G4_Med, a Geant4 benchmarking tool for medical physics applications

P. Arce[1], D. Bolst[2], M-C. Bordage[3], P. Cirrone[4], M.A. Cortes-Giraldo[5], D. Cutajar[2], G. Cuttone[4], L. Desorgher[6], P. Dondero[7], A. Dotti[8], B. Faddegon[9], C. Fedon[10], S. Guatelli[2], S. Incerti[11], V. Ivanchenko[12], D. Konstantinov[13], I. Kyriakou[14], G. Latyshev[13], A. Le[2], C. Mancini-Terracciano[15], A. Mantero[7], M. Maire[16], M. Novak[17], C. Omachi[18], L. Pandola[19], A. Perales[20], Y. Perrot[21], G. Petringa[4], J.M. Quesada[5], J. Ramos-Méndez[9], F. Romano[22], D. Sakata[2], L.G. Sarmiento[23], T. Sasaki[24], I. Sechopoulos[10], E. Simpson[25], T. Toshito[18], D. H. Wright[26]

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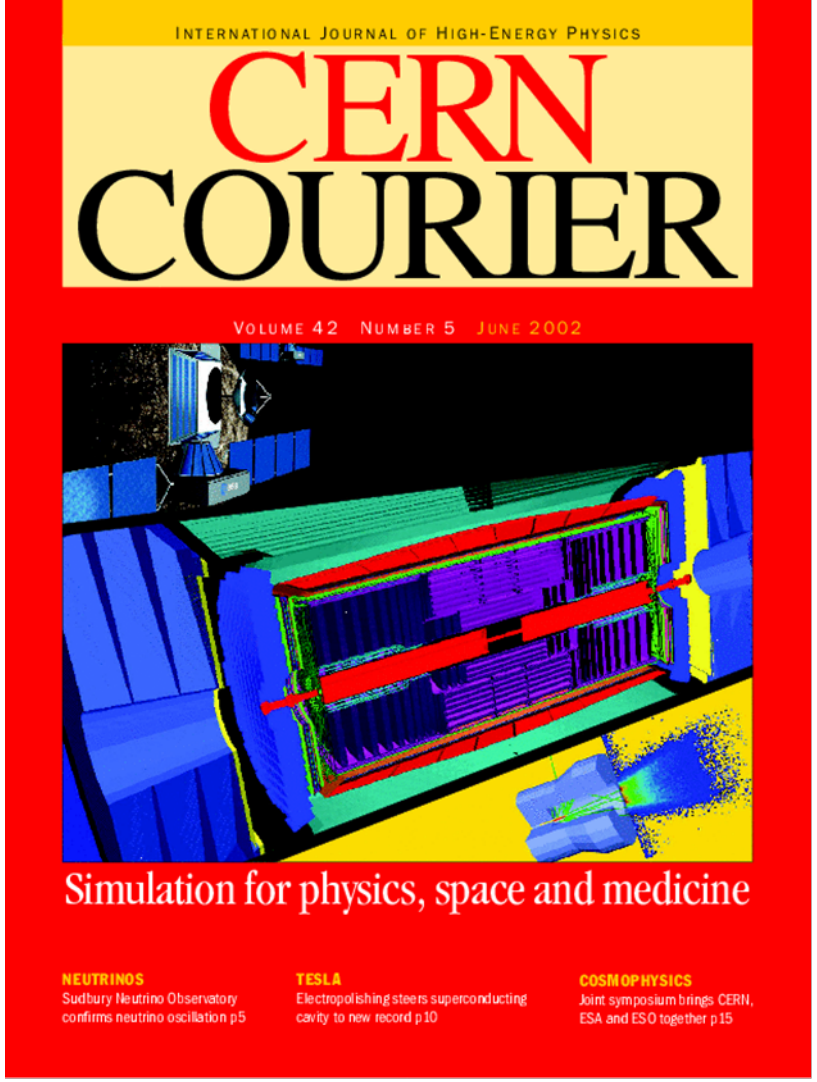
Geant4

- Monte Carlo code modelling particle transport and interactions in matter
  - Maintained by a large international Collaboration (> 100 members)
  - www.geant4.org

Geant4 Collaboration Meeting, October 2017, Wollongong, Australia

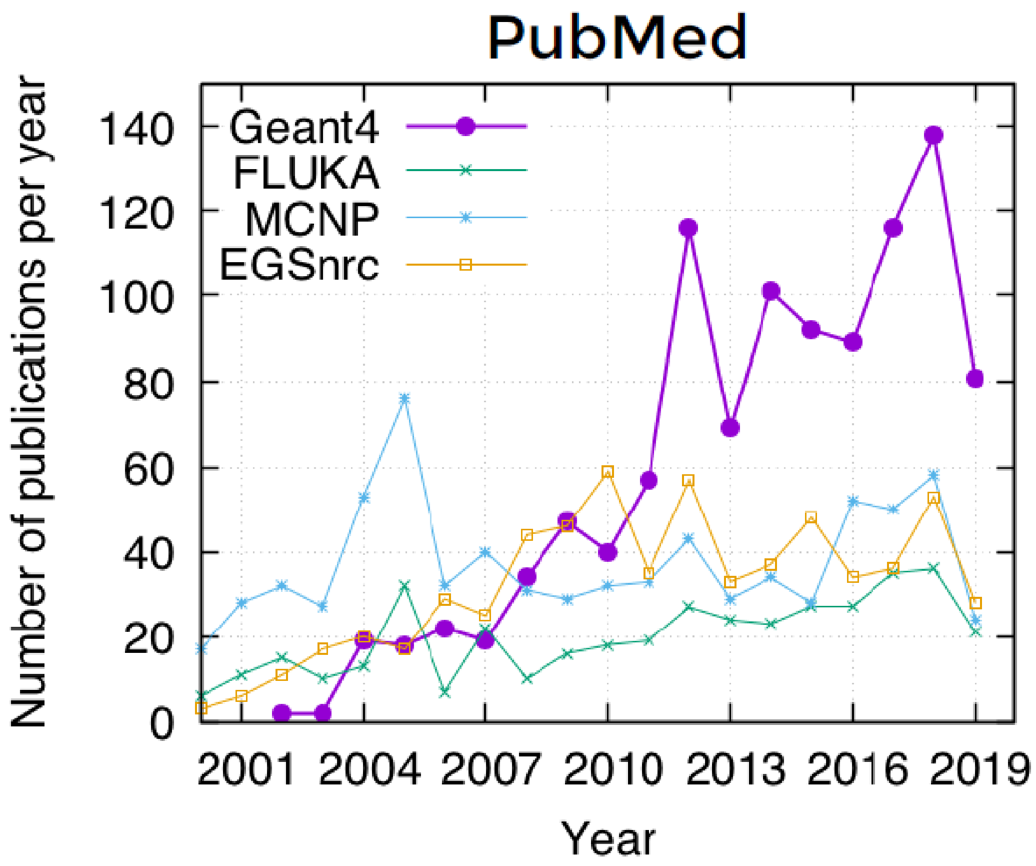


Geant4 Collaboration, NIM A, Vol: 506, pp: 250-303 has >9000 citations

Most cited publication authored by CERN excluding the Review of Particle Properties

