

Geant4 and Fano cavity : where are we ?

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Monte Carlo techniques in radiotherapy delivery and verification
Third McGill International Workshop
Montreal - 2007

Outline

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

Fano cavity principle

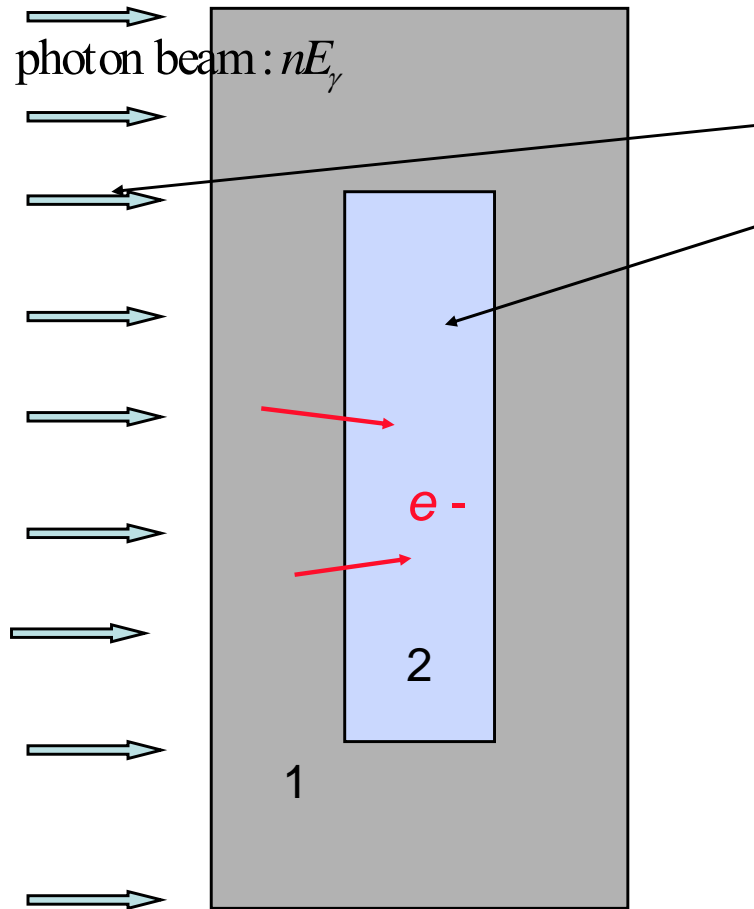
Electron transport algorithm in Geant4
step limitation - end of step

Evolution of the electron transport algorithm
mean energy loss and energy fluctuation computation
multiple scattering

Global effect

Fano cavity principle

Materials 1 and 2 : same A, but different density ρ_1 and $\rho_2 \Rightarrow \left(\frac{1}{\rho} \frac{dE}{dx} \right)_1 = \left(\frac{1}{\rho} \frac{dE}{dx} \right)_2$



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

dose in material 2: D

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

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

Under *charged particle equilibrium* condition :

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

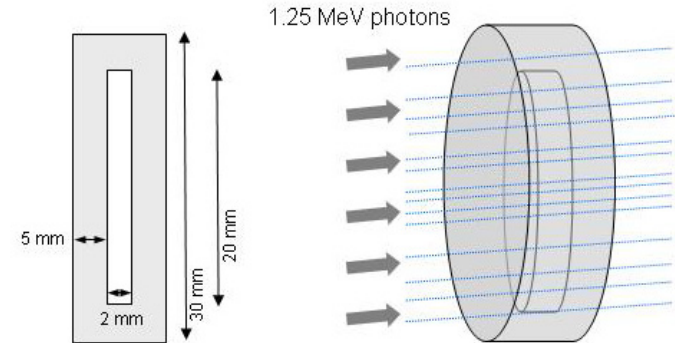
i.e. independent of the tracking parameters of the simulation

Geant4 v 6.2 results

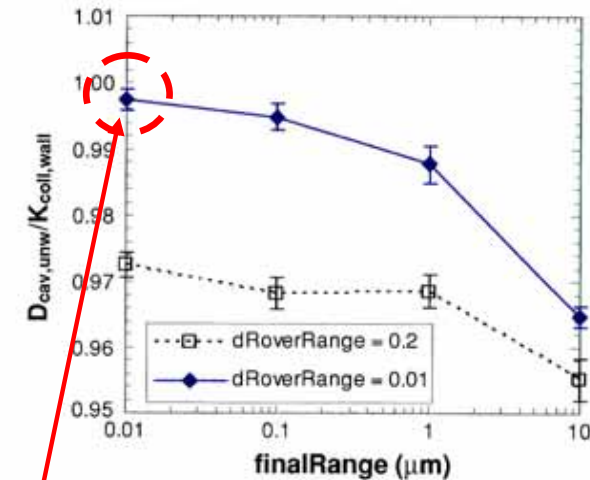
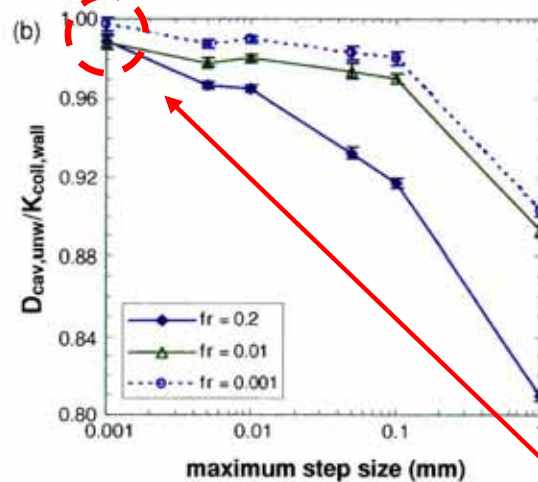
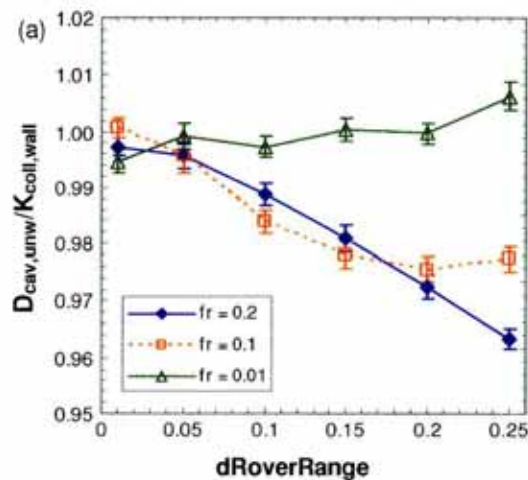
E. Poon and al. (Phys. Med. Biol, Feb 2005)

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

Defining $K = \left(\frac{\mu_{tr}}{\rho} \right) \Phi$ basic equation becomes $\frac{D}{K} = 1$



