G4_Med, a Geant4 benchmarking tool for medical physics applications

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ENSAR2 workshop: GEANT4 in nuclear physics

CIEMAT, Madrid (Spain)

April 24th, 2019

Motivation & Goals

- Geant4 medical users community is numerous and very well established.
  - **>200 publications in 2018**.
- A frequent requirement from users is to **get** an **optimal physics list** for each type of simulation in the medical domain.
- Many users use a best guess physics list based on official examples and sometimes tune geometry models to match experimental data (e.g. Linac treatment head or nozzle sims).
- The **Geant4 Medical Simulation Benchmarking Group** was created to:
  - Identify of high-quality data to produce key benchmarks in the medical field.
  - Include these benchmarks into regression tests.
  - Provide physics list recommendations for frequent scenarios in medical physics:
    - **Gamma attenuation, bremsstrahlung…**
    - **Electron stopping power and scattering**
    - **Proton & light-ion Bragg curves.**
    - **Fragmentation reactions, neutron yields, etc.**

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.

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

Tested Geant4 Physics Constructors and Lists

Hadronic Physics Constructors (1)

- **QGSP_BIC_HP**
  - **G4EmStandardPhysics_option4** is used by default since Geant4-10.5.
  - **Elastic hadronic scattering:**
    - CHIPS model for **p** & **n**. High-precision (HP) evaluated data libraries for **n** below 20 MeV.
    - Geant3/Gheisha for d, t, a. For generic ions, derived from $\sigma_T - \sigma_{inel}$ (Glauber-Gribov).
  - **Hadronic inelastic scattering:**
    - Incident **p** & **n**: Barashenkov Nucleon-Nucleus to get total inelastic XS (<91GeV); Binary cascade (BIC) model for incident below ~10 GeV, followed by Pre-compound and Evaporation models. For for **n** below 20 MeV, evaluated data are used (HP).
    - Other projectiles: Glauber model with Gribov corrections to get total inelastic XS; intra-nuclear cascade is modeled with *LightIonBinaryCascade* model, followed by Pre-compound & Evaporation.
  - **Neutron capture & induced fission:**
    - HP data libraries below 20 MeV.

- **QGSP_BIC_EMY** is same as previous, but…
  - **No HP libraries** for neutrons.
  - G4EmStandardPhysics_**option3** is used.

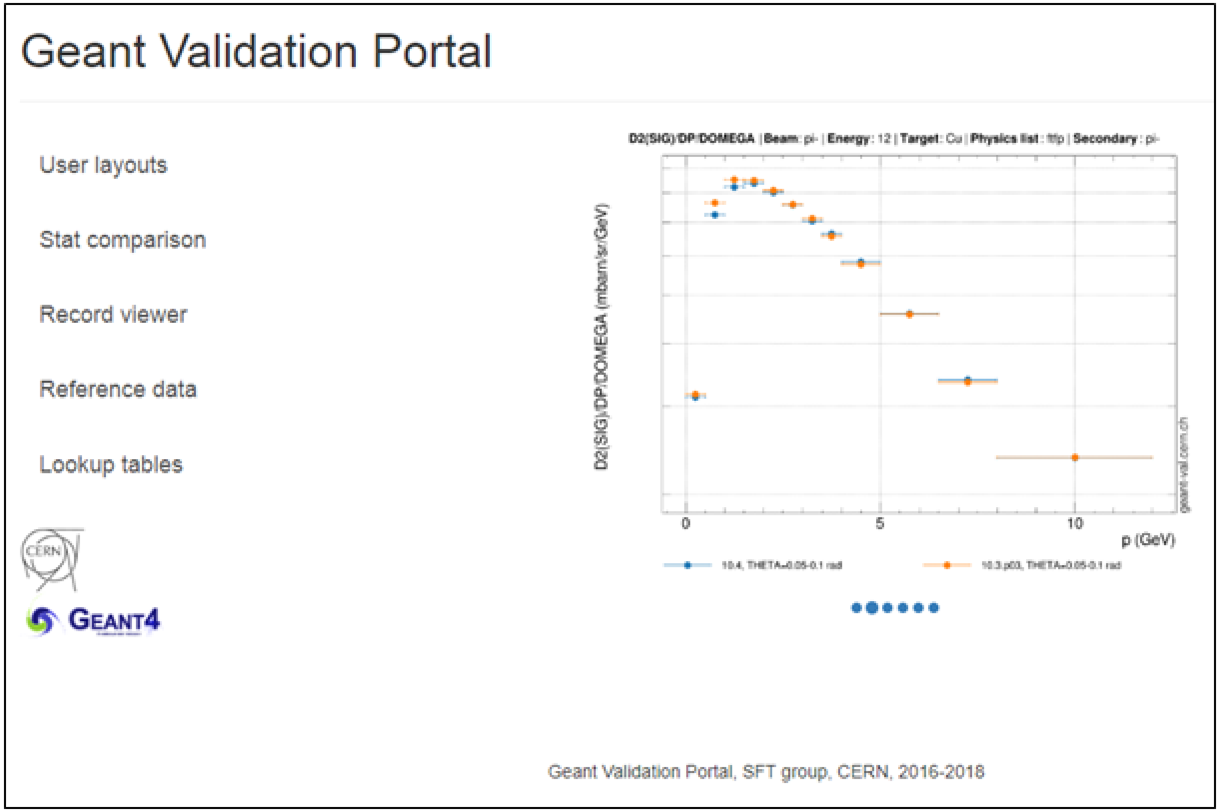
Tested Geant4 Physics Constructors and Lists

