

FLUKA and its applications in radiotherapy

Aafke Kraan
INFN Pisa

Email: aafke.kraan@pi.infn.it
INFN office 147a

Outline

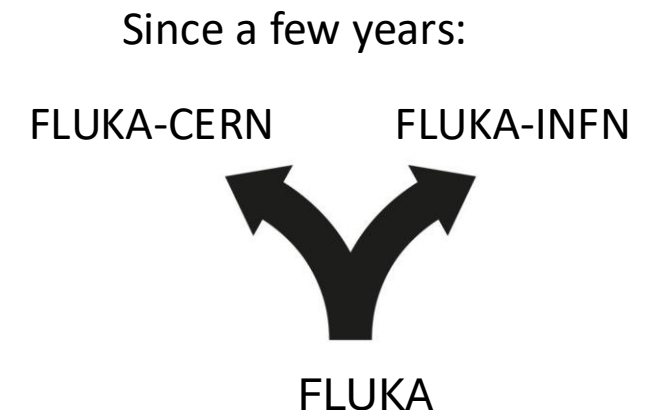
- The FLUKA code
 - History
 - What is FLUKA?
 - Physica applications
 - Physics
 - Electromagnetic physics
 - Hadronic physics
- Learning how to run FLUKA code
 - Website and installation
 - Running FLUKA with Flair: the graphical user interface
- Examples of applications to particle therapy

FLUKA

Application of Monte Carlo to particle transport and interaction:

- 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
- First foundations in 1962 by Johannes Ranft (Leipzig) and Hans Geibel (CERN): MC for high-energy proton beams
- Developed and maintained by various authors, under an INFN-CERN agreement Copyright 1989-2018 CERN and INFN
- From 2019: division...
- About 700.000 lines of code

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



FLUKA

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 μ 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: working principle

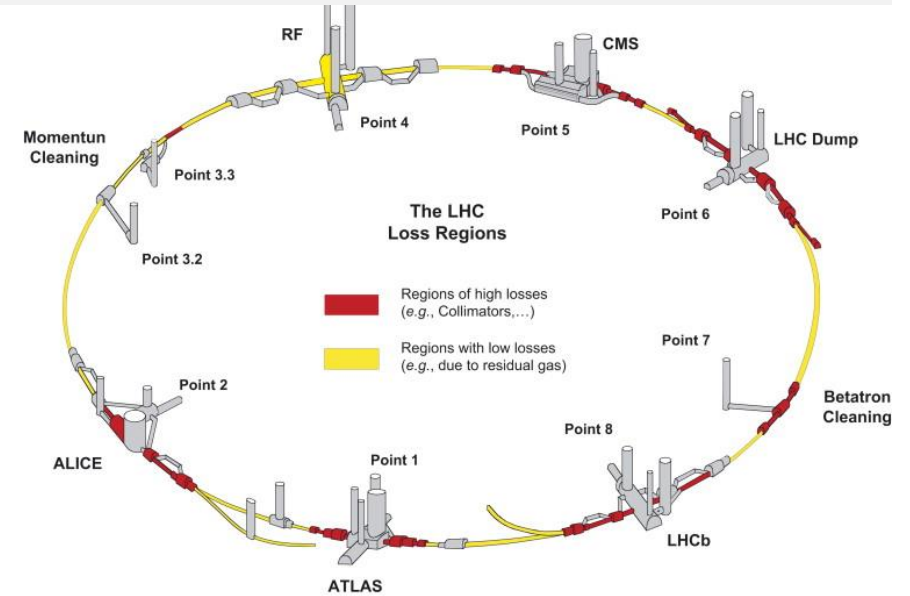
Sound and updated physics models

- Based, as far as possible, on original and well-tested microscopic models
 - Individual particles simulated (protons, neutrons, pions, photons, electrons, ions, etc.)
 - Based on fundamental interactions (strong, electromagnetic, weak forces)
 - Nuclear structure and reaction mechanisms
- 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” → **The user has no responsibility in the choice of physics models!** (different from GEANT4)
- Results in complex cases, as well as properties and scaling laws, arise naturally from the underlying physical models
- Conservation laws implemented at the level of machine accuracy
- 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
- Continuous development
- Easy to use for basic applications

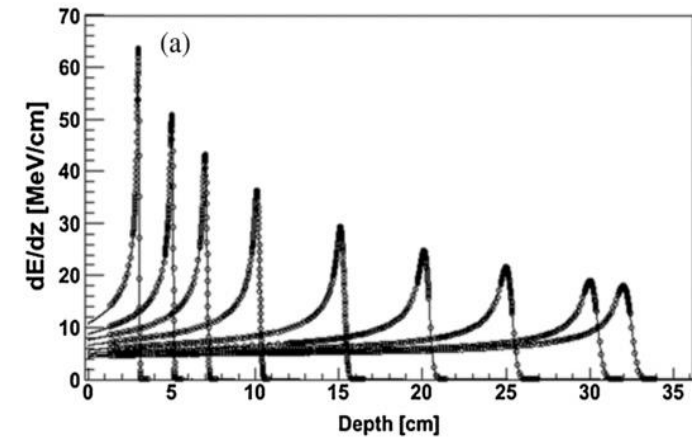
FLUKA: physics applications

- Cosmic ray physics
- Neutrino physics
- Accelerator design (→ n_ToF, CNGS, LHC systems)
- Particle physics: calorimetry, tracking and detector simulation etc→ALICE, ICARUS, ...)
- Accelerator-Driven Systems systems, waste transmutation
- Shielding design
- Dosimetry and radioprotection
- Space radiation
- Hadrontherapy
- Neutronics

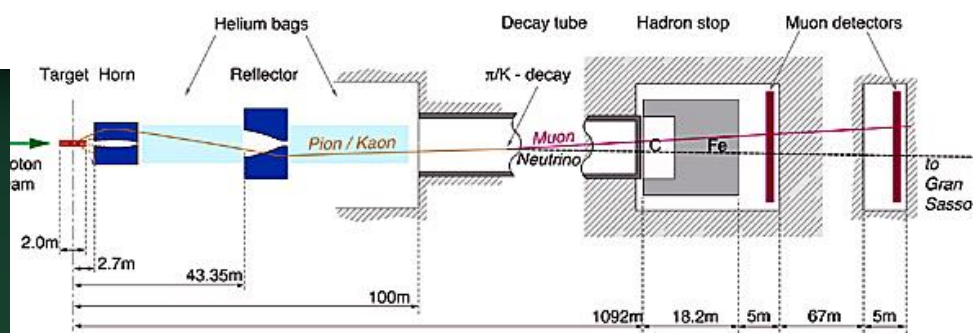
Distribution of high loss and low loss regions around the LHC.



Sarchiapone et al, FLUKA Monte Carlo simulations and benchmark measurements for the LHC beam loss monitors , NIM A 581, Issues 1–2, 2007, 511-516



Molinelli S, et al. Phys Med Biol (2013) 58:3837–47.



Neutrino fluxes at Lab Naz Gran Sasso from the full FLUKA simulation (ICARUS, now at Fermilab)

FLUKA: medical physics applications

- Nuclear Medicine
 - Dosimetry
- Radiotherapy & hadron therapy
 - Simulation of therapy devices (nozzle etc)
 - Treatment simulations
 - Dose simulations
 - Monitoring applications
 - Imaging
 - Brachytherapy
- Shielding/radiation protection
- Commissioning of facilities
- Design of instruments, dosimetry

FLUKA electromagnetic interactions 1

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

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

FLUKA electromagnetic interactions 2

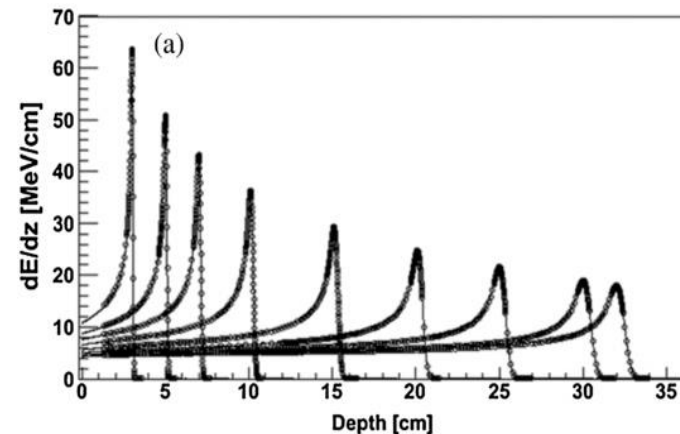
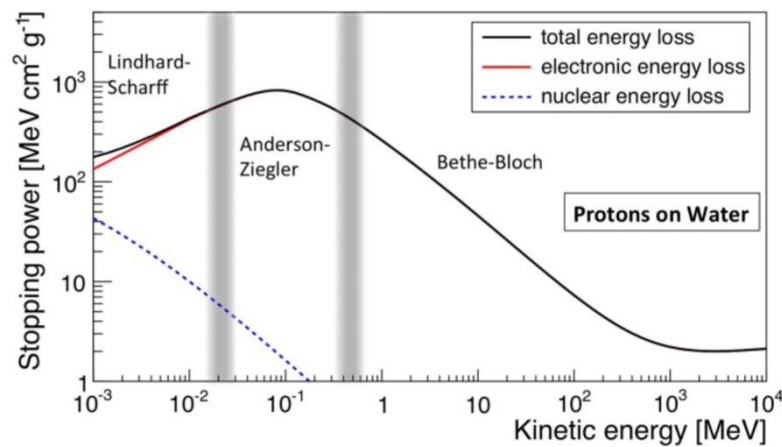
- **Ionization energy losses:**

- 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

Mainly from Coulomb scattering with atomic **electrons**, but particles undergo Coulomb scattering also with atomic **nuclei (nuclear stopping power)**

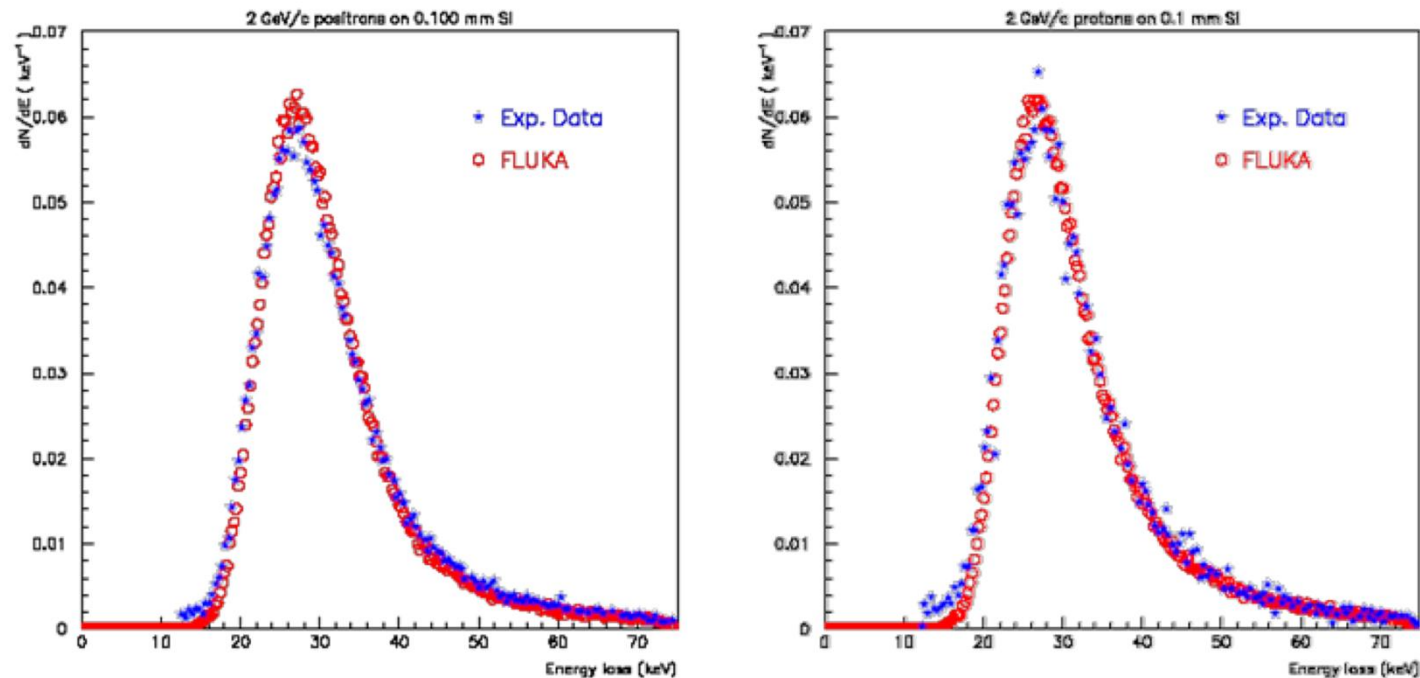


Molinelli S, et al. Phys Med Biol (2013) 58:3837–47.

NB not only electromagnetic interactions make the Bragg peak shape, also nuclear...

FLUKA electromagnetic interactions 3

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



Experimental and calculated energy loss distributions for 2 GeV/c positrons (left) and protons (right) traversing 100 μm of Si, from J.Bak et al. NPB288, 681 (1987)

FLUKA: hadronic interactions

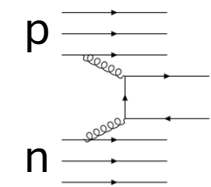
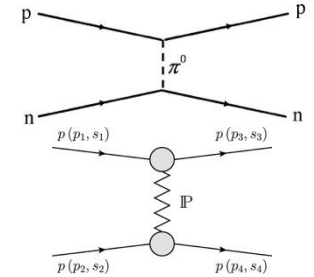
In general there are two kinds of nuclear reactions:

Elastic interactions are those that do not change the internal structure of the projectile/target and do not produce new particles.

- Their effect is to transfer part of the projectile energy to the target (lab system), or equivalently to deflect in opposite directions target and projectile in the Centre-of-Mass system with no change in their energy.
- There is no threshold for elastic interactions.

Non-elastic reactions are those where new particles are produced and/or the internal structure of the projectile/target is changed (e.g. the nucleus is excited).

- A specific non-elastic reaction has usually an energy threshold below which it cannot occur (the exception being neutron capture).

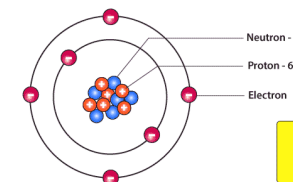


Reminder

Hadron = fundamental particle composite (made of quarks)

Nucleus = bound system of hadrons (protons and neutrons)

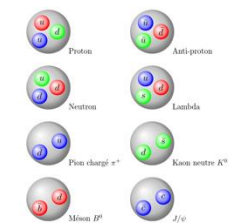
Nucleus



BYJU'S
The Learning App



Hadrons



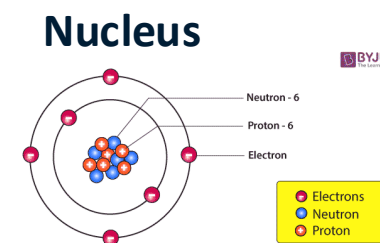
FLUKA: hadronic physics

Hadron-Hadron			
Elastic, exchange Phase shifts data, eikonal	$P < 3-5 \text{ GeV}/c$ Resonance prod and decay	low $E \pi, K$ Special	High Energy DPM hadronization
Hadron-Nucleus		Nucleus-Nucleus	
PEANUT Sophisticated GINC Gradual onset of Glauber-Gribov multiple interactions Preequilibrium Coalescence		$E < 0.1 \text{ GeV}/u$ BME Complete fusion+ peripheral	$0.1 < E < 5 \text{ GeV}/u$ rQMD-2.4 modified new QMD
		$E > 5 \text{ GeV}/u$ DPMJET DPM+ Glauber+ GINC	
Evaporation/Fission/Fermi break-up γ deexcitation			

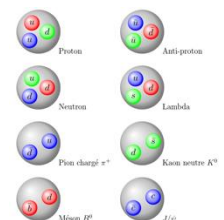
Figure from INFN
Milano

Hadron = fundamental particle composite (made of quarks)
 Nucleus = bound system of hadrons (protons and neutrons)

First, hadron-hadron interactions must be understood carefully

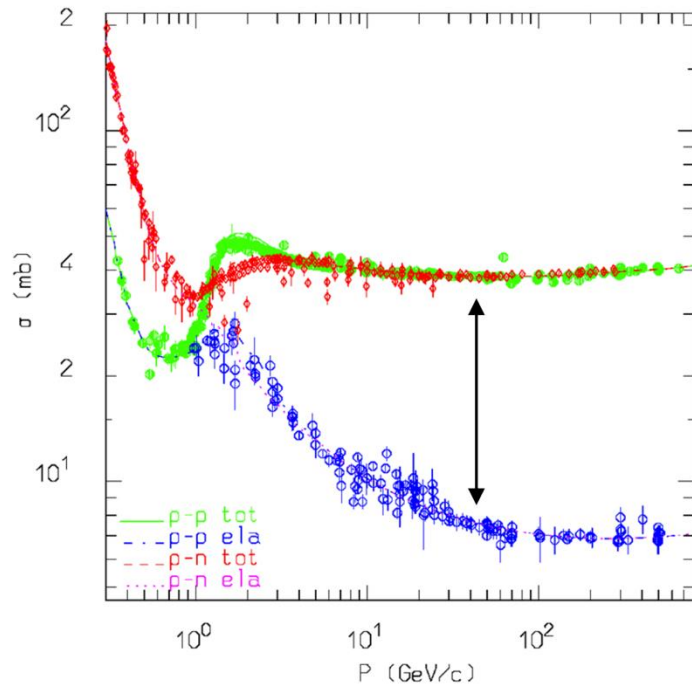


Hadrons



FLUKA: non-elastic interactions

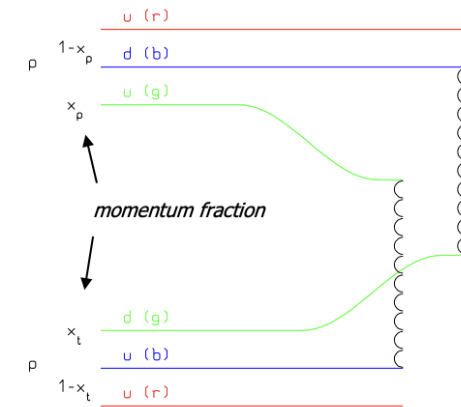
In order to understand Hadron-Nucleus (hA) nuclear reactions, one has to understand first **Hadron-Nucleon (hN)** reactions, since nuclei are made up by protons and neutrons



High Energies: Dual Parton Model/Quark Gluon String Model etc

Interacting strings (quarks held together by the gluon-gluon interaction into the form of a string). Each of the two hadrons splits into **2 colored partons** → combination into **2 colorless chains** → **2 back-to-back jets**.

Each jet is then **hadronized** into physical hadrons.

