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# Particles and Processes in Geant4

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Geant4 Advanced Course

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# Outline

- Geant4 interface to physics
  - Geant4 basic interfaces to physics
  - Geant4 particles
  - Geant4 processes
  - Physics Lists
- Elecromagnetic (EM) physics
  - EM physics overview
  - EM physics constructors
  - User interface to EM physics

# Geant4 basic interface to physics

- The interface of Geant4 kernel to physics is abstract
- Base physics abstract classes are following:
  - The **`G4ParticleDefinition`** objects shared between threads
  - The **`G4VProcess`** thread local objects
  - The **`G4ProcessManager`** thread local interface class
- Configuration of physics is prepared in the G4VUserPhysicsList mandatory user class
- These interfaces are stable for ~20 years allowing users to work with different Geant4 versions and providing a basis for new developments
  - Concrete physics is implemented in physics models and cross section classes
  - Alternative models and cross sections are provided in Geant4 libraries
  - A user may be also a developer of a custom particle, process, physics model, or cross section

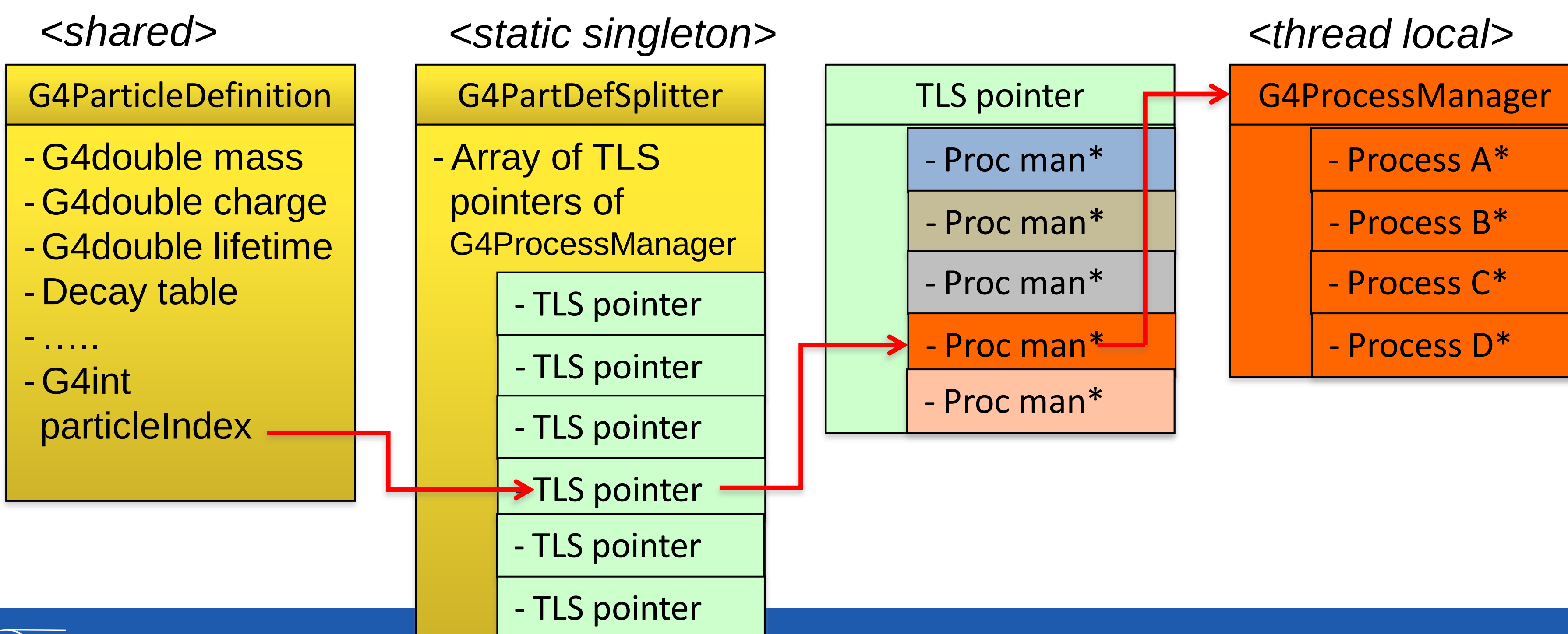
# GEANT4 PARTICLES

# Geant4 particles

- G4ParticleDefinition is the main object keeping static information about particles
  – Name, mass, charge, quantum numbers, decay table….
- “Stable” particles
  – Leptons: $e^{\pm}$, $\mu^{\pm}$, ….
  – Bosons: G4Gamma, G4OpticalPhoton, ….
  – Geantino is a particle without any interaction
  – “Stable” hadrons: $\pi^{\pm}$, $K^{\pm}$, ….
  – Light ions: d, t, $^{3}He$, $^{4}He$
  – G4GenericIon is used to define physics for all other ions
- “Unstable” hadrons normally do not tracked by Geant4 but used internally by hadronic models
  – Quarks, di-quarks, ρ(770), ω(783)…

# Split class – case of particle definition

- In Geant4, each particle type has its own dedicated object of G4ParticleDefinition class.
  - Static quantities : mass, charge, life time, decay channels, etc.,
    - To be shared by all threads.
  - Dedicated object of G4ProcessManager : list of physics processes this particular kind of particle undertakes.
    - Physics process object must be thread-local.

