ENERGY LOSS BY IONIZATION : GEANT 4 STATUS

Results about the energy loss by ionizing particles from Geant4 simulations are sometimes confusing. The purpose of this short note is to compare several calculations in order to clarify what Geant 4 actually does.

"Models" are (and will be referred as) :

1. *Geant 3 and Geant 4* :
   We use the "examples/extended/electromagnetic/TestEm3/" code coming with the standard distributions. This package was recommended by Geant4 people for this kind of testing procedure.
   We ran 5000 events for each calculation.
   The Geant3 version is 3.21 and the Geant 4 versions are 5.2 and 6.0.
2. *SRIM calculations :*
   Stopping and Range of Ions in Matter from J. F. Ziegler and J. P. Biersack.
   We use the SRIM-2003.20 distribution. The particle energies are limited to 5 GeV/amu and we only get the mean value of the energy loss.
   SRIM is a reference in the heavy ions community and will be taken as our reference.
3. *NIST*
   For protons only the The National Institute of Standards and Technology makes available stopping power data from *http ://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html*
4. *PDG*
   The Particle Data Group gives μ stopping power at *http ://pdg.lbl.gov/AtomicNuclearProperties/*
   The $\frac{dE}{dx}$ and range algorithms are described in D.E. Groom, N.V. Mokhov, and S.I. Striganov, "Muon stopping-power and range tables, 10 MeV–100 TeV," Atomic Data and Nuclear Data Tables 78, 183-356 (2001).
5. *BB*
   A simple calculation using the Bethe-Bloch formula. Relativistic effects are taken into account. The CsI is approximated to a single material with A=130 and Z=54.

Introduction

Energy loss by ionization is described by the well known Bethe-Bloch formula :

$$-\frac{dE}{dx} = Cz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ln \frac{2m_e \beta^2 \gamma^2}{I} - \beta^2 \right]$$

where

$C = 0.3071$	$MeV g cm^{-2}$,
z^2	is the incident particle charge,
Z, A	is the atomic number and the mass of the material, respectively.
m_e	is the electron mass,
γ, β	the special relativity parameters

A result is that for particles with same velocity, i.e. same $\gamma\beta$, the $\frac{dE}{dx}$ scales with the particle's charge z^2.
We will use this property to compare energy losses from Carbon ions, protons and muons.
For convenience, we give for each $\beta\gamma = \frac{P_{tot}}{Mass}$ the associated total kinetic energy.

Note that the formula above is written in the non relativistic case, however calculations labelled "BB" are relativistic.

For the Geant simulations, the quoted values are **mean ± rms**.
In order to get rid of the $\frac{dE}{dx}$ energy dependance, **all simulations are performed with a thickness $\Delta x = 1mm$ of CsI**. Indeed the computed values (SRIM, NIST, PDG and BB) are compared using $\Delta E = \Delta x * \frac{dE}{dx}$.
All plots are done with $\Delta x = 1.99cm$ of CsI.

RESULTS

Carbon

Table 1 shows the comparisons for Carbon nuclei. Mean values of the Geant simulations agree with SRIM with the trend to underestimate the energy loss.
However, the rms from G3 to G4 are found very different, the effect getting bigger as the ion energy increases.
It should be noted that the results are stable from G4v5.2 to G4v6.0.
Figure 1 shows an exemple on Carbon nuclei at 108 GeV (9 GeV/u) in the case of a LAT-CAL CsI log (CsI 1.99 cm thick).

Proton

Table 2 shows the comparisons for protons. The same behavior than for Carbon is found here : mean values are underestimated as the incident energy increases.
This result might not be surprising since in Geant, energy losses for ions are first calculated for protons with same $\beta\gamma$'s as for the ions, then scaled with z^2.
The point is that the rms values are stable from geant3 to geant4. It is then likely that the Geant3/Geant4 discrepency for ions comes from the fluctuation calculations.

