Version 11.0

Particle and Processes

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Geant4 Advanced Course

Outline

- Geant4 basic interfaces to physics
- Geant4 particles
- Geant4 processes
- Physics Lists
- Ions and exotic particles
- Geant4 cuts
- How to control/modify 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

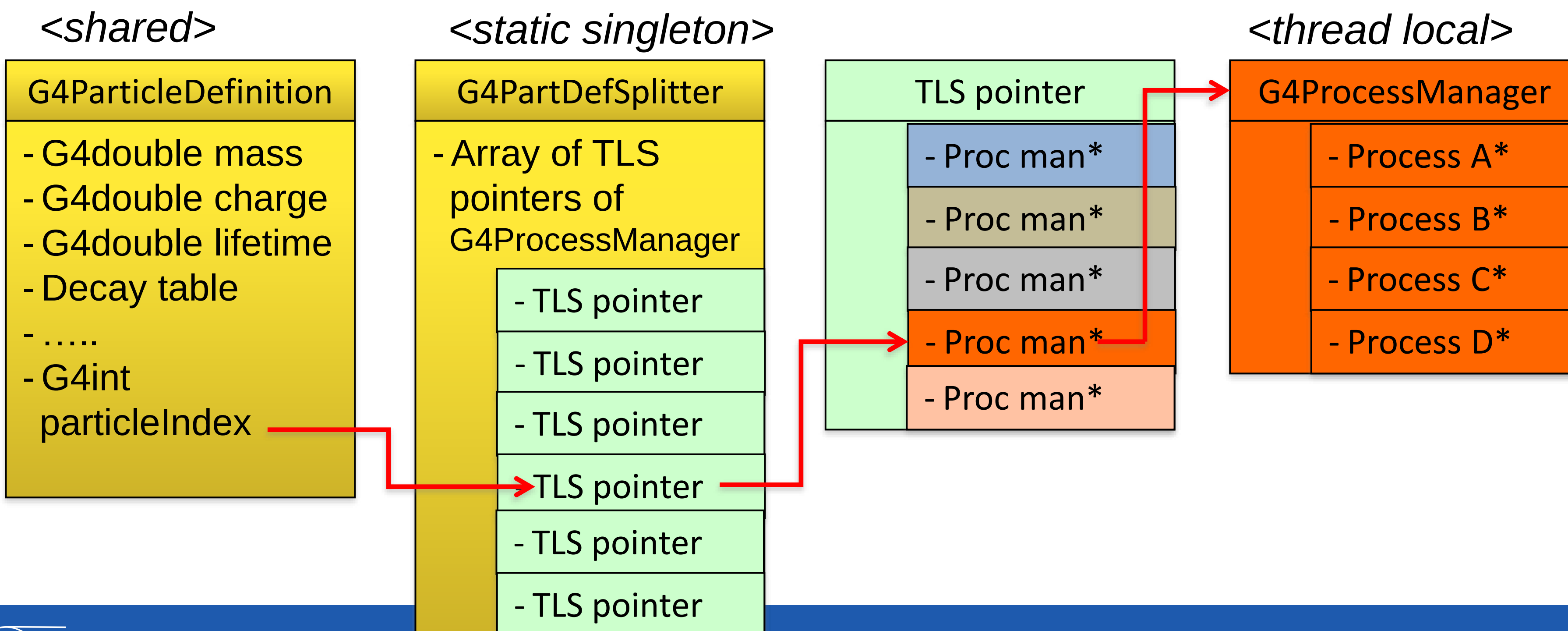
GEANT4 PARTICLES

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, and anti-ions
  - 12 hyper- and anti-hyper- nuclei are added in Geant4 11.0
  - G4GenericIon is used to define physics for all other ions
- "ShortLived" 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, lifetime, decay channels, etc.,
    - Are shared by all threads
  - Dedicated object of G4ProcessManager : list of physics processes which this particle undertakes.
    - Physics process object must be thread-local
    - Thread local storage is used (TLS)

