Validation of Geant4 for hadron therapy

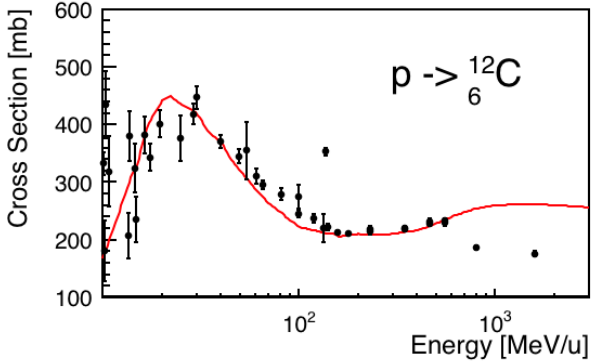
- Cross sections
- Fragmentation
- Regression testing

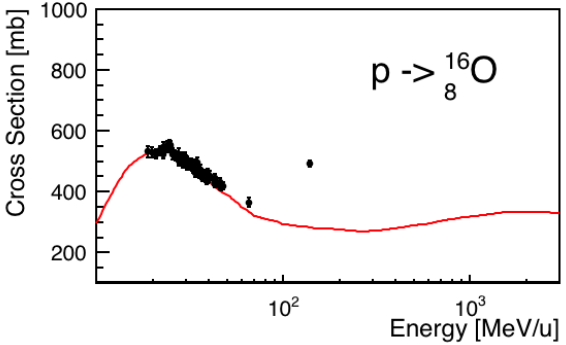
Geant4 Collaboration Meeting 2018, Lund

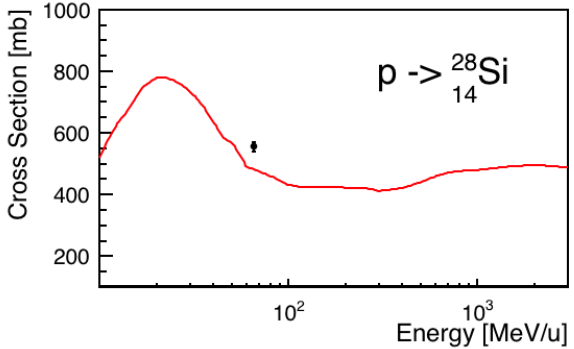
Cross sections

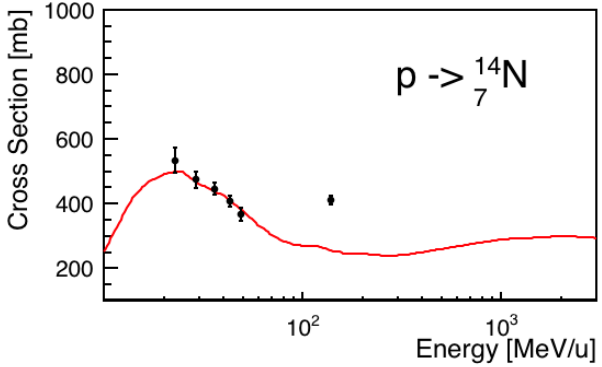
- Authors:
  - J. Allen, D. Sakata and S. Guatelli (CMRP, UOW)
  - E. Simpson (ANU, Canberra)
- Compare cross sections calculated by means of G4ComponentGGNuclNuclXsc against XFOR
  - For targets and energies of interest for hadrontherapy (E < 400 MeV/nucl)