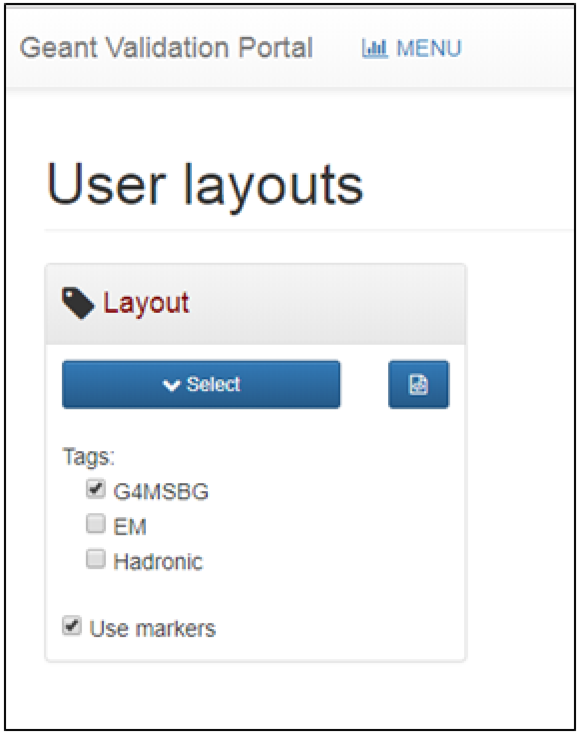
Hadronic Physics Constructors (2)

- **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.

- In **hadronic fragmentation tests**, these constructors were tested to model final state:
  - `G4IonBinaryCascade`
    - *LightIonBinaryCascade* model.
  - `G4IonQMDPhysics`
    - Quantum Molecular Dynamics (QMD) model.
  - `G4IonINCLXXPhysics`
    - Liège Intranuclear-Cascade model (INCL).

Integration in *geant-val* for Automatized Regression Tests





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

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

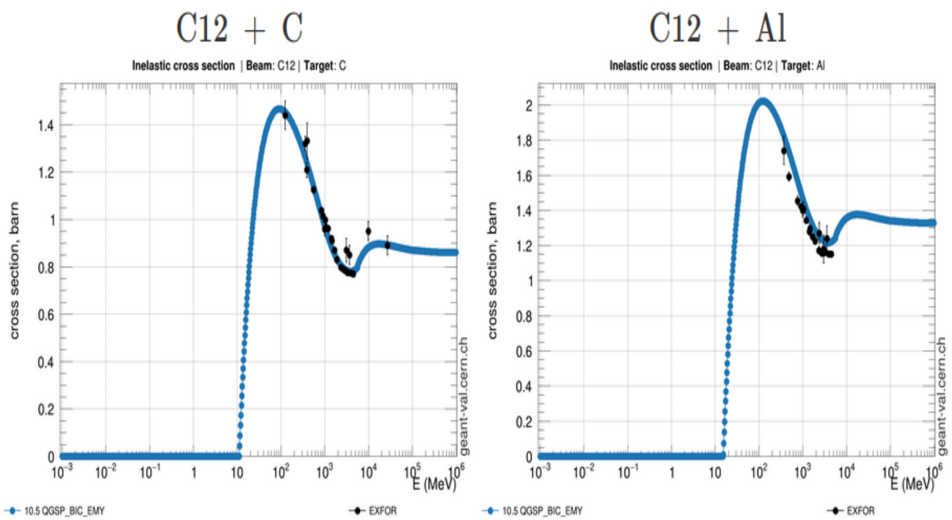
Tests for Electromagnetic Physics Constructors

1. Photon attenuation coefficients (`PhotonAttenuation`)
2. Electron collision stopping power (`ElecDEDX`)
3. Electron low energy backscattering (`ElecBackScat`)
4. Electron forward scattering (`ElecForwScat`)
5. Bremsstrahlung from thick targets (`Bremsstrahlung`)
6. Low-energy electron Dose Point Kernels (`LowEElecDPK`)
7. Fano Cavity test (`FanoCavity`)
8. Microdosimetry (`Microyz`)
9. Brachytherapy (`Brachy-Ir`)
10. Monoenergetic x-ray internal breast dosimetry (`Mammo`)

Tests for EM & Hadronic Physics Constructors

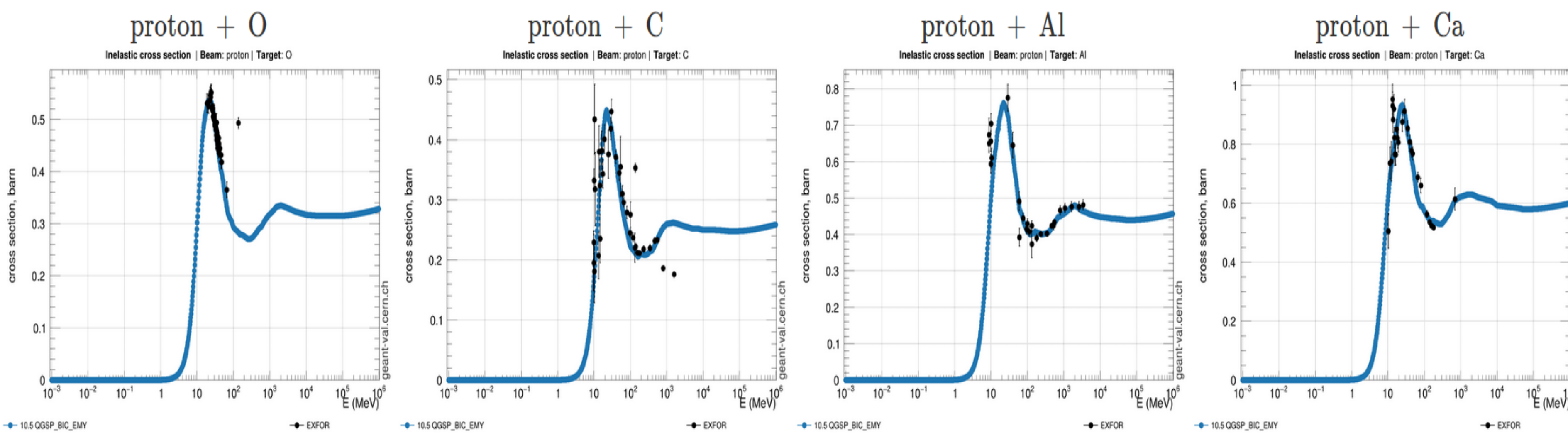
1. Nucleus-nucleus hadronic inelastic scattering cross sections (**`NucNucInelXS`**)
2. Validation of neutron yields with proton & carbon ion beams (**`ProtonC12NeutronYield`**)
3. Cross section of isotope production for carbon ion therapy (**`C12FragCC`**)
4. Carbon-12 fragmentation (**`C12Frag`**)
5. Carbon-12 fragmentation at low energy (**`LowEC12Frag`**)
6. Bragg curves of low energy protons in water (**`LowEProtonBraggPeak`**)
7. Light ion Bragg curves (**`LightIonBraggPeak`**)
8. RBE calculation in proton therapy (**`LowEProtonRBE`**)

