# Cross-sections measurements in hadrontherapy and space radiation protection

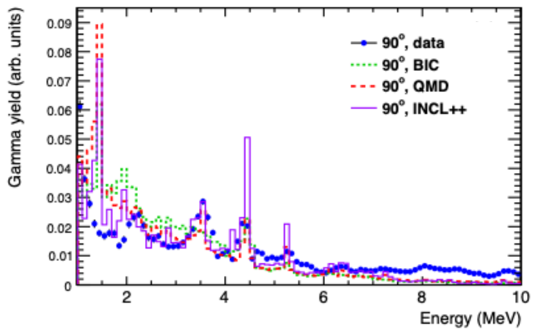
Marie Vanstalle

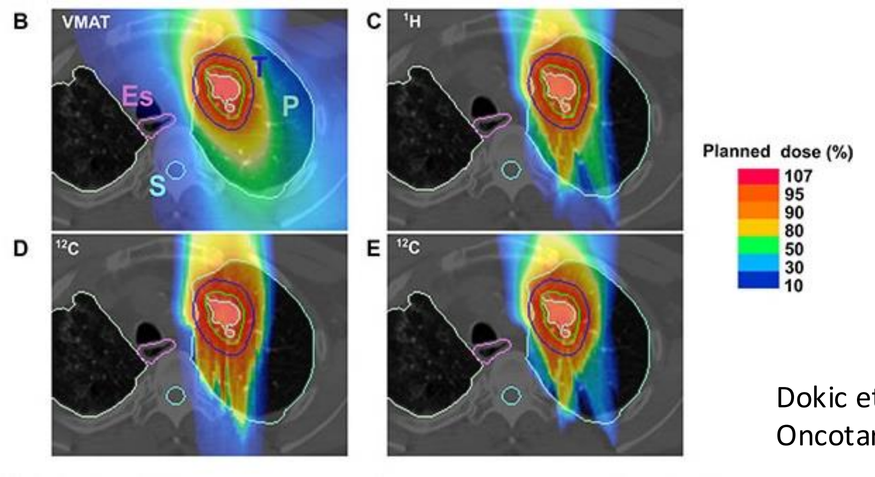
*On behalf of the FOOT collaboration*

# Why do we need cross-sections measurements?

Characterization of secondary particles fields

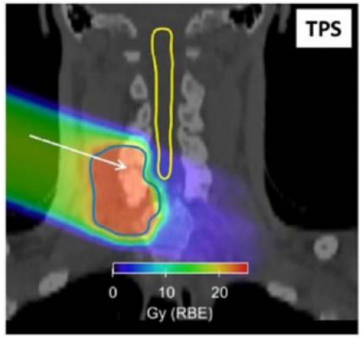
Online monitoring of the dose




Hadrontherapy

Impact of fragmentation on dose delivered in treatments

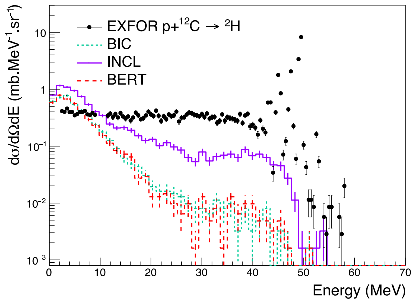



Extrait de **Battistoni et al.**, *"The FLUKA code: an accurate simulation tool for particle therapy"*, Frontiers in Oncology (2016).

Beam of $^{1}$H, $^{4}$He, $^{7}$Li, $^{12}$C, $^{16}$O between 80 and 400 MeV/u

Dokic et al., « Next generation multi-scale biophysical… », Oncotarget, 2016

Monte Carlo benchmarking




**It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong.**

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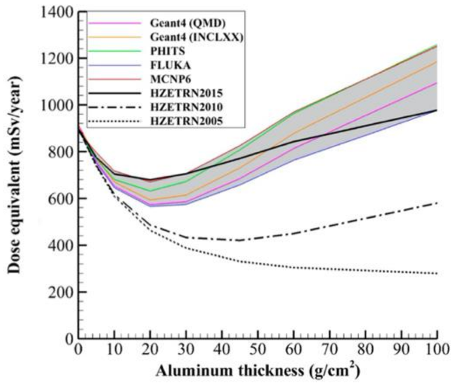
# Why do we need cross-sections measurements?

Characterization of secondary particles fields

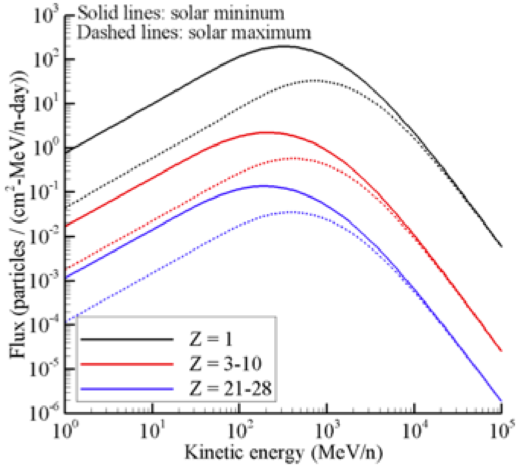
Impact of fragmentation on dose received by astronauts




From **Norbury et al.**, *"Advances in space radiation physics and transport at NASA"*, Life Sciences in Space Research (2019).

Space radiation protection

Monte Carlo benchmarking




Galactic cosmic rays (GCR) of $^1$H, $^4$He, $^7$Li, $^{12}$C, $^{16}$O $^{56}$Fe between 400 and 4000 MeV/u + Solar Particle Events (SPE)

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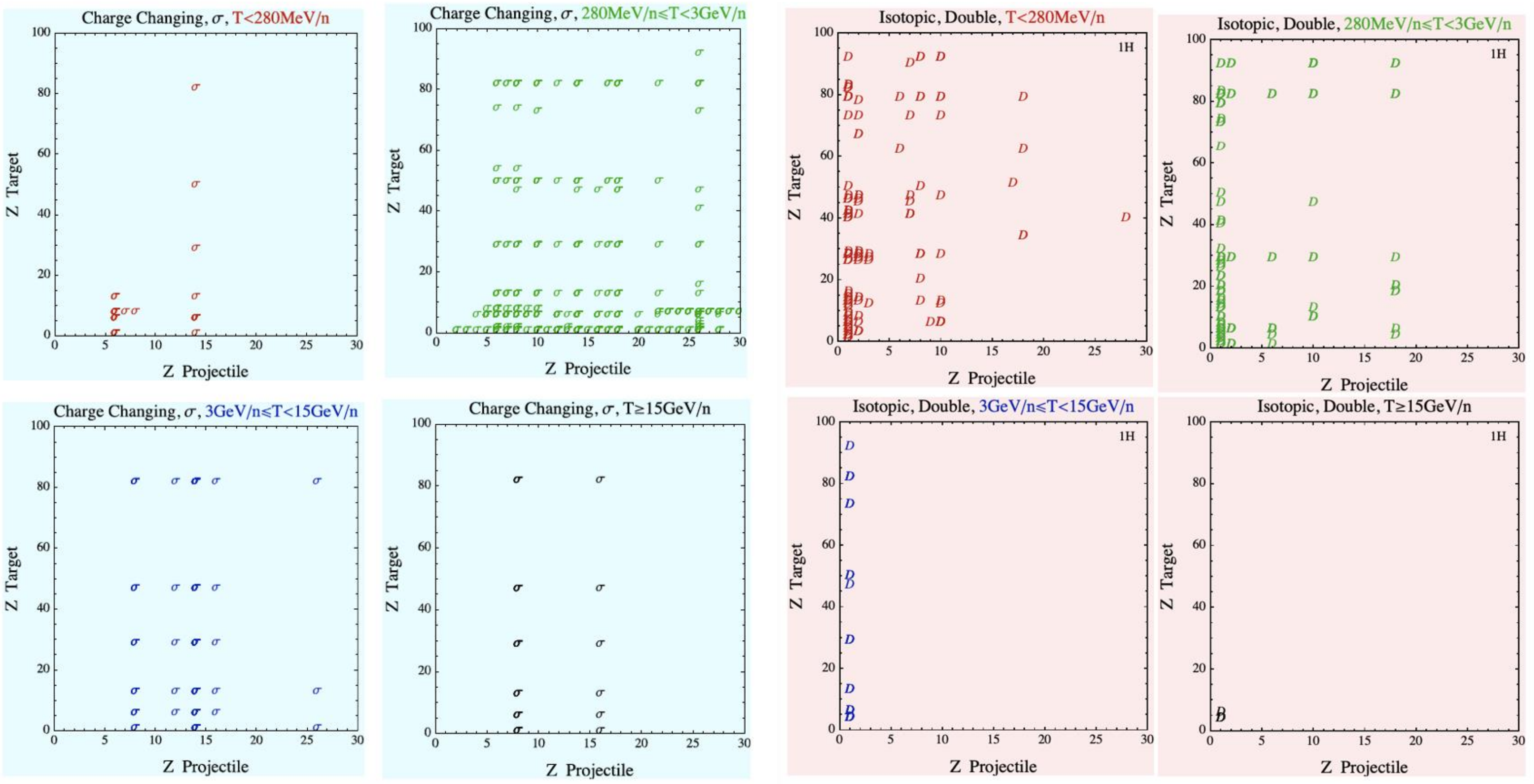
# Why do we need cross-sections measurements?

