Simulation of the Fano cavity setup

Sabine Elles, Vladimir Ivanchenko,
Michel Maire, Laszlo Urban

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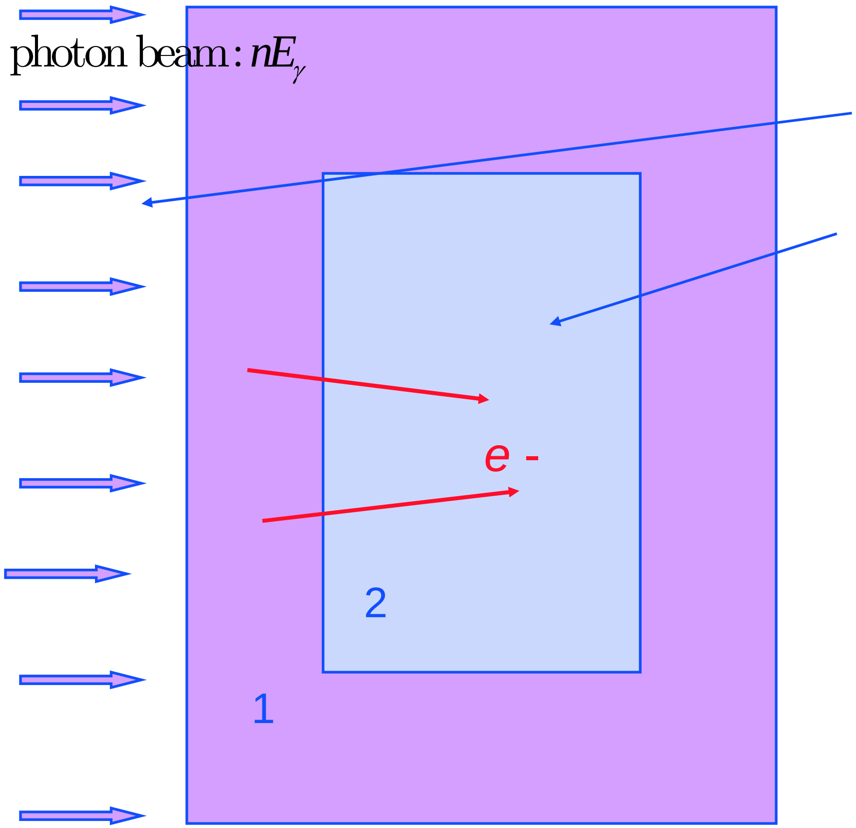
Outline

The Fano cavity setup allows to test the quality of low energy electrons transport algorithms

- Fano cavity principle
- Step limitation in Geant4
- Compute mean energy loss
- Compute energy fluctuation
- Apply multiple scattering
- Global effect

Fano cavity principle

Materials 1 and 2 : same A, but different density ρ1 and ρ2 $\Rightarrow \left(\frac{1}{\rho}\frac{dE}{dx}\right)_1 = \left(\frac{1}{\rho}\frac{dE}{dx}\right)_2$



photon beam : nE_γ

beam energy fluence : $\Phi = \frac{nE_\gamma}{S_1}$

dose in material 2 : D

energy transfert coefficient : $\mu_{tr}(E_\gamma) = \sigma_{tot}(E_\gamma)\frac{\langle T\rangle}{E_\gamma}$

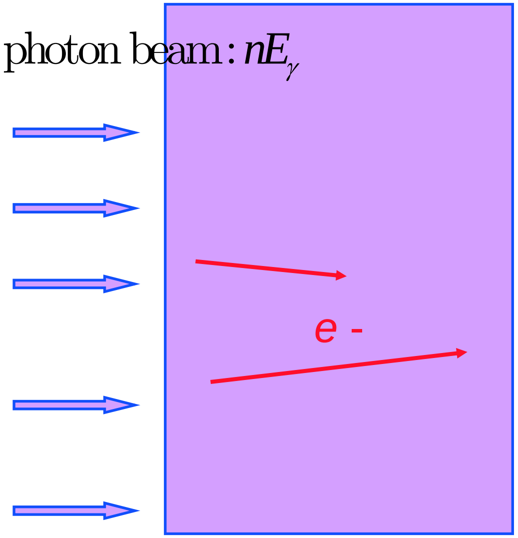
$\langle T\rangle$ is the mean kinetic energy of emited e^-

Under *charged particle equilibrium* condition :

$$\frac{D}{\Phi(E_\gamma)} = \left(\frac{\mu_{tr}(E_\gamma)}{\rho}\right)_1$$

any deviation from this equality indicates artefacts in the e- transport algorithms

