DeSyT-2025

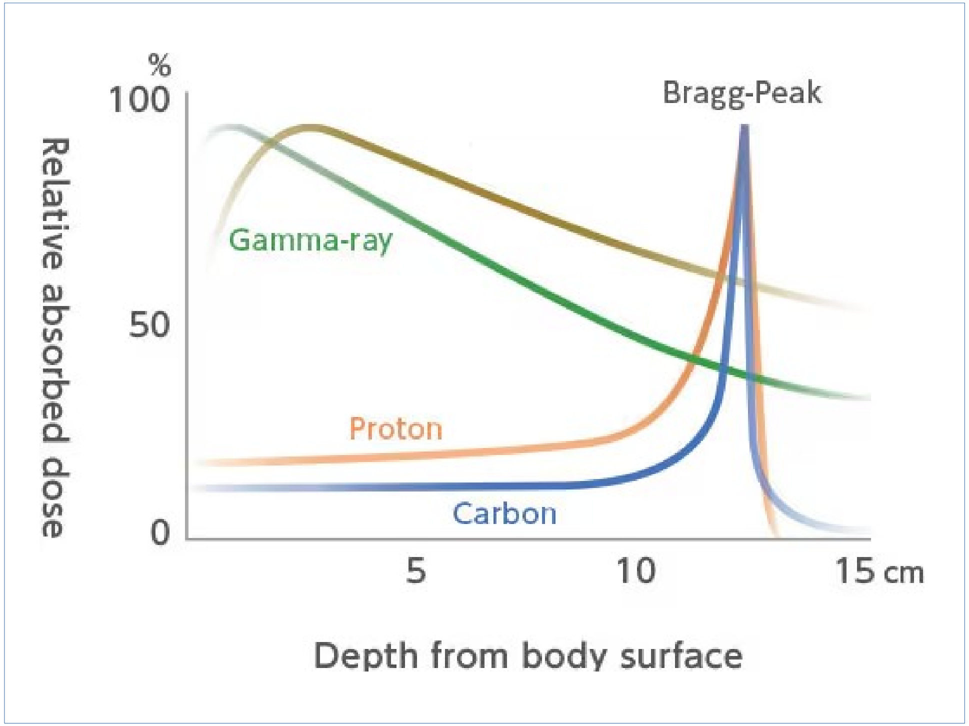
# Measurements of nuclear fragmentation cross sections with the FOOT experiment

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

***DeSyT-2025***
*Catania, Italy*

24/02/2025

# Particle Therapy



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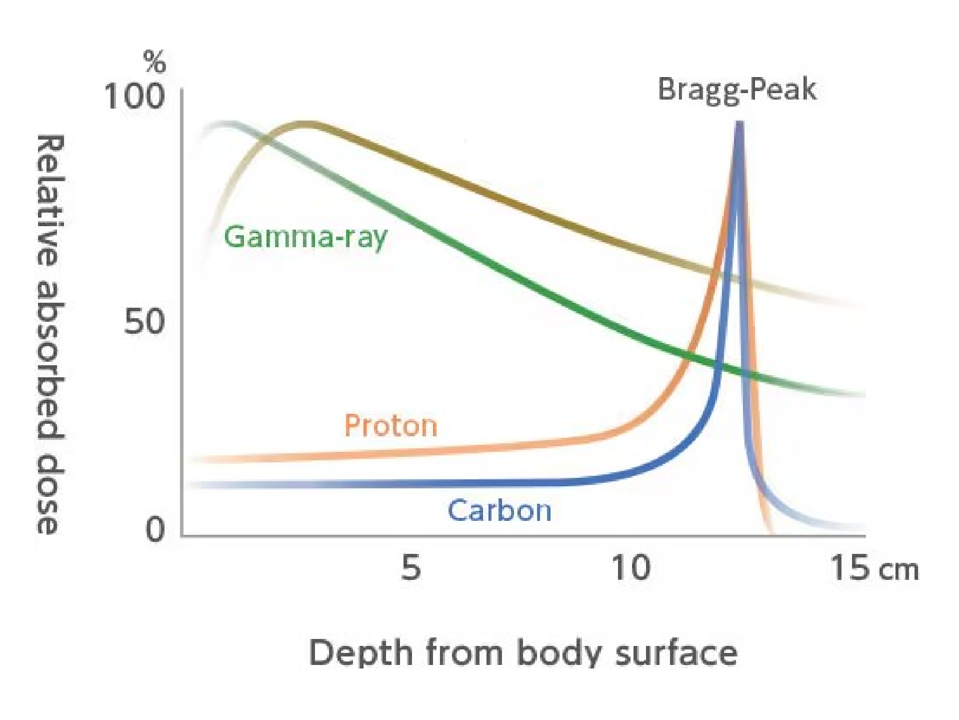
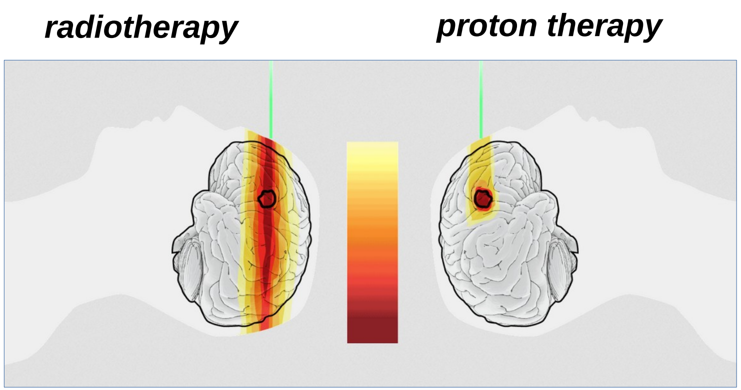
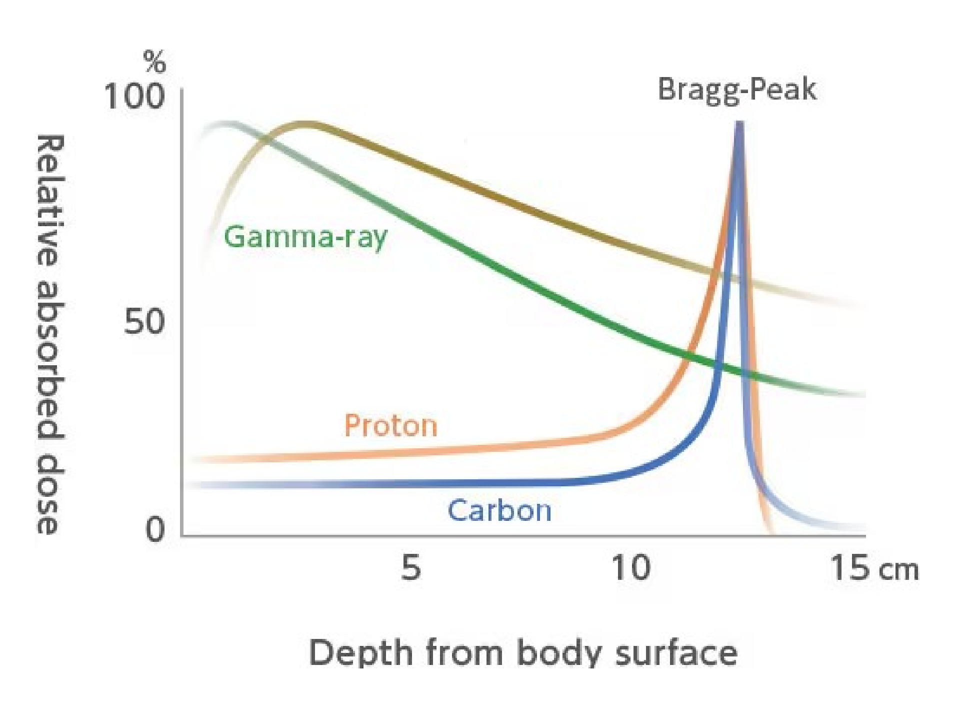


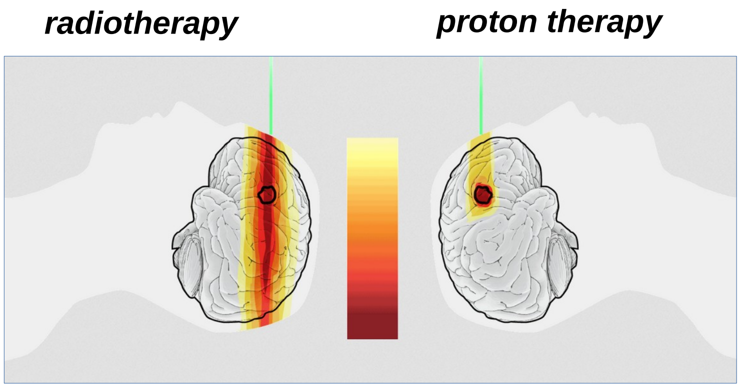

[1] 


Particle therapy vs radiotherapy:

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

# Particle Therapy



[1]

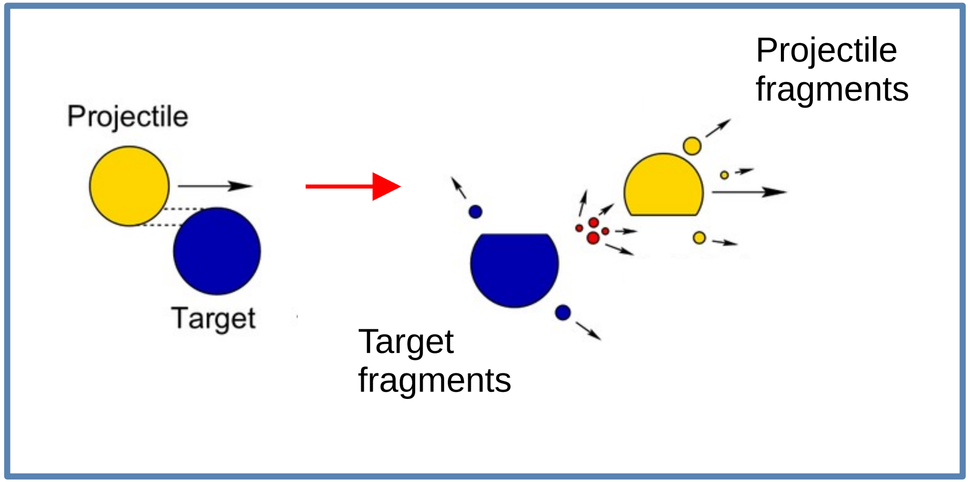
Particle therapy vs radiotherapy:

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



[1] https://www.washingtonpost.com/graphics/2018/health/proton-beam-therapy/

# Nuclear Fragmentation



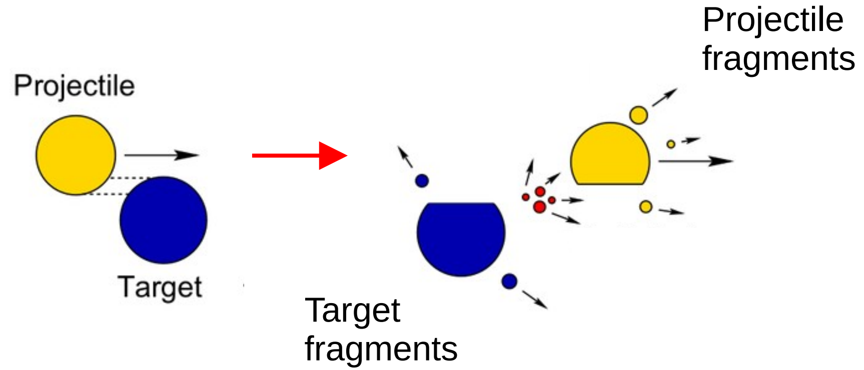

**Target** fragments:

- ✗ Short range
- ✗ High energy impact in entrance channel

**Projectile** fragments:

- ✗ Longer range than beam
- ✗ Dose beyond the Bragg peak

# Nuclear Fragmentation

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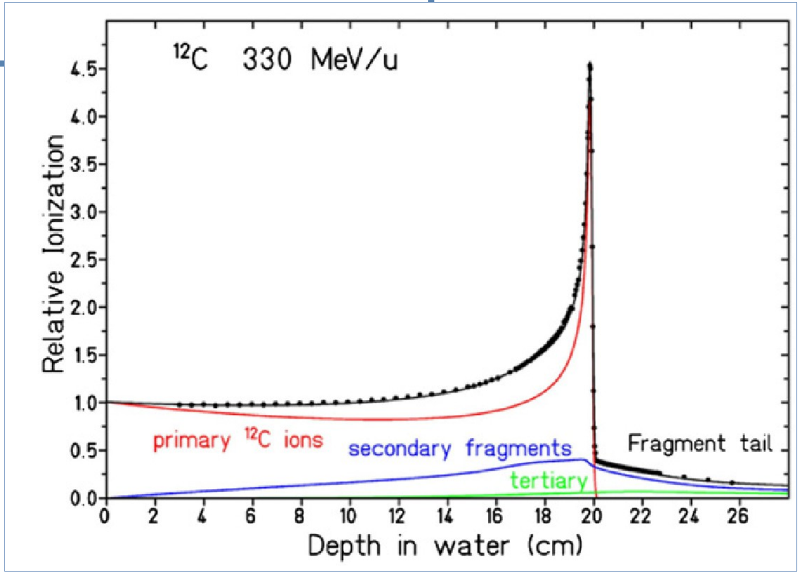