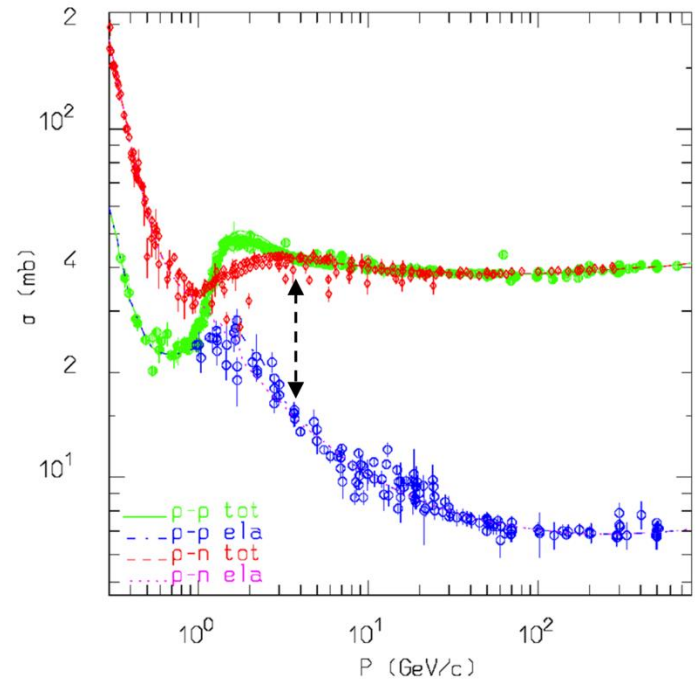


Adapted from:

https://indico.cern.ch/event/956531/contributions/4020228/attachments/2122494/3572697/20_Hadronic_interactions_2020_online.pdf

FLUKA: non-elastic interactions

In order to understand Hadron-Nucleus (hA) nuclear reactions, one has to understand first **Hadron-Nucleon (hN)** reactions, since nuclei are made up by protons and neutrons



Intermediate Energies

All reactions proceed through an **intermediate state** containing at least one resonance (dominance of the $\Delta(1232)$ resonance and of the N^* resonances)

$N_1 + N_2 \rightarrow N_1' + N_2' + \pi$ threshold around 290 MeV, important above 700 MeV

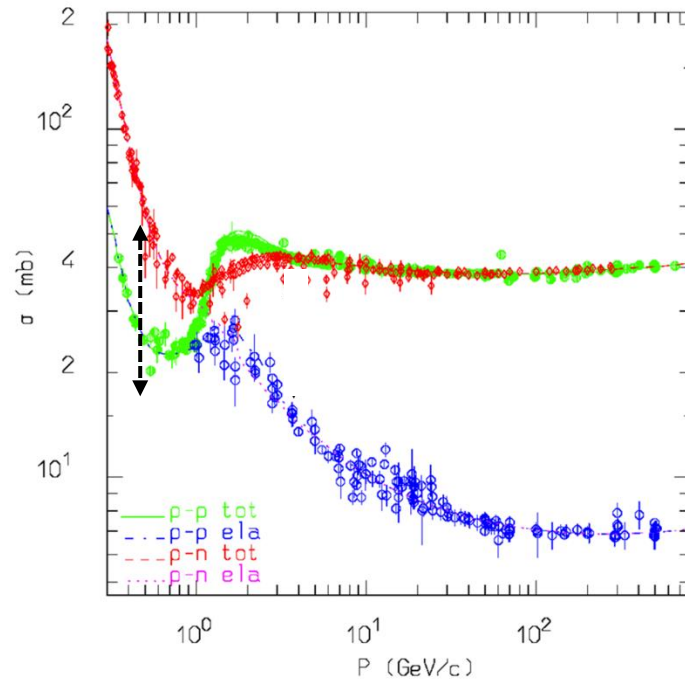
$\pi + N \rightarrow \pi' + \pi'' + N'$ opens at 170 MeV

Adapted from:

https://indico.cern.ch/event/956531/contributions/4020228/attachments/2122494/3572697/20_Hadronic_interactions_2020_online.pdf

FLUKA: non-elastic interactions

In order to understand Hadron-Nucleus (hA) nuclear reactions, one has to understand first **Hadron-Nucleon (hN)** reactions, since nuclei are made up by protons and neutrons



Low energies:

no rigorous models exist to describe them, most MC codes use phenomenological models...

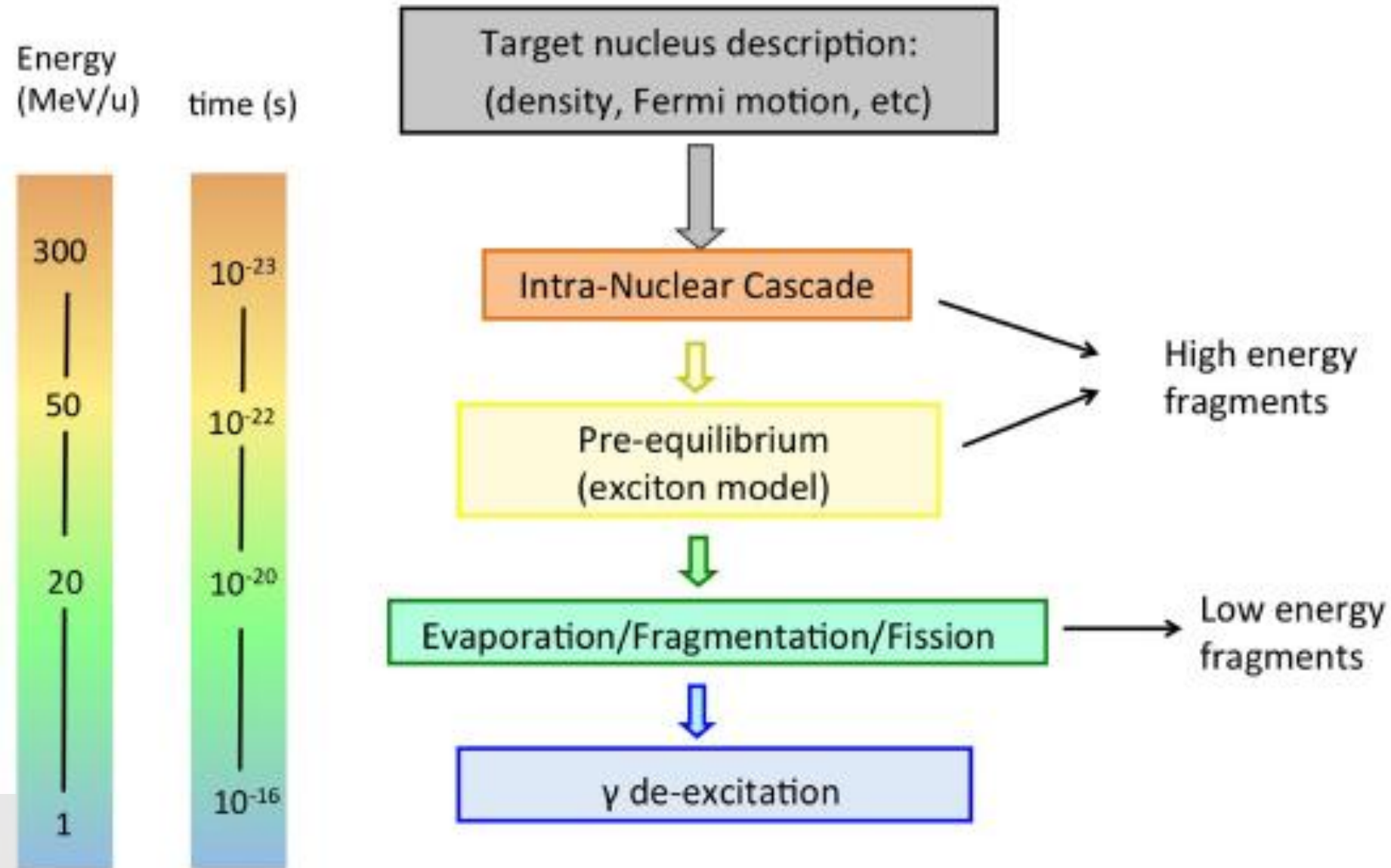
(most relevant for hadron therapy)
(50-250 MweV/u for protons and 100-450 MeV/u for carbon ions)

Figure from:
https://indico.cern.ch/event/956531/contributions/4020228/attachments/2122494/3572697/20_Hadronic_interactions_2020_online.pdf

FLUKA hadronic physics: hadron-nucleus interaction stages

Nuclear interaction stages

PEANUT model



AK, Front.Oncology, 2015,
adapted from A. Ferrari

FLUKA hadronic physics: nucleus-nucleus interaction models

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

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.*)

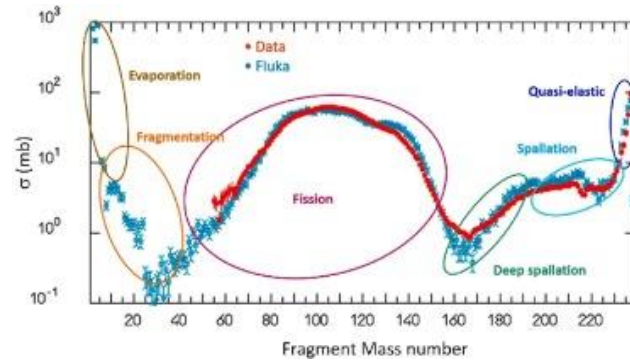
$E < 0.1 \text{ GeV/n}$

Boltzmann Master Equation (BME) theory

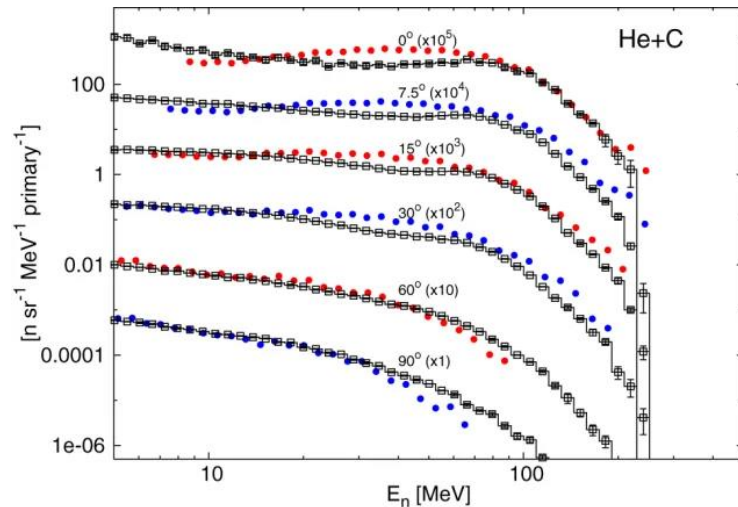
BME (original code by E.Gadioli *et al.*,
FLUKA-implementation by F.Cerutti *et al.*)

FLUKA hadronic physics: nuclear interactions

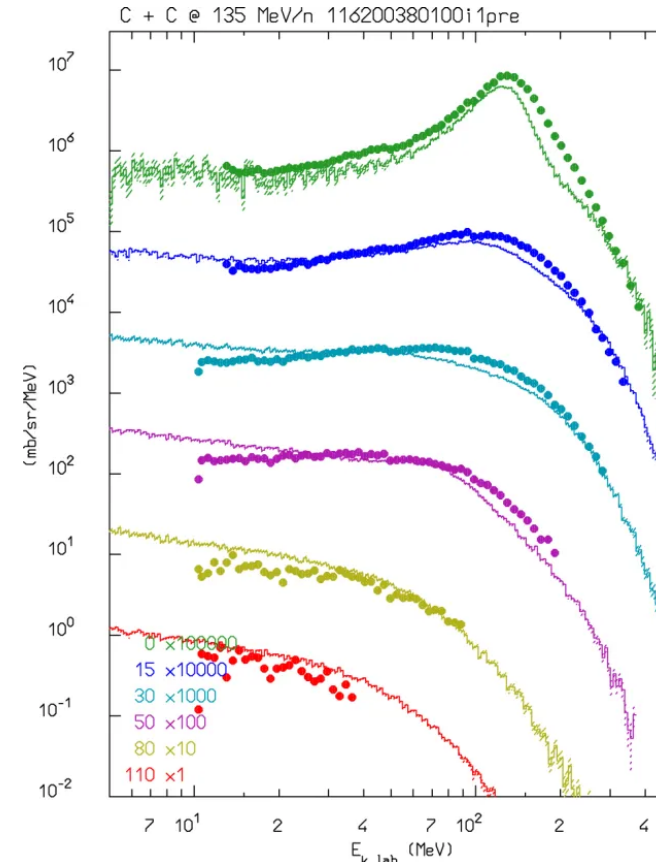
Extensively validated (3 examples here)



Fragment mass distribution from 1 GeV protons on ^{238}U , from EPJ - Nuclear Sciences & Technologies 10, 2024, The FLUKA code: Overview and new developments



Double differential spectra of neutrons from 100 MeV/n alphas on a thick carbon target, scaled as indicated at the different angles with respect to the beam direction., Battistoni G, et al, The FLUKA Code: An Accurate Simulation Tool for Particle Therapy. Front. Oncol. 6:116.

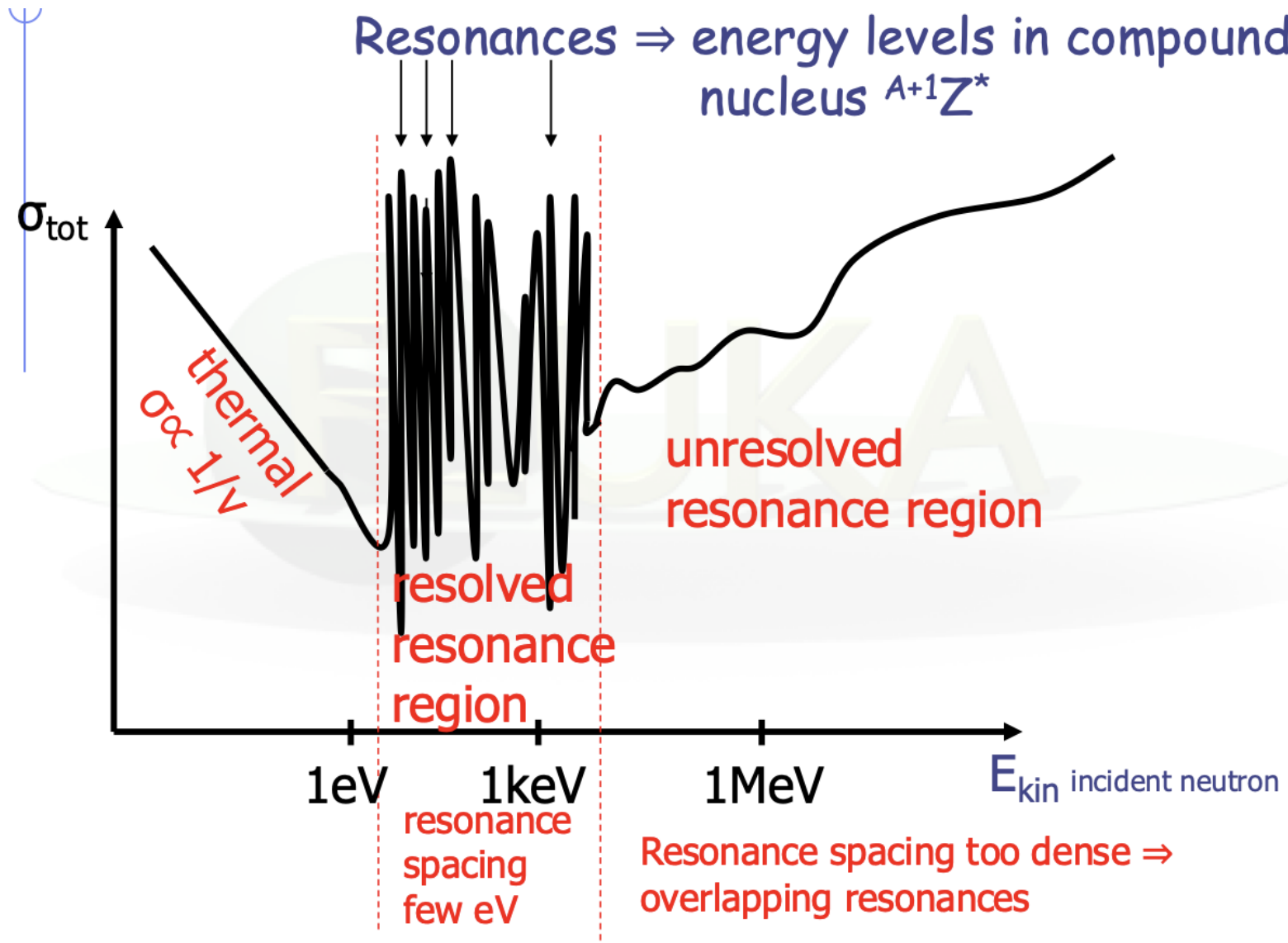


Sato H, et al, Measurements of double differential neutron production cross sections by 135 Mev/nucleon He, C, Ne and 95 Mev/nucleon Ar ions. *Phys Rev C* (2001)

Double differential neutron production for 135 MeV/n ^{12}C interactions in a thin carbon target. FLUKA–RQMD predictions as a function of neutron energy at several detection angles are shown as histograms and compared with experimental data (dots) from Ref. (57).

However even in FLUKA not all cross sections are perfectly predicted, for example some uncertainties in the context of range monitoring studies in particle therapy (some of the beta+ emitters, prompt gamma's)

FLUKA hadronic physics: neutron cross section



FLUKA hadronic physics: Evaluated Nuclear Data Files

- Evaluated nuclear data files (ENDF, JEFF, JENDL...)
 - comprehensive libraries of nuclear reaction and structure data, representing best-fit values derived from experimental measurements and theoretical modeling.
 - typically used **only for neutron cross sections**: they provide neutron σ (cross sections) for $E < 20 \text{ MeV}$ for all channels
 - σ 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. So these programs act as translators.
They take the "raw" ENDF files and process them, so they can be used in a MC code.

Point-wise and Group-wise cross sections

- In neutron transport codes in general two approaches used:
 - point-wise (“continuous” cross sections): Point-wise follows cross section precisely (continuous, detailed energy-dependent data) but is can be time and memory consuming
 - group-wise transport: average data over specific energy bins. 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 hadronic physics: Evaluated Nuclear Data Files

Evaluated Nuclear Data File (ENDF) Database Version of 2026-01-09

Software Version of 2024-10-08



News & History
2026/02 New library: [TENDL-2025](#) TALYS-based Evaluated Nuclear Data Library, 2025
2025/08 New libraries:
1) [FENDL-3.2c](#) Fusion Evaluated Nuclear Data Library, IAEA, 2025 [page]
2) [JEFF-4.0](#) Evaluated nuclear data library of the OECD Nuclear Energy Agency, 2025 [page]
2025/07 Updated libraries:
[JEFF-4.0](#) Evaluated nuclear data library of the OECD Nuclear Energy Agency, 2025 [page]
[TENDL-2025](#) TALYS-based Evaluated Nuclear Data Library, 2025 [page]
[FENDL-3.2c](#) Fusion Evaluated Nuclear Data Library, IAEA, 2025 [page]

Core nuclear reaction database contain recommended, evaluated cross sections, spectra, angular distributions, fission product yields, photo-atomic and thermal scattering law data, with emphasis on neutron induced reactions. The data were analyzed by experienced nuclear physicists to produce recommended libraries for one of the national nuclear data projects (USA, Europe, Japan, Russia and China). All data are stored in the internationally-adopted ENDF-6 format maintained by CSEWG. See database summary [\[here\]](#).

