Elemental and angular differential fragmentation cross section measurements with the FOOT experiment

400 MeV/nucleon ^{16}O beam on C, C_2H_4 and H targets

Matilde Dondi on behalf of the **FOOT collaboration**

European Nuclear Physics Conference 2025
23 September 2025
Caen, France

Nuclear fragmentation measurements

Hadron therapy

- Cancer treatment with charged particles
- p, ^{12}C or ^{16}O
- Energies from 200 to 400 MeV/nucleon

Space radiation protection

- Space radiation environment:
  ions from H to ^{56}Fe, with focus on $Z \leq 8$
- Energies up to 1000 MeV/nucleon

Space radiation protection

Human missions in deep space:

- Space radiation environment: Galactic Cosmic Rays (**GCR**) and Solar Particle Events (**SPE**)
- **No natural radiation protection** unlike on Earth

Durante, M., & Cucinotta, F. A. (2011). Physical basis of radiation protection in space travel. Reviews of Modern Physics, 83(4), 1245–1281. https://doi.org/10.1103/RevModPhys.83.1245

Space radiation protection

A travel to Mars?

- **1.8 mSv/day** during the **travel** + **0.64 mSv/day** on **Mars**
  On **Earth 2.64 mSv/year**

- Much **higher radiation** on Mars

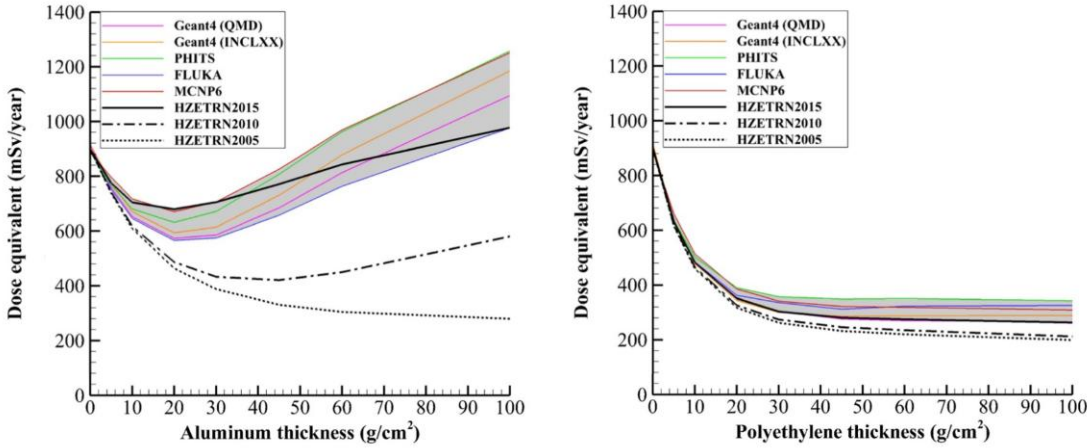
How to reduce exposure?

- **Effective shielding!**

Durante, M. (2014). Space radiation protection: Destination Mars. Life Sciences in Space Research, 1, 2–9. https://doi.org/10.1016/j.lssr.2014.01.002

Space radioprotection

From transport codes:



- **Polyethylene**: a good candidate for shielding
- Significant **differences in dose predictions** between models

Norbury, J. W., et al. (2019). Advances in space radiation physics and transport at NASA. Life Sciences in Space Research, 22, 98–124. https://doi.org/10.1016/j.lssr.2019.07.003

Space radioprotection

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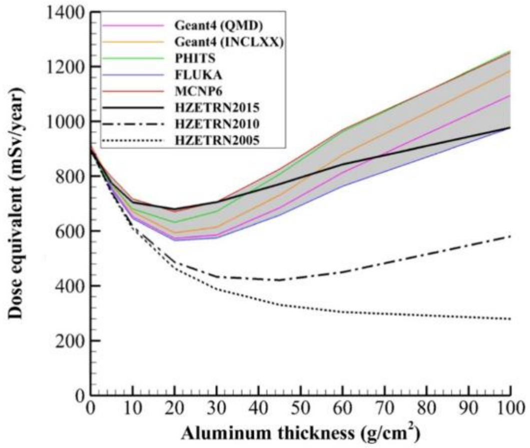
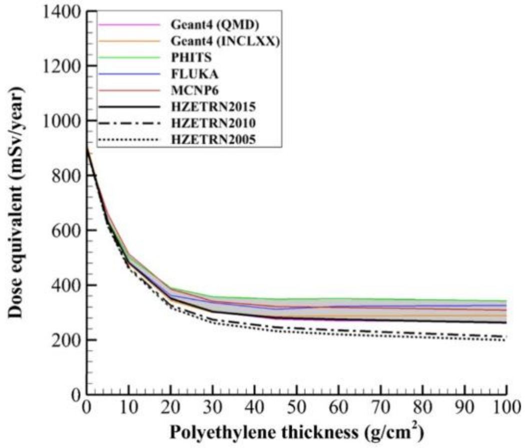




- **Polyethylene**: a good candidate for shielding
- Significant **differences in dose predictions** between models

Limited nuclear data for accurate models required for human missions in deep space

Norbury, J. W., et al. (2019). Advances in space radiation physics and transport at NASA. Life Sciences in Space Research, 22, 98–124. https://doi.org/10.1016/j.lssr.2019.07.003

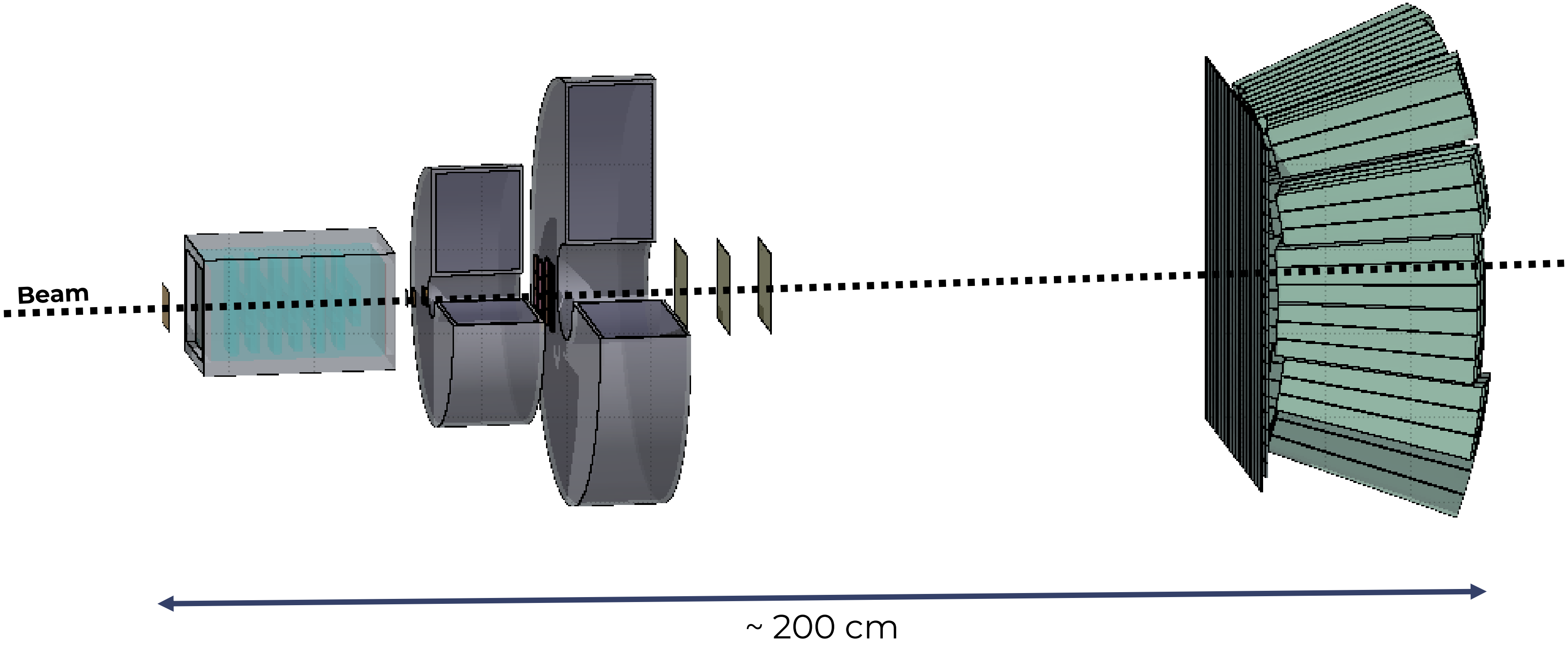
FOOT (FragmentatiOn Of Target) experiment

Double differential nuclear fragmentation cross section measurements:

