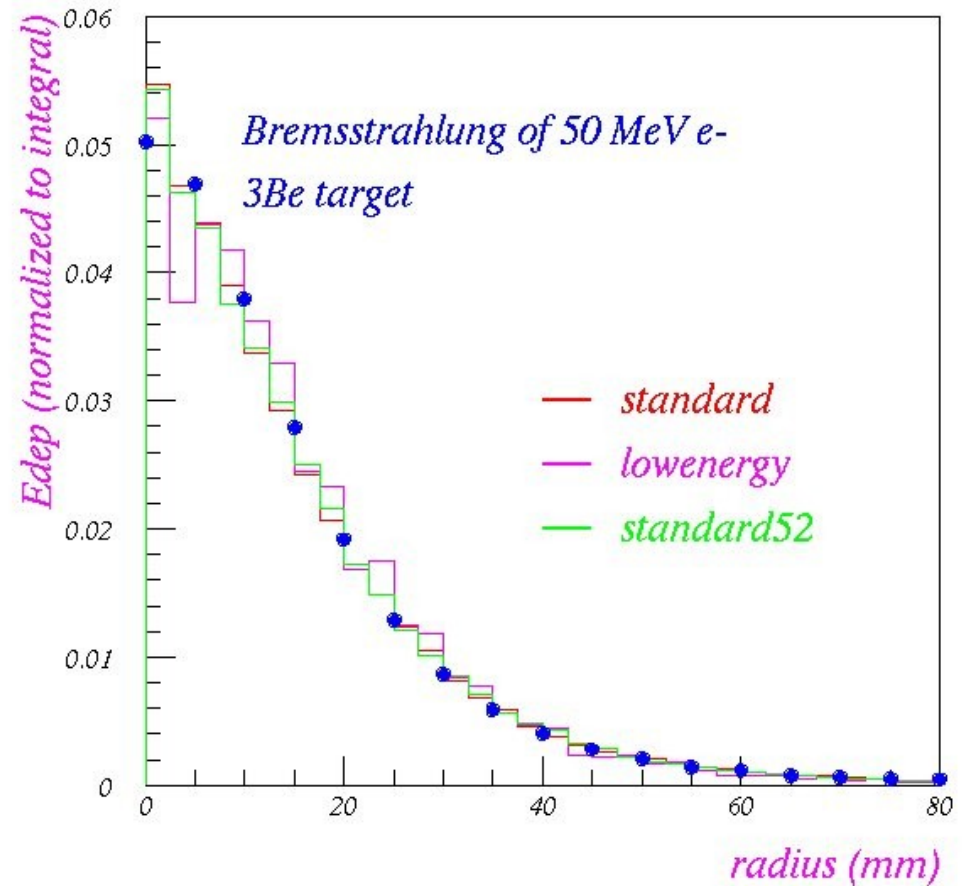
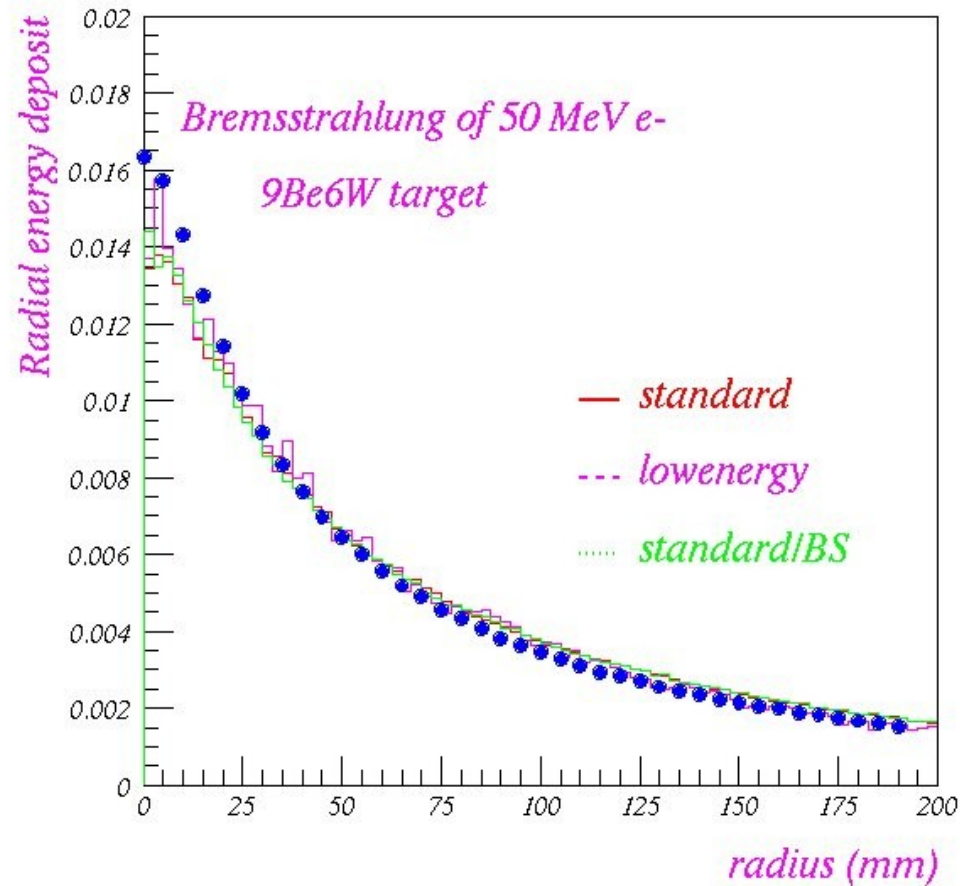
Bragg peaks of p and ^{12}C in water

