EuNPC September 22-26 Caen, France

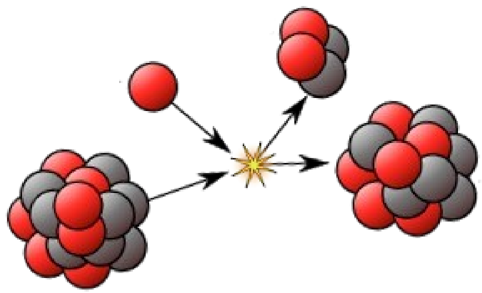
# First Fragmentation Cross Section Measurements with the Full FOOT setup

## $^{12}$C 200 MeV/u on 5 mm C target

***EuNPC 2025***
*Caen, France*
*23/09/2025*

**Giacomo Ubaldi**
University of Bologna, Italy
on behalf of the FOOT collaboration

# Why study nuclear fragmentation?



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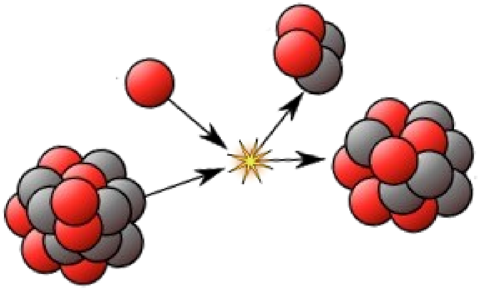
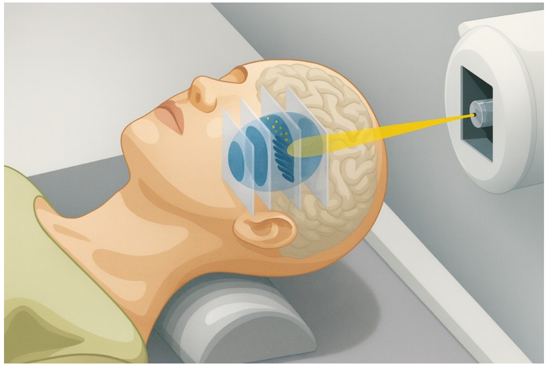


***Particle Therapy***

p, $^{12}C$, $^{16}O$ @ 200-400 MeV/u



Since they influence the dose delivery,
to **improve** the effectiveness of
the **Treatment Planning System** (TPS)

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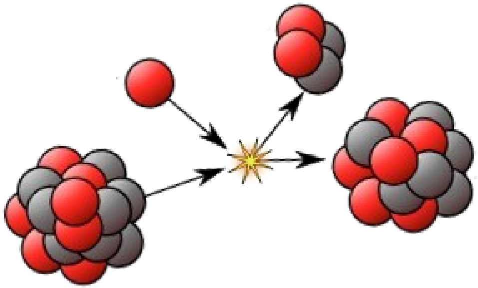

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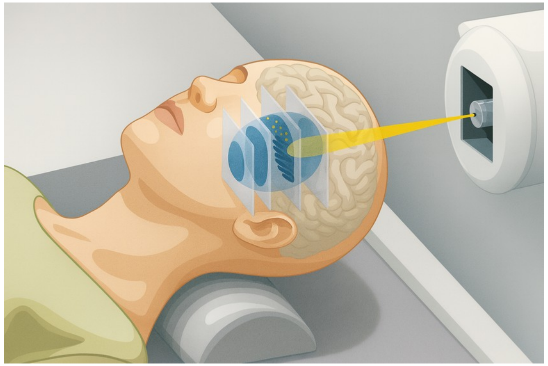

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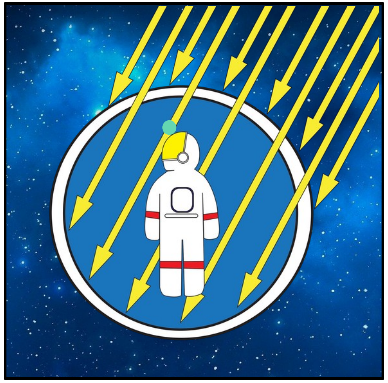
***Radioprotection in space***

light ions (p, He, Li, C, O), peak @ 700-800 MeV/u



Since they can interact with astronauts,
to **optimize spacecraft shielding**
and **risks model**

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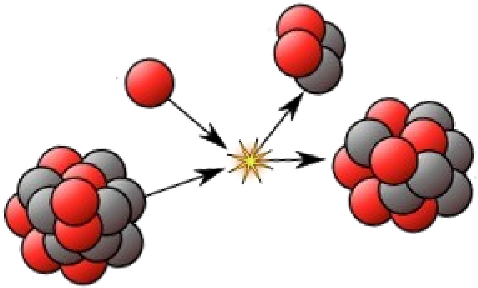

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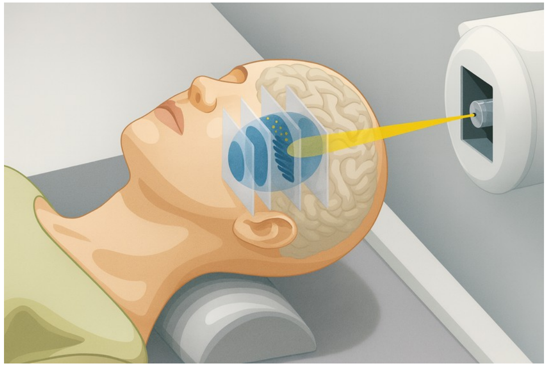

Since they influence the dose delivery, to **improve** the effectiveness of the **Treatment Planning System** (TPS)

**nuclear cross section measurements needed!**

$$\frac{d\sigma}{d\Omega} \qquad \frac{d\sigma}{dE_k}$$

$$\sigma_R = \int_0^{\Omega} \int_0^{\infty} \frac{d^2\sigma}{dE_K d\Omega} dE_K d\Omega$$

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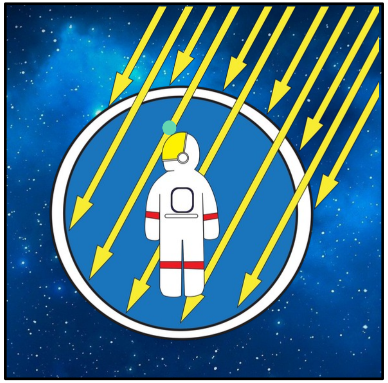

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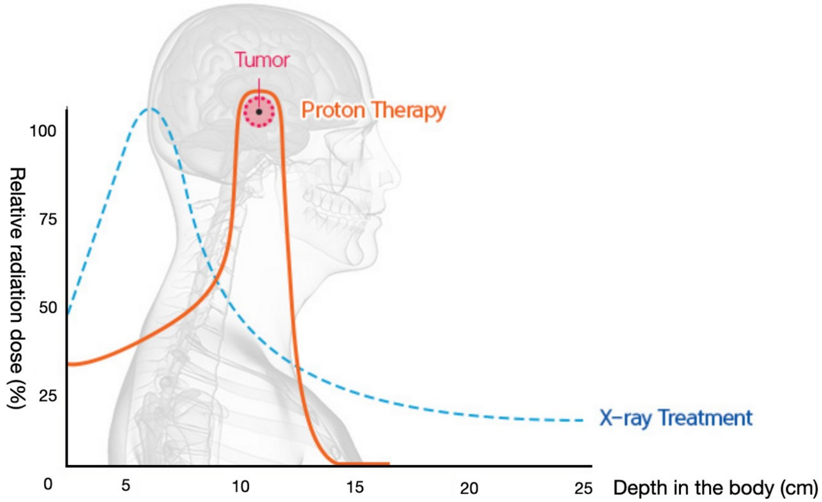
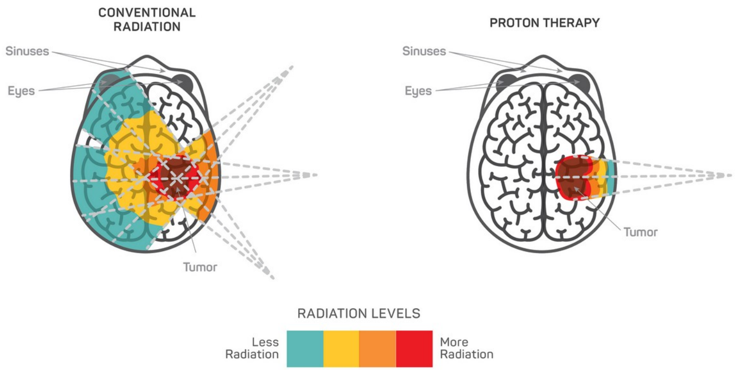



Particle therapy vs radiotherapy:

- ✔ **Finite range**
- ✔ **Localized dose profile**
- ✔ **Spare of healthy tissues**



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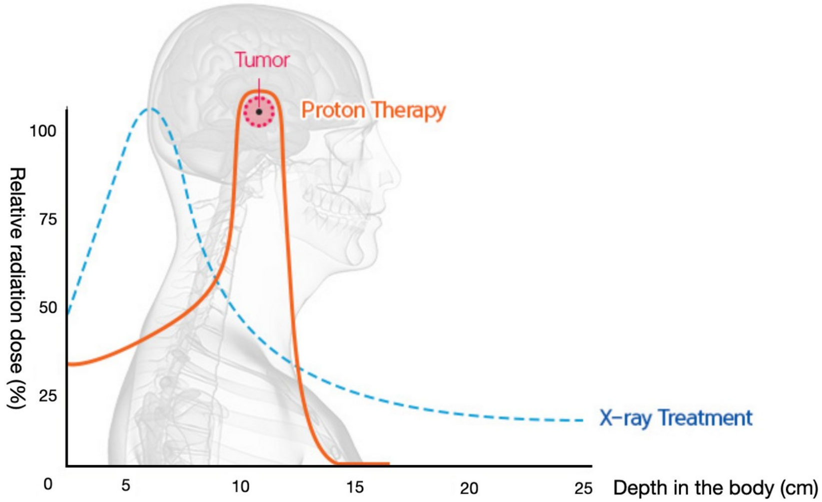


Particle therapy vs radiotherapy:

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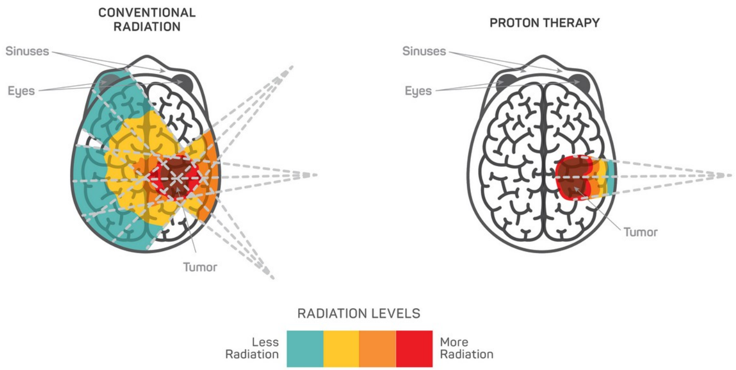
- ⚠ **Nuclear Fragmentation**



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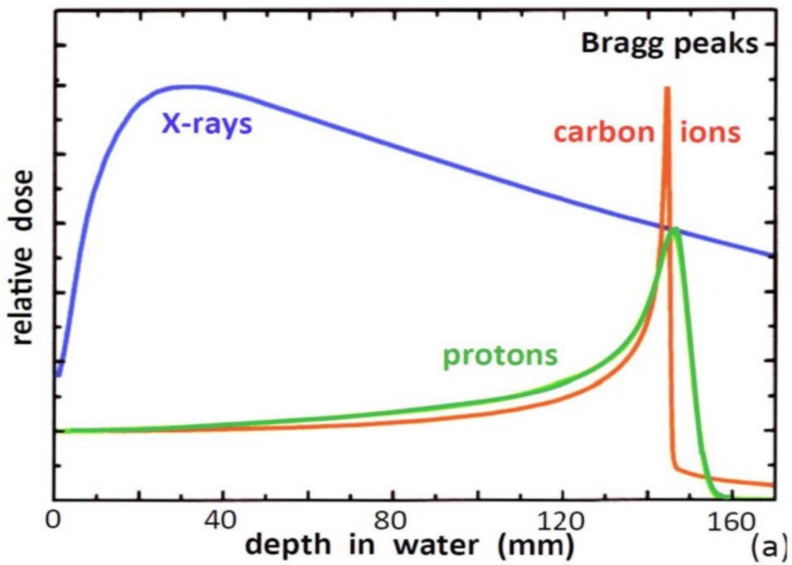

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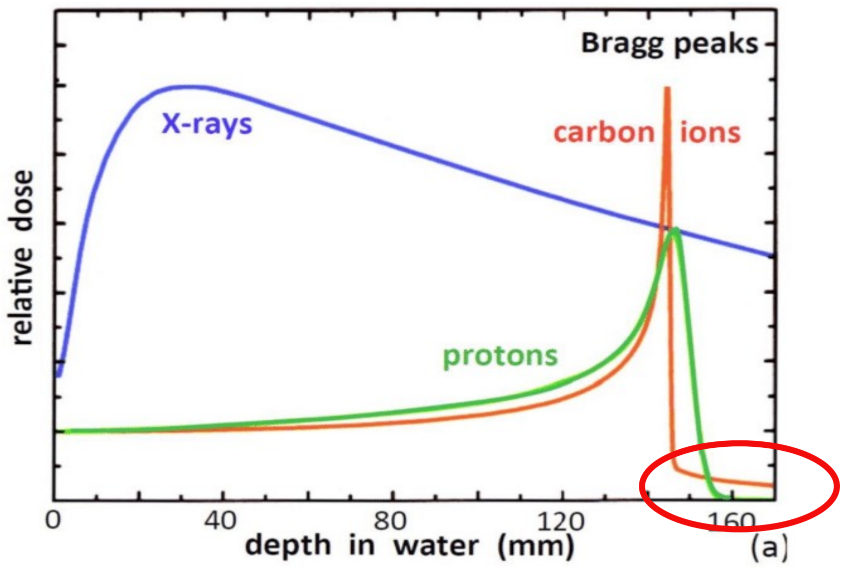

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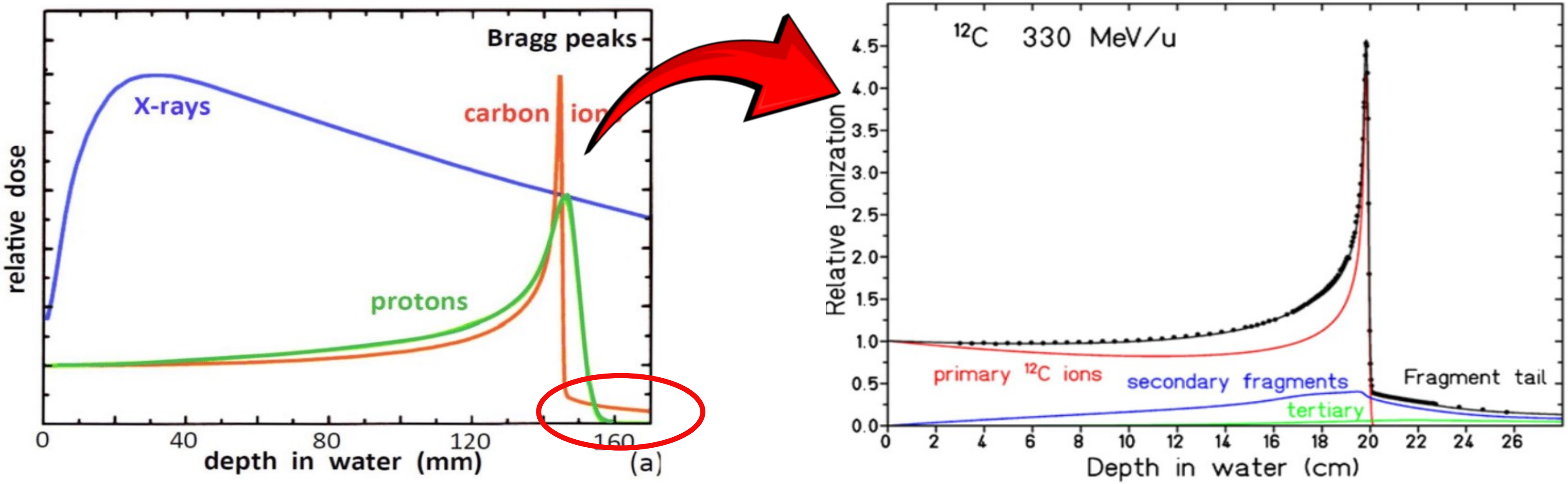

