Improvements on FLUKA for medical applications

Giulia Arico’

12-13 March 2018
PSI, Villigen, Switzerland
OMA topical workshop on
Facility Design Optimization for Treatment

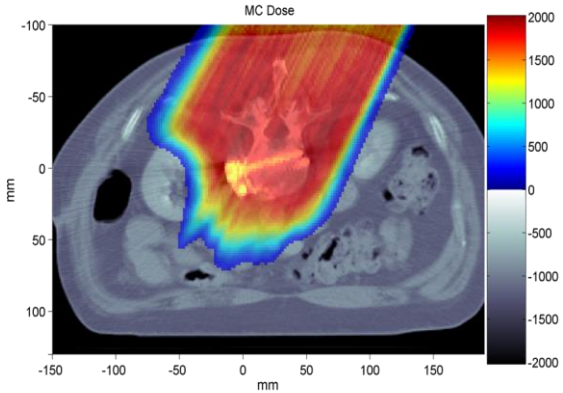
Overview

Overview:

- **Introduction**
  - Radiotherapy
  - Hadrontherapy
  - FLUKA
  - Medical applications
- **Method**
- **Results**
- **Summary**
- **Outlook**

Improvements on

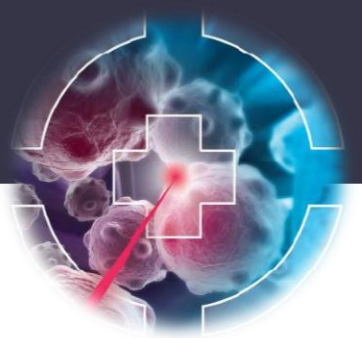
FLUKA



for medical applications

Source:
Parodi K *et al* (2007) IJROBP **68** 920-934

Radiotherapy



Basic concepts:

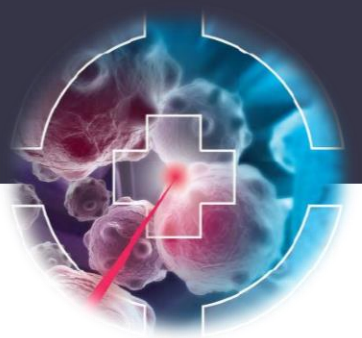
Main goal: kill tumor cells while healthy tissues are spared as much as possible

Absorbed dose: mean energy delivered to matter per unit mass by ionizing radiation ($\mathrm{d}\bar{E}/dm$) [Gy].

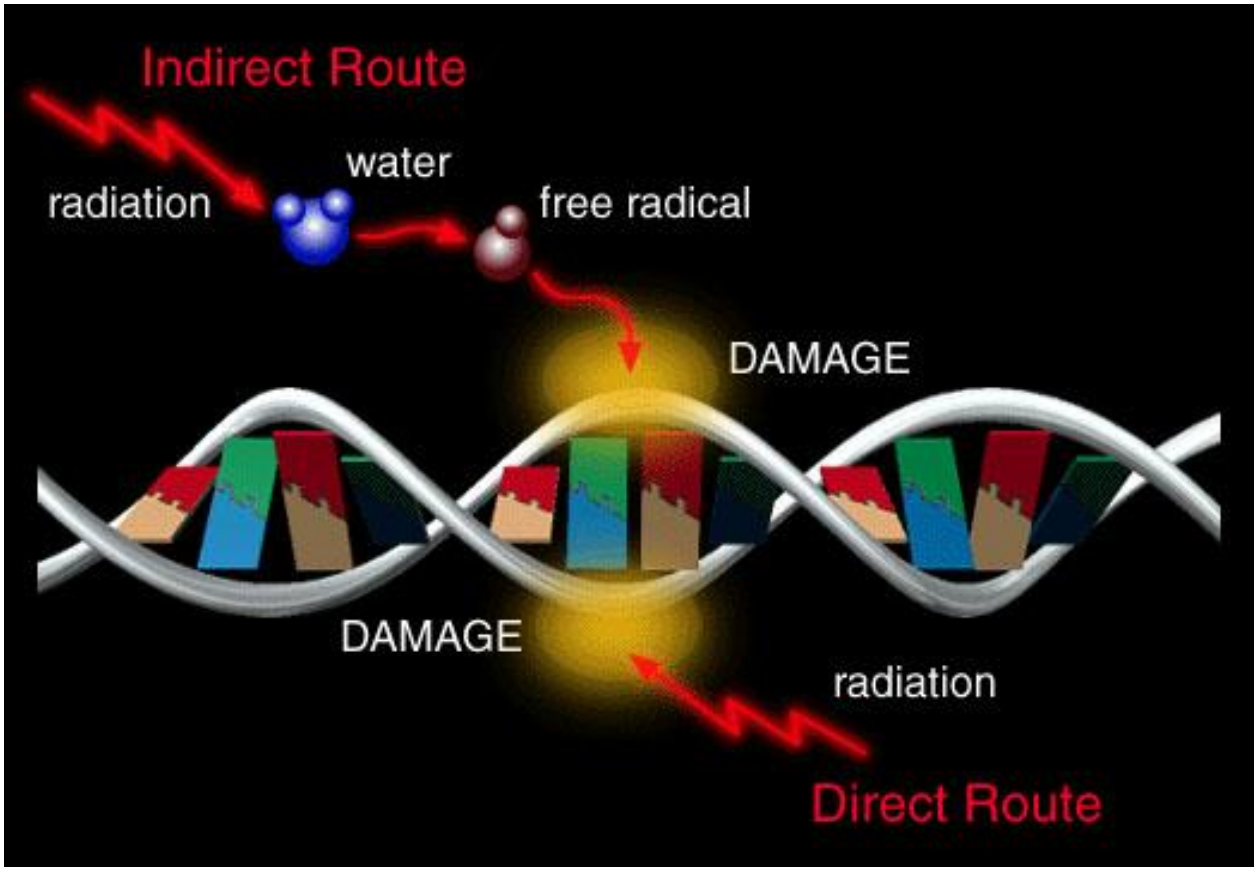
Linear energy transfer: energy transferred to matter per unit path by ionizing radiation (dE/dx) [N or KeV/μm].

Relative biological effectiveness: ratio of the biological effectiveness between a reference and a given ionizing radiation for the same biological effect $\left(\left.\frac{D_{ref}}{D_{rad}}\right|_{iso-effect}\right)$.

Radiotherapy



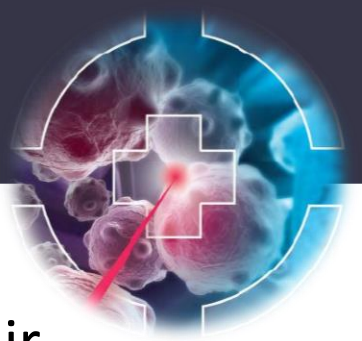
Radiation can damage cells' DNA causing their death.
Damage can be induced **directly** or **indirectly**



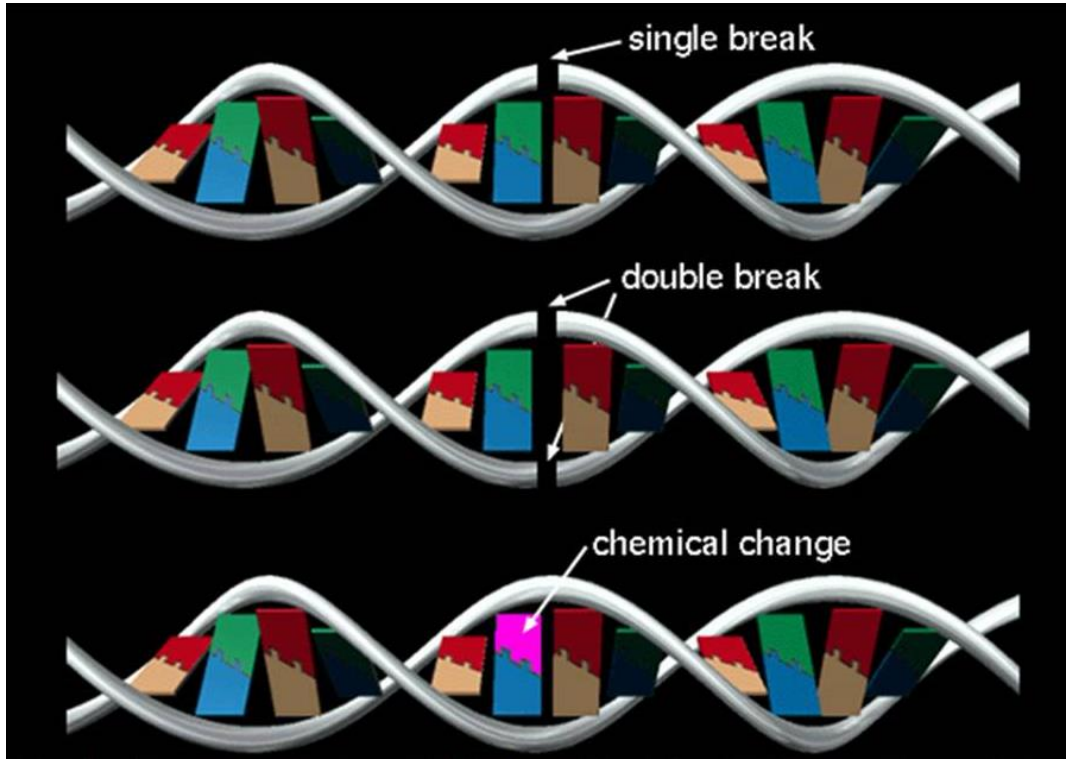
Free radicals:
OH-
H+
H^0
HO^0

Source:
Nepomuceno J. (2011) Research Gate, Antioxidants in Cancer Treatment.

Radiotherapy



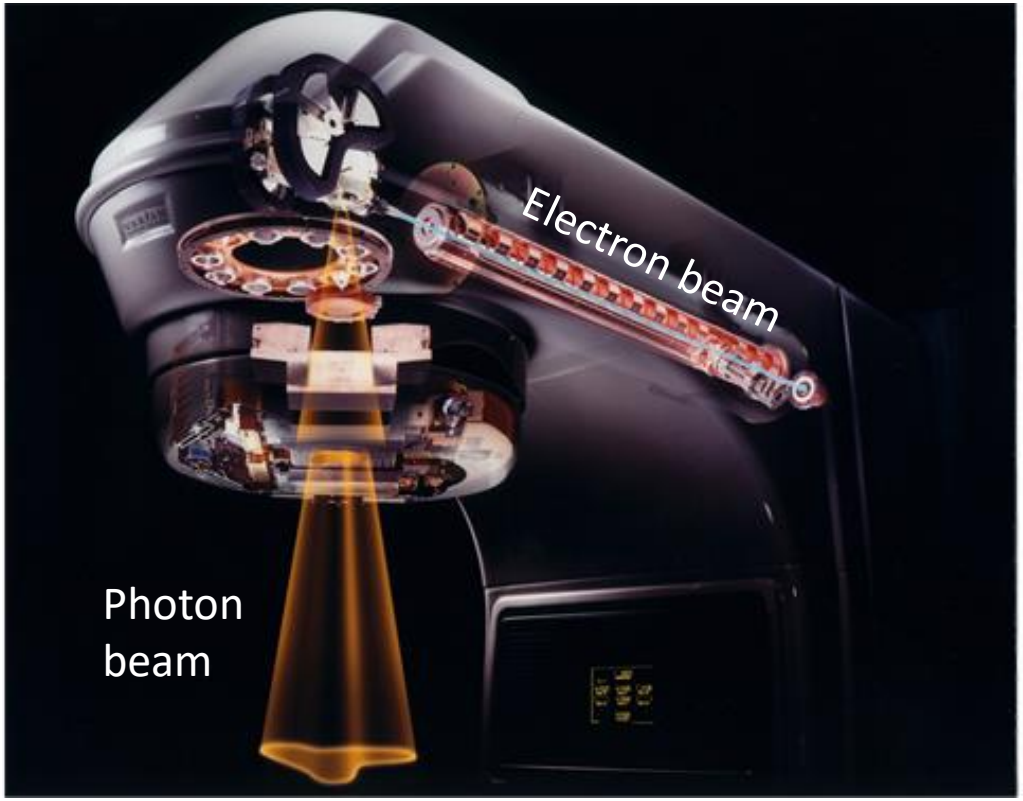
Radiation can cause single break → easy to repair
double break → difficult to repair
chemical change → mutation



Source:
http://prismsuk.blogspot.ch/2016/02/dna-double-stranded-breaks-heads-its.html

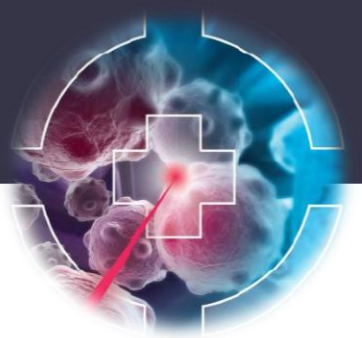
Radiotherapy

Photons are the most common type of radiation. It is a high-dose X-ray beam obtained from rather small linear accelerators.



Source:
Vernimmen FJ et al (2014) JCT **5**(1) 6

Radiotherapy



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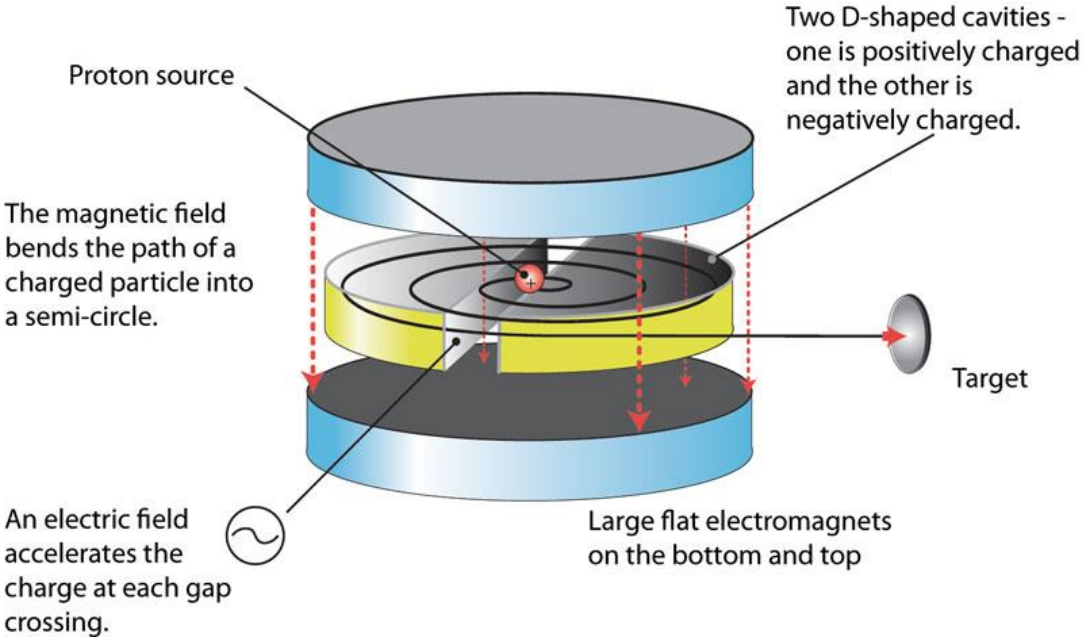
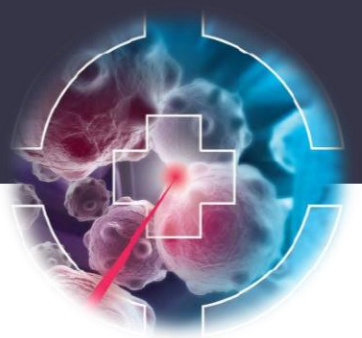
Neutrons are high LET-radiation. A cyclotron produces and accelerates protons, magnets aim the beam to a beryllium targets and neutrons are produced. Only 3 facilities in USA.



