Geant4 Electromagnetic Physics Introduction

Editors:
Michel Maire (LAPP, Annecy, France)
Vladimir Ivanchenko (CERN & EMSU, Moscow)
Sebastien Incerti (CNRS/IN2P3, France)
on behalf of the
Geant4 Standard EM and Low Energy EM Physics Working groups

Geant4 tutorial
15-19 February 2010, CERN
V. Ivanchenko

Outline

- Electromagnetic (EM) physics overview
  - **Introduction**
  - **Structure of Geant4 EM sub-packages**
  - **Processes and models**
- Geant4 cuts
  - Cut in range and energy thresholds
- How to invoke EM physics in Geant4
  - **EM Physics Lists**
  - **How to extract physics?**

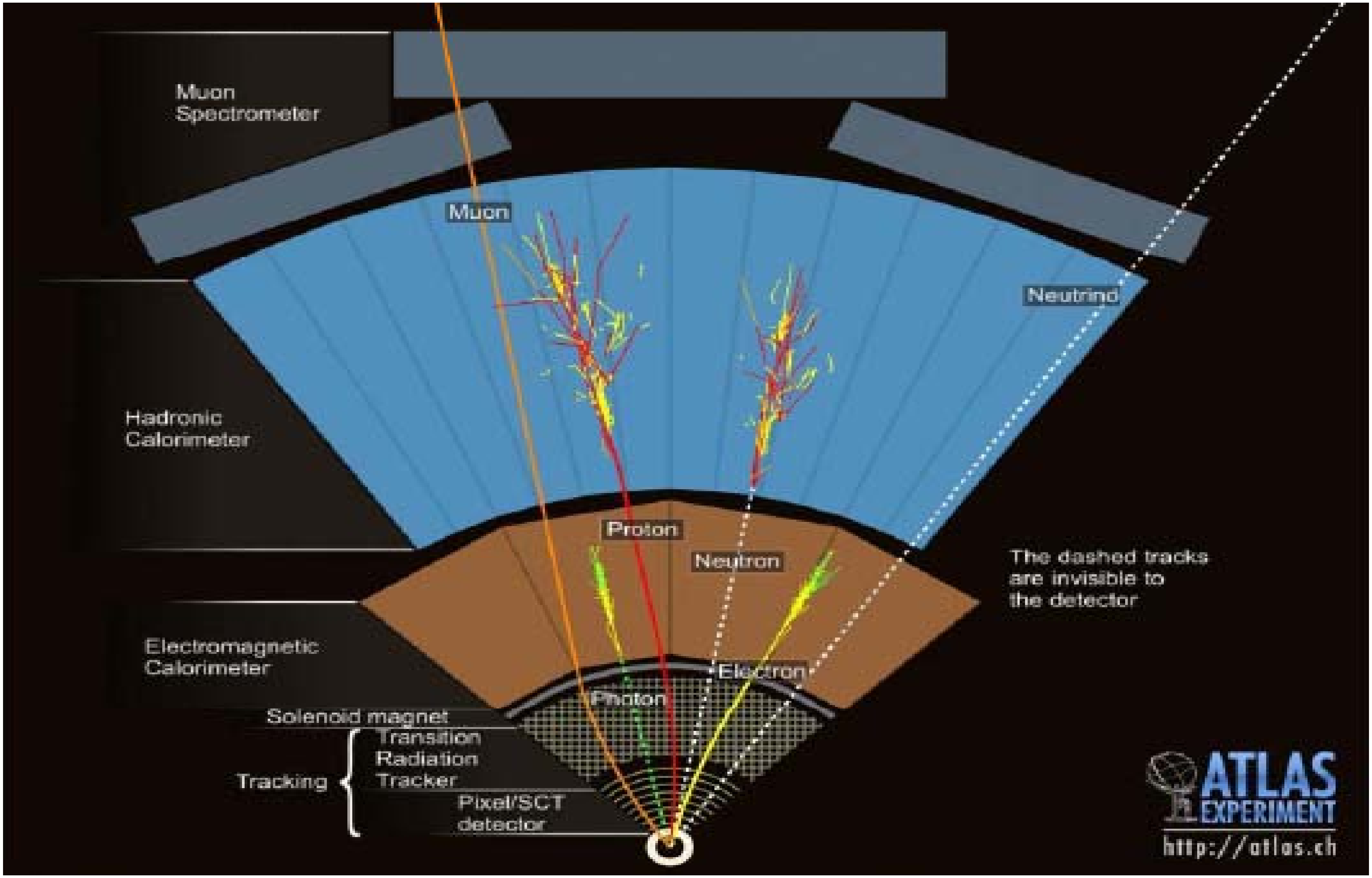