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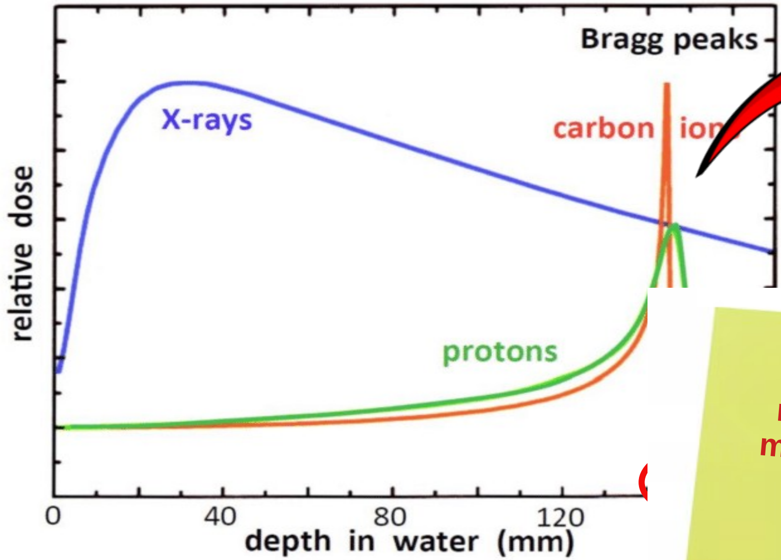


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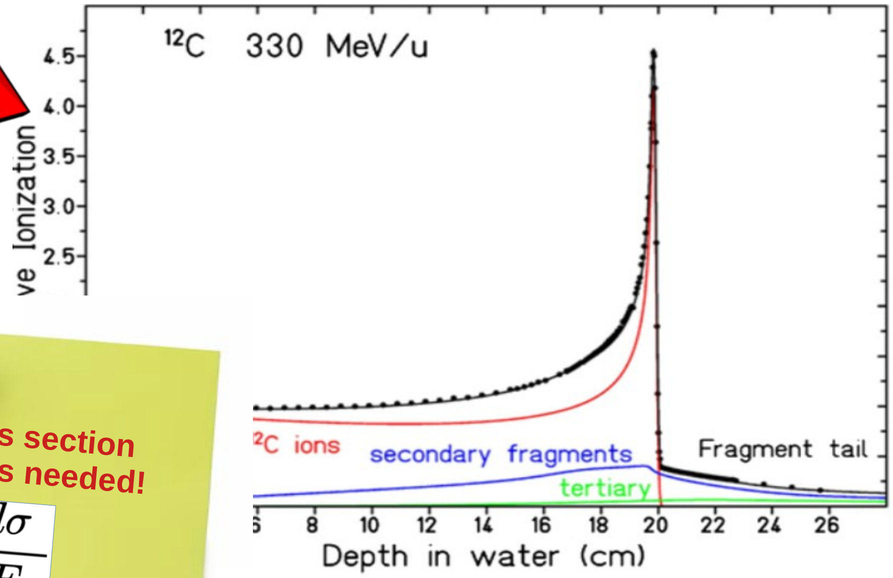
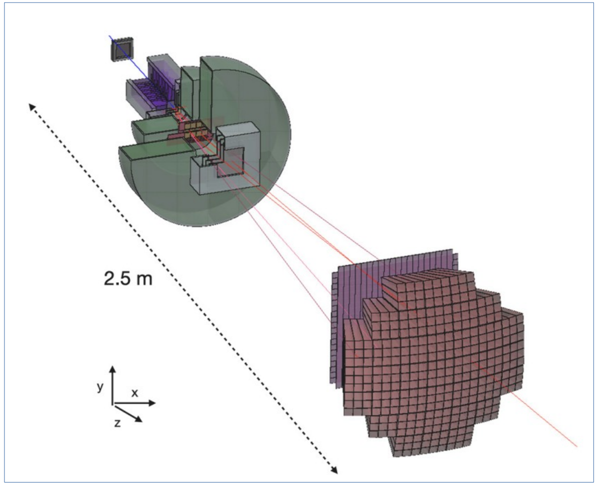


# The FOOT experiment

**Goal:**

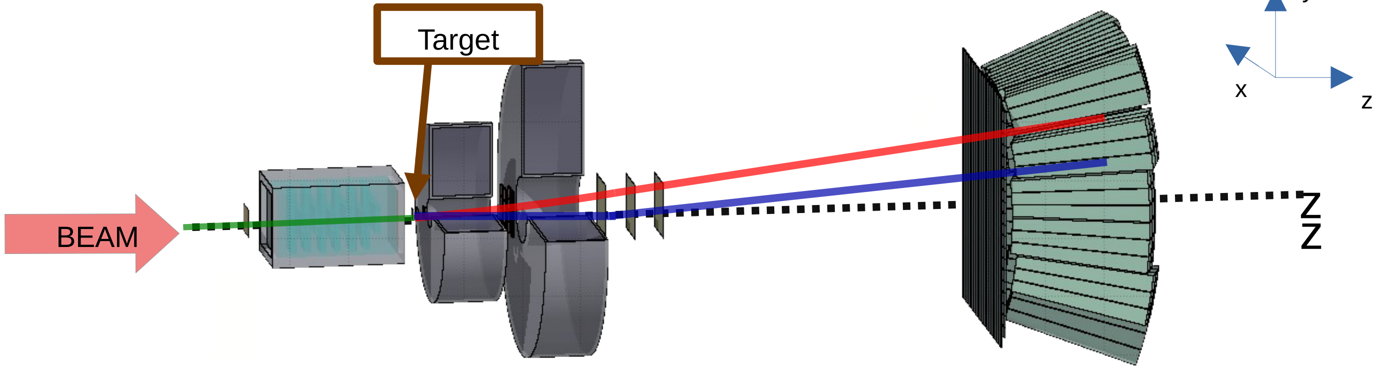
**Double differential nuclear fragmentation cross section measurements** $\frac{d^2\sigma}{d\Omega\, dE_{kin}}$ with resolution better than 5%

- Fixed target collisions
- Beam kinetic energies between 200 MeV/n and 800 MeV/n for **particle therapy** and **space radioprotection** topics
- **Table top setup** to be moved according to beam facility availability
- Direct / inverse kinematics cross section measurements

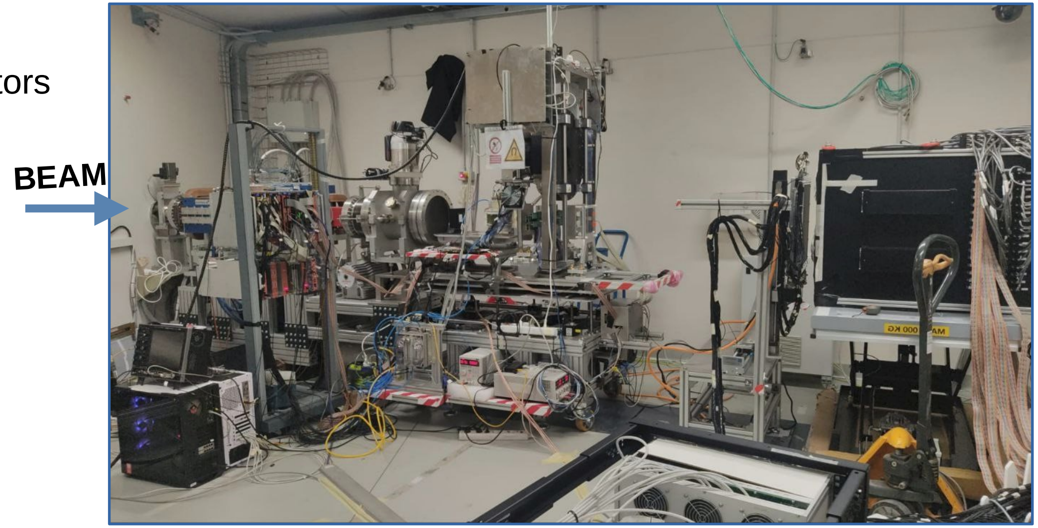



***electronic setup***

# The electronic setup




- Designed for “heavy” fragments (**3 ≤ Z ≤ 10**)
- Angular acceptance of ~ 10°
- **Particle Identification** thanks to the several specialized detectors
- Real time acquisition
- **Final setup completed in 2024!**



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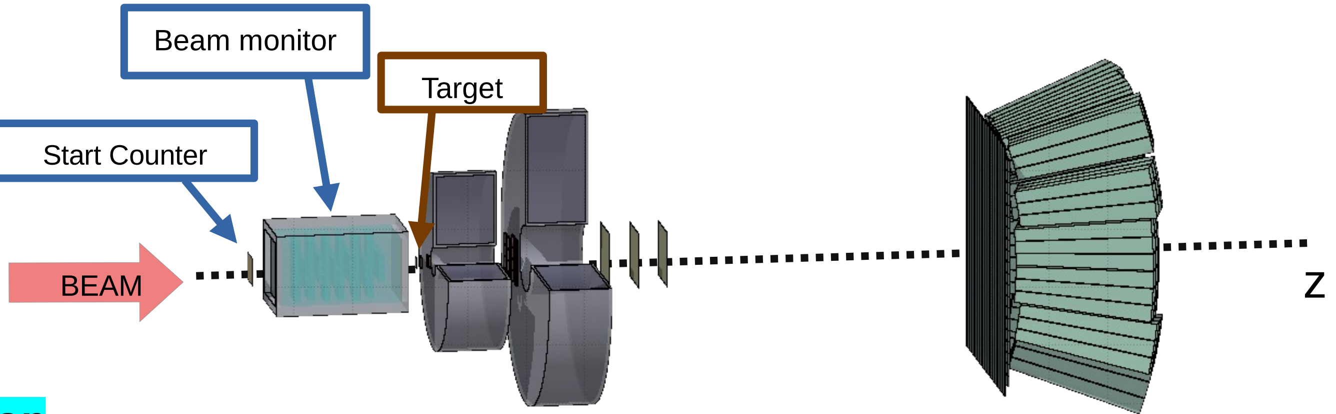
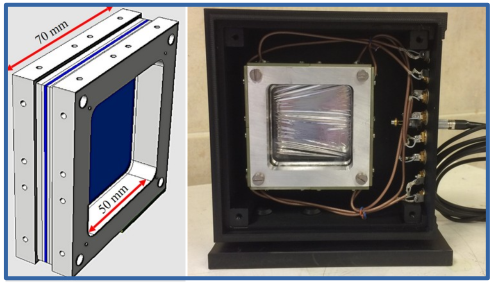



***Upstream region***
monitoring the beam before impinging on target

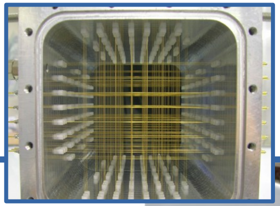


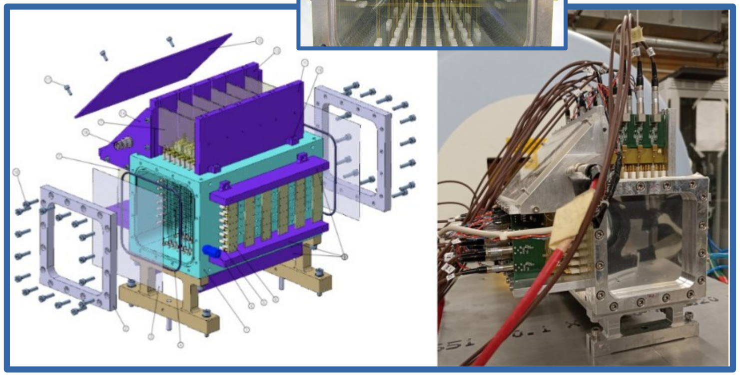

## Start Counter

**start of ToF** (**$\sigma_t$ ~ 40 ps**)
250 μm – 1 mm thick plastic scintillator
5x5 $cm^2$ active area
48 SiPMs, 8 channels readout

## Beam monitor

**beam momentum and direction** (**$\sigma_\theta$ < 0.5 °**)
Drift chamber
$Ar/CO_2$ (80%/20%)
12 layers with 3 cells each





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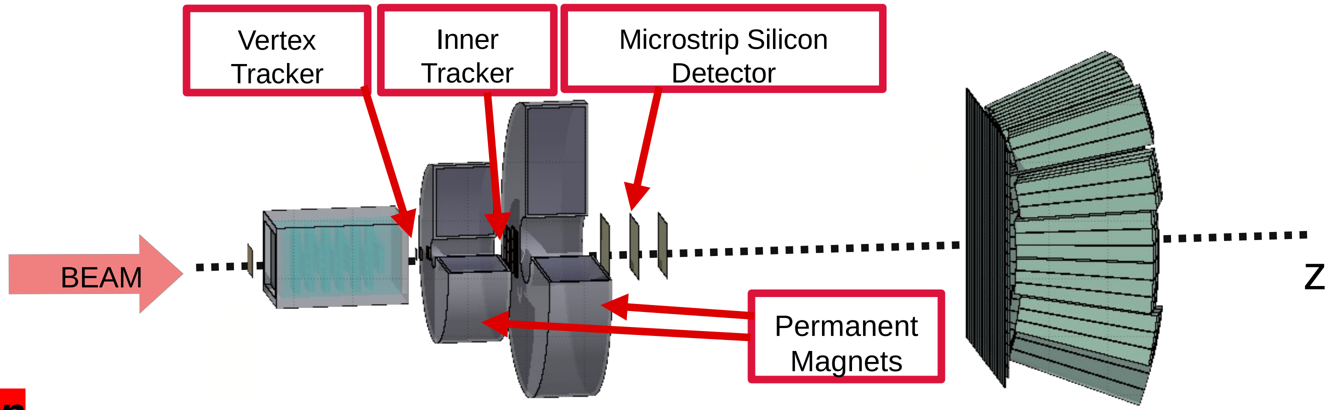
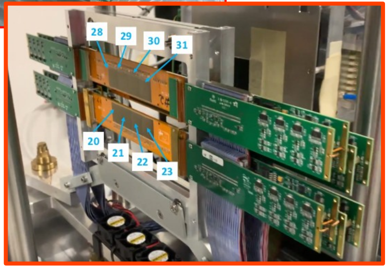



***Tracking region***

reconstruction of the track of the fragments and momentum measurement (**$\sigma_p$ / p < 4%**)

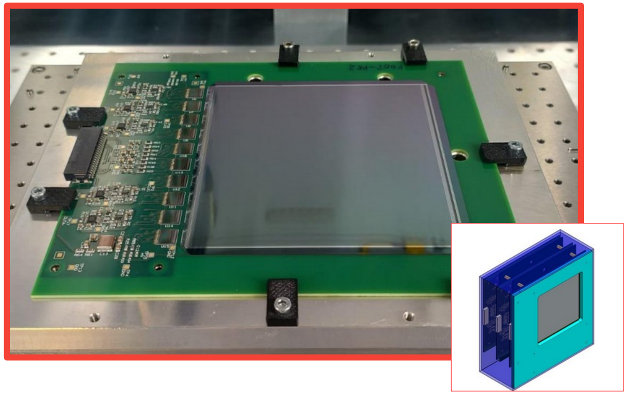


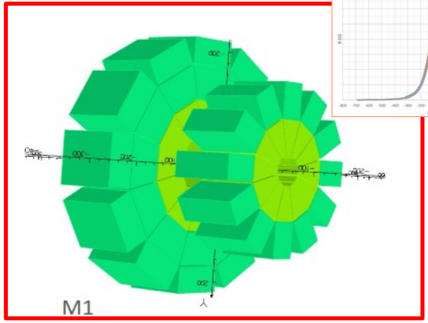

## Vertex & Inner Tracker

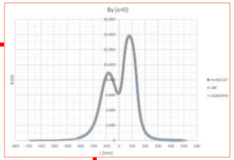
MIMOSA-28 Si Pixel detector
20 µm pitch, 50 µm depth
4 planes for Vertex
2 planes for Inner Tracker

## Microstrip Detector

Si Strip detector
9 x 9 cm2 active area
150 µm readout pitch
3 pairs of X-Y layers