Ionization chamber



Most accurate results for Fano test

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

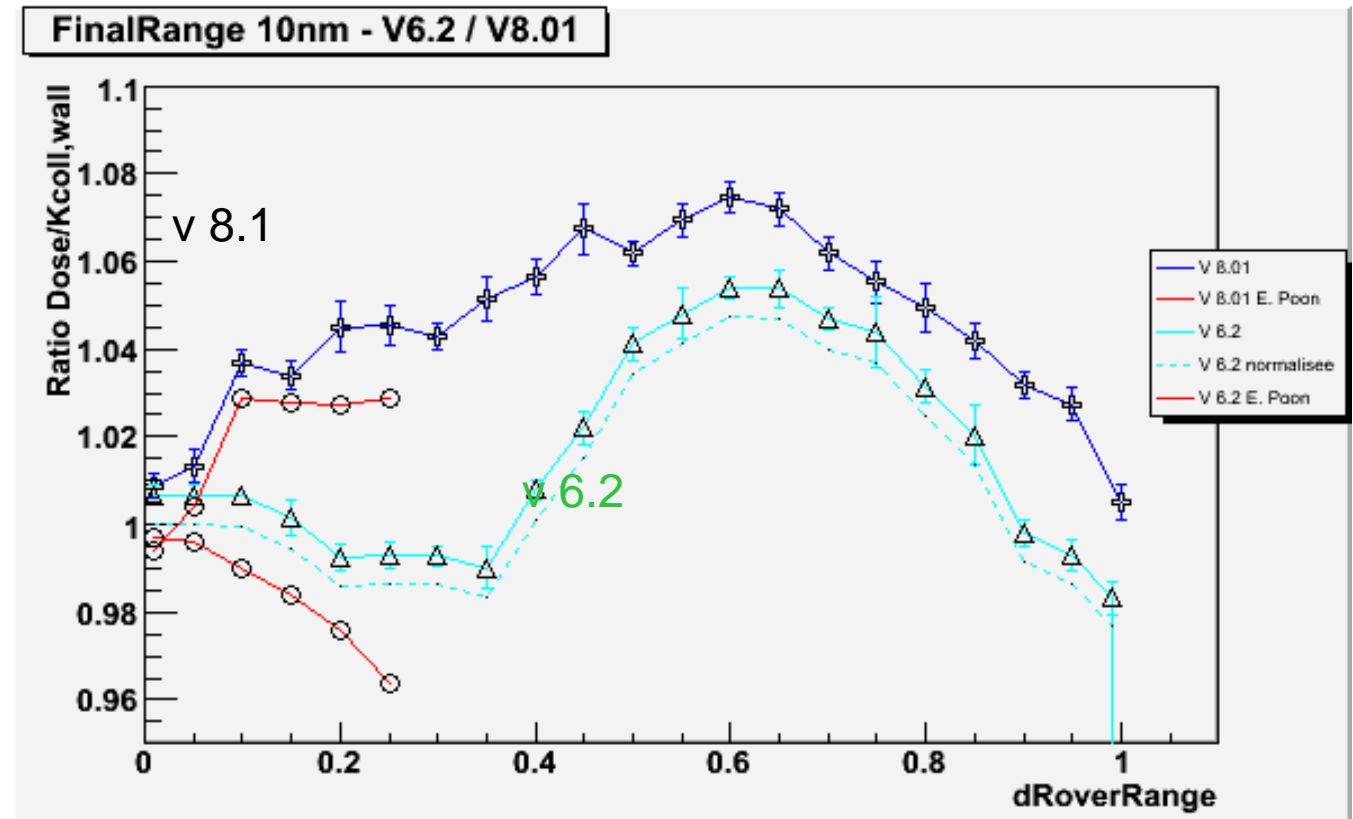
Work done under Continuous Slow Down Approximation (CSDA)

Geant4 v 6.2 vs 8.01

First step : reproduce 6.2 results and test 8.01 release

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

~ $4 \cdot 10^8$ events per point



v 6.2 : aberrant point for dRoverRange = 1

Electron transport algorithm in Geant4 : e⁻ step limitation from physics

There are 4 step limitation constraints :

Ionization and brems production threshold (*aka Cut*) ①

Continuous energy loss

max fractional energy loss per step. $\text{Step}/\text{Range} < dR\text{overRange}$
down to a certain limit : *finalRange* ②

Multiple scattering

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

$\text{step} = \text{RangeFactor} * \max(\text{range}, \lambda)$ ③ (λ : transport mean free path)

geometry : force more than 1 step in any volume : *GeomFactor* ④

Electron transport algorithm in Geant4 : end of a step

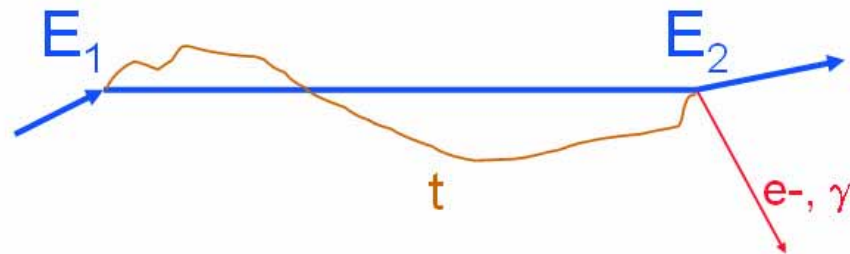
multiple scattering \Rightarrow true path length t computation

compute mean energy loss along t : $\langle \Delta E \rangle$

add energy loss fluctuation : $dE = f(\langle \Delta E \rangle)$

multiple scattering again \Rightarrow lateral displacement and deflection

secondary generation, if any : e^- or γ , energy T_{kin}



Energy balance

$$E_1 - E_2 = \langle \Delta E \rangle + dE + T_{\text{kin}}$$

Evolution of the electron transport algorithm since version 8.0

The main evolutions concern :

Mean energy loss and energy fluctuation computation

$$E_1 - E_2 = \langle \Delta E \rangle + dE + T_{\text{kin}}$$

Step limitations constraints for multiple scattering process

new default values for *RangeFactor* and *GeomFactor*

Single scattering while crossing boundaries

Mean energy loss computation $\langle \Delta E \rangle$ alone

Mean energy loss computation algorithm :

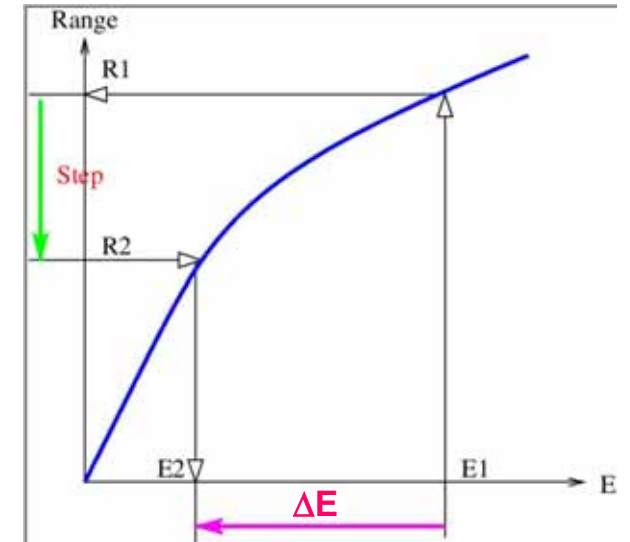
$\langle \Delta E \rangle$ is computed from Range and inverse Range tables :

$$\langle \Delta E \rangle = E(R_1) - E(R_2)$$

For small steps a linear approximation is used :

$$\langle \Delta E \rangle = (dE/dx) * \text{step}$$

under the constraint : $\text{step}/\text{Range} < \text{linLossLimit}$



Problem : the default *linLossLimit* (0.05) value was too big

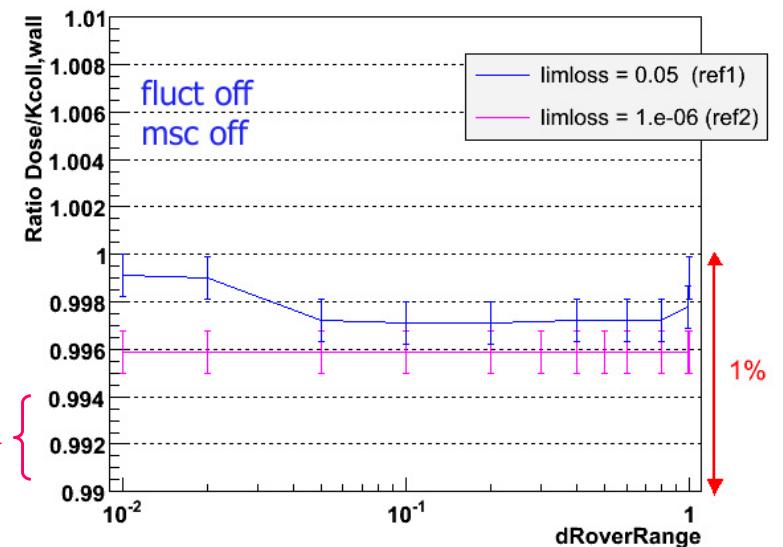
Test case : fluct and msc are switched off

⇒ e- transport deterministic and only governed by *dRoverRange*
(for a fixed value of *finalRange* = 10 μm)

