How to check the proton csda range ?

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Csda range

$$R(E) = \int_{e=0}^{e=E} \frac{1}{f(e)} de \qquad f(e) \equiv \left(\frac{dE}{dx}\right)_{full} = \text{Bethe - Bloch formula}$$

- Full = unrestricted = no delta-rays generation

  → infinity cut (> maximum transferable energy)

- In addition :

  no energy fluctuation (straggling)

  no multiple scattering

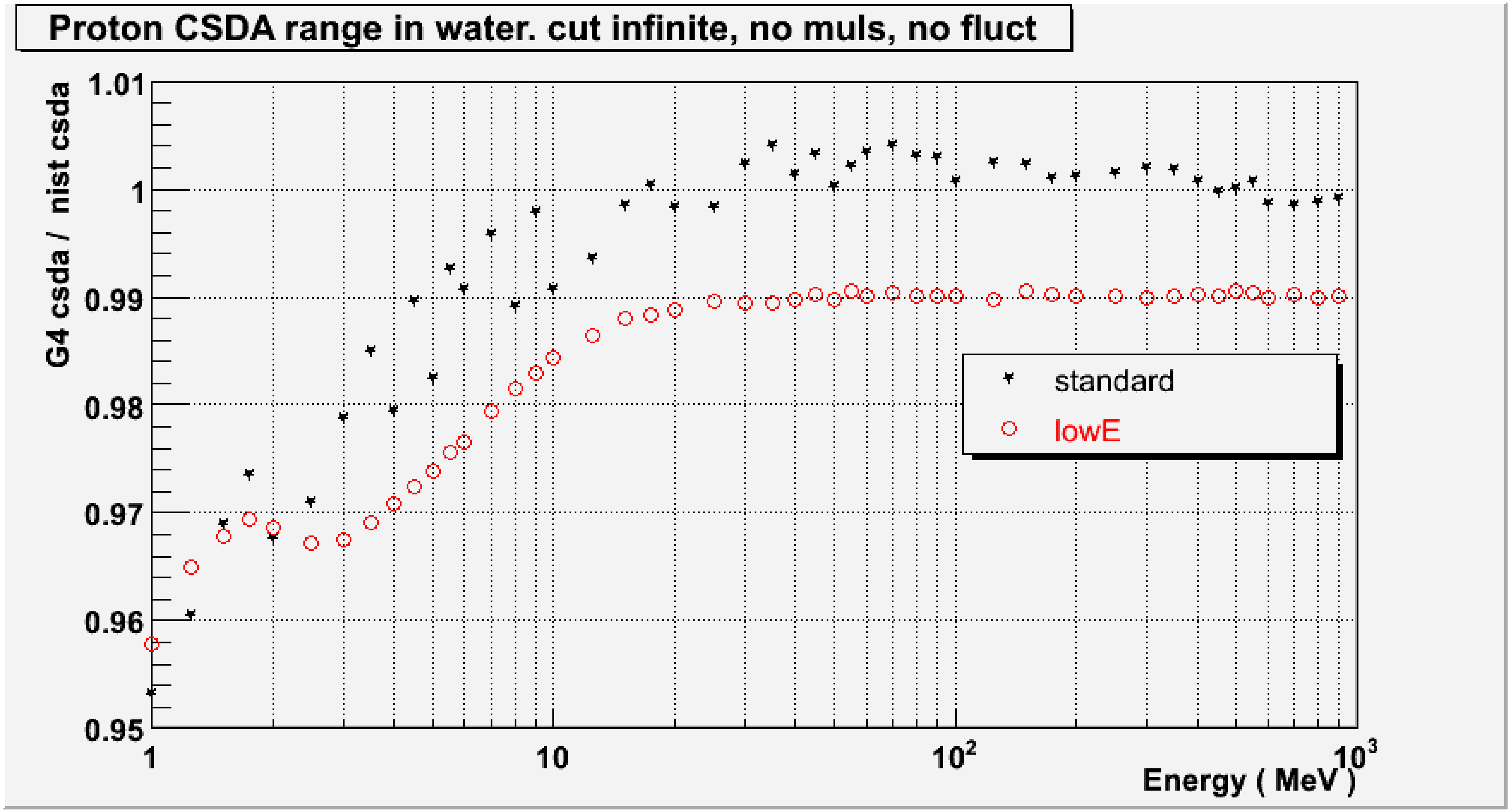
```
********************************************************************************************
* G4Track Information:   Particle = proton,   Track ID = 1,   Parent ID = 0
********************************************************************************************

Step#      X         Y         Z        KineE     dEStep    StepLeng   TrakLeng    Volume     Process
    0     -5 cm      0 fm      0 fm   100 MeV     0 eV       0 fm       0 fm      Water     initStep
    1   2.71 cm      0 fm      0 fm     0 eV    100 MeV   7.71 cm    7.71 cm      Water        hIoni


---------------------------------------------------------
 Primary particle :
 true Range = 7.7068 cm     rms = 2.52 Ang
 proj Range = 7.7068 cm     rms = 2.52 Ang
 proj/true  = 1
 transverse dispersion at end = 0 fm

      mass true Range from simulation = 7.7068 g/cm2
       from PhysicsTable (csda range) = 7.7068 g/cm2
---------------------------------------------------------
```

```
#
# Macro file for "TestEm1.cc"
#
# compute the csda range of the primary particle
# with or without fluctuations
#
/testem/det/setMat Water
/testem/det/setSize 10 cm
#
/testem/phys/addPhysics  standard
###/testem/phys/addPhysics  livermore
#
/run/initialize
#
# prevent any secondary production
/testem/phys/setCuts 1 km
#
# eliminate straggling
/process/inactivate msc
/process/eLoss/fluct false
#
/process/eLoss/StepFunction 1. 1 mm
#
/testem/gun/setDefault
/gun/particle proton
/gun/energy 100 MeV
#
/run/beamOn 20000
```