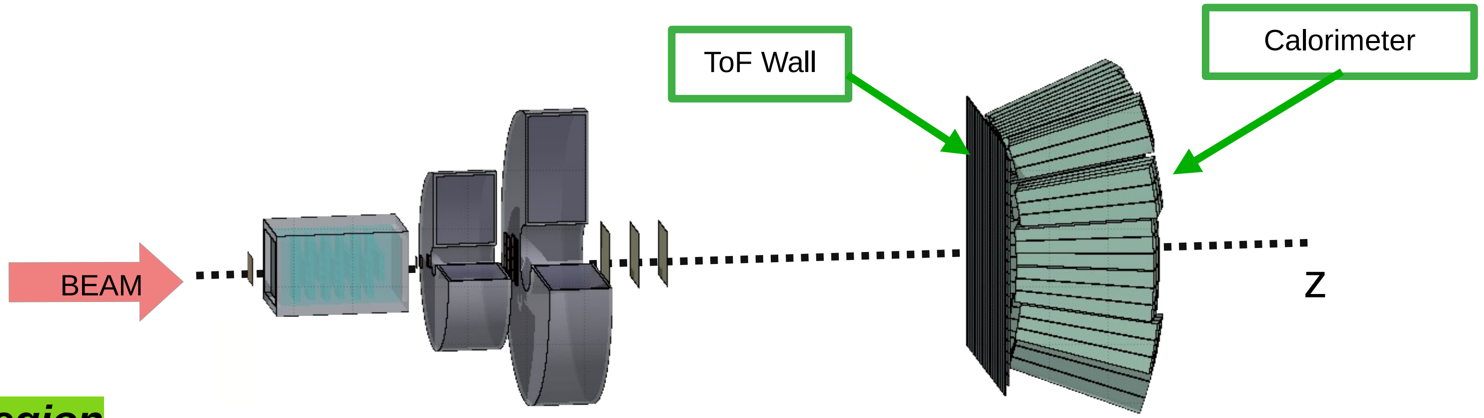


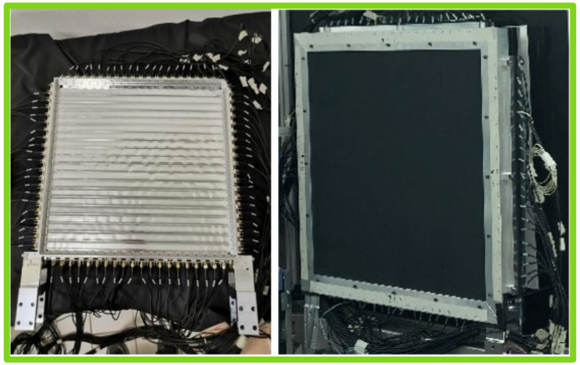
## Magnets

Hallbach configuration
B field in y axis (max 0.9 and 1.1 T)

# The electronic setup




***Downstream region***
particle identification (charge and mass number)



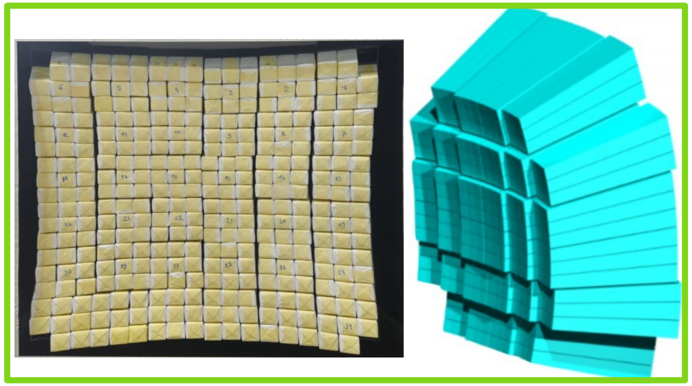
## ToF Wall

**stop of ToF ($\sigma_t$ ~ 40 ps)**
**energy loss ($\sigma_{Eloss}/E_{loss}$ ~ 5%)**
plastic scintillator bars
44x2x0.3 $cm^3$ dimension
2 layers of 20 bars
SiPM readout

**charge reconstruction**

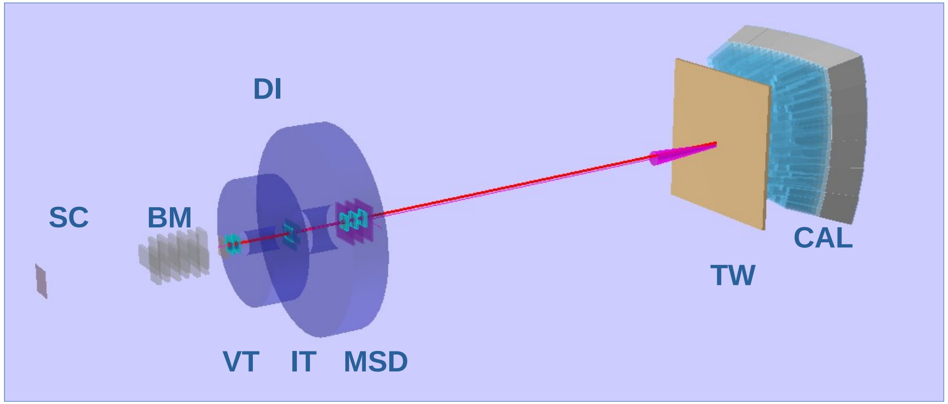
## Calorimeter

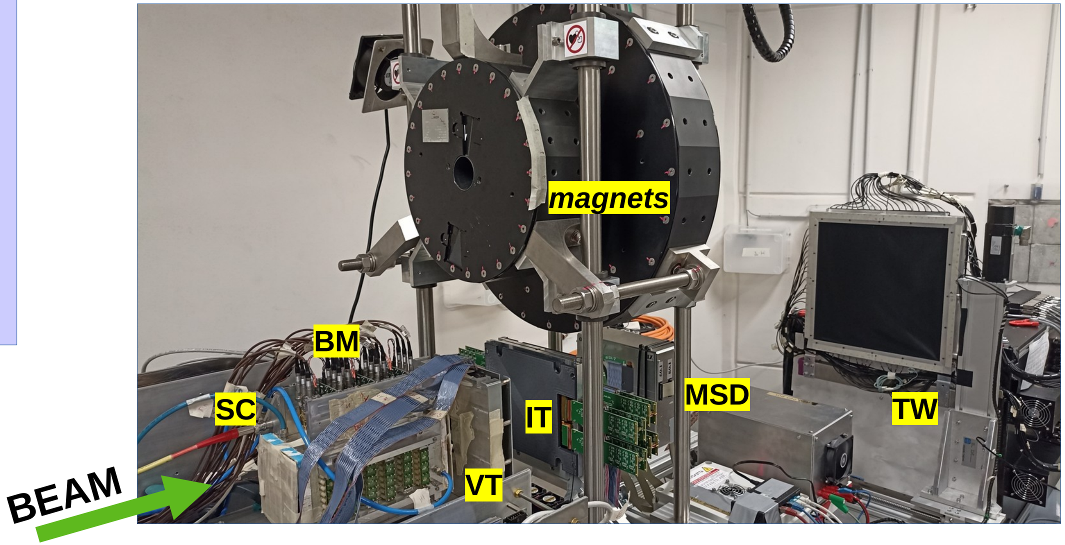
**kinetic energy ($\sigma_{Ekin}$ ~ 2 %)**
BGO **scintillator**
320 crystals



# CNAO2024 experimental campaign

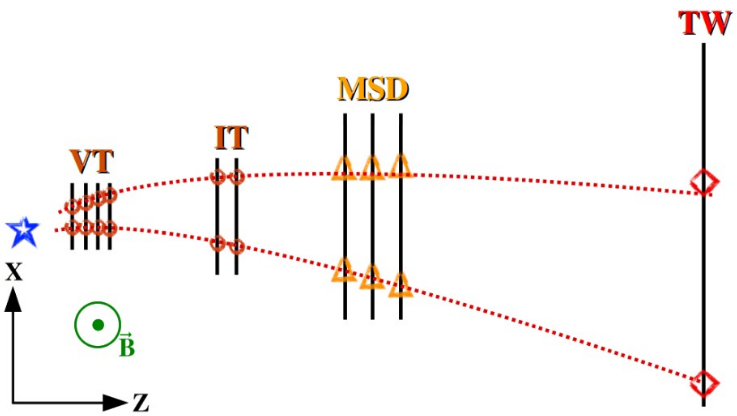
- Data-taking at CNAO in November 2024
- $^{12}$**C 200 MeV/u** on 5 mm **C target** with **B** field
- Total setup
- *~ 1.8 M **experimental** data*
- *10 M **FLUKA simulated** data*




- **VT, MSD, TW** considered
- **Global tracking** reconstruction

# Tracking Reconstruction




Clusters of every detector are collected in a **global track** using **GENFIT** library,

- Setup geometry and magnets map loaded
- Start from **VT tracklets**
- Projection to (if present) **planes of IT**
- **Kalman Filter** extrapolation to **MSD**
- **Kalman Filter** extrapolation to **TW**
- Possible Z from **TW** → track representation
- Fit the track candidates and extract fitted **global track,** with **Z, momentum, β, emission angle θ**

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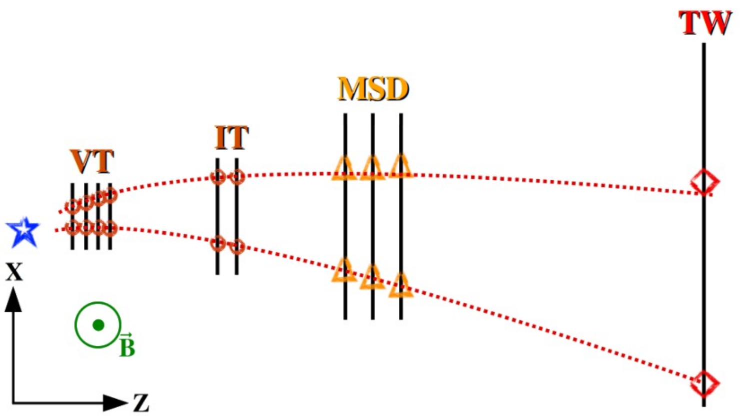


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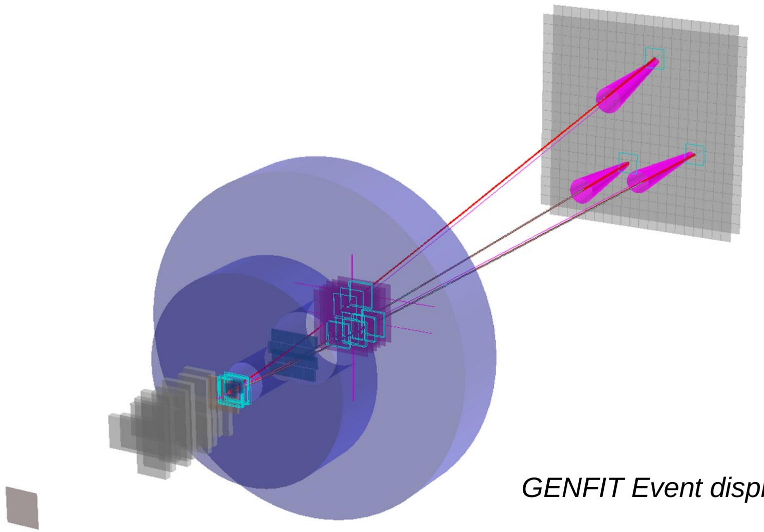
**First tracking reconstruction in magnetic field of the FOOT apparatus for experimental data!**

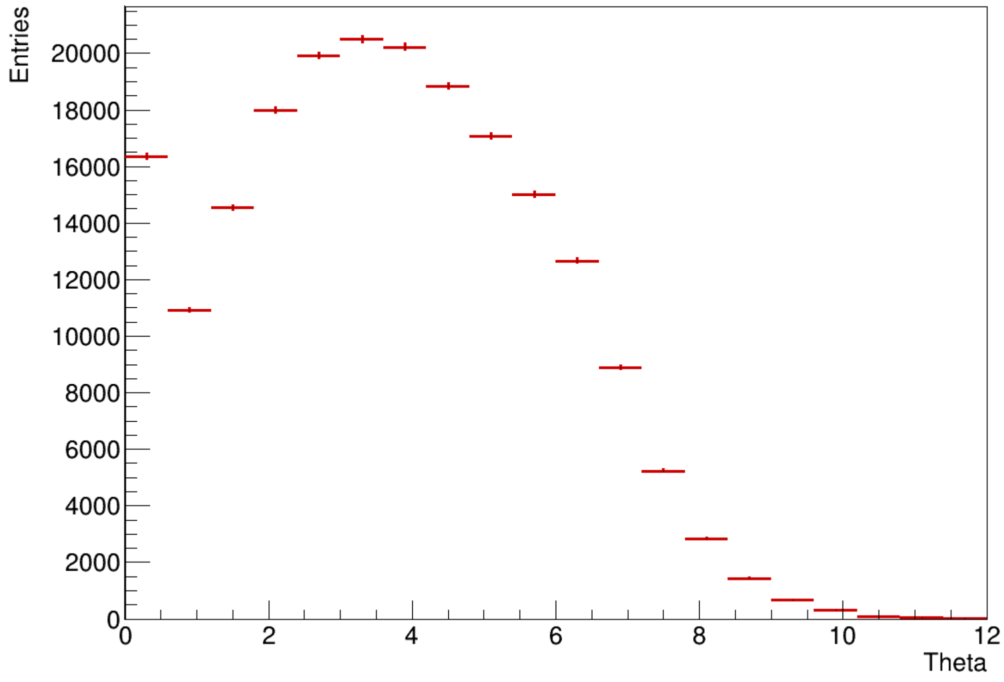


*GENFIT Event display, run 7077*

# Yield cuts

The following cuts are used in the analysis:

*es. Z=2*
*from simulation*




**Reconstruction**

- global track using **GENFIT**
- it has a **VTX tracklet**
  BM – VT tracklet match
  BM has only 1 track for the event
- it is made of at least **9 clusters** (~70% of totals)
- it considers **MSD** and **IT** clusters
- it has a **TW point**

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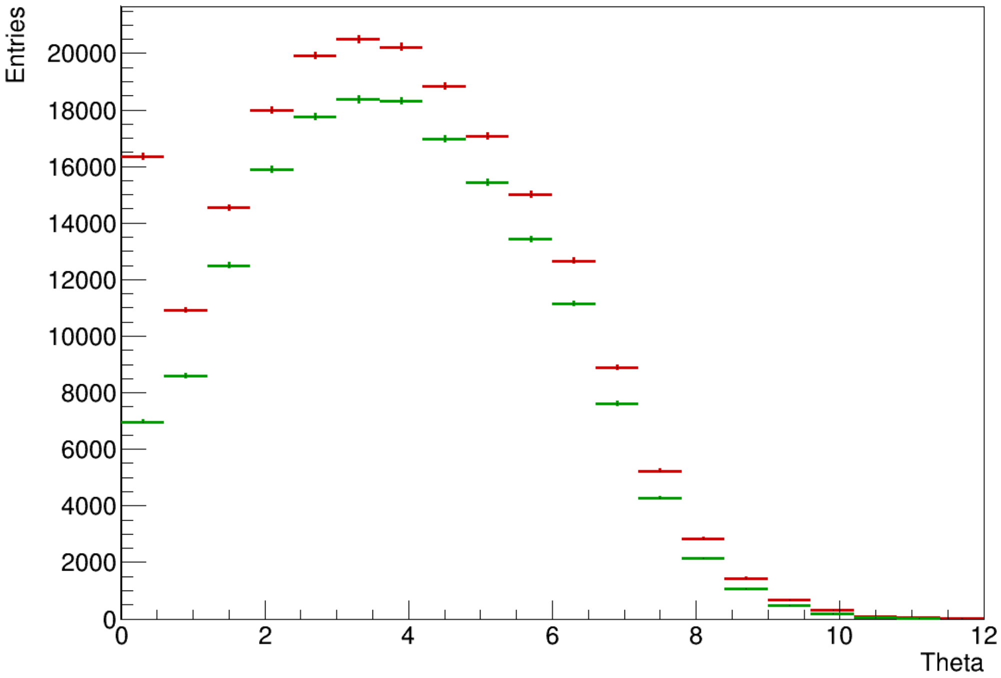
**Reconstruction**

**Quality cut**

- p value > 0.01
- | worst cluster residual | < 0.04 cm



# Yield cuts

The following cuts are used in the analysis:

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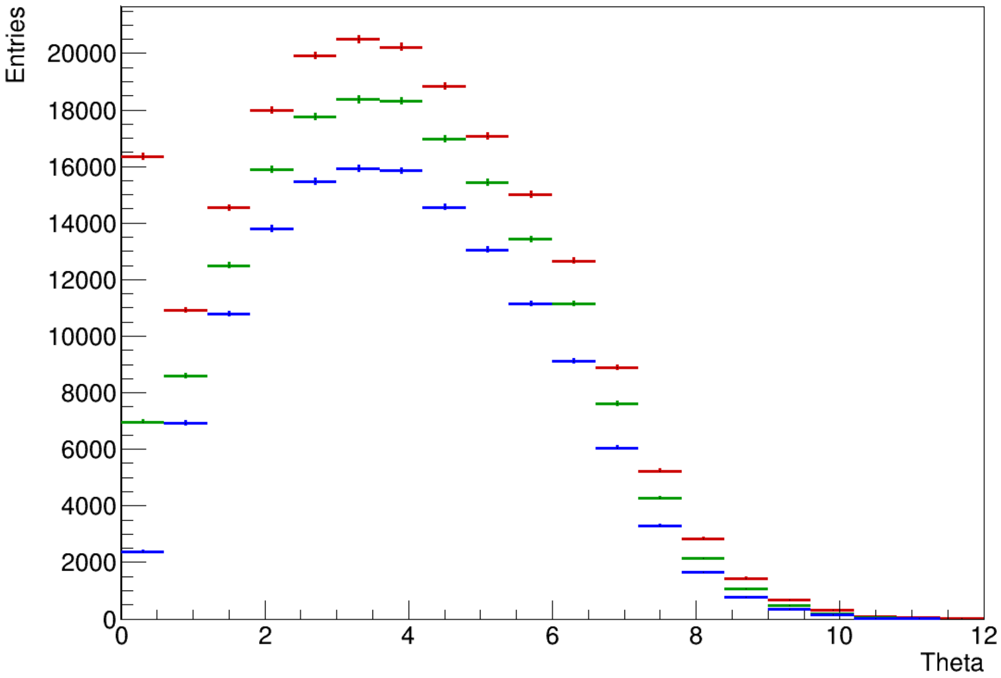
**Reconstruction**
**Quality cut**
**Single track cut**
- cuts the events with only 1 track



# Yield cuts

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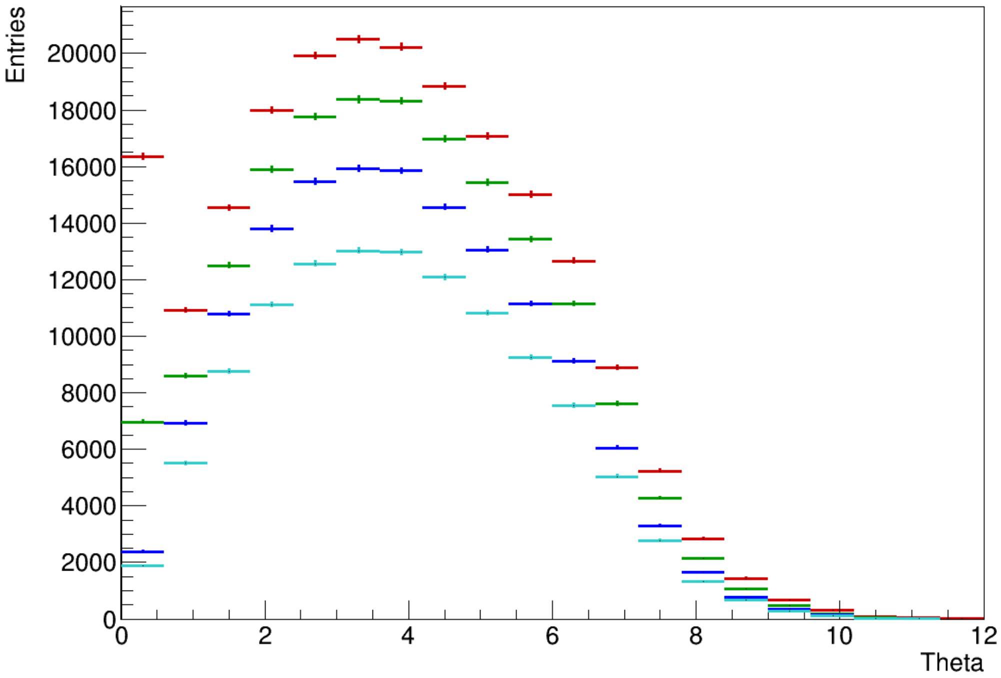
**Reconstruction**
**Quality cut**
**Single track cut**
**TW point cut**

- consider only tracks with different TW points
- the number of tracks is the same of TW points



# Cross Section closure test

- Closure test to evaluate reliability and robustness of the analysis methods performed on **FLUKA simulated data**
- Comparison of reconstructed and reference cross section

$$\frac{d\sigma}{d\theta}(Z,\theta) = \frac{Y(Z,\theta)}{N_{beam}\ N_{target}\ \Omega_{\theta}\ \epsilon(Z,\theta)}$$

$$\text{ratio plot} = \frac{\sigma_{reco} - \sigma_{MC}}{\sigma_{MC}}$$

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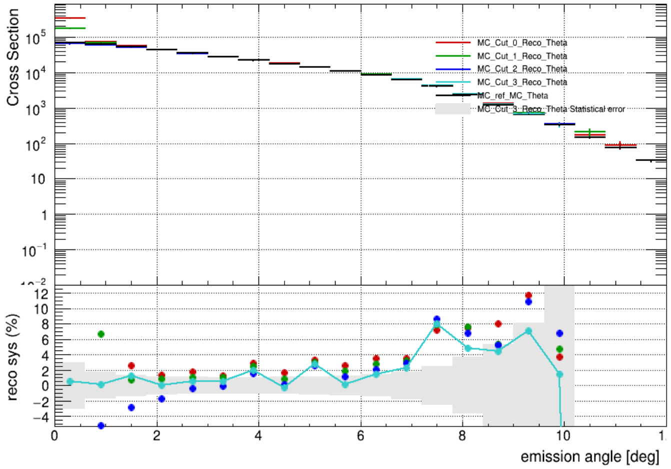
[mb/sr] ***He***

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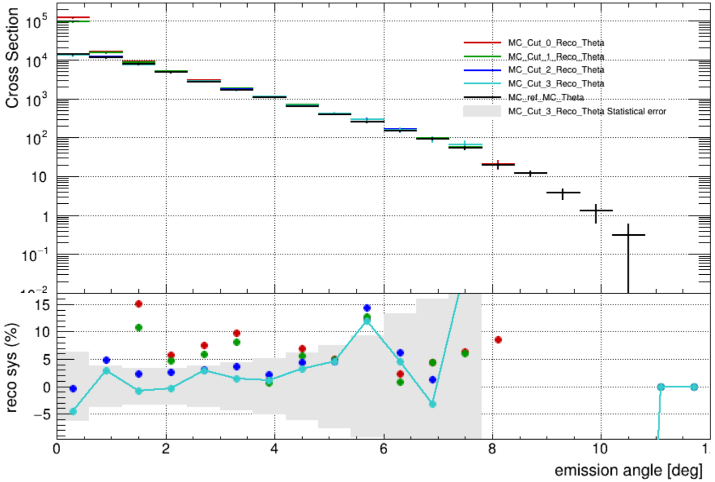


Reconstruction
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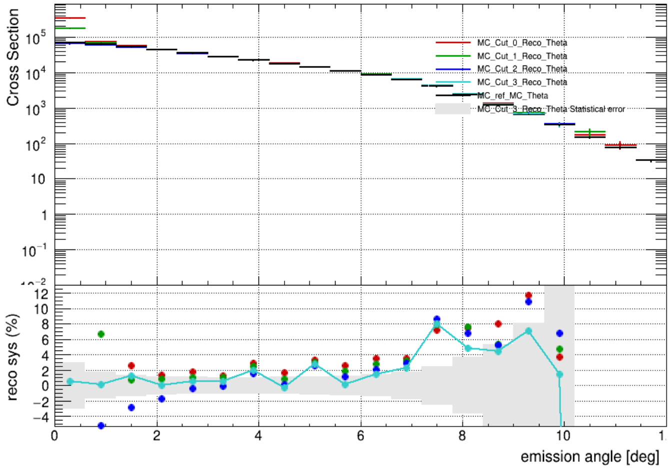


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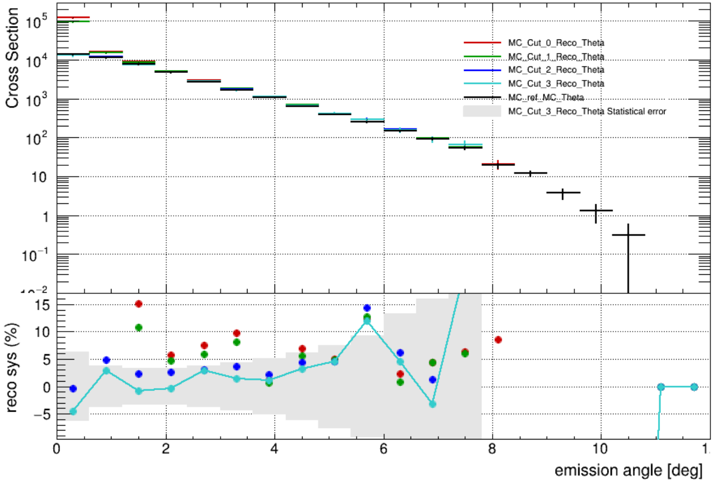


**Reconstruction**
**Quality cut**
**Multi-tracks cut**
**TW point cut**
**MC reference**
last cut stat error

- Efficiencies evaluated on global track reconstruction performance
- Cuts progressively improve closure test
- Systematic discrepancy **inside the statystical error**, **lower than ±5%** up to highest angles
- Confirmation of robustness, application to experimental data

# Cross Section measurements

$$\frac{d\sigma}{d\theta}(Z,\theta) = \frac{Y(Z,\theta)}{N_{beam}\ N_{target}\ \Omega_\theta\ \epsilon(Z,\theta)}$$

$$\sigma(Z) = \int_{\theta_i}^{\theta_f} \frac{d\sigma}{d\theta}(Z,\theta)\, d\theta$$

- Differential cross section results on **experimental data**
- normalized to **total elemental cross section**
- using last cut for yields
- using efficiencies obtained by MC FLUKA simulation

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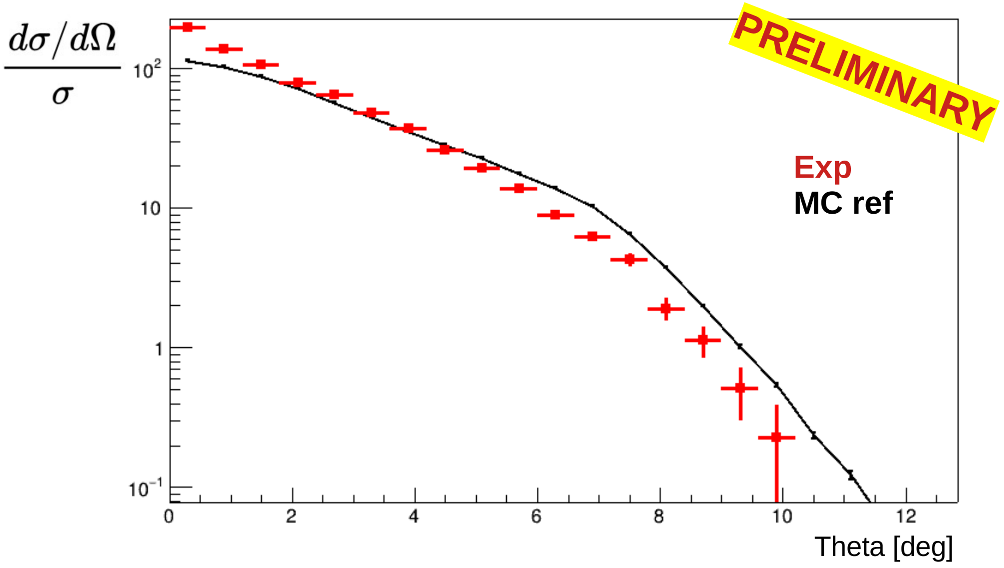
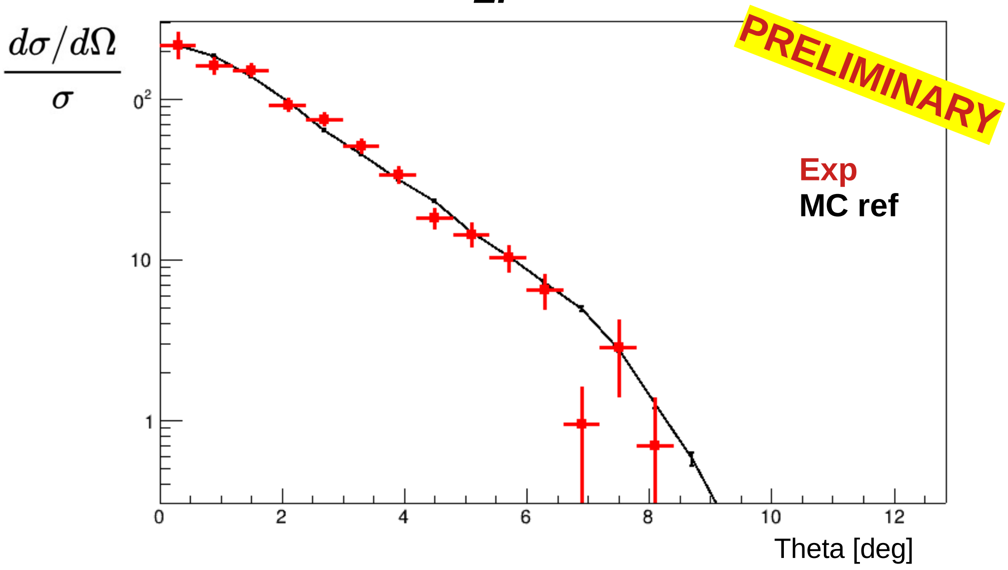



***Li***



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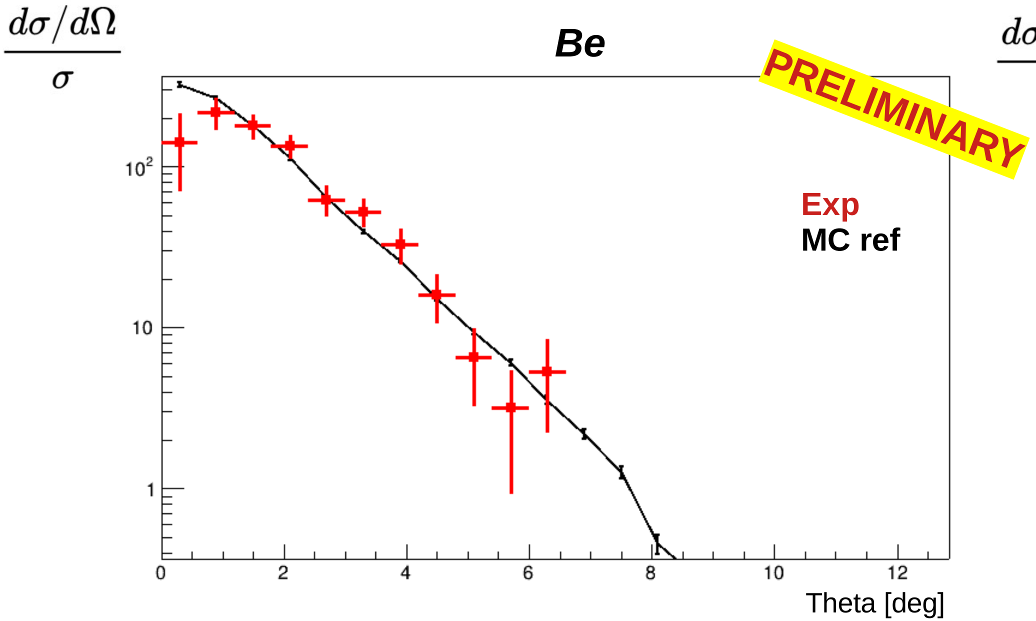
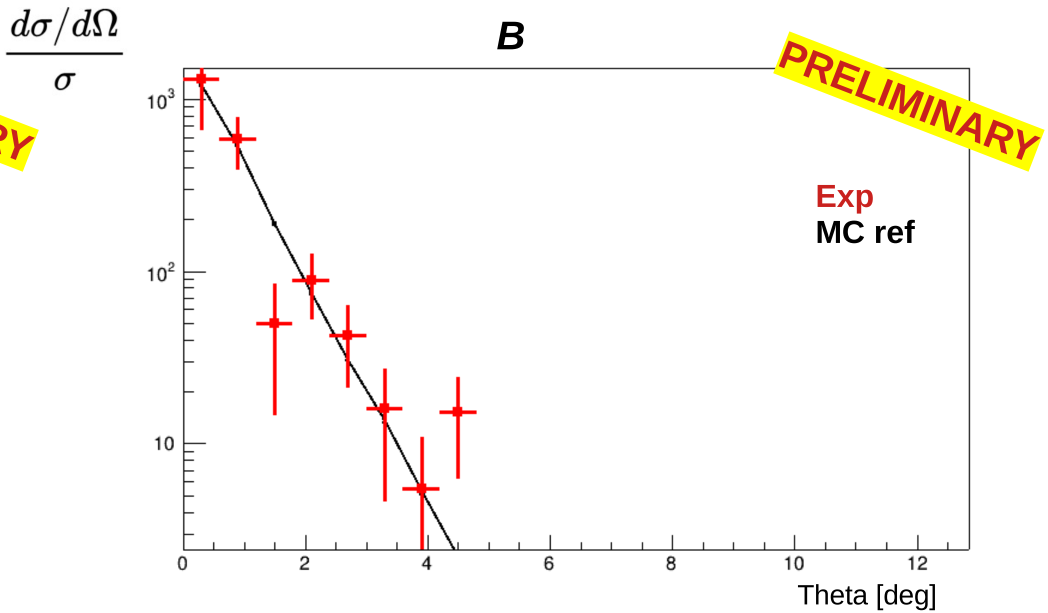
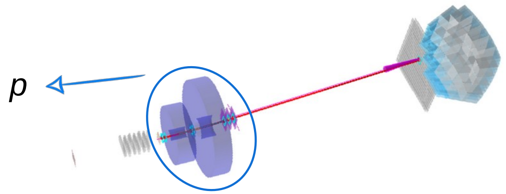



- First angular differential **cross sections measurements** of **200 MeV/u $^{12}$C on C**, with FOOT full setup, in B field
- Systematical error to be introduced according to agreement with MC closure test
- **Behaviour in agreement with what expected** by MC_ref,
- although several aspects to inspect (VT efficiency, MSD clustering, magnets mapping alignment...)