Nucleus-Nucleus Inelastic Scattering Cross Section



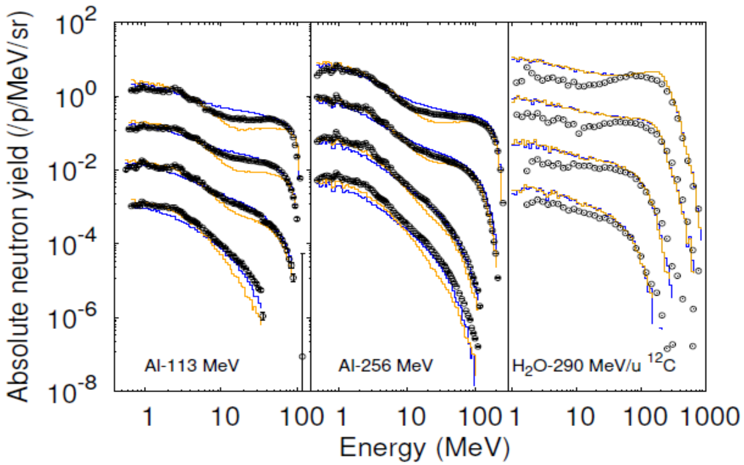
- Calculation of total inelastic cross section based on Glauber representation + Gribov screening correction (head-on collision).

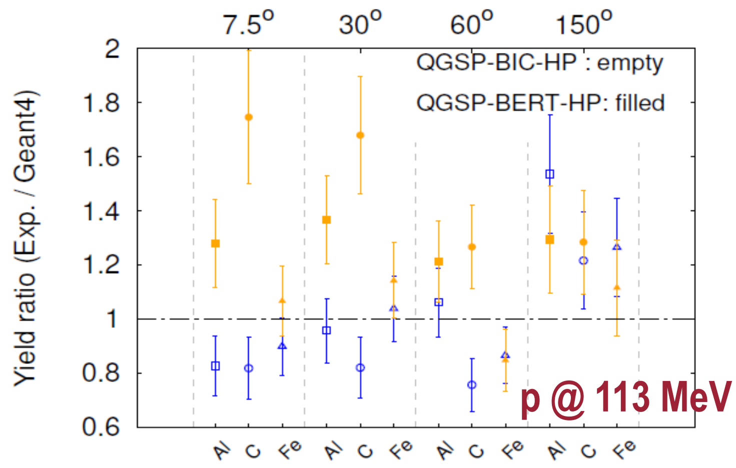
> Ref. Data from EXFOR
> **Zerkin & Pritychenko, NIM A 888 (2018)**

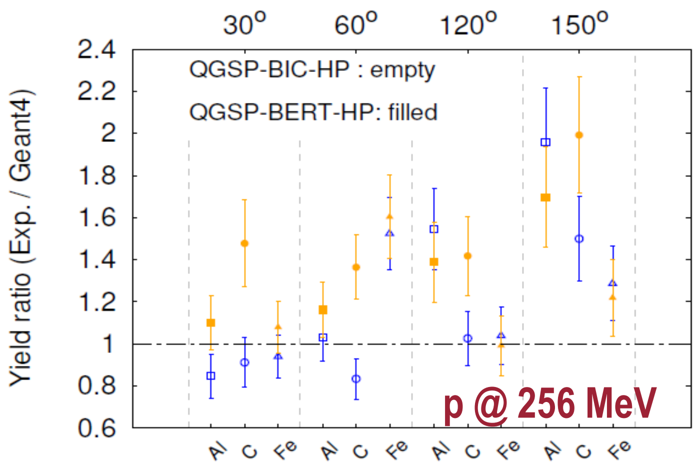


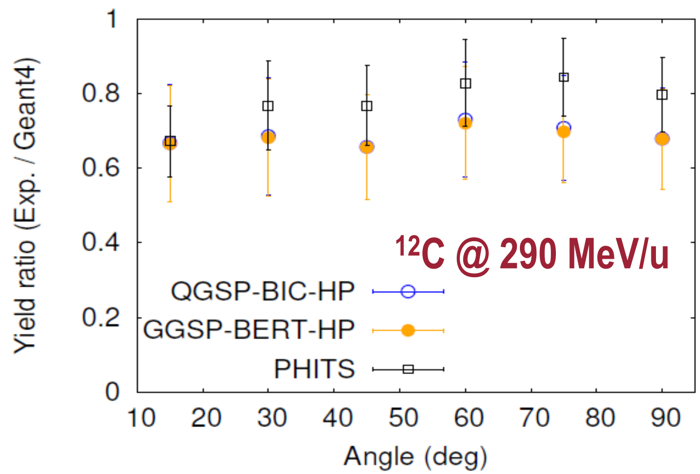
Geant Validation Portal, SFT group, CERN, 2016-2018

