

The slide features a decorative layout with blue lines and corner markers. A vertical line on the left and a horizontal line at the top intersect at a small circle in the top-left corner. A horizontal line at the bottom and a vertical line on the right intersect at a small circle in the bottom-right corner. The title text is positioned between the top and bottom horizontal lines.

# Codici Monte Carlo in Fisica Medica

Giuseppe Battistoni  
INFN Milano

# Analog versus condensed history MC

## Condensed history MC simulation

- ❖ Many “small-effect” (“soft”) interactions can be grouped into few condensed history “steps”
- ❖ Sample of the cumulative effect from proper distributions of grouped single interactions (multiple scattering, stopping power,...)
- ❖ “Hard” collisions (e.g.,  $\delta$ -ray production) can be explicitly simulated in an analog matter



**Approach followed in all general purpose MC codes**

## Example of $e^-$ track

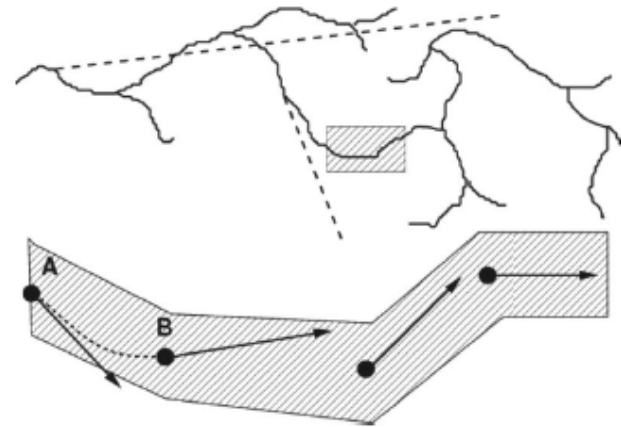


FIG. 1. Illustration of a class II condensed history scheme for electron transport. The upper portion shows a complete electron track including secondary electrons and photons (shown with dashed lines and not including their interactions) with energies above the hard collision thresholds. The lower portion is a magnified view of the shaded box.

*I Chetty et al, Report of the AAPM  
Task Group 105, Med Phys 34, 2007*

# General Purpose Codes (condensed history) applied to Medical Physics

**PENELOPE** (electrons/positrons/photons)

**FLUKA**

**MCNP** (mostly for neutrons  
→ Boron Neutron Capture Therapy)

**GEANT4**

**GATE**

**TOPAS**

**GAMOS**

....

**MC Codes (condensed history) dedicated to specific  
medical applications (Hadrontherapy)**

**PHITS**

**SHIELD-HIT**

# Penelope

## Penetration and ENergy LOss of Positrons and Electrons

50 eV - 1 GeV

Used for: Dose Calculation, X-Ray tube modelling, Beam Modelling

Notice: cross sections provides for energies underneath 1 keV are subject to large uncertainties which is also true for other codes that claim to simulate transportation down to such low energies

Additional tool **PENGEOM**: flexible geometry tool, which allows for automatic particle tracking in complex geometries.

The OECD/NEA Data Bank distributes the PENELOPE software.

NEA (2019), *PENELOPE 2018: A code system for Monte Carlo simulation of electron and photon transport*, Workshop Proceedings, Barcelona, Spain, 28 January - 1 February 2019, OECD Publishing, Paris, <https://doi.org/10.1787/32da5043-en>.



# MCNP

## Monte Carlo N-Particle

1 keV - thousands of TeV

34 similar kinds of particles and about 2000 ions.

Used for dose Calculation, Shielding, Beam Modelling, particle tracking - transport through matter, BNCTetc

Developed at Los Alamos National Laboratories, is one of the most important general purpose three-dimensional MC codes. It is well known in nuclear physics and used for studies including criticality, shielding, and detector response, but also dosimetry and many other applications, including medical ones.

Pointwise cross-section data typically are used, although group-wise data also are available. For neutrons, all reactions given in a particular cross-section evaluation (such as ENDF/B-VI) are accounted for. Thermal neutrons are described by both the free gas and S(alpha,beta) models. Rich collection of variance reduction techniques; a flexible tally (=scoring) structure and an extensive collection of cross-section data.

*T. Goorley et al. Initial MCNP6 release overview MCNP6 version 0.1. Nucl Technol. (2012). 180:298-315.*

<https://mcnpx.lanl.gov/>

# SHIELD-HIT



**SHIELD-HIT12A** is a Monte Carlo particle transport program which is modified for proton and heavy ion particle therapy reserach. It was forked from SHIELD-HIT in 2008 with the aim to modernize and implement new features, increasing the applicability for medical physics.

*N Bassler et al 2014 J. Phys.: Conf. Ser. 489 012004*

*DC Hansen, A Lühr, R Herrmann, N Sobolevsky, N Bassler; Recent improvements in the SHIELD-HIT code; International Journal of Radiation Biology, January 2012, Vol. 88, No. 1-2 , Pages 195-199;*

*David C Hansen, Armin Lühr, Nikolai Sobolevsky and Niels Bassler; Optimizing SHIELD-HIT for carbon ion treatment; Physics in Medicine and Biology, 2012, Vol. 57, No. 8, Pages 2393*

<https://shieldhit.org/>

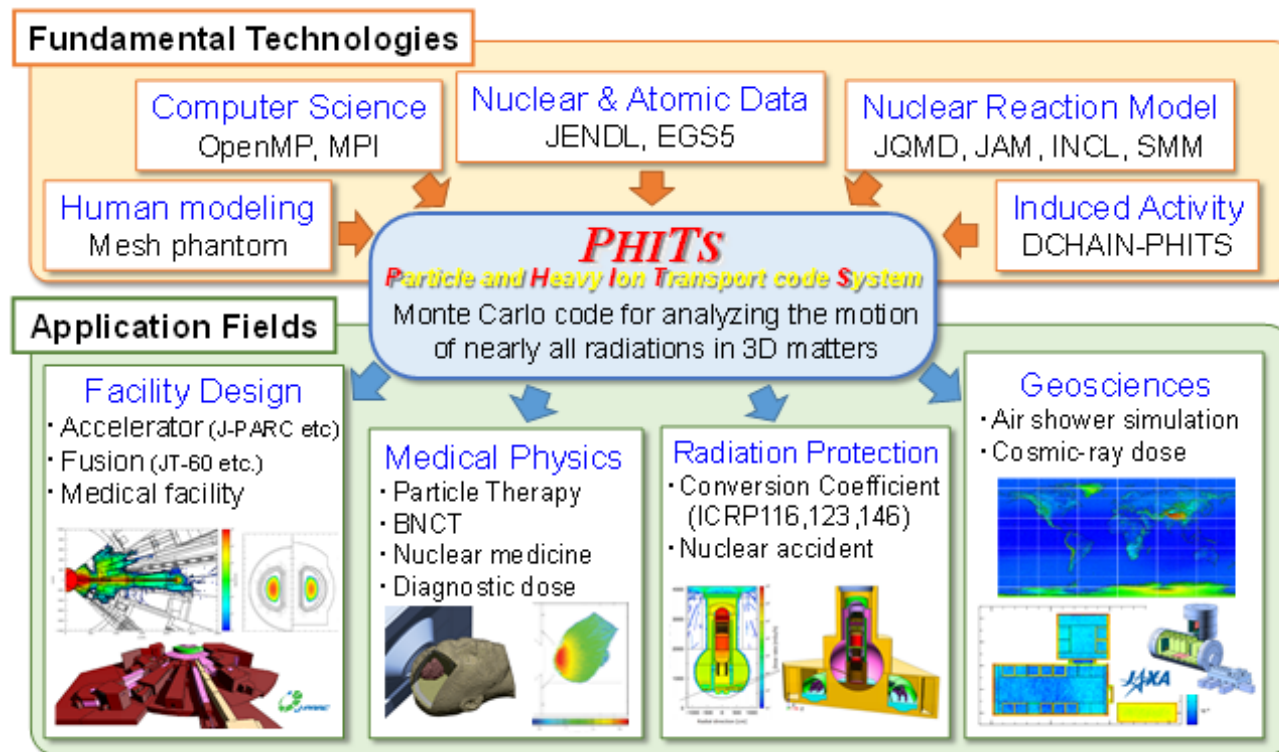
# PHITS

Particle and Heavy Ion Transport code System

# PHITS

<https://phits.jaea.go.jp/>

**PHITS** (Particle and Heavy Ion Transport code System) is a general purpose Monte Carlo particle transport simulation code developed under collaboration between JAEA, RIST, KEK and several other institutes. It can deal with the transport of all particles over wide energy ranges, using several nuclear reaction models and nuclear data libraries.



# GEANT4



50 eV - thousands of TeV

Mainly used for development of Software packages, core toolkit.

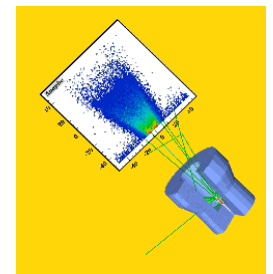
**GEANT** (GEometry ANd Tracking) software toolkit that encapsulates modern design and state of art developing techniques using Monte Carlo modelling methods to explain the movement of elementary particles through matter.

The base of Geant4 is a plenty set of physics models to take care of particle-matter encounters covering a large area of energy range. In few words we can say that the software toolkit encapsulates information and modelling methods used from many sources around the world.

**Notice:** Penelope is imported in **GEANT4** a e.m. physics package

*P. Arce, et al., Report on G4-Med, a Geant4 benchmarking system for medical physics applications developed by the Geant4 Medical Simulation Benchmarking Group, Medical Physics, 48, n. 1 (2021) 19-56*  
<https://doi.org/10.1002/mp.14226>

<https://geant4.web.cern.ch/>



# Geant4 is a toolkit: you have to build a specific application for your problem

- **The user needs coding in order to:**
  - ✓ Define the geometrical setup, including volumes and materials
  - ✓ Set Particles, **physics processes/models**
  - ✓ Production thresholds
  - ✓ Define how an event starts
  - ✓ Primary track generation
  - ✓ Extract information useful to you
- **You may also need to:**
  - ✓ Visualize geometry, trajectories and physics output
  - ✓ Make use of (Graphical) User Interface
  - ✓ You can define your own UI commands
  - ✓ ...

The "Physics List" concept

*many types of different geometrical descriptions*

*Specific C++ classes are provided to build all this*

# Physics in Geant4

- *EM processes*
- *Hadronic processes*
- *Photon/lepton-hadron processes*
- *Optical photon processes*
- *Decay processes*
- *Event biasing techniques*

Each cross-section table or physics model (final state generation) has its own applicable energy range. Combining more than one tables / models, one physics process can have enough coverage of energy range for wide variety of simulation applications.

Geant4 provides sets of alternative physics models so that the user can freely choose appropriate models according to the type of his/her application:

it is the user's responsibility to choose reasonable set of physics processes/models that fits to his/her needs.

← The "Physics List"

The user must have a good understanding of the physics required

## Geant4 Application for Emission Tomography)

50 eV - thousands of TeV

Hadrons, electrons, photons, positrons, can implement geant4 particles

Used for PET, SPECT, CT, Radiotherapy, Dosimetry, Proton Therapy, Thermal Therapy, etc

**GATE** is a software package that combines photography, radiotherapy, and dosimetry in one environment. It was created to conduct experiments with PET and SPECT.

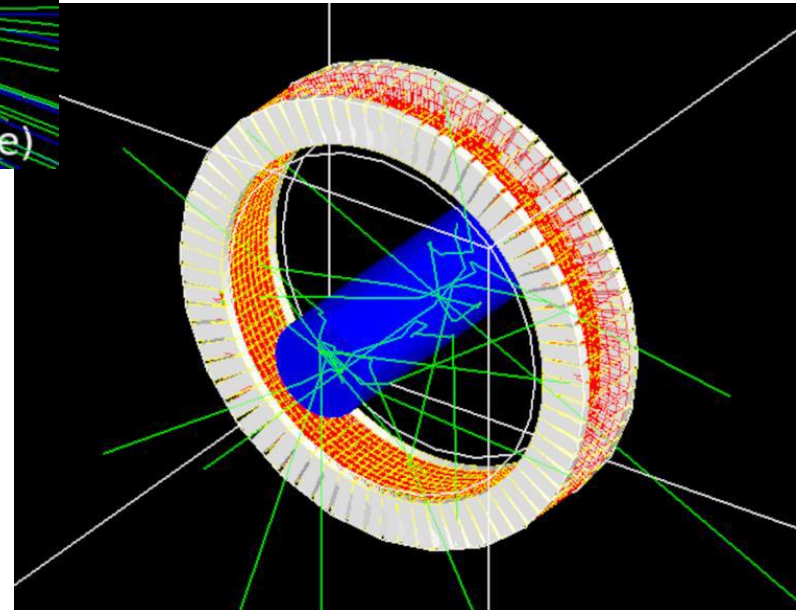
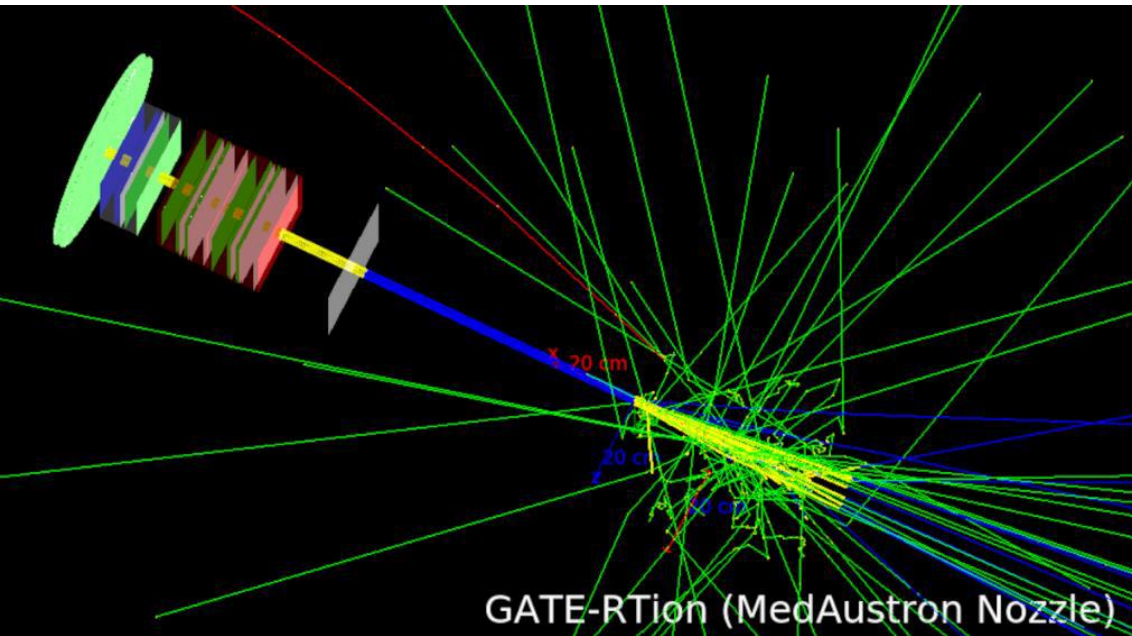
Since 6.0 version, new software has been introduced devoted to radiation therapy simulations, including linear accelerator simulations .

**GATE** utilizes the GEANT4 toolkit classes to provide a scalable, flexible scripts for computational experimentation in nuclear medicine. In particular the software allows the modelling phenomena of electronics and mechanical parts of the detector.

*D. Sarrut, et al., "A review of the use and potential of the GATE Monte Carlo simulation code for radiation therapy and dosimetry applications" Medical Physics, 41 (2014) <https://aapm.onlinelibrary.wiley.com/doi/full/10.1118/1.4871617>*

# GATE

## Geant4 Application for Emission Tomography



# GAMOS

## Geant4-based Architecture for Medicine-Oriented Simulations

Hadrons, electrons, photons, positrons, can implement geant4 particles  
50 eV - thousands of TeV

Used for PET, SPECT, Compton Camera, Shielding, Radiotherapy, etc.

**GAMOS** is a MC emulation platform built on the Geant4 toolkit, with the exception that it is more user-friendly and more scalable than GEANT4. It allows inexperienced people make experimentations and build their project without bothering to write in C++. It requires just a basic understanding of **Geant4**.

The scripting language of **GAMOS** makes it simple to implement the most basic specifications capable of reproducing Medical Physics experimentation. The plugin technology, together with a modular architecture, extensive documentation, and a series of examples and tutorials, helps users to fully leverage **GEANT4**'s functionality by writing new user code or reusing existing **GEANT4** code and combining it seamlessly with existing **GAMOS** modules.

[http://fismed.ciemat.es/GAMOS/gamos\\_publications.php](http://fismed.ciemat.es/GAMOS/gamos_publications.php)



# TOPAS

## TOol for PArticle Simulations

Hadrons, electrons, photons, positrons, can implement geant4 particles

50 eV - thousands of TeV

Used for Linacs, Proton therapy, Dose calculations, Radiotherapy

**TOPAS** bundles and expands the Geant4 libraries to take advantage of a more sophisticated Monte Carlo simulation which includes most types of radiotherapy available systems so that medical physicists can find it more easily to use.

**TOPAS** can emulate effectively photon and particle therapy systems, build a human geometry from CT DICOM pictures, score doses, calculate fluence, and other parameters

Though proton therapy was the most common early use of **TOPAS**, it is now accessible for usage in all radiation treatment domains, as well as some medical imaging applications. **TOPAS** is currently being expanded to include radiation biology (see later) and scientific education.