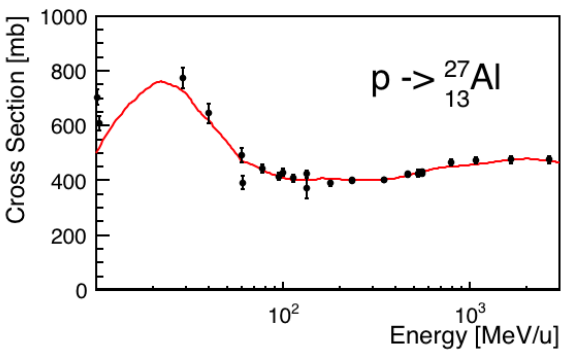
Incident protons

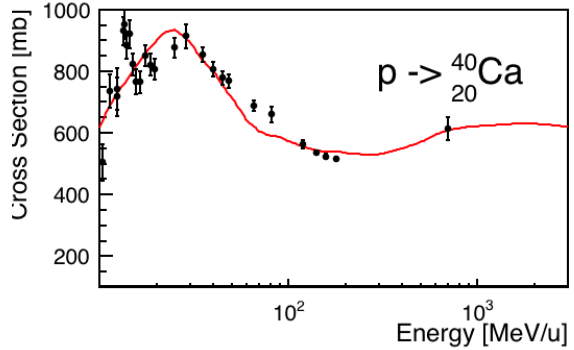




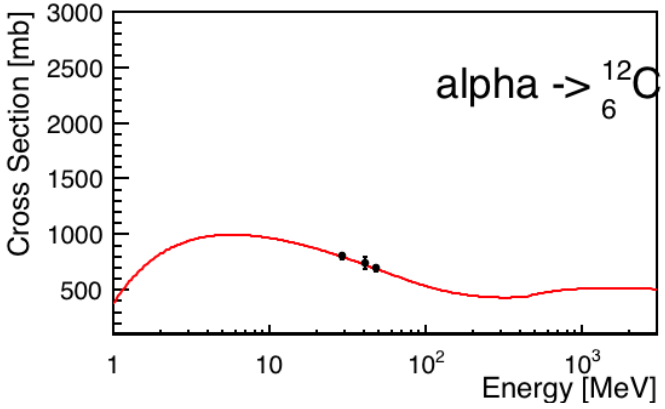


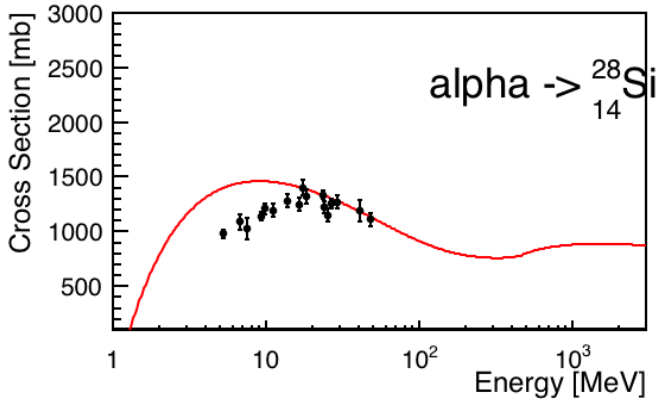


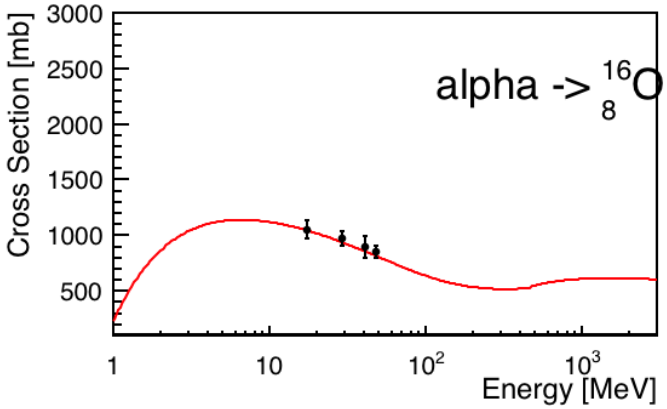


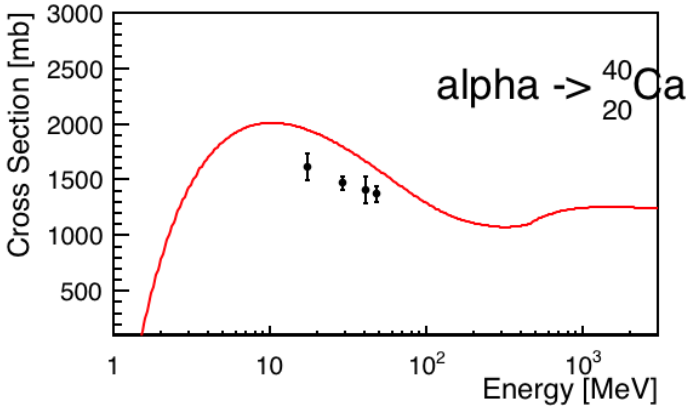


Incident alpha particles

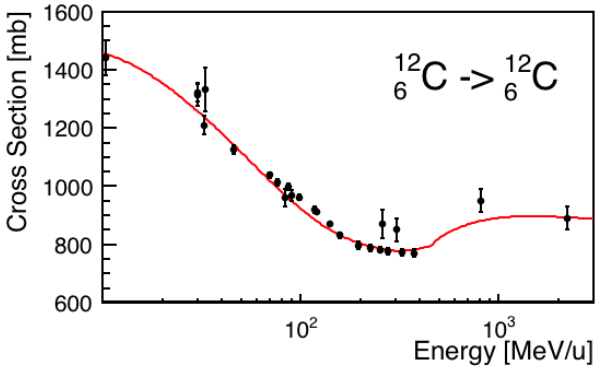


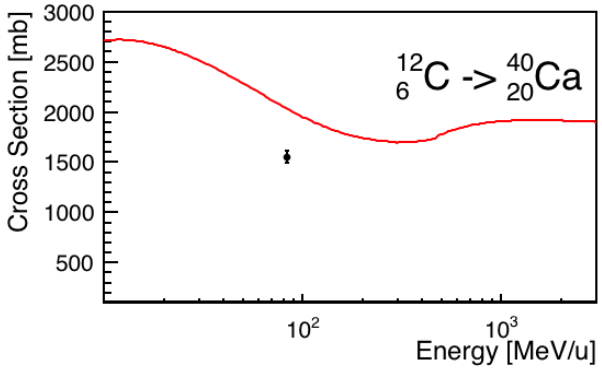


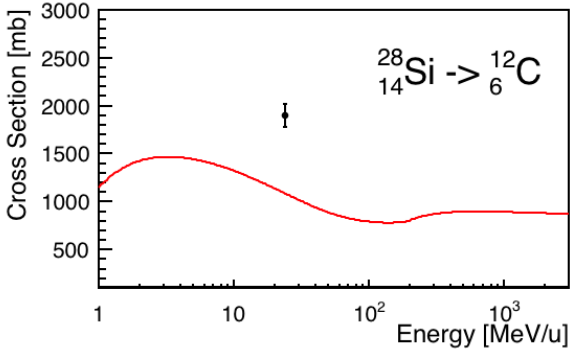


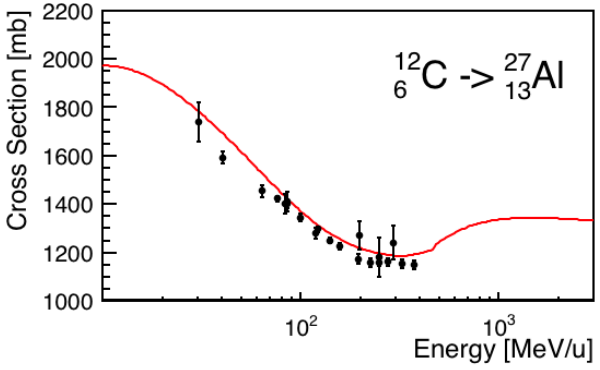


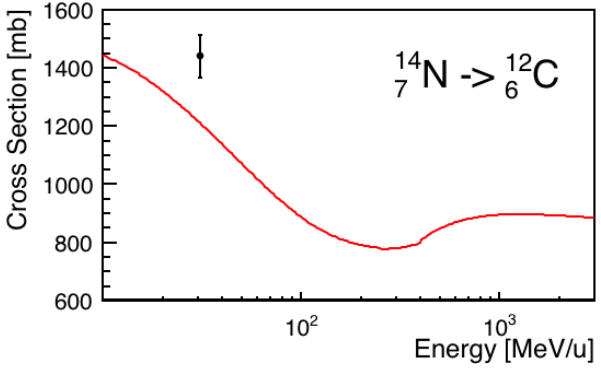
Carbon, Nitrogen, Silicon projectiles

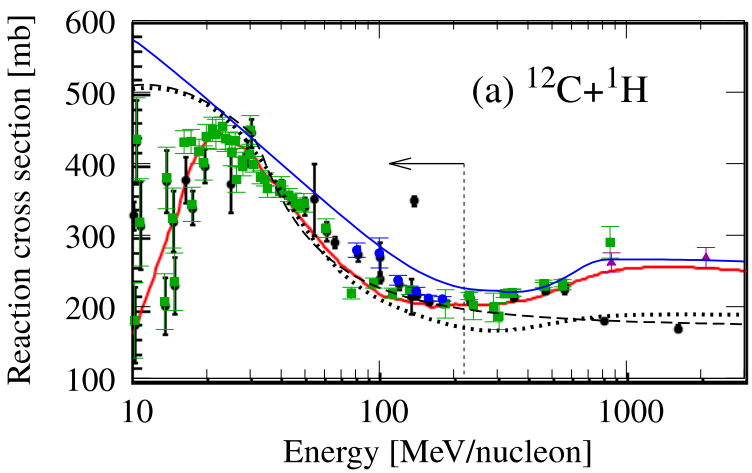


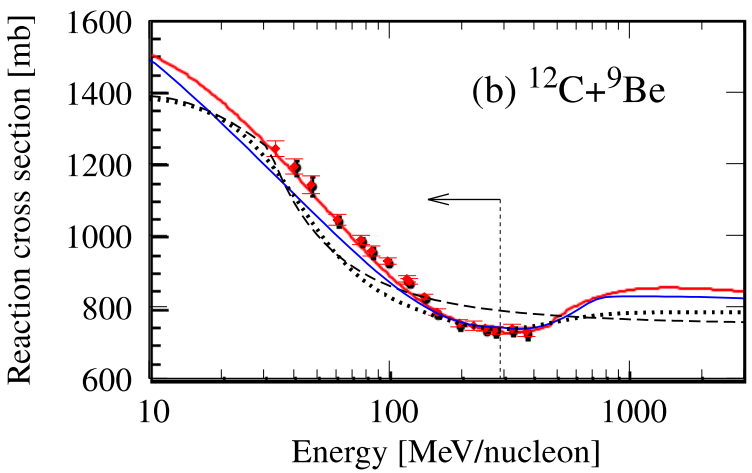


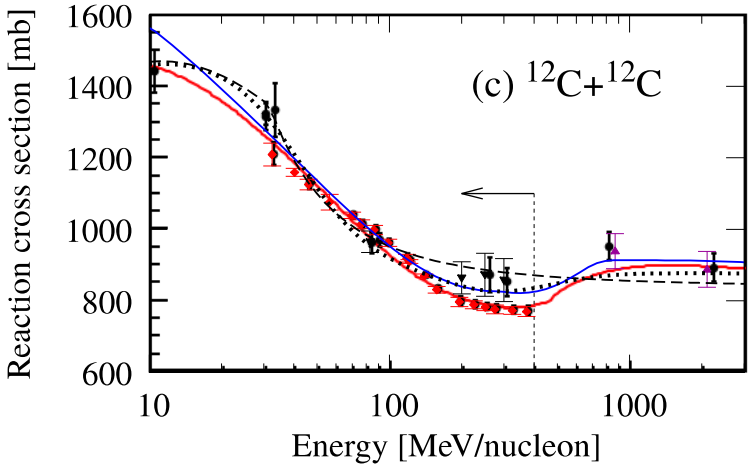


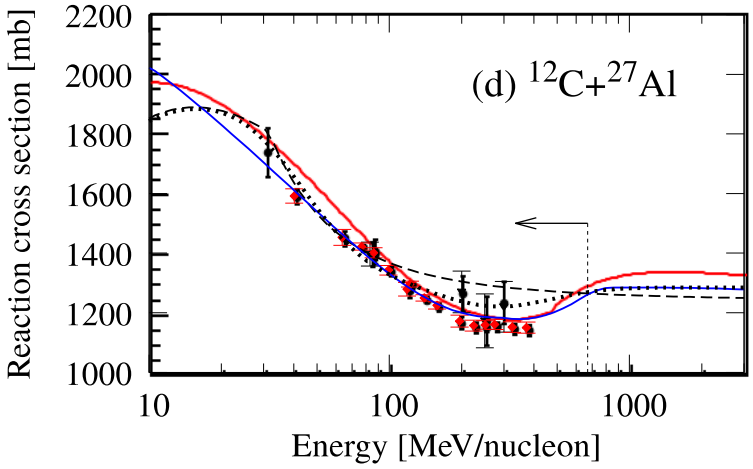





(a) ^{12}C+^{1}H
Reaction cross section [mb]
Energy [MeV/nucleon]


(b) ^{12}C+^{9}Be
Reaction cross section [mb]
Energy [MeV/nucleon]


(c) ^{12}C+^{12}C
Reaction cross section [mb]
Energy [MeV/nucleon]


(d) ^{12}C+^{27}Al
Reaction cross section [mb]
Energy [MeV/nucleon]

Validation of Geant4 fragmentation models for clinical ion beams between ^{4}He and ^{20}Ne

D. Bolst[1], G.A.P. Cirrone[2], G. Cuttone[2], G. Folger[3], S. Incerti[4,5], V. Ivanchenko[3,6], T. Koi[7], D. Mancusi[8], L. Pandola[2], F. Romano[2,9], A. Rosenfeld[1] and S. Guatell[1]

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[2]INFN, Laboratori Nazionali del Sud, Catania, Italy
[3]The European Organisation for Nuclear Research (CERN)
[4]CNRS/IN2P3, Centre d'Etudes Nucl´eaires de Bordeaux-Gradignan, France
[5]Universit´e Bordeaux, Centre d'Etudes Nucl´eaires de Bordeaux-Gradignan, France
[6]Tomsk State University, Tomsk, Russia
[7]SLAC National Accelerator Laboratory, 2575 Sand Hill Rd, Menlo Park, USA
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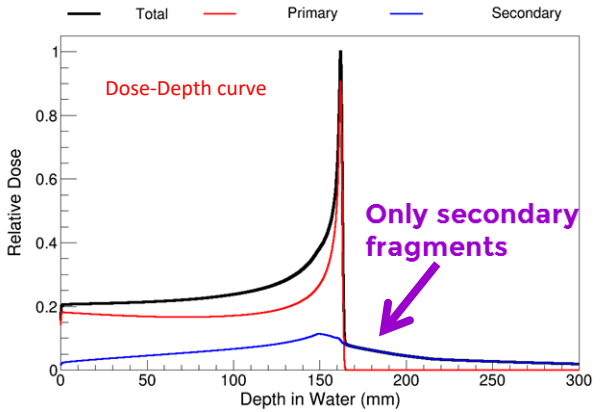
[9]National Physical Laboratory, Acoustic and Ionizing Radiation Division, Teddington, Middlesex, UK