Thick-Target Neutron Yields
Proton & Carbon Beams









Ref. data from:
Meier et al., Nucl Sci Eng 102 (1989); Nucl Sci Eng 104 (1990)
Satoh et al., NIM B 387 (2016)

- Proton beams completely stopped in target
- ^{12}C on 18 cm water target

Isotope Production Cross Sections with ^{12}C Beams

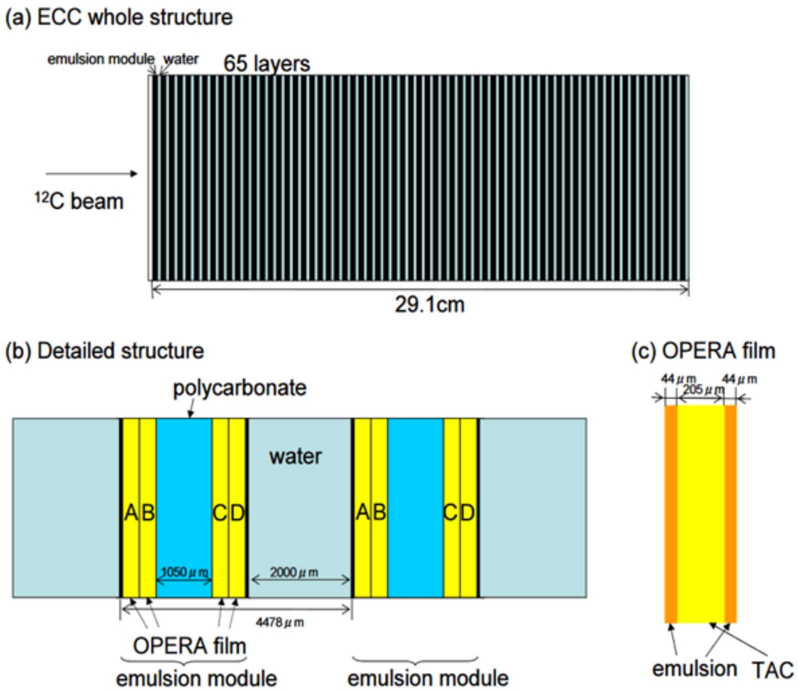
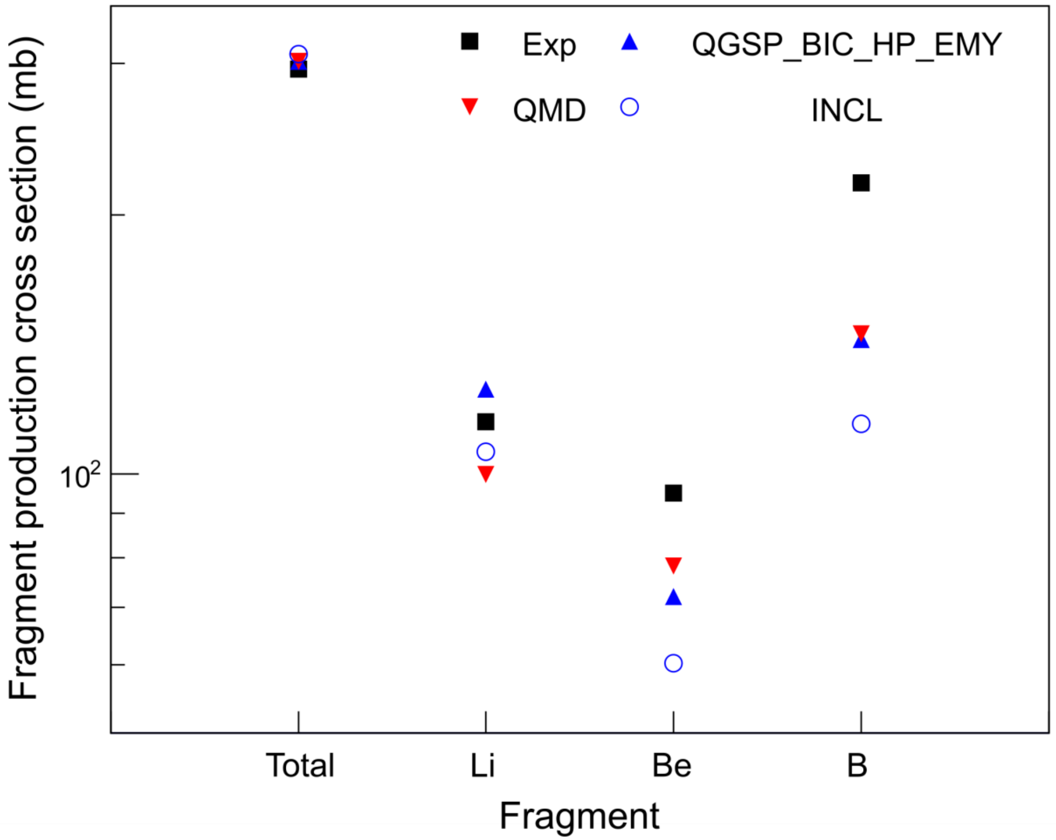