- Important lack of data between 10 MeV/u and 10 GeV/u ⇒ energies of interest for hadrontherapy and space radiation safety

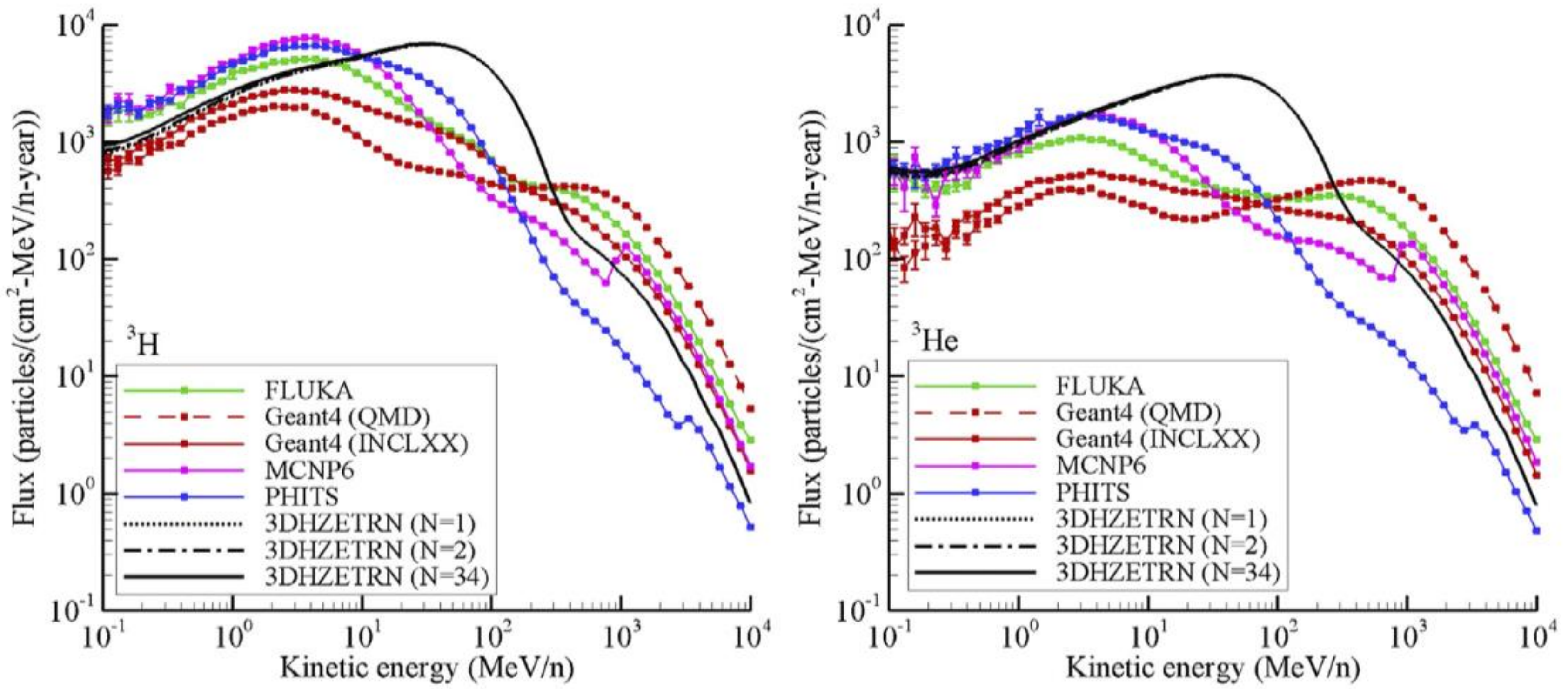



From **Norbury et al.**, "*Nuclear data for space radiation*", Radiat. Meas. (2012).

**Needed data :** charge-changing cross sections ($\sigma_Z$) and double differential cross-sections ($\frac{d^2\sigma}{dEd\theta}$)

# Why do we need cross-sections measurements?

- Important discrepancies between models used in radiation protection




Extracted from Norbury et al., *Are Further Cross Section Measurements Necessary for Space Radiation Protection or Ion Therapy Applications? Helium Projectiles*, Frontiers in Physics, 2020.

Predicted spectra of $^3$H and $^3$He after 60 g.cm$^{-2}$ of aluminum shielding

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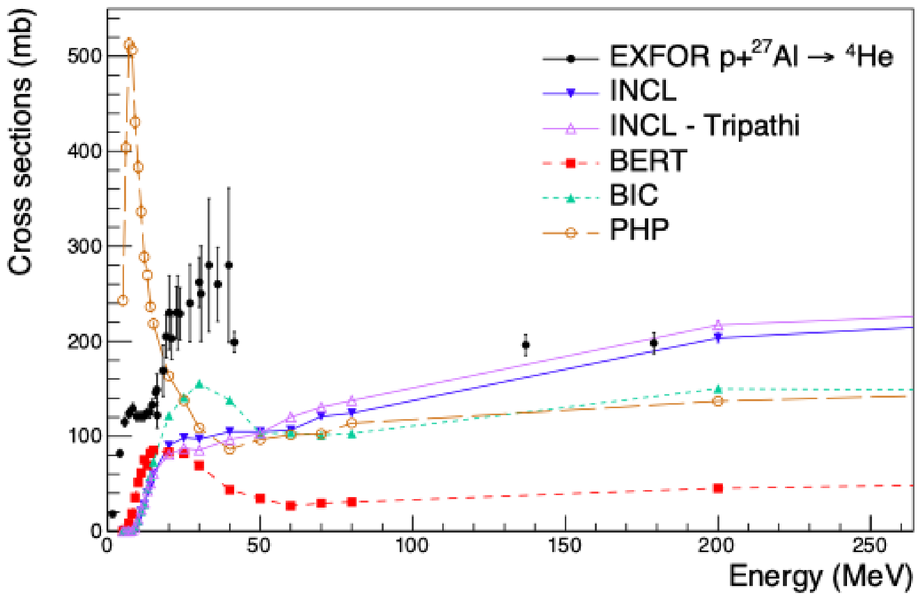
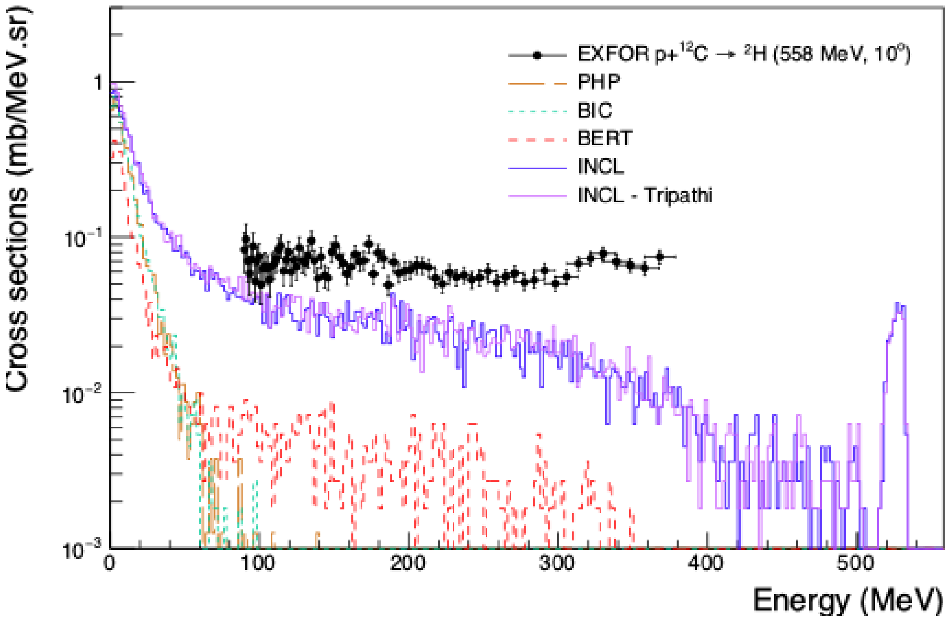
# Why do we need cross-sections measurements?

