GeantV – New Electromagnetic Physics Modelling

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Outline

- Introduction, motivation
- Reviewed models for electron/positron interactions
  - General remarks
  - Multiple scattering
  - Bremsstrahlung, ionisation
- First hints toward EM shower simulation with GeantV
- Conclusion and plans

Introduction, motivation

- **Electromagnetic shower simulation:**
  - the main goal is to be able to simulate EM showers with GeantV in case of HEP applications
  - electron/positron and gamma interactions focusing on HEP energy range
  - a good opportunity to review the models currently used in Geant4

- **Start with electron/positron interactions:**
  - they are tricky:
    - energy loss processes (continuous-discrete; production threshold dependence)
    - elastic scattering (multiple scattering)
    - they are the most complex from the physics framework point of view
  - their importance:
    - electron is the most frequently produced particle in HEP detector simulations
    - the result of the simulation (visible energy, resolution) strongly depend on the accuracy of the models

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Reviewed models for e-/e+ interactions: general remarks

- **Models have been reviewed/modified at different levels:**
  - theoretical level:
    - some of the models have been re-derived from scratch (multiple scattering)
    - others have been changed only partially (LPM effect) or not (ionisation)
  - implementation level:
    - all the models have completely new implementation (also true for the material description)
    - more “vector-friendly” and efficient final state sampling algorithms
- **Some modifications have already been done in Geant4:**
    - all the theoretical improvements
    - the multiple scattering model has been implemented in Geant4
- **What is currently available in GeantV:**
    - bremsstrahlung and ionisation has been fully implemented and used in the GeantV physics list
    - the EM part of the physics framework for “normal” EM processes, models
- **I’m both a Geant4 and GeantV (physics) developer:**
    - you will see results obtained both with Geant4 and GeantV (obtained by using exactly the same physics settings)
    - when I say “we” or “our”: I refer to either Geant4 and/or GeantV

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Reviewed models for e-/e+ interactions: multiple scattering

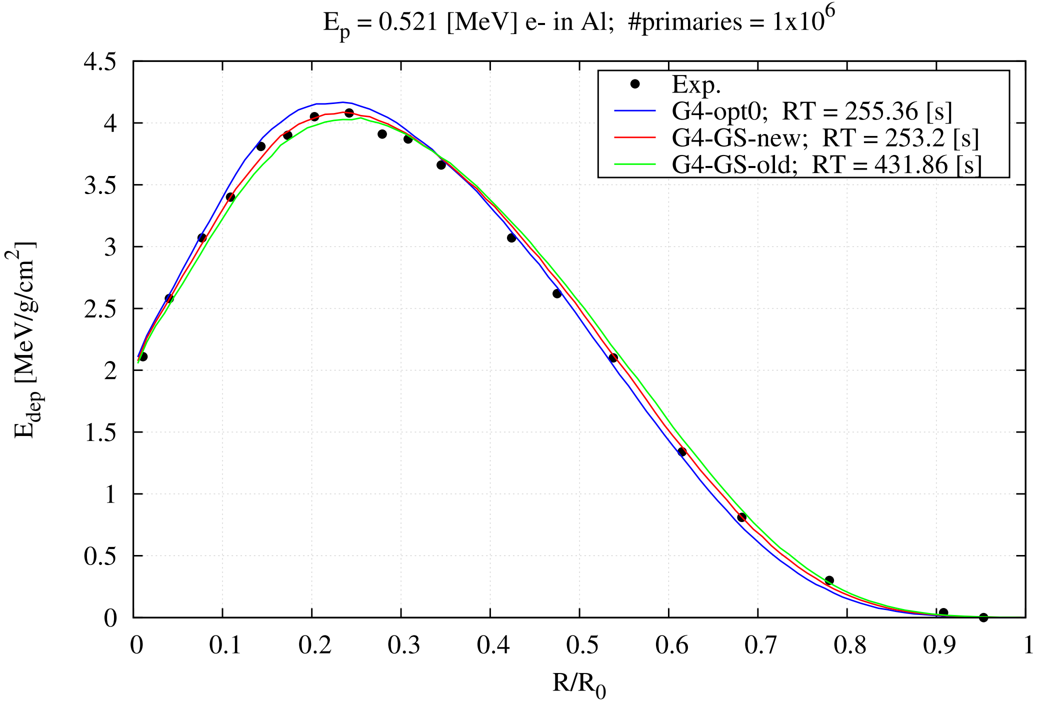
- **The original Geant4 Goudsmit-Saunderson model:**
  - was intended to be the multiple scattering model developed by Kawrakow and Bielajew[*]
  - missed some of the most important points of the theoretical model
  - the implemented model was very inefficient, showed some artefacts in the angular distributions

- **The new version (see more):**
  - incorporates all the ingredients of the theoretical model, that has been re-derived from scratch
  - including one of the most important part: a variable transformation that makes the precomputed angular distributions extremely smooth
  - this made possible to apply very fast and accurate sampling algorithm to obtain the angular deflection (that is the most expensive and important part of a multiple scattering model)
  - new stepping algorithm has also been implemented
  - the old version of the model was replaced with a new one (in Geant4 10.2.beta only the name has been kept) and this new version has been continuously improved

* [S.Goudsmit,J.L.Saunderson, PR 57(1940)24-29; I.Kawrakow,A.F.Bielajew, NIMB 134(1998)325-336;

Reviewed models for e-/e+ interactions: multiple scattering

- **The effects of the new treatment of the angular distributions:**
  - significant speed-up (~40% RT reduction in this example)



* [**Exp**: G.J.Lockwood et al. Sandia report SAND79-0414.UC-34a, February 1987; Geant4 electromagnetic/TestEm11

Reviewed models for e-/e+ interactions: multiple scattering

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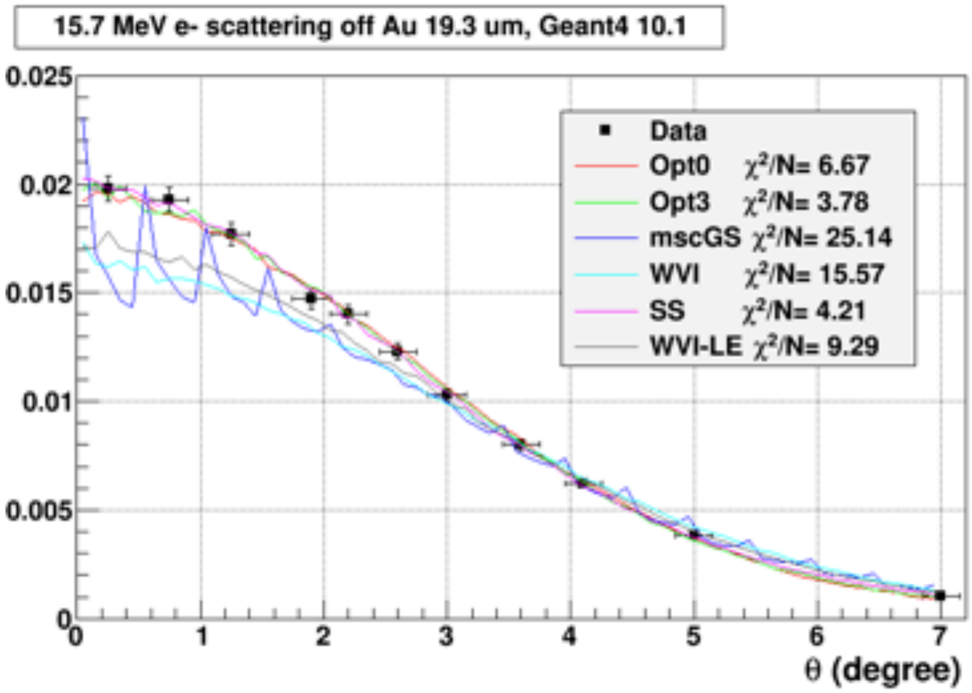
  - significant speed-up
  - **old**: sampling artefacts