PhD student David Bolst, CMRP, University of Wollongong

Validation of Geant4 physics models for HIT: regression testing

Mixed radiation field produced by a Carbon Ion Beam with clinical energy (290 MeV/u)



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Validation of Geant4 fragmentation for Heavy Ion Therapy

David Bolst [a], Giuseppe A.P. Cirrone [b], Giacomo Cuttone [b], Gunter Folger [c], Sebastien Incerti [d,e], Vladimir Ivanchenko [c,f], Tatsumi Koi [g], Davide Mancusi [h], Luciano Pandola [b], Francesco Romano [b,i], Anatoly B. Rosenfeld [a], Susanna Guatelli [a,*]

[a] Centre for Medical Radiation Physics, University of Wollongong, Australia
[b] INFN, Laboratori Nazionali del Sud, Catania, Italy
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[d] CNRS/IN2P3, Centre d'Etudes Nucléaires de Bordeaux-Gradignan, France
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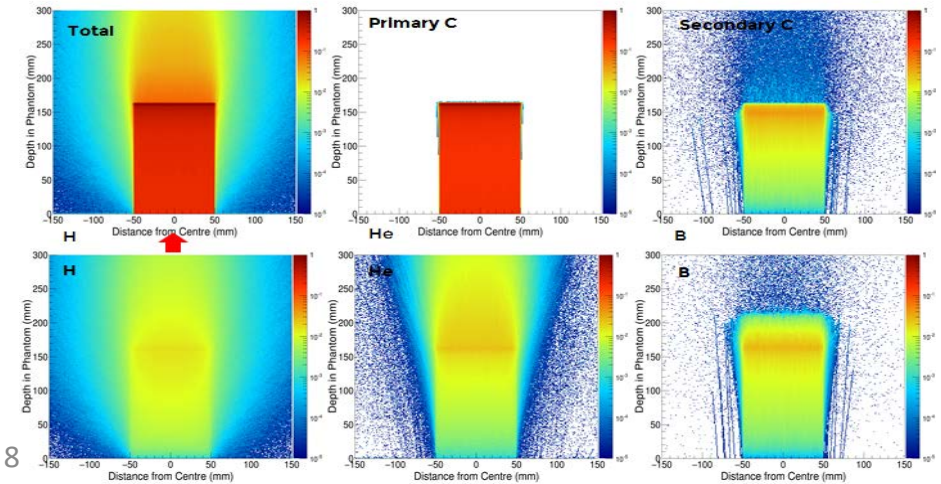
[h] French Alternative Energies and Atomic Energy Commission (CEA), Saclay, France
[i] National Physical Laboratory, Acoustic and Ionizing Radiation Division, Teddington TW11 0LW, Middlesex, UK



Adopted reference data

Publication	Beam	Target	Fragment Data
Rovituso et al. [6]	120/200 MeV/u ^{4}He	Water PMMA	Yields, angular and energy distribution
Aricó et al. [7]	220.5 MeV/u ^{4}He	Water PMMA	Yields
Marafini et al. [8]	102/125/145 MeV/u ^{4}He	PMMA	Angular and energy distribution
Schall et al. [9]	670 MeV/u ^{12}C 670 MeV/u ^{14}N 670 MeV/u ^{16}O	Water	Yields
Matsufuji et al. [10]	290 MeV/u ^{12}C 400 MeV/u ^{20}Ne	PMMA	Yields
Matsufuji et al. [11]	290 MeV/u ^{12}C	Water	Angular
Gunzert-Marx et al. [12]	200 MeV/u ^{12}C	Water	Yield, Angular, Energy

Table 1: Summary of fragmentation data used for testing.

[6] M. Rovituso, C. Schuy, U. Weber, S. Brons, M. A. Corts-Giraldo, C. L. Tessa, E. Piasetzky, D. Izraeli, D. Schardt, M. Toppi, E. Scifoni, M. Krmer, and M. Durante, "Fragmentation of 120 and 200 mev u 1 4 he ions in water and pmma targets," *Physics in Medicine Biology*, vol. 62, no. 4, p. 1310, 2017.

[7] G. Aricó, T. Gehrke, J. Jakubek, R. Gallas, S. Berke, O. Jkel, A. Mairani, A. Ferrari, and M. Martikov, "Investigation of mixed ion fields in the forward direction for 220.5 mev/u helium ion beams: comparison between water and pmma targets," *Physics in Medicine Biology*, vol. 62, no. 20, p. 8003, 2017.

[8] M. Marafini, R. Paramatti, D. Pinci, G. Battistoni, F. Collamati, E. D. Lucia, R. Faccini, P. M. Frallicciardi, C. Mancini-Terracciano, I. Mattei, S. Muraro, L. Piersanti, M. Rovituso, A. Rucinski, A. Russomando, A. Sarti, A. Sciubba, E. S. Camillocci, M. Toppi, G. Traini, C. Voena, and V. Patera, "Secondary radiation measurements for particle therapy applications: nuclear fragmentation produced by 4 he ion beams in a pmma target," *Physics in Medicine Biology*, vol. 62, no. 4, p. 1291, 2017.

[9] I. Schall, D. Schardt, H. Geissel, H. Irnich, E. Kankeleit, G. Kraft, A. Magel, M. Mohar, G. Mnzenberg, F. Nickel, C. Scheidenberger, and W. Schwab, "Charge-changing nuclear reactions of relativistic light-ion beams (5 z 10) passing through thick absorbers," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 117, no. 3, pp. 221 – 234, 1996.

[10] N. Matsufuji, A. Fukumura, M. Komori, T. Kanai, and T. Kohno, "Influence of fragment reaction of relativistic heavy charged particles on heavy-ion radiotherapy," *Physics in Medicine Biology*, vol. 48, no. 11, p. 1605, 2003.

[11] N. Matsufuji, M. Komori, H. Sasaki, K. Akiu, M. Ogawa, A. Fukumura, E. Urakabe, T. Inaniwa, T. Nishio, T. Kohno, and T. Kanai, "Spatial fragment distribution from a therapeutic pencil-like carbon beam in water," *Physics in Medicine Biology*, vol. 50, no. 14, p. 3393, 2005.

[12] K. Gunzert-Marx, H. Iwase, D. Schardt, and R. S. Simon, "Secondary beam fragments produced by 200mevu 1 12 c ions in water and their dose contributions in carbon ion radiotherapy," *New Journal of Physics*, vol. 10, no. 7, p. 075003, 2008.

Model of the experimental set-up in the simulation study

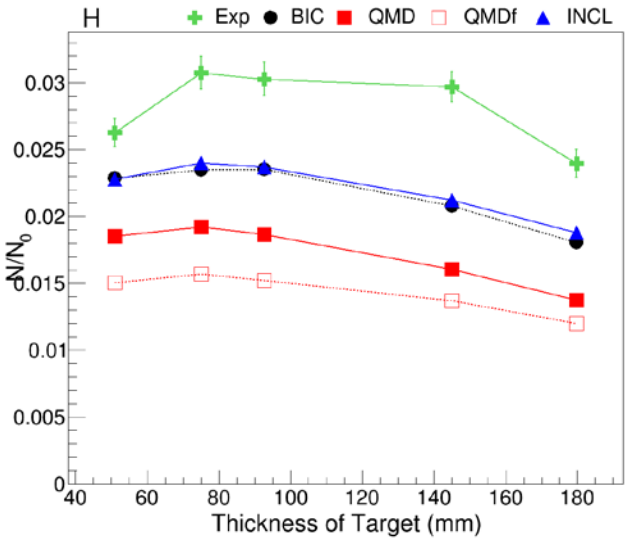
Results shown using 10.2p3

SELECTION OF RESULTS

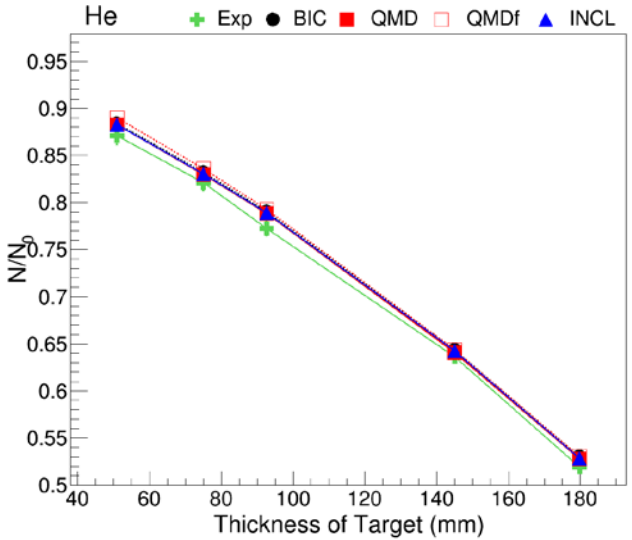
220.5 MeV/u ^{4}He incident on water

Reference: Arico et al, 2017

Radiation yield - H



Attenuation of the incident beam

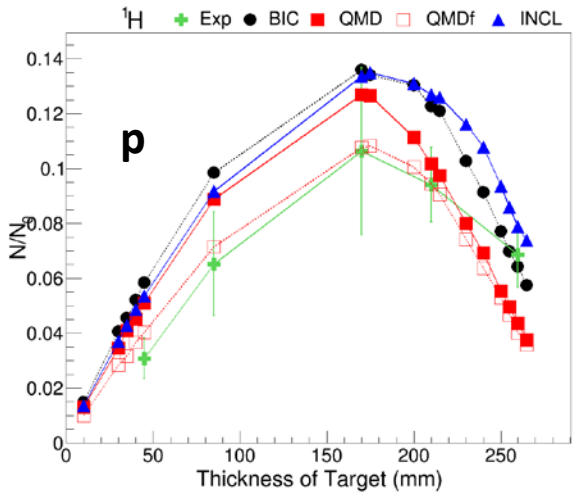


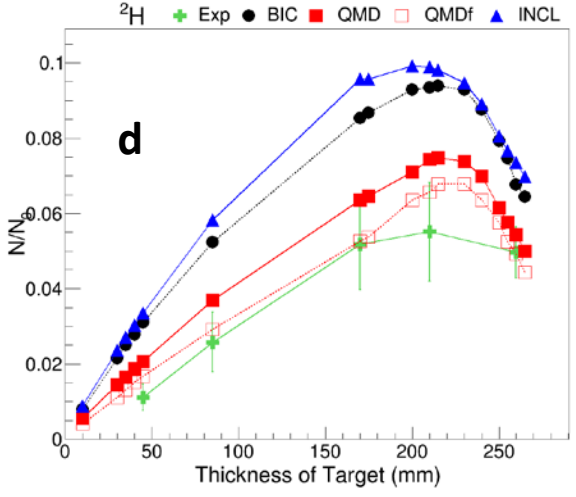
Range of the incident beam ~308 mm (WET)