Energy transfer coefficient

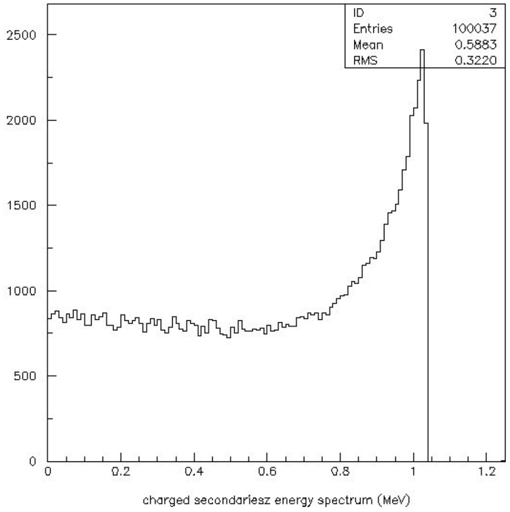


$$\mu_{tr}(E_\gamma) = \frac{1}{E_\gamma}\int_{T_{\min}}^{T_{\max}} \frac{d\sigma_{tot}}{dT}\, T\, dT = \sigma_{tot}(E_\gamma)\frac{\langle T\rangle}{E_\gamma}$$

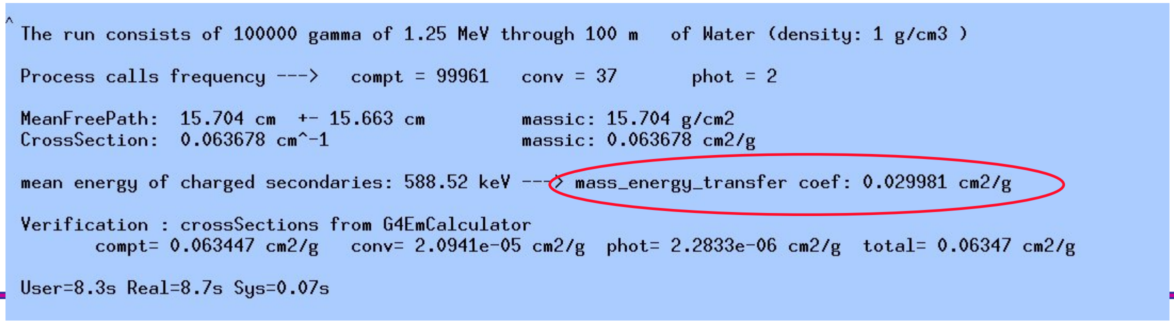
σ_{tot} : total cross section per volume

T : kinetic energy of emited e^-

$$\left(\frac{\mu_{tr}(1.25\ \mathrm{MeV})}{\rho}\right)_{water} = 0.02998\ \mathrm{cm}^2/\mathrm{g}$$



From TestEm14:



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^
 The run consists of 100000 gamma of 1.25 MeV through 100 m   of Water (density: 1 g/cm3 )

 Process calls frequency --->   compt = 99961   conv = 37       phot = 2

 MeanFreePath:  15.704 cm  +- 15.663 cm         massic: 15.704 g/cm2
 CrossSection:  0.063678 cm^-1                  massic: 0.063678 cm2/g

 mean energy of charged secondaries: 588.52 keV ---> mass_energy_transfer coef: 0.029981 cm2/g

 Verification : crossSections from G4EmCalculator
           compt= 0.063447 cm2/g   conv= 2.0941e-05 cm2/g   phot= 2.2833e-06 cm2/g   total= 0.06347 cm2/g

 User=8.3s Real=8.7s Sys=0.07s
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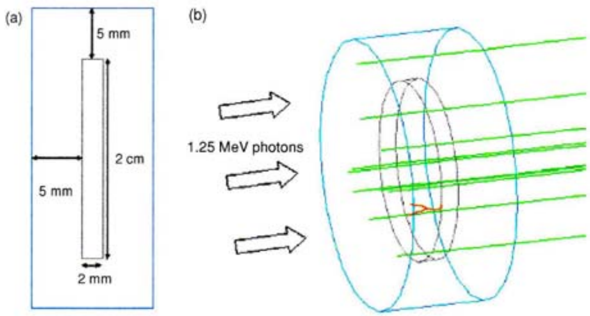
Geant4 v 6.2 results