Source:
https://wallscover.com/cyclotron.html

Radiotherapy



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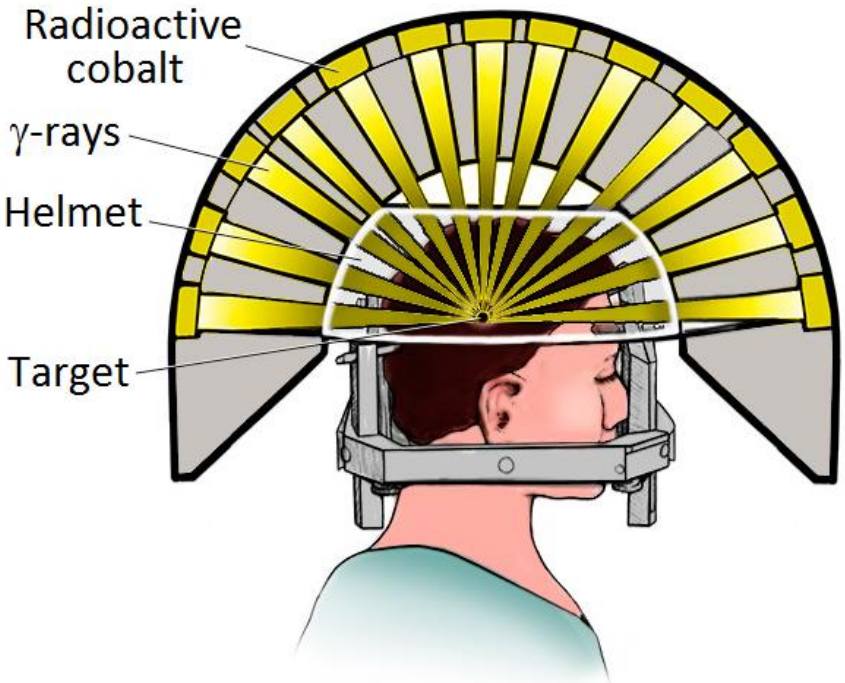
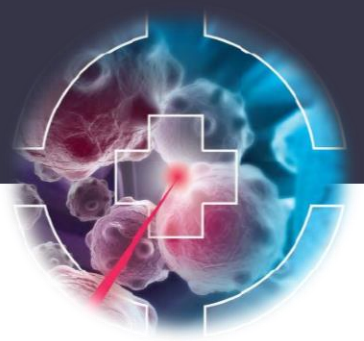
Gamma rays are produced from Cobalt sourced gamma ray photons. Gamma Knife uses stereotactic surgery for small tumors in the brain.



Source: https://www.mayoclinic.org/tests-procedures/stereotactic-radiosurgery/multimedia/gamma-knife-delivery-of-radiation/img-20130344

Radiotherapy



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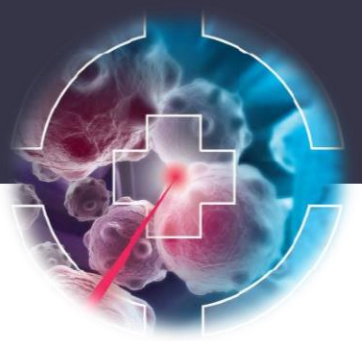
Gamma rays are produced from Cobalt sourced gamma ray photons. Gamma knife uses stereotactic surgery for small tumors in the brain.

Charged particles mainly interact with atomic electrons and loss energy by excitation and ionization.

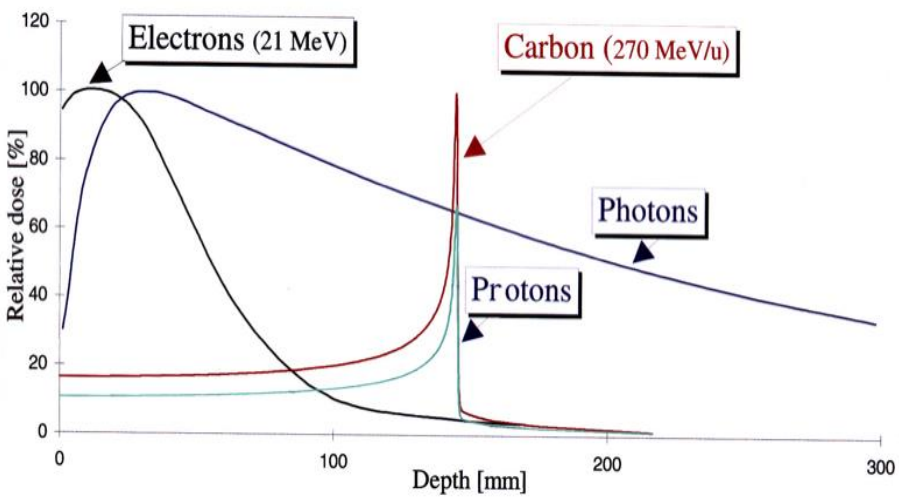
- **Electrons** are suitable for skin tumors. Usually used in combination with other therapies.
- **Protons** and **heavier ions** are accelerated in cyclotrons or synchrotrons or synchrocyclotrons. Suited for deep-seated tumors.

Hadrontherapy



Hadrontherapy make uses of **protons** and **heavier ions.**
Rationale: inverse depth-dose profile in comparison to photons and electrons.

Single Bragg peak

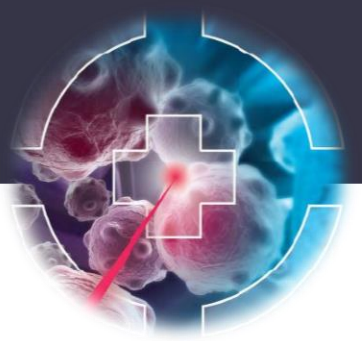


Photons : Photoelectric effect, Compton scattering, pair production

Charged particles : interactions with atomic electrons (**energy loss**) and with atomic nuclei (**deflections and fragmentation**)

Source:
http://www.quantumdiaries.org/2012/page/31

Hadrontherapy



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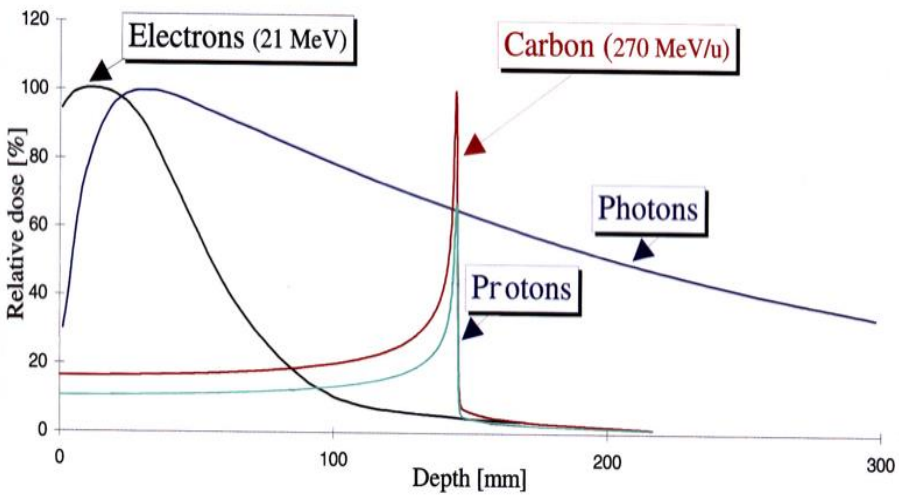
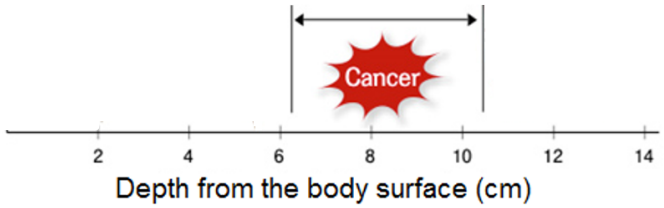
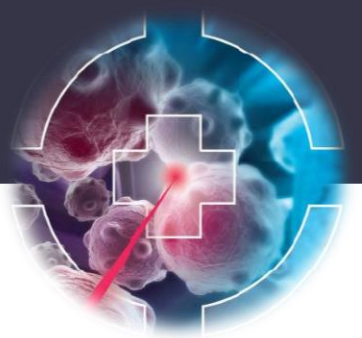


Clinical case



Source:
http://www.quantumdiaries.org/2012/page/31
http://www.bestcyclotron.com/particletherapy

Hadrontherapy



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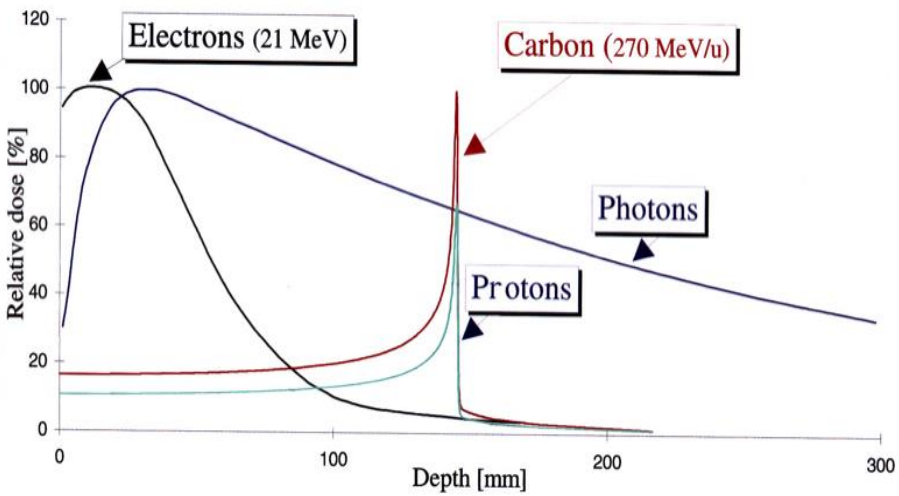
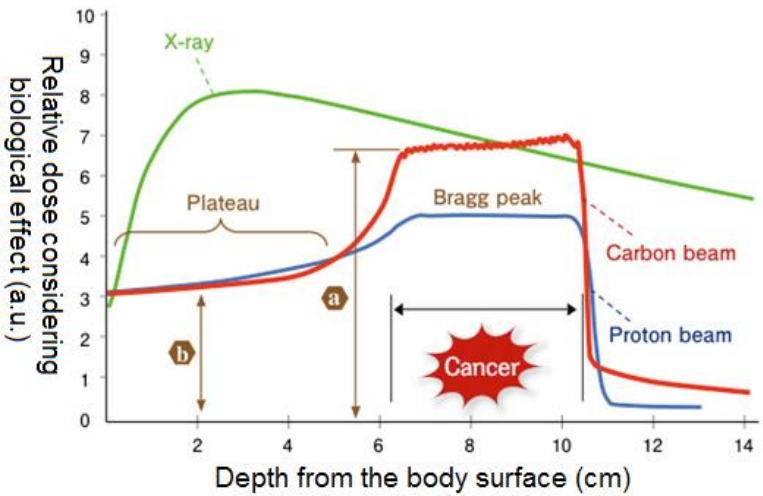


Spread out Bragg peak



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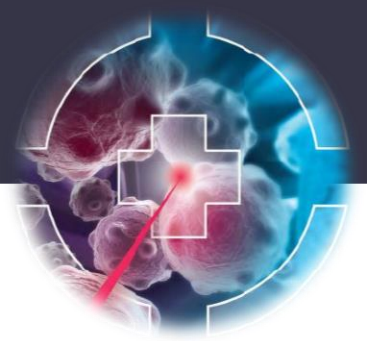
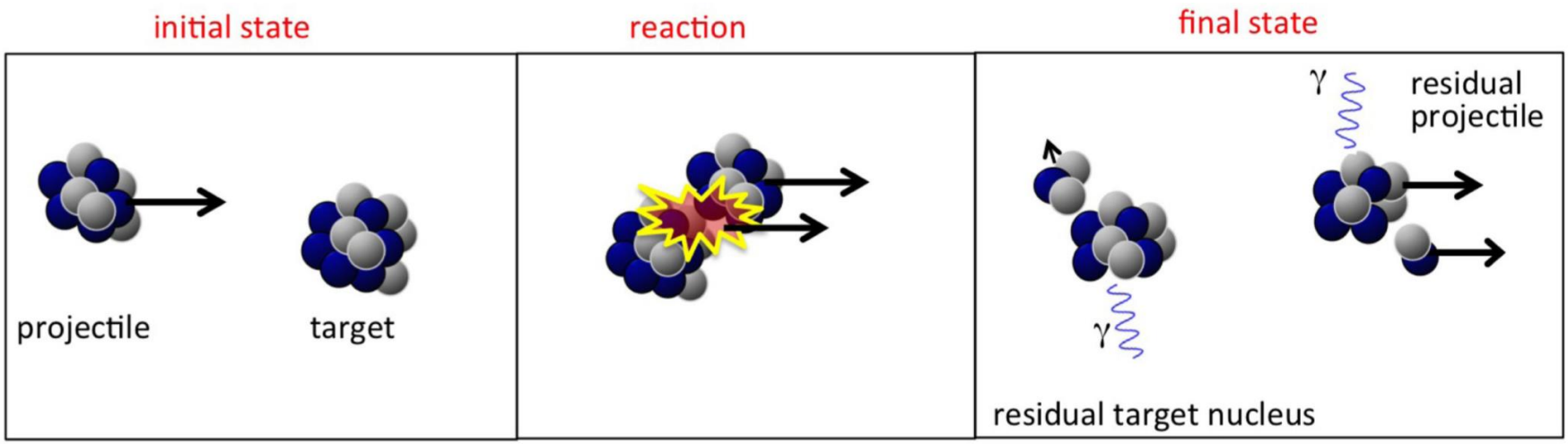
Hadrontherapy

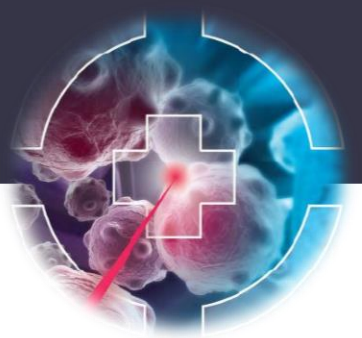


- ✓ **Rationale** for hadrontherapy : more convenient depth-dose profile in comparison to photons and electrons, in the case of deep-seated tumors.
- ✗ However, nuclear interactions between primary ions and patient tissues may cause primary particle **fragmentation**



Source:
Kraan AC 2015 Front. Oncol. 5:150

Hadrontherapy



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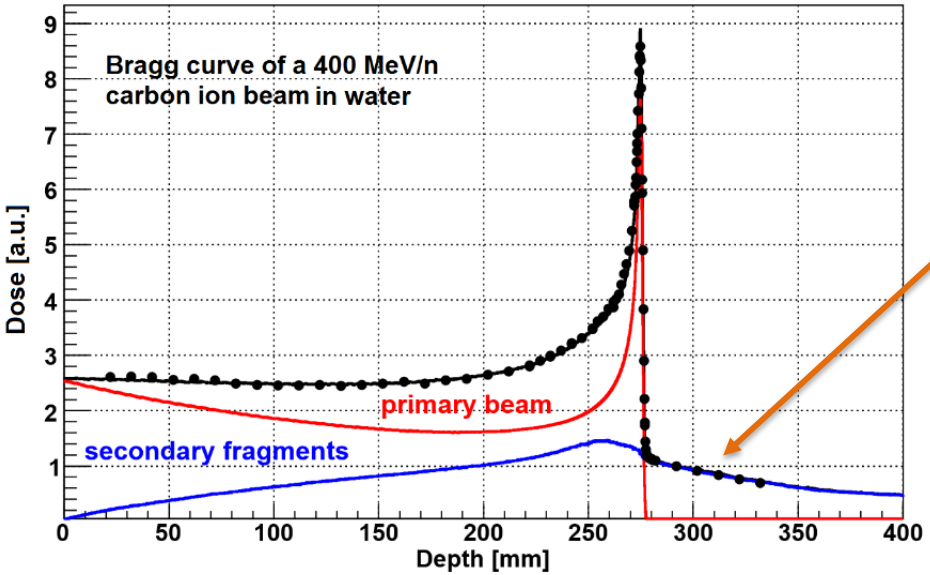
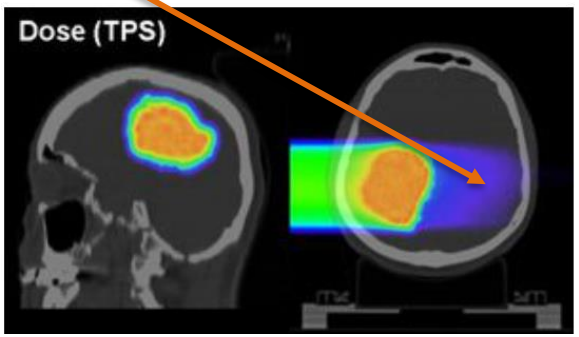