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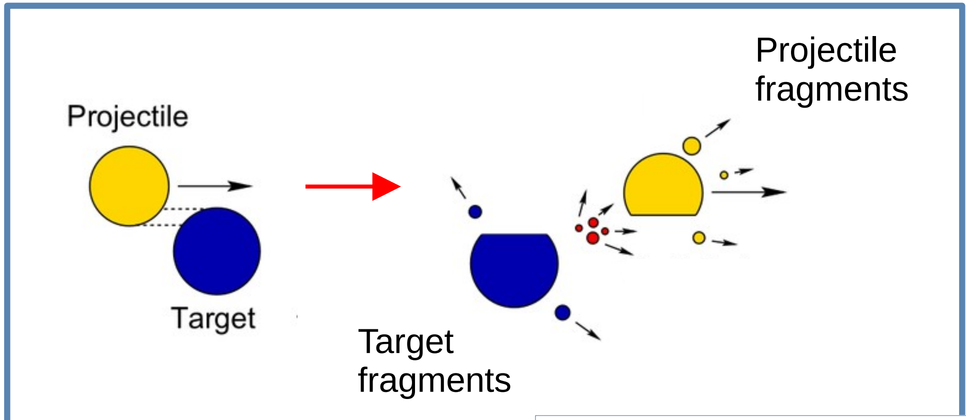


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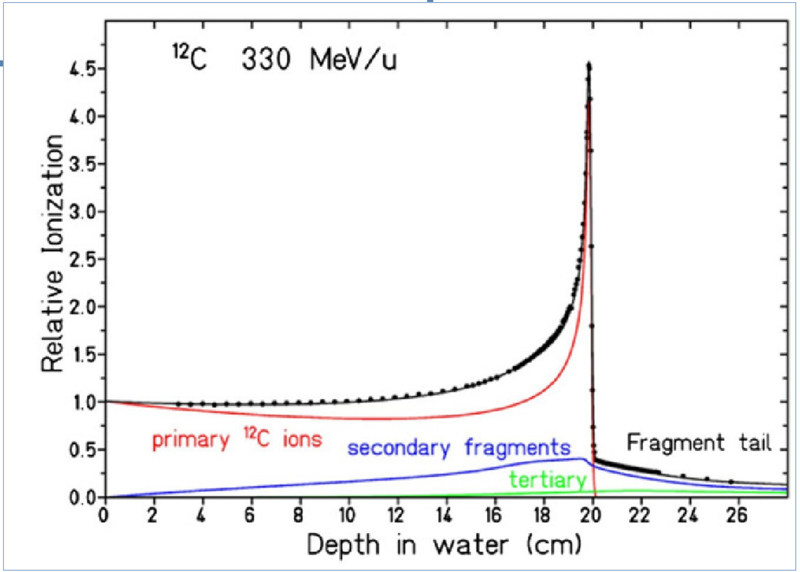
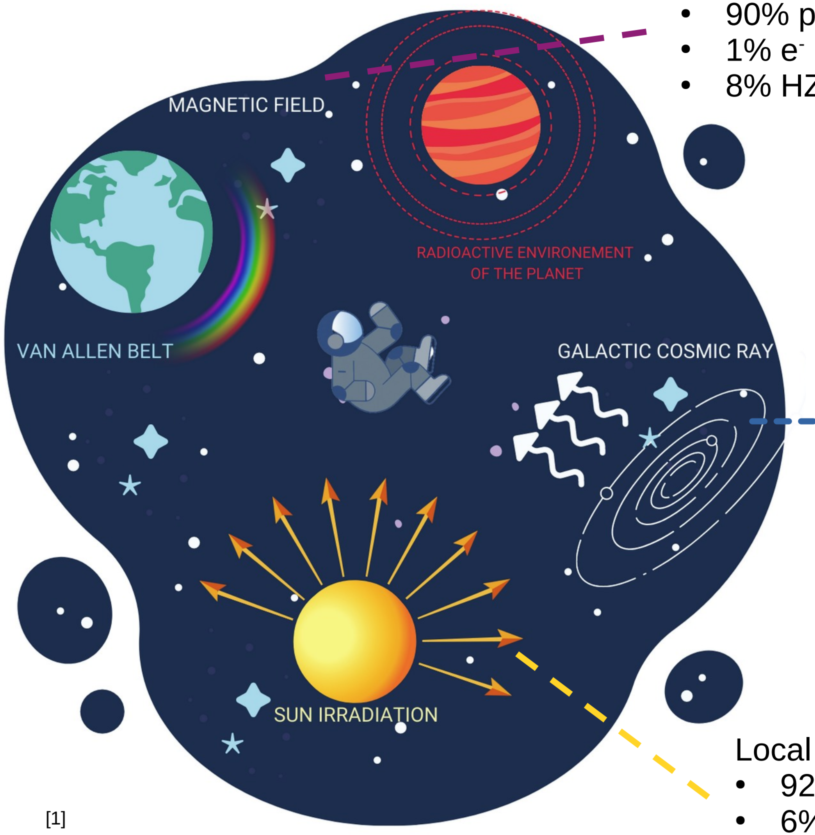



**nuclear cross section measurements needed** to improve Treatment Planning Systems

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

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

# Space radioprotection




[1]

Particles captured by *Earth magnetosphere*

- 90% p (< **100 MeV**)
- 1% $e^-$ (< 10 MeV)
- 8% HZE

Originated by astrophysical environments inside and outside *the galaxy*

- 90% p
- 9% He
- 1% HZE

0.001-$10^{14}$ GeV/n
(peak at **0.1-1 GeV/n**)

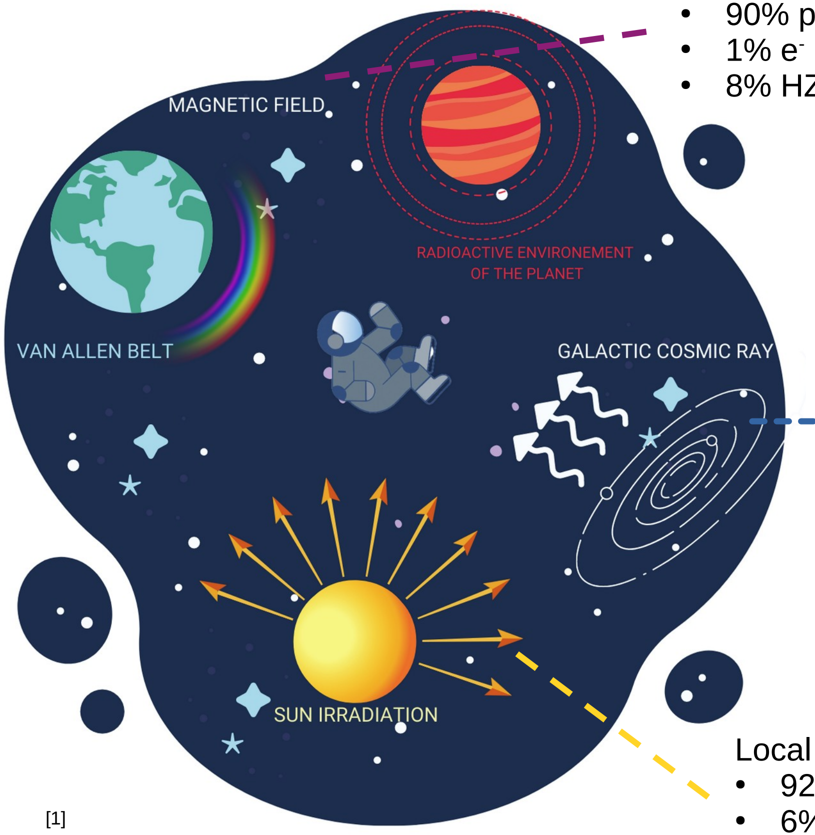
Local outbursts on the *Sun surface*

- 92% p
- 6% He
- 2% HZE
- **<1 GeV/n**



[1] https://2021.igem.org/Team:Sorbonne_U_Paris/Description

# Space radioprotection

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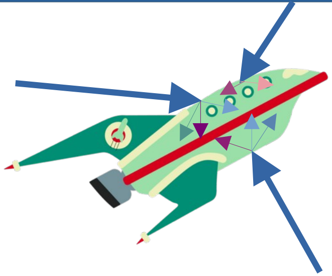
**Nuclear Fragmentation** effects on:
- Space craft hull and structure
- Shielding
- Astronaut's body



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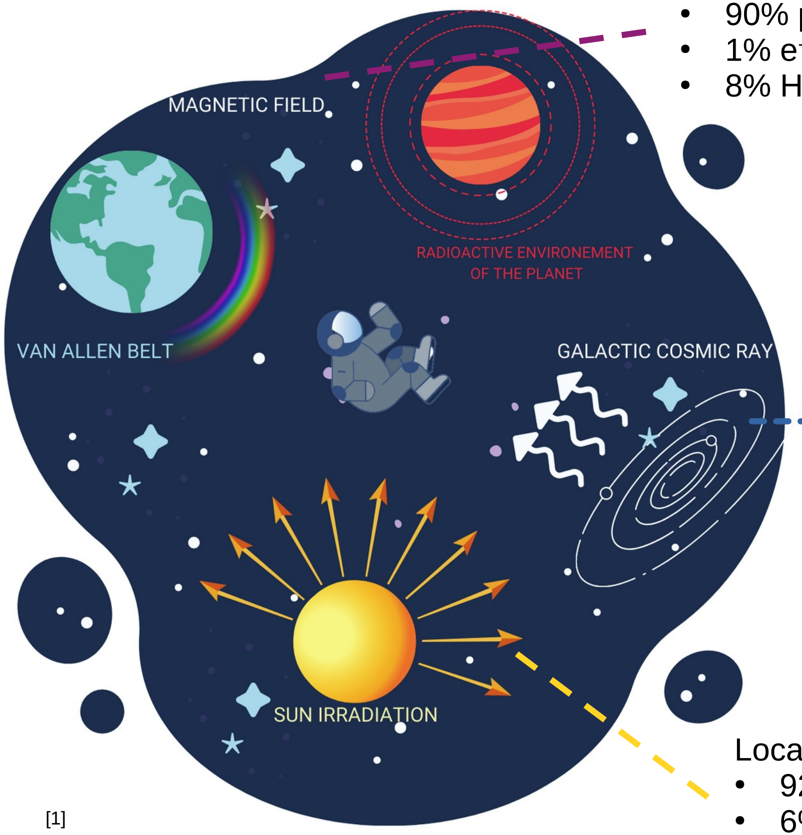


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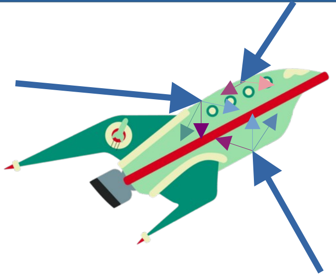
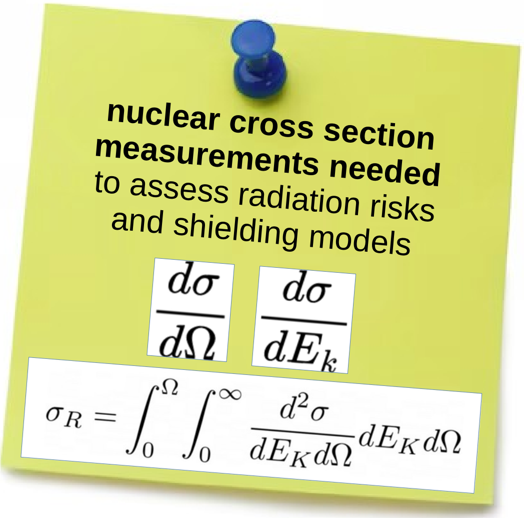







[1] https://2021.igem.org/Team:Sorbonne_U_Paris/Description

# The FOOT collaboration

https://web.infn.it/foot/



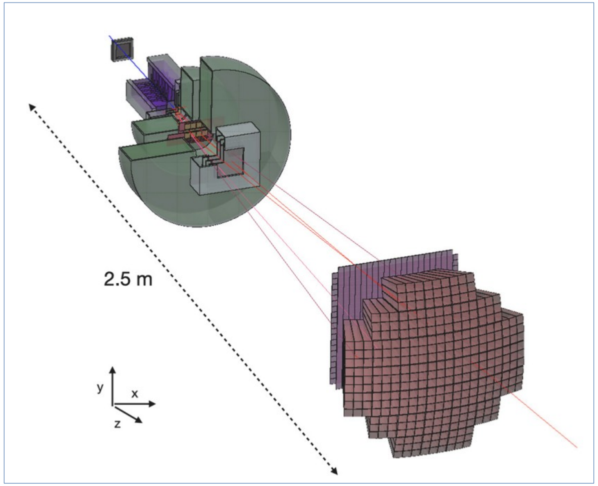
- **93** Authors, **35** Institutions
- **7** countries (Italy, France, Germany, Japan, Cuba, USA, India)
- **3** continents (Europe, Asia, America)

# The FOOT experiment

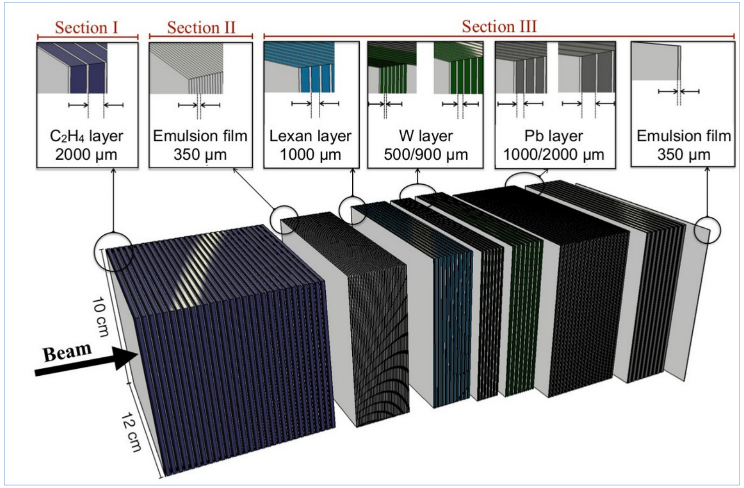
**Goal:**

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

- Fixed target collisions
- Beam 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