Applications

- Verification of radiotherapy Treatment Planning Systems
- Improvement/optimisation of QA instrumentation
- Dosimetry and production of radiopharmaceuticals
- Imaging (e.g. PET, SPECT, CT)
- Detector design
- Radiation protection in Earth Labs, aviation and space
  - Design shielding solutions



Courtesy of Carlo Mancini, Sapienza, Rome, Italy

Geant4 Medical Simulation Benchmarking Group

https://twiki.cern.ch/twiki/bin/view/Geant4/G4MSBG

- Created in 2014.
- **Current Coordination Team:**
  - **Coordinator: Susanna Guatelli (Univ. Wollongong, Australia)**
  - **Deputy-coordinator: Pedro Arce (CIEMAT, Spain)**
- 37 researchers; 25 institutions from 12 different countries

Motivation & Goals

https://twiki.cern.ch/twiki/bin/view/Geant4/G4MSBG

- Geant4 offers many **pre-built physics lists**. Which one is more adequate for a specific medical physics application scenario?
- G4-Med project:
    - 18 tests to benchmark Geant4 pre-built physics lists for medical physics applications
        - Against reference data and experimental measurements
    - Executed at CERN in regression testing
- Goals:
    - Provide physics list recommendations
    - Monitor physics capability of Geant4

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TWiki > Geant4 Web > G4MSBG (2019-04-23, LucianoPandola)

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Welcome to the Twiki web page of the G4MSBG initiative: G4-Med

Purpose

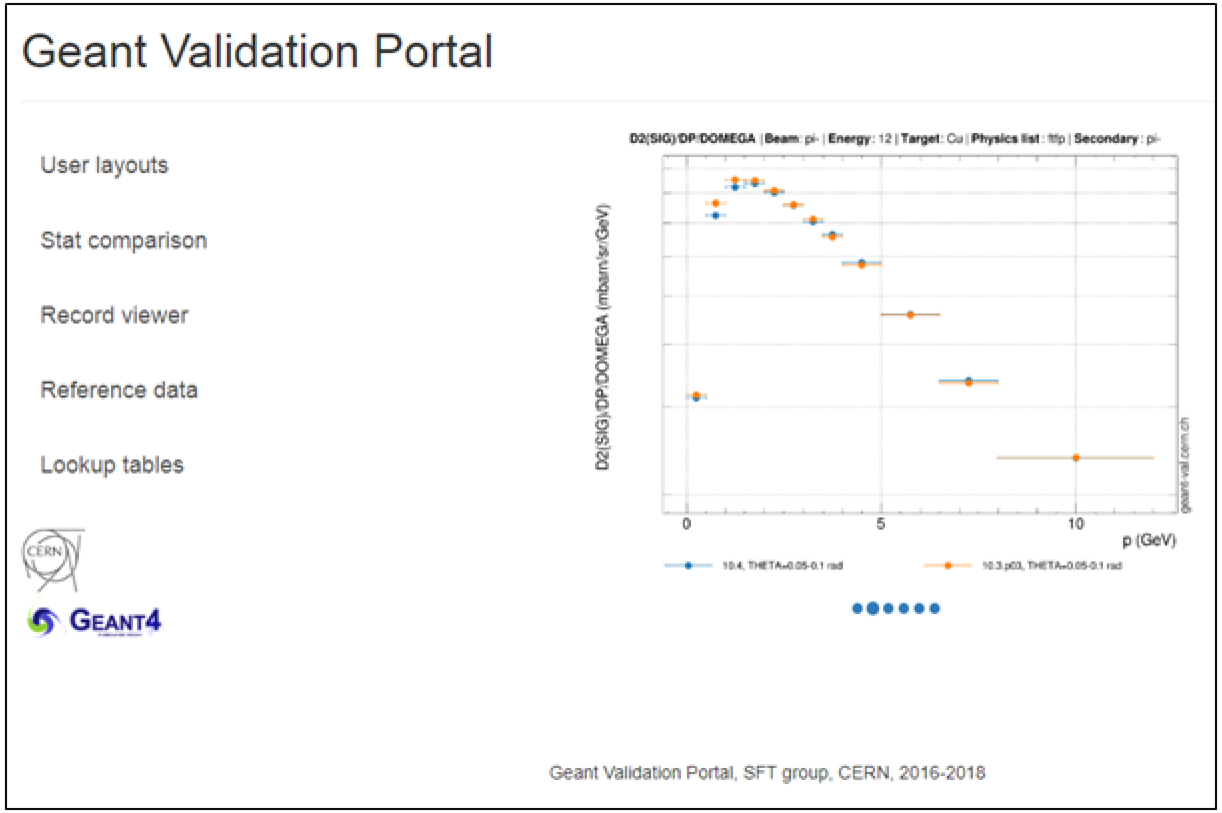
The aim of the Geant4 Medical Physics Benchmarking Group (G4MSBG) is to develop a fully automatised Geant4 benchmarking and regression testing system for medical physics applications, called G4-Med. A set of Geant4 Physics Constructors and Lists of interest for medical physics applications are tested. The tests are integrated in the geant-val test system to be executed for benchmarking and regression testing. The test are executed using the CERN computing infrastructure.

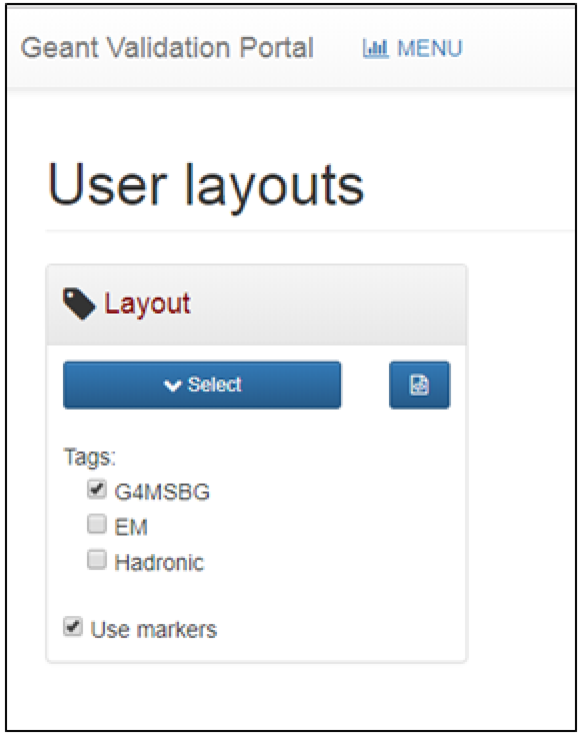
List of current tests

Currently the G4-Med system includes 18 tests.

