Guide For Physics Lists

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Scope of this Manual

This guide is a description of the physics lists class which is one of the mandatory user classes for a GEANT4 application. For the most part the "reference" physic lists included in the source distribution are described here as well the modularity and electronic options. Some use cases and areas of application are also described.

PHYSICS LIST GUIDE

The Physics List is one of the three mandatory user classes of the GEANT4 toolkit. In this class all GEANT4 particles and their interaction processes should be instantiated. This class should inherit from the base class `G4VUserPhysicsList` and should be given to G4RunManager:

```
G4MTRunManager* runManager = new G4MTRunManager;
runManager->SetUserInitialization(physicsList);
```

Here `physicsList` is a pointer to the user defined class. Initially [eal03], it was proposed for users to create custom class based on variants of PhysicsList in GEANT4 example applications. After first GEANT4 official releases, a conception of reference Physics Lists was introduced [eal06]. In the beginning, the default GEANT4 Physics List was QGSP_BERT [eal09]. Since the GEANT4 release 10.0 the default Physics List becomes FTFP_BERT [eal16]. The main advantage of working with the reference Physics List is in common method of instantiation of physics objects in GEANT4 tests, in GEANT4 examples, and in user applications. GEANT4 developers develop and validate these physics configurations and any user or group of users may reproduce the same physics in their GEANT4 applications. GEANT4 developers establish various tests and benchmarks, which are used for validation and verification of the GEANT4 toolkit before making a new public version. Users may compare results obtained in the same conditions in different setups.

Number of reference Physics Lists is not small, because there are many alternative physics models in the toolkit applicable for simulation of very different problems. Reference Physics Lists are available in GEANT4 `physics_list` sub-library. All these classes inherit from virtual interface `G4VModularPhysicsList` (which is an extension of the base class `G4VUserPhysicsList`. The advantages of the modular design are in maintenance of modules by different GEANT4 working groups, independent development of particular modules, possibility for combining of various modules (following `G4VPhysicsConstructor` interface) in reference Physics Lists and in user custom Physics Lists. There are following types of modules:

- electromagnetic physics;
- extra physics processes for gamma and leptons;
- decay;
- hadron elastic;
- hadron inelastic;
- stopping particles capture processes;
- ion nuclear interactions;
- step limiters;
- others.

The last category may include any type of physics processes, for example, optical, exotic physics, thermal neutron transport model, and others. A user may customise reference Physics List using following interfaces of the `G4VModularPhysicsList` class:

- `void RegisterPhysics(G4VPhysicsConstructor* );`
- `void ReplacePhysics(G4VPhysicsConstructor* );`
- `void RemovePhysics(G4VPhysicsConstructor* );`

The following reference Physics Lists are available in the `physics_lists` sub-library:

- *FTFP_BERT*
- FTFP_BERT_ATL
- FTFP_BERT_HP
- FTFP_BERT_TRV
- FTFP_INCLXX
- FTFQGSP_BERT
- FTF_BIC
- LBE
- NuBeam
- *QBBC*
- QBBC_ABLA
- *QGSP_BERT*
- QGSP_BERT_HP
- *QGSP_BIC*
- QGSP_BIC_AllHP
- QGSP_BIC_HP
- QGSP_BIC_HPT
- QGSP_FTFP_BERT
- QGSP_INCLXX
- QGS_BIC
- *Shielding*
- ShieldingLEND

These Physics List classes may be included directly to the user code. It is also possible instantiate reference Physics List by name using helper class `G4PhysListFactory`. Variants of usage of this helper class are demonstrated in GEANT4 extended examples:

- `geant4/examples/extended/hadronic/Hadr00.cc` - for multi-threaded mode;
- `geant4/examples/extended/hadronic/Hadr01.cc` - for sequential mode.

In the case of usage of this helper class, an additional possibility does exist to extend electromagnetic physics configuration by simply adding an extension to a physics list name, for example `FTFP_BERT_EMZ` means , that the default electromagnetic physics is substituted by the configuration providing the most accurate simulation of electromagnetic physics (see details in *EM physics constructors*). Following extensions are available:

- `EMV` *EM Opt1* less precise, but faster set of electromagnetic physics is used. Otherwise known as electromagnetic option 1.
- `EMX` *EM Opt2* less precise, but faster set of electromagnetic physics is used. Otherwise known as electromagnetic option 2.
- `EMY` *EM Opt3* it uses a set of EM processes with accurate simulation of gamma and charged particle transport. Only the Urban multiple scattering model is used for all charged particles and all energies. Also known as electromagnetic option 3, the detailed physics causes longer execution times than the standard package.
- `EMZ` *EM Opt4* the best set of electromagnetic physics models selected from the low energy and standard packages. With its concentration on the best possible physics, electromagnetic option 4 is slower than the standard EM package.
- `LIV` *EM Liv* is made on top of electromagnetic option 3 by substitution of standard models for gamma and electrons from Livermore set of models.
- `PEN` *EM Pen* is made on top of electromagnetic option 3 by substitution of standard models for gamma, electrons and positrons from Penelope-2008 set of models.
- `_GS` *EM GS* is made on top of the default electromagnetic configurations by substitution of the Urban multiple scattering model for electrons and positrons by the Goudsmit-Saunderson model.
- `_LE` *EM LE* is made on top of the default electromagnetic configurations by substitution of the Urban multiple scattering model for electrons and positrons by the LowEWentzelVI model. Also, using 5D gamma conversion model and Lindhard-Sorensent model for ion ionisation.

- `WVI` *EM WVI* is made on top of the default electromagnetic configurations by substitution of the Urban multiple scattering model for electrons and positrons by the WentzelVI model and ATIMA ion ionisation model.
- `_SS` *EM SS* is made on top default electromagnetic configurations by substitution of all multiple scattering models by single scattering models.

The additions on top of any reference Physics list may be implemented via the ReplacePhysics interface:

- `G4RadioactiveDecayPhysics`
- `G4NeutrinoPhysics`
- `G4ChargeExchangePhysics`
- `G4OpticalPhysics`

For those using shared object libraries, the extensible physics list factory `g4alt::G4PhysListFactory` is an option. This factory extends the capability of the original factory and can be substituted in by changing the include header and adding `using namespace g4alt`. This code is demonstated in the extended example.

- `geant4/examples/extended/physicslists/extensibleFactory`

This factory is different from the one described above by allowing one's own custom physics lists to be registered with the factory, as well as allowing for the customization of physics lists with physics constructors. The later uses "_" for `ReplacePhysics()` and "+" for `RegisterPhysics()`, such that valid physics lists might look like:

- `FTFP_BERT_HP_EMZ+G4RadioactiveDecayPhysics` which starts with a standard physics list `FTFP_BERT_HP`, substitutes the `EMZ` electromagnetic configuration, and adds radioactive decay.
- `MySpecialPhysList_GS+G4OpticalPhysics+G4NeutronTrackCut` which uses a pre-registered custom build physics list, substitutes `_GS` EM physics, and adds `G4OpticalPhysics` and `G4NeutronTrackCut`.

REFERENCE PHYSICS LISTS

A detailed description of key reference physics lists which are included within the source tree of the GEANT4 toolkit. An incomplete selection of diverse lists is described here in terms of the components within the list and possible use cases and application domains.

2.1 FTFP_BERT

It is the current GEANT4 default [eal16].

2.1.1 Hadronic Component

The purely hadronic part of this physics list consists of elastic, inelastic, and capture processes. Each process is built from a set of cross section sets and interaction models which provide the detailed physics implementation.

Inelastic models

The inelastic hadron-nucleus processes are implemented by the Fritiof parton model (FTF), Bertini and Precompound models. The Bertini intranuclear cascade is responsible for p, n, π^+, π^-, K^+, K^-, K_L, K_S, Λ, Σ^+, Σ^-, Σ^0, Ξ^-, Ξ^0 and Ω^- interactions between 0 to 6 GeV. The FTF model handles these same particles, but over the range 3 GeV to 100 TeV. It also handles anti-protons, anti-neutrons, anti-deuterons, anti-tritons, anti-^{3}He, anti-alphas and anti-hyperons from 0 to 100 TeV/n.

Where Bertini and FTF overlap in particle type and energy range, Bertini is invoked with a probability that decreases linearly from 1.0 to 0.0, and FTF is invoked with the complementary probability.

When the FTF model is used, the Precompound model (P) is also invoked to de-excite the remnant nucleus after the initial high energy interaction. The precompound model in turn calls the Fermi breakup, neutron and light ion evaporation and photon evaporation models as needed. When the Bertini model is used, its own, simpler precompound and de-excitation models are invoked.

Inelastic nucleus-nucleus scattering for all incident A is handled by the Binary Light Ion Cascade (BIC) between 0 and 6 GeV/n, and by the FTF model between 3 GeV/n and 100 TeV/n. The scheme for choosing models in overlapping energy regions is the same as that for FTFP and BERT.

For baryons and mesons, which includes b- and c- quarks, the FTFP model is used.

The hadronic interaction of gammas is handled by the photo-nuclear process in which gammas below 6 GeV are interacted using the Bertini cascade, and above 3 GeV by the Quark-gluon String (QGS) model. Below 200 MeV low-energy model based on de-exitation module is used. Muons, electrons and positrons also interact via transfer of virtual photons. These interactions are handled by G4MuonVDNuclearModel and G4ElectroVDNuclearModel which are applied at all energies.

Inelastic cross sections

G4BGGNucleonInelasticXS is used for protons, G4NeutronInelasticXS for neutrons, and G4BGGPionInelasticXS for pions. In these cross sections Barashenkov parameterisation is used below 20 GeV and Glauber-Gribov above.

For kaons, hyperons and anti-hyperons the Glauber-Gribov set (G4ComponentGGHadronNucleusXsc) is used at all energies.

All nucleus-nucleus cross sections are provided by G4ComponentGGNuclNuclXsc at all projectile energies. This class is the Glauber-Gribov nucleus-nucleus cross section parameterisation. When the projectile is an anti-proton, anti-neutron, anti-deuteron, anti-triton, anti-^{3}He or anti-alpha, the G4ComponentAntiNuclNuclearXS class provides the cross sections using the Glauber-Gribov parameterisation.

For baryons and mesons, which include b- and c- quarks, cross section is implemented using G4ComponentGGHadronNucleusXsc.

Hadronic gamma interaction cross sections are supplied by G4PhotoNuclearCrossSection which is used at all gamma energies. G4ElectroNuclearCrossSection is used at all energies for e^+ and e^-, while G4KokoulinMuonNuclearXS is used for μ^+ and μ^- at all energies.

Elastic models

Elastic scattering of protons and neutrons use G4ChipsElasticModel from 0 to 100 TeV. This model uses the Kossov parameterised cross sections.

For almost all other hadrons the G4HadronElastic model is used for some or all of the energy range. This model is a two-exponential momentum transfer model updated from the old Gheisha code. It is used at all energies by kaons, hyperons, deuterons, tritons, ^{3}He, alphas and anti-neutrons.

Elastic π^+ and π^- scattering is implemented by the G4ElasticHadrNucleusHE coherent scattering model for all energies.

For anti-protons, anti-neutrons, anti-deuterons, anti-tritons, anti-^{3}He and anti-alphas, G4HadronElastic is used from 0 to 100 MeV/n. Above 100 MeV/n these particles are handled by the G4AntiNuclElastic model.

There is currently no elastic scattering model for nuclear projectiles with $A > 4$.

Elastic cross sections

G4BGGNucleonElasticXS is used for protons, G4NeutronElasticXS for neutrons, and G4BGGPionElasticXS for pions. In these cross sections Barashenkov parameterisation is used below 91 GeV and Glauber-Gribov above.

For kaons, hyperons, anti-hyperons and light ions the G4ComponentGGNuclNuclXsc elastic cross section is used.

anti-p, anti-d, anti-t, anti-^{3}He and anti-alpha use the Glauber model cross section in G4ComponentAntiNuclNuclearXS at all energies.

No elastic cross sections are available for projectiles with $A > 4$.

Capture and stopping

Neutron capture uses the G4NeutronRadCapture model with the G4NeutronCaptureXS cross sections. Muon capture or decay at rest is handled by the G4MuonMinusCapture process.

The capture of negative pions and kaons once they have stopped is handled by the BertiniCaptureAtRest model which uses the Bertini cascade. The capture of anti-p, anti-d, anti-t, anti-³He, anti-alpha is handled by the FritiofCapture-AtRest model which uses the Fritiof string model.

2.1.2 Electromagnetic Component

This physics list uses "standard" GEANT4 electromagnetic physics as built by the G4EmStandardPhysics constructor. It is implemented for γ, e^-, e^+, μ^-, μ^+, τ^-, τ^+, and all stable charged hadrons/ion (see details in *EM physics constructors*).

There is no treatment of optical photons in this physics list, optical physics should be added on top of any reference or user custom physics.

2.1.3 Decay Component

The decay of all long-lived hadrons and leptons is handled by the G4Decay process. It does not handle the decay of hadronic resonances like deltas, which should be decayed within hadronic models and heavy-flavor particles like D and B mesons or charmed hyperons.

2.1.4 Neutron tracking cut

Neutrons may be killed if they fall below the energy cut (zero by default) or above the time cut (10 microsecond by default). These cuts may be modified via UI commands.

2.1.5 Recommended Use Cases

FTFP_BERT is recommended for collider physics applications. It usually produces the best agreement with test beam calorimeter data, including shower shape, energy response and resolution.

It is also recommended for cosmic ray applications where good treatment of very high energy particles is required. Note, however, that is not suited to very high energy collisions of order 10 TeV or more.

2.1.6 Related Physics Lists

- **FTFP_BERT_HP**: identical to FTFP_BERT except that neutrons of 20 MeV and lower use the High Precision neutron models and cross sections to describe elastic and inelastic scattering, capture and fission, the last process is added. additionally radioactive decay is activated. The G4NDL database is required for this physics list.
- **FTFP_BERT_HPT**: (available only in the physics list factory) identical to FTFP_BERT_HP except that a special treatment of elastic scattering of thermal neutrons is activated.
- **FTFP_BERT_ATL**: identical to FTFP_BERT except that transition between the FTF model and the Bertini cascade is changed: [9, 12] GeV. This was a requirement from the ATLAS experiment at LHC.
- **FTFP_BERT_TRV**: identical to FTFP_BERT except that several electromagnetic and hadronic models are substituted by their alternative.
- **FTFP_INCLXX**: identical to FTFP_BERT except that the Bertini cascade is substituted by the INCL++ cascade. Moreover, for antiproton annihilation at rest, INCL++ model is used instead of the FTF model.

- **FTFP_INCLXX_HP**: identical to FTFP_INCLXX except that neutrons of 20 MeV and lower use the High Precision neutron models and cross sections to describe elastic and inelastic scattering, capture and fission. The G4NDL database is required for this physics list. Moreover, RadioactiveDecay is activated.
- **FTFP_INCLXX_HPT**: (available only in the physics list factory) identical to FTFP_INCLXX_HP except that a special treatment of elastic scattering of thermal neutrons is activated.
- **FTFQGS_BERT**: identical to FTFP_BERT except that QGS string model is used for string fragmentation (while FTF is used for string formation).
- **FTF_BIC**: identical to FTFP_BERT except that the Binary cascade is used as by the FTF model instead of internal FTF cascade code for rescattering of secondary particles within nucleus.
- **Electromagnetic options**: different configurations of electromagnetic physics are available *EM physics constructors*), which may be used instead of the default electromagnetic physics.

2.2 QBBC

It is recommended for medical and space physics simulations [eal11].

2.2.1 Hadronic Component

The purely hadronic part of this physics list consists of elastic, inelastic, and capture processes. Each process is built from a set of cross section sets and interaction models which provide the detailed physics implementation. For neutron physics a general neutron process is enabled by default. It may be disabled via G4HadronicParameters interface.

Inelastic models

The inelastic hadron-nucleus processes are implemented by the FTF, Bertini, Binary, and Precompound models. The Bertini intranuclear cascade is responsible for π^+, π^-, K^+, K^-, K_L, K_S, Λ, Σ^+, Σ^-, Σ^0, Ξ^-, Ξ^0 and Ω^- interactions between 0 to 6 GeV. For protons and neutrons the Binary cascade is applied between 0 and 1.5 GeV, the Bertini cascade is applied from 1 to 6 GeV. The Fritiof parton model (FTF) handles these same particles, but over the range 3 GeV to 100 TeV. It also handles anti-protons, anti-neutrons, anti-deuterons, anti-tritons, anti-^{3}He, anti-alphas and anti-hyperons from 0 to 100 TeV/n.

Where Bertini and FTF overlap in particle type and energy range, Bertini is invoked with a probability that decreases linearly from 1.0 to 0.0 and FTF is invoked with the complementary probability.

When the FTF model or the Binary cascade are used, the Precompound model (P) is also invoked to de-excite the remnant nucleus after the initial high energy interaction. The precompound model in turn calls the Fermi breakup, neutron and light ion evaporation and photon evaporation models as needed. When the Bertini model is used, its own, simpler precompound and de-excitation models are invoked.

Inelastic nucleus-nucleus scattering for all incident A is handled by the Binary Light Ion Cascade (BIC) between 0 and 6 GeV/n, and by the FTF model between 3 GeV/n and 100 TeV/n. The scheme for choosing models in overlapping energy regions is the same as that for FTFP and BERT.

The hadronic interaction of gammas is handled by the photo-nuclear process in which gammas below 6 GeV are interacted using the Bertini cascade, and above 3 GeV by the Quark-gluon String (QGS) model. Below 200 MeV low-energy model based on de-exitation module is used. Muons, electrons and positrons also interact via transfer of virtual photons. These interactions are handled by G4MuonVDNuclearModel and G4ElectroVDNuclearModel which are applied at all energies.

Inelastic cross sections

G4ParticleInelasticXS is used for protons, G4NeutronInelasticXS for neutrons, and G4BGGPionInelasticXS for pions. In these cross sections Barashenkov parameterisation is used from 20 MeV to 20 GeV and Glauber-Gribov above. Below 20 MeV ParticleHP data are used for neutrons and light ions.

For kaons, hyperons and anti-hyperons the Glauber-Gribov set (G4ComponentGGHadronNucleusXsc) is used at all energies.

Nucleus-nucleus cross sections for ions with $A > 4$ are provided by G4ComponentGGNuclNuclXsc at all projectile energies. This class is the Glauber-Gribov nucleus-nucleus cross section parameterisation.

For d, t, ^{3}He, ^{4}He G4ParticleInelasticXS is used.

When the projectile is an anti-proton, anti-neutron, anti-deuteron, anti-triton, anti-^{3}He or anti-alpha, the G4ComponentAntiNuclNuclearXS class provides the cross sections using the Glauber-Gribov parameterisation.

Hadronic gamma interaction cross sections are supplied by G4PhotoNuclearCrossSection which is used at all gamma energies. G4ElectroNuclearCrossSection is used at all energies for e^+ and e^-, while G4KokoulinMuonNuclearXS is used for μ^+ and μ^- at all energies.