Muons

Table 3 shows the comparisons for muons. The purpose of those calculations was to check the consistency with protons. For a given $\beta\gamma$, the plots should be the same since only electromagnetic processes are taken into account. This is pretty much the case, and Fig 3 gives an illustration with a **G4v5.2** calculation for protons and muons with $\beta\gamma = 5.167$ and for 1.99 cm of CsI.

We do not have SRIM values for μ's but on an other hand, Bethe-Bloch calculations are quite precise and in very good agreement with the Particle data Group data up to $\beta\gamma = 4.077$. At high energies, confidence should be given to the PDG values.

Geant3 and Geant4 v5.2 gives similar results, with underestimated values for the mean $\frac{dE}{dx}$ still present.

The 6.0 release gives very strange results as illustrated on figures 4 and 5. The mean $\frac{dE}{dx}$ gets even worse and the rms's are off as compared to those from G4v5.2 by a substential factor, the discrepency getting smaller with increasing incident energies.

Figures 6 shows the energy loss spectra from 20 GeV muons in a LAT calorimeter tower. Figures 7 gives the comparison between the first and the last layers.

$\beta\gamma$	Ec (GeV)	BB	SRIM	G3 v3.21	G4 v5.2	G4 v6.0
0.777	2.976	36.28	36.24	37.83±1.16	36.74±1.16	36.71±1.20
1.162	5.952	25.97	25.83	26.72±1.39	26.26±1.15	26.20±1.17
1.808	11.916	21.35	21.13	21.44±1.66	21.31±1.26	21.16±1.27
2.968	23.832	20.19	19.83	19.56±2.11	19.56±1.43	19.51±1.41
4.077	35.736	20.51	20.02	19.35±2.36	19.27±1.39	19.36±1.47
5.167	47.652	21.05	20.43	19.50±2.66	19.38±1.39	19.37±1.35
10.615	108.0	23.42	n.a.	20.28±3.65	20.01±1.44	19.94±1.47

TAB. 1: Comparison of the Carbon $\frac{dE}{dx}$ (in MeV/mm) from several models. See text.

$\beta\gamma$	Ec (GeV)	BB	NIST	SRIM	G3 v3.21	G4 v5.2	G4 v6.0
0.777	0.25	1.007	1.010	1.030	1.044 ±0.191	1.02 ±0.185	1.02 ±0.190
1.162	0.5	0.721	0.724	0.737	0.734 ±0.195	0.728 ±0.205	0.735 ±0.217
1.808	1.	0.593	0.600	0.604	0.595 ±0.218	0.584 ±0.202	0.582 ±0.230
2.968	2.	0.561	0.558	0.568	0.537 ±0.199	0.539 ±0.259	0.528 ±0.189
4.077	3.	0.570	0.564	0.574	0.530 ±0.205	0.528 ±0.243	0.524 ±0.192
5.167	4.	0.584	0.576	0.586	0.537 ±0.206	0.532 ±0.252	0.533 ±0.238
10.615	9.066	0.650	0.629	n.a.	0.559 ±0.230	0.536 ±0.202	0.545 ±0.200

TAB. 2: Comparison of the Proton $\frac{dE}{dx}$ (in MeV/mm) from several models. See text.

$\beta\gamma$	Ec (GeV)	BB	PDG	G3 v3.21	G4 v5.2	G4 v6.0
1.808	0.113	0.592	0.597	0.588 ±0.208	0.588 ±0.214	0.585±0.156
2.968	0.225	0.560	0.561	0.544 ±0.227	0.535 ±0.226	0.517±0.157
4.077	0.338	0.568	0.566	0.540 ±0.233	0.541 ±0.244	0.518±0.178
5.167	0.450	0.583	0.578	0.538 ±0.221	0.542 ±0.247	0.527±0.231
10.615	1.021	0.648	0.628	0.563 ±0.227	0.559 ±0.284	0.536±0.226

TAB. 3: Comparison of the Muon $\frac{dE}{dx}$ (in MeV/mm) from several models. See text.

