Geant 4

Particles and Processes

http://cern.ch/geant4

The full set of lecture notes of this Geant4 Course is available at

http://www.ge.infn.it/geant4/events/nss2003/geant4course.html

Physics

From the Minutes of LCB (LHCC Computing Board) meeting on 21/10/1997:

"It was noted that experiments have requirements for **independent, alternative physics models**. In Geant4 these models, differently from the concept of packages, allow the user to **understand** how the results are produced, and hence improve the **physics validation**. Geant4 is developed with a modular architecture and is the ideal framework where existing components are integrated and new models continue to be developed."

Physics: general features

- Ample variety of physics functionalities
- Uniform treatment of electromagnetic and hadronic processes
- Abstract interface to physics processes
  - Tracking independent from physics
- Distinction between processes and models
  - often multiple models for the same physics process (complementary/alternative)
- Open system
  - Users can easily create and use their own models
- <u>Transparency</u> *(supported by encapsulation and polymorfism)*
  - Calculation of cross-sections independent from the way they are accessed (data files, analytical formulae etc.)
  - Distinction between the calculation of cross sections and their use
  - Calculation of the final state independent from tracking
- Modular design, at a fine granularity, to expose the physics
- Explicit use of units throughout the code
- Public distribution of the code, from one reference repository worldwide

Data libraries & Units

- Systematic collection and evaluation of experimental data from many sources worldwide

- Databases
  – ENDF/B, JENDL, FENDL, CENDL, ENSDF,JEF, BROND, EFF, MENDL, IRDF, SAID, EPDL, EEDL, EADL, SANDIA, ICRU etc.

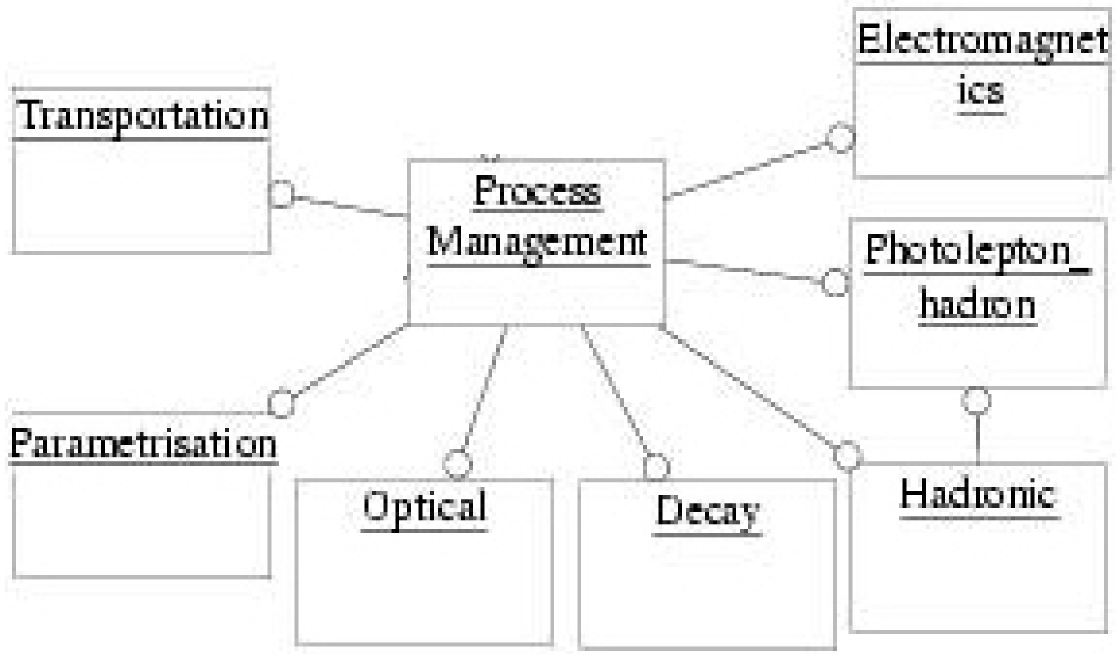
- Collaborating distribution centres
  – NEA, LLNL, BNL, KEK, IAEA, IHEP, TRIUMF, FNAL, Helsinki, Durham, Japan etc.