- Important discrepancies between models and data




**Necessity to measure the missing cross-sections in order to improve constraints on the models**




What accuracy do we need on cross-sections for radiobiology?

$\frac{d\sigma}{dE} \sim 10\%$ $\frac{d^2\sigma}{dEd\Omega} \sim 5\%$

$\sigma_Z \sim 2\%$ $\sigma_A \sim 5\%$

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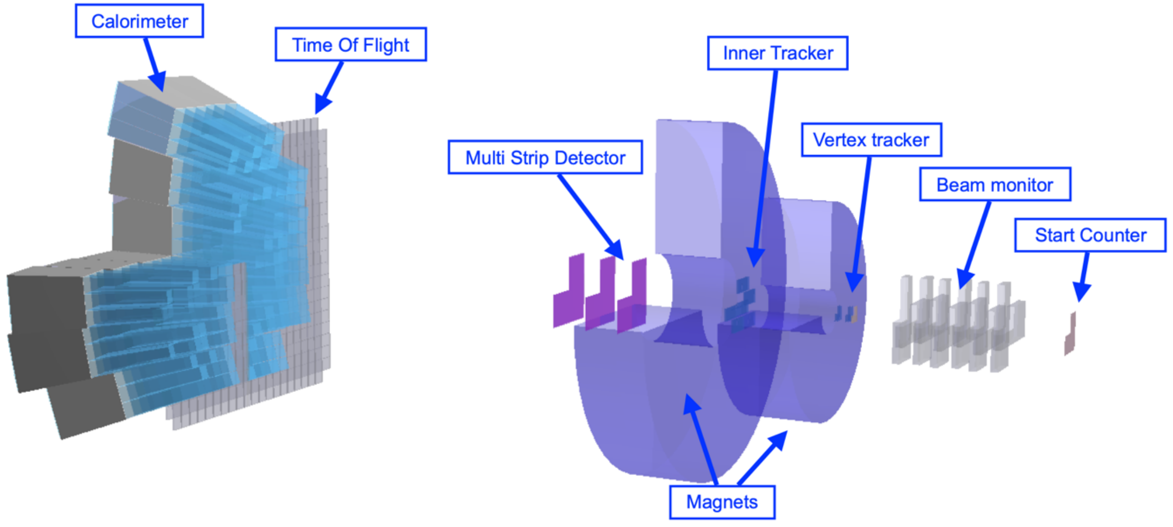
# How do we measure cross-sections?

- Satellites + ISS ⇒ problem: located in LEO (Low Earth Orbit)
- Ground-based experiments ⇒ accelerators facilities
  - Low energy range (space): hadrontherapy facilities (CNAO, HIT,…) ⇒ $^{4}$He, $^{7}$Li, $^{12}$C, $^{16}$O & $^{56}$Fe ion beams
  - High energy range ≥ 1 GeV/u: FAIR (Darmstadt, Germany), NRSL (Brookhaven)

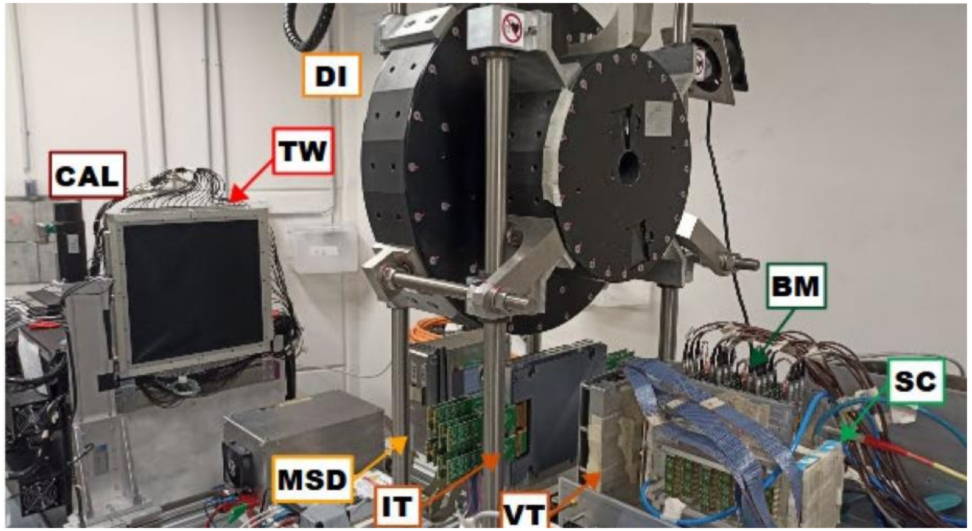

# A focus on FOOT project

- FOOT (FragmentatiOn Of Target) : **double differential cross-sections measurements** of $^{12}C$, $^{16}O$, $^{4}He$, $^{56}Fe$ @200-700 MeV/u on C, $(C_2H_4)_n$ , PMMA target
  - Goal: cross-sections measurements with 5% of accuracy (double differential)
  - Ground-based experiments at GSI and CNAO
- Z identification ⇒ Start counter (SC) + ToF wall (TW)
- A identification ⇒ magnetic spectrometer: beam monitoring (BM) + vertex detector (VTX) + inner tracker (IT) + multi-strip detector (MSD)
- Total energy ⇒ calorimeter (CAL)

Direct + inverse kinematic approach




+ emulsion setup to measure fragments of Z<3 and up to 70º

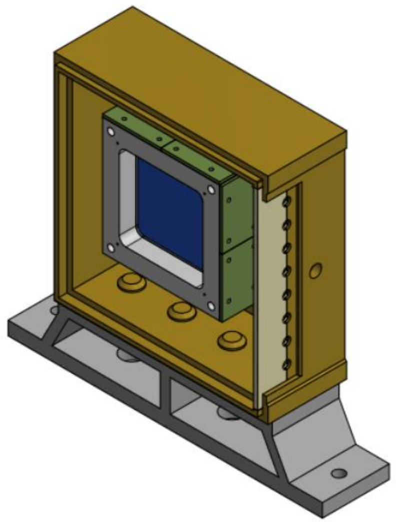



What performances do we want?