⇒ new default : *linLossLimit* = 1.e-06

complete stability
but shift ~ 4 per mille

MaxStepSize 1m / finalRange 10um - fanoCavity-basic limloss



Energy loss fluctuation computation dE alone

In simulation, we cannot use Landau distribution which assumes **no** δ -rays production

⇒ double counting

Geant has its own model of fluctuations which is cut and material dependent

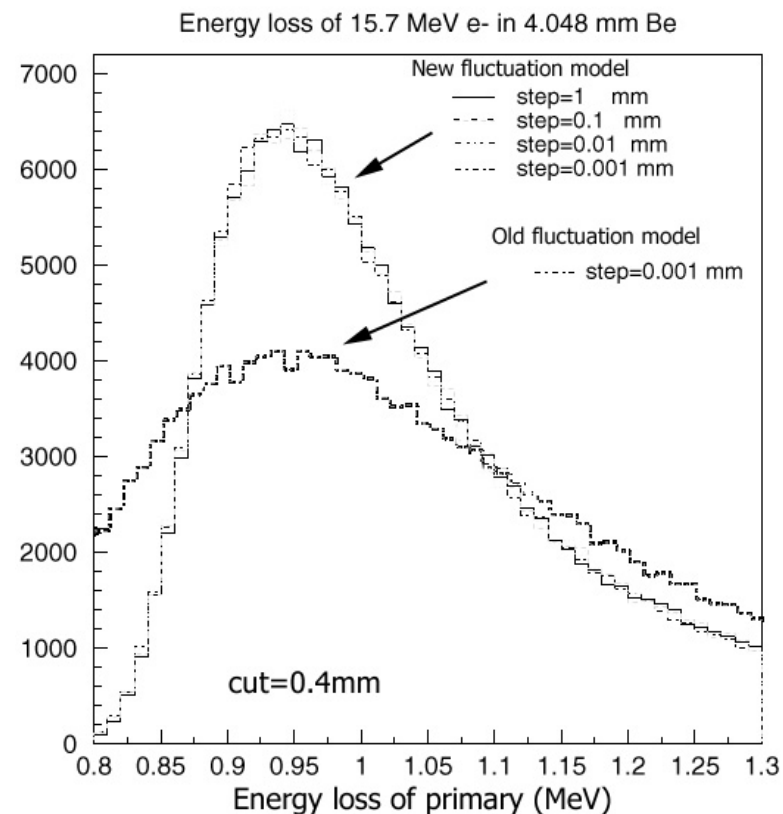
(L. Urban, NIM A362(1995) 416)

Problem :

the model was deficient for small energy loss : small steps or in gas

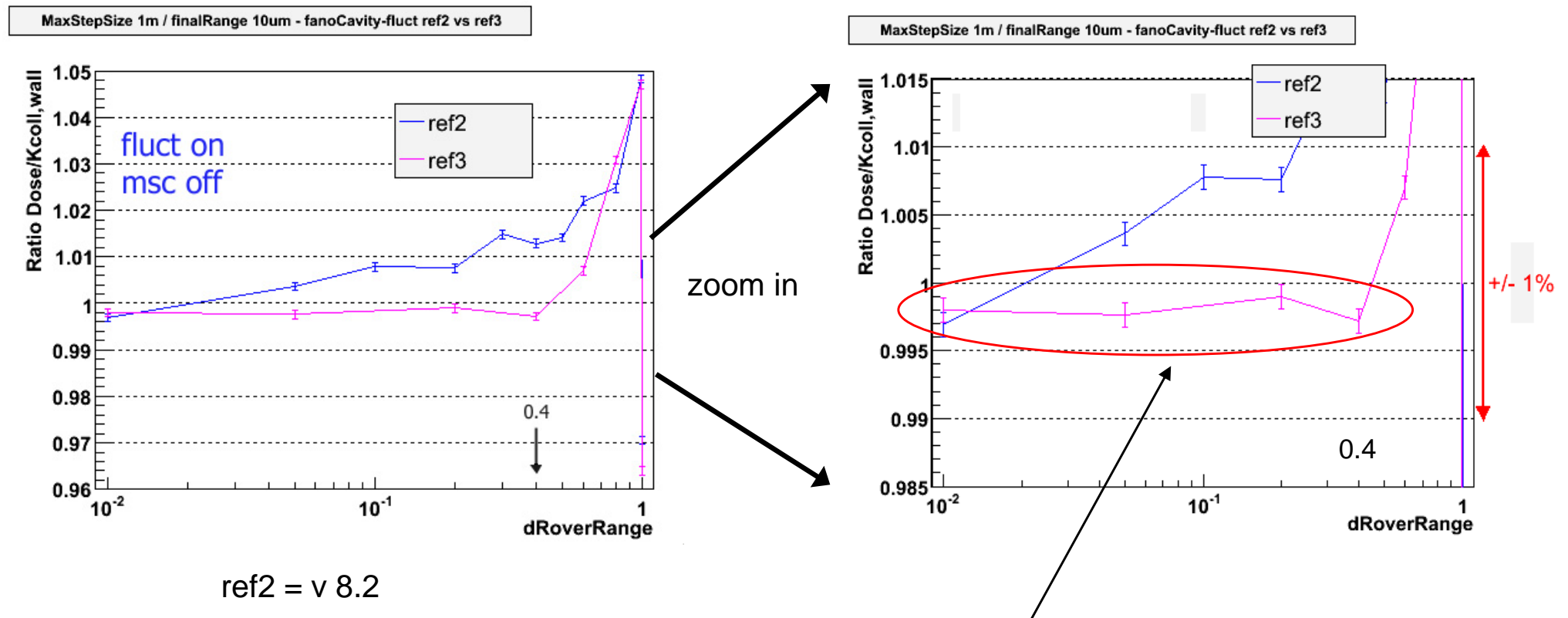
⇒ enhanced model in Geant4 8.2 ref3

(Geant4 Physics Reference Manual, April 2007)



Energy loss fluctuation computation dE alone

Fano cavity response (multiple scattering is switched off)



⇒ Stability ~ 3 per mille

Step limitations constraints for multiple scattering

Step limitations

[*RangeFactor* : 0.2 → 0.02, applied to the whole track (v8.0, January 2006)
GeomFactor : 1 → 3

Multiple scattering final state

single Coulomb scattering near boundaries (ref3, April 2007)

few very small steps ($\sim \lambda$ elastic) while crossing boundaries over a thickness
defined by *skin** λ

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)

⇒ $u \cdot d = f(\lambda)$ taken from Lewis theory

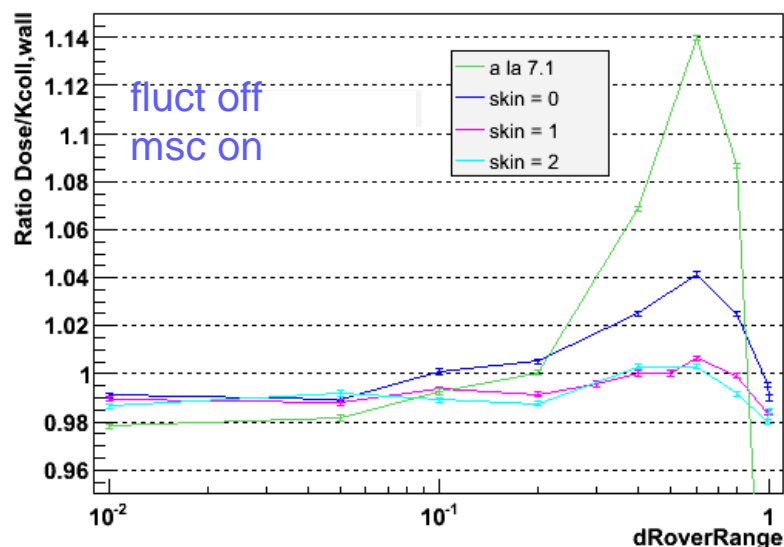
angular distribution : both central part and tail slightly modified

Step limitations constraints - multiple scattering alone

Fano cavity response (fluctuation is switched off)