* [**Exp**: A.O.Hanson et al., Phys. Rev. 84(1951)534 ; Geant4 electromagnetic/TestEm5

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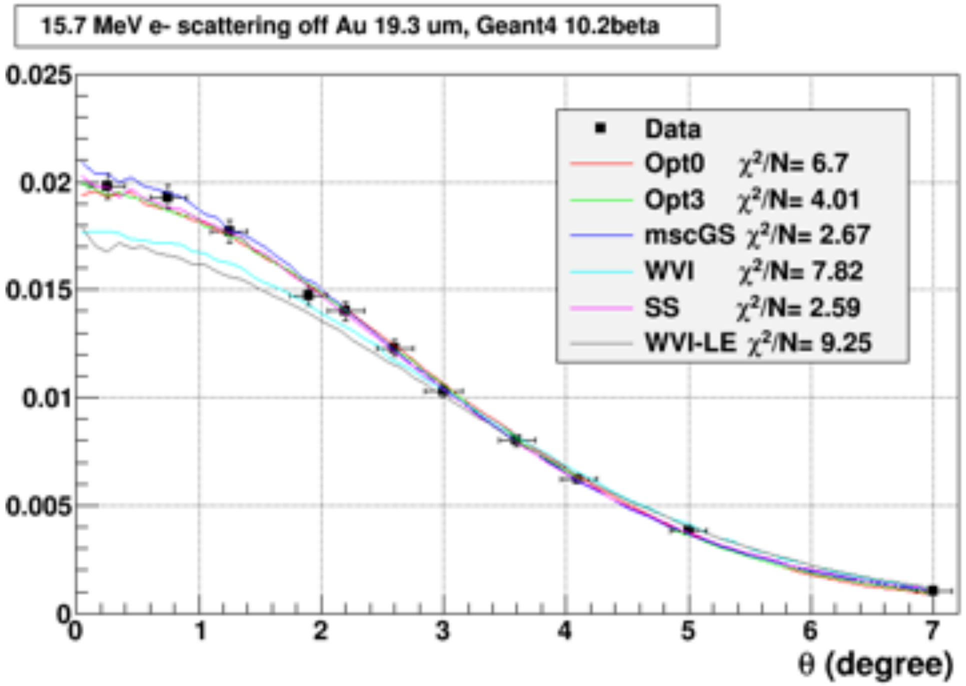
  - old : sampling artefacts
  - **new**: no any sampling artefacts



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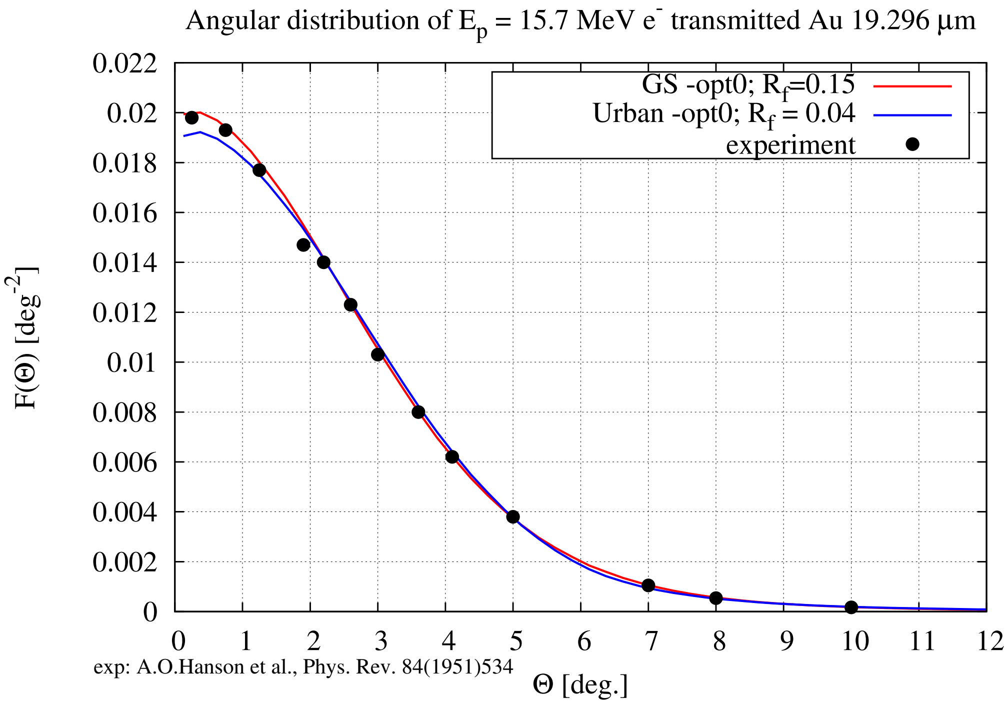

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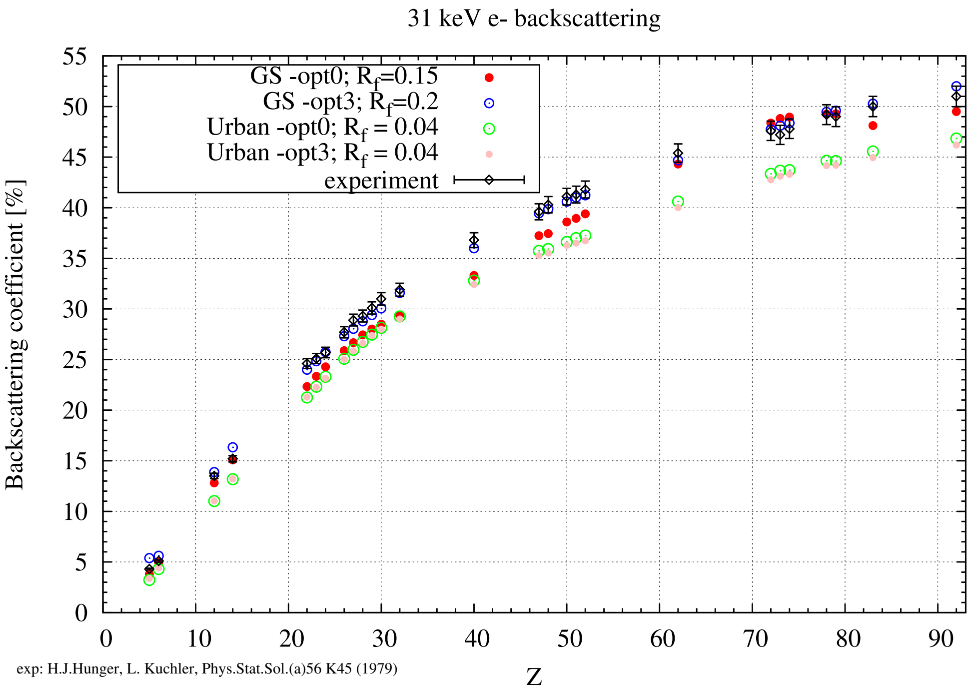
- **The effect of the new stepping algorithm (*):**
  - more accurate longitudinal and lateral distributions
  - more accurate stepping