Elastic models

Elastic scattering of protons and neutrons use G4ChipsElasticModel from 0 to 100 TeV. This model uses the Kossov parameterised differential cross sections. For total cross sections are G4NeutronElasticXS for neutrons, G4BGGNucleonElasticXS for proton, and G4BGGPionElasticXS for pions.

For almost all other hadrons and ions the G4HadronElastic model is used for some or all of the energy range. This model is a two-exponential momentum transfer model updated from the old Gheisha code and tunned for elastic scatteing data for proton and pion projectile below 1 GeV. It is used at all energies by kaons, hyperons, deuterons, tritons, ^{3}He, alphas and anti-neutrons.

Elastic π^+ and π^- scattering is implemented by the G4ElasticHadrNucleusHE coherent scattering model for all energies.

For anti-protons, anti-neutrons, anti-deuterons, anti-tritons, anti-^{3}He and anti-alphas, G4HadronElastic is used from 0 to 100 MeV/u. Above 100 MeV/u these particles are handled by the G4AntiNuclElastic model.

Elastic cross sections

G4BGGNucleonElasticXS is used for protons, G4NeutronElasticXS for neutrons, and G4BGGPionElasticXS for pions. In these cross sections Barashenkov parameterisation is used from zero to 20 GeV and Glauber-Gribov above. For neutrons HP data are used in the interval 0 - 20 MeV.

For kaons, hyperons, anti-hyperons, and ions the G4ComponentGGNuclNuclXsc elastic cross section is used.

anti-p, anti-d, anti-t, anti-^{3}He and anti-alpha use the Glauber model cross section in G4ComponentAntiNuclNuclearXS at all energies.

Capture and stopping

Neutron capture uses the G4NeutronRadCapture model with the G4NeutronCaptureXS cross sections. Muon capture or decay at rest is handled by the G4MuonMinusCapture process.

The capture of negative pions and kaons once they have stopped is handled by the BertiniCaptureAtRest model which uses the Bertini cascade. The capture of anti-p, anti-d, anti-t, anti-^{3}He, anti-alpha is handled by the FritiofCapture-AtRest model which uses the Fritiof string model.

2.2.2 Electromagnetic Component

This physics list uses "standard" GEANT4 electromagnetic physics as built by the G4EmStandardPhysics constructor. It is implemented for γ, e^-, e^+, μ^-, μ^+, τ^-, τ^+, and all stable charged hadrons/ion (see details in *EM physics constructors*).

There is no treatment of optical photons in this physics list, optical physics should be added on top of any reference or user custom physics.

2.2.3 Decay Component

The decay of all long-lived hadrons and leptons is handled by the G4Decay process. It does not handle the decay of hadronic resonances like deltas, which should be decayed within hadronic models and heavy-flavor particles like D and B mesons or charmed hyperons.

Muon capture or decay at rest is handled by the G4MuonMinusCapture process.

2.2.4 Neutron tracking cut

Neutrons may be killed if they fall below the energy cut (zero by default) or above the time cut (10 microsecond by default). These cuts may be modified via UI commands.

2.2.5 Recommended Use Cases

QBBC is recommended for applications where accurate simulation for low-energy transport of protons and neutrons is needed. It usually produces the best agreement in the energy range below 1 GeV for thin target experiments. For higher energies it is the same as the default FTFP_BERT physics *FTFP_BERT*. It is recommended for medical and space applications [eal11].

2.2.6 Related Physics Lists

- **QBBC_ABLA**: identical to QBBC except that the ABLA model is used for nuclear de-excitation instead of Precompound/de-excitation, for charged pions and nucleons projectiles. This physics list is for testing purposes.
- **Electromagnetic options**: different configurations of electromagnetic physics are available *EM physics constructors*), which may be used instead of the default electromagnetic physics.

2.3 QGSP_BERT

It is the former GEANT4 default [eal09].

2.3.1 Hadronic Component

The purely hadronic part of this physics list consists of elastic, inelastic, and capture processes. Each process is built from a set of cross section sets and interaction models which provide the detailed physics implementation.

Inelastic models

The inelastic hadron-nucleus processes are implemented by the quark-gluon model (QGS), the Fritiof parton model (FTF), Bertini and Precompound models. The Bertini intranuclear cascade is responsible for p, n, π^+, π^-, K^+, K^-, K_L, K_S, Λ, Σ^+, Σ^-, Σ^0, Ξ^-, Ξ^0 and Ω^- interactions between 0 to 6 GeV. The QGS model handles protons, neutrons, pions and kaons above 12 GeV. The FTF model handles these same particles, but over the range 3 GeV to 25 GeV, it also handles anti-protons, anti-neutrons, anti-deuterons, anti-tritons, anti-^{3}He, anti-alphas and anti-hyperons from 0 to 100 TeV/n.

Where Bertini and FTF overlap in particle type and energy range, Bertini is invoked with a probability that decreases linearly from 1.0 to 0.0 and FTF is invoked with the complementary probability. Similar algorithm is applied in common energy area for FTF and QGS.

When the FTF and QGS models are used, the Precompound model (P) is also invoked to de-excite the remnant nucleus after the initial high energy interaction. The precompound model in turn calls the Fermi breakup, multi-fragmentation, neutron evaporation and photon evaporation models as needed. When the Bertini model is used, its own, simpler precompound and de-excitation models are invoked.

Inelastic nucleus-nucleus scattering for all incident A is handled by the Binary Light Ion Cascade (BIC) between 0 and 6 GeV/n, and by the FTF model between 3 GeV/n and 100 TeV/n. The scheme for choosing models in overlapping energy regions is the same as that for FTFP and BERT.

The hadronic interaction of gammas is handled by the photo-nuclear process in which gammas below 6 GeV are interacted using the Bertini cascade, and above 3 GeV by the Quark-gluon String (QGS) model. Muons, electrons and positrons also interact via transfer of virtual photons. These interactions are handled by G4MuonVDNuclearModel and G4ElectroVDNuclearModel which are applied at all energies.

Inelastic cross sections

G4BGGNucleonInelasticXS is used for protons, G4NeutronInelasticXS for neutrons, and G4BGGPionInelasticXS for pions. In these cross sections Barashenkov parameterisation is used below 91 GeV and Glauber-Gribov above.

For kaons, hyperons and anti-hyperons the Glauber-Gribov set (G4ComponentGGHadronNucleusXsc) is used at all energies.

All nucleus-nucleus cross sections are provided by G4ComponentGGNuclNuclXsc at all projectile energies. This class is the Glauber-Gribov nucleus-nucleus cross section parameterisation. When the projectile is an anti-proton, anti-neutron, anti-deuteron, anti-triton, anti-^{3}He or anti-alpha, the G4ComponentAntiNuclNuclearXS class provides the cross sections using the Glauber-Gribov parameterisation.

Hadronic gamma interaction cross sections are supplied by G4PhotoNuclearCrossSection which is used at all gamma energies. G4ElectroNuclearCrossSection is used at all energies for e^+ and e^-, while G4KokoulinMuonNuclearXS is used for μ^+ and μ^- at all energies.

Elastic models

Elastic scattering of protons and neutrons use G4ChipsElasticModel from 0 to 100 TeV. This model uses the Kossov parameterised cross sections.

For almost all other hadrons the G4HadronElastic model is used for some or all of the energy range. This model is a two-exponential momentum transfer model updated from the old Gheisha code. It is used at all energies by kaons, hyperons, deuterons, tritons, ^{3}He, alphas and anti-neutrons.

Elastic π^+ and π^- scattering is implemented by the G4ElasticHadrNucleusHE coherent scattering model for all energies.

For anti-protons, anti-neutrons, anti-deuterons, anti-tritons, anti-^{3}He and anti-alphas, G4HadronElastic is used from 0 to 100 MeV/n. Above 100 MeV/n these particles are handled by the G4AntiNuclElastic model.

There is currently no elastic scattering model for nuclear projectiles with $A > 4$.

Elastic cross sections

G4BGGNucleonElasticXS is used for protons, G4NeutronElasticXS for neutrons, and G4BGGPionElasticXS for pions. In these cross sections Barashenkov parameterisation is used below 91 GeV and Glauber-Gribov above.

For kaons, hyperons, anti-hyperons and light ions the G4ComponentGGNuclNuclXsc elastic cross section is used.

anti-p, anti-d, anti-t, anti-^{3}He and anti-alpha use the Glauber model cross section in G4ComponentAntiNuclNuclearXS at all energies.

No elastic cross sections are available for projectiles with $A > 4$.

Capture and stopping

Neutron capture uses the G4NeutronRadCapture model with the G4NeutronCaptureXS cross sections. Muon capture or decay at rest is handled by the G4MuonMinusCapture process.

The capture of negative pions and kaons once they have stopped is handled by the BertiniCaptureAtRest model which uses the Bertini cascade. The capture of anti-p, anti-d, anti-t, anti-^{3}He, anti-alpha is handled by the FritiofCaptureAtRest model which uses the Fritiof string model.

2.3.2 Electromagnetic Component

This physics list uses "standard" GEANT4 electromagnetic physics as built by the G4EmStandardPhysics constructor. It is implemented for γ, e^-, e^+, μ^-, μ^+, τ^-, τ^+, and all stable charged hadrons/ion (see details in *EM physics constructors*).

There is no treatment of optical photons in this physics list, optical physics should be added on top of any reference or user custom physics.

2.3.3 Decay Component

The decay of all long-lived hadrons and leptons is handled by the G4Decay process. It does not handle the decay of hadronic resonances like deltas, which should be decayed within hadronic models and heavy-flavor particles like D and B mesons or charmed hyperons.

Muon capture or decay at rest is handled by the G4MuonMinusCapture process.

2.3.4 Neutron tracking cut

Neutrons may be killed by energy cut (zero by default) or by time cut (10 microsecond by default). These cuts may be modified via UI commands.

2.3.5 Recommended Use Cases

QGSP_BERT can be used for collider physics applications, as an alternative to the recommended physics list FTFP_BERT.

It is can also be used for cosmic ray applications where good treatment of very high energy particles is required. Note, however, that is not suited to very high energy collisions of order 10 TeV or more.

2.3.6 Related Physics Lists

- **QGSP_BERT_HP**: identical to QGSP_BERT except that neutrons of 20 MeV and lower use the new version (alternative to the one of FTFP_BERT_HP) of the High Precision neutron models and cross sections to describe elastic and inelastic scattering, capture and fission, the last process is added. Additionally radioactive decay is activated. The G4NDL database is required for this physics list.
- **QGSP_BERT_HPT**: (available only in the physics list factory) identical to QGSP_BERT_HP except that a special treatment of elastic scattering of thermal neutrons is activated.
- **QGSP_FTFP_BERT**: currently identical to QGSP_BERT (it was different before and it might change in the future).
- **QGSP_INCLXX**: identical to QGSP_BERT except that the Bertini cascade is substituted by the INCL++ cascade. Moreover, for antiproton annihilation at rest, INCL++ model is used instead of the FTF model.
- **QGSP_INCLXX_HP**: identical to QGSP_INCLXX except that neutrons of 20 MeV and lower use the High Precision neutron models and cross sections to describe elastic and inelastic scattering, capture and fission. The G4NDL database is required for this physics list. Moreover, RadioactiveDecay is activated.
- **QGSP_INCLXX_HPT**: (available only in the physics list factory) identical to QGSP_INCLXX_HP except that a special treatment of elastic scattering of thermal neutrons is activated.
- **Electromagnetic options**: different configurations of electromagnetic physics are available *EM physics constructors*), which may be used instead of the default electromagnetic physics.

2.4 QGSP_BIC

2.4.1 Hadronic Component

The purely hadronic part of this physics list consists of elastic, inelastic, and capture processes. Each process is built from a set of cross section sets and interaction models which provide the detailed physics implementation.

Inelastic models

The inelastic hadron-nucleus processes are implemented by the Quark-gluon String (QGS), the Fritiof parton model (FTF), Bertini, Binary, and Precompound models. The Bertini intranuclear cascade is responsible for π^+, π^-, K^+, K^-, K_L, K_S, Λ, Σ^+, Σ^-, Σ^0, Ξ^-, Ξ^0 and Ω^- interactions between 0 to 6 GeV. The Binary cascade is applied for neutrons and protons between 0 and 6 GeV. The QGS model is applied for p, n, π^+, π^-, K^+, K^-, K_L, K_S, above 12 GeV. The FTF model handles the same particles, but over the range 3 GeV to 25 GeV. For hyperons, FTF is applied from 3 GeV to 100 TeV. FTF also handles anti-protons, anti-neutrons, anti-deuterons, anti-tritons, anti-^{3}He, anti-alphas and anti-hyperons from 0 to 100 TeV/n.

When the QGS, FTF, and Binary models are used, the Precompound model (P) is also invoked to de-excite the remnant nucleus after the initial high energy interaction. The precompound model in turn calls the Fermi breakup, neutron and light ion evaporation and photon evaporation models as needed. When the Bertini model is used, its own, simpler precompound and de-excitation models are invoked.

Inelastic nucleus-nucleus scattering for all incident A is handled by the Binary Light Ion Cascade (BIC) between 0 and 6 GeV/n, and by the FTF model between 3 GeV/n and 100 TeV/n. The scheme for choosing models in overlapping energy regions is the same as that for FTFP and BERT.

The hadronic interaction of gammas is handled by the photo-nuclear process in which gammas below 6 GeV are interacted using the Bertini cascade, and above 3 GeV by the Quark-gluon String (QGS) model. Muons, electrons and positrons also interact via transfer of virtual photons. These interactions are handled by G4MuonVDNuclearModel and G4ElectroVDNuclearModel which are applied at all energies.

Inelastic cross sections

G4BGGNucleonInelasticXS is used for protons, G4NeutronInelasticXS for neutrons, and G4BGGPionInelasticXS for pions. In these cross sections Barashenkov parameterisation is used below 91 GeV and Glauber-Gribov above.

For kaons, hyperons and anti-hyperons the Glauber-Gribov set (G4ComponentGGHadronNucleusXsc) is used at all energies.

All nucleus-nucleus cross sections are provided by G4ComponentGGNuclNuclXsc at all projectile energies. This class is the Glauber-Gribov nucleus-nucleus cross section parameterisation. When the projectile is an anti-proton, anti-neutron, anti-deuteron, anti-triton, anti-^{3}He or anti-alpha, the G4ComponentAntiNuclNuclearXS class provides the cross sections using the Glauber-Gribov parameterisation.

Hadronic gamma interaction cross sections are supplied by G4PhotoNuclearCrossSection which is used at all gamma energies. G4ElectroNuclearCrossSection is used at all energies for e^+ and e^-, while G4KokoulinMuonNuclearXS is used for μ^+ and μ^- at all energies.

Elastic models

Elastic scattering of protons and neutrons use G4ChipsElasticModel from 0 to 100 TeV. This model uses the Kossov parameterised cross sections.

For almost all other hadrons the G4HadronElastic model is used for some or all of the energy range. This model is a two-exponential momentum transfer model updated from the old Gheisha code. It is used at all energies by kaons, hyperons, deuterons, tritons, ^{3}He, alphas and anti-neutrons.

Elastic π^+ and π^- scattering is implemented by the G4ElasticHadrNucleusHE coherent scattering model for all energies.

For anti-protons, anti-neutrons, anti-deuterons, anti-tritons, anti-^{3}He and anti-alphas, G4HadronElastic is used from 0 to 100 MeV/n. Above 100 MeV/n these particles are handled by the G4AntiNuclElastic model.

There is currently no elastic scattering model for nuclear projectiles with $A > 4$.

Elastic cross sections

G4BGGNucleonElasticXS is used for protons, G4NeutronElasticXS for neutrons, and G4BGGPionElasticXS for pions. In these cross sections Barashenkov parameterisation is used below 91 GeV and Glauber-Gribov above.

For kaons, hyperons, anti-hyperons and light ions the G4ComponentGGNuclNuclXsc elastic cross section is used.

anti-p, anti-d, anti-t, anti-^{3}He and anti-alpha use the Glauber model cross section in G4ComponentAntiNuclNuclearXS at all energies.

No elastic cross sections are available for projectiles with $A > 4$.

Capture and stopping

Neutron capture uses the G4NeutronRadCapture model with the G4NeutronCaptureXS cross sections. Muon capture or decay at rest is handled by the G4MuonMinusCapture process.

The capture of negative pions and kaons once they have stopped is handled by the BertiniCaptureAtRest model which uses the Bertini cascade. The capture of anti-p, anti-d, anti-t, anti-^{3}He, anti-alpha is handled by the FritiofCapture-AtRest model which uses the Fritiof string model.

2.4.2 Electromagnetic Component

This physics list uses "standard" GEANT4 electromagnetic physics as built by the G4EmStandardPhysics constructor. It is implemented for γ, e^-, e^+, μ^-, μ^+, τ^-, τ^+, and all stable charged hadrons/ion (see details in *EM physics constructors*).

There is no treatment of optical photons in this physics list, optical physics should be added on top of any reference or user custom physics.

2.4.3 Decay Component

The decay of all long-lived hadrons and leptons is handled by the G4Decay process. It does not handle the decay of hadronic resonances like deltas, which should be decayed within hadronic models and heavy-flavor particles like D and B mesons or charmed hyperons.

2.4.4 Neutron tracking cut

Neutrons may be killed if they fall below the energy cut (zero by default) or above the time cut (10 microsecond by default). These cuts may be modified via UI commands.

2.4.5 Recommended Use Cases

QGSP_BIC can be used for collider physics applications, as an alternative to the recommended physics list FTFP_BERT.

It is can also be used for cosmic ray applications where good treatment of very high energy particles is required. Note, however, that is not suited to very high energy collisions of order 10 TeV or more.

2.4.6 Related Physics Lists

- **QGSP_BIC_HP**: identical to QGSP_BIC except that neutrons of 20 MeV and lower use the High Precision neutron models and cross sections to describe elastic and inelastic scattering, capture and fission. The G4NDL database is required for this physics list. Moreover, RadioactiveDecay is activated.
- **QGSP_BIC_HPT**: identical to QGSP_BIC_HP except that a special treatment of elastic scattering of thermal neutrons is activated.
- **QGSP_BIC_AllHP**: identical to QGSP_BIC_HP except that for protons and light ions (d, t, He3, and alpha), ParticleHP is used below 200 MeV.
- **QGSP_BIC_AllHPT**: (available only in the physics list factory) identical to QGSP_BIC_AllHP except that a special treatment of elastic scattering of thermal neutrons is activated.
- **Electromagnetic options**: different configurations of electromagnetic physics are available *EM physics constructors*), which may be used instead of the default electromagnetic physics.

2.5 Shielding

It is recommended for simulation of deep shielding. Neutrons of 20 MeV and lower use the High Precision neutron models and cross sections to describe elastic and inelastic scattering, capture and fission. The G4NDL database is required for this physics list.

2.5.1 Hadronic Component

The purely hadronic part of this physics list consists of elastic, inelastic, capture and fission processes. Each process is built from a set of cross section sets and interaction models which provide the detailed physics implementation.

