# Status of the G4-Med tests for bio-medical applications

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On behalf of the Geant4 Medical Simulation Benchmarking Group

**27th Geant4 Collaboration Meeting, Rennes, France, 26th-30th September, 2022**

# Tests with Geant4 11.p01 in geant-val

## Tests done with:

- Bremmstrahlung
- Fano Cavity
- Dose Point Kernels
- LowEProtonBraggBeak
- Microyz
- Photon attenuation
- Brachy-Ir
- ElecBackscattering
- ElecForwardScattering
- NeutronYield
- Mammo
- BraggPeakGSI_MT
- LowEC12Frag
- NucNuclInelXS
- ProtonC12BraggPeak

## In the process

- CCCTest
- C-12 Frag
- TestDEDX2
- Hadrontherapy
- Heavy ion therapy

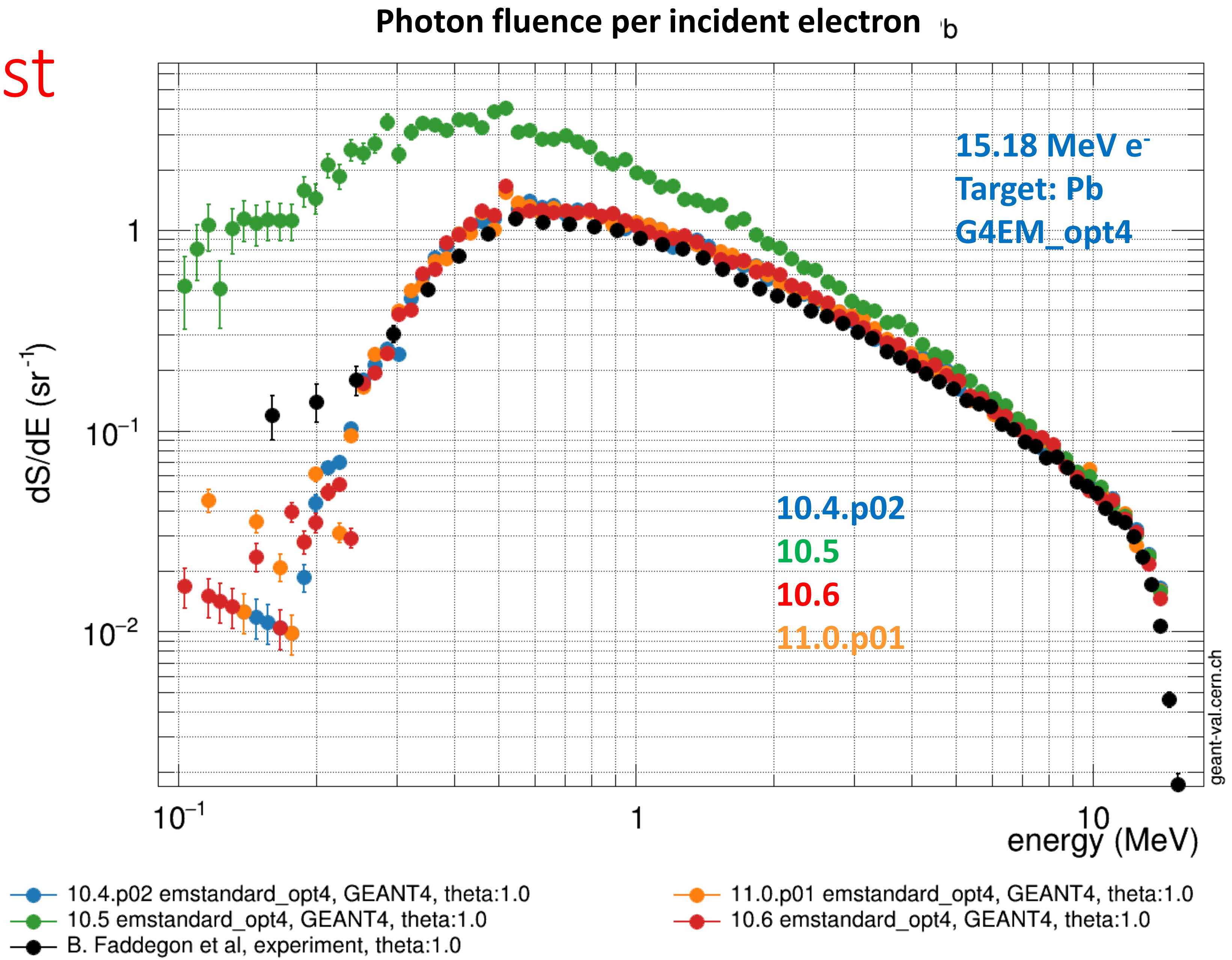
- All tests are migrated to Geant4 11.00.p01
- Analysis is performed with Geant4 analysis (no dependency from external ROOT libraries) apart from C-12 Frag test (under migration)
- All tests have a History file to track changes

# Results

- **Regression testing**: Geant4 10.5, 10.6, 11.0 p01
- **To note**:
  - I will just comment tests where there are differences with respect to Arce et al, Med Phys, 48 (1), 2021 (data obtained with Geant4 10.5)
  - At this stage the comparison is only qualitative

# Bremsstrahlung test

- 10.5 is the "outlier"
- Consistent behaviour for all tested EM physics constructors (Livermore, Penelope, EMStandard_option4, GS)
- Option3 should be added to the test



