The application of the FLUKA Monte Carlo code in medical physics

G. Battistoni(*), G. Aricò, F. Ballarini, J. Bauer, T.T. Böhlen,
M. P. Carante, F. Cerutti, M. Chin, C. Cuccagna,
R. Dos Santos Augusto, A. Fontana, A. Embriaco, A. Ferrari,
W. Kozłowska, G. Magro, A. Mairani, S. Muraro,
K. Parodi, P. Ortega, P.R. Sala, F. Salvat-Pujol,
P. Schoofs, T. Tessonier, V. Vlachoudis

(*) INFN Milano

The FLUKA code

http://www.fluka.org

>8000 registered users

A general purpose tool for calculations of particle transport and interactions with matter: from LHC to microdosimetry

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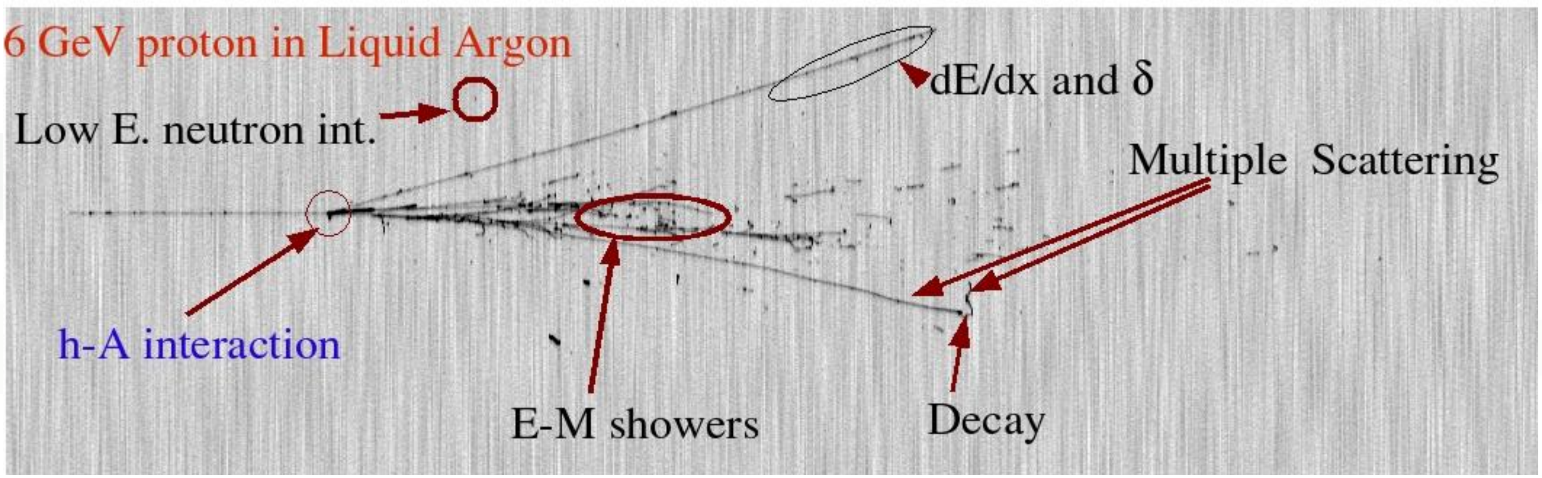

- High accuracy physics models/“microscopic” approach. Benchmarked with exp. data
- Conservation laws implemented at the level of machine accuracy
- Continuous development
- Easy to use for basic applications

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

FLUKA appearing/mentioned in several talks/posters at MCMA2017

F. Horst: Novel data relevant for helium ion therapy ... ID 172
S. Muraro: MC codes and Range Monitoring in Particle Therapy... ID 67
A. Mairani: MC-based RBE investigations in hadrontherapy ID 64
E. Fiorina: MC simulation tool in-beam PET ID 143
A. Fontana: MC calculation of reaction cross sections for innovative radionuclides ID 14
C. Cuccagna: Beam characterization for the TULIP accelerator... ID 155
M. Marafini et al.: Elastic scattering in FLUKA code for MONDO experiment... ID 1
A. Embriaco: FLUKA validation of MONET code ID 18
S.M. Valle: Detector MC study for measurement of nuclear reaction cross sect. ID 164
C. Cuccagna: Advances in the FLUKA PET tools ID 183
P.M. Altieri: MC simulation studies on a beam monitor... ID 5
M. Chauvine: OpenDose project !D 155
W. Kozlowska: Evolutionary Algorithms for Monte Carlo Treatment Planning ID 154
S. Mein: MC calculation of RBE and in-vitro validation for helium ion-therapy ID 129
A. Schiavi: Fred: A new GPU-based fast-MC ID 161
J. Wu, Y.Liu.: Database of neutron shielding for a 250-MeV proton accelerator ID 43
C. Lee, J.S. Kim: Meas. of the induced neutron ambient dose equiv. during proton therapy in scanning model ID 98
F. Ballarini: The BIANCA biophysical/MC model... ID 37

Applications in Medical Physics and related disciplines

- Nuclear Medicine
  - Dosimetry
- Radiotherapy
  - Simulation of therapy devices
  - Simulations/Check of treaments
- Hadrontherapy
  - Shielding
  - Commissioning of facilities
  - Treatment planning and forward checks
  - Predictions for monitoring applications (imaging for hadrontherapy)
  - Design of instruments, dosimetry
  - Calculation for shielding and rad. protection in facilities

Nuclear Medicine

Radioactive source decay

FLUKA contains data about **decaying schemes of radioactive isotopes**, allowing to select an isotope as radiation source. Complete databases are generated from the data collected **from National Nuclear Data Center** (NNDC) at Brookhaven National Laboratory.

Phys. Med. Biol. 58 (2013) 8099–8120 doi:10.1088/0031-9155/58/22/8099

Use of the FLUKA Monte Carlo code for 3D patient-specific dosimetry on PET-CT and SPECT-CT images*

F Botta[1], A Mairani[2,10], R F Hobbs[3], A Vergara Gil[4], M Pacilio[5], K Parodi[6], M Cremonesi[1], M A Coca Pérez[7], A Di Dia[1], M Ferrari[1], F Guerriero[1], G Battistoni[8], G Pedroli[1], G Paganelli[9], L A Torres Aroche[7] and G Sgouros[3]

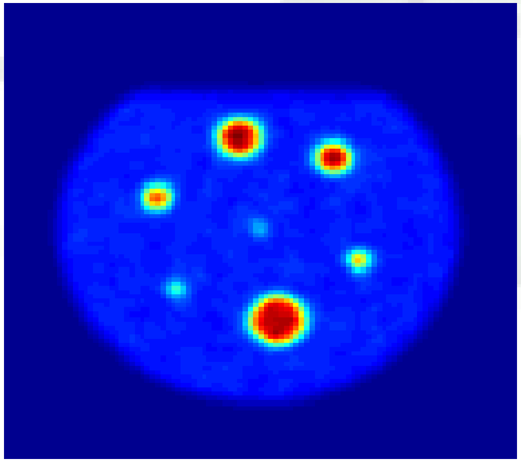
Nuclear Medicine

Calculation of absorbed dose at voxel level starting from 3D images of activity distribution (SPECT, PET images)

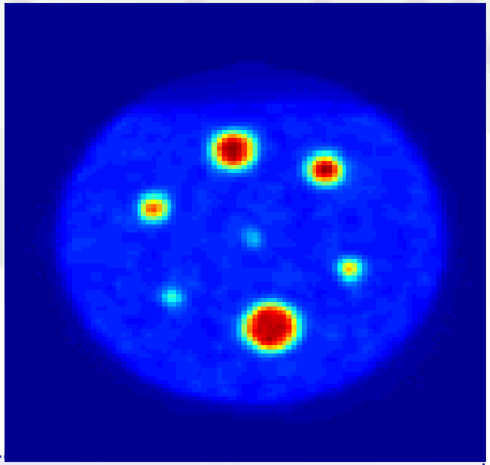
Simulations of hot sphere in homogeneous water

^{90}Y spectrum

Voxel-by-Voxel ratio
Integral DVH
Profiles



VOXEL Dosimetry



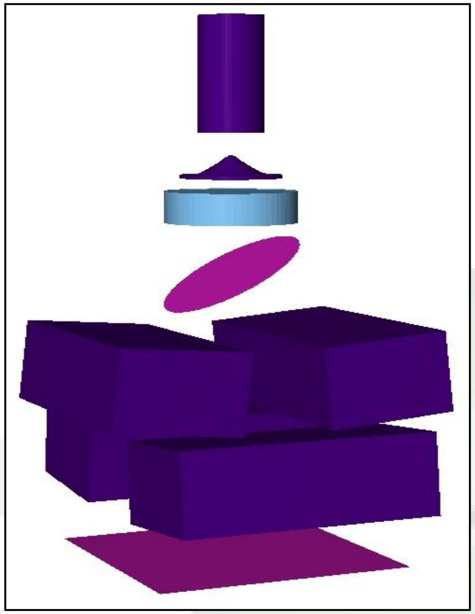
MONTE CARLO 10^9 particles

Dose Point Kernel
F. Botta et al.
INFN and IEO
Collaboration, 2011

With 10^9 particles simulated, FLUKA and VOXEL DOSIMETRY (a standard analytic procedure in nuclear medicine) results in water agree within 5%

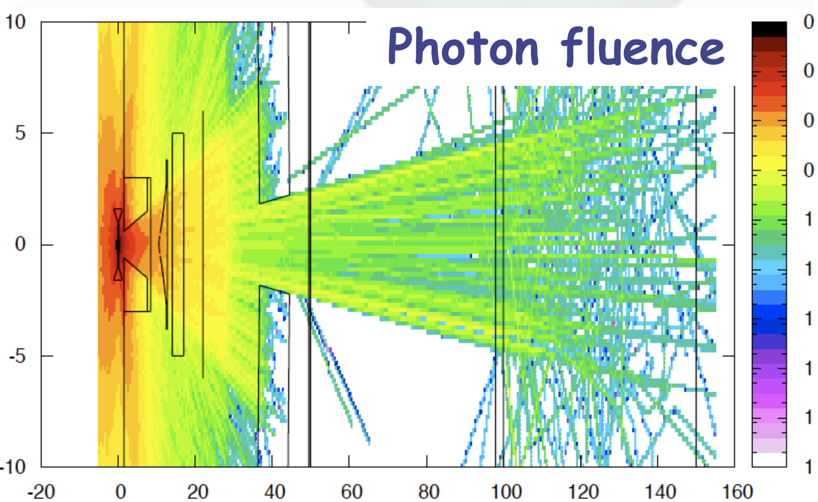
See talk about OpenDose project where ICRP reference phantoms will be used

Radiotherapy Studies: exanple of Simulation of a 6MV Linac (Varian)



Geometry details provided by courtesy of Varian

E.M. physics in FLUKA comparable to Penelope quality



Dosimetric validation

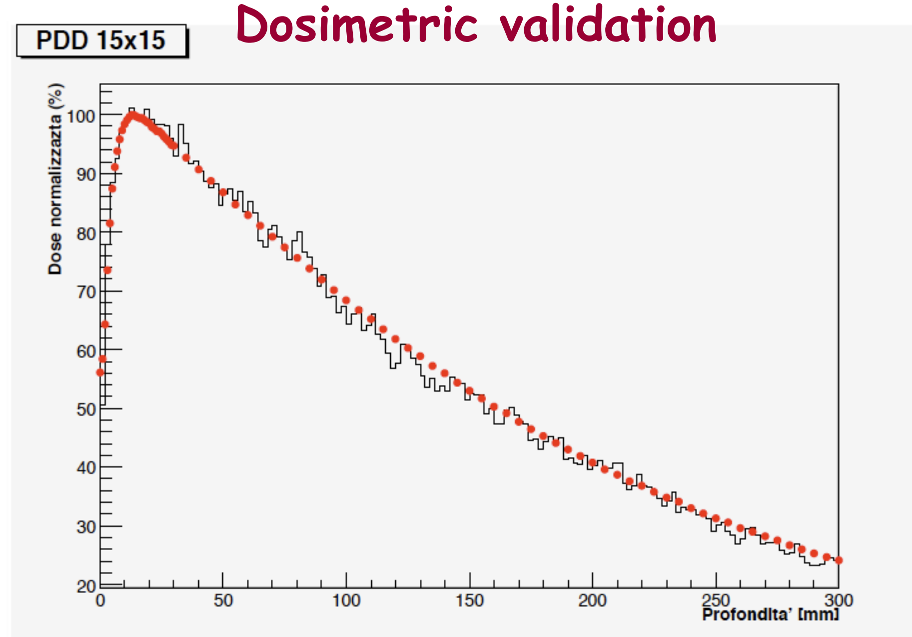
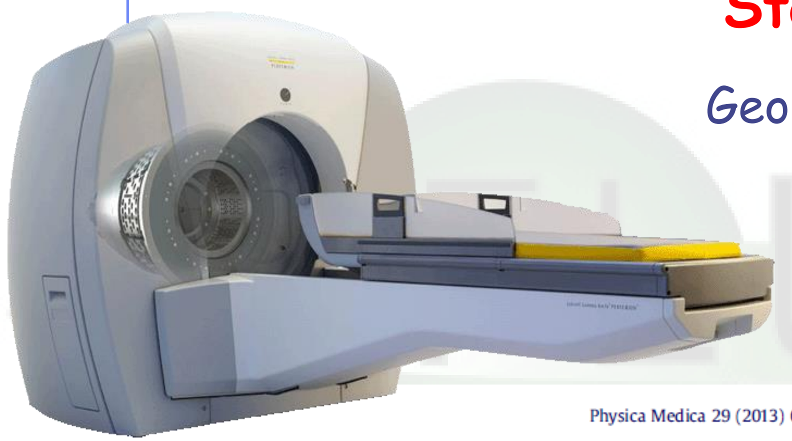


Figura 3.7: Curve di dose in profondità simulate con energia nominale pari a 6 MV; i pallini rossi sono le misure sperimentali e la linea nera rappresenta le simulazioni teoriche.