Standard Request Examples: [1](#) [2](#) [3](#) [4](#) [5](#) [6](#) [7](#) Go to: [Advanced Request](#); [ENDF-Database Explorer](#); EE-View: [CS](#), [CS1](#), [DA](#)

Parameters:

Target »
Reaction »
Quantity »

[More Parameters...](#)

Libraries: All Selected

How to plot

Major Libraries Special Libraries
 IAEA Project Libraries Archival
 Derived

Options:

Sort by: Reactions Evaluations

Clone Request:

Feedback:

Comments/Questions?

Note:

all criteria are optional (selected by checking)
selected criteria are combined for search with logical **AND**
criteria separated in a field by ";" are combined with logical **OR**
wildcards and intervals are available
pointwise libraries contain reconstructed resonances using parameters from MF=2 and applied Doppler broadening at a given temperature.

Statistics of usage: visits: 4865, requests: 27956, since 06-Jan-2026

Original ENDF libraries and files for FTP downloading: [\[ENDF-Archive\]](#)

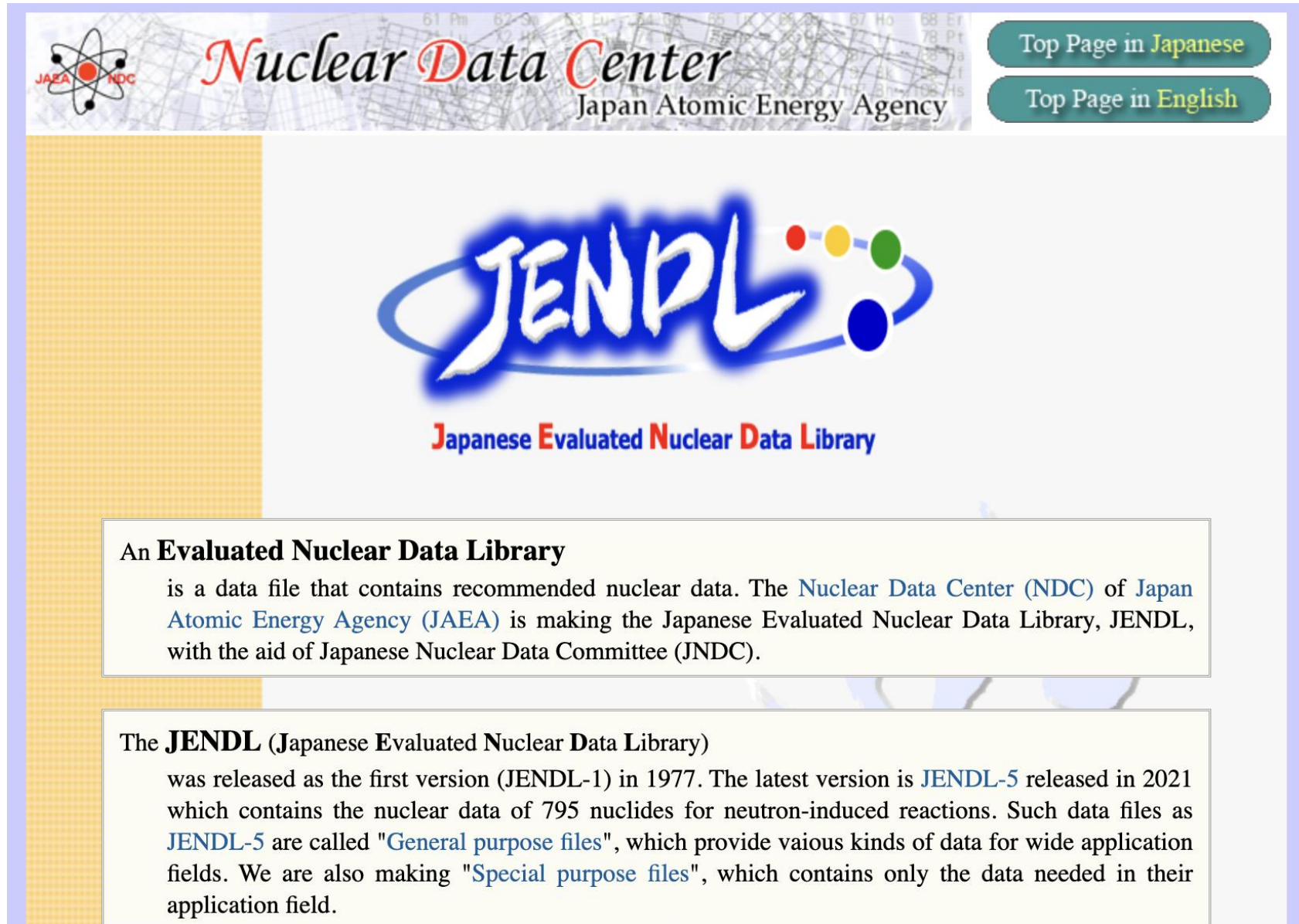
Extensive temperature dependent pointwise libraries: [Point-2018](#) (ENDFB-VIII.0), [Pointwise2020](#) (TENDL-2019)

Database Manager: Roberto Capote Noy, NDS, International Atomic Energy Agency (Roberto.CapoteNoy@iaea.org)

Web and Database Programming: Viktor Zerkov, NDS, International Atomic Energy Agency (nds.contact-point@iaea.org)

Data Source: [IAEA-NDS](#), [WPEC](#), [CSEWG](#), [IPPE](#), [CNDC](#), [JAEA](#), [NRG](#), [CCFE](#), [FZK](#)

FLUKA hadronic physics: Evaluated Nuclear Data Files



The image shows a screenshot of the Nuclear Data Center website. At the top left is the JAEA NDC logo. The main header reads "Nuclear Data Center" in a stylized font, with "Japan Atomic Energy Agency" below it. To the right are two buttons: "Top Page in Japanese" and "Top Page in English". The central focus is the JENDL logo, which consists of the word "JENDL" in a blue, stylized font with a blue swoosh underneath, and five colored dots (red, yellow, green, blue, and purple) to the right. Below the logo is the text "Japanese Evaluated Nuclear Data Library".

An Evaluated Nuclear Data Library
is a data file that contains recommended nuclear data. The [Nuclear Data Center \(NDC\)](#) of [Japan Atomic Energy Agency \(JAEA\)](#) is making the Japanese Evaluated Nuclear Data Library, JENDL, with the aid of Japanese Nuclear Data Committee (JNDC).

The **JENDL (Japanese Evaluated Nuclear Data Library)** was released as the first version (JENDL-1) in 1977. The latest version is [JENDL-5](#) released in 2021 which contains the nuclear data of 795 nuclides for neutron-induced reactions. Such data files as [JENDL-5](#) are called "[General purpose files](#)", which provide various kinds of data for wide application fields. We are also making "[Special purpose files](#)", which contains only the data needed in their application field.

FLUKA hadronic physics: Evaluated Nuclear Data Files

← → ↻ oecd-nea.org/dbdata/jeff/ 🔍 ☆ 📁 | a Relaunch



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[SINBAD](#)

Nuclear Data Links

[IAEA NDS \(Vienna\)](#)

[NNDC \(Brookhaven\)](#)

[NRDC](#)

More info on

[Evaluated nuclear data](#)

[Experimental nuclear data](#)

[Nuclear structure data](#)

Joint Evaluated Fission and Fusion (JEFF) Nuclear Data Library



JEFF-DOCS
1982 - To date



EFF-DOCS
1984 - To date



JEFF Reports
1985 - To date

JEFF library releases

The JEFF suite of nuclear data libraries contains a number of different data types, including neutron and proton interaction data, radioactive decay data, fission yields data, and thermal scattering law data.

JEFF-3.3 : Released in November 2017

The JEFF-3.3 nuclear data library has been officially released in November 2017. It includes a thorough update to its neutron, decay data and fission yields library and adopts other sub-libraries (incident proton, alpha, gamma, triton, He-3 and deuteron) from TENDL-2017. Access the [JEFF-3.3 release](#).

JEFF collaboration

The JEFF project meets twice a year, in spring and fall, during the NEA Nuclear Data Week in a 4 to 5 day technical programme, with the aim to promote co-operation between experimentalists, evaluators and end-users of nuclear data involved in both projects.

Contact

Test Libraries

[JEFF-4T5 \[2025\]](#)

[JEFF-4T4 \[2024\]](#)

[JEFF-4T3 \[2023\]](#)

[JEFF-4T2 \[2022\]](#)

[JEFF-4T1 \[2021\]](#)

[JEFF-4T0 \[2020\]](#)

Official Releases

[JEFF-3.3 \[Latest Release\]](#)

[JEFF-3.2](#)

[JEFF-3.1.2](#)

[JEFF-3.1.1](#)

[JEFF-3.1](#)

[JEFF-3.0](#)



[JEF-2.2](#)

JEFF Documentation

[JEFF docs](#) 🔒

FLUKA: website

← → ↻ fluka.eu/Fluka/www/html/fluka.php? ☆ 📁 📄 a Relaunch to update ⋮



Fluka >> Documentation >> **Download** My Account Tools >> Discuss >> Team >>

Quick launch:

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Last version:

FLUKA 2025.1.2, November 12th 2025
(last respin 2025.1.2)
flair-2.3-0f 05-May-2025

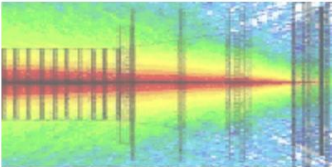
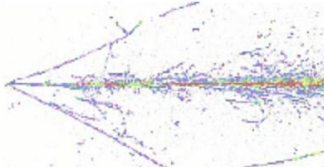
News:

-- Fluka Course and new Fluka Release (10.11.2025)
New Beginner Course: Dresden, 23-27 March 2026 [Register Here](#)

FLUKA 2025.1.2 has been released.

A A A 

FLUKA is a fully integrated particle physics MonteCarlo simulation package. It has many applications in high energy experimental physics and engineering, shielding, detector and telescope design, cosmic ray studies, dosimetry, medical physics and radio-biology.



FLUKA: website

fluka.eu/Fluka/www/htmls/fluka.php?id=secured_intro



Relaunch to update

Quick launch:

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Installation list
Manual Online
Resources
Contact us

Last version:

FLUKA 2025.1.2, November 12th 2025
(re-spin 2025.1.2)
2.3-Of 05-May-2025

News:

FLUKA Course and new FLUKA base
(11.2025)
Beginner Course: Dresden, 23-27
March 2026 [Register Here](#)

FLUKA 2025.1.2 has been released.

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Important Note:

In order to be able to download software from the FLUKA website it is **mandatory to be registered as FLUKA user**. Follow the registration process or proceed to the download area if you already are a registered FLUKA user.

Until you register you will have access to certain places on the website.

FLUKA user registration:

If you don't have your FUID (i.e. **fuid-XXXX**) assigned:

Educational/research users:

[REGISTER](#)

Commercial users:

[REGISTER](#)

FLUKA Downloads:

Download FLUKA binary packages:
(only for registered users)

[DOWNLOAD FLUKA](#)

Download FLUKA trial version:
(only for registered and approved **commercial users**)

[DOWNLOAD TRIAL](#)

If you wish to get information concerning your account and/or manage details/password etc. use **Account Info** functions:

[ACCOUNT INFO](#)

FLUKA: input and output

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

FLUKA: input example

- FLUKA is driven by the user almost completely by means of an input file (.inp) which contains directives issued in the form of DATA CARDS
- The standard release provides a simple case to test the installation: example.inp (Production of particles in p-Be collisions with a 50GeV/c proton beam.)
- Different examples are used along this course, which will be varied in different ways for didactic reasons
- For most of basic applications, users do not need to write code
- This is of course not always possible, therefore at some time FLUKA users need to learn how to code and link User Routines...

Simple example of basic input

```

TITLE
FLUKA Course Exercise
*...+...1...+...2...+...3...+...4...+...5...+...6...+...7...+...*
DEFAULTS
BEAM          -3.5 -0.082425  -1.7  0.0  0.0  1.0PROTON
BEAMPOS       0.0  0.0  0.1  0.0  0.0  0.0
  
```

Primary beam

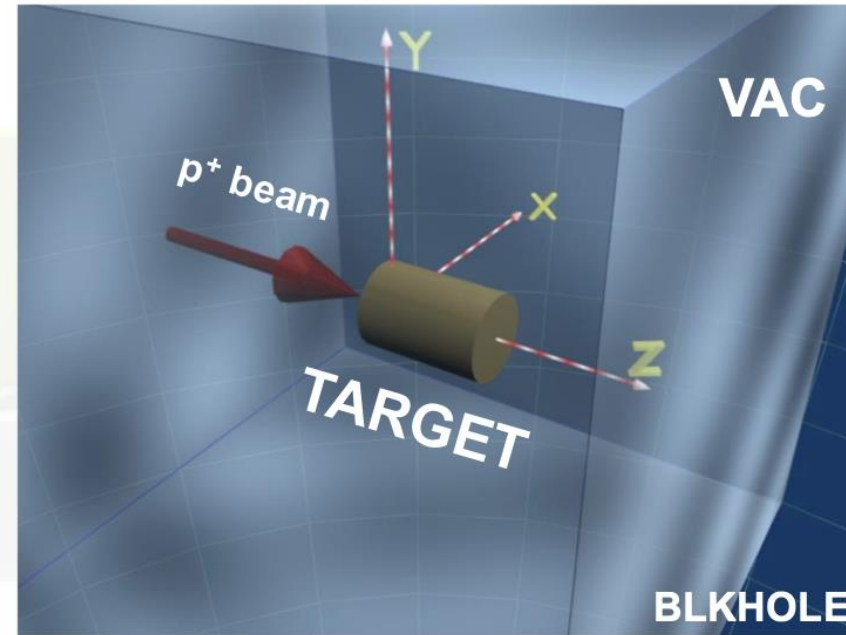
NEW-DEFA

COMBNAME

Geometry

```

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 TARG0.0 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
  
```



Assignin materials

```

*...+...1...+...2...+...3...+...4...+...5...+...6...+...7...+...*
ASSIGNMA      BLCKHOLE  BLKHOLE
ASSIGNMA      VACUUM    VAC
ASSIGNMA      LEAD      TARGET
*...+...1...+...2...+...3...+...4...+...5...+...6...+...7...+...*
RANDOMIZ       1.0
START         10.0  0.0
STOP
  
```

FLUKA 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).*

FLUKA geometry

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 2nd 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.

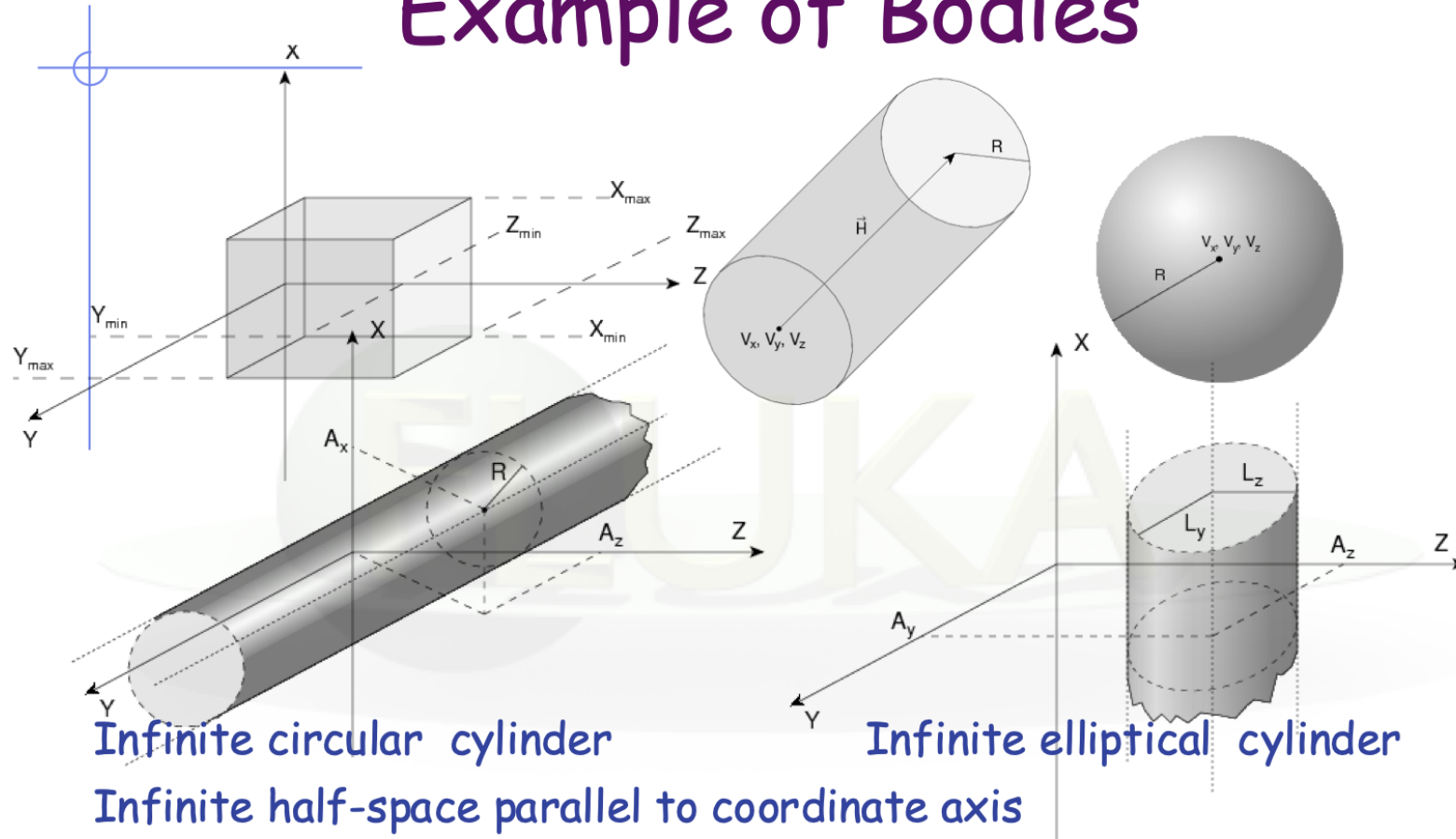
FLUKA geometry

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

FLUKA geometry

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:

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

FLUKA geometry

Concept of Region

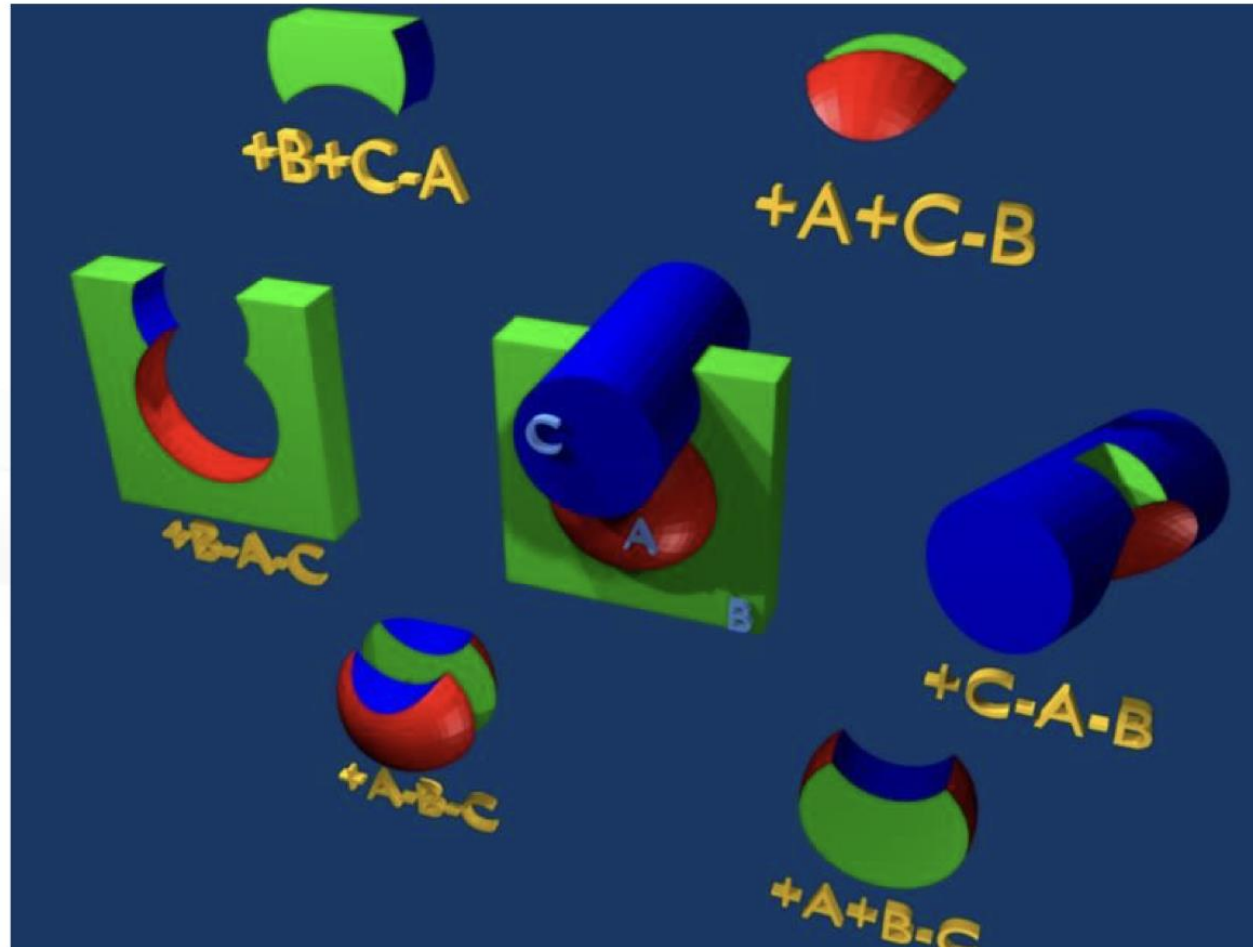
Regions are defined as combinations of bodies obtained by boolean operations:

	Union	Subtraction	Intersection
Free Format		-	+
Fixed format	OR	-	+
Mathematically	\cup	-	\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.

FLUKA geometry

Illustration of Region building using Boolean operators



FLUKA geometry

The screenshot displays the FLUKA geometry software interface. The main window is titled "X + [untitled] - flair" and contains four orthographic views of a particle detector geometry:

- Front View (Red):** Shows a central region with a green circle and a red dot, labeled "VOID".
- Top View (Green):** Shows a central region with a green circle and a red dot, labeled "VOID".
- Left View (Blue):** Shows a central region with a green circle and a red dot, labeled "VOID".
- Back View (Magenta):** Shows a central region with a green circle and a red dot, labeled "VOID".

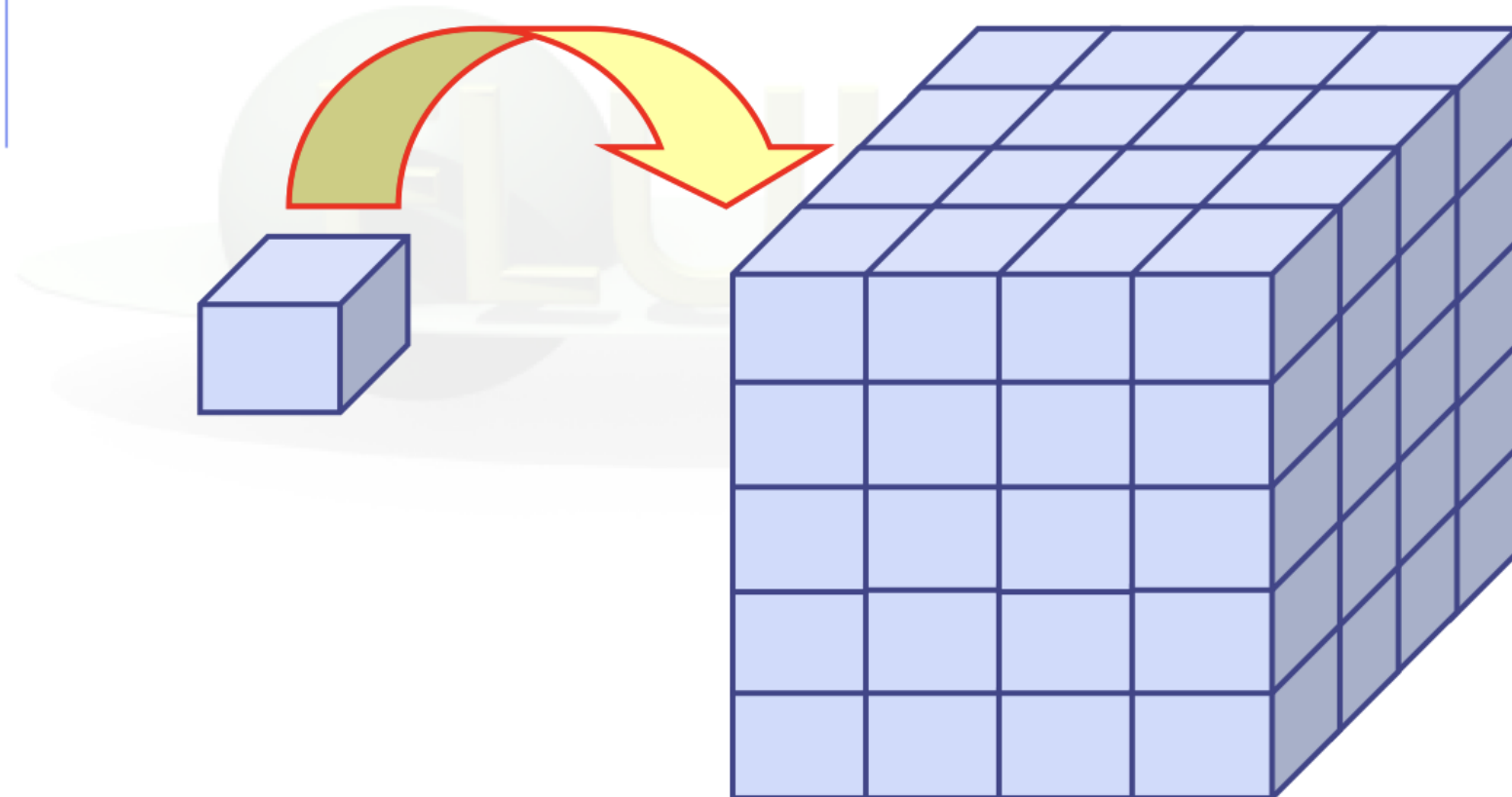
The interface includes a menu bar with options: Flair, Input, Geometry, Run, Plot. A toolbar contains various tools: Cut, Paste, Copy, Select, Info, Pan, Orbit, Body, Zone, Region, ROT-DEFI, Object, Clone, Delete, Lock, Wireframe, Visibility, Selection, Reload, Layer, Layout, Reset. A geometry tree on the left lists objects:

Type	Name
SPH	blkbody
SPH	void
RCC	target
REGION	VOID
REGION	TARGET
BEAM	

The status bar at the bottom shows the current position: np: +, x: 35.87899241, y: 0, z: -76.87236966.

FLUKA geometry: voxels

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



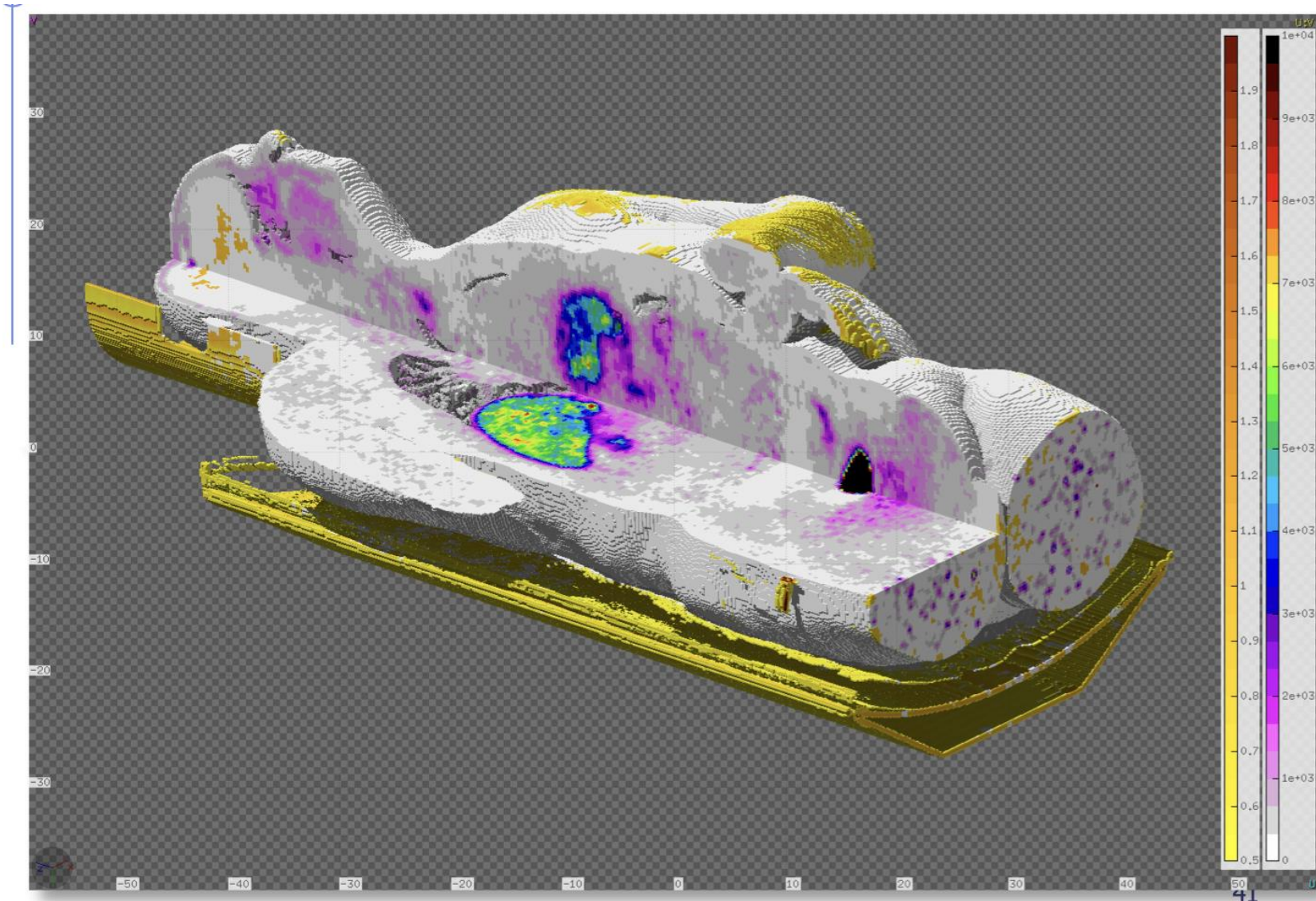
FLUKA geometry: processing DICOM files

The screenshot shows the FLUKA software interface with the following components:

- Menu Bar:** File, Edit, Flair, Input, Geometry, Run, Plot, Calculator.
- Toolbar:** Paste, Copy, Cut, DICOM, Slice, Information, Voxel, Search, Viewer.
- Slices Table:**

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	-459.89
- Viewer:** A 3D visualization of a CT scan slice showing a cross-section of a pelvis. A yellow rectangular box highlights a specific region of interest.
- Dicom Panel:**
 - x: 349, y: -105, Dicom: -2000, Value: -3024
 - Visible pixels: 928
 - Level: [Slider]
 - Window: 669
 - Crop: X: [Input], Y: [Input], Z: [Input] Current

FLUKA geometry: PET-CT



Scoring and results

- 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)
- FLUKA offers numerous different built-in estimators, i.e., directly from the input file the users can request scoring the respective quantities they are interested in. Built-in scoring is recommended as:
 - It covers most of the common needs
 - It has been extensively tested
 - It takes BIASING weights automatically into account
 - It has refined algorithms for track subdivision
 - It comes with utility programs that allow to evaluate statistical errors
- For additional requirements FLUKA user routines are provided

Scoring and results: built-in routines

- **USRTRACK, USRCOLL** score average $\frac{d\phi}{dE}$ (differential fluence) of a given type or family of particles in a given region
- **USRBDX** scores average $\frac{d^2\phi}{dEd\Omega}$ (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
 - The output of SCORE will be printed in the main (standard) output, written on logical output unit LUNOUT (pre-defined as 11 by default)
- All other detectors write their results into logical output units assigned by the user (**the unit numbers must be >20**)

Scoring and results: USRBIN

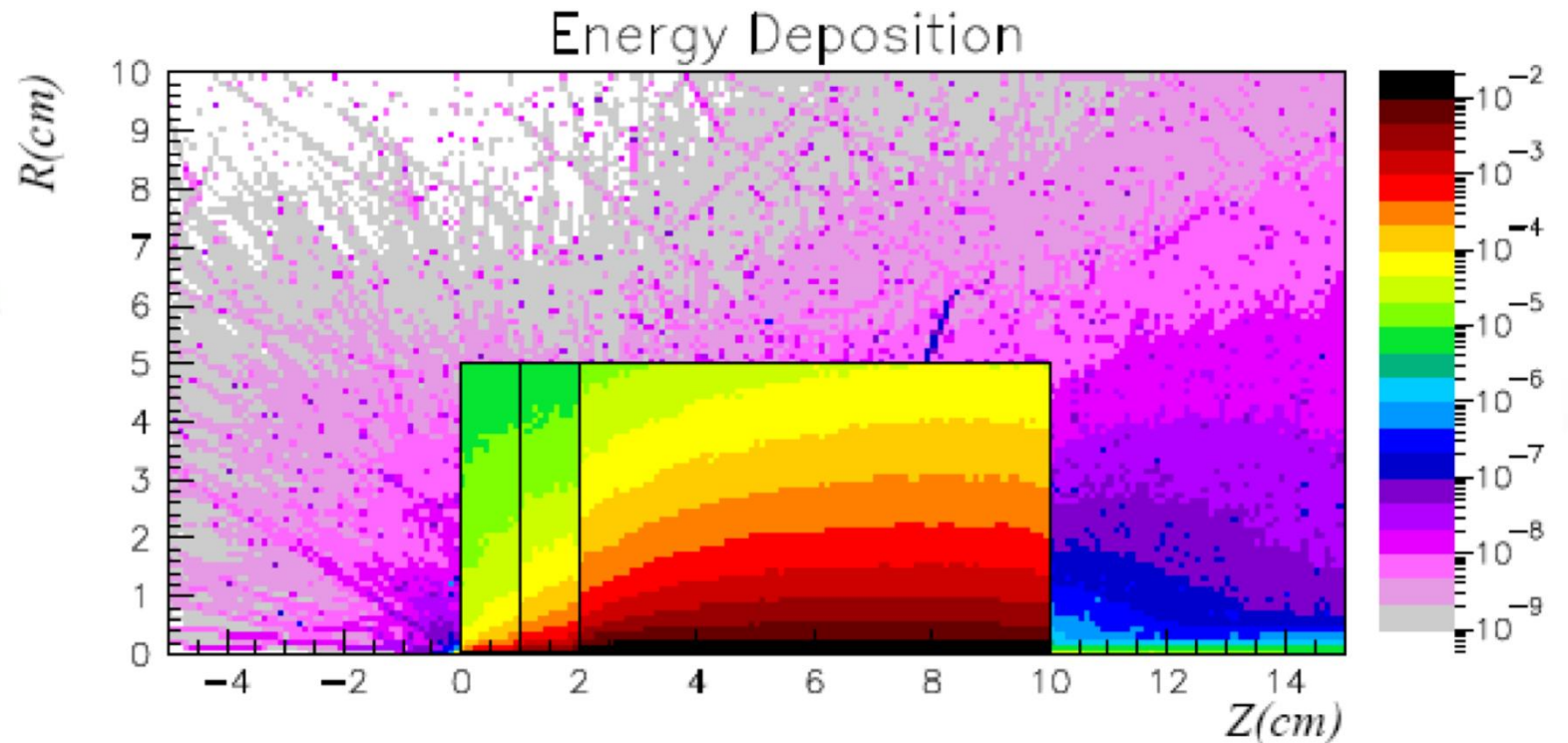
** energy deposition

```
USRBIN    11.0    ENERGY    -40.0    10.0    15.0 TargEne
USRBIN    0.0     -5.0    100.0    200.0 &
```

This is an **R-Z- Φ** binning (what(1)=**11**), scoring energy deposition (generalized particle **ENERGY**, or 208), writing the **unformatted** output on unit **40**, spanning **0<R<10** in 100 bins, spanning **0 < ϕ < 2 π** in 1 bin (default), **-5<z<15** in 200 bins,

WHAT(2) =
ENERGY

Energy deposition
from a 3.5 GeV
proton beam hitting
at [0.,0.,0.] directed
along z results are
normalized to
GeV/cm³ per primary



Scoring and results: USRBIN

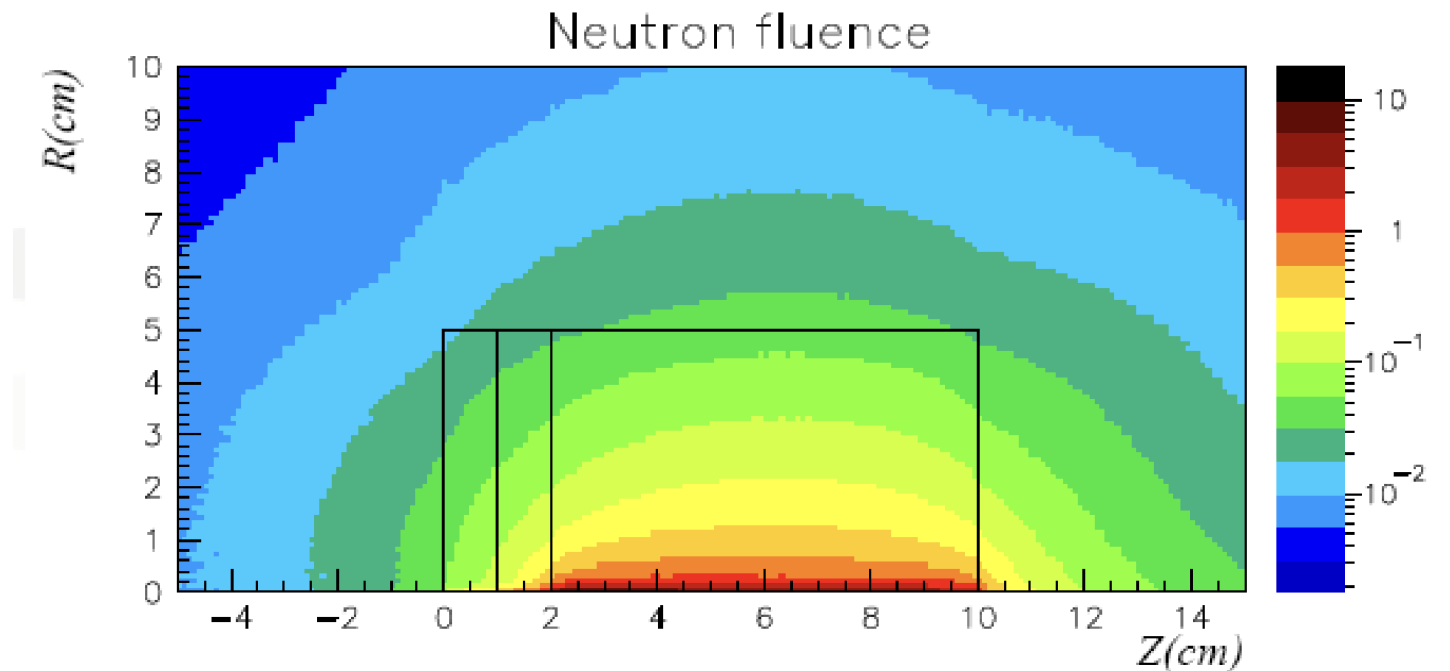
** neutron fluence

*	R-Z	EM energy	output unit	Rmax	axis Y	Zmax
*	Rmin	axis X	Zmin	# R-bins	# Phi-bins	# Z-bins
USRBIN	11.0	NEUTRON	-40.0	10.0		15.0 TargNeu
USRBIN	0.0		-5.0	100.0		200.0 &

This is a R-Z- Φ binning (what(1)=11), scoring neutron fluence, writing the unformatted output on unit 40, spanning $0 < R < 10$ in 100 bins, spanning $0 < \phi < 2\pi$ in 1 bin (default), $-5 < z < 15$ in 200 bins.