Electromagnetic (EM) physics overview

Geant4 Electromagnetic Physics

- Release with the 1st version of Geant4 with EM physics based on Geant3 experience (1998)
- Significant permanent development in many aspects of EM processes simulation since the beginning up to now
- Many years is used for large HEP experiments
  - BaBar, SLAC (since 2000)
  - LHC experiments ATLAS, CMS and LHCb (since 2004)
- Many common requirements for HEP, space, medical and other applications
- EM web page (common for Standard and Low-energy working groups):

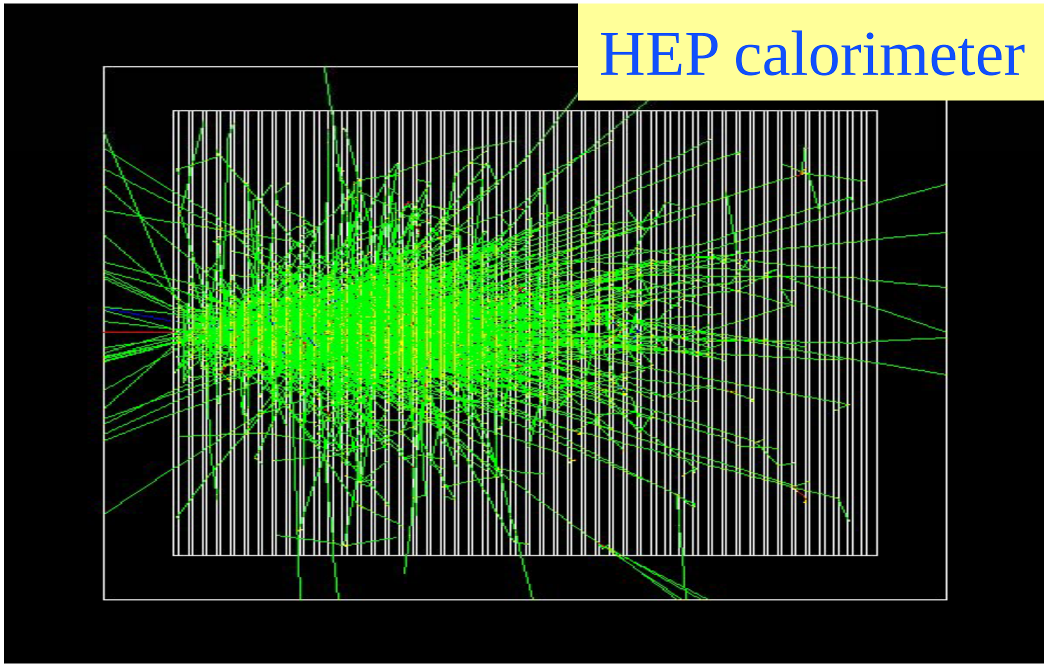
http://cern.ch/geant4/collaboration/working_groups/electromagnetic/index.shtml