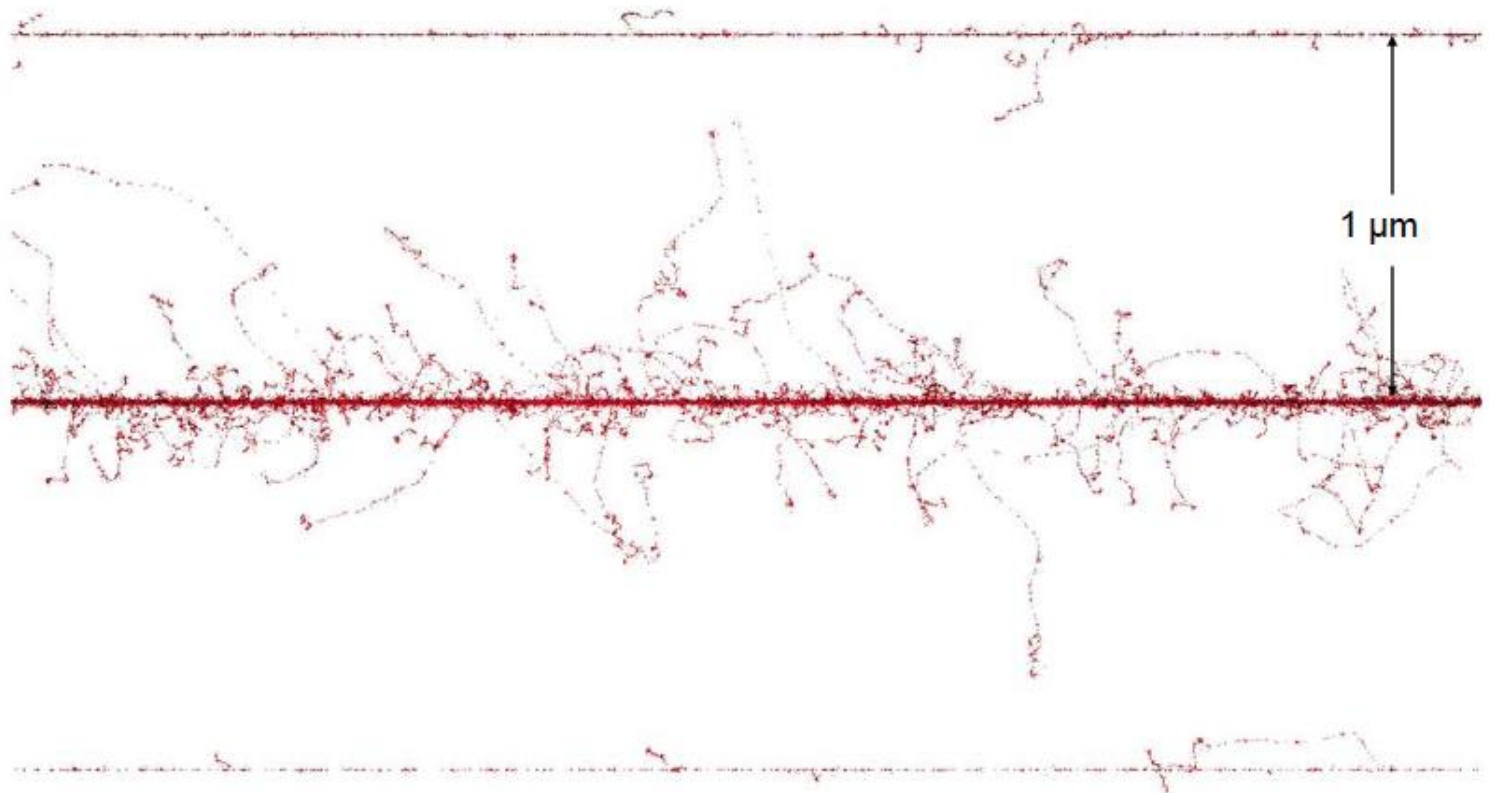
<http://www.topasmc.org/>

# Track Structure MC - 1

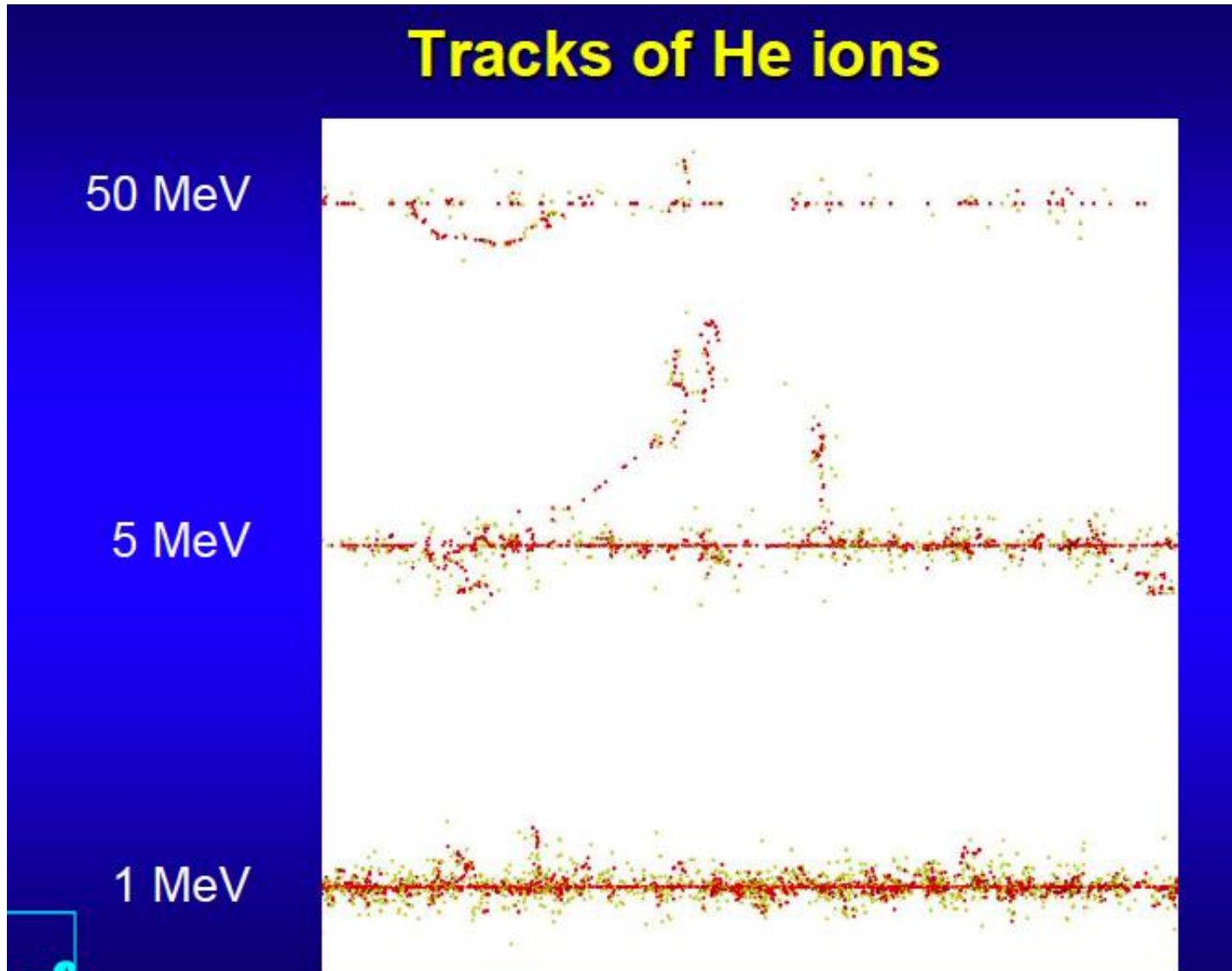
$^4\text{He}$   
25 MeV

$^{16}\text{O}$   
40 MeV

6 MeV  
p



# Track Structure MC - 2



## Track Structure codes - 3

Track structure codes are in general able to perform calculations on microscopic (nanometric) volume scales in liquid water, making their application in simulations of actual clinical cases highly unpractical from the point of view of computing power.

However, they remain fundamental, together with mathematical models of the cell structure, for the investigation of all basic mechanisms related to biological effects of radiation.

**PARTRAC:** performs calculations on microscopic scales in liquid water

*M. Dingfelder et al.. Electron inelastic-scattering cross sections in liquid water. Radiat Phys Chem. (1998). 53, 1-18.*

**TRAX:** can deal with different materials.

*Wälzlein C, Krämer M, Scifoni E, Durante M. Advancing the modeling in particle therapy: from track structure to treatment planning. Appl Radiat Isot. (2014). 83:171-6.*

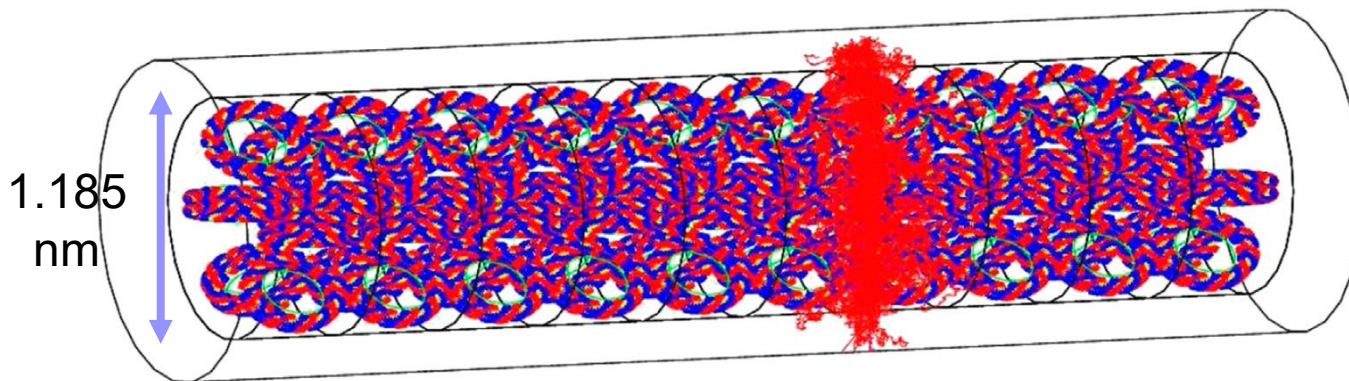
Results obtainable by these codes can in principle be coupled with the radiation field simulation achievable with general purpose MC codes.

## Track Structure codes -3

**GEANT4-DNA:** It was started in the context of the studies for radiation protection in space missions. The code currently includes the interactions of light particles (electrons) and ions including hydrogen and helium isotopes down to the eV scale in liquid water.

<http://geant4-dna.org/>

It allows to implement the geometry of biological targets at submicrometric scales. It can use either a voxelized or an atomistic approach. The latter allows to model targets at nanometric scales, such as the DNA molecule, using the combination of standard mathematical volumes.



Visualization of a whole chromatin fiber irradiated by a single 500 keV He<sup>+</sup> particle,

*S. Incerti et al., The GEANT4-DNA project. Int J Model Simul Sci Comput. (2010). 1. 157-78.*

A chemistry model can be coupled to simulate indirect radiation effects

## Track Structure codes - 4

**TOPAS** has an extension was developed called **TOPAS-nBio**, which is aimed at the modeling of detailed biological effects at the nanometer scale, facilitating and extending the use of **GEANT4-DNA** models for subcellular geometries, physics, and chemistry processes.

*J. Schuemann et al., TOPAS-nBio: an extension to the TOPAS simulation toolkit for cellular and subcellular radiobiology. Radiat Res. (2019). 191, 25-38.*



<https://gray.mgh.harvard.edu/research/software/258-topas-nbio>

Un esempio di Codice Monte Carlo e  
di sua applicazione in Fisica Medica:

FLUKA e le sue applicazioni in  
radioterapia e adroterapia

Giuseppe Battistoni  
INFN Milano

# The FLUKA code

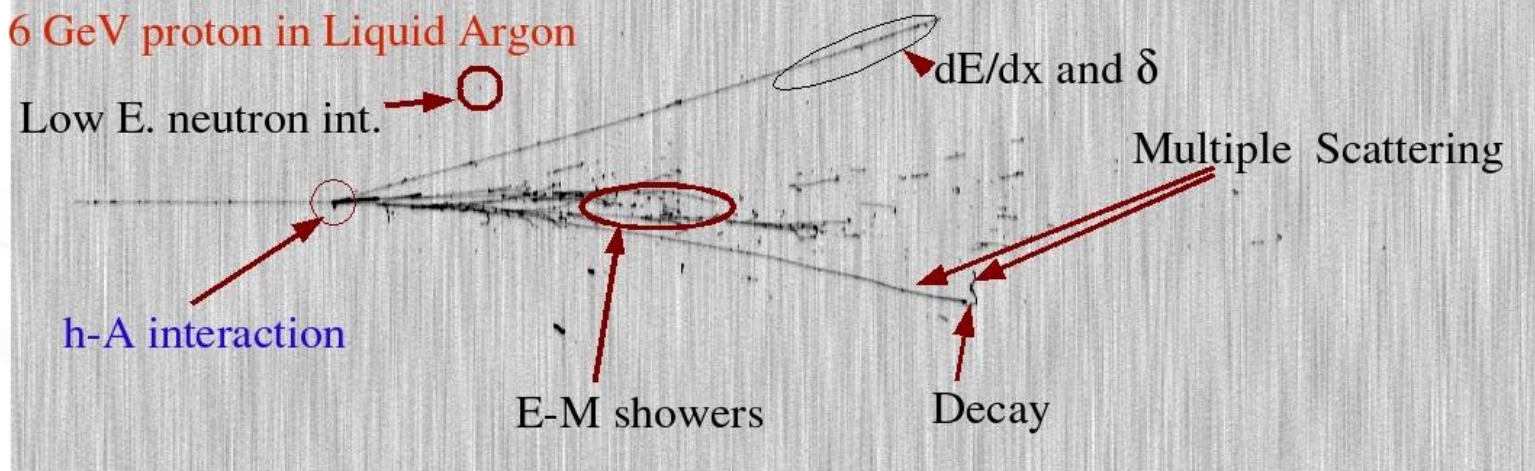


<http://www.fluka.eu>

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

**Main authors:** A. Fassò, A. Ferrari, J. Ranft, P.R. Sala

**Contributing authors:** G. Battistoni, F. Cerutti, M. Chin, T. Empl, M.V. Garzelli, M. Lantz, A. Mairani, V. Patera, S. Roesler, G. Smirnov, F. Sommerer, V. Vlachoudis



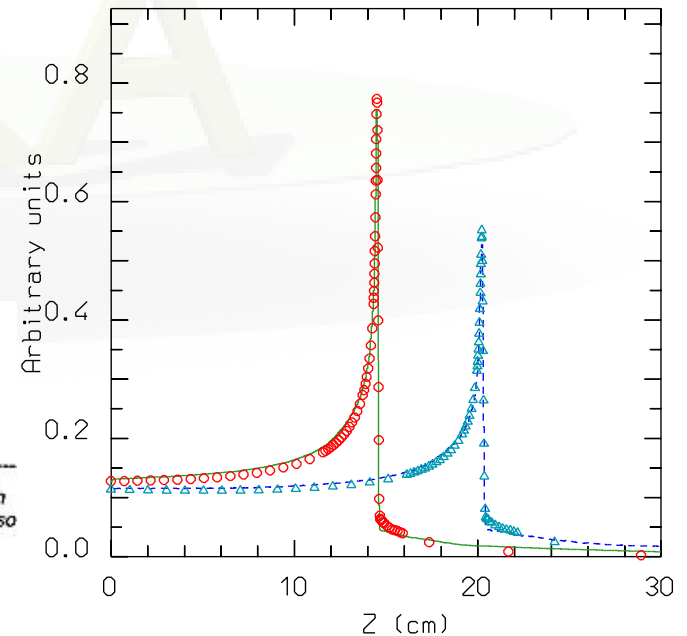
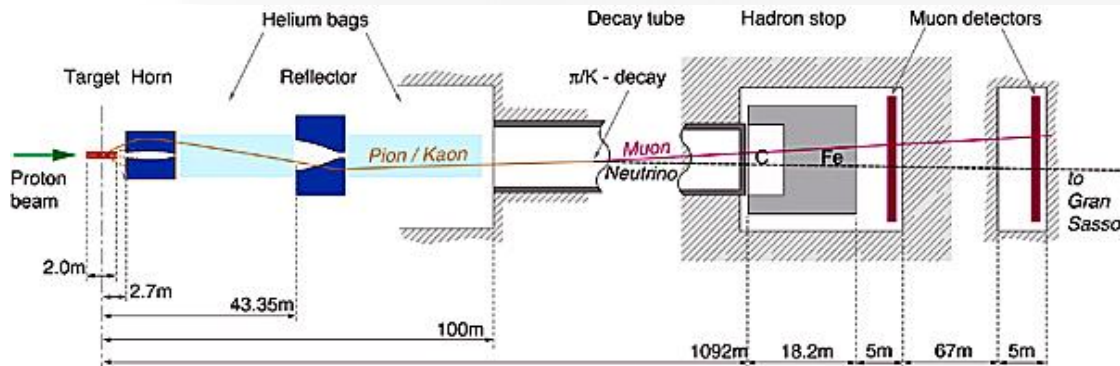
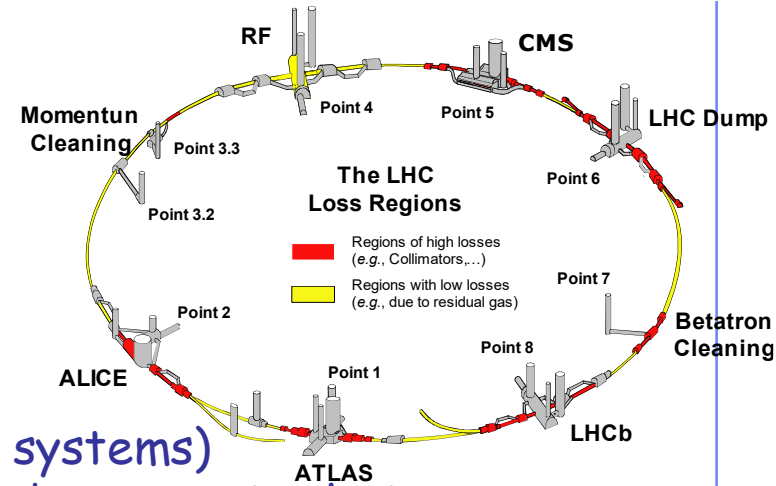
- High accuracy physics models/"microscopic" approach. Benchmarked with exp. data
- Conservation laws implemented at the level of machine accuracy
- Continuous development
- Easy to use for basic applications

# FLUKA Description

- ❑ FLUKA is a general purpose tool for calculations of particle transport and interactions with matter, covering an extended range of applications: from proton and electron accelerator shielding to target design, calorimetry, activation, dosimetry, detector design, Accelerator Driven Systems, cosmic rays, neutrino physics, radiotherapy etc.
- ❑ 60 different particles + Heavy Ions
  - Hadron-hadron and hadron-nucleus interaction "0"- TeV
  - Electromagnetic and  $\mu$  interactions 1 keV - 10000 TeV
  - Nucleus-nucleus interaction up to 10000 TeV/n
  - Charged particle transport and energy loss
  - Neutron transport and interactions 0-20 MeV
  - Transport in magnetic field
  - Optical photon simulation
  - Combinatorial (boolean) and Voxel geometries
  - Double capability to run either fully analogue and/or biased calculations
  - On-line evolution of induced radioactivity and dose
  - User-friendly GUI interface thanks to the Flair interface

# FLUKA Applications

- Cosmic ray physics
- Neutrino physics
- Accelerator design (→ n\_ToF, CNGS, LHC systems)
- Particle physics: calorimetry, tracking and detector simulation etc.  
→ ALICE, ICARUS, ...)
- ADS systems, waste transmutation, (→ "Energy amplifier", FEAT, TARC, ...)
- Shielding design
- Dosimetry and radioprotection
- Space radiation
- Hadrontherapy
- Neutronics



# The FLUKA Code design principles

- Sound and updated physics models
  - Based, as far as possible, on original and well-tested **microscopic models**
  - Optimized by comparing with experimental data **at single interaction level**:  
"theory driven, benchmarked with data"
  - Final predictions obtained with **minimal free parameters** fixed for all energies, targets and projectiles
  - Basic **conservation laws fulfilled "a priori"**
    - **Results in complex cases, as well as properties and scaling laws, arise naturally from the underlying physical models**
    - **Predictivity where no experimental data are directly available**
  - **Correlations** among all particles produced in a single interactions must be preserved (example: energy-angle correlations)

It is a "condensed history" MC code

# The FLUKA philosophy:

- Contrary to Geant4, FLUKA it is not a toolkit:
  - The user has no responsibility in the choice of physics models, there is no “physics list”. Different models are automatically chosen by the code according to particle, energy range, etc.
  - In general, it is impossible for common users to force “unphysical” choices (example: switching off multiple scattering or energy loss)
  - Instruments are provided to use FLUKA in a large variety of problems without the need of building a specific application
    - Geometry and materials can be defined without coding
    - predefined output scoring for dose, LET, radiation activity etc.
  - In any case, it is always possible, by means of user routines, to code and build specific applications and define specific user outputs

# The History

## The early days

### The beginning:

1962: Johannes Ranft (Leipzig) and Hans Geibel (CERN):  
Monte Carlo for high-energy proton beams

### The name:

1970: study of event-by-event fluctuations in a NaI  
calorimeter (FLUktuierende KAskade)

Early 70's to ≈1987: J. Ranft and coworkers (Leipzig University) with contributions  
from Helsinki University of Technology (J. Routti, P. Aarnio) and CERN  
(G.R. Stevenson, A. Fassò)

Link with EGS4 in 1986, later abandoned

## The modern code: some dates

Since 1989: mostly INFN Milan (A. Ferrari, P.R. Sala): little or no remnants of  
older versions. Link with the past: J. Ranft and A. Fassò

1990: LAHET / MCNPX: high-energy hadronic FLUKA generator No further update

1993: G-FLUKA (the FLUKA hadronic package in GEANT3). No further update

1998: FLUGG, interface to GEANT4 geometry

2000: grant from NASA to develop heavy ion interactions and transport

2001: the INFN FLUKA Project

2003-2019: CERN-INFN collaboration to develop, maintain and distribute FLUKA

# Applications in Medical Physics and related disciplines

- Nuclear Medicine
  - Dosimetry
- Radiotherapy
  - Simulation of therapy devices
  - Simulations/Check of treatments
- 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

# Using FLUKA

**Platform:** Linux with g77 (in 32bit mode)  
and gfortran (on 64bit machines)

Mac OSX with gfortran

Standard Input:

- Command/options driven by "data cards" (ascii file).  
**Graphical interface is available!!!!**
- Standard Geometry ("Combinatorial geometry"): input by "data cards"