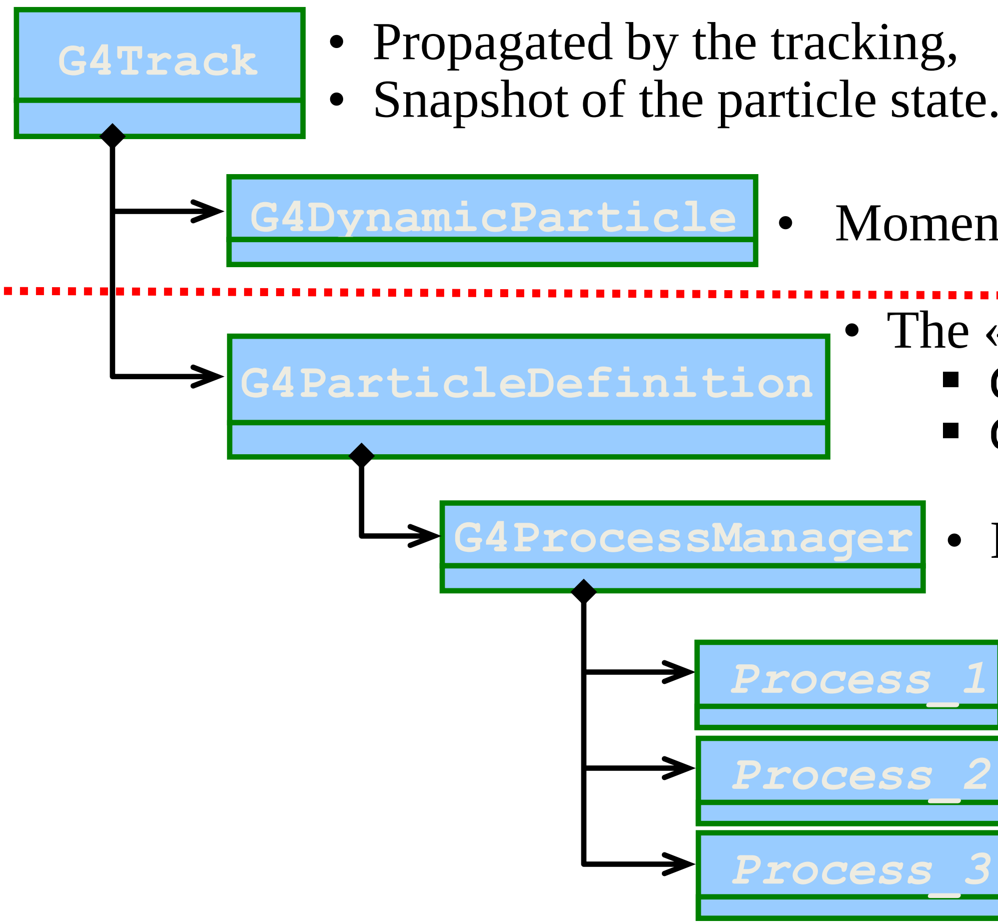


GEANT4 PROCESSES

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::GetProcessSubType();
    - This method is recommended to be used for MC truth
    - The list of sub-types is stable since introduced and only extended 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



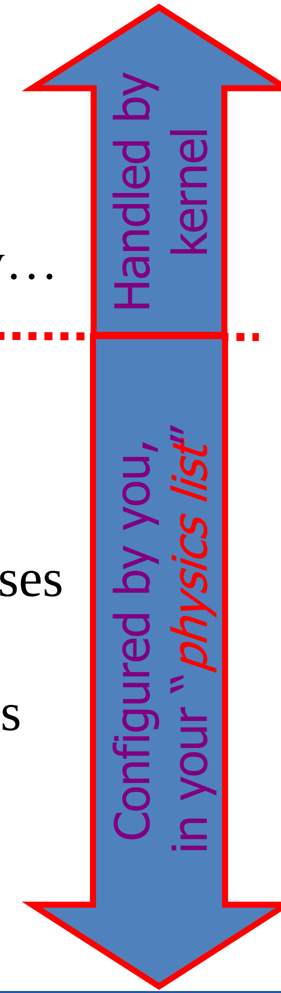
- Propagated by the tracking,
- Snapshot of the particle state.

