History of GEANT4 multiple scattering of muons

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History

- I have been following the multiple scattering of muons at LHC energies since 1999
- A comparison with L3 experiment LEP I data (45 GeV muons) showed 20 % discrepancy
  - GEANT4 workshop at ESTEC (20-24 september 1999)

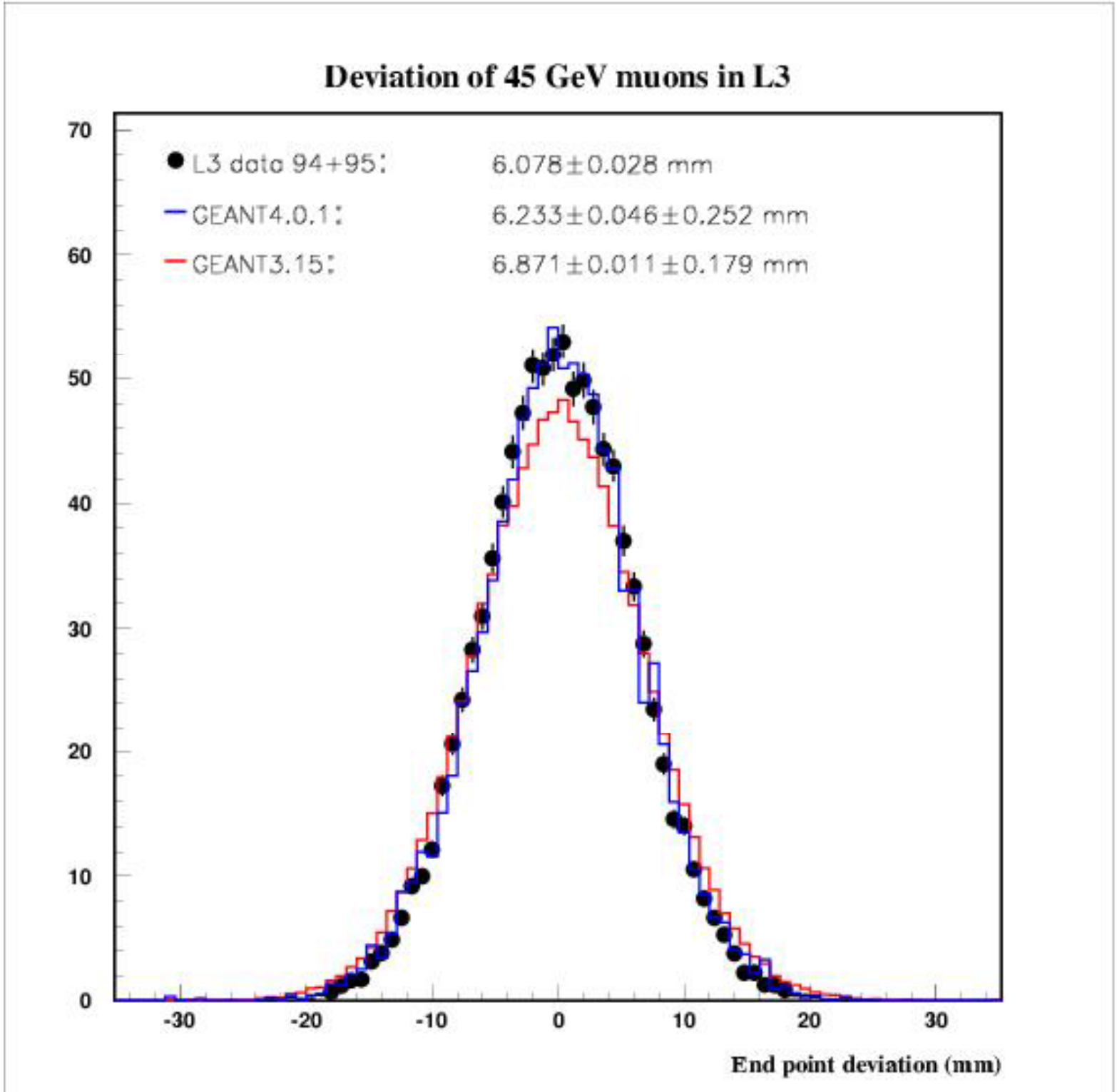
  http://cmsdoc.cern.ch/~arce/G4MuonPhysics/geant4_workshop99/l3g3g4.ps
- I found a 'nuclear size effect' correction that was missing
  - I tuned the free parameter with data of pions, kaons and protons from 50 to 200 GeV traversing different single material blocks

