SOCIETÀ ITALIANA
DI FISICA

The FOOT experiment:
A first measurement of nuclear fragmentation cross-sections for hadrontherapy

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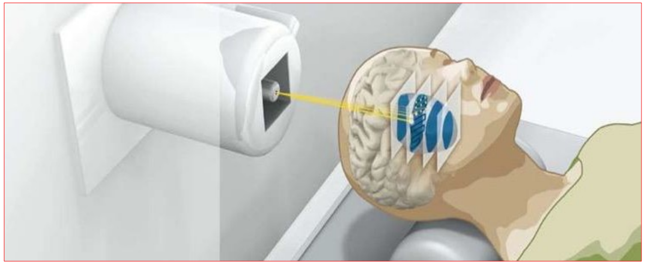
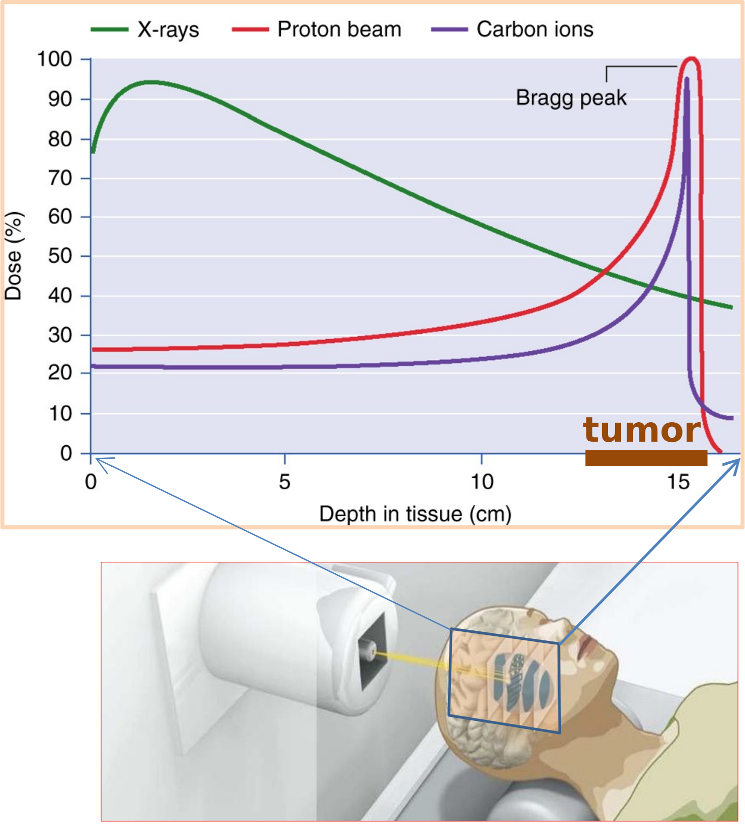
Hadrontherapy



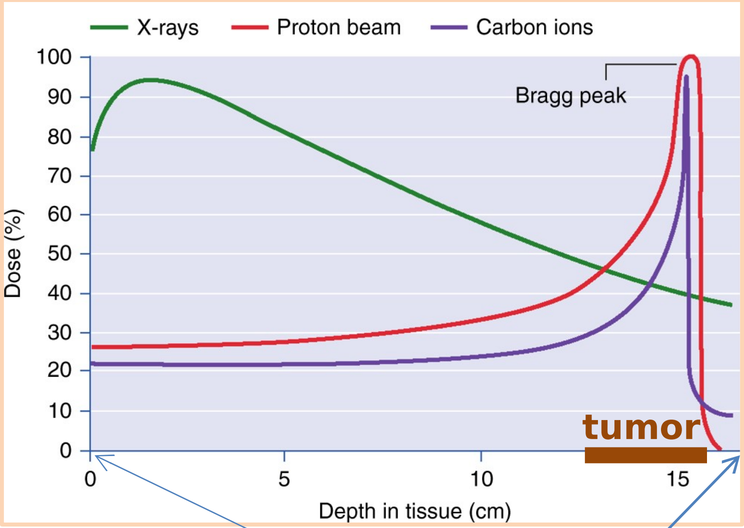
Hadrontherapy

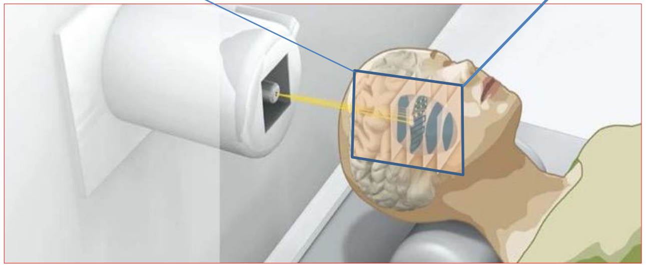


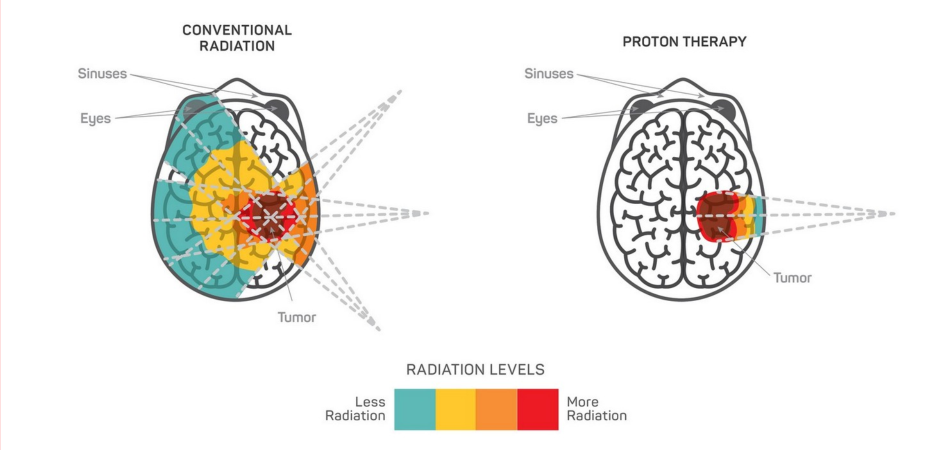
Hadrontherapy vs radiotherapy:

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

Hadrontherapy







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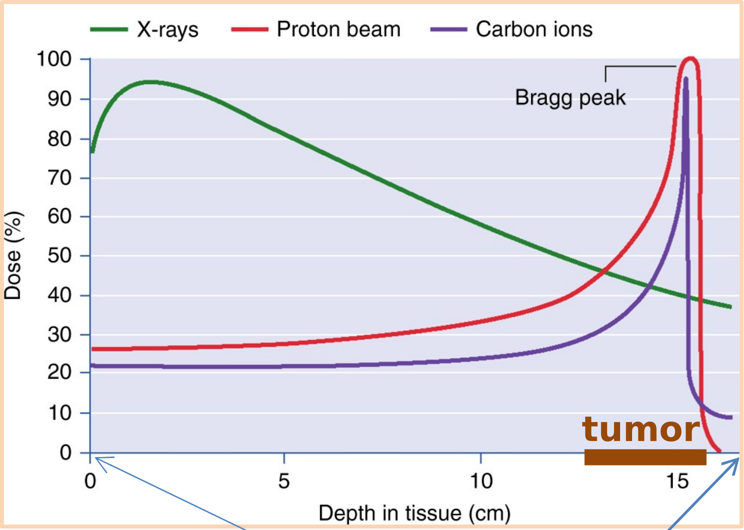
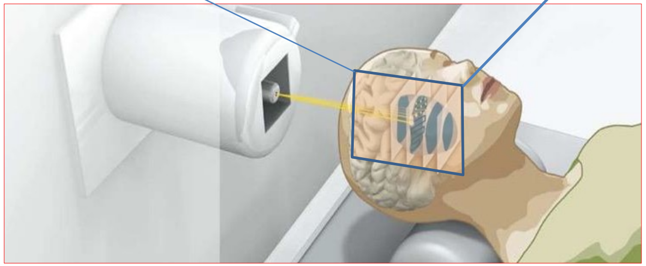
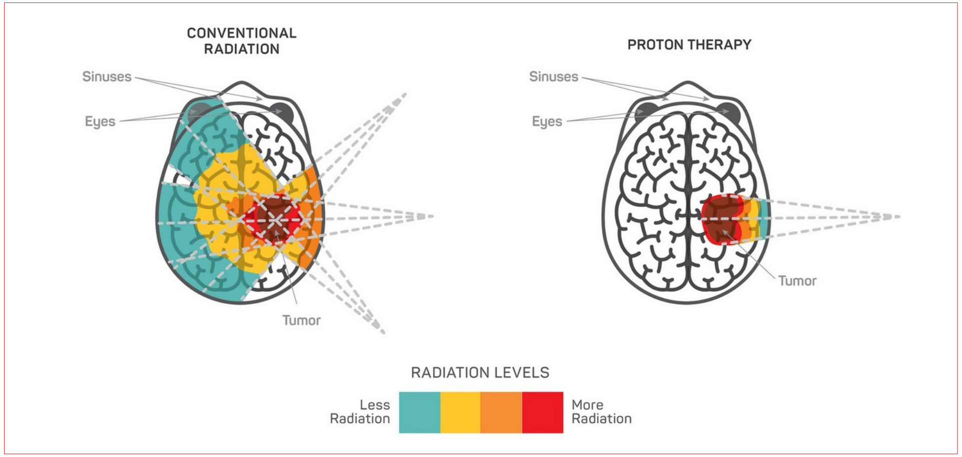
Hadrontherapy