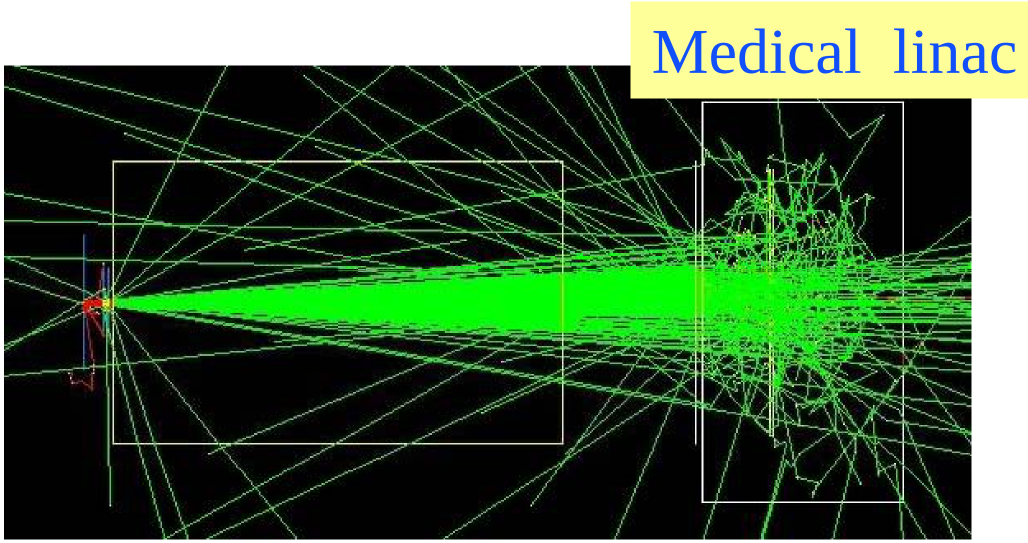
Geant4 simulation of ATLAS experiment at LHC, CERN



Gamma and Electron Transport

- **Photon processes:**
  - γ conversion into e^+e^- pair
  - Compton scattering
  - Photoelectric effect
  - Rayleigh scattering
  - Gamma-nuclear interaction in hadronic sub-package CHIPS
- **Electron and positron processes:**
  - Ionization
  - Coulomb scattering
  - Bremsstrahlung
  - Nuclear interaction in hadronic sub-package CHIPS
- **Positron annihilation**
- **HEP & many other Geant4 applications with electron and gamma beams**





Geant4 EM packages

- *Standard*
  - γ, e up to 100 TeV
  - hadrons up to 100 TeV
  - ions up to 100 TeV
- *Muons*
  - up to 1 PeV
  - Energy loss propagator
- *Xrays*
  - X-ray and optical photon production processes
- *High-energy*
  - Processes at high energy (E>10GeV)
  - Physics for exotic particles
- *Polarisation*
  - Simulation of polarized beams
- *Optical*
  - Optical photon interactions

- Low-energy
  - Livermore *library* γ, e- from 10 eV up to 1 GeV
  - Livermore library based polarized processes
  - PENELOPE code rewrite , γ, e- , e+ from 250 eV up to 1 GeV
  - hadrons and ions up to 1 GeV
  - Microdosimetry models (Geant4-DNA project) from 7 eV to 10 MeV
  - Atomic deexcitation
- Adjoint
  - New sub-library for reverse Monte Carlo simulation from the detector of interest back to source of radiation
- **Utils – general EM interfaces**

Software design

- Since Geant4 9.3beta (June, 2009) the design is uniform for all EM packages
  - Allowing a coherent approach for high-energy and low-energy applications

- A physical interaction or process is described by a process class
  - Naming scheme : « G4ProcessName »
  - For example, G4Compton for photon Compton scattering
  - Assigned to Geant4 particle type
  - Inherit from G4VEmProcess base class

- A physical process can be simulated according to several models, each model being described by a model class
  - Naming scheme : « G4ModelNameProcessNameModel »
  - For example, G4LivermoreComptonModel
  - Models can be assigned to certain energy ranges and G4Regions
  - Inherit from G4VEmModel base class