The Leksell Gamma Knife Perfexion:

The **Leksell Gamma Knife Perfexion** (LGK-PFX) **Elekta AB Instruments Stockholm, Sweden.**

Geometry details provided by courtesy of Elekta



Physica Medica 29 (2013) 656–661

Contents lists available at SciVerse ScienceDirect

Physica Medica

journal homepage: http://www.physicamedica.com

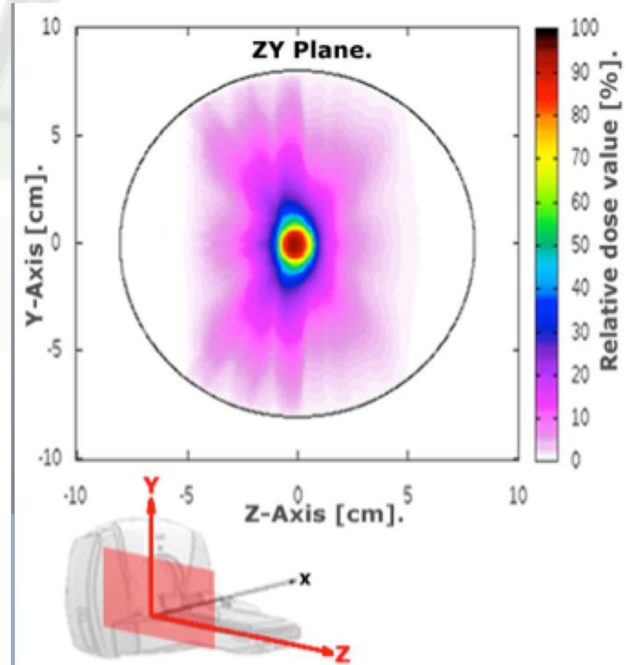
ELSEVIER

Original paper

FLUKA Monte Carlo simulation for the Leksell Gamma Knife Perfexion radiosurgery system: Homogeneous media

Giuseppe Battistoni [a,1], Fabrizio Cappucci [a,*], Nicola Bertolino [b,2], Maria Grazia Brambilla [c,3], Hae Song Mainardi [c,4], Alberto Torresin [c,5]

[a] I.N.F.N. Section of Milan, Via Celoria 16, 20133 Milano, Italy
[b] Health Department, I.R.C.C.S. Neurologic Institute C. Besta, Italy
[c] Medical Physics Department, Niguarda Ca' Granda Hospital, Italy



E.M. Physics of FLUKA
(down to 1 keV for e^+e^-,100 eV for photons)

- Interactions of leptons/photons
  - Photon interactions
    - Photoelectric
    - Compton
    - Rayleigh
    - Pair production
    - Photonuclear
    - Photomuon production
  - Electron/positron interactions
    - Bremsstrahlung
    - Scattering on electrons
    - e^+ Annihilation
  - *(Muon interactions*
    - *Bremsstrahlung*
    - *Pair production*
    - *Nuclear interactions)*

takes into account photon polarization atomic bonds and orbital motion (Compton, Rayleigh)

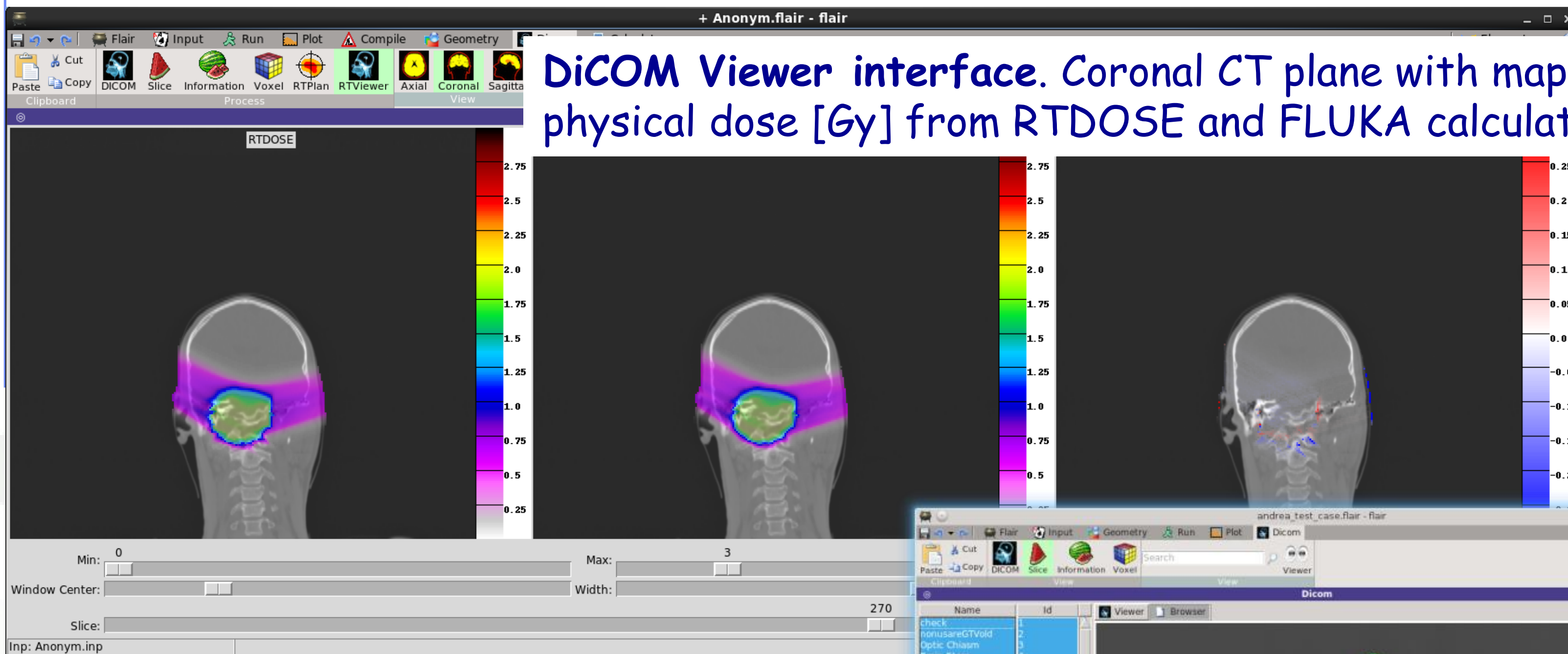
takes into account orbital motion of atomic electron (e^+ Annihilation)

- Ionization energy losses
  - Continuous
  - Delta-ray production
- Transport
  - Multiple scattering
  - Single scattering

These are common to all charged particles, although traditionally associated with EM

Importing DICOM images into FLUKA geometry

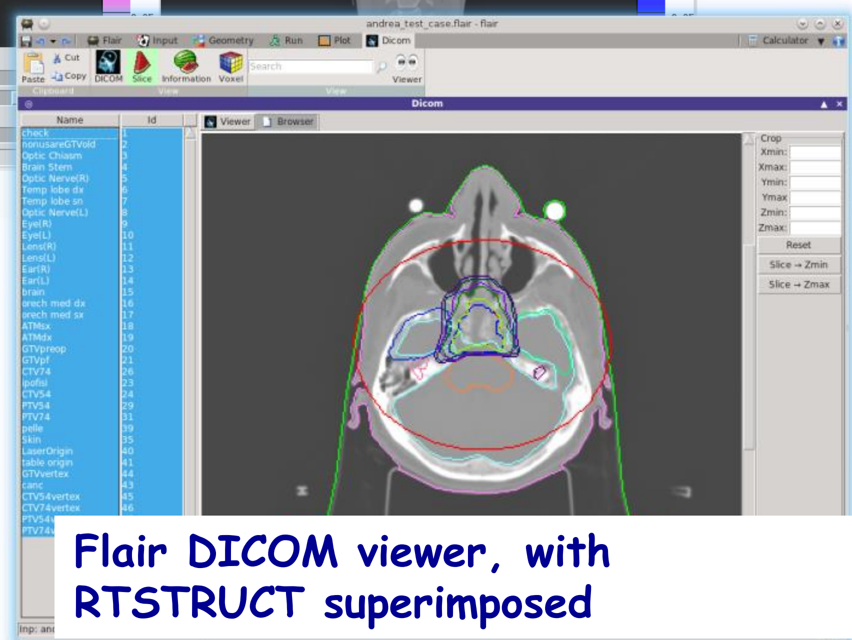
Handled by User Graphical interface: Flair (developed in python & C++)



DiCOM Viewer interface. Coronal CT plane with mapped physical dose [Gy] from RTDOSE and FLUKA calculation.

Based on Pydicom

- DICOM CT, MR, importer
- Automatic material assignment using the Schneider parameterization
- Importing ROI RTstructures
- Importing RTPlan
- Generation of DVH plots and comparison plots with RTDOSE



Flair DICOM viewer, with RTSTRUCT superimposed

Hadrontherapy

A long history of applications and developments for hadrotherapy
- FLUKA used at CNAO for TPS database generation, patient plan verification, forward calculation of patient plans, eye treatment studies, radio-biology related studies…etc
- At HIT for TPS database generation, patient plan verification, forward calculations of patient plans, imaging related studies…etc

frontiers in Oncology

Front. Oncol. 6:116.
doi: 10.3389/fonc.2016.00116

The FLUKA Code: An Accurate Simulation Tool for Particle Therapy

Giuseppe Battistoni[1], Julia Bauer[2], Till T. Boehlen[3], Francesco Cerutti[4], Mary P. W. Chin[4], Ricardo Dos Santos Augusto[4,5], Alfredo Ferrari[4], Pablo G. Ortega[4], Wioletta Kozłowska[4,6], Giuseppe Magro[7], Andrea Mairani[7,8], Katia Parodi[5,8], Paola R. Sala[1,4], Philippe Schoofs[4], Thomas Tessonnier[2] and Vasilis Vlachoudis[4]*