- The use of evaluated data is important for the validation of physics results of the experiments

- Geant4 is independent from the system of units
  – all numerical quantities expressed with their units explicitly

Processes

- Processes describe how particles interact with material or with a volume
- Three basic types
  - **At rest** process
    (eg. decay at rest)
  - **Continuous** process
    (eg. ionisation)
  - **Discrete** process
    (eg. Compton scattering)



- Transportation is a process
  - interacting with volume boundary
- A process which requires the shortest interaction length limits the step

Outline

- What is tracked

  G4ParticleDefinition
  G4DynamicParticle
  G4Track

- The process interface

  G4VProcess
  How processes are used in tracking

- The production cuts

  Why production cuts are needed
  The cuts scheme in Geant4

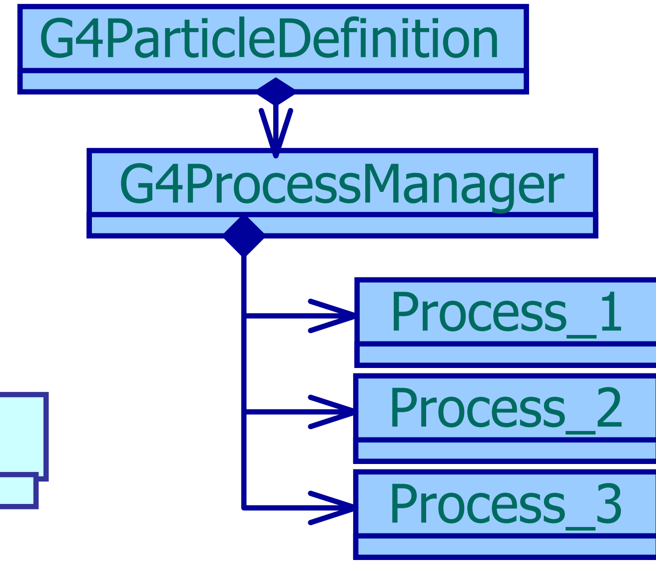
- Building the PhysicsLists

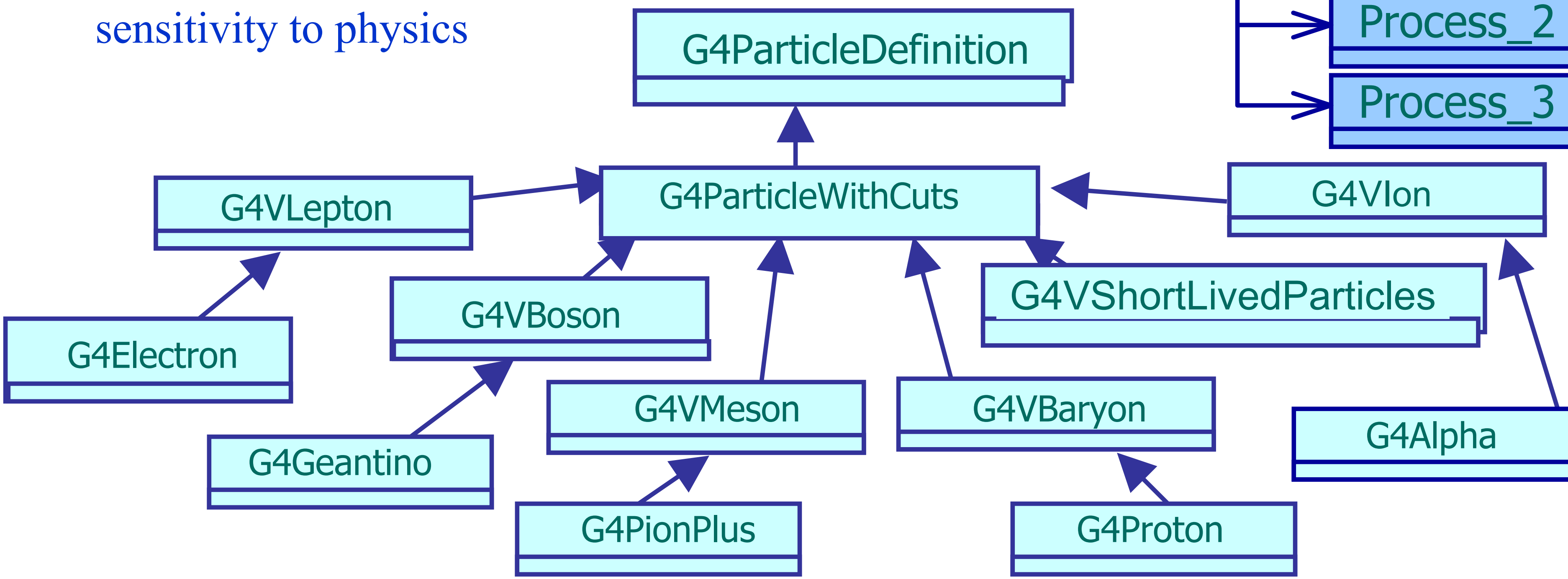
  G4VUserPhysicsList
  Concrete physics lists