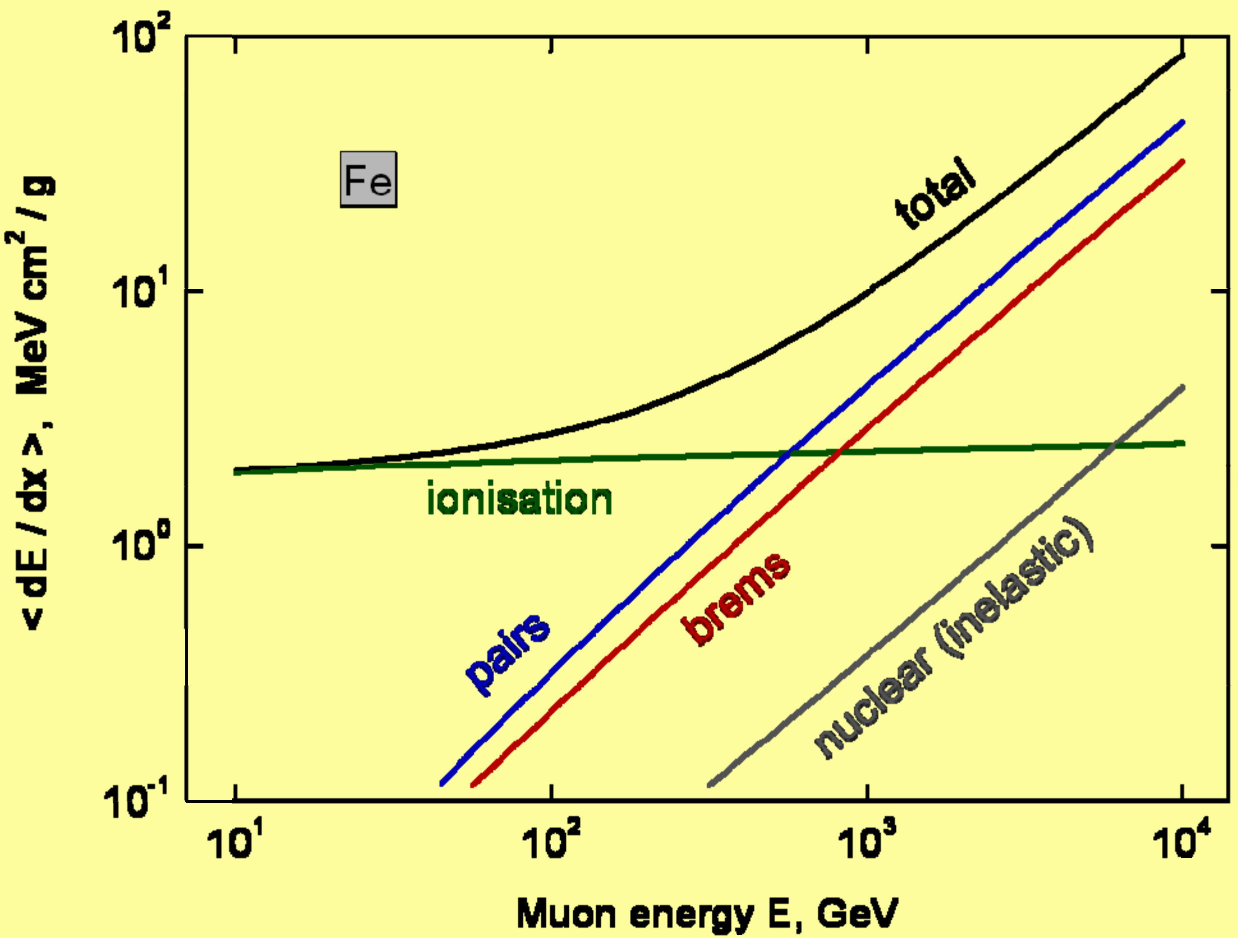
- Model classes provide the computation of
  - Cross section and stopping power
  - Sample selection of atom in compound
  - Final state (kinematics, production of secondaries…)

Example: Muon Energy Loss

- Continuous energy loss
  - Contribution from processes:
    - » Ionization
    - » Bremsstrahlung
    - » Production of e^+e^-
- Ionisation and delta-electron production
  - G4BetheBlochModel
- Below 200 keV – ICRU'49 parameterization of dEdx
  - G4BraggIonModel
- Radiative corrections to ionization at E > 1 GeV
  - G4MuBetheBlochModel