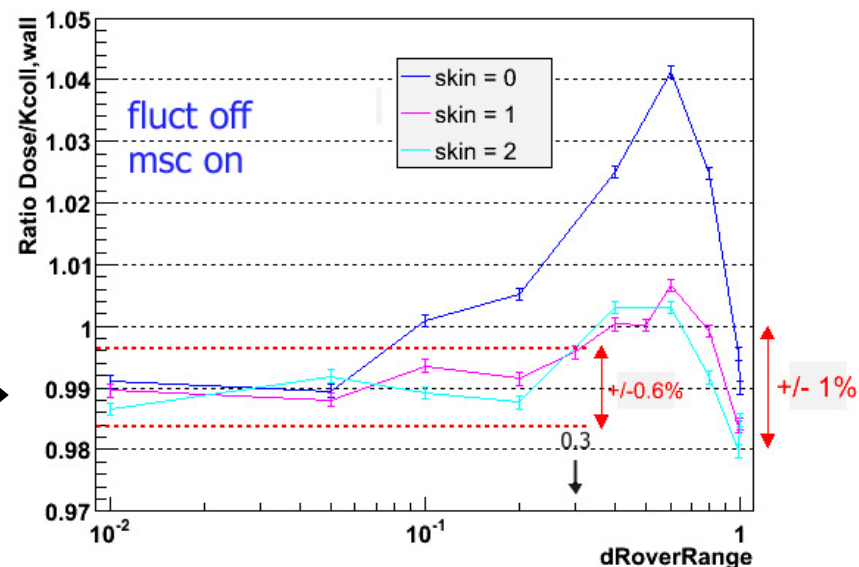
Comparison with release 7.1

MaxStepSize 1m / finalRange 10um - fanoCavity-msc geant4-08-02-ref-03



Release 8.2

MaxStepSize 1m / finalRange 10um - fanoCavity-msc geant4-08-02-ref-03



zoom in

'a la 7.1' : RangeFactor = 0.2

skin = 0 :

- no single scattering at boundary
- no computation to linear distance to boundary

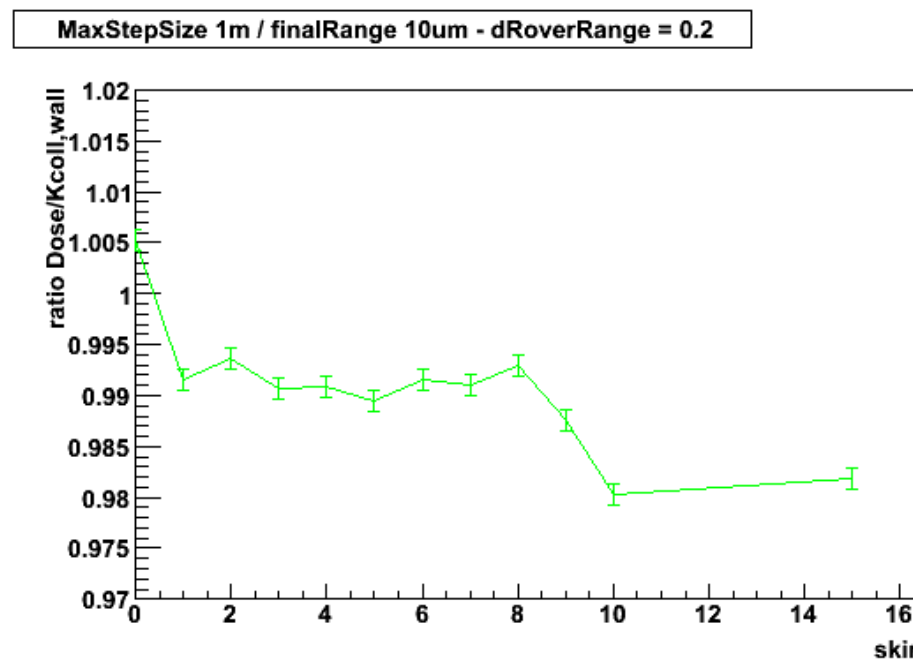
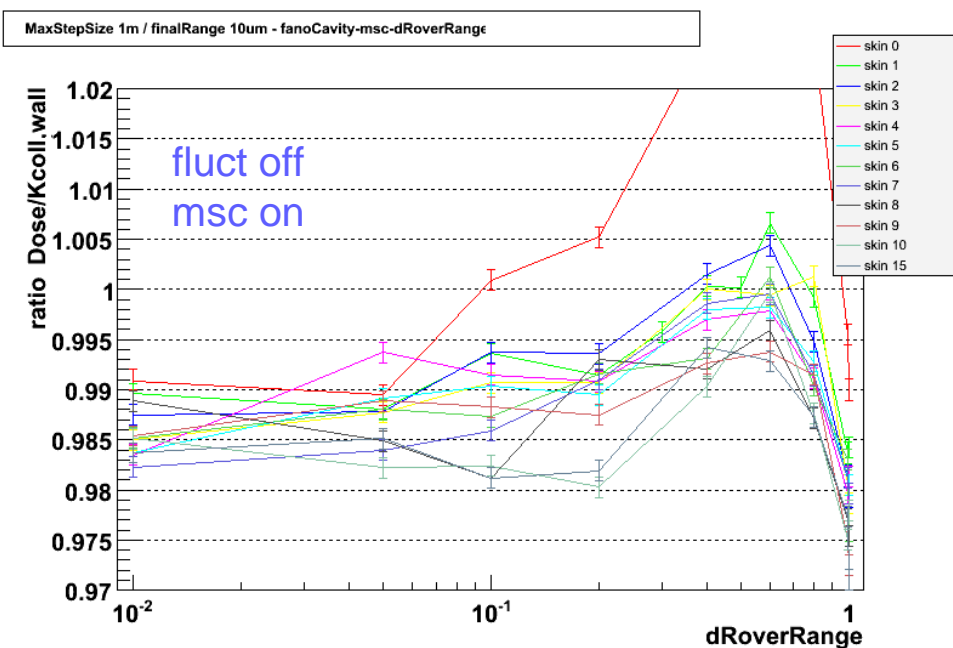
⇒ stability within ~ 0.6 %
but shift ~1%

Step limitations constraints - multiple scattering alone

Fano cavity response (fluctuation is switched off)

for *Skin* = 0 to 10

vs *Skin* for dRoverRange=0.2



⇒ limit skin value : ~ 4-5

Geant4 release 8-2-ref3 and Fano cavity

All modifications presented in this talk are implemented in release 8-2-ref3

Global effect are shown here :

Default parameter value :