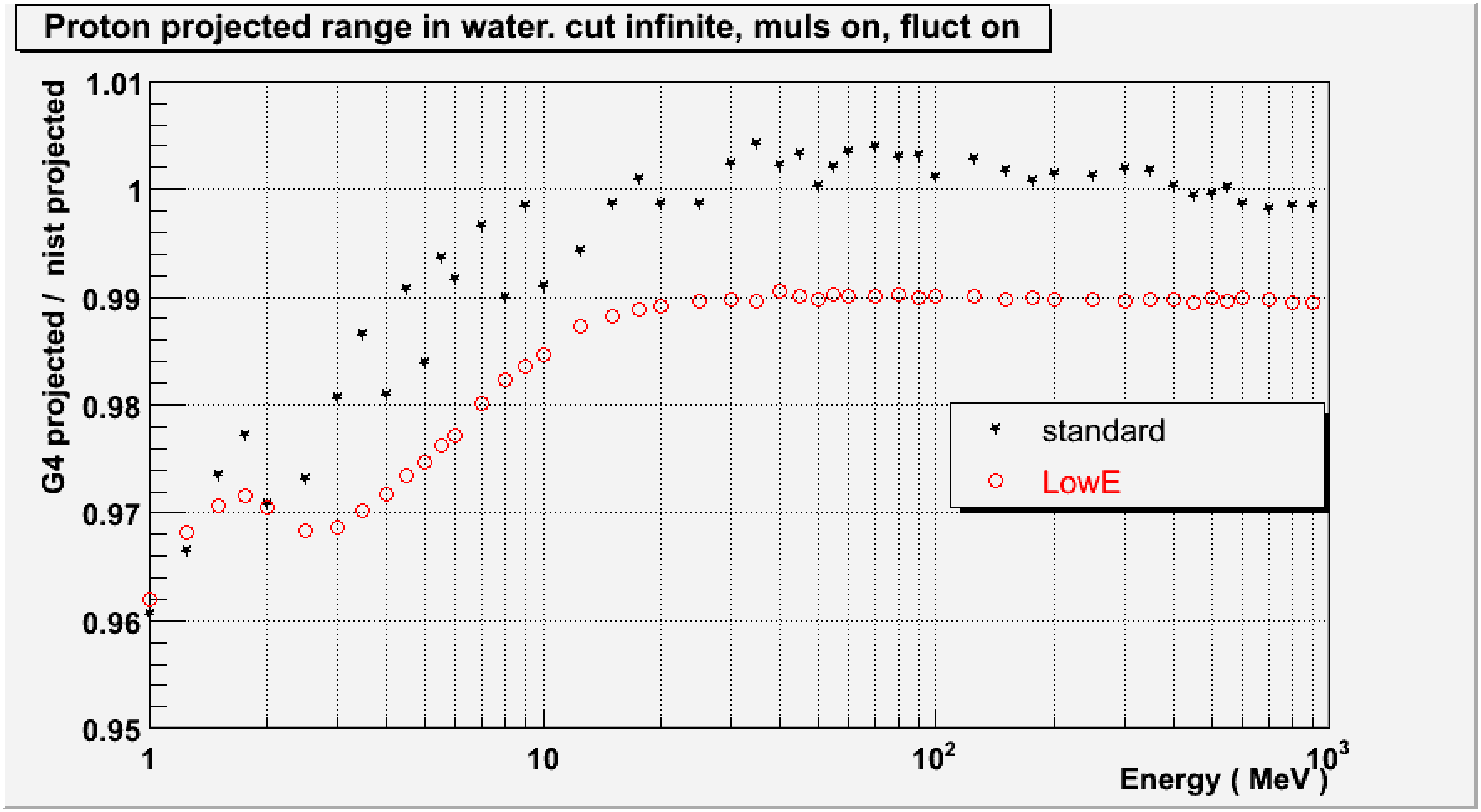
proton 100 MeV in water

nist : 7.718 g/cm^2

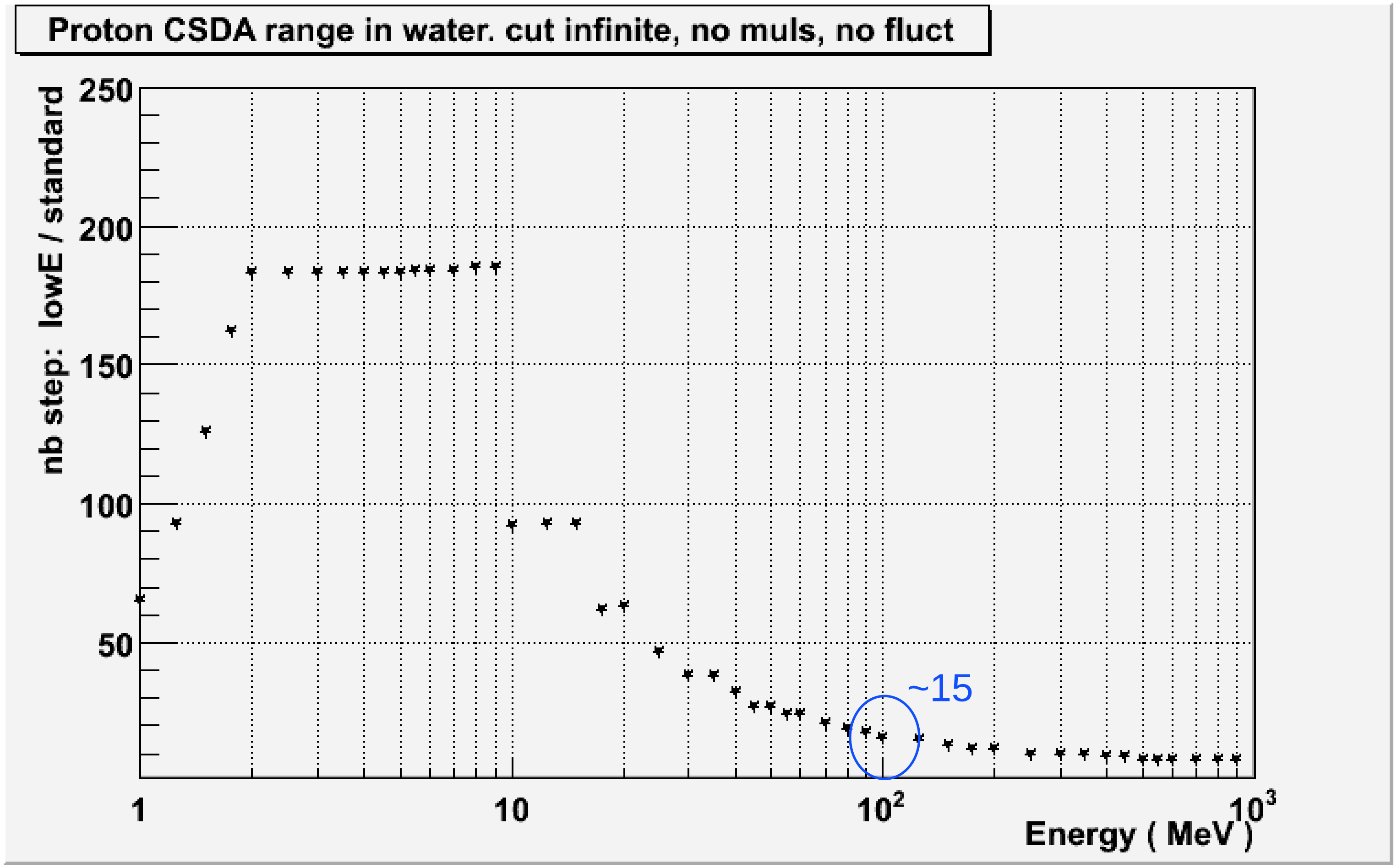
Csda range : Geant4 / Nist



Projected range : Geant4 / Nist



Nb steps : lowE / stand



Geant4: e^- step limitation from physics

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