Dose delivered by secondary lighter particles behind the tumor



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The FLUKA International Collaboration

G. Aricò, C. Bahamonde Castro, M.I. Besana, M. Brugger, F. Cerutti, A. Cimmino, R. Dos Santos, L. Esposito, Alfredo Ferrari, R. Garcia Alia, J. Idarraga Munoz, W. Kozlowska, A. Lechner, M. Magistris, A. Mereghetti, E. Nowak, S. Roesler, F. Salvat-Pujol, P. Schoofs, E. Skordis, G. Smirnov, C. Theis, A. Tsinganis, Heinz Vincke, Helmut Vincke, V. Vlachoudis, J.Vollaire CERN

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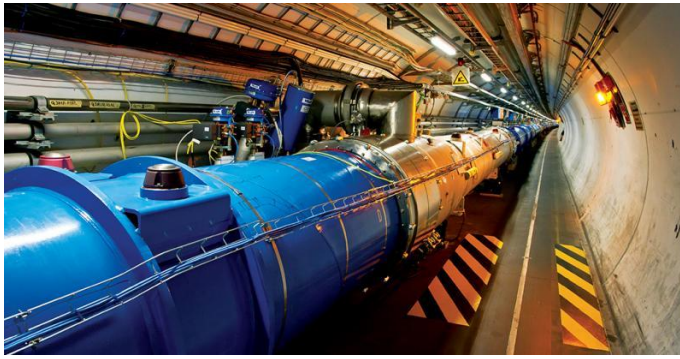
P. Garcia Ortega IUFFYM, Spain I. Rinaldi, INP Lyon, France
M. Chin, Malaysia

A. Fassò, M.V. Garzelli, E. Gadioli, J. Ranft

- a fully integrated particle physics Monte Carlo simulation code, developed by CERN-INFN
- simulations of particle transport and interactions with matter
- widely used in physics for :
  - particle accelerator and detector design
  - shielding
  - dosimetry
  - calorimetry
  - activation
  - medical applications → **Hadrontherapy**



LHC at CERN

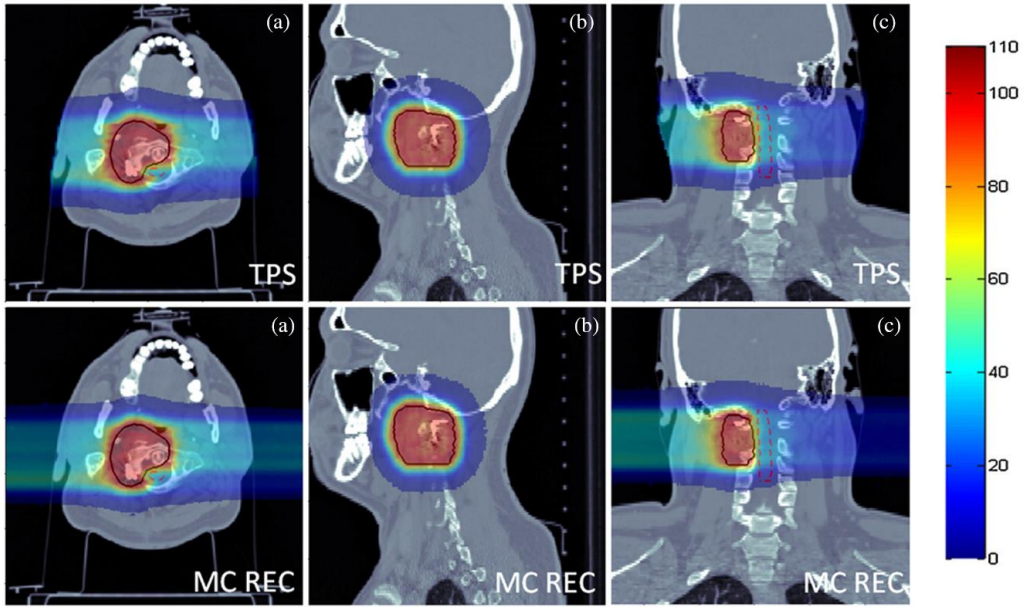
Source:
https://home.cern/topics/large-hadron-collider

Medical applications

At CNAO (Italy), HIT and MIT (Germany), patients are treated with protons and carbon ions.

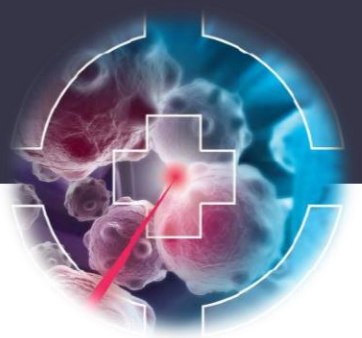
In those facilities FLUKA is used:

- to **generate input data** for the treatment planning systems
- to **validate the dose calculations**



Source:
Mairani A *et al* PMB **58** (2013) 2471-2490

Medical applications



- **Treatment planning systems** currently used are based on pencil beam algorithms → Fast dose calculations
- **Monte Carlo simulations** are more accurate as they consider more complex physics → nowadays only used for complex cases

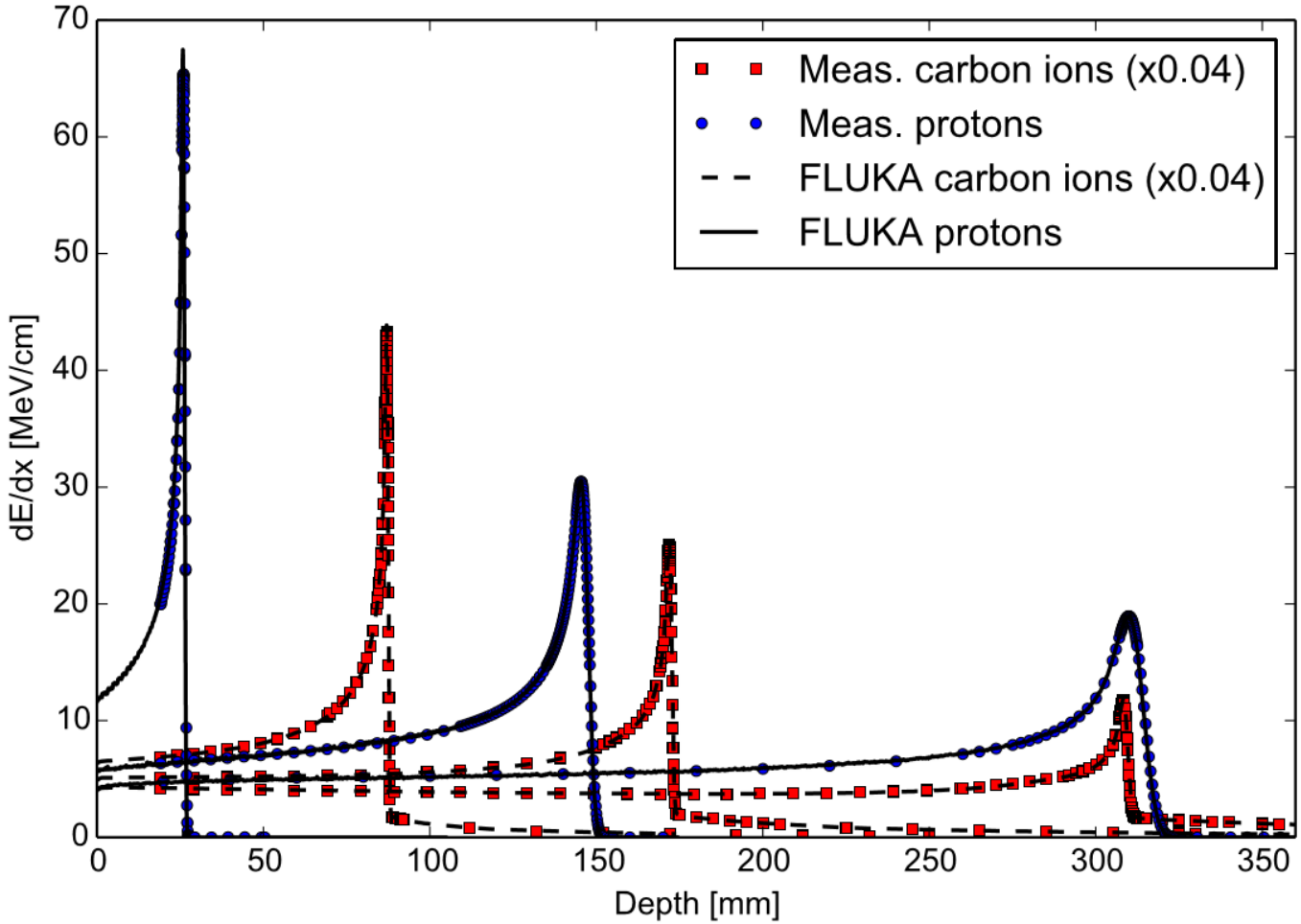
Monte Carlo based treatment planning

Mairani A et al 2013 Phys. Med. Biol. 58 2471-2490
Böhlen T *et al* Journal of Radiation Research, 2013, 54, i77–i81

Source:
Mairani A *et al* PMB **58** (2013) 2471-2490

Medical applications

Single Bragg Peaks



Data acquired at HIT:

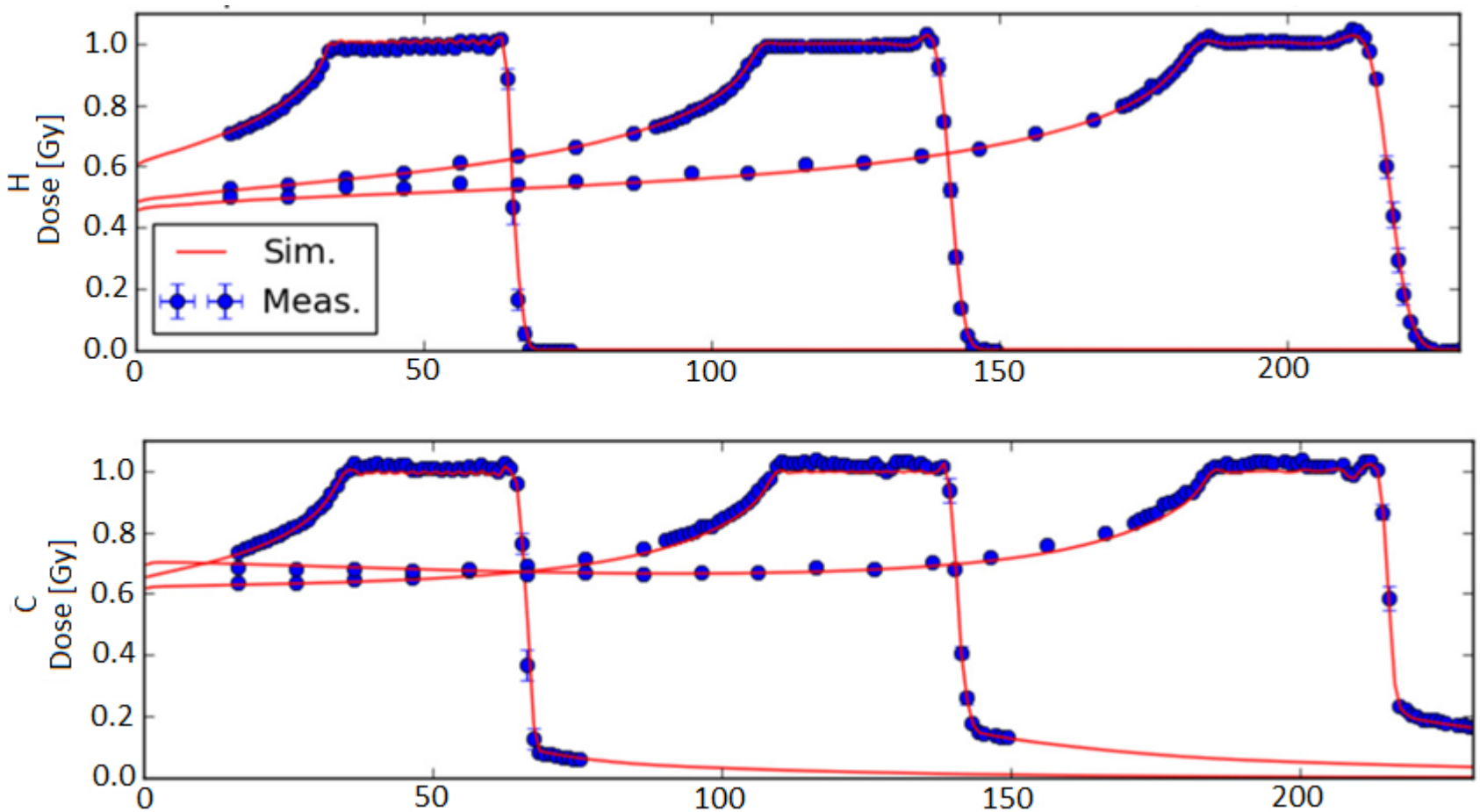
E_p = 54.10 MeV
142.66 MeV
221.05 MeV

E_C = 200.28 MeV/u
299.94 MeV/u
430.10 MeV/u

Source:
Battistoni G *et al* (2016) Front Oncol 6:116

Medical applications

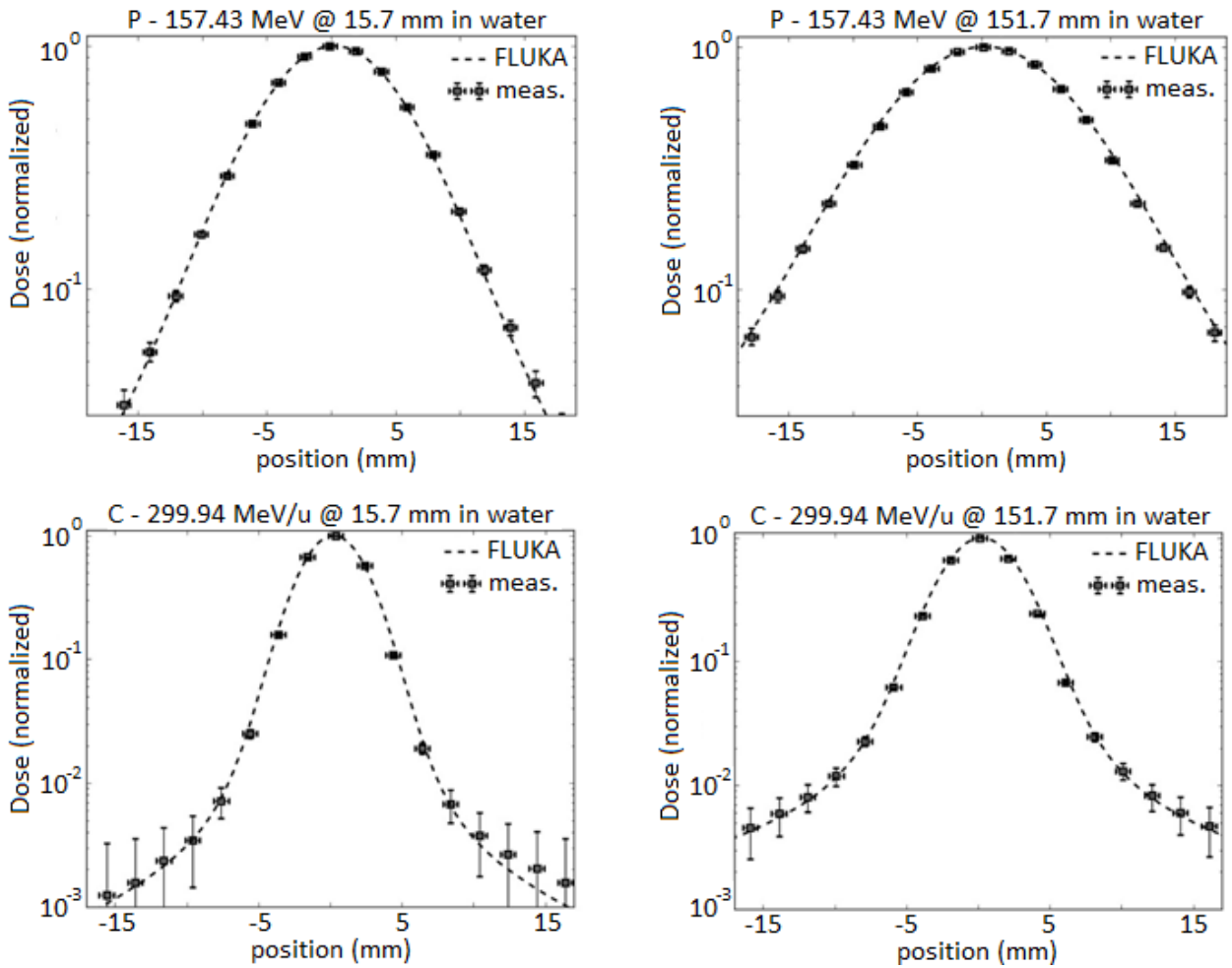
Spread out Bragg Peaks



Source:
Tessonnier T *et al* PMB.**62**(2017) 6579-6594

Medical applications

Lateral dose profiles



Source:
Battistoni G *et al* (2016) Front Oncol 6:116

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  - Analysis
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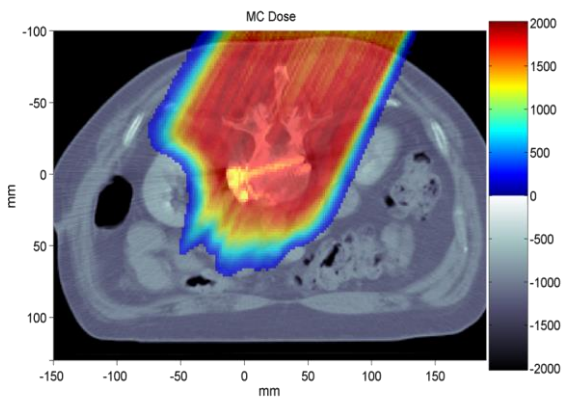
Improvements on



for medical applications

Source:
Parodi K *et al* (2007) IJROBP **68** 920-934

Experimental setup

Incident beam : He and C ions

Beam energies : 50 – 430 MeV/u

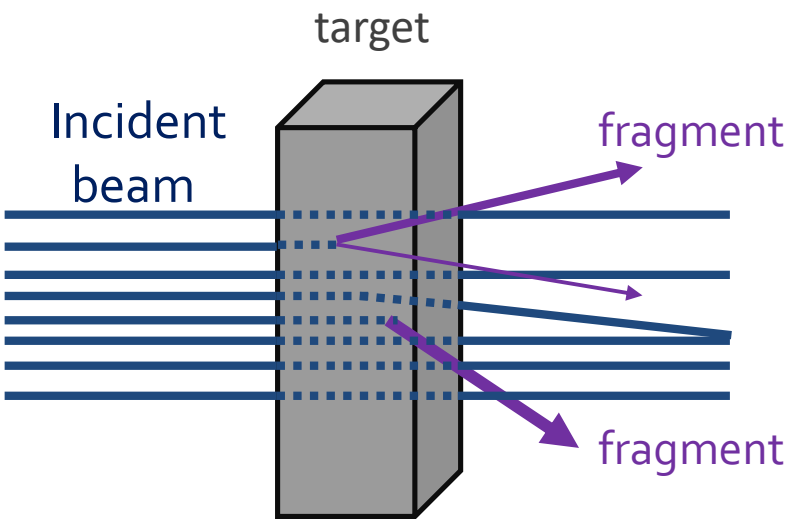
Targets : C, O, Al, Ti, Au,
water, PMMA

Possible scenarios :

no nuclear reaction

fragmentation

scattering



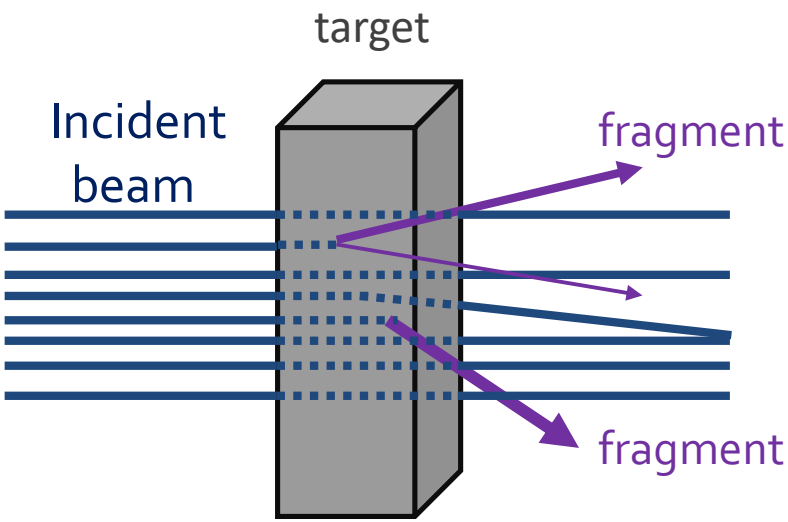
Experimental setup

Thin targets:

analysis of the nuclear reaction cross sections

i) mass changing

ii) charge changing



Thick targets:

analysis of the

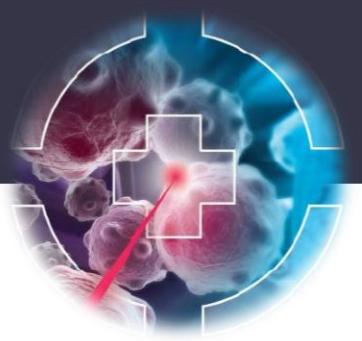
i) beam attenuation

ii) fragment yields

ii) angular distributions

iii) energy distributions

Analysis



Ongoing work:

i) Improvements of the nuclear reaction cross sections for **helium ion** beams

- **Beneficiary** : HIT and future helium ion therapy centers

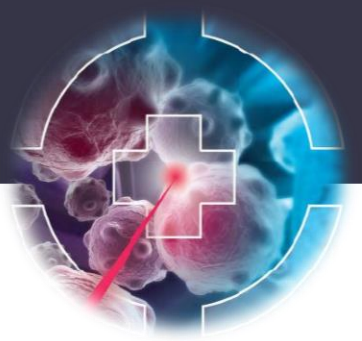
ii) Improvements of the physics models for **carbon ion** beams.

- **Beneficiaries**: CNAO, HIT and MIT facilities

iii) … and for **heavy-heavy ion collisions**

- **Beneficiary** : astrophysics and space research

Analysis



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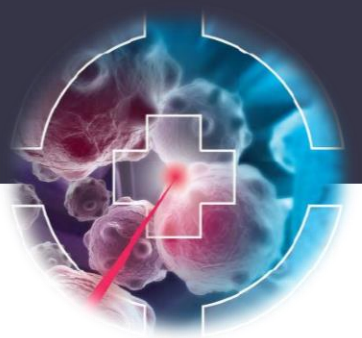


Reaction processes in BME (<125 MeV/u):

Higher impact parameter

- **C**omplete **FUS**ion: projectile and target nuclei interact and merge in a composite nucleus (P+T → C)
- **Trans**fer: pickup reaction where the smaller nucleus is fully overlapped by the density distribution of the bigger one and collects some of the partner nucleons
- **3body:** projectile and target nuclei interact with partial overlap of the density distributions, a hot region is produced (middle source X) and 3 outgoing fragments result
  (P+T → B+Y+X, with B and Y proj- and target-like)
- **I**ncomplete **FUS**ion: as 3 body, with the middle source absorbed by one nucleus (P+T → B+W or P+T → Z+Y)
- **"Inel**astic" collisions: either the projectile or the target loses a single nucleon, possibly absorbed by the partner nucleus

Overview

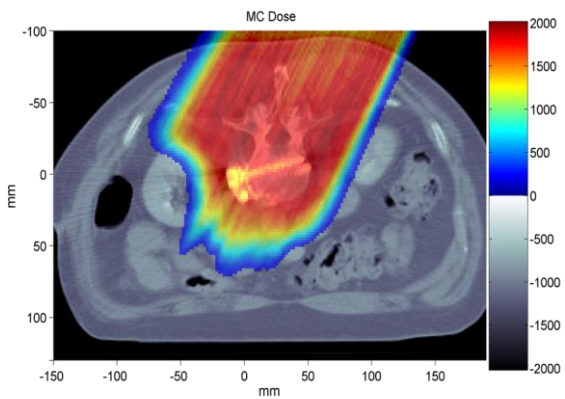
Overview:

- **Introduction**
- **Method**
- **Results**
  - C(C,X)R @ 50 MeV/u (Ganil)
  - Ti(C,X)R @ 50 MeV/u (Ganil)

$$\frac{d\sigma}{d\Omega} \qquad \frac{d^2\sigma}{d\Omega dE}$$

- **Summary**
- **Outlook and Conclusions**

Improvements on

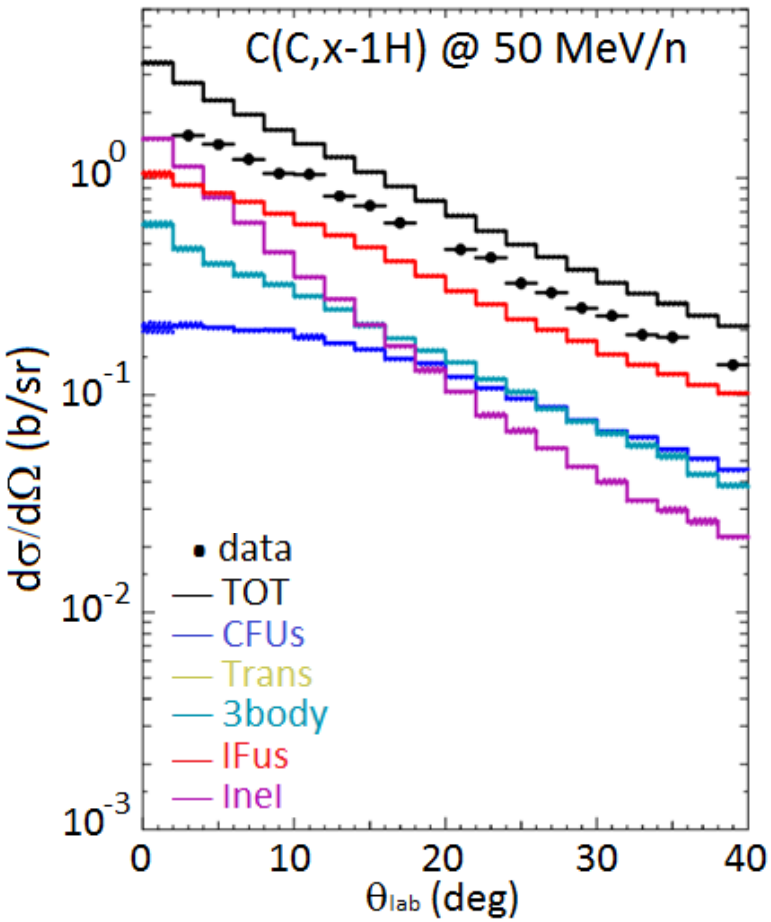


for medical applications

Source:
Parodi K *et al* (2007) IJROBP **68** 920-934

Preliminary results

Symmetric system: C-C



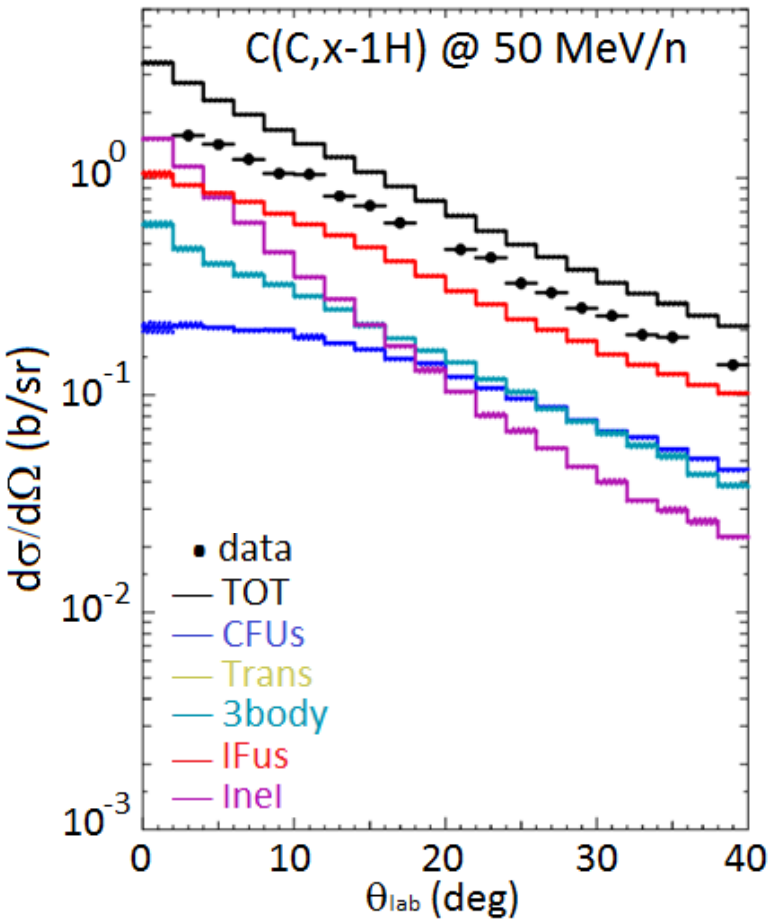
Fragmentation of carbon ions on graphite was analysed.