$$\frac{\sigma(p)}{p} < 5\% \quad \frac{\sigma(\Delta E)}{E} < 5\% \quad \sigma_{ToF} < 100\ ps$$

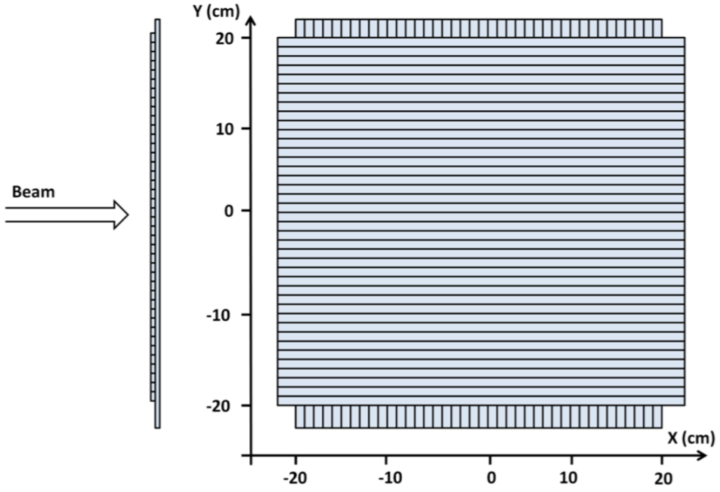
# A focus on FOOT project

- Z identification ⇒ Start counter (SC) + ToF wall (TW)



SC: 250 µm-thick plastic scintillator (EJ-204), active surface 5×5 cm²

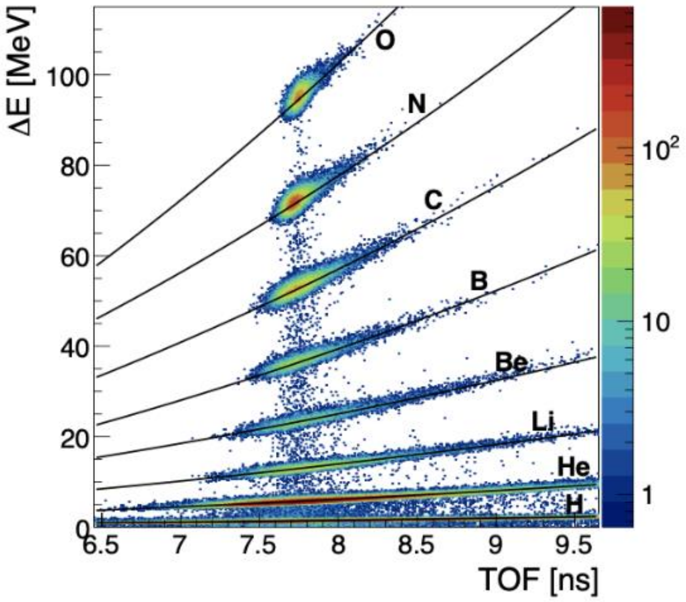
- Start of Time-of flight measurement
- Trigger
- Measure the incoming flux




TW: 2 layers of 20 scintillators bars (0.3 cm-thick, 2 cm-wide, 44 cm-long) arranged orthogonally, active area 40×40 cm²

- Stop of Time-of flight measurement
- Deposited energy ΔE
- Hit positions

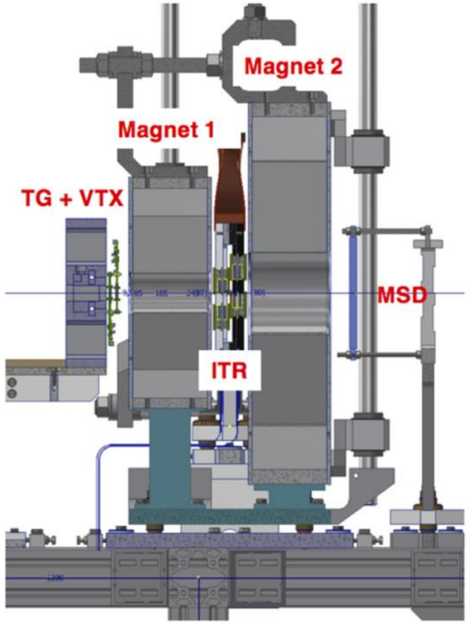
**Fragment Z identification thanks to** ΔE-ToF map

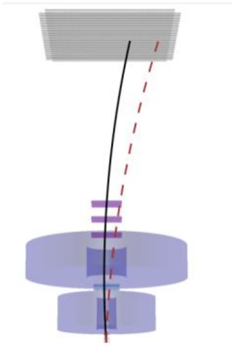


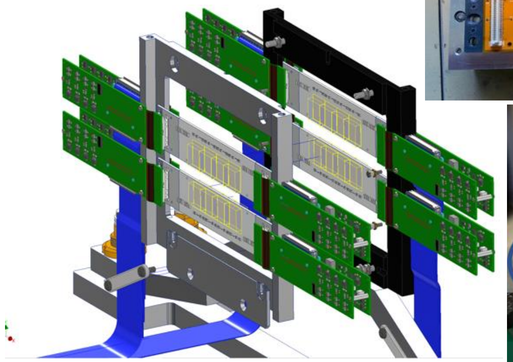

From Battistoni et al., « Measuring the impact of nuclear interaction in particle therapy and in radioprotection in space: the FOOT experiment », Frontiers in Physics, 2021.

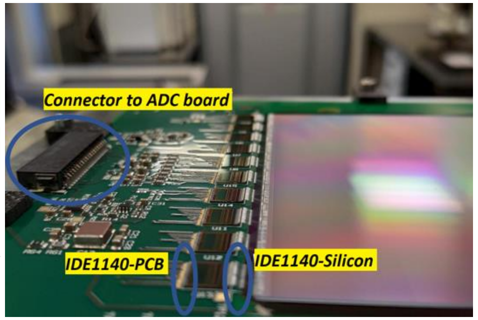
# A focus on FOOT project

- A identification ⇒ magnetic spectrometer: beam monitoring (BM) + vertex detector (VTX) + inner tracker (IT) + multi-strip detector (MSD)







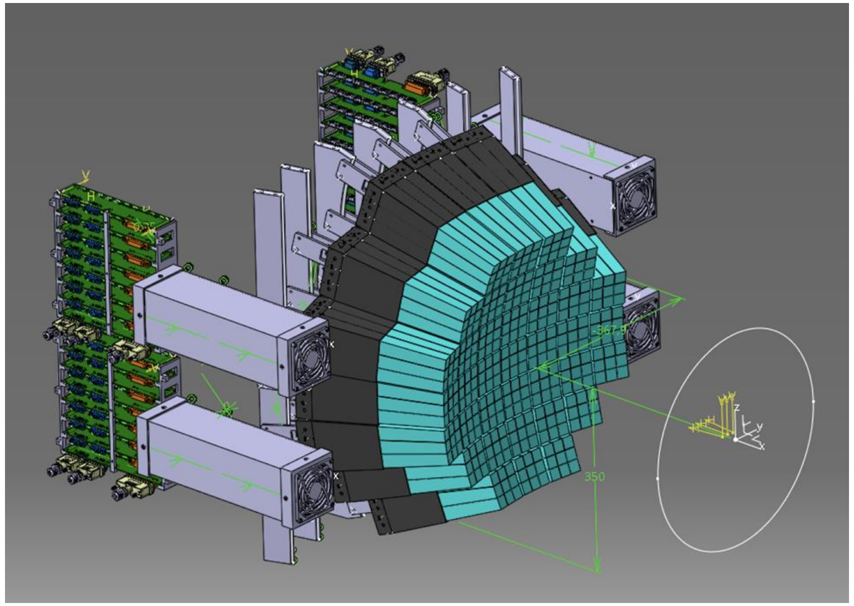

VTX: 4 planes of MIMOSA-28 CMOS pixel sensors, 50 µm-thick of Si, 1×1 $cm^2$
IT: 2×2 ladders of 4 CMOS MIMOSA-28 (PLUME)
MSD: 6 planes of silicon strip detectors (3X + 3Y) of 150 µm-thick each, 10×10 $cm^2$