  → indirect effect : the mean free path between discrete interactions depend of Cut

- Continuous energy loss
  - Max fractional energy loss per step. dR/R < *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 = fr.max(range,λ) fr = *facRange*
  - Geometry : force more than 1 step in any volume : *facGeom*

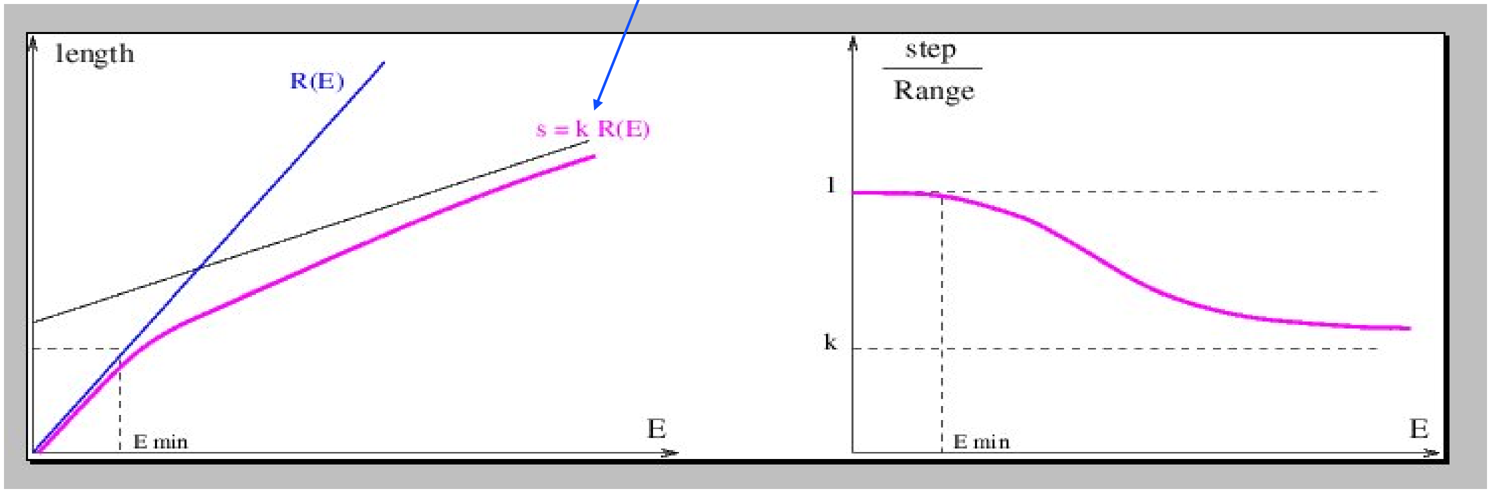
Step limitation from continuous energy loss