# First attempt to momentum reconstruction

**Momentum p** reconstructed from bending of the global track in the tracking region



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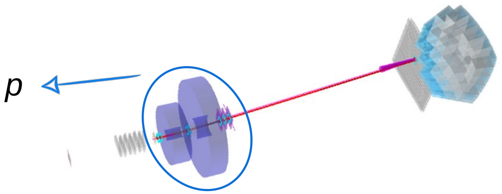
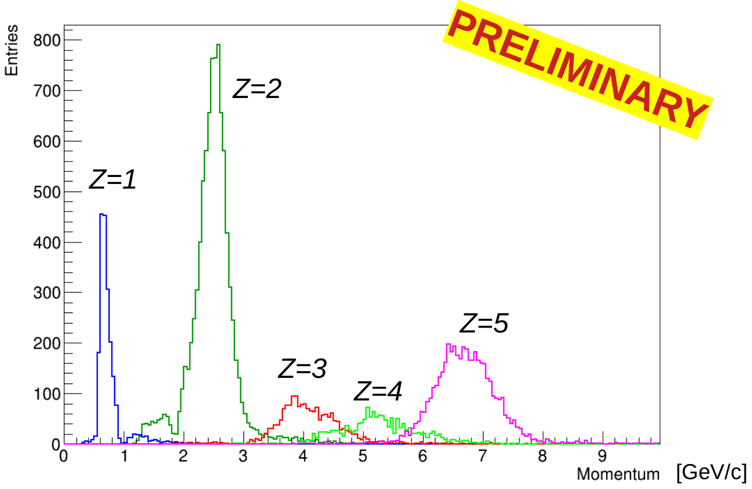
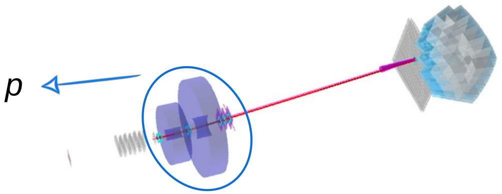


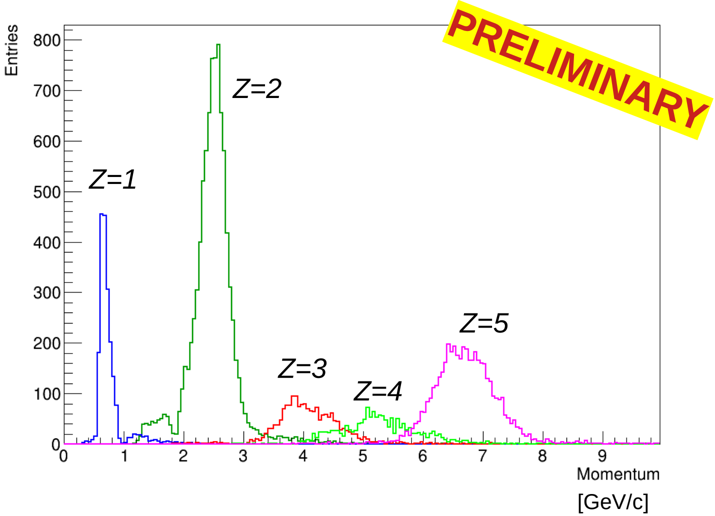




- no cuts applied, noisy events to be removed

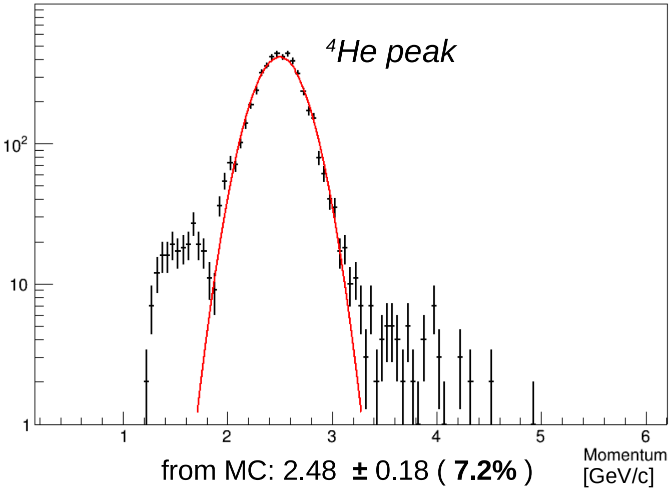
# First attempt to momentum reconstruction

**Momentum p** reconstructed from bending of the global track in the tracking region



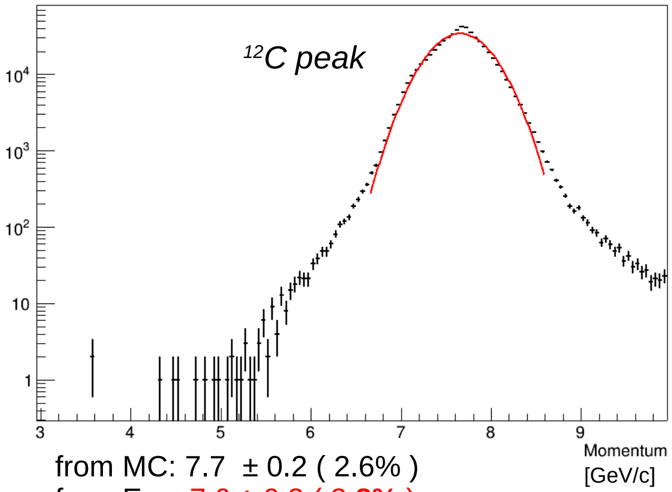




**He**




from MC: 2.48 ± 0.18 ( **7.2%** )
from Exp: 2.49 ± 0.23 ( **9.2%** )

**C**




from MC: 7.7 ± 0.2 ( 2.6% )
from Exp: 7.6 ± 0.3 ( 3.8% )

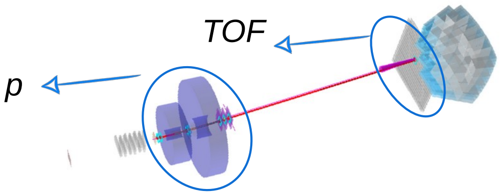
- no cuts applied, noisy events to be removed
- applying cuts, distribution comparable to MC, in agreement with FOOT resolution requirements

# First attempt to mass reconstruction

$$A = \frac{p}{\beta\gamma m_u}$$

**Atomic mass A** can be computed combining

- momentum **p** from GENFIT global track
- **TOF** from TW point



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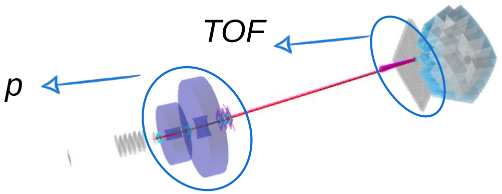
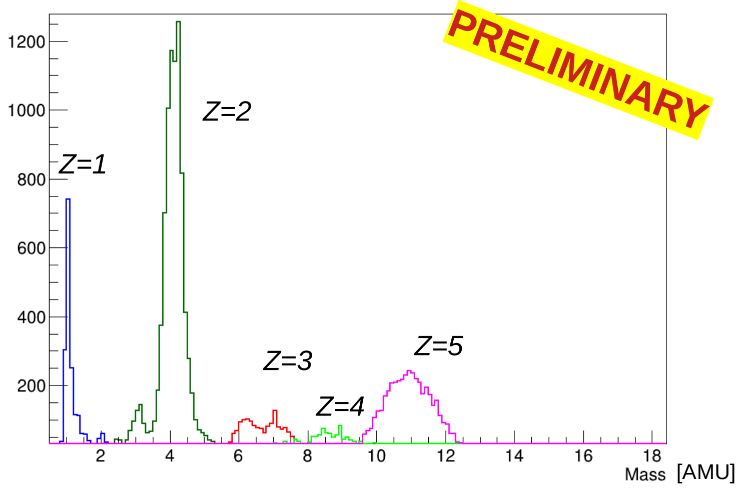


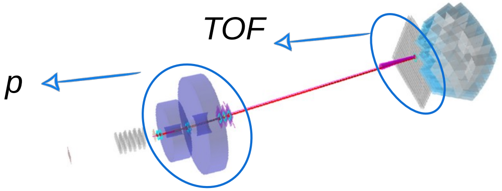



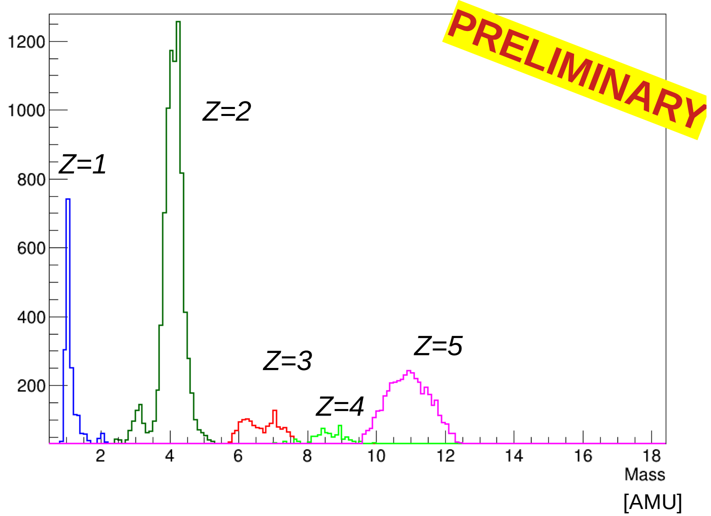

- no cuts applied,
- distinction of the main isotopes (es Z=2, A=4)

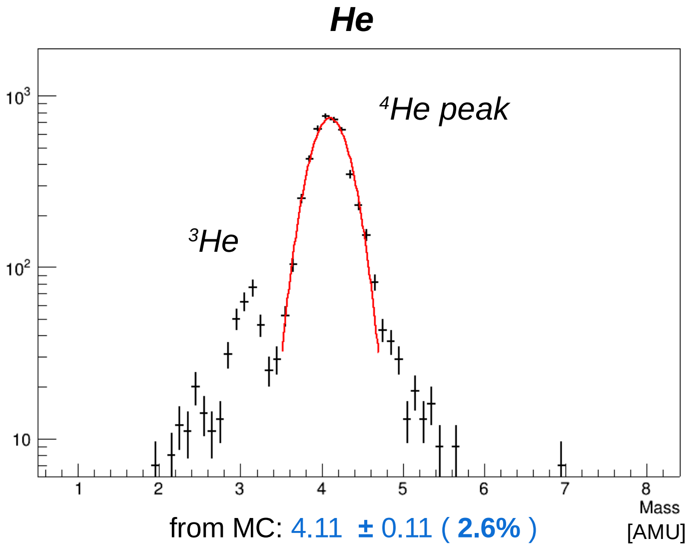
# First attempt to mass reconstruction

$$A = \frac{p}{\beta\gamma m_u}$$

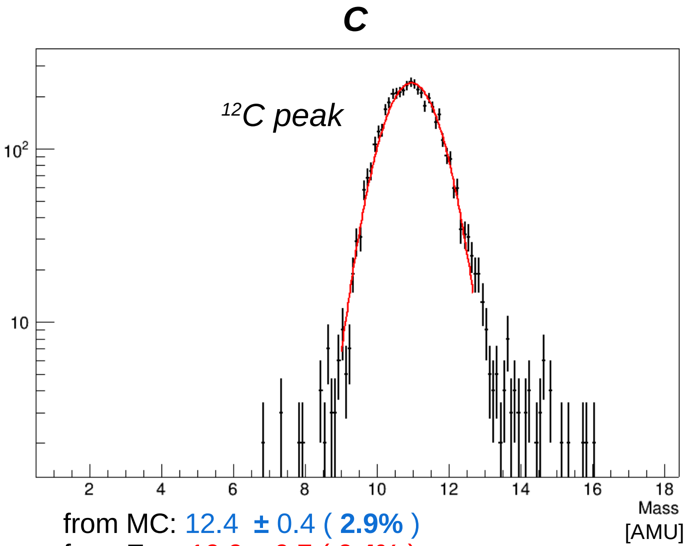
**Atomic mass A** can be computed combining
- momentum **p** from GENFIT global track
- **TOF** from TW point




from MC: 4.11 ± 0.11 ( **2.6%** )
from Exp: 4.01 ± 0.24 ( **5.9%** )




from MC: 12.4 ± 0.4 ( **2.9%** )
from Exp: 10.9 ± 0.7 ( **6.4%** )

- no cuts applied,
- distinction of the main isotopes (es Z=2, A=4)
- after cuts, systematical underestimation
- for main isotopes distribution comparable to MC, in agreement with FOOT resolution requirements

# Conclusions

- Nuclear fragmentation cross section measurements with the FOOT experiment
- Fundamental interest in several fields, among which **particle therapy** and **space radioprotection**

- First results with the full setup!
- Preliminary differential cross section measurements of $^{12}$**C 200 MeV/u** on 5 mm **C target**
- Preliminary momentum and mass reconstruction, promising for ongoing analysis toward **isotopic cross sections**