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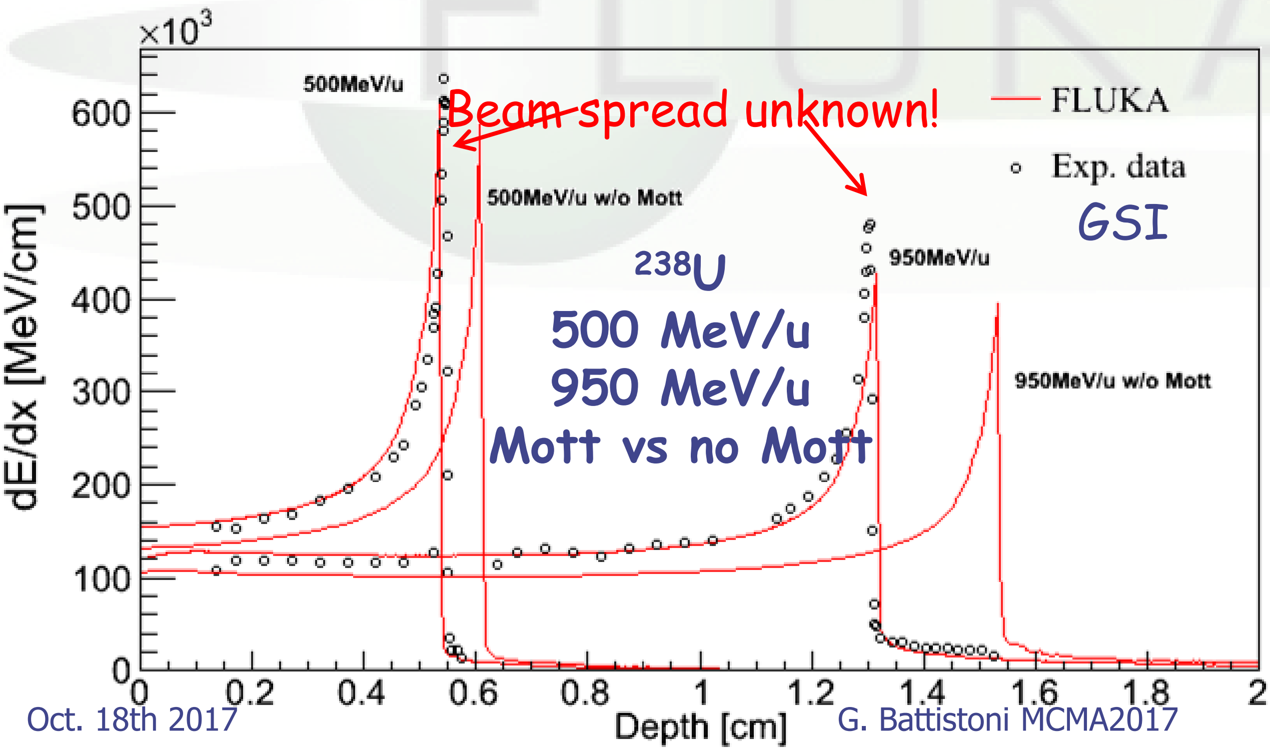
Electronic Stopping Power

- Before 2009: Ions scaled from p or α particles through $(Z_{eff})^2$, Z_{eff} from parameterisations
- Since 2009-2011:
  - Added Z^3 (Barkas) , Z^4 (Bloch) corrections
  - Re-calculation of Z_{eff} and shell corrections
  - ***Mott corrections***
  - ..and more..

Of course there is also nuclear stopping power etc.



Refinements recently implemented in the electronic stopping power in FLUKA resulted in a reduced spread of ionization potential values used for the different projectiles: 0.5 eV as compared to 1.7 eV as previously reported

The importance of nuclear models

- While nuclear recoils result typically in negligible spatial modifications of the delivered dose, secondary nucleons, particles, and fragments produced in nuclear reactions can considerably affect the spatial pattern of energy deposition and must be carefully taken into account.
- In the case of heavy ions, nuclear fragmentation reactions are responsible for the deterioration of the physical selectivity in the longitudinal and transversal dimension especially around the Bragg peak region. The amount of fragments produced generally increases with the mass and charge of the primary particle.

Nuclear environment in FLUKA: PEANUT

(PreEquilibrium Approach to NUclear Thermalization)

Target nucleus description (density, Fermi motion, etc)

↓

Glauber-Gribov cascade with formation zone

↓

Generalized IntraNuclear cascade

↓

Preequilibrium stage with current exciton configuration and excitation energy
(all non-nucleons emitted/decayed + all nucleons below 30-100 MeV)

↓

Recently, competition of gamma ray emission with particle evaporation has also been implemented.

The low excitation stages of nuclear interactions are presently under strong development

t (s)

10^{-23}

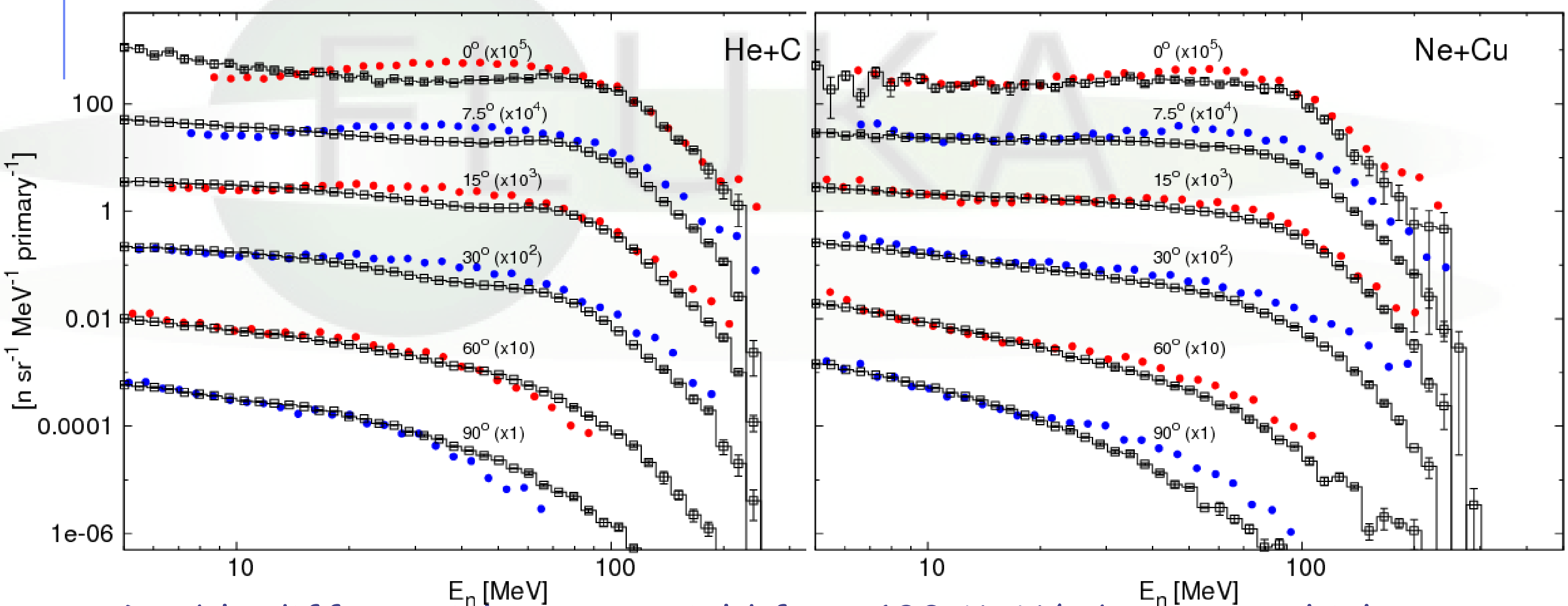
10^{-22}

10^{-20}

10^{-16}

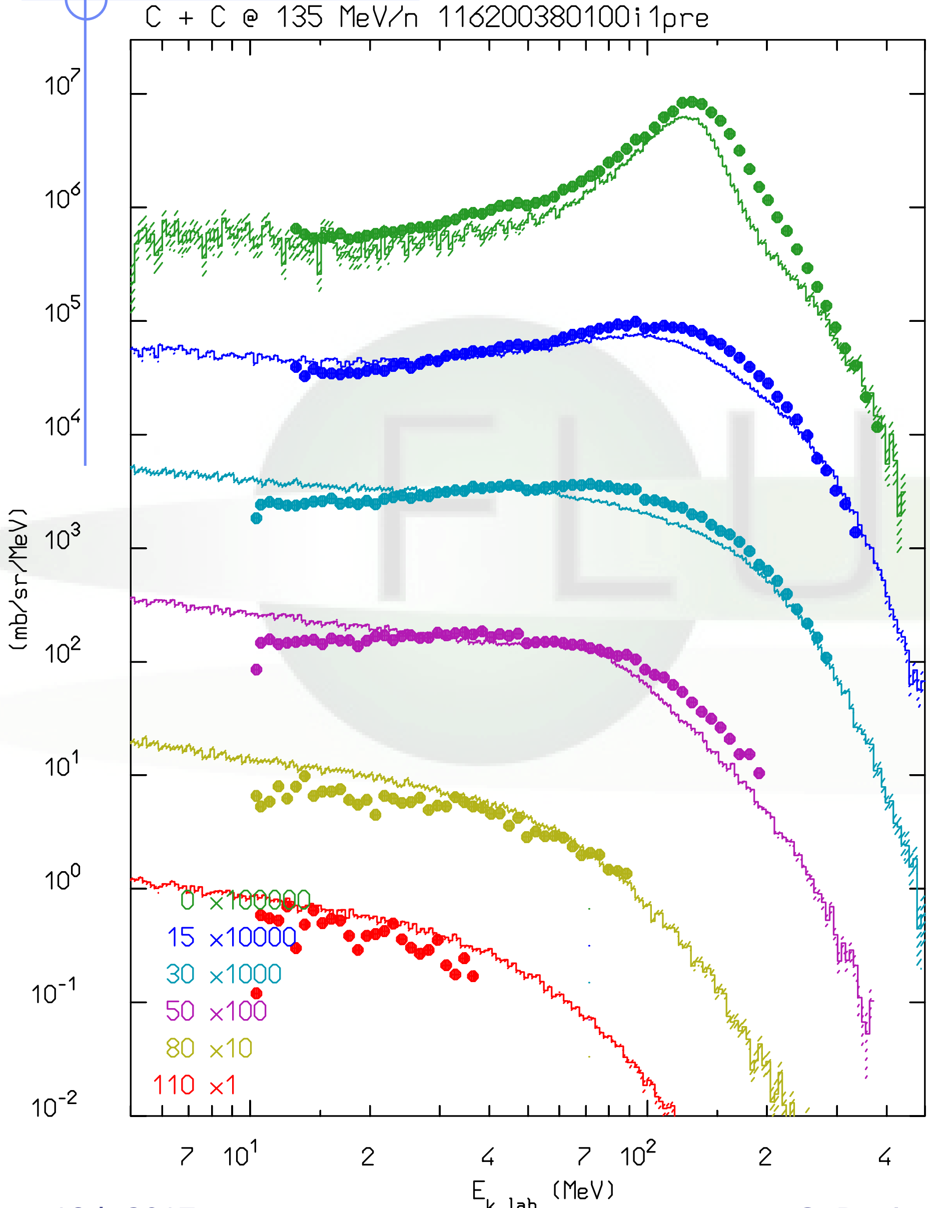
Low energy ion interactions : BME

E < 0.15/0.12 GeV/n : Boltzmann Master Equation (BME) theory (E.Gadioli et al.). thermalization of a composite nucleus by sampling from the results of the numerical integration of the BMEs. Recently interfaced with PEANUT in order to treat the first de-excitation stage of all nuclei for which BME information is not (yet) available: **particularly important for reactions induced by α.**



Double differential neutron yield from 100 MeV/n beams on thick targets
FLUKA vs experimental data from Nucl. Sci. Eng. 132, 30 (1999)