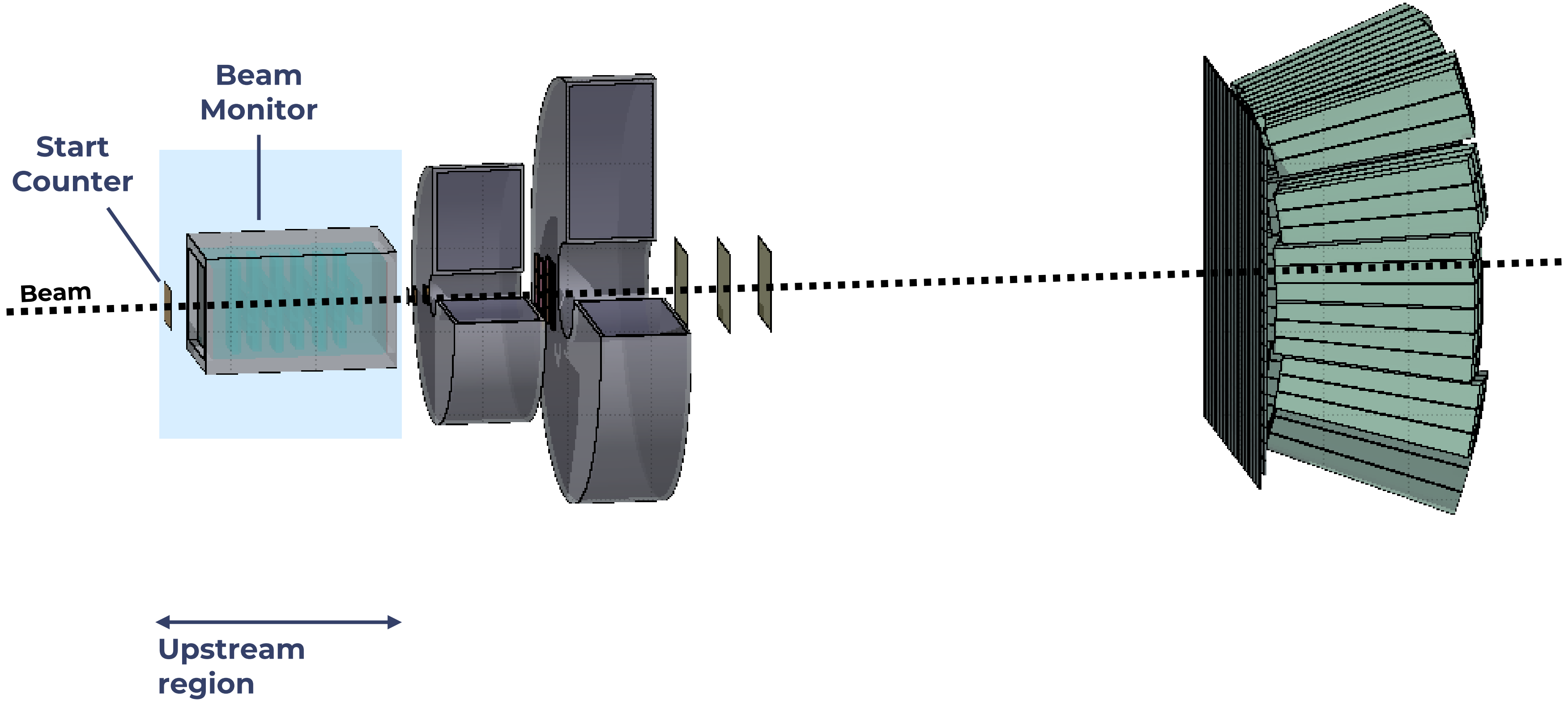
- Studies projectile and target **fragmentation**
- **Fixed target** experiment (C, C_2H_4 and $C_5O_2H_8$ targets)
- **Light ion beams** (like C and O) of E_{kin} **200 - 800 MeV/nucleon**
- Two setups: emulsion setup (low Z fragments) and **electronic setup**

Battistoni, G., et al. (FOOT Collaboration). (2021). Measuring the impact of nuclear interaction in particle therapy and in radio protection in space: The FOOT experiment. Frontiers in Physics, 8, 568242. https://doi.org/10.3389/fphy.2020.568242