Standard Output and Scoring:

- Apparently limited but highly flexible and powerful
- **Output processing and plotting interface available**

# A Simple Example of basic input

Geometry

```

TITLE
FLUKA Course Exercise
*...+...1...+...2...+...3...+...4...+...5...+...6...+...7...+...*
DEFAULTS

```

Primary beam

BEAM	-3.5	-0.082425	-1.7	0.0	0.0	1.0	PROTON
BEAMPOS	0.0	0.0	0.1	0.0	0.0	0.0	

```

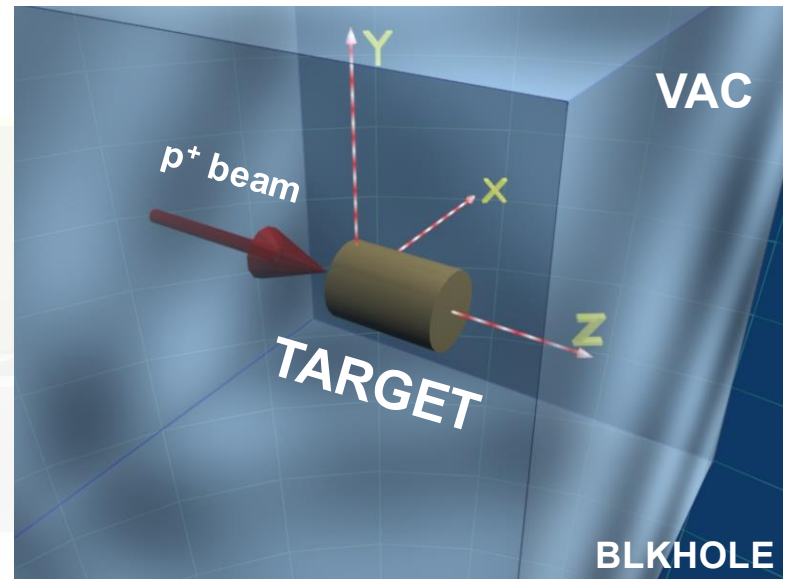
*...+...1...+...2...+...3...+...4...+...5...+...6...+...7...+...*
GEOBEGIN

```

```

0 0 Cylindrical Target
SPH BLK 0.0 0.0 0.0 10000.
* vacuum box
RPP VOI -1000. 1000. -1000. 1000. -1000. 1000.
* Lead target
RCC TARG 0.0 0.0 0.0 0.0 0.0 10. 5.
END
* Regions
* Black Hole
BLKHOLE 5 +BLK -VOI
* Void around
VAC 5 +VOI -TARG
* Target
TARGET 5 +TARG
END
GEOEND

```



```

*...+...1...+...2...+...3...+...4...+...5...+...6...+...7...+...*
ASSIGNMA BLCKHOLE BLKHOLE
ASSIGNMA VACUUM VAC
ASSIGNMA LEAD TARGET

```

Assignin materials

```

*...+...1...+...2...+...3...+...4...+...5...+...6...+...7...+...*
RANDOMIZ 1.0
START 10.0 0.0
STOP

```



# THE FLUKA COMBINATORIAL GEOMETRY

# Introduction

Principle of Combinatorial Geometry: Basic convex shapes (**bodies**) such as cylinders, spheres, parallelepipeds, etc. are combined to more complex shapes called **regions**. This combination is done by the boolean operations **union**, **intersection** and **subtraction**.

*The **Combinatorial Geometry** of FLUKA was initially similar to the package developed at ORNL for the neutron and gamma-ray transport program Morse (M.B. Emmett ORNL-4972 1975) which was based on the original combinatorial geometry by MAGI (Mathematical Applications Group, Inc., W. Guber et al, MAGI-6701 1967).*

# Basic Concepts

Four concepts are fundamental in the FLUKA **CG**:

- **Bodies** - basic **convex objects**, plus **infinite planes**, **infinite cylinders** and **generic quadric surfaces**
- **Zones** - sub-regions defined only with intersection and subtraction of bodies
- **Regions** - defined as boolean operations of bodies (union of zones)

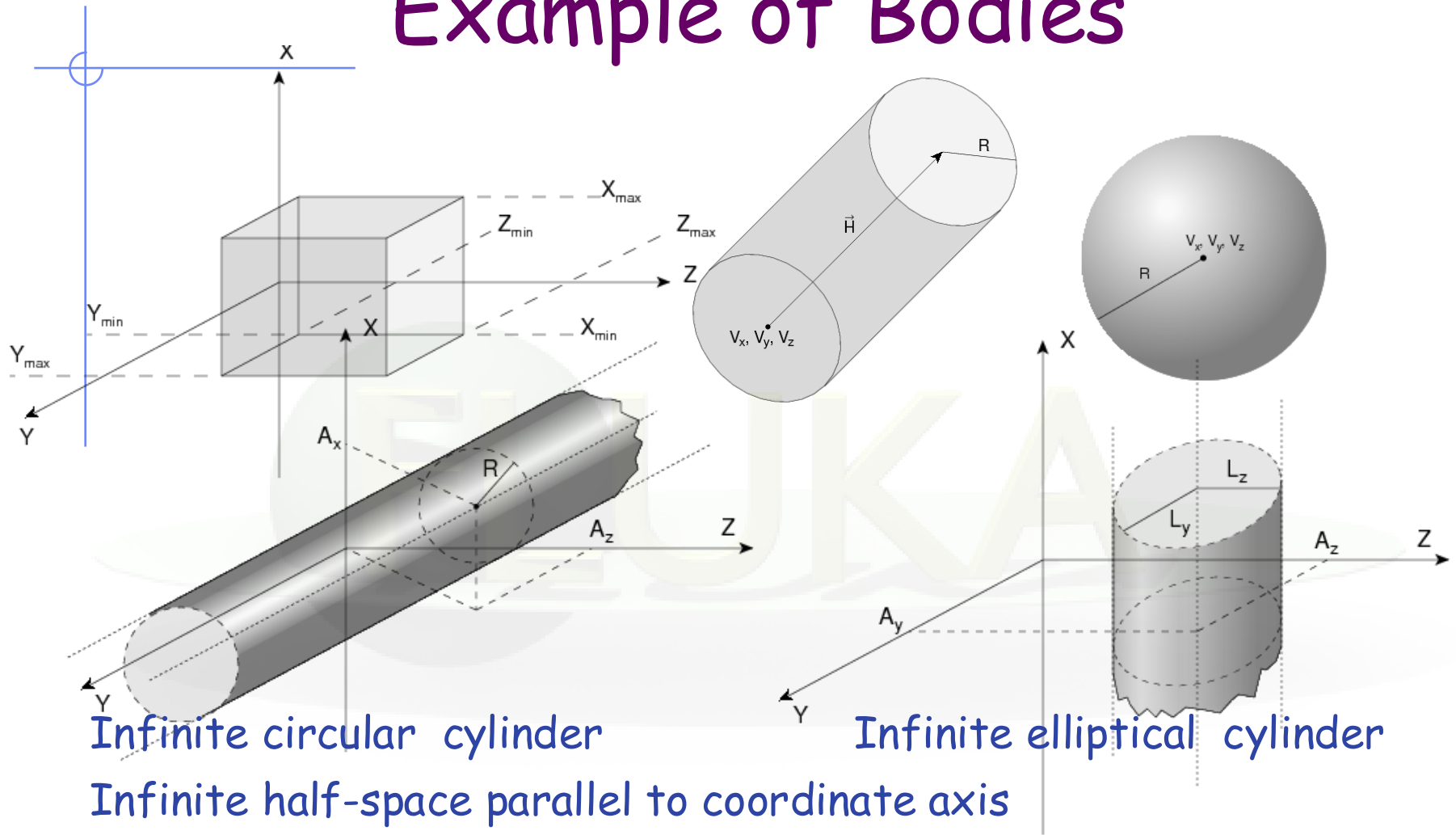
In the original description (Morse) **bodies were convex solid bodies** (finite portions of space completely delimited by surfaces of first or second degree, i.e. planes or quadrics). In FLUKA, the definition has been extended to include **infinite cylinders** (circular and elliptical), **planes** (half-spaces), and generic **quadrics** (surfaces described by 2<sup>nd</sup> degree equations)

Use of such "**infinite bodies**" is encouraged since it makes input less error-prone. They also provide a more accurate and faster tracking.

# Bodies

- Each body divides the space into two domains **inside** and **outside**. The **outside** part is pointed to by the **normal** to the surface.
- 3-character code of available bodies:
  - **RPP:** Rectangular Parallelepiped
  - **SPH:** SPHere
  - **XYP, XZP, YZP:** Infinite half space delimited by a coordinate plane
  - **PLA:** Generic infinite half-space, delimited by a PLANE
  - **XCC, YCC, ZCC:** Infinite Circular Cylinder, parallel to coordinate axis
  - **XEC, YEC, ZEC:** Infinite Elliptical Cylinder, parallel to coordinate axis
  - **RCC:** Right Circular Cylinder
  - **REC:** Right Elliptical Cylinder
  - **TRC:** Truncated Right angle Cone
  - **ELL:** ELLipsoid of revolution
  - **QUA:** QUAdric

# Example of Bodies



Infinite circular cylinder

Infinite elliptical cylinder

Infinite half-space parallel to coordinate axis

Arbitrarily oriented infinite half-space

Arbitrary generic quadric: corresponding to the equation:

$$A_{xx} x^2 + A_{yy} y^2 + A_{zz} z^2 + A_{xy} xy + A_{xz} xz + A_{yz} yz + A_x x + A_y y + A_z z + A_0 = 0$$

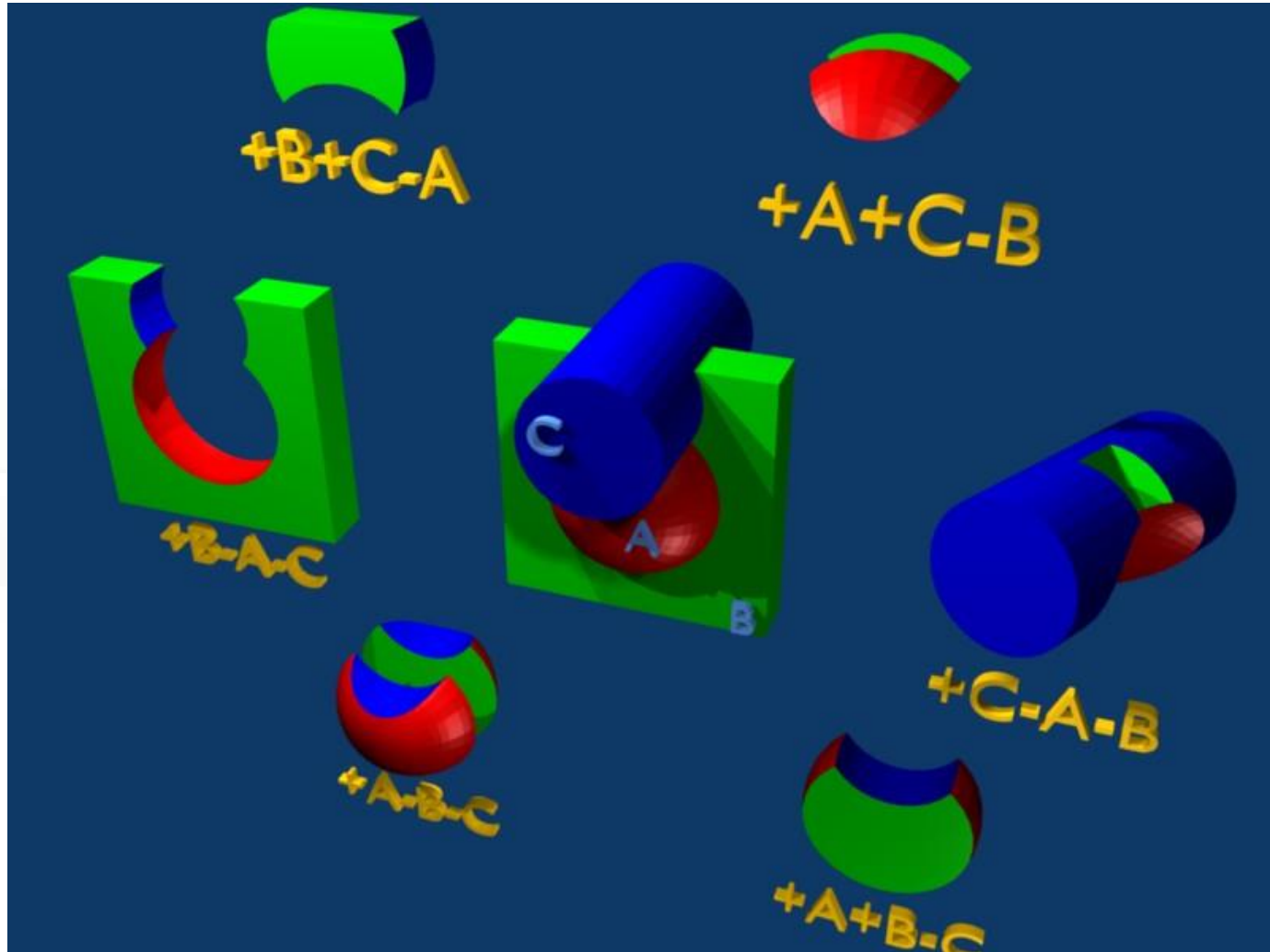
# Concept of Region

**Regions** are defined as combinations of bodies obtained by boolean operations:

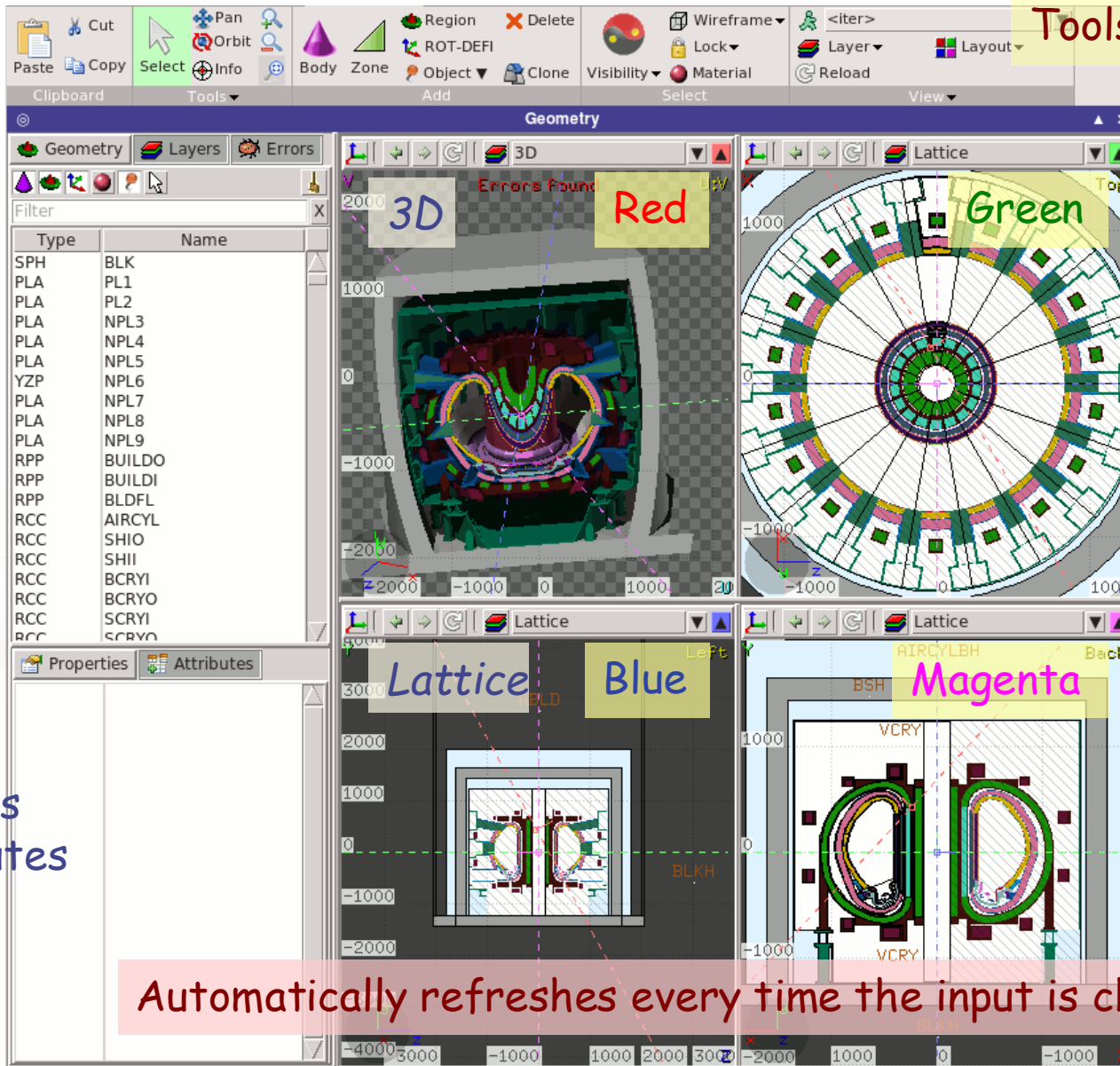
	Union	Subtraction	Intersection
<b>Free Format</b>		-	+
Fixed format	OR	-	+
Mathematically	U	-	$\cap$

**Regions** are not necessarily simply connected (they can be made as the union of two or more non contiguous or partially **overlapping zones**) but must be of **homogeneous material composition**.