# Conclusions

***Thanks for the attention!***

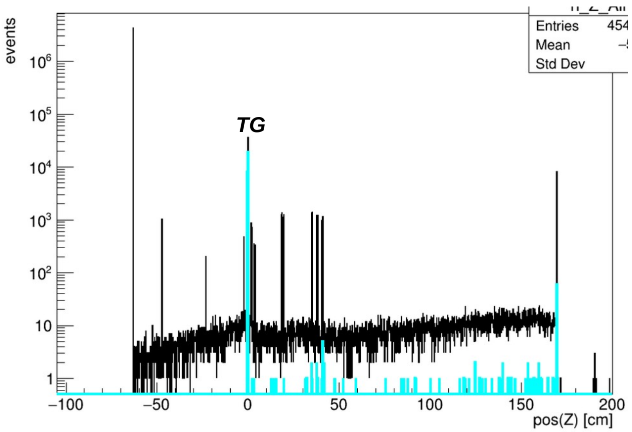
# back-up slides

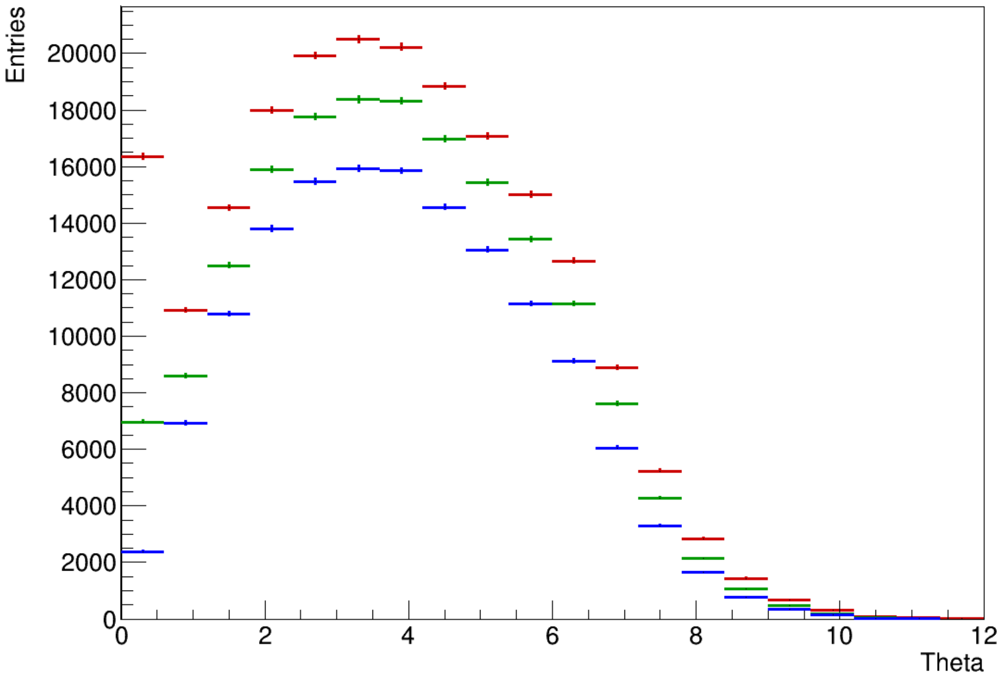
# Yield cuts

The following cuts are used in the analysis:

*es. Z=2*
*from simulation*

**Reconstruction**
**Quality cut**
**Multi-tracks cut**
- cuts the events with only 1 track



# The FOOT physics program

| Physics aim | Beam | Target | Energy (MeV/u) | Inverse or direct |
|---|---|---|---|---|
| Target Frag. PT | $^{12}C$ | C, $C_2H_4$ | 200 | inv |
| Target Frag. PT | $^{16}O$ | C, $C_2H_4$ | 200 | inv |
| Beam Frag. PT | $^{12}C$ | C, $C_2H_4$, PMMA | 350 | dir |
| Beam Frag. PT | $^{16}O$ | C, $C_2H_4$, PMMA | 400 | dir |
| Beam Frag. PT | $^{4}He$ | C, $C_2H_4$, PMMA | 250 | dir |
| Rad. Prot.space | $^{4}He$ | C, $C_2H_4$, PMMA | 700 | dir |
| Rad. Prot.space | $^{12}C$ | C, $C_2H_4$, PMMA | 700 | dir |
| Rad. Prot.space | $^{16}O$ | C, $C_2H_4$, PMMA | 700 | dir |

Several facilities avaliable:

**CNAO** (Pavia, Italy)

**GSI** (Darmstadt, Germany)

**HIT** (Heidelberg, Germany)

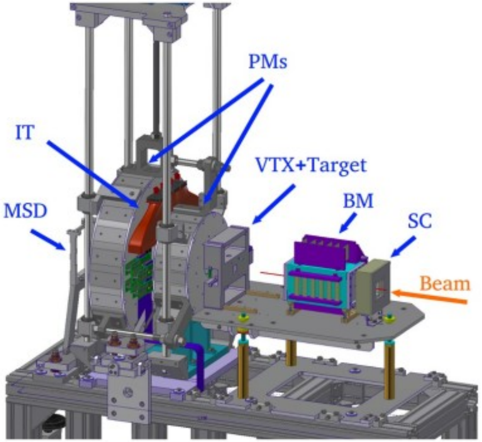
# Physics data taking done up to now

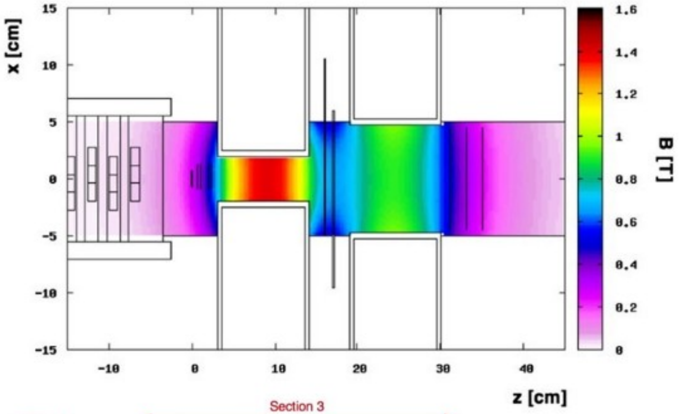
| Beam | Target | Energy MeV/u | Statistics (millions) | Integral Differential elemental | Integral Differential isotopic | direct | inverse | Emulsions | campaign |
|---|---|---|---|---|---|---|---|---|---|
| O | C<br>C2H4 | 200<br>400 | 0.06 | angle | NO | YES | NO | Yes<br>Yes | GSI 2019<br>GSI 2020 |
| O | C<br>C2H4<br>C<br>C2H4 | 200<br>200<br>400<br>400 | 14.2<br>12.2<br>5.5<br>6.5 | angle | NO | YES | NO | Yes | GSI 2021 |
| He | C | 100<br>140<br>200<br>220 | 18.5<br>19.6<br>13.5<br>14.4 | angle | NO | YES | NO | No | HEID 2022 |
| C | C | 200 | 4.1 | angle | NO | YES | NO | | CNAO 2022 |
| C | C<br>C2H4 | 200<br>200 | 3.2<br>2.0 | Angle<br>Energy | YES | YES | YES | Yes | CNAO 2023 |
| C | C | 200 | Mostly tests VTX, IT, Calo, NIT | Angle | YES | YES | NO | NIT tests | CNAO 2024 |

# Next Physics data taking

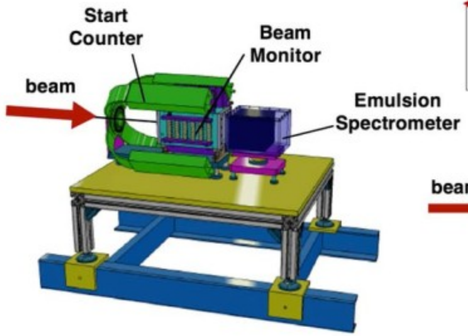
| Beam | Target | Energy MeV/u | Integral Differential elemental | Integral Differential isotopic | Emulsions | Campaign |
|---|---|---|---|---|---|---|
| C | C, C2H4 | 100-200 | Angle<br>Energy | YES | YES<br>(NIT?) | CNAO 2025 |
| O | C | 500-700 (?) | Angle<br>Energy | YES | YES | GSI 2026 |
| C | C, C2H4 | 200-300 | Angle<br>Energy | YES | - | CNAO 2026 |
| P | C | 100-220 | Angle<br>Energy | YES | NIT | CNAO 2026 |
| C | C, C2H4<br>PMMA | 320-400 | Angle<br>Energy | YES | YES | CNAO 2027 |
| He | C, C2H4<br>PMMA | 200-400(?) | Angle<br>Energy | YES | YES | CNAO 2027 |

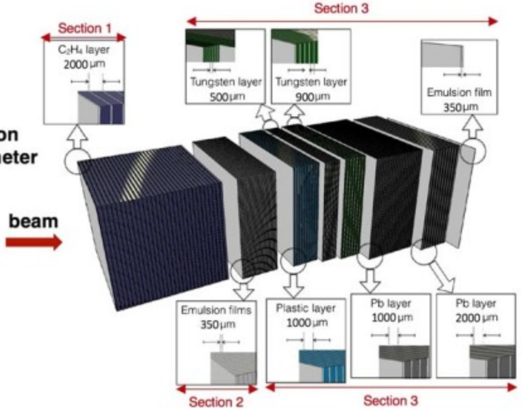
# Setup overview




$$p = mc\beta\gamma$$
$$E_{\text{kin}} = mc^2(\gamma - 1)$$
$$E_{\text{kin}} = \sqrt{p^2c^2 + m^2c^4} - mc^2$$



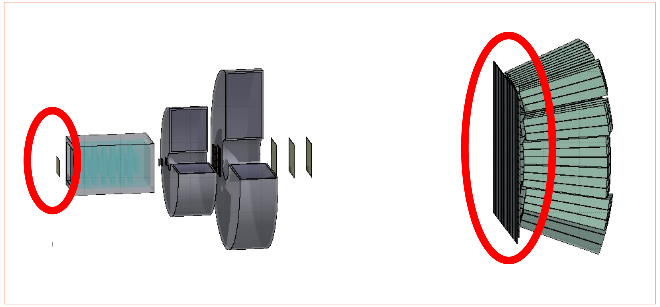

- $\sigma(p)/p$ at level of $4 - 5\%$;
- $\sigma(T_{\text{tof}})$ at level of 100 ps;
- $\sigma(E_{\text{kin}})/E_{\text{kin}}$ at level of $1 - 2\%$;
- $\sigma(\Delta E)/\Delta E$ at level of $5\%$;

# Fragments identification

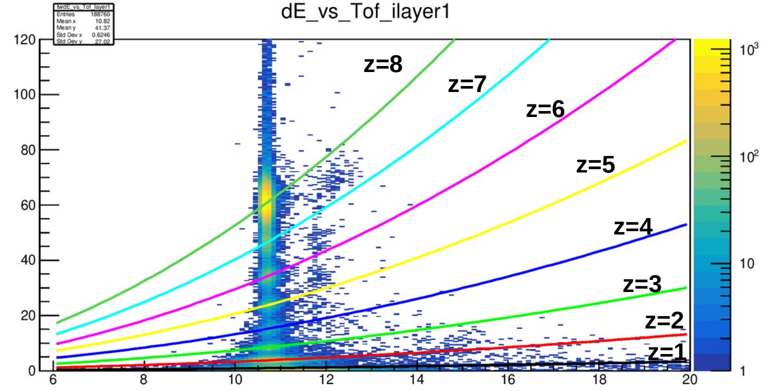
- From Bethe – Bloch formula I can get **z**:

$$-\frac{dE}{dx} = 4\pi N_e r_e^2 m_e c^2 \frac{z^2}{\beta^2}\left(\ln\frac{2m_e c^2 \beta^2\gamma^2}{I} - \beta^2 - \frac{\delta(\gamma)}{2}\right)$$

- **Infos taken from SC and TW**

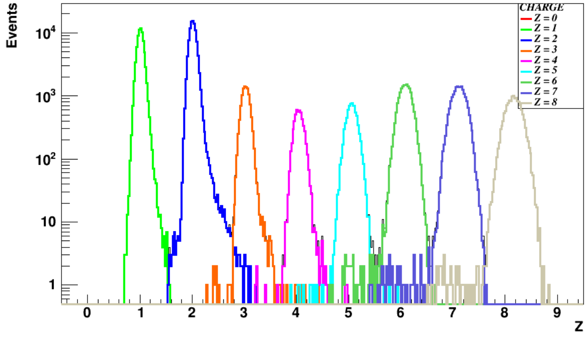


dE




ToF

TW charge reconstruction algo

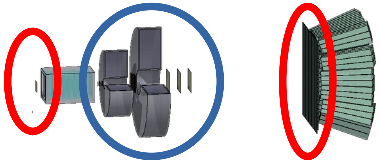



**Charge discrimination**

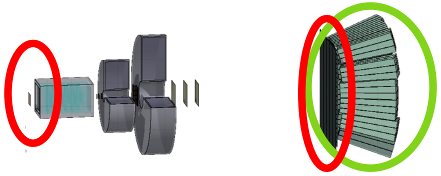
# Isotope identification

- Mass reconstruction using all FOOT subdetectors:

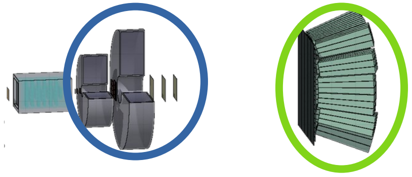
$$A_1 = \frac{p}{U\beta c\gamma}$$



$$A_2 = \frac{E_k}{Uc^2(\gamma - 1)}$$



$$A_3 = \frac{p^2c^2 - E_k^2}{2Uc^2E_k}$$



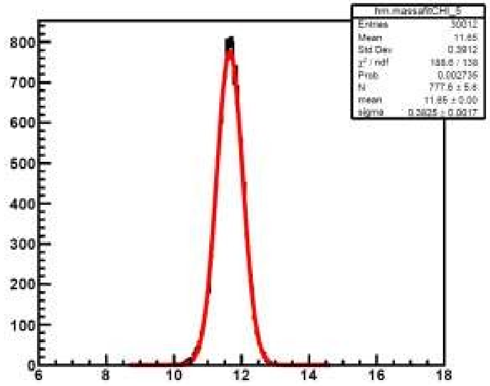
- In our data no tracker and calorimeter → mass measurement only in MC data!

- Augmented Lagrangian

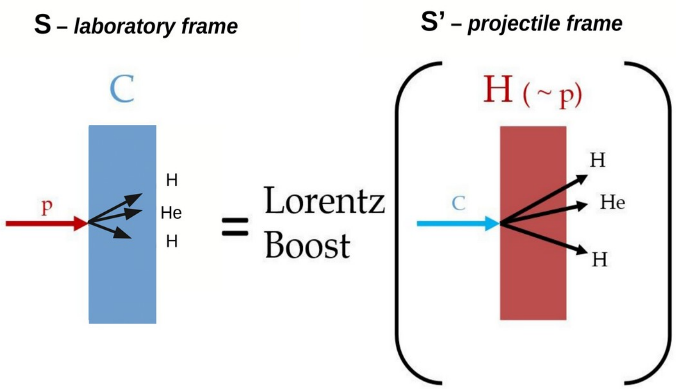
$$L(\vec{x}, \lambda, \mu) \equiv f(\vec{x}) - \sum \lambda_a c_a(\vec{x}) + \frac{1}{2\mu}\sum c_a^2(\vec{x})$$

$$f(\vec{x}) = \left(\frac{TOF - T}{\sigma_{TOF}}\right)^2 + \left(\frac{p - P}{\sigma_p}\right)^2 + \left(\frac{E_k - K}{\sigma_{E_k}}\right)^2$$

$A_{\chi 2}$ = 11.66 ± 0.38
risoluz. 3.2 %
$\chi 2 < 5$



# Inverse kinematic approach




$$ct' = \gamma(ct - \beta z)$$
$$x' = x$$
$$y' = y$$
$$z' = \gamma(z - \beta ct)$$

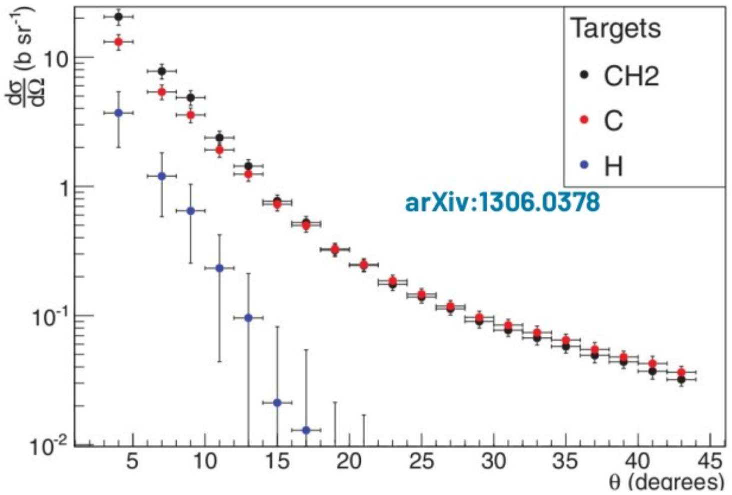
$$E'/c = \gamma(E/c - \beta p_z)$$
$$p'_x = p_x$$
$$p'_y = p_y$$
$$p'_z = \gamma(p_z - \beta E/c)$$