bragg peak works well for heavy particles



EM physics validation - 5

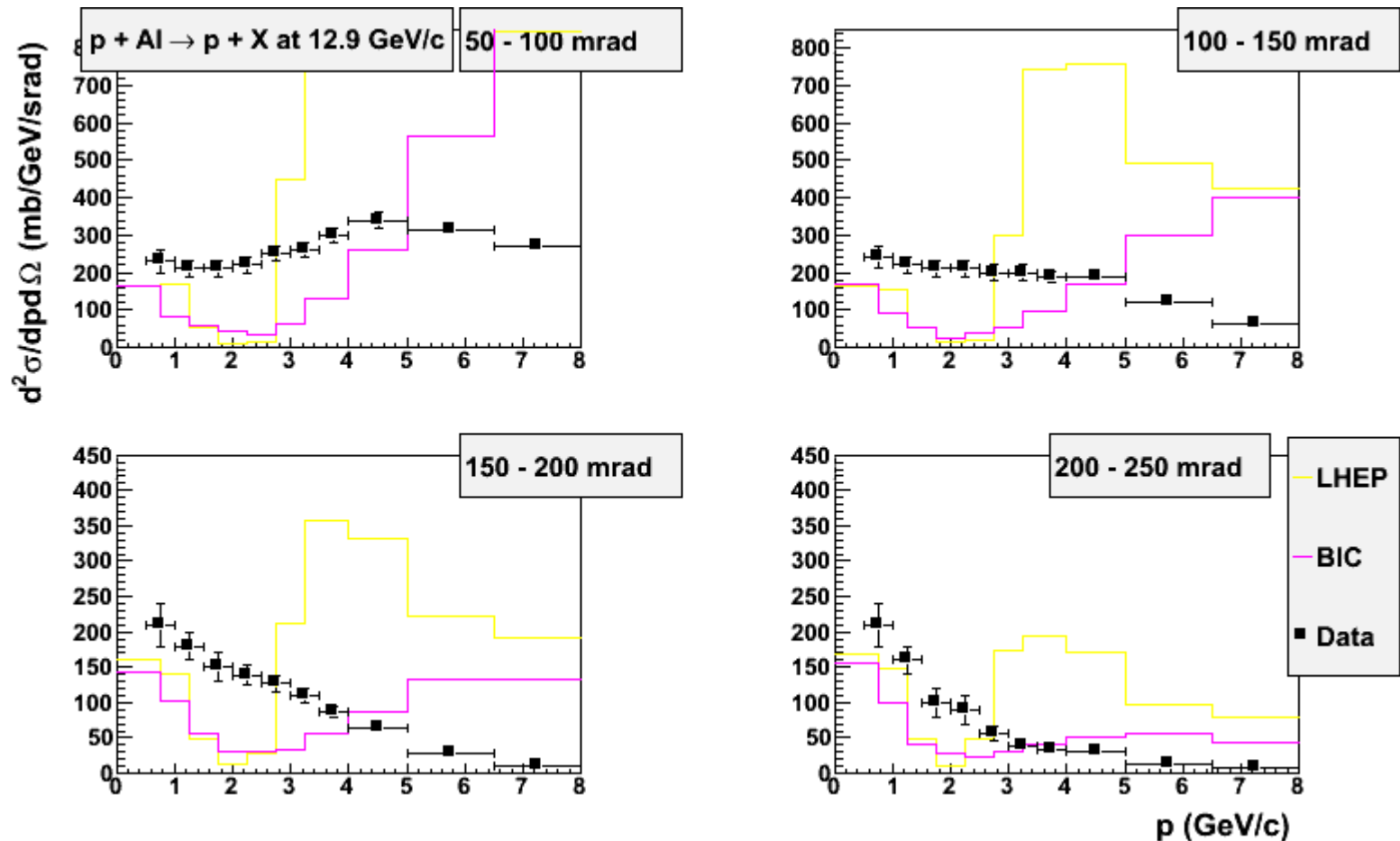
Radial energy deposition for bremsstrahlung photons by 50 MeV e^- in different targets