WHAT(2)=
NEUTRON

To get neutron fluence results are normalized to particles/cm² per primary



Scoring and results: USRBIN

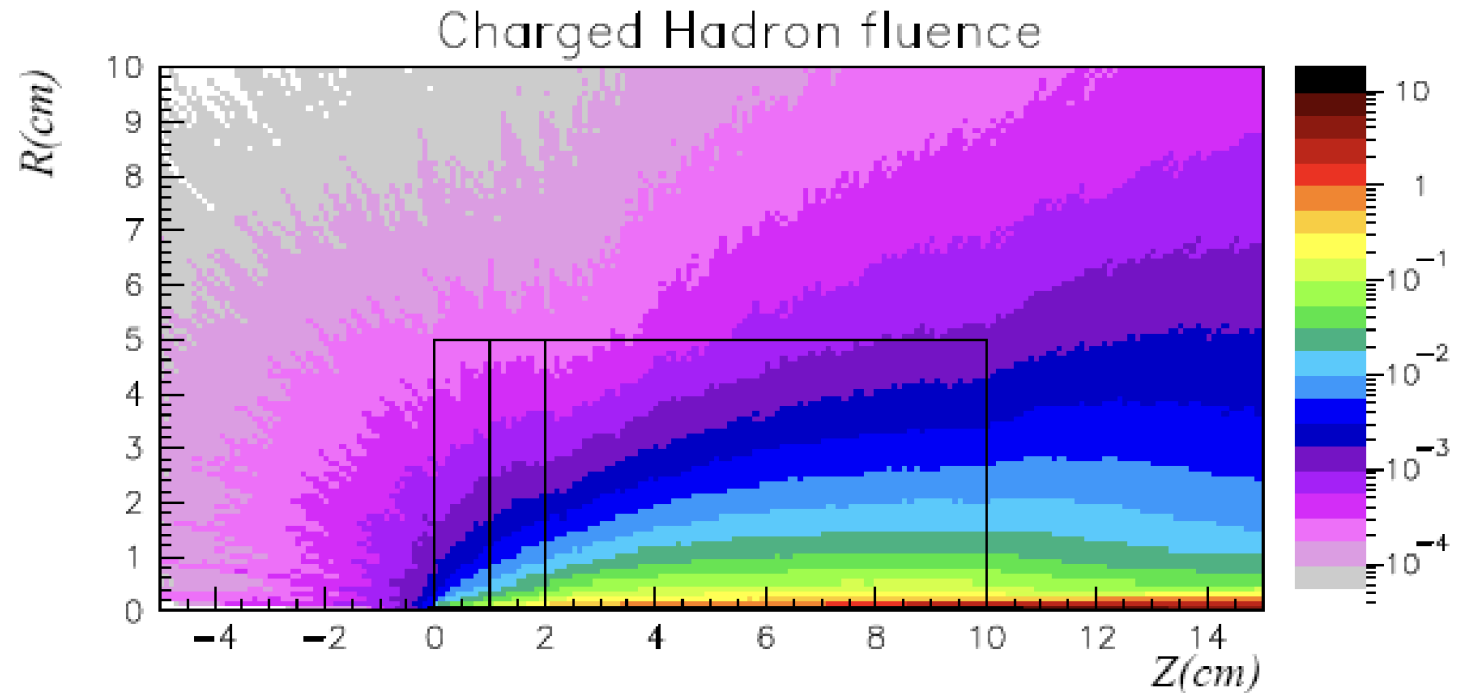
```
** charged hadron fluence
```

```
*           R-Z  EM energy  output unit      Rmax  axis Y  Zmax
*           Rmin  axis X    Zmin    # R-bins # Phi-bins # Z-bins
USRBIN     11.0  HAD-CHAR   -40.0      10.0      15.0 TargNeu
USRBIN      0.0                -5.0     100.0     200.0 &
```

This is a R-Z- Φ binning (what(1)=11), scoring charged hadron fluence, writing the unformatted output on unit 40, spanning $0 < R < 10$ in 100 bins, spanning $0 < \phi < 2\pi$ in 1 bin (default), $-5 < z < 15$ in 200 bins.

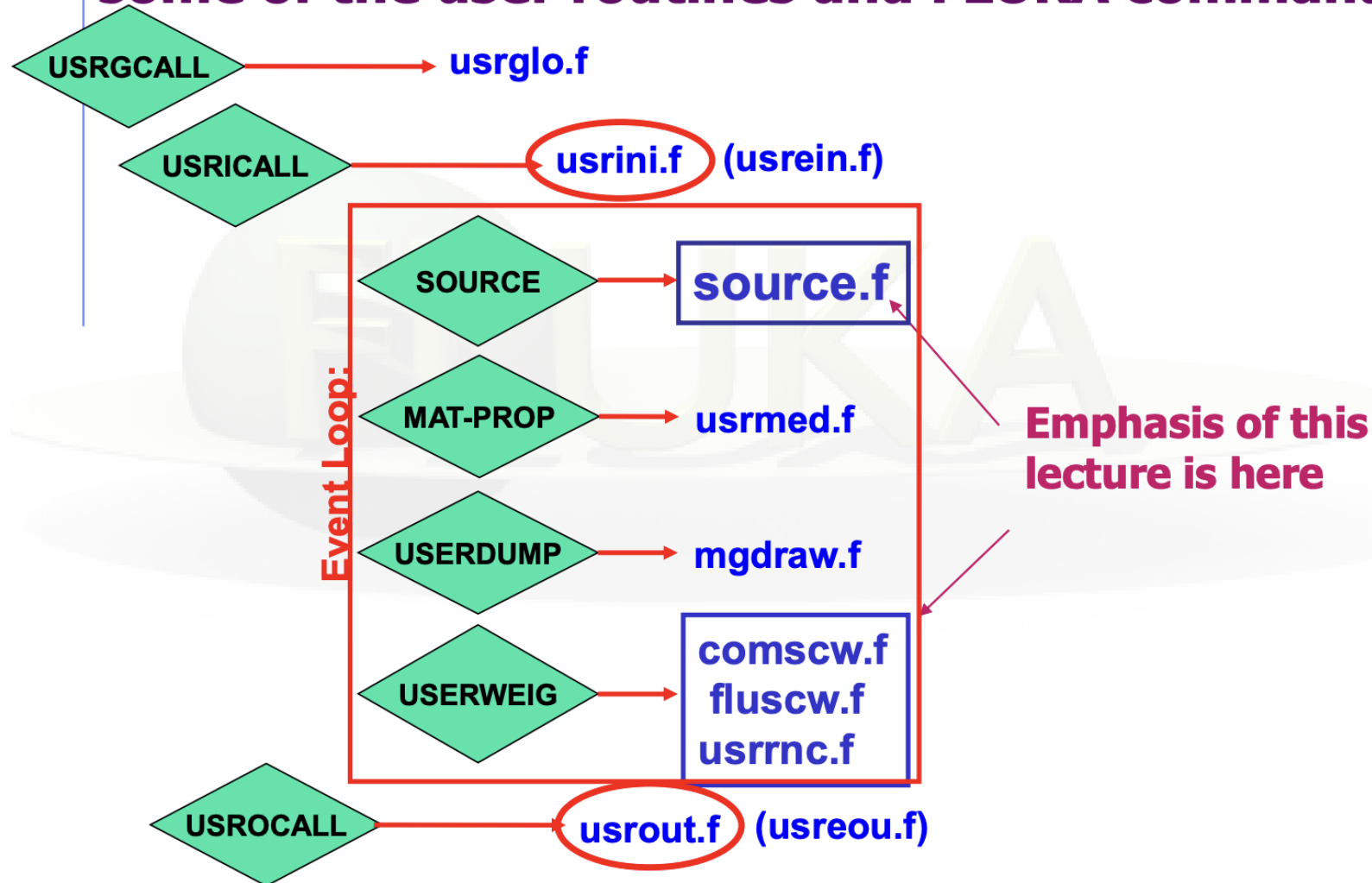
WHAT(2)= **HAD-CHAR**

to get charged hadron fluence. Results are normalized to particles/cm² per primary



FLUKA main routines

A first look at the correspondence between some of the user routines and FLUKA commands



FLUKA main routines

To run **FLUKA**, the main execution command is:

```
rfluka -Nn -Mm inputfile
```

N = first cycle number to run. It tells FLUKA **where to start counting cycles**

M= nr of cycles to run

The nr of histories to simulate is in the input file!



FLUKA: example applications

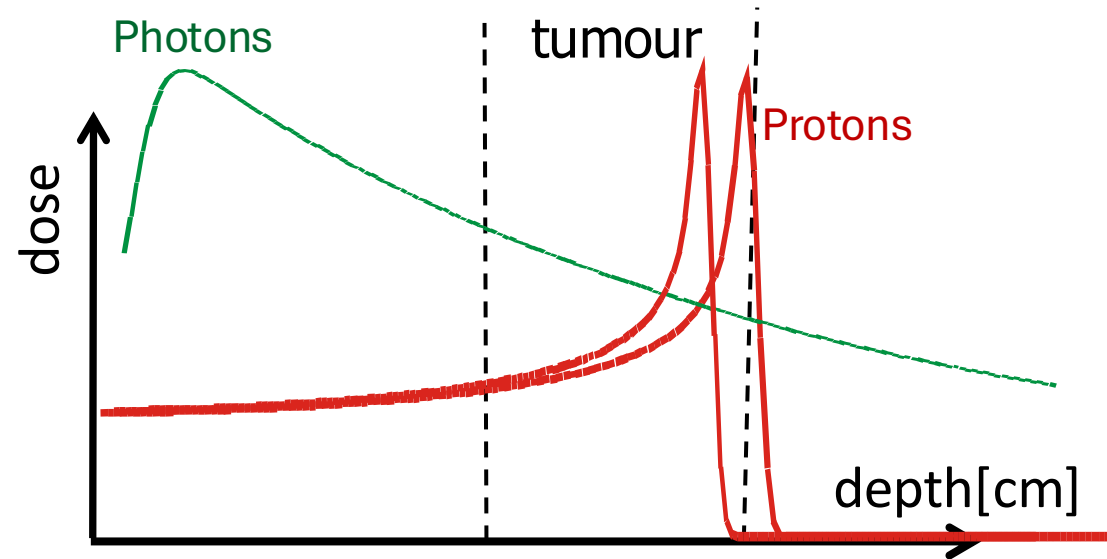
Particle therapy

Compared to photons, protons have a more selective energy deposition

Photons : high dose delivered in front and behind tumor

Protons/carbon ions : Bragg Peak

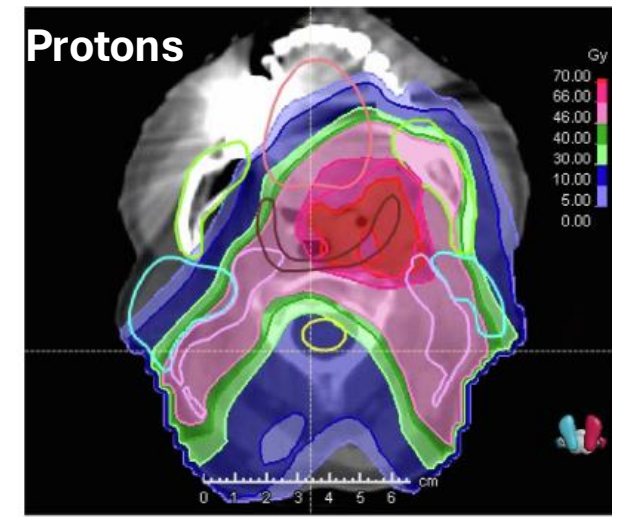
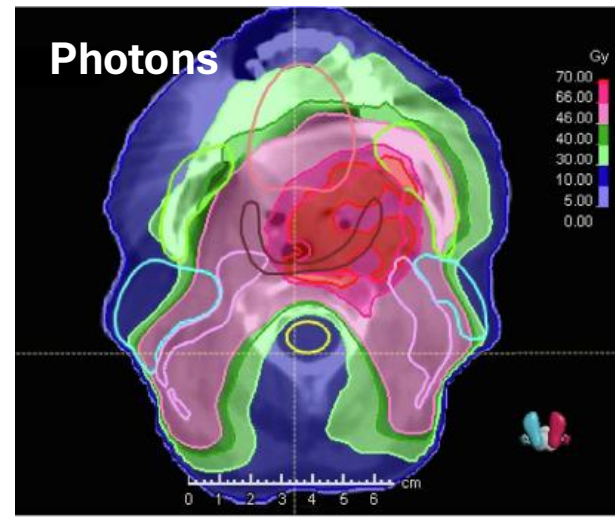
- Nr of particles \rightarrow height
- Energy \rightarrow depth
- \rightarrow More conformal dose!



From: A. Beddok et. al., Radiotherapy and Oncology 147 (2020) 30–39

Intensity Modulated Proton/Carbon Therapy:
combining thousands of beams

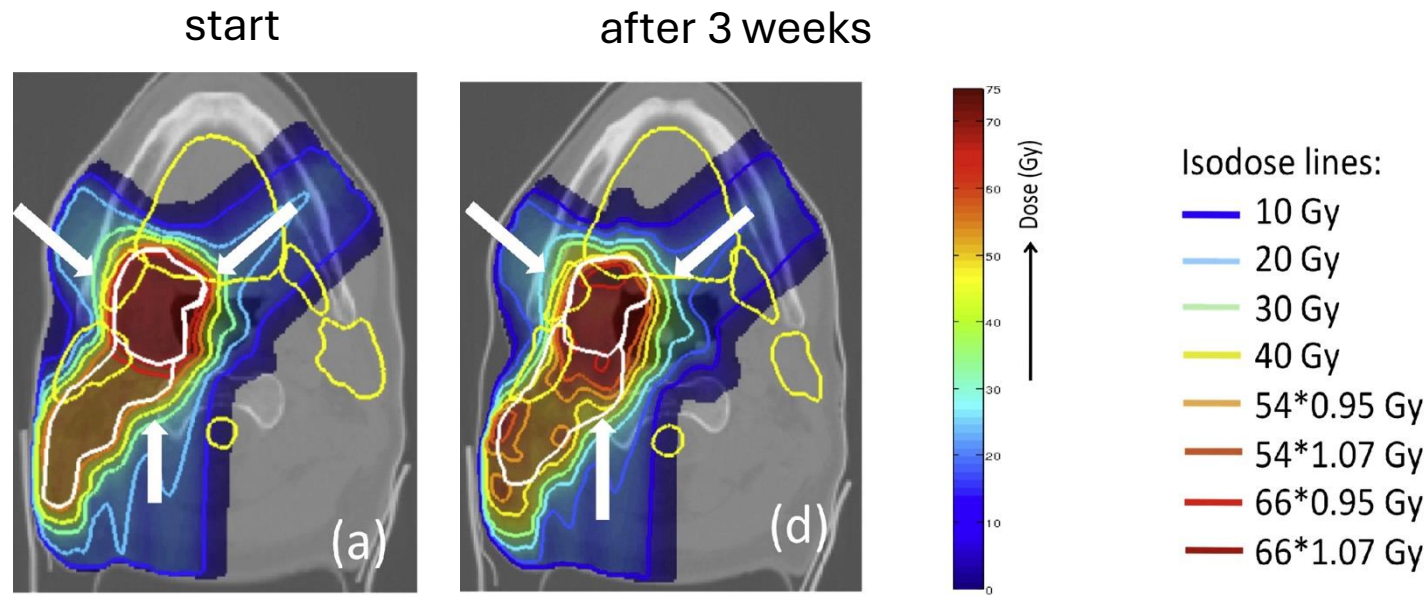
Treatment typically takes 4-6 weeks (20-30
treatment **fractions**)



Particle therapy treatment monitoring

- Particle therapy is accurate but also sensitive to uncertainties...
- Among sources of uncertainties are anatomical changes → dose distortions
- Example of site where this can be problematic: head and neck tumors
- Often a control CT scan is made after X treatments, with X depending on clinical experience/personal choice of the radiation oncologist → adapt treatment?
- Treatment should be monitored!
 - For patients who change: to be sure to perform the control CT in time → adapt
 - For patients who do not change: to avoid unnecessary control CT's

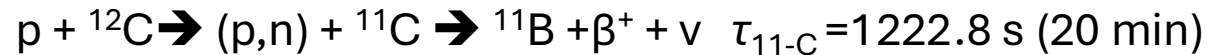
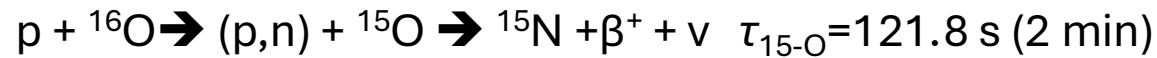
From
Kraan et al
Int J Radiat
Oncol Biol
Phys
2013;87(5):
888-96.