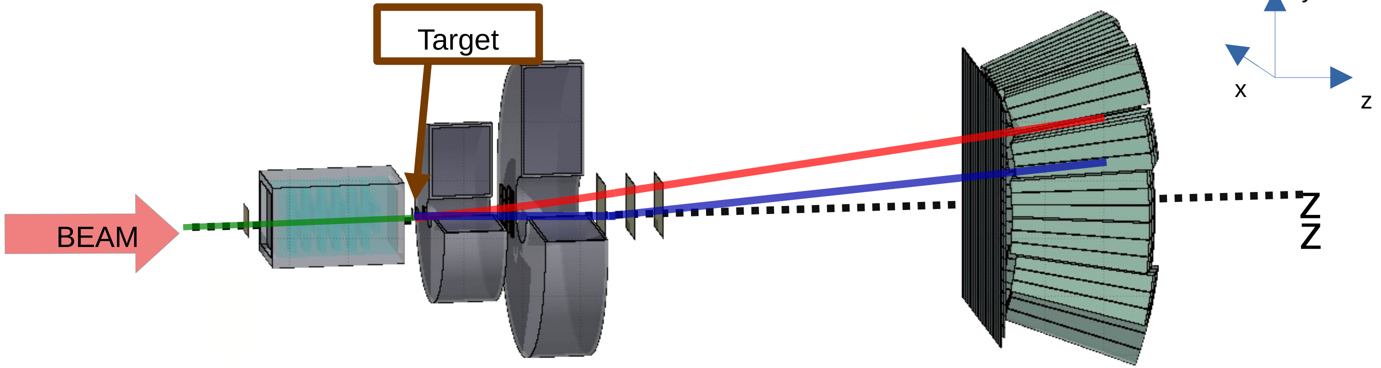



*electronic setup*

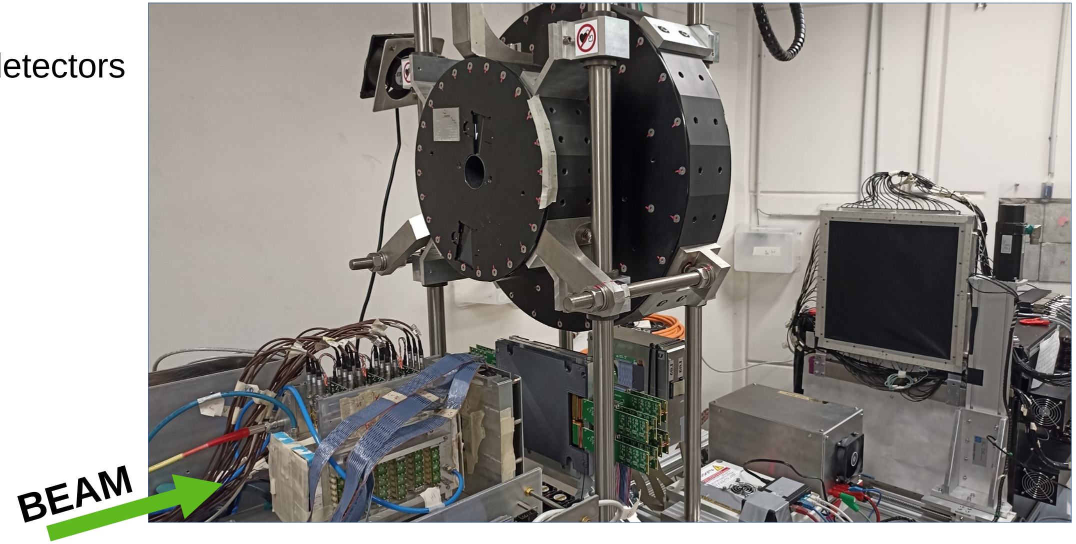



*emulsion setup*

# 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 2023!



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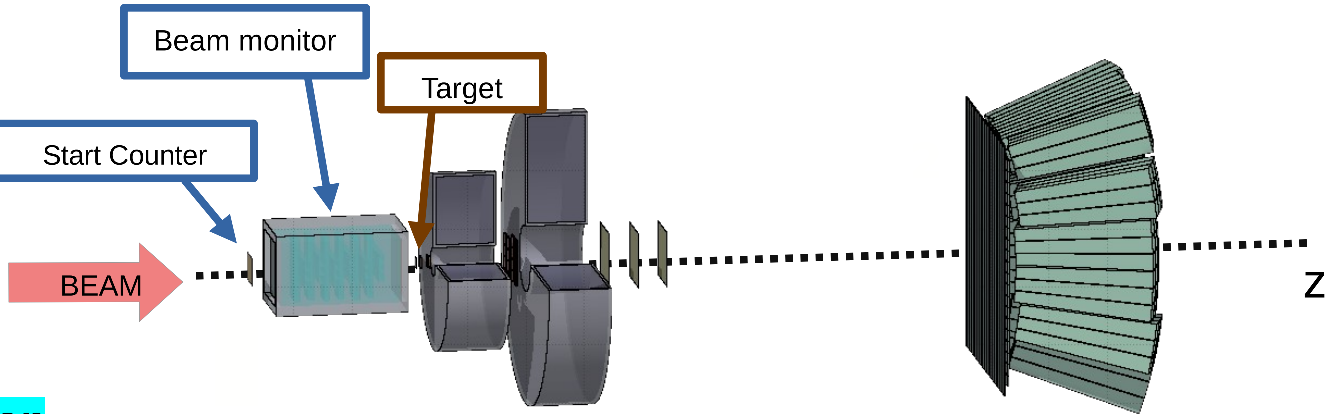
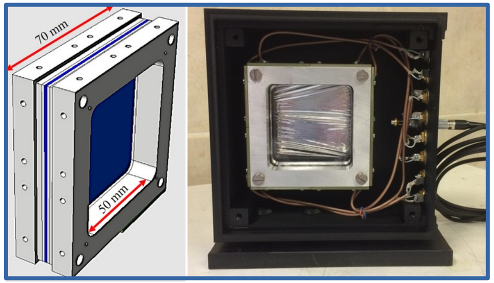



***Upstream region***
monitoring the beam before impinging on target

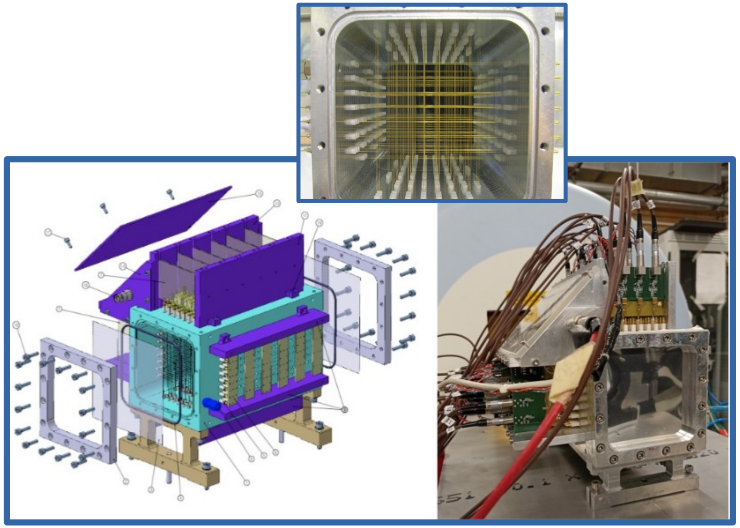



## Start Counter

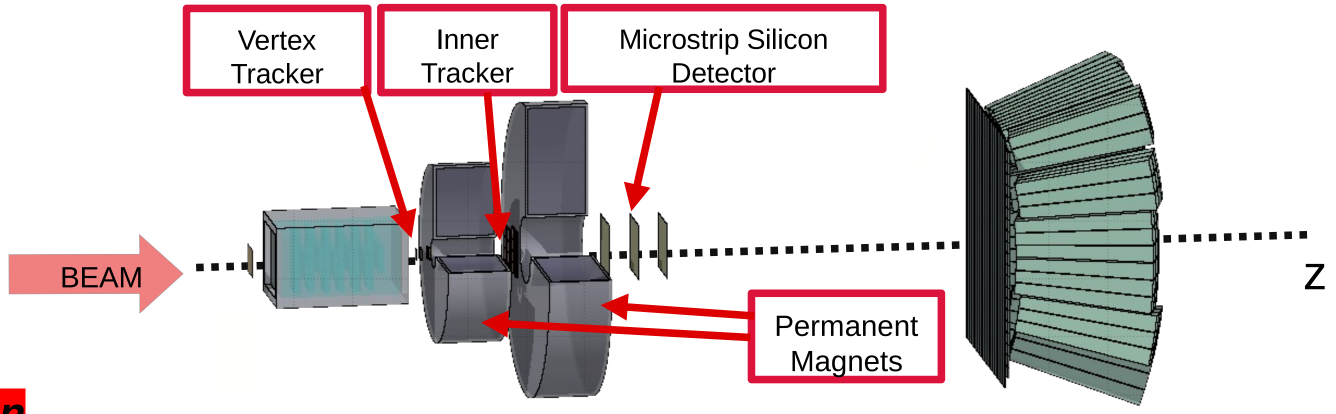
**start of ToF** (**$\sigma_t$ ~ 40 ps**)
250 μm – 1 mm thick plastic scintillator
5x5 $cm^2$ active area
48 SiPMs, 8 channels readout

## Beam monitor

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

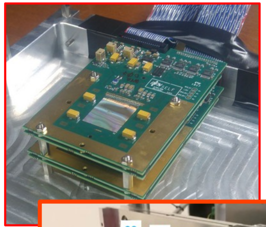


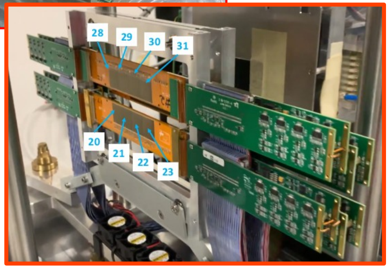
# The electronic setup




***Tracking region***

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



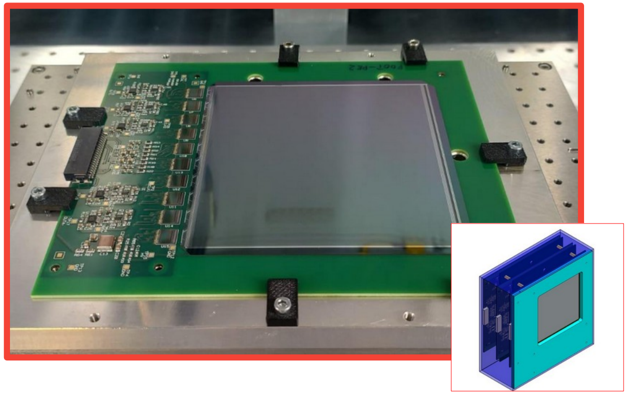


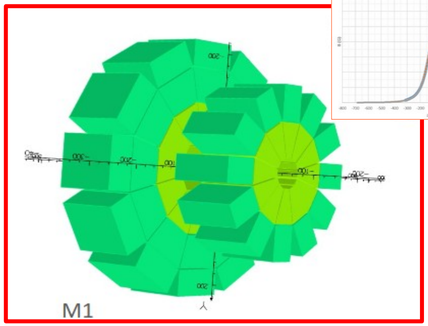

## Vertex & Inner Tracker

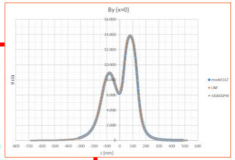
MIMOSA-28 Si Pixel detector
20 µm pitch, 50 µm depth
4 planes for Vertex
2 planes for Inner Tracker

## Microstrip Detector

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



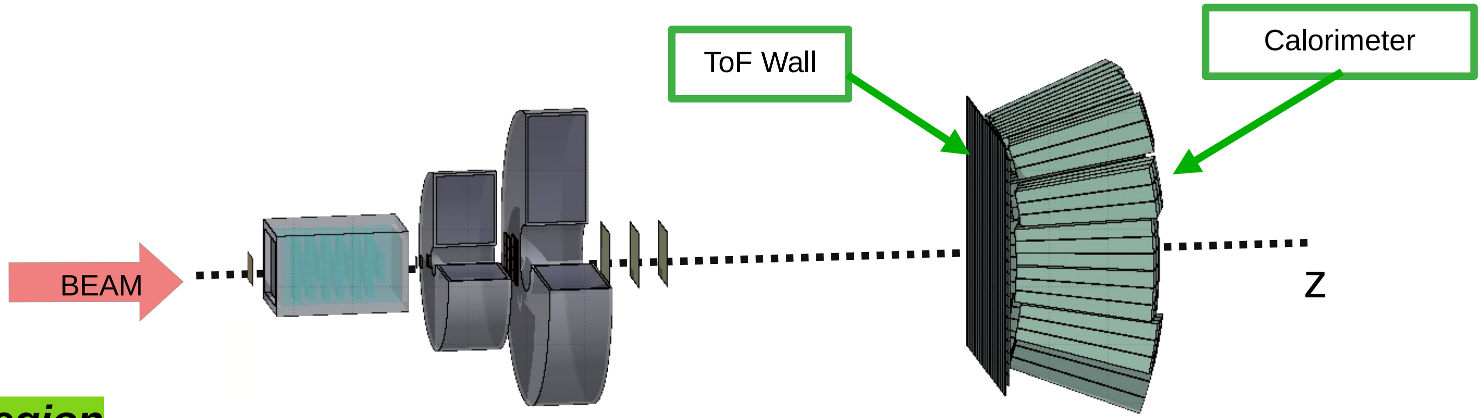


## Magnets

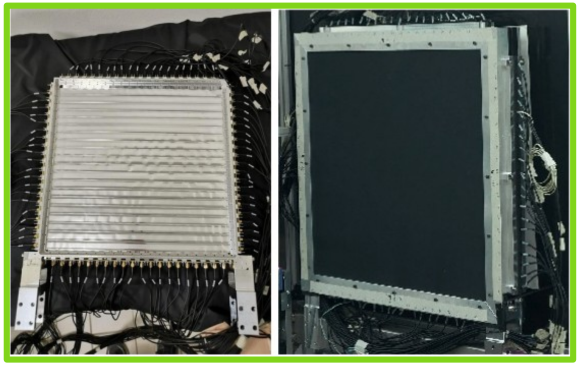
Hallbach configuration
B field in y axis (max 0.9 and 1.1 T)