RangeFactor = 0.02

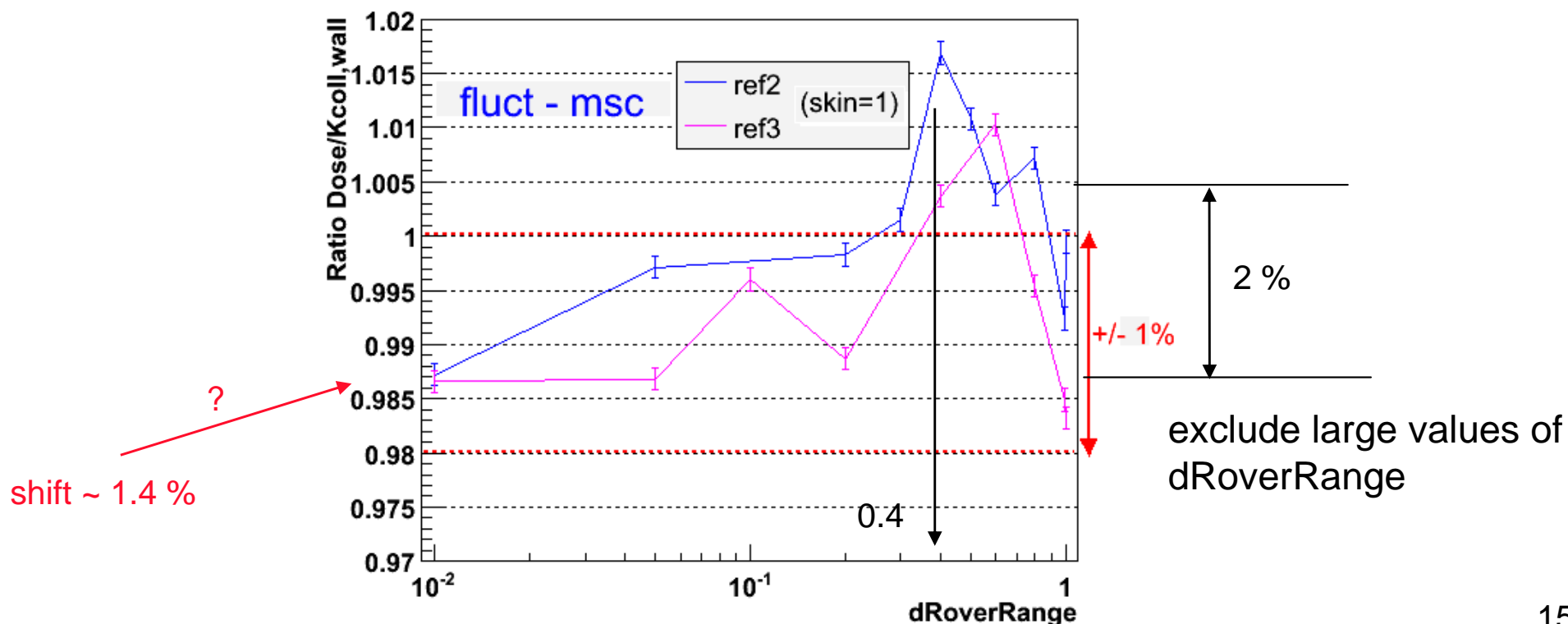
GeomFactor = 3

linLossLimit = 1.e-06

skin = 1 (in G4 9.0)

Release 8.2 vs 8-2-ref3

MaxStepSize 1m / finalRange 10um - fanoCavity-msc-fluct ref2 vs ref3



Summary

We analyzed the modifications of the Geant4 e- transport algorithms in the context of the Fano cavity setup.

Stability of the mean energy loss computation has been slightly 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 constraints on step limitation

- single Coulomb scattering near boundaries

⇒ stability ~1.5 % for $dRoverRange < 0.3$

Additional comments

Need to be completed

- understand the systematic shifts

- study the effect of other parameters

 - ⇒ 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**](#)

see README

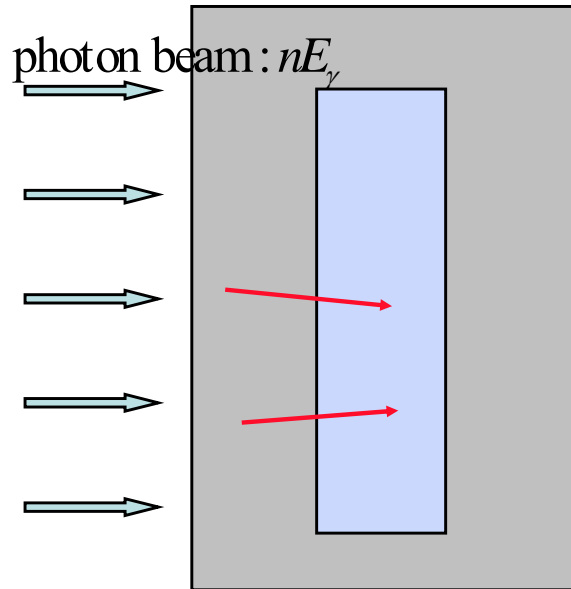
It is automatically executed by System Test Team before every release

Geant4 releases : v6 ⇒ v8

- v6.2 June 2004
- v7.0 January 2005
- v7.1 June 2005
- v8.0 January 2006
- v8.1 June 2006
- v8.2 January 2007
- v8.3 May 2007
- v9.0 June 2007 ?

Backup slides

Energy transfer coefficient

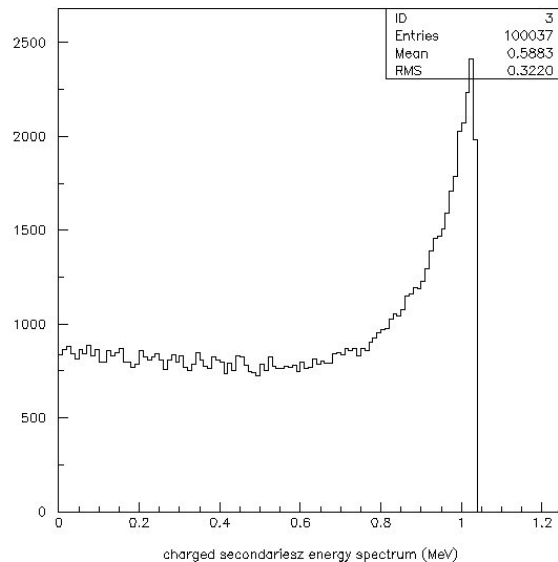


$$\mu_{tr}(E_\gamma) = \frac{1}{E_\gamma} \int_{T_{\min}}^{T_{\max}} \frac{d\sigma_{tot}}{dT} T dT = \sigma_{tot}(E_\gamma) \frac{\langle T \rangle}{E_\gamma}$$

σ_{tot} : total cross section per volume

T : kinetic energy of emitted e^-

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



From TestEm14:

```

^ The run consists of 100000 gamma of 1.25 MeV through 100 # 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

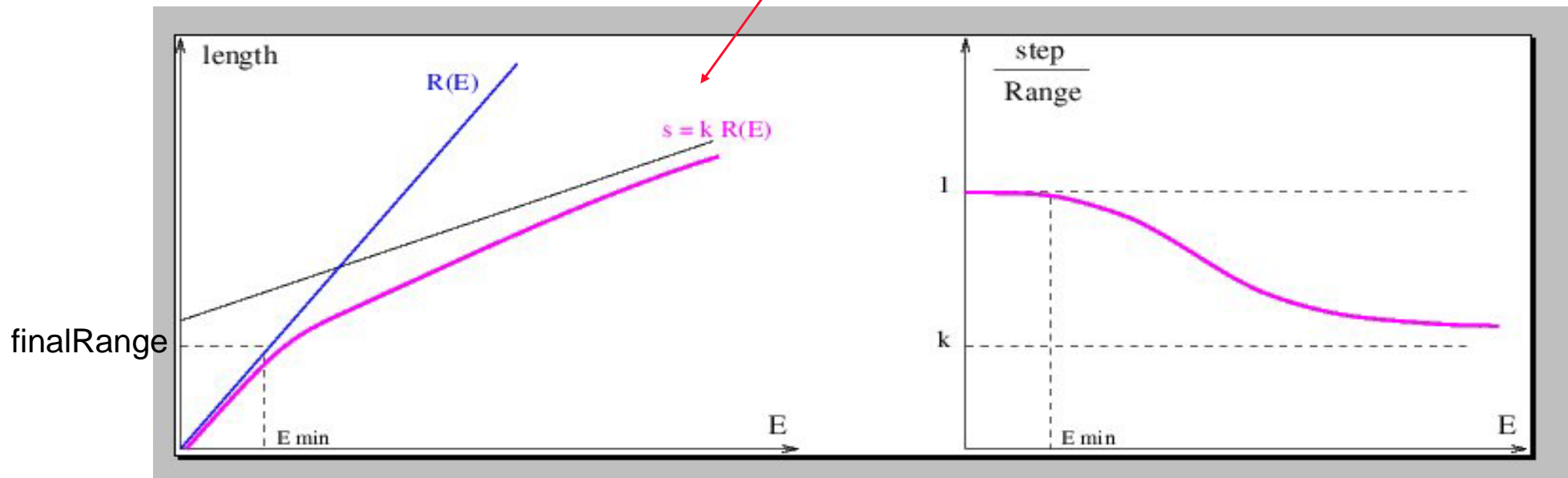
Verification : crossSections from G4EmCalculator
compt= 0.063447 cm2/g   conv= 2.0941e-05 cm2/g   phot= 2.2833e-06 cm2/g   total= 0.06347 cm2/g
User=8.3s Real=8.7s Sys=0.07s
    
```