Test	geant-val layout	Authors
Photon attenuation coefficients	PhotonAttenuation	S. Guatelli, L. Pandola
Electron stopping powers	ElectronDEDX	V. Ivanchenko
Low energy electron backscattering	ElectronBackScat	P. Dondero, A. Mantero,V. Ivanchenko, M. Novak
Electron scattering from foils at 13-20 MeV kinetic energies	ElecForwScat	B. Faddegon, J. Ramos-Méndez
Bremsstrahlung yield	Bremsstrahlung	B. Faddegon,J. Ramos-Méndez
Fano cavity	Fano cavity	P. Arce , M. Maire, M. Novak
Electron Dose Point Kernel	LowEElecDPK	S. Incerti, M.-C. Bordage, I. Kyriakou, Y. Perrot
Microdosimetry	Microyz	S. Incerti, I. Kyriakou
Brachytherapy - dose rate	Brachy-ir	S. Guatelli, D. Cutajar
Dosimetry - clinical 5-6 MeV electron beam	To be added	L. Desorgher
Dosimetry for mammography	Mammo	C. Fedon, I. Sechopoulos
Hadronic nucleus-nucleus inelastic cross section	NucNucInelXS	D. Sakata, S. Guatelli, E. Simpson
Bragg curves in water for 67.5 MeV protons	LowEProtonBraggPeak	B. Faddegon, J. Ramos-Méndez
Absolute neutron yield for protons	ProtonC12NeutronYield	B. Faddegon, J. Ramos-Méndez
Production cross sections of different fragments	C12FragCC	C. Omachi, T. Toshito, T. Sasaki
62 MeV /n C-12 fragmentation on Carbon target	LowEC12Frag	C. Mancini-Terracciano
400 MeV/n C-12 fragmentation	C12Frag	D. Bolst, S. Guatelli, F. Romano
Estimation of proton radiobiological damage	LowEProtonRBE	G. Petringa, GAP Cirrone L. Pandola, G. Cuttone
Light ion (proton, 3He, carbon) range and depth dose curves in water	LightIonBraggPeak	M. Cortes-Giraldo, A. Perales, J. M. Quesada Molina

Integration in *geant-val* for Automatized Regression Tests





https://geant-val.cern.ch/

Publication: Luc Freyermuth, Dmitri Konstantinov, Grigorii Latyshev, Ivan Razumov, Witold Pokorski, Alberto Ribon
EPJ Web Conf. 214 05002 (2019)
DOI: 10.1051/epjconf/201921405002

G4_Med is integrated in ***geant-val*** to execute regularly automatized regression tests on the CERN computing infrastructure

Tests included in G4-Med

https://twiki.cern.ch/twiki/bin/view/Geant4/G4MSBG

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Tested Geant4 Physics Constructors and Lists

Electromagnetic Physics Constructors

- **G4EmStandardPhysics** (a.k.a. “option0”)
  - Usually used as reference by Geant4 physics developers for high-energy physics.
- **G4EmStandardPhysics_option3** (“**EMY**” suffix in physics list naming convention)
  - Based of G4EmStandardPhysics with more accurate settings to model dE/dx, nuclear stopping & fluorescence.
- **G4EmStandardPhysics_option4** (“**EMZ**” suffix)
  - Deemed to be the most accurate combination of Geant4 models, regardless of CPU efficiency.
- **G4EmLivermorePhysics** (“**LIV**” suffix)
  - Includes data-driven low-energy models for **e^-** ionization and **γ** based on the Livermore evaluated data libraries.
- **G4EmPenelopePhysics** (“**PEN**” suffix)
  - Includes low-energy models for **e^-**, **e^+** & **γ** re-engineered from PENELOPE code

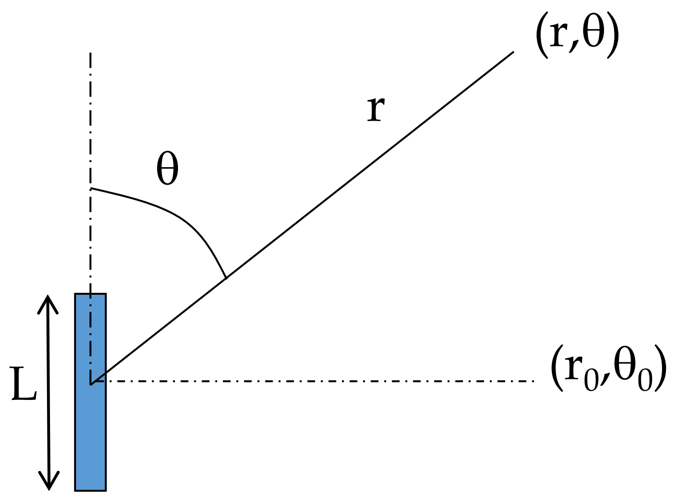
EM Physics Lists (CH)

Geant4	*Opt0*	*Opt3*	*Opt4*	*Livermore*	*Penelope*
Rayleigh scattering and photoelectric effect	Livermore				Penelope
Compton scattering	Standard	G4KleinNishinaModel	*G4LowEPComptonModel* [18] for $E < 20MeV$ *	Livermore for $E < 1GeV$ *	Penelope for $E < 1GeV$ *
Gamma conversion	Standard	Standard	Penelope for $E < 20MeV$ Standard for $E > 20MeV$	*G4BetheHeitler5DModel* [19], for $E < 1GeV$, Standard for $E > 1GeV$	Penelope for $E < 1GeV$, Standard for $E > 1GeV$
e^- and e^+ ionisation	Standard	Standard	Livermore for e^- for $E < 100keV$, Penelope for e^+ for $E < 100keV$, Standard for $E > 100keV$	Livermore for $E < 100keV$ Standard for $E > 100keV$	Penelope
e^- and e^+ bremsstrahlung	Standard	*G4SeltzerBergerModel* for $E < 1GeV$, *G4eBremsstrahlungRelModel* for $E > 1GeV$			Penelope
e^+ annihilation	Standard				Penelope
e^- and e^+ multiple scattering	Urban model [20] for $E < 100MeV$, Wentzel for $E > 100MeV$	Default model	Goudsmit-Saunderson model [21], [22] for $E < 100MeV$		
Coulomb Scattering	on	off	on		
MscStepLimiting Type	*fUseSafety*	*fUseDistanceToBoundary*	*fUseSafetyPlus*	*fUseSafetyPlus*	*fUseSafetyPlus*
Bremsstrahlung angular distribution	*ModifiedTsai*	*2BS*			*Penelope*