* [I.Kawrakow,A.F.Bielajew, NIMB 142(1998)253-280

Geant4 electromagnetic/TestEM5

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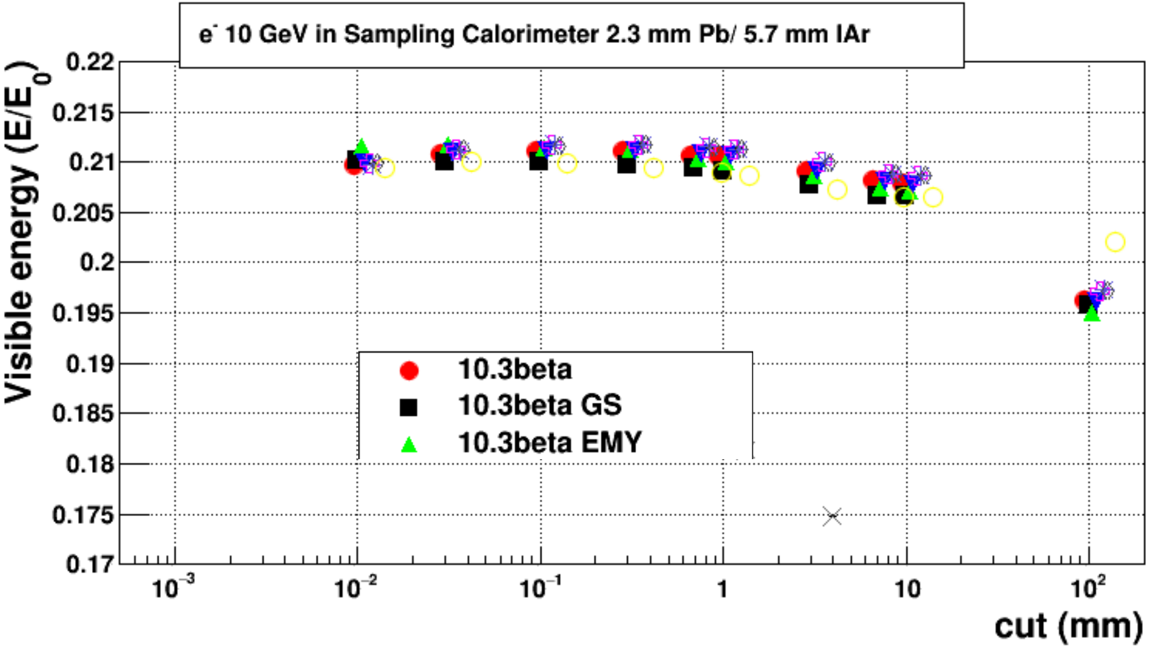

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Geant4 electromagnetic/TestEM3

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Simplified ATLAS barrel calorimeter: 10 [GeV] e^-, cut 1 [mm]

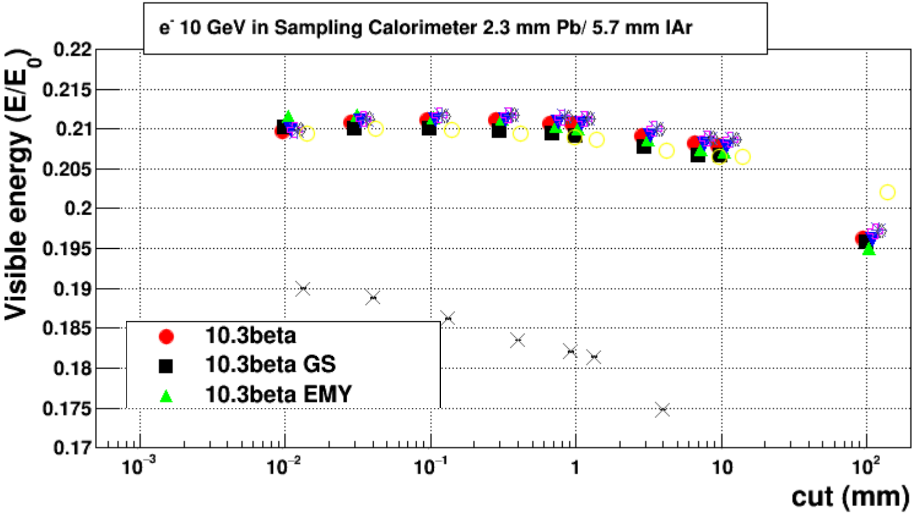
	Geant4 EM-std-opt0	Geant4 EM-std-GS	GS/opt0
#gammas	5.08E+03	5.08E+03	1
#electrons	8.7E+03	8.71E+03	1.001
#positrons	539	538	0.998
#charged steps	35594.2	30131.3	0.846
#neutral steps	36433.9	36650	1.006

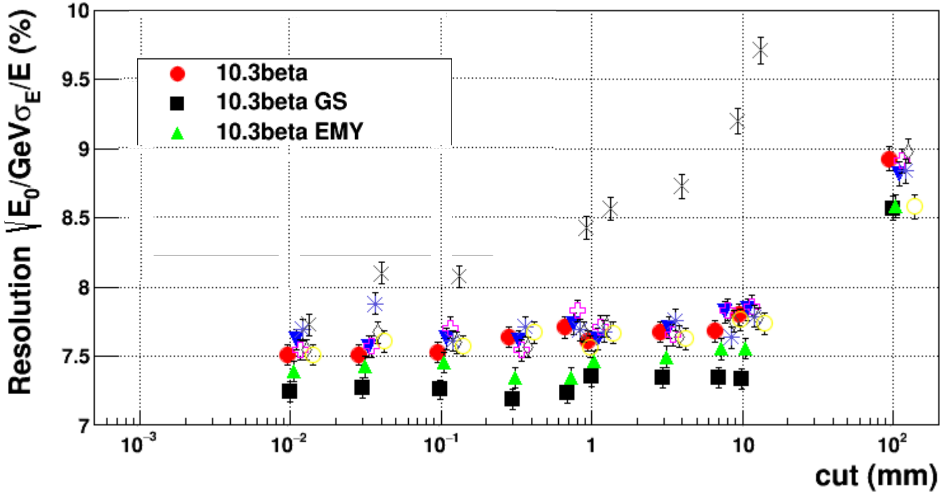
* [I.Kawrakow,A.F.Bielajew, NIMB 142(1998)253-280

Geant4 electromagnetic/TestEM3

Reviewed models for e-/e+ interactions: multiple scattering

- **Open problem:**
  - more accurate multiple scattering models/stepping-settings result in underestimated resolution
  - energy loss fluctuation model and its stability against varying step lengths must be investigated