Hadronic physics validation - 1

Hadronic generation of inelastic processes compared with the HARP experiment

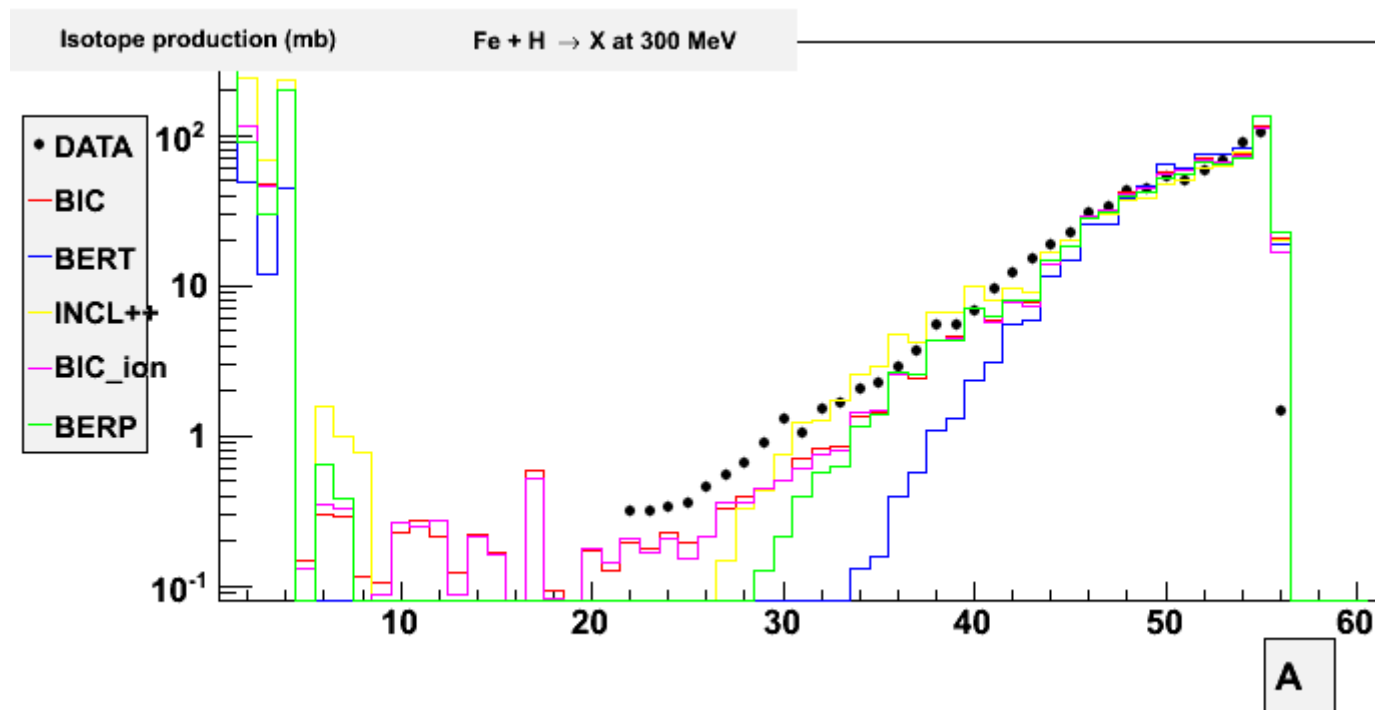
$p + \text{Al} \rightarrow p + X$, 12.9 GeV/c