Brachytherapy test

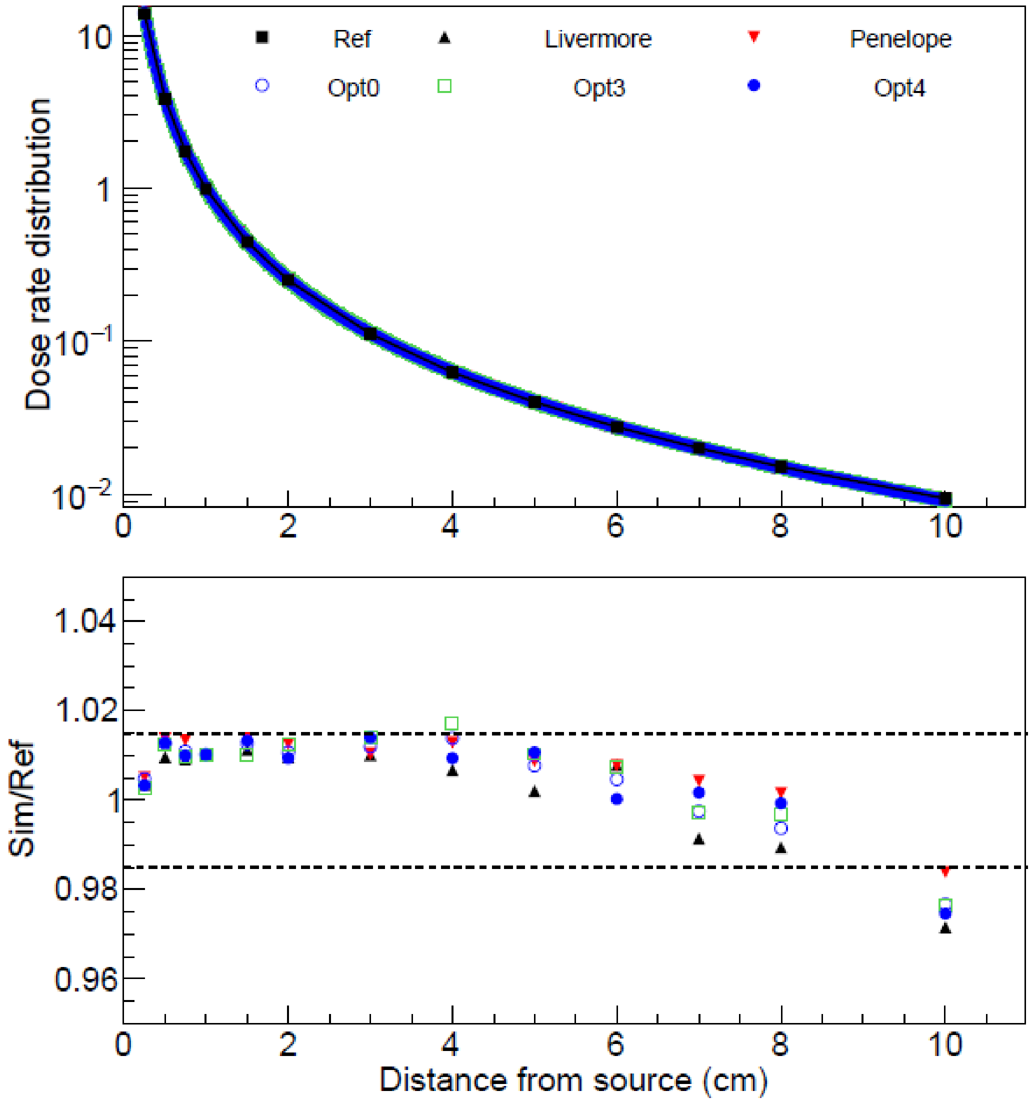
D. Cutajar, S. Guatelli, A. Le, A. Rosenfeld
University of Wollongong

- Based on the Advanced Example *brachytherapy*
- ^{192}Ir Flexisource (HDR brachytherapy)



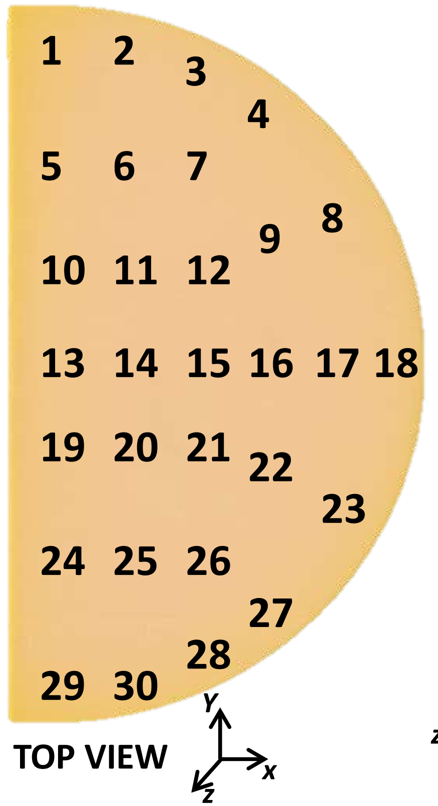
- Comparison against D. Granero, et al, (2006) Med. Phys. 33 (12), pp: 4578-82.

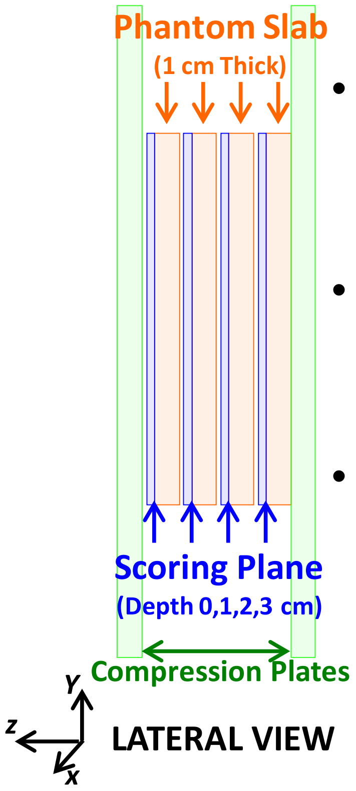
- Agreement within 2σ with reference data for all EM constructors