G4ParticleDefinition

- intrisic particle properties: *mass, width, spin, lifetime…*
- sensitivity to physics

- This is realized by a G4ProcessManager attached to the G4ParticleDefinition
- G4ProcessManager manages the list of processes the user wants the particle to be sensitive to
- G4ParticleDefinition does not know by itself its sensitivity to physics





G4ParticleDefinition is the base class for defining concrete particles

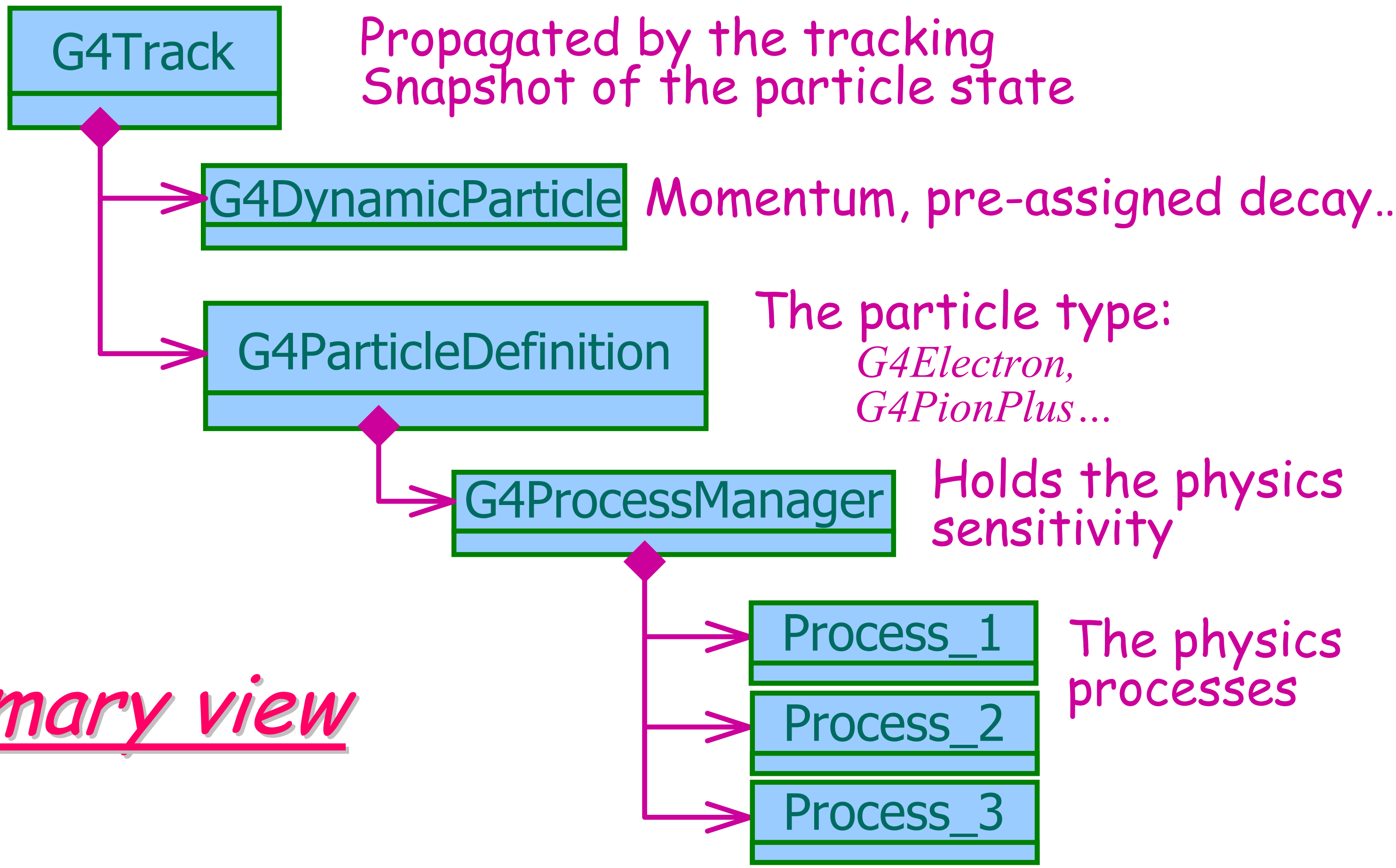
More about particle design

G4DynamicParticle

- Describes the purely dynamic part *(i.e. no position, nor geometrical information…)* of the particle state:
  - momentum, energy, polarization
- Holds a G4ParticleDefinition pointer
- Retains eventual pre-assigned decay information
  - decay products
  - lifetime

G4Track

- Defines the class of objects propagated by Geant4 tracking
- Represents a snapshot of the particle state
- Aggregates
  - a G4ParticleDefinition
  - a G4DynamicParticle
  - geometrical information:
    - position, current volume …
  - track ID, parent ID;
  - process which created this G4Track
  - weight, used for event biaising



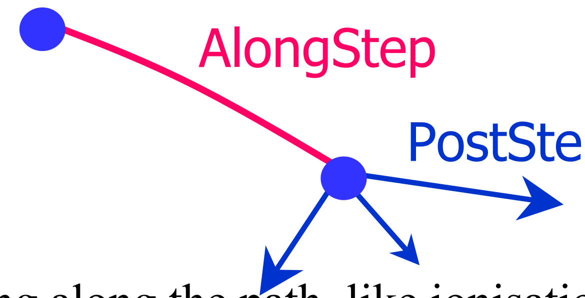
Summary view

The classes involved in building the PhysicsList are:

- the G4ParticleDefinition concrete classes
- the G4ProcessManager
- the processes

G4VProcess

Abstract class defining the common interface of all processes in Geant4



- Define three kinds of actions:
  - AtRest actions: decay, annihilation …
  - AlongStep actions: continuous interactions occuring along the path, like ionisation
  - PostStep actions: point-like interactions, like decay in flight, hard radiation…
- A process can implement *any combination* of the three AtRest, AlongStep and PostStep actions: eg: decay = AtRest + PostStep
- Each action defines two methods:
  - GetPhysicalInteractionLength()

    used to limit the step size
    - *either because the process triggers an interaction or a decay*
    - *or in other cases, like fraction of energy loss, geometry boundary, user's limit…*
  - DoIt()