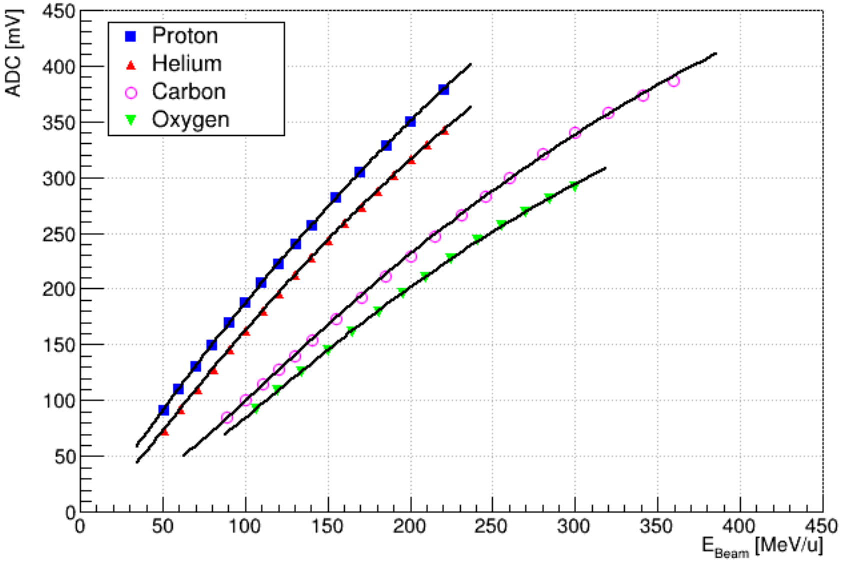
- Particle trajectory measurement
- Provide the momentum of the particle

From Battistoni et al., « Measuring the impact of nuclear interaction in particle therapy and in radioprotection in space: the FOOT experiment », Frontiers in Physics, 2021.

# A focus on FOOT project

- Total energy ⇒ calorimeter (CAL)



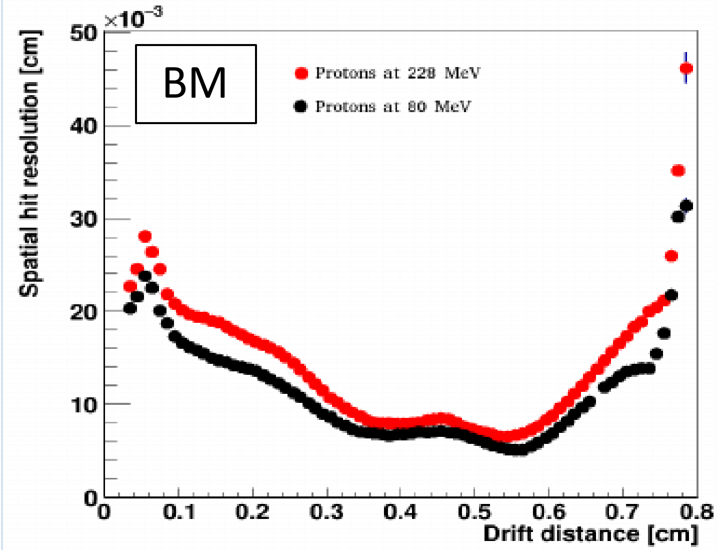


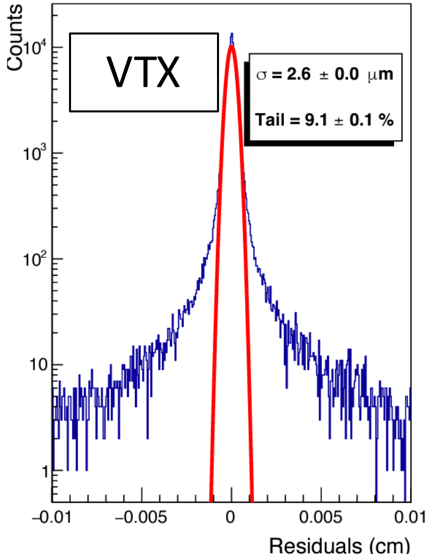

CAL: 320 BGO scintillators, truncated pyramid shape, 20×20 mm$^2$ (front) & 29×29 mm$^2$, length of 240 mm

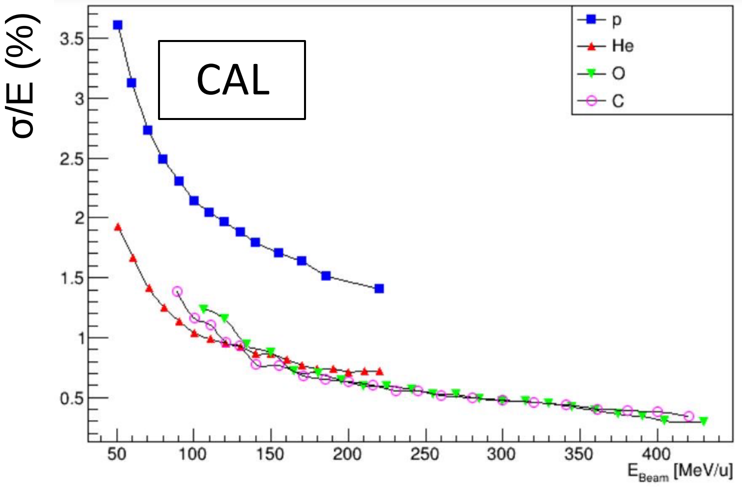
- Total energy measurement
- Can provide extra (A,Z) identification coupled with TW

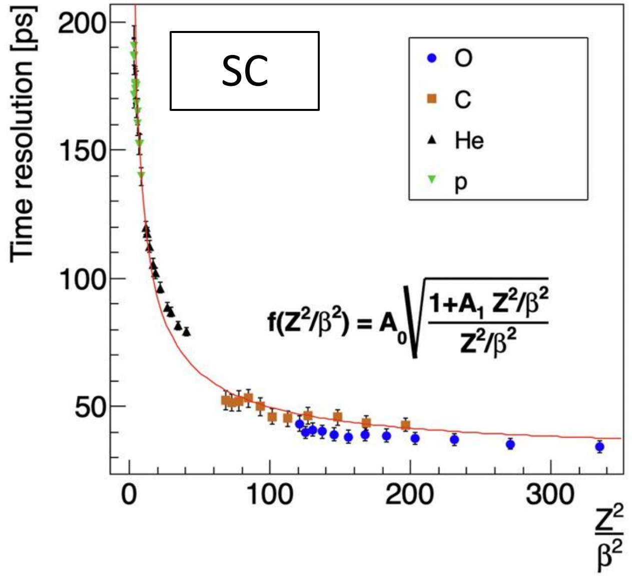
Calibration curves of calorimeter
Work from Alessandro Valetti