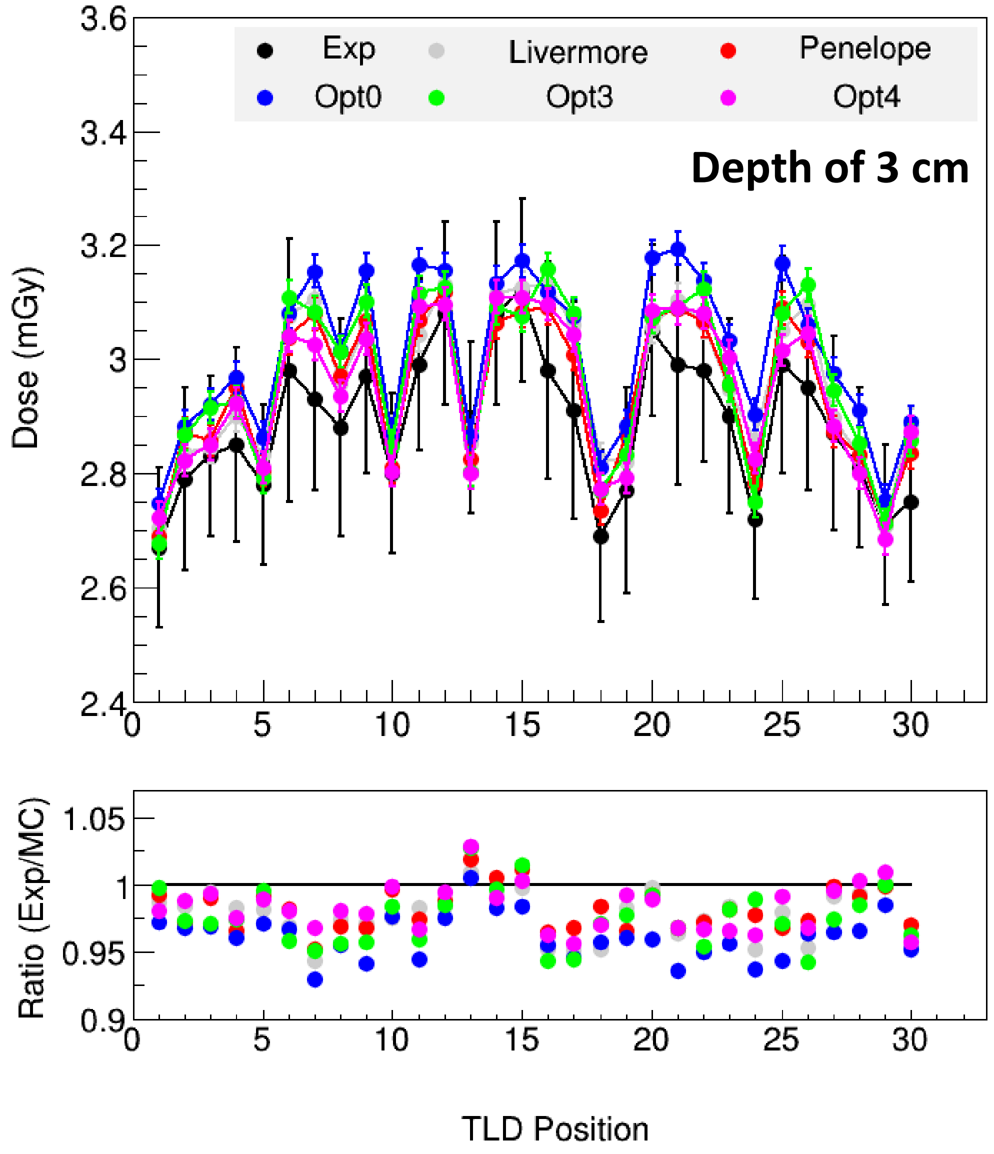
Internal breast dosimetry

C. Fedon and I. Sechopoulos, Radboudumc (NL)





- Typical breast phantom (50% glandular 50% adipose)
- Dose scored in 30 positions at 4 different depths
- Comparison with experimental measurements (TLDs) at 20 keV



- Agreement within 1σ with the experimental measurements
- Best performance (on average) with ***"Opt4"***
- Performance of ***"Opt 0"*** worsens with increasing depth

C. Fedon et al., "Internal breast dosimetry: monoenergetic" **Med. Phys. 45 (2018)**
C. Fedon et al., "Internal breast dosimetry: spectrum" **Med. Phys. 45 (2018)**

Tested Geant4 Physics Constructors and Lists

Hadronic Physics Constructors

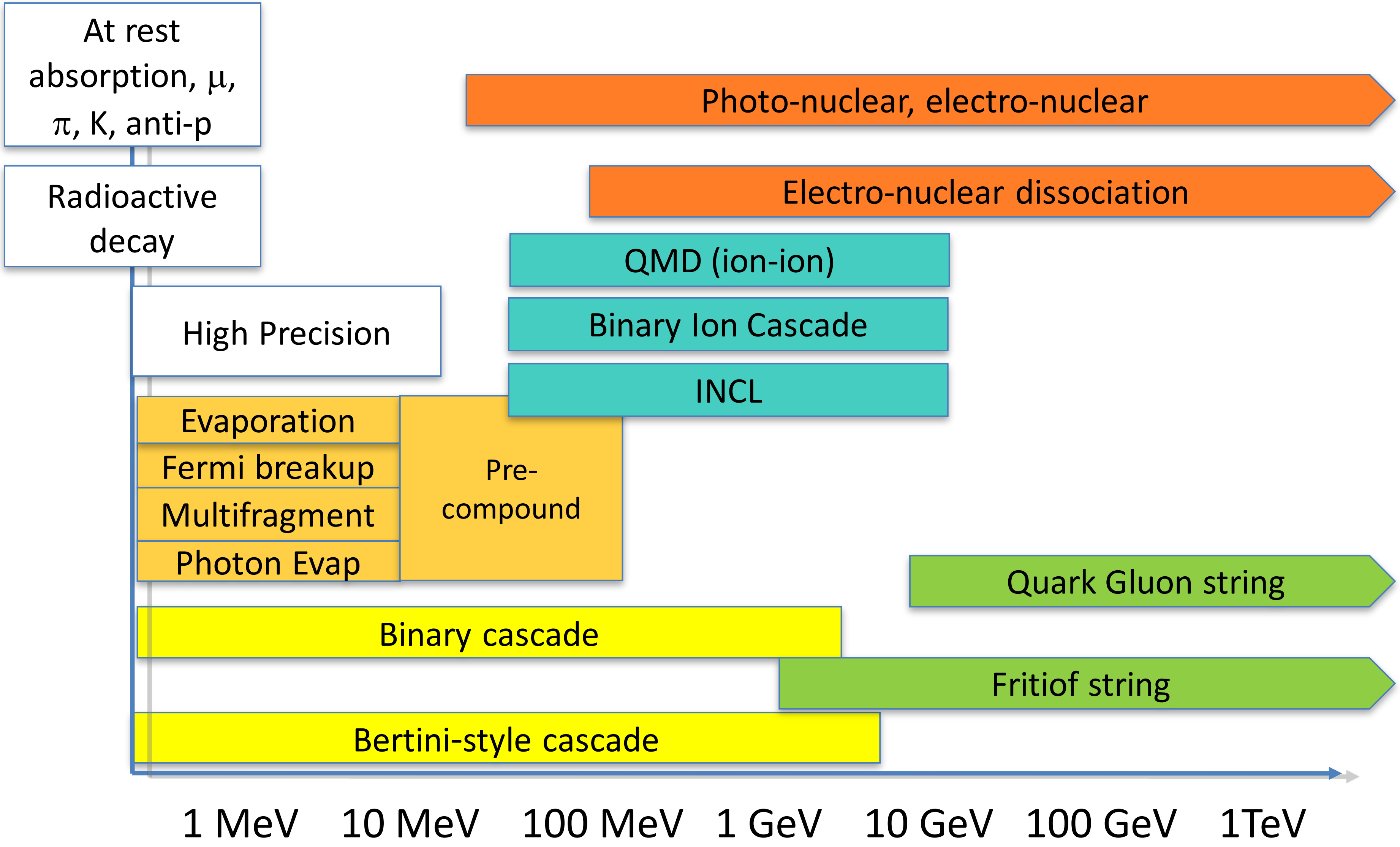
For proton therapy

- **QGSP_BIC_HP**
  - **G4EmStandardPhysics_option4** is used by default since Geant4-10.5.
- **QGSP_BIC_EMY** is same as previous, but…
  - **No HP libraries** for neutrons.
  - G4EmStandardPhysics_**option3** is used.
- **QGSP_BERT_HP** differs from QGSP_BIC_HP in:
  - EM interactions are modeled with "**option0**".
  - For incident **p** & **n**, Bertini model (own Precompound+Evaporation) is used for hadronic inelastic scattering.

For carbon ion therapy:

- **G4IonBinaryCascade -** *LightIonBinaryCascade* model.
- **G4IonQMDPhysics -** Quantum Molecular Dynamics (QMD) model.
- **G4IonINCLXXPhysics -** Liège Intranuclear-Cascade model (INCL).