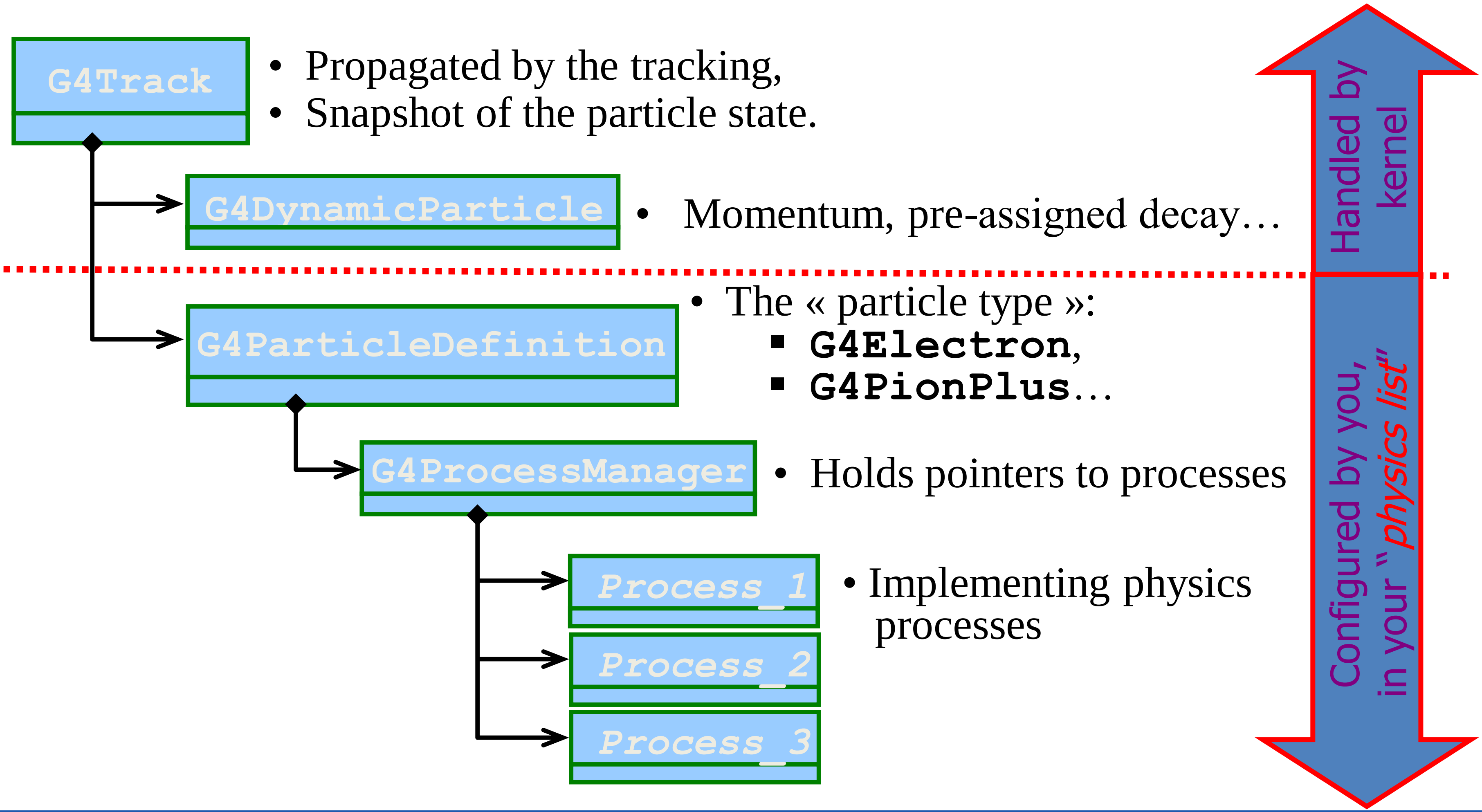


# GEANT4 PROCESSES

# Geant4 process

- Processes are classified as:
  - Electromagnetic
  - Hadronic
  - Decay
  - Parameterized
  - Transportation
  - ……..
- Any process has process has type and sub-type
  - const G4String& G4VProcess::GetProcessType();
  - G4int G4VProcess::GetSubType();
    - This method is recommended to be used for MC truth
    - The list of sub-types are only updated with new processes
- Any process may be initialized using virtual methods:
  - **G4bool IsApplicable(const G4ParticleDefinition &);**
    - Used to check if a process can handle the given particle type
  - void PreparePhysicsTable(const G4ParticleDefinition&);
  - void BuildPhysicsTable(const G4ParticleDefinition&);
    - Used for initialization of internal data of the process before run

# From G4Track to processes



# Geant4 Physics: Electromagnetic

- the standard EM part: provides a complete set of EM interactions (processes) of charged particles and gammas from 1 keV to ~PeV
  - Used practically in all kind of Geant4 applications
- the low energy EM part: includes special treatments for low energy e-/+, gammas and charged hadrons:
  - more sophisticated approximations valid down to lower energies e.g. more atomic shell structure details
  - some of these processes will be valid down to below keV but some can be used only up to few GeV
- optical photons: interactions special only for long wavelength photons
  - processes for reflection/refraction, absorption, wavelength shifting, (special) Rayleigh scattering
  - G4OpticalPhoton is the particle type
- Phonon physics is also implemented within Geant4