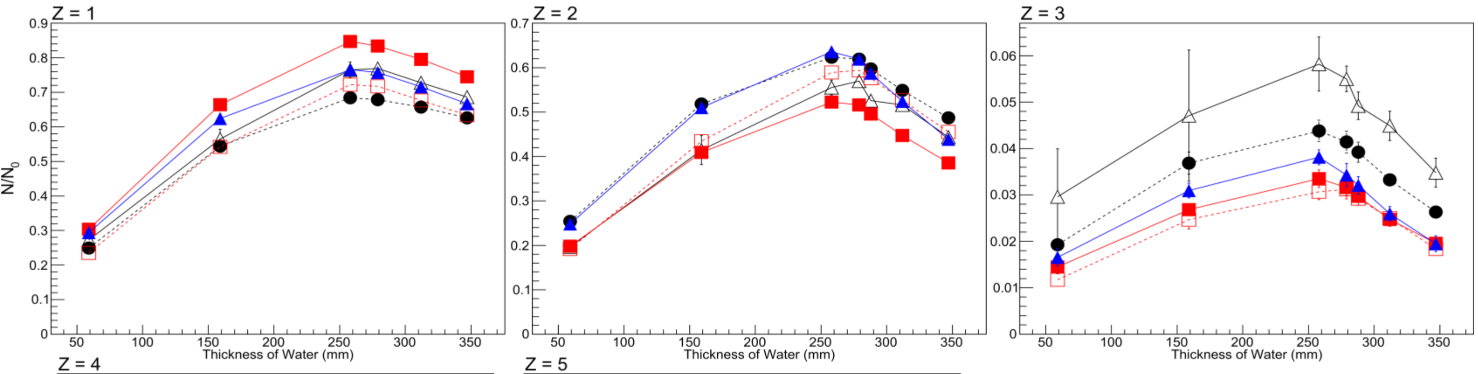
FIG. 1: (Color online) (a) A schematic view of the whole structure of the Emulsion Cloud Chamber (ECC). It has 65 layers of emulsion modules and water targets. (b) Detailed structure of the ECC. An emulsion module consists of four emulsion sheets and a polycarbonate plate. (c) Cross section of an OPERA film. An OPERA film has emulsion layers coated on both sides of a TAC base.

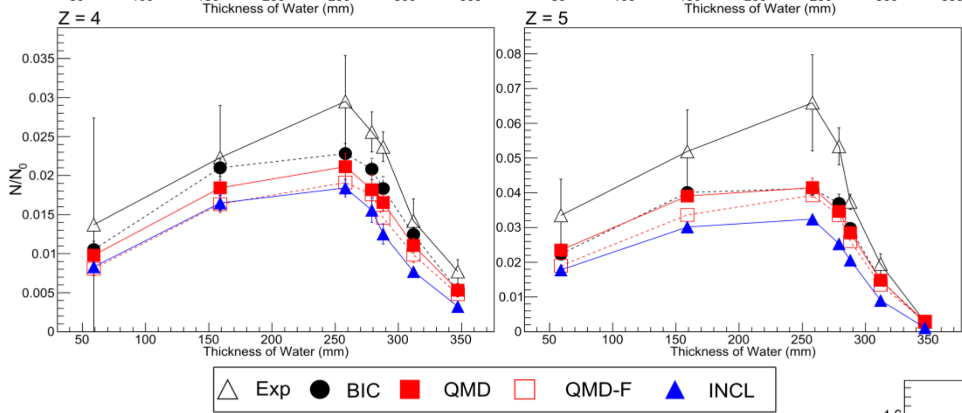


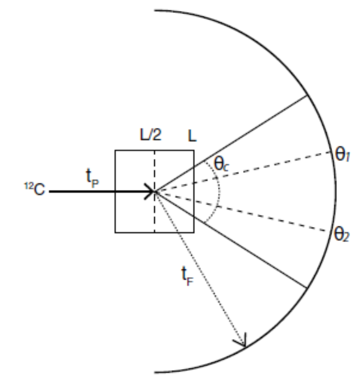
Ref. data: **T. Toshito et al., Phys Rev C 75 (2007)**

- BIC & QMD provide a better overall agreement with ref. data
- Total fragment production cross section is equal between BIC, QMD & INCLXX

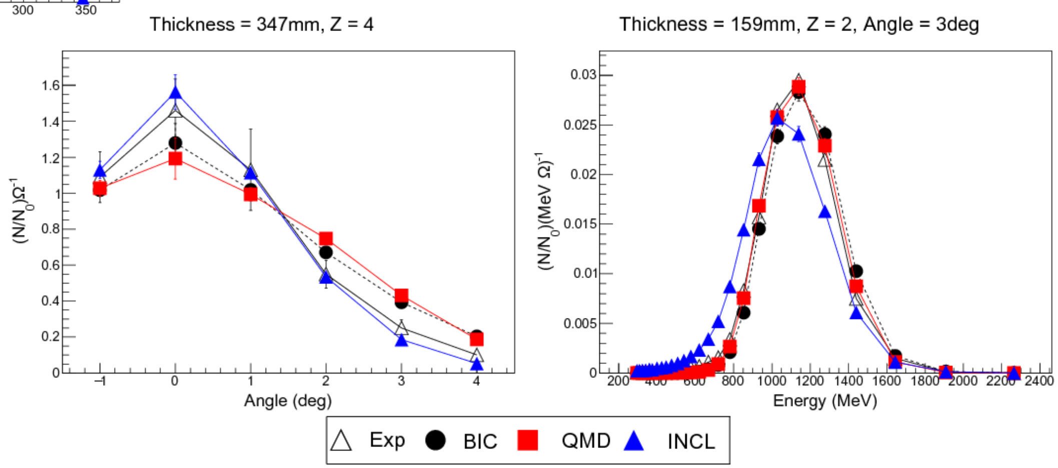
Fragment Yields for ^{12}C @ 400 MeV/u on Water Target