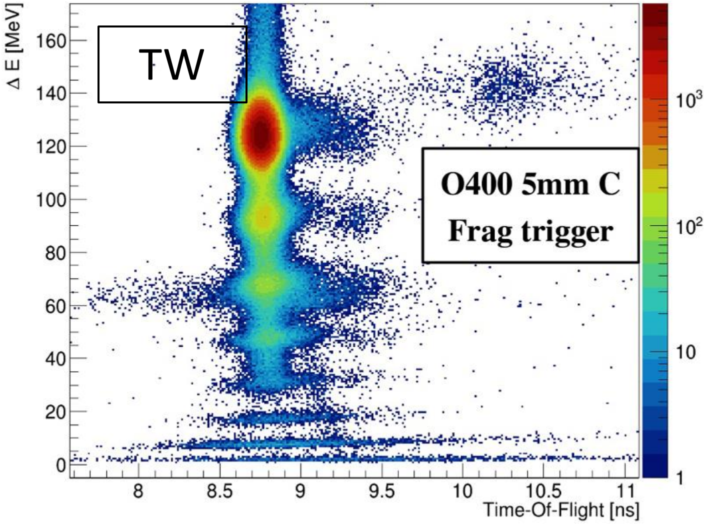
# Detectors performances




**What performances do we achieve?**

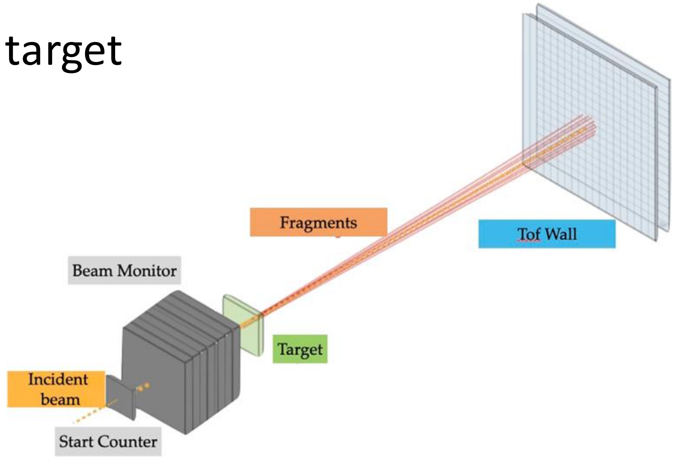
$\frac{\sigma(E_{kin})}{E_{kin}} < 3\%$ $\quad \frac{\sigma(p)}{p} < 5\%$

$\frac{\sigma(\Delta E)}{E} \sim 4 - 5\%$ $\quad \sigma_{ToF} < 70\ ps$

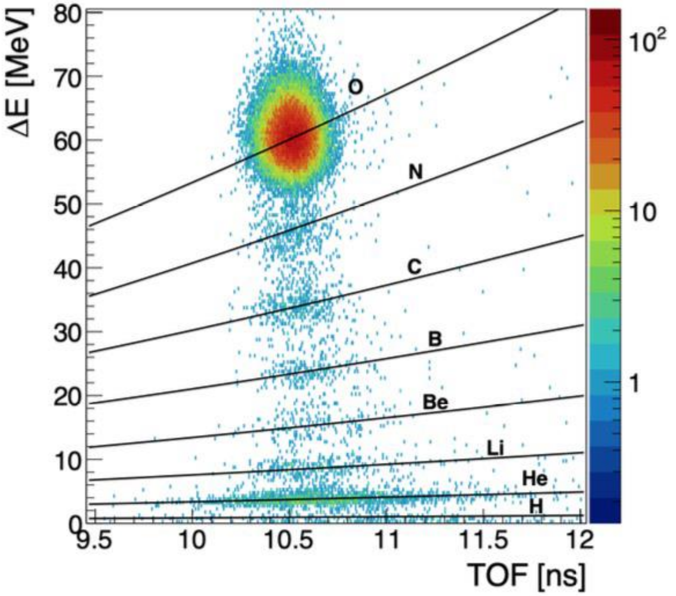
Courtesy of Marco Toppi

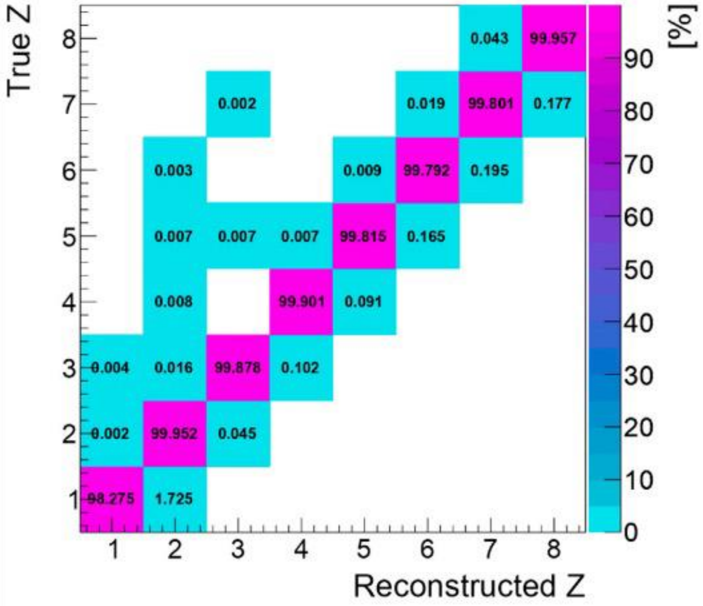
# First measured cross-sections

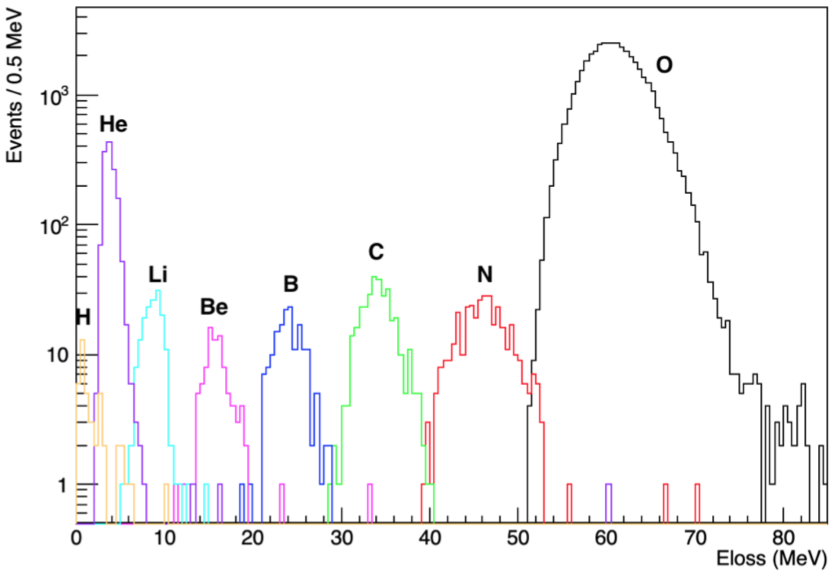
- First published charge-changing cross sections ($\sigma_Z$): $^{16}$O @ 400 MeV/u on 5 mm $^{12}$C target
  - Simplified setup (no magnetic spectrometer)
  - Experiment carried out @ GSI