# Geant4 Physics: Hadronic

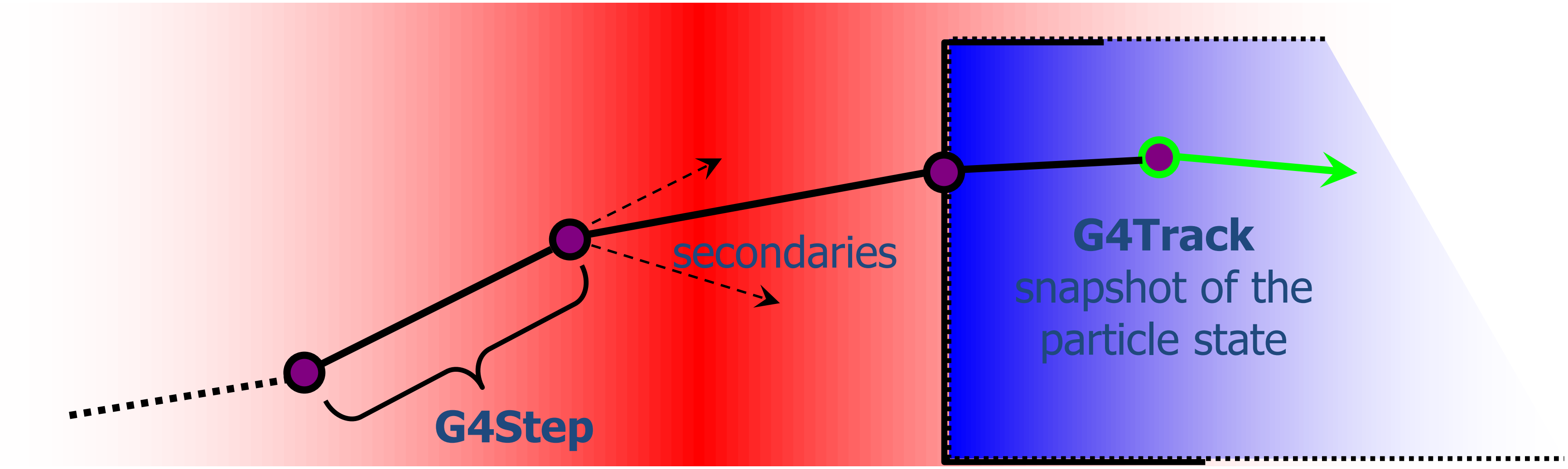
- Pure hadronic interactions for 0 to 100 TeV
  - elastic, inelastic, capture, fission
- Radioactive decay:
  - both at-rest and in-flight
- Photo-nuclear interaction from ~1 MeV up to 100 TeV
- Lepto-nuclear interaction from ~100 MeV up to 100 TeV
  - e+ and e- induced nuclear reactions
  - muon induced nuclear reactions
- Recently introduced processes of neutrino-nuclear interactions

# Geant4 Physics: Decay, Parameterized and Transportation

- decay processes includes:
  - weak decay (leptonic, semi-leptonic decay, radioactive decay of nuclei)
  - electromagnetic decay ($\pi^0$, $\Sigma^0$, etc.)
  - strong decay not included by default
    - they are part of hadronic models
    - may be assigned by a user to a particle
- parameterized process:
  - assigned to G4LogicalVolume
  - instead of step-by-step simulation provides hits in the logical volume and list of particles living the volume
  - for example, EM shower generation in a calorimeter based on parameters obtained from averaged events
- transportation process:
  - responsible for propagating a particle through the geometry in electromagnetic or gravitational field
  - needs to be assigned to each "stable" particle

# Geant4 tracking

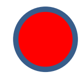
- **`G4Track`** is the object "pushed" step by step by the tracking :



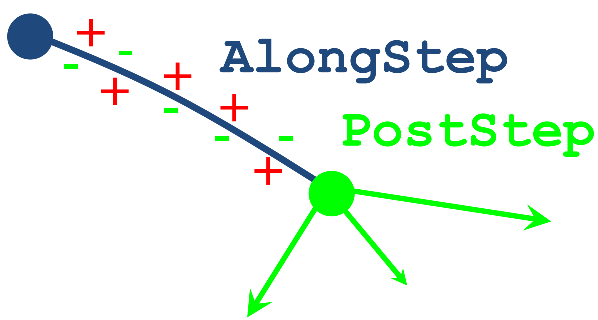

- Moving by one step is the responsibility of the "stepping"
  - Which is the core engine of the "tracking" machinery
- These moves/steps are defined by physics or by geometry
  - Step length limit is a result of competition of processes
  - Any process may change the **`G4Track`**, let's see how
  - G4Transportation stops track at the volume boundary

# G4VProcess: 3 kind of actions

- Abstract class defining the common interface of all processes in Geant4:
  - Used by all processes
    - including transportation, etc…
  - Defined in `source/processes/management`
- Three kinds of actions:
  - `AtRest` actions:



    - Decay, $e^+$ annihilation …
  - `AlongStep` actions:
    - To describe continuous (inter)actions, occurring along the path of the particle, like ionisation;




  - `PostStep` actions:
    - For describing point-like (inter)actions, like decay in flight

# G4VProcess : actions summary

- The virtual «action» methods are following:
  - `AtRestGetPhysicalInteractionLength(), AtRestDoIt();`
  - `AlongStepGetPhysicalInteractionLength(), AlongStepDoIt();`
  - `PostStepGetPhysicalInteractionLength(), PostStepDoIt();`
- Optional run time virtual methods:
  - **StartTracking(G4Track*);**
    - Allowing the process preparation for a new G4Track
  - **EndTracking();**
    - End of given G4Track

# G4VProcess: extensions

- A process can implement any combination of the three **`AtRest`**, **`AlongStep`** and **`PostStep`** actions:
  - decay = **`AtRest`** + **`PostStep`**
- If you plan to implement your own process:
  - A set on intermediate classes exist implementing various combinations of actions:
    - For example:
      - **`G4VDiscreteProcess`**: only **`PostStep`** actions
      - **`G4VContinuousDiscreteProcess`**: **`AlongStep + PostStep`** actions

# G4ProcessManager

- It is a Geant4 kernel class
  - A user should not change it
- **G4ProcessManager** maintains three vectors of actions :
  - One for the **AtRest** methods of the particle;
  - One for the **AlongStep** ones;
  - And one for the **PostStep** actions.