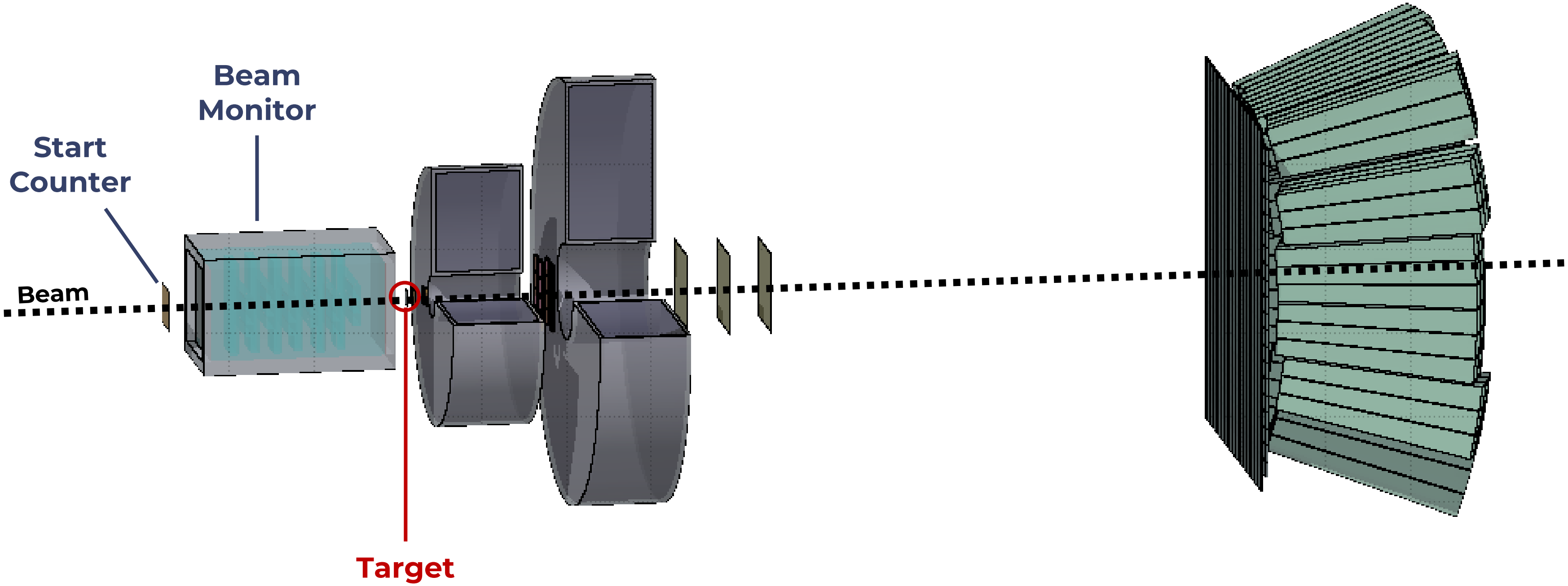
FOOT: electronic setup



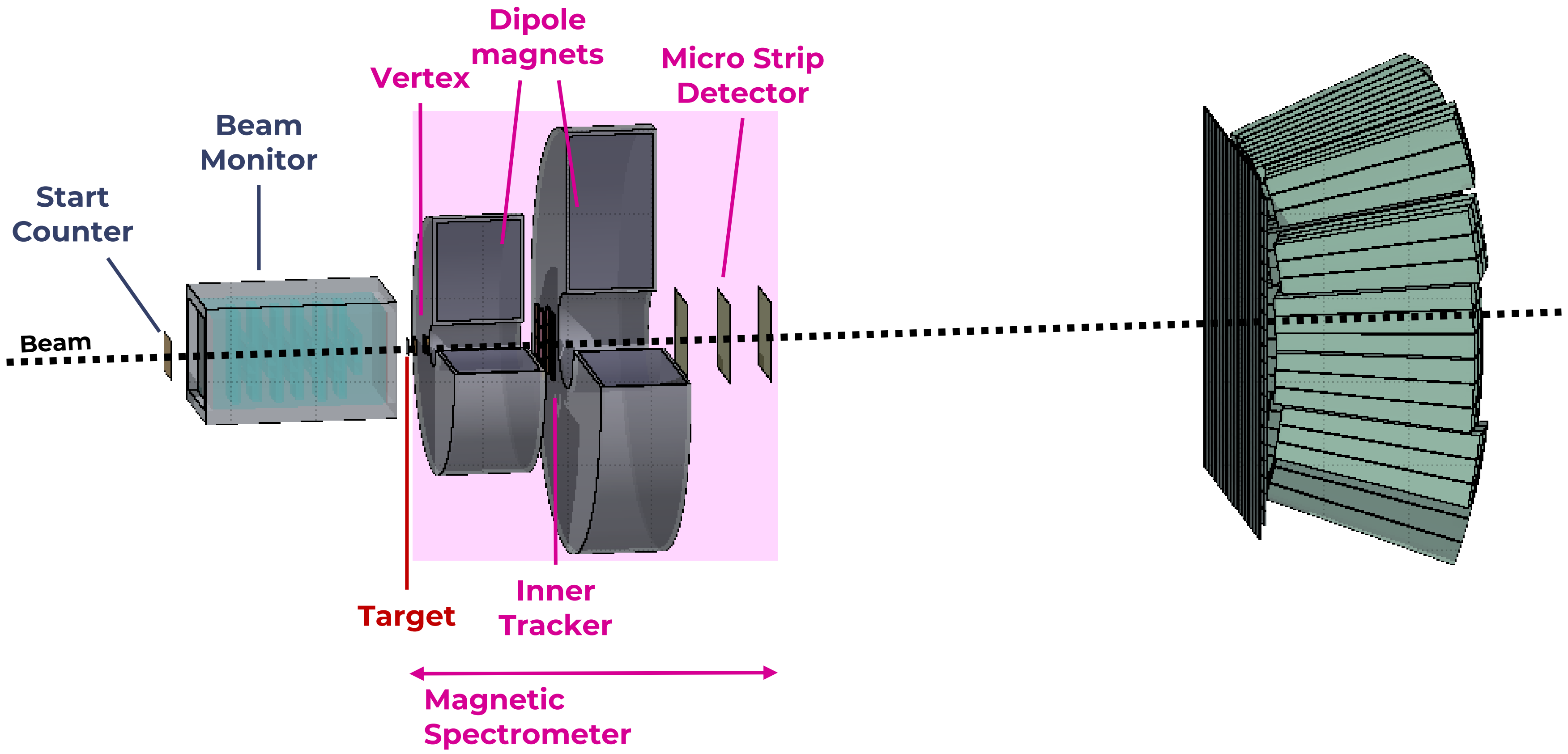
FOOT: electronic setup



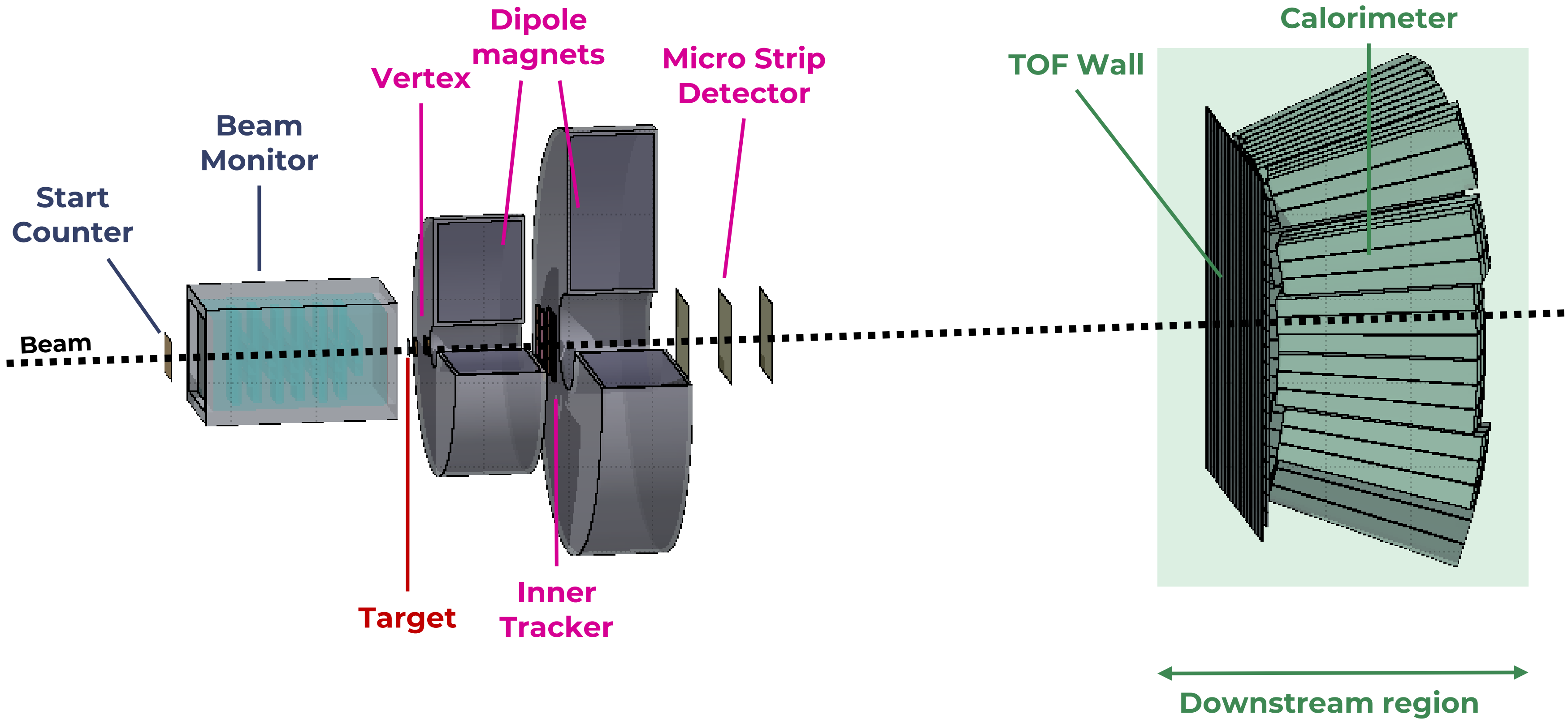
FOOT: electronic setup



FOOT: electronic setup



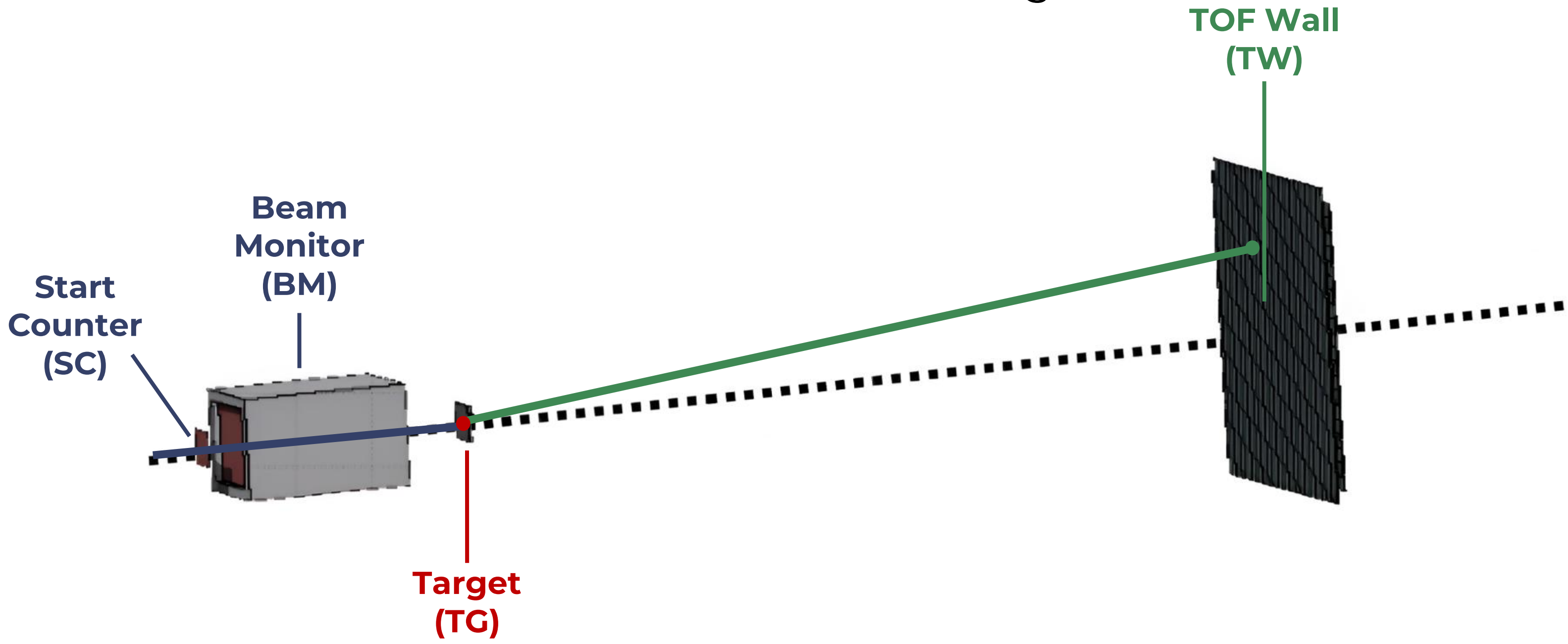
FOOT: electronic setup



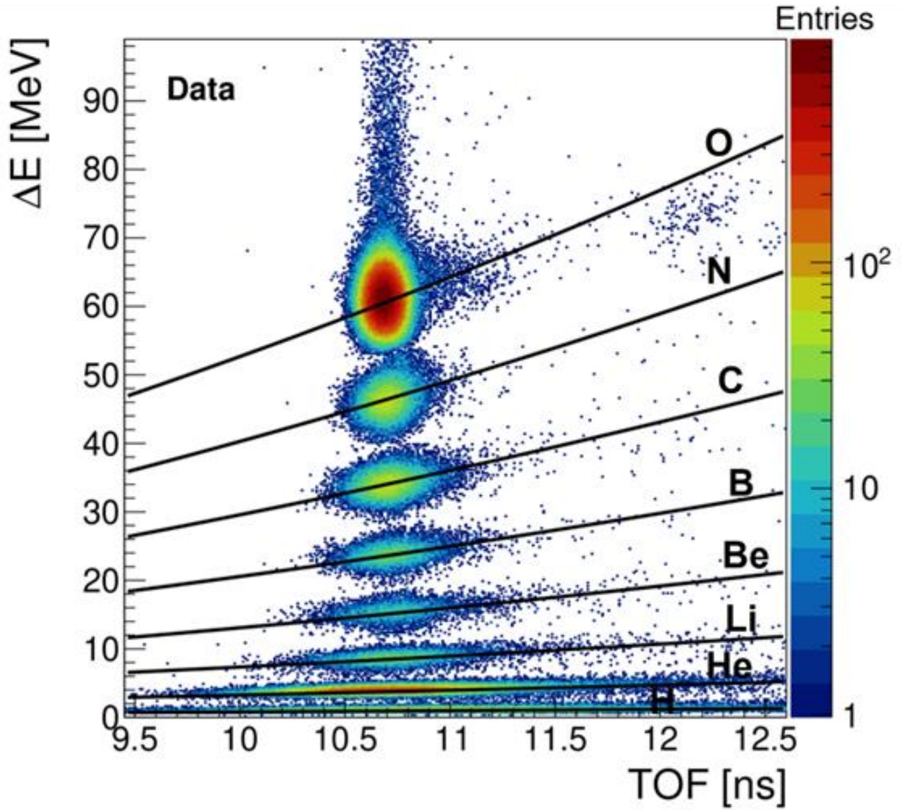
GSI setup

Elemental and **angular differential cross section:**

400 MeV/nucleon ^{16}O beam on **C** and **C_2H_4** targets



GSI data analysis: charge identification



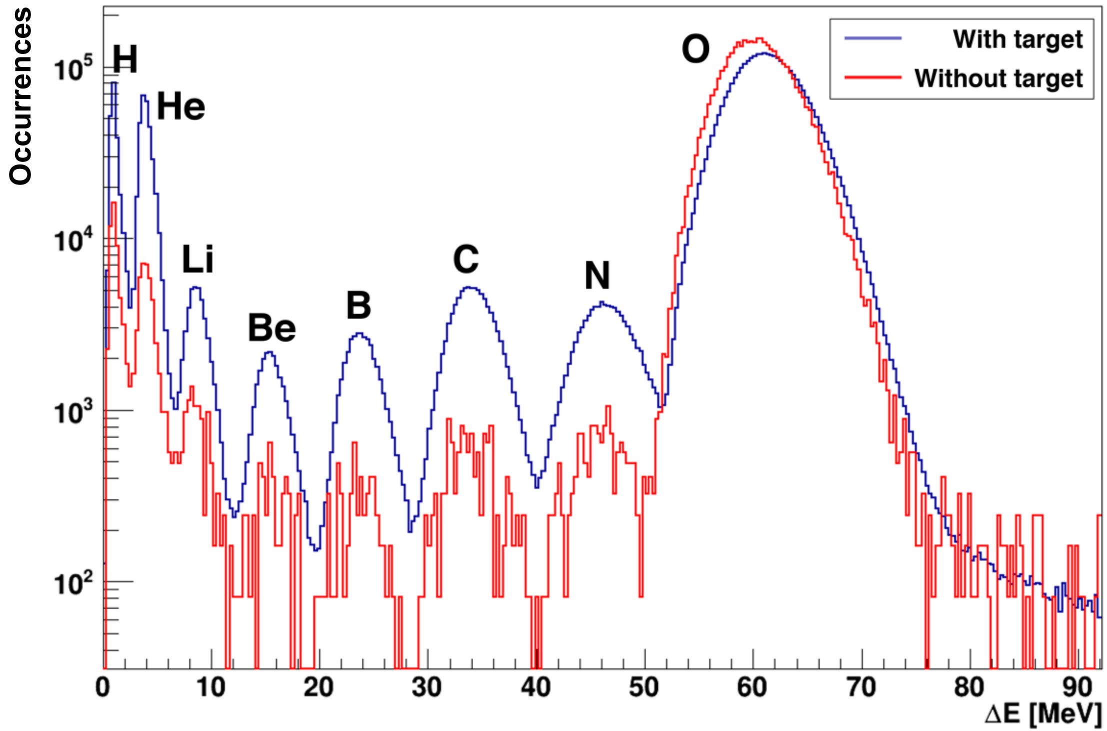
400 MeV/u $^{16}O + C_2H_4$

GSI data analysis: background

Out-of-target fragmentation (in air):