Inelastic models

The inelastic hadron-nucleus processes are implemented by the Fritiof parton model (FTF), Bertini and Precompound models. The Bertini intranuclear cascade is responsible for $p, n, \pi^+,\ \pi^-,\ K^+,\ K^-,\ K_L,\ K_S,\ \Lambda,\ \Sigma^+,\ \Sigma^-,\ \Sigma^0,\ \Xi^-,\ \Xi^0$ and Ω^- interactions between 0 to 6 GeV. The FTF model handles these same particles, but over the range 3 GeV to 100 TeV. It also handles anti-protons, anti-neutrons, anti-deuterons, anti-tritons, anti-^{3}He, anti-alphas and anti-hyperons from 0 to 100 TeV/n.

Where Bertini and FTF overlap in particle type and energy range, Bertini is invoked with a probability that decreases linearly from 1.0 to 0.0, and FTF is invoked with the complementary probability.

When the FTF model is used, the Precompound model (P) is also invoked to de-excite the remnant nucleus after the initial high energy interaction. The precompound model in turn calls the Fermi breakup, neutron and light ion evaporation and photon evaporation models as needed. When the Bertini model is used, its own, simpler precompound and de-excitation models are invoked.

Inelastic nucleus-nucleus scattering for all incident A is handled by the Binary Light Ion Cascade (BIC) between 0 and 6 GeV/n, and by the FTF model between 3 GeV/n and 100 TeV/n. The scheme for choosing models in overlapping energy regions is the same as that for FTFP and BERT.

The hadronic interaction of gammas is handled by the photo-nuclear process in which gammas below 6 GeV are interacted using the Bertini cascade, and above 3 GeV by the Quark-gluon String (QGS) model. Muons, electrons and positrons also interact via transfer of virtual photons. These interactions are handled by G4MuonVDNuclearModel and G4ElectroVDNuclearModel which are applied at all energies.

Inelastic cross sections

G4BGGNucleonInelasticXS is used for protons, G4NeutronInelasticXS for neutrons, and G4BGGPionInelasticXS for pions. In these cross sections Barashenkov parameterisation is used below 91 GeV and Glauber-Gribov above.

For kaons, hyperons and anti-hyperons the Glauber-Gribov set (G4ComponentGGHadronNucleusXsc) is used at all energies.

All nucleus-nucleus cross sections are provided by G4ComponentGGNuclNuclXsc at all projectile energies. This class is the Glauber-Gribov nucleus-nucleus cross section parameterisation. When the projectile is an anti-proton, anti-neutron, anti-deuteron, anti-triton, anti-^{3}He or anti-alpha, the G4ComponentAntiNuclNuclearXS class provides the cross sections using the Glauber-Gribov parameterisation.

Hadronic gamma interaction cross sections are supplied by G4PhotoNuclearCrossSection which is used at all gamma energies. G4ElectroNuclearCrossSection is used at all energies for e^+ and e^-, while G4KokoulinMuonNuclearXS is used for μ^+ and μ^- at all energies.

Elastic models

Elastic scattering of protons and neutrons use G4ChipsElasticModel from 0 to 100 TeV. This model uses the Kossov parameterised cross sections.

For almost all other hadrons the G4HadronElastic model is used for some or all of the energy range. This model is a two-exponential momentum transfer model updated from the old Gheisha code. It is used at all energies by kaons, hyperons, deuterons, tritons, ^{3}He, alphas and anti-neutrons.

Elastic π^+ and π^- scattering is implemented by the G4ElasticHadrNucleusHE coherent scattering model for all energies.

For anti-protons, anti-neutrons, anti-deuterons, anti-tritons, anti-^{3}He and anti-alphas, G4HadronElastic is used from 0 to 100 MeV/n. Above 100 MeV/n these particles are handled by the G4AntiNuclElastic model.

There is currently no elastic scattering model for nuclear projectiles with $A > 4$.

Elastic cross sections

G4BGGNucleonElasticXS is used for protons, G4NeutronElasticXS for neutrons, and G4BGGPionElasticXS for pions. In these cross sections Barashenkov parameterisation is used below 91 GeV and Glauber-Gribov above.

For kaons, hyperons, anti-hyperons and light ions the G4ComponentGGNuclNuclXsc elastic cross section is used.

For all ions the G4ComponentGGNuclNuclXsc elastic cross section is used. anti-p, anti-d, anti-t, anti-^{3}He and anti-alpha use the Glauber model cross section in G4ComponentAntiNuclNuclearXS at all energies.

Capture and stopping

Neutron capture uses the G4NeutronRadCapture model with the G4NeutronCaptureXS cross sections. Muon capture or decay at rest is handled by the G4MuonMinusCapture process.

The capture of negative pions and kaons once they have stopped is handled by the BertiniCaptureAtRest model which uses the Bertini cascade. The capture of anti-p, anti-d, anti-t, anti-^{3}He, anti-alpha is handled by the FritiofCaptureAtRest model which uses the Fritiof string model.

2.5.2 Electromagnetic Component

This physics list uses "standard" GEANT4 electromagnetic physics as built by the G4EmStandardPhysics constructor. It is implemented for γ, e^-, e^+, μ^-, μ^+, τ^-, τ^+, and all stable charged hadrons/ion (see details in *EM physics constructors*).

There is no treatment of optical photons in this physics list, optical physics should be added on top of any reference or user custom physics.

2.5.3 Decay Component

The decay of all long-lived hadrons and leptons is handled by the G4Decay process. It does not handle the decay of hadronic resonances like deltas, heavy-flavor particles like D and B mesons or charmed hyperons.

This physics list does invoke the G4RadioactiveDecay process, so unstable ions will be decayed.

Muon capture is handled by the G4MuonMinusCapture process.

2.5.4 Recommended Use Cases

Shielding is recommended for applications for neutron transport.

2.5.5 Related Physics Lists

- **Shielding_HP**: alias of (i.e. the same as) Shielding, available only in the physics list factory.
- **Shielding_HPT**: (available only in the physics list factory) identical to Shielding_HP except that a special treatment of elastic scattering of thermal neutrons is activated.
- **ShieldingM**: different transition from the Bertini model to the FTF model: from 9.5 to 9.9 GeV.
- **ShieldingM_HP**: alias of (i.e. the same as) ShieldingM, available only in the physics list factory.
- **ShieldingM_HPT**: (available only in the physics list factory) identical to ShieldingM_HP except that a special treatment of elastic scattering of thermal neutrons is activated.
- **ShieldingLEND**: different configurations of low-energy neutron transport with LEND option.
- **Electromagnetic options**: different configurations of electromagnetic physics are available *EM physics constructors*), which may be used instead of the default electromagnetic physics.

ELECTROMAGNETIC PHYSICS CONSTRUCTORS

A description of the various electromagnetic physics constructors and their effects on the simulation performance both in terms of computation (CPU) and physics precision.

3.1 EM physics constructors

Electromagnetic physics constructors were first published in [eal09], were extended in [eal11] and become stable in recent releases of GEANT4 [eal16]. The default electromagnetic physics is built by the `G4EmStandardPhysics` constructor (see details in *EM Opt0*).

Electromagnetic physics in all physics constructors is implemented for the following particles: γ, e^-, e^+, μ^-, μ^+, τ^-, τ^+, π^+, π^-, K^+, K^-, p, Σ^+, Σ^-, Ξ^-, Ω^-, anti(p, Σ^+, Σ^-, Ξ^-, Ω^-), d, t, ^3He, α, anti(d, t, ^3He, α), and `G4GenericIon`.

Several charmed mesons are also treated, D^+, D^-, D_s^+, D_s^-, Λ_c^+, Σ_c^+, Σ_c^{++}, Ξ_c^+, anti(Λ_c^+, Σ_c^+, Σ_c^{++}, Ξ_c^+), as well as two bottom mesons, B^+, B^-, B_c^+, B_c^-, Ω_b^-, Σ_b^+, Σ_b^-, Ξ_b^- anti(Ω_b^-, Σ_b^+, Σ_b^-, Ξ_b^-).

Internal tables for energy loss, range and cross sections are built from 100 eV to 100 TeV. These limits are defined based on LHC experiments requirements. Upper limits of applicability of various electromagnetic processes are larger and are process dependent. For example, muon models are valid up to 1 PeV. In order to provide particle transport for all use-cases, the operational energy range goes down to zero but below 1 keV the accuracy of the default set of models is degraded substantially.

The GEANT4 toolkit includes many alternative physics models, especially, for electromagnetic physics. There are several well established configurations recommended for different applications:

- `G4EmStandardPhysics_option1` *EM Opt1* - extension name EMV;
- `G4EmStandardPhysics_option2` *EM Opt2* - extension name EMX;
- `G4EmStandardPhysics_option3` *EM Opt3* - extension name EMY;
- `G4EmStandardPhysics_option4` *EM Opt4* - extension name EMZ;
- `G4EmLivermorePhysics` *EM Liv* - extension name LIV;
- `G4EmPenelopePhysics` *EM Pen* - extension name PEN;
- `G4EmStandardPhysicsGS` *EM GS* - extension name _GS;
- `G4EmLowEPPhysics` *EM LE* - extension name _LE;
- `G4EmStandardPhysicsWVI` *EM WVI* - extension name WVI;
- `G4EmStandardPhysicsSS` *EM SS* - extension name _SS;
- `G4EmDNAPhysics` *EM DNA*.

3.2 EM Opt0

The default electromagnetic physics is built by the `G4EmStandardPhysics` constructor (see details in *EM Opt0*).

For each particle type Standard EM models implement several processes. Processes cover physics from 0 to 100 TeV for all particles. Though the operational energy range goes down to zero, below 1 keV accuracy of these models is substantially lower.

Photons: e^-/e^+ pair production is implemented by the BetheHeitler model with the LPM effect at high energies and Compton scattering is implemented by the Klein-Nishina model. Photo-electric effect and Rayleigh scattering are both handled by the Livermore models. G4GammaGeneralProcess is used to combine all these processes.

Electrons and positrons: multiple Coulomb scattering is handled by the Urban model from 0 to 100 MeV and by the WentzelVI model from 100 MeV to 100 TeV, which is combined with the single Coulomb scattering model, which is applied for large angle scattering. *UseSafety* step limitation is used for multiple scattering. Bremsstrahlung is implemented by the eBremSB model and the eBremLPM model which takes into account the LPM effect at high energies. Ionisation is modelled by the Moller-Bhabha formulation, and positron annihilation is implemented by the eplus2gg model.

Muons: multiple Coulomb scattering is handled by the WentzelVI model combined with the single scattering model at all energies, and by the eCoulombScattering model at all energies. Bremsstrahlung is handled by the MuBrem model. Ionisation is implemented by several models depending on energy and particle type. From 0 to 200 keV, the Bragg model is used for μ^+ and the ICRU73Q0 parameterisation is used for μ^-. Above 200 keV the MuBetheBloch model is used for both μ^+ and μ^-. The muPairProduction model handles e+/e- pair production caused by either μ^+ or μ^-.

Pions, kaons, protons and anti-protons: multiple Coulomb scattering is performed by the WentzelVI model and Coulomb scattering by the eCoulombScattering model. Bremsstrahlung is handled by hBrem model. e^-/e^+ pair production by hadrons is implemented by the hPairProduction model. Ionisation is handled by several models depending on energy and particle type. For pions below 298 keV, Bragg model ionisation is used for π^+, and the ICRU73Q0 parameterisation is used for π^-. Above this energy BetheBloch ionisation is used. For kaons, the same ionisation models are used, but the change from low energy to high energy models occurs at 1.05 MeV. For protons, the Bragg model is used below 2 MeV and the BetheBloch above. For anti-protons ICRU73Q0 is used below 2 MeV and BetheBloch above.

alpha and G4GenericIon: only two EM processes are applied. Multiple Coulomb scattering in implemented by the Urban model at all energies. For ionisation below 2 MeV/u data are used. Priority of data is following: ICRU90, ICRU73, PSTAR, ASTAR, ICRU49. Above 2 MeV/u the Bethe-Bloch model is used.

3.3 EM Opt1

This physics list uses "standard" GEANT4 electromagnetic physics as built by the `G4EmStandardPhysics_option1` constructor.

For each particle type several processes are implemented. Processes cover physics from 0 to 100 TeV for gamma, e^- and e^+ and up to 1 PeV for muons. EM interactions of charged hadrons and ions cover the range 0 to 100 TeV. Though the operational energy range goes down to zero, below 1 keV accuracy of these models is substantially lower.

Photons: e^-/e^+ pair production is implemented by the BetheHeitler model with the LPM effect at high energies and Compton scattering is implemented by the Klein-Nishina model. Photo-electric effect and Rayleigh scattering are both handled by the Livermore models. *ApplyCuts* option is use to cut out low-energy e^-, produced by gamma processes.

Electrons and positrons: multiple Coulomb scattering is handled by the Urban model from 0 to 100 MeV and by the WentzelVI model from 100 MeV to 100 TeV, which is combined with the single Coulomb scattering model, which is applied for large angle scattering. *Minimal* step limitation is used for multiple scattering. Multiple scattering is combined with transportation in G4TransportationWithMsc process. Bremsstrahlung is implemented by the eBremSB

model and the eBremLPM model which takes into account the LPM effect at high energies. Ionisation is modelled by the Moller-Bhabha formulation, and positron annihilation is implemented by the eplus2gg model.

Muons: multiple Coulomb scattering is handled by the WentzelVI model combined with the single scattering model at all energies, and by the eCoulombScattering model at all energies. Bremsstrahlung is handled by the MuBrem model. Ionisation is implemented by several models depending on energy and particle type. From 0 to 200 keV, the Bragg model is used for mu+ and the ICRU73Q0 parameterisation is used for mu-. Between 200 keV and 1 GeV the BetheBloch model is used for both μ^+ and μ^-, and from 1 GeV to 100 TeV, the MuBetheBloch model is used for both μ^+ and μ^-. The muPairProduction model handles e+/e- pair production caused by either μ^+ or μ^-.

Pions, kaons, protons and anti-protons: multiple Coulomb scattering is performed by the WentzelVI model and Coulomb scattering by the eCoulombScattering model. Bremsstrahlung is handled by hBrem model. e^-/e^+ pair production by hadrons is implemented by the hPairProduction model. Ionisation is handled by several models depending on energy and particle type. For pions below 298 keV, Bragg model ionisation is used for π^+, and the ICRU73Q0 parameterisation is used for π^-. Above this energy BetheBloch ionisation is used. For kaons, the same ionisation models are used, but the change from low energy to high energy models occurs at 1.05 MeV. For protons, the Bragg model is used below 2 MeV and the BetheBloch above. For anti-protons ICRU73Q0 is used below 2 MeV and BetheBloch above.

Alpha and G4GenericIon: the same as in the default `G4EmStandardPhysics` constructor.

3.4 EM Opt2

This physics list uses "standard" GEANT4 electromagnetic physics as built by the `G4EmStandardPhysics_option2` constructor.

For each particle type several processes are implemented. Processes cover physics from 0 to 100 TeV for gamma, e^- and e^+ and up to 1 PeV for muons. EM interactions of charged hadrons and ions cover the range 0 to 100 TeV. Though the operational energy range goes down to zero, below 1 keV accuracy of these models is substantially lower.

Photons: e^-/e^+ pair production is implemented by the BetheHeitler model with the LPM effect at high energies and Compton scattering is implemented by the Klein-Nishina model. Photo-electric effect and Rayleigh scattering are both handled by the Livermore models.

Electrons and positrons: multiple Coulomb scattering is handled by the Urban model from 0 to 100 MeV and by the WentzelVI model from 100 MeV to 100 TeV, which is combined with the single Coulomb scattering model, which is applied for large angle scattering. *Simple* step limitation is used for multiple scattering. Bremsstrahlung is implemented by the eBremSB model and the eBremLPM model which takes into account the LPM effect at high energies. Ionisation is modelled by the Moller-Bhabha formulation, and positron annihilation is implemented by the eplus2gg model.

Muons: multiple Coulomb scattering is handled by the WentzelVI model combined with the single scattering model at all energies, and by the eCoulombScattering model at all energies. Bremsstrahlung is handled by the MuBrem model. Ionisation is implemented by several models depending on energy and particle type. From 0 to 200 keV, the Bragg model is used for mu+ and the ICRU73Q0 parameterisation is used for mu-. Between 200 keV and 1 GeV the BetheBloch model is used for both μ^+ and μ^-, and from 1 GeV to 100 TeV, the MuBetheBloch model is used for both μ^+ and μ^-. The muPairProduction model handles e+/e- pair production caused by either μ^+ or μ^-.

Pions, kaons, protons and anti-protons: multiple Coulomb scattering is performed by the WentzelVI model and Coulomb scattering by the eCoulombScattering model. Bremsstrahlung is handled by hBrem model. e^-/e^+ pair production by hadrons is implemented by the hPairProduction model. Ionisation is handled by several models depending on energy and particle type. For pions below 298 keV, Bragg model ionisation is used for π^+, and the ICRU73Q0 parameterisation is used for π^-. Above this energy BetheBloch ionisation is used. For kaons, the same ionisation models are used, but the change from low energy to high energy models occurs at 1.05 MeV. For protons, the Bragg model is used below 2 MeV and the BetheBloch above. For anti-protons ICRU73Q0 is used below 2 MeV and BetheBloch above.

Alpha and G4GenericIon: the same as in the default `G4EmStandardPhysics` constructor.

3.5 EM Opt3

This physics list uses "standard" GEANT4 electromagnetic physics as built by the `G4EmStandardPhysics_option3` constructor.

Processes cover physics from 0 to 100 TeV for all particles. Though the operational energy range goes down to zero, below 1 keV accuracy of these models is substantially lower.

For each particle type several processes are implemented. Photons: e^-/e^+ pair production is implemented by the BetheHeitler model with the LPM effect at high energies and Compton scattering is implemented by the Klein-Nishina model. Photo-electric effect and Rayleigh scattering are both handled by the Livermore models.

Electrons and positrons: multiple Coulomb scattering is handled by the Urban model from 0 to 100 TeV. *UseSafety* step limitation is used for multiple scattering. The value of the Range Factor is 0.03. Bremsstrahlung is implemented by the eBremSB model and the eBremLPM model which takes into account the LPM effect at high energies. Ionisation is modelled by the Moller-Bhabha formulation, and positron annihilation is implemented by the eplus2gg model.

Muons: multiple Coulomb scattering is handled by the the Urban model from 0 to 100 TeV. Bremsstrahlung is handled by the MuBrem model. Ionisation is implemented by several models depending on energy and particle type. From 0 to 200 keV, the Bragg model is used for μ^+ and the ICRU73Q0 parameterisation is used for μ^-. Above 200 keV the MuBetheBloch model is used for both μ^+ and μ^-. The muPairProduction model handles e+/e- pair production caused by either μ^+ or μ^-.