- Note, that the ordering of processes provided by/to the **G4ProcessManager** vectors is relevant and used by the stepping
  - There are few critical points you should be aware of
    - Multiple scattering can shift end point of a step
    - Scintillation, Cerenkov and some other processes assuming that step and energy deposition at the step are defined

# PHYSICS LISTS

## Physics Lists

- Physics List is an object that is responsible to:
  - specify all the particles that will be used in the simulation application
  - together with the list of physics processes assigned to each individual particles
- One out of the 3 mandatory objects that the user needs to provide to the G4RunManager in case of all Geant4 applications:
  - it provides the information when, how and what set of physics needs to be invoked
- Provides a very flexible way to set up the physics environment:
  - the user can chose and specify the particles that they want to be used
  - the user can chose the physics (processes) to assign to each particle

# Modular Physics Lists

- Current recommendation to use Physics List via inheritance from G4VModularPhysicsList which derives from G4VUserPhysicsList
- Main public methods:
  - G4VModularPhysicsList::RegisterPhysics(G4VPhysicsConstructor*)
    - Addition of physics constructor
  - G4VModularPhysicsList::ReplacePhysics(G4VPhysicsConstructor*)
    - Replacement of the same type of physics constructor
- Constructor types:
  - Electromagnetic, EM extra(lepton-nuclear)
  - Decay, Radioactive Decay
  - Hadron elastic, hadron inelastic
  - Ion elastic and inelastic
  - Stopping of negatively charged particles
  - Step limiters (tracking cuts)
  - Optical
  - User may add custom constructor
- Physics List and its components are unique objects, which called in each thread two methods
  - G4VPhysicsConstructor::ConstructParticle()
  - G4VPhysicsConstructor::ConstructProcess()
  - Only const class members are allowed

# Displaying processes and particles

- When your application has started and when the run manager has been initialized, you can:

- Check the physics processes attached and their ordering:
  - `/particle/select e-`
  - `/particle/processes/dump`
- Check what particles exist:
  - `/particle/list`
- Check a particle property:
  - `/particle/select e-`
  - `/particle/property/dump`
- Please type "help" to get the full set of commands for particle category

# Cuts definition

- Using UI interface Geant4 kernel change cuts and try to count number of steps in the same run
  - /run/setCut 0.01 mm
  - /run/beamOn 100
- Define cuts only for electrons
  - /run/setCutForAGivenParticle e- 10 um
  - /run/setCutForRegion GasDetector 0.1 mm
  - /run/dumpCouples
- How to change low-energy limit of production threshold
  - /cuts/setLowEdge 0.1 keV

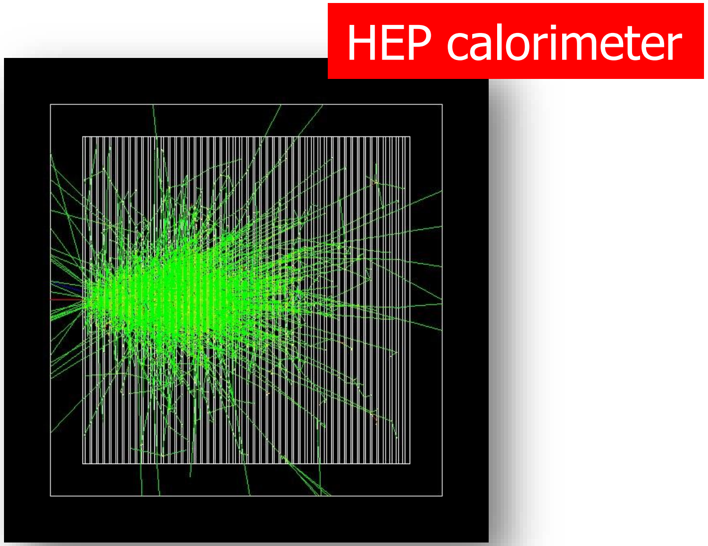
# Instantiation and ownership of physics objects

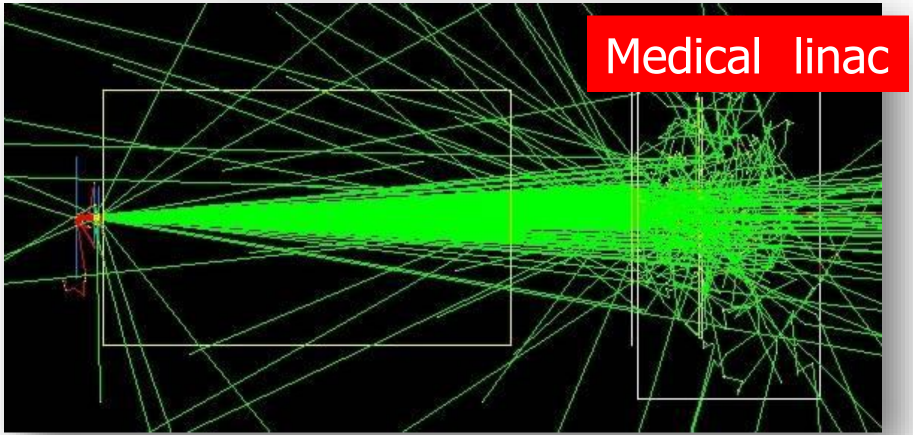
- G4PhysicsListHelper provides correct ordering for all processes from Geant4 libraries
  - G4PhysicsListHelper* helper = G4PhysicsListHelper::GetPhysicsListHelper();
  - helper->RegisterProcess(G4VProcess*, G4ParticleDefinition*);
- Custom process should be instantiated with defined ordering
  - G4ParticleDefinition* particle;
  - G4ProcessManager* man = particle->GetProcessManager();
  - man->AddDiscreteProcess(G4VDiscreteProcess*); // added to the end
  - man->AddProcess(G4VProcess*, idxAtRest, idxAlongStep, idxPostStep);
- Ownership of classes is not belonging to the Physics List class
  - G4ParticleDefinition classes are static shared between threads
  - G4VProcess classes are registered in process thread local store
  - Model classes for EM and hadronic physics are also registered in thread local store
  - Hadronic cross sections are registered in another thread local store
  - All registrations are done automatically
- All processes, models, and cross section classes should be instantiated via “new”
  - Should not be included by object in any class