- Momentum, pre-assigned decay…

- The « particle type »:
  - **`G4Electron`**,
  - **`G4PionPlus`**…

- Holds pointers to processes

- Implementing physics 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 models will be valid down to ~10 eV but cannot be used above upper limits, which vary from 1 MeV 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

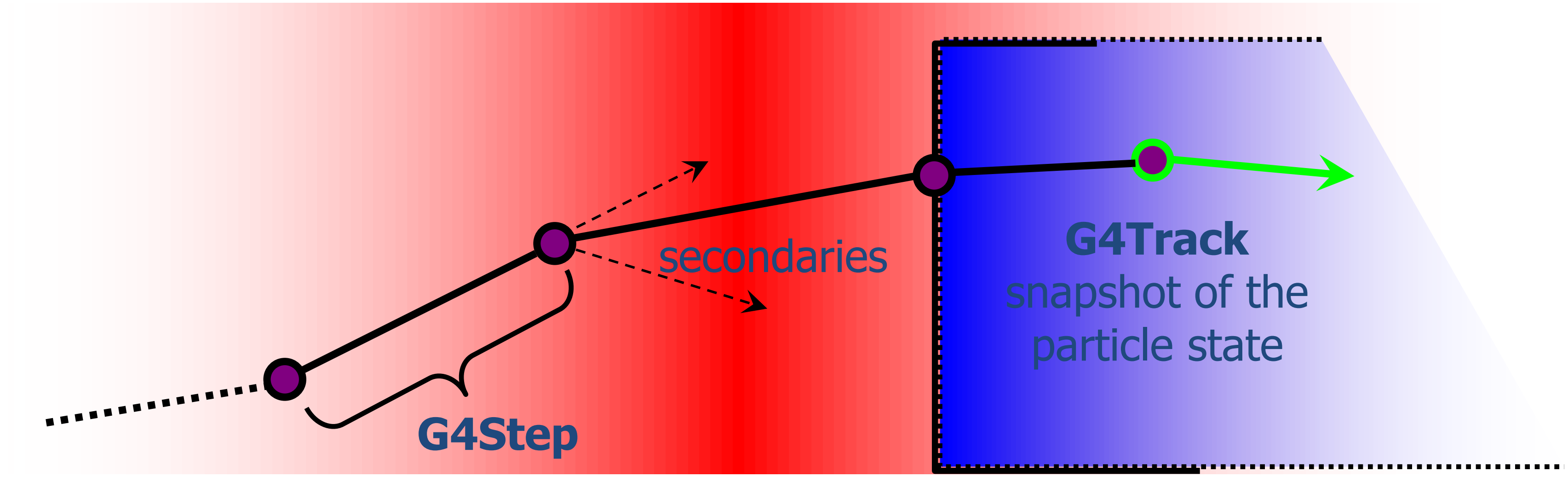
- Pure hadronic interactions for 0 to 100 TeV
  - elastic, inelastic, capture, fission
- Radioactive decay:
  - both at-rest and in-flight
- Photo-nuclear interaction from ~1 MeV up to 100 TeV
- Lepto-nuclear interaction from ~100 MeV up to 100 TeV
  - e+ and e- induced nuclear reactions
  - muon induced 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 (π^0, Σ^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 detailed simulation of the calorimeter response
- 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

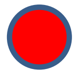
- **`G4Track`** is the object "pushed" step by step by the tracking :
- Moving by one step is the responsibility of the "stepping"
  - Which is the core engine of the "tracking" machinery



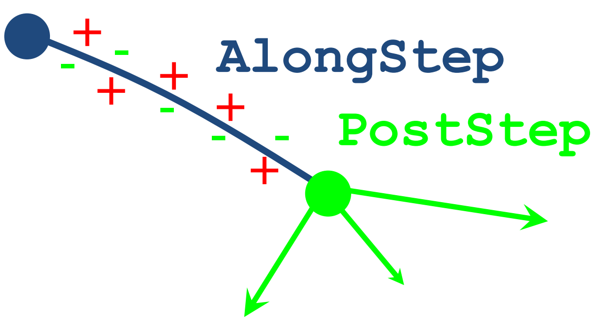
- These moves/steps are defined by physics or by geometry
  - Step length limit is a result of competition of processes
  - Processes involved at a step may change the **`G4Track`**
  - By default, G4Transportation stops track at the volume boundary
    - There are methods how to skip boundaries during tracking
    - Implementation exit, for example, for gamma tracking in ATLAS calorimeter