Hadronic physics validation - 2

IAEA benchmark of nuclear spallation models

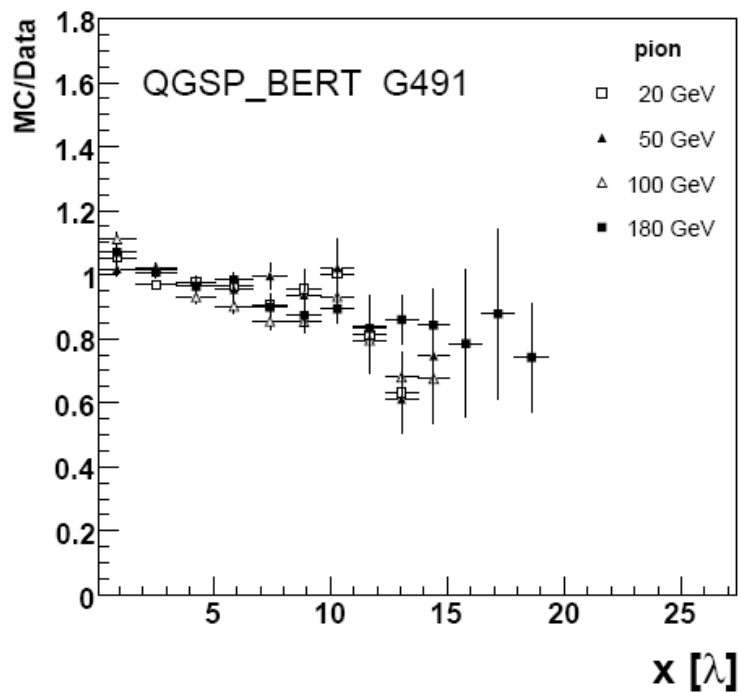
$p + \text{Fe} \rightarrow n + X$, 300 MeV



