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Tracking

Witold Pokorski, Alberto Ribon
CERN EP/SFT

GEANT4
A SIMULATION TOOLKIT

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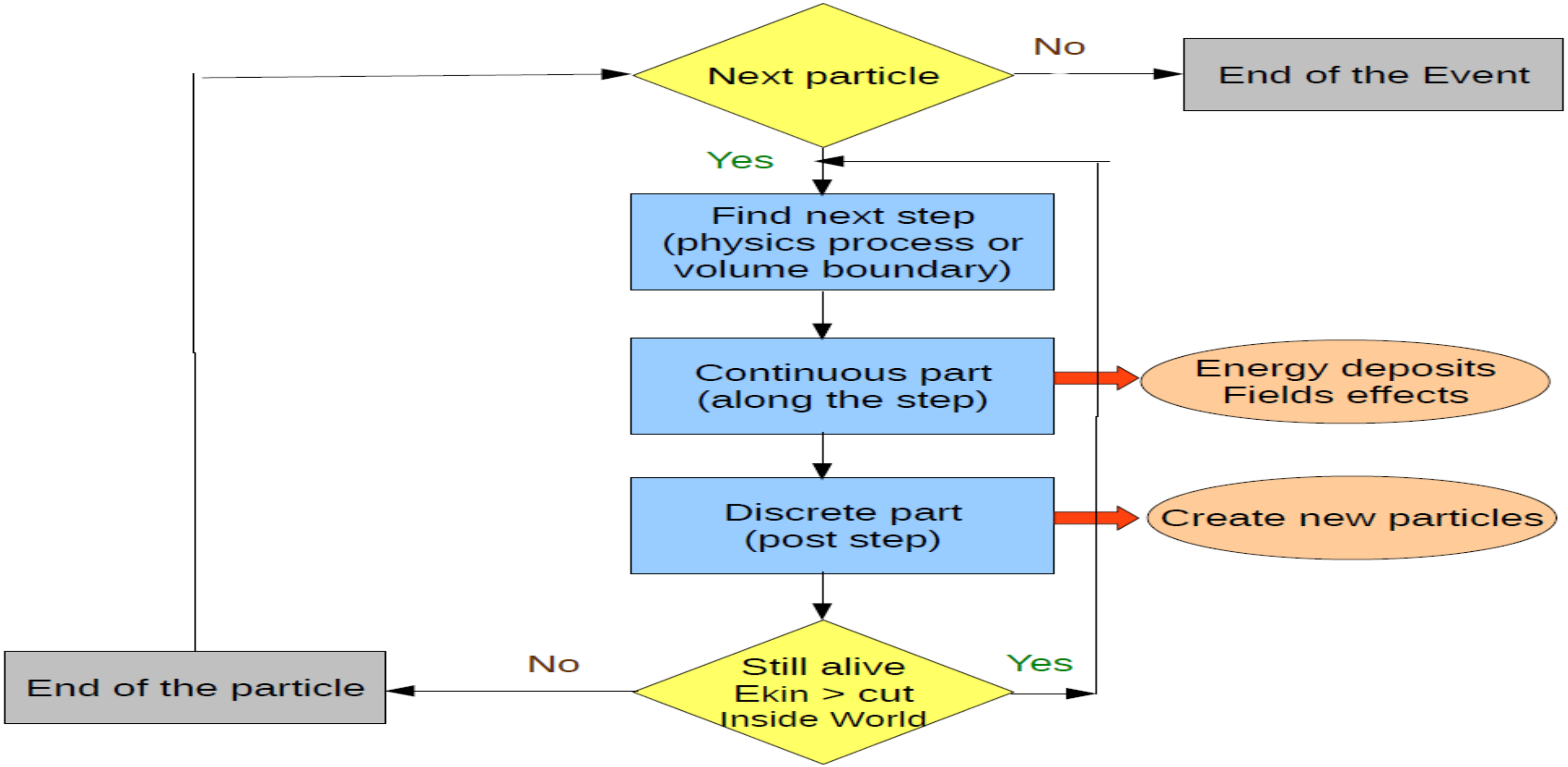
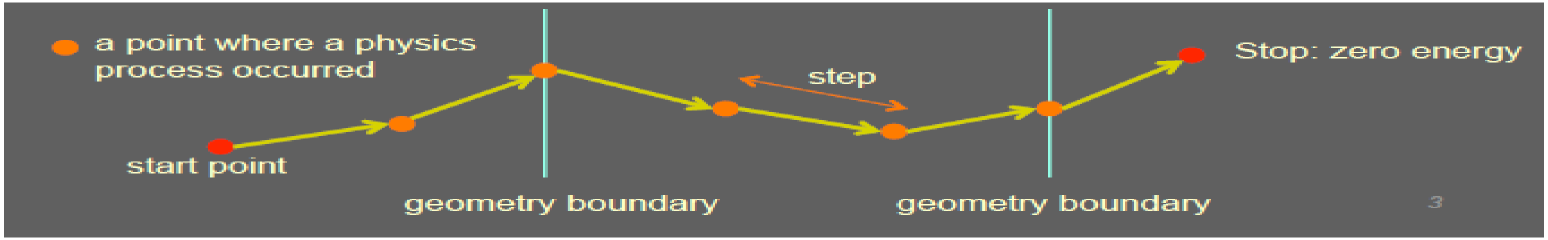
Where to Find Information