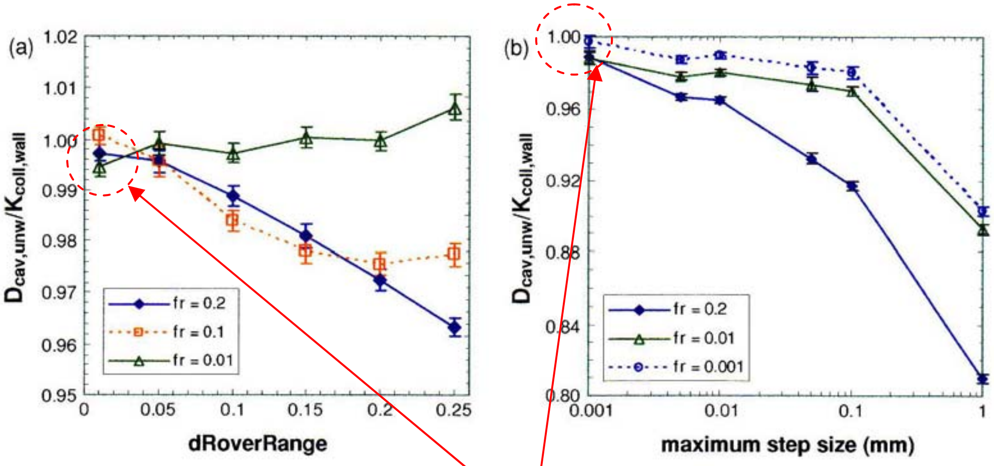
E. Poon and al. (Phys. Med. Biol, Feb 2005)

Evaluation of the consistency of the cavity response for different parameters of Geant4

$$\text{define } K = \frac{\Phi}{(\mu/\rho)} \quad \text{basic equation becomes : } \frac{\text{Dose}}{K} = 1$$