Pions, kaons, protons and anti-protons: multiple Coulomb scattering is performed by the Urban model and Coulomb scattering by the eCoulombScattering model. Bremsstrahlung is handled by hBrem model. e^-/e^+ pair production by hadrons is implemented by the hPairProduction model. Ionisation is handled by several models depending on energy and particle type. For pions below 298 keV, Bragg model ionisation is used for π^+, and the ICRU73Q0 parameterisation is used for π^-. Above this energy BetheBloch ionisation is used. For kaons, the same ionisation models are used, but the change from low energy to high energy models occurs at 1.05 MeV. For protons, the Bragg model is used below 2 MeV and the BetheBloch above. For anti-protons ICRU73Q0 is used below 2 MeV and BetheBloch above.

Alpha and G4GenericIon: three EM processes are applied. Multiple Coulomb scattering in implemented by the Urban model at all energies. For ionisation below 2 MeV/u data are used. Priority of data is following: ICRU90, ICRU73, PSTAR, ASTAR, ICRU49. The ICRU90 data for the stopping powers of protons, alpha, and ions are available for water, graphite, and air targets. Other data have less accuracy but are applicable for more combinations of projectile ion and target element/material. Above 2 MeV/u the Bethe-Bloch model is used for alpha and Lindhard-Sorensen model for ions. Nuclear stopping model is used below 1 MeV.

3.6 EM Opt4

This physics list uses "standard" GEANT4 electromagnetic physics as built by the `G4EmStandardPhysics_option4` constructor.

Photons: e^-/e^+ pair production is implemented by the BetheHeitler5D model with the LPM effect at high energies. The Compton scattering is implemented above 20 MeV by the Klein-Nishina model with Doppler broading effect taken into account. Below 20 MeV the Monarsh University model (*G4LowEPComptonModel*) for Compton scattering. Photo-electric effect and Rayleigh scattering are both handled by the Livermore models.

Electrons and positrons: multiple Coulomb scattering is handled by the Goudsmit-Sounderson model from 0 to 100 MeV and by the WentzelVI model from 100 MeV to 100 TeV, which is combined with the single Coulomb scattering model, which is applied for large angle scattering. *UseSafetyPlus* step limitation with *error free* approach near

geometry boundaries is used for multiple scattering. The value of the Range Factor is 0.08. Bremsstrahlung is implemented by the eBremSB model and the eBremLPM model which takes into account the LPM effect at high energies. Ionisation is modelled by the Moller-Bhabha formulation above 100 keV and using Penelope model below. Positron annihilation is implemented by the eplus2gg model. The process of e^-/e^+ pair production by electrons and positrons is also used.

Muons: multiple Coulomb scattering is handled by the WentzelVI model combined with the single scattering model at all energies, and by the eCoulombScattering model at all energies. Bremsstrahlung is handled by the MuBrem model. Ionisation is implemented by several models depending on energy and particle type. From 0 to 200 keV, the Bragg model is used for μ^+ and the ICRU73Q0 parameterisation is used for μ^-.

Above 200 keV and 1 GeV the MuBetheBloch model is used for both μ^+ and μ^-. The muPairProduction model handles e+/e- pair production caused by either μ^+ or μ^-.

Pions, kaons, protons and anti-protons: multiple Coulomb scattering is performed by the WentzelVI model and Coulomb scattering by the eCoulombScattering model. Bremsstrahlung is handled by hBrem model. e^-/e^+ pair production by hadrons is implemented by the hPairProduction model. Ionisation is handled by several models depending on energy and particle type. For pions below 298 keV, Bragg model ionisation is used for π^+, and the ICRU73Q0 parameterisation is used for π^-. Above this energy Bethe-Bloch ionisation is used. For kaons, the same ionisation models are used, but the change from low energy to high energy models occurs at 1.05 MeV. For protons, the Bragg model is used below 2 MeV and the BetheBloch above. For anti-protons ICRU73Q0 is used below 2 MeV and BetheBloch above.

Alpha and G4GenericIon: three EM processes are applied. Multiple Coulomb scattering in implemented by the Urban model at all energies. For ionisation below 2 MeV/u data are used. Priority of data is following: ICRU90, ICRU73, PSTAR, ASTAR, ICRU49. The ICRU90 data for the stopping powers of protons, alpha, and ions are available for water, graphite, and air targets. Other data have less accuracy but are applicable for more combinations of projectile ion and target element/material. Above 2 MeV/u the Bethe-Bloch model is used for alpha and Lindhard-Sorensen model for ions. Nuclear stopping model is used below 1 MeV.

3.7 EM Liv

This physics list uses "Livermore" GEANT4 electromagnetic physics as built by the `G4EmLivermorePhysics` constructor.

For each particle type, EM models implement several processes. Photons: e^-/e^+ pair production is implemented by the Bethe-Heitler 5D model below 80 GeV and relativistic Bethe-Heitler model above. The Compton scattering are implemented by the Livermore models up to 1 GeV and at high energies by the Klein-Nishina models, respectively. Photo-electric effect and Rayleigh scattering are both handled by Livermore models.

Electrons: multiple Coulomb scattering is handled by the GS model at low energy and by the WentzelVI model at higher energies, which is combined with the single Coulomb scattering model, which is applied for large angle scattering. Bremsstrahlung is implemented by the Seltzer-Berger model below 1 GeV and by the eBremsstrahlungRelModel model at high energies. Ionisation is modelled by the Livermore model.

Other interactions are configured identically as in the `G4EmStandardPhysics_option4` constructor.

3.8 EM Pen

This physics list uses "Penelope" GEANT4 electromagnetic physics as built by the `G4EmPenelopePhysics` constructor.

Specific low-energy Penelope models are used for gamma, e^-, and e^+ below 1 GeV. Above 1 GeV and for all other charged particles the configuration is the same as in the `G4EmStandardPhysics_option4` constructor.

3.9 EM GS

This physics list uses "standard" GEANT4 electromagnetic physics as built by the `G4EmStandardPhysicsGS` constructor. This configuration is same as in the default `G4EmStandardPhysics` constructor, except multiple scattering of e^- and e^+, which is handled by the Goudsmit-Sounderson model from 0 to 100 MeV.

3.10 EM LE

This physics list uses "standard" GEANT4 electromagnetic physics as built by the `G4EmLowEPPhysics` constructor. This configuration is same as in the default `G4EmStandardPhysics` constructor, except several additions.

Photons: e^-/e^+ pair production is implemented by the Bethe-Heitler 5D model below 80 GeV and relativistic Bethe-Heitler model above. The Compton scattering are implemented by the Monarsh University model (`G4LowEPComptonModel`) up to 20 MeV and by the Klein-Nishina model above 20 MeV.

For all charged particle and energies `G4LowEWentzelVIModel` is used for simulation of multiple scattering. The BS generator is used for simulation of bremsstrahlung angular distribution.

For protons and alpha ICRU90 data for 3 materials is used.

For ion ionisation of ions below 10 MeV/u ICRU73 model (`G4IonParametrisedLossModel`) is used, above 10 MeV/u the Lindhard-Sorensen model is applied (`G4LindhardSorensenIonModel`). Additionally, bremsstrahlung and e^-/e^+ pair production are implemented for ions.

3.11 EM WVI

This physics list uses "standard" GEANT4 electromagnetic physics as built by the `G4EmStandardPhysicsWVI` constructor. This configuration is same as in the default `G4EmStandardPhysics` constructor, except multiple scattering

For e^- and e^+ at all energies `G4WentzelVIModel` is used for simulation of multiple scattering combined with single elastic at large angles.

For ion ionisation of ions the Lindhard-Sorensen model is used.

3.12 EM SS

This physics list uses "standard" GEANT4 electromagnetic physics as built by the `G4EmStandardPhysicsSS` constructor. This configuration is same as in the default `G4EmStandardPhysics` constructor, except multiple scattering is not used and only elastic scattering process is applied for all changed particles.

3.13 EM DNA

The currently recommended Geant4-DNA physics lists are assembled in three constructors, `G4EmDNAPhysics_option2`, `G4EmDNAPhysics_option4` and `G4EmDNAPhysics_option6`.

These physics lists handle the discrete electromagnetic interactions of: photons, electrons, protons, neutral hydrogen, alpha particles and their charged states and all ions. Upper energy limit is 300 MeV. If DNA process/models are not available for given energy, then standard models and processes are used.

Physical interactions for electrons are: ionisation, electronic excitation, elastic scattering, and, for `G4EmDNAPhysics_option2`, vibrational excitation and attachment. Different models are adopted in the three recommended constructors. For example, inelastic interactions are described by the dielectric function theory or by alternative semi-empirical approaches.

Physical interactions of protons, neutral hydrogen, alpha particles and their charged states, heavier ions, and photons are handled identically by all three constructors. They are nuclear scattering, electronic excitation, ionisation, electron capture and electron loss. For ions heavier than alpha particles, only the ionisation process is available.

All details including energy ranges of applicability and performance comparison are presented in the Geant4-DNA web site (http://geant4-dna.in2p3.fr/styled-3/styled-8/index.html) or in this publication: Med. Phys. 45 (2018) e722-e739 (https://doi.org/10.1002/mp.13048).

Other alternative constructors are available but we currently recommend the usage of the above constructors.

3.14 Tables by constructor

Tables of electromagnetic processes for several common constructors. To generate these tables (in reStructuredText format), call:

```
G4LossTableManager::Instance()->DumpHtml()
```

For example, use example extended/electromagnetic/TestEm0, and set the environment variables `G4PhysListName` to be the name of the file to write (extension .rst will be added), and `G4PhysListDocDir` to be the name of the directory to write the file. Set the physics list in the macro file. Also set:

```
/process/em/verbose 1
```

3.14.1 emstandard_opt0

gamma

```
Photoelectric effect
phot:  SubType=12 BuildTable=0
    LambdaPrime table from 200 keV to 100 TeV in 61 bins
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
LivermorePhElectric : Emin=    0 eV  Emax=  100 TeV  SauterGavrila Fluo

Compton scattering
compt:  SubType=13 BuildTable=1
    Lambda table from 100 eV  to 1 MeV, 7 bins/decade, spline: 1
    LambdaPrime table from 1 MeV to 100 TeV in 56 bins
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
     Klein-Nishina : Emin=    0 eV  Emax=  100 TeV

Gamma conversion
conv:  SubType=14 BuildTable=1
    Lambda table from 1.022 MeV to 100 TeV, 18 bins/decade, spline: 1
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
   BetheHeitlerLPM : Emin=    0 eV  Emax=  100 TeV  ModifiedTsai

Rayleigh scattering
Rayl:  SubType=11 BuildTable=1
    Lambda table from 100 eV  to 100 keV, 7 bins/decade, spline: 0
    LambdaPrime table from 100 keV to 100 TeV in 63 bins
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
 LivermoreRayleigh : Emin=    0 eV  Emax=  100 TeV  CullenGenerator
```

e-

```
Coulomb scattering. Simulation of elastic scattering
  events individually. May be used in combination with multiple
  scattering, where Coulomb scattering is used for hard (large angle)
  collisions and multiple scattering for soft collisions.
CoulombScat:  integral:1  SubType=1 BuildTable=1
    Lambda table from 100 MeV to 100 TeV, 7 bins/decade, spline: 1
    ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
eCoulombScattering : Emin=  100 MeV Emax=  100 TeV

Multiple scattering. Simulates combined effects of elastic scattering
  at the end of the step, to save computing time. May be combined with
  Coulomb scattering in a 'mixed' scattering algorithm.
msc:    SubType= 10
    RangeFactor= 0.04, stepLimType: 1, latDisp: 1
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
          UrbanMsc : Emin=    0 eV  Emax=  100 MeV Nbins=42 100 eV  - 100 MeV
       WentzelVIUni : Emin=  100 MeV Emax=  100 TeV Nbins=42 100 MeV - 100 TeV

Ionisation
eIoni:    SubType=2
    dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
    Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
    StepFunction=(0.2, 1 mm), integ: 1, fluct: 1, linLossLim= 0.01
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
     MollerBhabha : Emin=    0 eV  Emax=  100 TeV
    CSDA range table up to 1 GeV in 49 bins

Bremsstrahlung
eBrem:    SubType=3
    dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
    Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
    LPM flag: 1 for E > 1 GeV,  VertexHighEnergyTh(GeV)= 100000
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
```

```
            eBremSB : Emin=    0 eV  Emax=    1 GeV  ModifiedTsai
            eBremLPM : Emin=    1 GeV Emax=  100 TeV  ModifiedTsai
```

e+

```
    Coulomb scattering. Simulation of elastic scattering
      events individually. May be used in combination with multiple
      scattering, where Coulomb scattering is used for hard (large angle)
      collisions and multiple scattering for soft collisions.
    CoulombScat:  integral:1  SubType=1 BuildTable=1
        Lambda table from 100 MeV to 100 TeV, 7 bins/decade, spline: 1
        ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
    eCoulombScattering : Emin=  100 MeV Emax=  100 TeV

    Positron annihilation
    annihil:  integral:1  SubType=5 BuildTable=0
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            eplus2gg : Emin=    0 eV  Emax=  100 TeV

    Multiple scattering. Simulates combined effects of elastic scattering
      at the end of the step, to save computing time. May be combined with
      Coulomb scattering in a 'mixed' scattering algorithm.
    msc:    SubType= 10
        RangeFactor= 0.04, stepLimType: 1, latDisp: 1
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            UrbanMsc : Emin=    0 eV  Emax=  100 MeV Nbins=42 100 eV  - 100 MeV
          WentzelVIUni : Emin=  100 MeV Emax=  100 TeV Nbins=42 100 MeV - 100 TeV

    Ionisation
    eIoni:   SubType=2
        dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
        Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
        StepFunction=(0.2, 1 mm), integ: 1, fluct: 1, linLossLim= 0.01
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
          MollerBhabha : Emin=    0 eV  Emax=  100 TeV
        CSDA range table up to 1 GeV in 49 bins

    Bremsstrahlung
    eBrem:   SubType=3
        dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
        Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
        LPM flag: 1 for E > 1 GeV,  VertexHighEnergyTh(GeV)= 100000
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            eBremSB : Emin=    0 eV  Emax=    1 GeV  ModifiedTsai
            eBremLPM : Emin=    1 GeV Emax=  100 TeV  ModifiedTsai
```

proton

```
    Coulomb scattering. Simulation of elastic scattering
      events individually. May be used in combination with multiple
      scattering, where Coulomb scattering is used for hard (large angle)
      collisions and multiple scattering for soft collisions.
    CoulombScat:  integral:1  SubType=1 BuildTable=1
        Lambda table from threshold  to 100 TeV, 7 bins/decade, spline: 1
        ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
    eCoulombScattering : Emin=    0 eV  Emax=  100 TeV

    Hadron multiple scattering. Simulates combined effects of elastic
      scattering at the end of the step, to save computing time. May
      be combined with Coulomb scattering in a 'mixed' scattering algorithm.
    msc:    SubType= 10
        RangeFactor= 0.2, stepLimType: 0, latDisp: 0
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
```

```
        WentzelVIUni : Emin=    0 eV  Emax=  100 TeV Nbins=84 100 eV  - 100 TeV

Hadron bremsstrahlung
hBrems:   SubType=3
    dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
    Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            hBrem : Emin=    0 eV  Emax=  100 TeV

Hadron pair production
hPairProd:   SubType=4
    dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
    Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
    Sampling table 17x1001; from 7.50618 GeV to 100 TeV
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        hPairProd : Emin=    0 eV  Emax=  100 TeV

Ionisation
hIoni:   SubType=2
    dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
    Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
    StepFunction=(0.2, 0.1 mm), integ: 1, fluct: 1, linLossLim= 0.01
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            Bragg : Emin=    0 eV  Emax=    2 MeV
        BetheBloch : Emin=    2 MeV Emax=  100 TeV
    CSDA range table up to 1 GeV in 49 bins
```

mu+

```
Coulomb scattering. Simulation of elastic scattering
  events individually. May be used in combination with multiple
  scattering, where Coulomb scattering is used for hard (large angle)
  collisions and multiple scattering for soft collisions.
CoulombScat:  integral:1  SubType=1 BuildTable=1
    Lambda table from threshold  to 100 TeV, 7 bins/decade, spline: 1
    ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
eCoulombScattering : Emin=    0 eV  Emax=  100 TeV

Muon multiple scattering. Simulates combined effects of elastic
  scattering at the end of the step, to save computing time. May be
  combined with Coulomb scattering in a 'mixed' scattering algorithm.
msc:   SubType= 10
    RangeFactor= 0.2, stepLimType: 0, latDisp: 0, polarAngLim(deg)= 180
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
      WentzelVIUni : Emin=    0 eV  Emax=  100 TeV Nbins=84 100 eV  - 100 TeV

Muon bremsstrahlung
muBrems:   SubType=3
    dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
    Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            MuBrem : Emin=    0 eV  Emax=  100 TeV

Pair production
muPairProd:   SubType=4
    dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
    Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
    Sampling table 21x1001; from 1 GeV to 100 TeV
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        muPairProd : Emin=    0 eV  Emax=  100 TeV

Muon ionisation
muIoni:   SubType=2
    dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
```

```
      Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
      StepFunction=(0.2, 0.1 mm), integ: 1, fluct: 1, linLossLim= 0.01
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            Bragg : Emin=    0 eV  Emax=  200 keV
        BetheBloch : Emin=  200 keV Emax=    1 GeV
      MuBetheBloch : Emin=    1 GeV Emax=  100 TeV
      CSDA range table up to 1 GeV in 49 bins
```

mu-

```
Coulomb scattering. Simulation of elastic scattering
  events individually. May be used in combination with multiple
  scattering, where Coulomb scattering is used for hard (large angle)
  collisions and multiple scattering for soft collisions.
CoulombScat:  integral:1  SubType=1 BuildTable=1
    Lambda table from threshold  to 100 TeV, 7 bins/decade, spline: 1
    ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
eCoulombScattering : Emin=    0 eV  Emax=  100 TeV

Muon multiple scattering. Simulates combined effects of elastic
  scattering at the end of the step, to save computing time. May be
  combined with Coulomb scattering in a 'mixed' scattering algorithm.
msc:   SubType= 10
    RangeFactor= 0.2, stepLimType: 0, latDisp: 0, polarAngLim(deg)= 180
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
      WentzelVIUni : Emin=    0 eV  Emax=  100 TeV Nbins=84 100 eV  – 100 TeV

Muon bremsstrahlung
muBrems:   SubType=3
    dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
    Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            MuBrem : Emin=    0 eV  Emax=  100 TeV

Pair production
muPairProd:   SubType=4
    dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
    Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
    Sampling table 21x1001; from 1 GeV to 100 TeV
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        muPairProd : Emin=    0 eV  Emax=  100 TeV

Muon ionisation
muIoni:   SubType=2
    dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
    Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
    StepFunction=(0.2, 0.1 mm), integ: 1, fluct: 1, linLossLim= 0.01
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
          ICRU73QO : Emin=    0 eV  Emax=  200 keV
        BetheBloch : Emin=  200 keV Emax=    1 GeV
      MuBetheBloch : Emin=    1 GeV Emax=  100 TeV
    CSDA range table up to 1 GeV in 49 bins
```