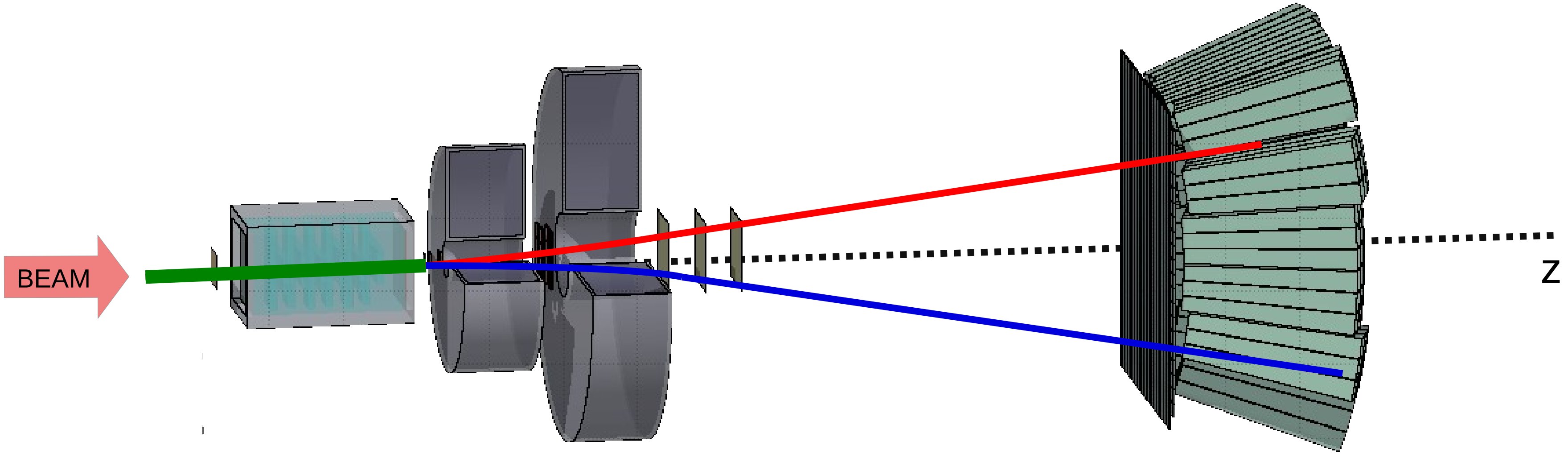
Hadrontherapy vs radiotherapy:

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

The FOOT experiment

Goal:
double differential **nuclear cross section** measurements with uncertainty < 5%

- Fixed target collisions
- Beam energies between 200 MeV/u and 700 MeV/u for **hadrontherapy** and **space radioprotection** topics
- **table top setup** to be moved according to beam facility availability



The FOOT experiment

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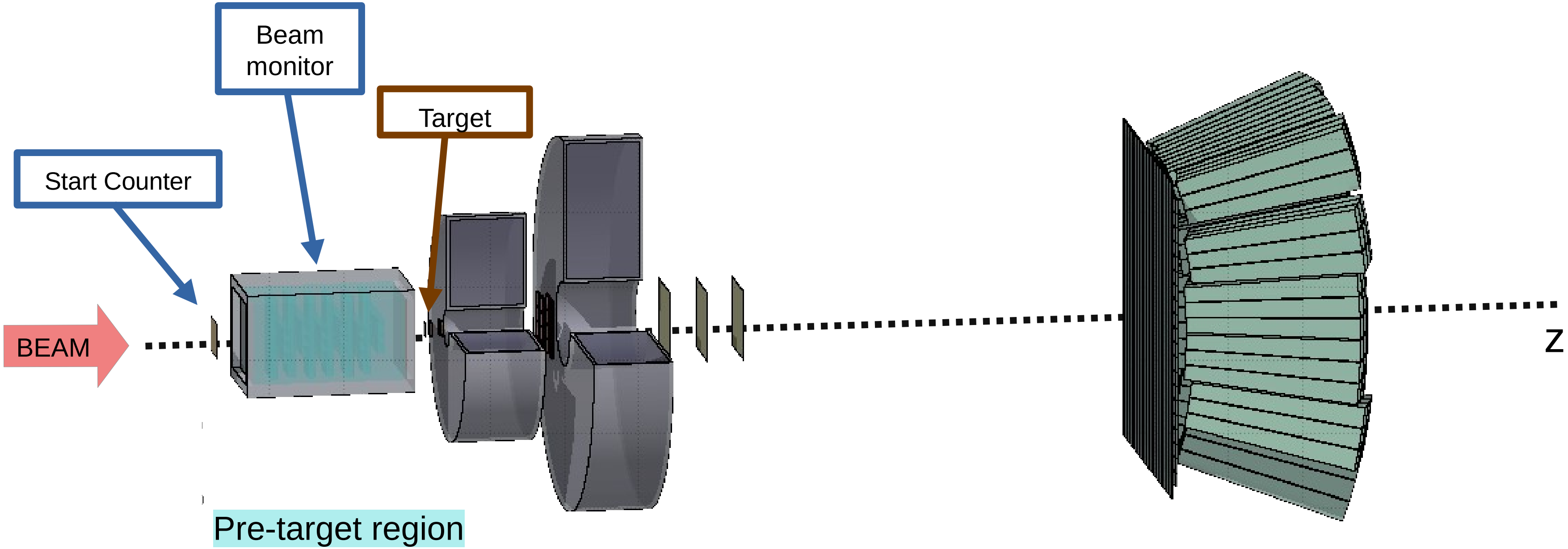
double differential **nuclear cross sections** mesurements with uncertainty < 5%