ΔE-ToF map ⇒ Z identification thanks to Bethe Bloch
Purity calculated by MC



# First measured cross-sections

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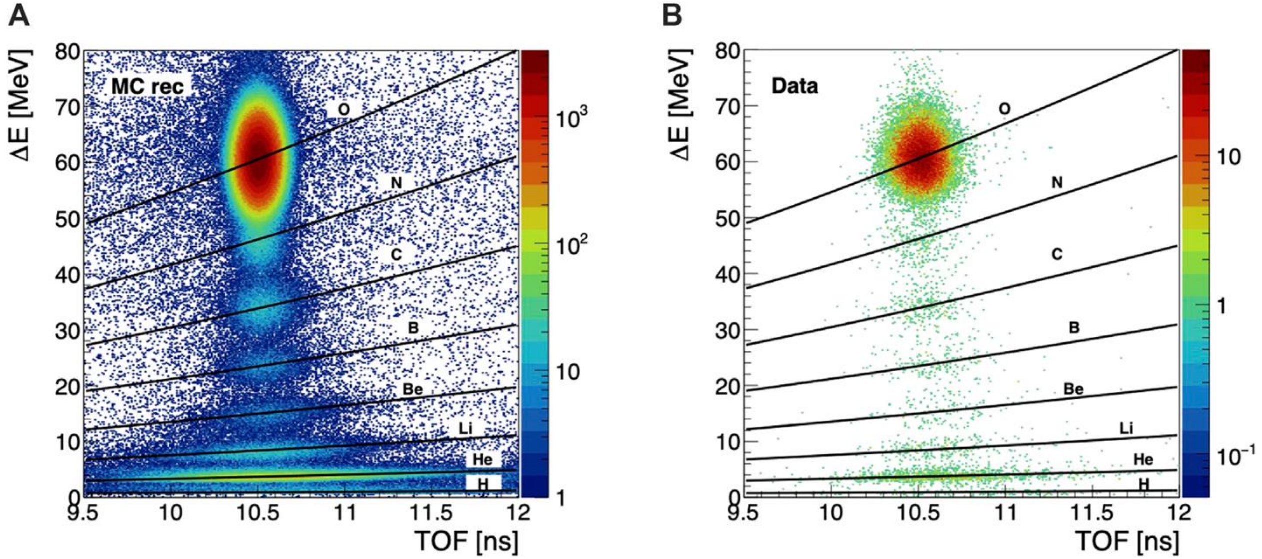
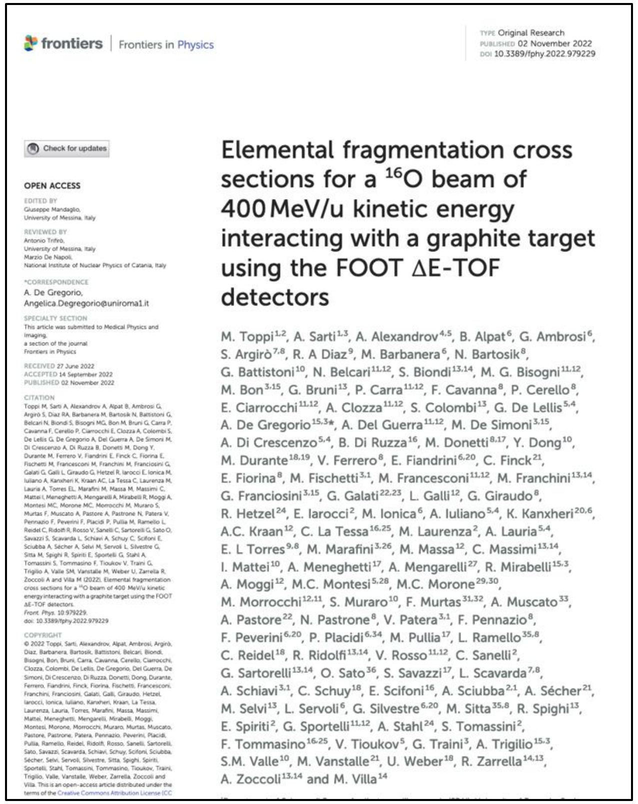
$$\sigma(Z) = \int_{E_{max}}^{E_{max}} \int_0^{\Delta\theta} \left(\frac{\partial^2\sigma}{\partial\theta\partial E_{kin}}\right) d\theta dE_{kin} = \frac{N_{frag}(Z)}{N_{prim} \cdot N_{TG} \cdot \varepsilon(Z)}$$

where

$$N_{TG} = \frac{\rho \cdot dx \cdot \mathcal{N}_A}{A}$$

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TYPE Original Research
PUBLISHED 02 November 2022
DOI 10.3389/fphy.2022.979229

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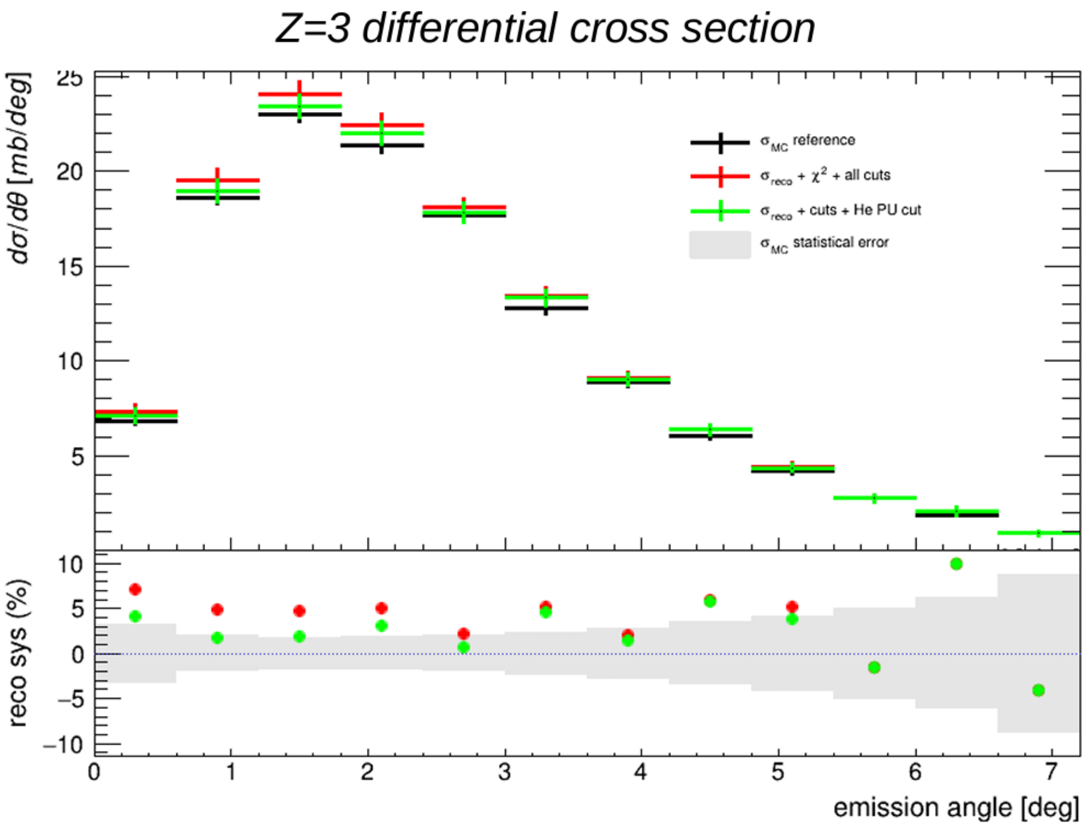
Elemental fragmentation cross sections for a $^{16}O$ beam of 400 MeV/u kinetic energy interacting with a graphite target using the FOOT ΔE-TOF detectors

M. Toppi[1,2], A. Sarti[1,3], A. Alexandrov[4,5], B. Alpat[6], G. Ambrosi[6], S. Argirò[7,8], R. A Diaz[9], M. Barbanera[6], N. Bartosik[8], G. Battistoni[10], N. Belcari[11,12], S. Biondi[13,14], M. G. Bisogni[11,12], M. Bon[3,15], G. Bruni[13], P. Carra[11,12], F. Cavanna[8], P. Cerello[8], E. Ciarrocchi[11,12], A. Clozza[11,12], S. Colombi[13], G. De Lellis[5,4], A. De Gregorio[15,3*], A. Del Guerra[11,12], M. De Simoni[3,15], A. Di Crescenzo[5,4], B. Di Ruzza[16], M. Donetti[8,17], Y. Dong[10], M. Durante[18,19], V. Ferrero[8], E. Fiandrini[6,20], C. Finck[21], E. Fiorina[8], M. Fischetti[3,1], M. Francesconi[11,12], M. Franchini[13,14], G. Franciosini[3,15], G. Galati[22,23], L. Galli[12], G. Giraudo[8], R. Hetzel[24], E. Iarocci[2], M. Ionica[6], A. Iuliano[5,4], K. Kanxheri[20,6], A.C. Kraan[12], C. La Tessa[16,25], M. Laurenza[2], A. Lauria[5,4], E. L Torres[9,8], M. Marafini[3,26], M. Massa[12], C. Massimi[13,14], I. Mattei[10], A. Meneghetti[17], A. Mengarelli[27], R. Mirabelli[15,3], A. Moggi[12], M.C. Montesi[5,28], M.C. Morone[29,30], M. Morrocchi[12,11], S. Muraro[10], F. Murtas[31,32], A. Muscato[33], A. Pastore[22], N. Pastrone[8], V. Patera[3,1], F. Pennazio[8], F. Peverini[6,20], P. Placidi[6,34], M. Pullia[17], L. Ramello[35,8], C. Reidel[18], R. Ridolfi[13,14], V. Rosso[11,12], C. Sanelli[2], G. Sartorelli[13,14], O. Sato[36], S. Savazzi[17], L. Scavarda[7,8], A. Schiavi[3,1], C. Schuy[18], E. Scifoni[16], A. Sciubba[2,1], A. Sécher[21], M. Selvi[13], L. Servoli[6], G. Silvestre[6,20], M. Sitta[35,8], R. Spighi[13], E. Spiriti[2], G. Sportelli[11,12], A. Stahl[24], S. Tomassini[2], F. Tommasino[16,25], V. Tioukov[5], G. Traini[3], A. Trigilio[15,3], S.M. Valle[10], M. Vanstalle[21], U. Weber[18], R. Zarrella[14,13], A. Zoccoli[13,14] and M. Villa[14]