3.14.2 emstandard_opt1

gamma

```
    Photoelectric effect
    phot:  applyCuts:1  SubType=12 BuildTable=0
        LambdaPrime table from 200 keV to 100 TeV in 61 bins
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
    LivermorePhElectric : Emin=    0 eV  Emax=  100 TeV  SauterGavrila Fluo

    Compton scattering
    compt:  applyCuts:1  SubType=13 BuildTable=1
        Lambda table from 100 eV  to 1 MeV, 7 bins/decade, spline: 1
        LambdaPrime table from 1 MeV to 100 TeV in 56 bins
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
         Klein-Nishina : Emin=    0 eV  Emax=  100 TeV

    Gamma conversion
    conv:  applyCuts:1  SubType=14 BuildTable=1
        Lambda table from 1.022 MeV to 100 TeV, 18 bins/decade, spline: 1
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
      BetheHeitlerLPM : Emin=    0 eV  Emax=  100 TeV  ModifiedTsai
```

e-

```
    Coulomb scattering. Simulation of elastic scattering
      events individually. May be used in combination with multiple
      scattering, where Coulomb scattering is used for hard (large angle)
      collisions and multiple scattering for soft collisions.
    CoulombScat:  integral:1  applyCuts:1  SubType=1 BuildTable=1
        Lambda table from 100 MeV to 100 TeV, 7 bins/decade, spline: 1
        ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
    eCoulombScattering : Emin=  100 MeV Emax=  100 TeV

    Multiple scattering. Simulates combined effects of elastic scattering
      at the end of the step, to save computing time. May be combined with
      Coulomb scattering in a 'mixed' scattering algorithm.
    msc:    SubType= 10
        RangeFactor= 0.2, stepLimType: 0, latDisp: 1
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            UrbanMsc : Emin=    0 eV  Emax=  100 MeV Nbins=42 100 eV  - 100 MeV
        WentzelVIUni : Emin=  100 MeV Emax=  100 TeV Nbins=42 100 MeV - 100 TeV

    Ionisation
    eIoni:   SubType=2
        dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
        Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
        StepFunction=(0.8, 1 mm), integ: 1, fluct: 1, linLossLim= 0.01
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
         MollerBhabha : Emin=    0 eV  Emax=  100 TeV
        CSDA range table up to 1 GeV in 49 bins

    Bremsstrahlung
    eBrem:   SubType=3
        dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
        Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
        LPM flag: 1 for E > 1 GeV,  VertexHighEnergyTh(GeV)= 100000
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
             eBremSB : Emin=    0 eV  Emax=    1 GeV  ModifiedTsai
            eBremLPM : Emin=    1 GeV Emax=  100 TeV  ModifiedTsai
```

e+

```
    Coulomb scattering. Simulation of elastic scattering
```

```
    events individually. May be used in combination with multiple
    scattering, where Coulomb scattering is used for hard (large angle)
    collisions and multiple scattering for soft collisions.
CoulombScat: integral:1  applyCuts:1  SubType=1 BuildTable=1
      Lambda table from 100 MeV to 100 TeV, 7 bins/decade, spline: 1
      ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
eCoulombScattering : Emin=  100 MeV Emax=  100 TeV

    Positron annihilation
annihil: integral:1  applyCuts:1  SubType=5 BuildTable=0
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
           eplus2gg : Emin=     0 eV  Emax=  100 TeV

Multiple scattering. Simulates combined effects of elastic scattering
  at the end of the step, to save computing time. May be combined with
  Coulomb scattering in a 'mixed' scattering algorithm.
msc:    SubType= 10
      RangeFactor= 0.2, stepLimType: 0, latDisp: 1
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
           UrbanMsc : Emin=     0 eV  Emax=  100 MeV Nbins=42 100 eV  - 100 MeV
        WentzelVIUni : Emin=  100 MeV Emax=  100 TeV Nbins=42 100 MeV - 100 TeV

    Ionisation
eIoni:    SubType=2
      dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
      Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
      StepFunction=(0.8, 1 mm), integ: 1, fluct: 1, linLossLim= 0.01
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        MollerBhabha : Emin=     0 eV  Emax=  100 TeV
      CSDA range table up to 1 GeV in 49 bins

    Bremsstrahlung
eBrem:    SubType=3
      dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
      Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
      LPM flag: 1 for E > 1 GeV,  VertexHighEnergyTh(GeV)= 100000
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            eBremSB : Emin=     0 eV  Emax=    1 GeV  ModifiedTsai
           eBremLPM : Emin=     1 GeV Emax=  100 TeV  ModifiedTsai
```

proton

```
    Coulomb scattering. Simulation of elastic scattering
      events individually. May be used in combination with multiple
      scattering, where Coulomb scattering is used for hard (large angle)
      collisions and multiple scattering for soft collisions.
CoulombScat: integral:1  applyCuts:1  SubType=1 BuildTable=1
      Lambda table from threshold  to 100 TeV, 7 bins/decade, spline: 1
      ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
eCoulombScattering : Emin=     0 eV  Emax=  100 TeV

    Hadron multiple scattering. Simulates combined effects of elastic
      scattering at the end of the step, to save computing time. May
      be combined with Coulomb scattering in a 'mixed' scattering algorithm.
msc:    SubType= 10
      RangeFactor= 0.2, stepLimType: 0, latDisp: 0
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        WentzelVIUni : Emin=     0 eV  Emax=  100 TeV Nbins=84 100 eV  - 100 TeV

    Hadron bremsstrahlung
hBrems:    SubType=3
      dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
      Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
```

```
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            hBrem : Emin=    0 eV  Emax=  100 TeV

Hadron pair production
hPairProd:    SubType=4
   dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
   Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
   Sampling table 17x1001; from 7.50618 GeV to 100 TeV
   ===== EM models for the G4Region  DefaultRegionForTheWorld ======
         hPairProd : Emin=    0 eV  Emax=  100 TeV

Ionisation
hIoni:   SubType=2
   dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
   Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
   StepFunction=(0.2, 0.1 mm), integ: 1, fluct: 1, linLossLim= 0.01
   ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            Bragg : Emin=    0 eV  Emax=    2 MeV
        BetheBloch : Emin=    2 MeV Emax=  100 TeV
   CSDA range table up to 1 GeV in 49 bins
```

mu+

```
Coulomb scattering. Simulation of elastic scattering
  events individually. May be used in combination with multiple
  scattering, where Coulomb scattering is used for hard (large angle)
  collisions and multiple scattering for soft collisions.
CoulombScat: integral:1  applyCuts:1  SubType=1 BuildTable=1
   Lambda table from threshold  to 100 TeV, 7 bins/decade, spline: 1
   ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
   ===== EM models for the G4Region  DefaultRegionForTheWorld ======
eCoulombScattering : Emin=    0 eV  Emax=  100 TeV

Muon multiple scattering. Simulates combined effects of elastic
  scattering at the end of the step, to save computing time. May be
  combined with Coulomb scattering in a 'mixed' scattering algorithm.
msc:   SubType= 10
   RangeFactor= 0.2, stepLimType: 0, latDisp: 0, polarAngLim(deg)= 180
   ===== EM models for the G4Region  DefaultRegionForTheWorld ======
     WentzelVIUni : Emin=    0 eV  Emax=  100 TeV Nbins=84 100 eV  – 100 TeV

Muon bremsstrahlung
muBrems:   SubType=3
   dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
   Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
   ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            MuBrem : Emin=    0 eV  Emax=  100 TeV

Pair production
muPairProd:   SubType=4
   dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
   Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
   Sampling table 21x1001; from 1 GeV to 100 TeV
   ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        muPairProd : Emin=    0 eV  Emax=  100 TeV

Muon ionisation
muIoni:   SubType=2
   dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
   Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
   StepFunction=(0.2, 0.1 mm), integ: 1, fluct: 1, linLossLim= 0.01
   ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            Bragg : Emin=    0 eV  Emax=  200 keV
        BetheBloch : Emin=  200 keV Emax=    1 GeV
      MuBetheBloch : Emin=    1 GeV Emax=  100 TeV
```

```
        CSDA range table up to 1 GeV in 49 bins
```

mu-

```
    Coulomb scattering. Simulation of elastic scattering
      events individually. May be used in combination with multiple
      scattering, where Coulomb scattering is used for hard (large angle)
      collisions and multiple scattering for soft collisions.
    CoulombScat:  integral:1  applyCuts:1  SubType=1 BuildTable=1
        Lambda table from threshold  to 100 TeV, 7 bins/decade, spline: 1
        ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
    eCoulombScattering : Emin=     0 eV  Emax=  100 TeV

    Muon multiple scattering. Simulates combined effects of elastic
      scattering at the end of the step, to save computing time. May be
      combined with Coulomb scattering in a 'mixed' scattering algorithm.
    msc:    SubType= 10
        RangeFactor= 0.2, stepLimType: 0, latDisp: 0, polarAngLim(deg)= 180
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
         WentzelVIUni : Emin=     0 eV  Emax=  100 TeV Nbins=84 100 eV  - 100 TeV

    Muon bremsstrahlung
    muBrems:    SubType=3
        dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
        Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
              MuBrem : Emin=     0 eV  Emax=  100 TeV

    Pair production
    muPairProd:    SubType=4
        dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
        Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
        Sampling table 21x1001; from 1 GeV to 100 TeV
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
           muPairProd : Emin=     0 eV  Emax=  100 TeV

    Muon ionisation
    muIoni:    SubType=2
        dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
        Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
        StepFunction=(0.2, 0.1 mm), integ: 1, fluct: 1, linLossLim= 0.01
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
             ICRU73QO : Emin=     0 eV  Emax=  200 keV
           BetheBloch : Emin=  200 keV Emax=    1 GeV
         MuBetheBloch : Emin=    1 GeV Emax=  100 TeV
        CSDA range table up to 1 GeV in 49 bins
```

3.14.3 emstandard_opt2

gamma

```
    Photoelectric effect
    phot:  SubType=12 BuildTable=0
        LambdaPrime table from 200 keV to 100 TeV in 61 bins
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
         PhotoElectric : Emin=     0 eV  Emax=  100 TeV  SauterGavrila Fluo

    Compton scattering
    compt:  SubType=13 BuildTable=1
        Lambda table from 100 eV  to 1 MeV, 7 bins/decade, spline: 1
        LambdaPrime table from 1 MeV to 100 TeV in 56 bins
```

```
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
      Klein-Nishina : Emin=     0 eV  Emax=  100 TeV

Gamma conversion
conv:  SubType=14 BuildTable=1
     Lambda table from 1.022 MeV to 100 TeV, 18 bins/decade, spline: 1
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
    BetheHeitlerLPM : Emin=     0 eV  Emax=  100 TeV  ModifiedTsai
```

e-

```
Coulomb scattering. Simulation of elastic scattering
  events individually. May be used in combination with multiple
  scattering, where Coulomb scattering is used for hard (large angle)
  collisions and multiple scattering for soft collisions.
CoulombScat:  integral:1  SubType=1 BuildTable=1
     Lambda table from 100 MeV to 100 TeV, 7 bins/decade, spline: 1
     ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
eCoulombScattering : Emin=  100 MeV Emax=  100 TeV

Multiple scattering. Simulates combined effects of elastic scattering
  at the end of the step, to save computing time. May be combined with
  Coulomb scattering in a 'mixed' scattering algorithm.
msc:   SubType= 10
     RangeFactor= 0.2, stepLimType: 0, latDisp: 0
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
         UrbanMsc : Emin=     0 eV  Emax=  100 MeV Nbins=42 100 eV  - 100 MeV
      WentzelVIUni : Emin=  100 MeV Emax=  100 TeV Nbins=42 100 MeV - 100 TeV

Ionisation
eIoni:   SubType=2
     dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
     Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
     StepFunction=(0.8, 1 mm), integ: 1, fluct: 1, linLossLim= 0.01
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
      MollerBhabha : Emin=     0 eV  Emax=  100 TeV
     CSDA range table up to 1 GeV in 49 bins

Bremsstrahlung
eBrem:   SubType=3
     dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
     Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
     LPM flag: 1 for E > 1 GeV,  VertexHighEnergyTh(GeV)= 100000
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
          eBremSB : Emin=     0 eV  Emax=    1 GeV  ModifiedTsai
         eBremLPM : Emin=     1 GeV Emax=  100 TeV  ModifiedTsai
```

e+

```
Coulomb scattering. Simulation of elastic scattering
  events individually. May be used in combination with multiple
  scattering, where Coulomb scattering is used for hard (large angle)
  collisions and multiple scattering for soft collisions.
CoulombScat:  integral:1  SubType=1 BuildTable=1
     Lambda table from 100 MeV to 100 TeV, 7 bins/decade, spline: 1
     ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
eCoulombScattering : Emin=  100 MeV Emax=  100 TeV

Positron annihilation
annihil:  integral:1  SubType=5 BuildTable=0
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
          eplus2gg : Emin=     0 eV  Emax=  100 TeV
```

```
Multiple scattering. Simulates combined effects of elastic scattering
  at the end of the step, to save computing time. May be combined with
  Coulomb scattering in a 'mixed' scattering algorithm.
msc:   SubType= 10
    RangeFactor= 0.2, stepLimType: 0, latDisp: 0
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
         UrbanMsc : Emin=    0 eV  Emax=  100 MeV Nbins=42 100 eV  - 100 MeV
      WentzelVIUni : Emin=  100 MeV Emax=  100 TeV Nbins=42 100 MeV - 100 TeV

Ionisation
eIoni:   SubType=2
    dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
    Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
    StepFunction=(0.8, 1 mm), integ: 1, fluct: 1, linLossLim= 0.01
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
      MollerBhabha : Emin=    0 eV  Emax=  100 TeV
    CSDA range table up to 1 GeV in 49 bins

Bremsstrahlung
eBrem:   SubType=3
    dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
    Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
    LPM flag: 1 for E > 1 GeV,  VertexHighEnergyTh(GeV)= 100000
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
          eBremSB : Emin=    0 eV  Emax=    1 GeV  ModifiedTsai
         eBremLPM : Emin=    1 GeV Emax=  100 TeV  ModifiedTsai
```

proton

```
Coulomb scattering. Simulation of elastic scattering
  events individually. May be used in combination with multiple
  scattering, where Coulomb scattering is used for hard (large angle)
  collisions and multiple scattering for soft collisions.
CoulombScat:  integral:1  SubType=1 BuildTable=1
    Lambda table from threshold  to 100 TeV, 7 bins/decade, spline: 1
    ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
eCoulombScattering : Emin=    0 eV  Emax=  100 TeV

Hadron bremsstrahlung
hBrems:   SubType=3
    dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
    Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            hBrem : Emin=    0 eV  Emax=  100 TeV

Hadron pair production
hPairProd:   SubType=4
    dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
    Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
    Sampling table 17x1001; from 7.50618 GeV to 100 TeV
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        hPairProd : Emin=    0 eV  Emax=  100 TeV

Ionisation
hIoni:   SubType=2
    dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
    Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
    StepFunction=(0.2, 0.1 mm), integ: 1, fluct: 1, linLossLim= 0.01
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            Bragg : Emin=    0 eV  Emax=    2 MeV
        BetheBloch : Emin=    2 MeV Emax=  100 TeV
    CSDA range table up to 1 GeV in 49 bins
```

mu+

```
Coulomb scattering. Simulation of elastic scattering
  events individually. May be used in combination with multiple
  scattering, where Coulomb scattering is used for hard (large angle)
  collisions and multiple scattering for soft collisions.
CoulombScat:  integral:1  SubType=1 BuildTable=1
    Lambda table from threshold  to 100 TeV, 7 bins/decade, spline: 1
    ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
eCoulombScattering : Emin=    0 eV  Emax=  100 TeV

Muon multiple scattering. Simulates combined effects of elastic
  scattering at the end of the step, to save computing time. May be
  combined with Coulomb scattering in a 'mixed' scattering algorithm.
msc:   SubType= 10
    RangeFactor= 0.2, stepLimType: 0, latDisp: 0, polarAngLim(deg)= 180
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
      WentzelVIUni : Emin=    0 eV  Emax=  100 TeV Nbins=84 100 eV  - 100 TeV

Muon bremsstrahlung
muBrems:   SubType=3
    dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
    Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            MuBrem : Emin=    0 eV  Emax=  100 TeV

Pair production
muPairProd:   SubType=4
    dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
    Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
    Sampling table 21x1001; from 1 GeV to 100 TeV
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        muPairProd : Emin=    0 eV  Emax=  100 TeV

Muon ionisation
muIoni:   SubType=2
    dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
    Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
    StepFunction=(0.2, 0.1 mm), integ: 1, fluct: 1, linLossLim= 0.01
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            Bragg : Emin=    0 eV  Emax=  200 keV
        BetheBloch : Emin=  200 keV Emax=    1 GeV
      MuBetheBloch : Emin=    1 GeV Emax=  100 TeV
    CSDA range table up to 1 GeV in 49 bins
```

mu-

```
Coulomb scattering. Simulation of elastic scattering
  events individually. May be used in combination with multiple
  scattering, where Coulomb scattering is used for hard (large angle)
  collisions and multiple scattering for soft collisions.
CoulombScat:  integral:1  SubType=1 BuildTable=1
    Lambda table from threshold  to 100 TeV, 7 bins/decade, spline: 1
    ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
eCoulombScattering : Emin=    0 eV  Emax=  100 TeV

Muon multiple scattering. Simulates combined effects of elastic
  scattering at the end of the step, to save computing time. May be
  combined with Coulomb scattering in a 'mixed' scattering algorithm.
msc:   SubType= 10
    RangeFactor= 0.2, stepLimType: 0, latDisp: 0, polarAngLim(deg)= 180
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
      WentzelVIUni : Emin=    0 eV  Emax=  100 TeV Nbins=84 100 eV  - 100 TeV

Muon bremsstrahlung
muBrems:   SubType=3
```

```
    dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
    Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
          MuBrem : Emin=    0 eV  Emax=  100 TeV

Pair production
muPairProd:   SubType=4
    dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
    Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
    Sampling table 21x1001; from 1 GeV to 100 TeV
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
       muPairProd : Emin=    0 eV  Emax=  100 TeV

Muon ionisation
muIoni:   SubType=2
    dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
    Lambda tables from threshold to 100 TeV, 7 bins/decade, spline: 1
    StepFunction=(0.2, 0.1 mm), integ: 1, fluct: 1, linLossLim= 0.01
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
         ICRU73QO : Emin=    0 eV  Emax=  200 keV
        BetheBloch : Emin=  200 keV Emax=    1 GeV
      MuBetheBloch : Emin=    1 GeV Emax=  100 TeV
    CSDA range table up to 1 GeV in 49 bins
```