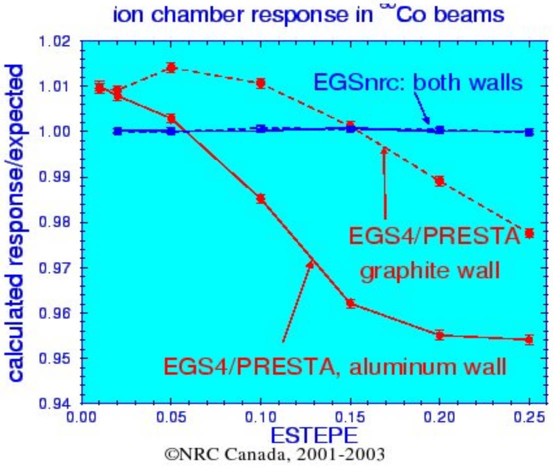
Ionization chamber



Most precision for Fano test

G4 6.2 default parameters : dRoverRange=1, fr=RangeFactor=0.2

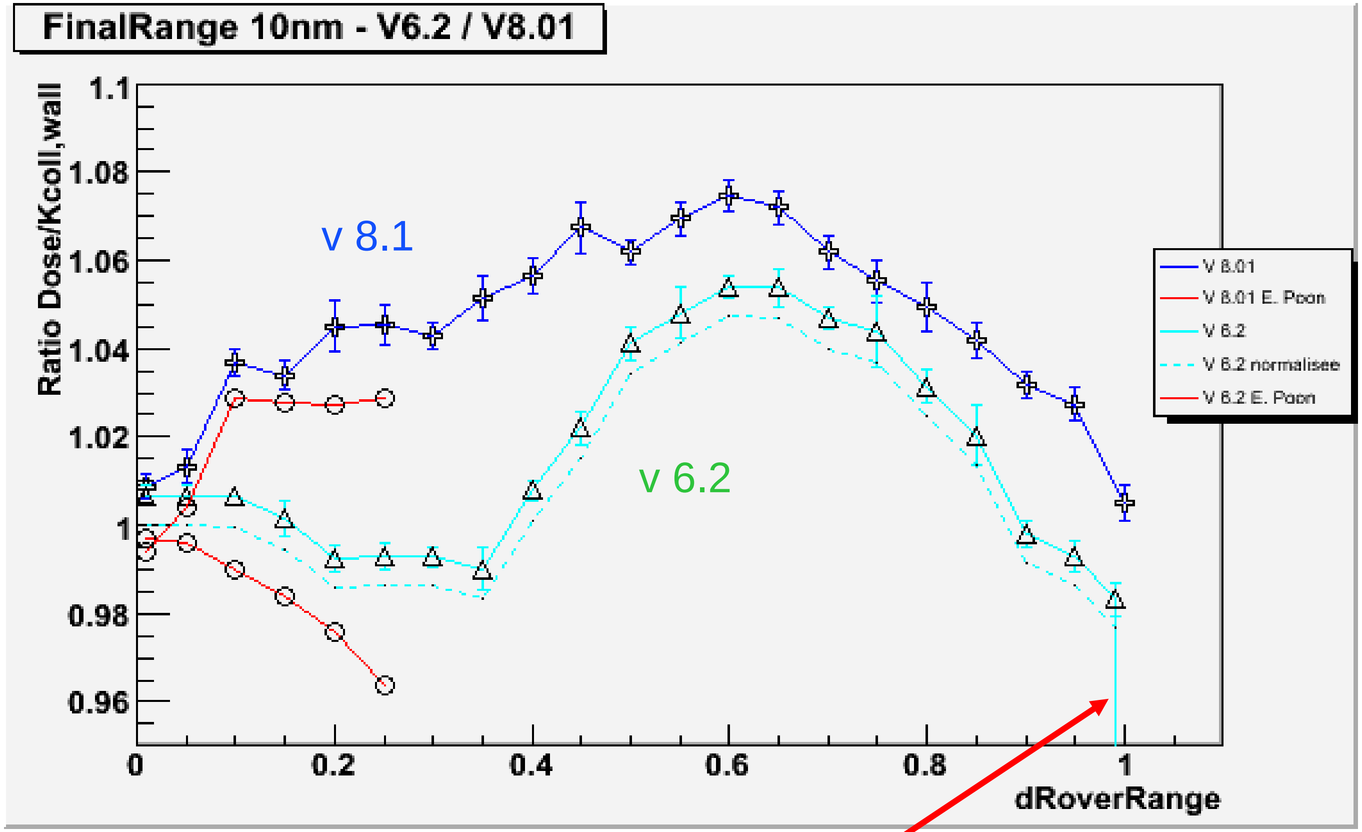
CSDA condition



I.Kawrakow *Med.Phys. 27-3 (2000) 499*

First results

v 6.2 :
 RangeFactor = 0.2
v 8.1 :
RangeFactor = 0.02



~4 10^8 events per point

v 6.2 : aberrant point for dRoverRange = 1

Geant4: e^- step limitation from physics

- Ionization and brems
  - production threshold *aka* *Cut*

  → indirect effect : the mean free path between discrete interactions depends on Cut

  continuous slowing-down approximation (CSDA) = NO secondary = big cut

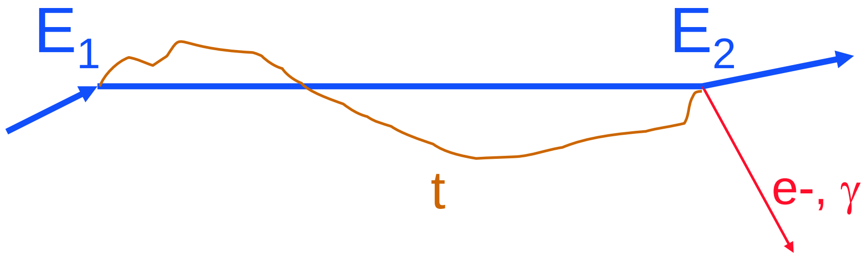
- Continuous energy loss
  - max fractional energy loss per step. Step/Range < *dRoverRange*
  - down to a certain limit : *finalRange*

- Multiple scattering
  - limit defined at first step and reevaluated after a boundary, to allow back scattering of low energy e^-

  → step = *RangeFactor* $*$ max(range,λ)
  - geometry : force more than 1 step in any volume : *GeomFactor*

What happens at end of step ?

- Multiple scattering 1 : compute true path length t
- Compute mean energy loss along t : <ΔE>
- Add energy loss fluctuation : de = f(<ΔE>)
- Multiple scattering 2 : compute final state
  - Lateral displacement and deflection
- Generate secondary, if any : e- or γ , energy tkin



$E_1 - E_2 = \langle\Delta E\rangle + de + tkin$

Compute mean energy loss <ΔE> alone

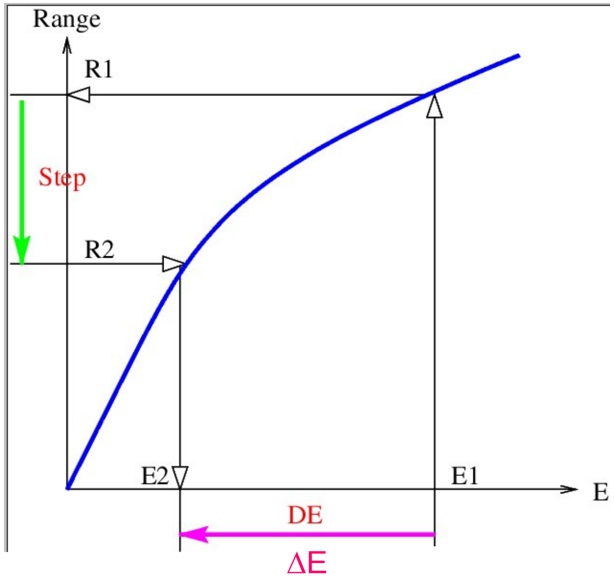
- <ΔE> is computed from Range and inverse Range tables :