# Fano Cavity test

- Extended example **FanoCavity**
- Change for G4EmStandardPhysics_option3

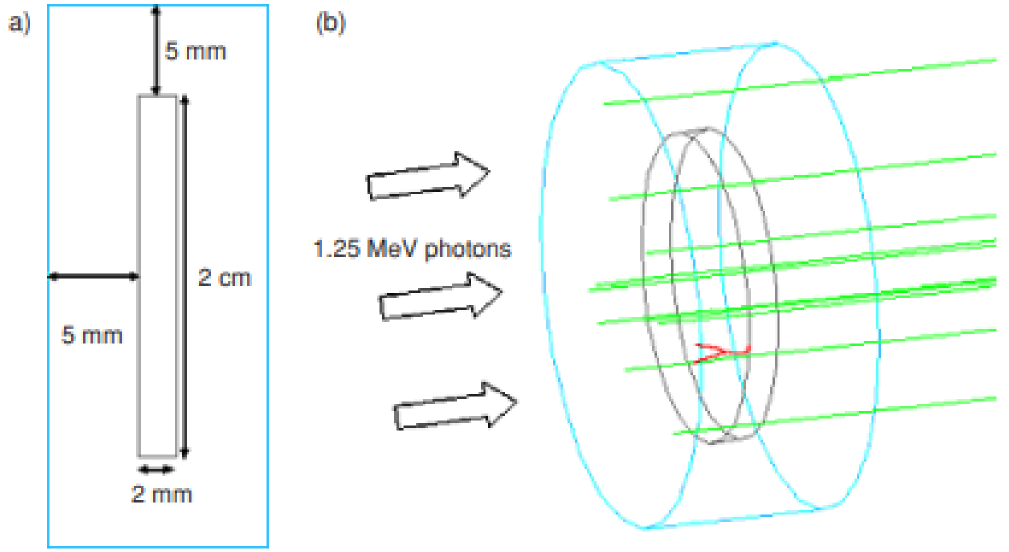
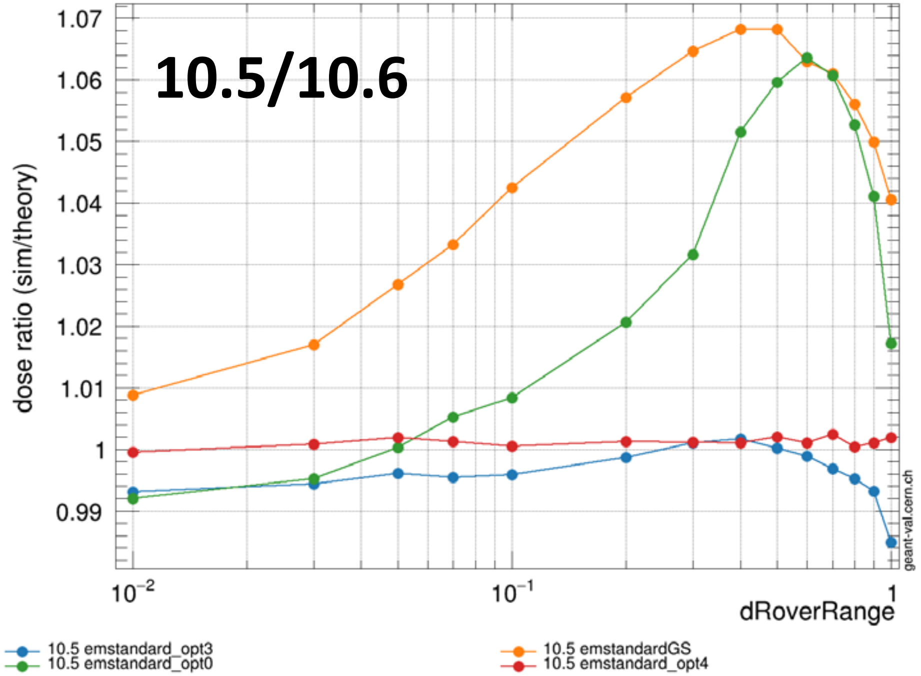
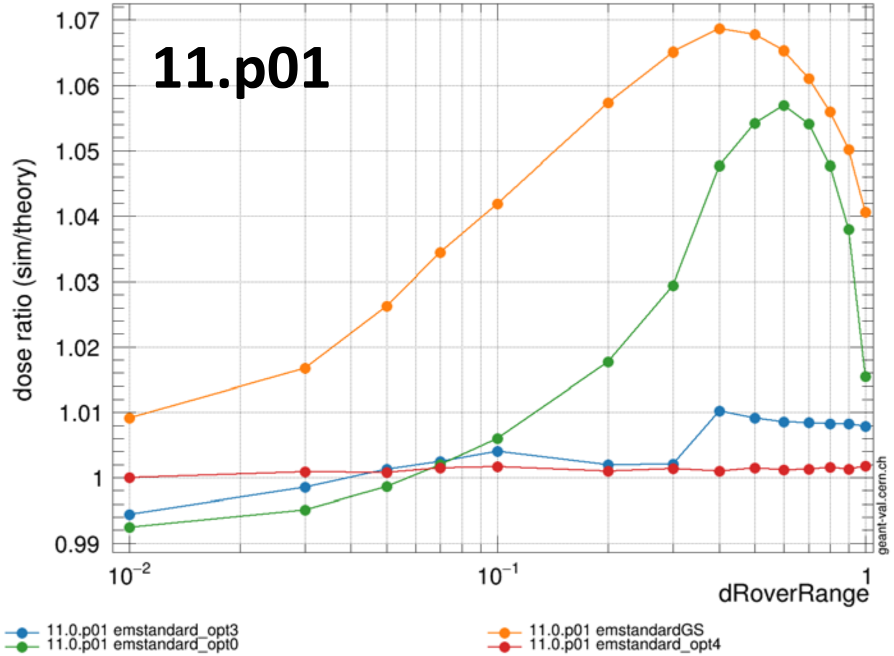



Image courtesy of Poon E, et al Phys Med Biol. 2005; 50:681.

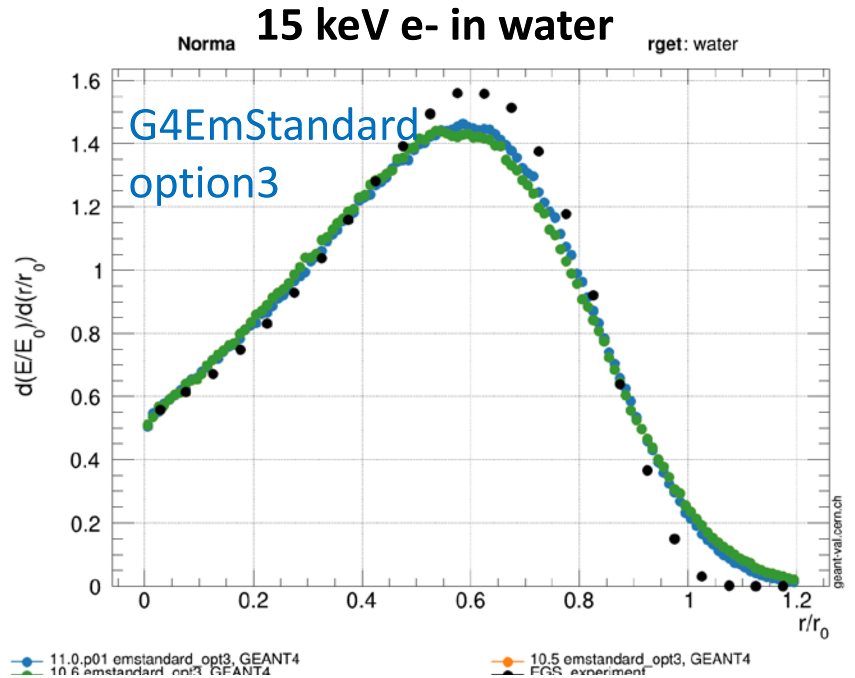
G4EmStandardGS
G4EmStandard_opt0
G4EmStandard_opt3
G4EmStandard_opt4

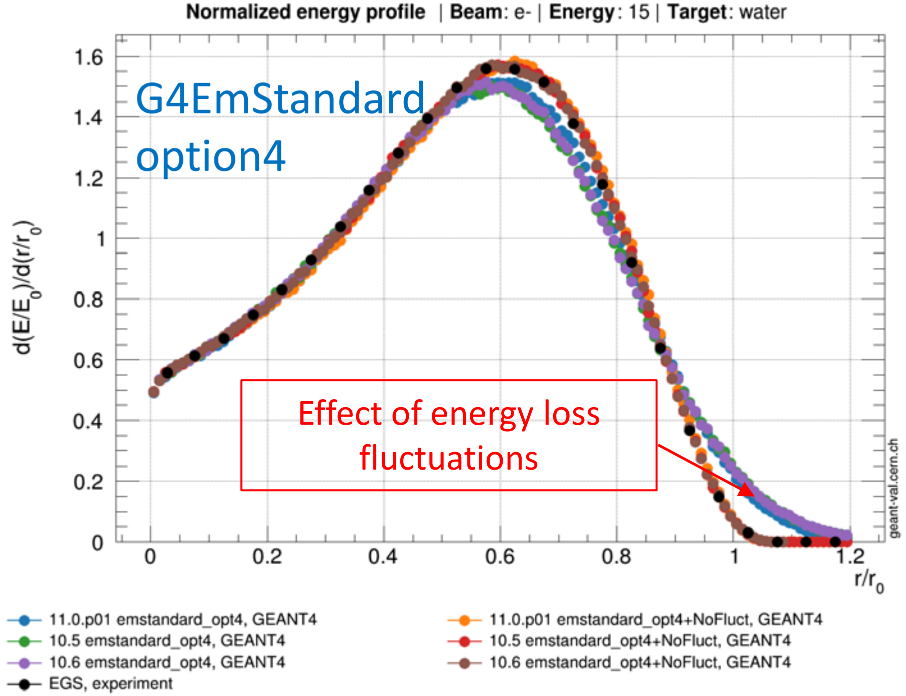


# Dose Point Kernel tests

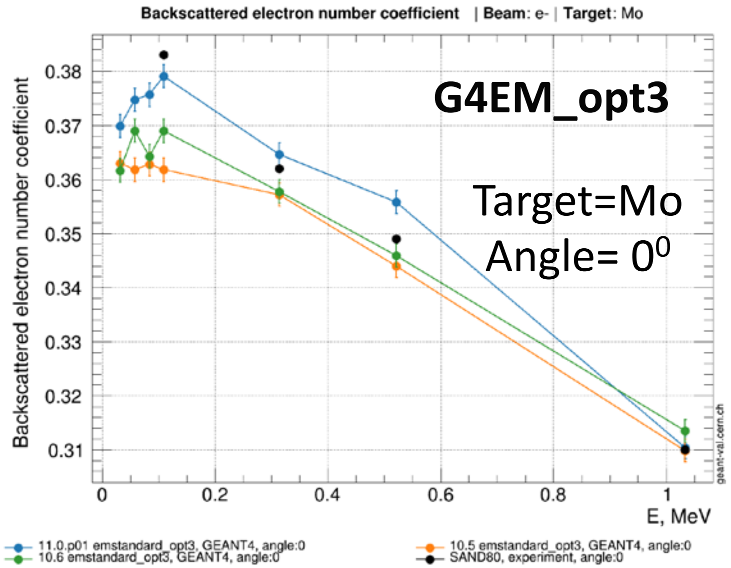
- Calculation of the radial energy deposition profiles from isotropic sources of electrons
- Comparison against EGSnrc with no energy loss fluctuations
  - Goudsmit–Saunderson (GS) in Opt4 provides better agreement
- Same agreement for all the Geant4 versions (10.5, 10.6 and 11.p01)