# Illustration of Region building using Boolean operators



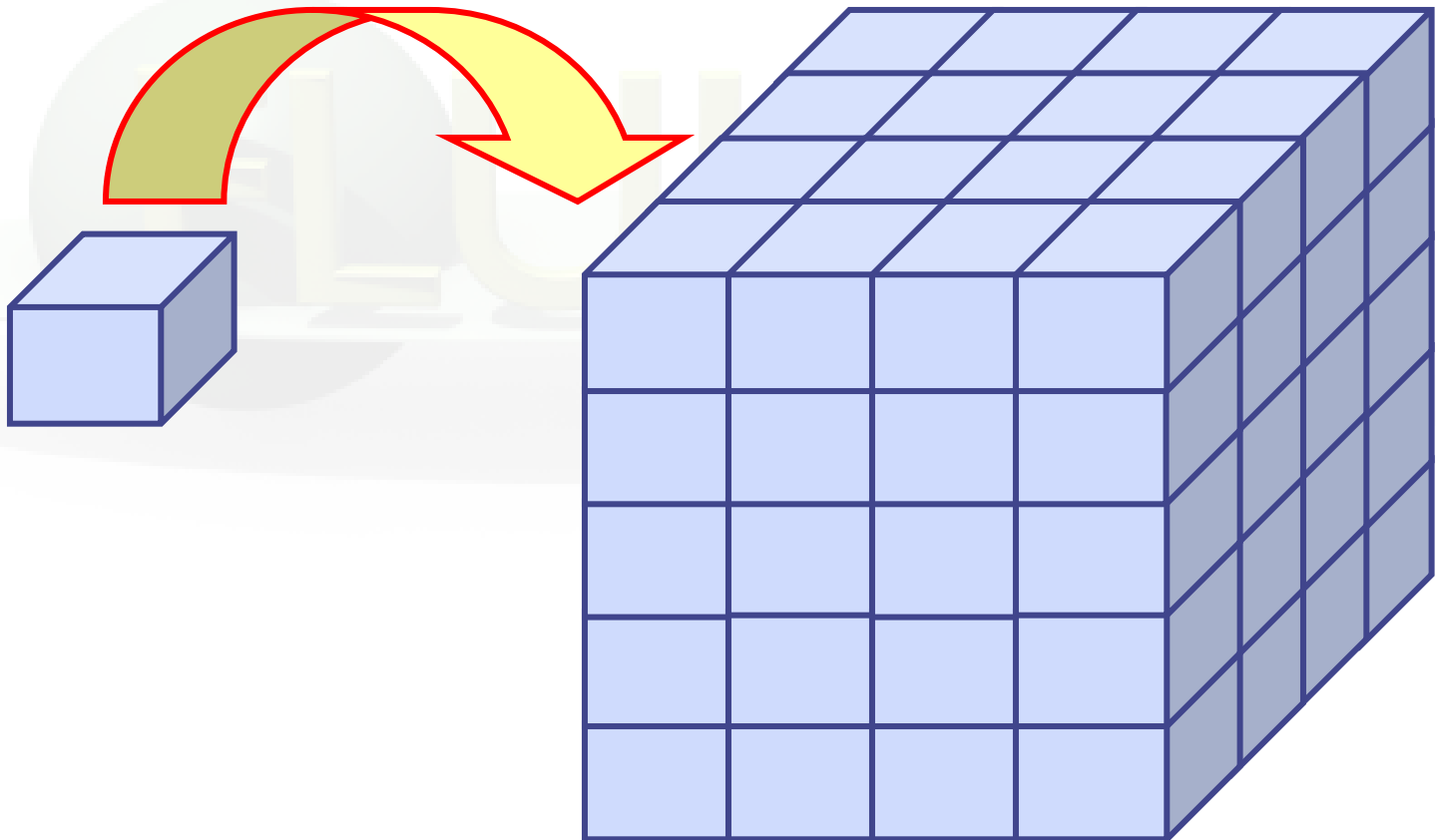
# Geometry Editor: Interface



Automatically refreshes every time the input is changed

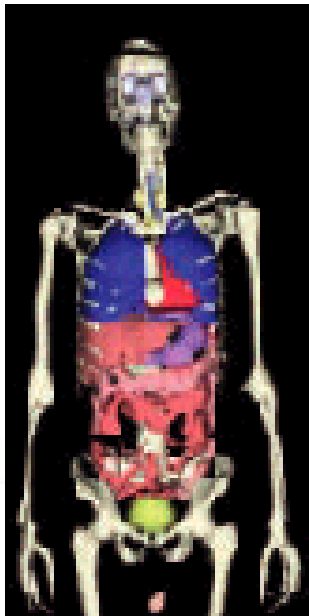
# The FLUKA voxel geometry

- It is possible to describe a geometry in terms of “**voxels**”, i.e., tiny parallelepipeds (all of equal size) forming a 3-dimensional grid



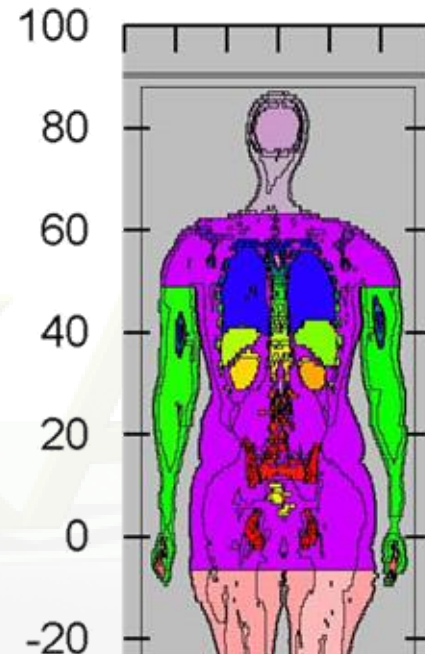
# Voxel geometries: examples

The anthropomorphic  
**GOLEM phantom**



Implementation in  
FLUKA  
(radioprotection  
applications)

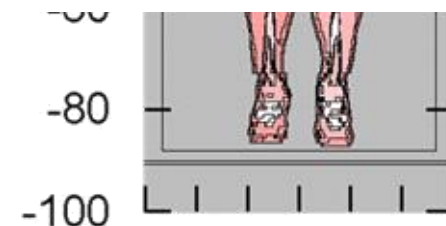
FLUKA golem section



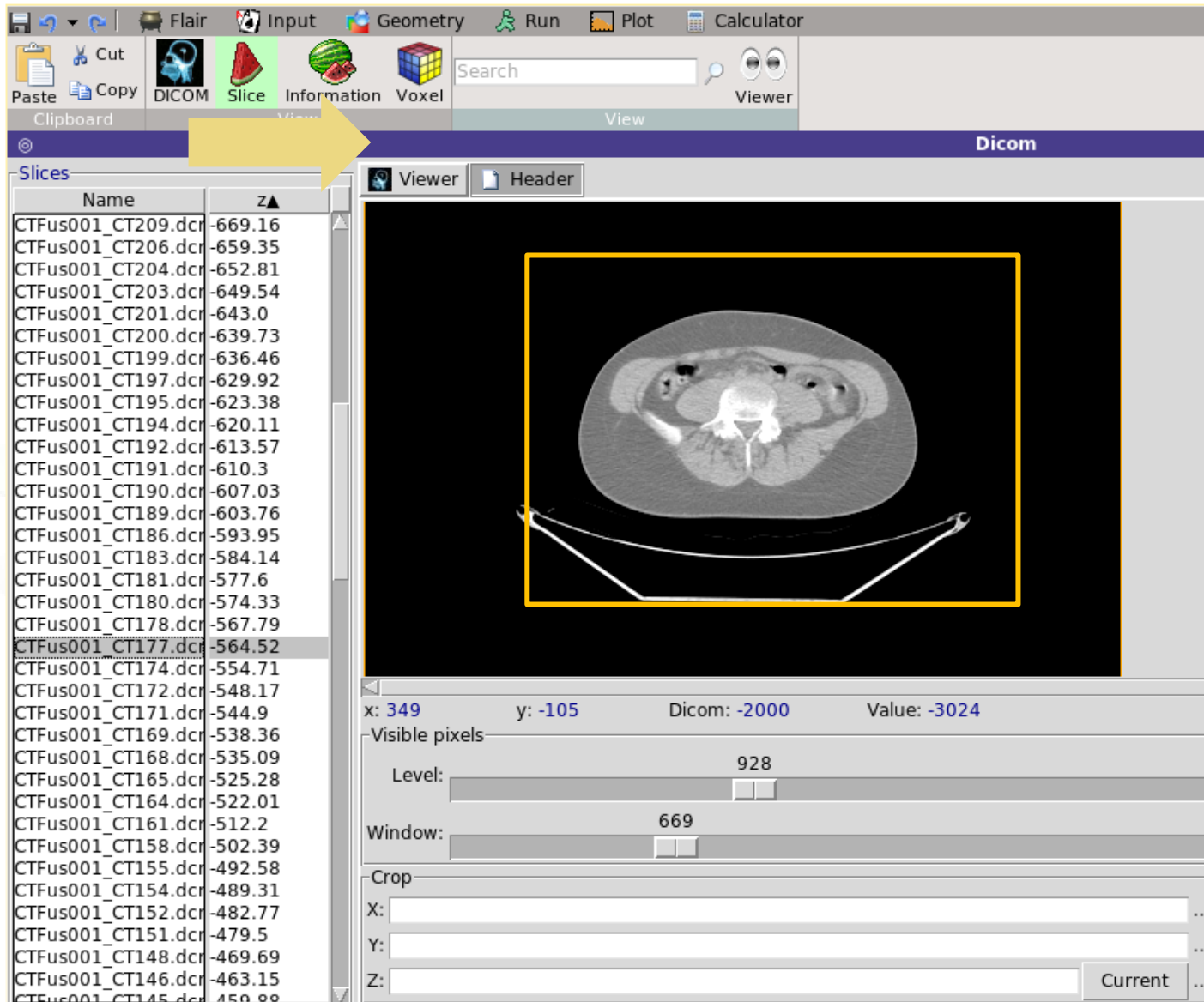
Now available the official ICRP Human Phantom  
ICRP Publication 110: Adult Reference Computational Phantoms - *Annals  
of the ICPR Volume 39 Issue 2*



Petoussi-Henss  
et al, 2002



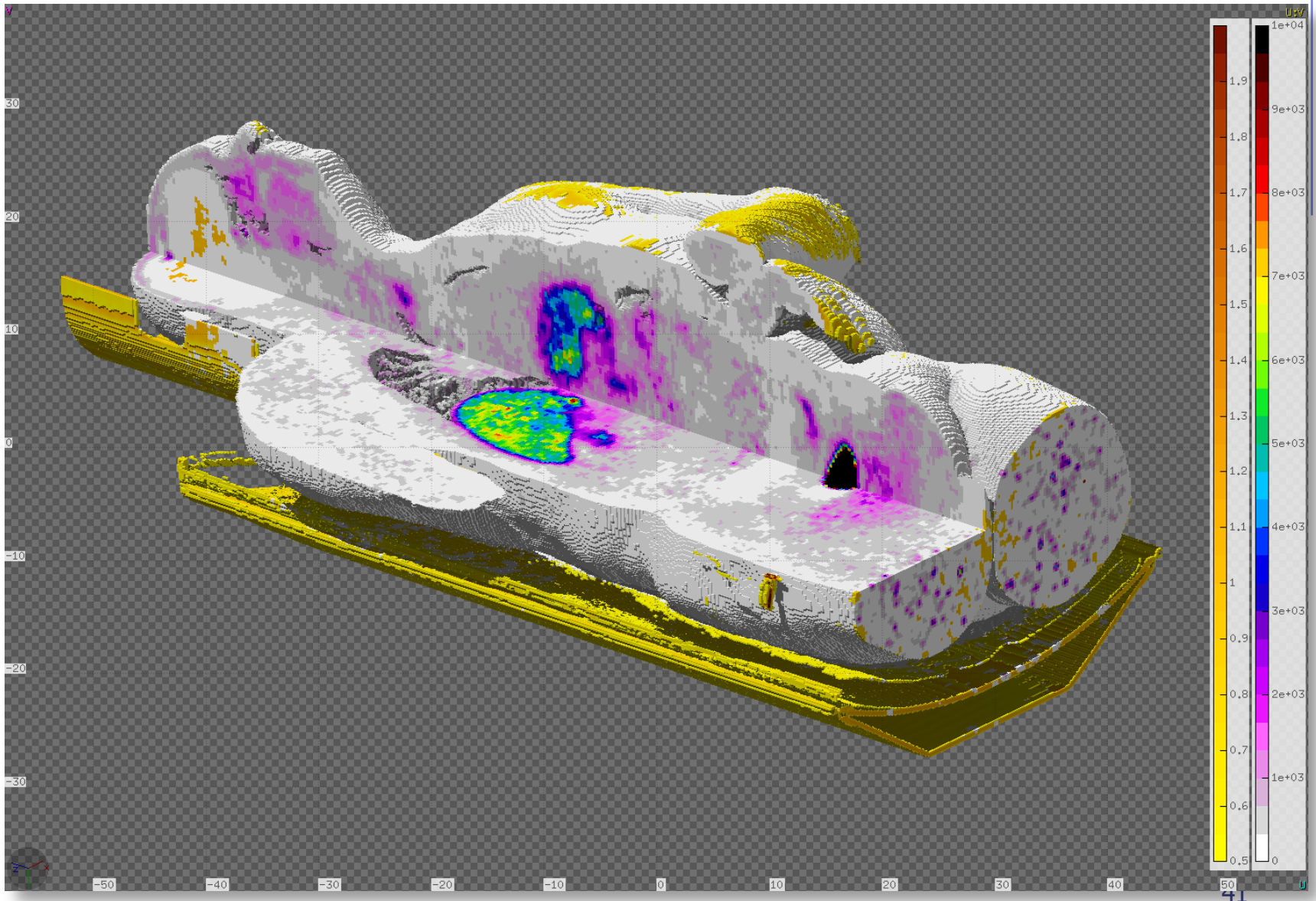
# Processing the DICOM files the FLUKA graphical interface



The screenshot displays the FLUKA graphical interface. The top menu bar includes options like Flair, Input, Geometry, Run, Plot, and Calculator. Below the menu is a toolbar with icons for Cut, Paste, Copy, DICOM, Slice, Information, Voxel, Search, and Viewer. A yellow arrow points to the 'Slice' icon. The main window is titled 'Dicom' and contains a 'Slices' list on the left and a 'Viewer' window on the right. The 'Slices' list shows a table of DICOM files with their names and z-axis positions. The 'Viewer' window displays a CT scan image of a human torso, with a yellow box highlighting a specific slice. Below the image, the viewer shows the coordinates of the slice: x: 349, y: -105, Dicom: -2000, Value: -3024. The viewer also has controls for 'Visible pixels', 'Level' (set to 928), and 'Window' (set to 669). At the bottom, there are 'Crop' controls for X, Y, and Z coordinates, with a 'Current' button.

Name	z
CTFus001_CT209.dcm	-669.16
CTFus001_CT206.dcm	-659.35
CTFus001_CT204.dcm	-652.81
CTFus001_CT203.dcm	-649.54
CTFus001_CT201.dcm	-643.0
CTFus001_CT200.dcm	-639.73
CTFus001_CT199.dcm	-636.46
CTFus001_CT197.dcm	-629.92
CTFus001_CT195.dcm	-623.38
CTFus001_CT194.dcm	-620.11
CTFus001_CT192.dcm	-613.57
CTFus001_CT191.dcm	-610.3
CTFus001_CT190.dcm	-607.03
CTFus001_CT189.dcm	-603.76
CTFus001_CT186.dcm	-593.95
CTFus001_CT183.dcm	-584.14
CTFus001_CT181.dcm	-577.6
CTFus001_CT180.dcm	-574.33
CTFus001_CT178.dcm	-567.79
CTFus001_CT177.dcm	-564.52
CTFus001_CT174.dcm	-554.71
CTFus001_CT172.dcm	-548.17
CTFus001_CT171.dcm	-544.9
CTFus001_CT169.dcm	-538.36
CTFus001_CT168.dcm	-535.09
CTFus001_CT165.dcm	-525.28
CTFus001_CT164.dcm	-522.01
CTFus001_CT161.dcm	-512.2
CTFus001_CT158.dcm	-502.39
CTFus001_CT155.dcm	-492.58
CTFus001_CT154.dcm	-489.31
CTFus001_CT152.dcm	-482.77
CTFus001_CT151.dcm	-479.5
CTFus001_CT148.dcm	-469.69
CTFus001_CT146.dcm	-463.15
CTFus001_CT145.dcm	-459.99

# Voxel geometry with PET-CT



# FLUKA Scoring & Results - Estimators

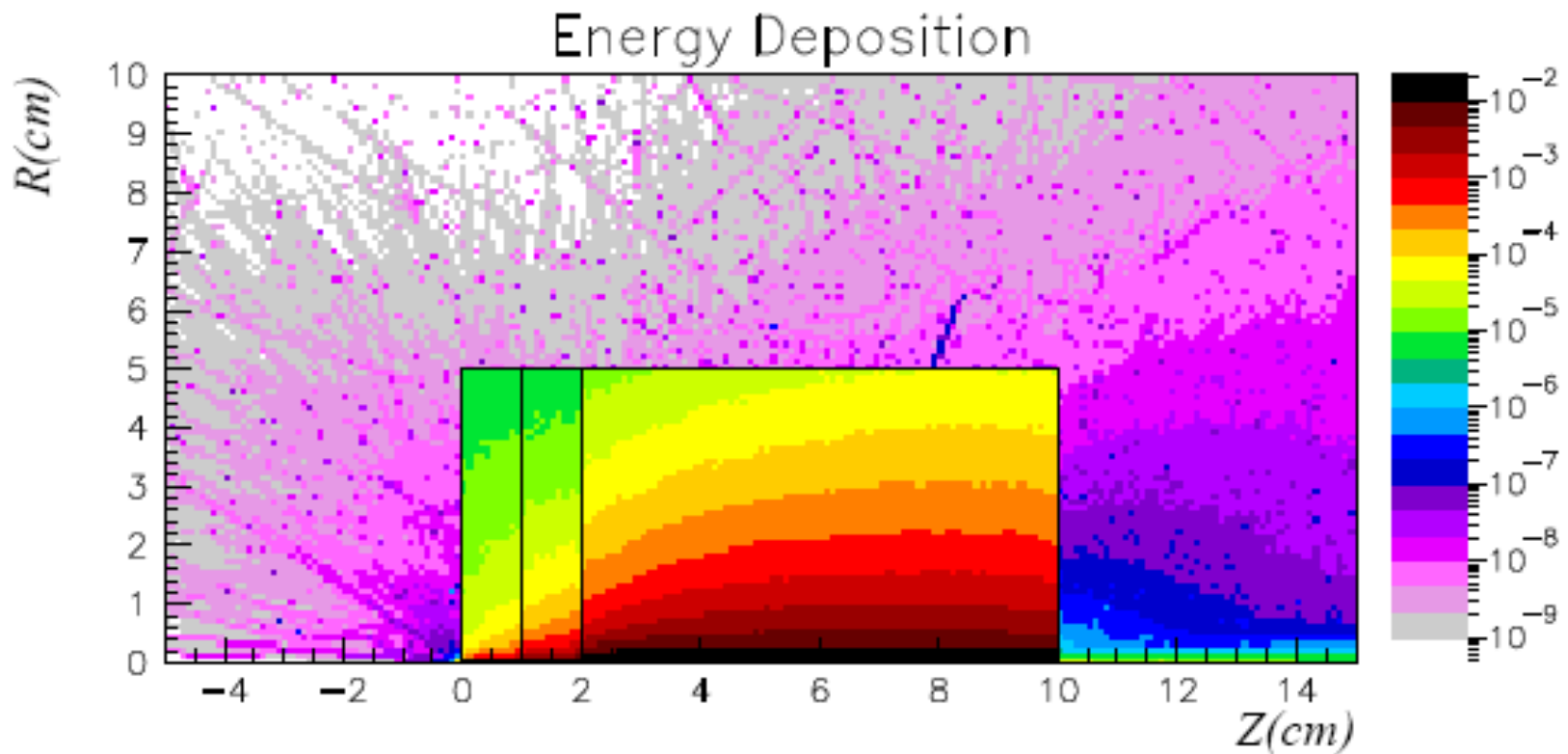
- It is often said that Monte Carlo (MC) is a “mathematical experiment”  
The MC equivalent of the result of a real experiment (*i.e.*, of a measurement) is called an estimator.
- Just as a real measurement, an estimator is obtained by sampling from a statistical distribution and has a statistical error (and in general also a systematic one).
- There are often several different techniques to measure the same physical quantity: in the same way the same quantity can be calculated using different kinds of estimators.
- FLUKA offers numerous different estimators, *i.e.*, directly from the input file the users can request scoring the respective quantities they are interested in.
- As the latter is implemented in a very complete way, users are strongly encouraged to preferably use the built-in estimators with respect to user-defined scoring
- For additional requirements FLUKA user routines are provided

# Built-In and User Scoring

- Several **pre-defined estimators** can be activated in FLUKA.
- One usually refers to these estimators as "**scoring**" capabilities
- Users have also the possibility to build their own scoring through user routines, HOWEVER:
  - **Built-in scoring** covers most of the **common needs, extensively tested**, has **refined algorithms** for track subdivision, comes with **utility programs** that allow to evaluate statistical errors takes **BIASING weights automatically into account**
- Scoring can be geometry dependent AND/OR geometry independent FLUKA can score **particle fluences, current, track length, energy spectra, Z spectra, energy deposition...**
- Either integrated over the "**run**", with proper normalization, OR **event-by event**
- Standard scoring can be weighted by means of **simple user routines**

# USRBIN → The Result

**WHAT(2) = ENERGY** :Energy deposition from a 3.5 GeV proton beam hitting at [0.,0.,0.] directed along z  
results are normalized to  $\text{GeV}/\text{cm}^3$  per primary