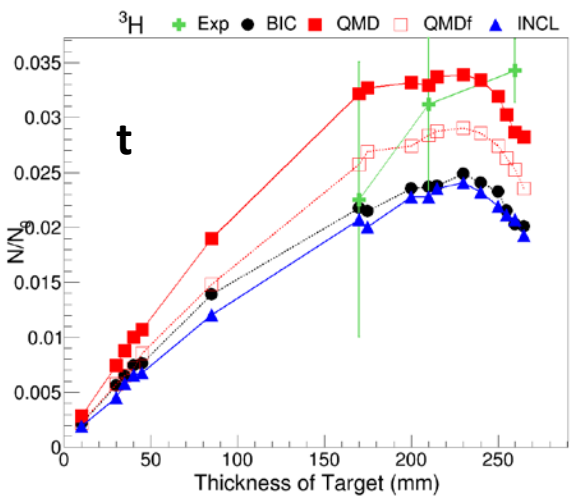
200 MeV/u ^{4}He on water target

Radiation yields

Reference: Rovituso et al, 2017





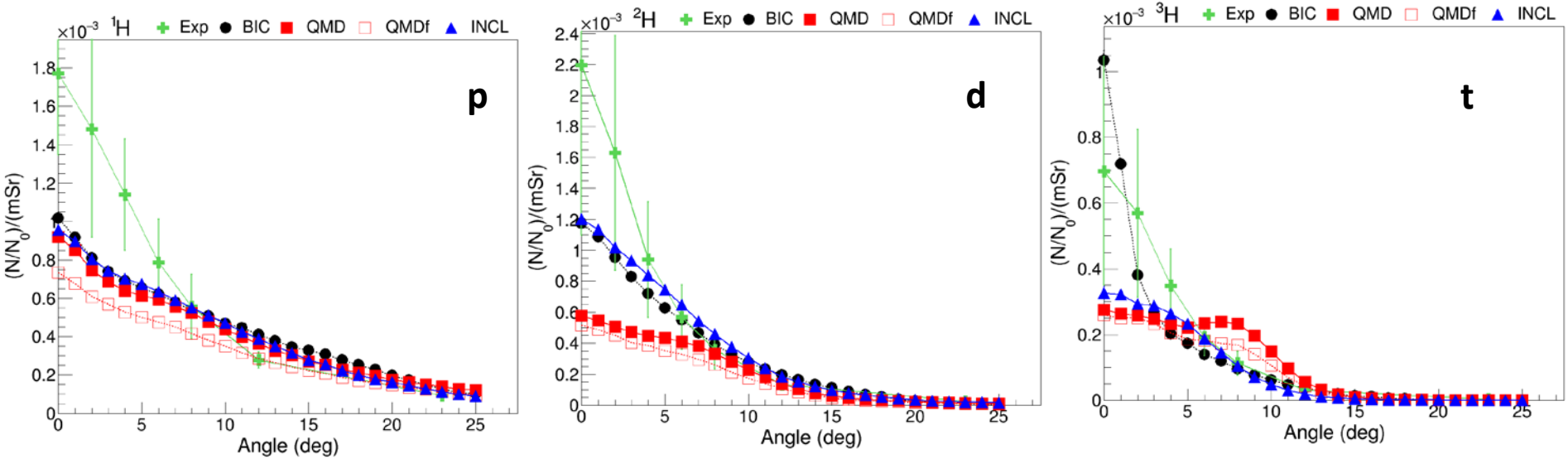


Range ~260 mm (WET)

200 MeV/u ^{4}He on Water target with 139.2 mm thickness

Angular distributions

Reference: Rovituso et al, 2017

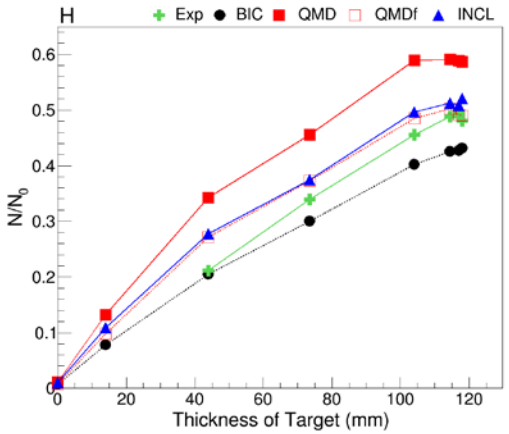


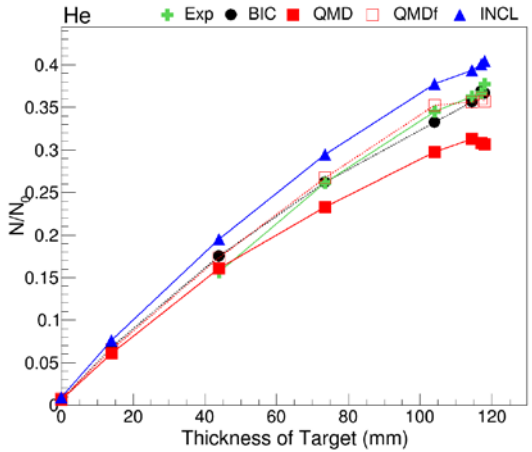
Range of the incident beam ~260 mm (WET)

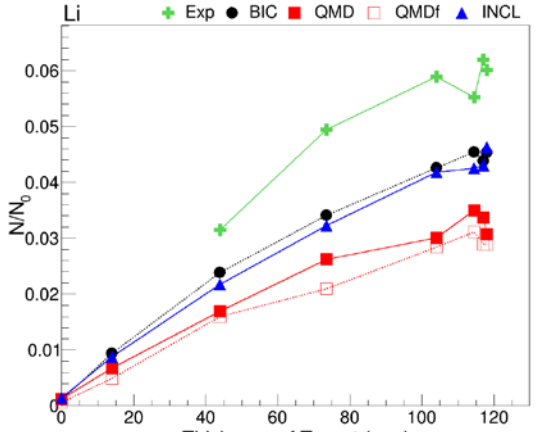
290 MeV/u ^{12}C incident on PMMA

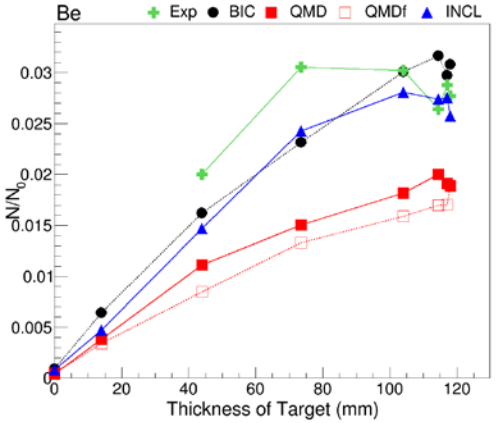
Radiation yields, Reference: Matsufuji et al, 2003

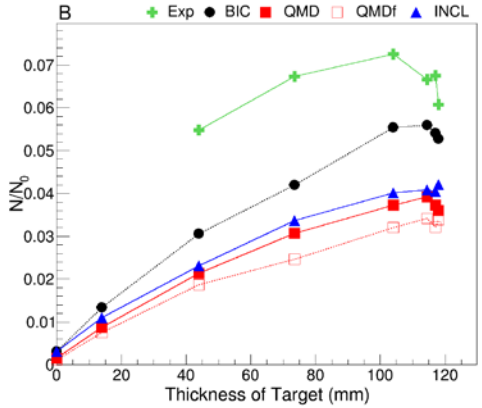
Range ~162 mm (WET)