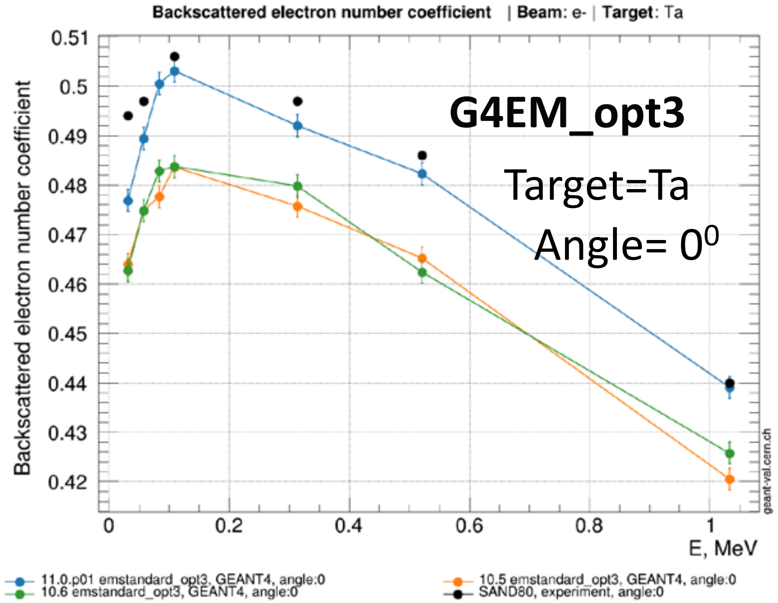


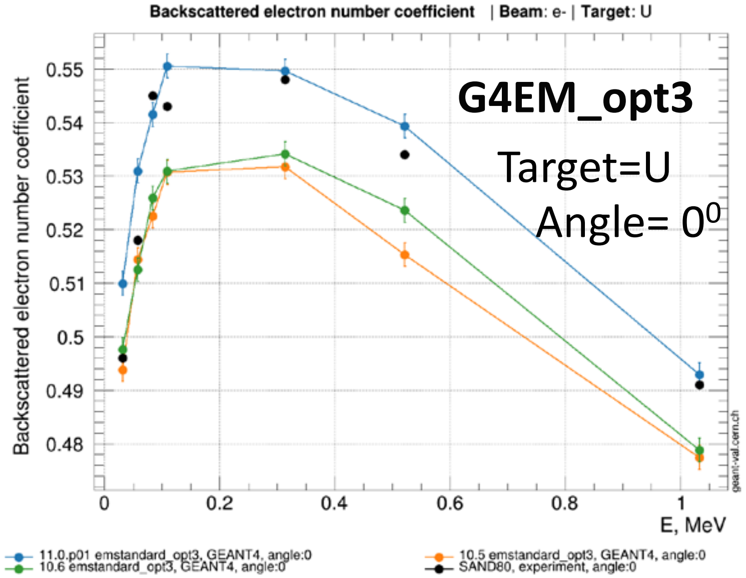



# Electron backscattering tests (1)

**10.5**, **10.6**, **11.0 p01**



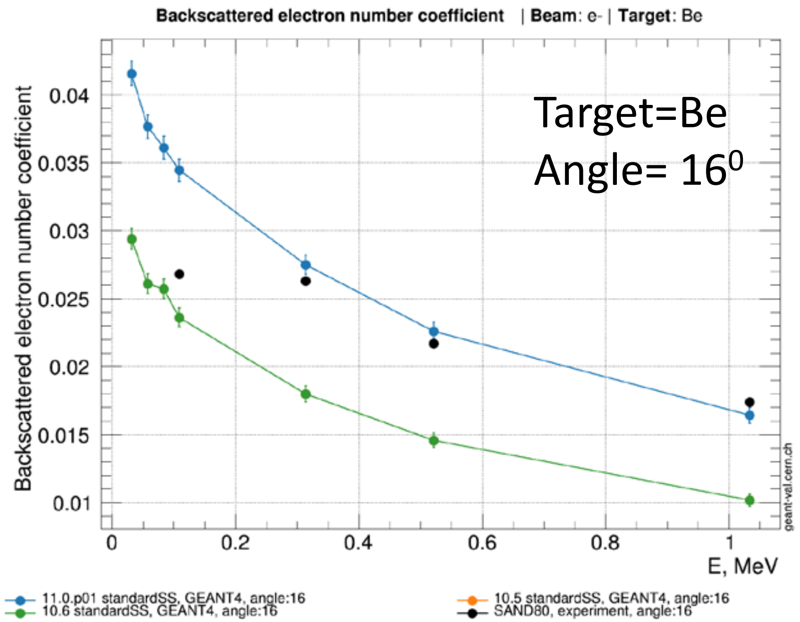



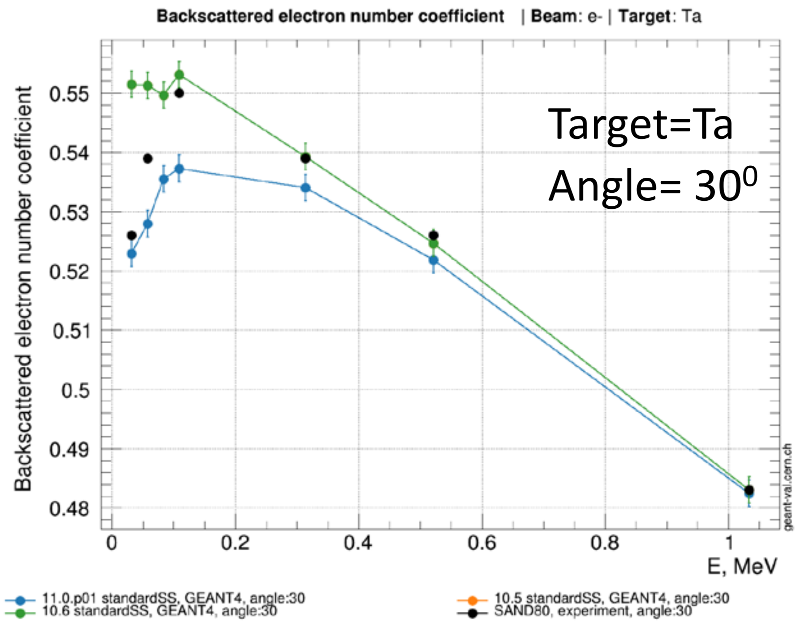

- Better agreement in terms of backscattering coefficient for high Z, for G4EmStandard_option3
  - Probably due to optimisation of the msc parameters
    - RangeFactor=0.03 (from 0.04)
    - Use of 'SafetyPlus' step limitation instead of 'DistanceToBoundary’