- Geant4 User Guides
  - **http://geant4.web.cern.ch/support/user_documentation**
  - User's Guide: For Application Developers
  - Physics Reference Manual
  - ...
- User Support
  - **http://geant4.web.cern.ch/support**
  - Bug reports and fixes
  - ...
- User Forum
  - **https://geant4-forum.web.cern.ch/**
  - Discussion between users and developers


Next particle
No
End of the Event
Yes
Find next step
(physics process or
volume boundary)
Continuous part
(along the step)
Energy deposits
Fields effects
Discrete part
(post step)
Create new particles
No
End of the particle
Still alive
Ekin > cut
Inside World
Yes


a point where a physics
process occurred
step
Stop: zero energy
start point
geometry boundary
geometry boundary

Classical vs Quantum approach

- In Geant4, a particle that flies through a detector is treated as a **classical particle**, i.e. **not** a **wave function**, but a point-like object which has a well-defined momentum at each instant:
  - Space-time position **(x, y, z, t)**
  - Energy-momentum **(p_x, p_y, p_z, E)**

  This is a reasonable approximation, given that in most practical situations particles are seen as "**tracks**" in macroscopic detectors

- Geant4 is based on a **semi-classical** approach, because the particles are treated classically, but their interactions - cross sections and final states - take often into account the *results* (not the computation) of quantum-mechanical effects

Run, Event, Particle, Track, Step, StepPoint, Trajectory, TrajectoryPoint

Run in Geant4

- A **run** is a collection of events
  - Consists of one event loop
  - Starts with the ***/run/beamOn*** command
- Within a run, conditions do not change, *i.e.* the user cannot change:
  - the detector setup
  - the settings of physics processes
- A run in Geant4 is represented by the class **G4Run** or a user-defined class derived from it
- **G4RunManager** is the manager class
- **G4UserRunAction** is the optional user hook

Event in Geant4

- An **event** is the basic unit of simulation in Geant4
- At beginning, primary tracks are generated and pushed into a stack
- A track is popped up from the stack one by one and tracked; resulting secondary tracks are pushed into the stack
  - This tracking lasts as long as the stack has a track
- When the stack becomes empty, the event is over
- The class **G4Event** represents an event; it has the following objects at the end of its (successful) processing:
  - List of primary vertices and particles (as input)
  - Hits and Trajectory collections (as output)
- **G4EventManager** is the manager class
- **G4UserEventAction** is the optional user hook