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

$$\frac{\text{step}}{\text{Range(E)}} \leq \text{dRoverRange}$$

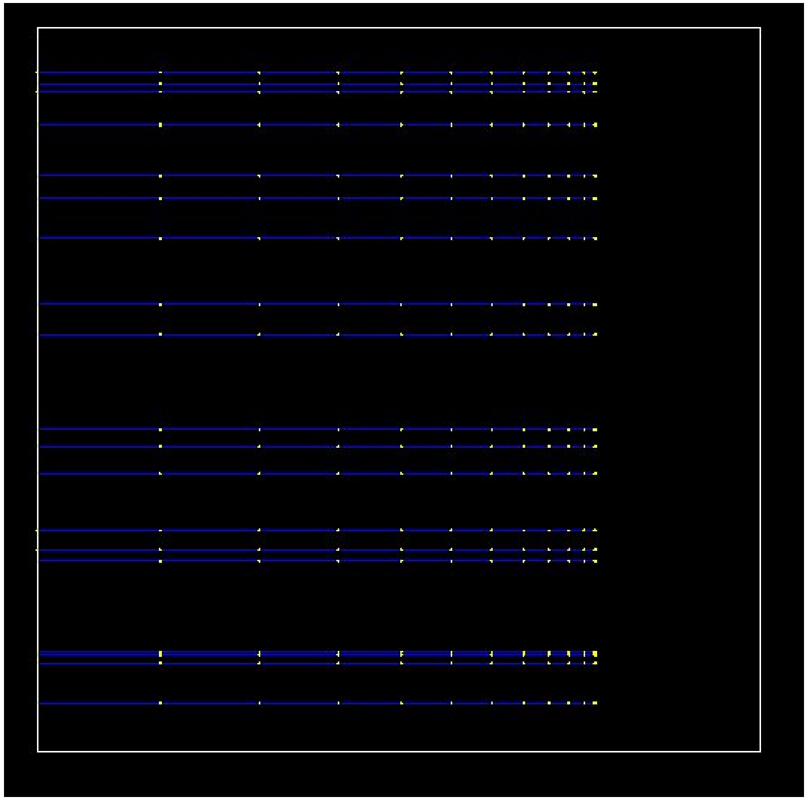
- This constraint must be relaxed when E → 0