# ELECTROMAGNETIC (EM) PHYSICS OVERVIEW

# Gamma and electron transport

- Photon processes
  - γ conversion into e+e- pair
  - Compton scattering
  - Photoelectric effect
  - Rayleigh scattering
  - *Gamma-nuclear interaction in hadronic sub-library (Bertini cascade)*
- Electron and positron processes
  - Ionization
  - Coulomb scattering
  - Bremsstrahlung
  - *Nuclear interaction in hadronic sub-library*
  - Positron annihilation
- Suitable for HEP & many other Geant4 applications with electron and gamma beams



# Geant4 EM sub-libraries

Located in $G4INSTALL/sources/processes/electromagnetic

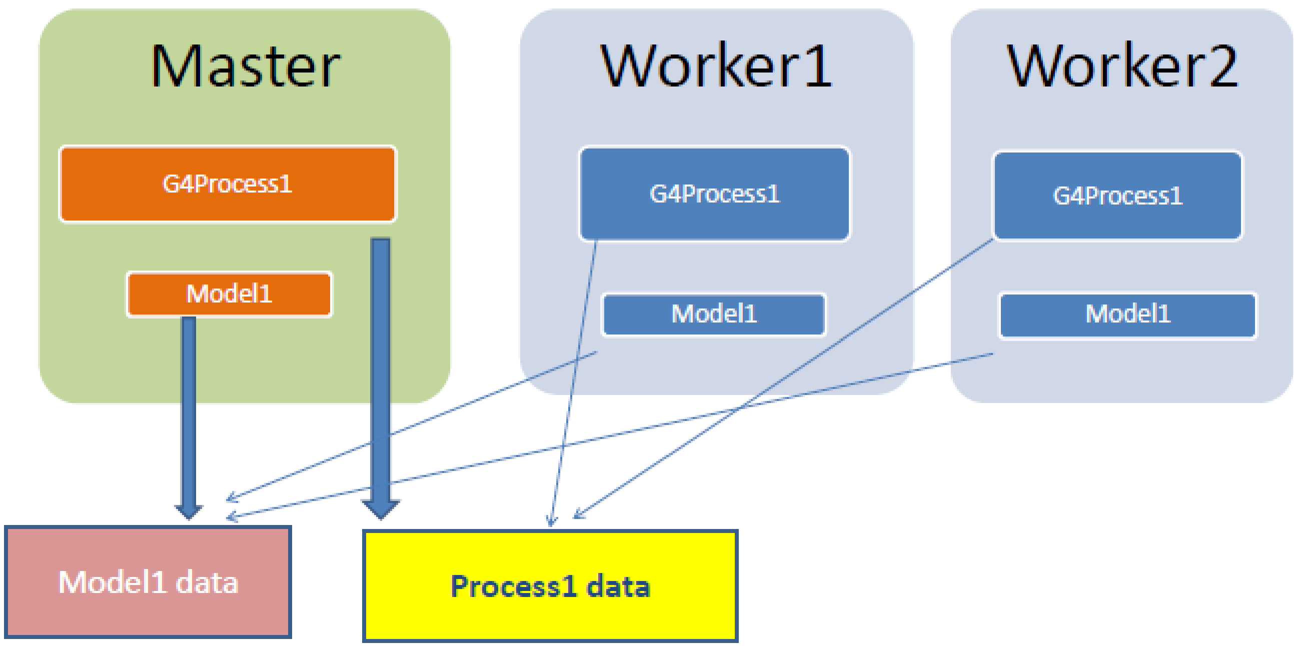
- Standard
  - $\gamma$, e up to 100 TeV
  - hadrons up to 100 TeV
  - ions up to 100 TeV
- Muons
  - up to 1 PeV
  - energy loss propagator
- X-rays
  - X-ray and optical photon production processes
- High-energy
  - processes at high energy (E>10GeV)
  - physics for exotic particles
- Polarisation
  - simulation of polarised beams
- Optical
  - optical photon interactions
- Low-energy
  - Livermore library $\gamma$, e- from 10 eV up to 1 GeV
  - Livermore library based polarized processes
  - PENELOPE 2008 code rewrite , $\gamma$, e- , e+ from 250 eV up to 6 GeV
  - hadrons and ions up to 1 GeV
  - atomic de-excitation (fluorescence + Auger)
- DNA
  - Geant4 DNA modes and processes
  - Micro-dosimetry models for radiobiology
  - rom 0.025 eV to 10 MeV
  - many of them material specific (water)
  - Chemistry in liquid water
- Adjoint
  - sub-library for reverse Monte Carlo simulation from the detector of interest back to source of radiation
- Utils : general EM interfaces and helper classes