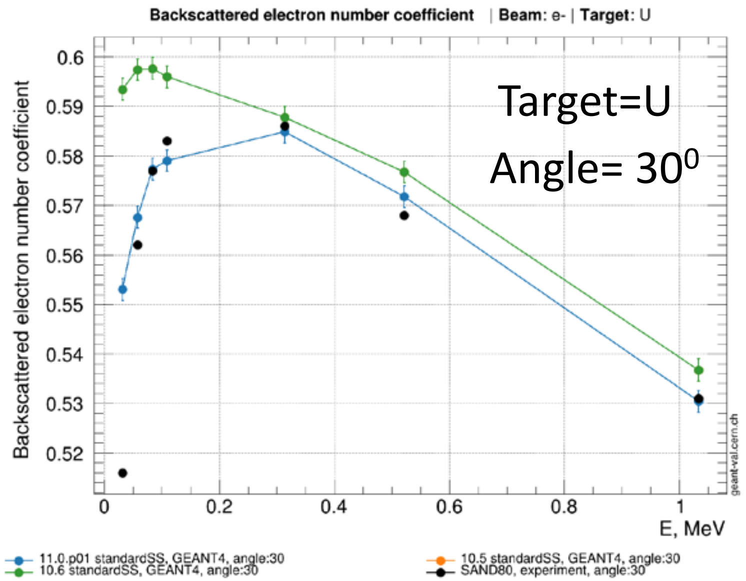
- No change for G4EmStandard_option4, G4EmStandard_GS

# Electron backscattering tests (2)

**G4EmStandardPhysics_SS**



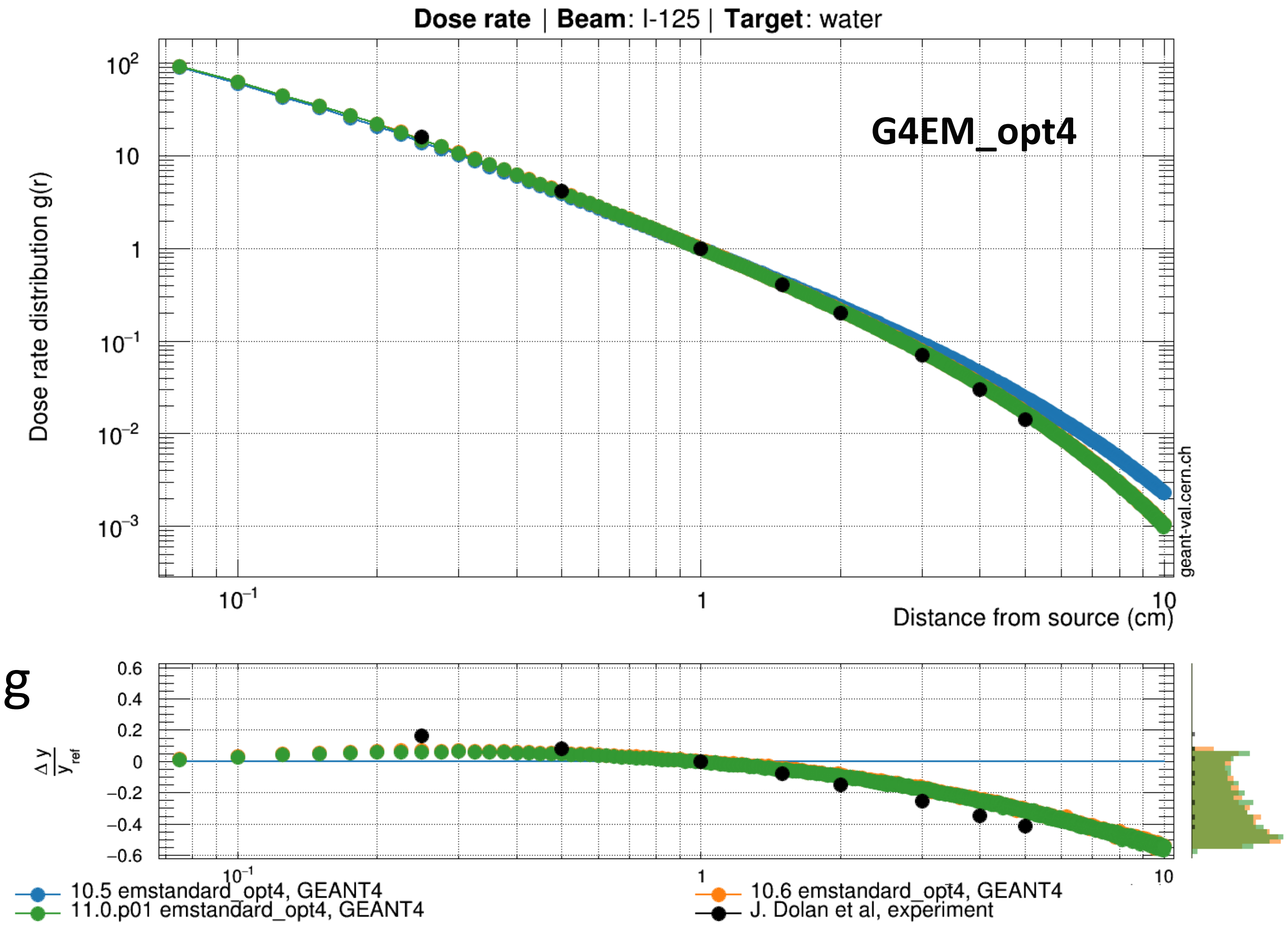

**10.6, 11.0 p01**

It seems there is a general improvement in the Single Scattering model

# Brachytherapy test

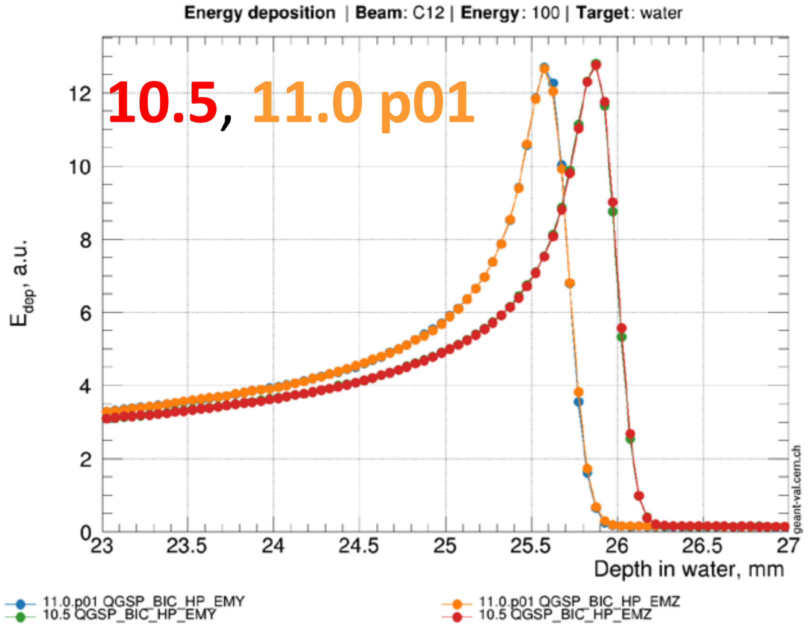


- I-125 brachytherapy source
- Exp measurements: Dolan J et al, Med. Phys. 33:12, 2006
- Since Geant4 10.6 better agreement with reference data at large distances for I-125.
- In G4Penelope, G4Livermore, G4EMOpt3, G4EmOpt4
- Probably due to multiple scattering
- Same results between 10.6 and 11.00.p01