3.14.4 emstandard_opt3

gamma

```
Photoelectric effect
phot: SubType=12 BuildTable=0
    LambdaPrime table from 200 keV to 100 TeV in 174 bins
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
LivermorePhElectric : Emin=    0 eV  Emax=  100 TeV  SauterGavrila Fluo

Compton scattering
compt: SubType=13 BuildTable=1
    Lambda table from 10 eV  to 1 MeV, 20 bins/decade, spline: 1
    LambdaPrime table from 1 MeV to 100 TeV in 160 bins
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
      KleinNishina : Emin=    0 eV  Emax=  100 TeV Fluo

Gamma conversion
conv: SubType=14 BuildTable=1
    Lambda table from 1.022 MeV to 100 TeV, 20 bins/decade, spline: 1
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
   BetheHeitlerLPM : Emin=    0 eV  Emax=  100 TeV  ModifiedTsai

Rayleigh scattering
Rayl: SubType=11 BuildTable=1
    Lambda table from 10 eV  to 100 keV, 20 bins/decade, spline: 0
    LambdaPrime table from 100 keV to 100 TeV in 180 bins
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
 LivermoreRayleigh : Emin=    0 eV  Emax=  100 TeV  CullenGenerator
```

e-

```
Multiple scattering. Simulates combined effects of elastic scattering
  at the end of the step, to save computing time. May be combined with
  Coulomb scattering in a 'mixed' scattering algorithm.
msc:   SubType= 10
    RangeFactor= 0.04, stepLimType: 3, latDisp: 1, skin= 1, geomFactor= 2.5
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
```

```
            UrbanMsc : Emin=    0 eV  Emax=  100 TeV Nbins=240 100 eV  - 100 TeV

    Pair production
    ePairProd:   SubType=4
        dE/dx and range tables from 10 eV  to 100 TeV in 260 bins
        Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
        Sampling table 25x1001; from 0.1 GeV to 100 TeV
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            ePairProd : Emin=    0 eV  Emax=  100 TeV

    Ionisation
    eIoni:   SubType=2
        dE/dx and range tables from 10 eV  to 100 TeV in 260 bins
        Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
        StepFunction=(0.2, 0.1 mm), integ: 1, fluct: 1, linLossLim= 0.01
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
          MollerBhabha : Emin=    0 eV  Emax=  100 TeV  deltaVI
        CSDA range table up to 1 GeV in 160 bins

    Bremsstrahlung
    eBrem:   SubType=3
        dE/dx and range tables from 10 eV  to 100 TeV in 260 bins
        Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
        LPM flag: 1 for E > 1 GeV,  VertexHighEnergyTh(GeV)= 100000
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
             eBremSB : Emin=    0 eV  Emax=    1 GeV  AngularGen2BS
            eBremLPM : Emin=    1 GeV Emax=  100 TeV  AngularGen2BS
```

e+

```
    Positron annihilation
    annihil:  integral:1  SubType=5 BuildTable=0
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            eplus2gg : Emin=    0 eV  Emax=  100 TeV

    Multiple scattering. Simulates combined effects of elastic scattering
      at the end of the step, to save computing time. May be combined with
      Coulomb scattering in a 'mixed' scattering algorithm.
    msc:   SubType= 10
        RangeFactor= 0.04, stepLimType: 3, latDisp: 1, skin= 1, geomFactor= 2.5
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            UrbanMsc : Emin=    0 eV  Emax=  100 TeV Nbins=240 100 eV  - 100 TeV

    Pair production
    ePairProd:   SubType=4
        dE/dx and range tables from 10 eV  to 100 TeV in 260 bins
        Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
        Sampling table 25x1001; from 0.1 GeV to 100 TeV
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            ePairProd : Emin=    0 eV  Emax=  100 TeV

    Ionisation
    eIoni:   SubType=2
        dE/dx and range tables from 10 eV  to 100 TeV in 260 bins
        Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
        StepFunction=(0.2, 0.1 mm), integ: 1, fluct: 1, linLossLim= 0.01
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
          MollerBhabha : Emin=    0 eV  Emax=  100 TeV  deltaVI
        CSDA range table up to 1 GeV in 160 bins

    Bremsstrahlung
    eBrem:   SubType=3
        dE/dx and range tables from 10 eV  to 100 TeV in 260 bins
        Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
        LPM flag: 1 for E > 1 GeV,  VertexHighEnergyTh(GeV)= 100000
```

```
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        eBremSB : Emin=     0 eV  Emax=     1 GeV  AngularGen2BS
        eBremLPM : Emin=     1 GeV Emax=  100 TeV  AngularGen2BS
```

proton

```
    Nuclear stopping
    nuclearStopping: SubType=8 BuildTable=0
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
     ICRU49NucStopping : Emin=     0 eV  Emax=     1 MeV

    Hadron multiple scattering. Simulates combined effects of elastic
      scattering at the end of the step, to save computing time. May
      be combined with Coulomb scattering in a 'mixed' scattering algorithm.
    msc:    SubType= 10
        RangeFactor= 0.2, stepLimType: 0, latDisp: 1
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            UrbanMsc : Emin=     0 eV  Emax=  100 TeV Nbins=240 100 eV  – 100 TeV

    Hadron bremsstrahlung
    hBrems:    SubType=3
        dE/dx and range tables from 10 eV  to 100 TeV in 260 bins
        Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
              hBrem : Emin=     0 eV  Emax=  100 TeV

    Hadron pair production
    hPairProd:    SubType=4
        dE/dx and range tables from 10 eV  to 100 TeV in 260 bins
        Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
        Sampling table 17x1001; from 7.50618 GeV to 100 TeV
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
          hPairProd : Emin=     0 eV  Emax=  100 TeV

    Ionisation
    hIoni:    SubType=2
        dE/dx and range tables from 10 eV  to 100 TeV in 260 bins
        Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
        StepFunction=(0.2, 0.05 mm), integ: 1, fluct: 1, linLossLim= 0.01
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
              Bragg : Emin=     0 eV  Emax=     2 MeV  deltaVI
           BetheBloch : Emin=     2 MeV Emax=  100 TeV  deltaVI
        CSDA range table up to 1 GeV in 160 bins
```

mu+

```
    Muon multiple scattering. Simulates combined effects of elastic
      scattering at the end of the step, to save computing time. May be
      combined with Coulomb scattering in a 'mixed' scattering algorithm.
    msc:    SubType= 10
        RangeFactor= 0.2, stepLimType: 0, latDisp: 1, polarAngLim(deg)= 180
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            UrbanMsc : Emin=     0 eV  Emax=  100 TeV Nbins=240 100 eV  – 100 TeV

    Muon bremsstrahlung
    muBrems:    SubType=3
        dE/dx and range tables from 10 eV  to 100 TeV in 260 bins
        Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
              MuBrem : Emin=     0 eV  Emax=  100 TeV

    Pair production
    muPairProd:    SubType=4
        dE/dx and range tables from 10 eV  to 100 TeV in 260 bins
        Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
```

3.14. Tables by constructor

```
        Sampling table 21x1001; from 1 GeV to 100 TeV
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
           muPairProd : Emin=     0 eV  Emax=  100 TeV

    Muon ionisation
    muIoni:   SubType=2
        dE/dx and range tables from 10 eV  to 100 TeV in 260 bins
        Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
        StepFunction=(0.2, 0.05 mm), integ: 1, fluct: 1, linLossLim= 0.01
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
                Bragg : Emin=     0 eV  Emax=  200 keV  deltaVI
            BetheBloch : Emin=   200 keV Emax=     1 GeV  deltaVI
          MuBetheBloch : Emin=     1 GeV Emax=  100 TeV
        CSDA range table up to 1 GeV in 160 bins
```

mu-

```
    Muon multiple scattering. Simulates combined effects of elastic
      scattering at the end of the step, to save computing time. May be
      combined with Coulomb scattering in a 'mixed' scattering algorithm.
    msc:    SubType= 10
        RangeFactor= 0.2, stepLimType: 0, latDisp: 1, polarAngLim(deg)= 180
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
             UrbanMsc : Emin=     0 eV  Emax=  100 TeV Nbins=240 100 eV  - 100 TeV

    Muon bremsstrahlung
    muBrems:    SubType=3
        dE/dx and range tables from 10 eV  to 100 TeV in 260 bins
        Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
               MuBrem : Emin=     0 eV  Emax=  100 TeV

    Pair production
    muPairProd:    SubType=4
        dE/dx and range tables from 10 eV  to 100 TeV in 260 bins
        Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
        Sampling table 21x1001; from 1 GeV to 100 TeV
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
           muPairProd : Emin=     0 eV  Emax=  100 TeV

    Muon ionisation
    muIoni:   SubType=2
        dE/dx and range tables from 10 eV  to 100 TeV in 260 bins
        Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
        StepFunction=(0.2, 0.05 mm), integ: 1, fluct: 1, linLossLim= 0.01
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
              ICRU73QO : Emin=     0 eV  Emax=  200 keV  deltaVI
            BetheBloch : Emin=   200 keV Emax=     1 GeV  deltaVI
          MuBetheBloch : Emin=     1 GeV Emax=  100 TeV
        CSDA range table up to 1 GeV in 160 bins
```

3.14.5 emstandard_opt4

gamma

```
    Photoelectric effect
    phot:  SubType=12 BuildTable=0
        LambdaPrime table from 200 keV to 100 TeV in 174 bins
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
    LivermorePhElectric : Emin=     0 eV  Emax=  100 TeV  SauterGavrila Fluo

    Compton scattering
```

```
compt:  SubType=13 BuildTable=1
    Lambda table from 100 eV  to 1 MeV, 20 bins/decade, spline: 1
    LambdaPrime table from 1 MeV to 100 TeV in 160 bins
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
 LowEPComptonModel : Emin=    0 eV  Emax=   20 MeV Fluo
     KleinNishina : Emin=   20 MeV Emax=  100 TeV Fluo

Gamma conversion
conv:  SubType=14 BuildTable=1
    Lambda table from 1.022 MeV to 100 TeV, 20 bins/decade, spline: 1
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
    BetheHeitler5D : Emin=    0 eV  Emax=  100 TeV  ModifiedTsai

Rayleigh scattering
Rayl:  SubType=11 BuildTable=1
    Lambda table from 100 eV  to 100 keV, 20 bins/decade, spline: 0
    LambdaPrime table from 100 keV to 100 TeV in 180 bins
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
 LivermoreRayleigh : Emin=    0 eV  Emax=  100 TeV  CullenGenerator
```

e-

```
Coulomb scattering. Simulation of elastic scattering
  events individually. May be used in combination with multiple
  scattering, where Coulomb scattering is used for hard (large angle)
  collisions and multiple scattering for soft collisions.
CoulombScat:  integral:1  SubType=1 BuildTable=1
    Lambda table from 100 MeV to 100 TeV, 20 bins/decade, spline: 1
    ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
eCoulombScattering : Emin=  100 MeV Emax=  100 TeV

Multiple scattering. Simulates combined effects of elastic scattering
  at the end of the step, to save computing time. May be combined with
  Coulomb scattering in a 'mixed' scattering algorithm.
msc:    SubType= 10
    RangeFactor= 0.08, stepLimType: 2, latDisp: 1
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
GoudsmitSaunderson : Emin=    0 eV  Emax=  100 MeV Nbins=120 100 eV  - 100 MeV
     WentzelVIUni : Emin=  100 MeV Emax=  100 TeV Nbins=120 100 MeV - 100 TeV

Pair production
ePairProd:   SubType=4
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    Sampling table 25x1001; from 0.1 GeV to 100 TeV
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        ePairProd : Emin=    0 eV  Emax=  100 TeV

Ionisation
eIoni:   SubType=2
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    StepFunction=(0.2, 0.01 mm), integ: 1, fluct: 1, linLossLim= 0.01
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
     LowEnergyIoni : Emin=    0 eV  Emax=  100 keV  deltaVI
      MollerBhabha : Emin=  100 keV Emax=  100 TeV  deltaVI
    CSDA range table up to 1 GeV in 140 bins

Bremsstrahlung
eBrem:   SubType=3
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    LPM flag: 1 for E > 1 GeV,  VertexHighEnergyTh(GeV)= 100000
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
```

```
            eBremSB : Emin=     0 eV  Emax=     1 GeV  AngularGen2BS
           eBremLPM : Emin=     1 GeV Emax=   100 TeV  AngularGen2BS
```

e+

```
Coulomb scattering. Simulation of elastic scattering
  events individually. May be used in combination with multiple
  scattering, where Coulomb scattering is used for hard (large angle)
  collisions and multiple scattering for soft collisions.
CoulombScat:  integral:1  SubType=1 BuildTable=1
    Lambda table from 100 MeV to 100 TeV, 20 bins/decade, spline: 1
    ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
eCoulombScattering : Emin=   100 MeV Emax=   100 TeV

Positron annihilation
annihil:  integral:1  SubType=5 BuildTable=0
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
          eplus2gg : Emin=     0 eV  Emax=   100 TeV

Multiple scattering. Simulates combined effects of elastic scattering
  at the end of the step, to save computing time. May be combined with
  Coulomb scattering in a 'mixed' scattering algorithm.
msc:   SubType= 10
    RangeFactor= 0.08, stepLimType: 2, latDisp: 1
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
GoudsmitSaunderson : Emin=     0 eV  Emax=   100 MeV Nbins=120 100 eV  – 100 MeV
      WentzelVIUni : Emin=   100 MeV Emax=   100 TeV Nbins=120 100 MeV – 100 TeV

Pair production
ePairProd:   SubType=4
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    Sampling table 25x1001; from 0.1 GeV to 100 TeV
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
         ePairProd : Emin=     0 eV  Emax=   100 TeV

Ionisation
eIoni:   SubType=2
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    StepFunction=(0.2, 0.01 mm), integ: 1, fluct: 1, linLossLim= 0.01
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
           PenIoni : Emin=     0 eV  Emax=   100 keV
      MollerBhabha : Emin=   100 keV Emax=   100 TeV  deltaVI
    CSDA range table up to 1 GeV in 140 bins

Bremsstrahlung
eBrem:   SubType=3
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    LPM flag: 1 for E > 1 GeV,  VertexHighEnergyTh(GeV)= 100000
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
           eBremSB : Emin=     0 eV  Emax=     1 GeV  AngularGen2BS
          eBremLPM : Emin=     1 GeV Emax=   100 TeV  AngularGen2BS
```

proton

```
Coulomb scattering. Simulation of elastic scattering
  events individually. May be used in combination with multiple
  scattering, where Coulomb scattering is used for hard (large angle)
  collisions and multiple scattering for soft collisions.
CoulombScat:  integral:1  SubType=1 BuildTable=1
    Lambda table from threshold  to 100 TeV, 20 bins/decade, spline: 1
    ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
```

```
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
eCoulombScattering : Emin=    0 eV  Emax=  100 TeV

Hadron multiple scattering. Simulates combined effects of elastic
  scattering at the end of the step, to save computing time. May
  be combined with Coulomb scattering in a 'mixed' scattering algorithm.
msc:    SubType= 10
    RangeFactor= 0.2, stepLimType: 0, latDisp: 1
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
      WentzelVIUni : Emin=    0 eV  Emax=  100 TeV Nbins=240 100 eV  – 100 TeV

Hadron bremsstrahlung
hBrems:    SubType=3
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            hBrem : Emin=    0 eV  Emax=  100 TeV

Hadron pair production
hPairProd:    SubType=4
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    Sampling table 17x1001; from 7.50618 GeV to 100 TeV
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        hPairProd : Emin=    0 eV  Emax=  100 TeV

Ionisation
hIoni:    SubType=2
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    StepFunction=(0.1, 0.02 mm), integ: 1, fluct: 1, linLossLim= 0.01
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            Bragg : Emin=    0 eV  Emax=    2 MeV  deltaVI
        BetheBloch : Emin=    2 MeV Emax=  100 TeV  deltaVI
    CSDA range table up to 1 GeV in 140 bins
```

mu+

```
Coulomb scattering. Simulation of elastic scattering
  events individually. May be used in combination with multiple
  scattering, where Coulomb scattering is used for hard (large angle)
  collisions and multiple scattering for soft collisions.
CoulombScat:  integral:1  SubType=1 BuildTable=1
    Lambda table from threshold  to 100 TeV, 20 bins/decade, spline: 1
    ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
eCoulombScattering : Emin=    0 eV  Emax=  100 TeV

Muon multiple scattering. Simulates combined effects of elastic
  scattering at the end of the step, to save computing time. May be
  combined with Coulomb scattering in a 'mixed' scattering algorithm.
msc:    SubType= 10
    RangeFactor= 0.2, stepLimType: 0, latDisp: 1, polarAngLim(deg)= 180
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
      WentzelVIUni : Emin=    0 eV  Emax=  100 TeV Nbins=240 100 eV  – 100 TeV

Muon bremsstrahlung
muBrems:    SubType=3
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            MuBrem : Emin=    0 eV  Emax=  100 TeV

Pair production
muPairProd:    SubType=4
```

```
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    Sampling table 21x1001; from 1 GeV to 100 TeV
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
       muPairProd : Emin=    0 eV  Emax=  100 TeV

Muon ionisation
muIoni:   SubType=2
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    StepFunction=(0.1, 0.02 mm), integ: 1, fluct: 1, linLossLim= 0.01
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            Bragg : Emin=    0 eV  Emax=  200 keV  deltaVI
        BetheBloch : Emin=  200 keV Emax=    1 GeV  deltaVI
      MuBetheBloch : Emin=    1 GeV Emax=  100 TeV
    CSDA range table up to 1 GeV in 140 bins
```

mu-

```
Coulomb scattering. Simulation of elastic scattering
  events individually. May be used in combination with multiple
  scattering, where Coulomb scattering is used for hard (large angle)
  collisions and multiple scattering for soft collisions.
CoulombScat:  integral:1  SubType=1 BuildTable=1
    Lambda table from threshold  to 100 TeV, 20 bins/decade, spline: 1
    ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
eCoulombScattering : Emin=    0 eV  Emax=  100 TeV

Muon multiple scattering. Simulates combined effects of elastic
  scattering at the end of the step, to save computing time. May be
  combined with Coulomb scattering in a 'mixed' scattering algorithm.
msc:   SubType= 10
    RangeFactor= 0.2, stepLimType: 0, latDisp: 1, polarAngLim(deg)= 180
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
     WentzelVIUni : Emin=    0 eV  Emax=  100 TeV Nbins=240 100 eV  - 100 TeV

Muon bremsstrahlung
muBrems:   SubType=3
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            MuBrem : Emin=    0 eV  Emax=  100 TeV

Pair production
muPairProd:   SubType=4
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    Sampling table 21x1001; from 1 GeV to 100 TeV
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
       muPairProd : Emin=    0 eV  Emax=  100 TeV

Muon ionisation
muIoni:   SubType=2
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    StepFunction=(0.1, 0.02 mm), integ: 1, fluct: 1, linLossLim= 0.01
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
          ICRU73QO : Emin=    0 eV  Emax=  200 keV  deltaVI
        BetheBloch : Emin=  200 keV Emax=    1 GeV  deltaVI
      MuBetheBloch : Emin=    1 GeV Emax=  100 TeV
    CSDA range table up to 1 GeV in 140 bins
```