- Particle identification by measuring all kinematic quantities



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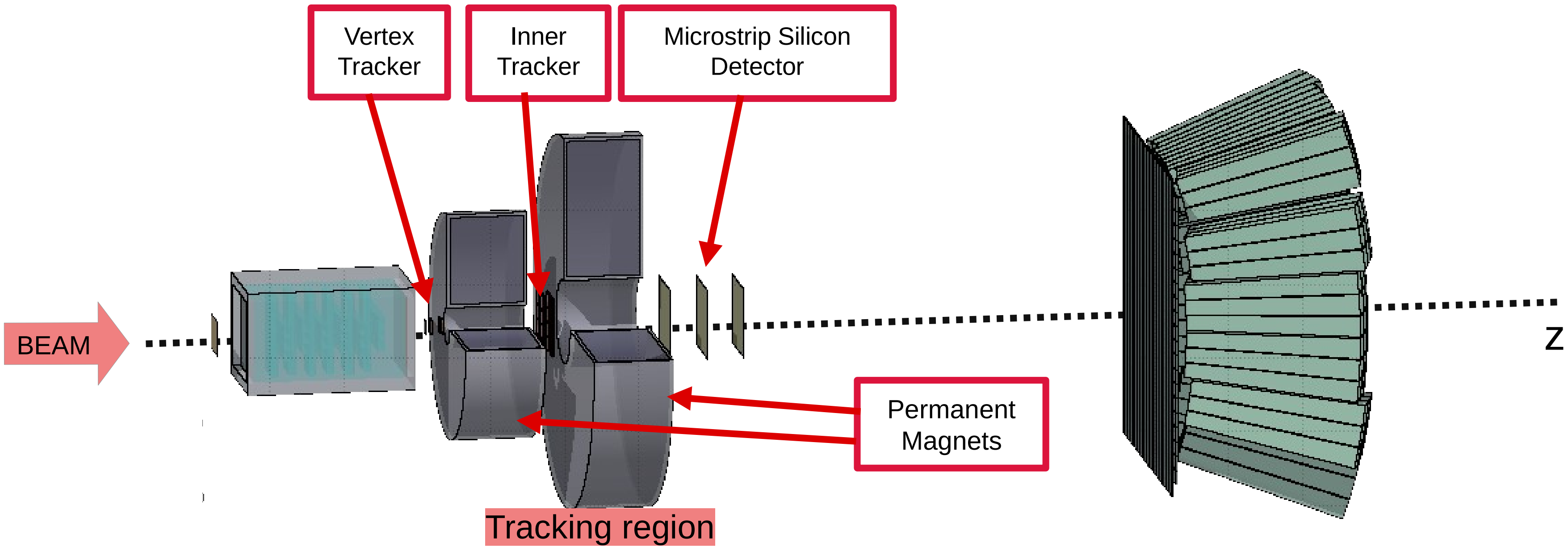

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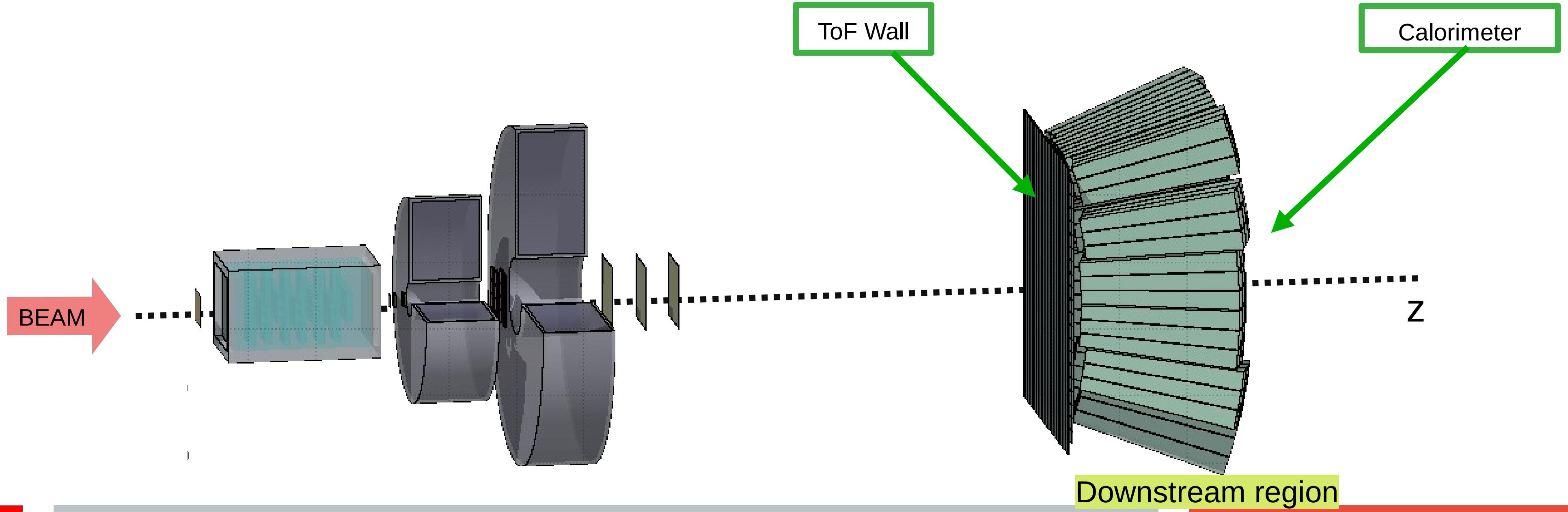
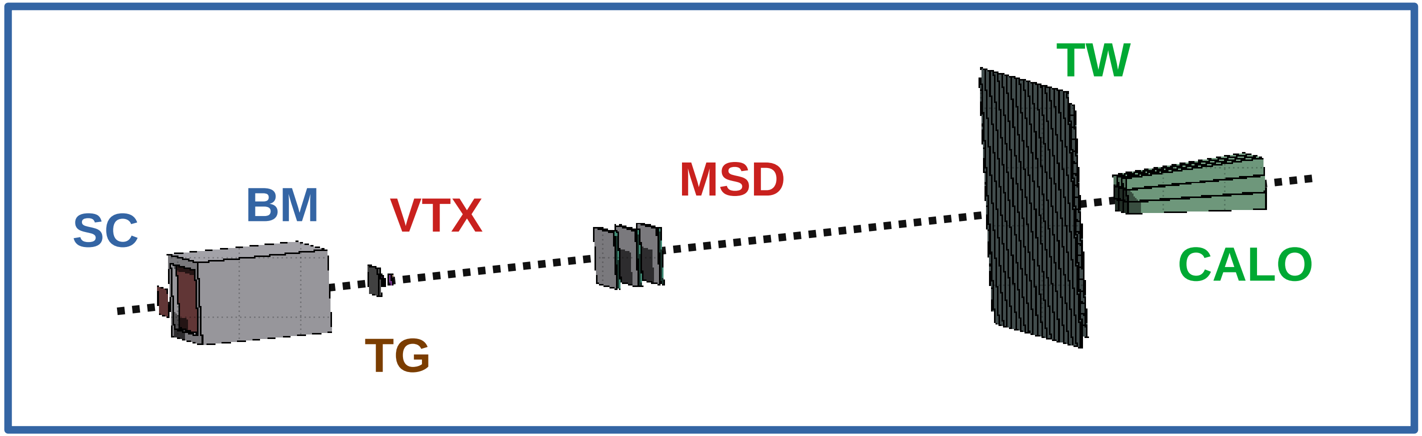
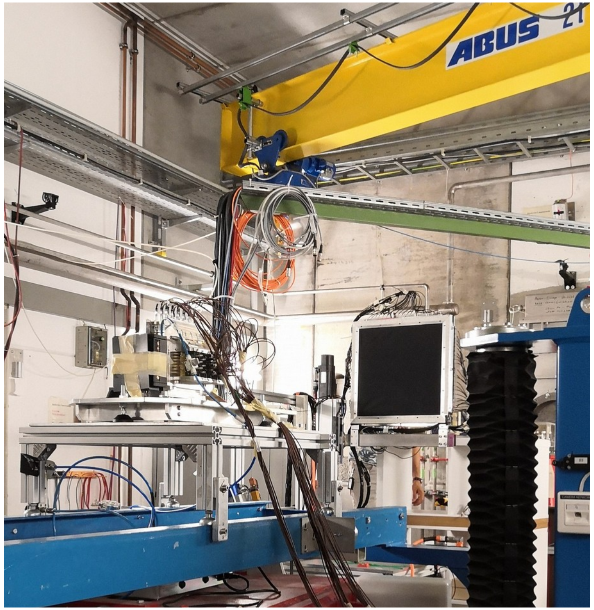


GSI 2021 Analysis

- Data-taking at GSI (Darmstadt, Germany) in 2021
- **^{16}O 400 MeV/u** on 5 mm **C target**
- Partial setup: no magnet, only one module of calorimeter





Specific goal:

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

Analysis procedure

To compute elemental cross-section:

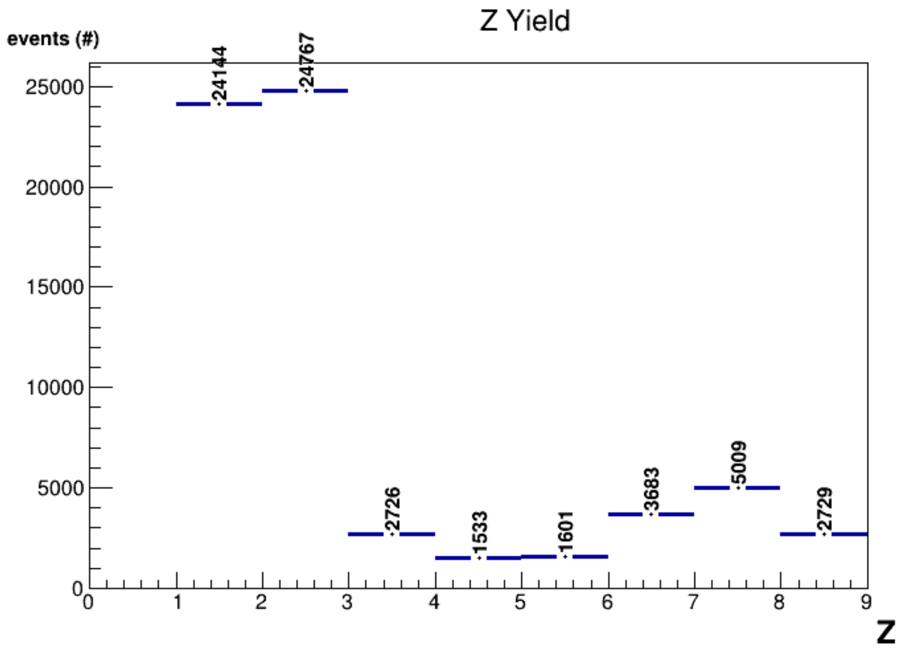
$$\sigma(Z) = \frac{Y(Z) - B(Z)}{N_{beam}\ N_{target}\ \epsilon(Z)}$$

- Starting from **MC dataset** to study Background and Efficiency from true values

Analysis procedure

To compute elemental cross-section:

$$\sigma(Z) = \frac{Y(Z) - B(Z)}{N_{beam}\ N_{target}\ \epsilon(Z)}$$



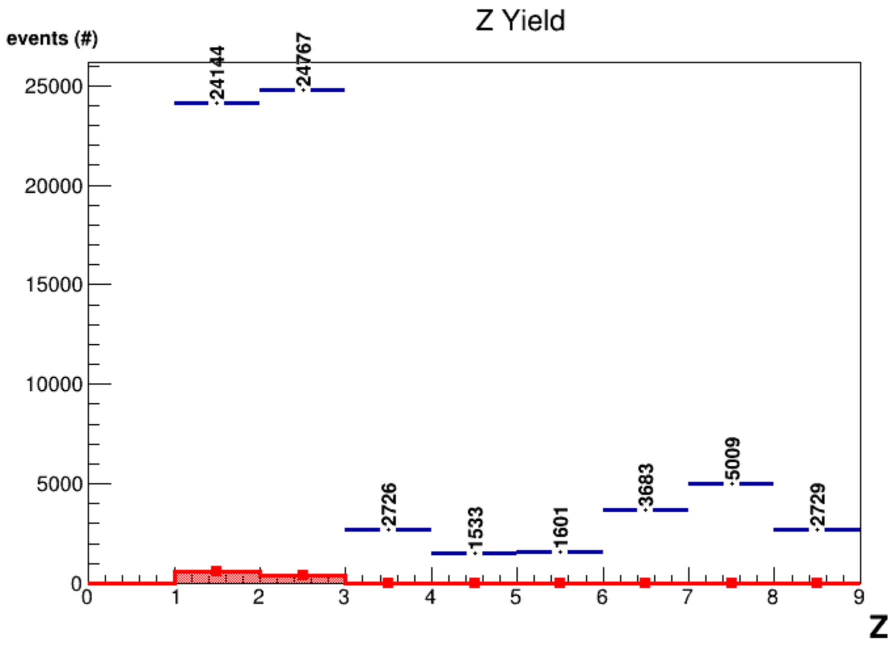
Yield of Z obtained from reconstructed tracks

- Exploiting charge reconstruction algorithm
- Exploiting tracking reconstruction algorithm
- Simulating a “trigger” in order to consider only fragments

Analysis procedure

To compute elemental cross-section:

$$\sigma(Z) = \frac{Y(Z) - B(Z)}{N_{beam}\, N_{target}\, \epsilon(Z)}$$



Background obtained from MC cuts on:

- Charge algorithm mis-reconstruction
- Tracking algorithm mis-reconstruction
- Trigger mis-reconstruction

Analysis procedure

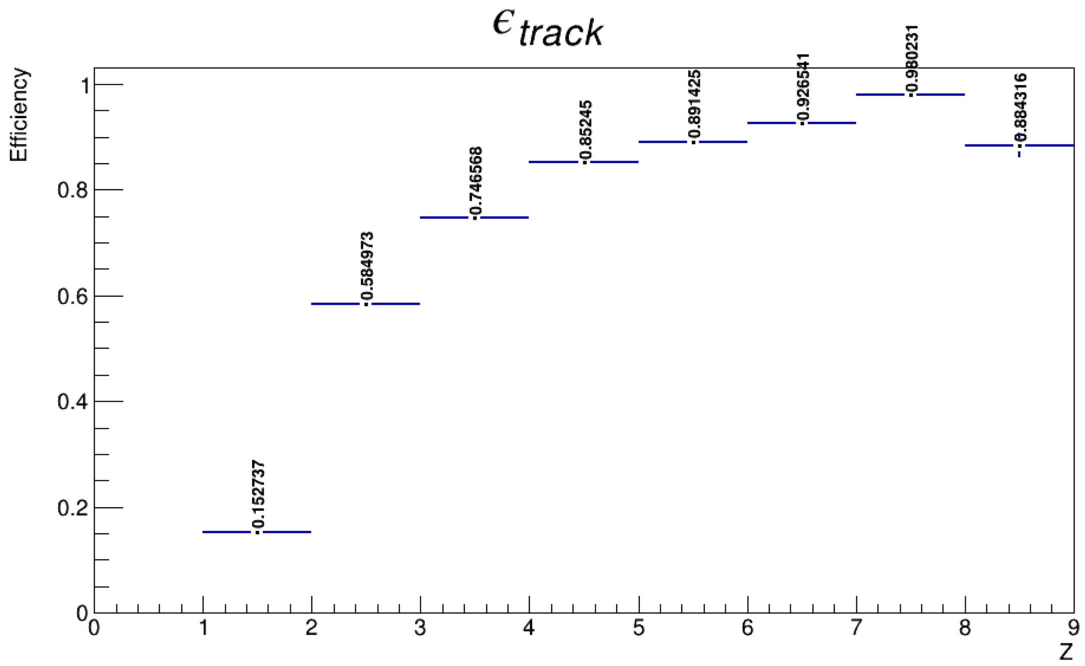
To compute elemental cross-section:

$$\sigma(Z) = \frac{Y(Z) - B(Z)}{N_{beam}\ N_{target}\ \epsilon(Z)}$$

Efficiency obtained as:

$$\epsilon_{track}(Z) = \frac{Y(Z)_{track}}{Y(Z)_{MC}}$$

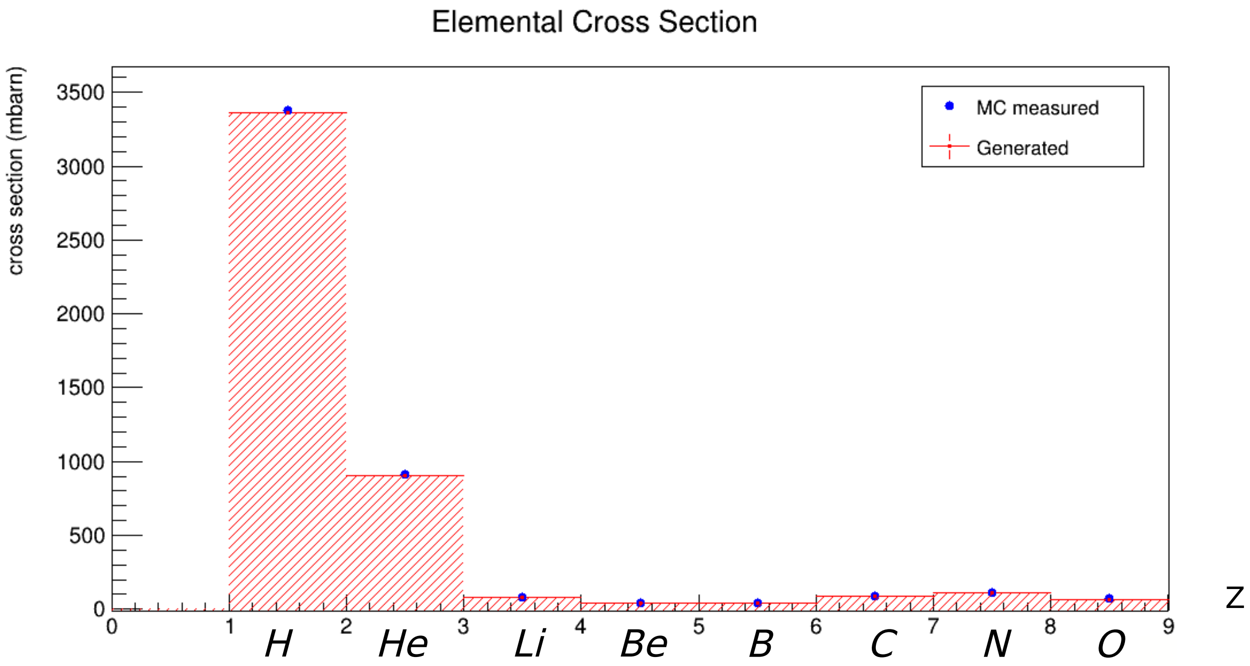
- where track is obtained by tracking algorithm
- MC particles are from the generated simulation



Elemental fragmentation cross-section

- Smeared MC dataset used as Yield
- Statistical uncertainties only

$$\sigma(Z) = \frac{Y(Z) - B(Z)}{N_{beam}\, N_{target}\, \epsilon(Z)}$$

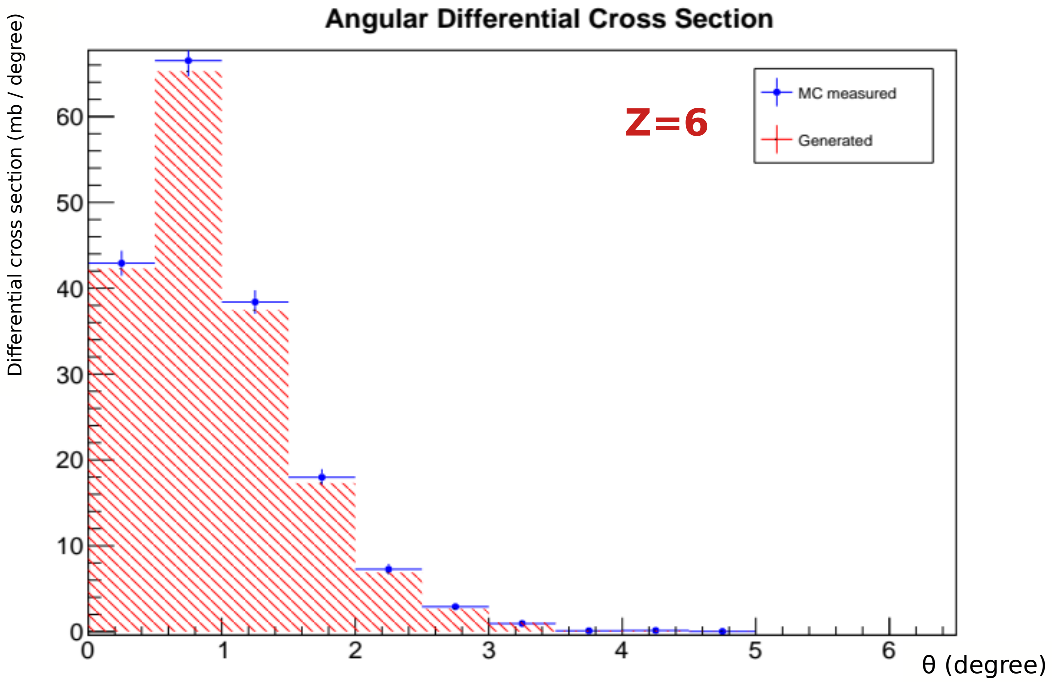


Fragment (Z)	σ_{meas} (mbarn)	σ_{MC} (mbarn)
1	3376 ± 30	3361 ± 8
2	911 ± 7	907 ± 5
3	80 ± 2	79 ± 1
4	40 ± 1	39 ± 1
5	40 ± 1	39 ± 1
6	87 ± 1	87 ± 1
7	112 ± 1	111 ± 2
8	68 ± 3	67 ± 1

Angular differential cross-section

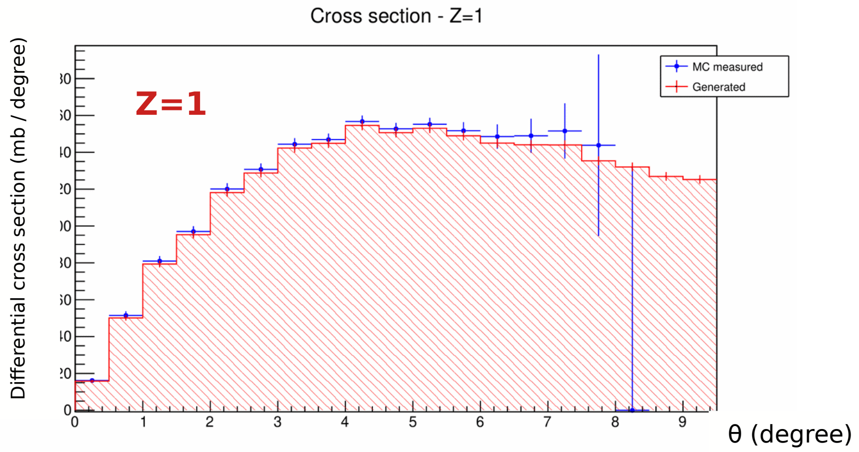
An analogous procedure has been followed to obtain angular differential cross section:

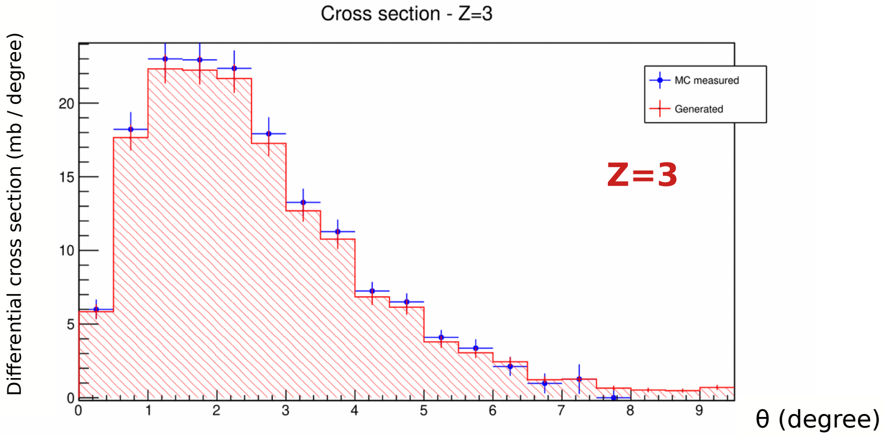
$$\frac{d\sigma(Z)}{d\theta} = \frac{Y(Z,\theta)}{N_{beam}\, N_{target}\, \Delta\theta\, \epsilon(Z,\theta)}$$