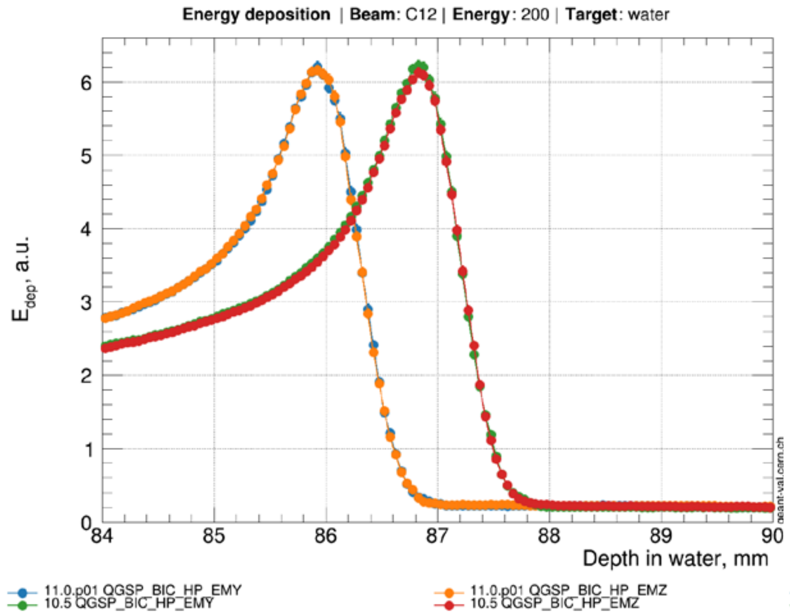


# Proton and carbon ion beam ranges in water

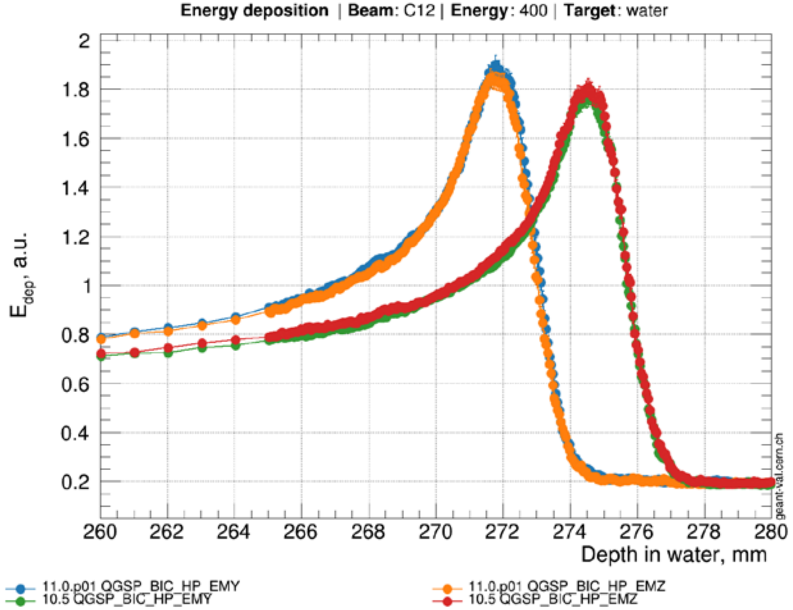
100 MeV/amu $^{12}C$




200 MeV/amu $^{12}C$




400 MeV/amu $^{12}C$




- Same results for incident protons and alpha particles
- Significant differences for carbon ions deriving from the new ion ionisation model G4LinhardSorensenIonModel with ICRU73 and ICRU90 data for energy < 2 MeV/amu, Linhard-Sorensen model above.
- Now this has been solved in the Geant4 11.1 beta release.
- Comment: it would be important to find a way to run all the tests before beta and public releases to support the development of Geant4 physics.

# The G4-Med suite

**UR:** extend the tests to  other medical applications

- 19 tests, on geant-val
- In-vivo PET C-12 test included after Geant4 10.5

**- Next in the pineline:**

- Include Geant4-DNA physics lists where applicable (e.g. Microdosimetry and DPK)
- X-ray small field dosimetry – Susanna Guatelli, Ilia Filipev and Giordano Biasi, CMRP, UOW – ready to be included in geant-val
- Include EPICS17 data libraries in the photon attenuation tests

**- Later:**

- Radioactive decay – L. Desorgher et al
- Nuclear medicine tests – A. Malaroda, S. Guatelli et al
- Photon energy fluence profile and thick target photon backscatter benchmark - By J. Carrasco Hernandez, B. Faddegon and Jose` Ramos Mendez, UCSF
- Calculation of the wall correction factors, kwall, for two graphite ionization chambers – P. Arce
- Include benchmark against ICRU Report 90: Stopping Powers of electrons (and positrons), protons, α particles and carbon ions for three key materials: graphite, air, and liquid water
- Include total inelastic cross section tests of production of C-10 and C-11 important for carbon ion in-vivo PET and Prompt Gamma imaging, E. Simpson, ANU: currently looking for a student to dedicate to this activity
- Validate Medical Linac advanced examples against EURADOS Report 2020-05

# New tests

# Yield and distribution of positron-emitting fragments in heavy ion beam therapy

A. Chacon, M. Safavi et al, ANSTO

Validation against in-house experimental measurements performed at HIMAC, QST, Chiba, Japan

Table 1: Beam parameters for each ion species and energy. All beams had an energy spread of 0.2 % of the nominal energy; 95% confidence intervals are listed for beam flux.

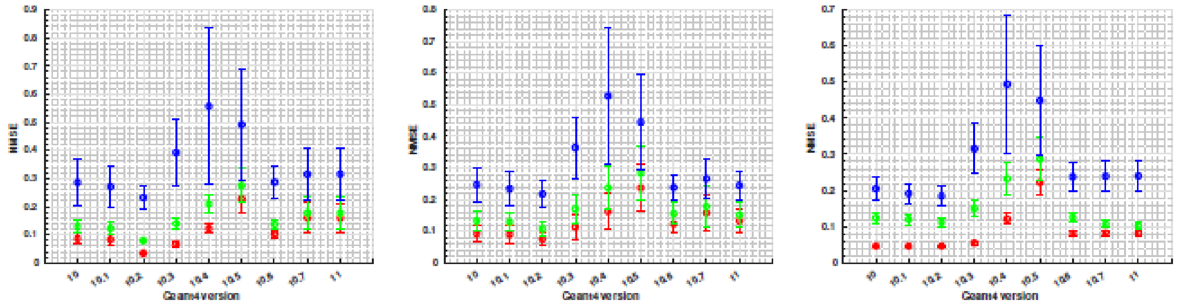
| Ion | Energy (MeV/u) | $\sigma_x$ (mm) | $\sigma_y$ (mm) | Beam flux (pps) |
|---|---|---|---|---|
| $^{12}C$ | 148.5 | 2.77 | 2.67 | $1.8{\times}10^9 \pm 3.8{\times}10^7$ |
| $^{12}C$ | 290.5 | 3.08 | 4.70 | $1.8{\times}10^9 \pm 6.4{\times}10^7$ |
| $^{12}C$ | 350 | 2.50 | 2.98 | $1.8{\times}10^9 \pm 4.6{\times}10^7$ |
| $^{16}O$ | 148 | 2.79 | 2.89 | $1.1{\times}10^9 \pm 2.8{\times}10^7$ |
| $^{16}O$ | 290 | 2.60 | 4.90 | $1.1{\times}10^9 \pm 7.0{\times}10^7$ |

normalised mean square error (NMSE)

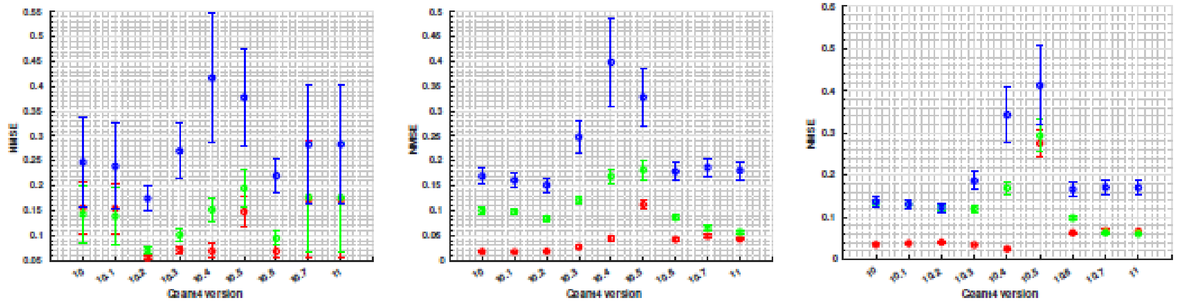
$$NMSE = \frac{\sum_{i=1}^{N_{reg}} |S_i - E_i|^2}{\sum_{i=1}^{N_{reg}} |E_i|^2}$$