# Software Design of EM Physics

- The uniform coherent approach for all EM packages
  - low energy and high energy models may work together
- A physical interaction or process is described by a process class
  - For example: G4ComptonScattering
    - Assigned to Geant4 particle types in Physics List
  - Three EM base processes:
    - G4VEmProcess
    - G4VEnergyLossProcess
    - G4VMultipleScattering
- 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…)

# EM Data Sharing for Geant4 MT

- The scalability of Geant4 application in the MT mode depends on how effectivly data management is performed
- Shared EM physics data:
  - tables for cross sections, stopping powers and ranges are kept by processes
  - Differential cross section data are kept by models
  - Material propertes are in material data classes
  - EM parameters established for Physics Lists in the G4EmParameters class

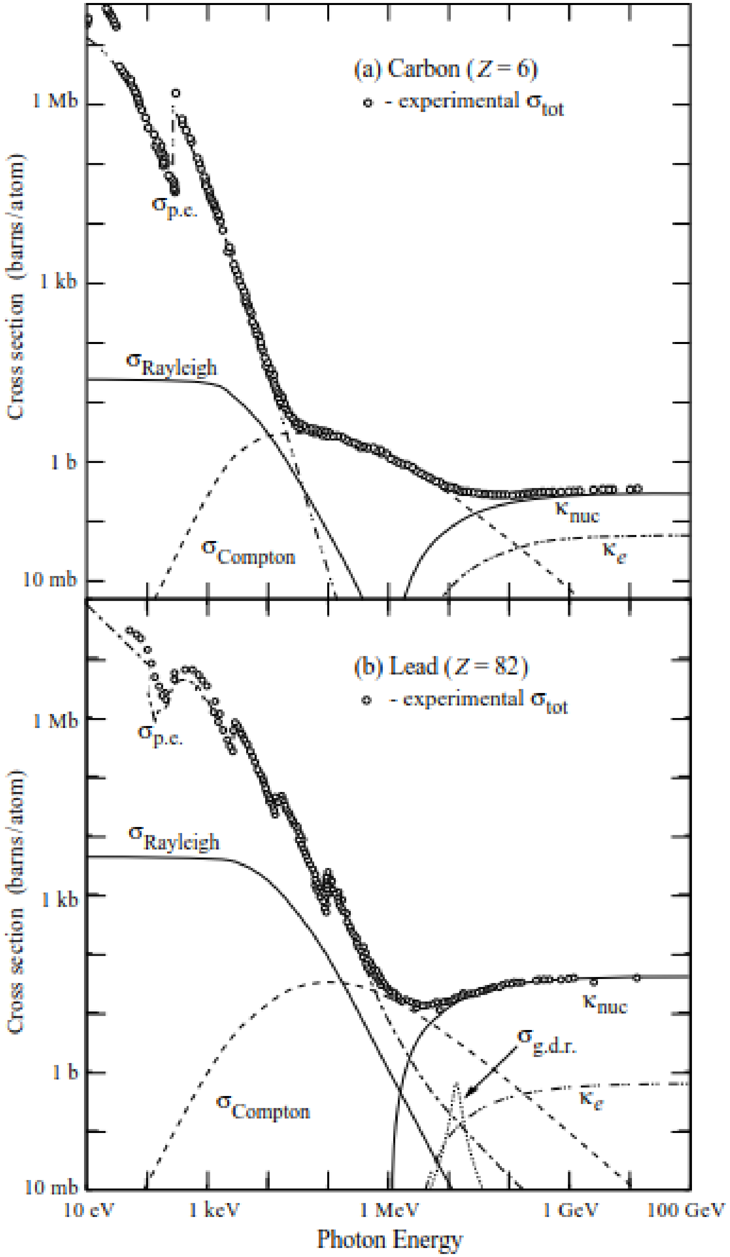



**Tables are filled by Master and have read-only access in run time**

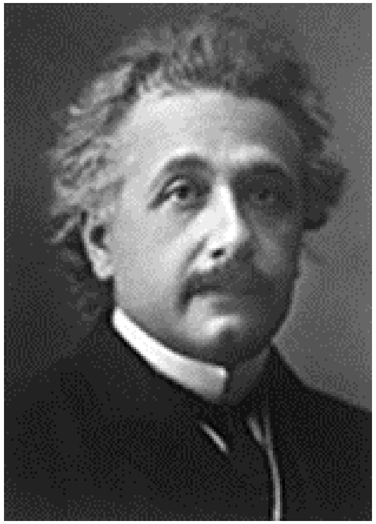
**In this scheme number of threads is not limited**

# Gamma processes

- Photo-effect is the main process for absorption of low-energy gamma
  - Rayleigh scattering should not be neglected
- At high energy gamma conversion dominates
- Gammas may be absorbed by nuclei due to giant dipole resonance



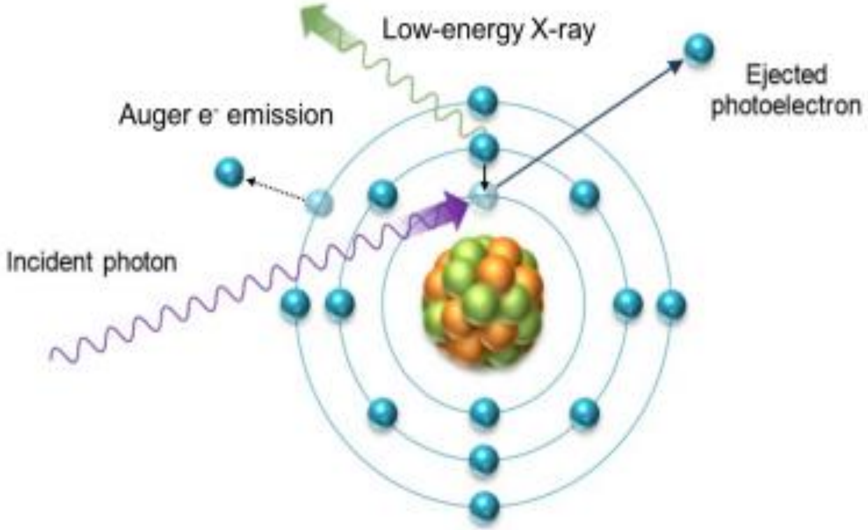
# Photo-electric effect – example of gamma process