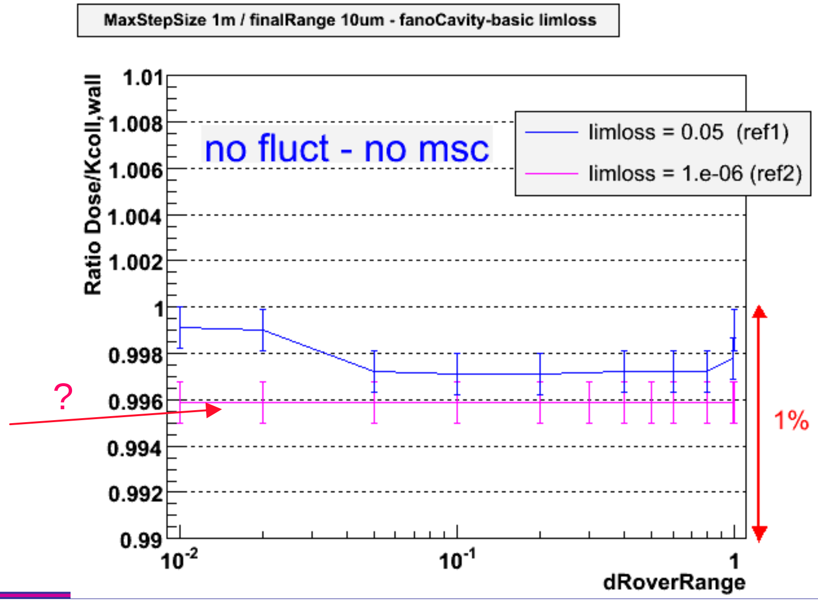
  $<\Delta E> = E(R_1) - E(R_2)$

- For small steps one uses linear approximation :

  $<\Delta E> = (dE/dx)*step$

  → linLossLimit parameter was too big
  → binning was unadequate





complete stability,

but shift ~ 4 per mille

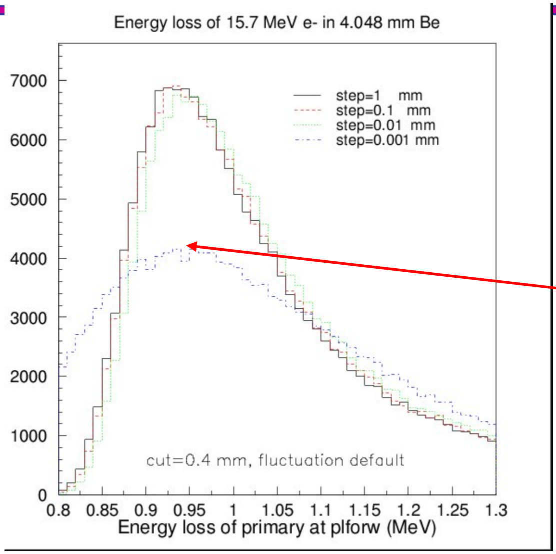
Energy loss fluctuations de

- In simulation, we cannot use Landau distribution which assumes no δ-rays production
  - → double counting

- Geant has his own model of fluctuations which is cut and material dependent (L. Urban, NIM A362(1995) 416)

- The model was deficient for small energy loss : small steps or gas
  - → Enhanced model in Geant4 8.2 ref3

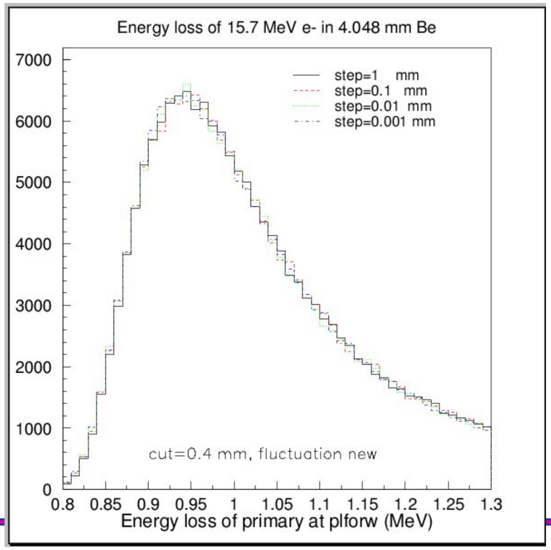
  (Geant4 Physics Reference Manual, April 2007)