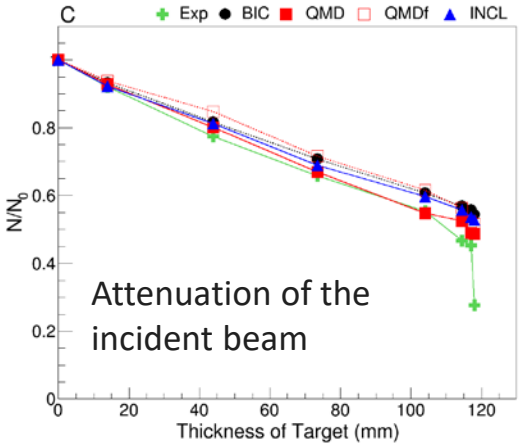








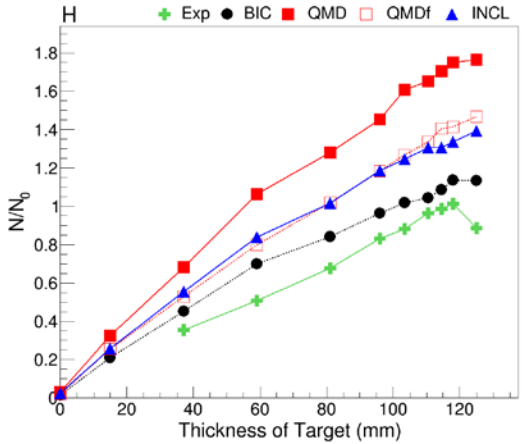


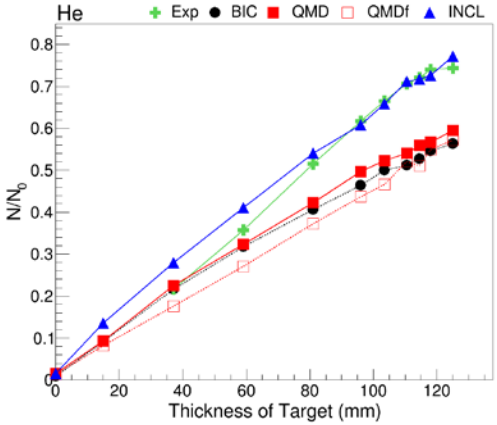


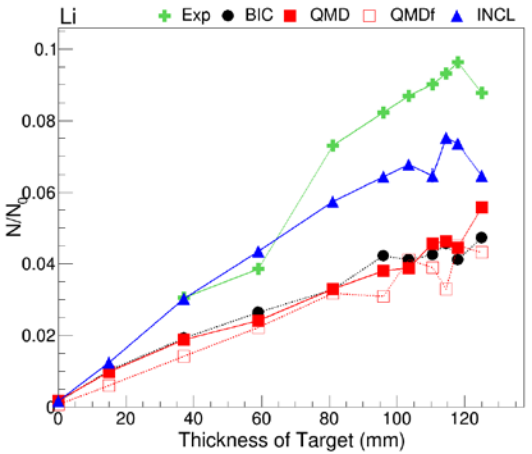
400 MeV/u ^{20}N on PMMA

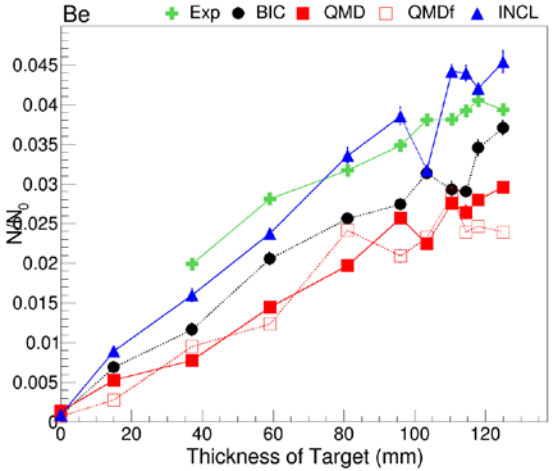
Range ~164 mm (WET)

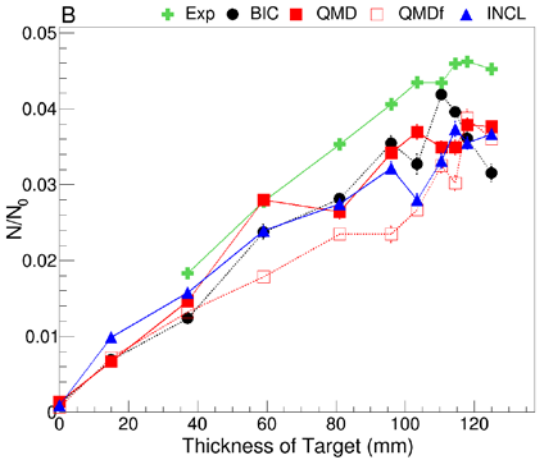
Reference: Matsufuji et al, 2003

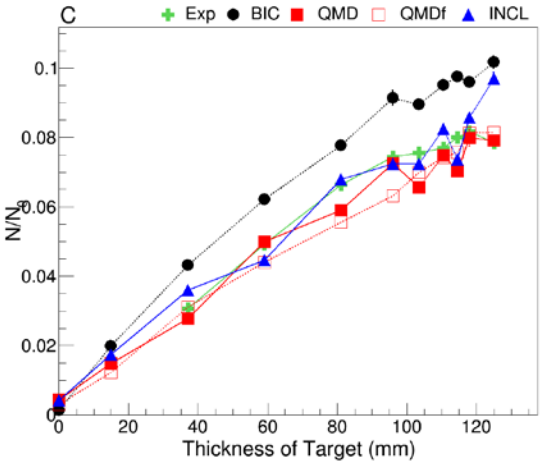








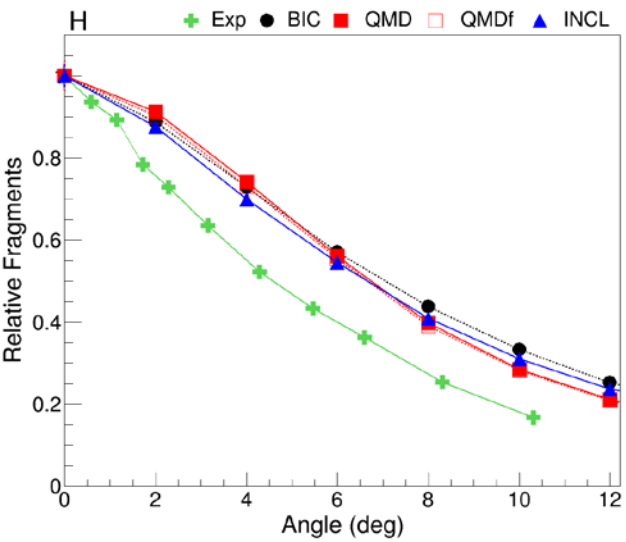


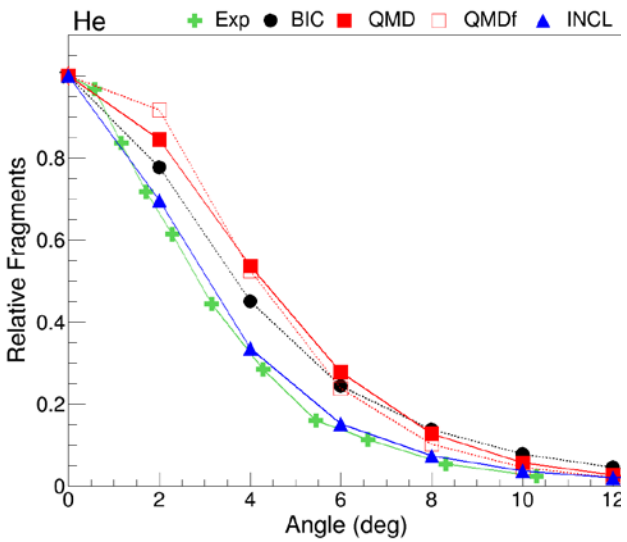


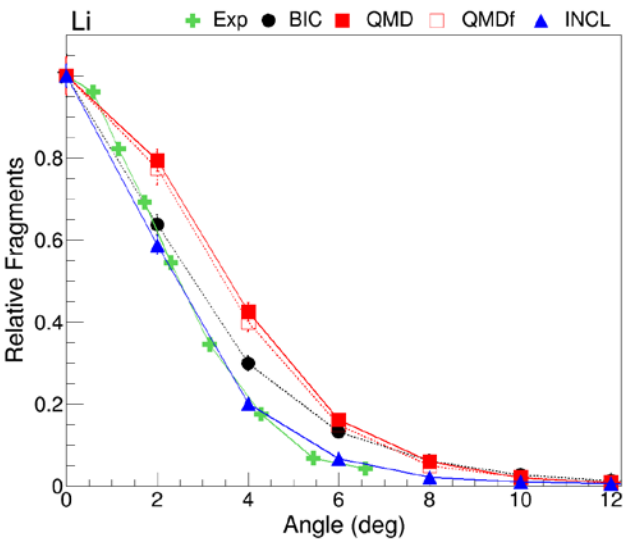
290 MeV/u ^{12}C incident on water

Range ~162 mm (WET)