G. Shen et al. **"Measurement of multiple scattering at 50 to 200 GeV/c"**. *Phys. Rev. D 20 (1979) 1584.*

  - Very good agreement with L3 data was then found

P. Arce, M. Wadhwa **CMS NOTE-2000/016 Deviation in Matter of 45 GeV Muons in GEANT3 and GEANT4. A Comparison with L3 Data**

  - Correction introduced in GEANT4 1.0

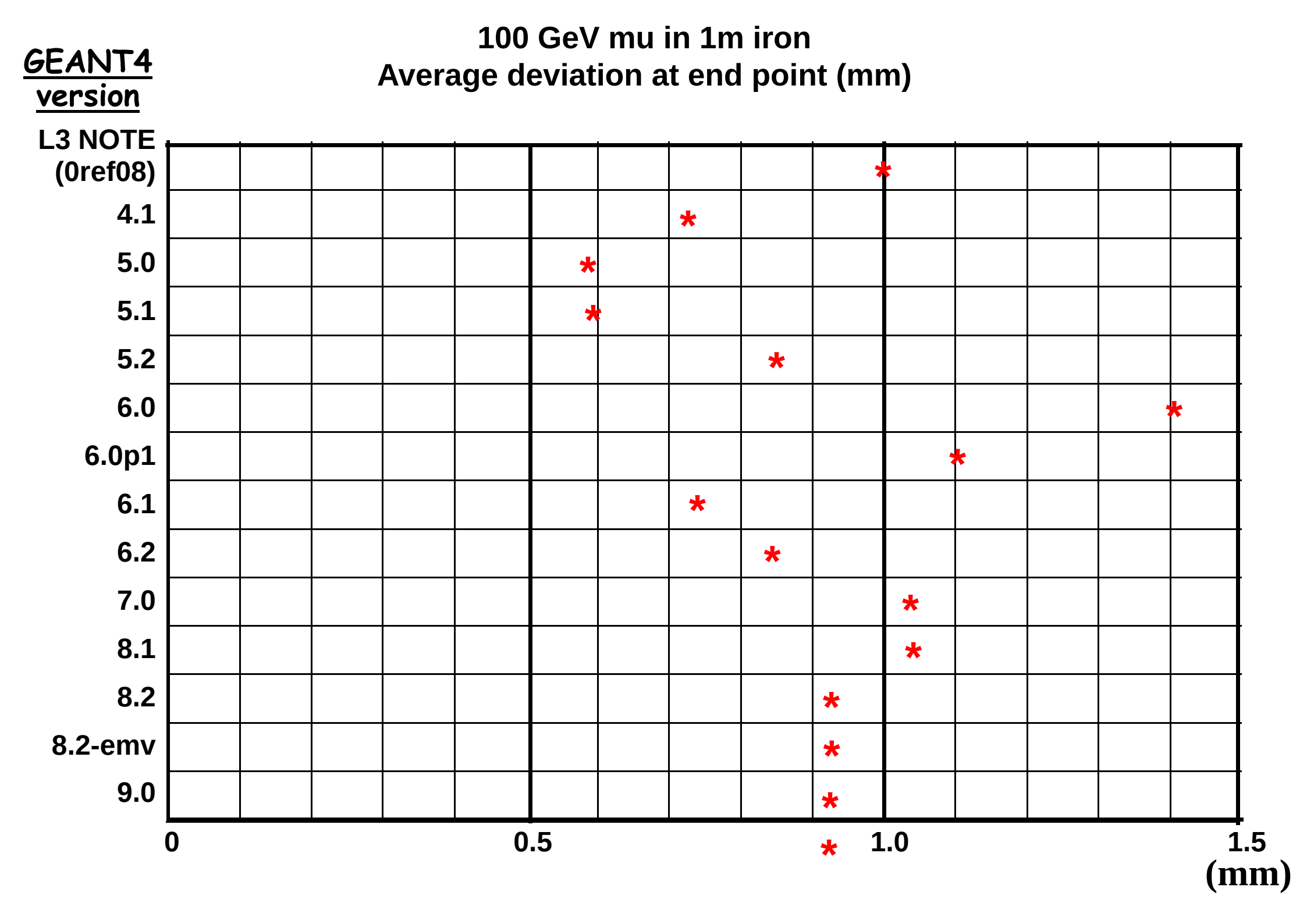

Deviation of 45 GeV muons in L3
L3 data 94+95: 6.078±0.028 mm
GEANT4.0.1: 6.233±0.046±0.252 mm
GEANT3.15: 6.871±0.011±0.179 mm
70
60
50
40
30
20
10
0
-30
-20
-10
0
10
20
30
End point deviation (mm)