- **Subtraction** of data from a no-target run

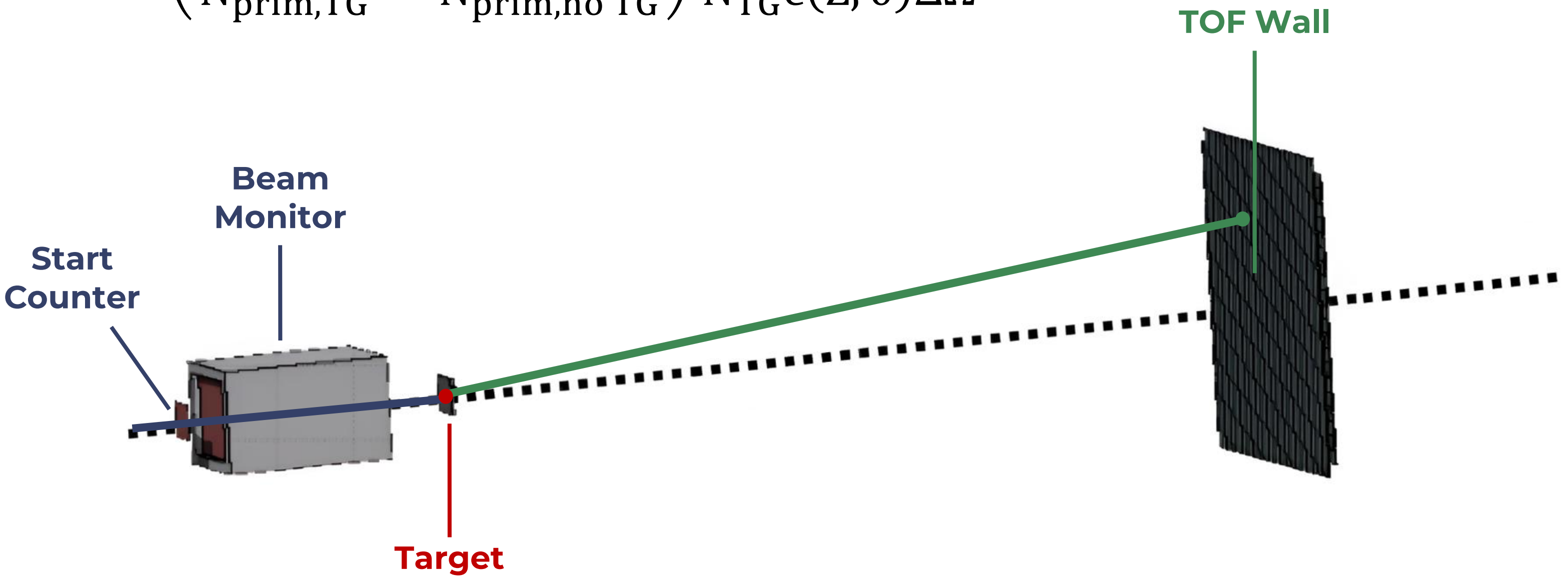
400 MeV/u $^{16}O + C_2H_4$



GSI data analysis: cross section

Angular cross section for different Z

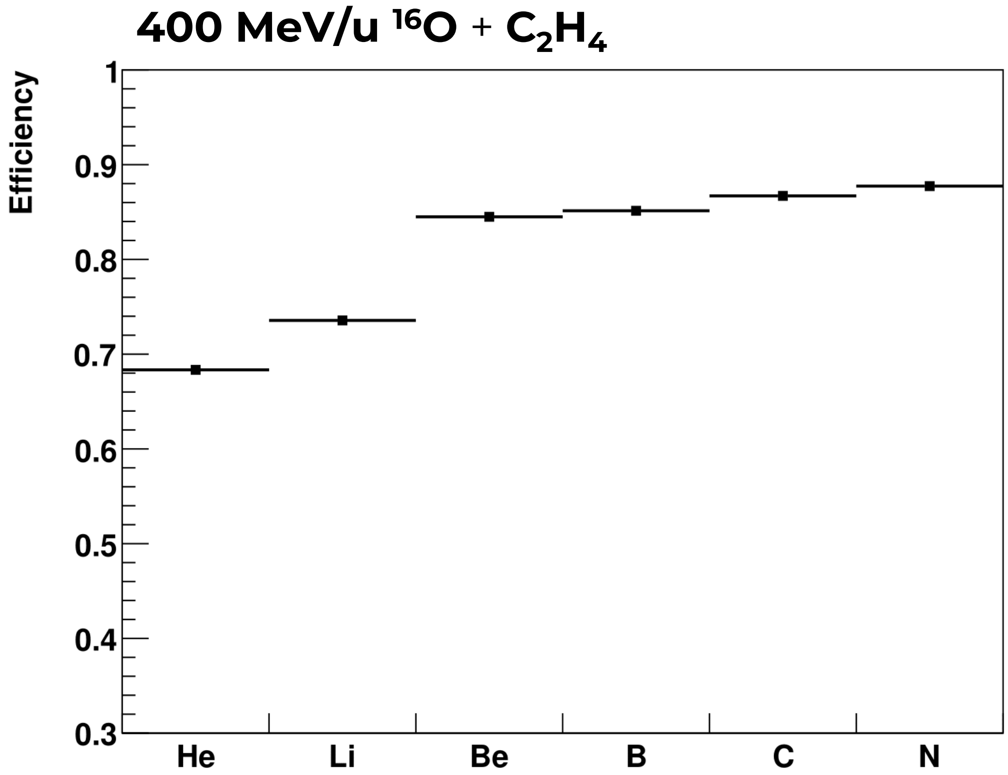
$$\frac{d\sigma}{d\Omega}(Z,\theta) = \left(\frac{Y_{TG}(Z,\theta)}{N_{prim,TG}} - \frac{Y_{no\ TG}(Z,\theta)}{N_{prim,no\ TG}}\right)\frac{1}{N_{TG}\epsilon(Z,\theta)\Delta\Omega}$$



GSI data analysis: MC sample

Monte Carlo simulation with **FLUKA**:

- **Purity** and **efficiency** corrections

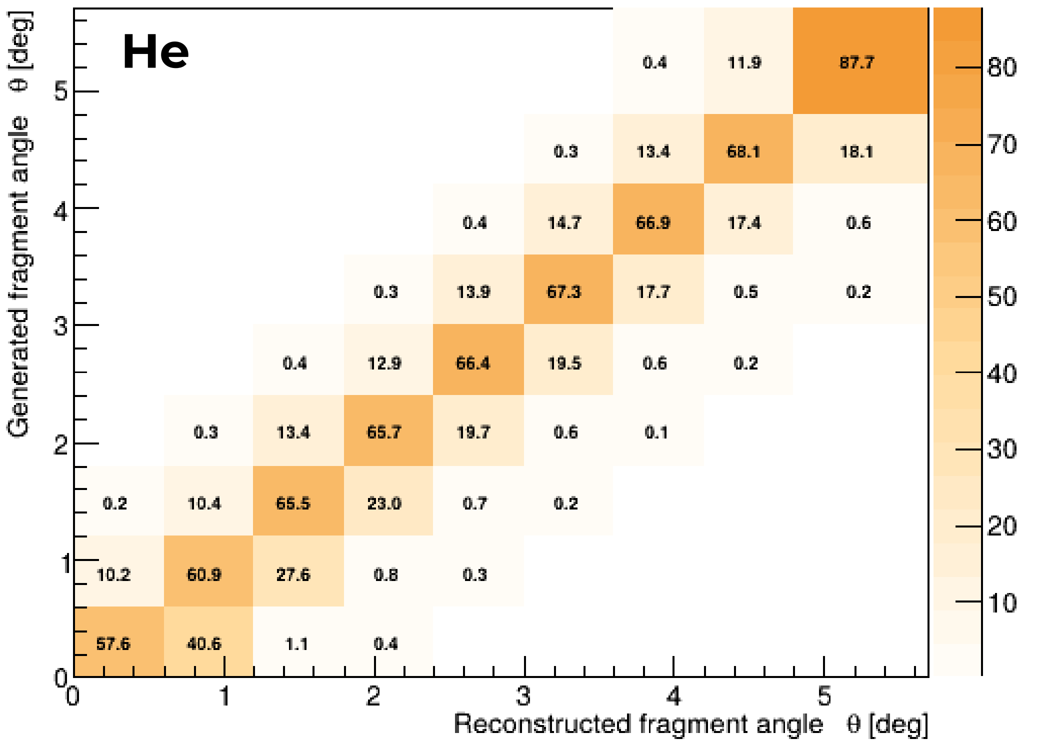


GSI data analysis: MC sample

Monte Carlo simulation with **FLUKA**:

- **Purity** and **efficiency** corrections
- **Angular unfolding** to correct the reconstructed angle