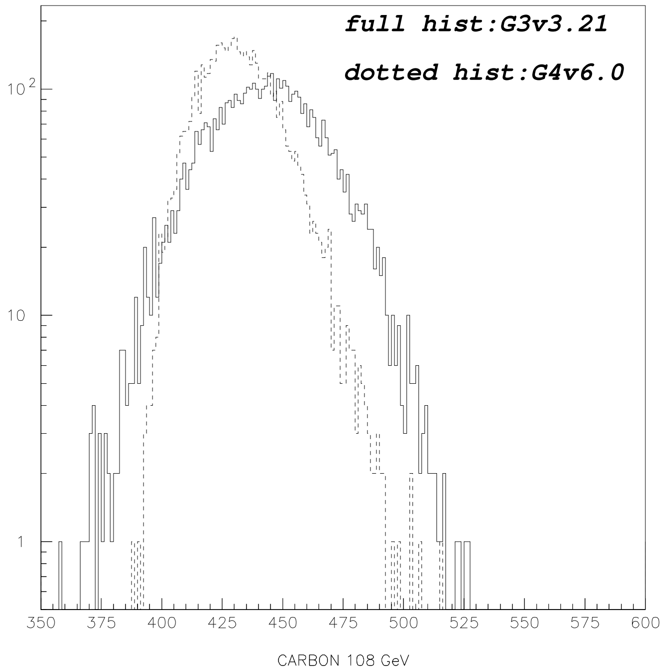

FIG. 1: *G3v3.21 and G4v5.2 results for Carbon nuclei at 108 GeV total kinetic energy. Absorber is 1.99 cm thick CsI.*

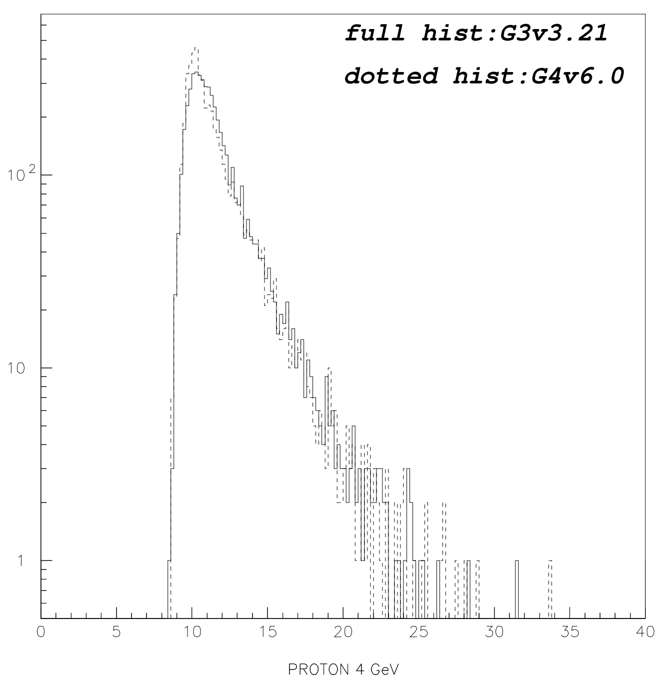

FIG. 2: *G3v3.21 and G4v5.2 results for protons at 4 GeV. Absorber is 1.99 cm thick CsI.*