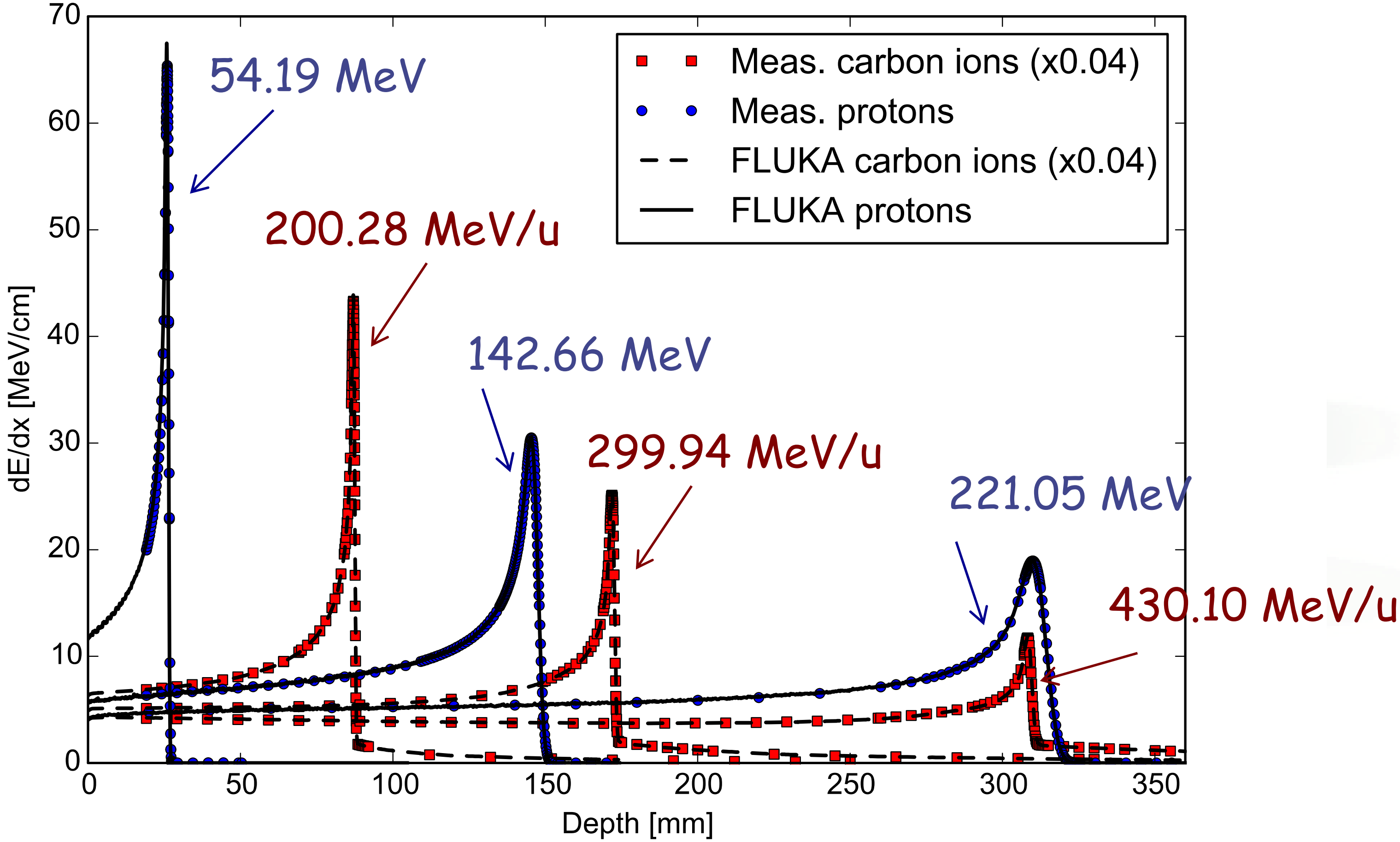
The rQMD model



relativistic
Quantum **M**olecular **D**ynamics

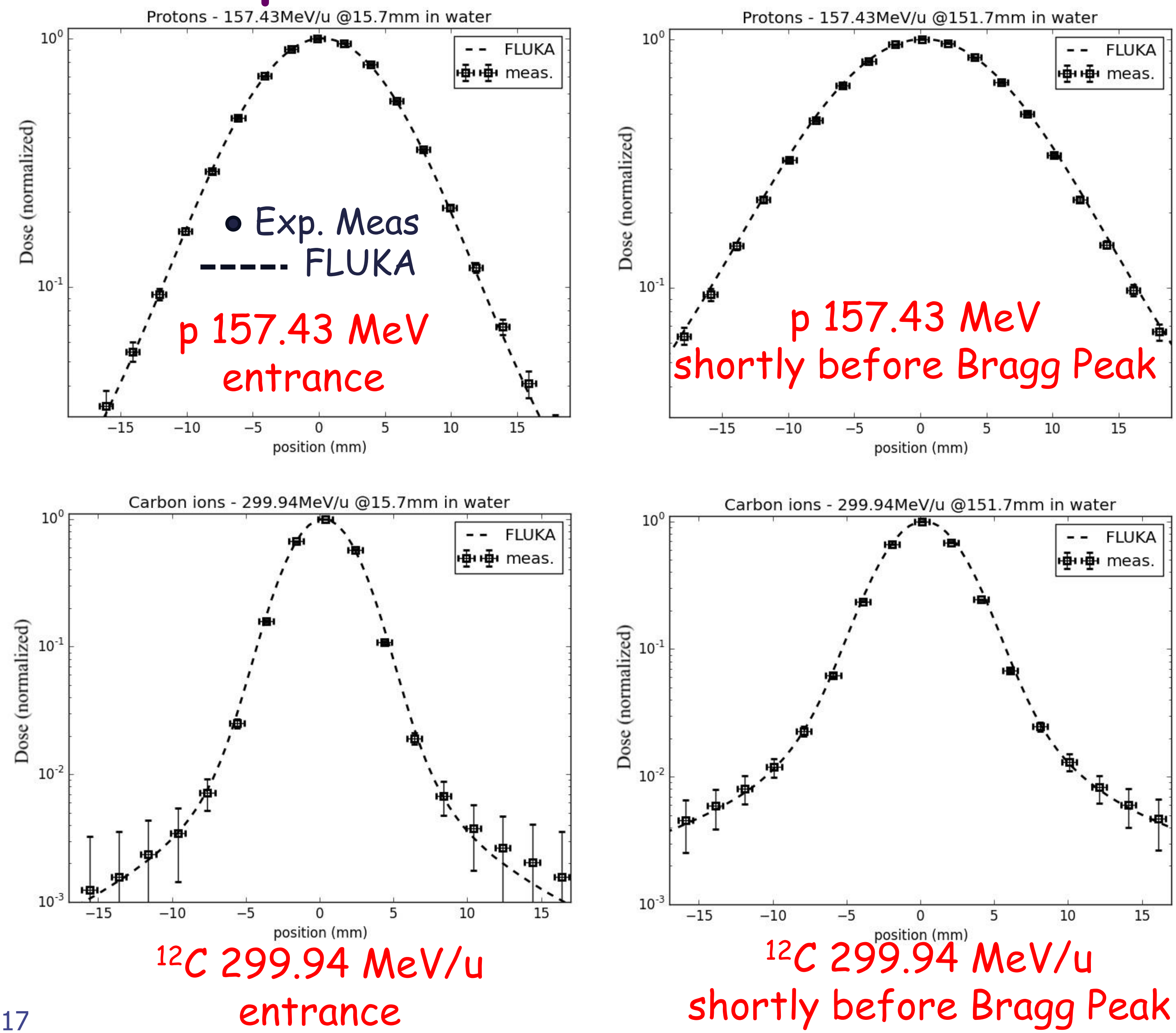
For ions in the few GeV/n energy range and down to 0.12-0.15 GeV/n, FLUKA uses an interface to a modified version of RQMD-2.4: a relativistic quantum molecular dynamics model that can also be run in intranuclear cascade mode. Excited fragments from RQMD are further processed by PEANUT.

Comparing Predictions for Depth-Dose curves and Lateral Dose Profiles



FlUKA simulations of depth-dose profiles of protons and carbon ions with therapeutic ranges in comparison with measured data at HIT.

Lateral profiles measured @HIT



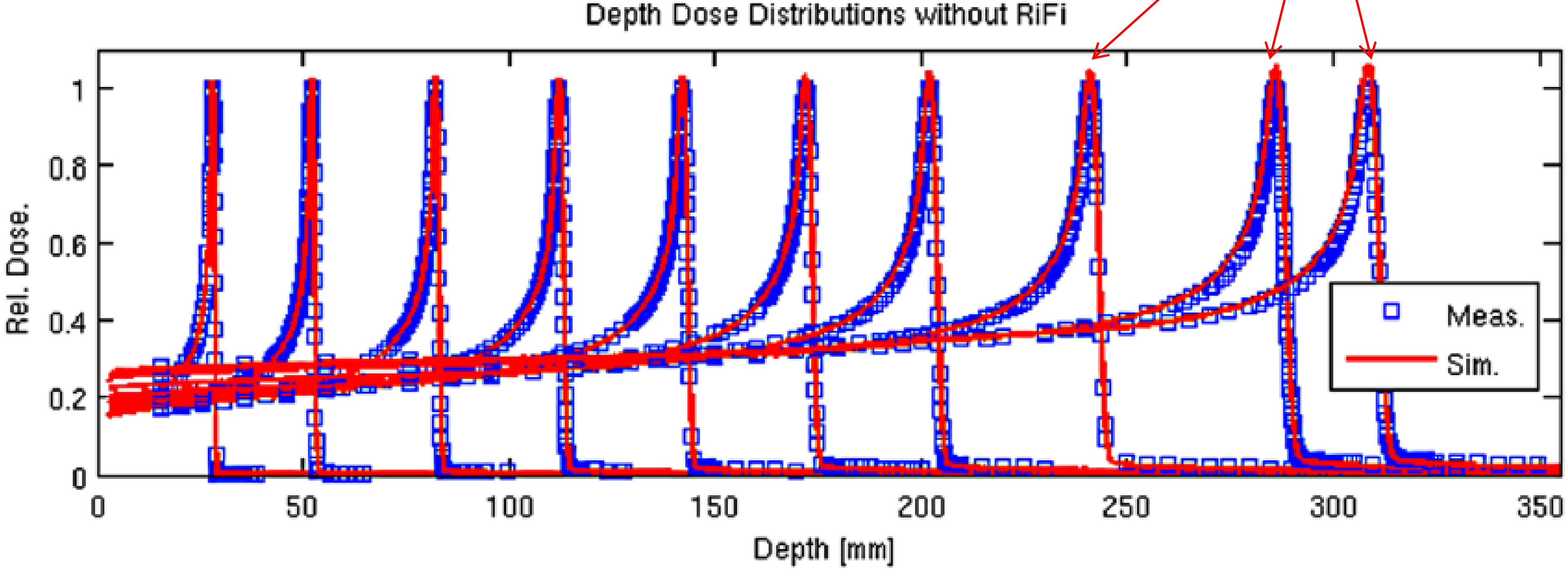
New ions for therapy

Helium ions at the heidelberg ion beam therapy center: comparisons between FLUKA Monte Carlo code predictions and dosimetric measurements

Phys. Med. Biol. **62** (2017) 6784–6803

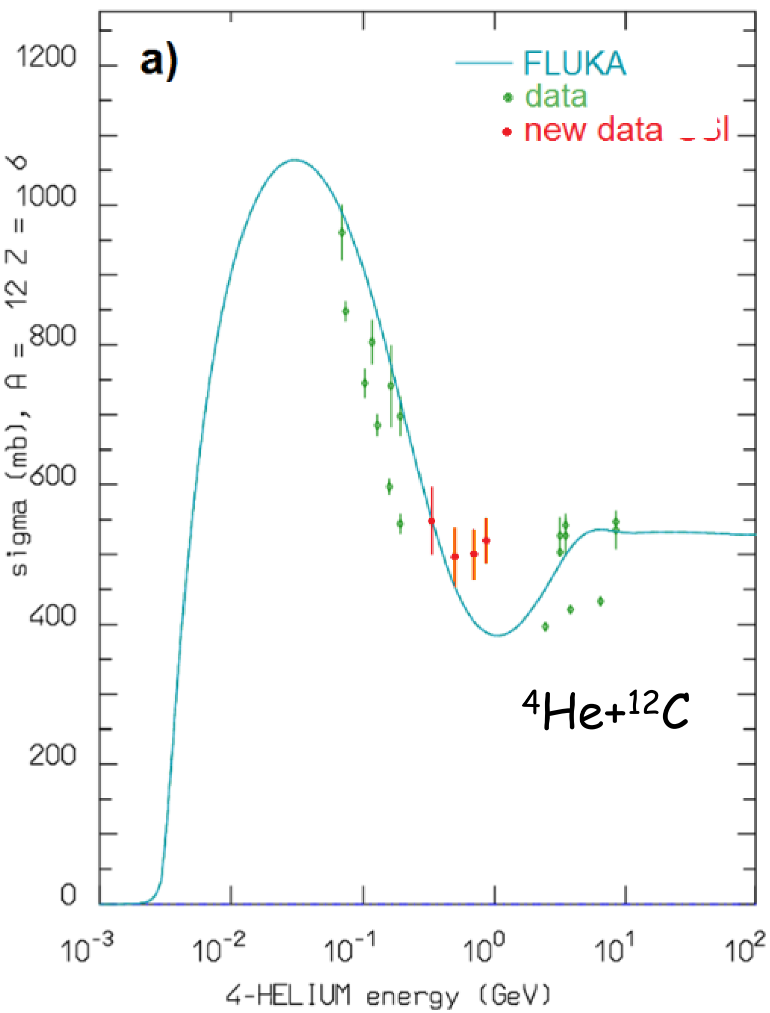
T Tessonnier[1,4], A Mairani[2,3], S Brons[2], P Sala[5,6], F Cerutti[6], A Ferrari[6], T Haberer[2], J Debus[1,2] and K Parodi[1,4]