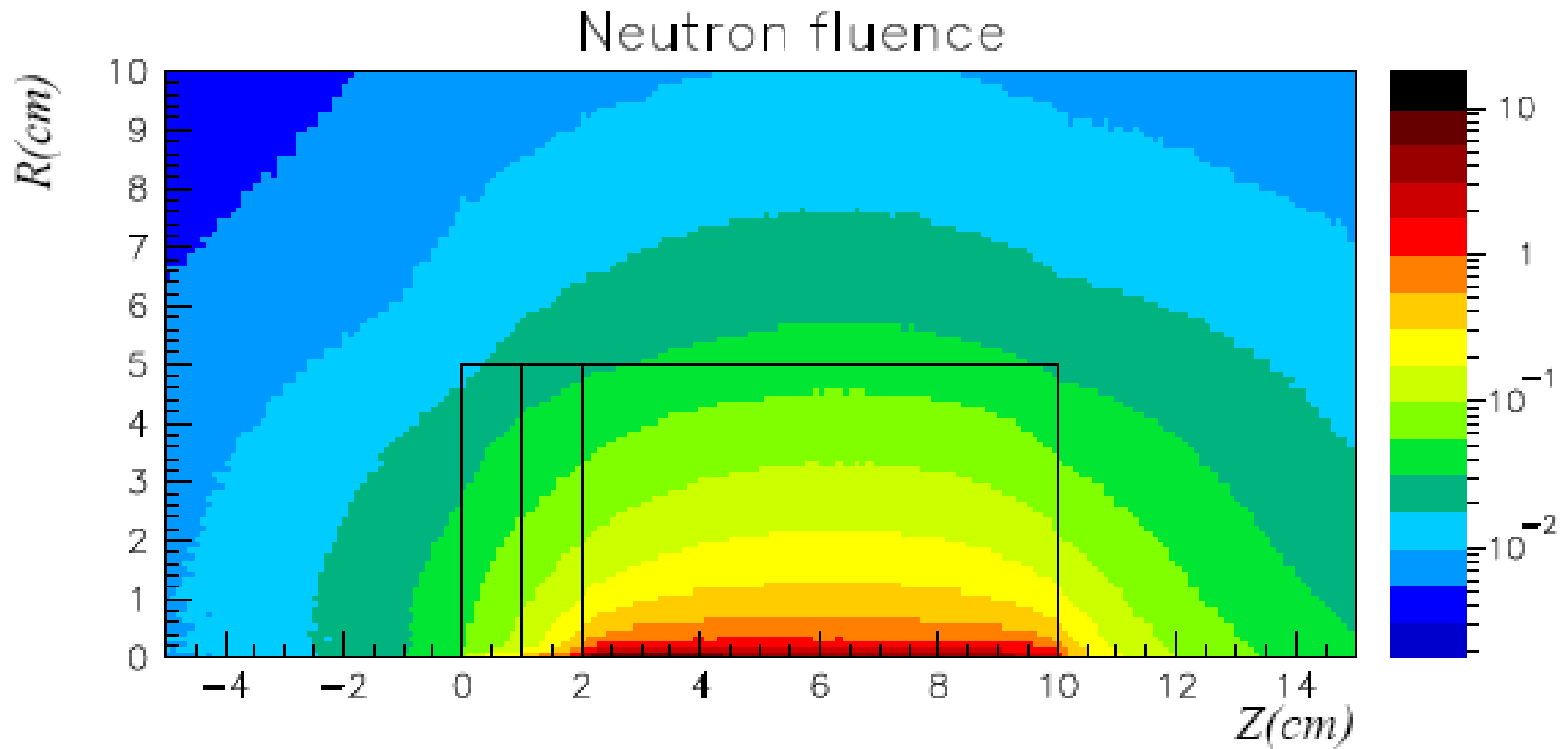


# Related Scoring Commands (main cases)

- **USRTRACK**, **USRCOLL** score average  $d\Phi/dE$  (differential fluence) of a given type or family of particles in a given region
- **USRBDX** scores average  $d^2\Phi/dEd\Omega$  (double-differential fluence or current) of a given type or family of particles on a given surface
- **USRBIN** scores the spatial distribution of energy deposited, or total fluence (or star density, or momentum transfer) in a regular mesh (cylindrical or Cartesian) described by the user
- **USRYIELD** scores a double differential yield of particles escaping from a surface. The distribution can be with respect to energy and angle, but also other more "exotic" quantities
- **SCORE** scores energy deposited (or star density) in all regions

# Example of USRBIN → Fluence (1)

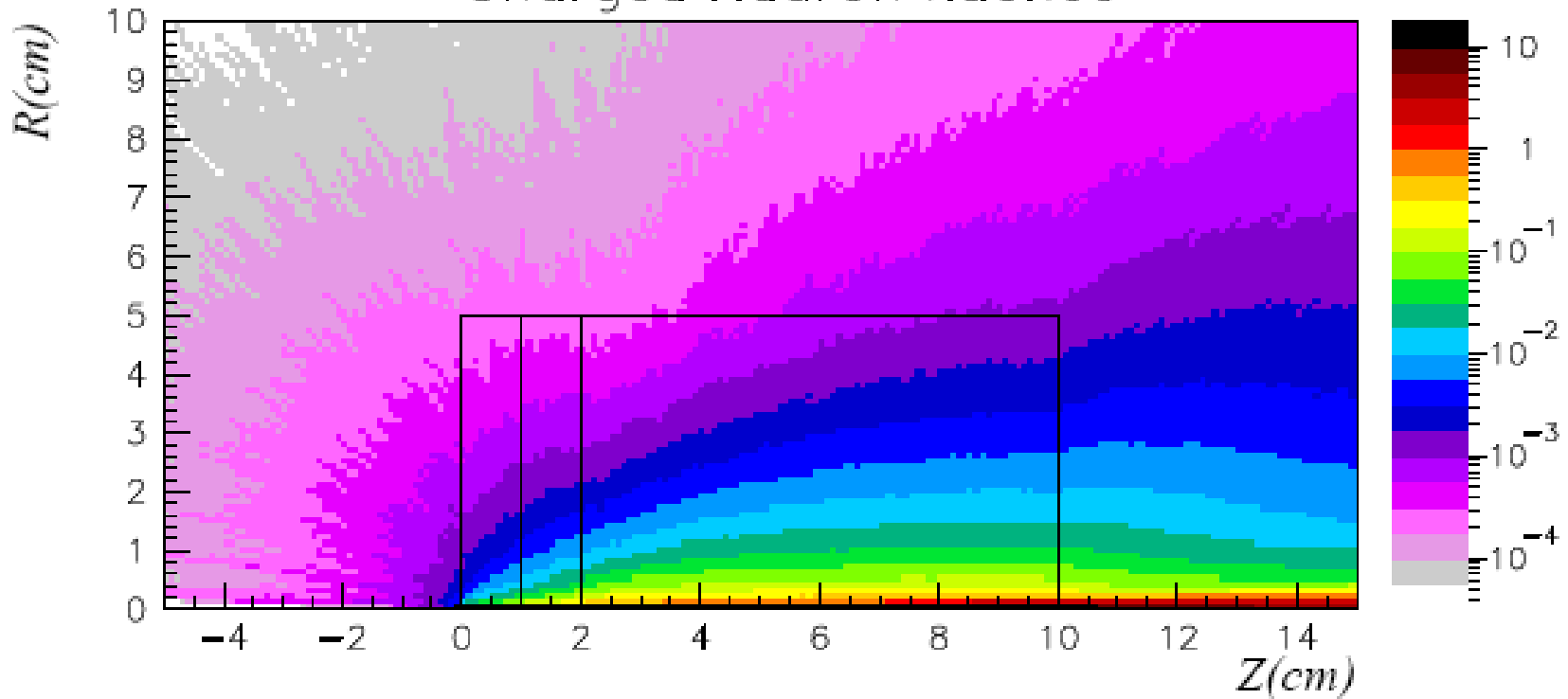
Same, **WHAT(2)= NEUTRON** to get neutron fluence  
results are normalized to particles/cm<sup>2</sup> per primary

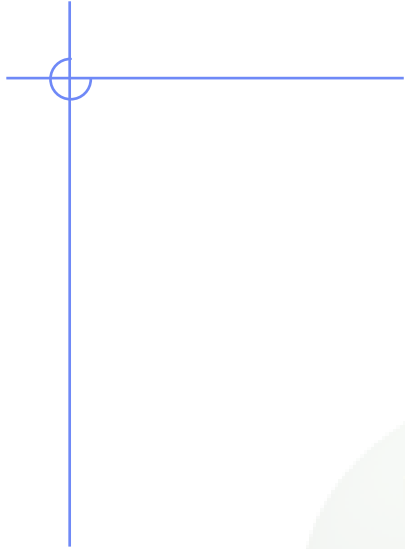


# Example of USRBIN → Fluence (2)

Same, **WHAT(2)**= HAD-CHAR to get charged hadron fluence

results are normalized to particles/cm<sup>2</sup> per primary  
Charged Hadron fluence





# SOMETHING ABOUT THE PHYSICS CONTENT OF FLUKA

# E.M. Interactions



- General settings
- Interactions of leptons/photons
  - Photon interactions
    - ◆ Photoelectric
    - ◆ Compton
    - ◆ Rayleigh
    - ◆ Pair production
    - ◆ Photonuclear
    - ◆ Photomuon production
  - Electron/positron interactions
    - ◆ Bremsstrahlung
    - ◆ Scattering on electrons
  - Muon interactions
    - ◆ Bremsstrahlung
    - ◆ Pair production
    - ◆ Nuclear interactions

- Ionization energy losses
    - Continuous
    - Delta-ray production
  - Transport
    - Multiple scattering
    - Single scattering
- These are common to all charged particles, although traditionally associated with EM*
- ⑩ Transport in Magnetic field

# Ionization energy losses

- Charged hadrons
  - Muons
  - Electrons/positrons
  - Heavy ions
- All share the same approach!*
- (some extra features are needed for **Heavy ions** )

Atomic energy losses:

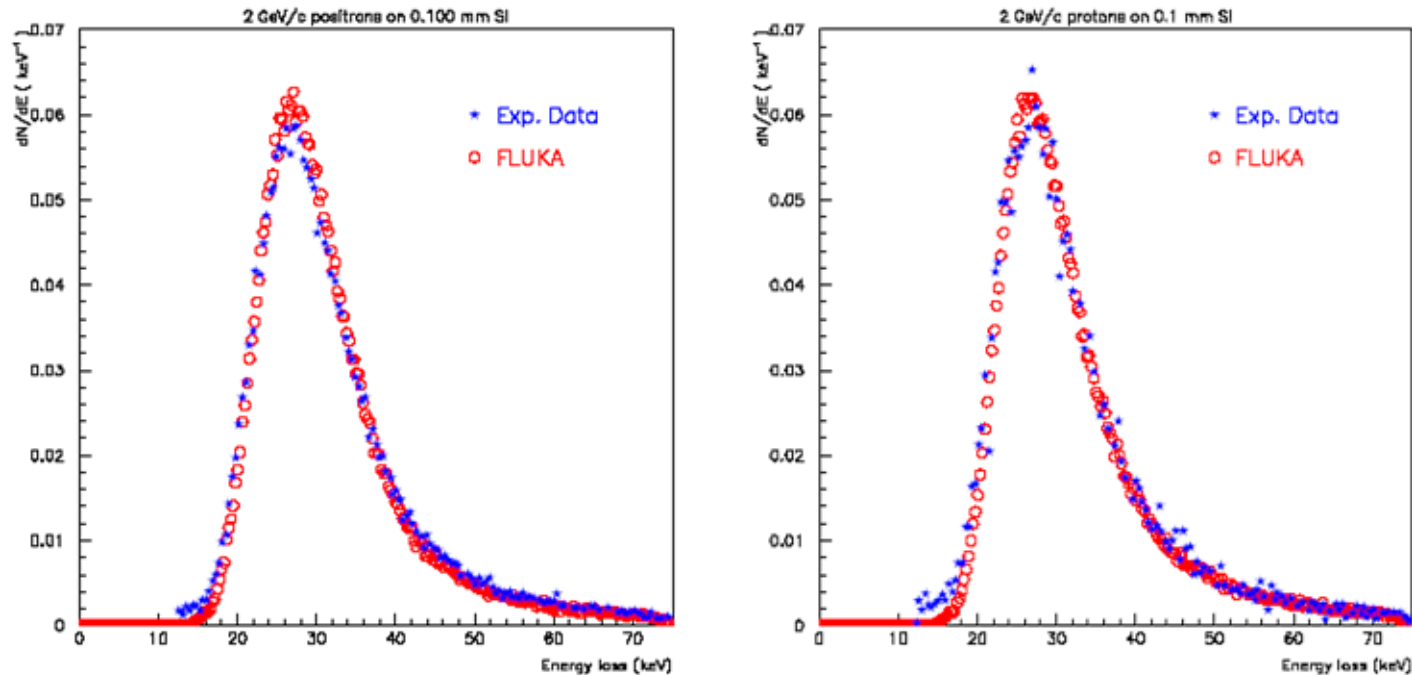
Bethe-Bloch + higher order ( $Z^3$ ,  $Z^4$ , Mott) corrections

Besides Coulomb scattering with atomic **electrons**, particles undergo Coulomb scattering also with atomic **nuclei**

The resulting energy losses, called nuclear stopping power, are smaller than the atomic ones, but are important for heavy particles

# Ionization fluctuations

FLUKA has a specific model which overcomes the limitations existing for Landau and Vavilov distributions



Experimental <sup>1</sup> and calculated energy loss distributions for 2 GeV/c positrons (left) and protons (right) traversing 100 $\mu$ m of Si

J.Bak et al. NPB288, 681 (1987)

# Transport thresholds

In a MC simulation particles are not tracked until they “have lost all their kinetic energy”, but until their energy drops to/below a preset **transport threshold**

When a particle's energy drops below threshold, what happens?

In FLUKA energy is deposited **on the spot** (for electrons) or **ranged out** (for heavier projectiles).

## General guidelines to set threshold energies?

It depends on the “granularity” of the geometry and/or of the scoring mesh. Energy/range tables are very useful.

- Consider the interest in a given region.
- **Warning 1:** to reproduce correctly electronic equilibrium, neighboring regions should have the same electron **energy** (NOT range) threshold. To be kept in mind for sampling calorimeters
- **Warning 2:** Photon thresholds should be lower than electron thresholds (photons travel farther)
- **Warning 3:** low thresholds for e-/e+/gammas are CPU eaters

# Transport thresholds - 2

Delta-ray production threshold:

- If production threshold  $<$  transport threshold: CPU wasted in producing and dumping particles on the spot
- If production threshold  $>$  transport threshold: the latter is increased.

Examine the particle's range

<https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html>

https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html - Chromium

https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html

NIST  
National Institute of  
Standards and Technology  
Physical Sciences Laboratory

estar\*  
stopping power  
and range tables  
for electrons

The ESTAR program calculates stopping power, density effect parameters, range, and radiation yield tables for electrons in various materials. Select a material and enter the desired energies or use the default energies. Energies are specified in MeV, and must be in the range from 0.001 MeV to 10000 MeV.

[Help](#) [Text version](#) [Material composition data](#)

Select a common material:  
13: Aluminum  
or enter a [unique material](#)

Graph stopping power:  
 Total Stopping Power  
 Collision Stopping Power  
 Radiative Stopping Power

Graph density effect parameter  
 Graph CSDA range  
 Graph radiation yield  
 No graph

Additional Energies (optional):  
Use energies from a file\*  
 No file chosen

or  
Use energies entered below (one per line)  
  
 Include default energies

Note: Only stopping powers and the density effect parameter will be calculated if additional energies are used.

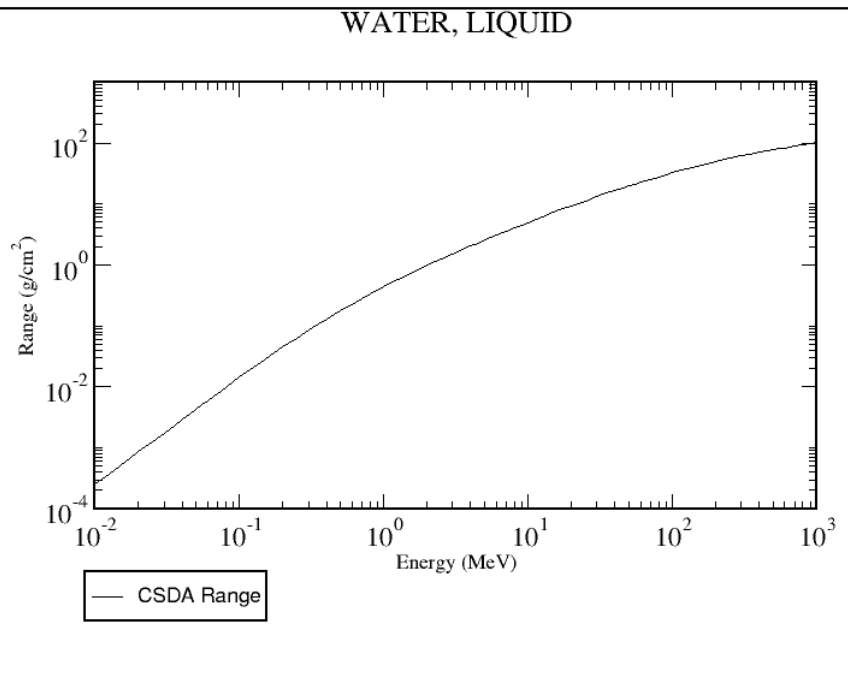
\* Your browser must be file-upload compatible.

[contents\\*](#)

# Transport thresholds - 3

Range for electrons in water

Water density:  $1 \text{ g/cm}^3 \rightarrow$  We may directly read range in cm



Transport threshold at 1 MeV?  $\rightarrow$  1-MeV  $e^-$  range is  $O(1 \text{ mm}) = 1000 \mu\text{m}$   
Depositing/killing them on the spot in a  $\sim 50 \mu\text{m}$  geometry is asking too much...