finalRange



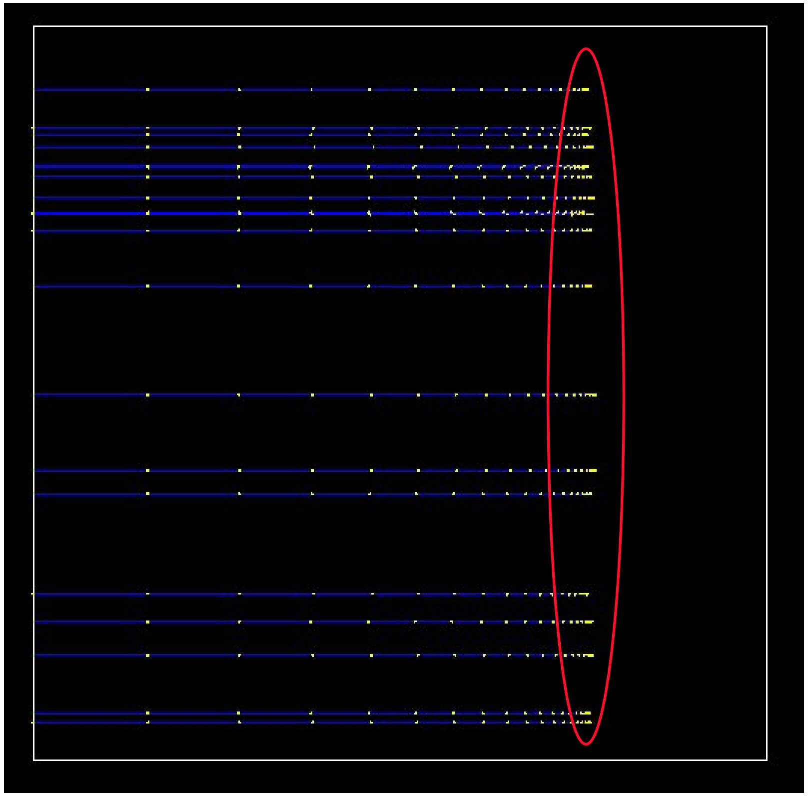
proton 100 MeV in water

standard



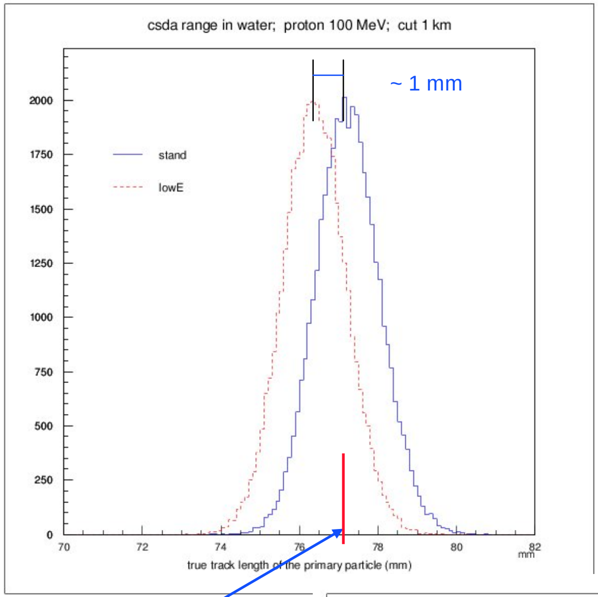
12 steps

lowE



~ 200 steps

proton 100 MeV in water

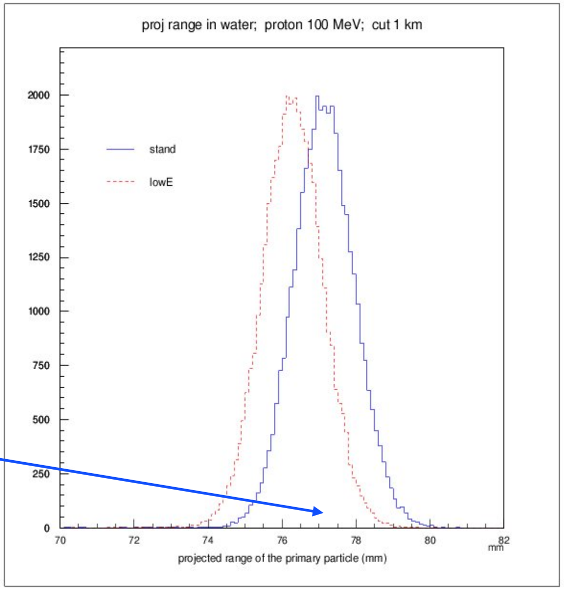



```
#
# Macro file for "TestEm11.cc"
#
# compute the csda range of the primary particle
# with or without fluctuations
#
/testem/det/setMat Water
/testem/det/setSizeX  10 cm
/testem/det/setSizeYZ 10 cm
#
/testem/phys/addPhysics  standard
##/testem/phys/addPhysics  livermore
#
/run/initialize
#
# eliminate straggling
##/process/eLoss/fluct false
##/process/inactivate msc
#
# prevent any secondary production
/testem/phys/setCuts 1 km
#
/gun/particle proton
/gun/energy 100 MeV
#
/testem/histo/setFileName stand
/testem/histo/setFileType hbook
/testem/histo/setHisto 1 200 70 80 mm    # edep profile
/testem/histo/setHisto 3 200 72 82 mm    # track length
/testem/histo/setHisto 5 200 72 82 mm    # proj range
#
/run/beamOn 40000
```