Slight exess of dose
See talk by F. Horst ID 172

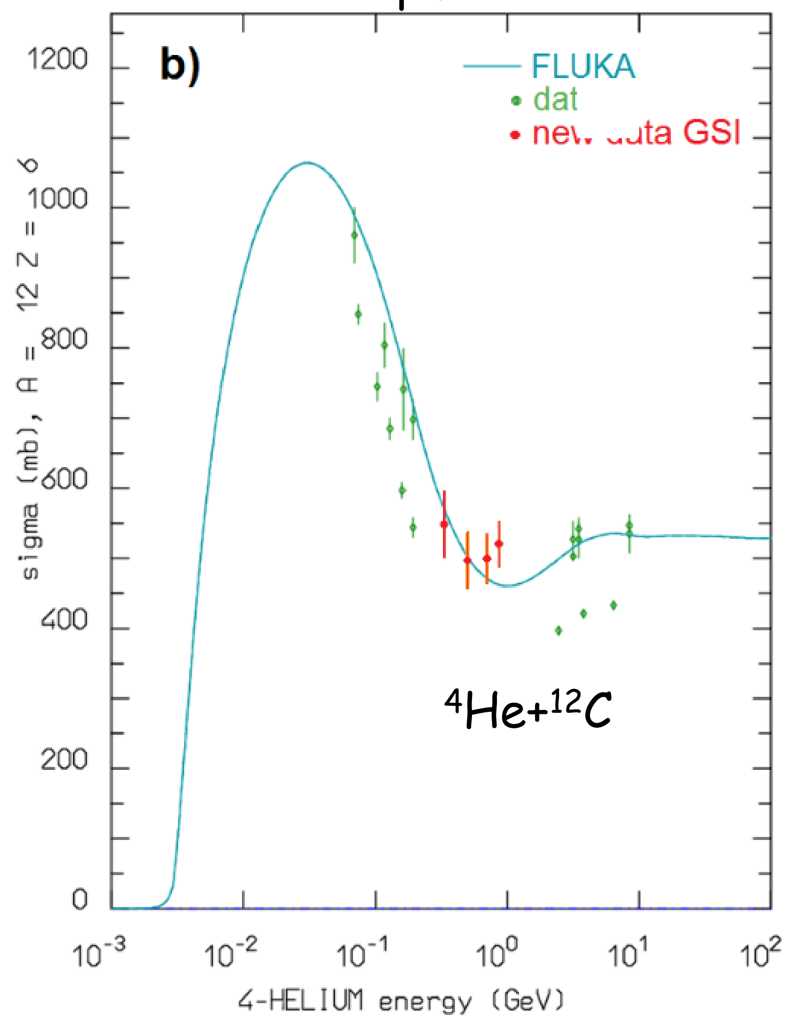


Development of 4He reaction cross section in FLUKA

Current FLUKA parametrization



Preliminary attempt of new development



TECHNISCHE HOCHSCHULE MITTELHESSEN

See talk by F. Horst ID 172

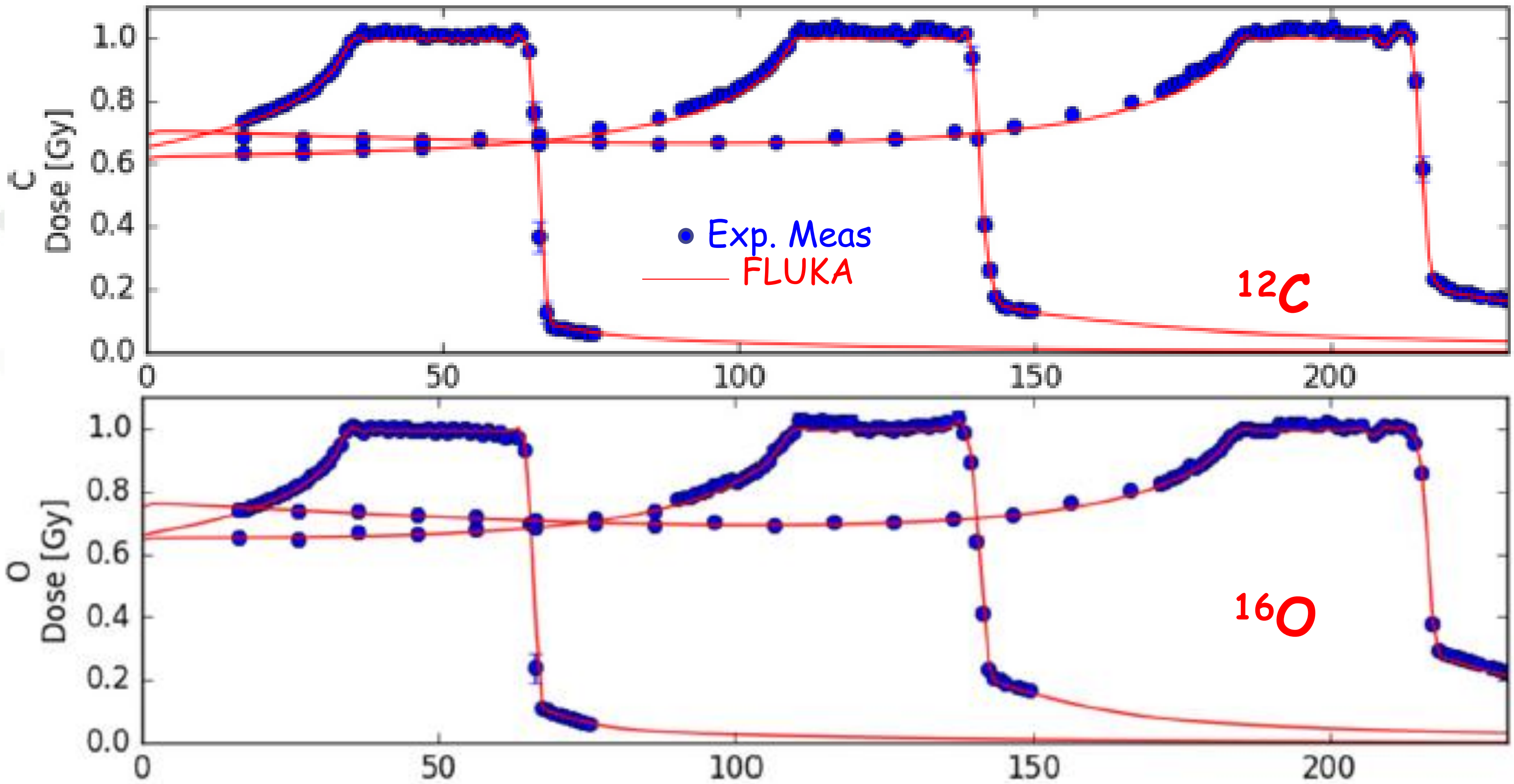
Dosimetric verification in water of a Monte Carlo treatment planning tool for proton, helium, carbon and oxygen ion beams at the Heidelberg Ion Beam Therapy Center

Phys. Med. Biol. **62** (2017) 6579–6594

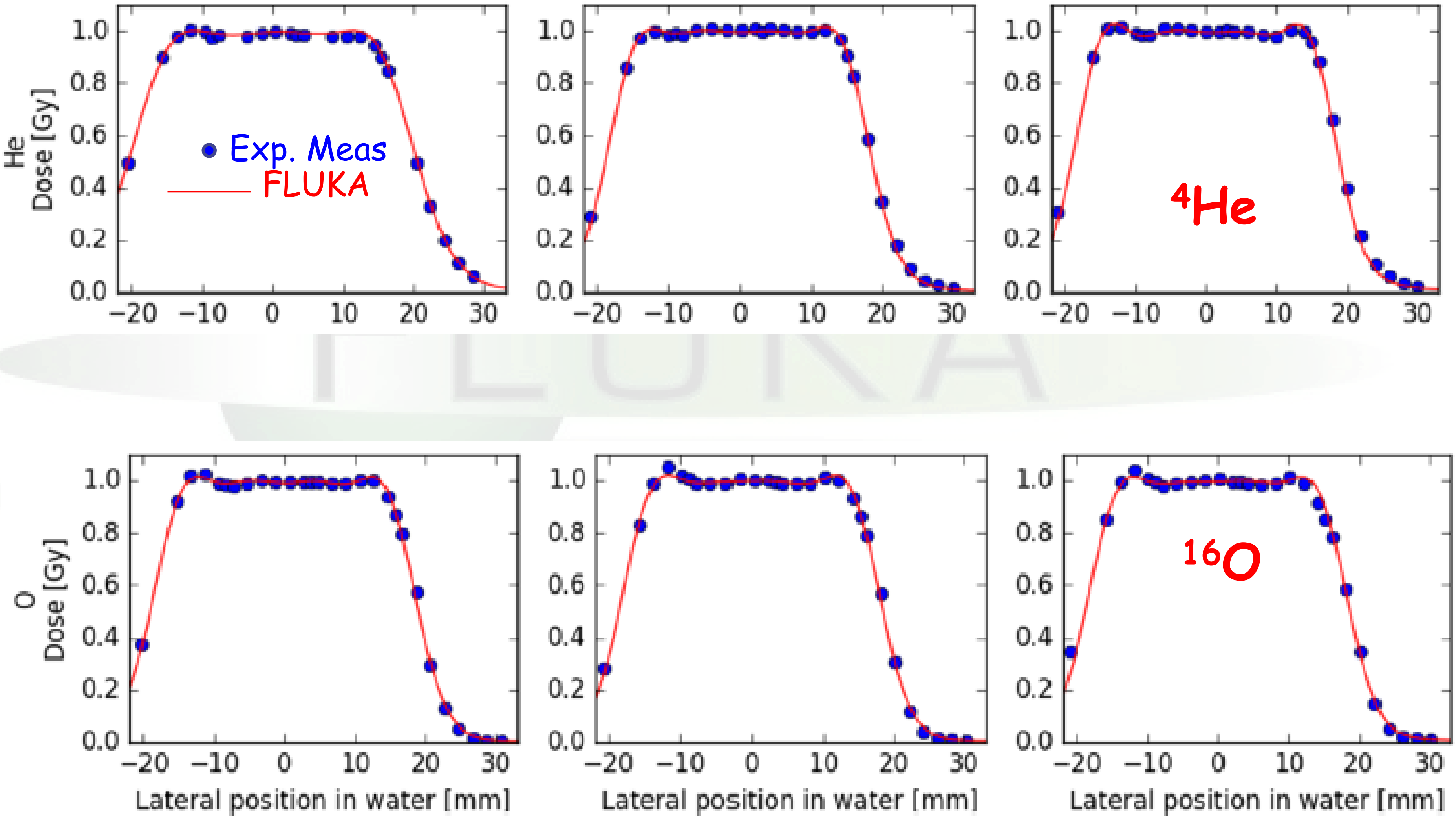
Physical Dose
in a cube in Water

T Tessonnier[1,2], T T Böhlen[3], F Ceruti[4], A Ferrari[4], P Sala[4,5], S Brons[6], T Haberer[6], J Debus[1,6], K Parodi[1,2] and A Mairani[6,7]

3 cm × 3 cm × 3 cm SOBPs



Lateral Dose distrib. for SOBs centered at 5, 12.5 and 20 cm



Biologically Oriented Scoring in FLUKA*

For each **energy deposition i,** FLUKA interpolates from the external database provided by the user the **$\alpha_{D,i}$ and $\beta_{D,i}$** parameters for the specific ion with a certain charge at a certain energy.