In the photo-electric absorption process a **photon is absorbed** by an atom and an **electron is emitted** with an energy:

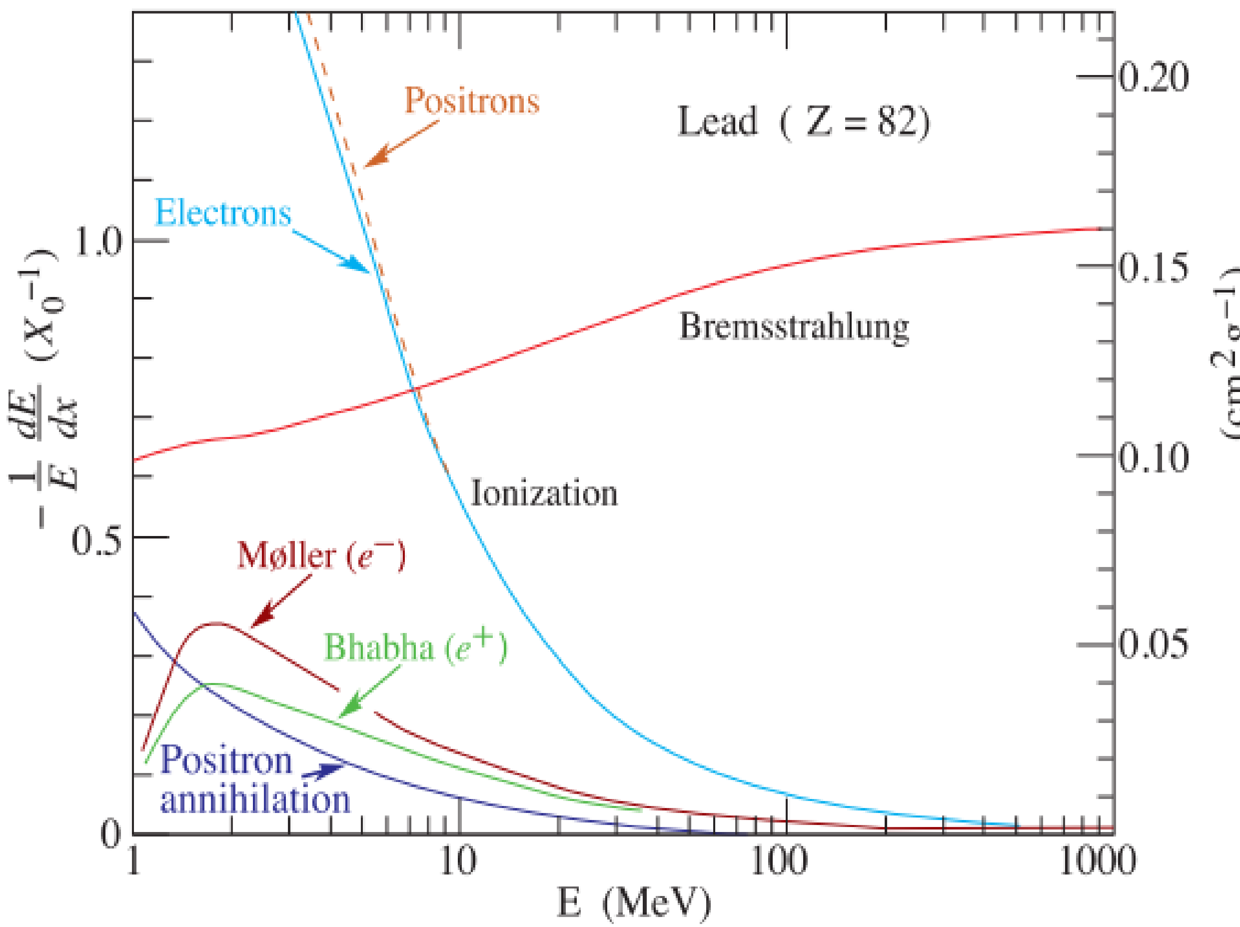
$$E_{photoelectron} = E_{\gamma} - B_{shell}(Z_i) \quad (1)$$

The atom, left in an excited state with a vacancy in the ionized shell, decays to its ground state through a cascade of radiative and non-radiative transitions with the **emission of characteristic x-rays** and **Auger and Coster-Kronig electrons**.