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

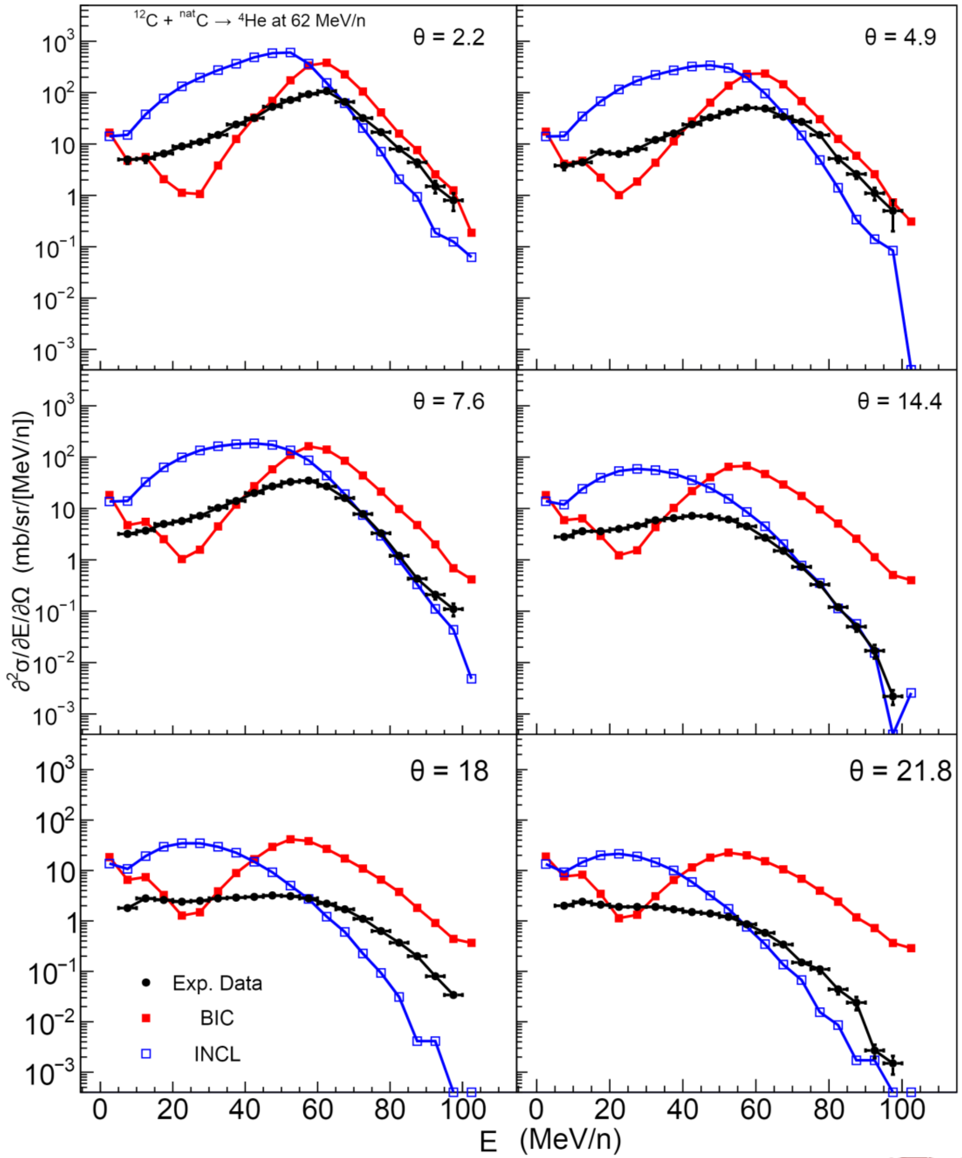


- INCL++ reproduced better angular distribution, but
- QMD & BIC provided better energy distributions.

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

Fragment Yields for ^{12}C @ 62 A MeV on ^{nat}C Target

- Thin target data
- QMD is not included as energy is below lower limit (100 A MeV)
- Distribution shape differ between BIC & INCL
- Limited reproducibility of data.



C. Mancini-Terraciano et al., IFMBE Proc. 68 (2019)
Ref. Data: **M. De Napoli et al., Phys. Med. Biol. 57 (2012)**

Bragg Curves for 67.5 MeV Protons in Water

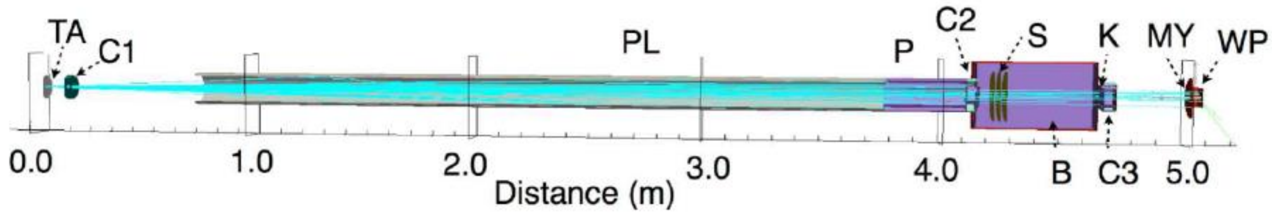
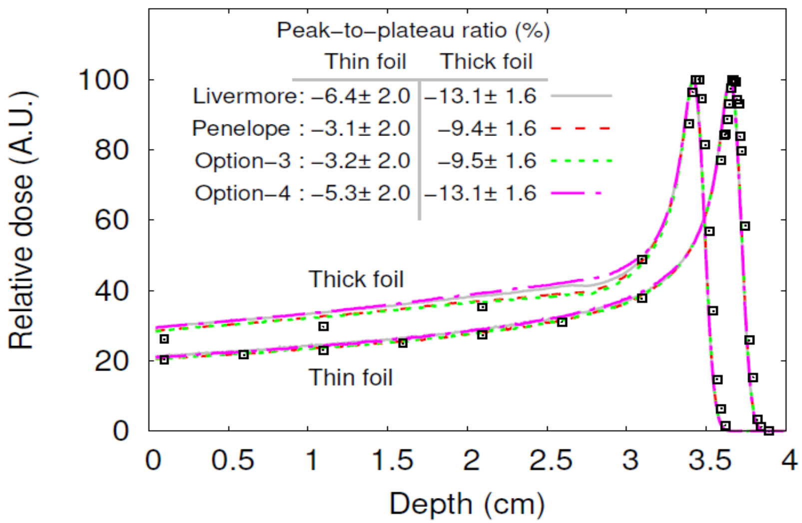
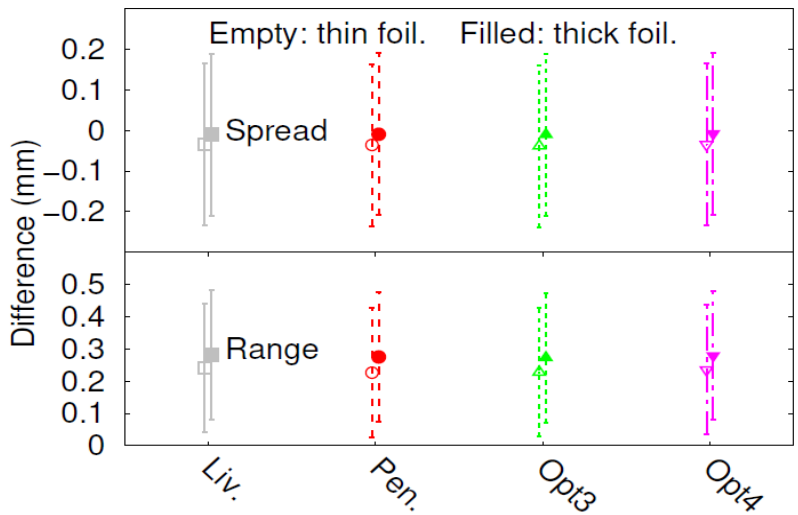