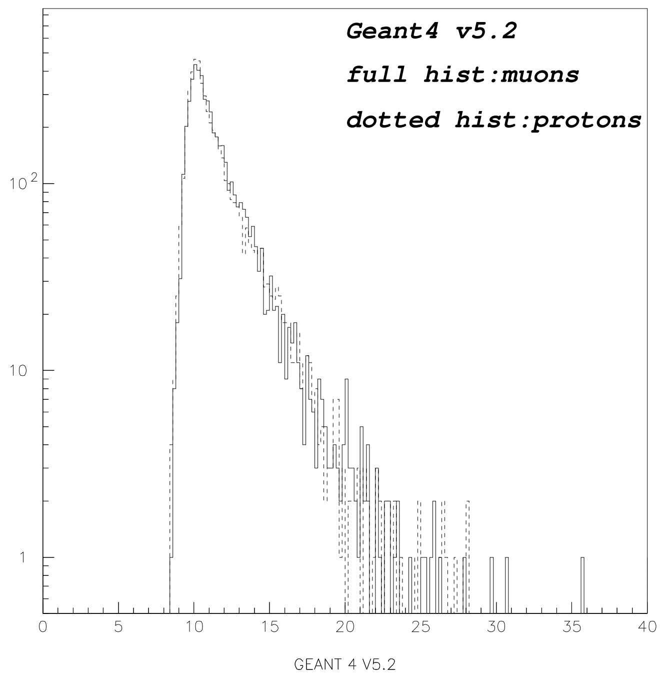

FIG. 3: *G4v5.2 results for protons and muons at* $\beta\gamma = 5.167$ *(4 GeV protons and 0.450 GeV muons). Absorber is 1.99 cm thick CsI.*

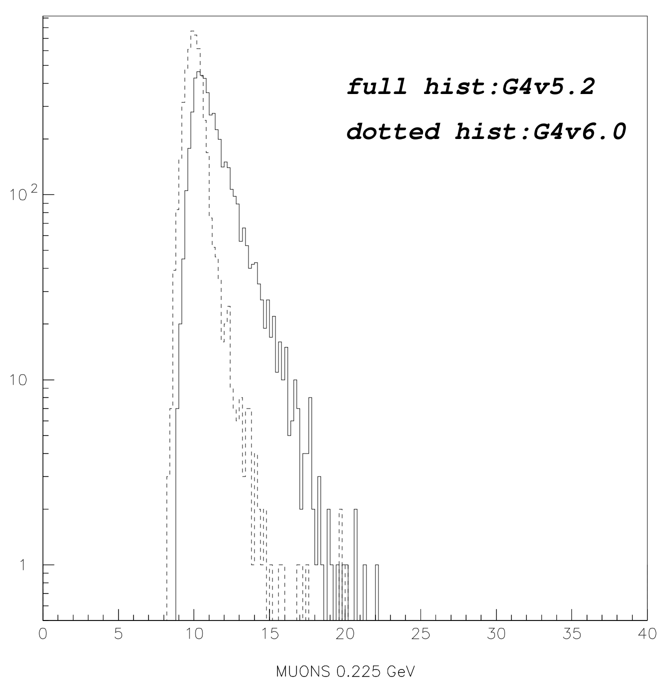

FIG. 4: *G4v5.2 and G4v6.0 results for muons at 0.225 GeV. Absorber is 1.99 cm thick CsI.*

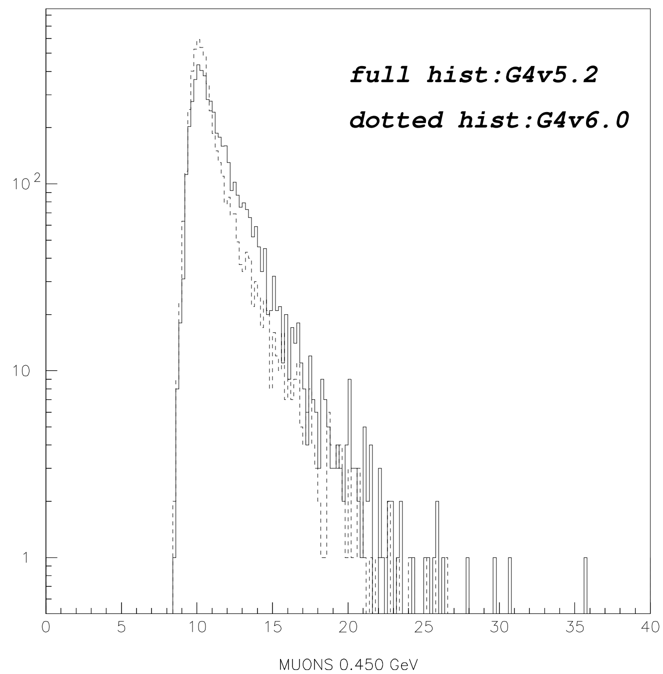

FIG. 5: *G4v5.2 and G4v6.0 results for muons 0.450 GeV. Absorber is 1.99 cm thick CsI.*