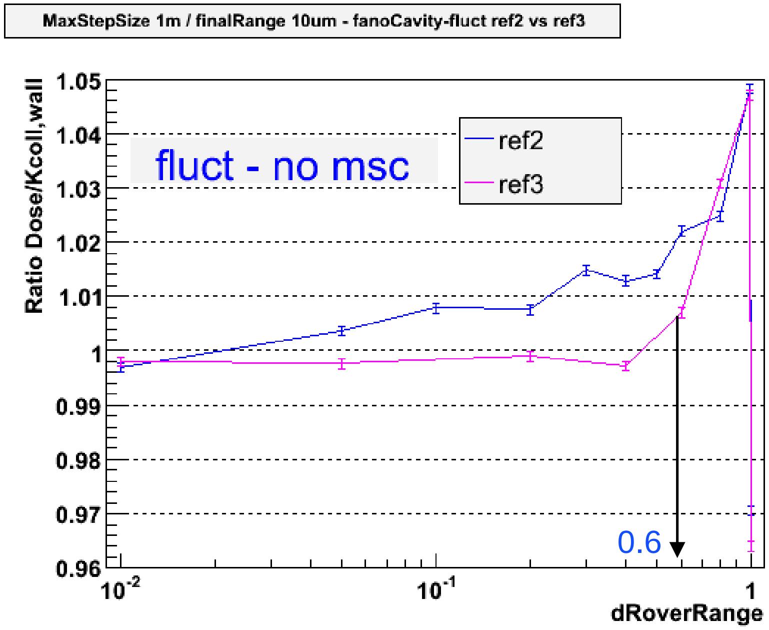
old=v 8.2

Step 1 μm

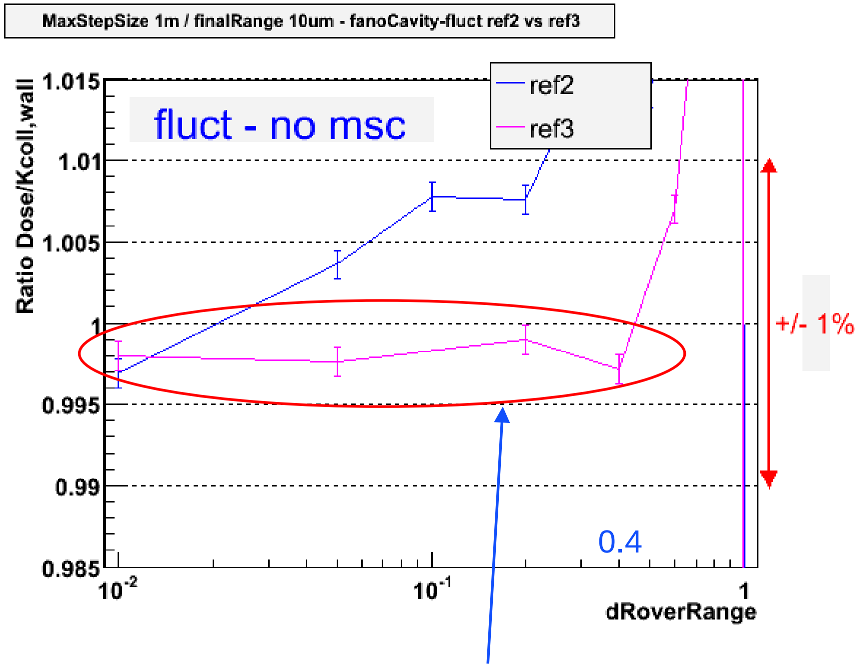
new=ref3



Energy loss fluctuations alone



zoom



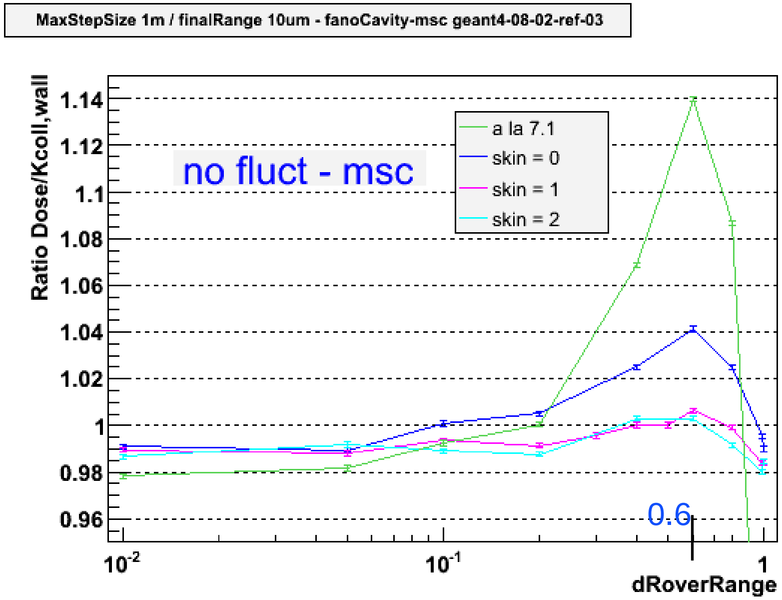
ref2 = v 8.2

Stability ~ 3 per mille

Multiple scattering : from 8.0 to 8.2 ref3

- RangeFactor : 0.2 →0.02, applied to the whole track (v8.0, January 2006)
- GeomFactor : 1→3
- single Coulomb scattering near boundaries (ref3, April 2007)
  - → few very small steps (~λ elastic) while crossing boundaries