400 MeV/u $^{16}O + C_2H_4$

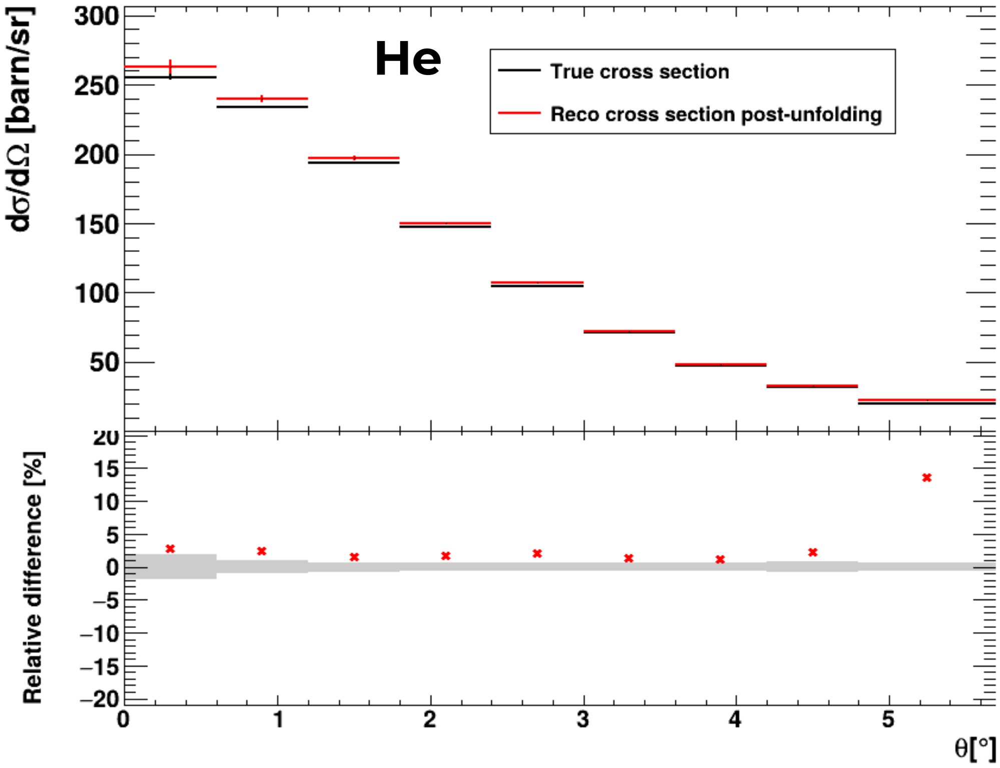


GSI data analysis: MC sample

Monte Carlo simulation with **FLUKA**:

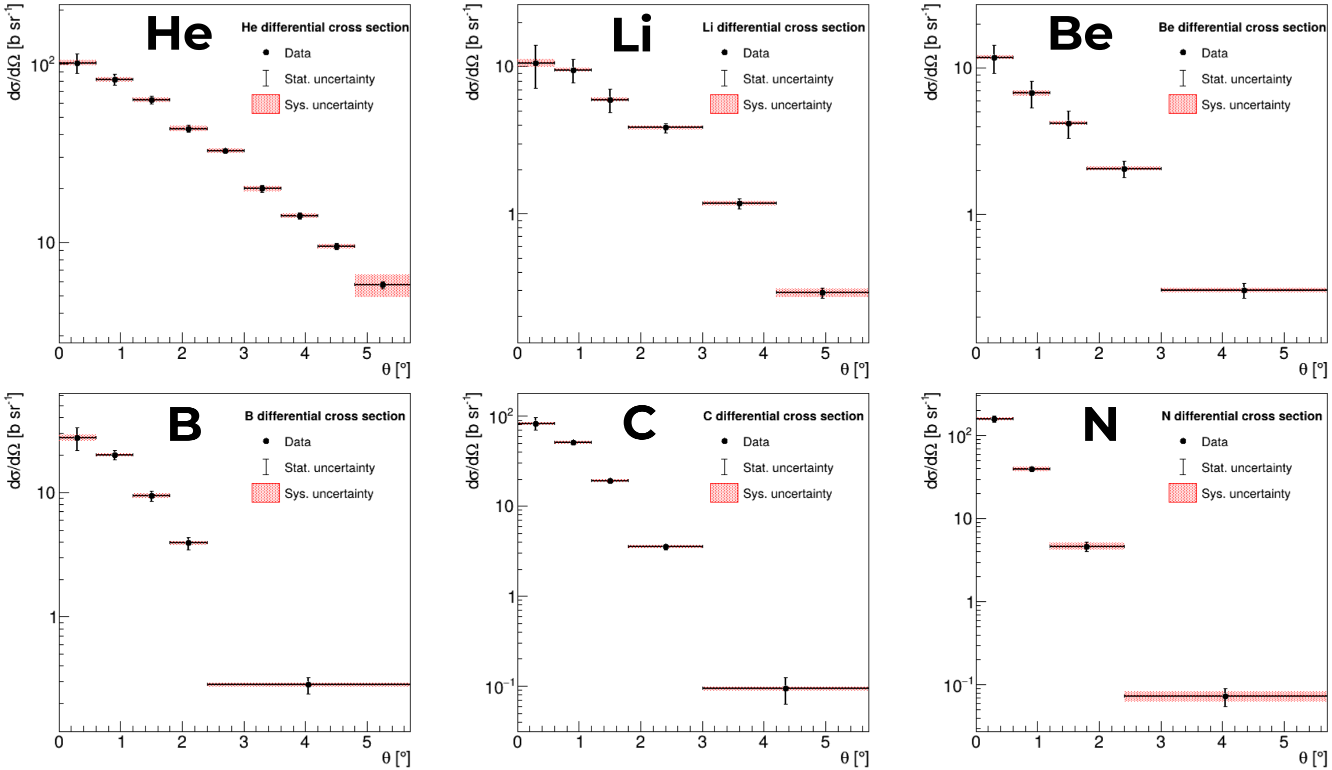
- **Purity** and **efficiency** corrections
- **Angular unfolding** to correct the reconstructed angle
- **Analysis validation: true cross section from MC** vs **reconstructed cross section on MC simulations** using the same analysis as physical data

400 MeV/u $^{16}O + C_2H_4$

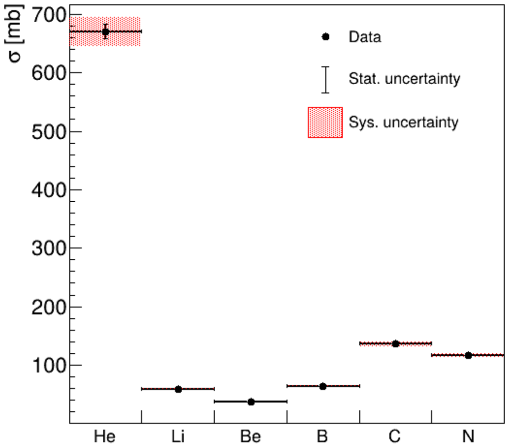


GSI results: 400 MeV/ nucleon ^{16}O + C

Angular cross section



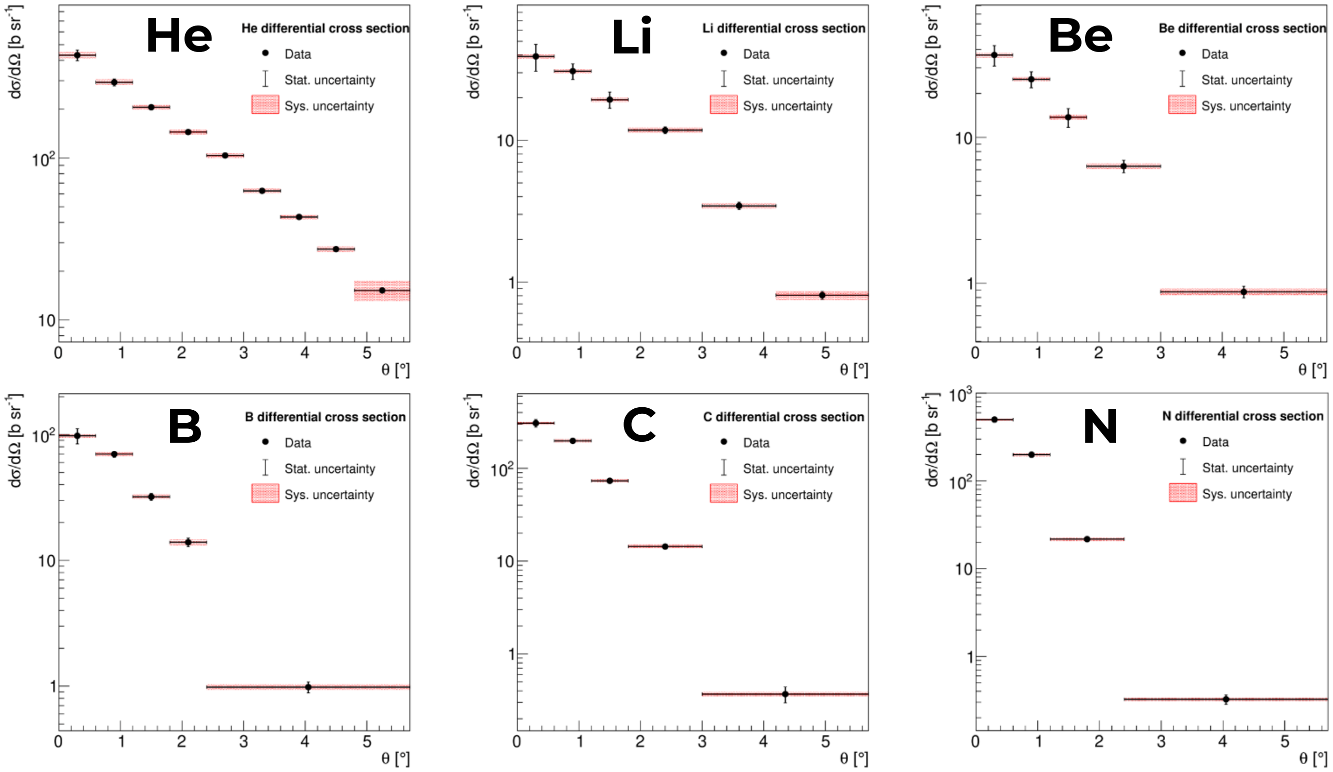
Elemental integral cross section



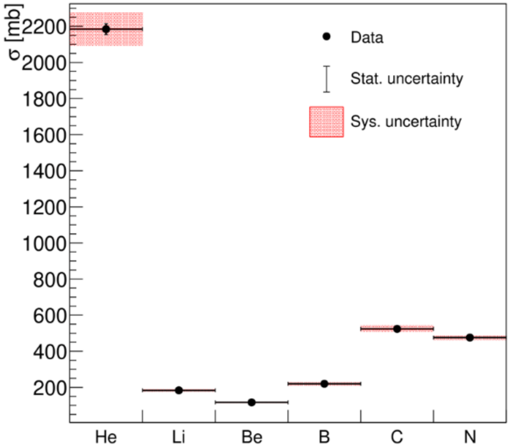
Ridolfi, R., Toppi, M., Mengarelli, A., Dondi, M., et al. (FOOT Collaboration). (2025). Angular differential and elemental fragmentation cross sections of a 400 MeV/nucleon 16O beam on a graphite target with the FOOT experiment. Physical Review C, 112(1), 014610. https://doi.org/10.1103/nmw9-ldrm