3.14.6 Livermore

gamma

```
    Photoelectric effect
    phot:  SubType=12 BuildTable=0
        LambdaPrime table from 200 keV to 100 TeV in 174 bins
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
    LivermorePhElectric : Emin=    0 eV  Emax=  100 TeV  SauterGavrila Fluo

    Compton scattering
    compt:  SubType=13 BuildTable=1
        Lambda table from 100 eV  to 1 MeV, 20 bins/decade, spline: 1
        LambdaPrime table from 1 MeV to 100 TeV in 160 bins
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
     LivermoreCompton : Emin=    0 eV  Emax=    1 GeV Fluo
        KleinNishina : Emin=    1 GeV Emax=  100 TeV Fluo

    Gamma conversion
    conv:  SubType=14 BuildTable=1
        Lambda table from 1.022 MeV to 100 TeV, 20 bins/decade, spline: 1
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        BetheHeitler5D : Emin=    0 eV  Emax=  100 TeV  ModifiedTsai

    Rayleigh scattering
    Rayl:  SubType=11 BuildTable=1
        Lambda table from 100 eV  to 100 keV, 20 bins/decade, spline: 0
        LambdaPrime table from 100 keV to 100 TeV in 180 bins
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
     LivermoreRayleigh : Emin=    0 eV  Emax=  100 TeV  CullenGenerator
```

e-

```
    Coulomb scattering. Simulation of elastic scattering
      events individually. May be used in combination with multiple
      scattering, where Coulomb scattering is used for hard (large angle)
      collisions and multiple scattering for soft collisions.
    CoulombScat:  integral:1  SubType=1 BuildTable=1
        Lambda table from 100 MeV to 100 TeV, 20 bins/decade, spline: 1
        ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
    eCoulombScattering : Emin=  100 MeV Emax=  100 TeV

    Multiple scattering. Simulates combined effects of elastic scattering
      at the end of the step, to save computing time. May be combined with
      Coulomb scattering in a 'mixed' scattering algorithm.
    msc:    SubType= 10
        RangeFactor= 0.08, stepLimType: 2, latDisp: 1
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
    GoudsmitSaunderson : Emin=    0 eV  Emax=  100 MeV Nbins=120 100 eV  – 100 MeV
        WentzelVIUni : Emin=  100 MeV Emax=  100 TeV Nbins=120 100 MeV – 100 TeV

    Pair production
    ePairProd:    SubType=4
        dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
        Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
        Sampling table 25x1001; from 0.1 GeV to 100 TeV
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            ePairProd : Emin=    0 eV  Emax=  100 TeV

    Ionisation
    eIoni:    SubType=2
        dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
        Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
        StepFunction=(0.2, 0.01 mm), integ: 1, fluct: 1, linLossLim= 0.01
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
```

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```
        LowEnergyIoni : Emin=     0 eV  Emax=  100 keV  deltaVI
         MollerBhabha : Emin=  100 keV Emax=  100 TeV  deltaVI
      CSDA range table up to 1 GeV in 140 bins

   Bremsstrahlung
   eBrem:    SubType=3
      dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
      Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
      LPM flag: 1 for E > 1 GeV,  VertexHighEnergyTh(GeV)= 100000
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            eBremSB : Emin=     0 eV  Emax=    1 GeV  AngularGen2BS
           eBremLPM : Emin=    1 GeV Emax=  100 TeV  AngularGen2BS
```

e+

```
   Coulomb scattering. Simulation of elastic scattering
     events individually. May be used in combination with multiple
     scattering, where Coulomb scattering is used for hard (large angle)
     collisions and multiple scattering for soft collisions.
   CoulombScat:  integral:1  SubType=1 BuildTable=1
      Lambda table from 100 MeV to 100 TeV, 20 bins/decade, spline: 1
      ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
   eCoulombScattering : Emin=  100 MeV Emax=  100 TeV

   Positron annihilation
   annihil:  integral:1  SubType=5 BuildTable=0
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            eplus2gg : Emin=     0 eV  Emax=  100 TeV

   Multiple scattering. Simulates combined effects of elastic scattering
     at the end of the step, to save computing time. May be combined with
     Coulomb scattering in a 'mixed' scattering algorithm.
   msc:    SubType= 10
      RangeFactor= 0.08, stepLimType: 2, latDisp: 1
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
   GoudsmitSaunderson : Emin=     0 eV  Emax=  100 MeV Nbins=120 100 eV  – 100 MeV
       WentzelVIUni : Emin=  100 MeV Emax=  100 TeV Nbins=120 100 MeV – 100 TeV

   Pair production
   ePairProd:    SubType=4
      dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
      Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
      Sampling table 25x1001; from 0.1 GeV to 100 TeV
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
          ePairProd : Emin=     0 eV  Emax=  100 TeV

   Ionisation
   eIoni:    SubType=2
      dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
      Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
      StepFunction=(0.2, 0.01 mm), integ: 1, fluct: 1, linLossLim= 0.01
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        MollerBhabha : Emin=     0 eV  Emax=  100 TeV  deltaVI
      CSDA range table up to 1 GeV in 140 bins

   Bremsstrahlung
   eBrem:    SubType=3
      dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
      Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
      LPM flag: 1 for E > 1 GeV,  VertexHighEnergyTh(GeV)= 100000
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            eBremSB : Emin=     0 eV  Emax=    1 GeV  AngularGen2BS
           eBremLPM : Emin=    1 GeV Emax=  100 TeV  AngularGen2BS
```

proton

```
Coulomb scattering. Simulation of elastic scattering
  events individually. May be used in combination with multiple
  scattering, where Coulomb scattering is used for hard (large angle)
  collisions and multiple scattering for soft collisions.
CoulombScat:  integral:1  SubType=1 BuildTable=1
    Lambda table from threshold  to 100 TeV, 20 bins/decade, spline: 1
    ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
eCoulombScattering : Emin=    0 eV  Emax=  100 TeV

Hadron multiple scattering. Simulates combined effects of elastic
  scattering at the end of the step, to save computing time. May
  be combined with Coulomb scattering in a 'mixed' scattering algorithm.
msc:   SubType= 10
    RangeFactor= 0.2, stepLimType: 0, latDisp: 1
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
      WentzelVIUni : Emin=    0 eV  Emax=  100 TeV Nbins=240 100 eV  - 100 TeV

Hadron bremsstrahlung
hBrems:    SubType=3
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
             hBrem : Emin=    0 eV  Emax=  100 TeV

Hadron pair production
hPairProd:    SubType=4
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    Sampling table 17x1001; from 7.50618 GeV to 100 TeV
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
         hPairProd : Emin=    0 eV  Emax=  100 TeV

Ionisation
hIoni:    SubType=2
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    StepFunction=(0.2, 0.05 mm), integ: 1, fluct: 1, linLossLim= 0.01
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
             Bragg : Emin=    0 eV  Emax=    2 MeV  deltaVI
         BetheBloch : Emin=    2 MeV Emax=  100 TeV  deltaVI
    CSDA range table up to 1 GeV in 140 bins
```

mu+

```
Coulomb scattering. Simulation of elastic scattering
  events individually. May be used in combination with multiple
  scattering, where Coulomb scattering is used for hard (large angle)
  collisions and multiple scattering for soft collisions.
CoulombScat:  integral:1  SubType=1 BuildTable=1
    Lambda table from threshold  to 100 TeV, 20 bins/decade, spline: 1
    ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
eCoulombScattering : Emin=    0 eV  Emax=  100 TeV

Muon multiple scattering. Simulates combined effects of elastic
  scattering at the end of the step, to save computing time. May be
  combined with Coulomb scattering in a 'mixed' scattering algorithm.
msc:   SubType= 10
    RangeFactor= 0.2, stepLimType: 0, latDisp: 1, polarAngLim(deg)= 180
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
      WentzelVIUni : Emin=    0 eV  Emax=  100 TeV Nbins=240 100 eV  - 100 TeV

Muon bremsstrahlung
muBrems:    SubType=3
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
```

```
        Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
             MuBrem : Emin=    0 eV  Emax=  100 TeV

    Pair production
    muPairProd:   SubType=4
        dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
        Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
        Sampling table 21x1001; from 1 GeV to 100 TeV
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
           muPairProd : Emin=    0 eV  Emax=  100 TeV

    Muon ionisation
    muIoni:   SubType=2
        dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
        Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
        StepFunction=(0.2, 0.05 mm), integ: 1, fluct: 1, linLossLim= 0.01
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
              Bragg : Emin=    0 eV  Emax=  200 keV  deltaVI
          BetheBloch : Emin=  200 keV Emax=    1 GeV  deltaVI
        MuBetheBloch : Emin=    1 GeV Emax=  100 TeV
        CSDA range table up to 1 GeV in 140 bins
```

mu-

```
    Coulomb scattering. Simulation of elastic scattering
      events individually. May be used in combination with multiple
      scattering, where Coulomb scattering is used for hard (large angle)
      collisions and multiple scattering for soft collisions.
    CoulombScat:  integral:1  SubType=1 BuildTable=1
        Lambda table from threshold  to 100 TeV, 20 bins/decade, spline: 1
        ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
    eCoulombScattering : Emin=    0 eV  Emax=  100 TeV

    Muon multiple scattering. Simulates combined effects of elastic
      scattering at the end of the step, to save computing time. May be
      combined with Coulomb scattering in a 'mixed' scattering algorithm.
    msc:   SubType= 10
        RangeFactor= 0.2, stepLimType: 0, latDisp: 1, polarAngLim(deg)= 180
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
          WentzelVIUni : Emin=    0 eV  Emax=  100 TeV Nbins=240 100 eV  - 100 TeV

    Muon bremsstrahlung
    muBrems:   SubType=3
        dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
        Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
             MuBrem : Emin=    0 eV  Emax=  100 TeV

    Pair production
    muPairProd:   SubType=4
        dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
        Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
        Sampling table 21x1001; from 1 GeV to 100 TeV
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
           muPairProd : Emin=    0 eV  Emax=  100 TeV

    Muon ionisation
    muIoni:   SubType=2
        dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
        Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
        StepFunction=(0.2, 0.05 mm), integ: 1, fluct: 1, linLossLim= 0.01
        ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            ICRU73QO : Emin=    0 eV  Emax=  200 keV  deltaVI
```

```
        BetheBloch : Emin=  200 keV Emax=    1 GeV  deltaVI
      MuBetheBloch : Emin=    1 GeV Emax=  100 TeV
    CSDA range table up to 1 GeV in 140 bins
```

3.14.7 Penelope

gamma

```
Photoelectric effect
phot:  SubType=12 BuildTable=0
    LambdaPrime table from 200 keV to 100 TeV in 174 bins
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
      PenPhotoElec : Emin=    0 eV  Emax=    1 GeV Fluo
     PhotoElectric : Emin=    1 GeV Emax=  100 TeV  SauterGavrila Fluo

Compton scattering
compt:  SubType=13 BuildTable=1
    Lambda table from 100 eV  to 1 MeV, 20 bins/decade, spline: 1
    LambdaPrime table from 1 MeV to 100 TeV in 160 bins
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        PenCompton : Emin=    0 eV  Emax=    1 GeV Fluo
      KleinNishina : Emin=    1 GeV Emax=  100 TeV Fluo

Gamma conversion
conv:  SubType=14 BuildTable=1
    Lambda table from 1.022 MeV to 100 TeV, 20 bins/decade, spline: 1
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
     PenConversion : Emin=    0 eV  Emax=    1 GeV
   BetheHeitlerLPM : Emin=    1 GeV Emax=  100 TeV  ModifiedTsai

Rayleigh scattering
Rayl:  SubType=11 BuildTable=1
    Lambda table from 100 eV  to 100 keV, 20 bins/decade, spline: 0
    LambdaPrime table from 100 keV to 100 TeV in 180 bins
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
       PenRayleigh : Emin=    0 eV  Emax=  100 GeV
```

e-

```
Coulomb scattering. Simulation of elastic scattering
  events individually. May be used in combination with multiple
  scattering, where Coulomb scattering is used for hard (large angle)
  collisions and multiple scattering for soft collisions.
CoulombScat:  integral:1  SubType=1 BuildTable=1
    Lambda table from 100 MeV to 100 TeV, 20 bins/decade, spline: 1
    ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
eCoulombScattering : Emin=  100 MeV Emax=  100 TeV

Multiple scattering. Simulates combined effects of elastic scattering
  at the end of the step, to save computing time. May be combined with
  Coulomb scattering in a 'mixed' scattering algorithm.
msc:    SubType= 10
    RangeFactor= 0.08, stepLimType: 2, latDisp: 1
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
GoudsmitSaunderson : Emin=    0 eV  Emax=  100 MeV Nbins=120 100 eV  - 100 MeV
      WentzelVIUni : Emin=  100 MeV Emax=  100 TeV Nbins=120 100 MeV - 100 TeV

Pair production
ePairProd:   SubType=4
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
```

```
     Sampling table 25x1001; from 0.1 GeV to 100 TeV
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
         ePairProd : Emin=    0 eV  Emax=  100 TeV

 Ionisation
 eIoni:    SubType=2
     dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
     Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
     StepFunction=(0.2, 0.01 mm), integ: 1, fluct: 1, linLossLim= 0.01
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
           PenIoni : Emin=    0 eV  Emax=    1 GeV
       MollerBhabha : Emin=    1 GeV Emax=  100 TeV
     CSDA range table up to 1 GeV in 140 bins

 Bremsstrahlung
 eBrem:    SubType=3
     dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
     Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
     LPM flag: 1 for E > 1 GeV,  VertexHighEnergyTh(GeV)= 100000
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
           PenBrem : Emin=    0 eV  Emax=    1 GeV
          eBremLPM : Emin=    1 GeV Emax=  100 TeV  ModifiedTsai
```

e+

```
 Coulomb scattering. Simulation of elastic scattering
   events individually. May be used in combination with multiple
   scattering, where Coulomb scattering is used for hard (large angle)
   collisions and multiple scattering for soft collisions.
 CoulombScat:  integral:1 SubType=1 BuildTable=1
     Lambda table from 100 MeV to 100 TeV, 20 bins/decade, spline: 1
     ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
 eCoulombScattering : Emin=  100 MeV Emax=  100 TeV

 Positron annihilation
 annihil:  integral:1  SubType=5 BuildTable=0
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
           PenAnnih : Emin=    0 eV  Emax=    1 GeV
           eplus2gg : Emin=    1 GeV Emax=  100 TeV

 Multiple scattering. Simulates combined effects of elastic scattering
   at the end of the step, to save computing time. May be combined with
   Coulomb scattering in a 'mixed' scattering algorithm.
 msc:    SubType= 10
     RangeFactor= 0.08, stepLimType: 2, latDisp: 1
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
 GoudsmitSaunderson : Emin=    0 eV  Emax=  100 MeV Nbins=120 100 eV  – 100 MeV
     WentzelVIUni : Emin=  100 MeV Emax=  100 TeV Nbins=120 100 MeV – 100 TeV

 Pair production
 ePairProd:    SubType=4
     dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
     Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
     Sampling table 25x1001; from 0.1 GeV to 100 TeV
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
         ePairProd : Emin=    0 eV  Emax=  100 TeV

 Ionisation
 eIoni:    SubType=2
     dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
     Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
     StepFunction=(0.2, 0.01 mm), integ: 1, fluct: 1, linLossLim= 0.01
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
           PenIoni : Emin=    0 eV  Emax=    1 GeV
```

```
      MollerBhabha : Emin=     1 GeV Emax=  100 TeV
     CSDA range table up to 1 GeV in 140 bins


  Bremsstrahlung
  eBrem:    SubType=3
     dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
     Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
     LPM flag: 1 for E > 1 GeV,  VertexHighEnergyTh(GeV)= 100000
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
           PenBrem : Emin=     0 eV  Emax=     1 GeV
          eBremLPM : Emin=     1 GeV Emax=  100 TeV  ModifiedTsai
```

proton

```
  Coulomb scattering. Simulation of elastic scattering
    events individually. May be used in combination with multiple
    scattering, where Coulomb scattering is used for hard (large angle)
    collisions and multiple scattering for soft collisions.
  CoulombScat:  integral:1  SubType=1 BuildTable=1
     Lambda table from threshold  to 100 TeV, 20 bins/decade, spline: 1
     ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
  eCoulombScattering : Emin=     0 eV  Emax=  100 TeV

  Hadron multiple scattering. Simulates combined effects of elastic
    scattering at the end of the step, to save computing time. May
    be combined with Coulomb scattering in a 'mixed' scattering algorithm.
  msc:    SubType= 10
     RangeFactor= 0.2, stepLimType: 0, latDisp: 1
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
       WentzelVIUni : Emin=     0 eV  Emax=  100 TeV Nbins=240 100 eV  – 100 TeV

  Hadron bremsstrahlung
  hBrems:    SubType=3
     dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
     Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
             hBrem : Emin=     0 eV  Emax=  100 TeV

  Hadron pair production
  hPairProd:    SubType=4
     dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
     Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
     Sampling table 17x1001; from 7.50618 GeV to 100 TeV
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
          hPairProd : Emin=     0 eV  Emax=  100 TeV

  Ionisation
  hIoni:    SubType=2
     dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
     Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
     StepFunction=(0.2, 0.05 mm), integ: 1, fluct: 1, linLossLim= 0.01
     ===== EM models for the G4Region  DefaultRegionForTheWorld ======
             Bragg : Emin=     0 eV  Emax=     2 MeV
         BetheBloch : Emin=     2 MeV Emax=  100 TeV
     CSDA range table up to 1 GeV in 140 bins
```

mu+

```
  Coulomb scattering. Simulation of elastic scattering
    events individually. May be used in combination with multiple
    scattering, where Coulomb scattering is used for hard (large angle)
    collisions and multiple scattering for soft collisions.
  CoulombScat:  integral:1  SubType=1 BuildTable=1
     Lambda table from threshold  to 100 TeV, 20 bins/decade, spline: 1
```

```
      ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
eCoulombScattering : Emin=    0 eV  Emax=  100 TeV

Muon multiple scattering. Simulates combined effects of elastic
  scattering at the end of the step, to save computing time. May be
  combined with Coulomb scattering in a 'mixed' scattering algorithm.
msc:    SubType= 10
    RangeFactor= 0.2, stepLimType: 0, latDisp: 1, polarAngLim(deg)= 180
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
      WentzelVIUni : Emin=    0 eV  Emax=  100 TeV Nbins=240 100 eV  – 100 TeV

Muon bremsstrahlung
muBrems:   SubType=3
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
          MuBrem : Emin=    0 eV  Emax=  100 TeV

Pair production
muPairProd:   SubType=4
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    Sampling table 21x1001; from 1 GeV to 100 TeV
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        muPairProd : Emin=    0 eV  Emax=  100 TeV

Muon ionisation
muIoni:   SubType=2
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    StepFunction=(0.2, 0.05 mm), integ: 1, fluct: 1, linLossLim= 0.01
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            Bragg : Emin=    0 eV  Emax=  200 keV
        BetheBloch : Emin=  200 keV Emax=    1 GeV
      MuBetheBloch : Emin=    1 GeV Emax=  100 TeV
    CSDA range table up to 1 GeV in 140 bins
```

mu-

```
Coulomb scattering. Simulation of elastic scattering
  events individually. May be used in combination with multiple
  scattering, where Coulomb scattering is used for hard (large angle)
  collisions and multiple scattering for soft collisions.
CoulombScat:  integral:1  SubType=1 BuildTable=1
    Lambda table from threshold  to 100 TeV, 20 bins/decade, spline: 1
    ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
eCoulombScattering : Emin=    0 eV  Emax=  100 TeV