Checking

- Since then I have checked the evolution of multiple scattering of high energy muons in each GEANT4 version

Simple benchmark:

- 1 m x 1m x 1m block of iron
- 10, 100, 1000 GeV muons
- Plot deviation of muons from straight line (99 % due to multiple scattering)
  - ✓Distance
  - ✓Angle
- plus many other muon physics variables…


100 GeV mu in 1m iron
Average deviation at end point (mm)
GEANT4 version
L3 NOTE (0ref08)
4.1
5.0
5.1
5.2
6.0
6.0p1
6.1
6.2
7.0
8.1
8.2
8.2-emv
9.0
0
0.5
1.0
1.5
(mm)

Changes in GEANT4 releases (I)

GEANT4 2.0

- Bug fixed in the multiple scattering.
- The nuclear size correction maybe not well adapted for electrons. A fix will come soon.

GEANT4 3.0

- Bug fixed in MultipleScattering: there was an error in computation of the transport cross section, the cross section was too small for low energy (below few MeV for electrons).

GEANT4 4.1

- **New parametrisation for angle distribution.**
- Modified boundary algorithm and some other minor fixes. Improvements and performance optimisation.

GEANT4_5.0

- **Bug fix in PostStepDoIt() for lateral displacement.**
- **Corrected angle distribution and fixes in the boundary algorithm.**
- This new parameterisation improves the ~100 MeV proton scattering.

GEANT4_5.1

- Important modifications in Multiple Scattering (both in default classes and STD version):
  - **new algorithm to reduce the step dependence**
  - **new sampling for the geometrical path-lengths.**
  - Introduced base class G4VMultipleScattering.

Changes in GEANT4 releases (I)

GEANT4 5.2

• **IMPORTANT** change in the angle distribution for muons/hadrons: **The width of the central part now corresponds to the value can be computed from the HighLand formula** (no change of this kind for e+/e-) --> small change in the width for low to medium energy (protons - 1 MeV - few hundred MeV) **but change up to 20 -25 % for high energy**.

• minor correction in the angle sampling algorithm, affects e+/e- too --> small change for very small and very big stepsize/range values.

• Fixed misprint at Tev energies.

• Fix minor problem in nuclear form-factor calculations

GEANT4 6.0

• Standard electromagnetic processes now adopt a **new design based on a model approach** for energy loss and multiple scattering.

• Added methods to define energy range for multiple-scattering table and to change the energy range of the model.

• **New Tuning of multiple scattering model**

• **Fixed problems for width and tails of angular distributions**.

• **Fixed numerical error for small stepsize in G4MscModel** (z sampling).

• **Bugfix in G4VMultipleScattering::AlongStepDoIt() and added check truestep <= range in G4MscModel**.

• Set highKinEnergy back to 100 TeV for multiple scattering.

• Set number of table bins to 120 for multiple scattering.

Changes in GEANT4 releases (I)

GEANT4 6.1

• Bug fixes in model variant of multiple-scattering; simplified calculation of energy dependence of internal parameters.

• **G4MscModel: corrections to path length conversion and theta angle.**

GEANT4 6.2

• **Changes in G4MscModel: t->z and z->t transformations** (true length to geometrical length and back) have been rewritten. The purpose is to reduce the step-size dependence of results, which was mainly connected with simulation of multiple scattering of low energy particles. It will affect the resolution of sampling calorimeters.

• **Change in the angular distribution for e+/e-: correction to the Highland formula for the central part of the distribution.**

GEANT4 7.0

• **Changes in the angle distribution (slightly modified Highland formula for the width of the central part, changes in the numerical values of some other parameters)** ---> approximately step independent distribution.

• Correction in SampleCosineTheta in order to avoid numerical precision problems at high energy/small step.

• Fix precision problem for very high energy ions in gases (or with small stepsize) has been solved in G4MscModel.