    - implements the actual action to be applied to the track
    - implements the related production of secondaries

Processes, ProcessManager and Stepping

- G4ProcessManager retains three vectors of actions:
  - one for the AtRest methods of the particle
  - one for the AlongStep ones
  - one for the PostStep actions
  - *these are the vectors which the user sets up in the PhysicsList and which are used by the tracking*

- The stepping treats processes generically
  - it does not know which process it is handling
- The stepping lets the processes
  - cooperate for AlongStep actions
  - compete for PostStep and AtRest actions

- Processes emit also signals to require particular treatment:
  - notForced: normal case
  - forced: PostStepDoIt action applied anyway;
  - conditionallyForced: PostStepDoIt applied if AlongStep has limited the step

Invocation sequence of processes: particle in flight

- At the beginning of the step, determine the step length
  - consider all processes attached to the current G4Track
  - define the step length as the smallest of the lengths among
    - all AlongStepGetPhysicalInteractionLenght()
    - all PostStepGetPhysicalInteractionLength()
- Apply all AlongStepDoIt() actions at once
  - changes computed from particle state at the beginning of the step
  - accumulated in G4Step
  - then applied to G4Track, by G4Step
- Apply PostStepDoIt() action(s) sequentially, as long as the particle is alive
  - apply PostStepDoIt() of the process which proposed the smallest step length
  - apply *forced* and *conditionnally forced* actions

Invocation sequence of processes: particle at rest

- If the particle is at rest, is stable and cannot annihilate, it is killed by tracking
  - more properly said: if a particle at rest has no *AtRest* actions defined, it is killed
- Otherwise determine the lifetime
  - Take the smallest time among all AtRestGetPhysicalInteractionLenght()
  - Called *physical interaction length*, but it returns a time
- Apply the AtRestDoIt() action of the process which returned the smallest time