Angular distributions





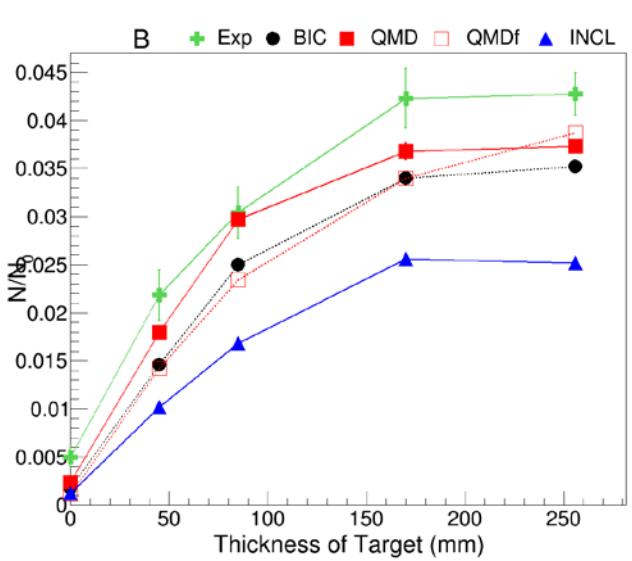


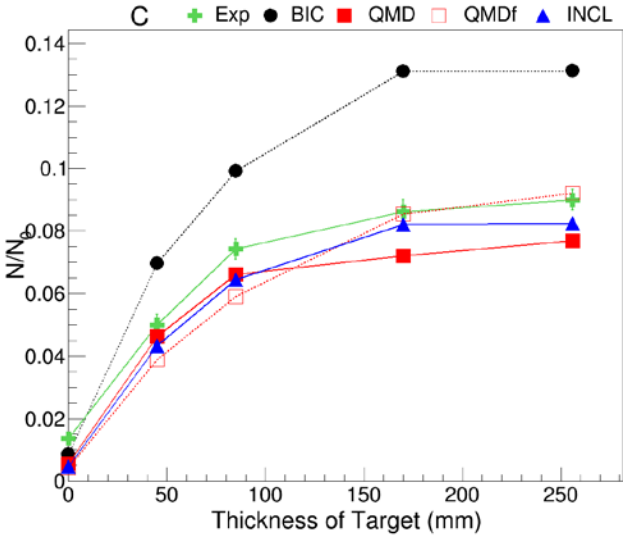
Simulation maximum is normalised to the 0 degrees of exp (experiment are given as arbitrary units)

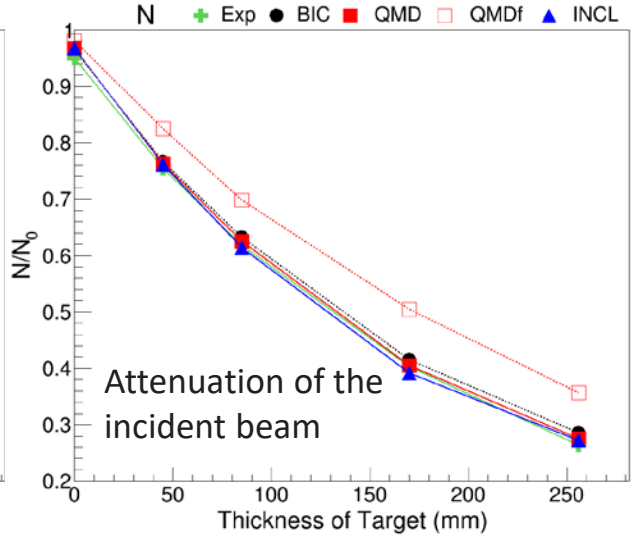
Reference: Matsufuji et al 2005

670 MeV/u N incident on water

Radiation yields





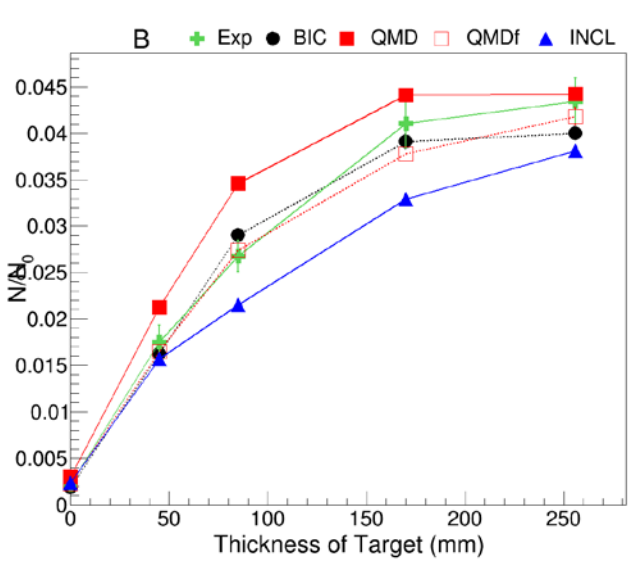


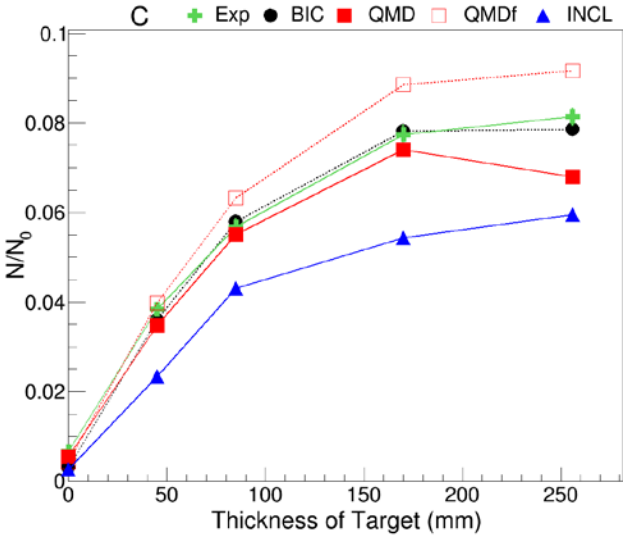
Reference: Schall et al. 1996 ^{12}C, ^{14}N, ^{16}O 1996

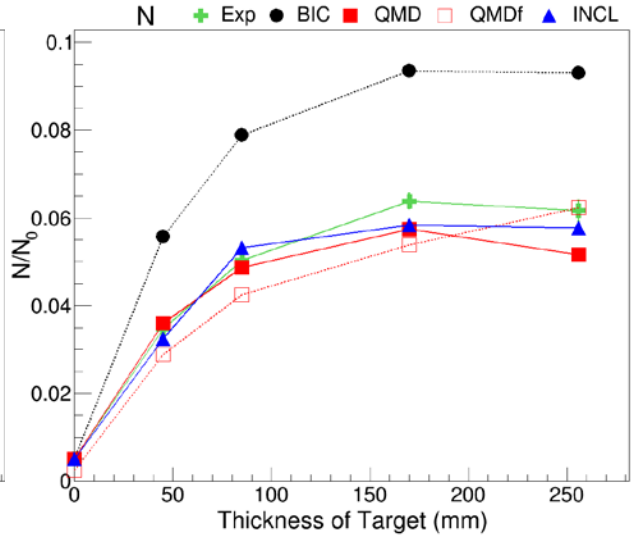
Range ~520 mm (WET)

670 MeV/u Oxygen on water target

Radiation yields







Reference: Schall et al. 1996 ^{12}C, ^{14}N, ^{16}O 1996

Range ~455 mm (WET)

Mean % difference: Helium Beams

Fragment yields

200 MeV/u Rovituso, 18° acceptance angle

Fragment	BIC	QMD	QMDf	INCL
p	44	47	50	46
d	28	49	60	25
t	67	55	66	71
He3	67	75	80	77
He4	22	22	25	22

★

220.5 MeV/u Arico (Water), 0.35° acceptance angle

Z	BIC	QMD	QMDf	INCL
1	23	39	49	21
2	2	1	2	1

★

220.5 MeV/u Arico (PMMA), 0.35° acceptance angle

Z	BIC	QMD	QMDf	INCL
1	19	38	50	20
2	1	1	2	1

★

Angular Distribution

120 MeV/u Rovituso

Fragment	BIC	QMD	QMDf	INCL
p	40	37	37	31
d	18	16	12	31
t	43	42	41	55
He3	49	56	55	61

200 MeV/u Rovituso

Fragment	BIC	QMD	QMDf	INCL
p	34	36	37	30
d	33	39	51	27
t	40	64	48	36

Difficult to say which model behaves better

★ **Attenuation of the incident beam**

Mean % differences: Incident carbon beams

Fragment yields

290 MeV/u Matsufuji

Z	BIC	QMD	QMDf	INCL
1	11	31	8	11
2	3	13	4	12
3	26	46	51	29
4	13	37	45	12
5	26	48	55	44
6	21	26	19	22

★

670 MeV/u Schall, ~2.3° acceptance angle

Z	BIC	QMD	QMDf	INCL
5	7	11	24	30
6	3	2	19	1

★

Angular Distribution

290 MeV/u Matsufuji (normalised)

Z	BIC	QMD	QMDf	INCL
1	41	35	34	35
2	78	69	57	20
3	24	51	45	9
4	65	113	95	22
5	96	363	323	13

200 MeV/u Guntzert-Marx

Fragment	BIC	QMD	QMDf	INCL
p	29	74	49	26
d	18	13	10	44
t	16	18	11	36
He3	60	70	73	68
He4	67	54	70	33

Mean % differences: Radiation yields

Oxygen beam

670 MeV/u Schall ~2.3° acceptance angle

Z	BIC	QMD	QMDf	INCL
5	7	15	5	16
6	3	8	11	30
7	54	8	12	7
8	2	2	15	2

469 MeV/u Schall ~2.3° acceptance angle

Z	BIC	QMD	QMDf	INCL
8	3	3	5	3

★ **Attenuation of the incident beam**

Nitrogen beam

Z	BIC	QMD	QMDf	INCL
5	22	11	22	45
6	43	12	11	10
7	4	2	21	2

Neon beam

400 MeV/u Matsufuji

Z	BIC	QMD	QMDf	INCL
1	20	85	48	46
2	21	18	26	6
3	48	48	55	20
4	22	37	39	13
5	19	17	30	21
6	24	6	7	9
7	13	25	31	17
8	39	45	40	64
9	22	51	55	36
10	13	13	11	12