Then **FLUKA sums up** properly **the mixed radiation effect** applying the Kellerer and Rossi theory of dual radiation action:

$$\sum \alpha_{D,i} D_i \qquad \sum \sqrt{\beta_{D,i}}\, D_i$$

Then the **average biological parameters** can be calculated at the end of the FLUKA run:

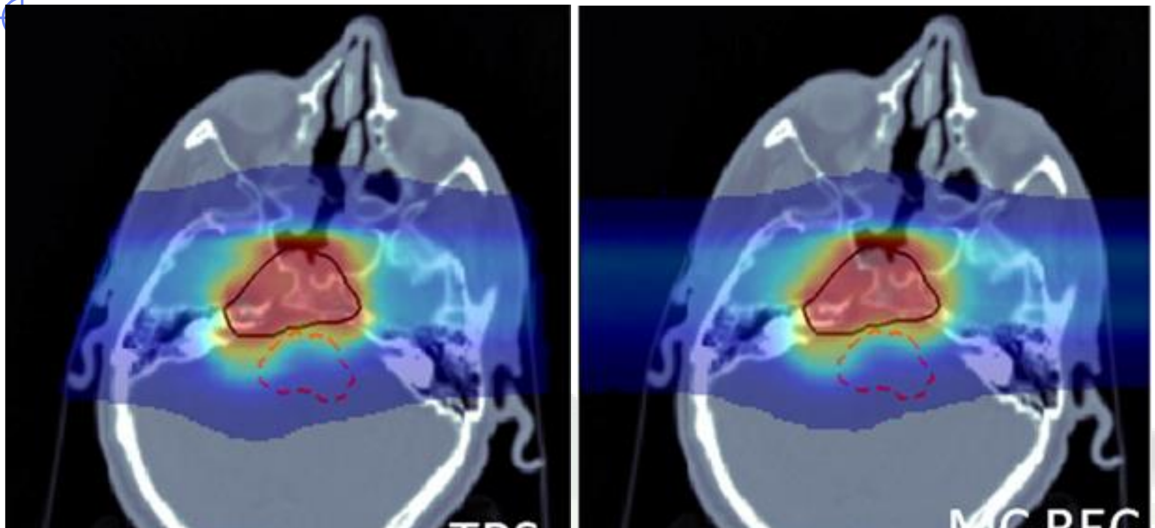
$$\bar{\alpha} = \frac{\sum \alpha_{D,i} D_i}{\bar{D}} \quad \text{and} \quad \bar{\beta} = \left(\frac{\sum \sqrt{\beta_{D,i}}\, D_i}{\bar{D}} \right)^2 \quad \text{with} \quad \bar{D} = \sum D_i$$

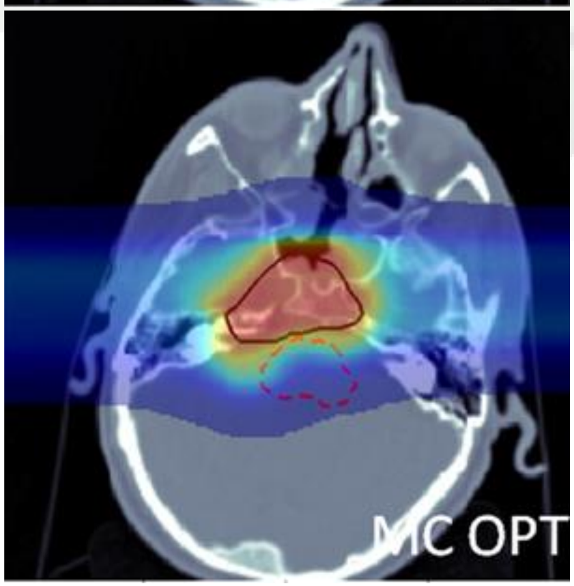
For example the **cell survival** can be calculated:

See talk by A. Mairani ID 64

$$S = \exp(-\bar{\alpha}\bar{D} - \bar{\beta}\bar{D}^2)$$

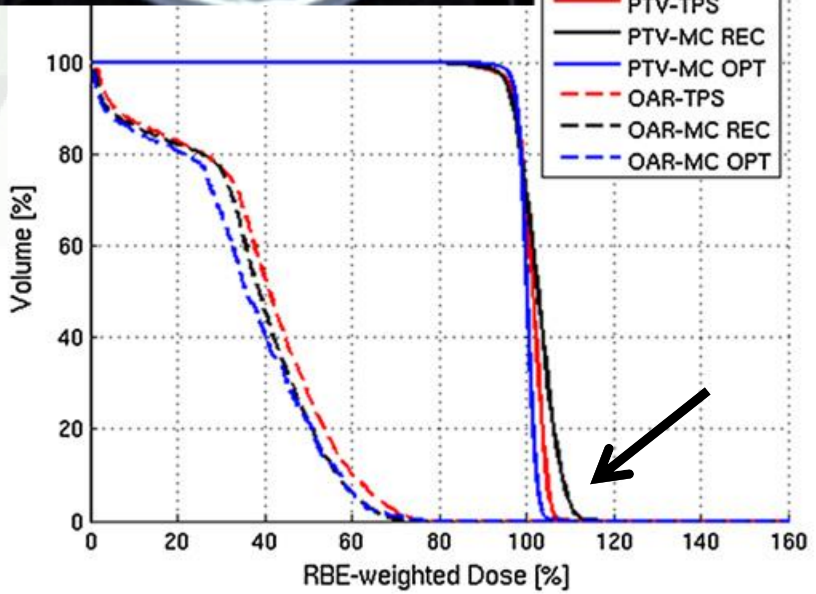
Monte Carlo-based Treatment Planning Tool





See talk by A. Mairani
ID 64

The FLUKA-based MCTP engine can be used to calculate biologically optimized treatment plans.



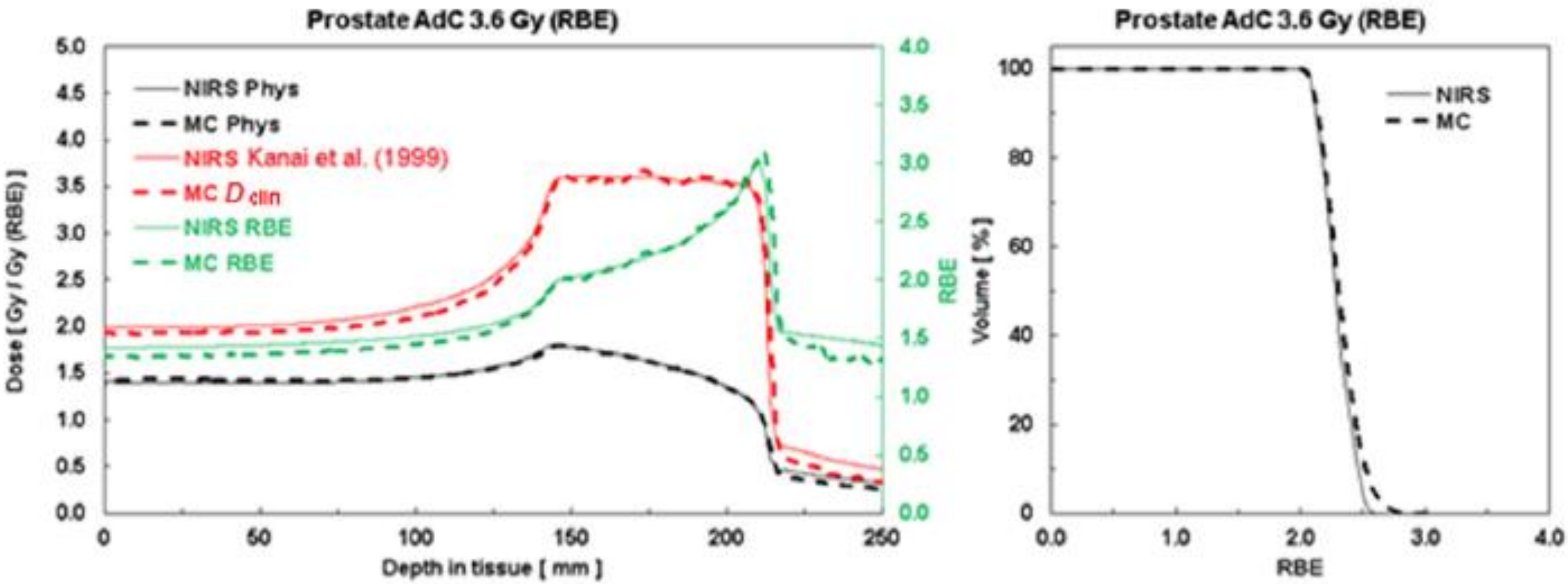
A. Mairani, et al. Physics in Medicine and Biology 58 (2013) 2471–2490

Phys. Med. Biol. 62 (2017) 3814

The FLUKA Monte Carlo code coupled with the NIRS approach for clinical dose calculations in carbon ion therapy

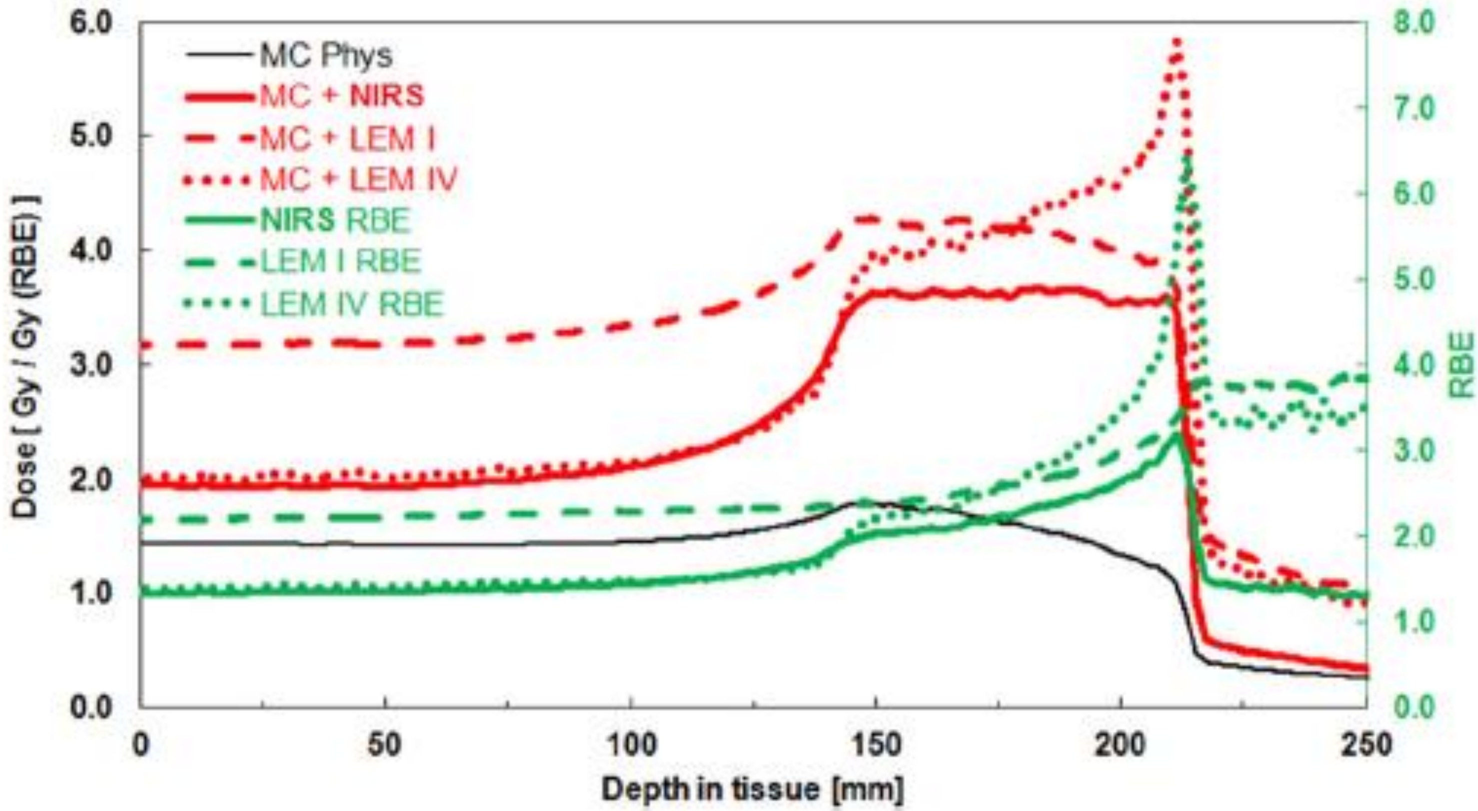
CNAO

G Magro[1], T J Dahle[2], S Molinelli[1], M Ciocca[1], P Fossati[1,3], A Ferrari[4], T Inaniwa[5], N Matsufuji[5], K S Ytre-Hauge[2] and A Mairani[1,6]