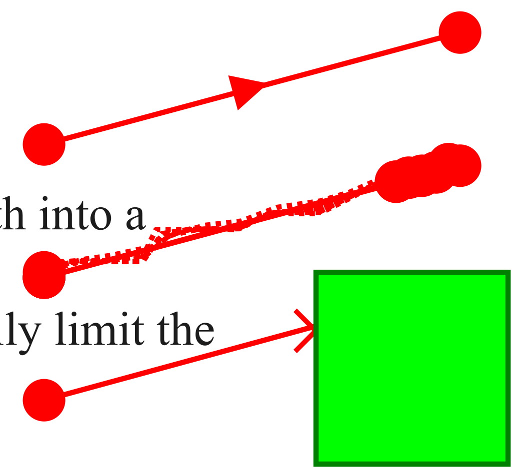
Processes ordering

- Ordering of following processes is critical:
  - assuming n processes, the ordering of the AlongGetPhysicalInteractionLength 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 limit the step



- Other processes ordering usually do not matter

Cuts in Geant4

- In Geant4 there are no tracking cuts
  - particles are tracked down to a zero range/kinetic energy

- Only production cuts exist
  - i.e. cuts allowing a particle to be born or not

Why are production cuts needed ?

- Some electromagnetic processes involve infrared divergences
  - this leads to an infinity [huge number] of smaller and smaller energy photons/electrons *(such as in Bremsstrahlung, δ-ray production)*
  - production cuts limit this production to particles above the threshold
  - the remaining, divergent part is treated as a continuous effect (i.e. *AlongStep* action)

Range vs. energy production cuts

- The production of a secondary particle is relevant if it can generate visible effects in the detector
  - otherwise *“local energy deposit”*
- A range cut allows to easily define such visibility
  - *“I want to produce particles able to travel at least 1 mm”*
  - criterion which can be applied uniformly across the detector (whole or “region”)
- The same energy cut leads to very different ranges
  - for the same particle type, depending on the material
  - for the same material, depending on particle type
- The user specifies a unique range cut in the PhysicsList
  - this range cut is converted into energy cuts
  - each particle *(G4ParticleWithCut)* converts the range cut into an energy cut, for each material
  - processes then compute the cross-sections based on the energy cut

Effect of production thresholds

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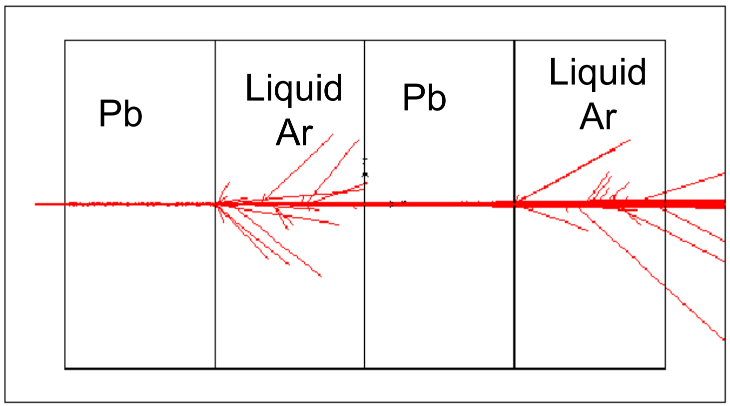
500 MeV incident proton