GSI results: 400 MeV/ nucleon $^{16}O + C_2H_4$

Angular cross section

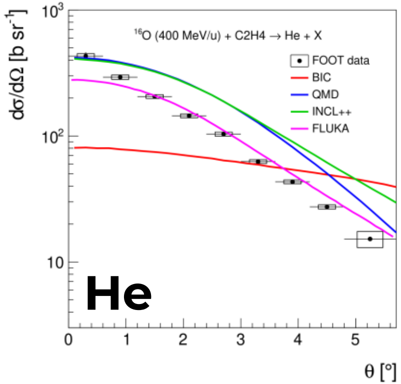


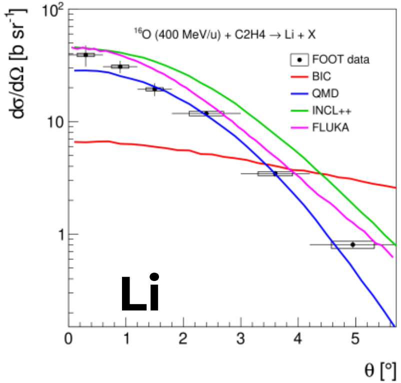
Elemental integral cross section

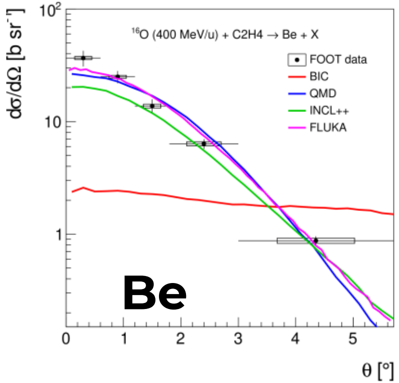


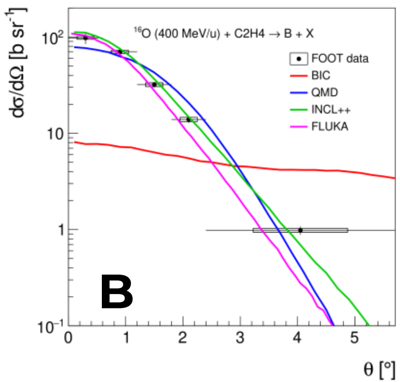
GSI results: comparison with models

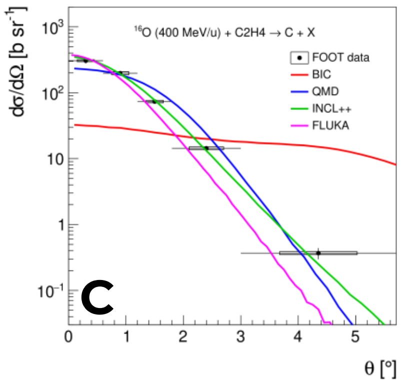
400 MeV/u ^{16}O + C_2H_4 : nuclear fragmentation models

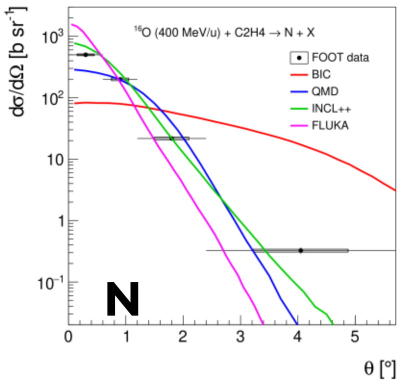












- FLUKA
- Geant4 hadronic models:
  - Quantum Molecular Dynamics (QMD)
  - Liège Intranuclear Cascade (INCL++)
  - Binary Ion Cascade (BIC)

GSI results: H target

$^{16}O + C_2H_4$ and **$^{16}O + C$** with same experimental conditions

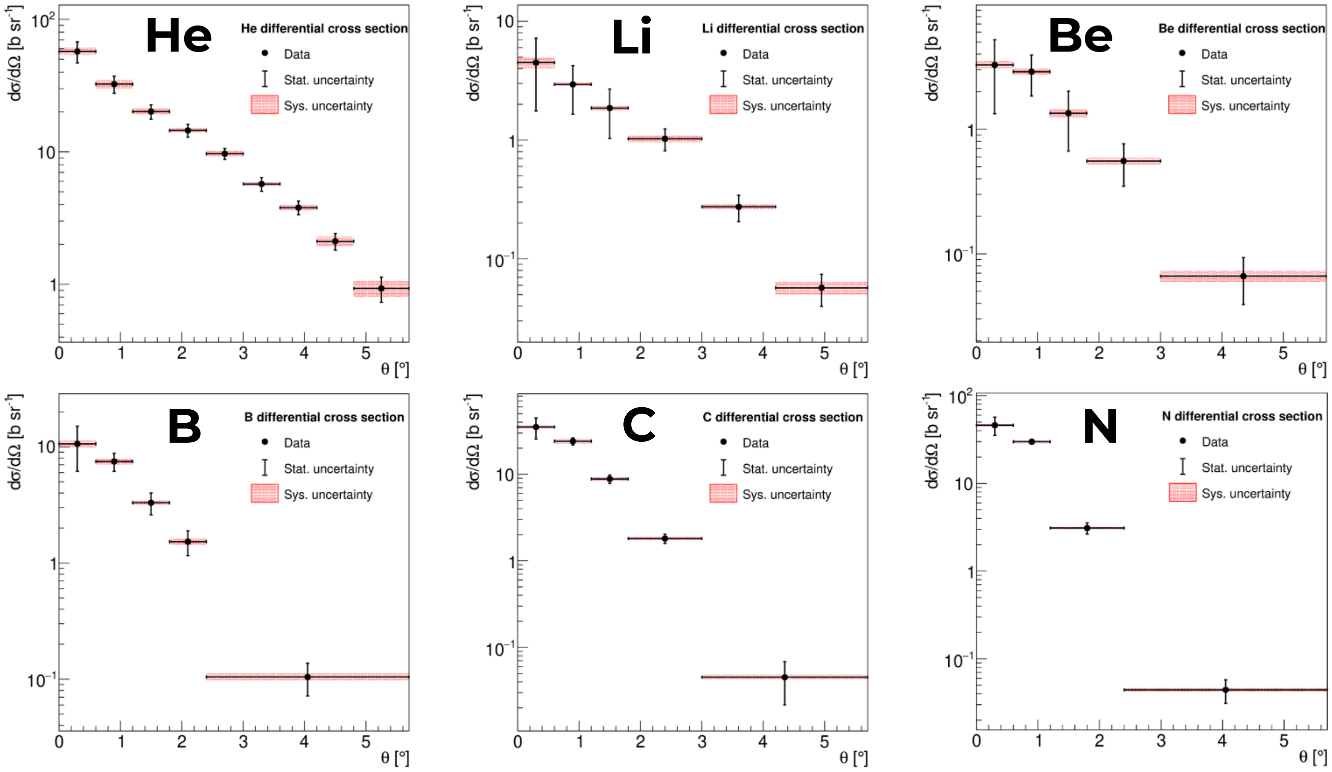
↓

^{16}O + H cross sections obtained via subtraction:

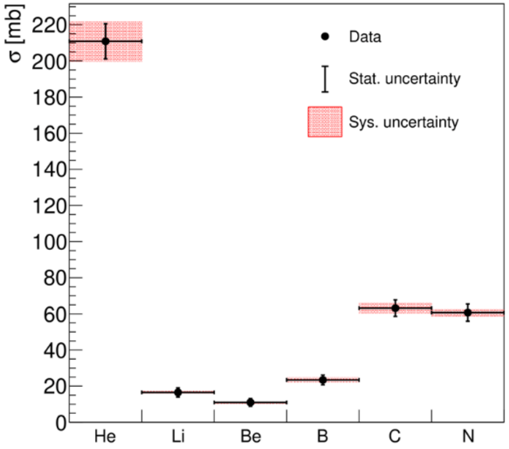
$$\sigma[\mathrm{H}] = \frac{\sigma[\mathrm{C_2H_4}] - 2\sigma[\mathrm{C}]}{4}$$