Changes in GEANT4 releases (I)

GEANT4 8.0

- **Major changes** have been introduced concerning the Multiple Scattering process:
- To improve the behaviour of low energy particles (electrons in particular, but affecting also hadrons), **the Multiple Scattering now limits the step size for the particles**. This restriction is undertaken using several criteria, and is applied systematically in all volumes and materials.
- In addition a model of the **correlation between lateral displacement and final direction** has been implemented (see the Physics Reference Manual for further information).
- As a result, **most physical observables become more** stable when varying production cuts (i.e. less 'cut dependent').
- There is a corresponding cost, **a CPU-time penalty**, when utilising the same value of the production thresholds. This penalty can be significant, depending on the user's setup and the cut values. For many use cases the increased stability will allow the choice of higher production thresholds, recovering computing performance while maintaining physics performance.
- To enable the user to investigate its benefits, a **mechanism is provided to deactivate this step limittion.** The new method, MscStepLimitation(bool) of G4MultipleScattering disables these new step limitations.
- In addition, in order to help the transition, the old version is available for this release 'frozen' in the class G4MultipleScattering71.
- Several examples (in extended/electromagnetic) provide sample physics lists which use this older version.
- G4MscModel:
    - Updated version: now taking into account **theta-phi correlation in the final state**.
    - Nuclear size correction is removed; it is now included in the tabulated cross section values for Tkin > 10 MeV.
- G4MultipleScattering71, G4mscModel71: new classes corresponding to the old frozen version of the multiple-scattering algorithms included in release 7.1.p01. Default facrange = 0.2.

Changes in GEANT4 releases (I)

GEANT4 8.1

- **Some improvements** are introduced to multiple scattering. As a consequence of these changes in the model, the following applies in this release:
  - **the simulation of the back-scattering is improved**;
  - **the scattering in very thin layers is better than the one in version 8.0**;
  - **the tail of the angular distribution is now material dependent;**
  - **the visible energy in sampling calorimeters is less sensitive to the value of the production threshold.**
- Step limit calculation moved to model part G4UrbanMscModel.
- Changed values of data members 'tkinlimit', 'factail';
- Providing possibility of reinitialization of 'facrange' and 'steppingAlgorithm' parameters between runs
- Changed default value of 'facgeom' (4 -> 3.5)
- Added set function for data member factail; z sampling by default.
- G4MscModel renamed G4UrbanMscModel:
- Changed the value of the parameter theta0, improved scattering in thin layers.
- Changes in ComputeTruePathLengthLimit(): modified 'scaling' of facrange for high energies, data member tlimitmin = max(lambda0/25, 5 nm).
- Changes in SampleCosineTheta(), **changed tail of angular distribution**.
- Removed some data members and code cleaning; revised z sampling.
- Now computing transport cross section and not mfp.
- Bug fix in the SampleCosineTheta() method and fixed a problem of non-initialized variable.
- Make stepping algorithm be active for ions by default.
- G4MscModel71: now computing transport cross section and not mfp.

Changes in GEANT4 releases (I)

GEANT4 8.2

• **Some improvements were introduced to multiple scattering, which provide improved results for large angle scattering; better particle transport near geometry boundaries and less cut dependence for sampling calorimeters** (see details in Physics Reference Manual). **Adjusted to MuScat experiment data.**

• **A new class G4hMultipleScattering has been created to provide faster simulation of hadron transport**. This class uses the same multiple scattering model configured to reduce step limitation. It is used for hadrons and ions in most physics lists.

• The change in response of calorimeters, due to the revision of the multiple scattering process (in its default configuration) is expected to be less than 1%. Larger differences are seen in the revised configuration, which does not apply most step limitations for electons and that is used in the QGSP_EMV physics list.

• Set default skin=1 only for e+-, for all other particles default skin=0.

• G4UrbanMscModel:

  • Fixed initialisation in ComputeTruePathLengthLimit(), fixed stepmin=1.e-6*mm.

  • Fixed problem of genreation of NaN inside method SampleCosineTheta(). theta0 parameter for SampleCosineTheta() is computed in a public function ComputeTheta0().

  • Adopting new approach for accessing geometrical safety, according to recent developments for parallel navigation.

  • No z sampling in ComputeGeomPathLength() by default.