Total muon energy loss

$$\frac{dE}{dx} = n\sum_i \left(\int_0^{Tcut} T \frac{d\sigma}{dT} dT \right)$$



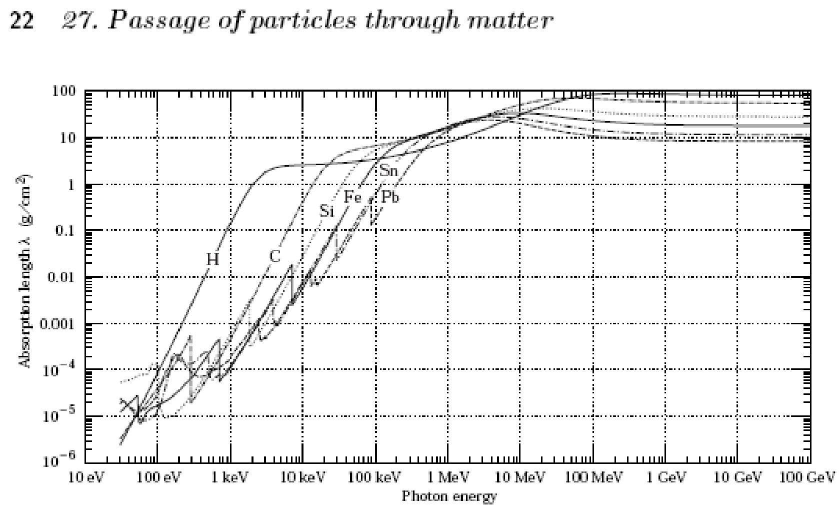
Comments

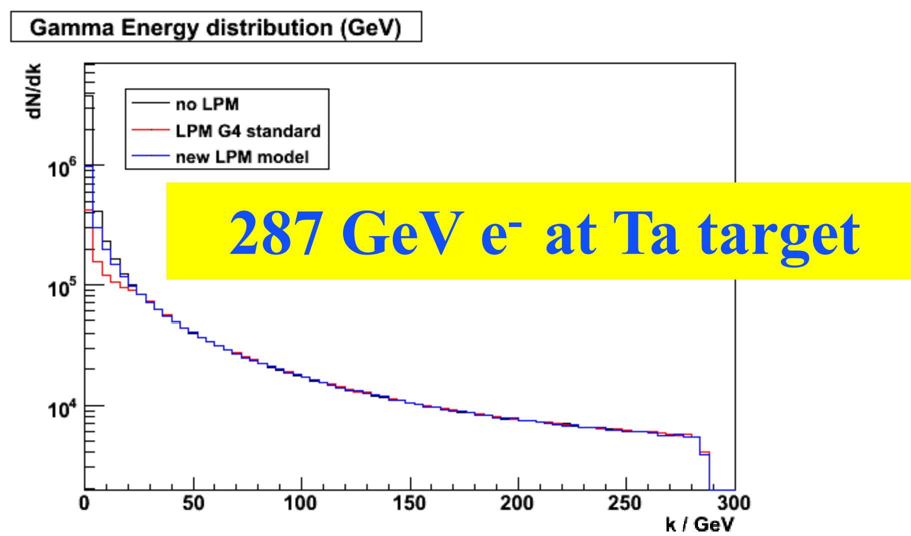
- The list of available processes and models is maintained by EM working groups in EM web pages
- It is shown in Geant4 extended and advanced examples how to use EM processes and models
- User feedback always welcome

Geant4 Cuts

Bremsstrahlung

- Bremsstrahlung spectrum grows to low energy as 1/k (k is the gamma energy)
- Low energy gamma has very small absorption length
- Simulation of all low-energy gamma is non-effective
- Cuts/production threshold are used in all Monte Carlo codes
- Gamma emission below production threshold is taken into account as continues energy loss
- Similar approach is used for ionisation process where spectrum is proportional to $1/T^2$