FIG. 1. Raw beam line used for benchmark measurements showing the Ta scattering foil (TA), the four sequentially placed collimating elements of the carbon collimator (C1), beam plug (PL), beam pipe (P), and second collimator (C2), the secondary emission monitor (S) enclosed in an evacuated box (B), the exit window (K) with the third collimator (C3), where the beam passes out of vacuum into air, and the Mylar window (MY) with water phantom (WP). See Table I in the Appendix for detailed geometry. A few simulated proton tracks are shown.

B. Faddegon et al., Med Phys 42 (2015)

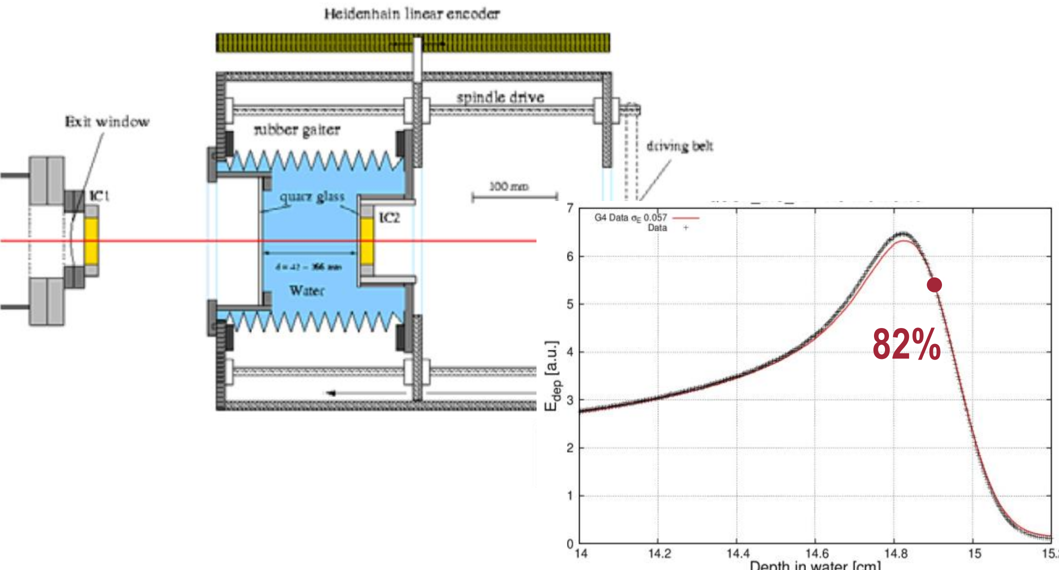




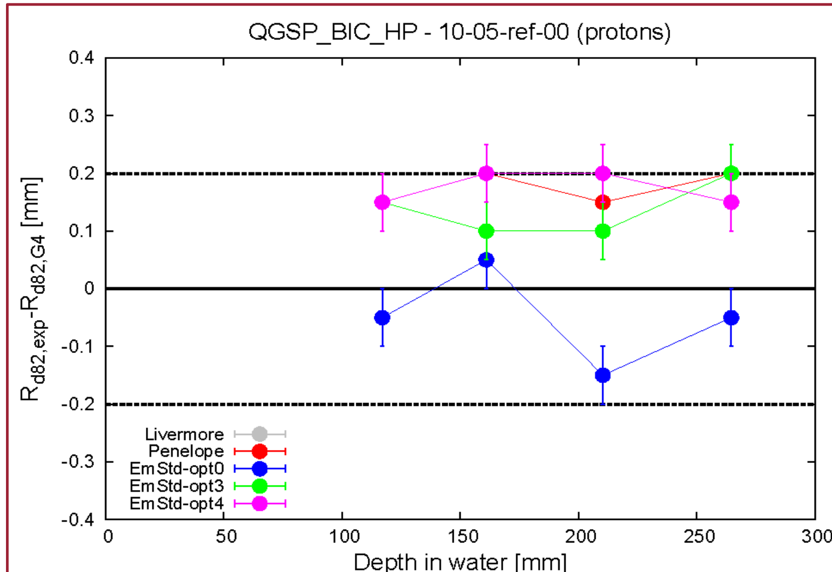
Differences calculated on fits using formula proposed by T. Bortfeld