GSI results: 400 MeV/ nucleon ^{16}O + H

Angular cross section

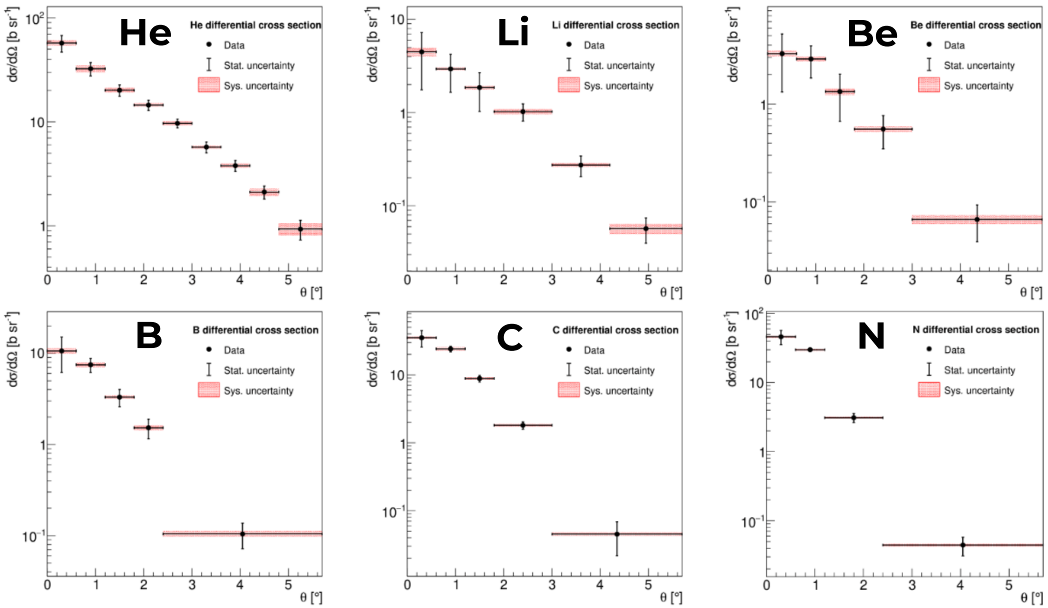


Elemental integral cross section



GSI results: 400 MeV/ nucleon ^{16}O + H

Angular cross section



Elemental integral cross section

Element	This work σ[mb]	Zeitlin et al. σ[mb]
He	$211 \pm 10\,(\text{stat}) \pm 10\,(\text{syst})$	–
Li	$17 \pm 3\,(\text{stat}) \pm 1\,(\text{syst})$	–
Be	$11 \pm 2\,(\text{stat}) \pm 1\,(\text{syst})$	–
B	$23 \pm 3\,(\text{stat}) \pm 1\,(\text{syst})$	25 ± 2
C	$63 \pm 5\,(\text{stat}) \pm 3\,(\text{syst})$	60 ± 4
N	$61 \pm 5\,(\text{stat}) \pm 2\,(\text{syst})$	58 ± 4

Zeitlin, C. et al. Fragmentation of 14N, 16O, 20Ne, and 24Mg nuclei at 290 to 1000 MeV/nucleon. Phys. Rev. C 83, 034909 (2011). https://doi.org/10.1103/PhysRevC.83.034909

Conclusions

- **FOOT experiment: nuclear fragmentation cross section** measurements for hadron therapy and space radioprotection
- **First angular and elemental cross sections** of a **400 MeV/nucleon ^{16}O** beam on **C** and **C_2H_4** targets for the production of **He**, **Li**, **Be**, **B**, **C** and **N fragments**
- **First angular cross sections** of a **400 MeV/nucleon ^{16}O** beam on **H** target from subtraction
- **Elemental cross sections** for **H** target: agreement with the limited data available
- GSI analysis completed and paper under preparation

Thank you for the attention!

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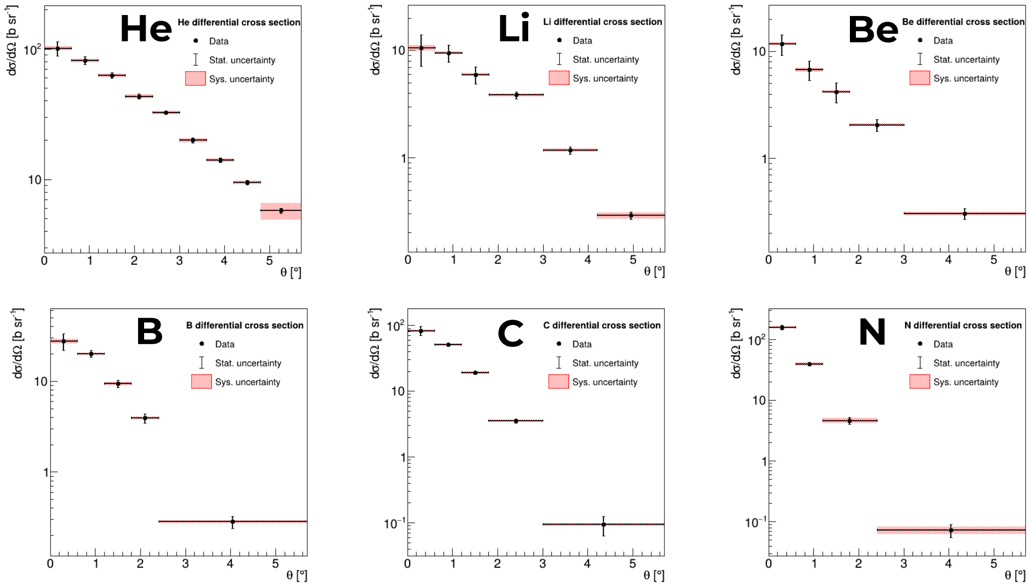
matilde.dondi@unibo.it

Backup slides

GSI results: 400 MeV/ nucleon ^{16}O + C

Angular cross section



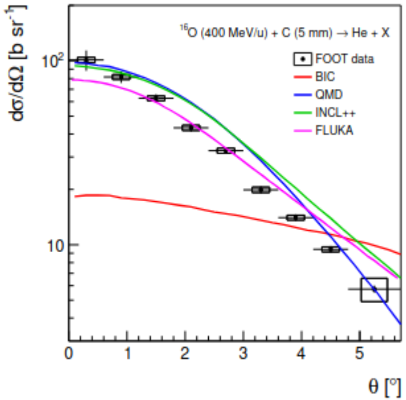
Elemental integral cross section

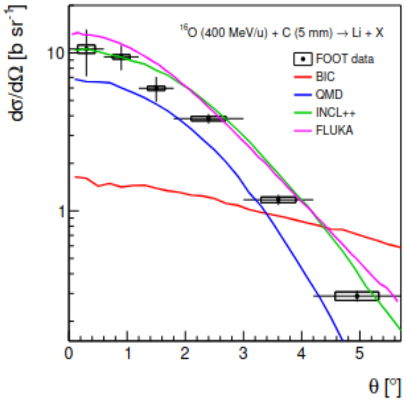
Element	This work σ[mb]	Zeitlin et al. σ[mb]
He	$671 \pm 12\,(\mathrm{stat}) \pm 25\,(\mathrm{syst})$	–
Li	$59 \pm 3\,(\mathrm{stat}) \pm 2\,(\mathrm{syst})$	–
Be	$37 \pm 3\,(\mathrm{stat}) \pm 1\,(\mathrm{syst})$	–
B	$63 \pm 4\,(\mathrm{stat}) \pm 2\,(\mathrm{syst})$	70 ± 3
C	$136 \pm 6\,(\mathrm{stat}) \pm 4\,(\mathrm{syst})$	131 ± 5
N	$117 \pm 6\,(\mathrm{stat}) \pm 4\,(\mathrm{syst})$	124 ± 4

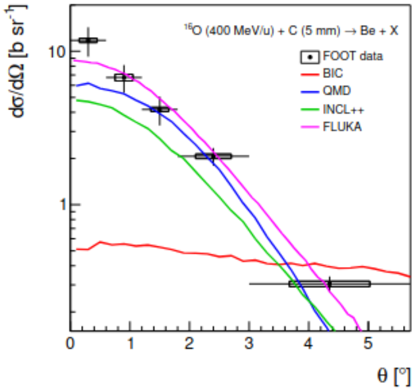
C. Zeitlin et al., “Fragmentation of 14N, 16O, 20Ne, and 24Mg nuclei at 290 to 1000 MeV/nucleon,” Phys. Rev. C 83, 034909 (2011). https://link.aps.org/doi/10.1103/PhysRevC.83.034909

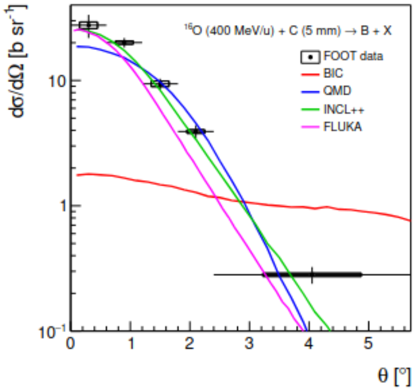
GSI results: comparison with models

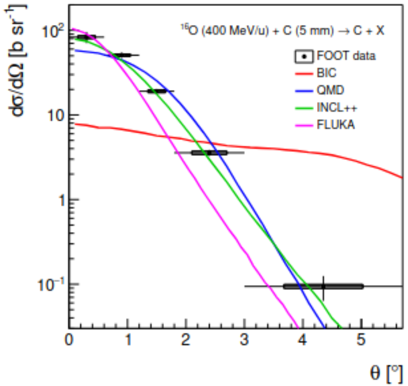
400 MeV/u ^{16}O + C : nuclear fragmentation models