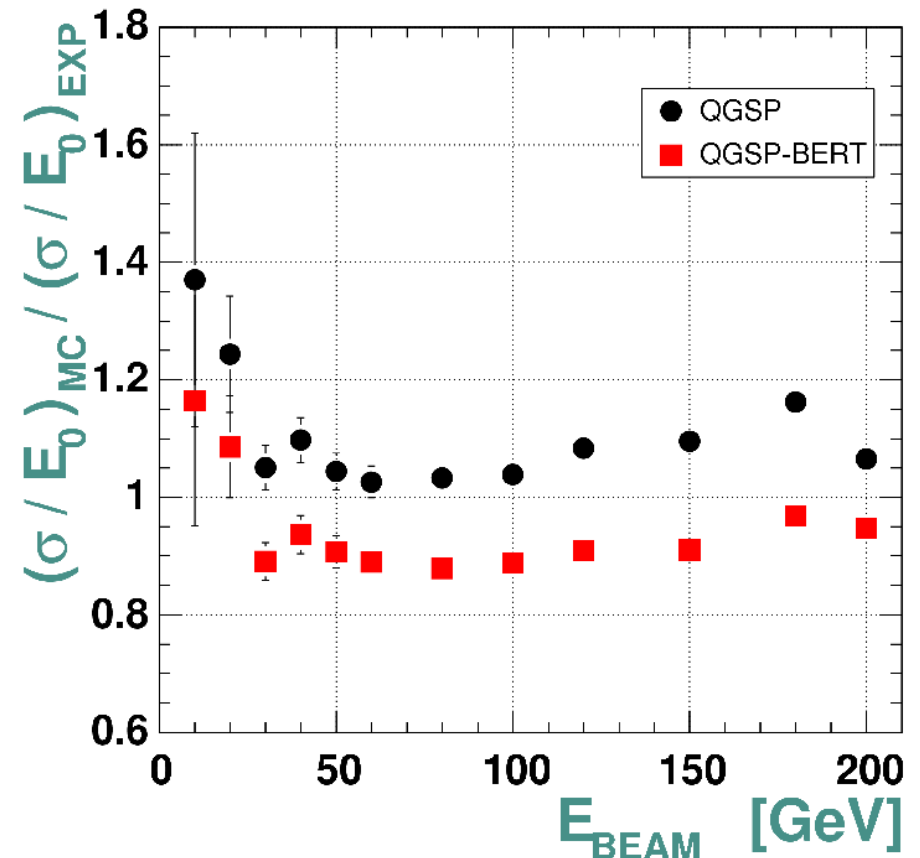
Hadronic physics validation - 3

Shower characteristics of ATLAS calorimeter

5.0 GeV π^- on ATLAS Tile cal.
Shower longitudinal profile

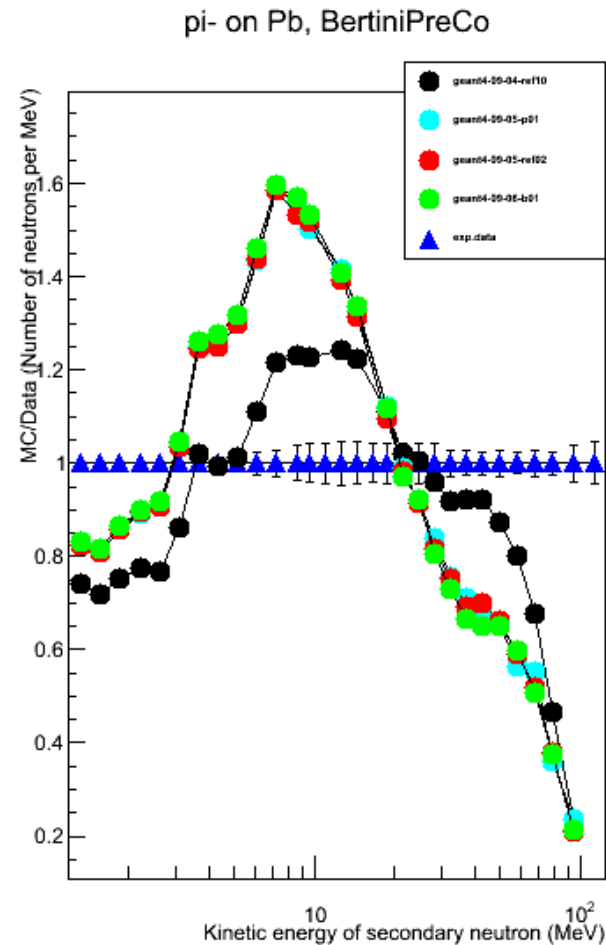
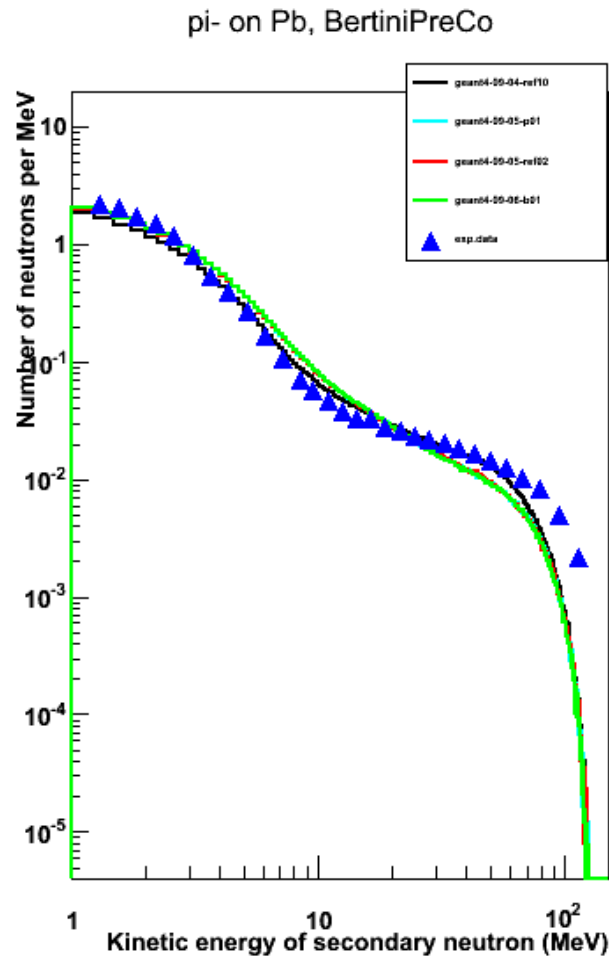