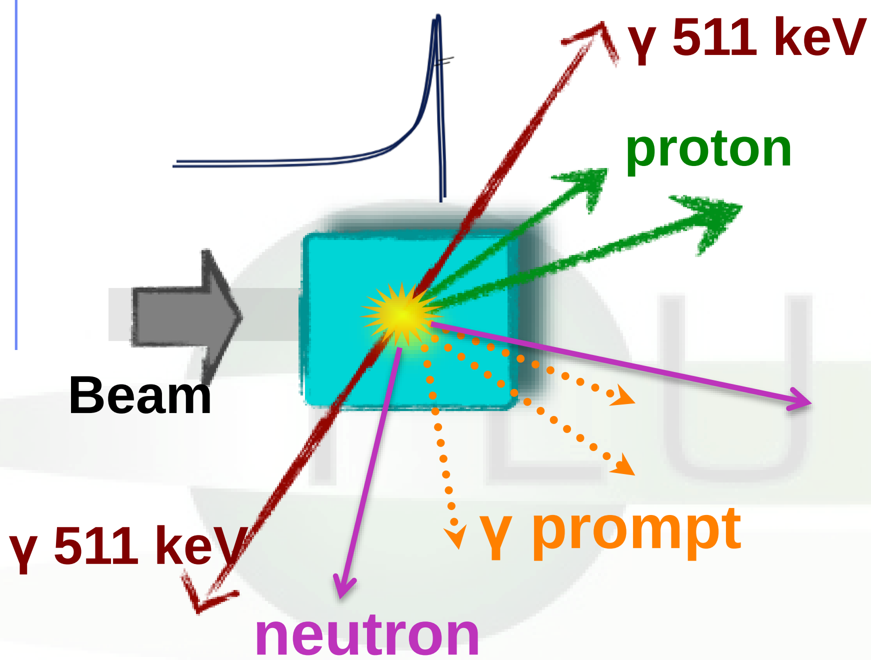
MC tools which allow flexible determination of the biological effect based on various radiobiological models to guarantee a fair comparison between clinical RBE-weighted dose data based on different calculation systems.

CNAO



Comparison of **effective dose profiles** acquired at the isocenter in the target volume for a prostate AdC (3.6 Gy (RBE)), as computed by the NIRS approach (solid line), the LEM I (dashed line) and LEM IV (dotted line) model coupled with the FLUKA MC code. The corresponding **physical dose profile** is also shown, together with **RBE depth profiles**

In vivo verification



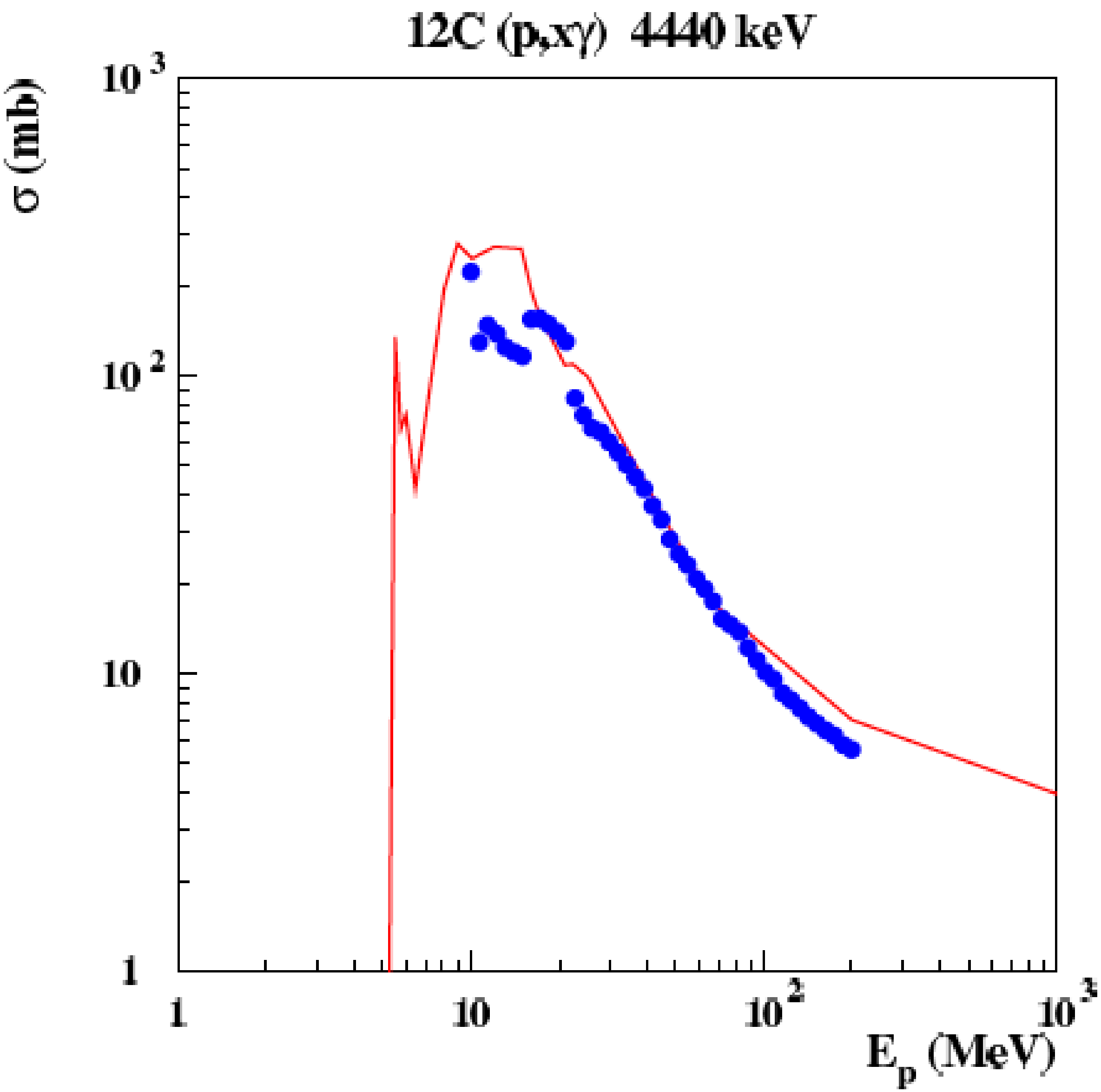
Secondary particle production during treatment can be used to perform range monitoring *(and maybe dose monitoring)*

Correlation of measurements af secondary particles with the spatial profile of dose deposition is performed/understood by means of comparison with MC predictions

FLUKA can be successfullu used for this purpose

see talks by
E. Fiorina (ID 143)
and
S. Muraro (ID 67)

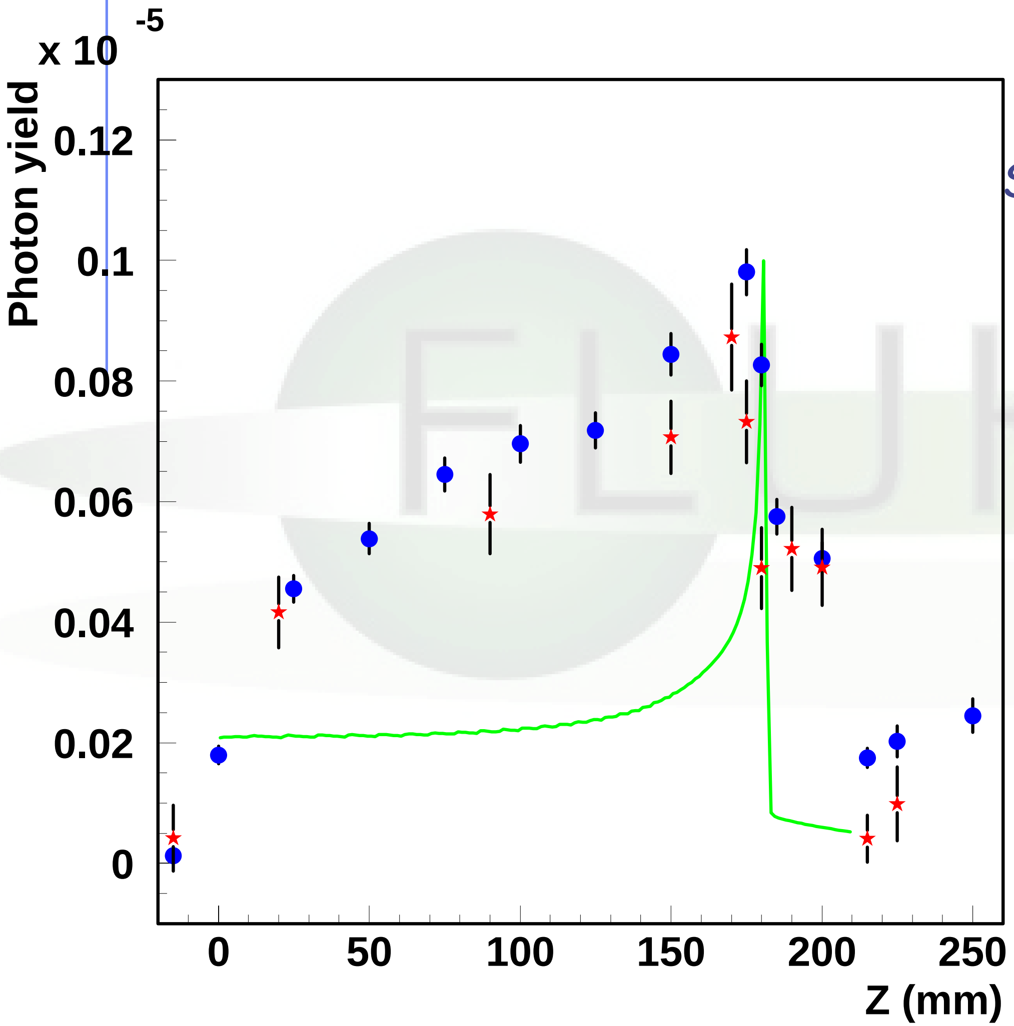
De-excitation (prompt) γ production



Excitation function for the emission of the discrete 4.440 MeV γ line from proton-induced reactions on carbon

de-excitation of
the 1st excited level in ^{12}C,
the 2nd excited level in ^{11}B,
the 2nd excited level in ^{11}C.

In vivo verification: prompt γ's



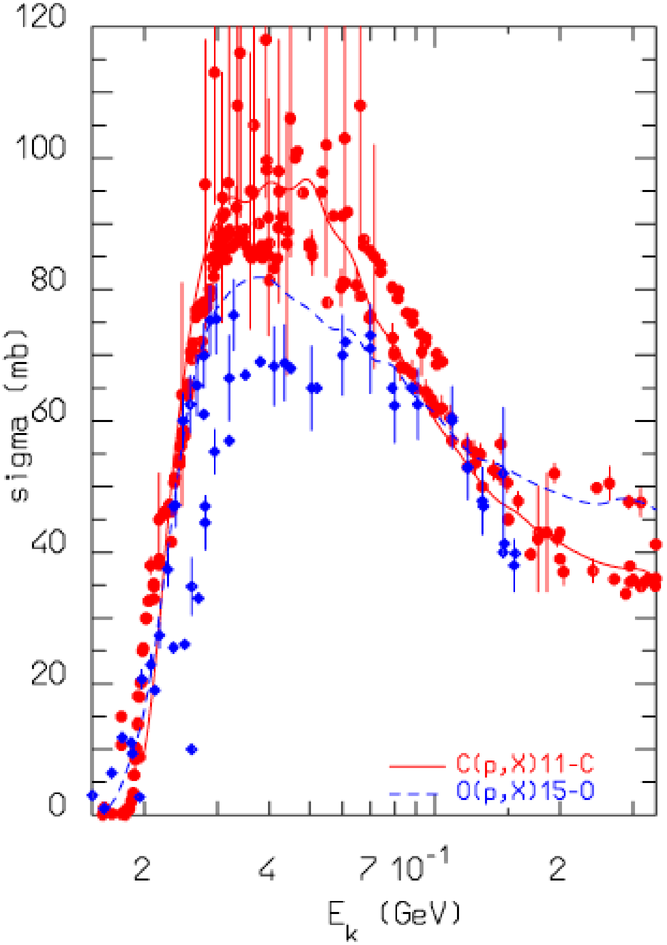
Simulated (blue circles) and measured [red asterisks] data are shown for carbon ion beam at 310 MeV/n for setup SIII (right, on water).