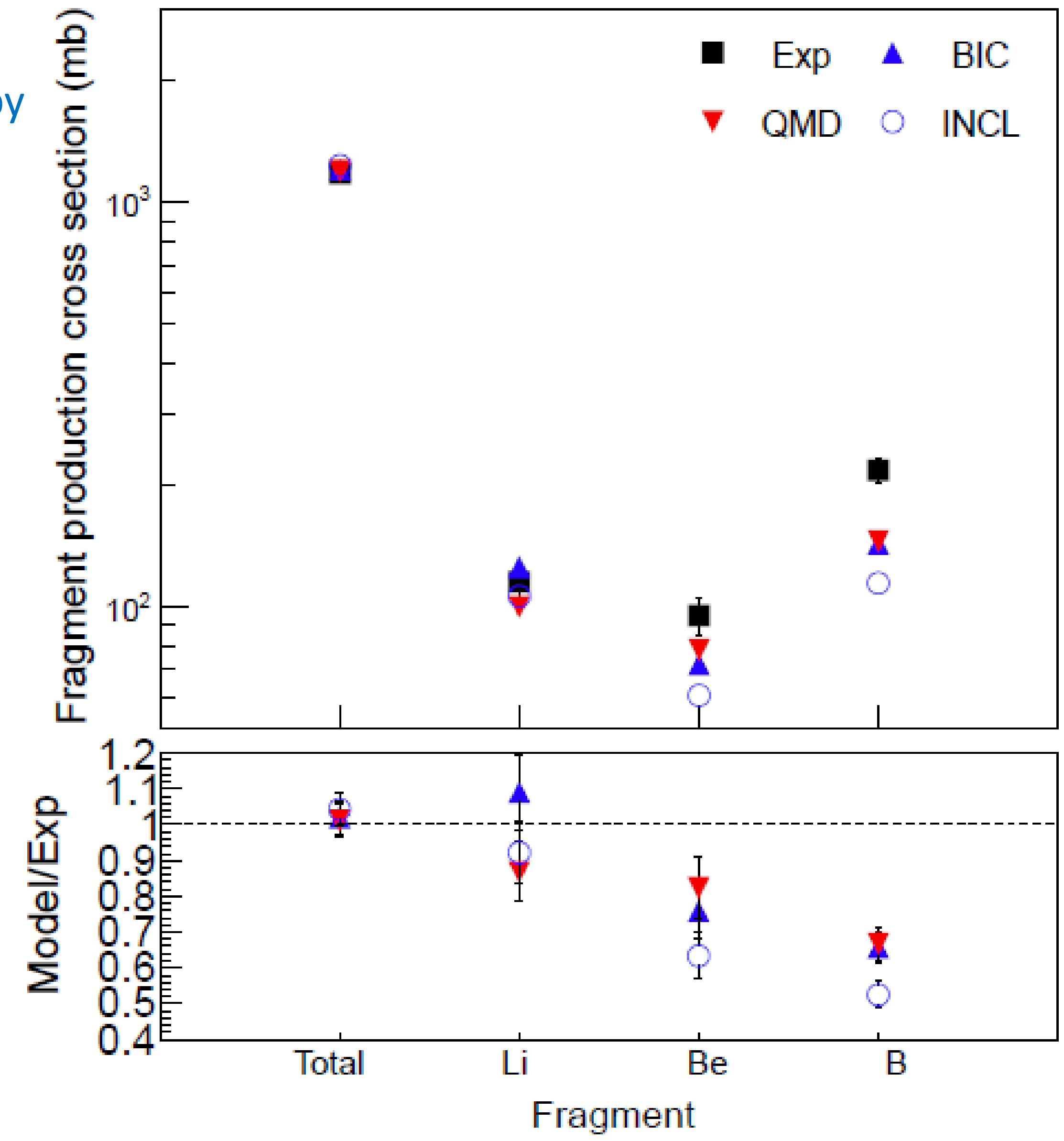
Partial Hadronic Model Inventory – *important for particle therapy*



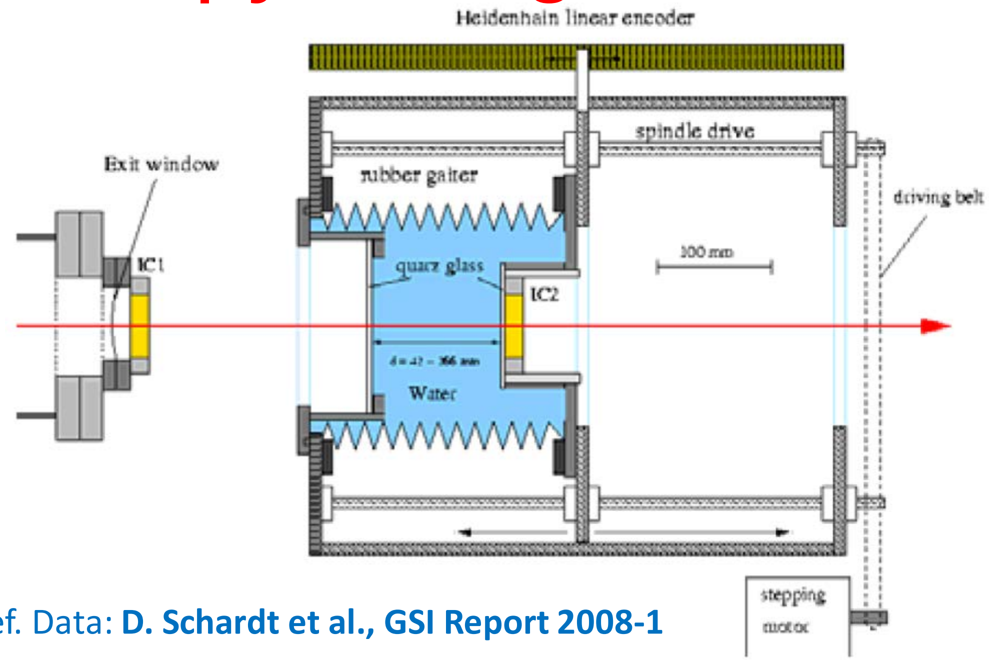
300 MeV/n ^{12}C ion charge-changing cross section

Authors: C. Omachi (Nagoya Proton Therapy Center, Nagoya, Japan, T. Sasaki (KEK, Japan), T. Toshito (Nagoya Proton Therapy Center, Nagoya, Japan)

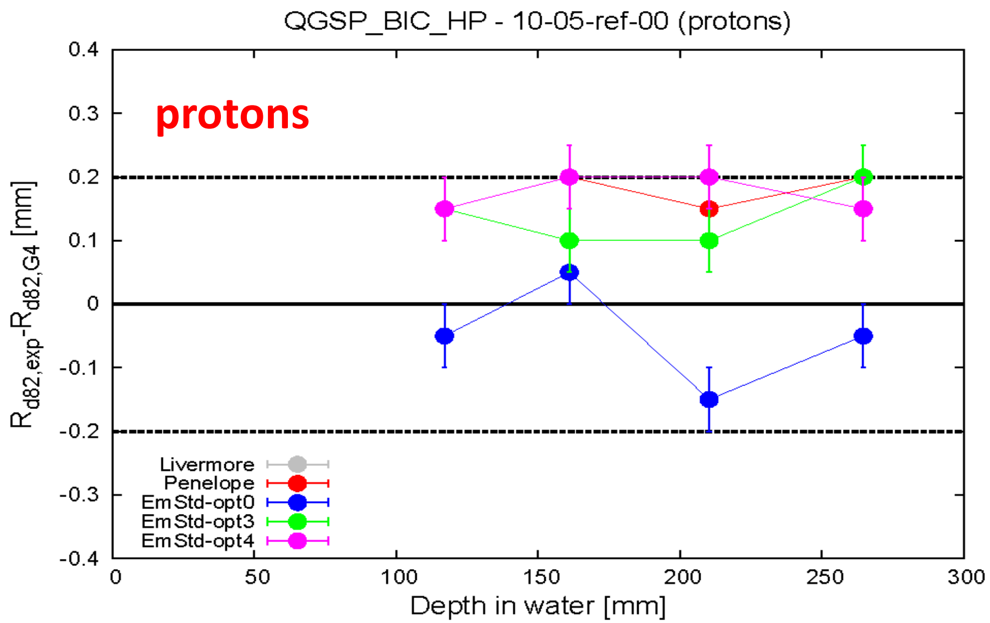
Experimental data obtained with an emulsion plate in the NIRS P152 experiment: Toshito et al 2007, Physical Review C, 75(5):054606, 2007.