# The electronic setup




***Downstream region***

particle identification (charge and mass number)



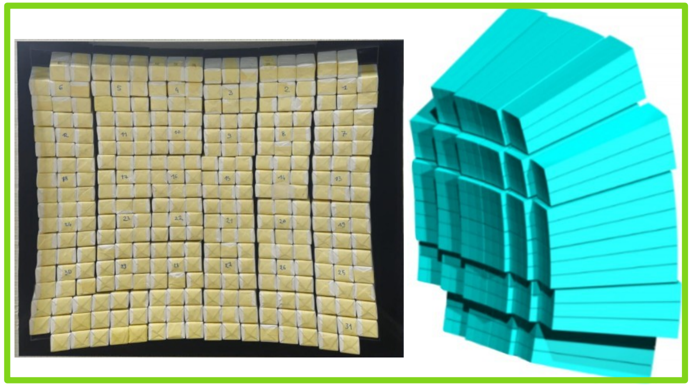
## ToF Wall

**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

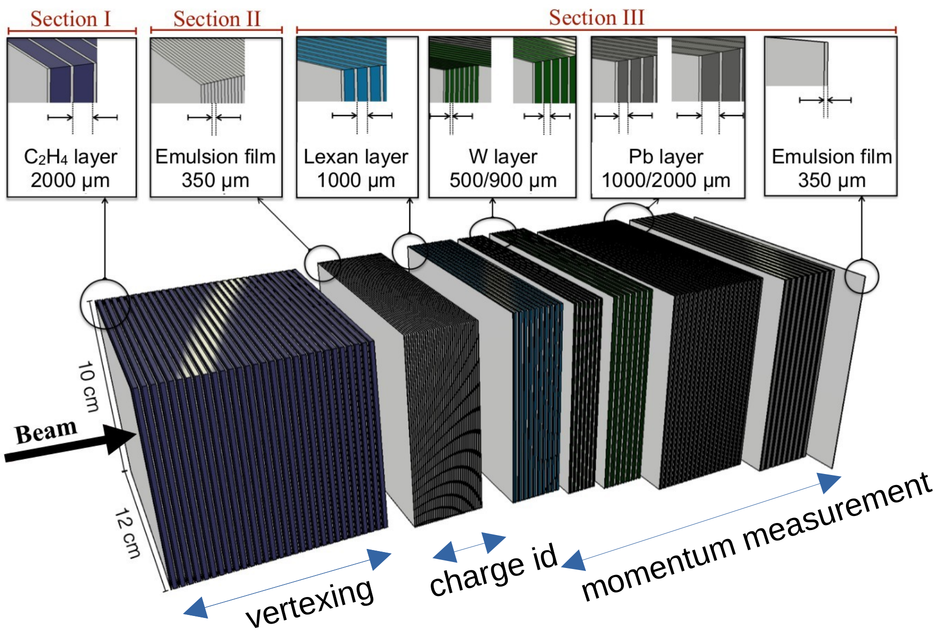
**charge reconstruction**

## Calorimeter

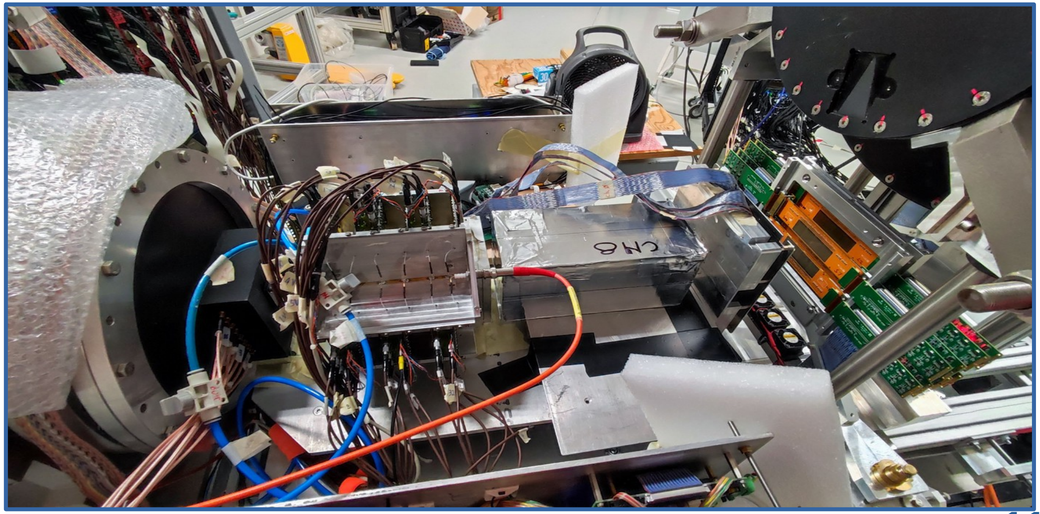
**kinetic energy ($\sigma_{Ekin}$ ~ 2 %)**
BGO **scintillator**
320 crystals



# The emulsion setup



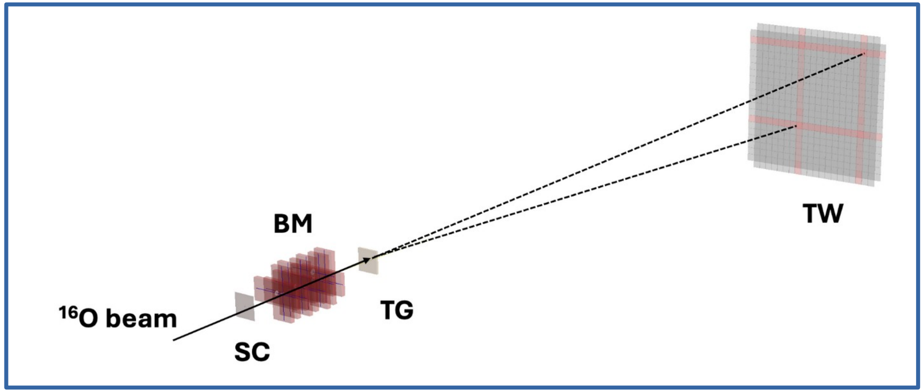

- Designed for light fragments (**Z≤ 3**)
- Spatial resolution up to **10 µm**
- Angular acceptance up to 70°
- Section:
  1. Emulsion + target
  2. Emulsion film
  3. Emulsion + passive layers
- No real time acquisition
- Beam and fragments reconstruction after emulsion development

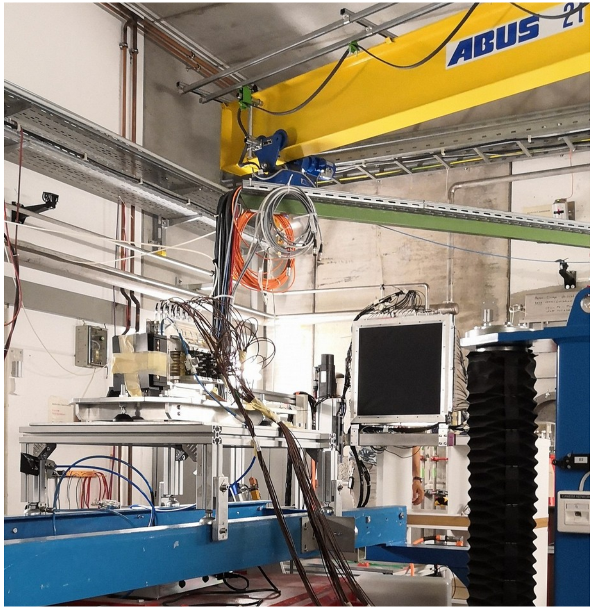


# Electronic setup: results

Angular differential and elemental fragmentation cross sections of a 400 MeV/nucleon $^{16}$O beam on a graphite target with the FOOT experiment [1]

- Paper of R. Ridolfi et al under review by the Journal!
- Data-taking at GSI (Darmstadt, Germany) in 2021
- **$^{16}$O 400 MeV/u** on 5 mm **$C/C_2H_4$ target**
- Partial setup: no magnet, only one module of calorimeter




**Specific goal:**

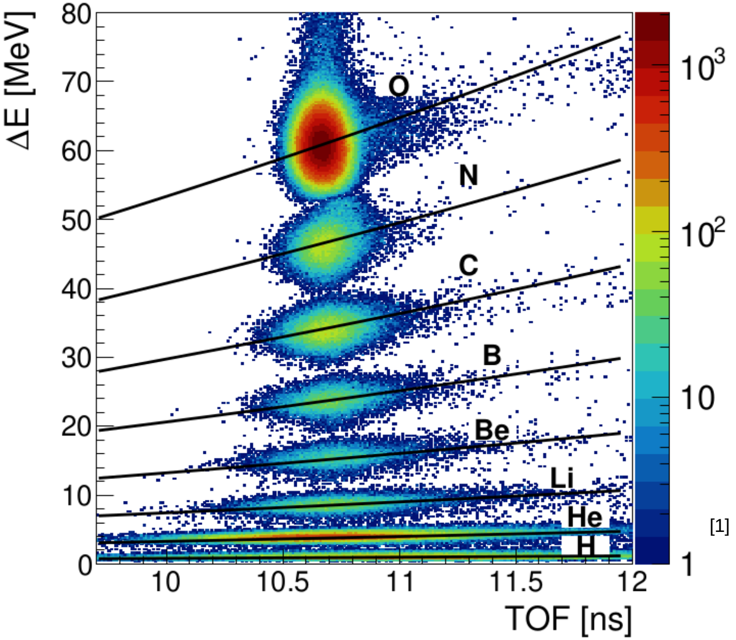
- Elemental (charge differential) fragmentation cross section
- Angular differential cross section in charge

# Electronic setup: results

### *charge identification*

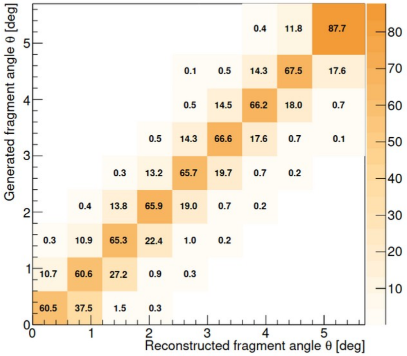
$$-\frac{dE}{dx} = 4\pi N_e r_e^2 m_e c^2 \frac{z^2}{\beta^2}\left(\ln\frac{2m_e c^2\beta^2\gamma^2}{I} - \beta^2 - \frac{\delta(\gamma)}{2}\right)$$

Quantities taken from SC and TW



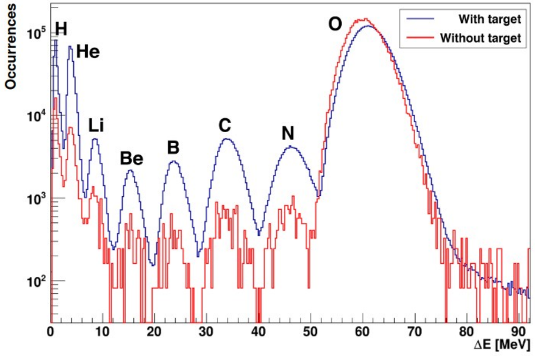

[1]

### *Unfolding procedure* (from MC)
for angle mixing




[1]

### *Background subtraction*
(from exp data)




[1]

# Electronic setup: results

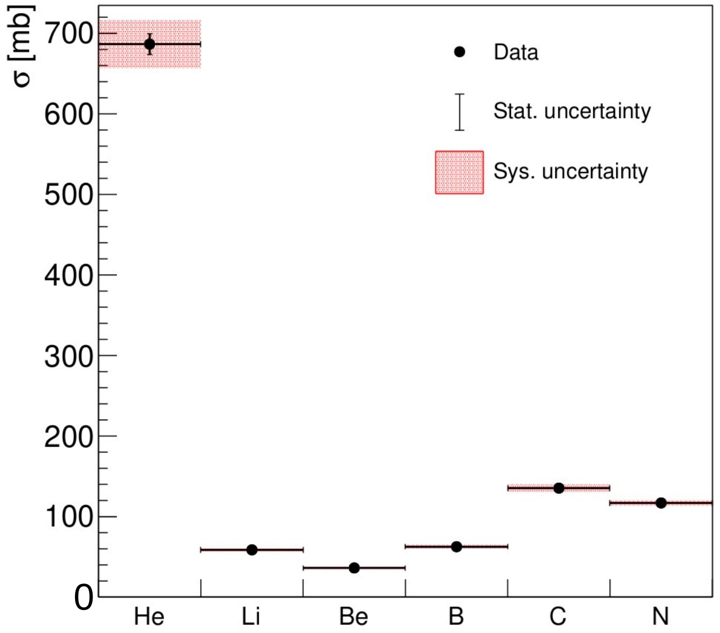
***elemental cross section***

$$\sigma_R = \int_0^{\Omega}\int_0^{\infty} \frac{d^2\sigma}{dE_K d\Omega} dE_K d\Omega = \frac{Y(Z)}{N_{\text{prim}} \cdot N_{\text{TG}} \cdot \varepsilon(Z)}$$

with polar angle θ ≤ 5.7°

| Element | $\sigma \pm \Delta_{stat} \pm \Delta_{sys}$ [mb] | $\Delta_{stat}/\sigma$ | $\Delta_{sys}/\sigma$ |
|---|---|---|---|
| He | $687 \pm 13 \pm 30$ | 1.9% | 4.3% |
| Li | $59 \pm 3 \pm 2$ | 5.4% | 3.2% |
| Be | $36 \pm 3 \pm 1$ | 7.6% | 3.2% |
| B | $63 \pm 4 \pm 3$ | 5.7% | 4% |
| C | $135 \pm 6 \pm 5$ | 4.5% | 3.7% |
| N | $117 \pm 6 \pm 4$ | 5.4% | 3% |

- systematic uncertainty lower than statistic one
- total relative error **from 5% to 10%**