# Which target?

Problem: hydrogen target

- ✗ gas is not allowed in all experimental rooms
- ✗ gas is too sparse (low interaction probability)

Polyethylene target $(C_2H_4)_n$ and Carbon target




$$\frac{d\sigma}{d\Omega}(H) = \frac{1}{4} \cdot \left( \frac{d\sigma}{d\Omega}(\mathrm{C_2H_4}) - 2 \cdot \frac{d\sigma}{d\Omega}(\mathrm{C}) \right)$$

# Angular distribution of fragments

Angular and kinetic energy distributions of different fragments
200 MeV/nucleon $^{16}O$ beam on a $C_2H_4$ target

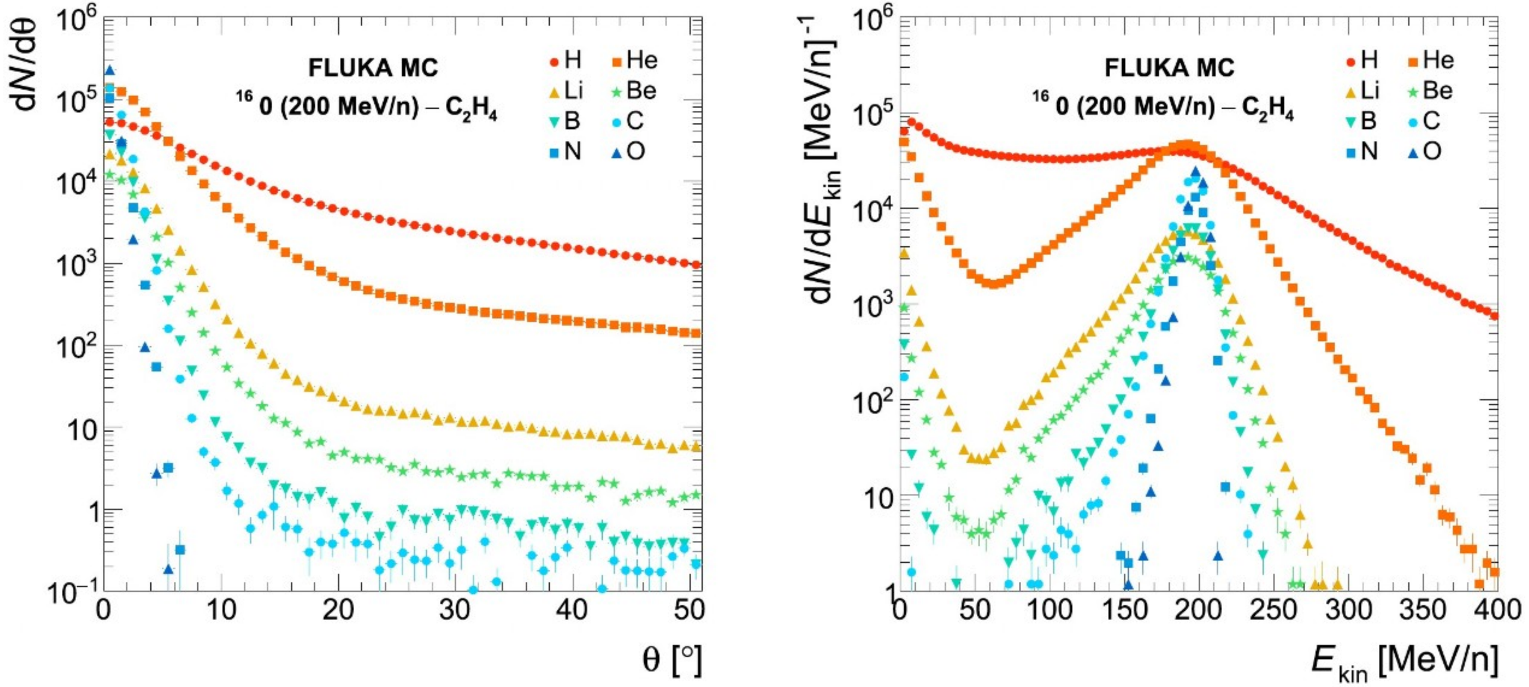
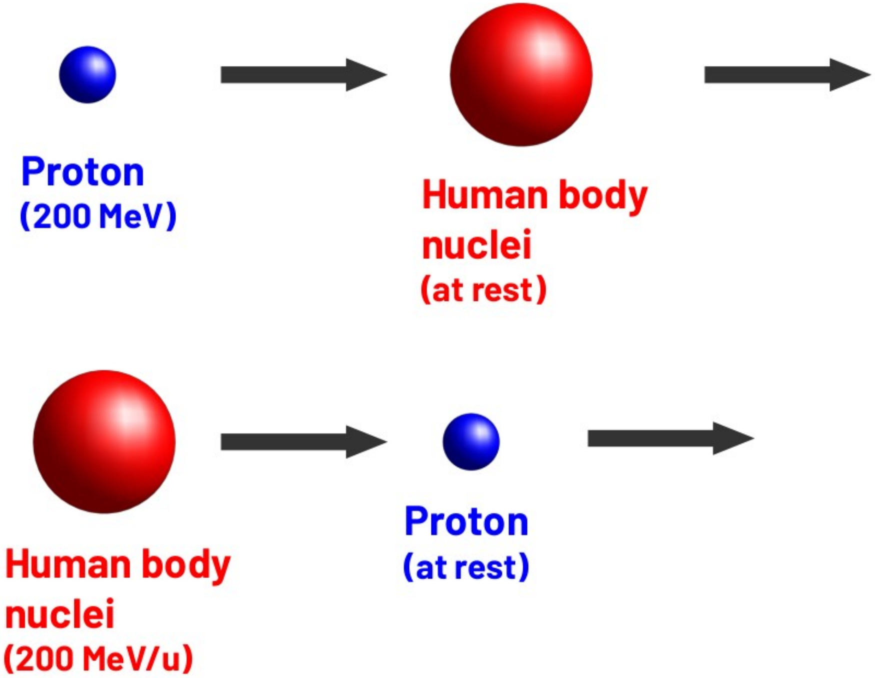



**FIGURE 1** | MC calculation [33, 34] of the angular **(Left)** and kinetic energy **(Right)** distributions of different fragments produced by a 200 MeV/nucleon $^{16}O$ beam impinging on a $C_2H_4$ target.

*Measuring the Impact of Nuclear Interaction in Particle Therapy and in Radio Protection in Space: the FOOT Experiment.*
Battistoni G, Toppi M, Patera V and The FOOT Collaboration (2021). Front. Phys. 8:568242. doi: 10.3389/fphy.2020.568242

# Projectile and target fragments




Fragments with low energy and short range (few cell diameters) ✗

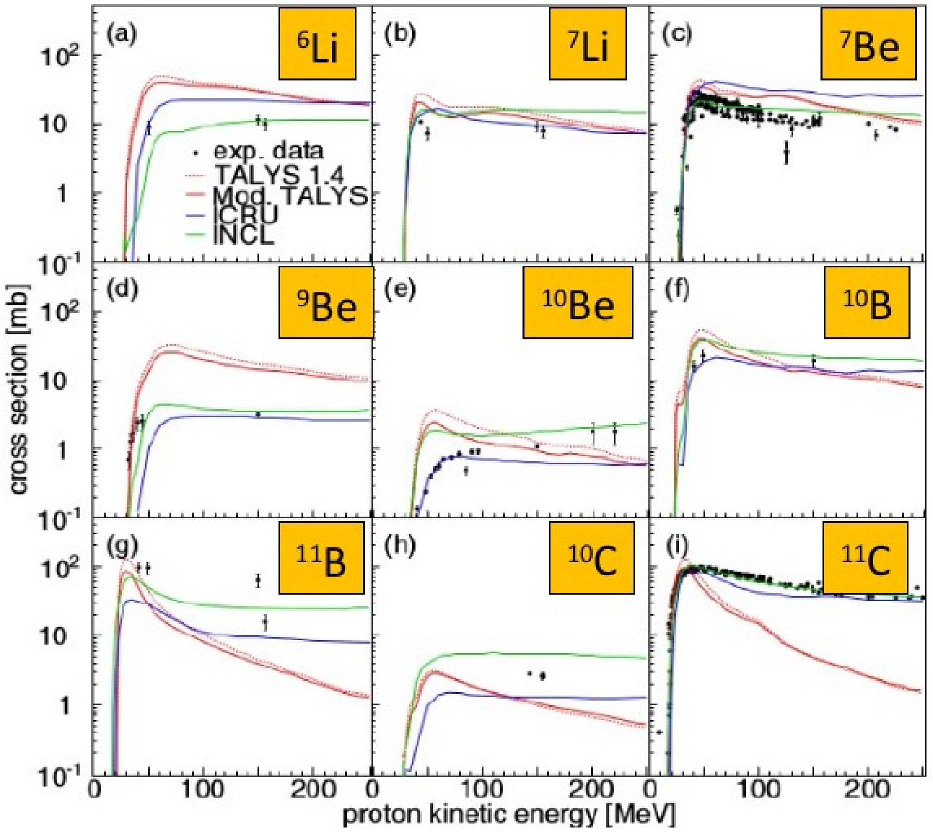
Very difficult to detect!

- ***Emulsion setup***
- ***Electronic setup (inverse kinematic)***

Fragments with higher energy and longer range! ✓

- ***Electronic setup***
- ***Emulsion setup (Z<4)***

# Cross section measurements in literature

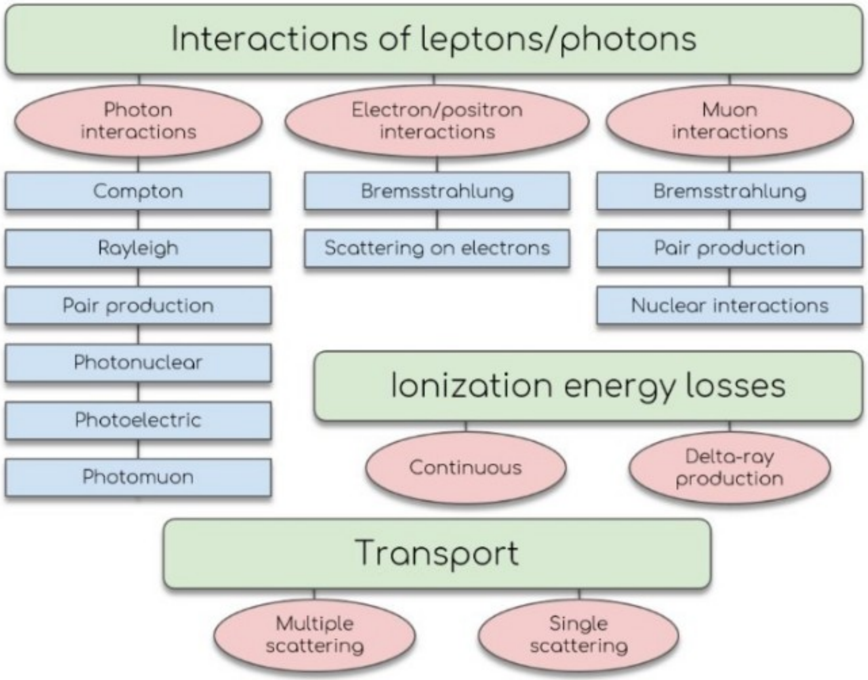



$$p + C$$

- Very few points
- Function of proton energy
- No information on fragment kinematics!

**Missing data in literature!!**

# FLUKA MC models for FOOT




Electromagnetic interactions models in FLUKA

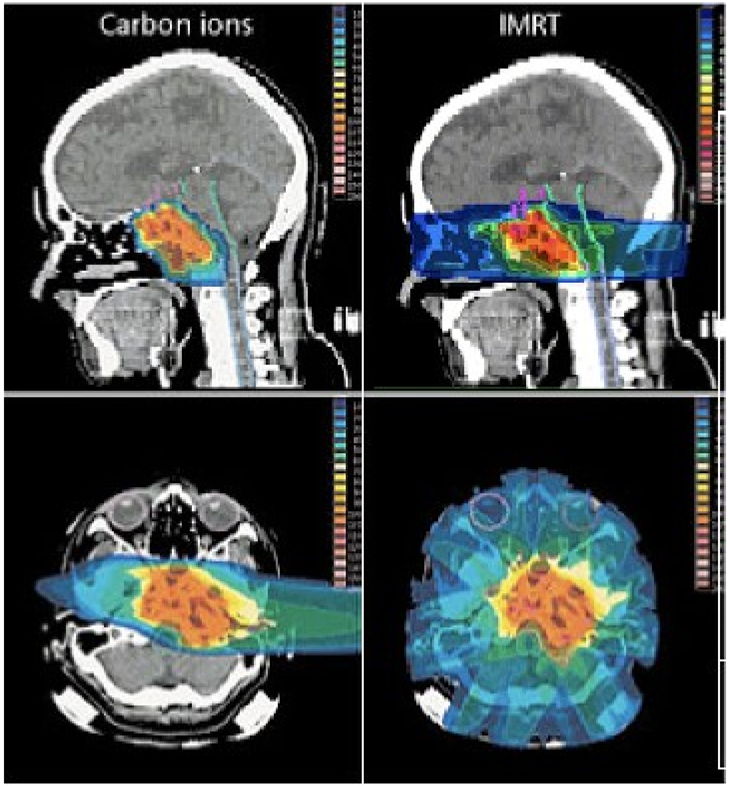
**Handron-nucleus interactions:**

- PreEquilibrium Approach to NUclear Thermalization (PEANUT) model for particles with P<3-5 GeV/c based on Generalized Intra-Nuclear Cascade (GINC) model
- Pre-equilibrium emission of light nuclei (A<5)
- Evaporation, Fission, Fragmentation and γ de-excitation

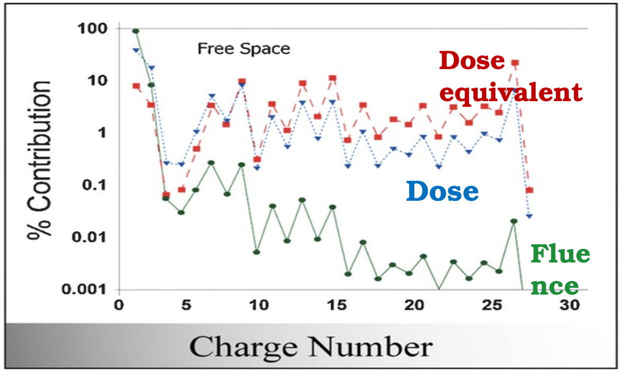
**Nucleus-nucleus interactions**

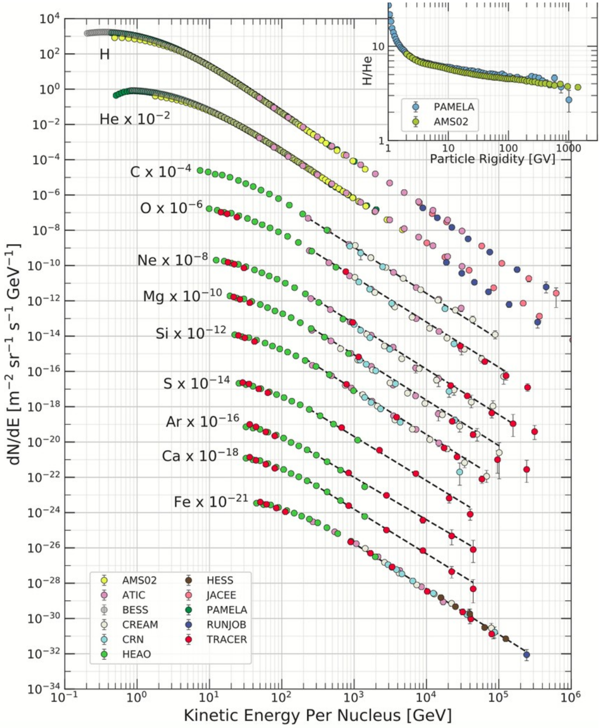
- Boltzmann-Master Equation model (E<100 MeV/u): Thermalization of composite nuclei by means of two-body interactions and secondary particles emissions
- Relative Quantum Molecular Dynamics (0.1 - 5 GeV/u): Collision simulated minimizing the Hamiltonian equation of motion considering the Gaussian wave functions of all the nucleons in the nucleus overlapping region

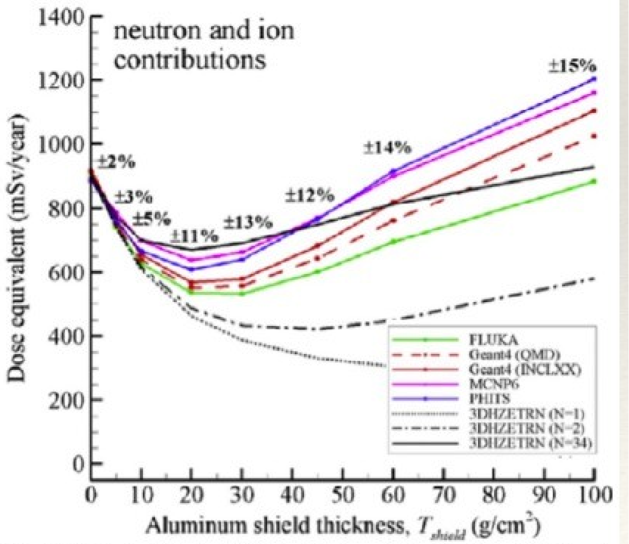
# Hadrontherapy vs conventional radiotherapy



# Space particle fluxes and dose




Slaba TC, Bahadori AA, Reddell BD, Singleterry RC, Clowdsley MS, Blattnig SR. Optimal shielding thickness for galactic cosmic ray environments. *Life Sci Space Res.* (2017) 12: 1–15. doi:10.1016/j.lssr.2016.12.003.