Step limitation from continuous energy loss

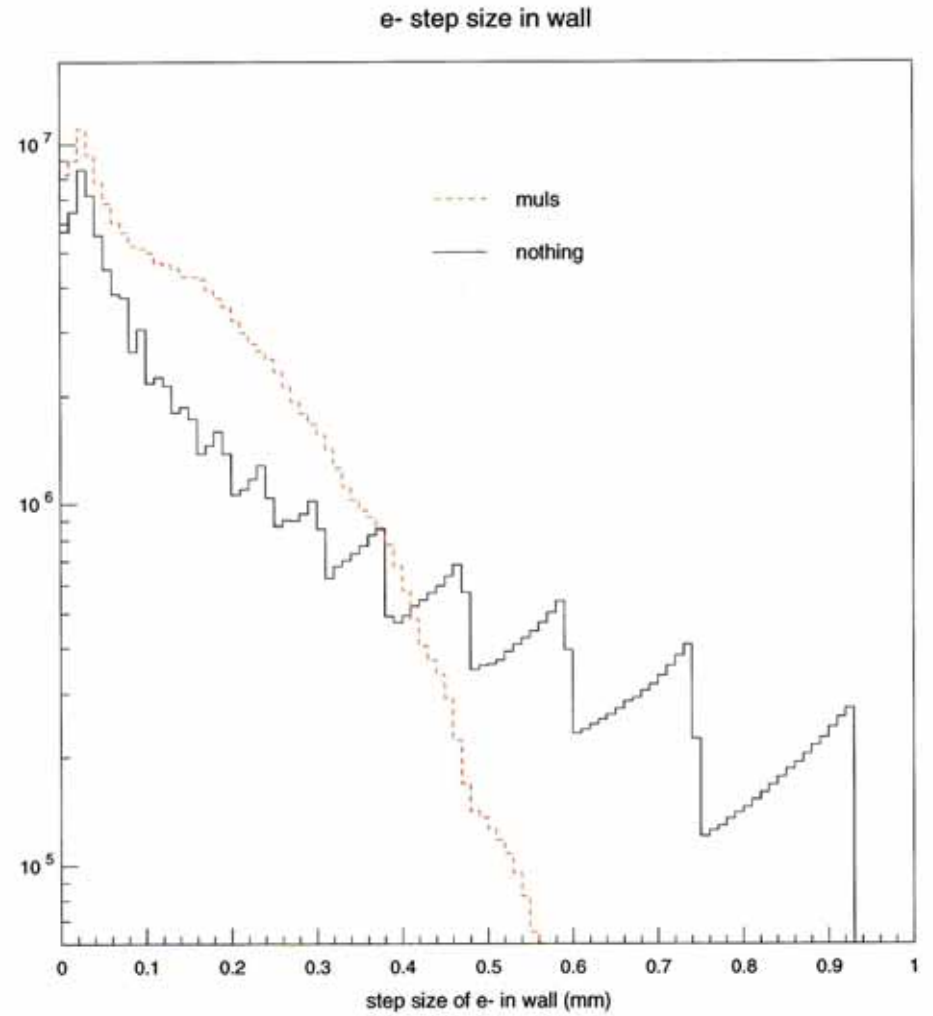
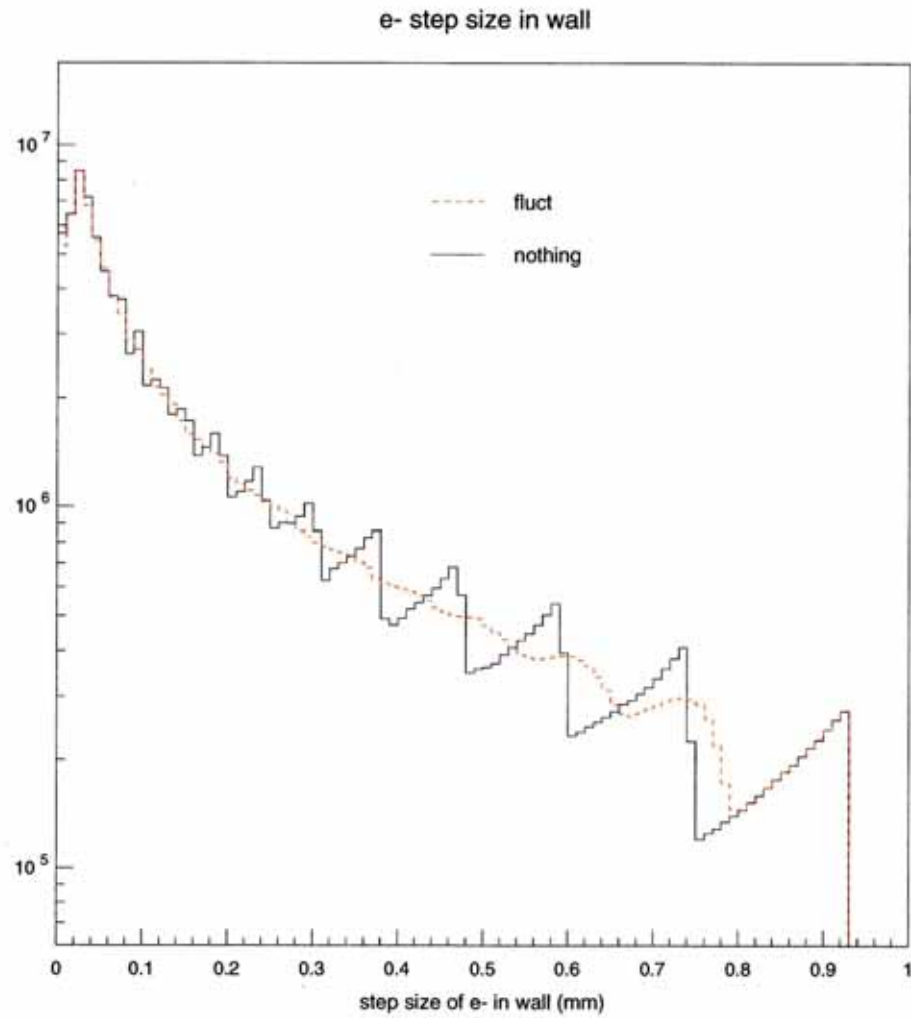
- The cross sections depend on the energy. The step size must be small enough to ensure a small fraction of energy loss along the step :

$$\frac{\text{step}}{\text{Range}(E)} \leq \text{dRoverRange} \quad \left\{ \begin{array}{l} 1 \text{ in G4 v6. and v7.} \\ 0.2 \text{ elsewhere} \end{array} \right.$$