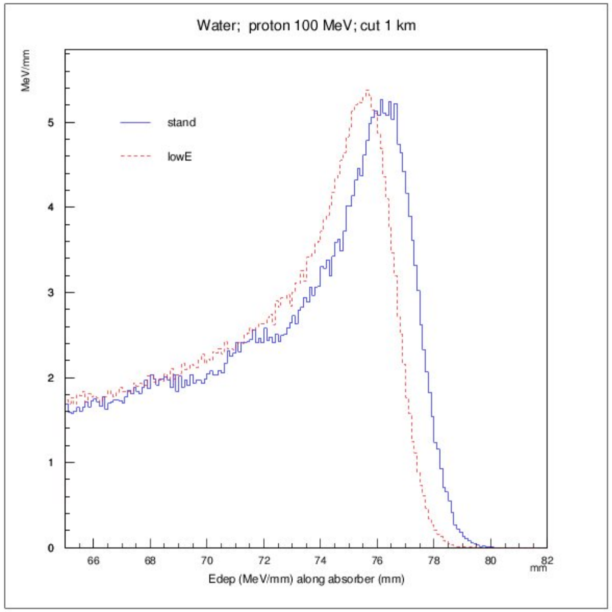
csda condition

time : lowE / stand > 10

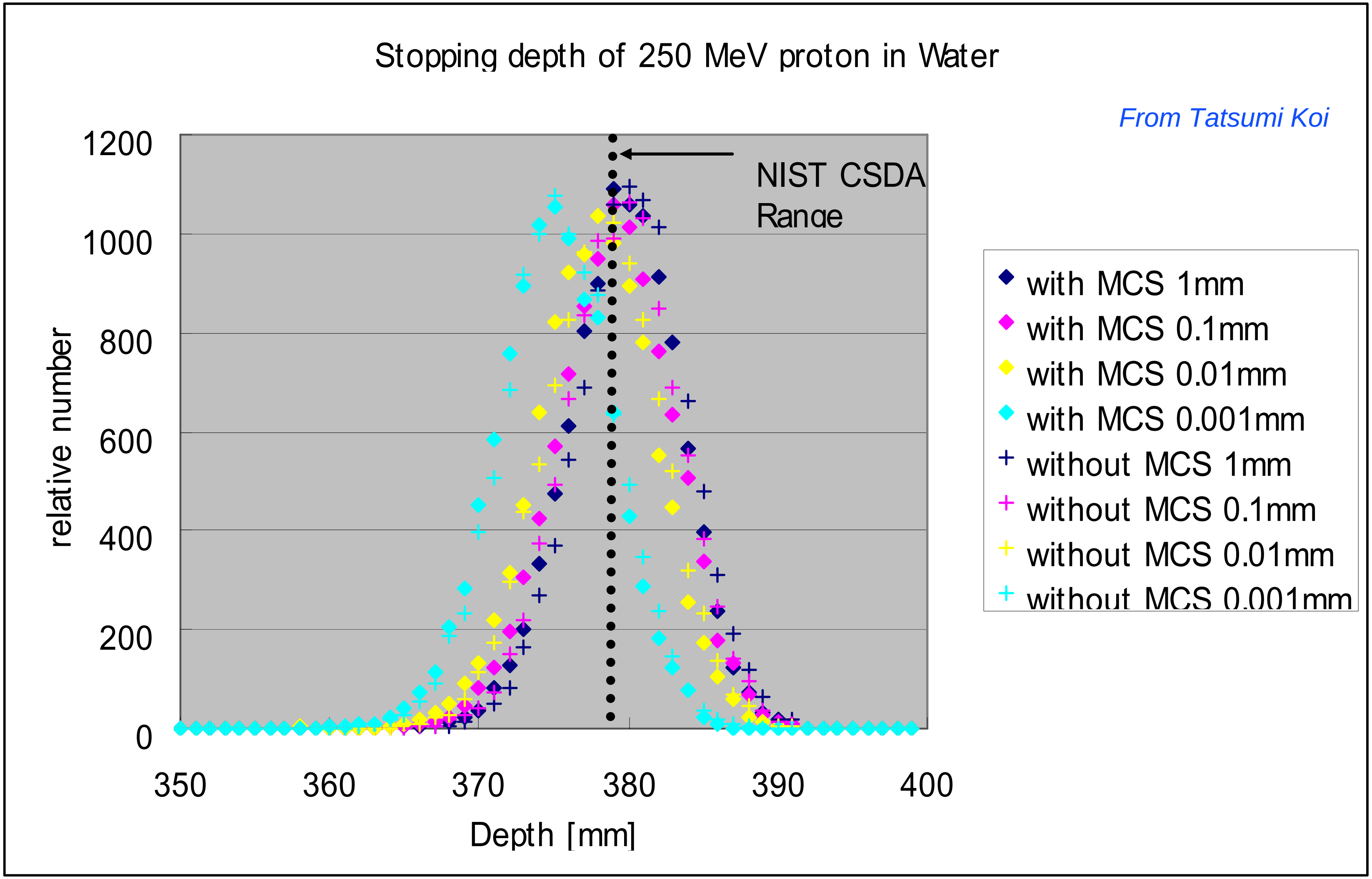
nist :
77.18 mm



nist : 77.07 mm

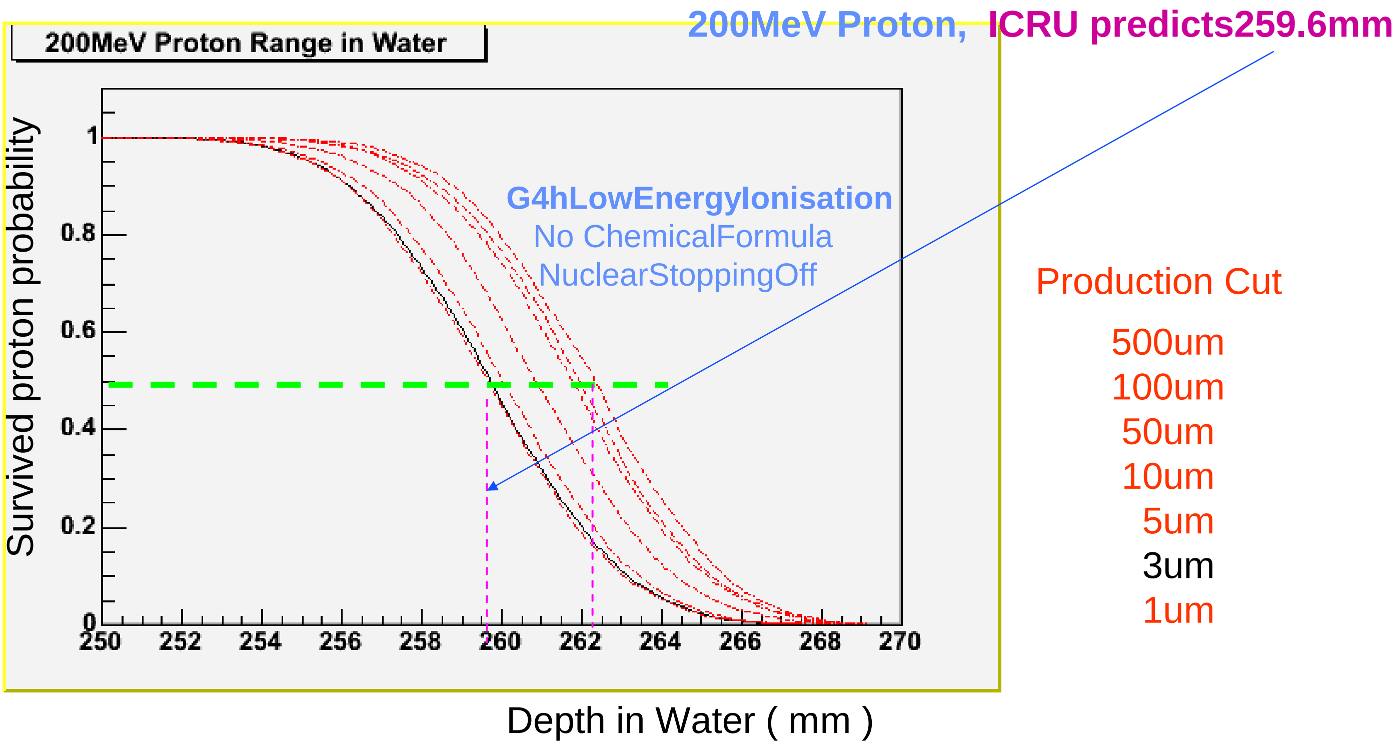


Is range shifting with cuts-values?



Cuts-value dependance ?