[1]



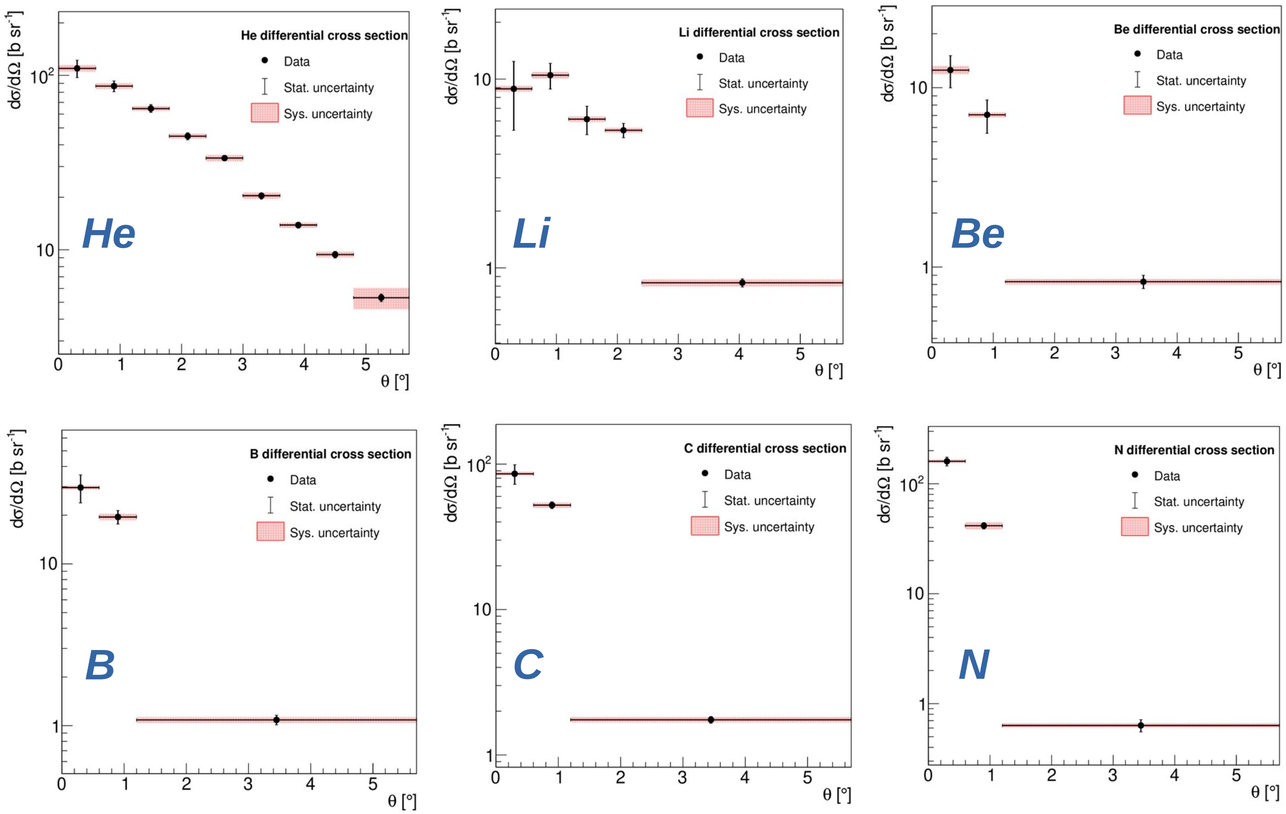
[1] https://doi.org/10.48550/arXiv.2501.00553

# Electronic setup: results

***angular differential cross section***

$$\frac{d\sigma}{d\Omega}(Z)$$

- first measurements for the FOOT experiment!
- number of bins chosen considering the available statistics
- total relative error affected by statistic, **from 3% to 20%** (except for Li)




[1]



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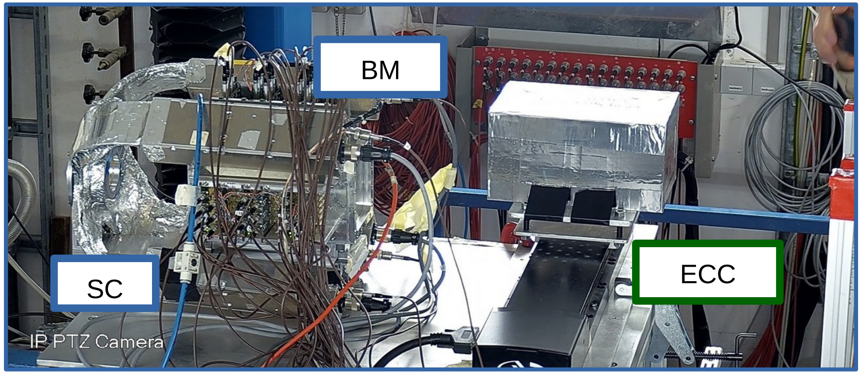
# Emulsion setup: preliminary results

Charge identification of fragments produced in $^{16}O$ beam interactions at 200 *MeV/n* and 400 *MeV/n* on C and $C_2H_4$ targets

frontiers

[1]

- Paper of G. Galati et al published!
- Data-taking at GSI (Darmstadt, Germany) in 2019 and 2020
- **$^{16}O$ 200, 400 MeV/u** on 5 mm **$C/C_2H_4$ target**
- SC + BM for primary beam monitoring before emulsions




**Specific goal:**

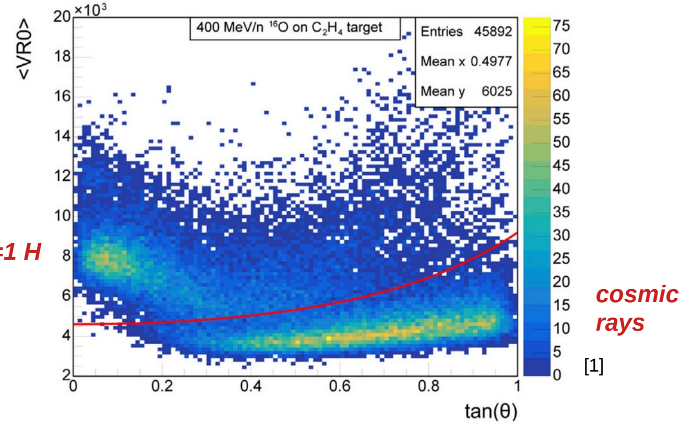
- Elemental (charge differential) fragmentation cross section
- Angular differential cross section in charge



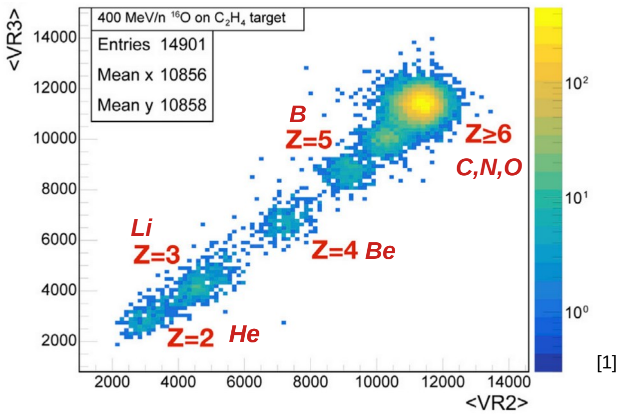
[1] https://doi.org/10.3389/fphy.2023.1327202

# Emulsion setup: preliminary results

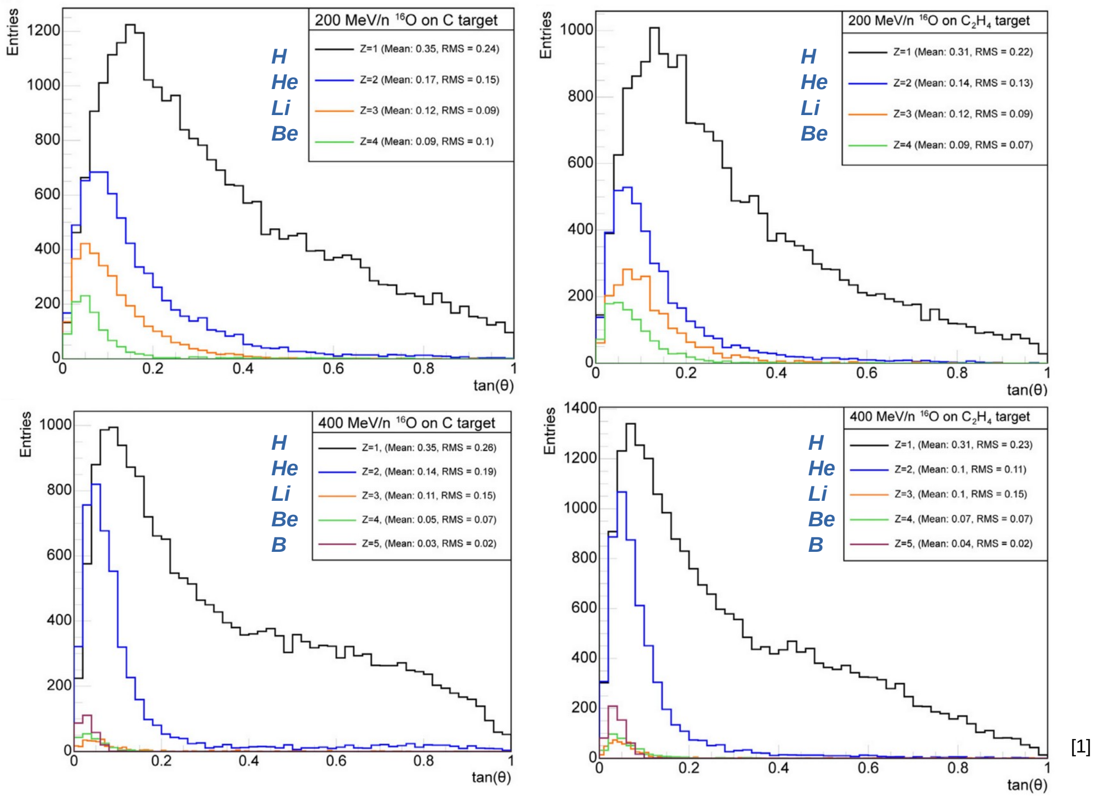
*Cosmic ray* ***cut-based rejection***




***PCA approach*** *for Z>1*




***charge identification***




- total relative error affected by systematic, **around 5%**



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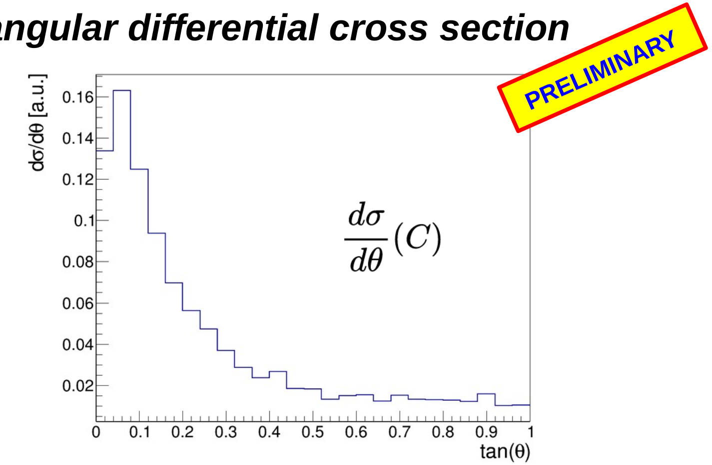
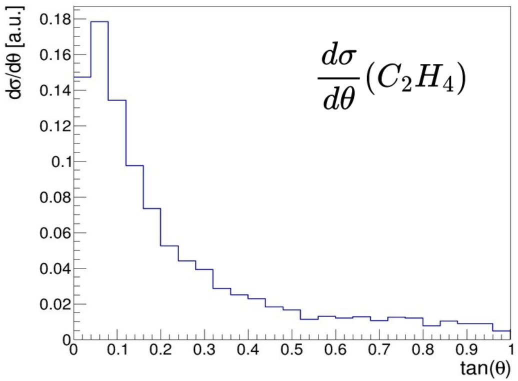
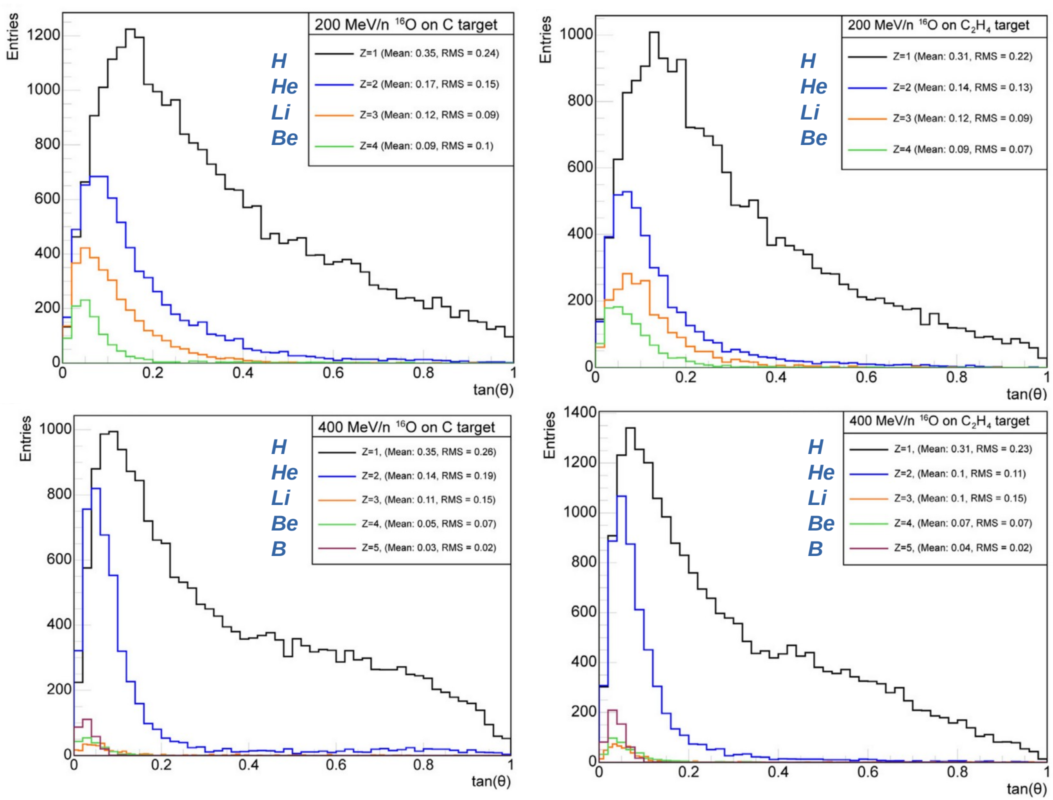
# Emulsion setup: preliminary results