Muon multiple scattering. Simulates combined effects of elastic
  scattering at the end of the step, to save computing time. May be
  combined with Coulomb scattering in a 'mixed' scattering algorithm.
msc:    SubType= 10
    RangeFactor= 0.2, stepLimType: 0, latDisp: 1, polarAngLim(deg)= 180
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
      WentzelVIUni : Emin=    0 eV  Emax=  100 TeV Nbins=240 100 eV  – 100 TeV

Muon bremsstrahlung
muBrems:   SubType=3
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
          MuBrem : Emin=    0 eV  Emax=  100 TeV
```

```
Pair production
muPairProd:   SubType=4
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    Sampling table 21x1001; from 1 GeV to 100 TeV
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        muPairProd : Emin=    0 eV  Emax=  100 TeV

Muon ionisation
muIoni:   SubType=2
    dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
    Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
    StepFunction=(0.2, 0.05 mm), integ: 1, fluct: 1, linLossLim= 0.01
    ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        ICRU73QO : Emin=    0 eV  Emax=  200 keV
       BetheBloch : Emin=  200 keV Emax=    1 GeV
     MuBetheBloch : Emin=    1 GeV Emax=  100 TeV
    CSDA range table up to 1 GeV in 140 bins
```

3.15 Tables by particle

3.15.1 Gamma

Table 3.1: Models used for gamma processes for different EM physics constructors.

title	Rayleigh	Photoelectric	Compton	Gamma conversion
Opt0	LivermoreRayleigh 0-100 TeV	LivermorePhElectric 0-100 TeV	KleinNishina 0-100 TeV	BetheHeitlerLPM 0-100 TeV
Opt1	none	LivermorePhElectric 0-100 TeV	KleinNishina 0-100 TeV	BetheHeitlerLPM 0-100 TeV
Opt2	none	PhotoElectric 0-100 TeV	KleinNishina 0-100 TeV	BetheHeitlerLPM 0-100 TeV
Opt3	LivermoreRayleigh 0-100 TeV	LivermorePhElectric 0-100 TeV	KleinNishina 0-100 TeV	BetheHeitlerLPM 0-100 TeV
Opt4	LivermoreRayleigh 0-100 TeV	LivermorePhElectric 0-100 TeV	LowEPComptonModel 0-20 MeV KleinNishina 20 MeV-100 TeV	BetheHeitler5D 0-100 TeV
Livermore	LivermoreRayleigh 0-100 TeV	LivermorePhElectric 0-100 TeV	LivermoreCompton 0-1 GeV KleinNishina 1 GeV-100 TeV	BetheHeitler5D 0-100 TeV
Penelope	PenRayleigh 0-100 GeV	PenPhotoElec 0-1 GeV PhotoElectric 1 GeV-100 TeV	PenCompton 0-1 GeV KleinNishina 1 GeV-100 TeV	PenConversion 0-1 GeV BetheHeitlerLPM 1 GeV-100 TeV

3.15.2 Electron

Table 3.2: Models used for electron processes for different EM physics constructors.

	Coulomb scattering	Multiple scattering	Pair pro-duction	Ionisation	Bremsstrahlung
Opt0	eCoulombScattering 100 MeV-100 TeV	UrbanMsc 0-100 MeV WentzelVIUni 100 MeV-100 TeV	none	MollerBhabha 0-100 TeV	eBremSB 0-1 GeV eBremLPM 1 GeV-100 TeV
Opt1	eCoulombScattering 100 MeV-100 TeV	UrbanMsc 0-100 MeV; WentzelVIUni 100 MeV-100 TeV	none	MollerBhabha 0-100 TeV	eBremSB 0-1 GeV eBremLPM 1 GeV-100 TeV
Opt2	eCoulombScattering 100 MeV-100 TeV	UrbanMsc 0-100 MeV WentzelVIUni 100 MeV-100 TeV	none	MollerBhabha 0-100 TeV	eBremSB 0-1 GeV eBremLPM 1 GeV-100 TeV
Opt3	none	UrbanMsc 0-100 TeV	ePair-Prod 0-100 TeV	MollerBhabha 0-100 TeV	eBremSB 0-1 GeV eBremLPM 1 GeV-100 TeV
Opt4	eCoulombScattering 100 MeV-10 TeV	GoudsmitSaunderson 0-100 MeV WentzelVIUni 100 MeV-100 TeV	ePair-Prod 0-100 TeV	LowEnergyIoni 0-100 keV MollerBhabha 100 keV-100 TeV	eBremSB 0-1 GeV eBremLPM 1 GeV-100 TeV
Livermore	eCoulombScattering 100 MeV-100 TeV	GoudsmitSaunderson 0-100 MeV WentzelVIUni 100 MeV-100 TeV	ePair-Prod 0-100 TeV	LowEnergyIoni 0-100 keV MollerBhabha 100 keV-100 TeV	eBremSB 0-1 GeV eBremLPM 1 GeV-100 TeV
Penelope	eCoulombScattering 100 MeV-100 TeV	GoudsmitSaunderson 0-100 MeV WentzelVIUni 100 MeV-100 TeV	ePair-Prod 0-100 TeV	PenIoni 0-1 GeV MollerBhabha 1 GeV-100 TeV	PenBrem 0-1 GeV eBremLPM 1 GeV-100 TeV

3.15.3 Positron

Table 3.3: Models used for positron processes for different EM physics constructors.

	Coulomb scattering	Multiple scattering	Pair pro-duc-tion	Ionisation	Annihilation	Bremsstrahlung
Opt0	eCoulomb-Scattering 100 MeV-100 TeV	UrbanMsc 0-100 MeV WentzelVIUni 100 MeV-100 TeV	none	MollerBhabha 0-100 TeV	eplus2gg 0-100 TeV	eBremSB 0-1 GeV eBremLPM 1 GeV-100 TeV
Opt1	eCoulomb-Scattering 100 MeV-100 TeV	UrbanMsc 0-100 MeV WentzelVIUni 100 MeV-100 TeV	none	MollerBhabha 0-100 TeV	eplus2gg 0-100 TeV	eBremSB 0-1 GeV eBremLPM 1 GeV-100 TeV
Opt2	eCoulomb-Scattering 100 MeV-100 TeV	UrbanMsc 0-100 MeV WentzelVIUni 100 MeV-100 TeV	none	MollerBhabha 0-100 TeV	eplus2gg 0-100 TeV	eBremSB 0-1 GeV eBremLPM 1 GeV-100 TeV
Opt3	none	UrbanMsc 0-100 TeV	ePair-Prod 0-100 TeV	MollerBhabha 0-100 TeV	eplus2gg 0-100 TeV	eBremSB 0-1 GeV eBremLPM 1 GeV-100 TeV
Opt4	eCoulomb-Scattering 100 MeV-100 TeV	GoudsmitSaunderson 0-100 MeV WentzelVIUni 100 MeV-100 TeV	ePair-Prod 0-100 TeV	PenIoni 0-100 keV MollerBhabha 100 keV-100 TeV	eplus2gg 0-100 TeV	eBremSB 0-1 GeV eBremLPM 1 GeV-100 TeV
Livermore	eCoulomb-Scattering 100 MeV-100 TeV	GoudsmitSaunderson 0-100 MeV WentzelVIUni 100 MeV-100 TeV	ePair-Prod 0-100 TeV	MollerBhabha 0-100 TeV	eplus2gg 0-100 TeV	eBremSB 0-1 GeV eBremLPM 1 GeV-100 TeV
Penelope	eCoulomb-Scattering 100 MeV-100 TeV	GoudsmitSaunderson 0-100 MeV WentzelVIUni 100 MeV-100 TeV	ePair-Prod 0-100 TeV	PenIoni 0-1 GeV MollerBhabha 1 GeV-100 TeV	PenAnnih 0-1 GeV eplus2gg 1 GeV-100 TeV	PenBrem 0-1 GeV eBremLPM 1 GeV-100 TeV

Chapter 3. Electromagnetic physics constructors

HADRONIC PHYSICS

A description of various hadronics physics options which can be controlled via the physics list constructors. The *Reference Physics Lists* chapter describes a lot of hadronic modelling options which are available for domain applications within Geant4. Here extra features will be described which can help understand better the systematic uncertainties associated with hadronic physics simulation.

4.1 New UI commands in hadronics

To switch off completely all the print-out of hadronic physics (default is 1):

```
/process/had/verbose 0
```

To change the default (100 TeV) upper energy limit, e.g. 1 PeV :

```
/process/had/maxEnergy 1000.0 TeV
```

To switch on the *Coalescence Model for Cosmic-Ray applications* (default is off):

```
/process/had/enableCRCoalescence true
```

To set values used for checking energy conservation in hadronic interactions:

- Level of detail reported when energy is not conserved (default is 0, i.e. no report):

    ```
    /process/had/heptst/reportLevel ...
    ```

    (replaces the previous command: `/heptst/reportLevel`)
- Relative energy non-conservation level (default -1.0):

    ```
    /process/had/heptst/processRelLevel ...
    ```

    (replaces the previous command: `/heptst/processRelLevel`)
- Absolute energy non-conservation level (default -1.0):

    ```
    /process/had/heptst/processAbsLevel ...
    ```

    (replaces the previous command: `/heptst/processAbsLevel`)

For ParticleHP:

- To enable building of *ParticleHP* as with *HP*, use the new CMake option `GEANT4_BUILD_PHP_AS_HP` when building GEANT4 - i.e. `cmake ... -GEANT4_BUILD_PHP_AS_HP=ON ...`. Note: the environment variable **PHP_AS_HP** is deprecated and will be removed in the next major release, GEANT4 **11**.
- New UI command to enable Wendt fission model (default: false):

```
/process/had/particle_hp/use_Wendt_fission_model true
```

For completeness, here are the other UI commands related to *ParticleHP*:
- Force use of the *Photon Evaporation model*, instead of the neutron capture final state (default: false)

    ```
    /process/had/particle_hp/use_photo_evaporation true
    ```

- Use only exact isotope data files, instead of allowing nearby isotope files to be used, if the exact file is not available, the cross section will be set to zero (default: false):

    ```
    /process/had/particle_hp/skip_missing_isotopes true
    ```

- Switch off the Doppler broadening due to the thermal motion of the target nucleus, with a significant CPU performance advantage (default: false):

    ```
    /process/had/particle_hp/neglect_Doppler_broadening true
    ```

- Disable the adjustment of final state for getting better conservation (default: false):

    ```
    /process/had/particle_hp/do_not_adjust_final_state true
    ```

- Enable the generation of fission fragments (default: false):

    ```
    /process/had/particle_hp/produce_fission_fragment true
    ```

- Enable the use of NRESP71 model for neutron on Carbon reaction (default: false):

    ```
    /process/had/particle_hp/use_NRESP71_model true
    ```

- Set verbose level of the ParticleHP package (default: 1):

    ```
    /process/had/particle_hp/verbose ...
    ```

Note that now the values of these options are printed out at initialization (unless switched off by `/process/had/verbose 0`).

For Radioactive Decays:

- Set the time threshold for radioactive decays of ions, above which these decays are ignored

    ```
    /process/had/rdm/thresholdForVeryLongDecayTime value
    ```

This command has been introduced in Geant4 version 11.0. In Geant4 version 11.0 and 11.1 (and their patches), the default value was 10^27 ns, corresponding to about twice the age of the universe. Since G4 11.2, the default has been changed to 1 year. This change aimed to avoid confusing results in applications where a time window is not explicitly defined, and the effect of very slow radioactive decays of ions is assumed to be negligible - which is not always true! For applications where radioactive decays of ions do play an important role, it is recommended to increase the default time threshold of these decays to a very high value, e.g.

```
/process/had/rdm/thresholdForVeryLongDecayTime 1.0e+60 year
```

4.2 Scaling factors for cross sections

For the evaluation of systematic errors due to uncertainties in the Geant4 hadronic cross sections we recommend the following approach. Scaling up (e.g. by 10%, by using a scaling factor of 1.10) or down (e.g. using a scaling factor of 0.90) the cross sections, independently for elastic and inelastic interactions, and independently for different types of hadrons. Currently, this is possible for the following three categories of hadrons:

- nucleons : proton and neutron together
- pions : π^+ and π^- together
- all the rest of hadrons :

- kaons,
- hyperons,
- anti-baryons,
- light ions,
- light anti-ions,
- charm and bottom hadrons all together

The choice of scaling value is up to the user and should be considered in the context of estimating sytematic uncertainties along with a knowledge of accuracy of the experimental data for which the cross-section was produced.

Public methods of the singleton class G4HadronicParameters allow to enable the scaling of cross sections (disabled by default), and to set the scaling factors (by default 1.0) for the 6 cases considered: the three above hadron categories, for the two types of interactions, elastic and inelastic.

An example of how to use them is the following:

```
// First enable the scaling of cross section (by default disabled):
G4HadronicParameters::Instance()->SetApplyFactorXS( true );

// Scaling up the nucleon inelastic cross sections by 10%
G4HadronicParameters::Instance()->SetXSFactorNucleonInelastic( 1.10 );

// Scaling down the nucleon elastic cross sections by 15%
G4HadronicParameters::Instance()->SetXSFactorNucleonElastic( 0.85 );

// Scaling up the pion inelastic cross sections by 7%
G4HadronicParameters::Instance()->SetXSFactorPionInelastic( 1.07 );

// Scaling down the pion elastic cross sections by 12%
G4HadronicParameters::Instance()->SetXSFactorPionElastic( 0.88 );

// Scaling up all the other hadrons (excluding nucleons and pions)
// inelastic cross sections by 20%
G4HadronicParameters::Instance()->SetXSFactorHadronInelastic( 1.20 );

// Scaling down all the other hadrons (excluding nucleons and pions)
// elastic cross sections by 25%
G4HadronicParameters::Instance()->SetXSFactorHadronElastic( 0.75 );
```

(Note that, contrary to what shown in the example above, for evaluation of systematic errors, it makes more sense to scale up and down these 6 cases independently and invidually.)

Currently only the above C++ calls are available for users to scale the cross sections (i.e. no UI commands), and they should be issued before the run initialization.

The choice of scaling value is up to the user and should be used as a basis for understanding systematic variations according to the uncertainties in the base cross-section and not as a means of tuning results to fit data.

4.3 Charm and bottom hadronic physics

Elastic and inelastic nuclear interactions of charm and bottom hadrons are enabled in most physics lists, in particular those of interest for HEP. (The main exception is `QGSP_BIC` and its derived physics lists - `QGSP_BIC_HP` and `QGSP_BIC_AllHP` - which are typically used for low-energy applications.)

For charm and bottom hadron-nuclear (elastic and inelastic) cross sections, the Glauber-Gribov approach, which is used also for all other hadrons, has been extended to cover heavy hadrons.

For final-state elastic nuclear scattering of charm and bottom hadron projectiles, a simple treatment is utilized (an improved version of Gheisha's two-exponential momentum transfer parameterization).

For final-state inelastic nuclear scattering of charm and bottom hadron projectiles, both Geant4 string models (FTF and QGS) have been extended to deal with charm and bottom quarks and diquarks carried by the heavy projectile hadron, as well as with the possibility of creating charm-anti_charm and bottom-anti_bottom pairs from the vacuum during the string fragmentation phase.

Cascade models (Bertini, Binary, INCL) are currently not applicable for heavy hadrons and string models cannot handle them properly at very low energies. Therefore, we use FTFP down to 100 MeV, and below we use a dummy model that returns as final state the initial state unchanged.

Note that, for most applications, this is a safe simplification, giving that nearly all slowly moving charm and bottom hadrons decay before any hadronic interaction can occur.

The QGS-based physics lists use, as for other hadrons, QGSP for charm and bottom inelastic interactions above 12 GeV, whereas FTFP is used below 25 GeV. The other, FTF-based physics lists, use FTFP at all energies (indeed, as explained above, below 100 MeV we used a simplified approach).

The vast majority of charm and bottom hadrons created in high-energy collisions decay inside the beam pipe or in the inner part of the tracker detector before undergoing any nuclear interaction.

The decays of these heavy hadrons are usually pre-defined by a Monte Carlo event generator. This approach cannot, obviously, be applied for the secondary heavy hadrons, i.e. charm and bottom hadrons that are created by inelastic nuclear interactions of the primary hadrons. For these secondary heavy hadrons, a very simple approach is currently used in Geant4 to deal with their decays: one single, fully hadronic decay is defined for each "long"-lived charm and bottom hadron, with a simple multi-body phase-space treatment of the decay kinematics.

4.4 Use of QGS for hyperons, anti-hyperons and anti-nucleons

QGS-based physics lists use now QGS for hyperons, anti-hyperons, anti_proton and anti_neutron projectiles at energies above 12 GeV (and FTF below 25 GeV, whereas in previous Geant4 versions, FTF was used for all energies - for these hadrons in QGS-based physics lists). Note that light anti-ions (anti-deuteron, anti-triton, anti-He3 and anti-alpha) cannot currently be handled by the QGS string model.

4.5 Coalescence Model for Cosmic-Ray applications

A new coalescence model, G4CRCoalescence, has been introduced. By considering the list of secondaries produced by a string model, the model forms deuterons and antideuterons from, respectively, proton-neutron and antiproton-antineutron pairs with close momenta. This can be useful in particular for Cosmic-Ray applications. By default, the coalescence model is disabled. It can be switched on via either a C++ call to the method:

```
G4HadronicParameters::Instance()->SetEnableCRCoalescence( true )
```

or the new UI command:

```
/process/had/enableCRCoalescence true
```

when using any reference physics list, as well as any custom physics list that uses one of the string models, FTF or QGS.

4.6 New low-energy gamma-nuclear final-state model

A new gamma-nuclear final-state model, `G4LowEGammaNuclearModel`, based on precompound de-excitation, is used below 200 MeV, while Bertini cascade is used above 199 MeV up to 6 GeV, and QGSP above 3 GeV.

This applies to all reference physics lists, with the only exception of `ShieldingLEND`, where `G4LENDorBERTModel` is used below 20 MeV, and `Bertini` is used above 19.9 MeV (as usual, up to 6 GeV, and QGSP above 3 GeV, while `G4LowEGammaNuclearModel` is not used at all in this case).

Status of this Document

Guide describing Physics Lists and their possible application in more detail.

- Rev 1.0: First sphinx version implemented for GEANT4 Release 10.4, 8th Dec 2017
- Rev 2.0: Updates and fixes in documentation for GEANT4 Release 10.4, 15th May 2018
- Rev 3.0: GEANT4 Release 10.5, 11th December 2018
- Rev 3.1: GEANT4 Updates and fixes - especially to search functionality, 5th March 2019
- Rev 4.0: GEANT4 Release 10.6, 6th December 2019
- Rev 5.0: GEANT4 Release 10.7, 4th December 2020
- Rev 6.0: GEANT4 Release 11.0, 10th December 2021
- Rev 7.0: GEANT4 Release 11.1, 9th December 2022
- Rev 7.1: Addition of extensible physics list factory, 21st April 2023
- Rev 7.2: GEANT4 Fixes to http links, 15th July 2023
- Rev 8.0: GEANT4 Release 11.2, 8th December 2023

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