- An overestimation on the production of secondary protons in FLUKA was observed (factor of 1.5-2)
- ✓ The angular distribution of most of the other secondary fragments were well reproduced by FLUKA (see next slides)

Experimental data from:
Divay C *et al* 2017, Phys. Rev. C **95** 044602

Preliminary results

Symmetric system: C-C



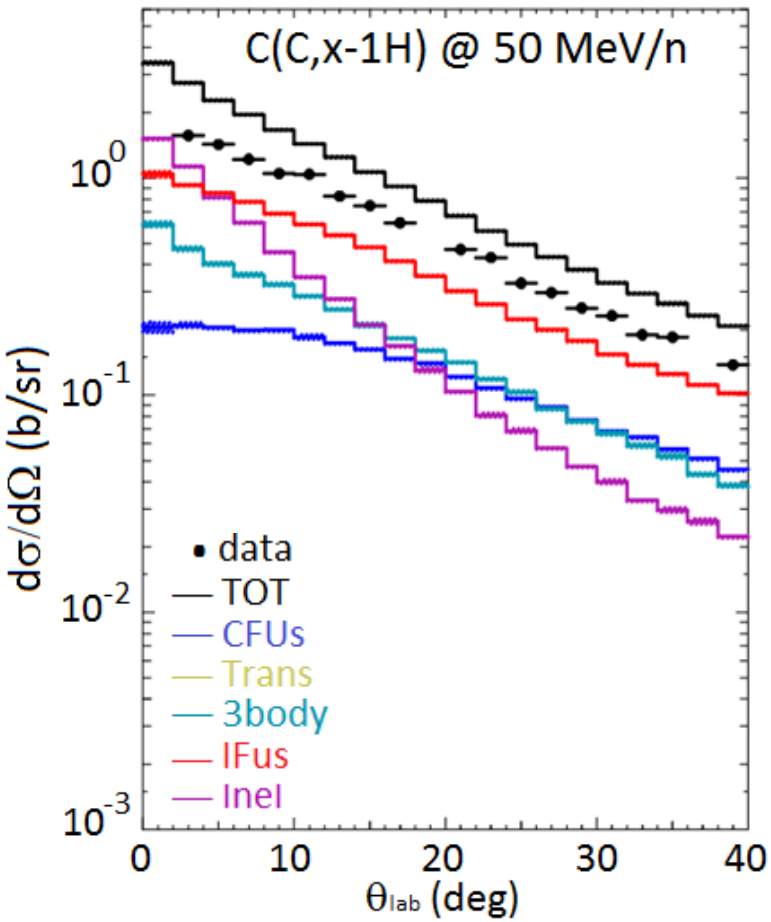
Valid for 50 MeV/n:

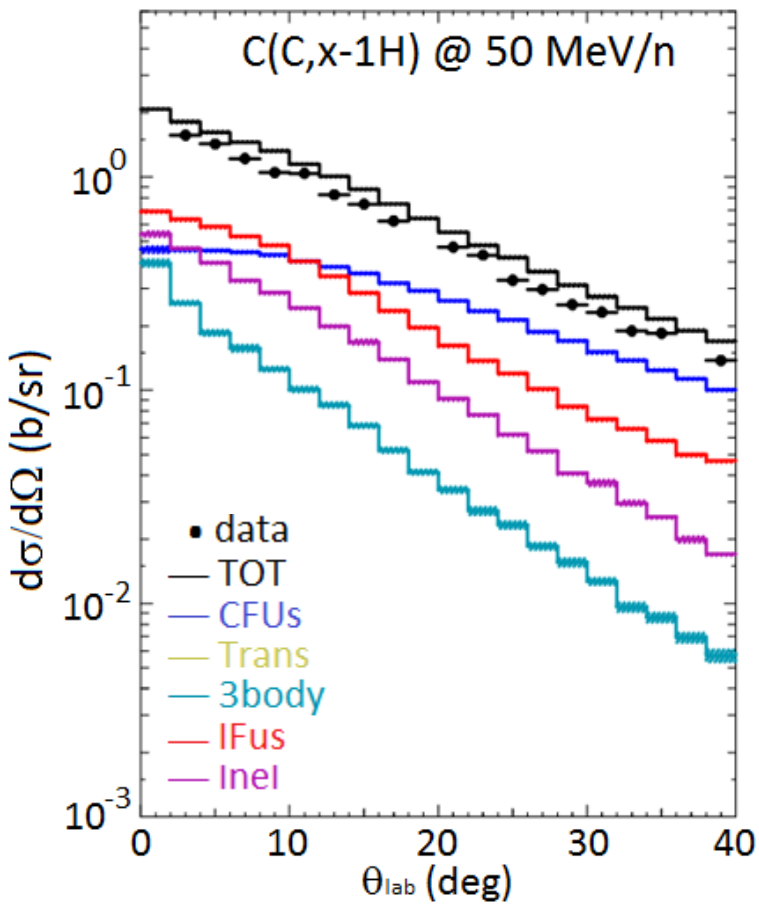
- Lower fractional energy loss for intermediate impact parameter mechanism
- Increased complete fusion cross section (to compensate for ^{3}H and ^{3}He)
- Single nucleon break-up (large b), broader angular distribution

Experimental data from:
Divay C *et al* 2017, Phys. Rev. C **95** 044602

Preliminary results

Symmetric system: C-C





Experimental data from:
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Preliminary results

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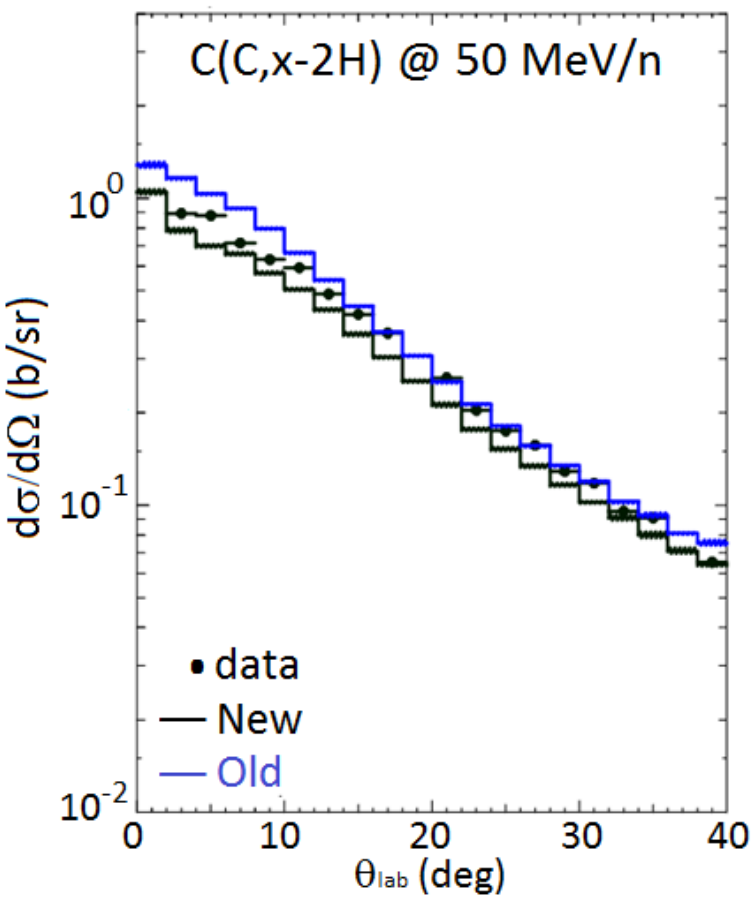

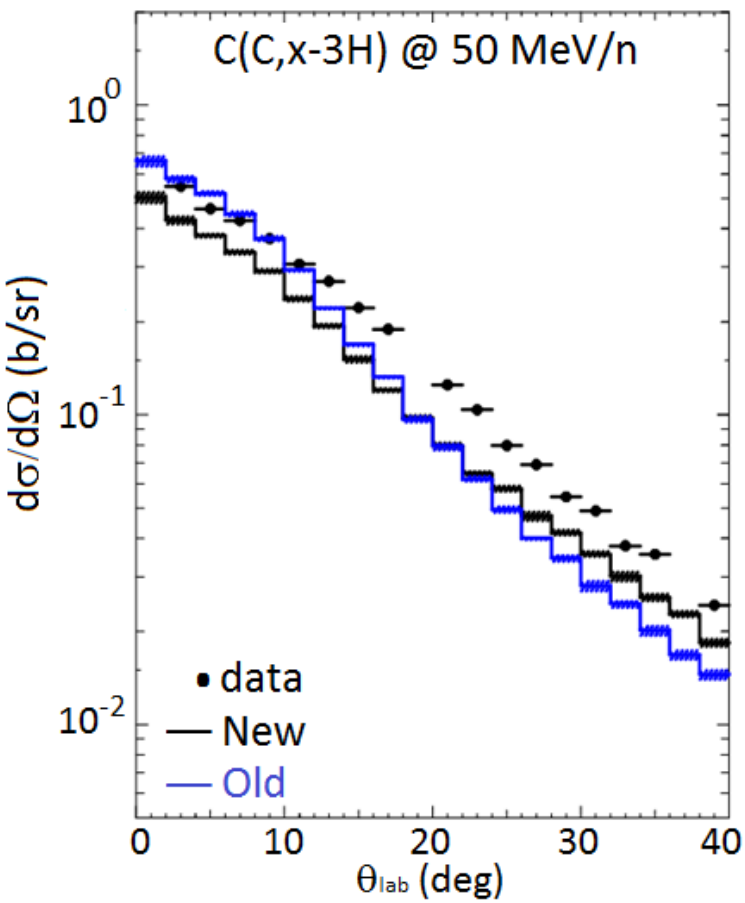

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Preliminary results

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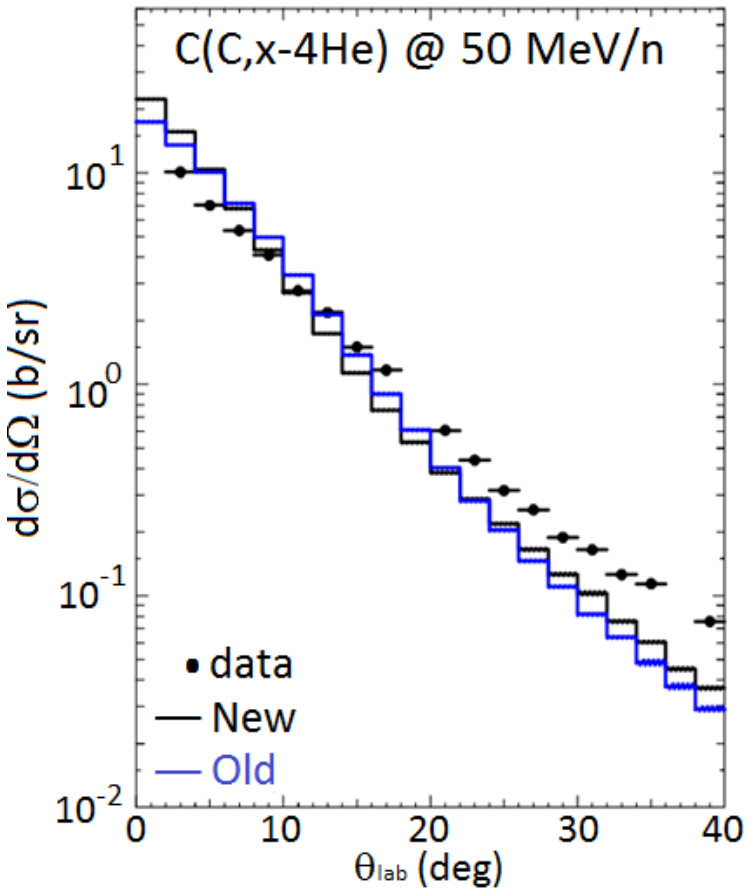

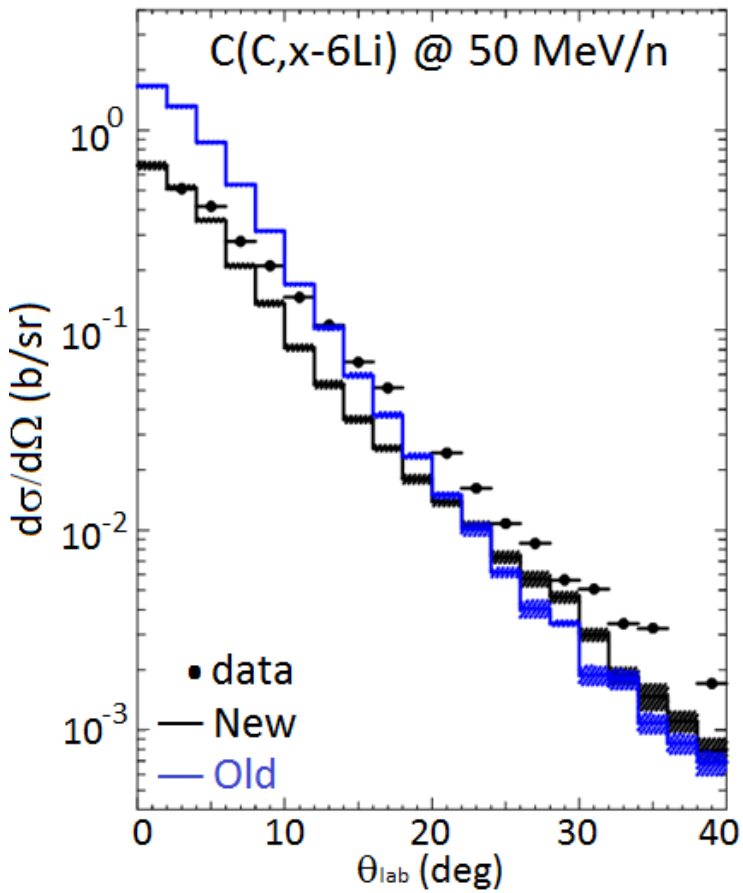

Experimental data from:
Divay C *et al* 2017, Phys. Rev. C **95** 044602

Preliminary results

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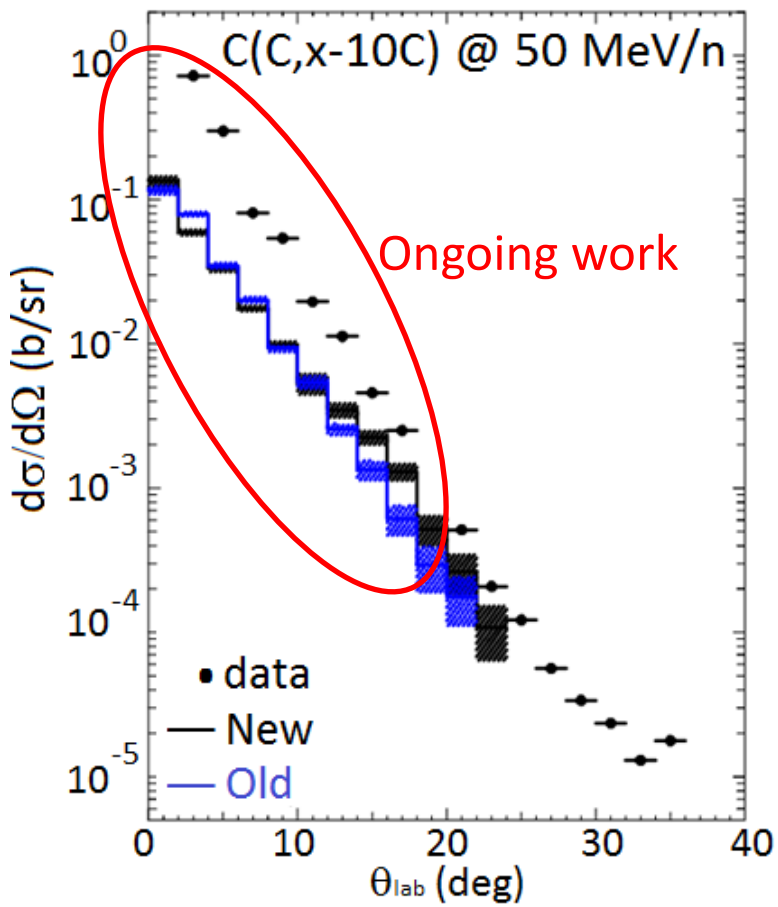