# Electron processes

- At low energies ionisation dominates
- Above critical energy bremsstrahlung is the main process
  – Radiation energy loss exceed ionization energy loss



# EM PHYSICS CONSTRUCTORS

# EM Physics Lists Components

- A Physics list is the mandatory user class making the general interface between the physics the user needs and the Geant4 kernel
- List of particles: for which EM physics processes are defined
  - $\gamma$, $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$ , p, $\Sigma^{\pm}$, $\Xi^{-}$, $\Omega^{-}$ , anti($\Sigma^{\pm}$, $\Xi^{-}$, $\Omega^{-}$)
  - $\tau^{\pm}$, $B^{\pm}$, $D^{\pm}$, $D_s^{\pm}$, $\Lambda_c^{+}$, $\Sigma_c^{+}$, $\Sigma_c^{++}$, $\Xi_c^{+}$ , anti($\Lambda_c^{+}$, $\Sigma_c^{+}$, $\Sigma_c^{++}$, $\Xi_c^{+}$)
  - d, t, He3, He4, GenericIon, anti(d, t, He3, He4)

- The G4ProcessManager of each particle maintains a list of processes

- Geant4 provides several configurations of EM physics lists called constructors (G4VPhysicsConstructor) in the physics_lists library of Geant4

- These constructors can be included into a modular Physics list in a user application (G4VModularPhysicsList)

# Standard EM Physics Constructors

Geant4 standard EM Physics Constructors for HEP applications

- Description of Coulomb scattering (the same):
  - $e^{\pm}$ : Urban - MSC model below 100 [MeV] and the Wentzel - WVI + Single scattering (mixed simulation) model above 100 [MeV]
  - muon and hadrons: Wentzel - WVI + Single scattering (mixed simulation) model
  - ions: Urban - MSC model
- But different MSC stepping algorithms and/or parameters: speed v.s. accuracy

| Constructor | Components | Comments |
|---|---|---|
| `G4EmStandardPhysics` | Default: nothing or _EM0 (QGSP_BERT, FTFP_BERT,…) | for ATLAS and other HEP simulation applications |
| `G4EmStandardPhysics_option1` | Fast: due to simpler MSC step limitation, cuts used by photon processes (FTFP_BERT_EMV) | similar to one used by CMS; good for crystals but not good for sampling calorimeters (i.e. with more detailed geometry) |
| `G4EmStandardPhysics_option2` | Experimental: similar to option1 with updated photoelectric model but no-displacement in MSC (FTFP_BERT_EMX) | similar to one used by LHCb |

# EM Physics Constructors for medical applications

Combined Geant4 EM Physics Constructors

- The primary goal is more the physics accuracy over the speed
- Combination of standard and low-energy EM models for more accurate physics description
- More accurate models for $e^{\pm}$ MSC (Goudsmit-Saunderson(GS)) and more accurate stepping algorithms (compared to HEP)
- Stronger continuous step limitation due to ionisation (as others given per particle groups)
- Recommended for more accuracy sensitive applications: medical (hadron/ion therapy), space

| Constructor | Components | Comments |
|---|---|---|
| `G4EmStandardPhysics_option3` | Urban MSC model for all particles | proton/ion therapy |
| `G4EmStandardPhysics_option4` | most accurate combination of models (particle type and energy); GS MSC model with Mott correction and error-free stepping for $e^{\pm}$) | the ultimate goal is to have the most accurate EM physics description |
| `G4EmLivermorePhysics` | Livermore models for $e^-$ , γ below 1 GeV and standard above; same GS MSC for $e^{\pm}$ as in option4) | accurate Livermore based low energy $e^-$ and γ transport |
| `G4EmPenelopePhysics` | PENELOPE models for $e^{\pm}$, γ below 1 GeV and standard above; same GS MSC for $e^{\pm}$ as in `option4`) | accurate PENELOPE based low energy $e^-$, $e^+$ and γ transport |

# EM Physics Constructors for testing of new models

Experimental Geant4 EM Physics Constructors

- Supposed to be used only by the developers for validations and model developments
- The main difference is in the description of the Coulomb scattering (GS, WVI, SS)

| Constructor | Components | Comments |
|---|---|---|
| `G4EmStandardPhysicsGS` | standard EM physics and the GS MSC model for $e^{\pm}$ with HEP settings | may be considered as an alternative to EM0 i.e. for HEP |
| `G4EmStandardPhysicsWVI` | WentzelWVI + Single Scattering mixed simulation model for Coulomb scattering | high and intermediate energy applications |
| `G4EmStandardPhysicsSS` | single scattering (SS) model description of the Coulomb scattering | validation and verification of the MSC and mixed simulation models |
| `G4EmLowEPPhysics` | Monarsh University Compton scattering model, 5D gamma conversion model, WVI-LE model | testing some low energy models |
| `G4EmLivermorePolarized` | polarized gamma models | a (polarized) extension of the Livermore physics models |

# USER INTERFACE TO EM PHYSICS

# EM parameters

- EM parameters of any EM physics list may be modified at initialization of Geant4 using C++ interface to the G4EmParameter class or via UI commands
- Example of interfaces of G4EmParameters:
  - SetMuHadLateralDisplacement()
  - SetMscMuHadRangeFactor()
  - SetMscMuHadStepLimitType()
- Corresponding UI commands:
  - /process/msc/MuHadLateralDisplacement
  - /process/msc/RangeFactorMuHad
  - /process/msc/StepLimitMuHad
- Some other UI commands:
  - /process/em/deexcitationIgnoreCut true
  - /process/eLoss/UseAngularGenerator true
  - /process/em/lowestElectronEnergy 50 eV
  - /process/em/lowestMuHadEnergy 100 keV
  - ....

# User Interfaces and Helper Classes

- Geant4 UI commands to define cuts and other EM parameters
- G4EmCalculator
  - easy access to cross sections and stopping powers (TestEm0)
- G4EmParameters
  - C++ interface to EM options alternative to UI commands
- G4EmSaturation
  - Birks effect (recombination effects)
- G4ElectronIonPair
  - sampling of ionisation clusters in gaseous or silicon detectors
- G4EmConfigurator
  - add models per energy range and geometry region
- G4NIELCalculator
  - Helper class allowing computation of NIEL at a step, which should be added in user stepping actions or sensitive detector (TestEm1)

# 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 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/TestEm0
  Look in particular at the RunAction.cc class

# THANK YOU