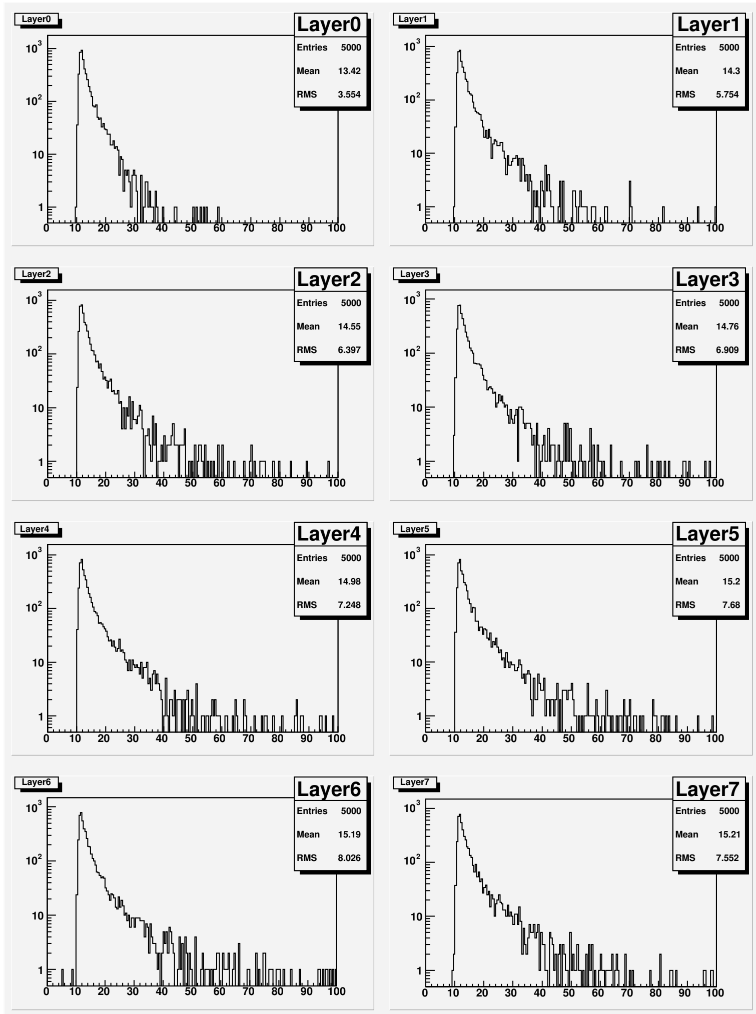

FIG. 6: *G4v6.0 results for 20 GeV muons. Absorber is 8 layers of 1.99 cm thick CsI.*

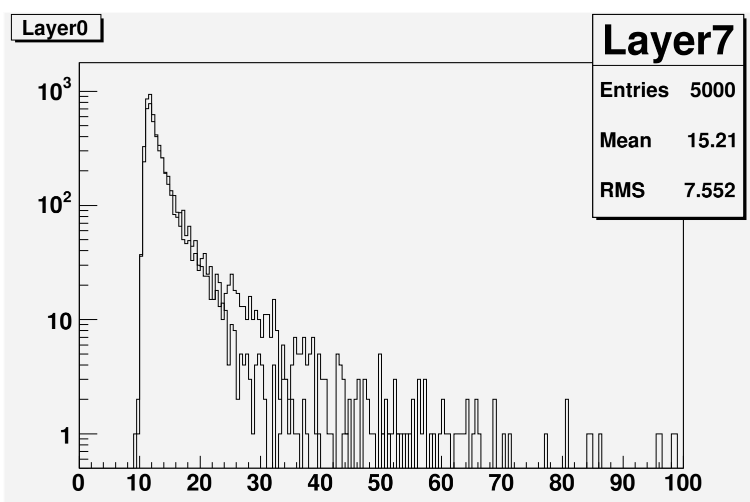

FIG. 7: *G4v6.0 results for 20 GeV muons. Comparison between first and last layers.*