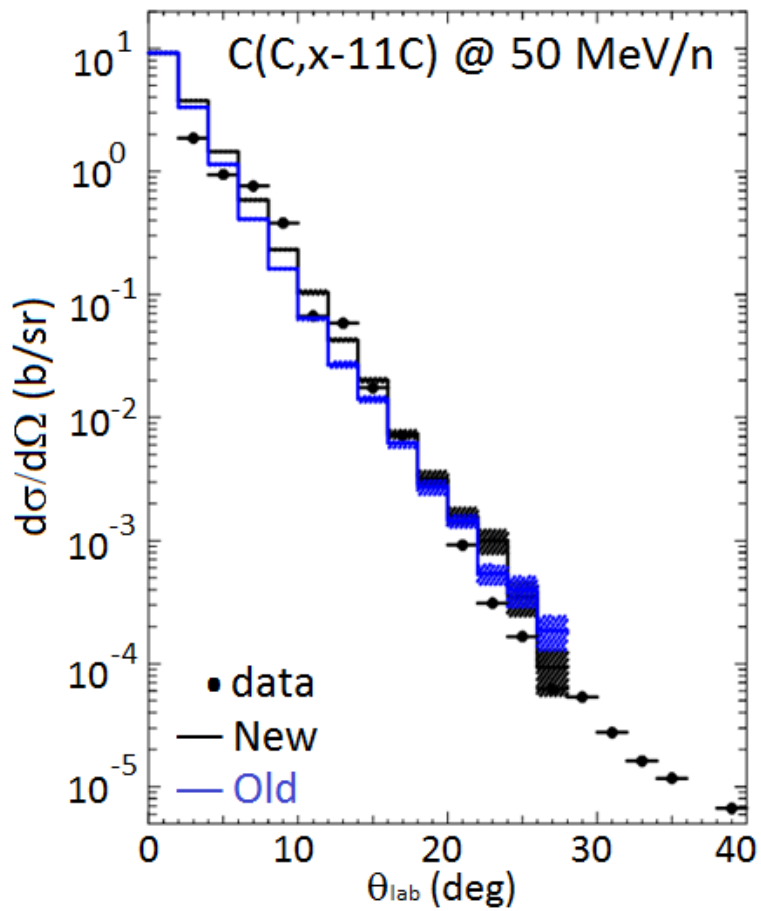

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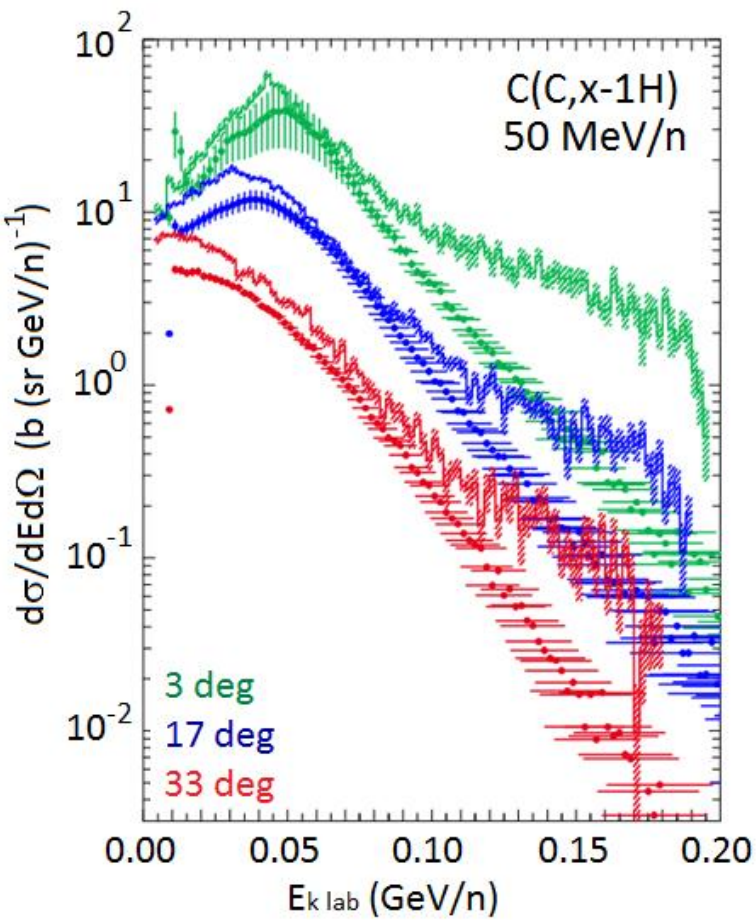

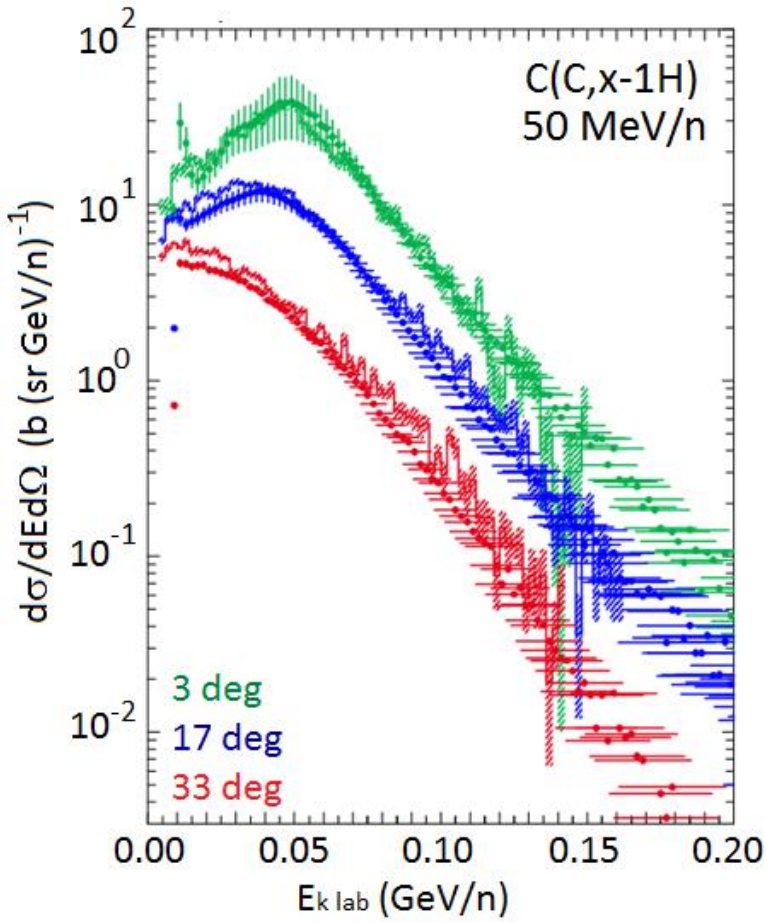

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Preliminary results

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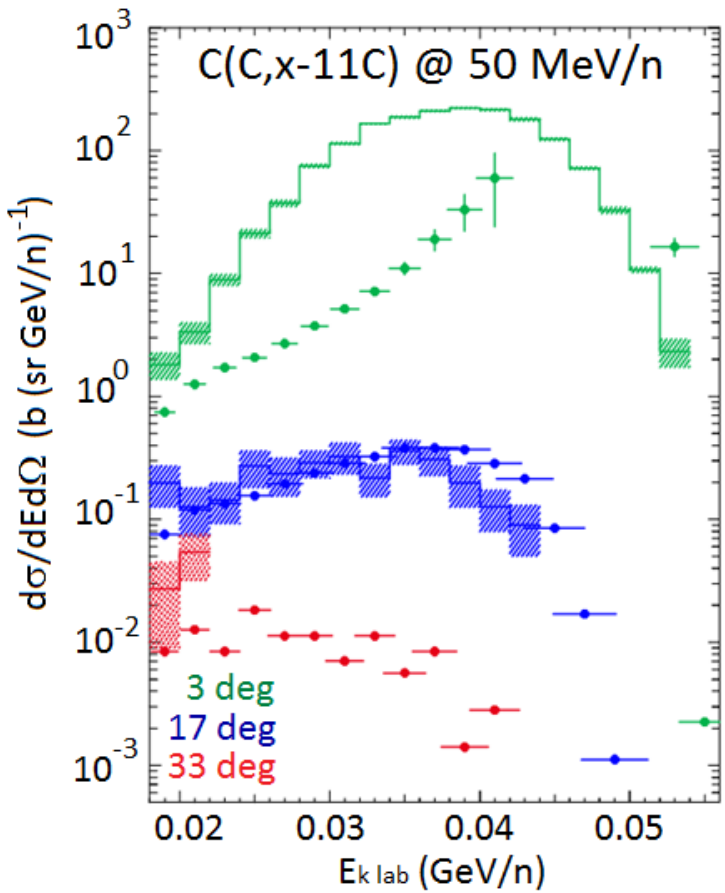
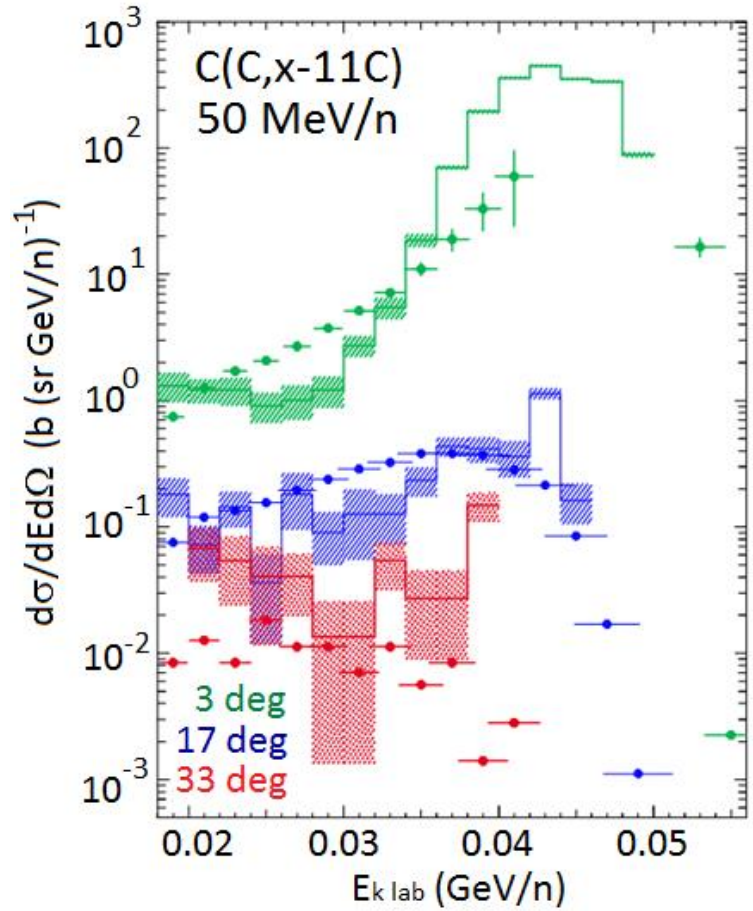
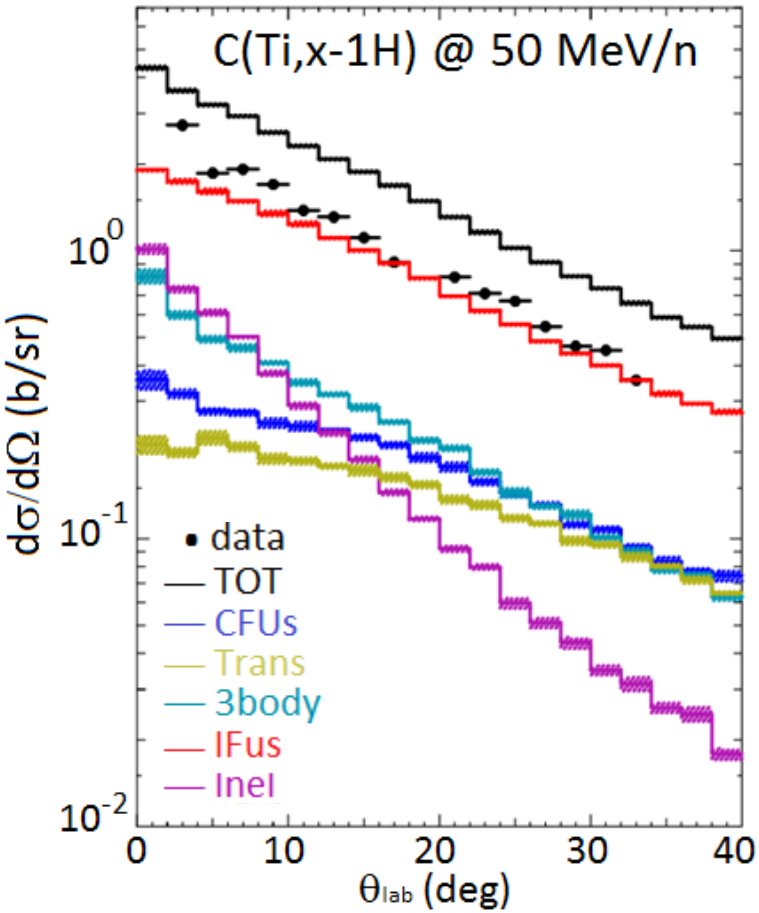




Experimental data from:
Divay C *et al* 2017, Phys. Rev. C **95** 044602

Preliminary results

Asymmetric system: C-Ti



Fragmentation of carbon ions on titanium was analysed.

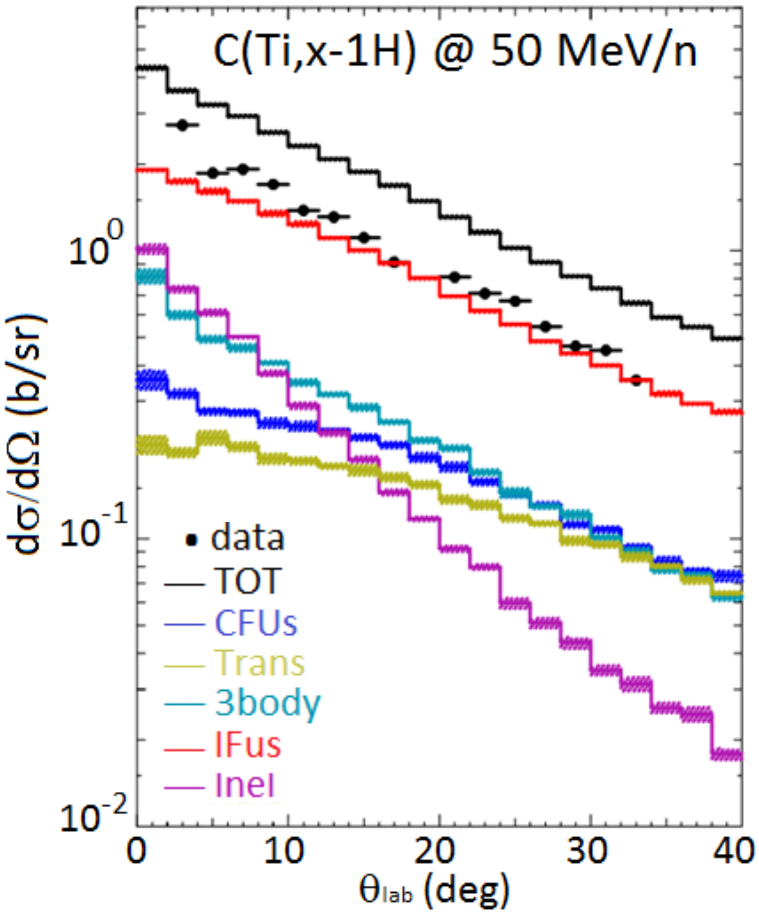
- An overestimation on the production of secondary protons in FLUKA was observed (like C-C collisions)