***angular differential cross section***




***charge identification***

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# Conclusions

- Nuclear fragmentation cross section measurements with the FOOT experiment
- Fundamental interest in several fields, among which **particle therapy** and **space radioprotection**
- Both setups are promising for charge reconstruction and **cross section measurements**

- Cross section **results** from both setups!
- Ongoing data taking campaigns (CNAO2025, GSI2026, CNAO2026..) and analysis (HIT 2022, CNAO 2023, CNAO 2024…)
- Electronic setup completed from 2023: ongoing analysis toward **isotopic cross sections**

# Conclusions

## ***Thanks for the attention!***

*Valle del Bove - Etna*

# back-up slides

# 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)

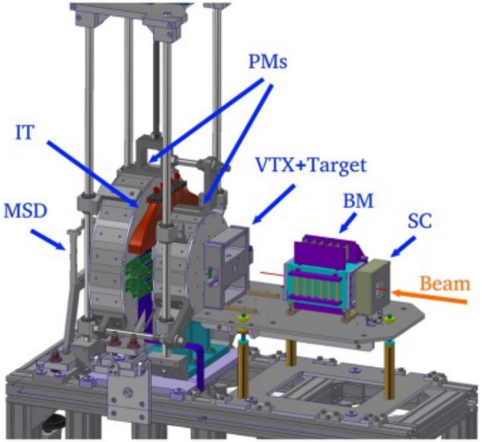
# Physics data taking done up to now

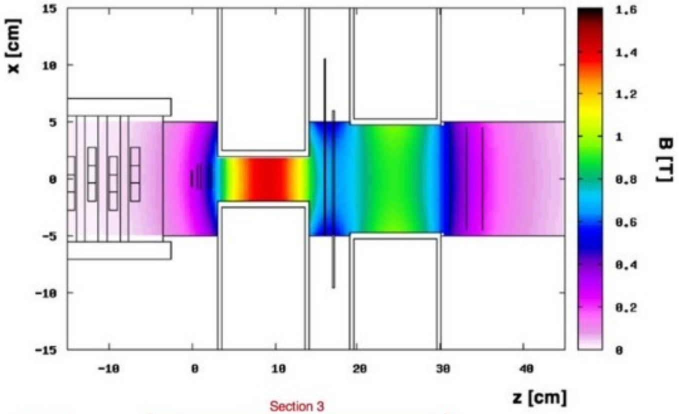
| Beam | Target | Energy MeV/u | Statistics (millions) | Integral Differential elemental | Integral Differential isotopic | direct | inverse | Emulsions | campaign |
|---|---|---|---|---|---|---|---|---|---|
| O | C<br>C2H4 | 200<br>400 | 0.06 | angle | NO | YES | NO | Yes<br>Yes | GSI 2019<br>GSI 2020 |
| 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

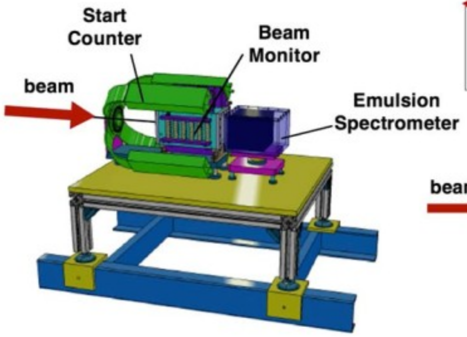
| Beam | Target | Energy MeV/u | Integral Differential elemental | Integral Differential isotopic | Emulsions | Campaign |
|---|---|---|---|---|---|---|
| C | C, C2H4 | 100-200 | Angle<br>Energy | YES | YES<br>(NIT?) | CNAO 2025 |
| O | C | 500-700 (?) | Angle<br>Energy | YES | YES | GSI 2026 |
| C |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

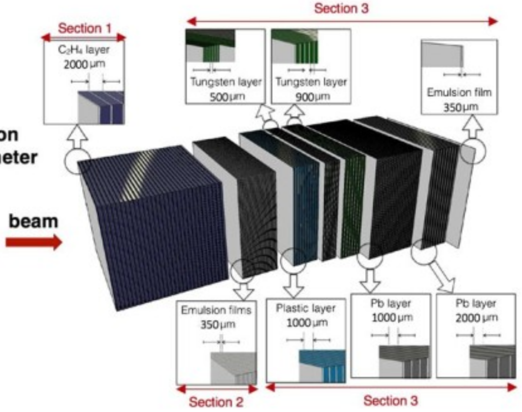
# Setup overview




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




- $\sigma(p)/p$ 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 $5\%$;

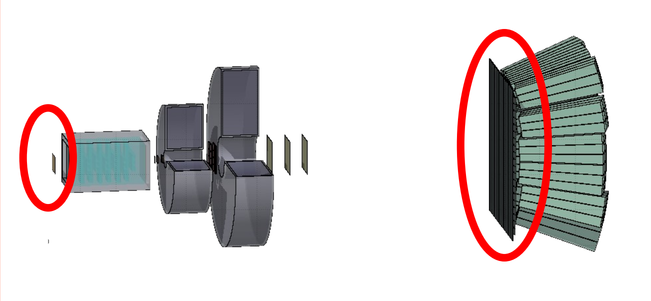
# Fragments identification

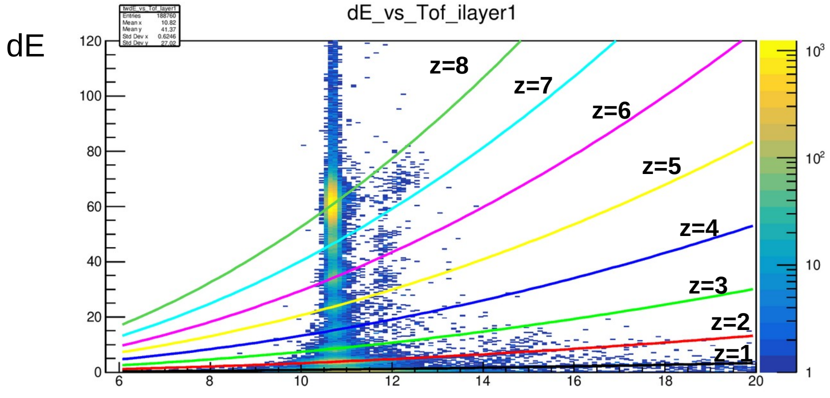
Fragments identification

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

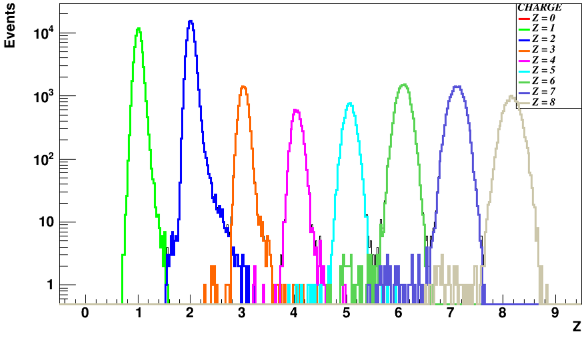
$$-\frac{dE}{dx} = 4\pi N_e r_e^2 m_e c^2 \frac{z^2}{\beta^2}\left(\ln\frac{2m_e c^2\beta^2\gamma^2}{I} - \beta^2 - \frac{\delta(\gamma)}{2}\right)$$

- **Infos taken from SC and TW**






TW charge reconstruction algo

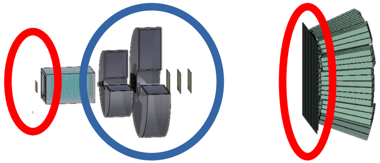
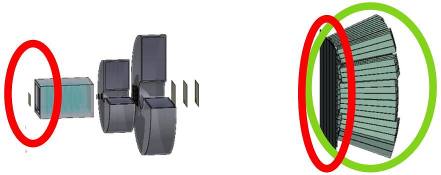
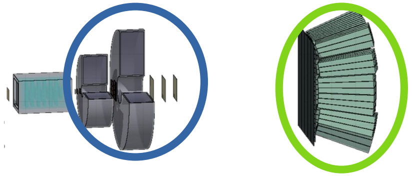



**Charge discrimination**

# Isotope identification

- Mass reconstruction using all FOOT subdetectors:

$$A_1 = \frac{p}{U\beta c\gamma} \qquad A_2 = \frac{E_k}{Uc^2(\gamma - 1)} \qquad A_3 = \frac{p^2c^2 - E_k^2}{2Uc^2E_k}$$

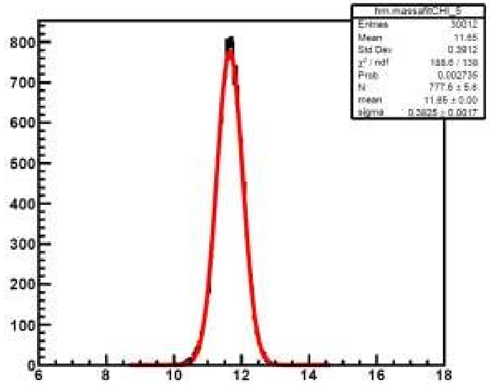




- In our data no tracker and calorimeter → mass measurement only in MC data!
- **Augmented Lagrangian**

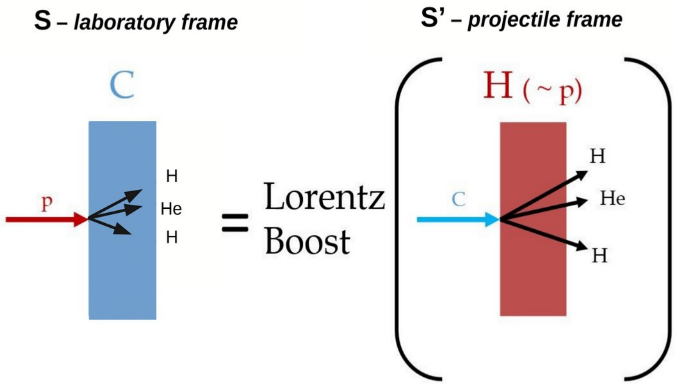
$$L(\vec{x}, \lambda, \mu) \equiv f(\vec{x}) - \sum \lambda_a c_a(\vec{x}) + \frac{1}{2\mu} \sum c_a^2(\vec{x})$$

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

$A\chi 2 = 11.66 \pm 0.38$
risoluz. 3.2 %
$\chi 2 < 5$



# Inverse kinematic approach




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

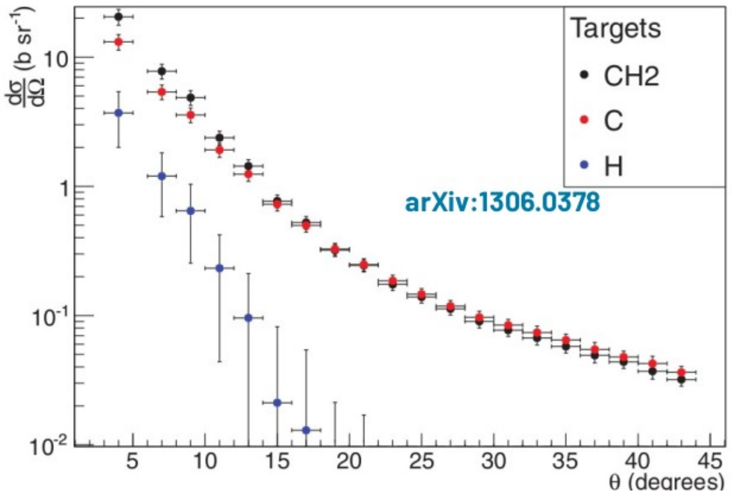
$$E'/c = \gamma(E/c - \beta p_z)$$
$$p'_x = p_x$$
$$p'_y = p_y$$
$$p'_z = \gamma(p_z - \beta E/c)$$