405 MeV/u Schall ~2.3° acceptance angle

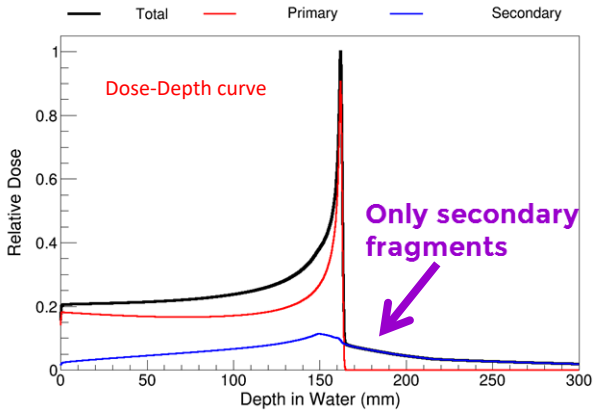
Z	BIC	QMD	QMDf	INCL
10	9	8	18	8

Conclusion

- Analysis of the results just started
- Now we are focusing on alpha incident particles. Once we have more solid analysis, regression testing.
- We are happy to participate at the Geant4 Hadronic Meetings to show the progress of this work

Validation of Geant4 physics models for HIT: regression testing

Mixed radiation field produced by a Carbon Ion Beam with clinical energy (290 MeV/u)



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Validation of Geant4 fragmentation for Heavy Ion Therapy

David Bolst [a], Giuseppe A.P. Cirrone [b], Giacomo Cuttone [b], Gunter Folger [c], Sebastien Incerti [d,e], Vladimir Ivanchenko [c,f], Tatsumi Koi [g], Davide Mancusi [h], Luciano Pandola [b], Francesco Romano [b,i], Anatoly B. Rosenfeld [a], Susanna Guatelli [a,*]

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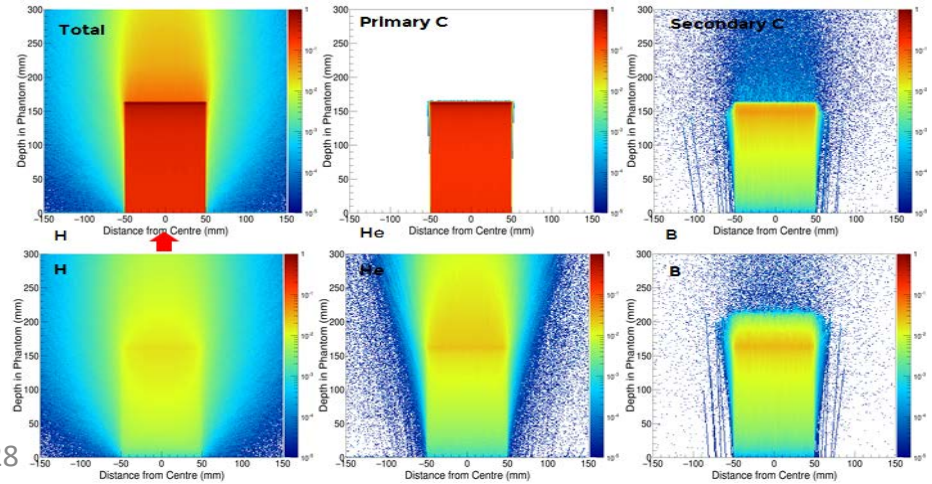
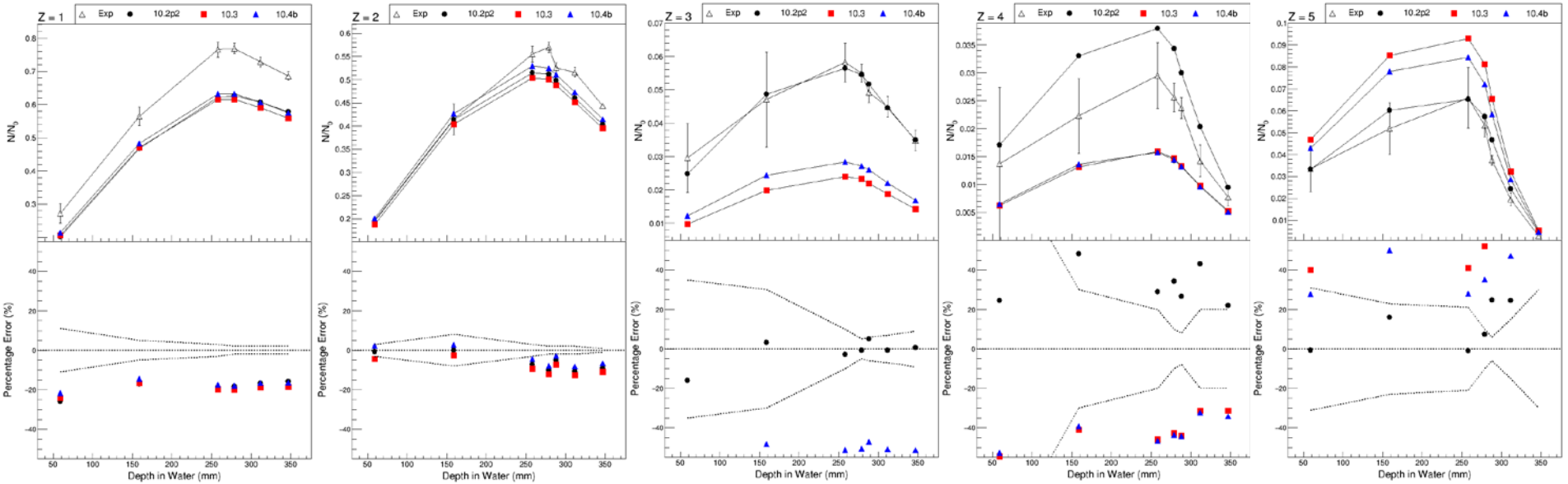
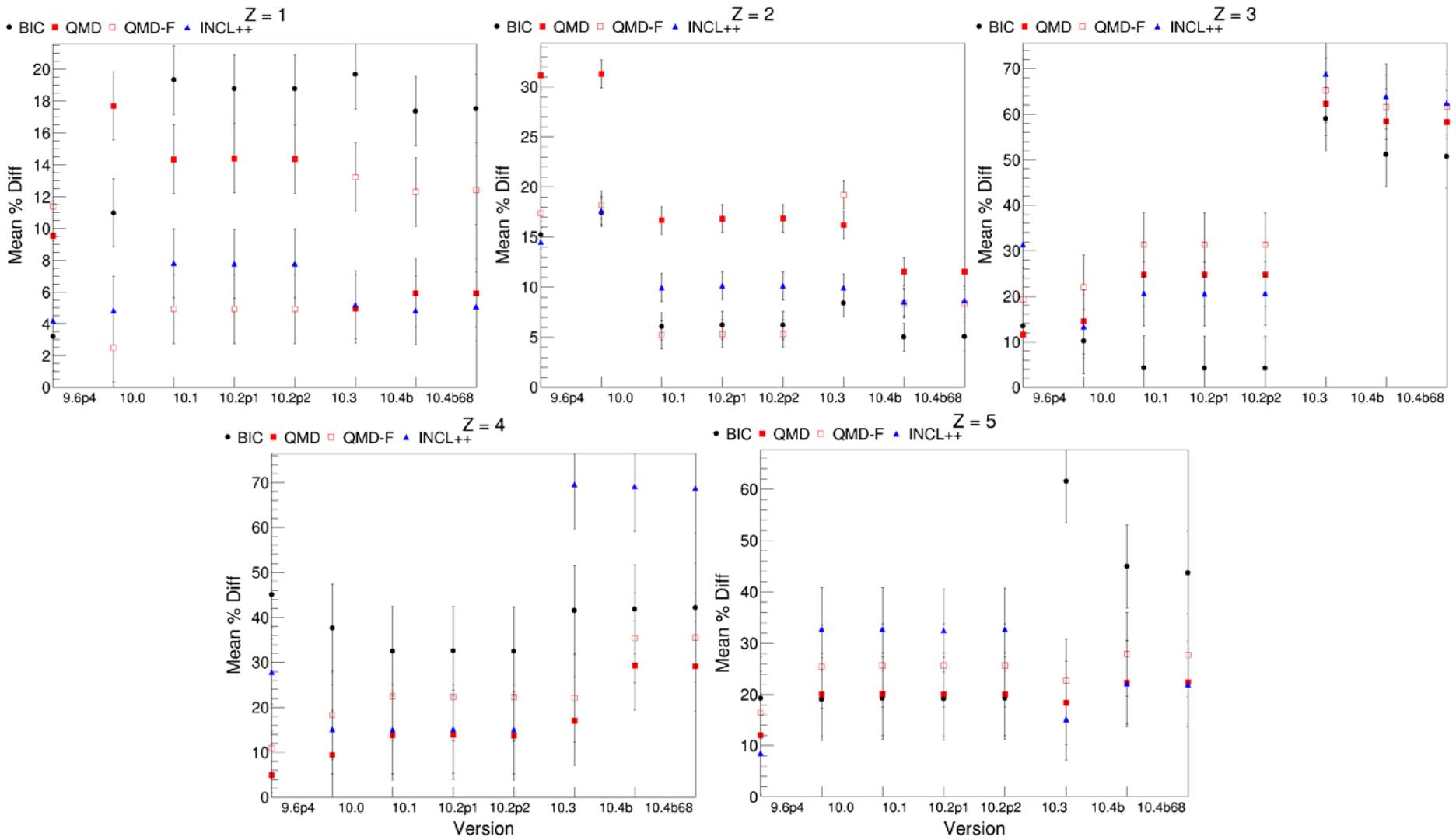