Geant4 electromagnetic/TestEM3

Reviewed models for e-/e+ interactions: multiple scattering

- **To do (regarding the physics model):**
  - study possibilities of introducing corrections: e.g. the currently used angular distributions are computed based on scattering on exponentially screened Coulomb potential (Mott correction)
  - review of Geant4 energy loss fluctuation model, investigate alternatives

- **To do (regarding GeantV):**
  - integration of multiple scattering into the new physics framework (current step)
  - study possibilities of track level vectorisation of the model

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Reviewed models for e-/e+ interactions: bremsstrahlung

- **Low energy [1 keV - 1 GeV]:**
  - the model based on NIST[1] bremsstrahlung DCS data tables available for electron energies [1 keV - 10 GeV] and for [Z=1-92]
  - includes contributions both from photon emission in the field of the nucleus and in the field of atomic electrons
    - analytical, extreme relativistic DCS above 50 MeV
    - DCS from PWA calculations by Tseng&Pratt[2] at below 2 MeV
    - spline interpolation between 2-50 MeV
  - considered to be the most reliable theoretical set of DCS for bremsstrahlung photon emission

- **DCSs must be handled numerically:**
  - completely different treatment than in Geant4:
    - thanks to (a chain of) variable transformations fast and accurate photon energy sampling is **possible** (including dielectric suppression effect correction as well)
    - no need of rejection that involves multi-dimensional (bicubic spline) interpolation
    - emitted photon energy can be sampled ~(1.7-3.4)x faster compared to the current Geant4 algorithm

[1 S.M.Seltzer, M.J.Berger, NIMB 12(1985)95-134; ADNDT 35(1986)345-418]   [2 H.K.Tseng, R.H.Pratt, PRA 3(1971)100-115]

Reviewed models for e-/e+ interactions: bremsstrahlung

- **High energy [1 GeV - 100 TeV]:**
  - the model based on an improved version[1] of the Bethe-Heitler[2] bremsstrahlung DCS
  - both relativistic and ultra relativistic models are implemented
  - Landau-Pomeranchuk-Migdal(LPM)[3] suppression is included in the ultra relativistic case under the complete screening approximation together with the dielectric suppression[4] according to Migdal's theory[5]
  - the relativistic model contains only the dielectric suppression correction
  - very different treatment than in Geant4:
    - thanks to (a chain of) variable transformations fast and accurate photon energy sampling is possible
    - no need of rejection that involves some non-trivial suppression function evaluations
    - emitted photon energy can be sampled ~(2.1-2.8)x faster compared to the current Geant4 algorithm

[1 Y.S.Tsai, RMP 46(1974)815] [2 H.Bethe,W.Heitler, In Proc. of the Roy. Soc. of London A, 146(1934)83-112]
[3 L.D.Landau, I.D. Pomeranchuk, Dokl.Akad.Nauk SSSR 92(1953)35; 92(1953)735] [4 M.L.Ter-Mikaelian, Dokl.Akad.Nauk SSSR 94(1954)1033]
[5 A.B.Migdal Phys.Rev. 103(1956)1811]

Reviewed models for e-/e+ interactions: bremsstrahlung

- **Suppression effects[1]:**
  - when high energy(ultra relativistic) electron emits low-energy photons by bremsstrahlung, the longitudinal momentum transfer between the electron and nucleus can be very small
  - due to the uncertainty principle, the momentum transfer must take place over a long distance (formation length)
  - the emission of bremsstrahlung photon can be suppressed if anything happens with the electron or photon along this distance that can disturb the coherence

- **the Landau-Pomeranchuk-Migdal effect[2]**
  - deflection due to multiple scattering of electrons along the formation length
  - interference of bremsstrahlung amplitude from before and after the scattering
  - photon emission can be suppressed if the average multiple scattering angle is higher than the typical photon emission angle

- **the dielectric suppression effect**
  - phase shift in the photon wave function due to Compton scattering
  - coherence is lost if the phase shift, accumulated along the formation length, is high enough
  - (when the photon energy approaches zero, this suppression removes the infrared divergence of the Bethe-Heitler cross section)

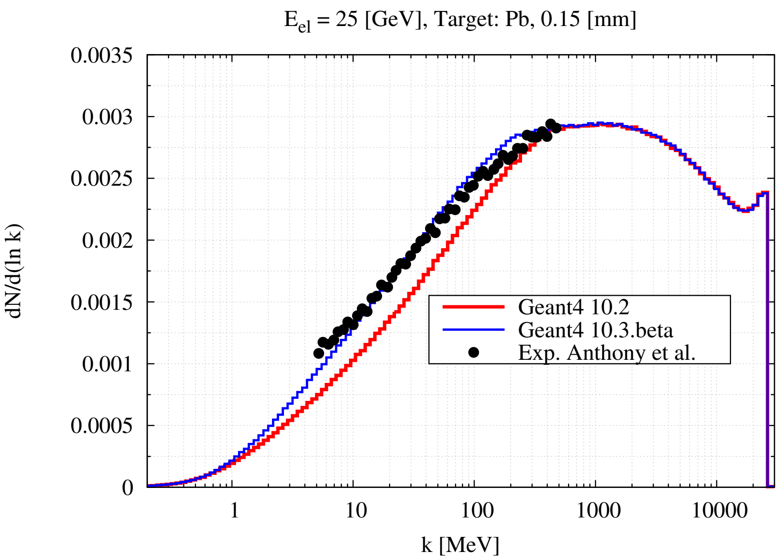
[[1] P.L.Anthony et. al, Phys.Rev.D. 56(1997)1373; S.Klein; RMP 71(1999)1501]

[[2] L.D.Landau, I.D. Pomeranchuk, Dokl.Akad.Nauk SSSR 92(1953)35; 92(1953)735; A.B.Migdal Phys.Rev. 103(1956)1811]

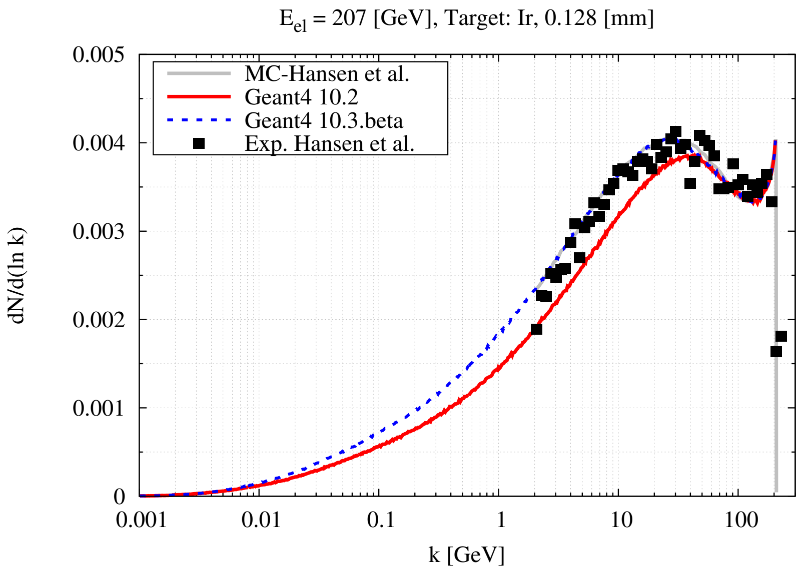
[[3] M.L.Ter-Mikaelian, Dokl.Akad.Nauk SSSR 94(1954)1033]