BIC,
QMD
INCL

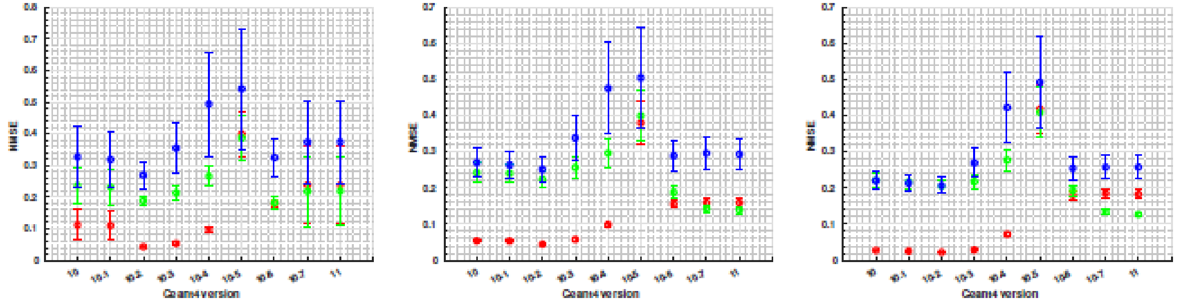
*A quantitative assessment of Geant4 for QA in ion beam therapy* 13



(a) PMMA phantom; 148.5 MeV/u beam (b) Gelatin phantom; 148.5 MeV/u beam (c) Polyethylene phantom; 148.5 MeV/u beam

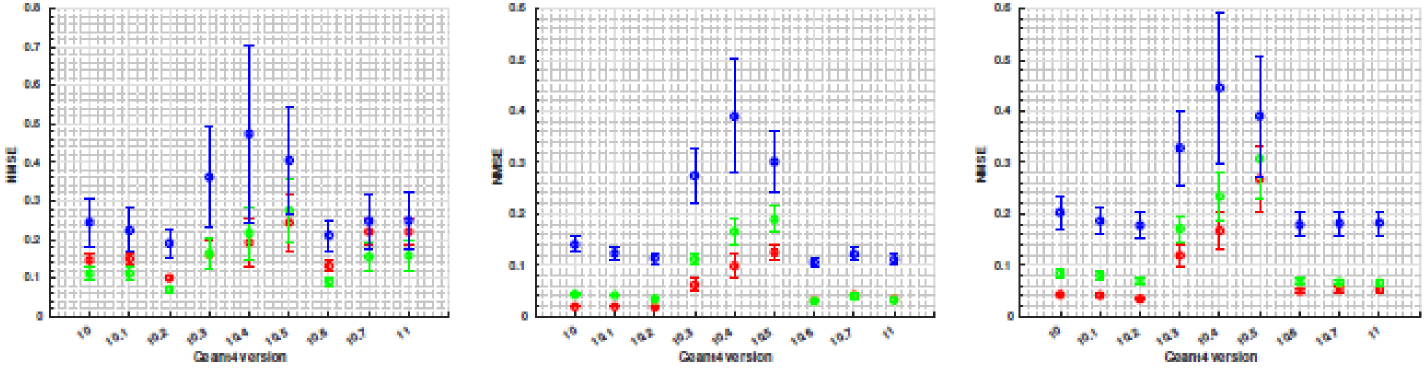


(d) PMMA phantom; 290.5 MeV/u beam (e) Gelatin phantom; 290.5 MeV/u beam (f) Polyethylene phantom; 290.5 MeV/u beam



(g) PMMA phantom; 350 MeV/u beam (h) Gelatin phantom; 350 MeV/u beam (i) Polyethylene phantom; 350 MeV/u beam

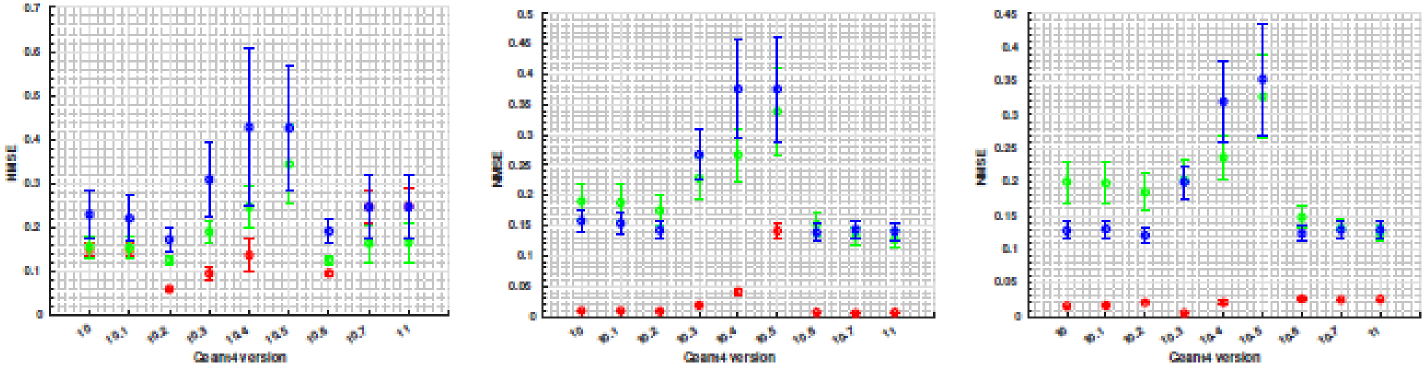
Figure 5: The NMSE in the build-up and Bragg peak region using carbon beams for *all positron emitting fragments*.



(a) PMMA phantom; 148 MeV/u beam

(b) Gelatin phantom; 148 MeV/u beam

(c) Polyethylene phantom; 148 MeV/u beam



(d) PMMA phantom; 290 MeV/u beam

(e) Gelatin phantom; 290 MeV/u beam

(f) Polyethylene phantom; 290 MeV/u beam

Figure 7: The NMSE in the build up and Bragg peak region using oxygen beams for *all positron emitting fragments.*

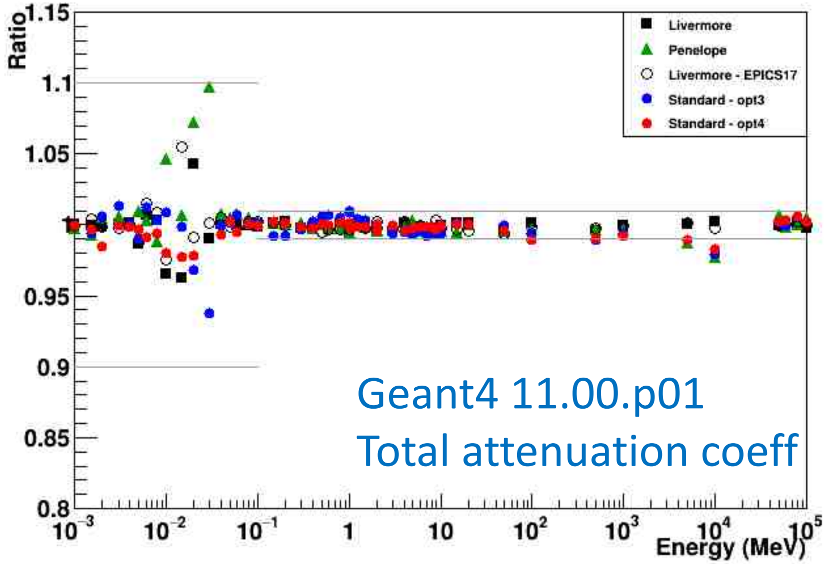
## Remarks:

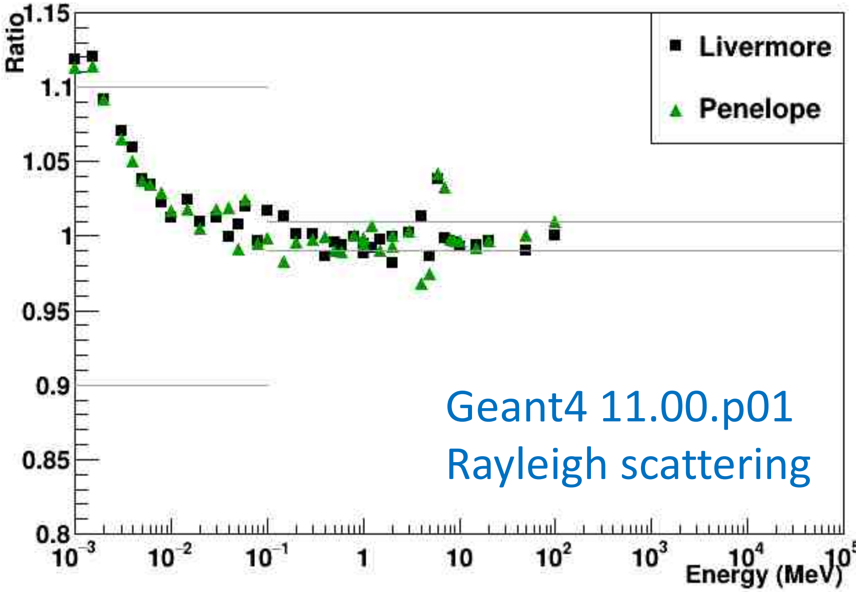
- The best model is BIC with Geant4 10.2

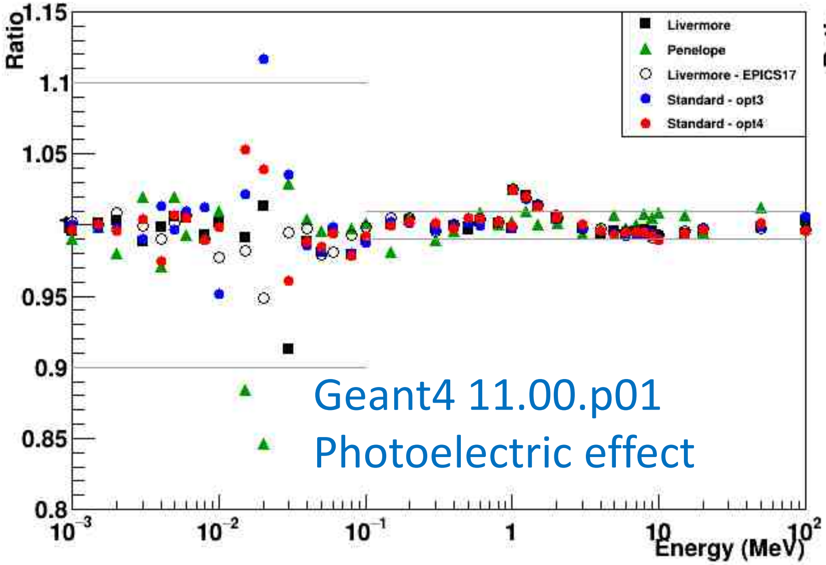
- 10.3-10.5 were generally the worst preforming across the test scenarios and these versions should be avoided if possible

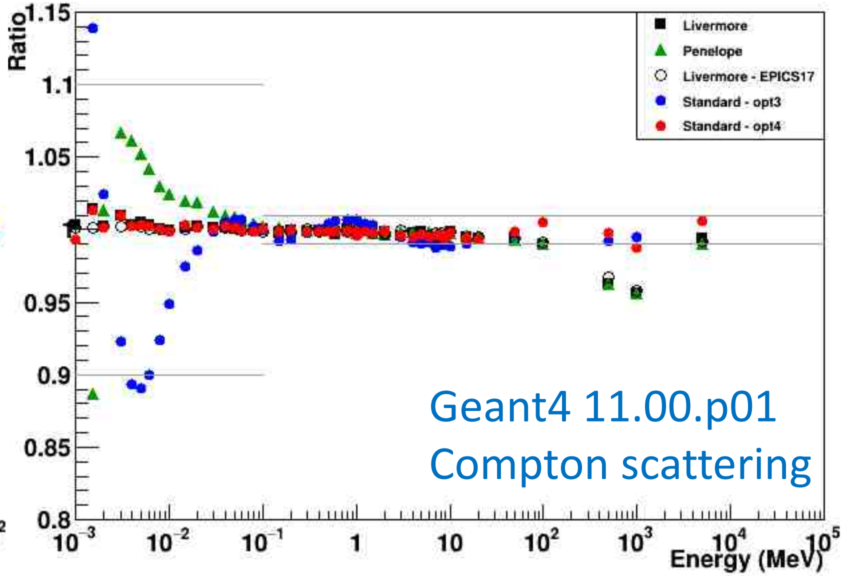
# Photon attenuation coefficients tests

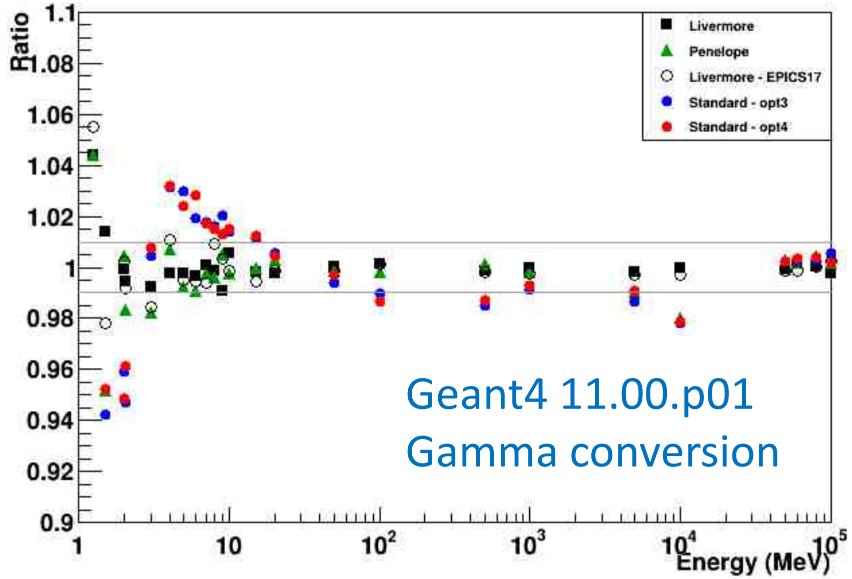
- Reference: NIST XCOM
- New: Included EPICS17
- The results of the photon attenuation tests in water do not change when comparing 10.5, 10.6 and 11.0 cand01, 11.00.p01