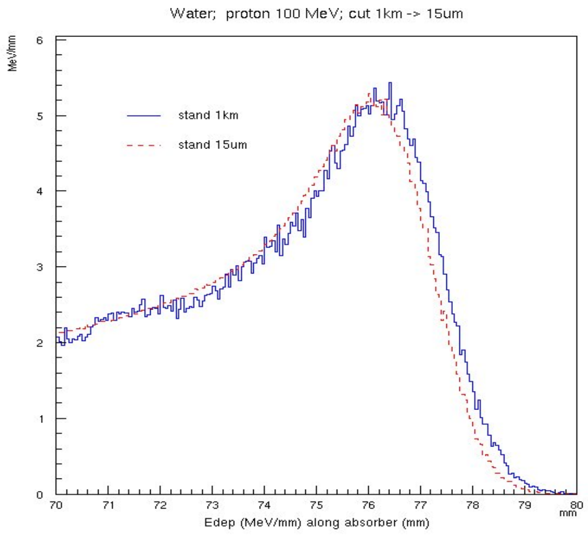
- Hadron therapy using protons for cancer treatment requests better than 1% agreement with measurements and ICRU/NIST protocol data.
- We had reported a proton range shift problem in water about 1 year before. i.e. the range of 200 MeV proton become longer about 3 mm than NIST range by applying a longer production cut.