Reviewed models for e-/e+ interactions: bremsstrahlung

- **Incorporation of the Landau-Pomeranchuk-Migdal effect was modified:**
  - there were some theoretical inconsistencies in the computation of suppression functions that have been corrected
  - the new model gives better agreement with the available experimental data (in Geant4 10.3.beta)



[**Exp:** P.L.Anthony et. al, Phys.Rev.D. 56(1997)1373]



[**Exp:** H. Hansen et. al, Phys.Rev.D. 69(2004)032001]

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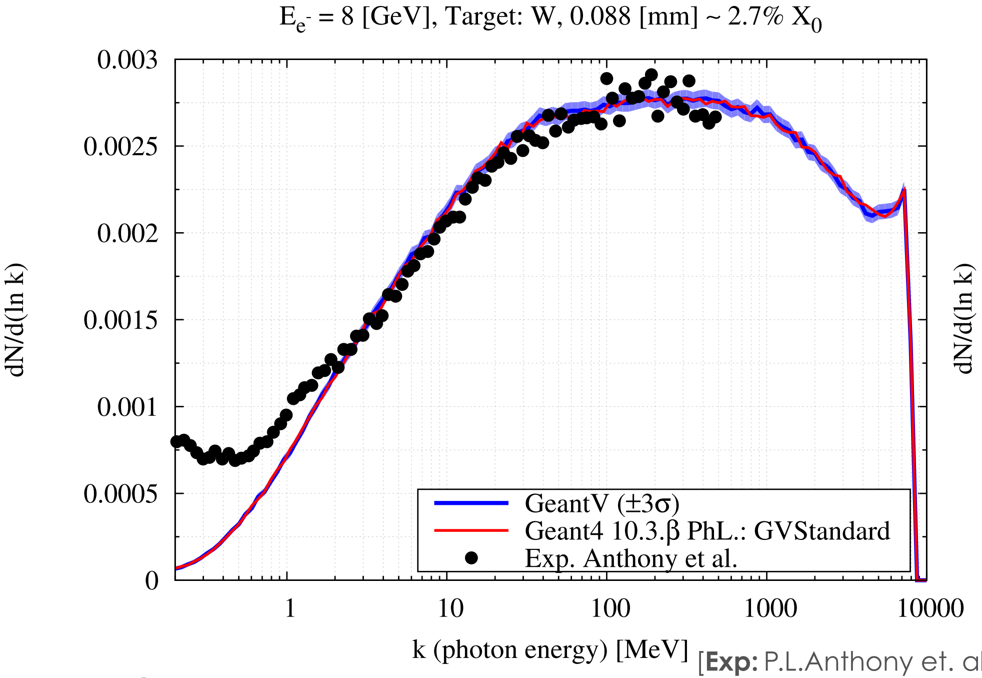
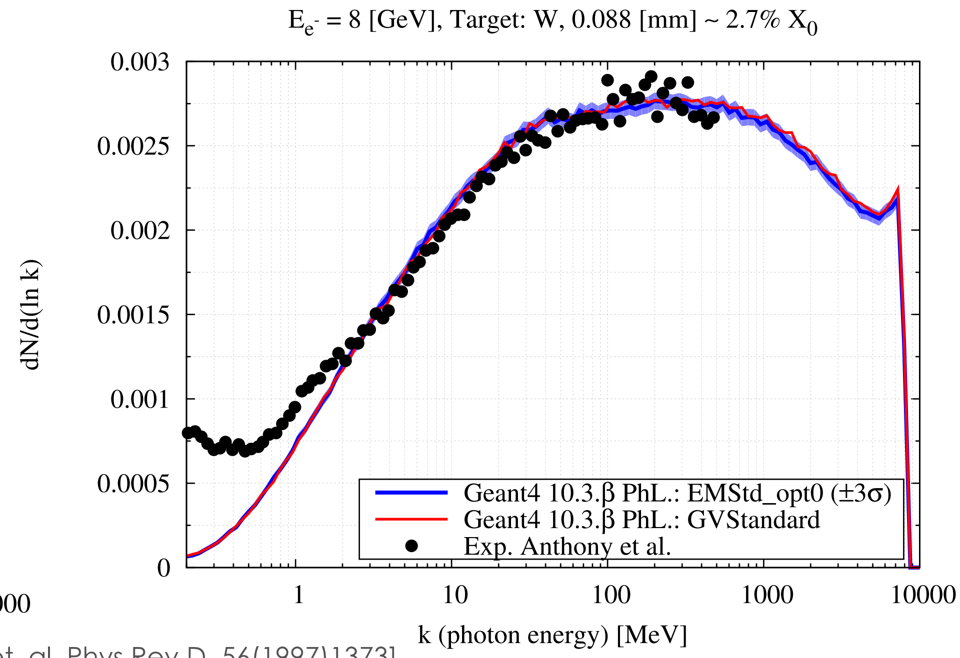
First hints toward EM shower simulation with GeantV

- **What is currently available in GeantV:**
  - a new general physics framework (as it was presented earlier: Alberto's talk)
  - the EM part of the physics framework for "normal" EM processes, models is fully implemented together with the general parts that are necessary (e.g. building, handling lambda tables)
  - models and processes for describing bremsstrahlung and ionisation have been fully implemented and used in the current GeantV physics list (multi threaded)
  - makes possible to perform physics simulation and one-to-one comparison with Geant4 (with the limited variety of physics processes)
  - time to see some examples Misi!