| Element | $\sigma_{frag} \pm \Delta_{stat} \pm \Delta_{sys}$ [mbarn] | $\Delta_{stat}/\sigma_{frag}$ | $\Delta_{sys}/\sigma_{frag}$ | $\sigma_{MC}$ [mbarn] |
|---|---|---|---|---|
| He | $789 \pm 35 \pm 67$ | 4.4 % | 8.5 % | $705 \pm 2$ |
| Li | $101 \pm 13 \pm 10$ | 12.5 % | 10.4 % | $74.9 \pm 0.6$ |
| Be | $33 \pm 9 \pm 3$ | 26 % | 10.3 % | $37.5 \pm 0.4$ |
| B | $78 \pm 11 \pm 6$ | 14 % | 8.5 % | $41.8 \pm 0.4$ |
| C | $131 \pm 14 \pm 4$ | 11 % | 2.8 % | $87.7 \pm 0.6$ |
| N | $117 \pm 14 \pm 6$ | 12 % | 4.8 % | $110.3 \pm 0.7$ |

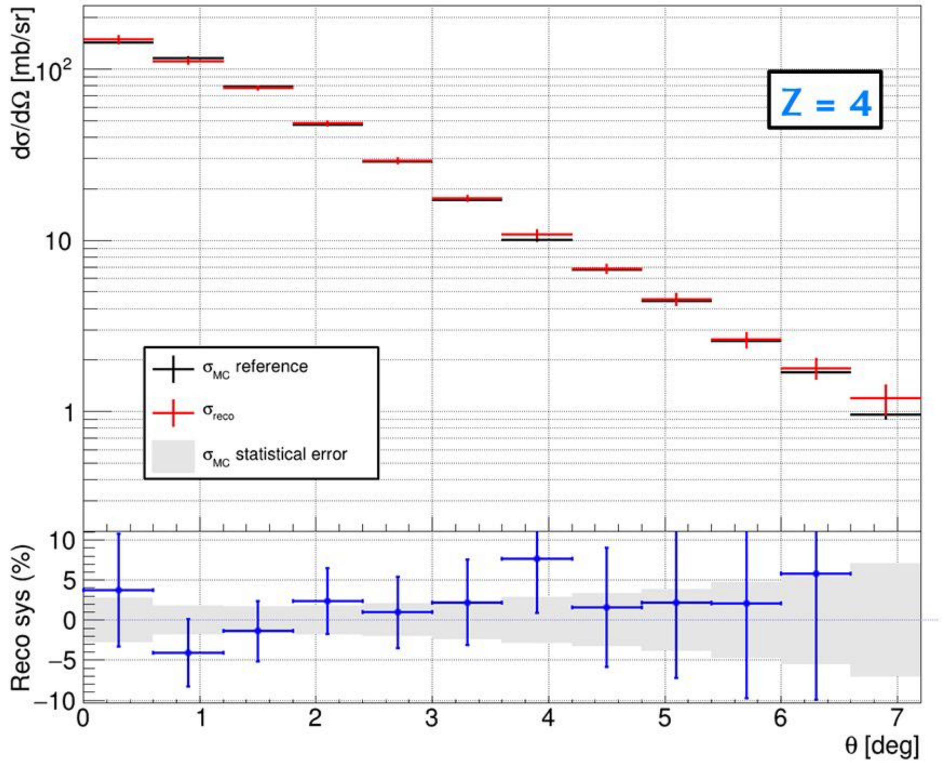
# **Preliminary** differential cross-sections

$^{16}O$ (400 MeV/u)+ $^{12}C \rightarrow {}^{7}Li$ + X (GSI – 2021)
Work from Giacomo Ubaldi




NB: MC performed with FLUKA

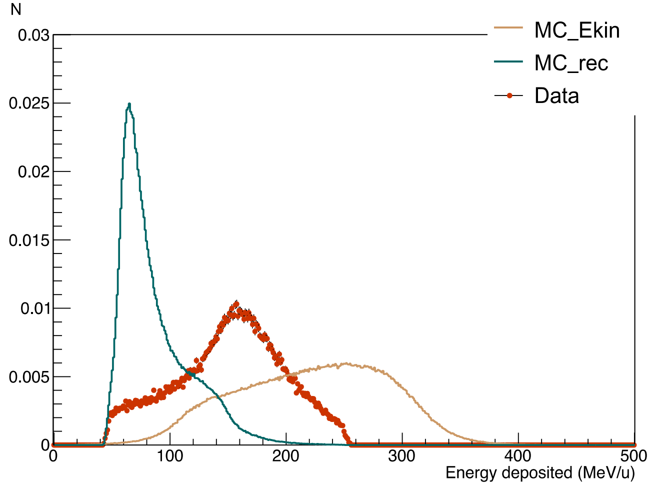
$^{12}C$ (200 MeV/u) + $^{12}C \rightarrow {}^{7}Be$ + X (CNAO – 2023)
Work from Roberto Zarrella



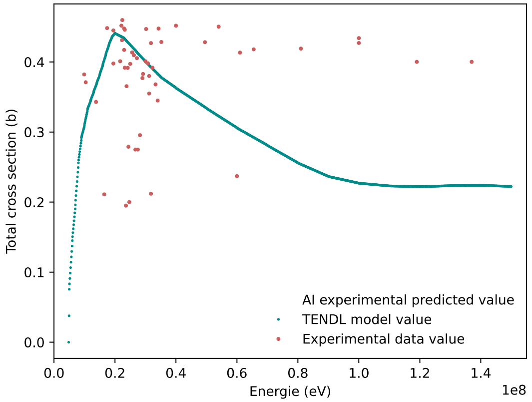
# Conclusions & prospects

- Prospects of FOOT experiment
  - Double differential cross-section analysis of CNAO experiment performed in 2023 still on-going
  - New experimental campaign will start in November 2024 @ CNAO
  - Long-term: upgrade of detectors, measurements at higher energies for space and with new ions ($^{4}$He, $^{56}$Fe)
  - Comparison with additional hadronic models from simulation (INCL, BIC, QMD…)

- Other experiments on-going
  - CLINM: measuring secondary particles yields coupled with radiolysis of molecules after thick target for space
  - Different studies on-going @ GSI
  - Secondary neutrons
  - … and many other…




CLINM project - $^{12}$C (400 MeV/u)+ RW3 (tissue-equivalent) → $^{4}$He + X (CNAO – 2023)
Work from Levana Gesson (Strasbourg university)




About deep learning => DINo (Deep learning Intelligence for Nuclear reactiOns) algorithm