# 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

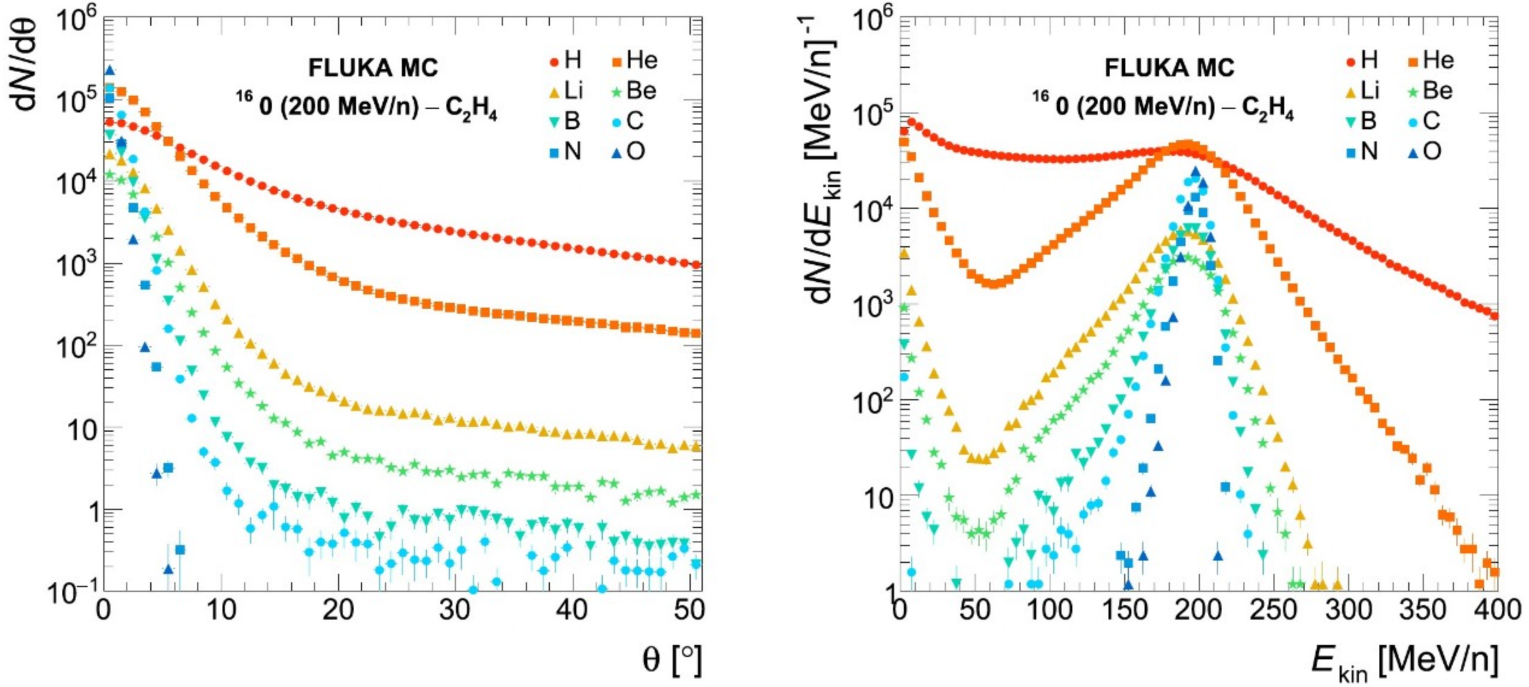
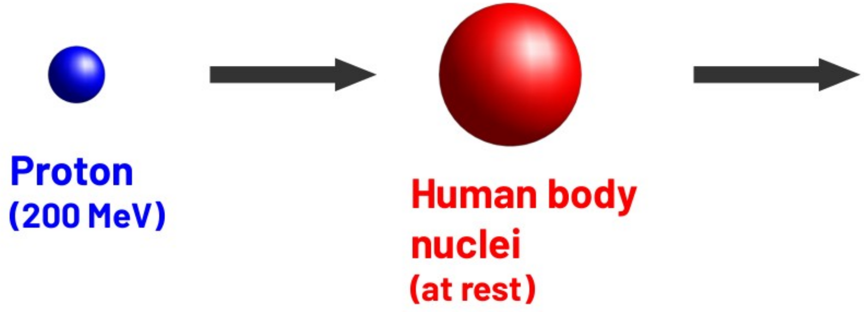



**FIGURE 1** | MC calculation [33, 34] of the angular **(Left)** and kinetic energy **(Right)** distributions of different fragments produced by a 200 MeV/nucleon $^{16}O$ beam impinging on a $C_2H_4$ target.

*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

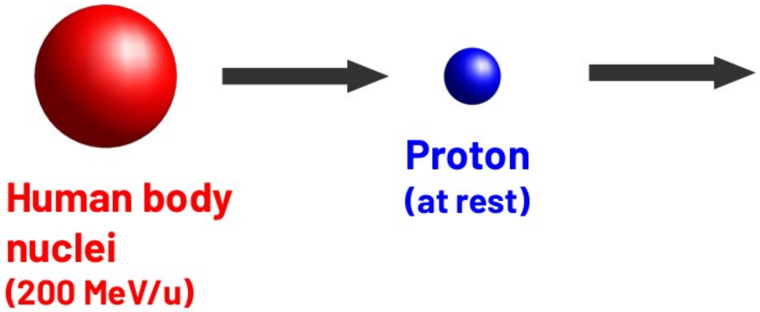
# Projectile and target fragments




Fragments with low energy and short range (few cell diametres)

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

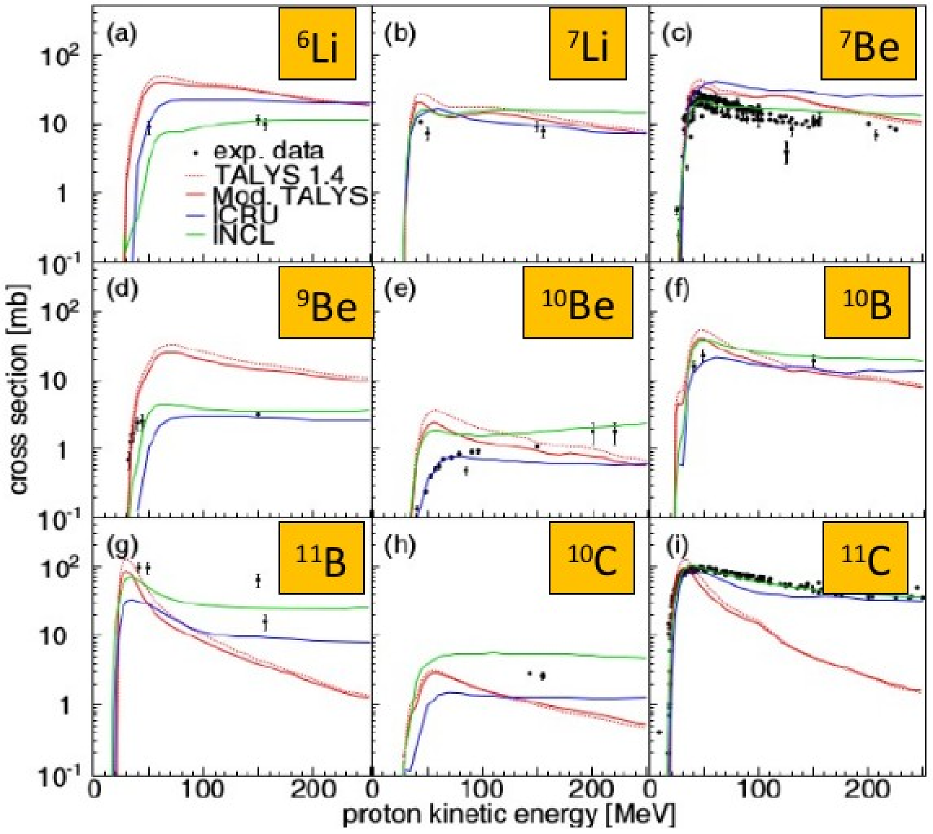
Very difficult to detect!




Fragments with higher energy and longer range!

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

# Cross section measurements in literature

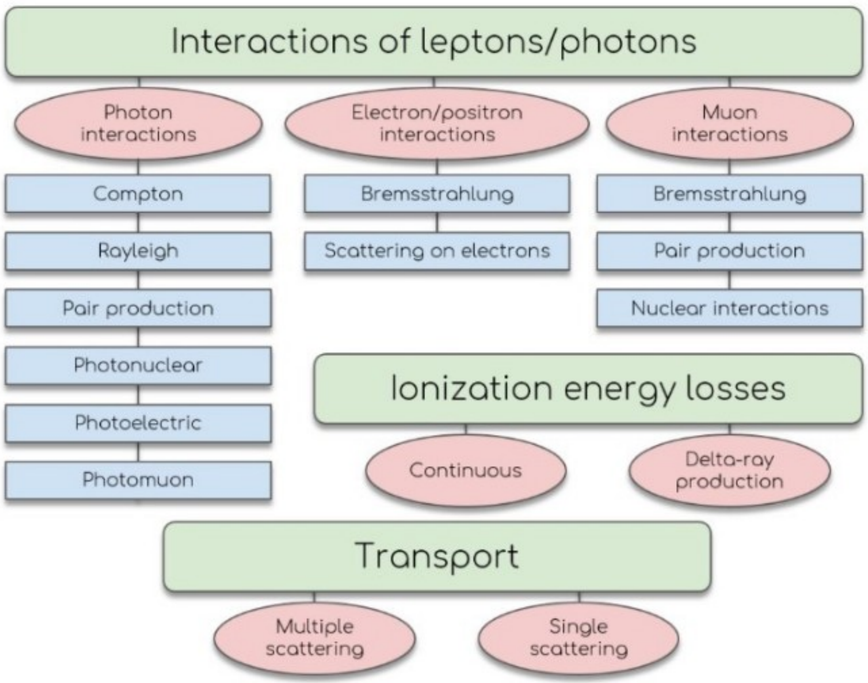



$$p + C$$

- 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

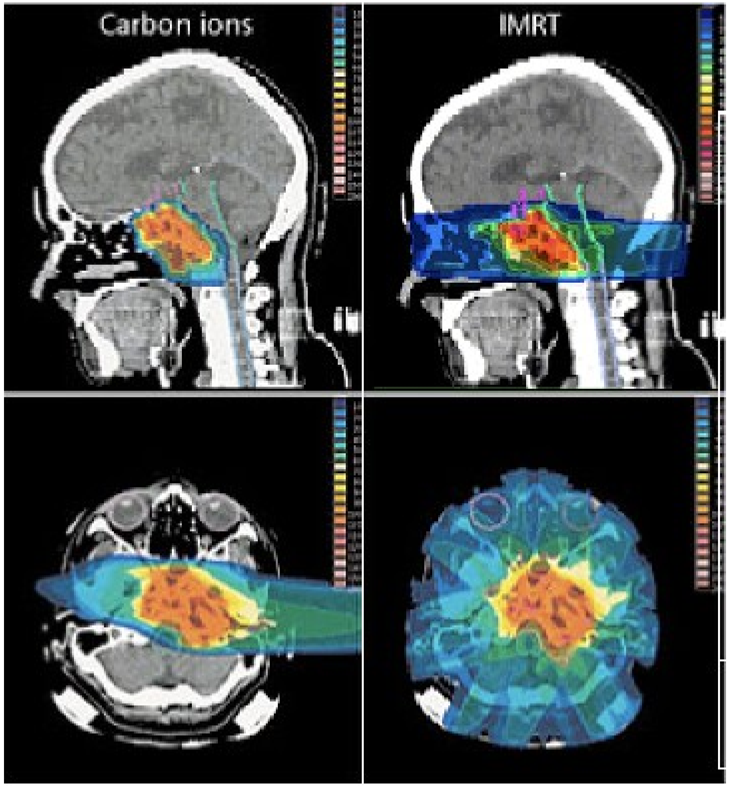
**Handron-nucleus interactions:**

- 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

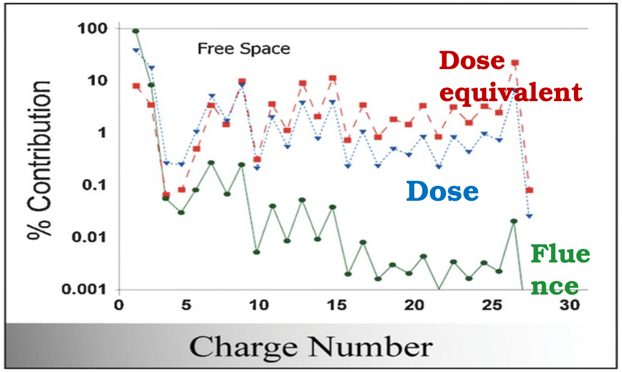
**Nucleus-nucleus interactions**

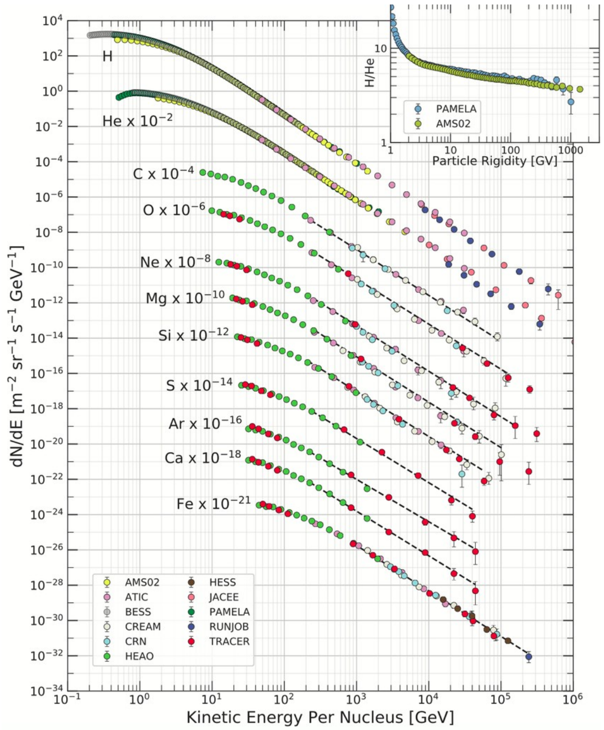
- Boltzmann-Master Equation model (E<100 MeV/u): Thermalization of composite nuclei by means of two-body interactions and secondary particles emissions
- Relative Quantum Molecular Dynamics (0.1 - 5 GeV/u): Collision simulated minimizing the Hamiltonian equation of motion considering the Gaussian wave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

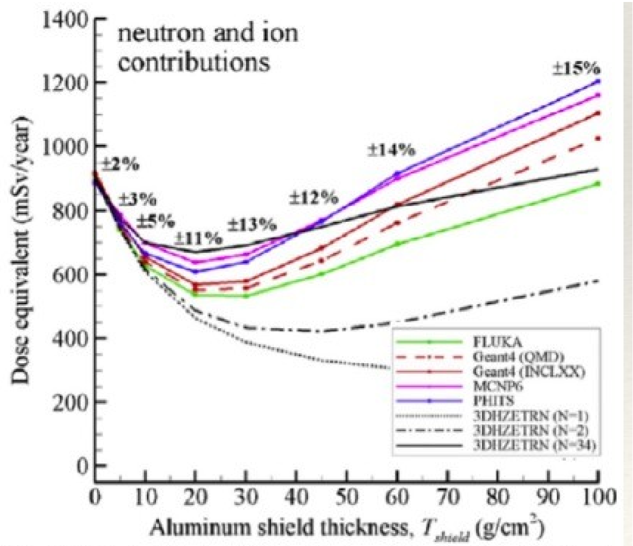
# Hadrontherapy vs conventional radiotherapy