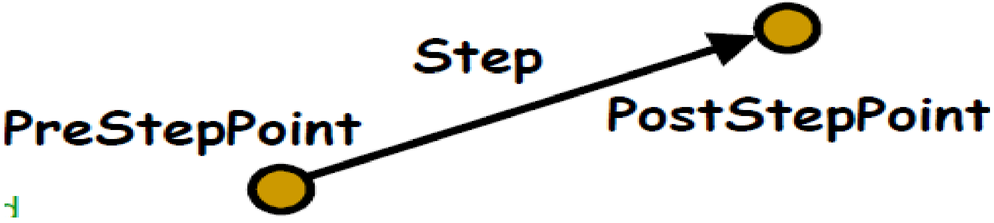
Particle in Geant4

- A **particle** in Geant4 is represented by 3 layers of classes
- **G4Track**
  - Position, geometrical information, *etc.*
  - This is a class representing a particle to be tracked
- **G4DynamicParticle**
  - "Dynamic" physical properties of a particle: momentum, energy, spin...
  - Each G4Track object has its own G4DynamicParticle object
  - This is a class representing an individual particle
- **G4ParticleDefinition**
  - "Static" properties of a particle: charge, mass, lifetime, *etc.*
  - **G4ProcessManager** describes the processes involving this particle
  - All G4DynamicParticle objects of the same kind of particle share the same G4ParticleDefinition

Track in Geant4

- A **track** is a snapshot of a particle
  - It has the physical quantities corresponding only to the current instance; it does not record previous quantities
  - Step is a “delta” information to a track; a track is not a collection of steps; instead, a track is updated by steps
- A track object is deleted when:
  - It goes out of the world volume
  - It disappears (*e.g.* it decays, or it has an inelastic scattering)
  - For an electron, it reaches the “lowest kinetic energy” (1 keV or 100 eV); for any other type of particle, it goes down to zero kinetic energy and no additional “AtRest” process is required
  - The user decides to kill it artificially
- No track object persists at the end of an event
  - For recording tracks, use trajectory class objects
- **G4Track** class represents a track; **G4TrackingManager** is the manager class
- **G4UserTrackingAction** is the optional user hook

Step in Geant4



- A step has two points and also “delta” information of a particle (energy loss on the step, time-of-flight spent by the step, *etc.*)
  - A point is represented by the **G4StepPoint** class
- Each point knows the volume (and material). In case a step is limited by a volume boundary, the end point physically stands on the boundary, and it logically belongs to the next volume
  - Because one step knows the materials of two volumes, boundary processes such as transition radiation or refraction can be simulated
- **G4Step** represents a step; **G4SteppingManager** is the manager class
- **G4UserSteppingAction** is the optional user hook

Trajectory and Trajectory Point in Geant4

- Track does not keep its trace.
  No track object persists at the end of an event
- **G4Trajectory** is the class which copies some of the **G4Track** information and persists till the end of an event
- **G4TrajectoryPoint** is the class which copies some of the **G4Step** information and persists till the end of an event
  - G4Trajectory has a vector of G4TrajectoryPoint objects
  - With the command ”***/tracking/storeTrajectory 1***“ at the end of event processing, G4Event has a collection of G4Trajectory objects; useful mainly for visualization
- Be careful not to store too many trajectories: memory growth
- G4Trajectory and G4TrajectoryPoint as provided by Geant4 store only the minimum information
  - Users can create their own trajectory / trajectory point to store more information

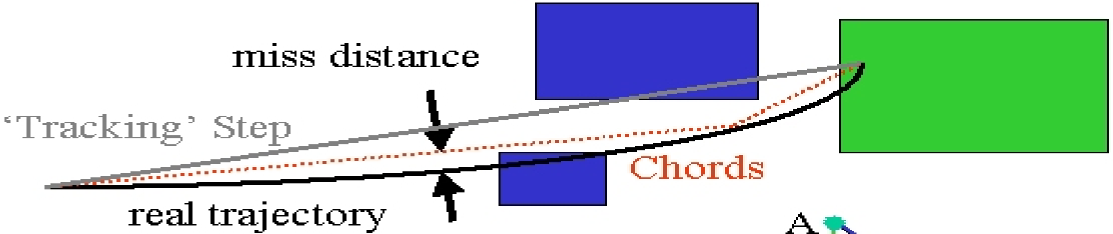
Tracking

Propagation in a Field (1/4)