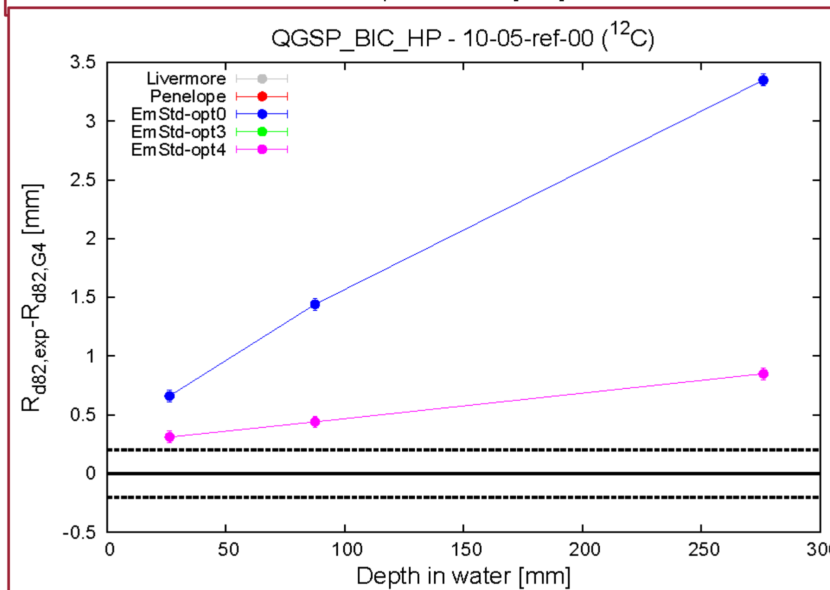
T. Bortfeld, Med Phys 24 (1997)

Bragg Curves in Water for Proton & ^{12}C Beams at Therapy Energies



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





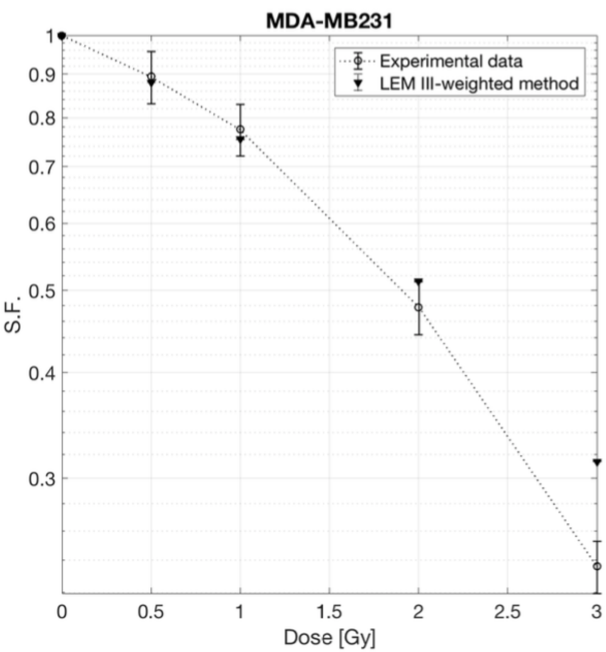
- Initial energy spread adjusted from experimental Bragg curves.
- Simplified geometry model for simulation
  - **Depths of 82% distal level are compared.**
- “option0” not accurate enough for ^{12}C, other EM constructors agree within 2-3 sigma.
- For proton beams, all physics lists agree within experimental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

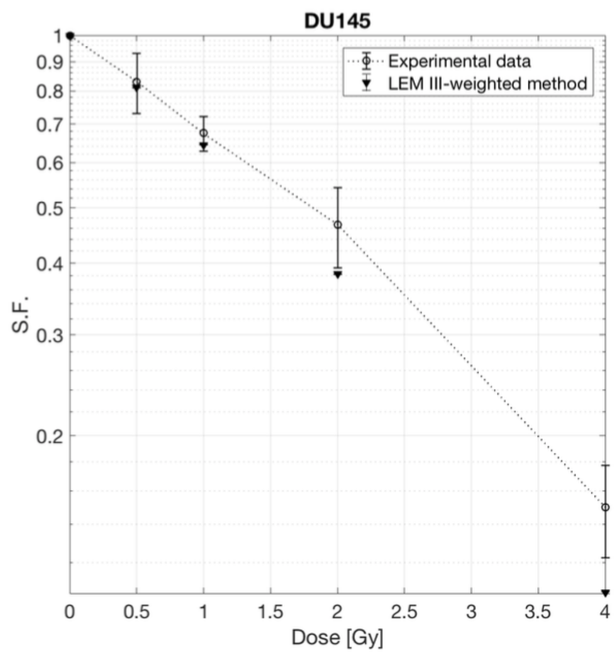
Survival fraction calculations with 62 MeV Proton Beams

Cell Survival Fraction (*S*)

$$S = e^{-\langle\alpha\rangle D - \langle\beta\rangle D^2} \quad \text{with} \quad \begin{cases} \langle\alpha\rangle = \dfrac{\sum_i \alpha_i D_i}{\sum_i D_i} \\ \langle\beta\rangle = \left(\dfrac{\sum_i \sqrt{\beta_i} D_i}{\sum_i D_i}\right)^2 \end{cases}$$

α_i and β_i precompiled for monoenergetic ions from Z=1 to Z=8.





- Geometry reproduced with ***Hadrontherapy*** example
- Cell irradiations done in water at 2 cm depth
- Prostate DU145 & breast cancer cell line MDA-MB-231
- Experimental survival fractions can be successfully derived with Geant4

G. Petringa et al., Phys Med 58 (2019)

More Test Results at TWiki Webpage & geant-val

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

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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

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.
  Shielding (_EMZ) physics list can be also used for carbon therapy.
- **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

Thanks for your attention!