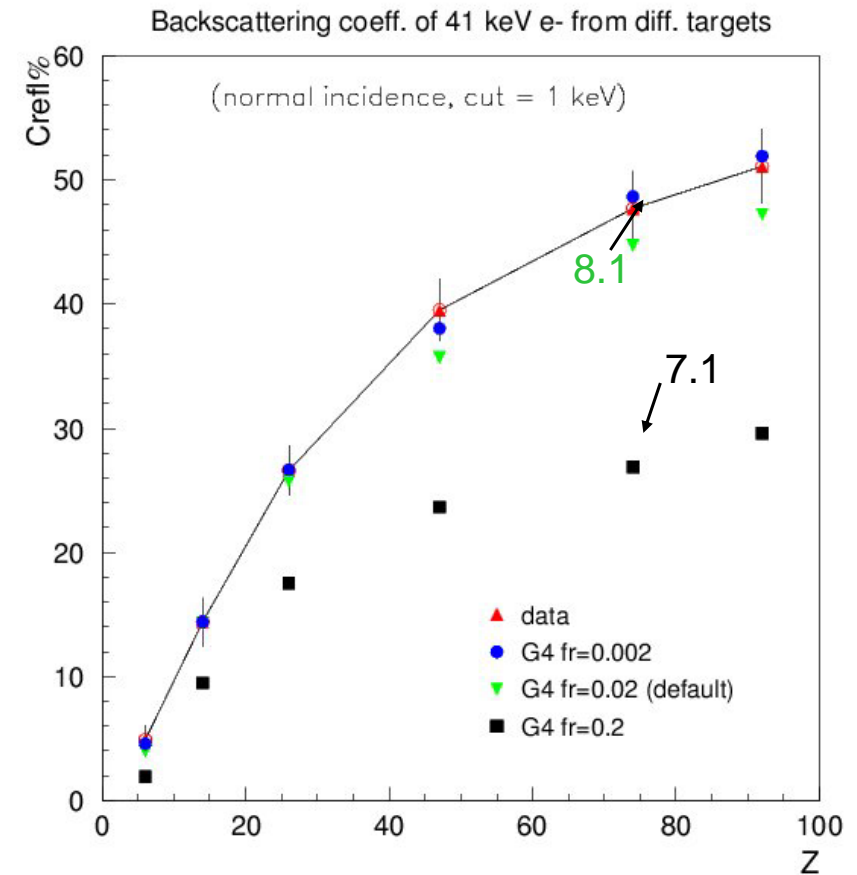
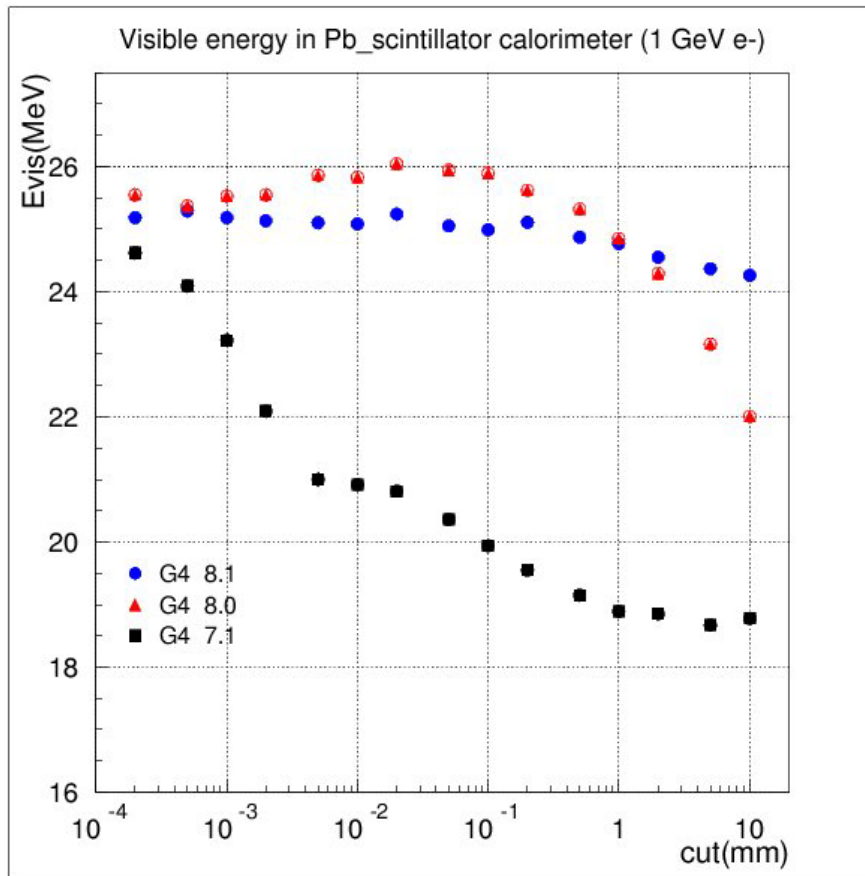
- This constraint must be relaxed when $E \rightarrow 0$



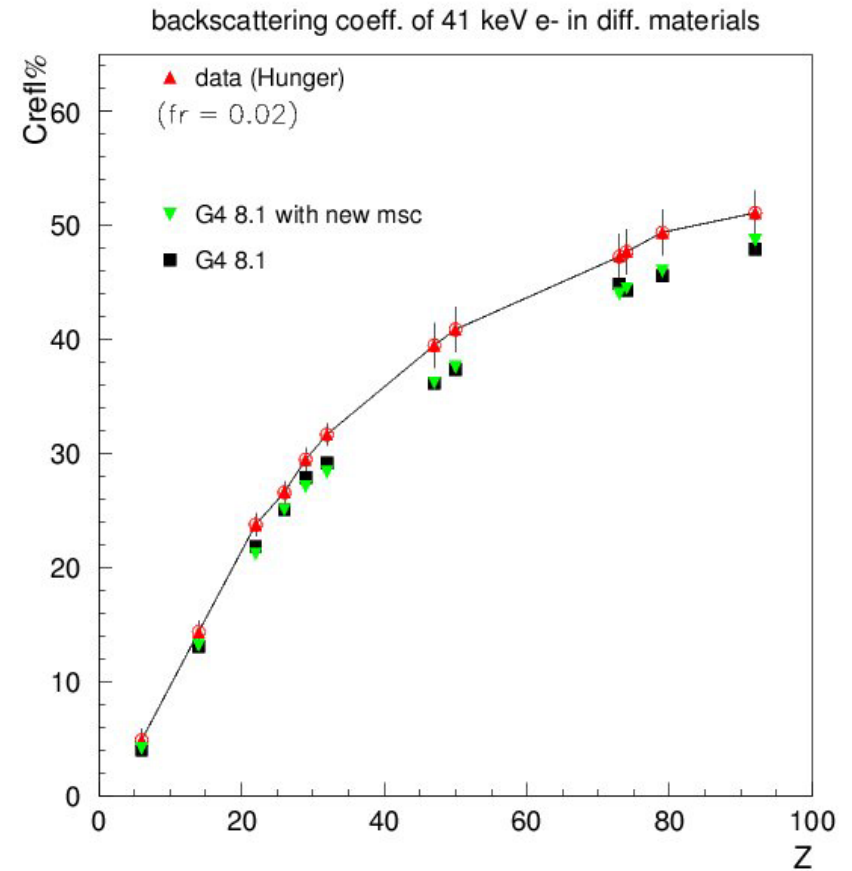
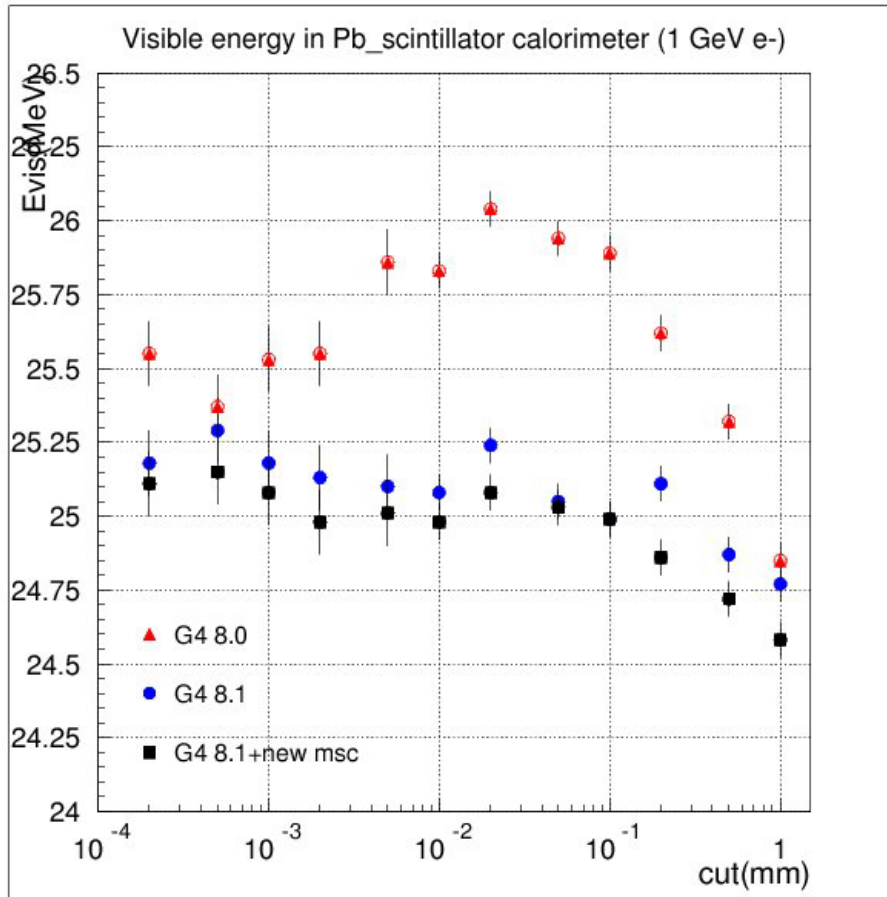
Step limitation competition