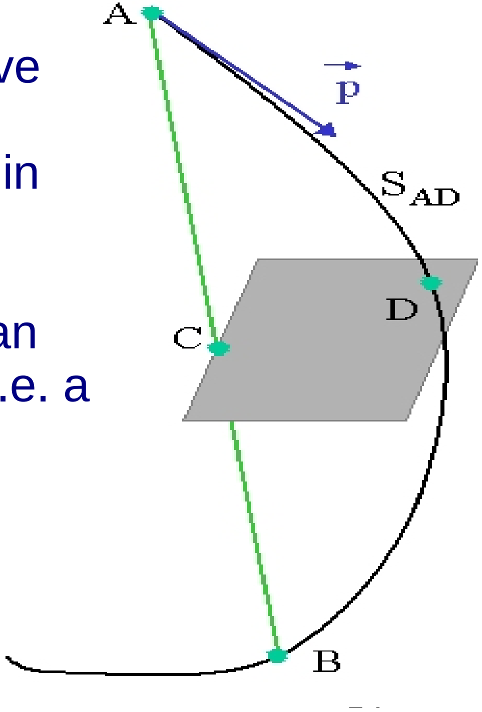
- Geant4 is capable of propagating tracks in a variety of fields:
  - **magnetic**, **electric**, **electromagnetic**, and **gravity** fields
  - uniform or non-uniform (in space and/or time)
  - with user-defined accuracy (trade-off between accuracy and performance)
- In order to propagate a track inside a field, the equation of motion of the particle in the field is integrated
  - This is done using approximated, numerical methods
  - In ***examples/extended/field/*** you can see some examples of magnetic, electric and gravity fields
  - The user can also create their own type of field, inheriting from **G4VField**, and specifying its associated Equation of Motion, inheriting from the class **G4EqRhs**

Propagation in a Field (2/4)

The curved path, in a tracking step, is broken up into linear chord segments



miss distance : maximum estimated distance between curve and chord



delta intersection : maximum estimated distance (CD) between the curve and chord intersection on a volume boundary.
This is an important parameter, related to the potential systematic errors in the momentum of reconstructed tracks.

delta one step : maximum estimated distance between the endpoint of an 'ordinary' integration step, which does not intersect a volume boundary (i.e. a physics step), and the curve endpoint

These are some of the parameters of the G4FieldManager which the user can tune to optimise between accuracy and performance

Propagation in a Field (3/4)

- Choosing a field :
  - Uniform fields: **G4UniformMagField**, **G4UniformElectricField**, **G4UniformGravityField**
  - Non-uniform fields: concrete classes derived from: **G4MagneticField**, **G4ElectricField**, **G4ElectroMagneticField**, **G4Field** must define the method: *void GetFieldValue(...)*
- Choosing a stepper :
  - Numerical integration is used to compute the motion in a general field. There are many general steppers from which to choose, of low and high order, and specialized steppers for pure magnetic fields
  - General: **G4DormandPrince745** (default), **G4ClassicalRK4** , **G4SimpleRunge** , **G4SimpleHeum** , **G4CashKarpRKF45**
  - Specialized for pure magnetic fields: **G4NystromRK4** , **G4HelixImplicitEuler** , **G4HelixExplicitEuler** , **G4HelixSimpleRunge**, *etc.*

Propagation in a Field (4/4)

- Example of how to create a global magnetic field:

```
G4UniformMagField* magField = new G4UniformMagField(G4ThreeVector(0.,0.,4.*Tesla));
G4FieldManager* fieldMgr =
  G4TransportationManager::GetTransportationManager()->GetFieldManager();
fieldMgr->SetDetectorField( magField );
fieldMgr->CreateChordFinder( magField );   // with default parameters
```

- Example of how to create a local magnetic field

```
logicVolume->SetFieldManager( localFieldManager, true );
```

- For more examples see: ***examples/extended/field/***
  - Tracking in magnetic field
  - Tracking in electric field
  - Tracking in overlapping fields (electric and magnetic)
  - Tracking in gravity field

Production Cuts (1/2)

- Production cuts for secondaries can be specified as range cuts, which are converted (at initialization) into energy thresholds (material-dependent) for secondary **gamma**s, **electron**s, positrons, “**proton**s”
- For **electron**s and **gamma**s, production cuts are absolutely needed in, respectively, ionization and bremsstrahlung processes to avoid the infrared singularity
  - $\sigma_{brems} \sim 1/E_\gamma$; $\sigma_{ionization} \sim 1/(T_e{*}T_e)$
- For positrons, the production cut is almost always ignored
  - i.e. positrons are always produced in e+e- pair-production, regardless of their energy (range) (because, in matter, they annihilate (even at rest) and always produce a pair of gammas that can fly...)
  - except for very high production cuts on gamma (greater than the electron mass, which is the minimum energy of each of the two gammas generated by a positron-electron annihilation…)
    - Use-case is for underground experiments, stopping positron in the mountain above