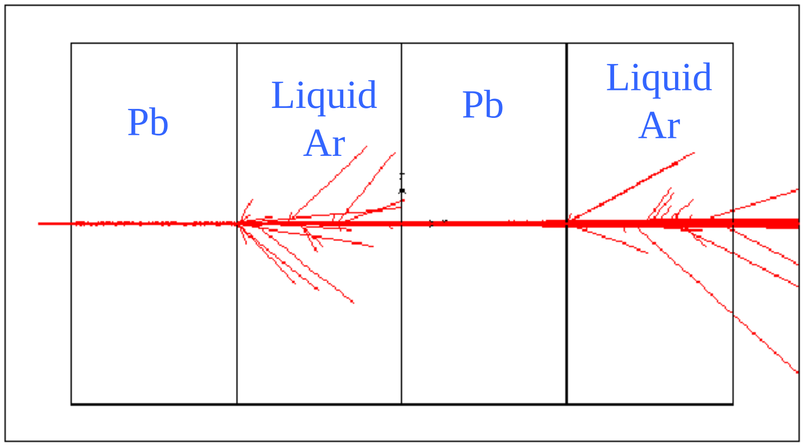


Geant4 Cuts

- No tracking cuts by default
- Unique production threshold definition via RANGE
- For a typical process (*G4hIonisation, G4eIonisation, …*) production threshold T_c subdivides continues and discrete part of energy loss:
  - Energy loss $\frac{dE}{dx} = n \int_0^{Tc} t \frac{d\sigma(t)}{dt} dt$
  - δ-electron production $\sigma = \int_{Tc}^{T\max} \frac{d\sigma}{dt} dt$
- By default energy loss is deposited at the step
- Optionally energy loss can be partially used
  - for generation of extra δ-electrons under the threshold when track is in vicinity of a geometry boundary (sub-cutoff)
  - for sampling of fluorescence and Auger–electrons emission

Effect of Production thresholds

500 MeV incident proton



Range threshold: 1.5 mm

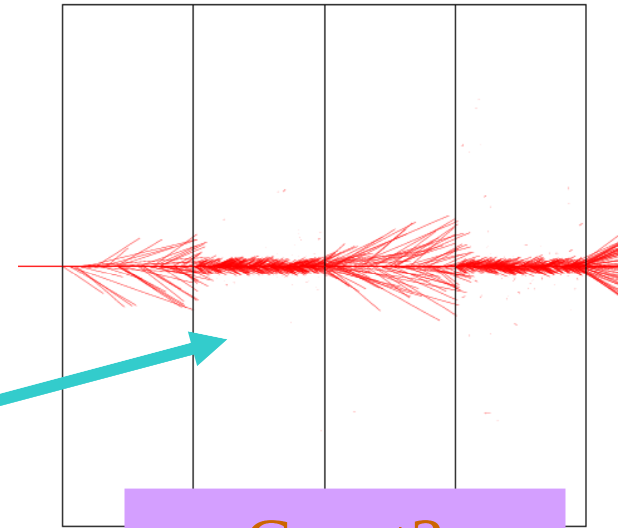
455 keV electron energy in liquid Ar

2 MeV electron energy in Pb

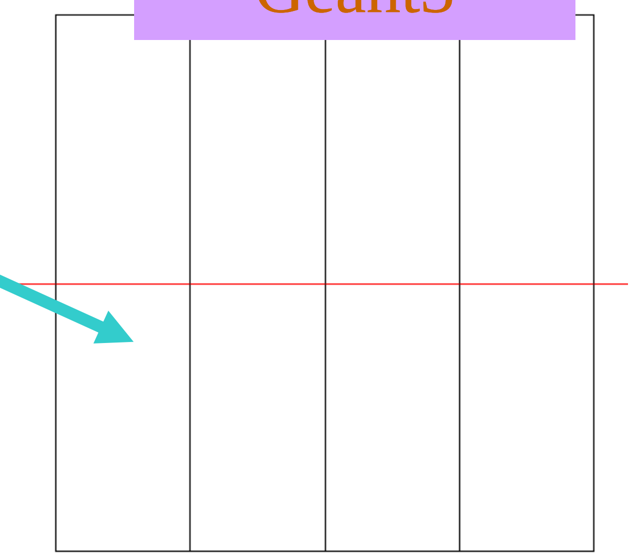
one must set the cut for delta-rays (DCUTE) either to the Liquid Argon value, thus producing many small unnecessary δ-rays in Pb,

or to the Pb value, thus killing the δ-rays production everywhere

DCUTE = 455 keV



Geant3



DCUTE = 2 MeV

What processes are using cuts?