Sampling calorimeter : cut dependance

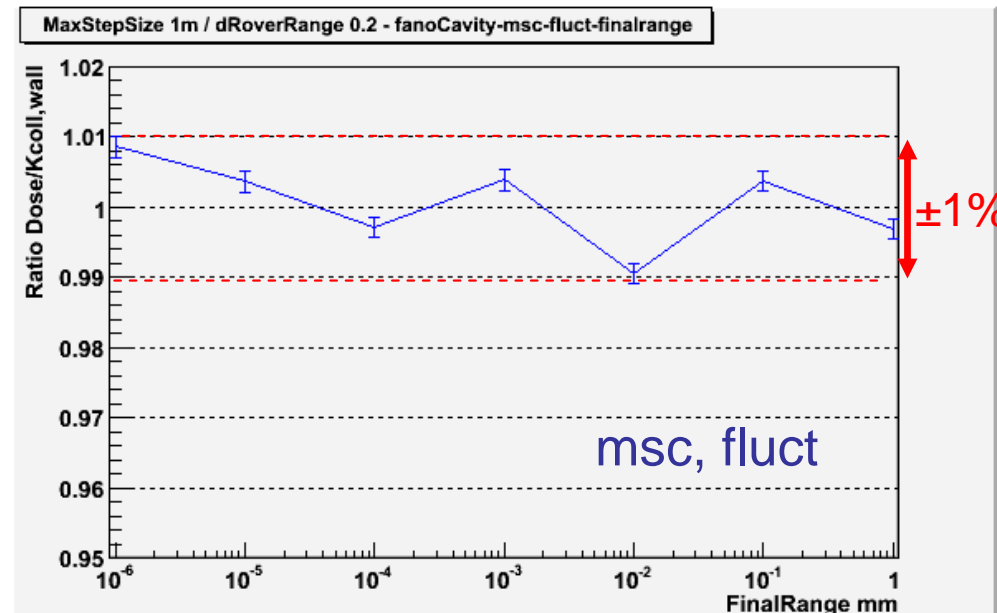
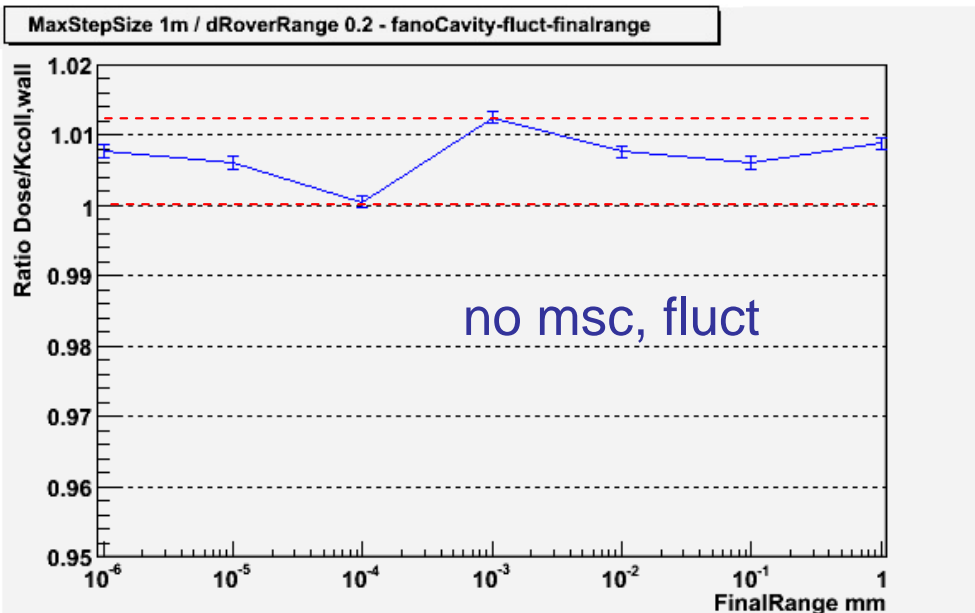
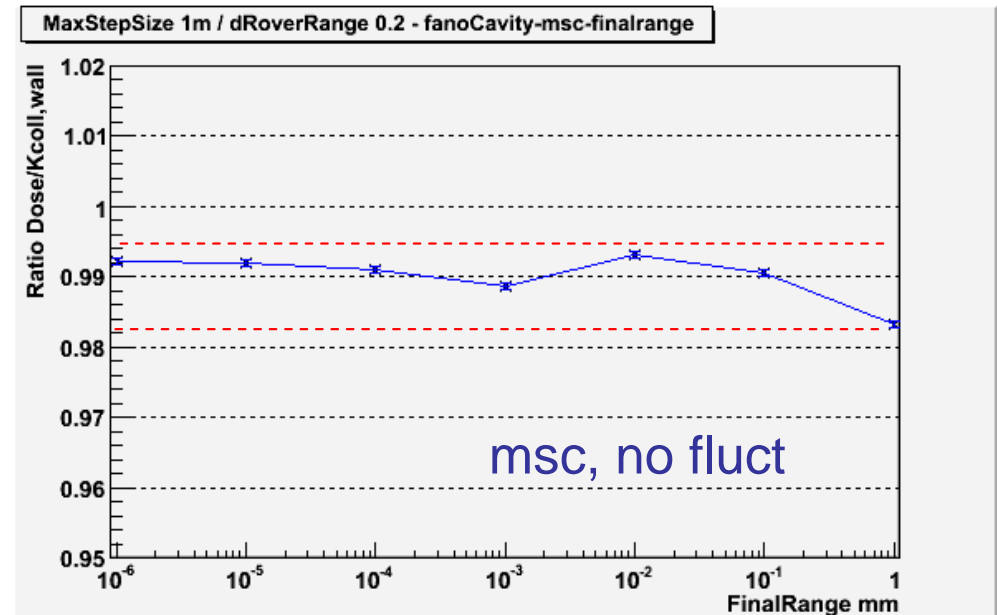
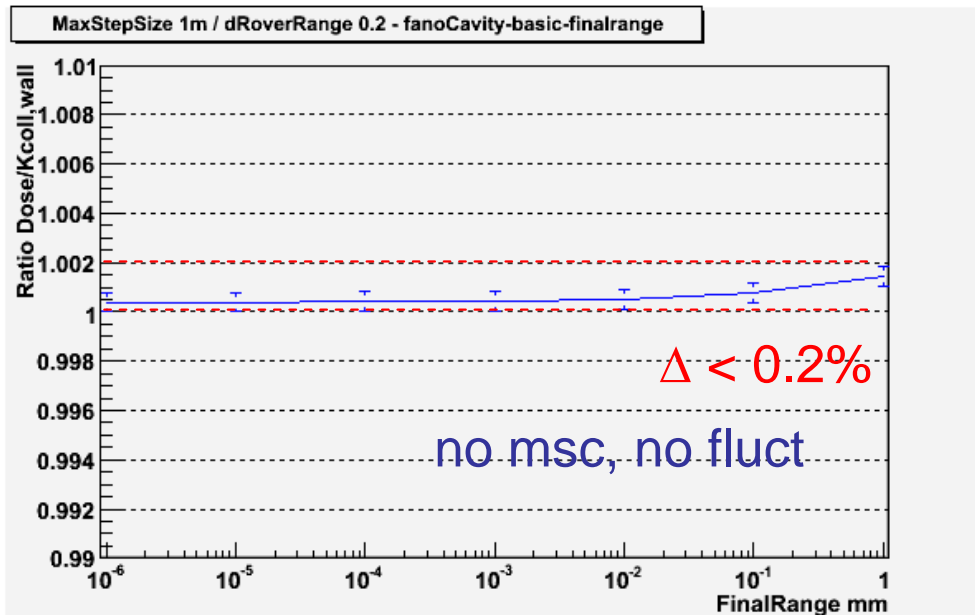


beyond 8.1 : single scattering and effective facrange



no big change, but slightly faster anyway

fanoCavity example : finalRange



Statistics : more than 10⁶ electron entering the cavity