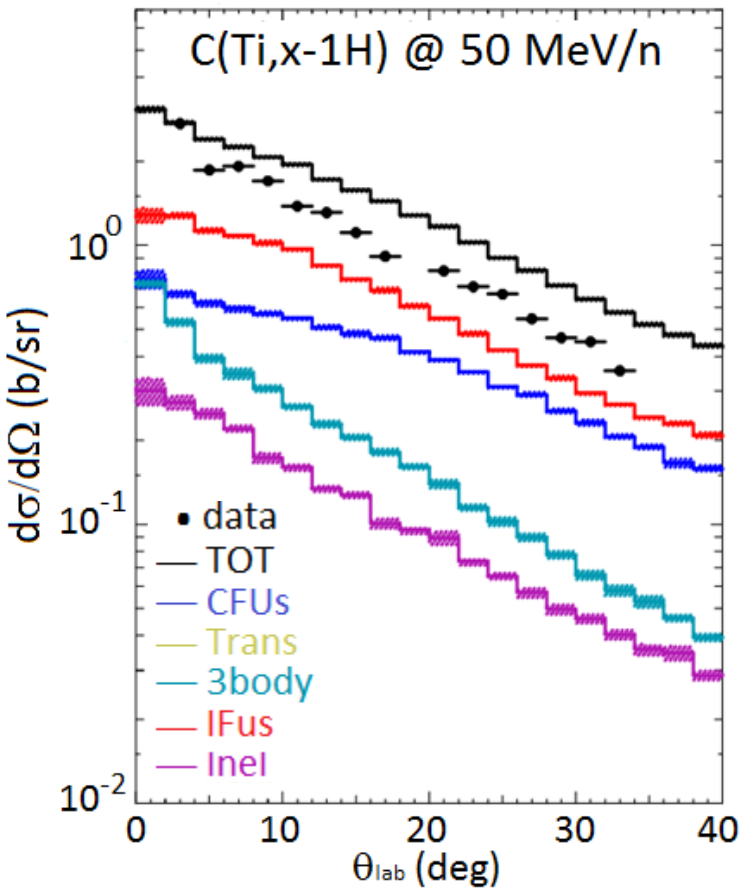
- **Initial test**:
  Same changes on the physics models as for C-C collisions

Experimental data from:
Divay C *et al* 2017, Phys. Rev. C **95** 044602

Preliminary results

Asymmetric system: C-Ti





Experimental data from:
Divay C *et al* 2017, Phys. Rev. C **95** 044602

Preliminary results

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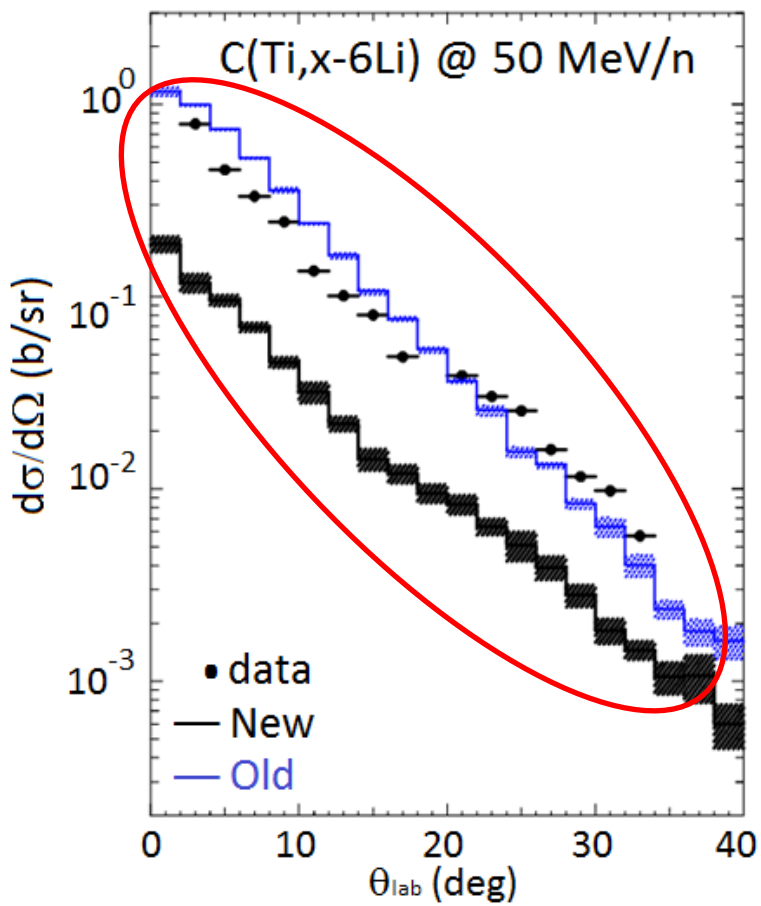

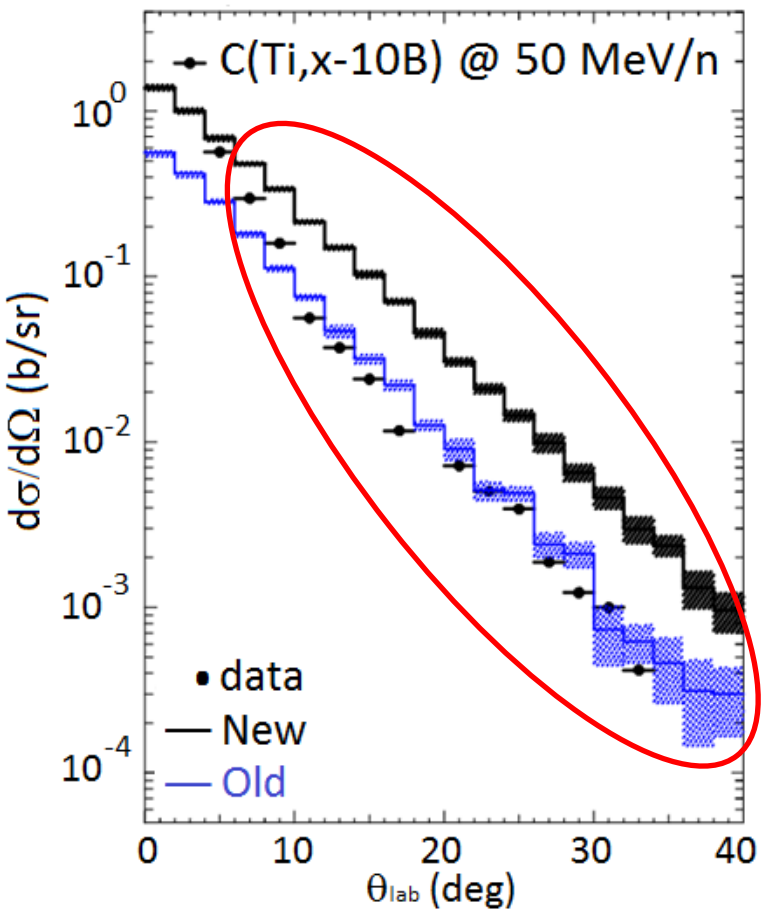

Experimental data from:
Divay C *et al* 2017, Phys. Rev. C **95** 044602

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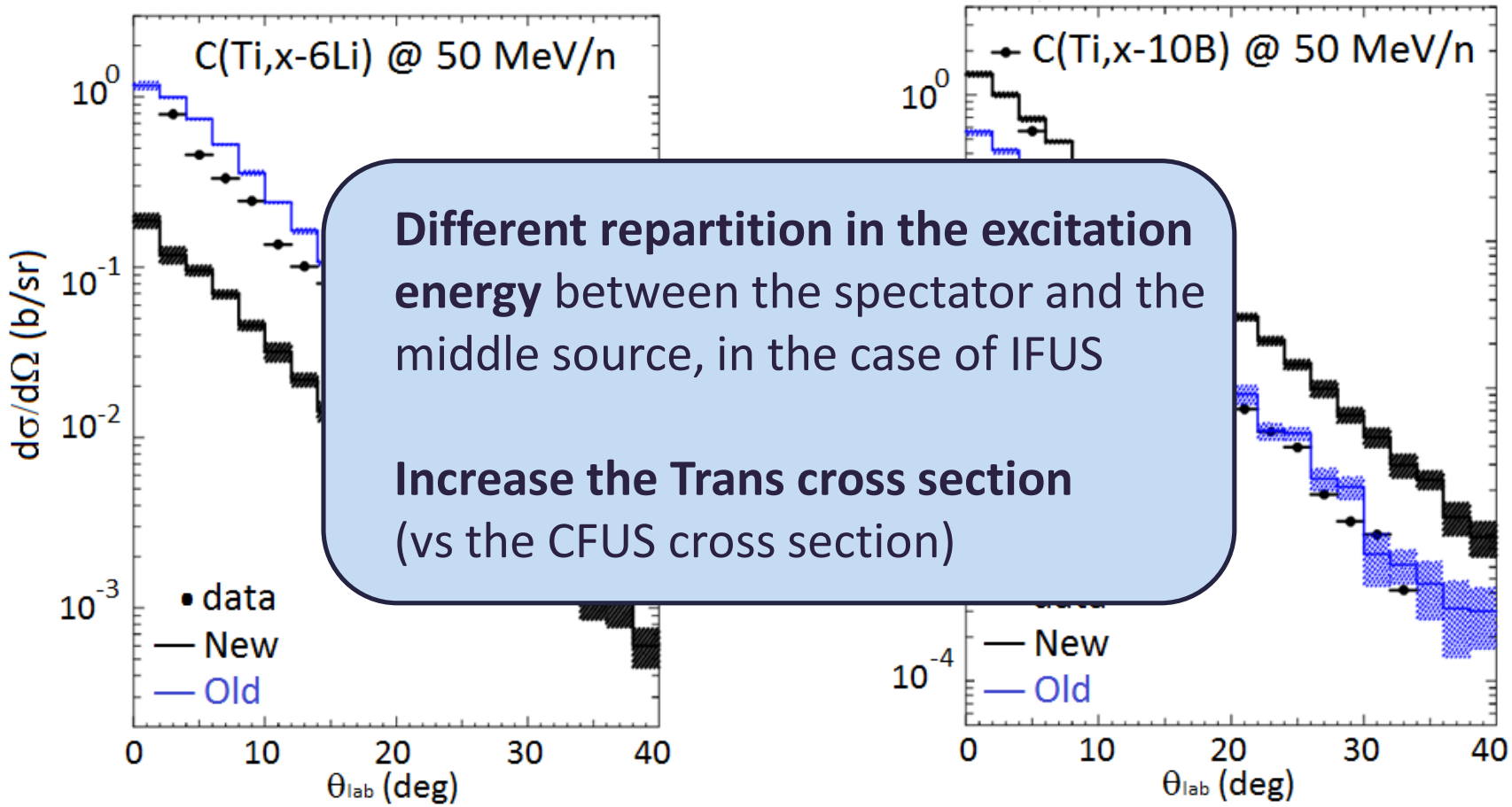


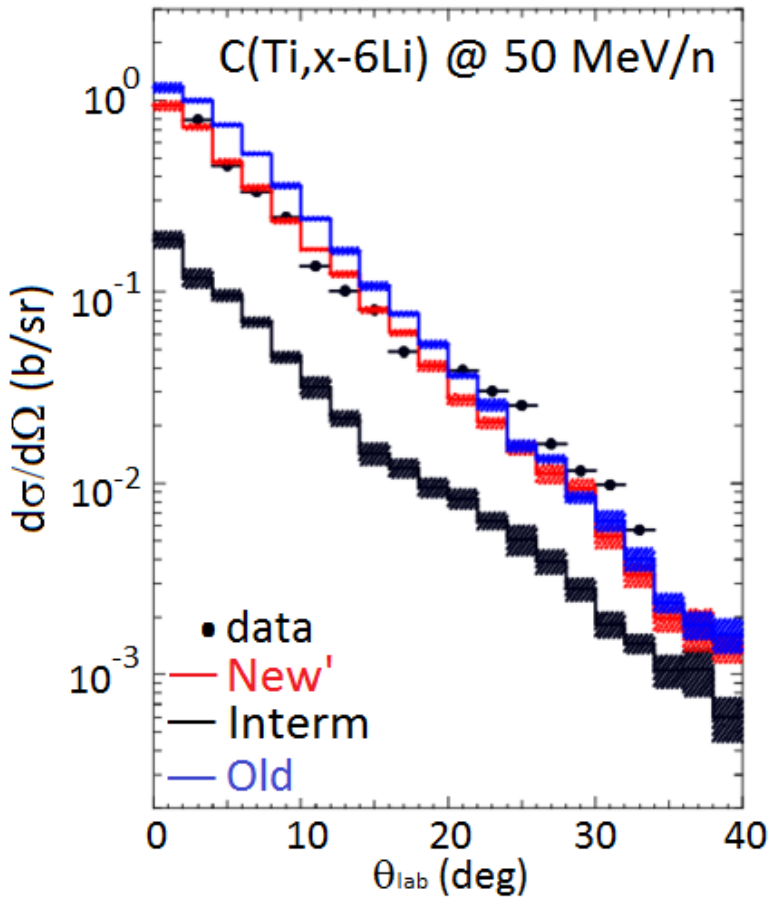
Different repartition in the excitation energy between the spectator and the middle source, in the case of IFUS

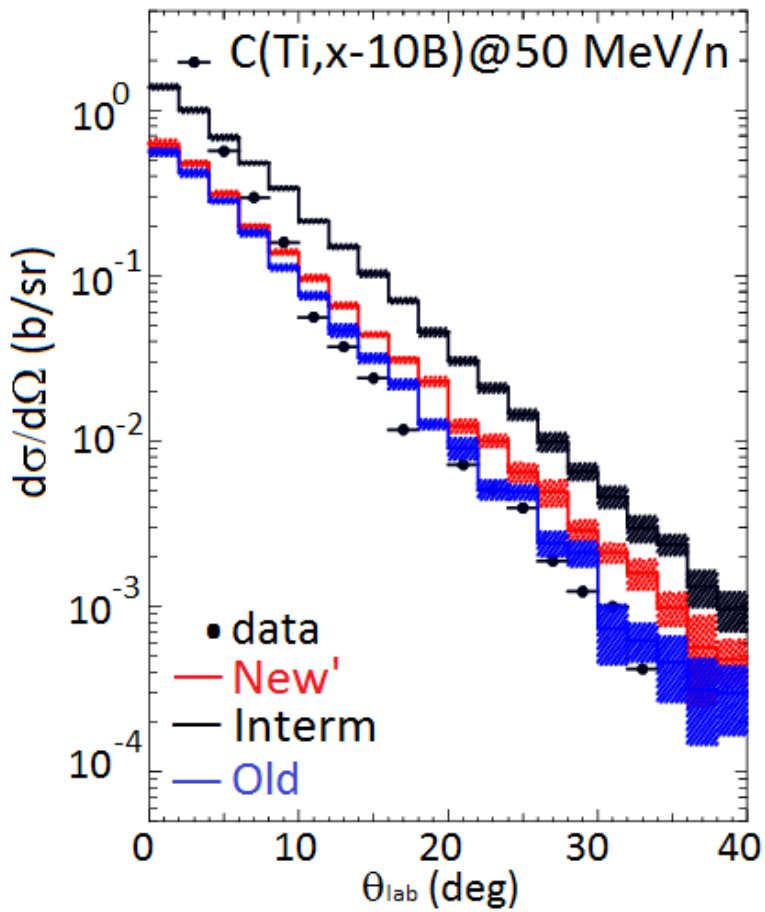
Increase the Trans cross section (vs the CFUS cross section)