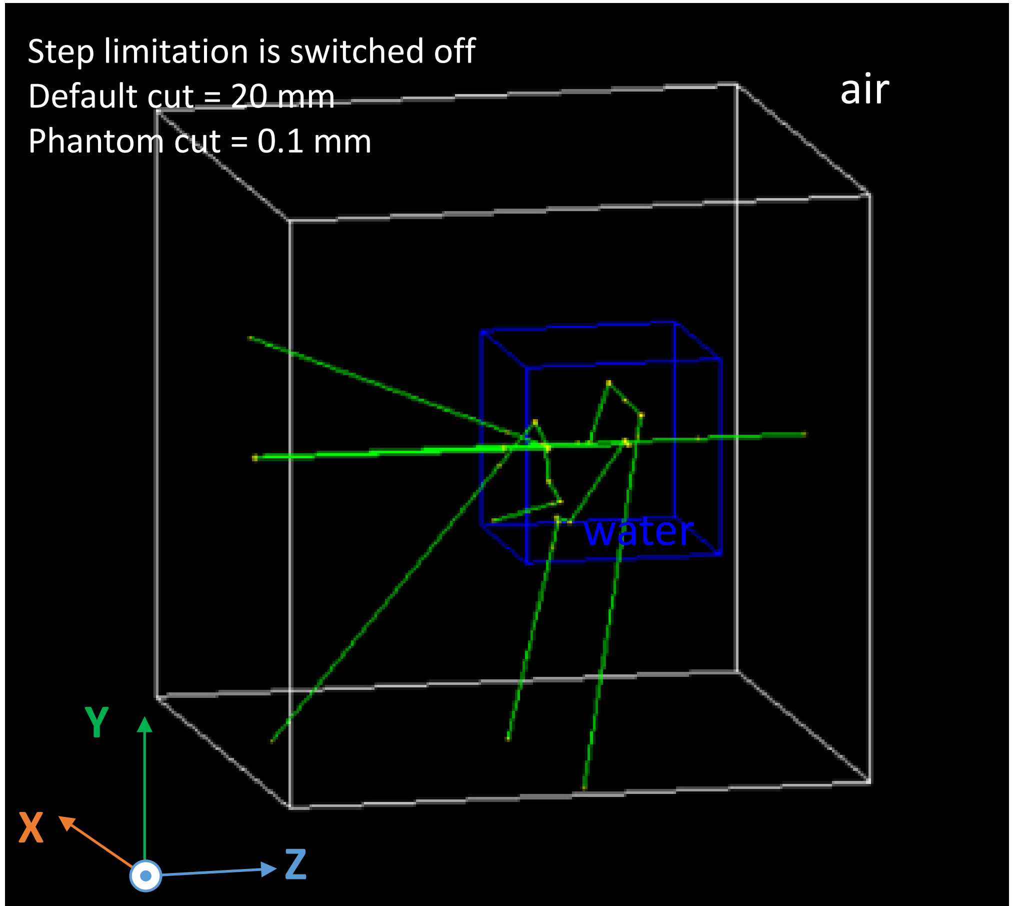



# Test for small field dosimetry

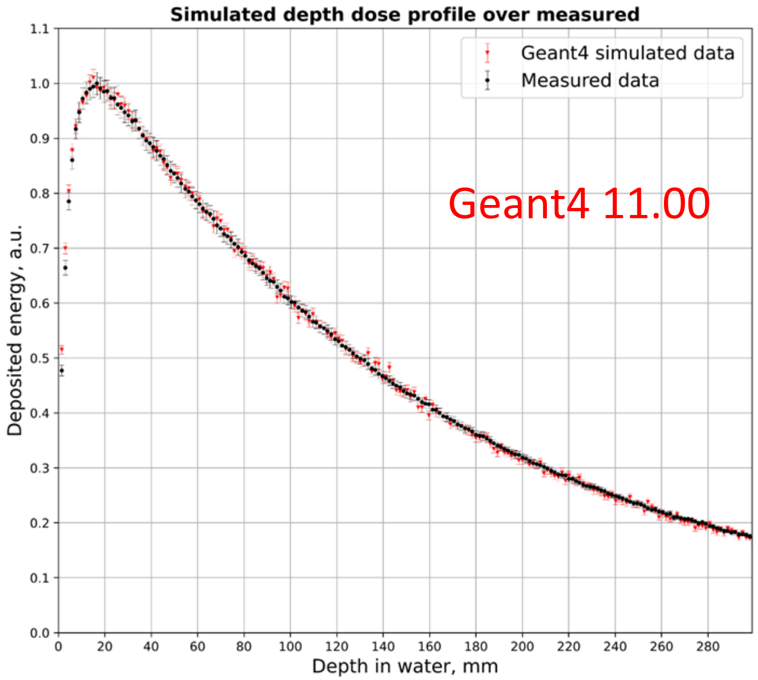
I. Filipev, G. Biasi, S. Guatelli, A. Rosenfeld,
University of Wollongong

**Source:**
CyberKnife with IRIS collimator
Field size: 60 mm
PHSP plane is at 40 cm from isocentre along Z axis

Phase-space files source:
[https://www-nds.iaea.org/phsp/photon/CyberKnife_IRIS/](https://www-nds.iaea.org/phsp/photon/CyberKnife_IRIS/)




Biasi G, et al. (2018) CyberKnife® fixed cone and Iris™ defined small radiation fields: Assessment with a high-resolution solid-state detector array. *Journal of applied clinical medical physics*,19:547-57.



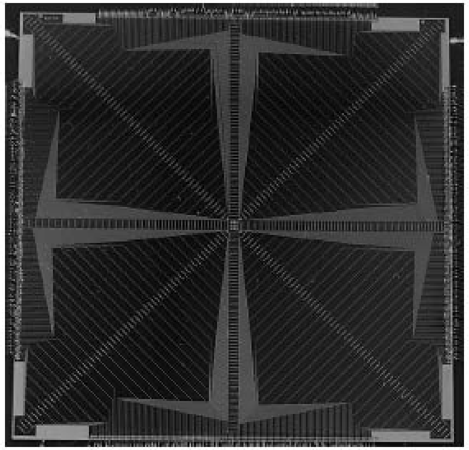
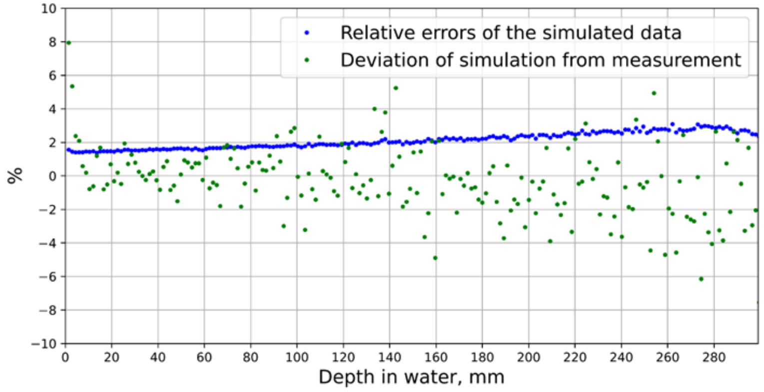



FIG. 2. The Octa is a 2D monolithic silicon array detector consisting of 512 diodes operated in passive mode and arranged in four intersecting orthogonal linear arrays. Each diode has a sensitive area of 0.032 $mm^2$ with pitch of 0.3 mm along the vertical and horizontal arrays and of 0.43 mm along the two diagonal arrays.



# Last comments

- geant-val
  - Excellent platform to run tests
  - Be able to run the tests of some reference tags
  - In a longer term vision, it would help to have documentation on how to set-up and run the tests
- Update on the webpage
  - Waiting that the new Geant4 web page gets alive
  - Use cases for medical physics: Webpage with recommendations, best physics list, for each use case, etc: collection of the use case.
  - Information on basic/extended/advanced examples for bio-med applications
- Paper number II
  - Focus on the technical aspects of improvements in the physics of Geant4 for the med phys community (starting now)
  - Regression testing of existing tests - Geant4 version: 10.5 vs 11.p01
  - New tests: in-vivo PET and small X-ray field dosimetry, Geant4 –DNA

TABLE II. Geant4 physics models to describe EM physics processes in Geant4 EM constructors under investigation.

| Geant4 | *Opt0* | *Opt3* | *Opt4* | *Livermore* | *Penelope* |
|---|---|---|---|---|---|
| Rayleigh scattering and photoelectric effect | Livermore | | | | PENELOPE |
| Compton scattering | Standard | *G4KleinNishina Model* | *G4LowEPComptonModel* for E < 20 MeV* Brown et al[36] | Livermore for E <1 GeV* | PENELOPE for E <1 GeV* |
| Gamma conversion | Standard | Standard | PENELOPE for E <20 MeV Standard for E >20 MeV | *G4BetheHeitler5DModel* for E <1 GeV, Standard for E >1 GeV Bernard et al 2013[37] | PENELOPE for E<1 GeV, Standard for E >1 GeV |
| $e^-$ and $e^+$ ionisation | Standard | Standard | Livermore for $e^-$ for E <100 keV, PENELOPE for $e^+$ for E <100 keV, Standard for E >100 keV | Livermore for E <100 keV Standard for E >100 keV | PENELOPE |
| $e^-$ and $e^+$ bremsstrahlung | Standard | *G4SeltzerBergerModel* for E <1 GeV, *G4eBremsstrahlungRelModel* for E >1 GeV | | | PENELOPE |
| $e^+$ annihilation | Standard | | | | PENELOPE |
| $e^-$ and $e^+$ multiple scattering | Urban model for E < 100 MeV (Ivanchenko et al[39]), Wentzel model for E >100 MeV | Urban model | Goudsmit–Saunderson model (Incerti et al 2018a[38]) for E <100 MeV Wentzel model for E >100 MeV | | |
| Coulomb scattering | on | off | On | | |
| Bremsstrahlung angular distribution | *ModifiedTsai* | *2BS* | | | PENELOPE |

*: *G4KleinNishinaModel* for higher energies. Geant4 10.5 is considered. For details on the models the reader should refer to the Geant4 Physics Reference Manual.[28]