π^- on ATLAS Forw. cal.
Energy resolution



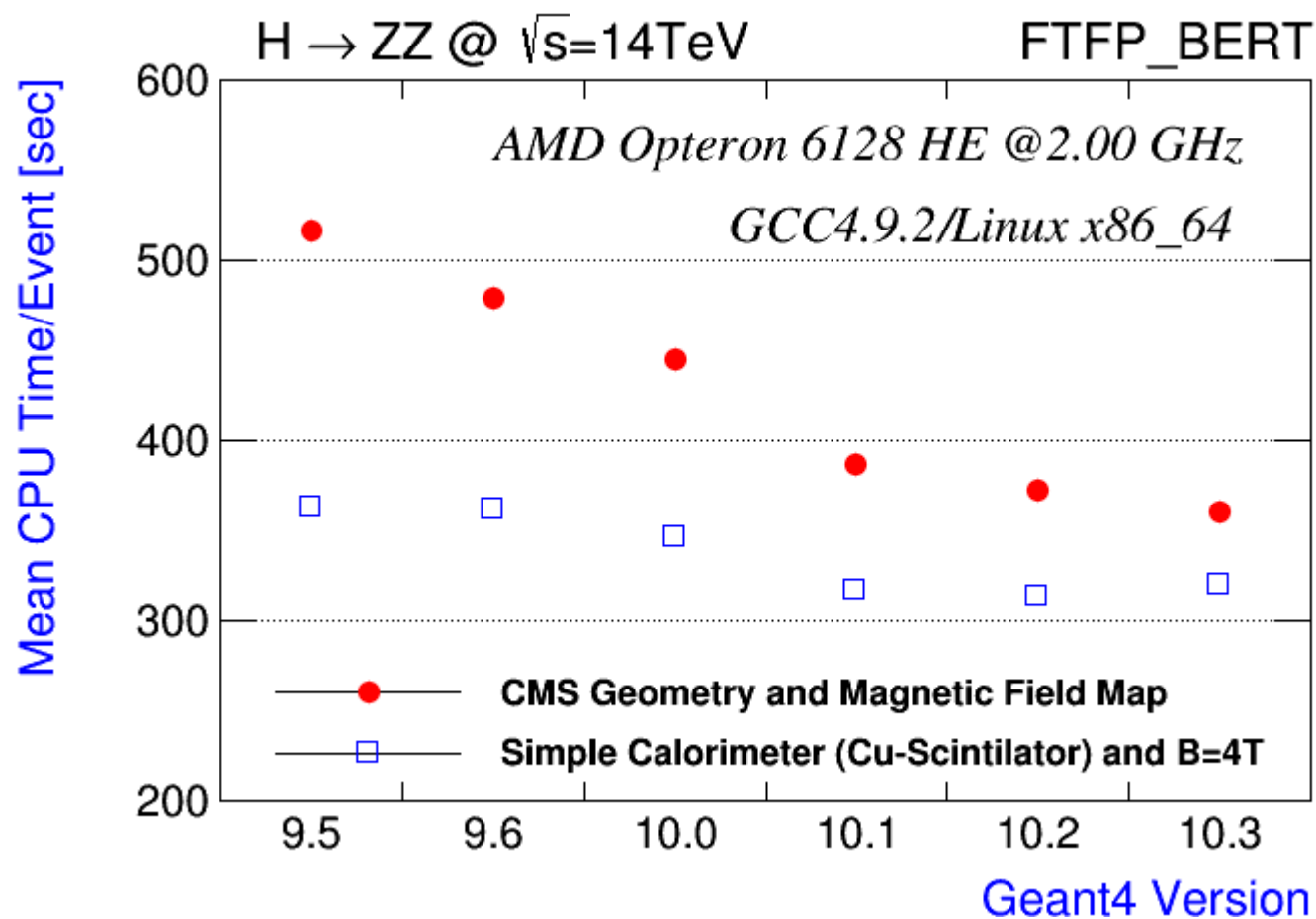
Hadronic physics validation - 4

Kinetic energy of secondary neutrons for 5.0 GeV π^- on Pb



Geant4 release performance - 1

Time to simulate a $H \rightarrow ZZ$ event using a simplified or the CMS calorimeter



Geant4 release performance - 2

Memory to simulate 51 $H \rightarrow ZZ$ events using a simplified calorimeter
(1 mem. count = 1 byte)