# 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

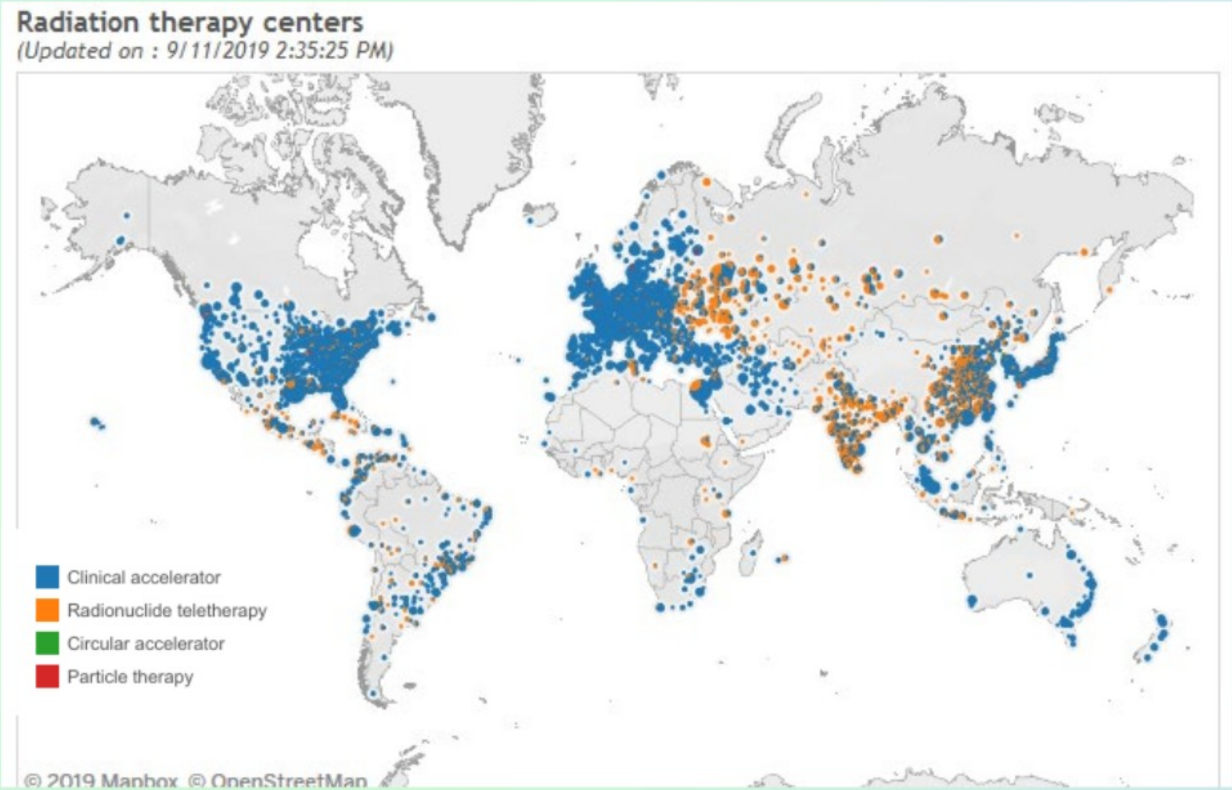
Carbon (and proton)

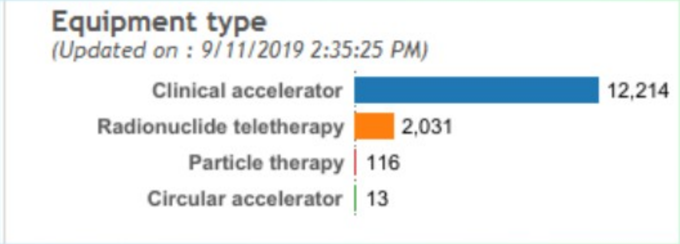
Facility (end of 2019):

- 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



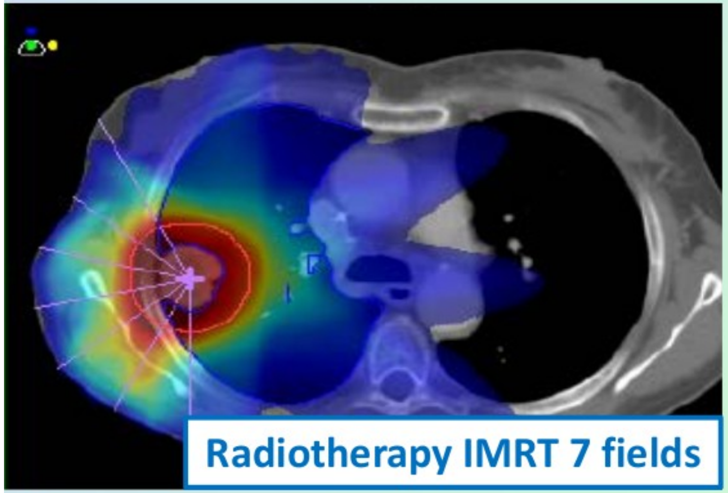

| Countries | RT centers | Equipment | Linac | Radionuclide Therapy | Circular Accelerator | Particle Therapy |
|---|---|---|---|---|---|---|
| 149 | 7477 | 14374 | 12214 | 2031 | 13 | 116 |

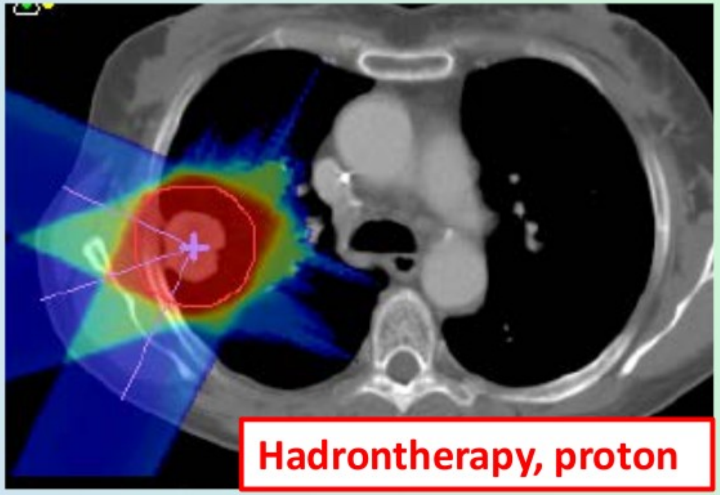
Linac → radiotherapy

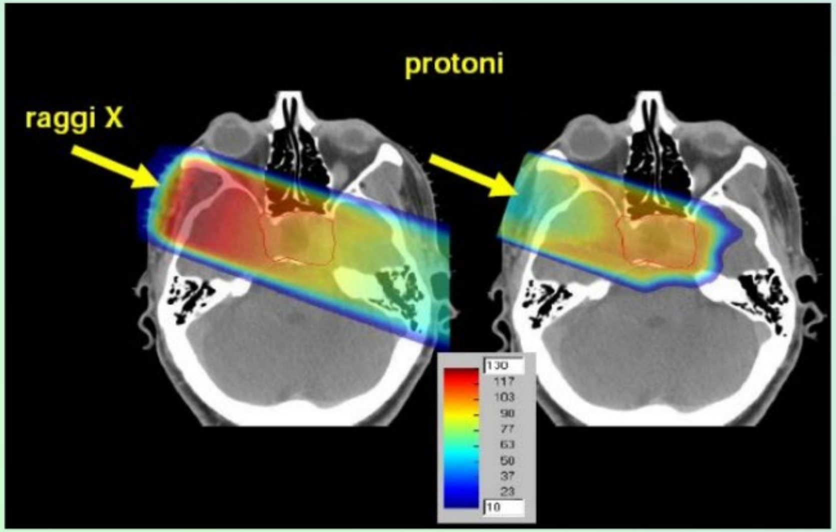
Circular Accelerator → microtrone and betatrone

*Courtesy of R. Spighi*

# *Hadrontherapy vs radiotherapy, 1*



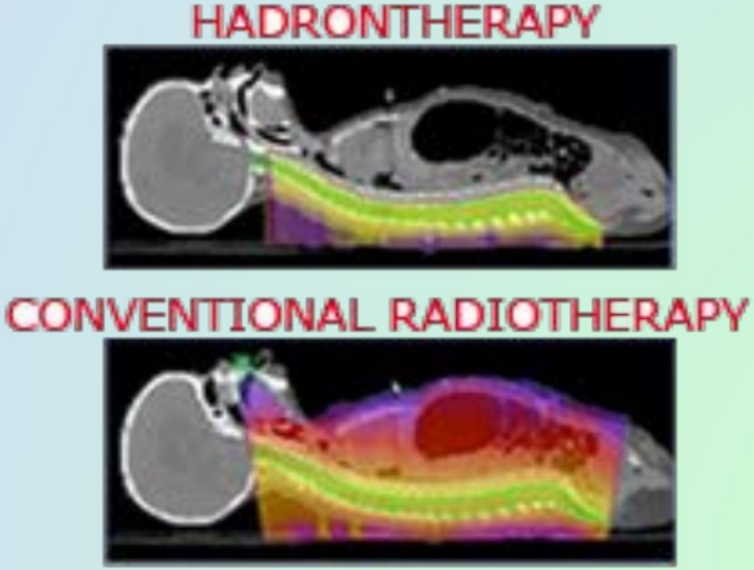



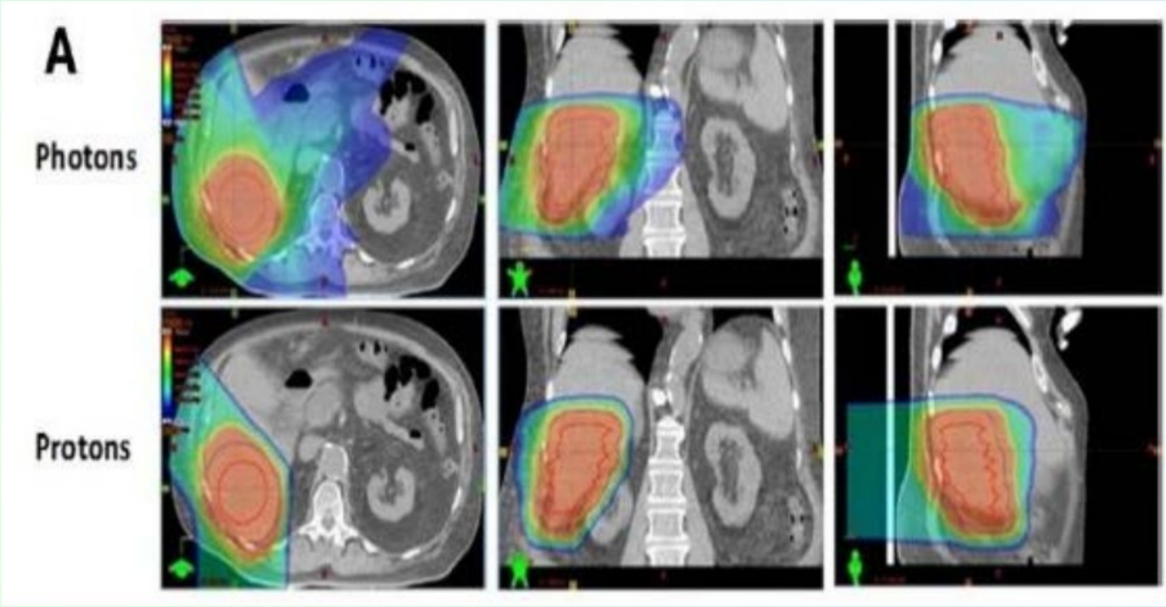

Pro and contra

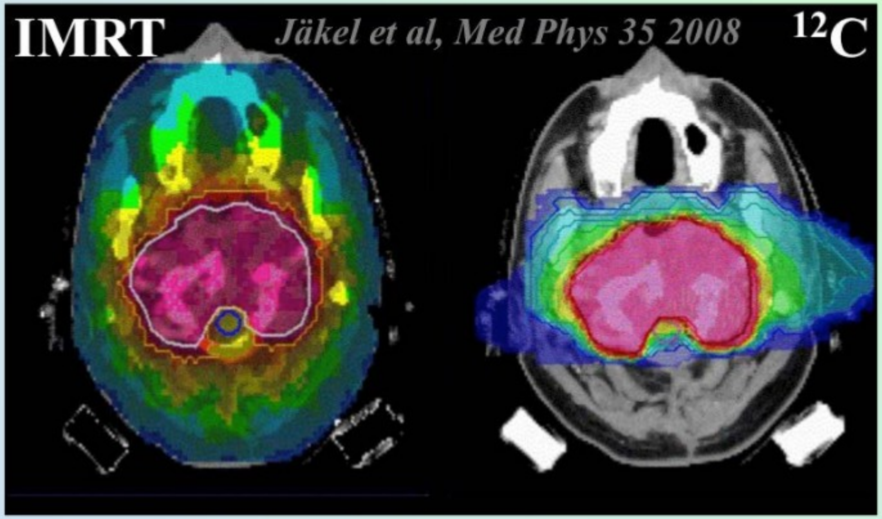
- Hadrontherapy: the released dose is better focused;
- Hadrontherapy: less dose before and after tumor region
- Costs:
  - accelerator for Hadrontherapy ~250 millions euros
  - Treatment ~ 5-10 than radiotherapy
  - Machine for radioterapy: tens thousands euros.

*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

Geneva - 16.10.13 - UA