Production Cuts (2/2)

- For "**protons**" , it has the following meaning:
  if **any hadron** (not necessarily a proton) **or ion** scatters elastically on a nucleus (of the detector material), this (recoiling, target) nucleus becomes a new G4Track (*i.e.* a particle to be transported by Geant4) only if its kinetic energy is above the value:

  *(**100* keV**) * proton_production_cut_in_mm*

  - *This threshold allows to save the CPU time that would be otherwise required to track a nucleus that would move less than a few hundreds nanometers !*

- Whenever a secondary particle (γ, e−, A) is not produced because it is below the production cut, its kinetic energy contributes to the so-called **"**continuous**"** or **"**along-the-step**"** energy deposition
  - As for the concept of "step", also this "continuous / along-the-step" energy deposition does not correspond to anything physically
  - But it is a convenient artifact to speed up the simulation

Which Processes are Using Cuts?

- Energy threshold for **gammas** is used in **bremsstrahlung**
- Energy threshold for **electrons** is used in **ionisation** and e+ e− pair−production process
- Energy thresholds for **gammas** & **electrons** can be used in **all discrete electromagnetic processes** (*e.g.* Compton, photoelectric, *etc.*) if the “ApplyCuts” option is activated

  /process/em/applyCuts *true*

- *Energy threshold for* positrons *is used in the e+e− pair−production process*
- Energy threshold for “**protons**“ − indeed a energy threshold for nuclear recoils − is used in case of **elastic scattering** of **any hadron or ion** projectile on a target nucleus

How to Set Production Cuts?

- A range cut value is set by default to **0.7 mm** in reference physics lists
  - Overriding the default of **1.0 mm** set in the base class
- This can be changed via UI (User Interface) command, *e.g.*

  /run/setCut *0.05 mm*

- There is a default minimum energy threshold, **990 eV** , which can be changed, *e.g.* ***/cuts/setLowEdge*** *500 eV*
- You can set a different value for each particle type, *e.g.*

  /run/setCutForAGivenParticle e- *0.05 m*
  /run/setCutForAGivenParticle gamma *1.0 cm*
  /run/setCutForAGivenParticle e+ 0.01 mm
  /run/setCutForAGivenParticle proton *0.2 mm*

- Production cuts can be set globally or per-region
- For complex detectors, the optimization of the range cuts per region is crucial for the CPU performance of the simulation !