# *Hadrontherapy:Facilities in the world, 1*



proton

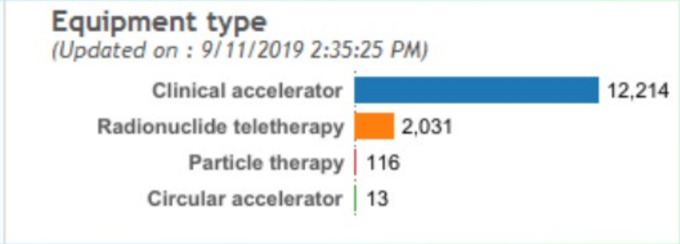
Carbon (and proton)

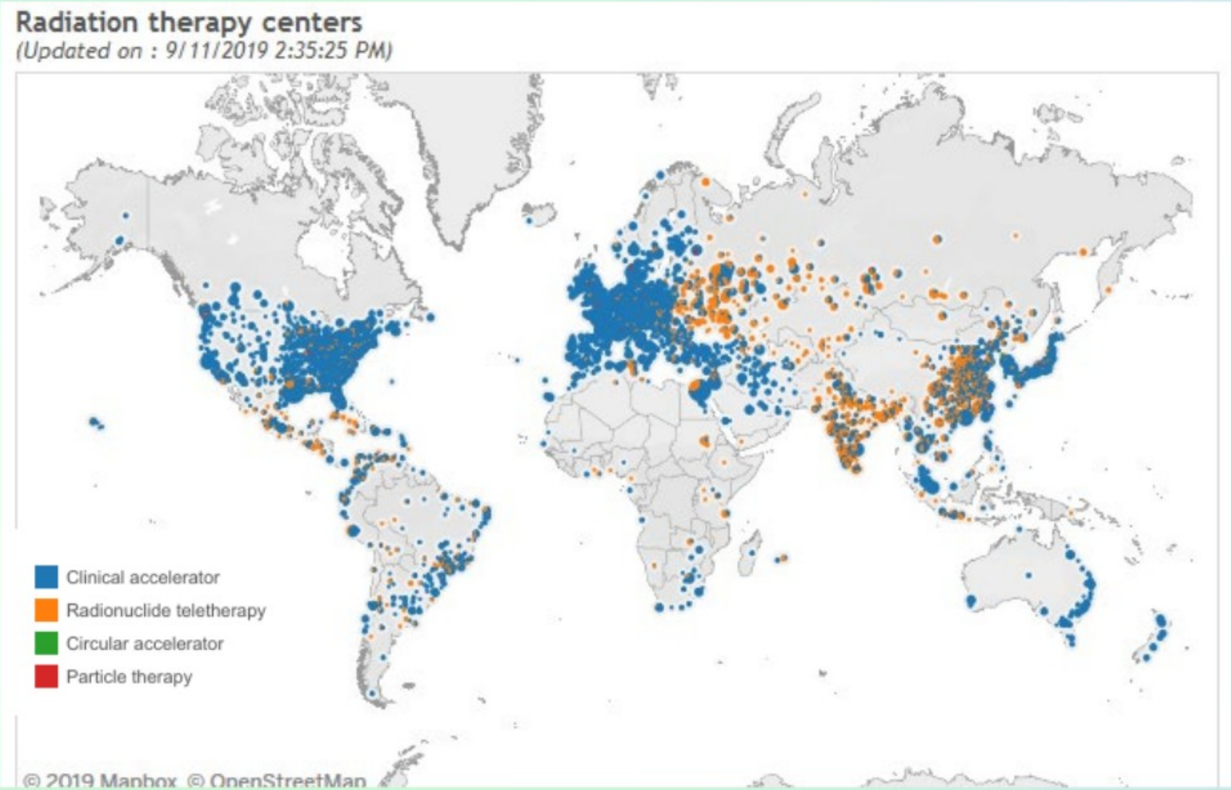
**Facility (end of 2019):**

- Operative: 116
  - beam
    - ~ 85% proton
    - ~ 5% protons and Carbon
    - 10% Carbon
    - **Under construction: 31**
  - Location
  - USA: 57,
  - West Europe: 23
  - East Europe and North Asia: 8
  - East Asia: 27
  - South Asia: 1

*Courtesy of R. Spighi*

# Radiotherapy & Hadrontherapy:Facilities in the world, 2



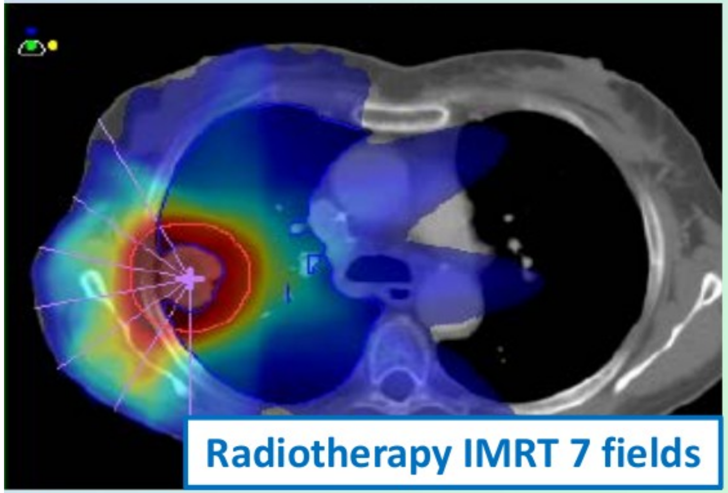

| Countries | RT centers | Equipment | Linac | Radionuclide Therapy | Circular Accelerator | Particle Therapy |
|---|---|---|---|---|---|---|
| 149 | 7477 | 14374 | 12214 | 2031 | 13 | 116 |

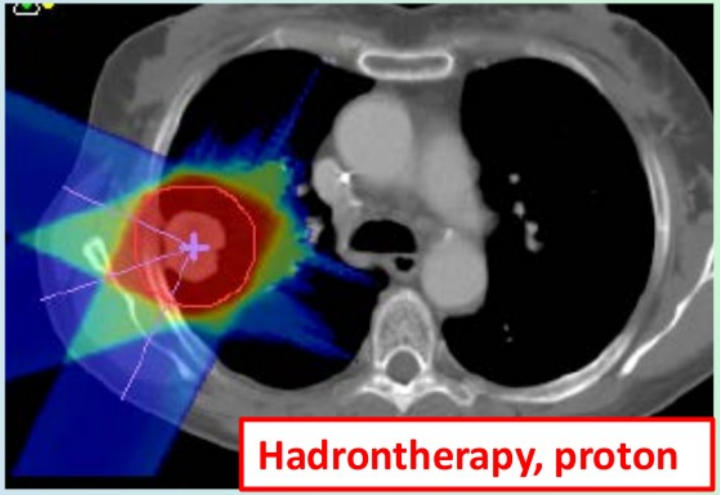
radiotherapy

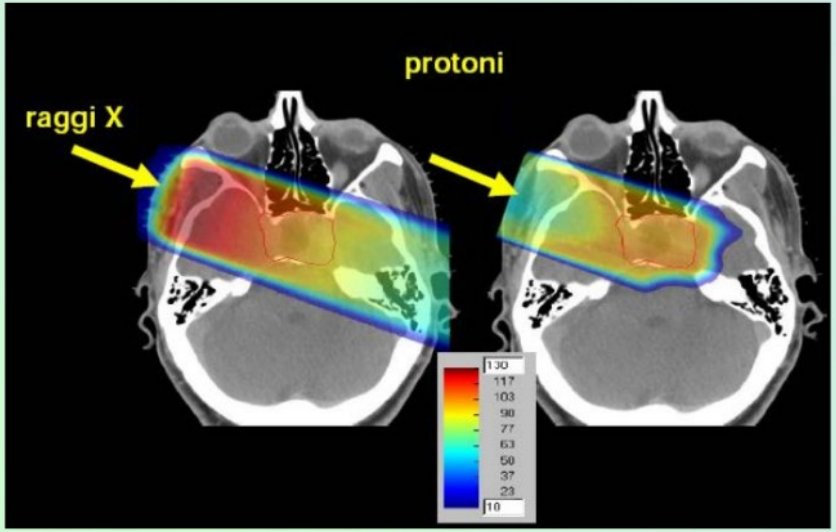
microtrone and betatrone

*Courtesy of R. Spighi*

## Hadrontherapy vs radiotherapy, 1



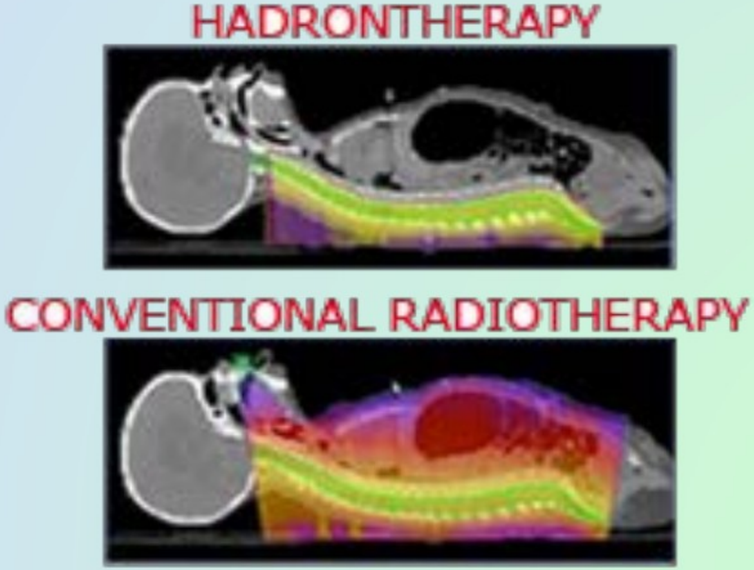



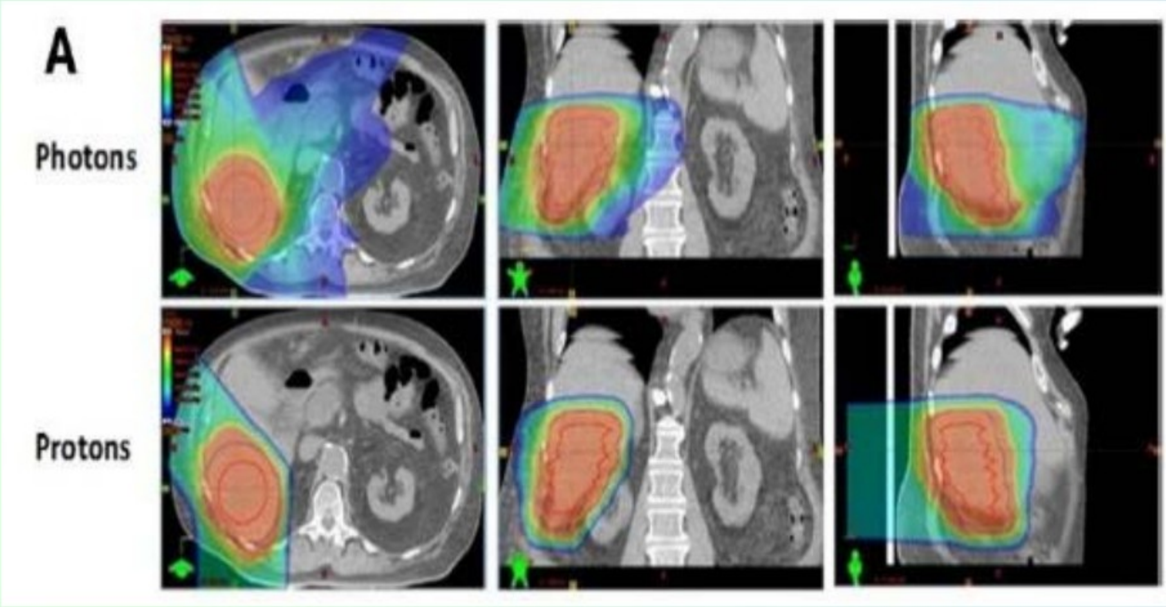

Pro and contra

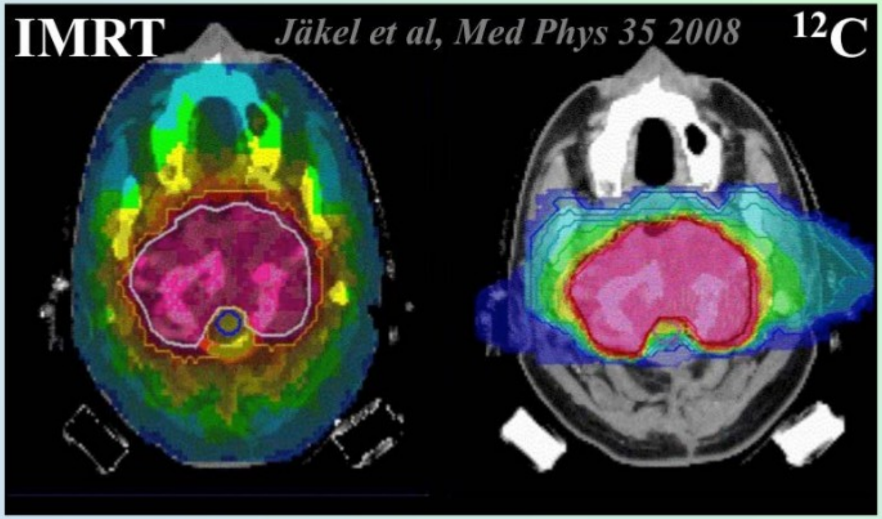
- Hadrontherapy: the released dose is better focused;
- Hadrontherapy: less dose before and after tumor region
- Costs:
  - accelerator for Hadrontherapy ~250 millions euros
  - Treatment ~ 5-10 than radiotherapy
  - Machine for radioterapy: tens thousands euros.

*Courtesy of R. Spighi*

# Hadrontherapy vs radiotherapy, 2




*Courtesy of R. Spighi*

*Courtesy of R. Spighi*

# Do you want some number? Here it is

Local control rate → to keep the tumor under control

bones
cartilage
Nose pharynx
Nervous system
eye
nose cavity
pancreas
hepato
salivary gland
soft tissue

| Indication | End point | Results photons | Results carbon HIMAC-NIRS | Results carbon GSI |
|---|---|---|---|---|
| Chordoma | local control rate | 30 – 50 % | 65 % | 70 % |
| Chondrosarcoma | local control rate | 33 % | 88 % | 89 % |
| Nasopharynx carcinoma | 5 year survival | 40 -50 % | 63 % | |
| Glioblastoma | av. survival time | 12 months | 16 months | |
| Choroid melanoma | local control rate | 95 % | 96 % (*) | |
| Paranasal sinuses tumours | local control rate | 21 % | 63 % | |
| Pancreatic carcinoma | av. survival time | 6.5 months | 7.8 months | |
| Liver tumours | 5 year survival | 23 % | 100 % | |
| Salivary gland tumours | local control rate | 24-28 % | 61 % | 77 % |
| Soft-tissue carcinoma | 5 year survival | 31 – 75 % | 52 -83 % | |

Similar to protons

Table by G. Kraft 2007

Results of carbon ions