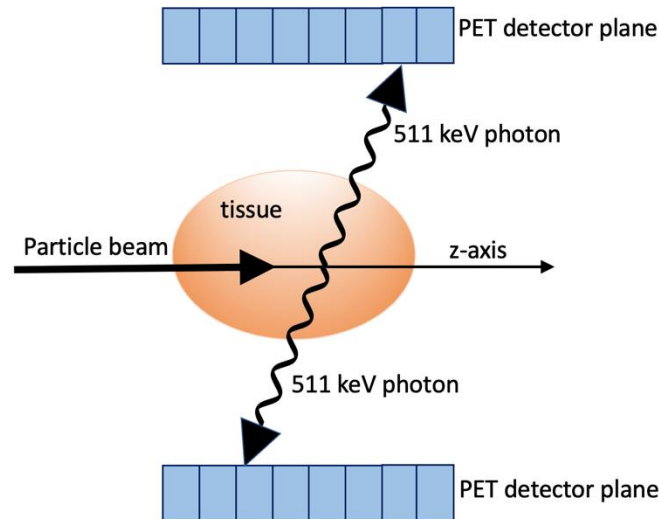
Treatment monitoring with PET

- Among the nuclear reaction products are β^+ emitters
- Decay after a short while into positron, which annihilates into 2 back-to-back photons
- Indirect correlation with dose!

E.g. proton beam:



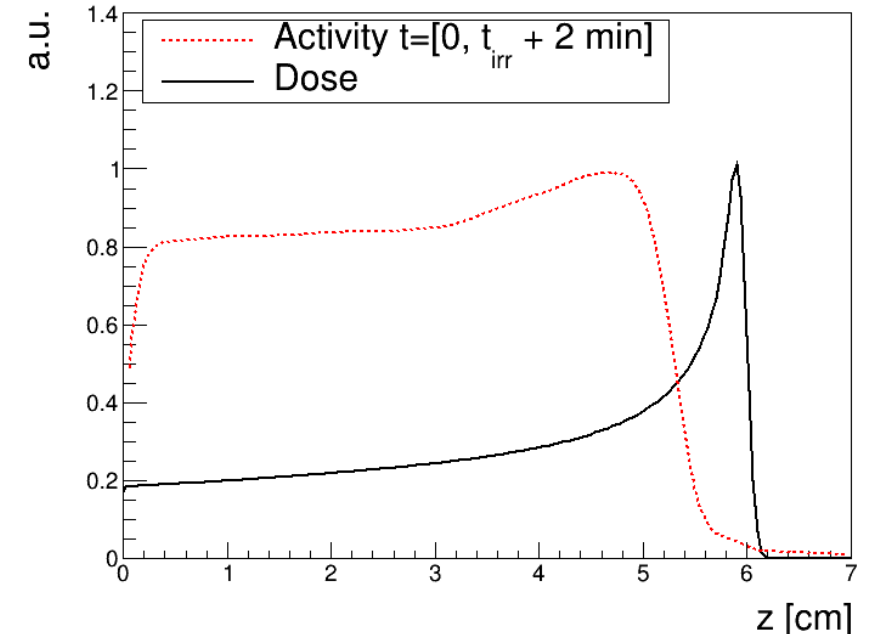
- Positron Emission Tomography (PET) can be used for in-vivo non-invasive treatment monitoring in proton therapy
- Monte Carlo simulations have played important role in development of this technique!



See:

- K. Parodi, J. C Polf, Review: In vivo range verification in particle therapy, Med Phys 2018 45(11)
- M. Durante, H. Paganetti, Re.p Prog. Phys. 2016;79(9):096702.
- A-C. Knopf, A. Lomax, Phys. Med. Biol 2013;58(15):R131-60.
- A.C. Kraan, Frontiers in Oncology 2015

FLUKA, 2022



Treatment monitoring with PET

First pioneer work by W. Enghardt et al. in the '90 with Carbon Ions (*GSI/Bastei tomograph*)

Off-line PET = dose delivery and PET in different rooms
(*MGH/Heidelberg/CHIBA*)

- Advantages

- Commercial 360° PET scanner no image artefacts

- Disadvantages:

- Patient re-positioning
- Data loss of very short living isotopes (e.g. ^{15}O)
- Radio-isotope wash-out



On-line PET = dose delivery and PET in same room

→ In Room-PET: data when beam is off

(*GSI/PISA-CNAO/CHIBA/MGH/HEIDELBERG*)

→ In-beam-PET: data when beam on (*PISA-Torino-CNAO/CHIBA-openPET*)

- Disadvantages:

- Image artefacts
- Small statistics (not much ^{11}C)



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On-line PET = dose delivery and PET in same room

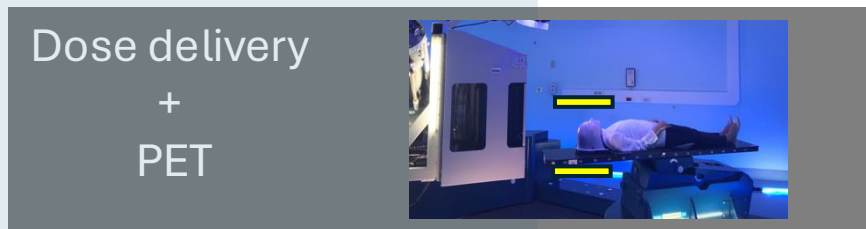
→ In Room-PET: data when beam is off

(*GSI/PISA-CNAO/CHIBA/MGH/HEIDELBERG*)

→ In-beam-PET: data when beam on (*PISA-Torino-CNAO/CHIBA-openPET*)

- Disadvantages:
 - Image artefacts
 - Small statistics (not much ^{11}C)

Today



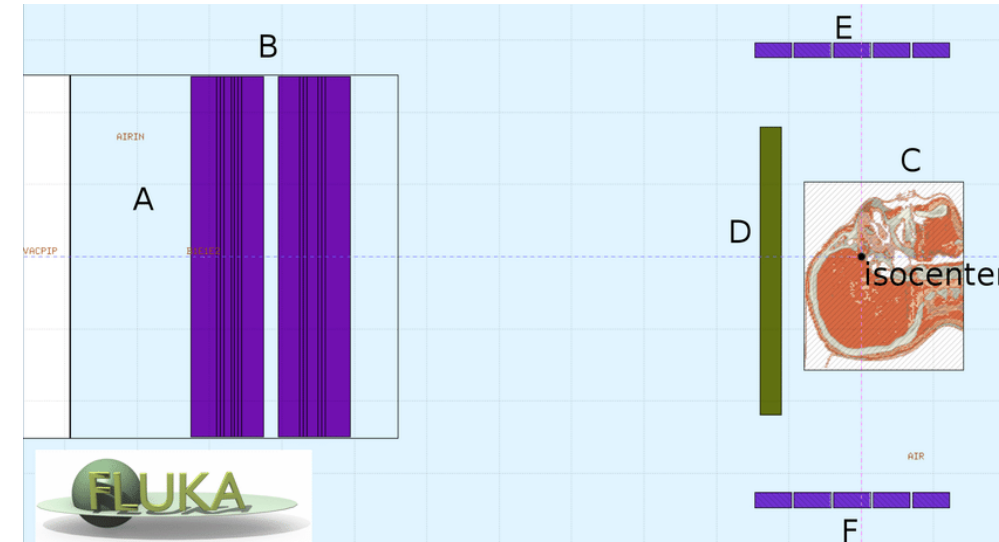
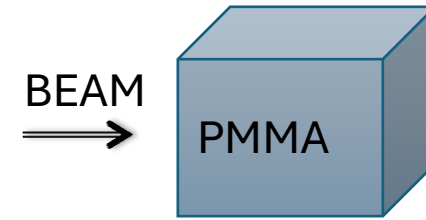
PET activity MC simulations: preclinical studies

FLUKA MC simulation

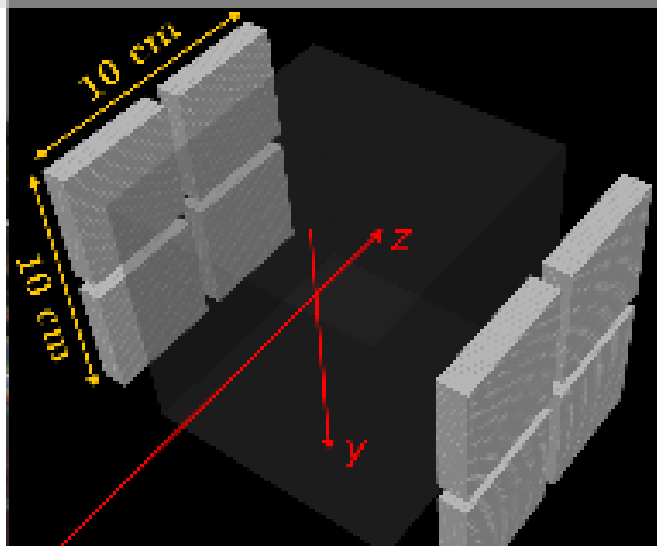
- Source: 15×10^9 protons on PMMA, 95 MeV
 - Time structure and beam size of CNAO beam (Centro Nazionale di Adroterapia Oncologica, Pavia)
- Geometry: CNAO beam line, phantom, PET detector
- Scoring: β^+ activity scored, developed for scope

Data

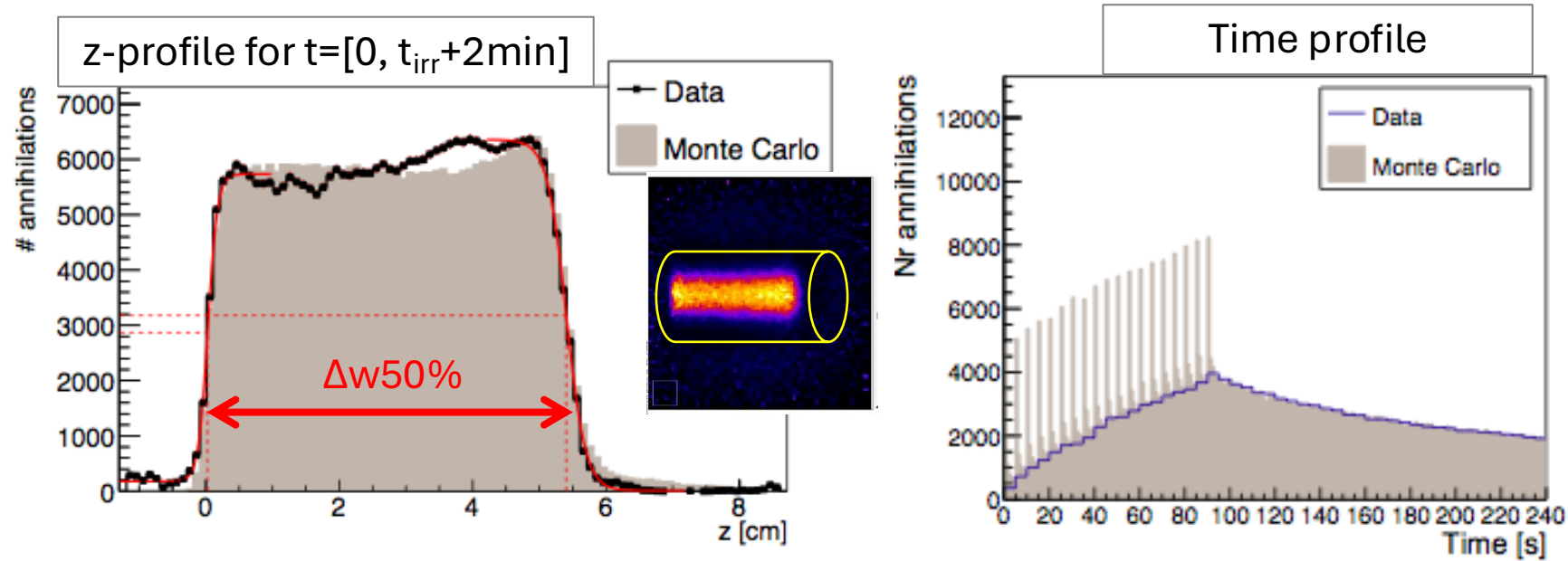
- DOPET planar PET system
 - Data taken at CATANA (Catania), CNAO (Pavia) and Bronowitz (Krakow, Poland)



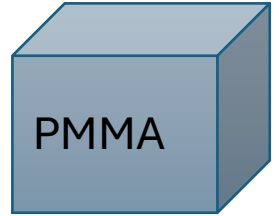
Rosso, V et al, Journal of Instrumentation. 8. C03021, 2021,
V Rosso et al 2013 JINST 8 C03021



PET activity MC simulations: preclinical studies



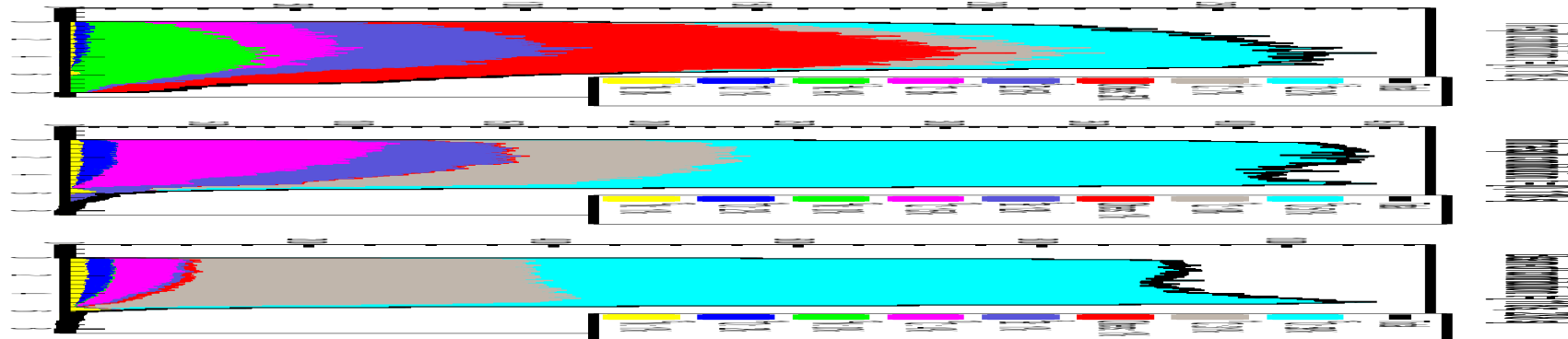
BEAM
→



Studies on homogeneous phantoms allowed to **validate** FLUKA MC framework



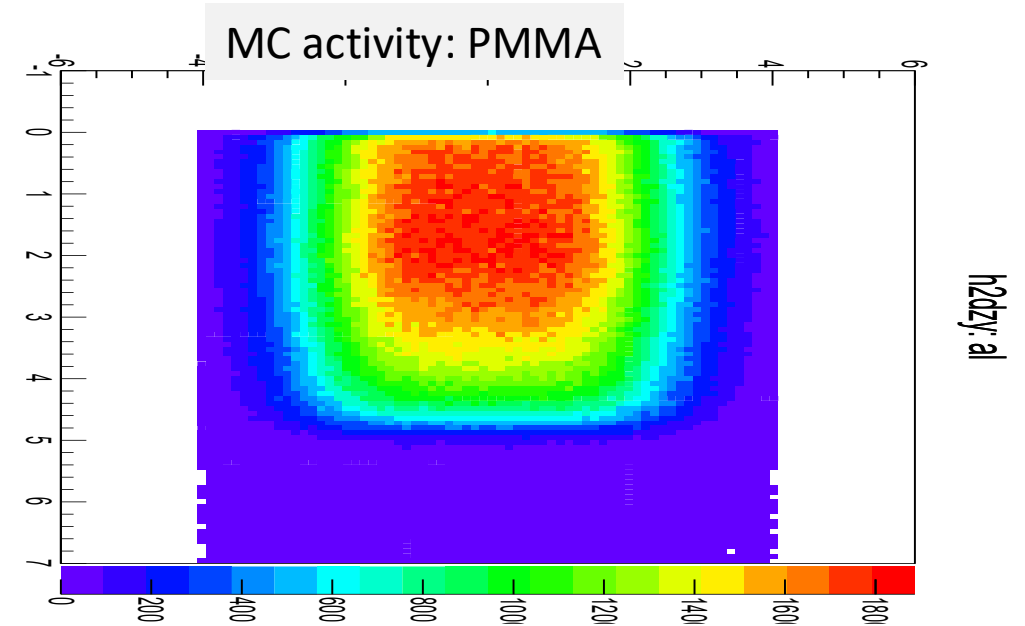
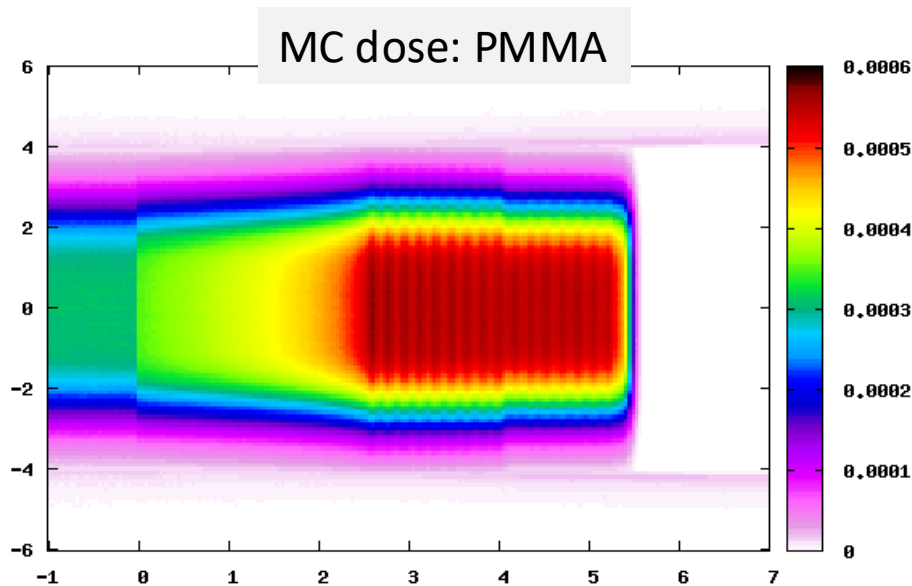
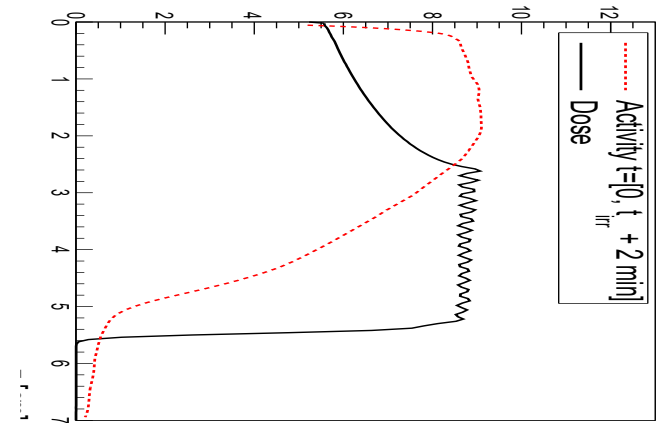
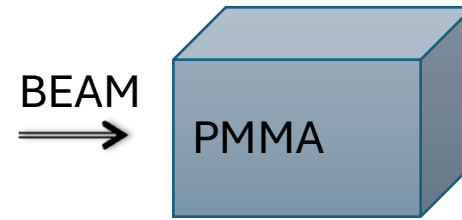
MC simulation