G4VProcess: 3 kind of actions

- **G4VProcess** is an abstract class defining the common interface of all processes in Geant4:
  - Used by all processes including G4Transportation
  - 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:
  - for example, 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
- For EM physics there are extra extensions:
  - G4VEmProcess, G4VEnergyLossProcess, G4VMultipleScattering
- For hadronic processes there are extensions:
  - G4HadronicProcess
  - G4HadronElasticProcess

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 a step and energy deposition at the step are defined
    - G4PhysicsListHelper class keeps information about process ordering for processes from Geant4 distribution

About process ordering

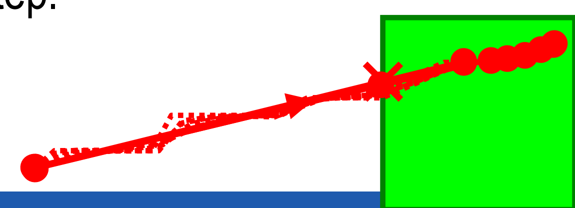
- The strongest rule for multiple-scattering, transportation, and G4Scintillation
- In your physics list, you should always have, for the ordering of the **AlongGetPhysicalInteractionLength(…)** methods:
  - Transportation last
    - For all particles
  - Multiple scattering second last
    - For charged particles only
      - assuming n processes

        [n-2] …

        [n-1] multiple scattering

        [n] transportation

- Why ?
  - Processes return a « true path length »;
  - The multiple scattering folds up this length into a ***shorter*** « geometrical » path length;
  - Based on this new length, the transportation can geometrically limits the step.



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
- Geant4 distribution includes the "physics_list" sub-library with many components and many predefined "reference" Physics Lists
  - Simulation results between different group of users may be compared

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

Cuts definition

- In past cuts were defined in SetCuts() method of physics list
  - After migration to the MT mode, we recommend not doing this
  - Cuts may be defined via UI commands
  - Details on Geant4 cuts will be described below
- 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
  - /cuts/setHighEdge 5 GeV
  - The highEdge limit cannot be above 10 GeV
    - Until now there was no need to increase this limit

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 stores
  - Hadronic cross sections are registered in another thread local store
  - All registrations and destructions are done automatically
- All processes, models, and cross section classes should be instantiated via "new"
  - Allowing sharing of processes/models between particles
  - Should not be included by object in any class
    - Does not guaranteed correct destruction order at different platforms

IONS AND EXOTIC PARTICLES

Geant4 Approach for Ions

- Light ions are individual Geant4 particles:
  - **G4Deuteron**
  - **G4Triton**
  - **G4He3**
  - **G4Alpha**
- Generic ion serves all other ions:
  - **G4GenericIon** - only one particle
  - Not a real particle (charge = +1, mass = Mp)
  - Serving for any kind of ion with Z>2
  - All concrete ions peak up processes and cross sections of the G4GenericIon
    - Scaling relations are used in run time
- Ion names
  - "**C12**" means that the carbon ion is in the ground state
  - "**Co60**[58.590]" is the first excitation state of Co60
  - Extra information about atomic shell may be filled to any ion

Exotic particles

- Not discovered particles are not part of Geant4 particle library
- To search exotics users should introduce non-existing particles in the user code
  - Such particles should be instantiated in **ConstructParticle**() method of one of custom G4VPhysicsConstructor, which is user responsibility
  - User should take care attaching processes to exotic particles in **ConstractProcess**() method
- Geant4 offers two extended examples
  - $G4INSTALL/examples/extended/exoticphysics/monopole
  - $G4INSTALL/examples/extended/exoticphysics/dmparticle
  - These examples demonstrate different variants of addition of extra particles and interactions
- In the monopole example additional classes are available for tracking of the magnetic monopole in magnetic field
  - **G4MonopoleTransportation**, **G4MonopoleEquation**