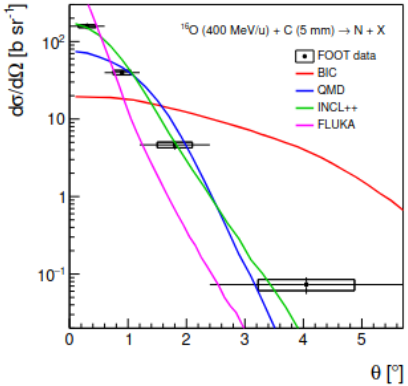












- FLUKA
- Geant4 hadronic models:
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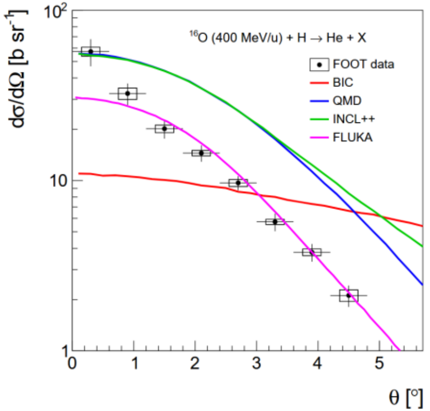
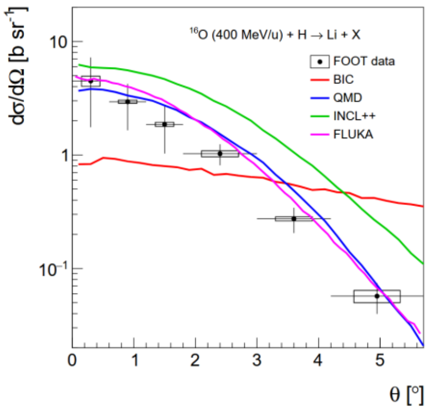
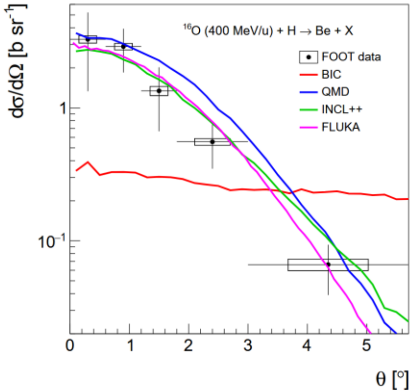
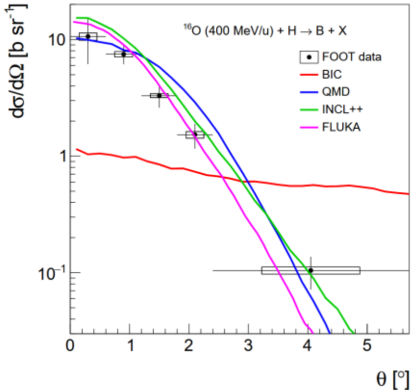
GSI results: comparison with models

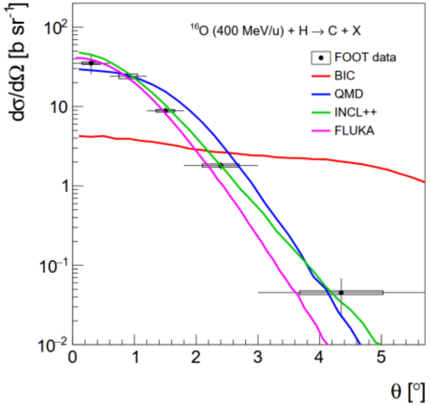
400 MeV/u ^{16}O + H : nuclear fragmentation models

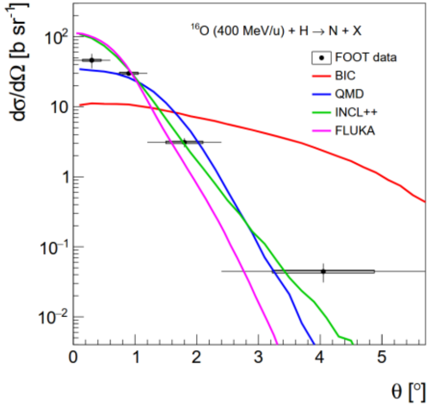












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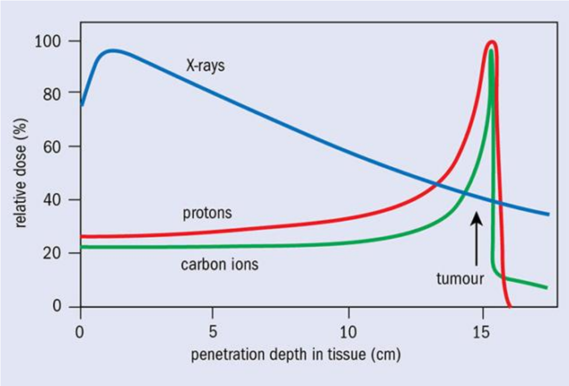
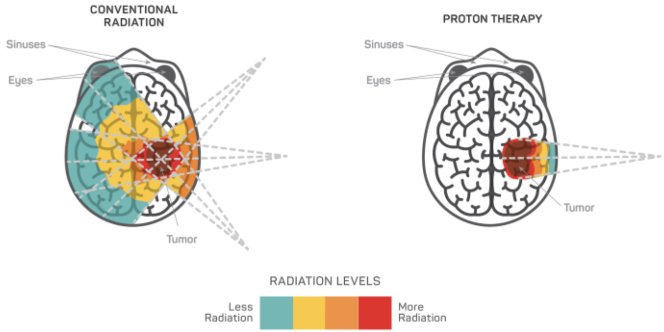
Hadron therapy



- Main dose release in the **Bragg peak**

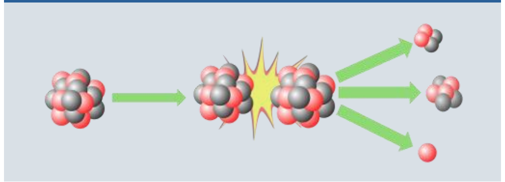


- Less damage to healthy tissues

Durante, M., & Paganetti, H. (2016). Nuclear physics in particle therapy: A review. *Reports on Progress in Physics, 79*(9), 096702. https://doi.org/10.1088/0034-4885/79/9/096702

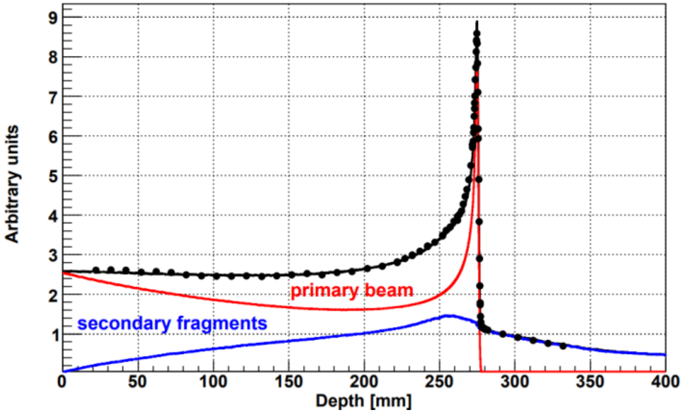
Nuclear fragmentation

Projectile fragmentation

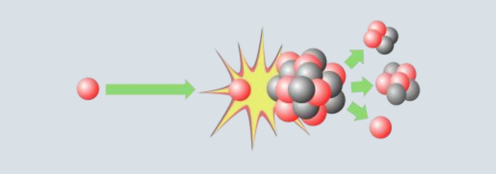


Long range fragments:

- dose release after the Bragg peak



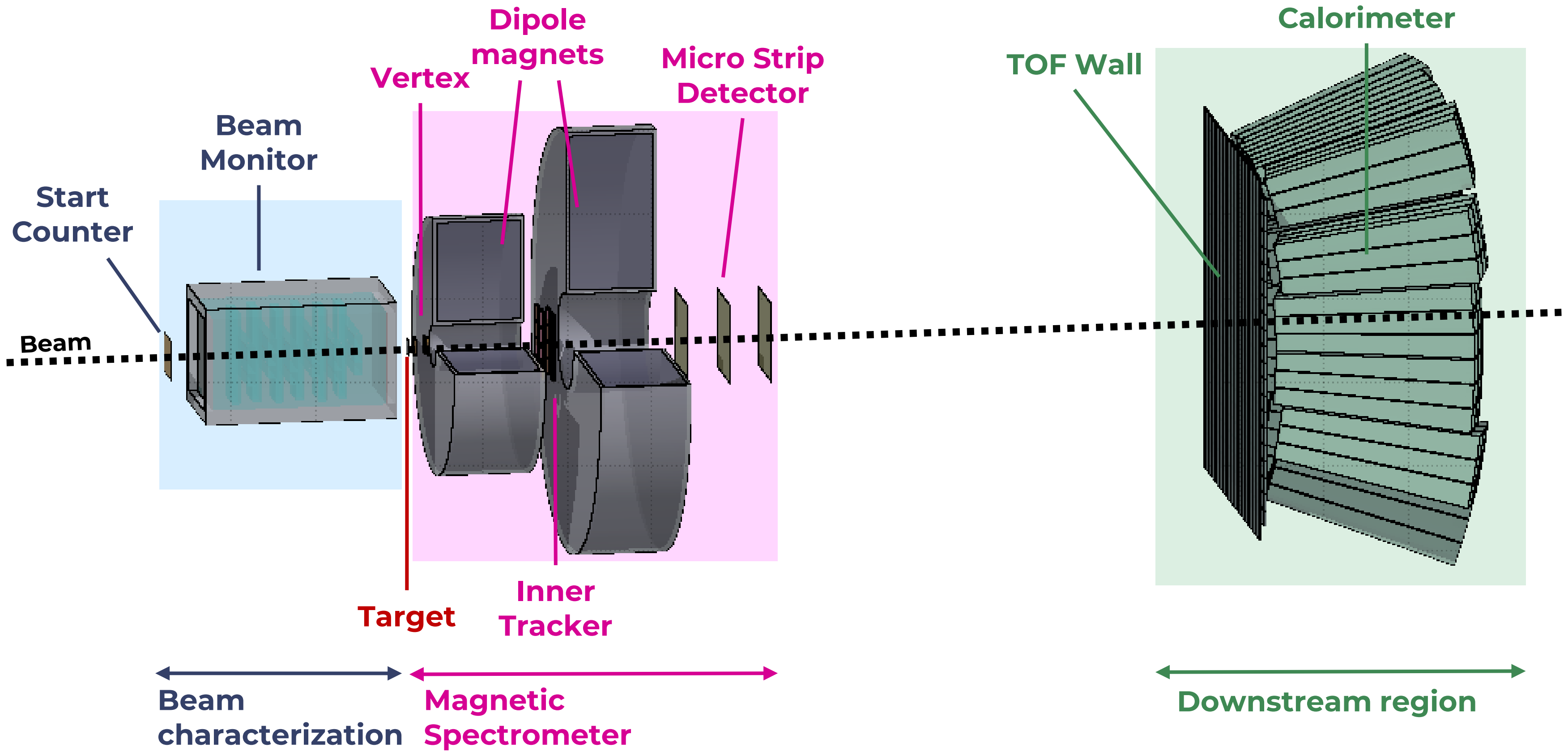
Target fragmentation



Low energy fragments:

- short range
- difficult to detect

FOOT: electronic setup



GSI data analysis: MC sample