Transport threshold at 10 keV?  $\rightarrow$  10-keV  $e^-$  range is  $O(10^{-4} \text{ cm}) = O(1 \mu\text{m})$   
Depositing them on the spot in a  $\sim 50 \mu\text{m}$  geometry is fine

# The FLUKA hadronic Models

Hadron-nucleus: PEANUT

Elastic, exchange  
Phase shifts  
data, eikonal

$P < 3-5 \text{ GeV}/c$   
Resonance prod  
and decay

hadron

hadron

low E  
 $\pi, K$   
Special

High Energy  
DPM  
hadronization

Sophisticated  
G-Intranuclear Cascade

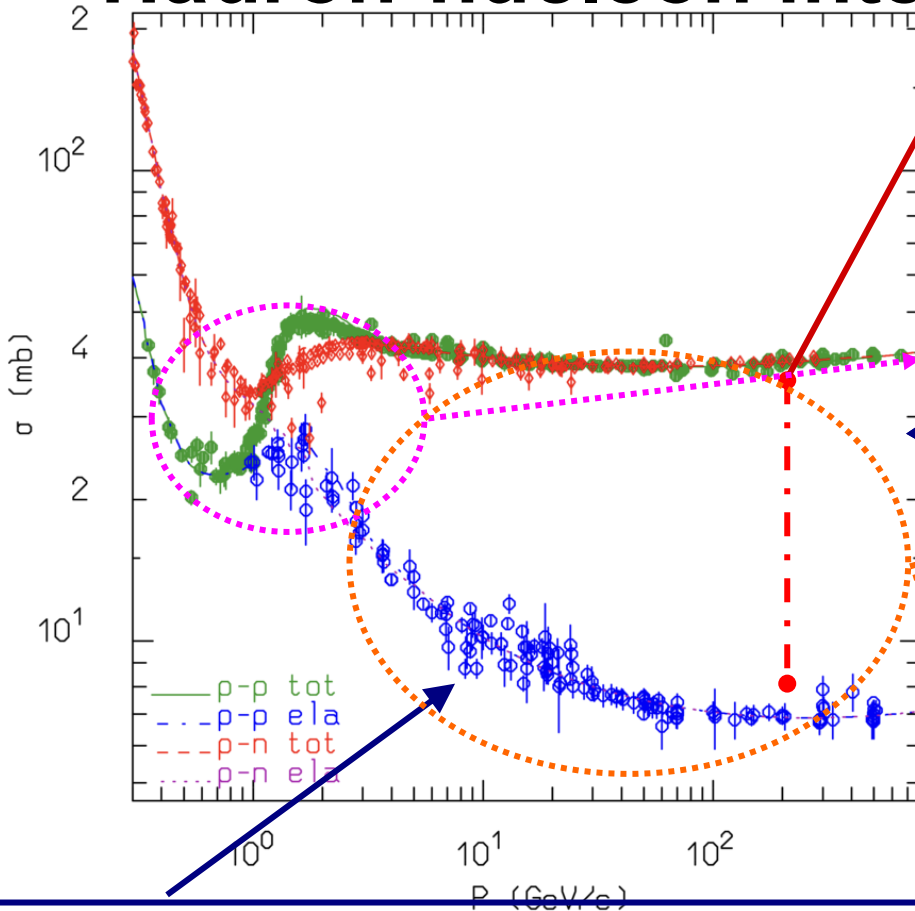
Gradual onset of  
Glauber-Gribov multiple  
interactions

Preequilibrium

Coalescence

Evaporation/Fission/Fermi break-up  
 $\gamma$  deexcitation

# Hadron-nucleon interaction models



Particle production interactions:  
two kinds of models

Those based on "resonance"  
production and decays, cover the  
energy range up to 3-5 GeV

Those based on quark/parton  
string models, which provide  
reliable results up to several tens  
of TeV

Elastic, charge exchange and strangeness exchange reactions:

- Available analysis and/or fits of experimental differential data
- At high energies, standard approximations are used

## Heavy ion interaction models in FLUKA - 1

$E > 5 \text{ GeV/n}$

The choice of the model is automatic. The user is not requested to provide specifications

Dual Parton Model (DPM)

DPMJET-III (original code by R.Engel, J.Ranft and S.Roesler, FLUKA-implementation by T.Empl *et al.*)

$0.1 \text{ GeV/n} < E < 5 \text{ GeV/n}$

Relativistic Quantum Molecular Dynamics Model (RQMD)

RQMD-2.4 (original code by H.Sorge *et al.*, FLUKA-implementation by A.Ferrari *et al.*)

$E < 0.1 \text{ GeV/n}$

Boltzmann Master Equation (BME) theory

BME (original code by E.Gadioli *et al.*, FLUKA-implementation by F.Cerutti *et al.*)

# Nuclear Interactions

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)



Evaporation/Fragmentation/Fission model



$\gamma$  deexcitation

$t$  (s)

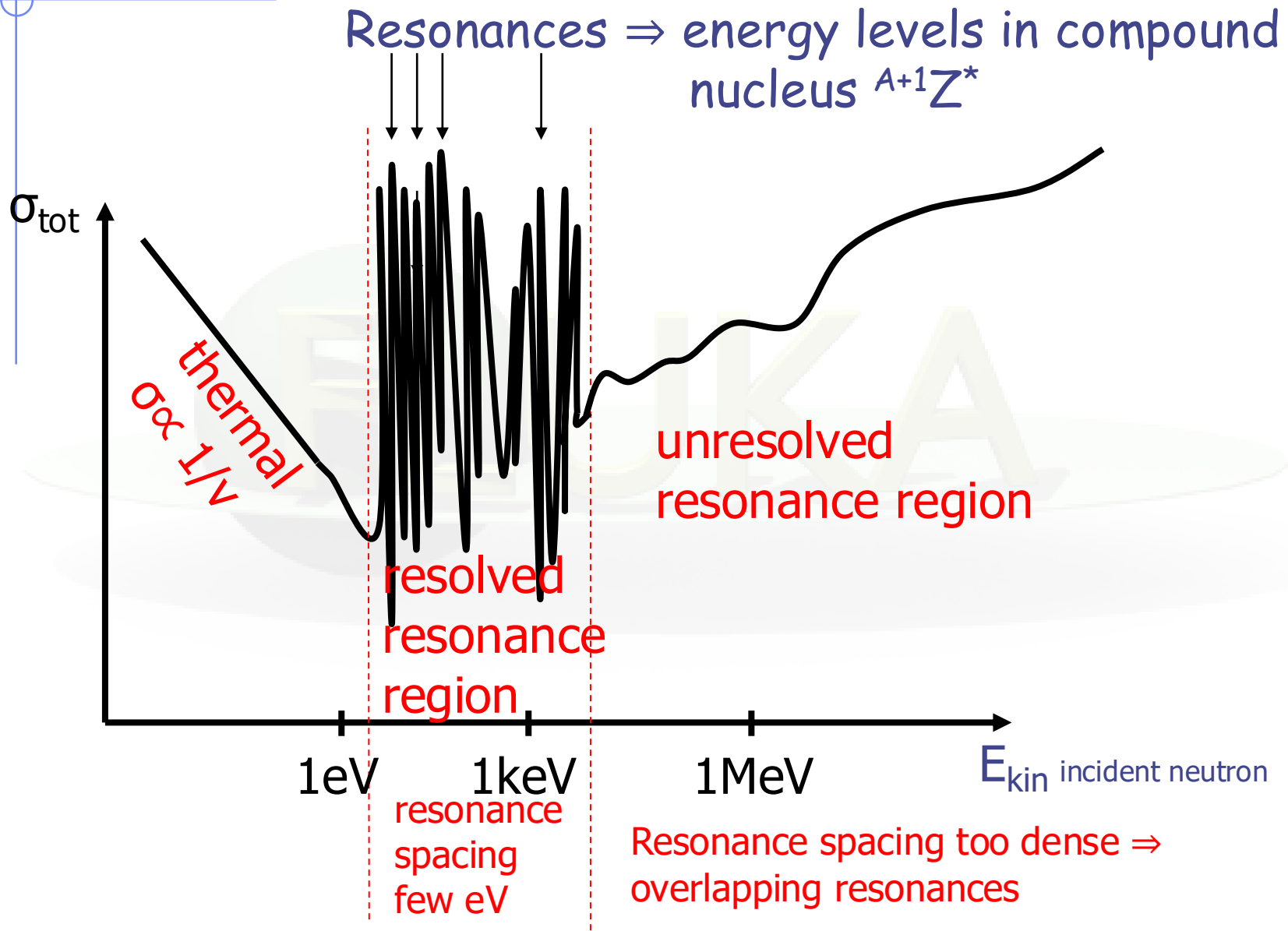
$10^{-23}$

$10^{-22}$

$10^{-20}$

$10^{-16}$

# Typical neutron cross section



# Evaluated Nuclear Data Files

- Evaluated nuclear data files (ENDF, JEFF, JENDL...)
  - typically provide neutron  $\sigma$  (cross sections) for  $E < 20 \text{ MeV}$  for all channels
  - $\sigma$  are stored as continuum + resonance parameters
  - Complex programs like NJOY, PREPRO convert the ENDF file to P-ENDF (point-wise cross sections), or G-ENDF (group-wise) including Doppler broadening etc.

## Point-wise and Group-wise cross sections

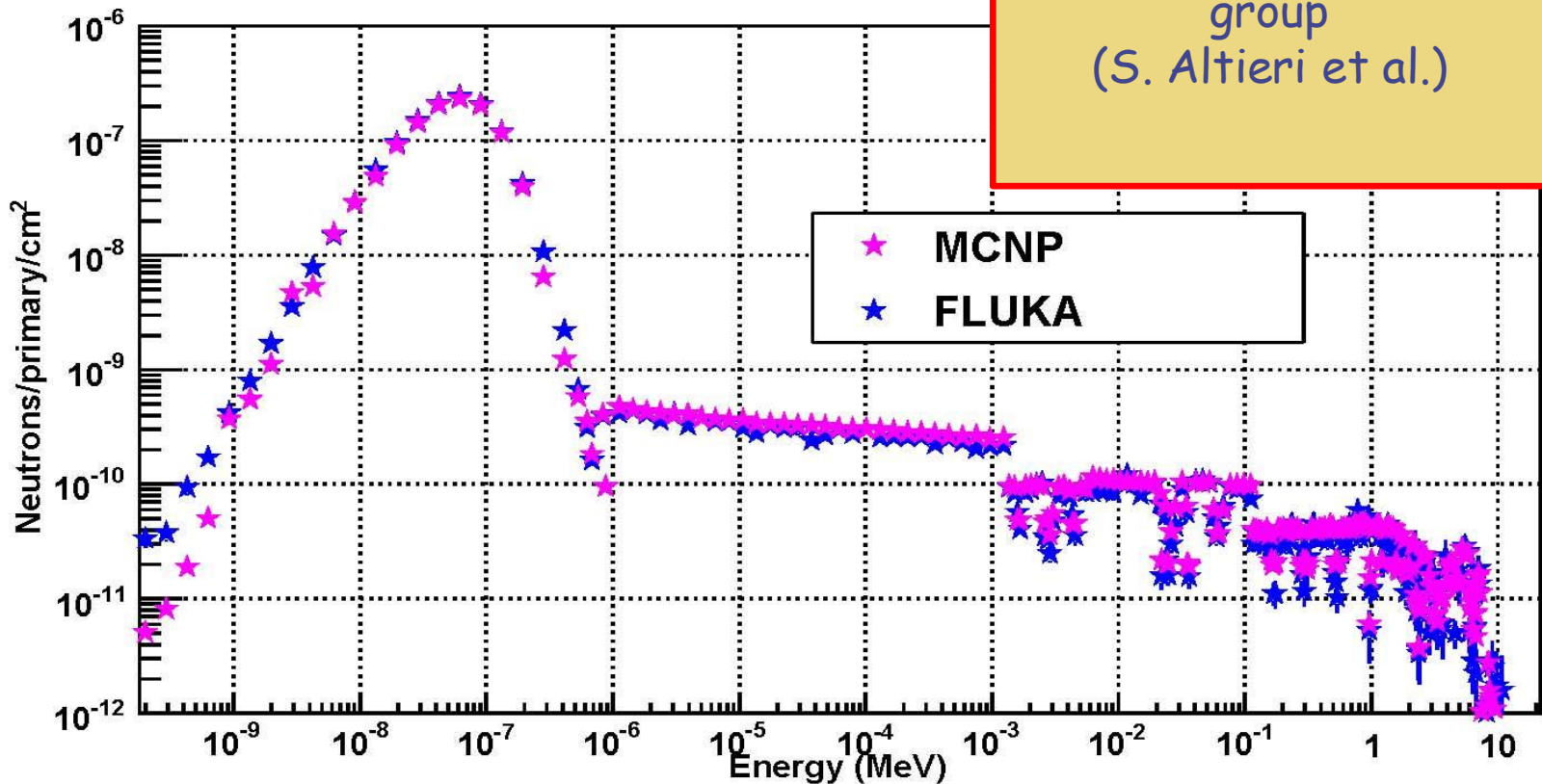
- In neutron transport codes in general two approaches used: point-wise (“continuous” cross sections) and group-wise transport
- Point-wise follows cross section precisely but is can be time and memory consuming
- Group approach is used in neutron transport codes because it is fast and gives good results for most applications



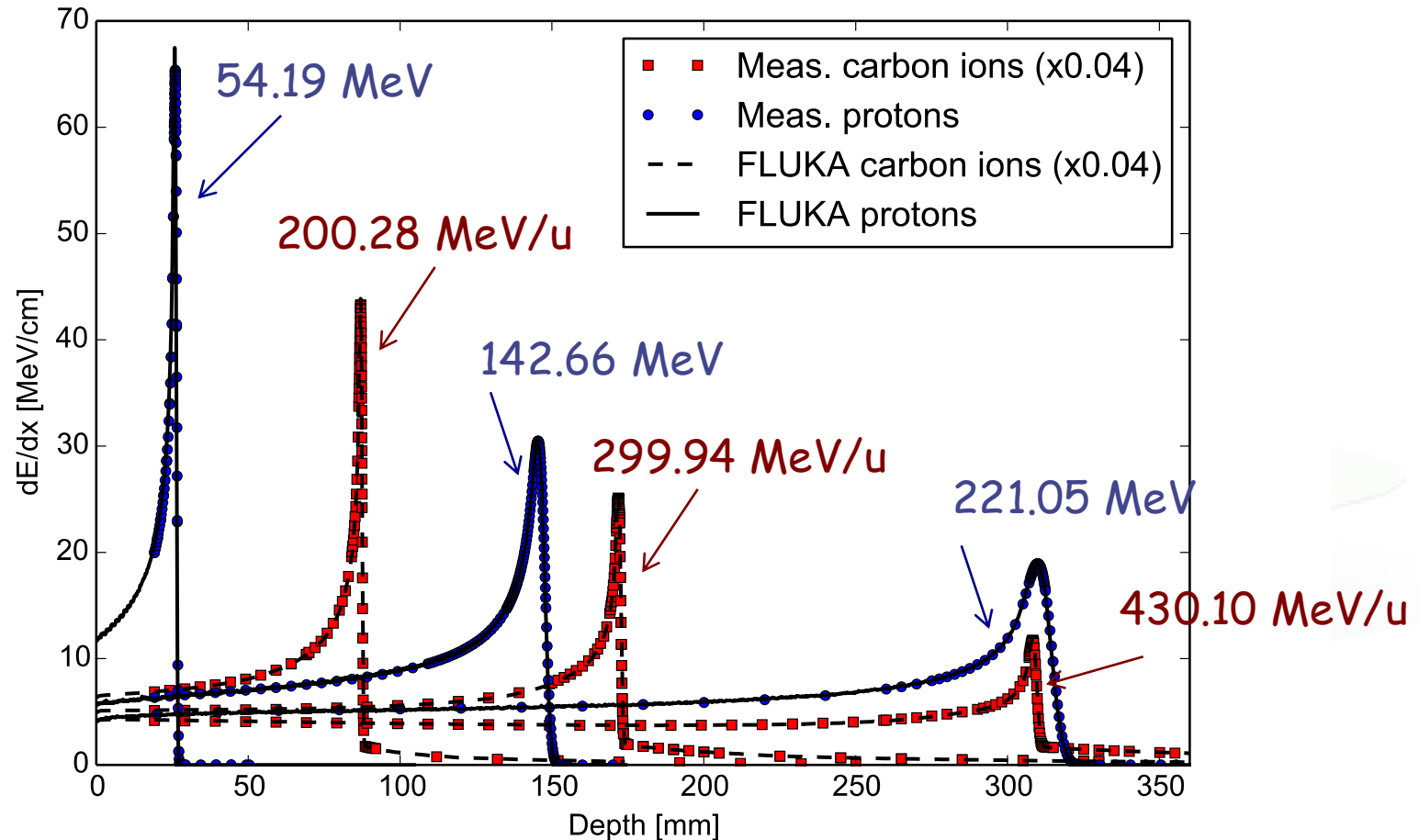
The most recent FLUKA versions has now the possibility of using PointWise neutron cross sections also for  $E < 20 \text{ MeV}$

# FLUKA Simulation of neutron spectrum from reactor LENA (Pavia) using groupwise neutron cross sections

Energy Spectra

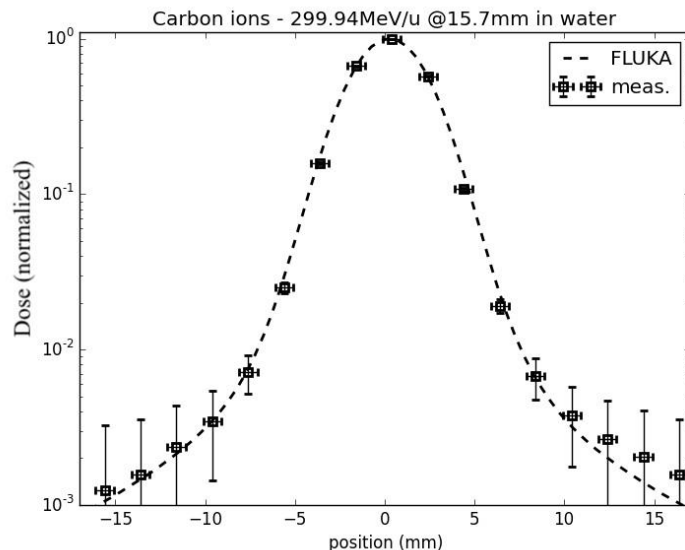
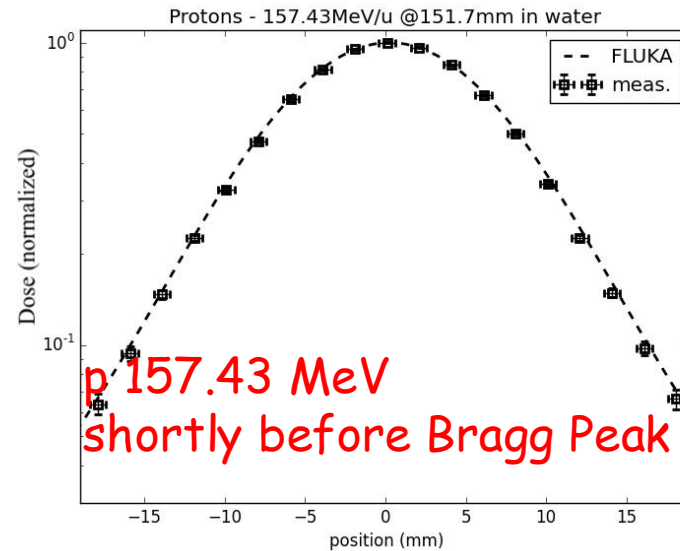
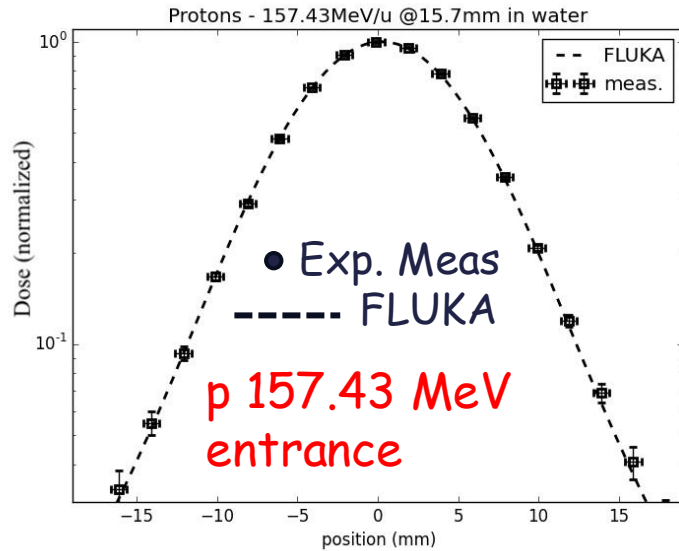


# Comparing Predictions for Depth-Dose curves and Lateral Dose Profiles

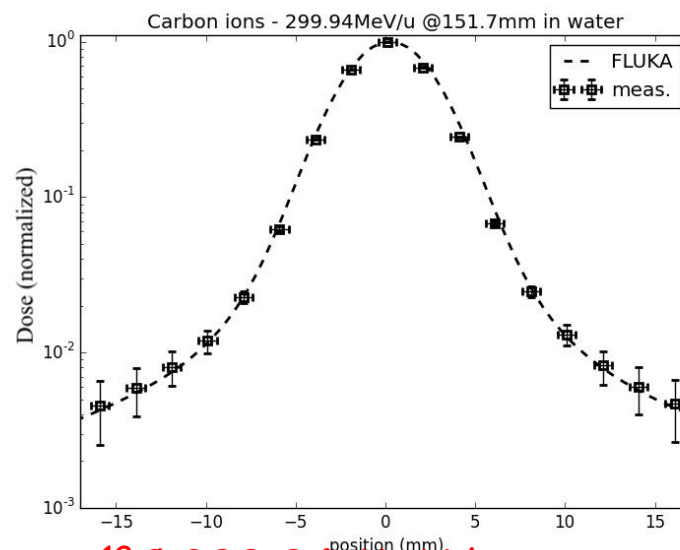


FLUKA simulations of depth-dose profiles of protons and carbon ions with therapeutic ranges in comparison with measured data at HIT.