PET activity MC simulations: preclinical studies

FLUKA MC simulation

- Source: protons according to treatment plan
 - 2 Gy plan, PTV 3 x 3 x 3 cm³ in 2 min
 - thousands of small pencil beams
 - 1E8 particles simulated (~1/100 of treatment plan)
- Geometry: CNAO beam line, phantom, PET detector
- Scoring: β^+ activity scored, developed for scope

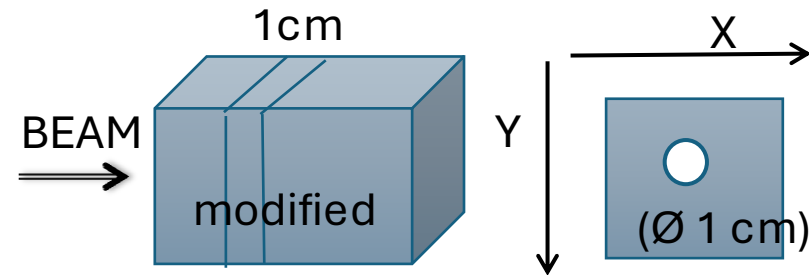


h2dy: al

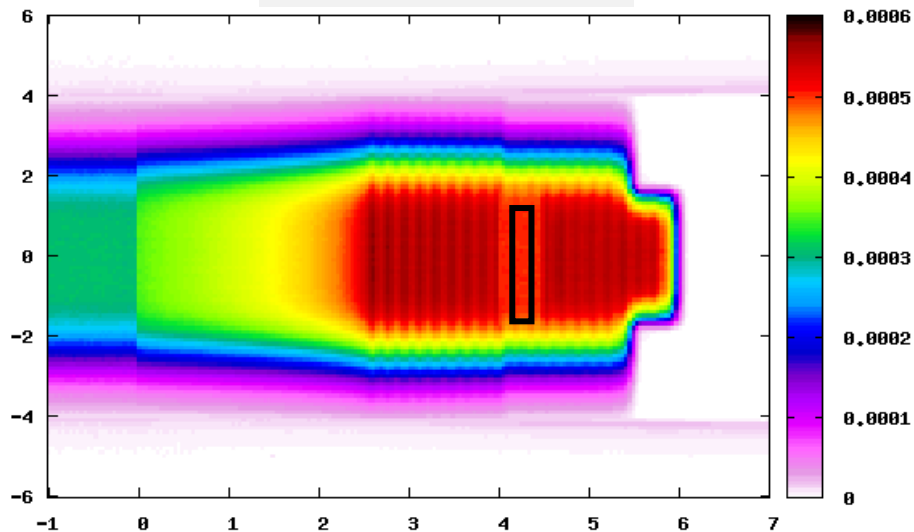
PET activity MC simulations: preclinical studies

FLUKA MC simulation

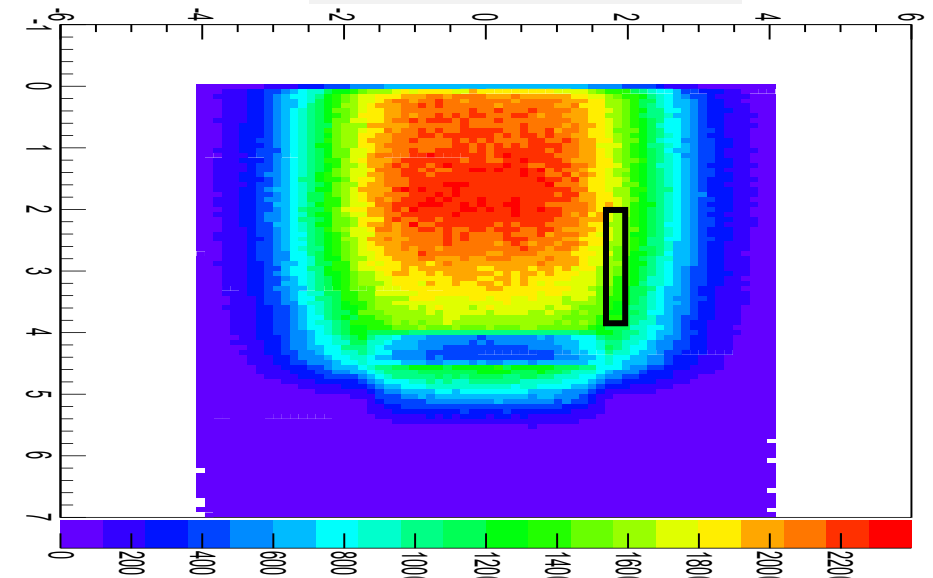
- Source: protons according to treatment plan
 - 2 Gy plan, PTV 3 x 3 x 3 cm³ in 2 min
 - thousands of small pencil beams
 - 1E8 particles simulated (~1/100 of treatment plan)
- Scoring: β^+ activity scored, developed for scope



MC dose: airhole

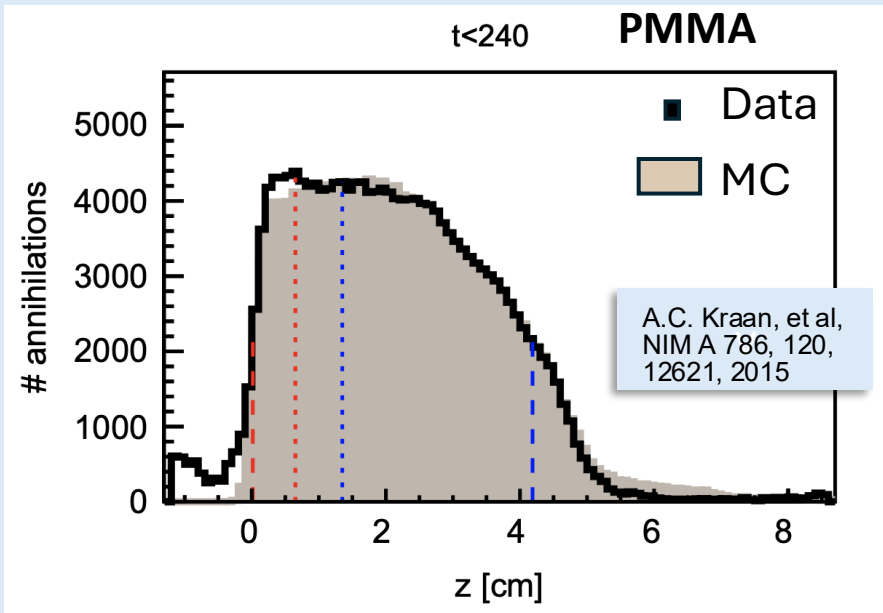
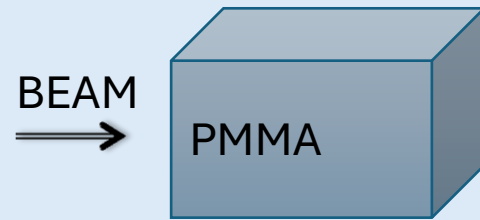


MC activity: air hole

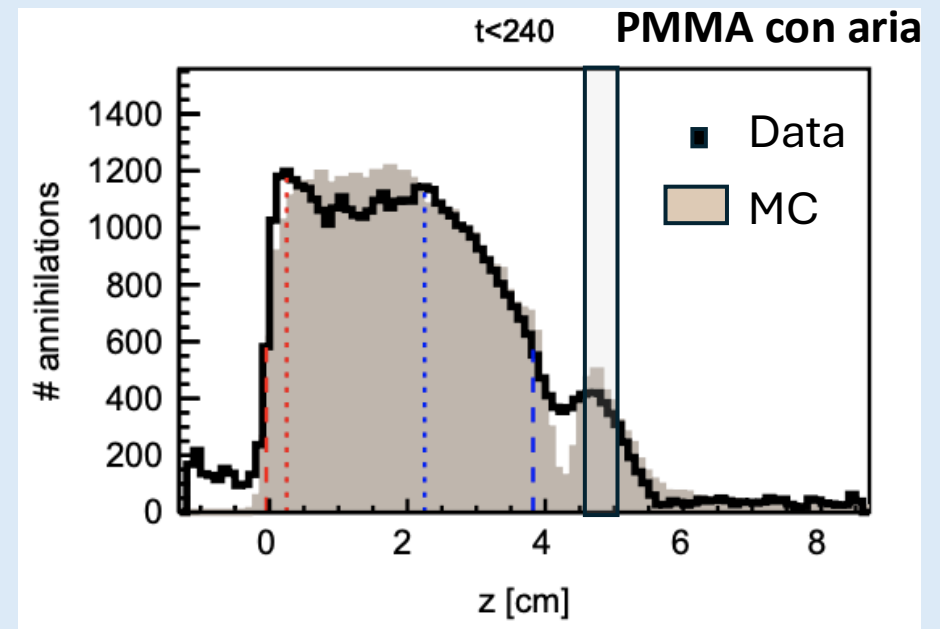
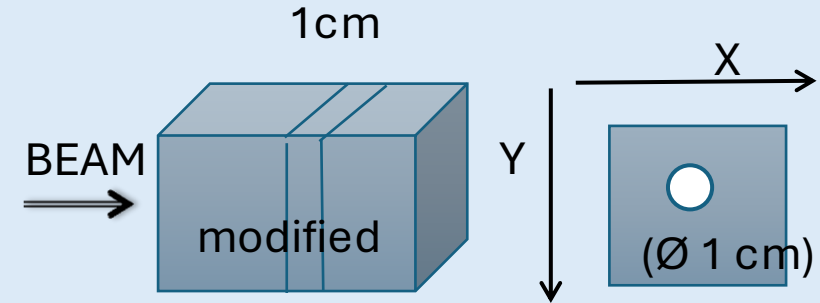


Interesting! Activity distribution is sensitive to precise location of hole!

PET activity MC simulations: preclinical studies



Validation of FLUKA



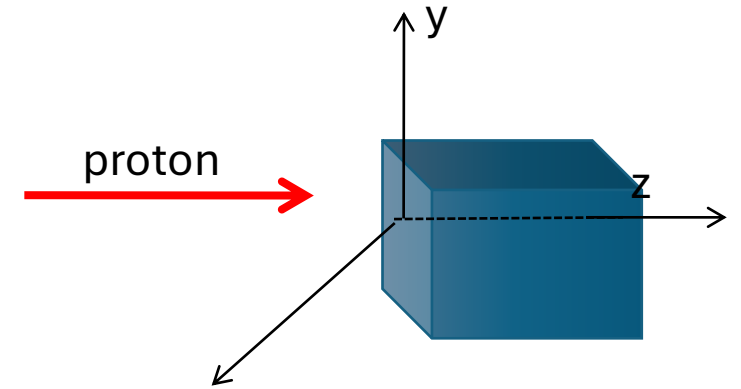
Some discrepancies

PET activity simulations with simple phantoms

Composition of tissue with activity measurements over time

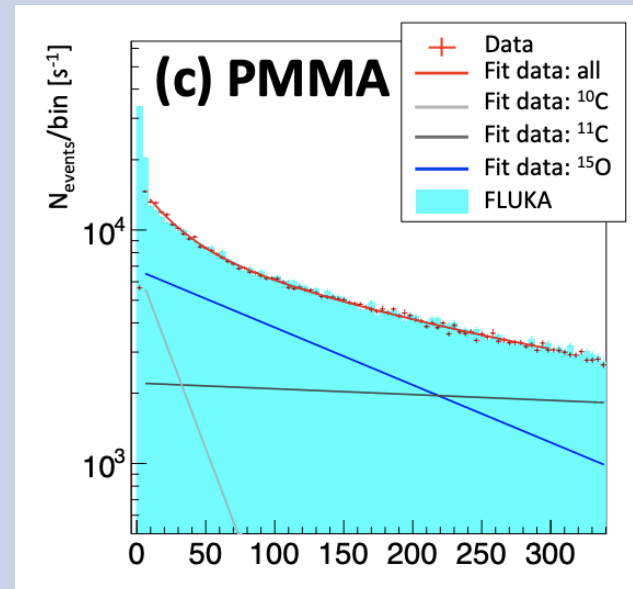
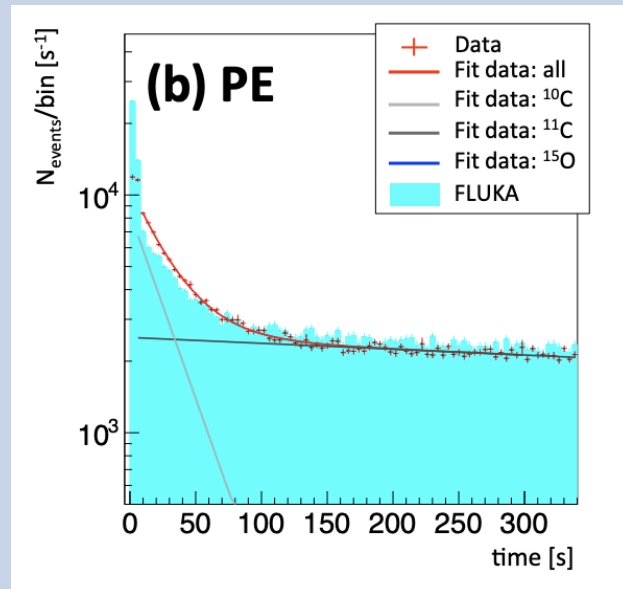
Goal:

- To investigate biological washout models + perfusion in patients
- To calculate the elemental composition of the irradiated tissue (detect changes of oxygenation in tumors?)

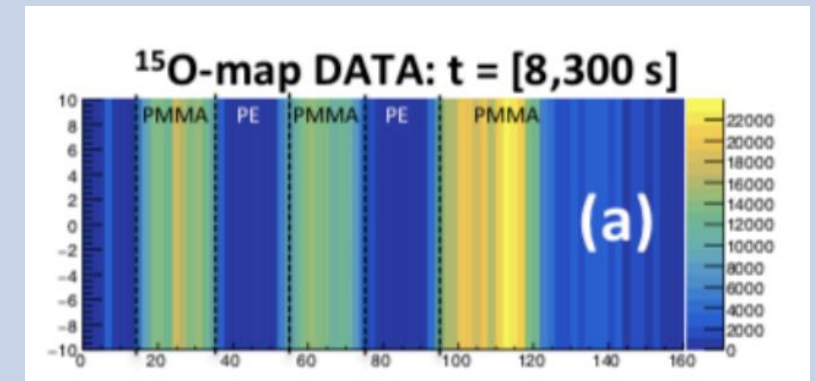


Correlare curve di decadimento al materiale

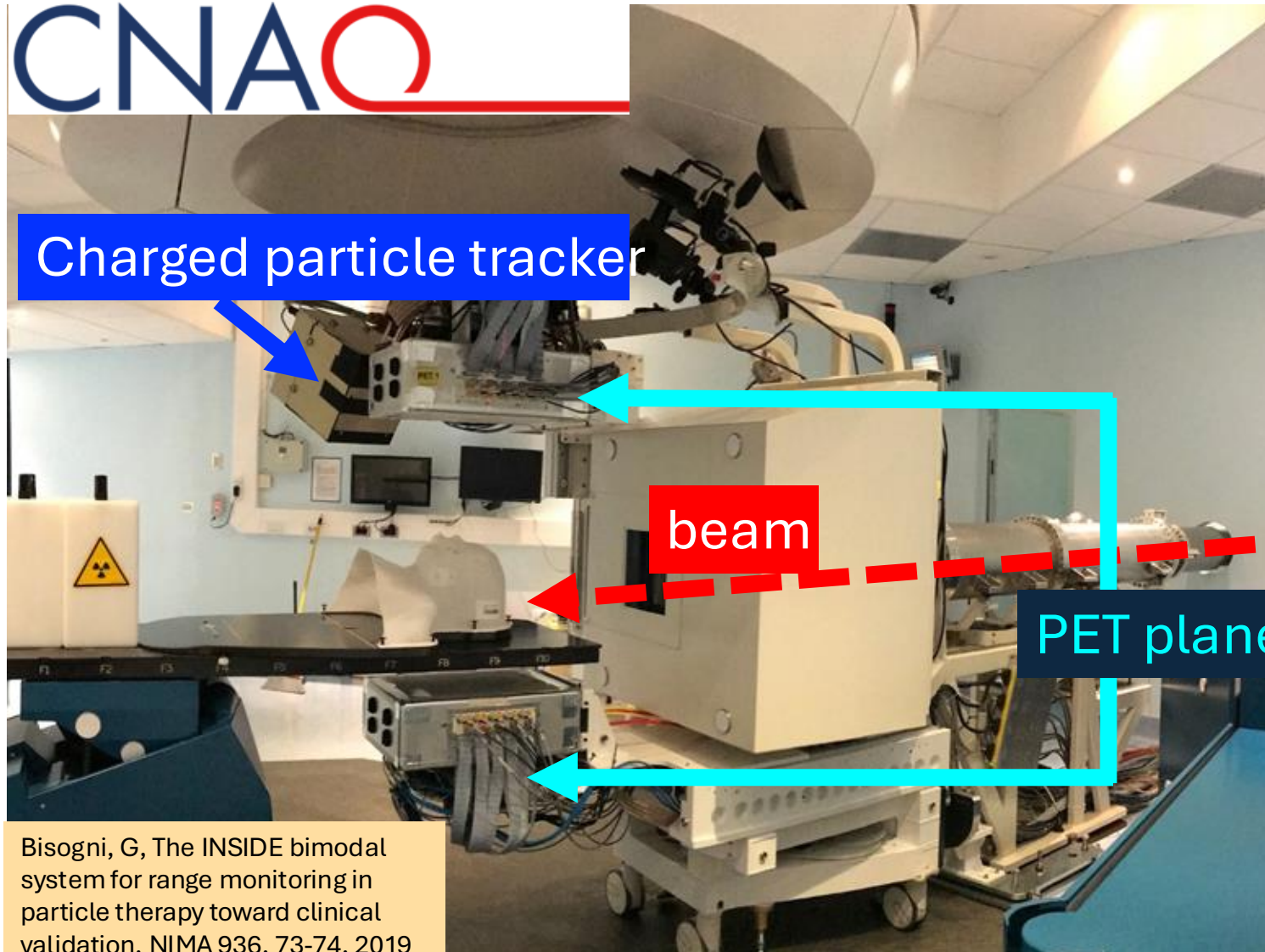
A.C. Kraan, et al,
JINST, JINST 14,
1, 2019, C02001