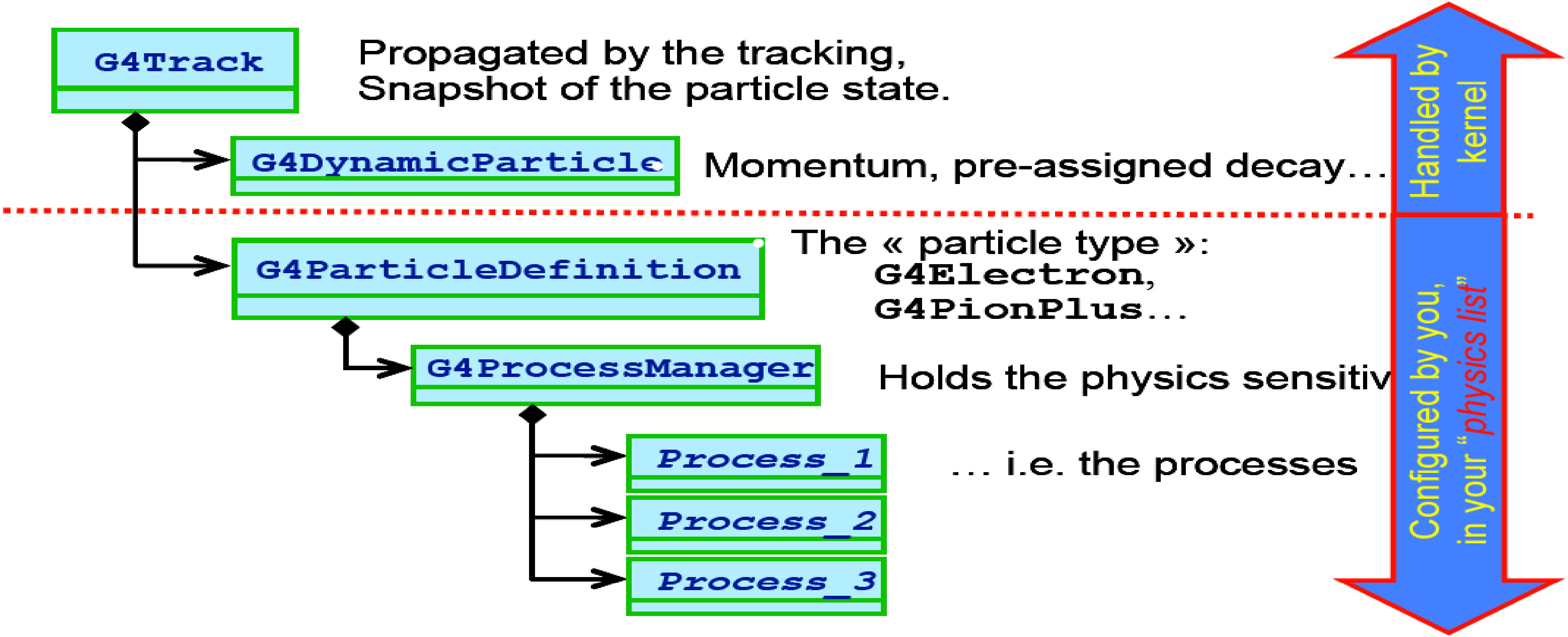
Special Tracking Cuts

- By default in Geant4, there are only production cuts, and **not tracking cuts** (except for electrons): the produced particles are tracked down to zero kinetic energy (range)
  - The treatment is reliable down to ~1 keV , below it is approximated
  - Electrons are killed when reaching **1 keV** (in default, Opt0, EM option), or **100 eV** (in more precise, Opt3 and Opt4, EM options)
- For optimization reasons, a user may limit the tracking of particular particle types in specified volumes
- Special user cuts are registered in the G4UserLimits class, associated to logical volumes. The current default list is:
  - max allowed step size
  - max total track length
  - max total time of flight
  - min kinetic energy
  - min remaining range

For an example, see: ***examples/basic/B2***

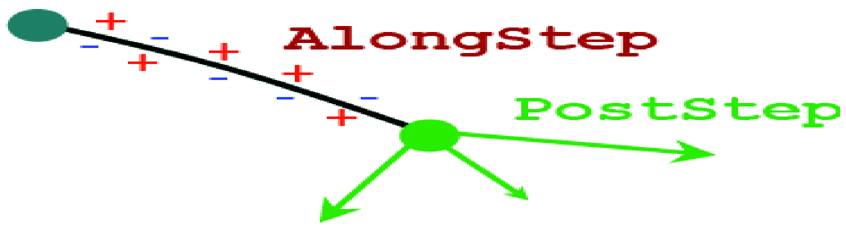
Processes

Track and Processes



Processes : 3 kinds of Actions

- Abstract class G4VProcess defines common interface of all processes
  - including Transportation
- Defines 3 kinds of actions:
  - **AtRest** actions
    - Decay at rest, e+ annihilation at rest, nuclear capture at rest, *etc.*
  - **AlongStep** actions
    - "Continuous" energy deposition (= production below threshold); fields' effect
  - **PostStep** actions
    - In-flight decays and interactions



- G4ProcessManager has 3 vectors of actions (per particle-type):
  - one for **AtRest** actions : these processes compete
  - one for **AlongStep** actions : these processes cooperate
  - one for **PostStep** actions : these processes compete

G4VProcess : action methods

- A process will implement any combination of the 3 actions :
  - **AtRest**
  - **AlongStep**
  - **PostStep**

  e.g. 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, *etc.*
      - The cross section for a in-flight physics process, or the mean lifetime for an at-rest process
  - **DoIt()**
    - Implements the **actual action** to be applied to the track
      - Typically the generation of the final state

Ordering of the Processes

- Process ordering, in general, is not critical…
- … except for multiple-scattering and transportation
- Assuming *n* processes, the ordering of the AlongStepGetPhysicalInteractionLength should be:
  - [n-2] …
  - [n-1] multiple scattering (before last)
  - [n] transportation (last)
- Why?
  - Processes return a "true path length"
  - 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