# Lateral profiles measured @HIT



$^{12}\text{C}$  299.94 MeV/u  
entrance

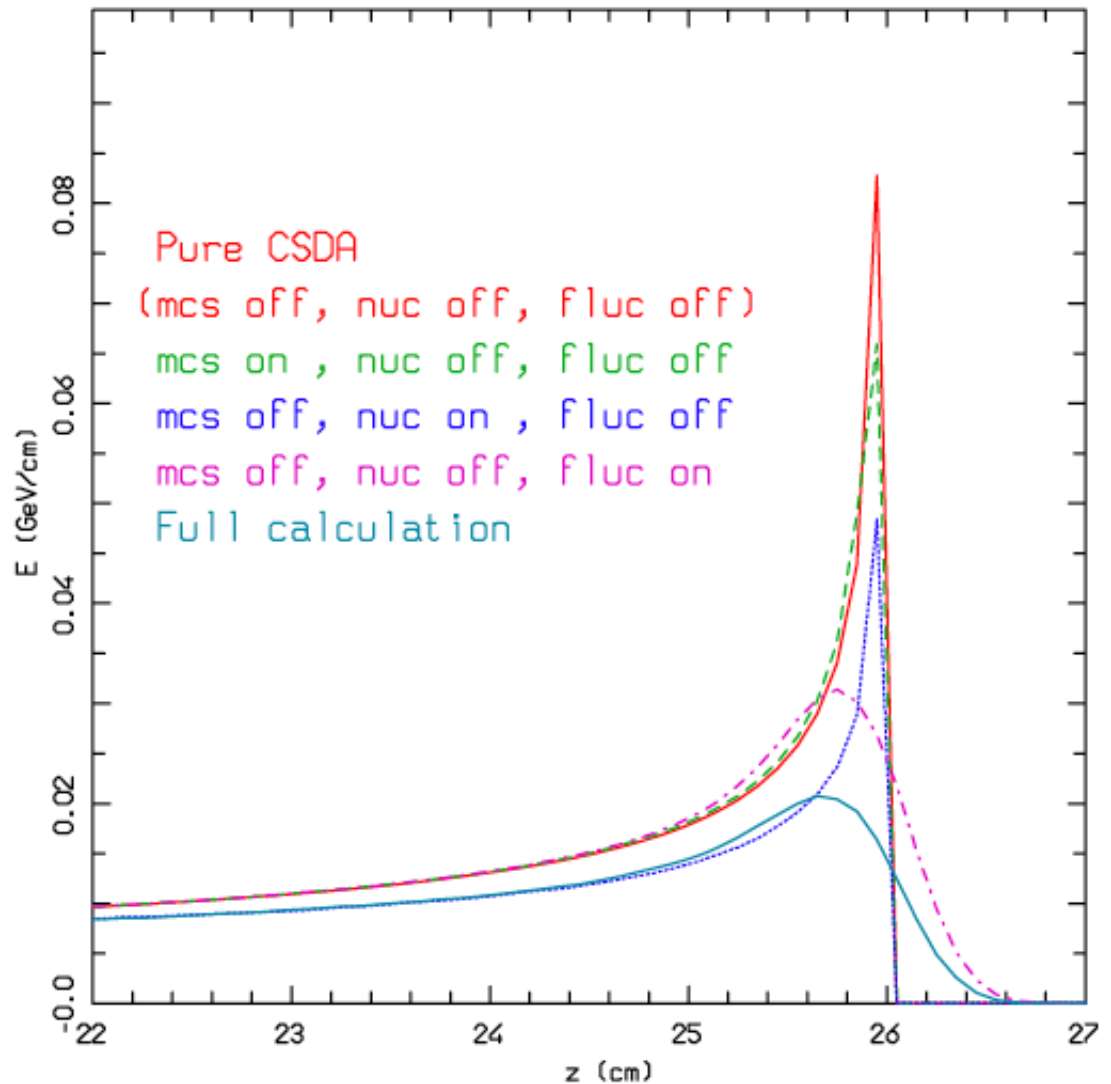


$^{12}\text{C}$  299.94 MeV/u  
shortly before Bragg Peak

# Playing with a proton beam

Dose vs depth  
energy deposition  
in water for a 200  
MeV p beam with  
various approximations  
for the physical  
processes taken into  
account

200 MeV p on water (pencil beam)

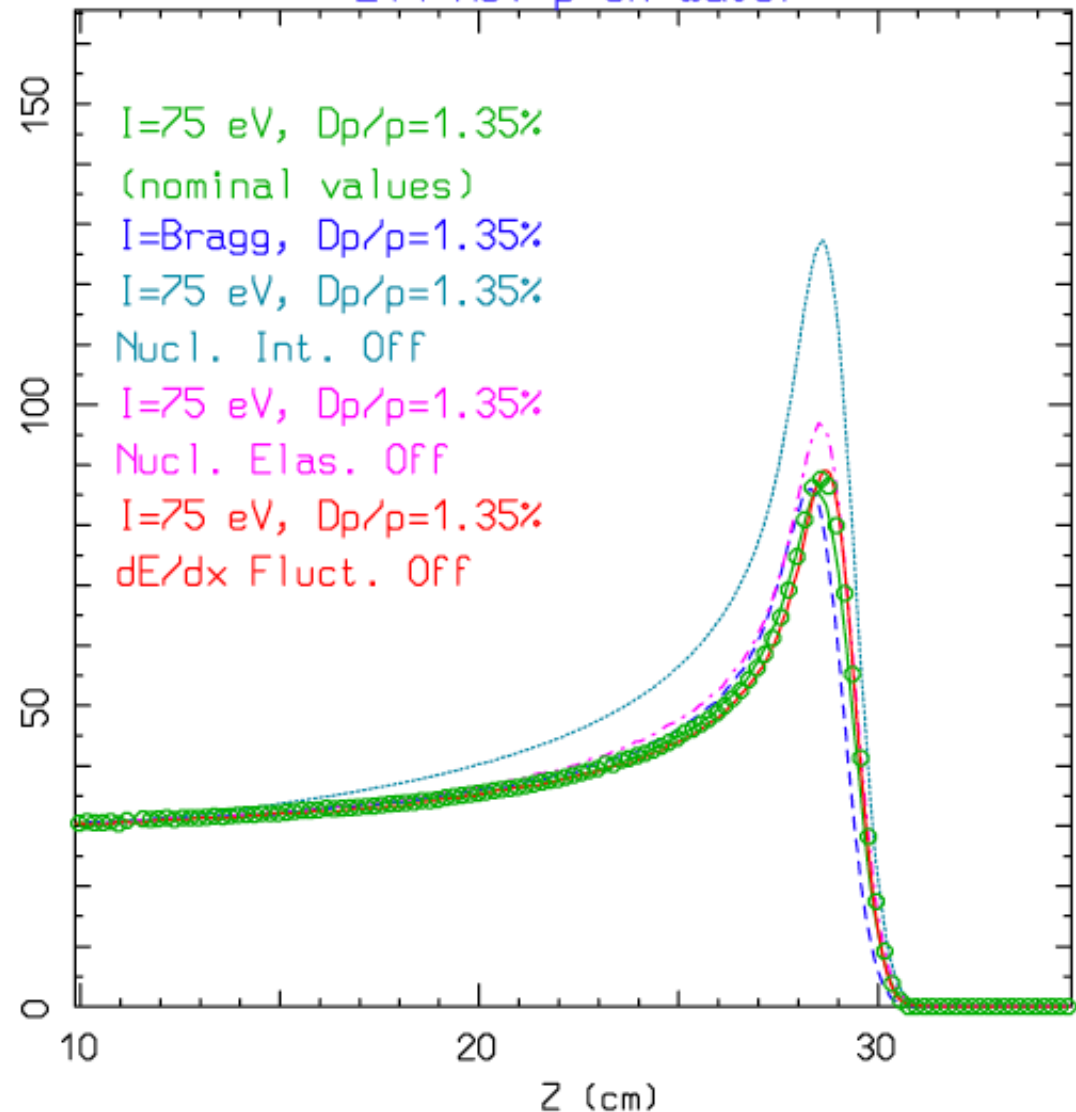


# Playing with a proton beam II part

214 MeV p on Water

Dose vs depth  
energy deposition  
in water for a 214  
MeV real p beam  
under various  
conditions.

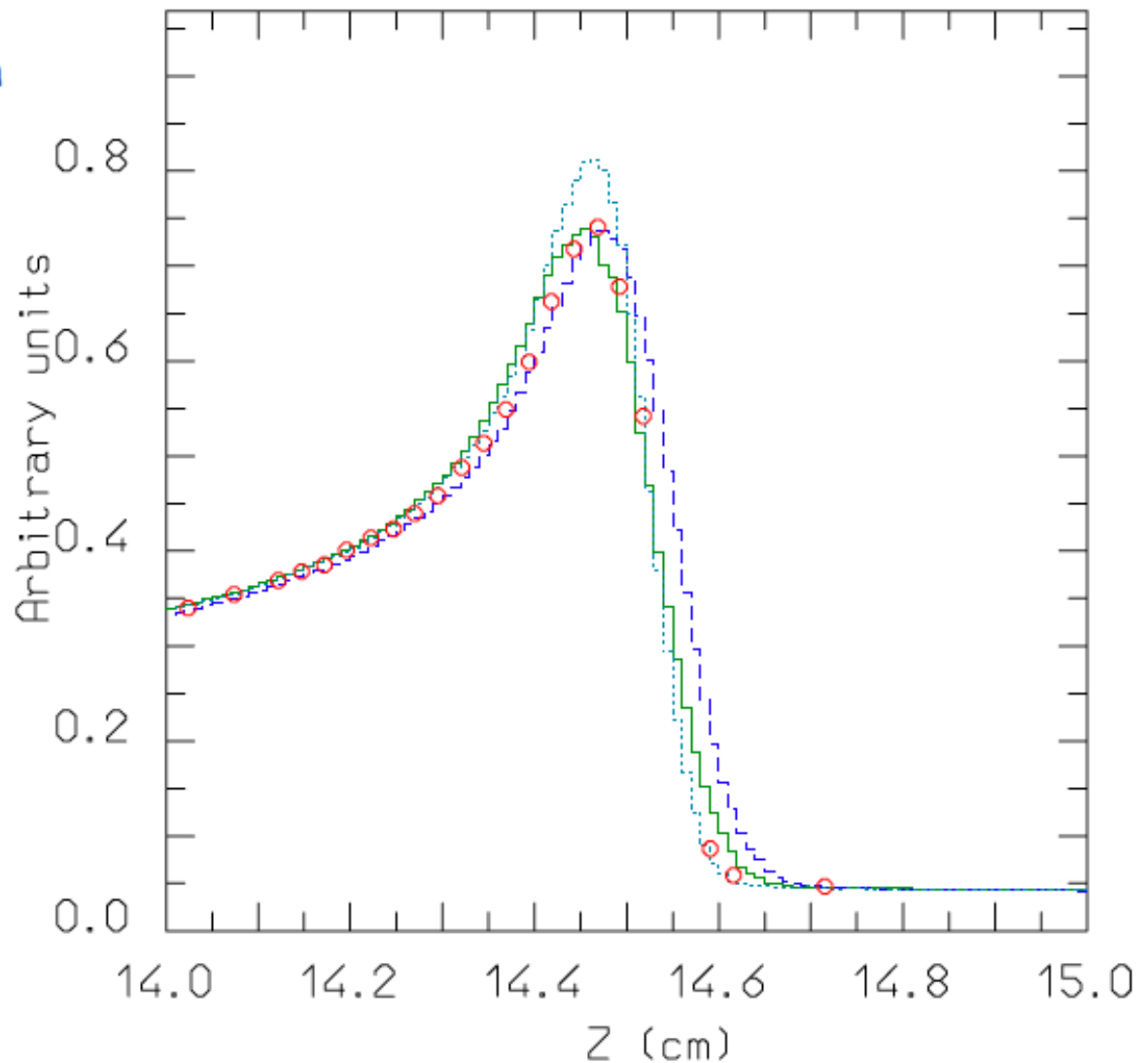
Exp. Data from PSI



## Bragg peaks vs exp. data: $^{12}\text{C}$ @ 270 MeV/n

Close-up of the dose vs depth distribution for 270 MeV/n  $^{12}\text{C}$  ions on a water phantom.

The green line is the FLUKA prediction with the nominal 0.15% energy spread. The dotted light blue line is the prediction for no spread, and the dashed blue one the prediction for  $I$  increased by 1 eV.

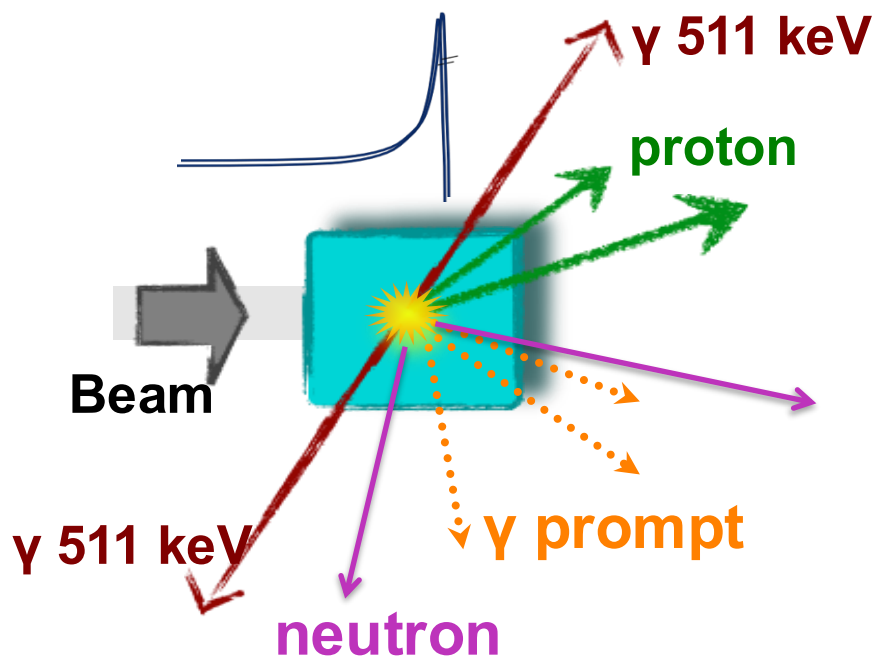


Exp. Data  
Jpn.J.Med.Phys. 18,  
1,1998



**APPENDIX 1:  
FLUKA APPLICATION TO RANGE  
MONITORING IN HANDRONTHERAPY**

# In vivo verification

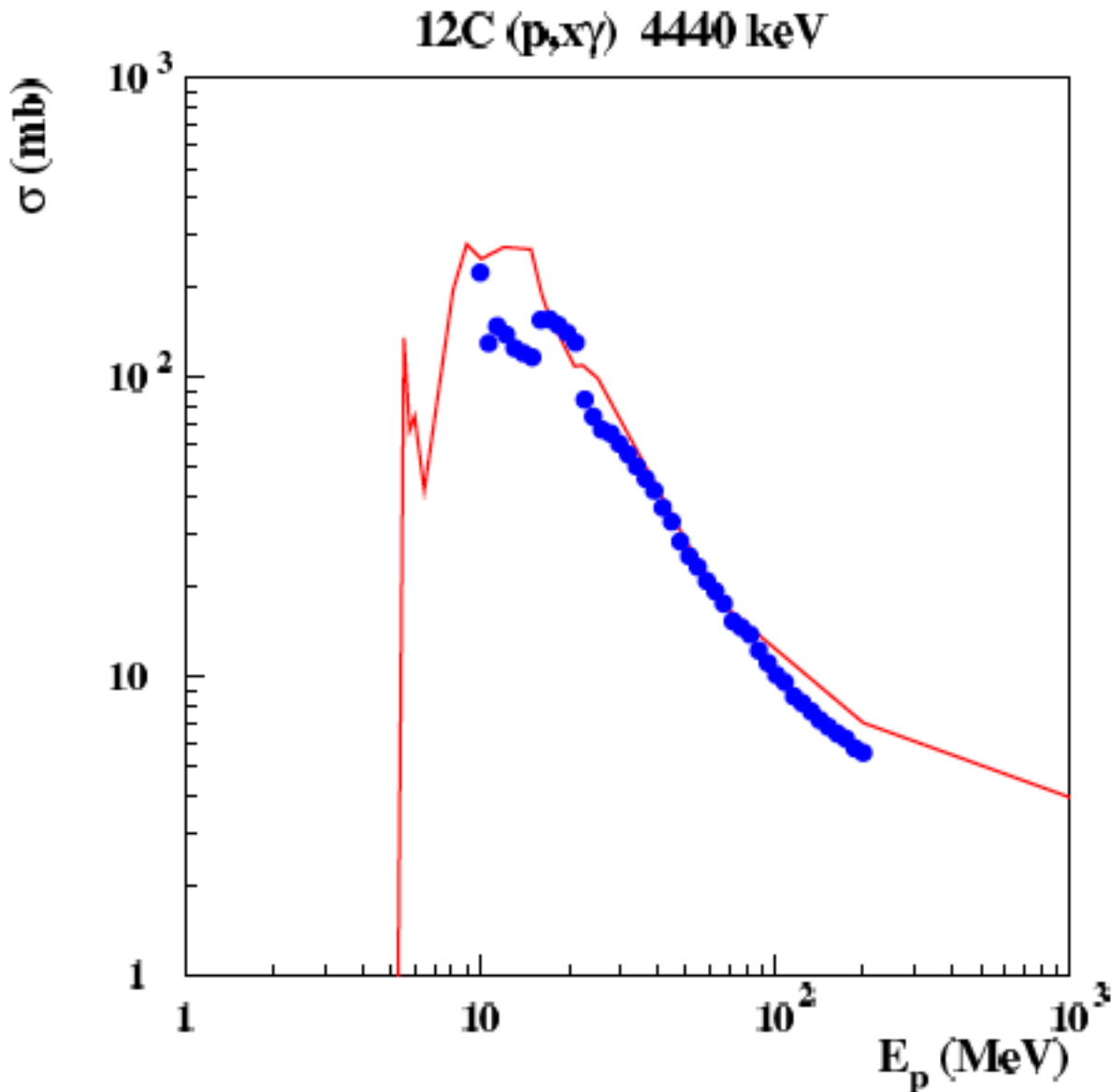


Secondary particle production during treatment can be used to perform range monitoring (and maybe dose monitoring)

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

FLUKA can be successfully used for this purpose

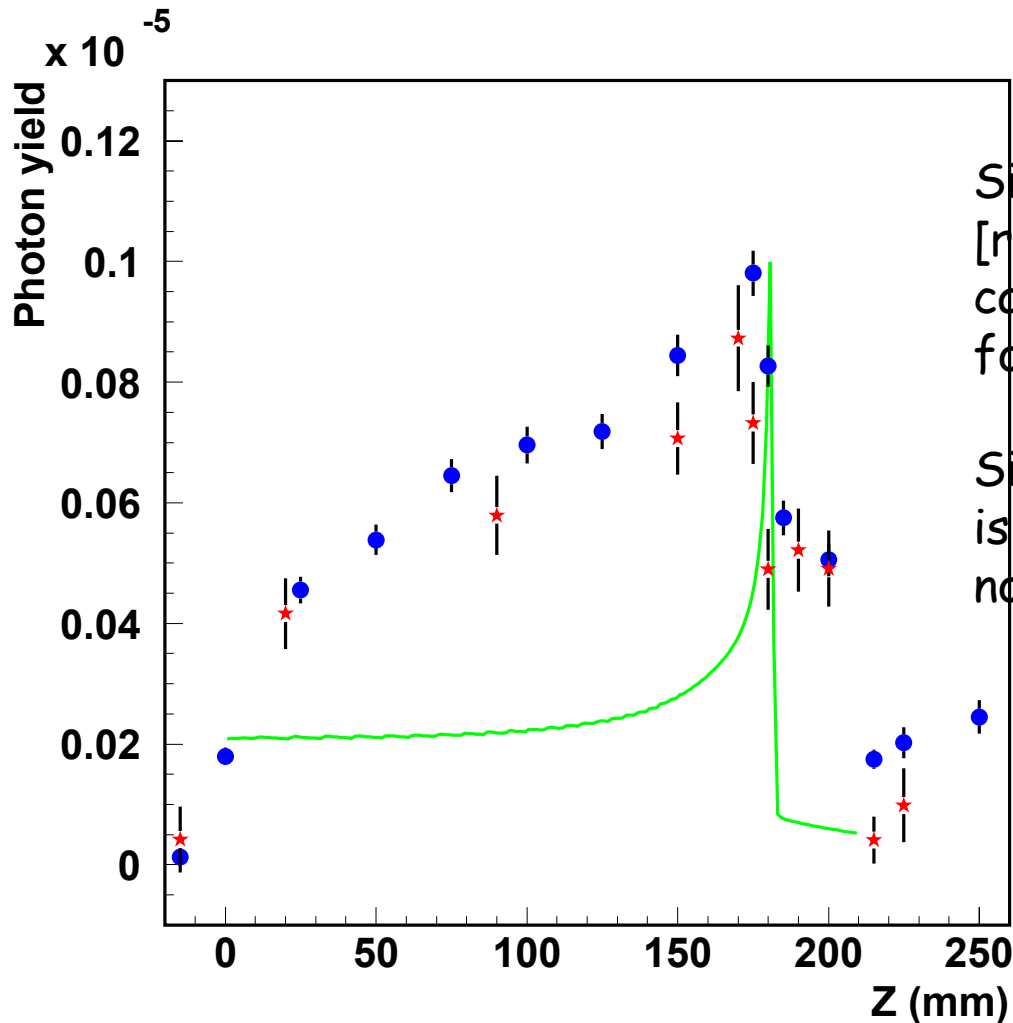
# De-excitation (prompt) $\gamma$ production



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

de-excitation of the 1<sup>st</sup> excited level in  $^{12}\text{C}$ , the 2<sup>nd</sup> excited level in  $^{11}\text{B}$ , the 2<sup>nd</sup> excited level in  $^{11}\text{C}$ .