^{15}O distribution



PET activity MC simulations: clinical studies



INSIDE: Innovative Solution for Dosimetry in Hadrontherapy

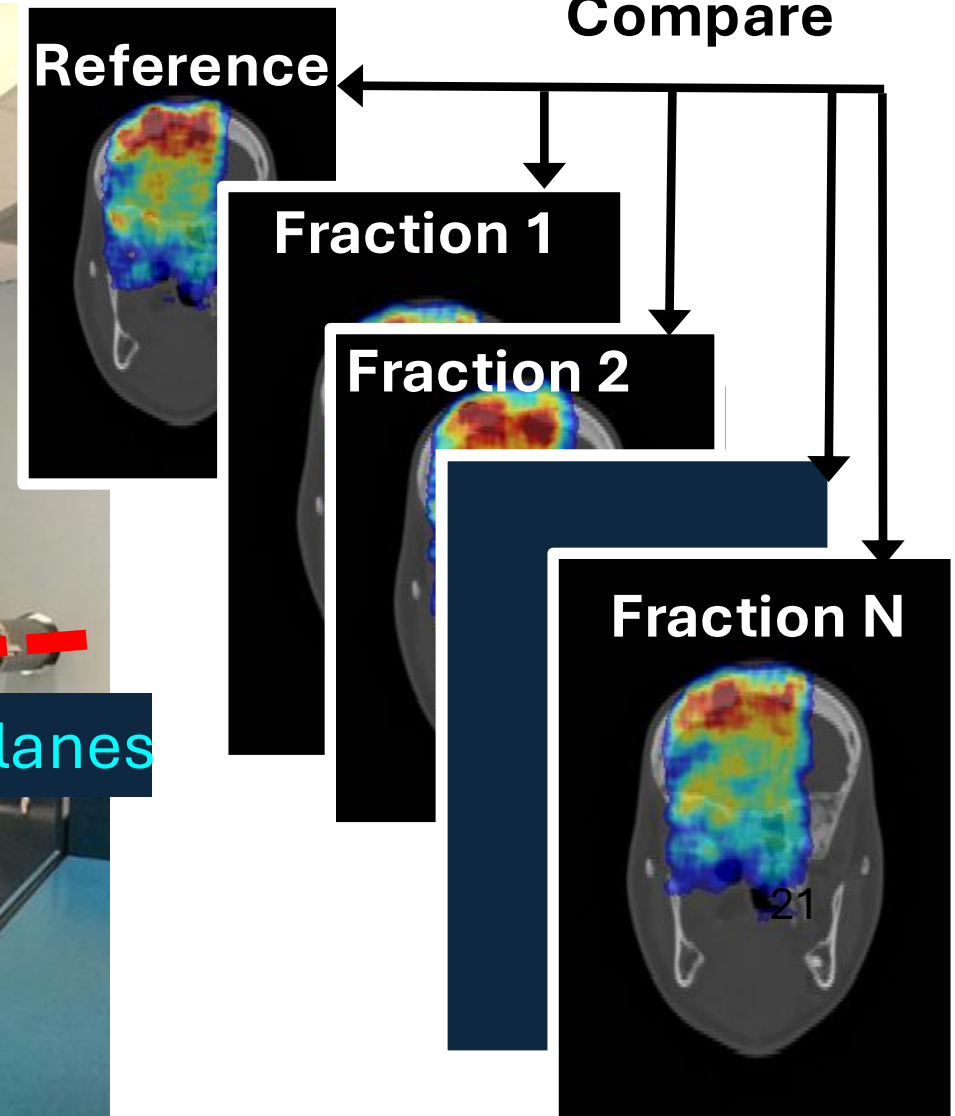
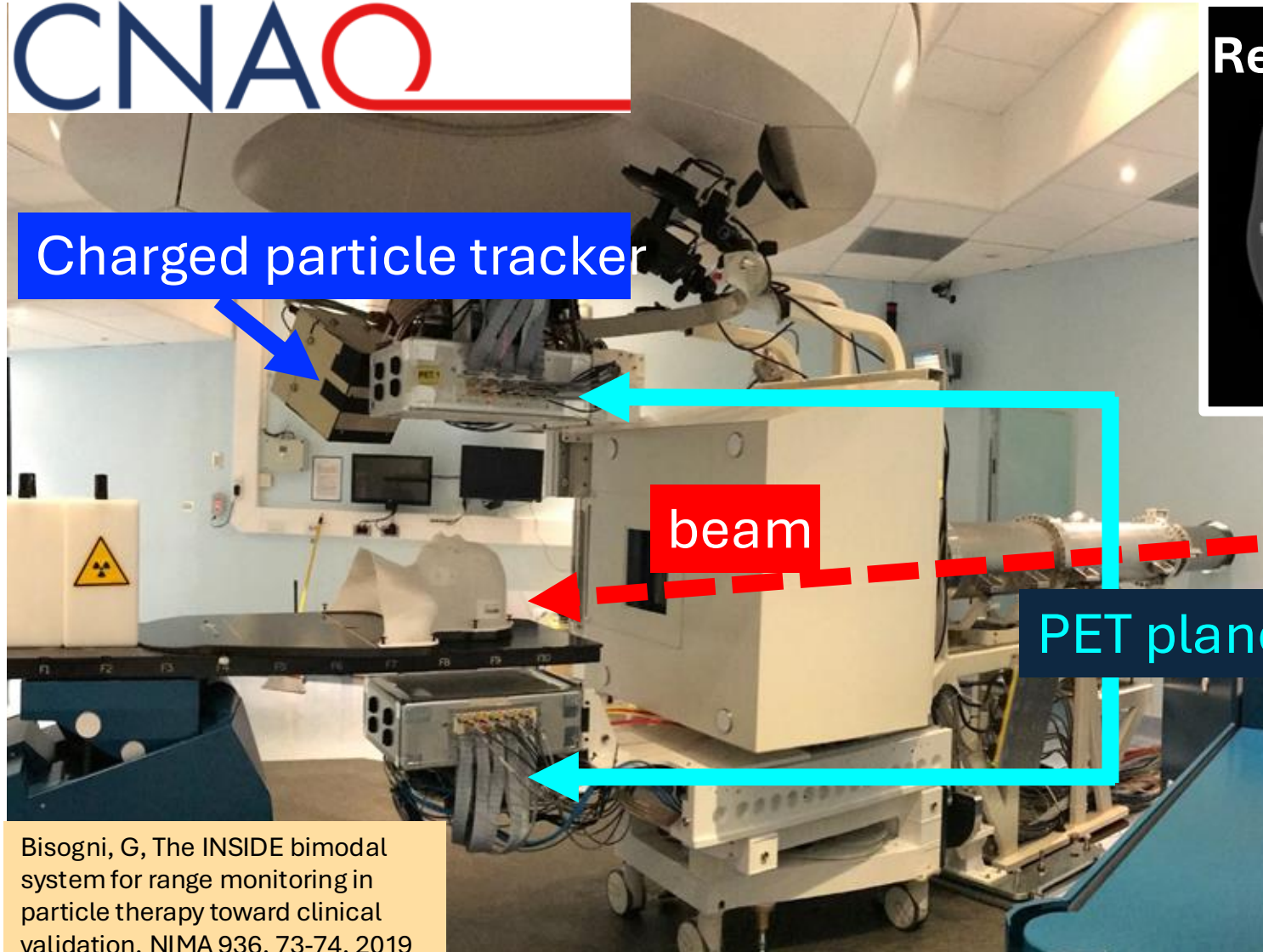
- Bimodal imaging system for non-invasive treatment monitoring
 - Planar PET system
 - Charged particles tracker
- Installed at CNAO (National Centre of Oncological Hadrontherapy, Pavia, Italy)
- Clinical trial 2019-2020
- Switched off since 2021... COVID and bureaucratic delays (regulations)
- **We are taking data for new patients (Master thesis work?)**

Bisogni, G, The INSIDE bimodal system for range monitoring in particle therapy toward clinical validation, NIMA 936, 73-74, 2019

G.M. Bisogni et al.:Journal of Medical Imaging4 (Dec. 2016), p. 011005.

PET activity MC simulations: clinical studies

CNAO



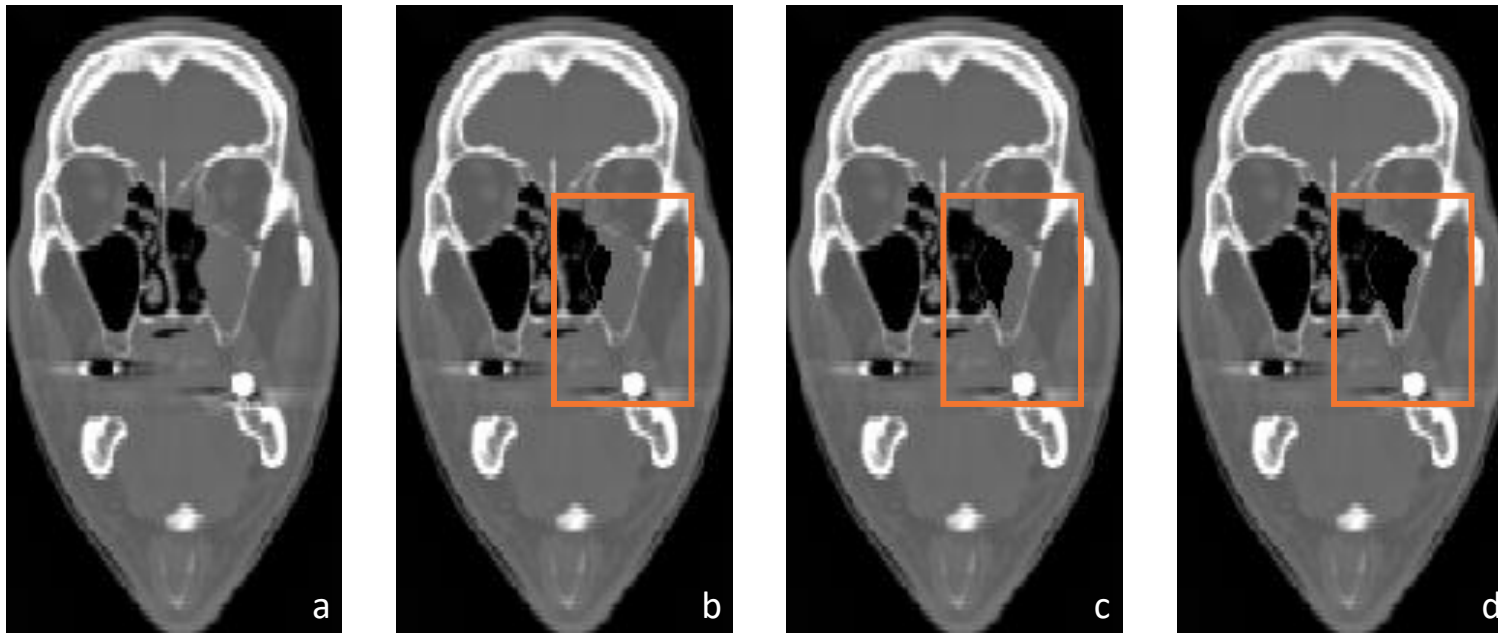
Bisogni, G, The INSIDE bimodal system for range monitoring in particle therapy toward clinical validation, NIMA 936, 73-74, 2019

PET activity MC simulations: clinical studies

Important role for MC simulations !

- To predict reference distribution
- To test analysis strategies and prepare analysis

Typical problem occurring during head—and-neck radiotherapy treatment



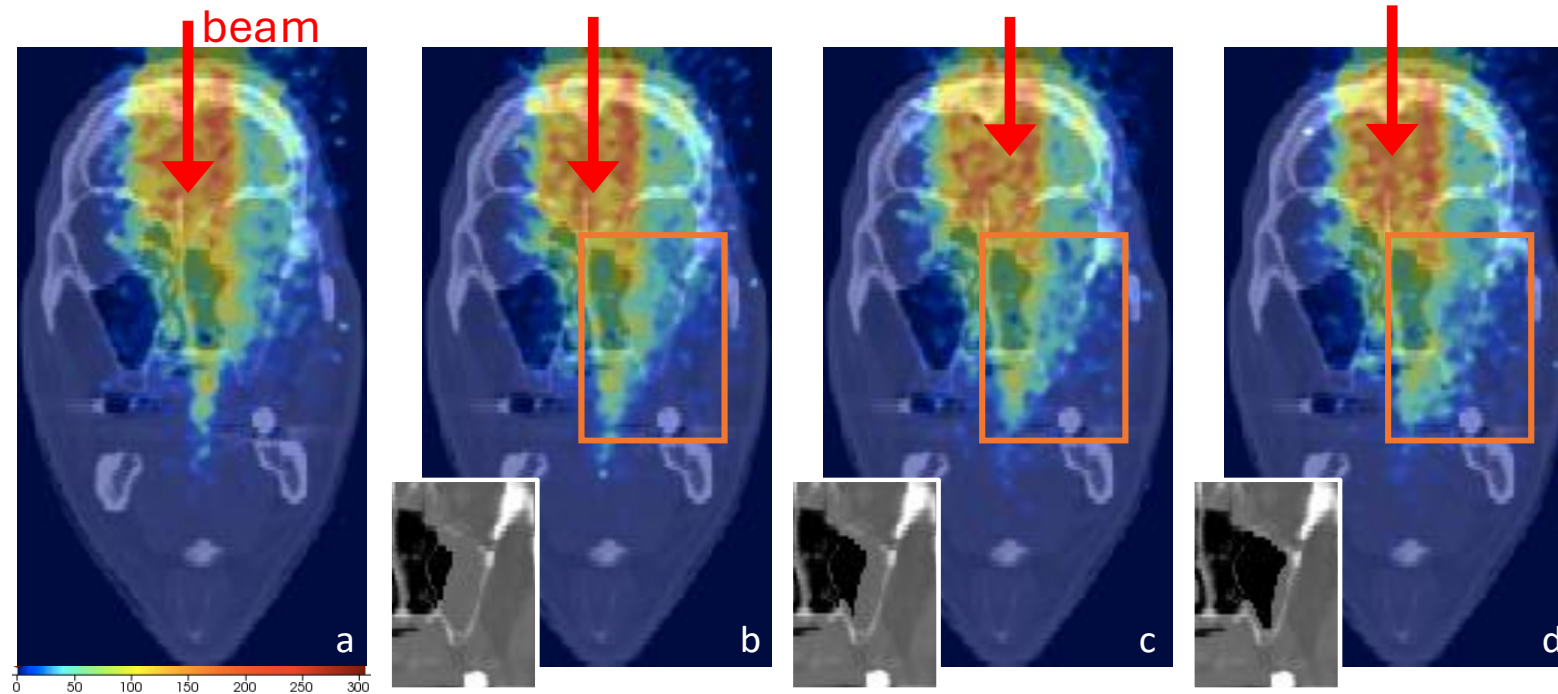
Can we use in-beam PET to catch these problems??

PET activity MC simulations: clinical studies

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A.C. Kraan et al., Med Phys 2022, 49(1):23-40

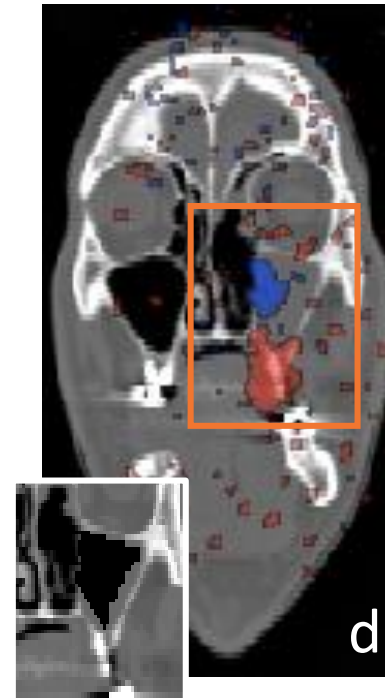
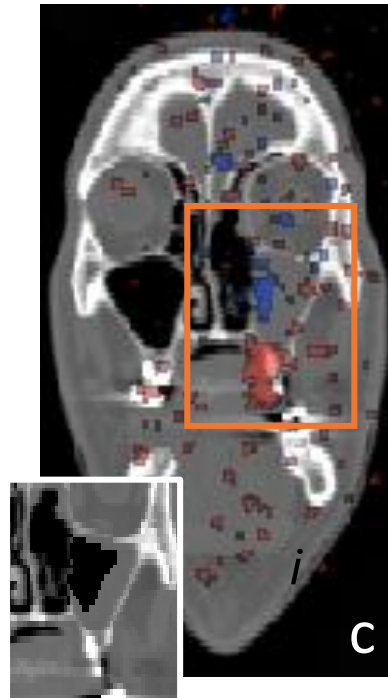
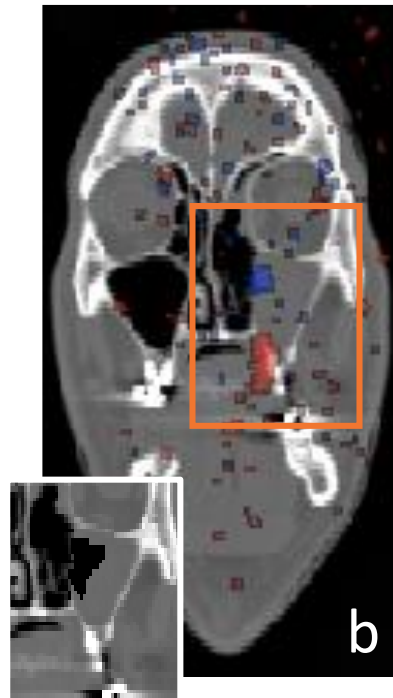
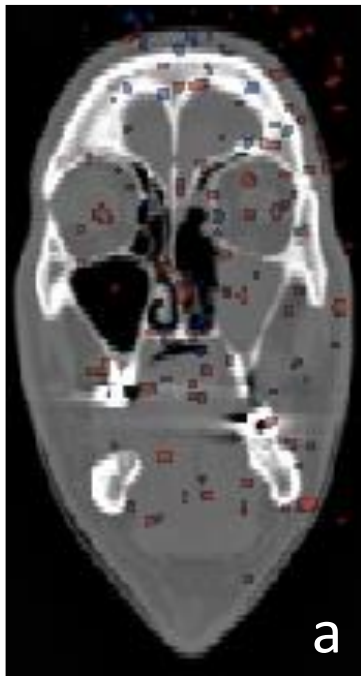
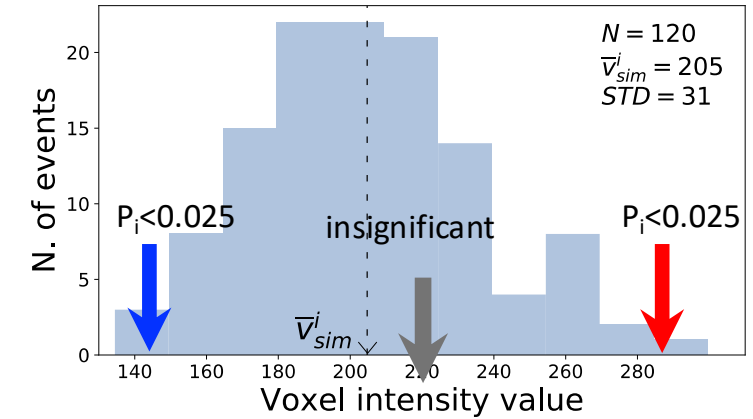
Can we use in-beam PET to catch these problems??

PET activity MC simulations: clinical studies

Important role for MC simulations!

Example of analysis tested on MC simulations

Statistical analysis: catch the voxels (for example on 100 samples), that are statistically not compatible with expectations



PET activity MC simulations: clinical studies

Important role for MC simulations!

Example of analysis tested on MC simulations

Gamma analysis: catch the regions that are incompatible with expectations

These methods can then be tested on data!

γ_{PET} -index
color scale