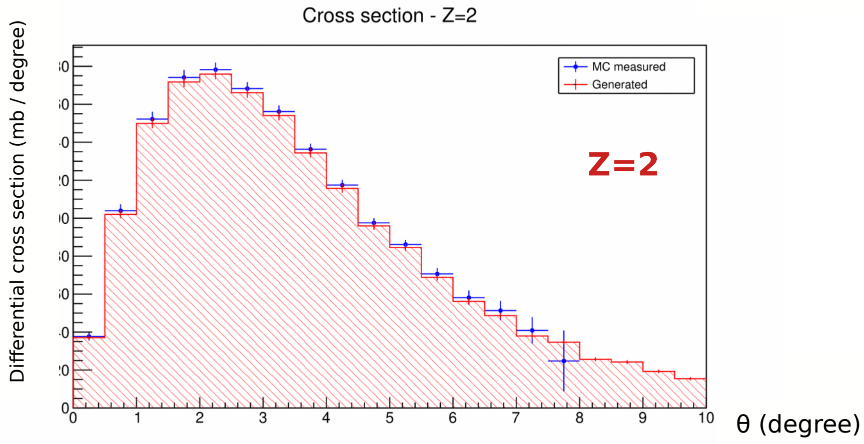


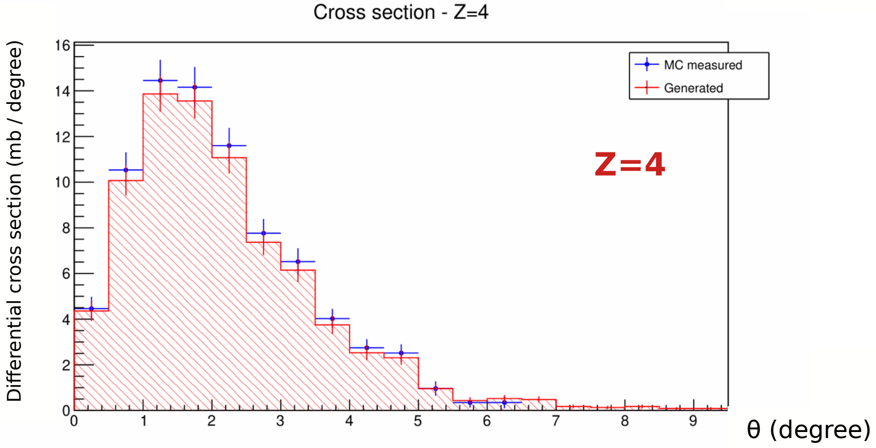
Angle $(degree)$	σ_{meas} (mb)	σ_{MC} (mb)
$0.0 \leq \theta < 0.5$	42.9 ± 1.5	42.3 ± 1.4
$0.5 \leq \theta < 1.0$	66.5 ± 1.8	65.3 ± 1.7
$1.0 \leq \theta < 1.5$	38.4 ± 1.4	37.4 ± 1.3
$1.5 \leq \theta < 2.0$	18.0 ± 1.0	17.3 ± 0.9
$2.0 \leq \theta < 2.5$	7.3 ± 0.6	6.9 ± 0.5
$2.5 \leq \theta < 3.0$	2.9 ± 0.4	2.7 ± 0.3
$3.0 \leq \theta < 3.5$	0.9 ± 0.2	1.1 ± 0.2
$3.5 \leq \theta < 4.0$	0.1 ± 0.1	0.1 ± 0.1
$4.0 \leq \theta < 4.5$	0.1 ± 0.1	0.1 ± 0.1

Angular differential cross-section

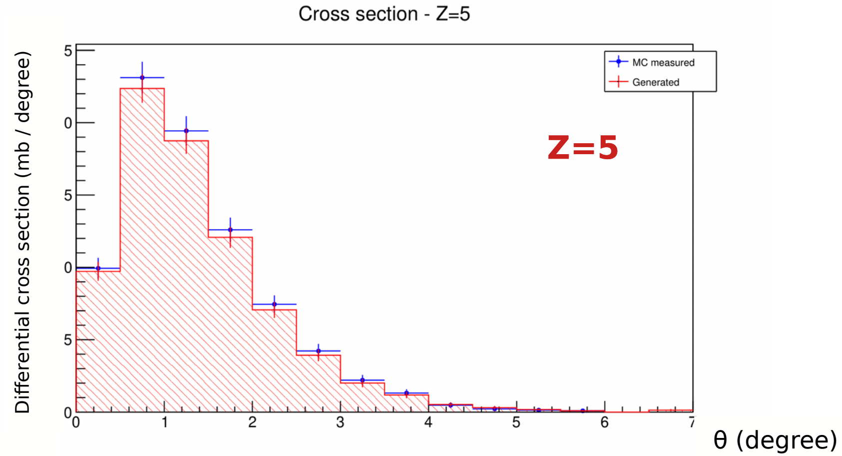


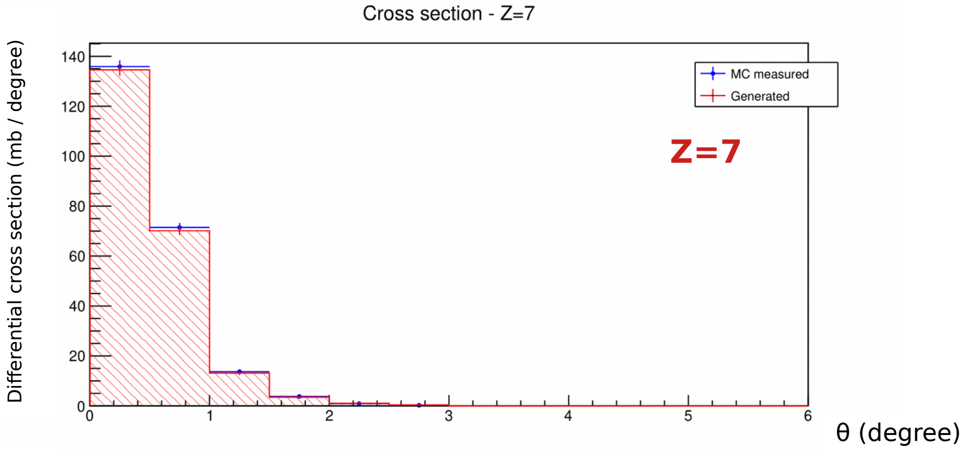


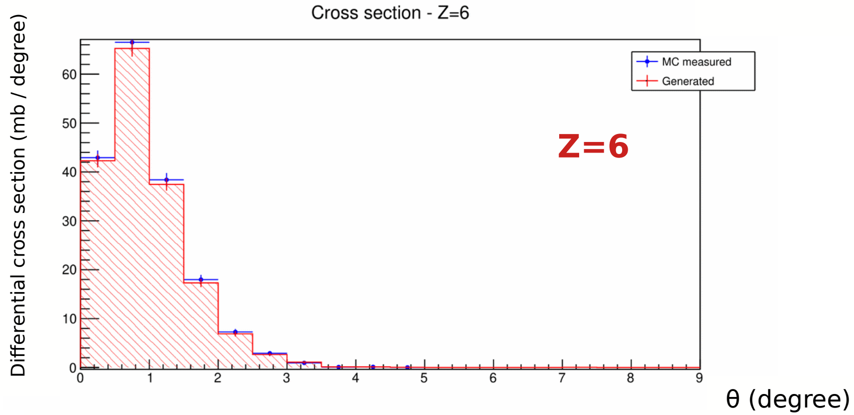


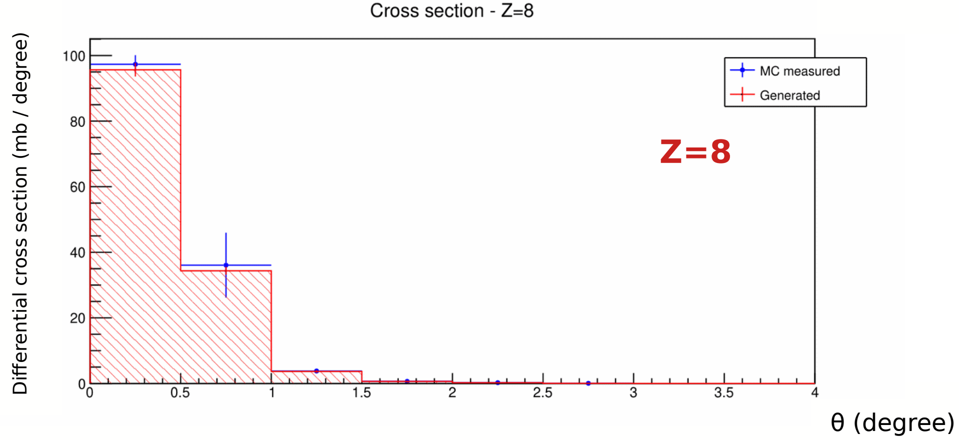


Angular differential cross-section









Conclusions

- First preliminary results of cross sections based on MC events with a **solid closure test**
- Study of background sources, corrections and efficiencies on MC level
- Low impact of statistic fluctuations

To do:

- Preliminary systematics uncertainties
- Including unfolding to correct for migrations
- Process real data
- Evaluating cross section differential also in kinematic energy and in mass
- Repeat the same steps for ^{16}O 200 MeV/u

Thank you for the attention!