# In vivo verification: prompt $\gamma$ 's

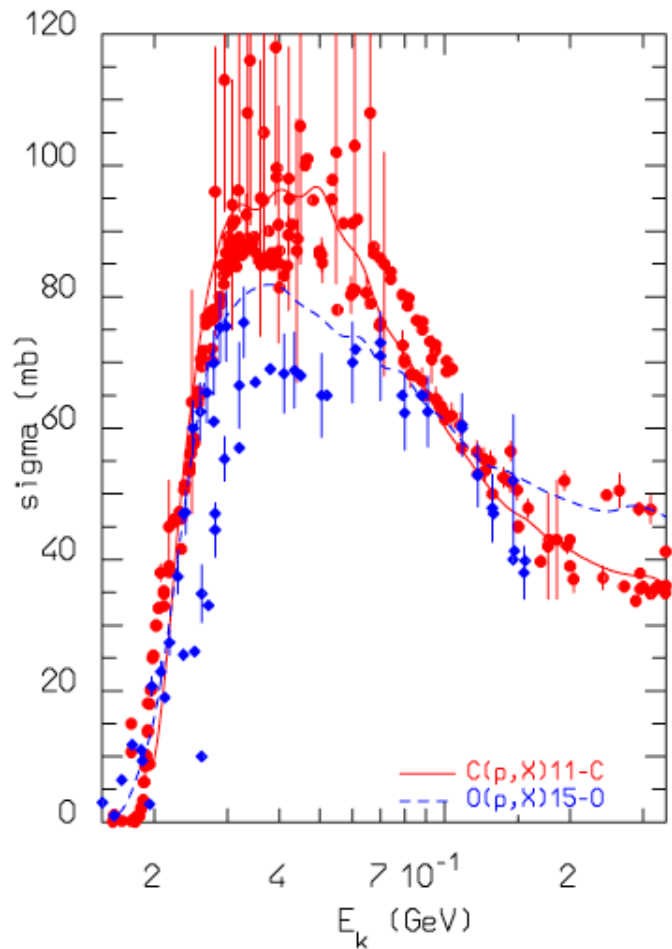


Simulated (blue circles) and measured [red asterisks] data are shown for carbon ion beam at 310 MeV/n for setup SIII (right, on water).

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

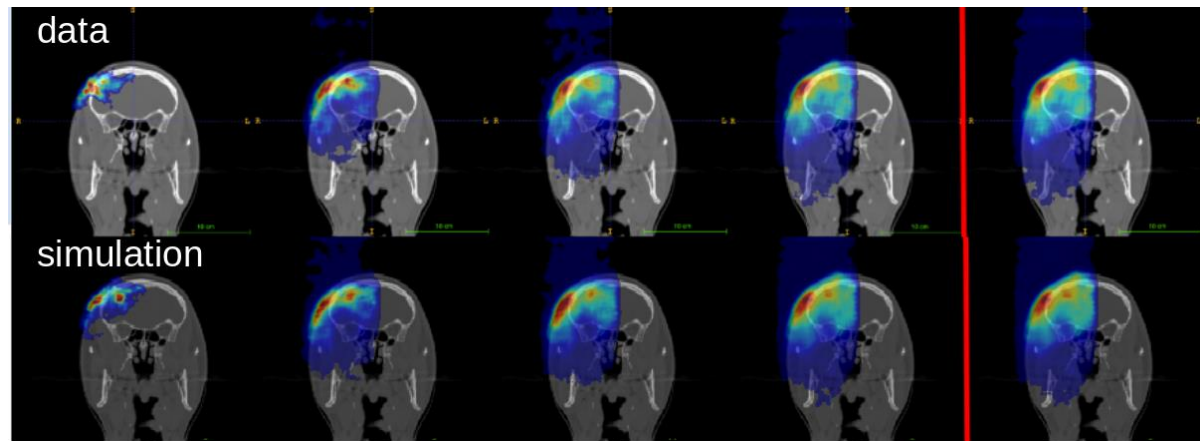
E. Testa Personal Communication, Data Shared on the FP7-ENVISION project Internal Website. (2012).

# About PET in-beam prediction capability



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

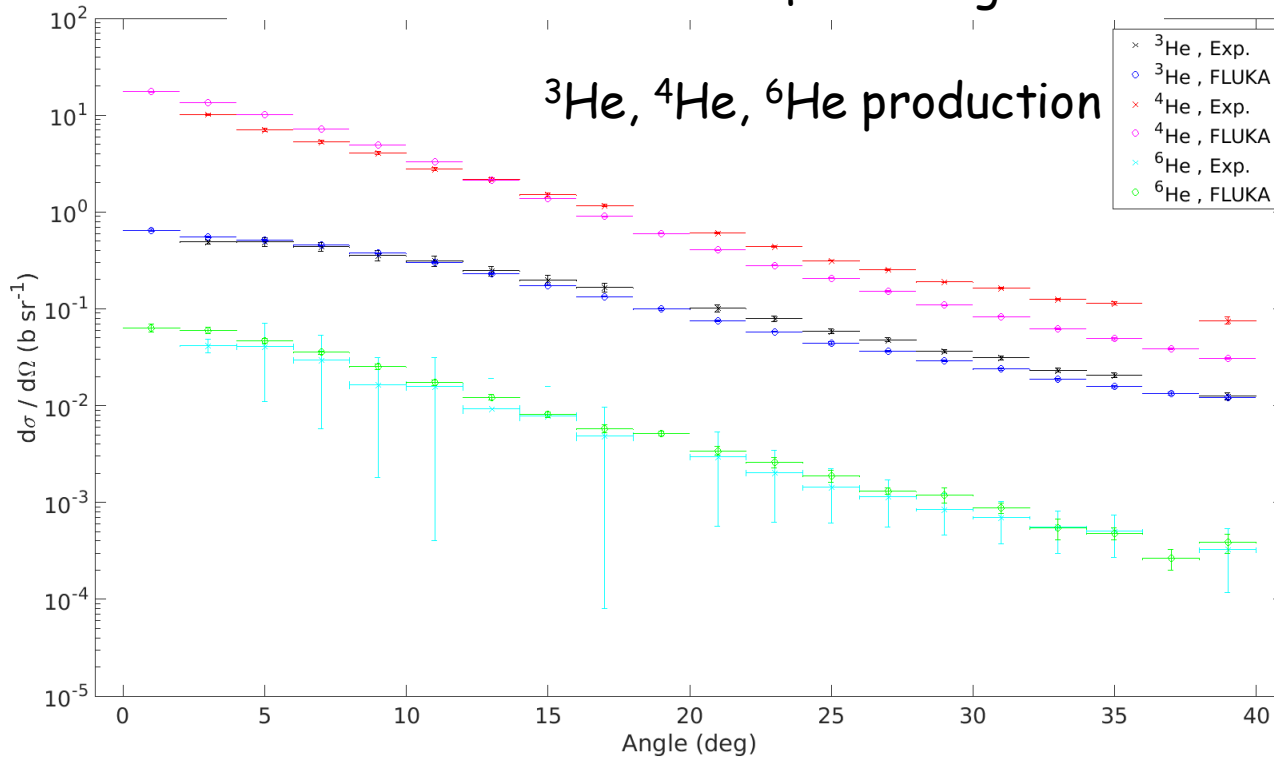
A clinical case



# Charged particle production

50 MeV/u 12C on a 250  $\mu\text{m}$  C target

G. Aricò (CERN/OMA)



Fluka vs Exp

Compare:

Blue - Black

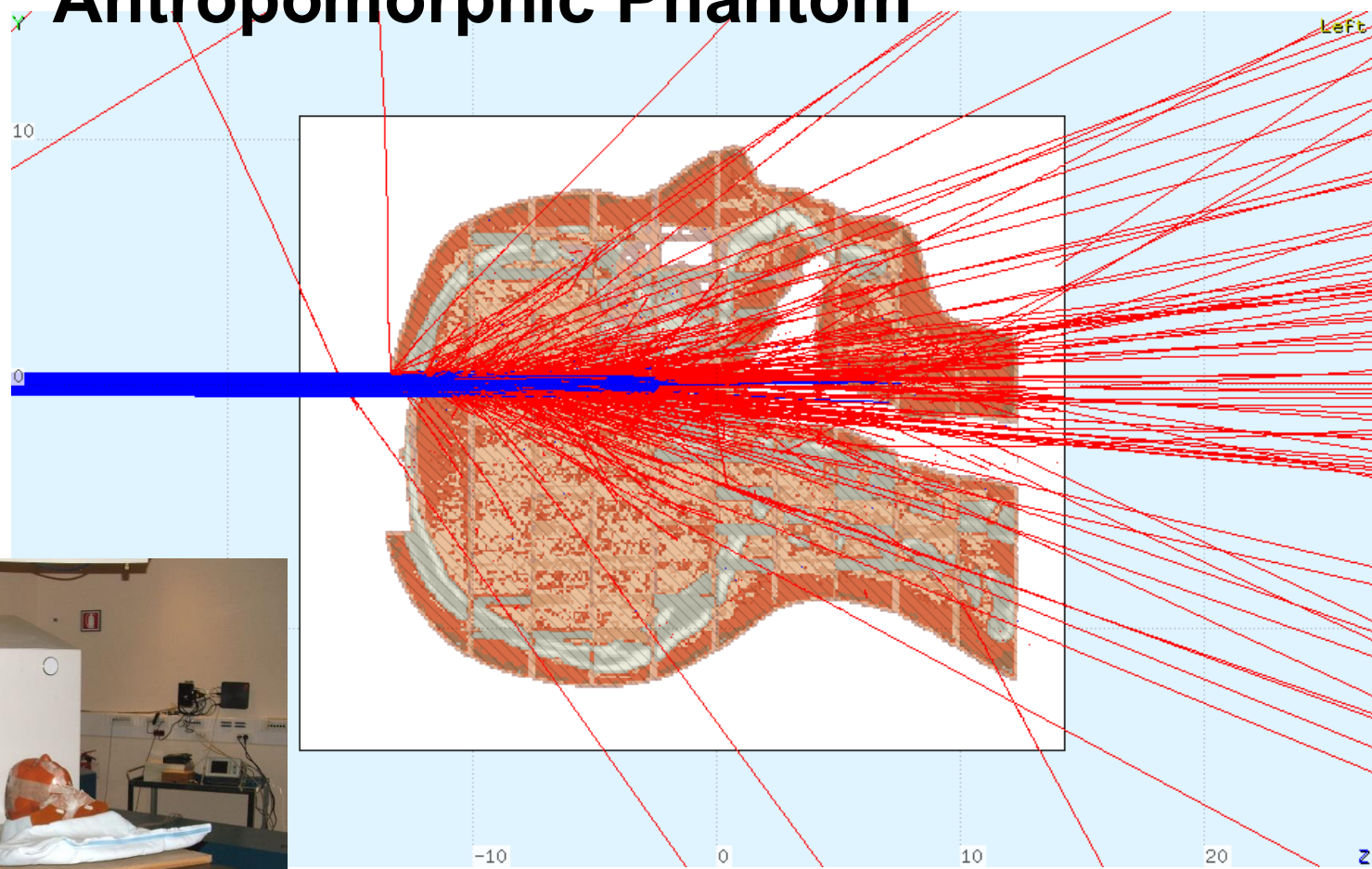
Magenta - Red

Green - Cyan

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

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

Inside





# **APPENDIX 2: HOW TO INTERFACE RADIOBIOLOGICAL DATABASES**

# 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**:

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

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:

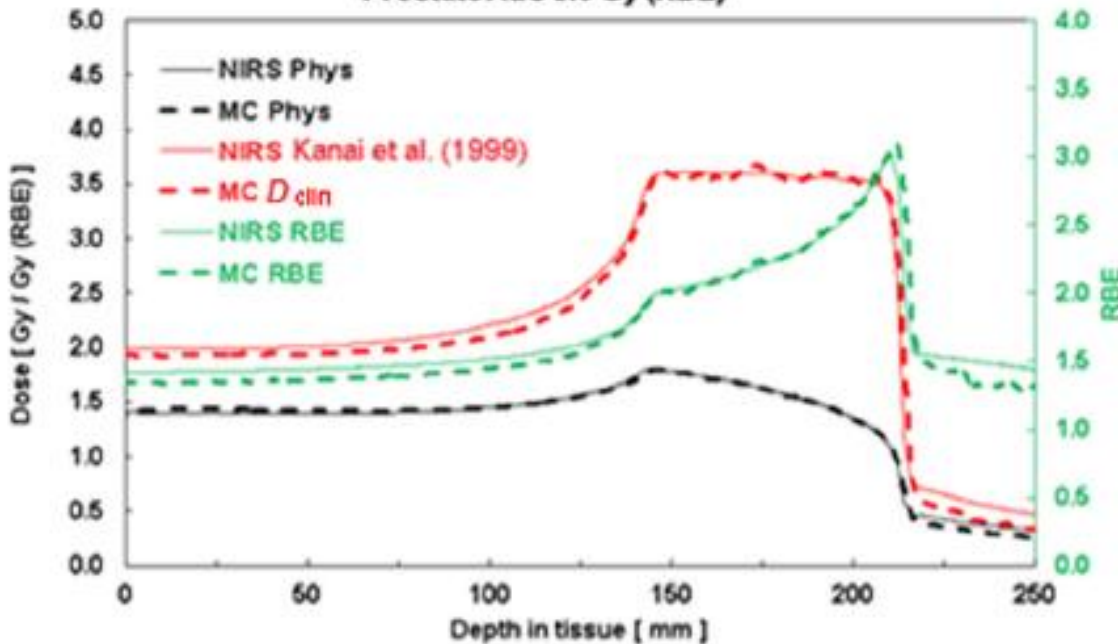
$$S = \exp(-\bar{\alpha}\bar{D} - \bar{\beta}\bar{D}^2)$$

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

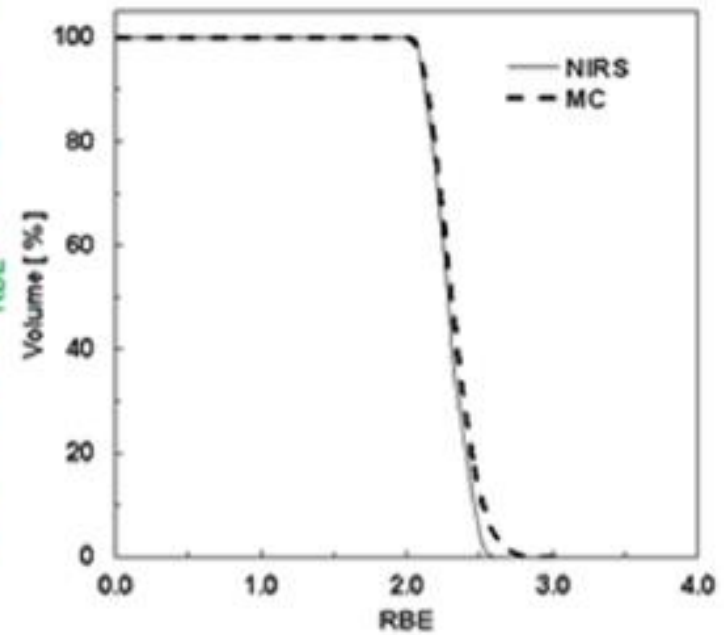
CNAO

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

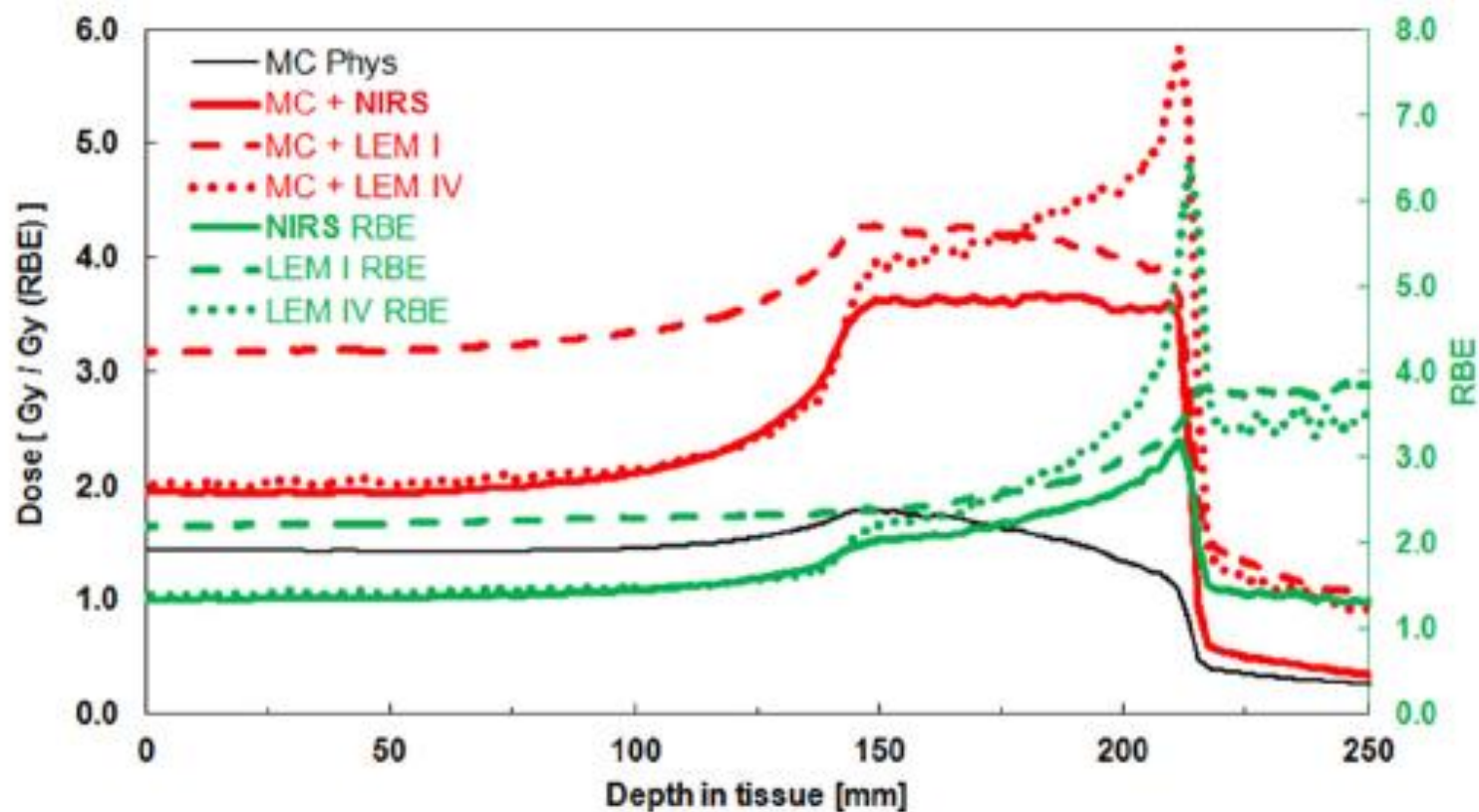
Prostate AdC 3.6 Gy (RBE)



Prostate AdC 3.6 Gy (RBE)



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.



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**