  - → apply approximate single Coulomb scattering
- better evaluation of lateral displacement : reevaluate safety radius before to perform lateral displacement
  - → displ < safety (*safety was often underestimated*)
- correlate final direction (u) with lateral displacement (d)
  - → u.d = f (λ) taken from Lewis theory
- angular distribution : both central part and tail slightly modified

Multiple scattering alone



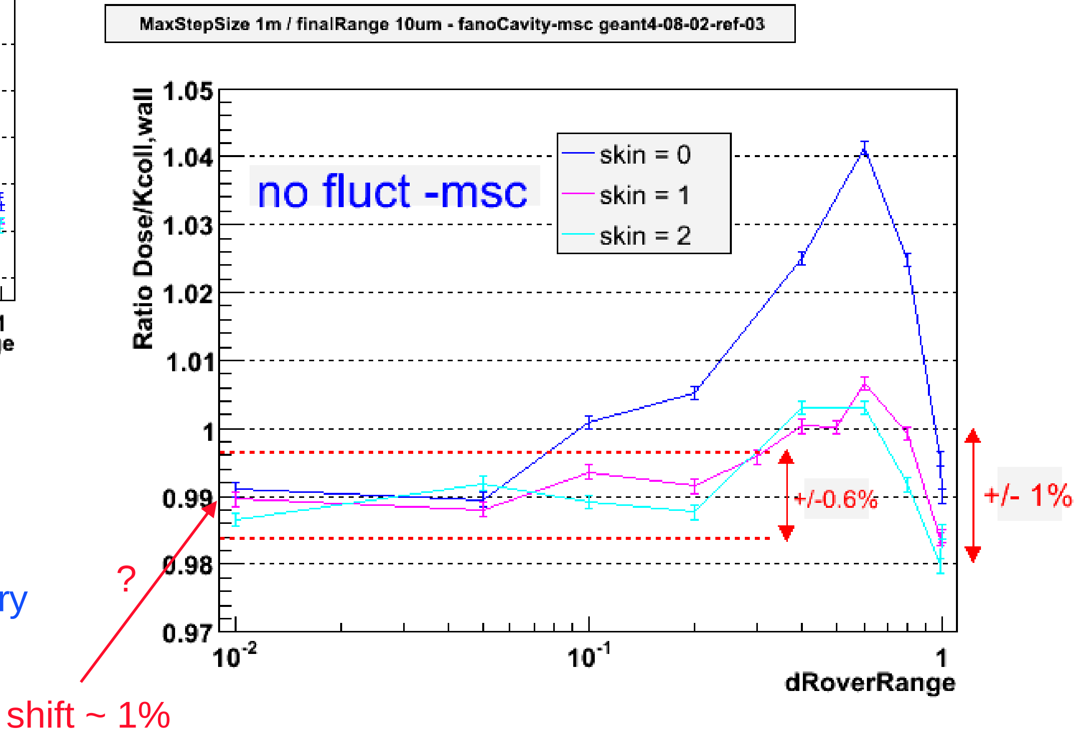
'a la 7.1' : RangeFactor = 0.2

skin = 0 :