400 MeV/u ^{12}C beam incident upon water (Haettner et al. 2013, PMB)

BIC 10.2p2, 10.3, 10.4B




Z = 1
Z = 2
Z = 3
Z = 4
Z = 5
BIC
QMD
QMD-F
INCL++
Mean % Diff
Version
9.6p4
10.0
10.1
10.2p1
10.2p2
10.3
10.4b
10.4b68

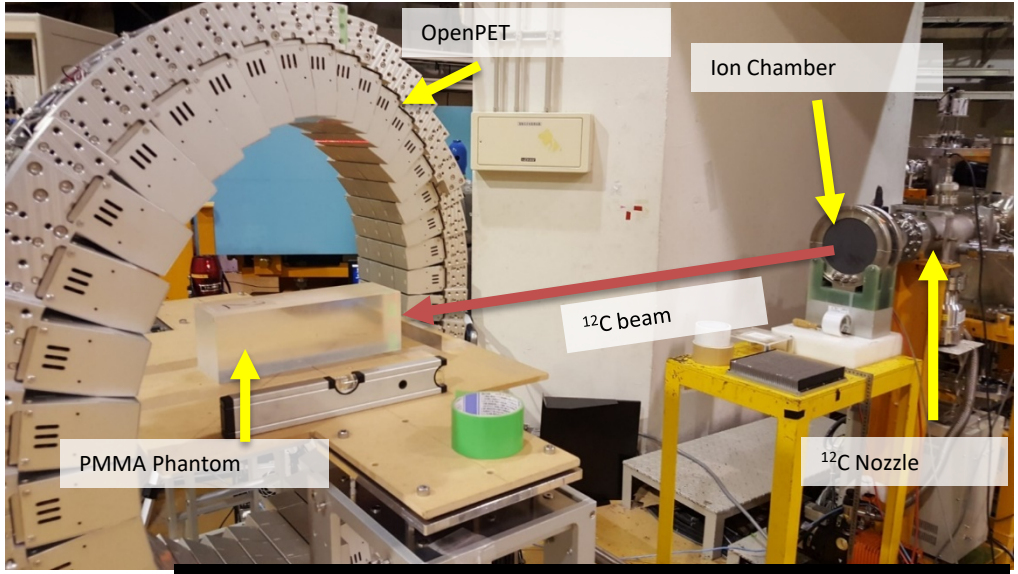
In-vivo PET

HIMAC, NIRS, Japan

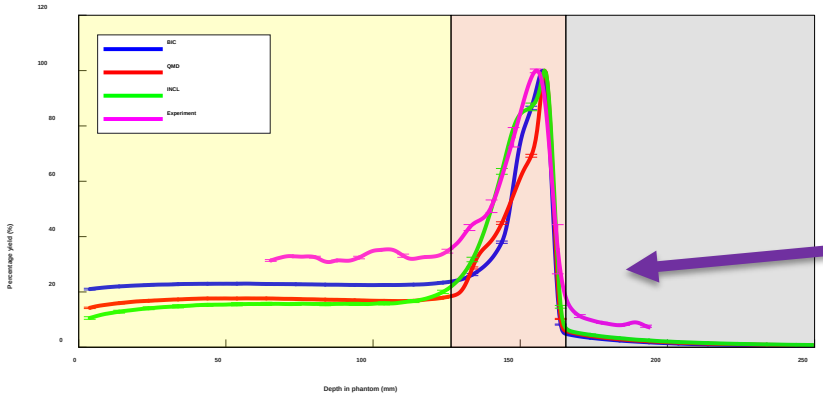
CMRP: A. Chacon, S. Guatelli, A. Rozenfeld

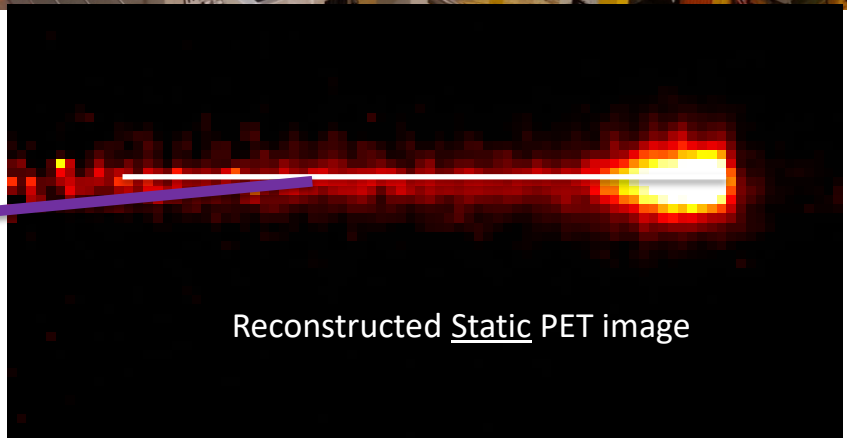
ANSTO: D. Prokopovich, M. Safavi-Naeini, M.C. Gregoire

NIRS: A. Mohammadi, M. Nitta, F. Nishikido, Y. Iwao, H. Tashima, E. Yoshida, T. Yamaya

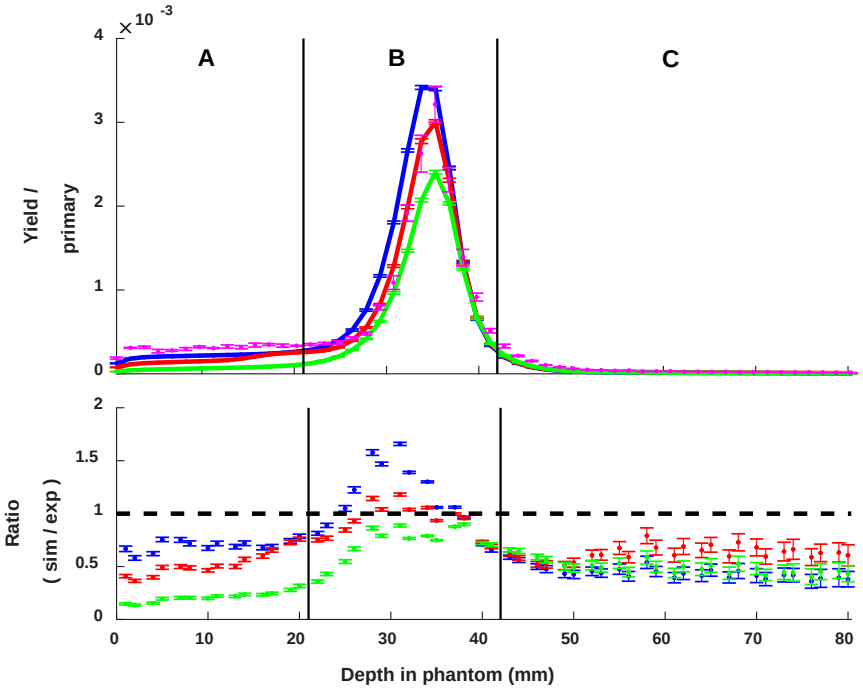


Geant4 Modelling for in-vivo PET

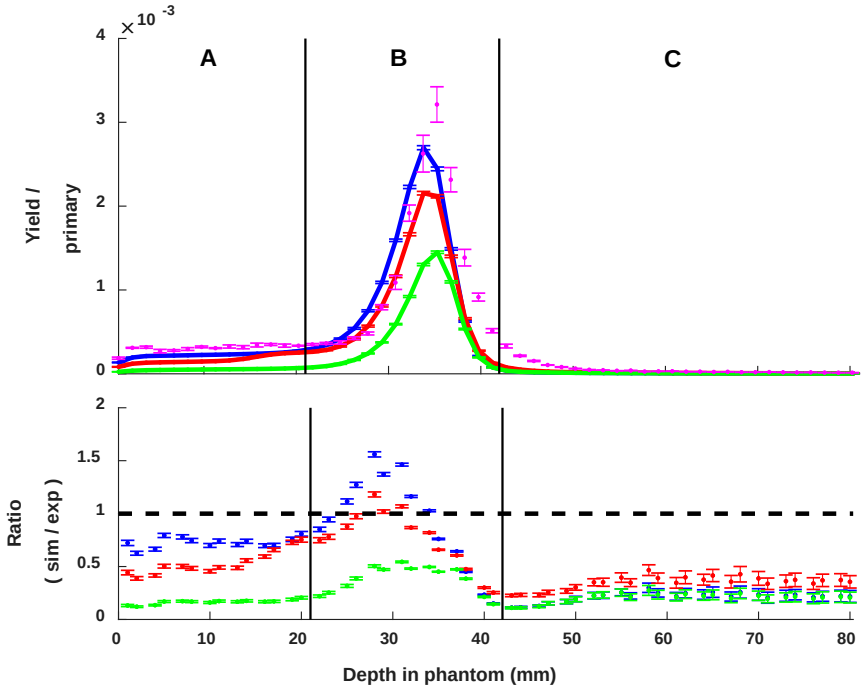




150 MeV/u ^{12}C incident on polyethylene



10.2



10.4

Conclusion

- Versions 10.1-10.2 much better than 10.4
- Is it possible to have a physics list for medical physics applications with fragmentation as it was in 10.2?
- We are happy to provide this test to be executed with Geant4 ref tags.