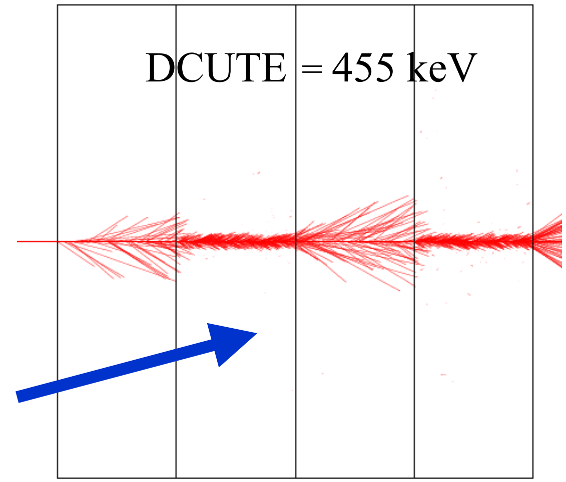
Threshold in range: 1.5 mm

455 keV electron energy in liquid Ar

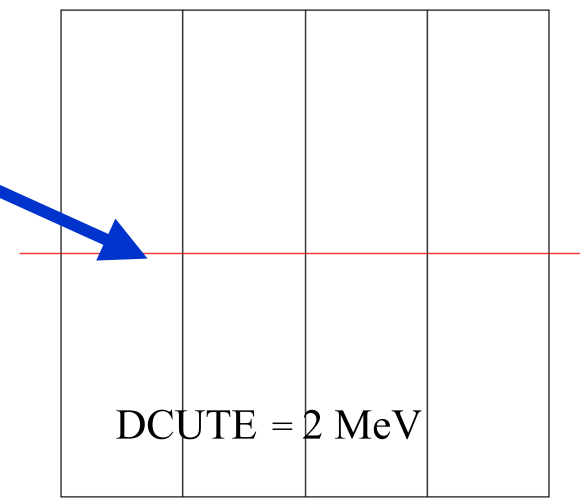
2 MeV electron energy in Pb

In Geant3

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



Violations of the production threshold

- In some cases particles are produced even if they are below the production threshold

- This is intended to let the processes *do the best they can*

- It happens typically for
  - decays
  - positron production:
    - in order to simulate the resulting photons from the annihilation
  - hadronic processes:
    - since no infrared divergences affect the cross-sections

- *Note these are not "hard-coded" exceptions, but a sophisticated, generic mechanism of the tracking*

G4VUserPhysicsList

- It is one of the mandatory user classes *(abstract class)*
- Pure virtual methods
  - ConstructParticles()
  - ConstructProcesses()
  - SetCuts()

to be implemented by the user in his/her concrete derived class

Electromagnetic physics

- electrons and positrons
- γ, X-ray and optical photons
- muons
- charged hadrons
- ions

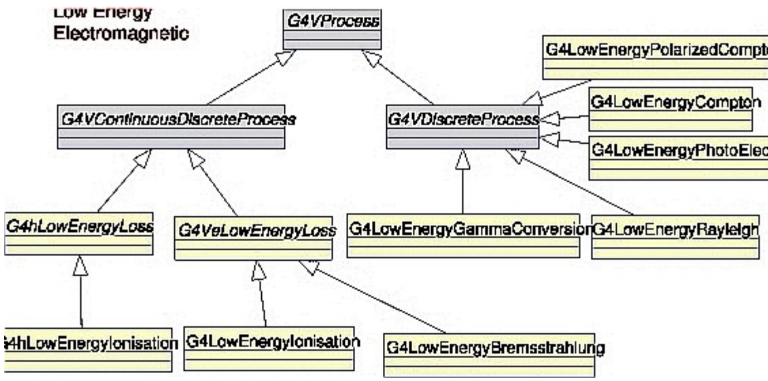
Comparable to Geant3 already in the α release (1997)

Further extensions *(facilitated by the OO technology)*

- High energy extensions
  - needed for LHC experiments, cosmic ray experiments…
- Low energy extensions
  - fundamental for space and medical applications, dark matter and ν experiments, antimatter spectroscopy etc.
- Alternative models for the same process

energy loss

- Multiple scattering
- Bremsstrahlung
- Ionisation
- Annihilation
- Photoelectric effect
- Compton scattering
- Rayleigh effect
- γ conversion
- e^+e^- pair production
- Synchrotron radiation
- Transition radiation
- Cherenkov
- Refraction
- Reflection
- Absorption
- Scintillation
- Fluorescence
- Auger



All obeying to the same abstract Process interface → transparent to tracking

Hadronic physics

- Completely different approach w.r.t. the past (Geant3)
  - native
  - transparent
  - no longer interface to external packages
  - clear separation between data and their use in algorithms
- Cross section data sets
  - transparent and interchangeable
- Final state calculation
  - models by particle, energy, material
- Ample variety of models
  - the most complete hadronic simulation kit on the market
  - Alternative/complementary models
  - it is possible to mix-and-match, with fine granularity
  - data-driven, parameterised and theoretical models
- Consequences for the users
  - no more confined to the black box of one package
  - the user has control on the physics used in the simulation, which contributes to the validation of experiment's results

Summary

- Transparency and modularity are the key characteristics of Geant4 physics
- Ample variety of processes and models
  - Openness to extension and evolution thanks to the OO technology
- The PhysicsList exposes, deliberately, the user to the choice of physics *(particles + processes)* relevant to his/her application
  - This is a critical task, but guided by the framework
  - Examples can be used as starting point
- Physics processes and models are documented in Geant4 Physics Reference Manual