GEANT4 CUTS

How tracks are created and killed

- G4Track can be created
  - By **G4VUserPrimaryGeneratorAction**
  - By any **G4VProcess**
- Geant4 particle is tracked until it is killed by one of Geant4 processes:
  - Transport out of the world volume
  - Inelastic interaction
  - Decay
  - Tracking low energy cut in the ionization process
  - **G4NeutronKiller** or **G4UserLimits**
  - If during tracking kinetic energy become zero and there is no processes **AtRest** the particle is killed by the stepping manager
- Any particle may be also killed by user action classes
- Geant4 introduced conception of "**cut in range**"
  - Physically this means required spatial accuracy of simulation
  - At initialization for each material a production threshold for kinetic energy of secondary particles is computed
    - This means different production thresholds for different materials
  - This is the main difference between Geant4 and other simulation tools, which implement only tracking cuts and cuts per volume

Cut and production thresholds for energy loss processes

- User defines cut in range expressed in units of length

- Using this range Geant4 kernel compute production threshold T_{cut} for each material during initialization
- For a typical process (G4hIonisation, G4eIonisation, …), the production threshold T_{cut} subdivides the continuous and discrete parts of energy loss:
  - Mean rate of energy lost due to soft energy transfers
  - Cross section for discrete δ-electron production
  - above T_{cut}
  - *Both energy loss and cross sections are restricted*

$$\frac{dE(E,T_{cut})}{dx} = n_{at} \int_0^{T_{cut}} T \frac{d\sigma(Z,E,T)}{dT} dT$$

$$\sigma(Z,E,T_{cut}) = \int_{T_{cut}}^{T_{\max}} \frac{d\sigma(Z,E,T)}{dT} dT$$

- At each step energy deposition is sampled by a fluctuation model using the computed mean energy loss

- Optionally, energy loss may be modified :
  - for the sampling of fluorescence and Auger–electrons emission
- 4-momentum balance is provided in all cases

What particles have cut in range?

- Cuts in range are defined for
  - Gamma
  - Electron
  - Positron
  - Proton
- Cut for proton is used for all hadrons and ions by elastic scattering processes
  - It is a cut on recoil ion kinetic energy
- By default, *cut in range* is defined globally
  - It is possible to have different cut in range for particle type
  - It is possible to define specific cut in range per G4Region
  - It is possible to set proton *cut in range* to zero
  - It is not possible to set other cuts below lowEdge limit

Which processes use cut in range ?

- It is not mandatory to use cuts
  - They are needed to secure CPU performance of simulation
- Energy thresholds (derived from cut in range) are used
  - for gamma are used in Bremsstrahlung
  - for electrons are used in ionisation and e+e- pair production processes
  - for positrons is used in the e+e- pair production process
  - for gamma and electrons are used optionally ("ApplyCuts" options) in some discrete processes
    - Photoelectric effect, Compton, gamma conversion
- Production threshold for gamma and e^{+-} obtained from range cut cannot be whatever
  - The default low energy limit is 1 keV
  - The default high energy limit is 10 GeV
  - May be changed via UI command:
    - /cuts/setLowEdge 100 keV
- Energy threshold for protons are used to define the threshold for kinetic energy of a nuclear recoil
  - EM single scattering process
  - Hadron elastic scattering

Tracking cuts

- Additionally, to cut in range it is possible to use various tracking cuts
  - Unwanted particles may be killed after the step if corresponded flag is proposed
- In the default physics configurations two types of tracking cuts are applied:
  - Low-energy thresholds for charged particles by ionization 1 keV
  - Time cut for neutron transport 10000 ns
- Tracking cuts values are customizable and can be changed via UI commands
- User may easily setup extra tracking cut or step limiter
  - The best is to add an extra custom G4VProcess
  - **G4NeutronKiller** is the example

HOW TO CONTROL/MODIFY PHYSICS?

Information on Geant4 initialisation

- By default, detailed information on Geant4 physics configuration is printed
  - Tables of parameters
    - EM physics
    - Nuclear de-excitation module
    - Radioactive decay
    - Particle HP
  - EM processes and models parameters
    - For selected particles
  - Hadronic processes, models, and cross sections
    - For selected particles
  - Printout may be disabled via UI command
    - /process/had/verbose 0
    - /process/em/verbose 0
- Set of physics parameters and physics constructors may be modified before initialization of physics
  - Initialization of physics is triggered by the /run/initilize UI command
  - Between runs limited number of parameters may be changed

THANK YOU