First hints toward EM shower simulation with GeantV

Modelling photon spectrum with GeantV





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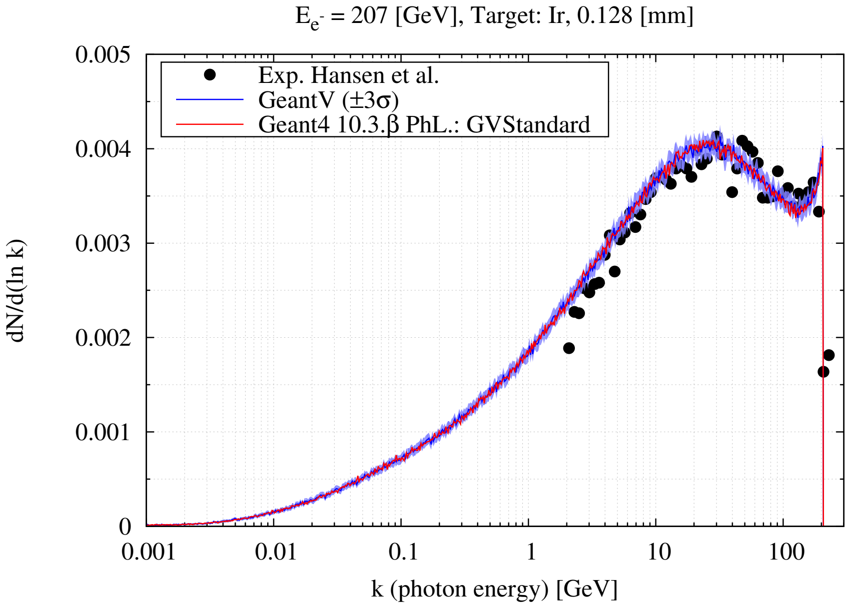
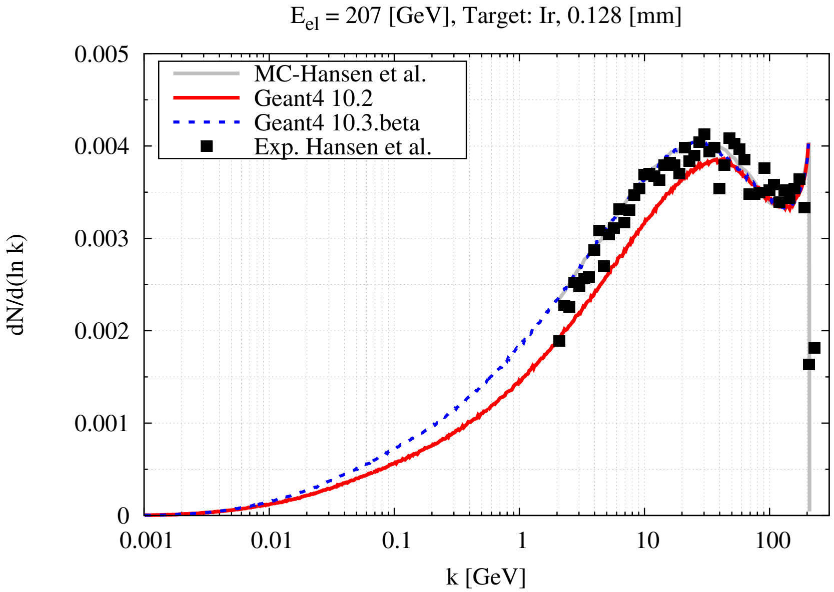
Modelling photon spectrum with GeantV





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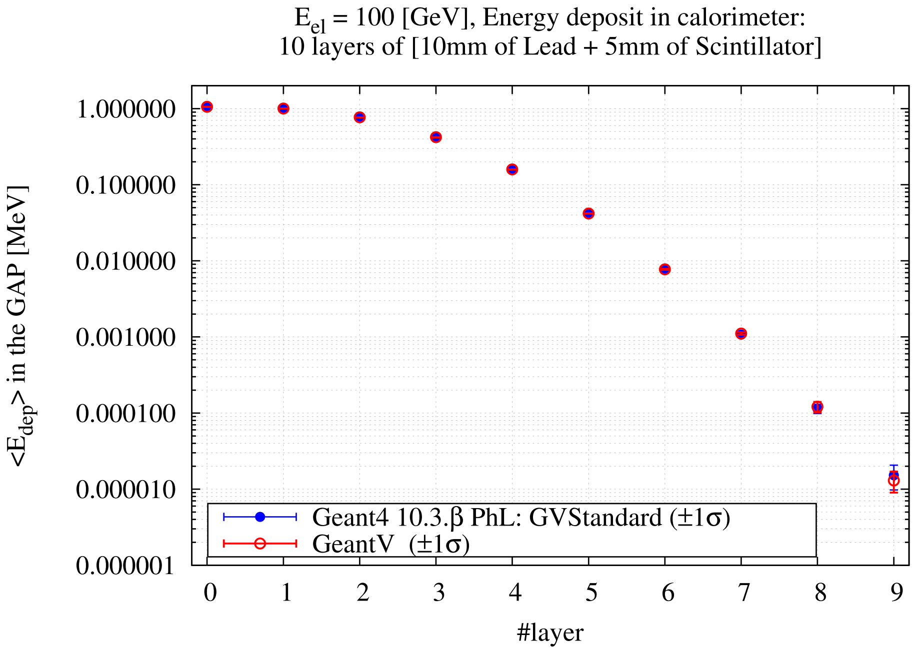
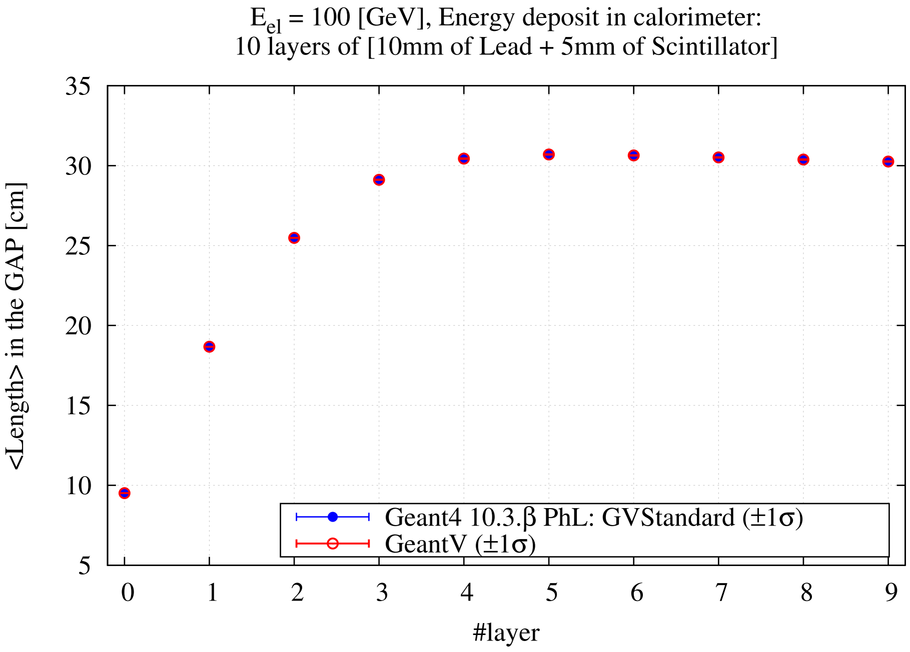
First hints toward EM shower simulation with GeantV