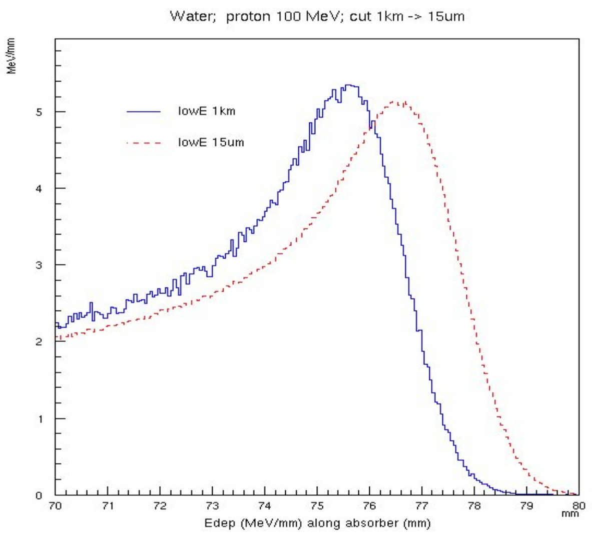


From Tsukasa Aso

not coherent with previous slide

proton 100 MeV in water : cut saga



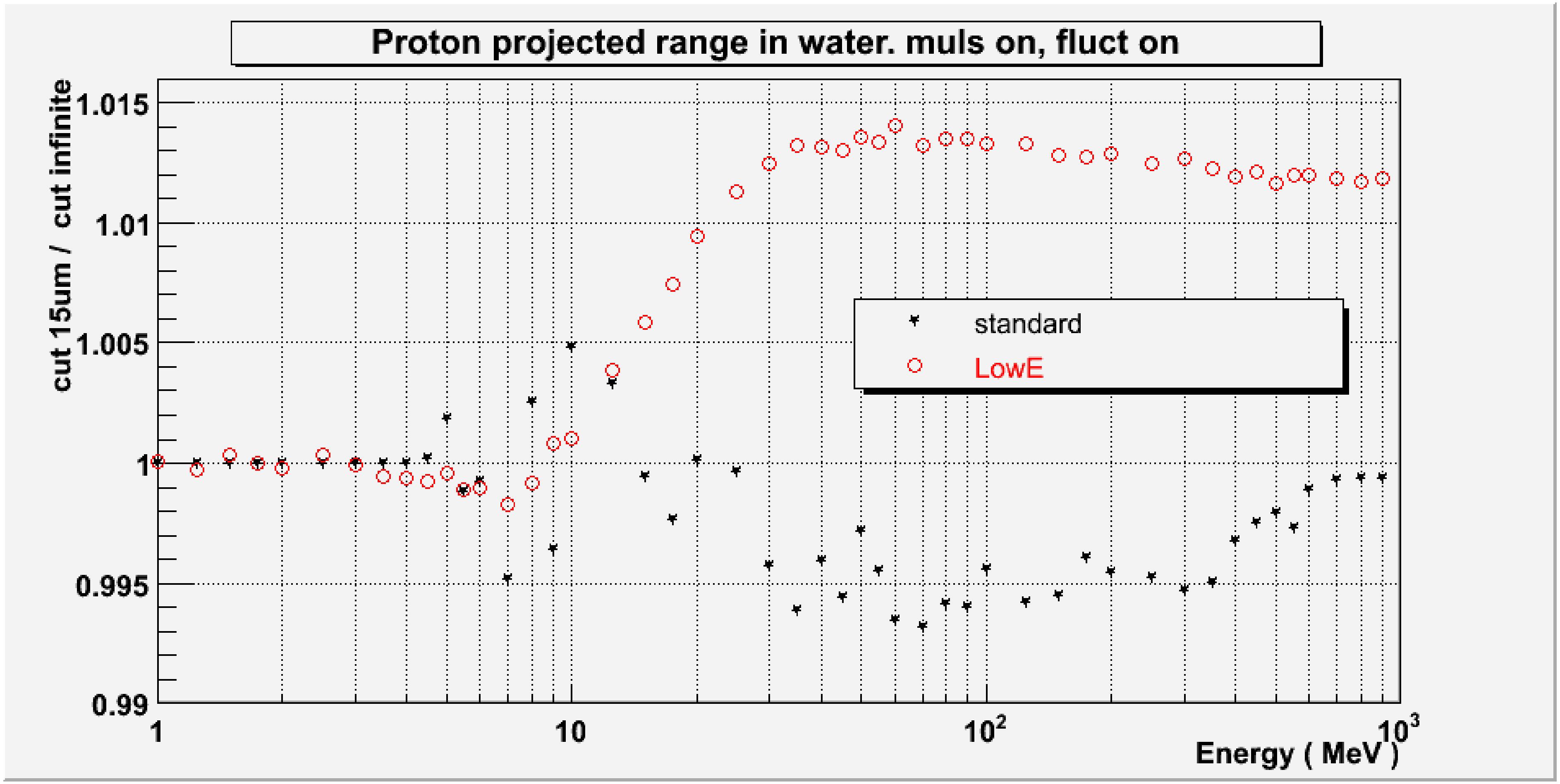


Proj. range	standard	lowE
cut 1 km	77.13 mm	76.29 mm
cut 15 um (~10 keV e^-)	76.82 mm	77.30 mm
$\frac{15\,um - 1km}{1km}$	- 0.4 %	+ 1.3 %
nist : 77.07 mm	- 0.3 %	+ 0.3 %

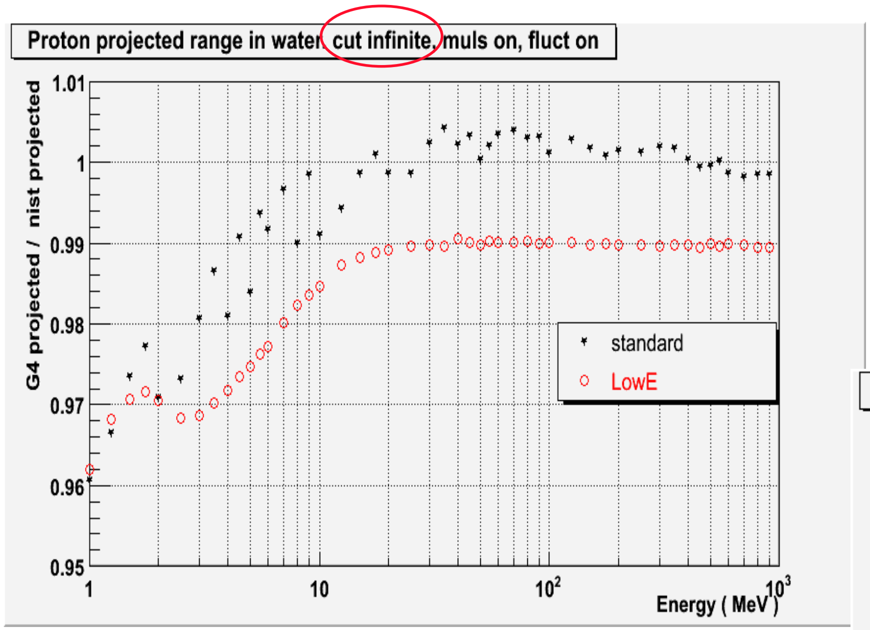
time: lowE/stand ~ 2

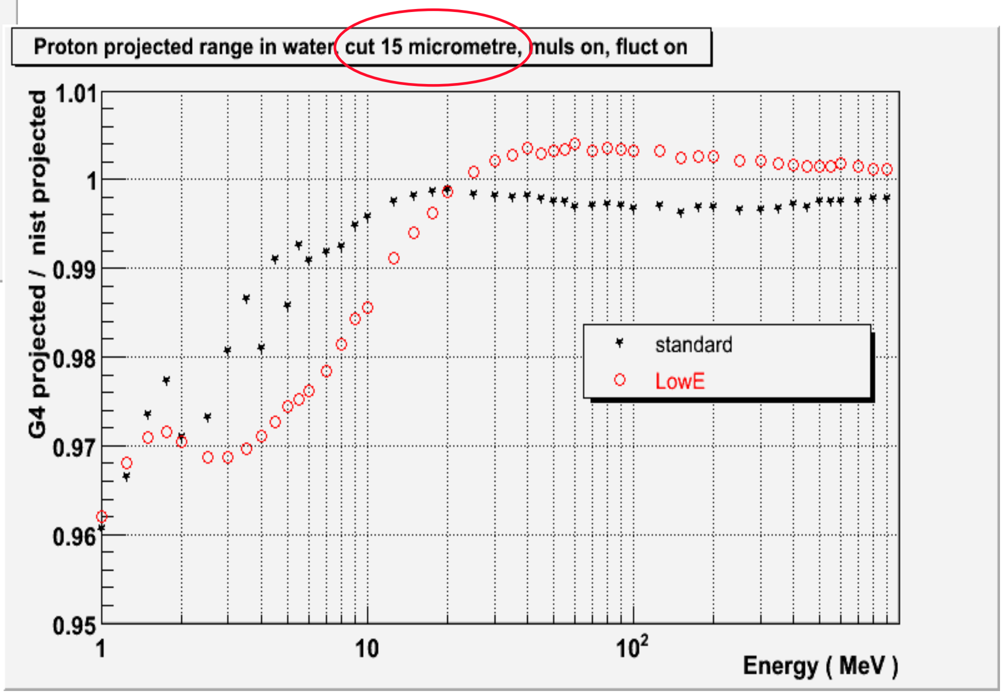
by chance ?

Projected range : cut 15 um / infinite



Projected range : Geant4 / Nist





proton range in water - summary

→ G4hLowEnergyIonisation (lowE) versus G4hIonisation (stand)

- In csda condition, lowE is off by 1% for all energies above ~ 20 MeV
- It is at least 10 time slower than stand, due to an excessive step limitation
- Proton range varies with production threshold
  - within 1% for stand
  - 1-2% for lowE
- With low cut, both agree with nist values at all energies above 20 MeV, within 0.5%
- Then, lowE is 'only' ~2 time slower than stand