- Energy thresholds for gamma are used in bremsstrahlung
- Energy thresholds for electrons are used in ionisation and e+e- pair production processes
- Energy threshold for positrons is used in the e+e- pair production process
- Energy thresholds for gamma and electrons are used optionally (“ApplyCuts” options) in all discrete processes
  - Photoelectric effect, Compton, gamma conversion
- Energy threshold for protons are used in processes of elastic scattering of hadrons and ions defining the threshold for kinetic energy of nuclear recoil
  - New feature available since December 2009

Comments

- Range cut approach was established for simulation of energy deposition inside solid or liquid media
  - Sampling and crystal calorimeters
  - Silicon tracking
- For specific user application if may be revised, for example, by defining different cuts in range for electron and gamma
  - Gaseous detectors
  - Muon system
- Tracking cuts may be useful (saving some CPU) for simulation of penetration via shielding or for simulation in non-sensitive part of the apparatus
  - Astrophysics applications

How to invoke EM physics in Geant4?

Physics List

- Physics Lists is the user class making general interface between physics and Geant4 kernel
  - It should include the list of particles
  - The G4ProcessManager of each particle maintains a list of processes
- There are 3 ordered lists of processes per particle which are active at different stage of Geant4 tracking:
  - AtRest (annihilation, …)
  - AlongStep (ionisation, bremsstrahlung, …)
  - PostStep (photo-electric, Compton, Cerenkov,….)
- Geant4 provided a set of different configurations of EM physics (G4VPhysicsConstructor) with physics_list library
- These constructors can be included into modular Physics List in user application (G4VModularPhysicsList)

EM Physics Constructors for Geant4 9.3

- G4EmStandardPhysics – default
- G4EmStandardPhysics_option1 – HEP fast but not precise
- G4EmStandardPhysics_option2 – Experimental
- G4EmStandardPhysics_option3 – medical, space
- G4EmLivermorePhysics
- G4EmLivermorePolarizedPhysics
- G4EmPenelopePhysics
- G4EmDNAPhysics

Combined Physics
Standard > 1 GeV
LowEnergy < 1 GeV

- Located at $G4INSTALL/source/physics_list/builders
- Advantage of using of these classes – they are tested on regular base and are used for regular validation

Example - G4EmStandard Physics

Only PostStep

- G4ProcessManager* pmanager

```
If ( particleName == “gamma”  ) {
    pmanager->AddDiscreteProcess(new G4PhotoElectricEffect);
    pmanager->AddDiscreteProcess(new G4ComptonScattering);
    pmanager->AddDiscreteProcess(new G4GammaConversion);
} else if ( particleName == “e+” ) {
    pmanager->AddProcess(new G4eMultipleScattering, -1,  1, 1);
    pmanager->AddProcess(new G4eIonisation,         -1,  2, 2);
    pmanager->AddProcess(new G4eBremsstrahlung,     -1,  3, 3);
    pmanager->AddProcess(new G4eplusAnnihilation,    0, -1, 4);
```

3 stages

- Numbers are process order;
  - G4Transportation is the 1st (order = 0) for AlongStep and PostStep
- “-1” means that the process is not active

Example G4EmPenelopePhysics

- Process class G4PhotoElectricEffect
- Default model in g4 9.3 is G4PEEffectModel (EM Standard)
- There are alternative Livermore and Penelope models
- Example of the combined EM Physics Lists:

```
………
G4double limit = 1.0*GeV;
If ( particleName == "gamma"  ) {
  G4PhotoElectricEffect* pef= new G4PhotoElectricEffect();
  G4PenelopePhotoElectricModel*  aModel = new
        G4PenelopePhotoElectricModel();
   aModel->SetHighEnergyLimit(limit);
   pef->AddEmModel(0, aModel);              // 1st parameter - order
   pmanager->AddDiscreteProcess(pef);
…….
```

How to extract Physics ?

- Possible to retrieve Physics quantities using a G4EmCalculator object
- Physics List should be initialized
- Example for retrieving the total cross section of a process with name procName:
  for particle partName and material matName

```
#include "G4EmCalculator.hh"
...
G4EmCalculator emCalculator;
G4Material* material =
  G4NistManager::Instance()->FindOrBuildMaterial(“matName);
G4double density = material->GetDensity();
G4double massSigma = emCalculator.ComputeCrossSectionPerVolume
   (energy,particle,procName,material)/density;
G4cout << G4BestUnit(massSigma, "Surface/Mass") << G4endl;
```

A good example: $G4INSTALL/examples/extended/electromagnetic/TestEm14
   Look in particular at the RunAction.cc class

Let us start exercises of task3a