Changes in GEANT4 releases (I)

GEANT4 8.2 (cont)

- G4UrbanMscModel:
  - **Step limitation algorithm has been modified**:
    - Minimum steplimit in 8.1: tlimitmin = max(lambda/25, 5 nanometer)
      Now: tlimitmin = max(lambda/25, 1.01*stepmin)
      where stepmin ~ lambda elastic.
    - Introduced possibility to have extreme small step(s) before boundary crossing (feature not active by default); it can be activated by setting the data member skin to a non-negative value; steplimit = stepmin, if the distance to the boundary (in the original direction) is smaller than skin*stepmin. The parameter skin is set to 1 by default.
    - The step restriction is weaker for particles with higher energy, i.e., bigger effective facrange value is used in this case; in 8.0/8.1 this scaling depended on Tkin, in the new version the scaling depends on lambda, giving smaller material dependence.
  - **Angular distribution has been changed**:
    - Single/plural scattering for step <= stepmin (in this case t = z + no lateral displacement).
    - Parameter theta0 has been (sligtly) modified.
    - The tail of the distribution has been modified, now the parameter describing the tail is material (i.e. Z) dependent.

Changes in GEANT4 releases (I)

GEANT4 8.3

- In all lists for electro-magnetic physics, the "skin" for multiple-scattering on boundaries is set to zero, meaning that **no computation of the linear distance to the geometrical boundaries is made by the multiple-scattering model**.
- G4UrbanMscModel:
  - Fix in the single scattering code for heavy particles, now the code can be used with skin=1 e+/e- and for heavy particles as well.
  - Added protections against NaN values in two places: sampling of theta when tau=0 in lateral displacement, and in method ComputeTrueStepLength() for the case of zero true length.
  - **Stepping algorithm changed for skin=0**, now there are 3 stepping modes:
    1. Stepping similar to that performed in release 7.1;
    2. skin=0 - designed for high energy simulations with or without magnetic field;
    3. skin=1 - designed for 'precision' simulations without magnetic field.
  - If skin>1, perform small steps with single scattering before and after boundary the boundary. The step is reduced before boundary for geomlimit less than geombig only.
  - Use tPathLength inside ComputeStep() instead of geombig.
- G4MultipleScattering, G4hMultipleScattering:
  - Use skin parameter from the base class (default skin=0).
- Use G4hMultipleScattering for muons and removed extra printouts
- Use default multiple-scattering setup in G4EmStandardPhysics72.
- **Use skin=0 (no use of ComputeStep() in multiple-scattering) in G4EmStandardPhysics** and G4EmStandardPhysics71.

Changes in GEANT4 releases (I)

GEANT4 9.0

• **An enumerator of step limitation algorithms of the multiple-scattering process has been introduced**. It replaces a boolean value . The step limitation types are:

- Minimal - equivalent to the original algorithm, as implemented in Geant4 7.1 and earlier releases.
- UseSafety - the current default, which makes use of the geometrical safety
- UseDistanceToBoundary - the most advanced, recommended for accuracy in the cases where no magnetic field is set.

• As in releases 8.0 to 8.2, the minimal option (which used to be called 'no step limitation') results in fewer steps, and typically provides less stability than the other options.

• **The structure of UI commands was changed**: a new directory /process/msc contains all commands for multiple scattering. New UI commands are added to control the parameters of the Multiple Scattering process:

- /process/msc/Skin
- /process/msc/RangeFactor
- /process/msc/GeomFactor
- /process/msc/StepLimit
- /process/msc/LateralDisplacement.

The interface to G4EmProcessOptions is modified to be consistent with this change. As a result, the possibility to change the values of parameters between runs is now extended to all parameters which can be defined via the UI.

• Reorganized methods for setting parameters of G4UrbanMscModel providing a possibility to change parameters between runs.

Changes in GEANT4 releases (I)

GEANT4 9.0 (cont)

- G4UrbanMscModel:
  - Reorganized initialisation and ComputeTruePathLengthLimit() method using G4MscStepLimitType enumerator to choose step limit algorithm.
  - **Optimisation of step limitation for skin>0 (about 5% CPU save)**.
  - Use G4SafetyHelper for computation of safety and distance to the boundary; removed pointer to G4Navigator.
- G4VMultipleScattering:
  - **Speedup code** by adding implementation of methods AlongStepGetPhysicalInteractionLength() and PostStepGetPhysicalInteractionLength().
  - **Cleanup comments and reorganized code for easier reading**; moved short methods to inline; added method to set multiple-scattering parameters.
- Added class G4MscStepLimitType

Summary

- GEANT4 multiple scattering showed 20% discrepancy with L3 LEP I 45 GeV muons
  - A nuclear size effect correction was added in 1999 (version 1.0) and it matched data from single material experiments and L3
- Since them it has suffered lots of adjustments, that have moved it in the range of +- 40%
- Since version 7.0 it looks more stable
- In version 8.2 readjusted to fit new data from MuScat experiment
  - 7% different w.r.t. to ’99 adjustment