GeantV results on simplified calorimeter





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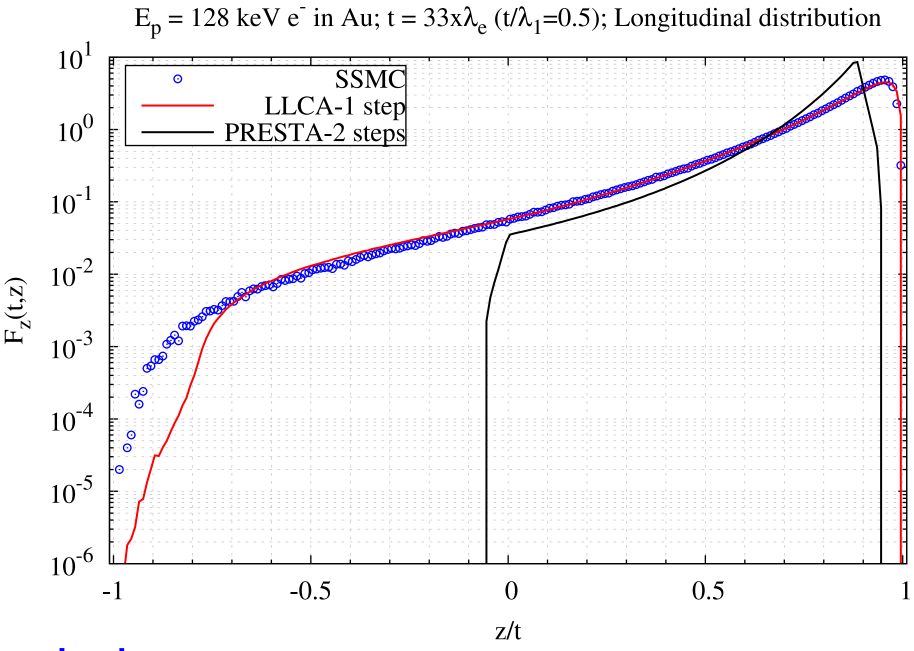
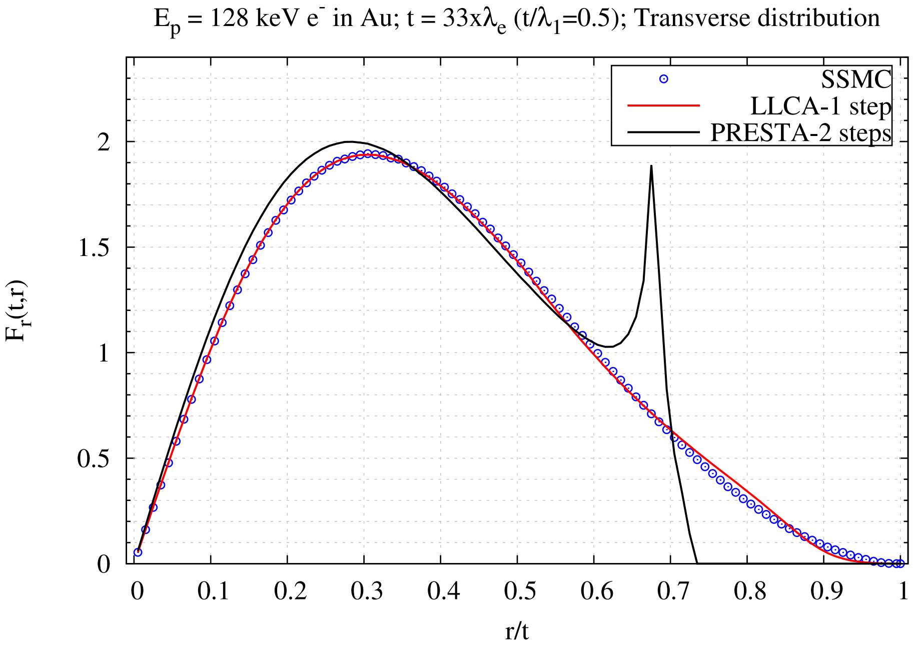
Conclusion and plans

- We have many:

Backup slides

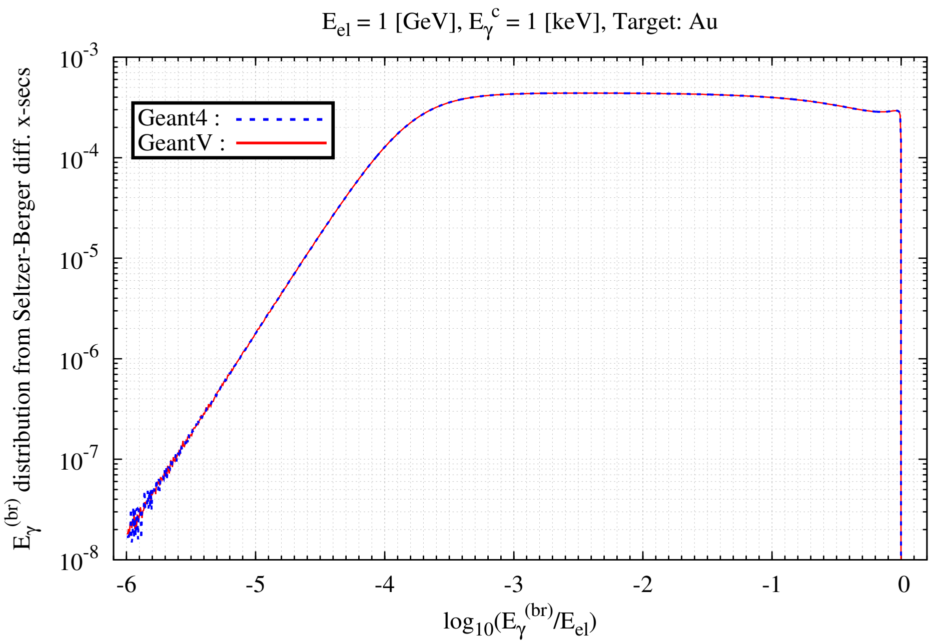
Backup: the new stepping algorithm (LLCA)