Experimental data from:
Divay C *et al* 2017, Phys. Rev. C **95** 044602

Preliminary results

Asymmetric system: C-Ti





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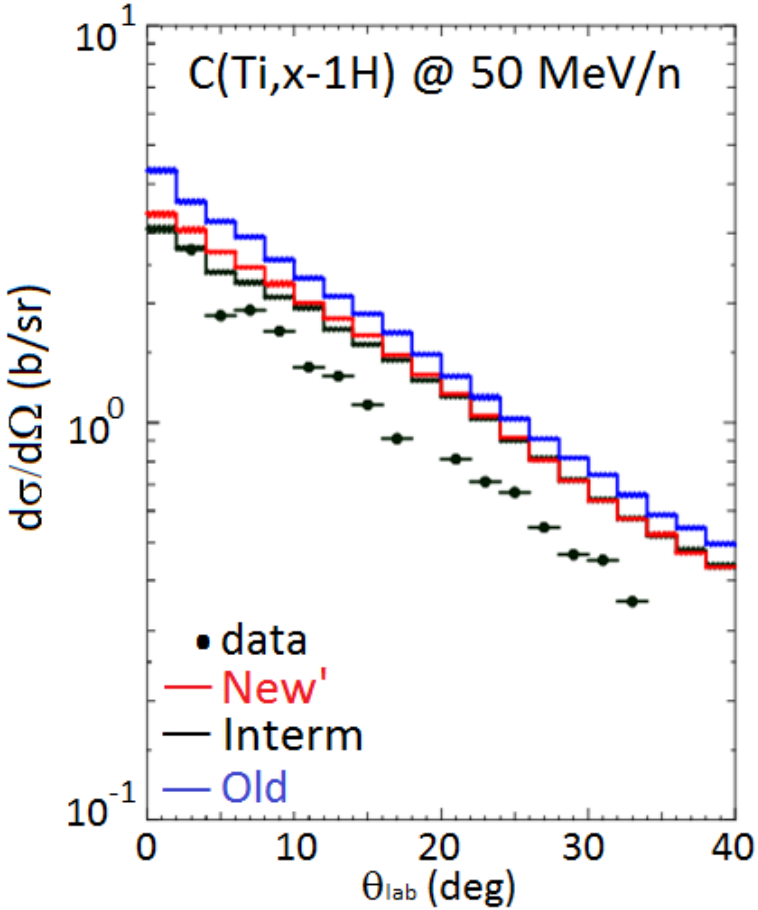

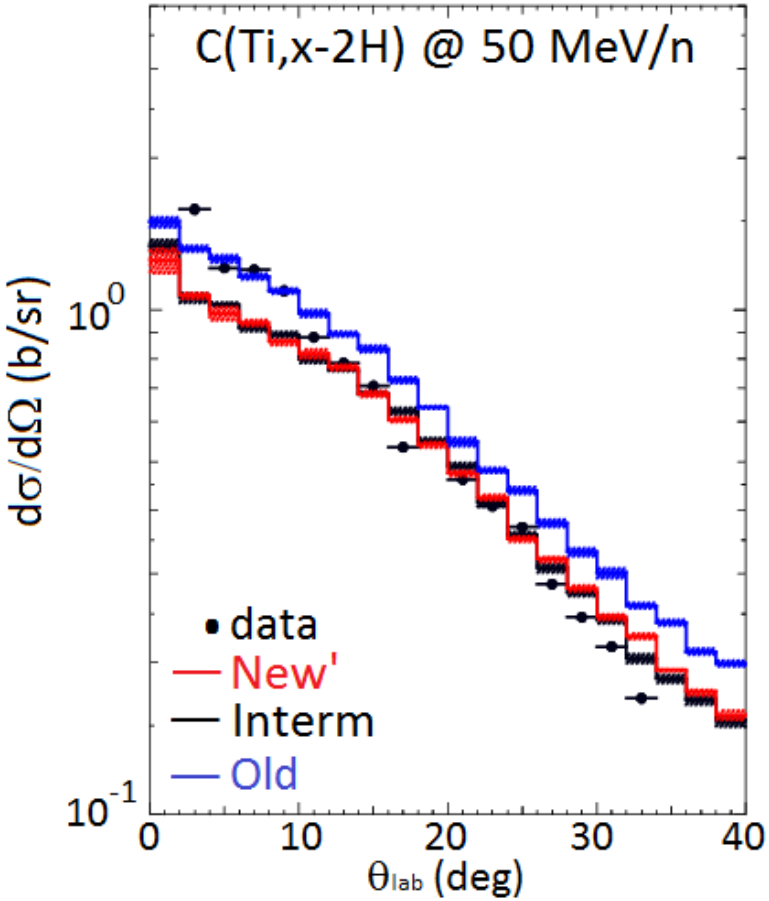

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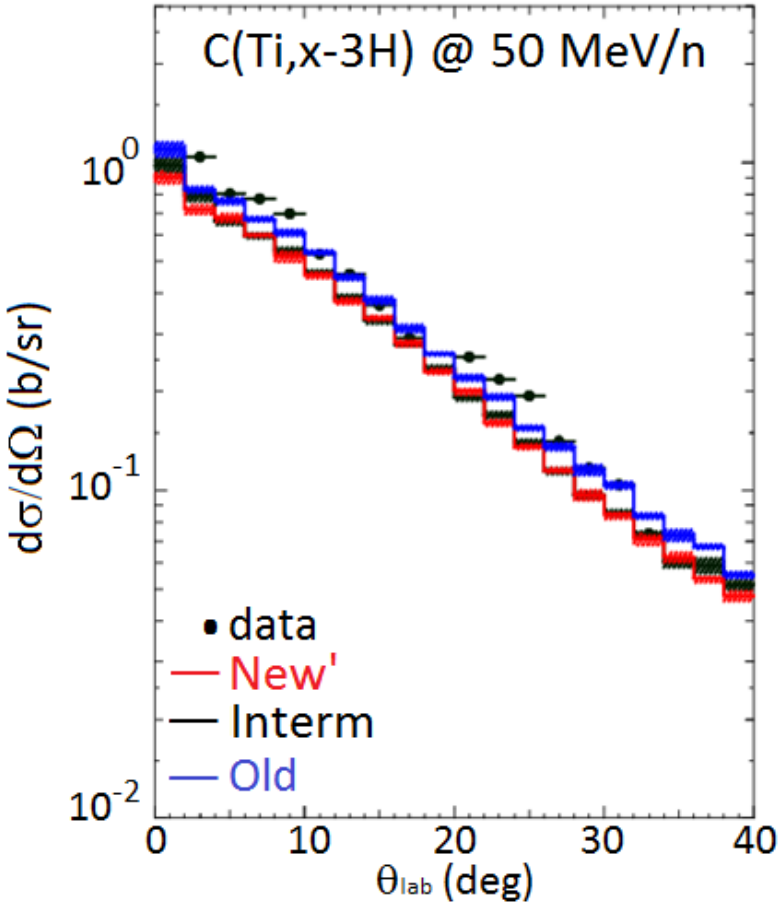
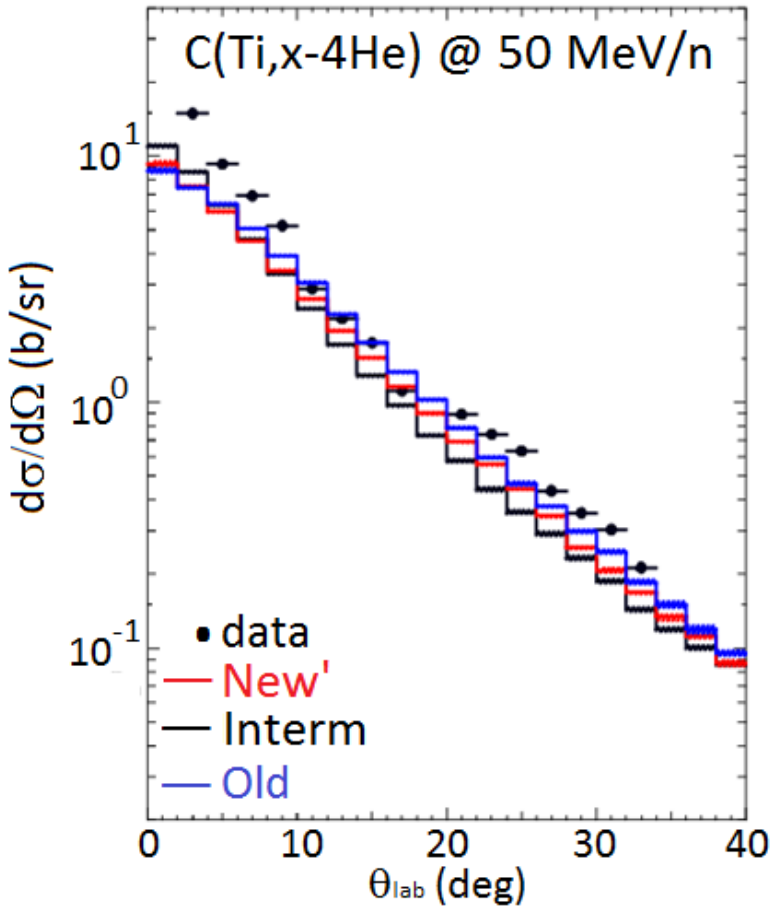
Asymmetric system: C-Ti





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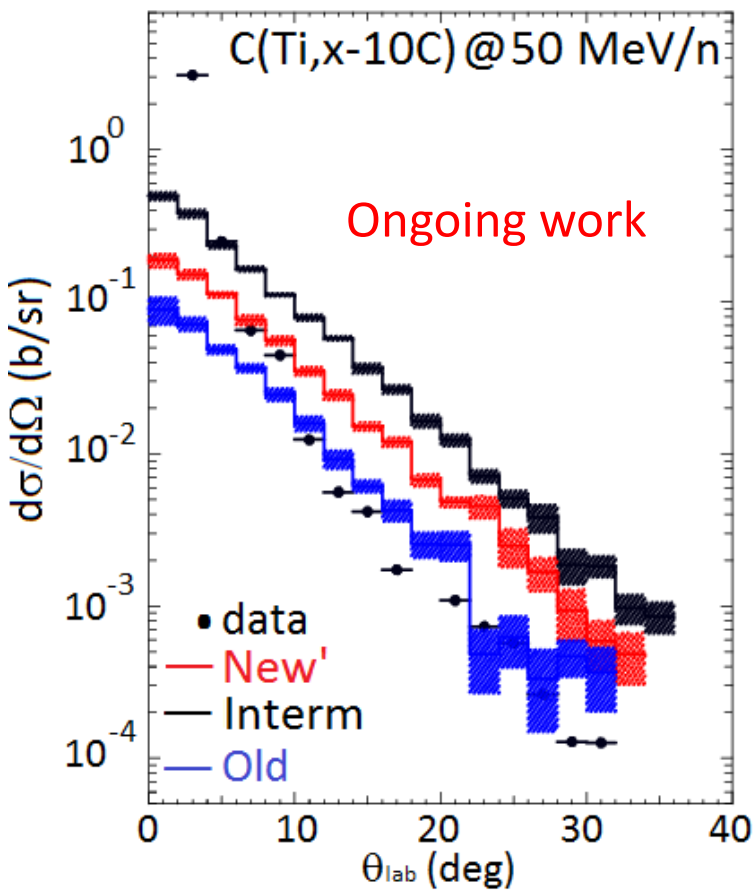
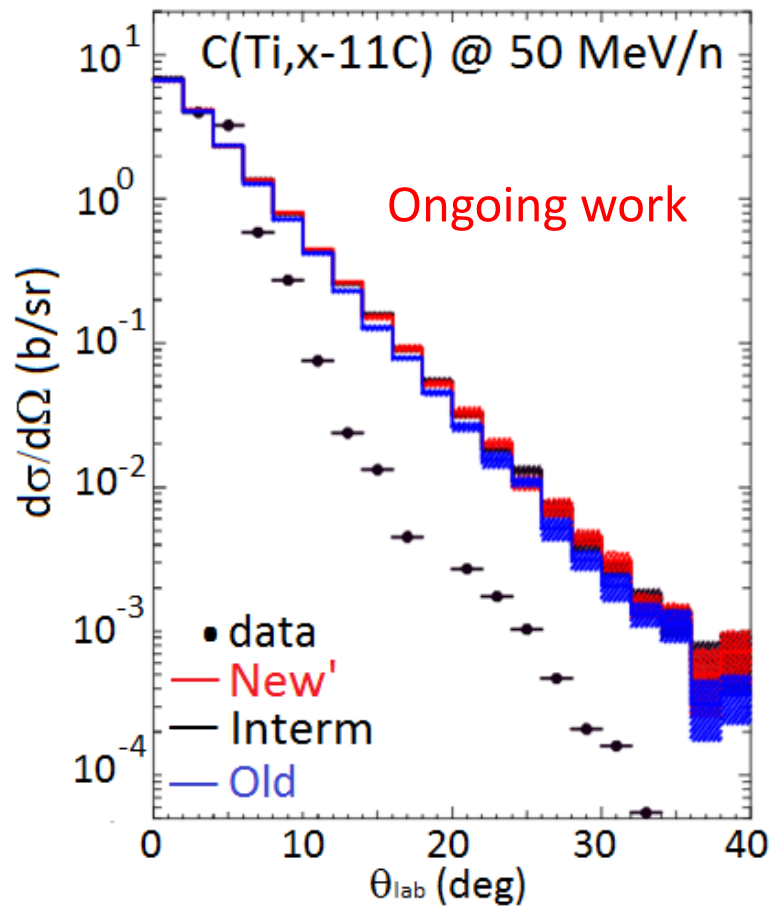




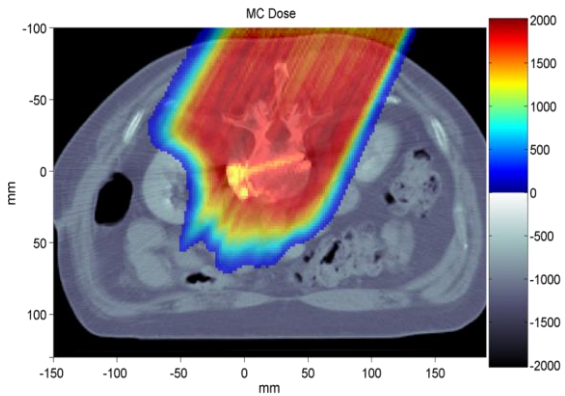
Experimental data from:
Divay C *et al* 2017, Phys. Rev. C **95** 044602

Overview

Overview:

- **Introduction**
- **Method**
- **Results**
- **Summary**
- **Outlook**

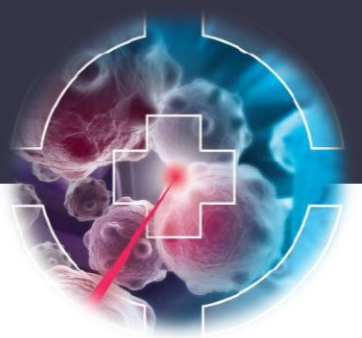
Improvements on



for medical applications

Source:
Parodi K *et al* (2007) IJROBP **68** 920-934

Summary



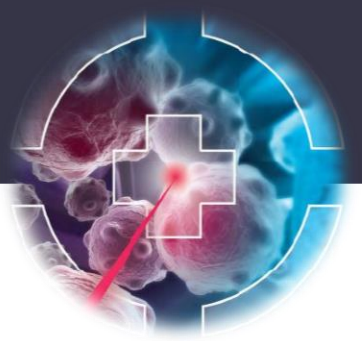
FLUKA has been used since many years for medical applications → Extensively benchmarked*

- **Present**: Analysis of single and double differential cross sections for 50 MeV/u ^{12}C ion beams in different materials
  - ✓ Good agreement was found in most of the cases
  - ✓ Improvements on the angular and energy distributions for secondary protons
  - ❑ Underestimation of ^{10}C and ^{11}C yield

- This work is ongoing

*Battistoni G *et al* (2016) Front Oncol 6:116
Böhlen T *et al* (2010) PMB **55** 5833-5847
Mairani A (2007) PhD Thesis Uni Pavia

Outlook



Ongoing work:

i) Improvements of the nuclear reaction cross sections for **helium ion** beams

- Recent measurements in collaboration with GSI and HIT

ii) Improvements of the physics models for **carbon ion** beams.

iii) … and for **heavy-heavy ion collisions**

- Analysis of the fragments production in BME and rQMD

Applications for **hadrontherapy**, **astrophysics** and **space radiation**

Thanks for your attention

Acknowledgments:

Francesco Cerutti[1)], Alfredo Ferrari[1)], Andrea Mairani[2),3)]

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