Simulated depth-dose distribution is also shown with arbitrary normalization.

E. Testa Personal Communication, Data Shared on the FP7-ENVISION project Internal Website. (2012).

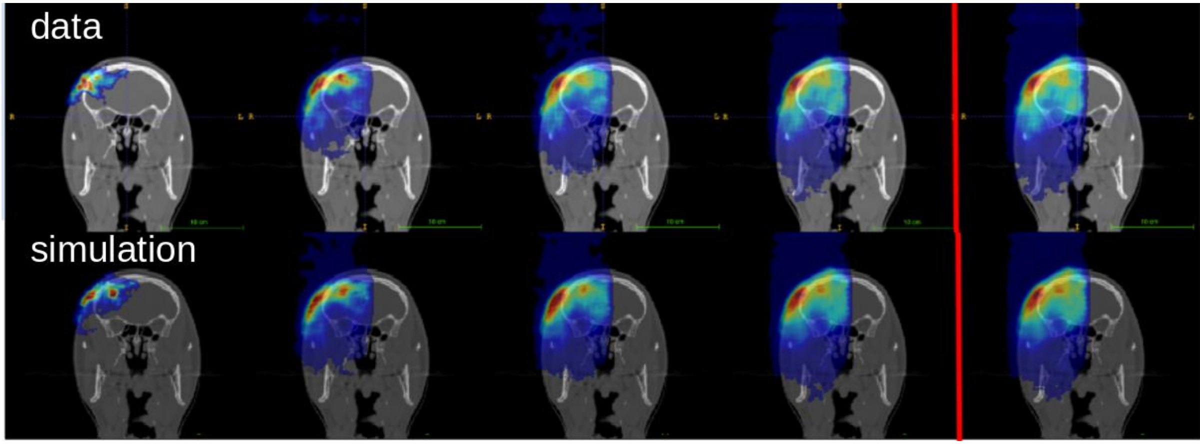
ENVISION

About PET in-beam prediction capability



FLUKA predictions for the reactions $^{nat,12}C(p,x)^{11}C$ and $^{nat,16}O(p,x)^{15}O$ cross sections as a function of projectile energy, compared against data retrieved from the eXFOr library

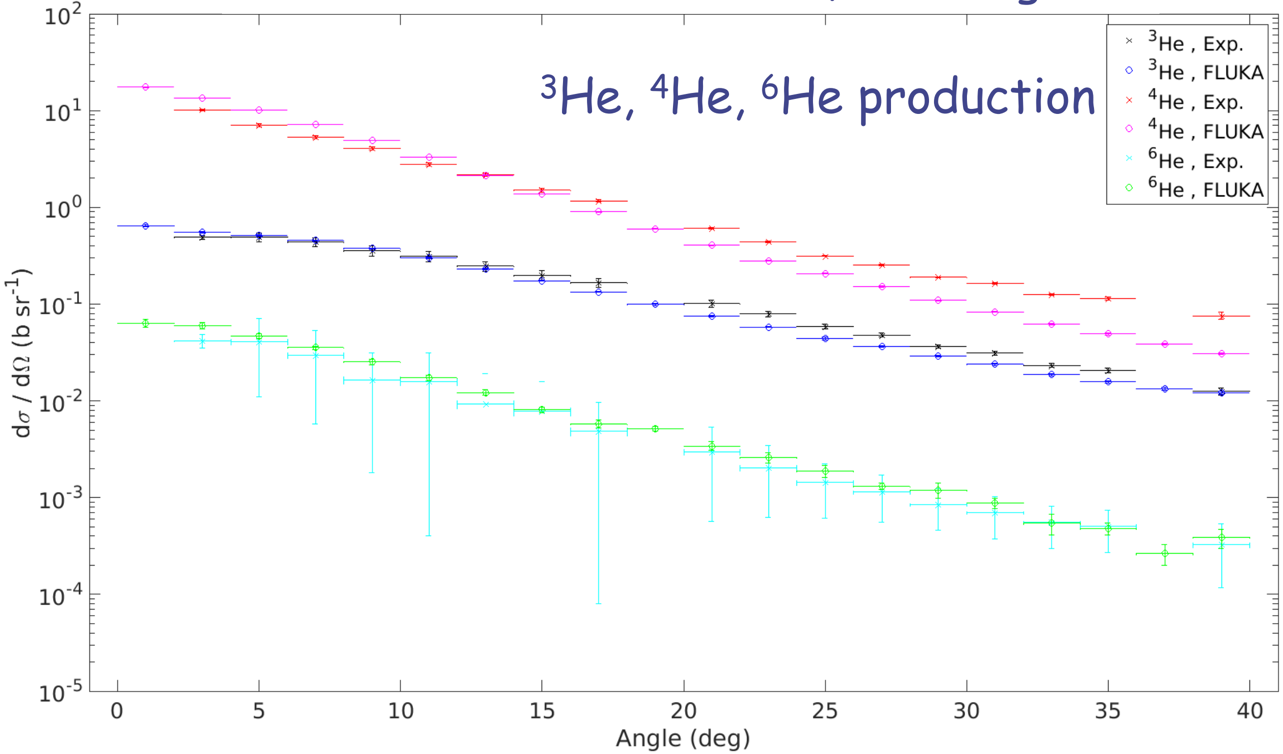
A clinical case (see talk by E. Fiorina ID 143)



Charged particle production

50 MeV/u 12C on a 250 μm C target

G. Aricò (CERN/OMA)



Fluka vs Exp

Compare:

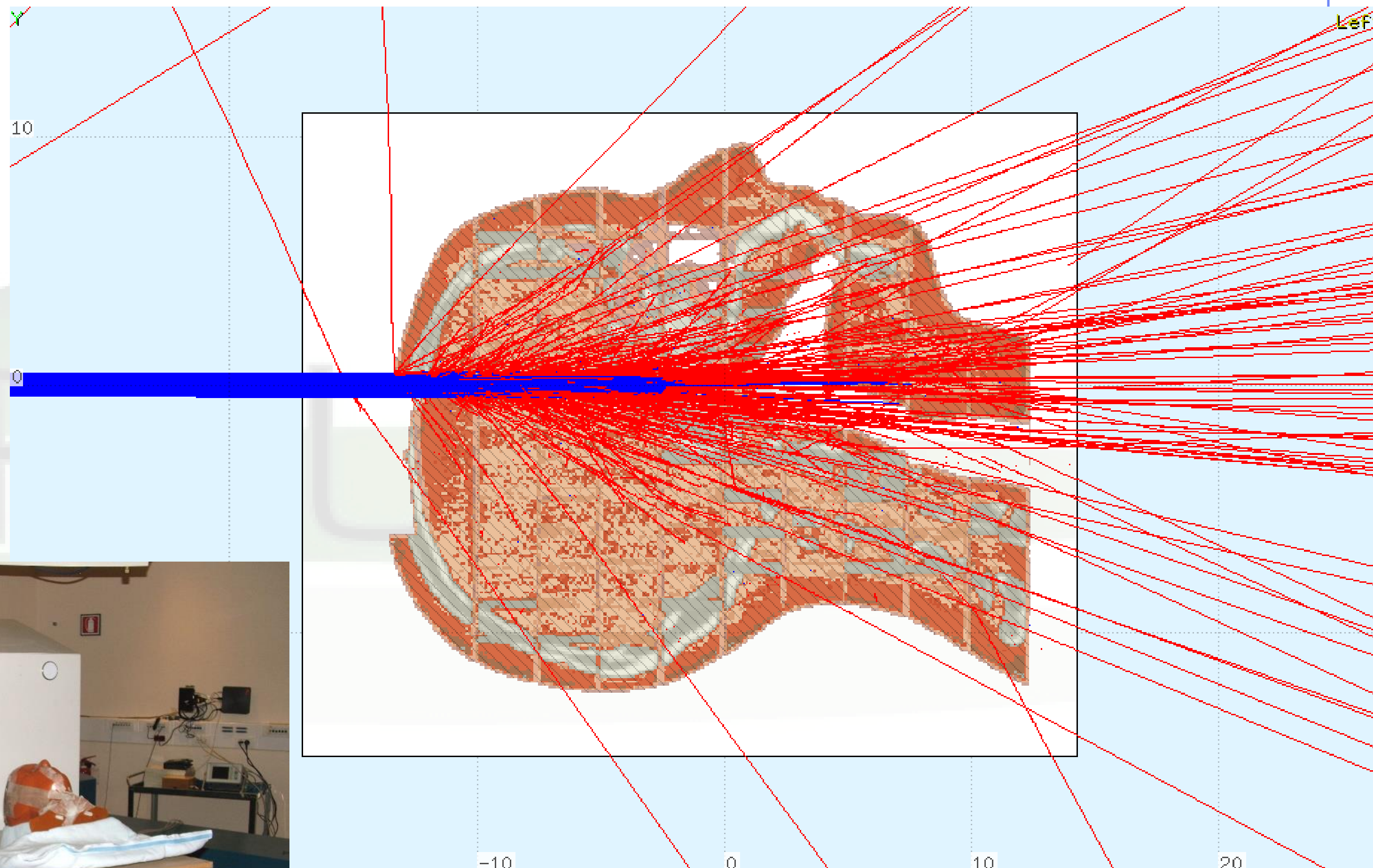
Blue - Black

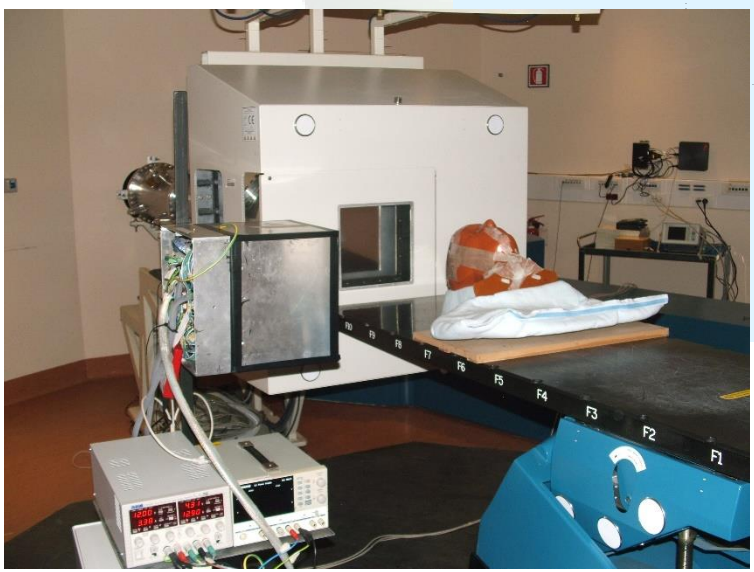
Magenta - Red

Green - Cyan

Exp. C. Divay et al, Phys. Rev. C95 (2017)

Simulation of CNAO 12C beam at 220 MeV/u on Antropomorphic Phantom





see talk by S. Muraro ID 67

Conclusions

- FLUKA find successful in different medical physics applications. Mostly used in the context of hadrontherapy
- Models and user tools are in constat evolution
- Some of the developments in progress relevat for medical applications:
  - Improvement of He cross section model
  - Deuteron interactions
  - Deuteron production (medium/heavy nuclei and spectra for all)
  - Progress to improve continuity between BME and rQMD nucleus-nucleus interaction models
  - Multiple isomers for the same A, Z for low energy neutrons,
  - Update the decay, and mass databases
  - Implement RT-STRUCT and RT-PLAN in the Flair interface