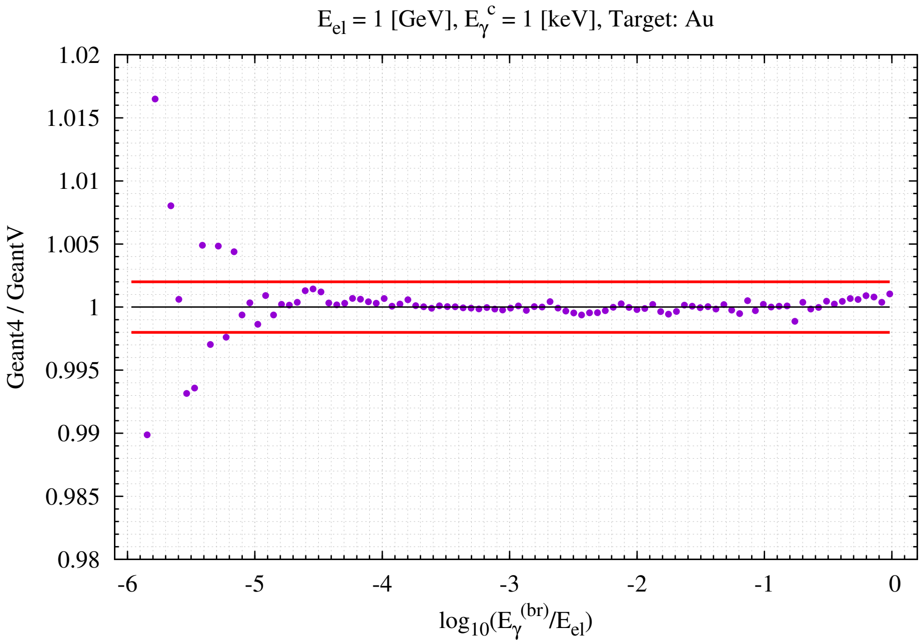




go back

Backup: low energy bremsstrahlung photon sampling





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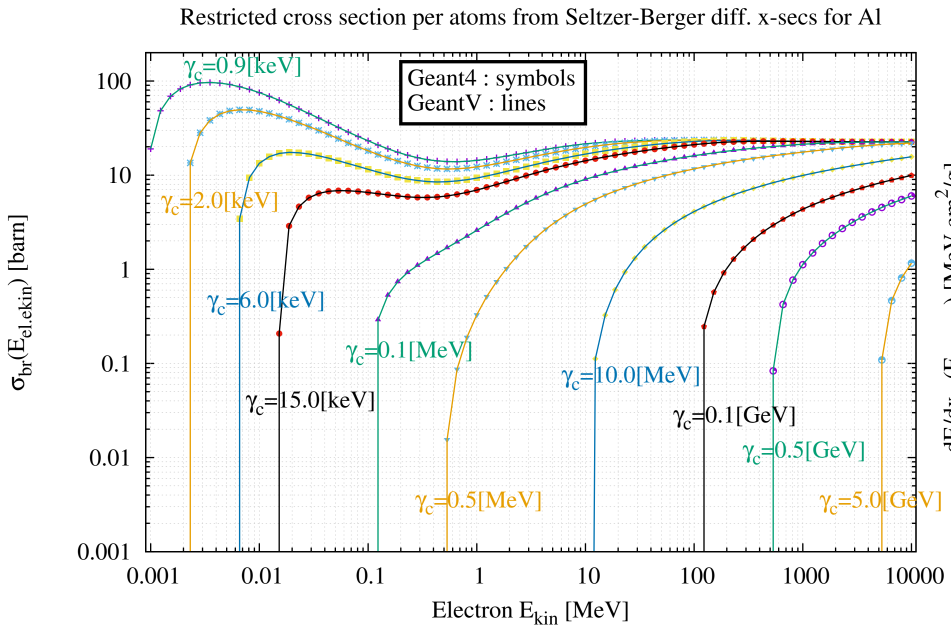
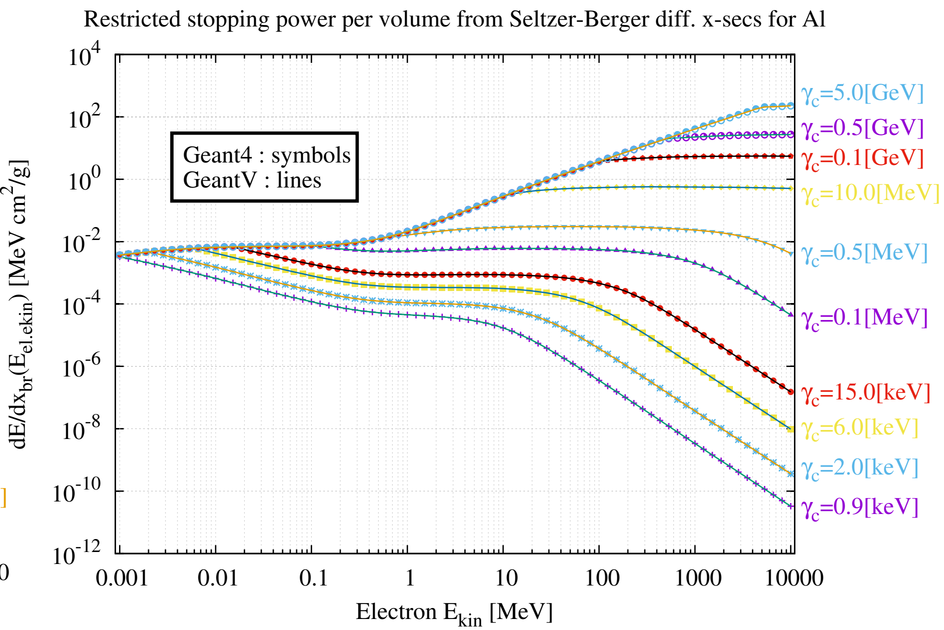
Backup: low energy bremsstrahlung restricted x-sections and stopping power





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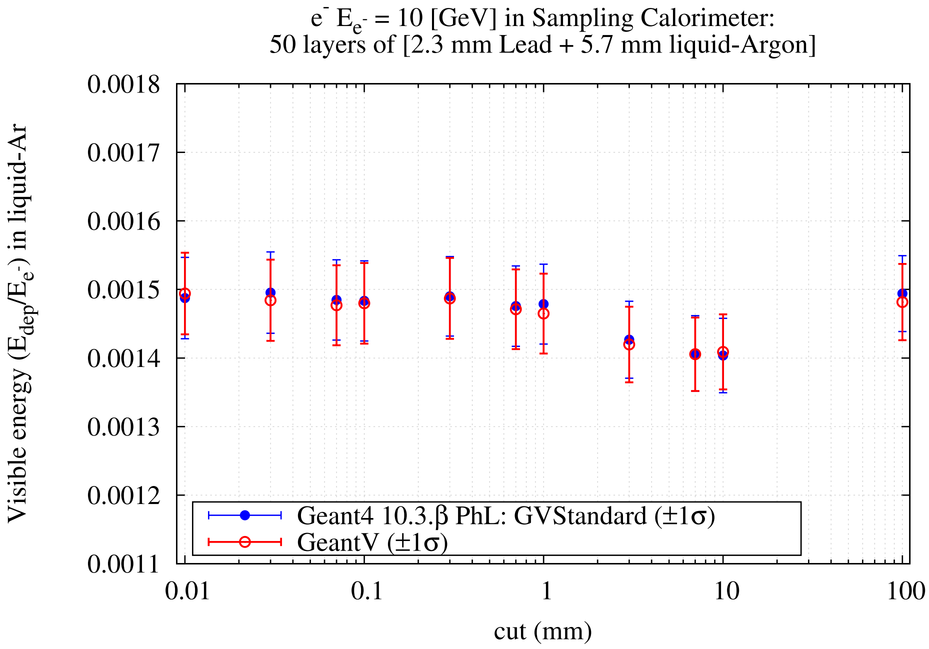
Backup: (for us)

	GeantV	Geant4	GeantV/ Geant4
mean #steps per event	1192.065582	1191.727026	**1.000284**

Backup: (for us)

GeantV results on ATLAS simplified barrel calorimeter



Backup: (for us)

GeantV results on ATLAS simplified barrel calorimeter (cut = 1 mm)

Geant4-PhL: EMStd-opt0

```
 Number of events processed : 10000
 User=1140.59s Real=1141.68s Sys=0.79s

-------------------------------------------------------------
 material       Edep            RMS            total tracklen

 Lead        : 7.7637 GeV :   73.18 MeV   5.45 m +-5.37cm
 liquidArgon: 2.1062 GeV :       51 MeV   10.4 m +-26   cm

-------------------------------------------------------------
 Beam particle e-   E = 10 GeV
 Mean number of gamma        5.08e+03
 Mean number of e-           8.7e+03
 Mean number of e+           539
 Mean number of charged steps   35594.2
 Mean number of neutral steps   36433.9
-------------------------------------------------------------
```

Geant4-PhL: GVStandard

```
 Number of events processed : 10000
 User=21.75s Real=21.76s Sys=0.01s

-------------------------------------------------------------
 material       Edep            RMS            total tracklen

 Lead        : 40.783 MeV :   15.27 MeV   3.06 cm +-1.14 cm
 liquidArgon: 14.786 MeV :   5.828 MeV   7.53 cm +-2.96 cm

-------------------------------------------------------------
 Beam particle e-   E = 10 GeV
 Mean number of gamma        49.6
 Mean number of e-           3.19
 Mean number of e+           0
 Mean number of charged steps   87.7605
 Mean number of neutral steps   4392.92
-------------------------------------------------------------
```