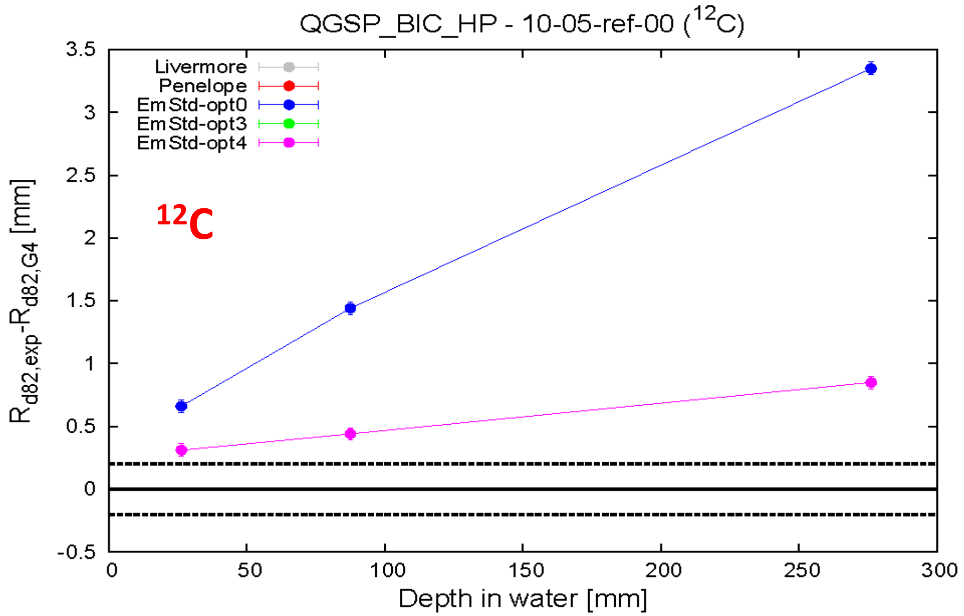


Bragg Curves in Water for Proton & C-12 Beams at Therapy Energies



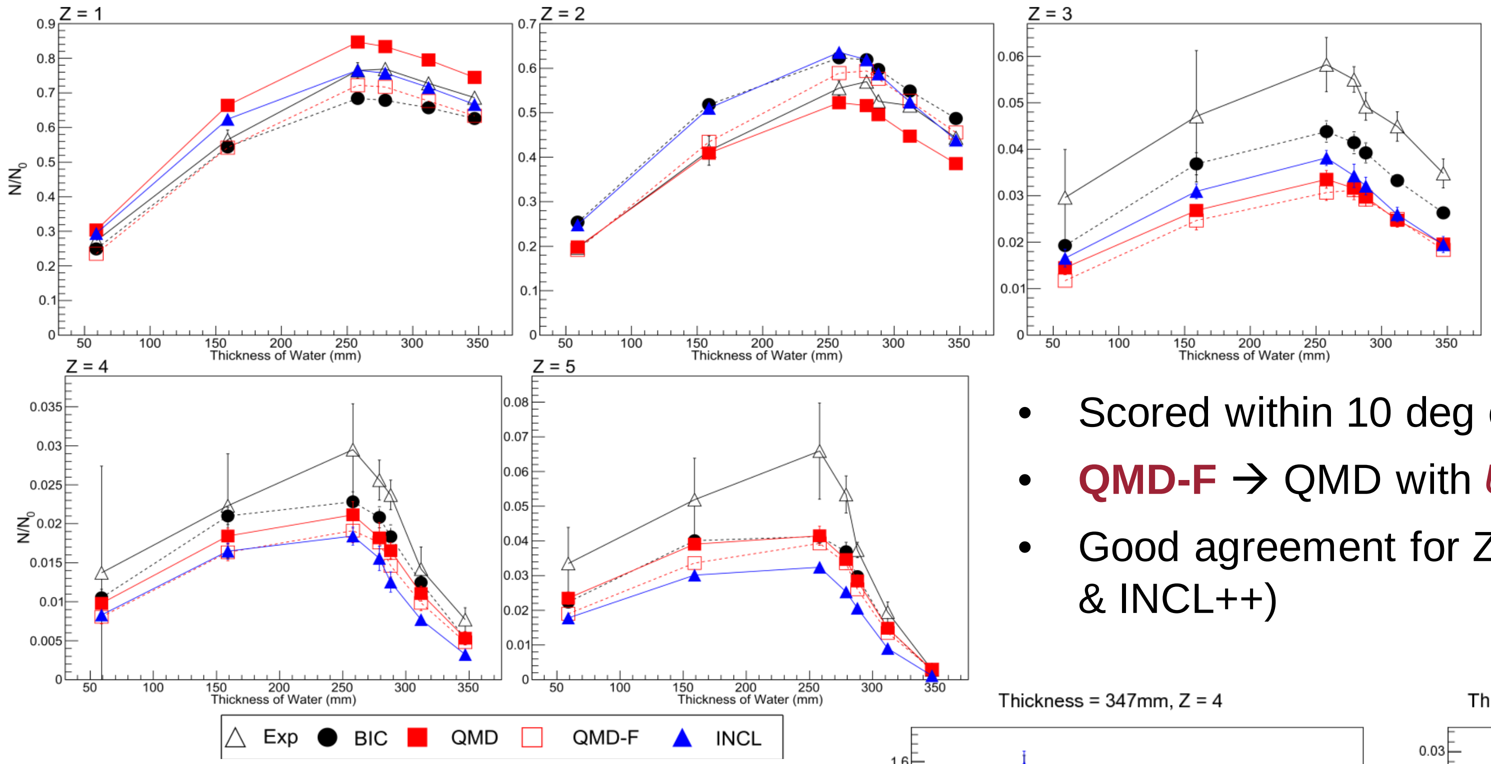
Ref. Data: **D. Schardt et al., GSI Report 2008-1**