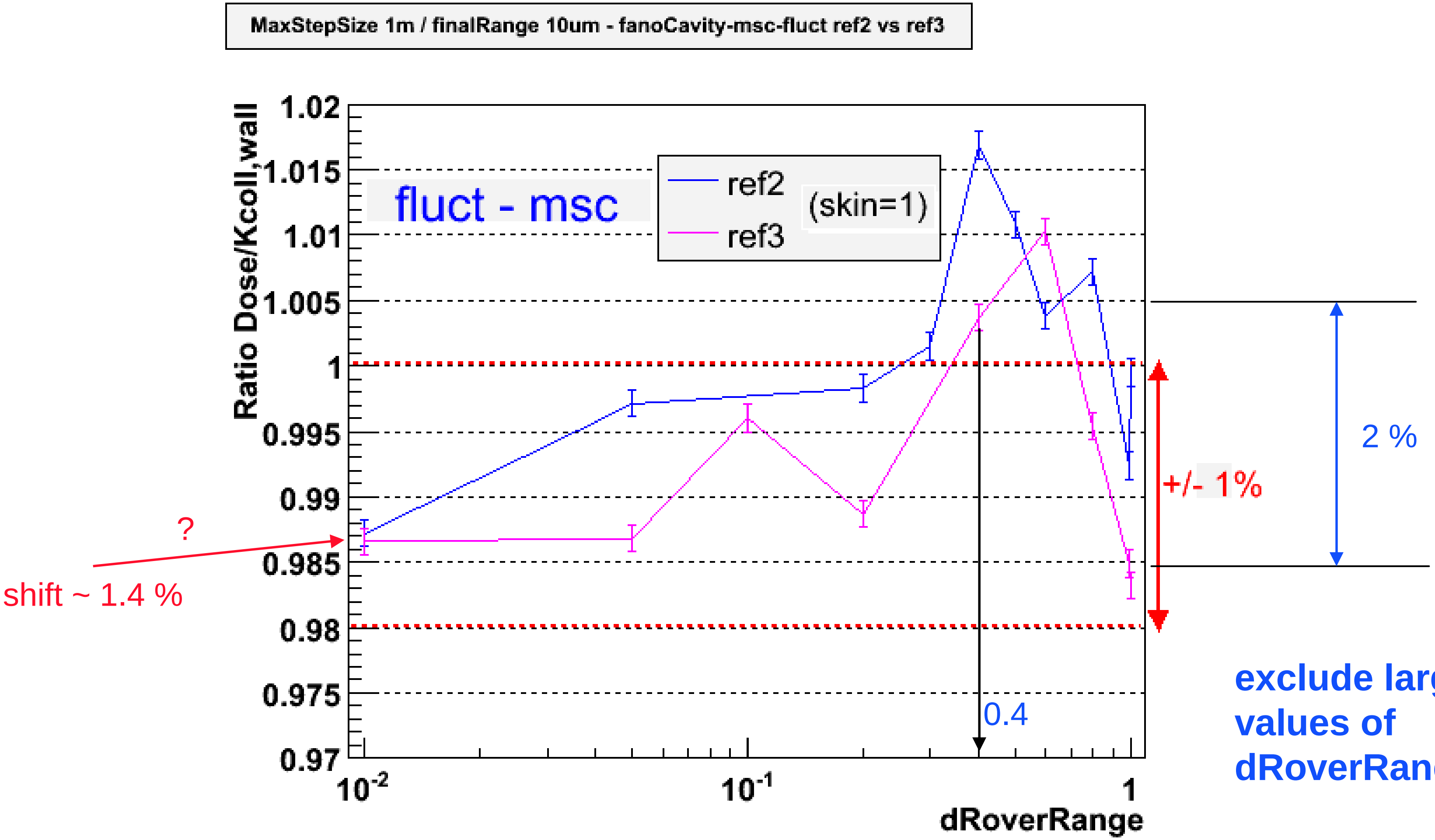
→no single scattering at boundary

→no computation to linear distance to boundary

zoom



all effects together



exclude large values of dRoverRange

Summary

- We analyzed the Geant4 e- transport algorithms in the context of the Fano cavity setup.
- Stability of the computation of mean energy loss along a step has been slighty improved (~2 per mille)
- Model of energy loss fluctuations has been changed for very small amount of matter. Stability ~3 per mille over a large range of step size limitation
- Multiple scattering model has been enhanced in various manners. Relevant features are :
  - strong constaint on step limitation
  - single Coulomb scattering near boundaries

  → stability ~1.2 % for reasonable step limitation
- With Geant4 v8.2-ref3, stable results within 2% can be reached

additional comments

- Need to be completed
  - understand the systematic shifts of ~ few per mille
  - study the effect of other paramaters
    - → finalRange, stepMax, productionCut …

- Recommended parameter values and options will be different for bioMedical requirements (highest precision) and HEP-calorimetry usage
  - → examples of Physics Lists

- Fano cavity setup is included in our public test serie :

  `/geant4/examples/extended/medical/fanoCavity`

  - it is automatically executed by System Test Team before every release
  - see README