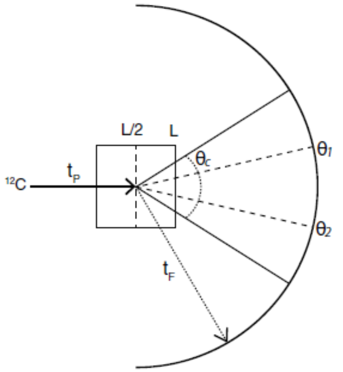




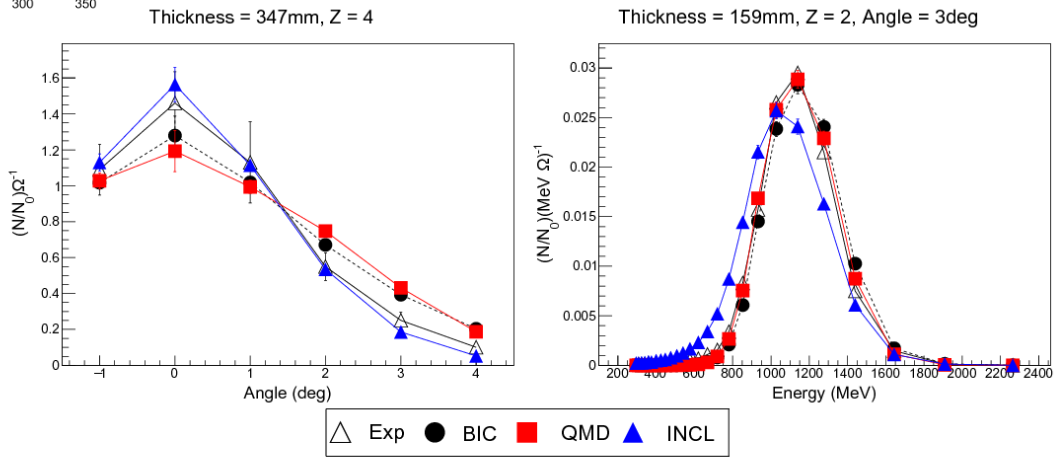
- Initial energy spread adjusted from experimental Bragg curves.
- Simplified geometry model for simulation
  - Depths of 82% distal level are compared.
- "option0" not accurate enough for ^{12}C, other EM constructors agree within 2-3 sigma.
- For proton beams, all physics constructors agree within experimental uncertainties.

Fragment Yields for ^{12}C @ 400 MeV/u on Water Target





- Scored within 10 deg cone
- **QMD-F** → QMD with *UseFRAG* on
- Good agreement for Z < 3 (especially QMD & INCL++)



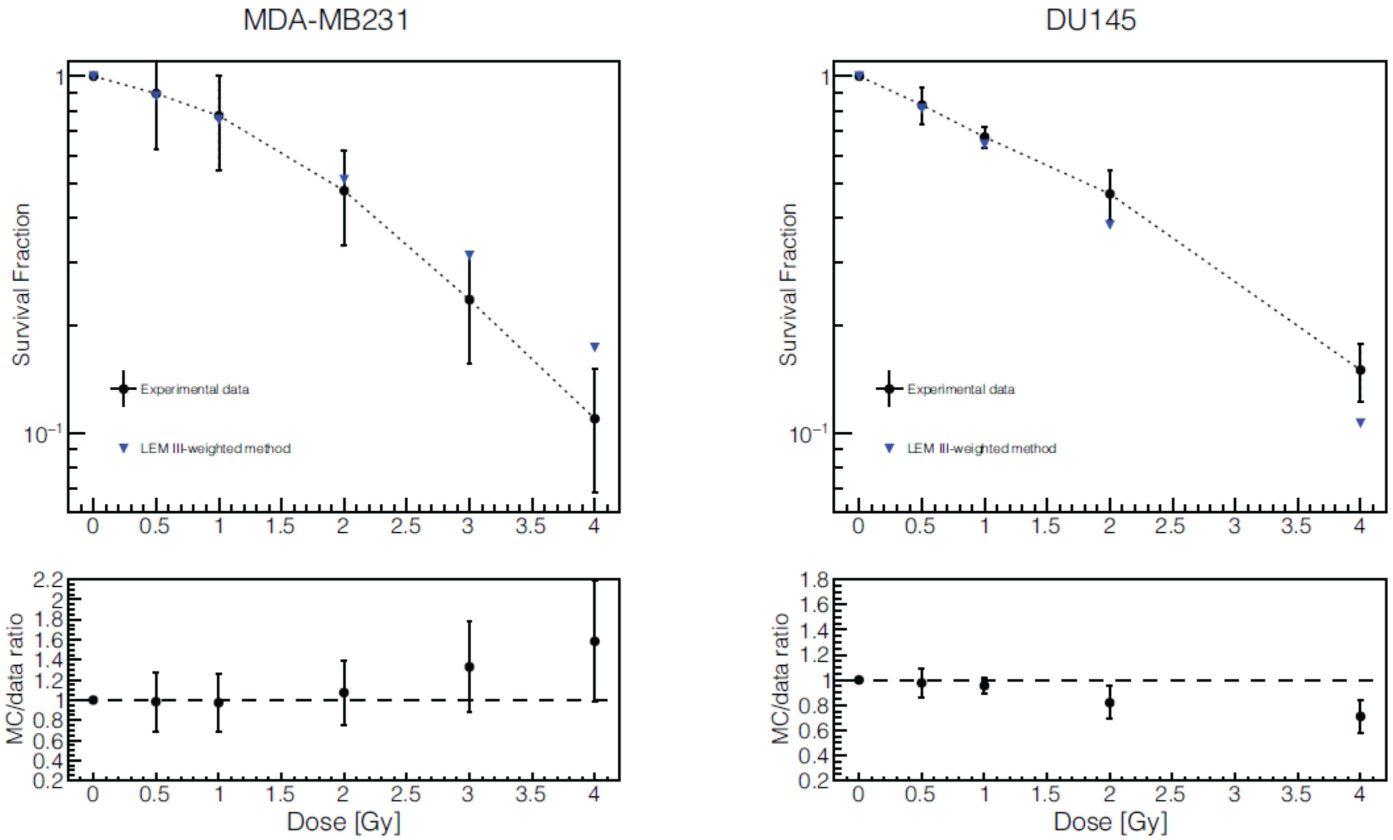
INCL++ reproduced better angular distribution, but QMD & BIC provided better energy distributions.

D. Bolst et al., NIM A 869 (2017)
Ref. Data: **E. Haettner et al., Phys. Med. Biol. 58 (2013)**

Test on cell survival curve modelling for proton therapy

Authors: G.A. P. Cirrone, G. Cuttone and G. Petringa, INFN LNS, Catania, Italy

- Reproduce in-vitro cell survival curves against experimental measurements, performed at the CATANA facility
  - at 20 mm depth in water, corresponding to the mid of a clinical 62 MeV modulated clinical proton beam
  - prostate DU145 cells and breast cancer cell line MDA-MB-231
  - Using Geant4 and LEM III
  - Against exp data (G. Petringa,et al., Physica Medica, vol. 58, pp. 72-80, 2019.



Documented in: G. Petringa,et al., “Radiobiological quantities in proton-therapy: Estimation and validation using geant4-based monte carlo simulations”, Physica Medica, vol. 58, pp. 72-80, 2019.

Conclusions & Outlook

- Currently, 18 tests have been included in *G4_Med* to benchmark EM and Hadronic physics capabilities of Geant4 for medical physics applications.
  - Some test physical quantities, others include more realistic scenarios.
- ***G4_Med*** is integrated in ***geant-val*** for regular executions on the CERN computing infrastructure.
- Overall, *G4EmStandardPhysics_option4* (**_EMZ**) is recommended for accurate simulations.
- **QGSP_BIC_HP** (_EMZ) physics list provides a good overall description.
- **Future work** will focus in two main aspects:
  - Inclusion of new tests and refinement of existing ones.
  - Assessment of the different physics list choices in terms of accuracy and CPU performance across future releases of the Geant4 toolkit.
- More information at our TWiki page: https://twiki.cern.ch/twiki/bin/view/Geant4/G4MSBG
- Paper accepted as a Special Issue of Medical Physics,

Thank you