Backup slides

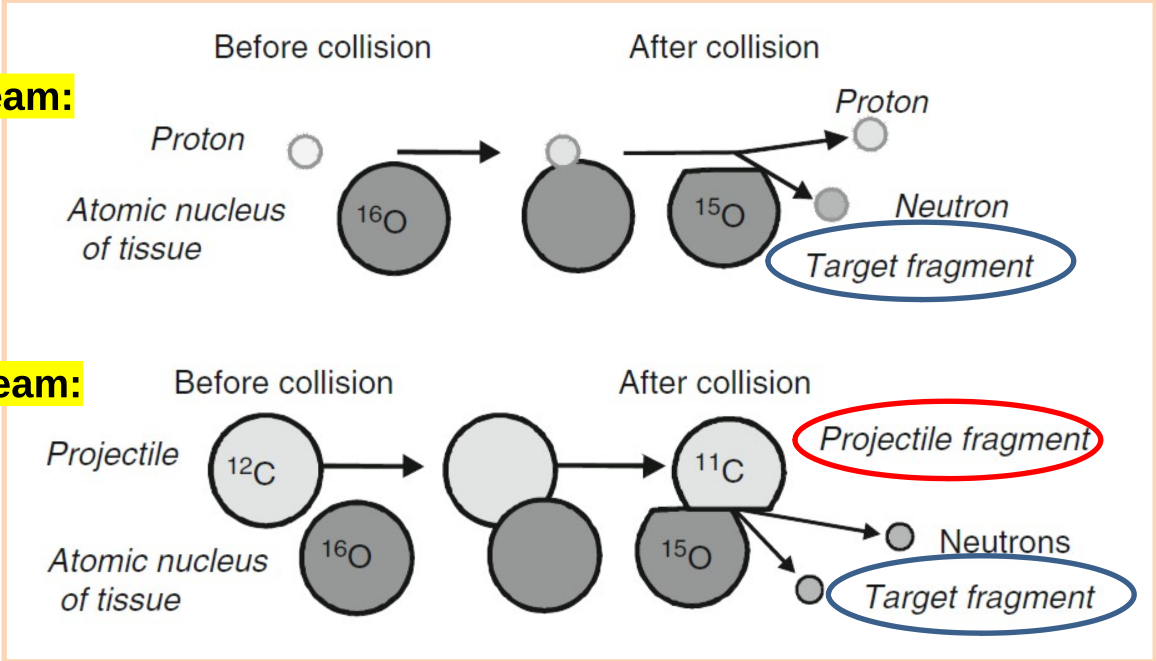
Nuclear fragmentation

Proton beam:

~ 200 MeV

Carbon beam:

~ 400 MeV/u



Target fragments:
- ✘ Short range
- ✘ High energy impact in entrance channel

Projectile fragments:
- ✘ Longer range than beam
- ✘ Dose beyond the Bragg peak

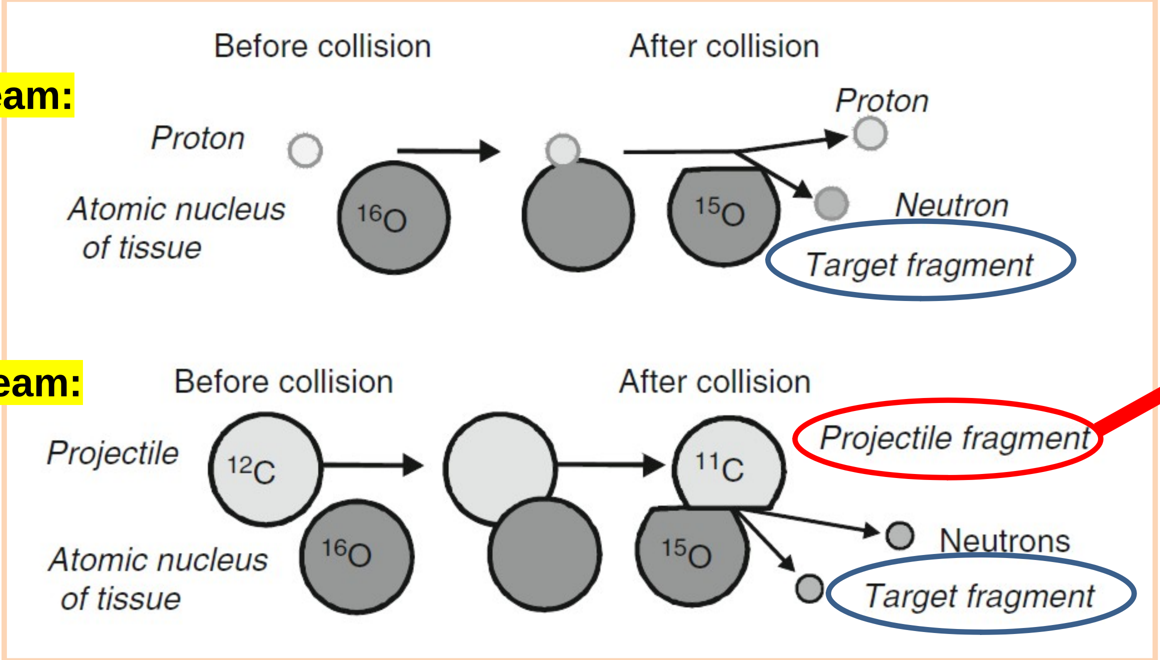
Nuclear fragmentation

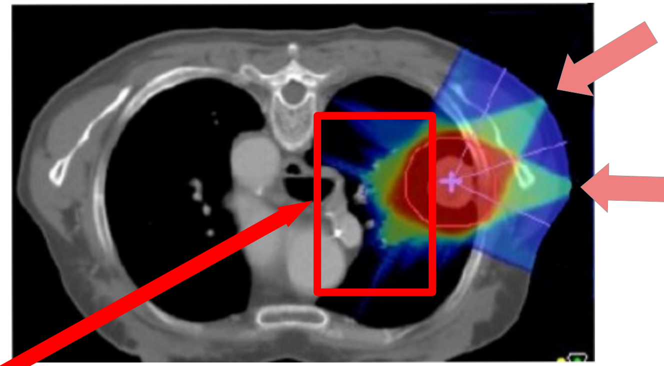
Proton beam:

~ 200 MeV

Carbon beam:

~ 400 MeV/u





Projectile fragments:

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

nuclear cross section
mesurements needed

GSI 2021 Analysis

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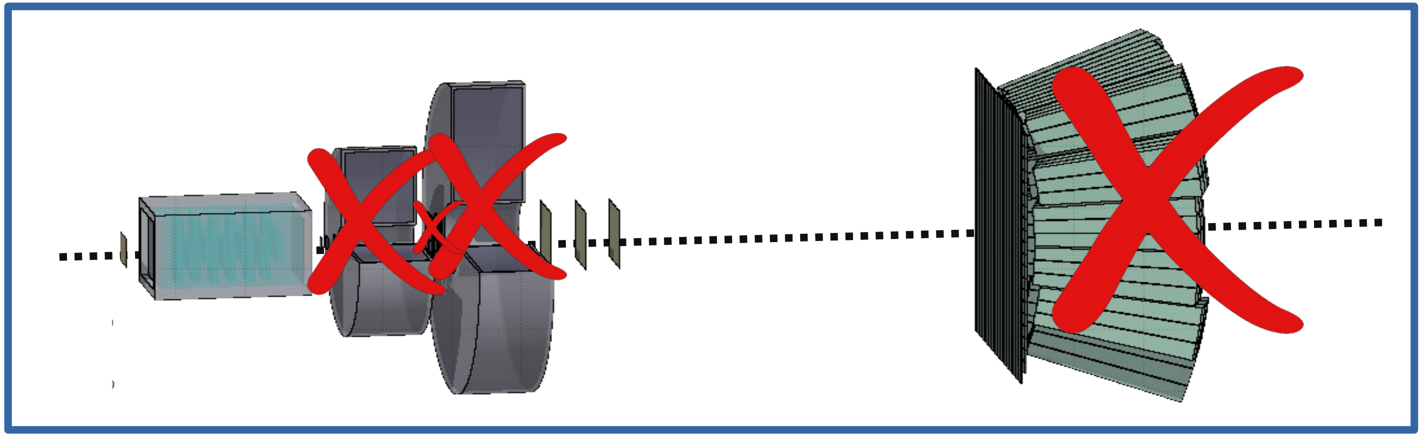
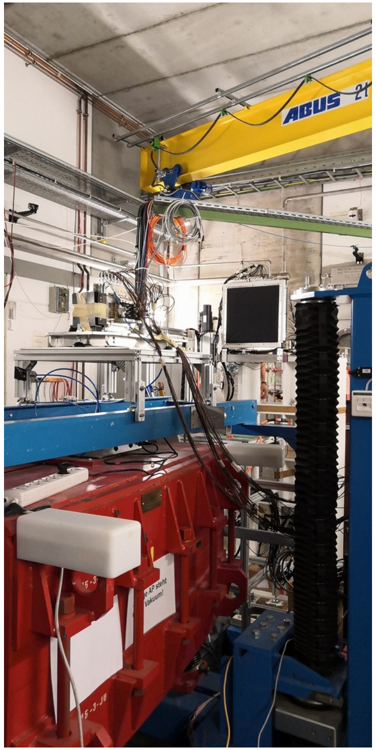




Specific goal:

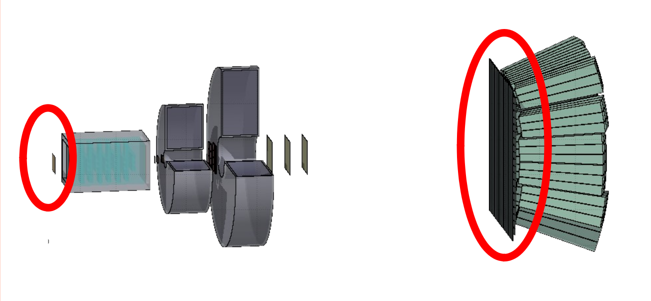
- Elemental (charge differential) fragmentation cross section
- Angular charge double differential cross section

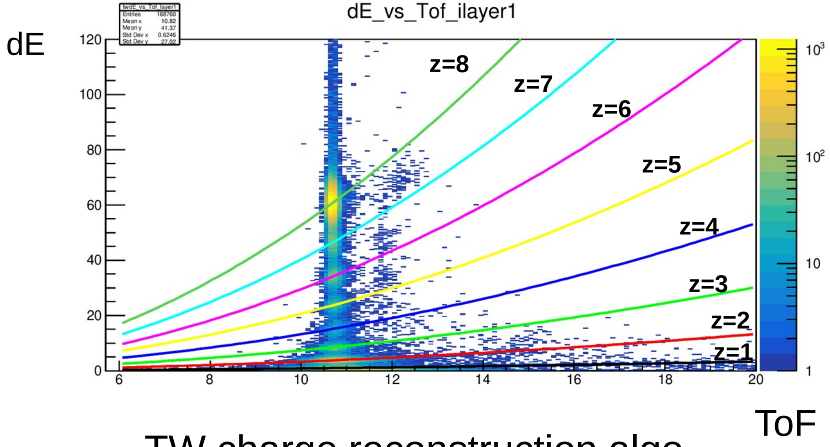
Fragments identification

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

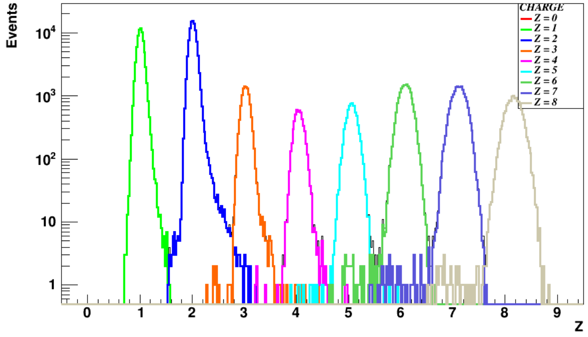
$$-\boxed{\frac{\mathrm{d}E}{\mathrm{d}x}} = 4\pi N_e r_e^2 m_e c^2 \frac{z^2}{\boxed{\beta^2}} \left(\ln \frac{2m_e c^2 \boxed{\beta^2} \gamma^2}{I} - \boxed{\beta^2} - \frac{\delta(\gamma)}{2} \right)$$

- **Infos taken from SC and TW**





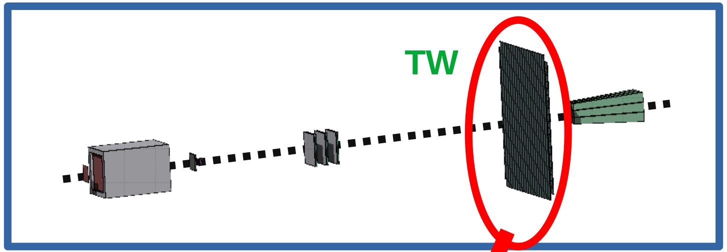
TW charge reconstruction algo

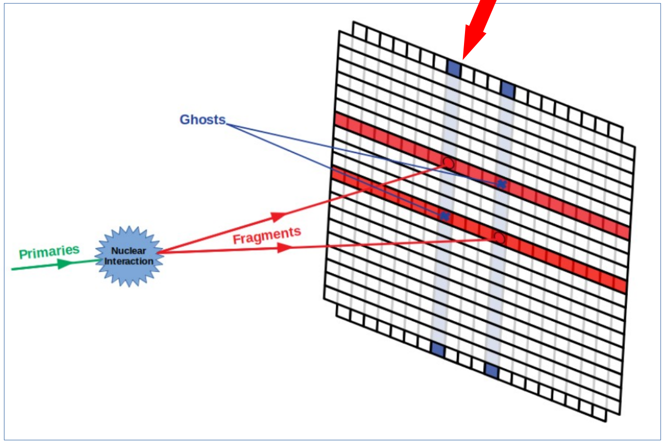


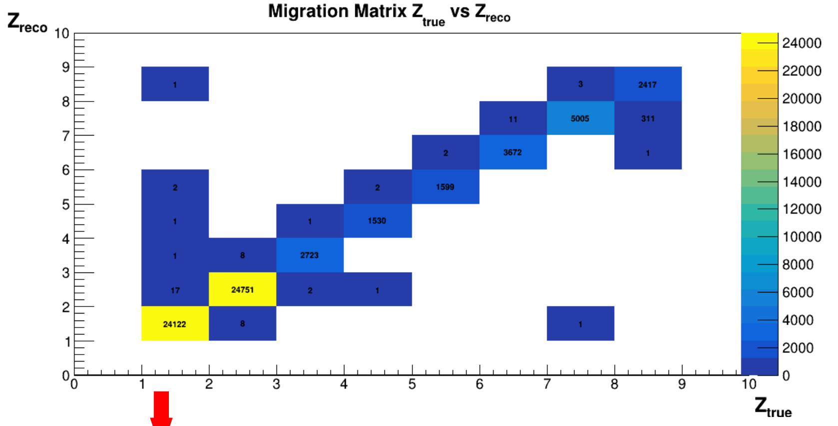
Charge discrimination

Track reconstruction, TW systematics

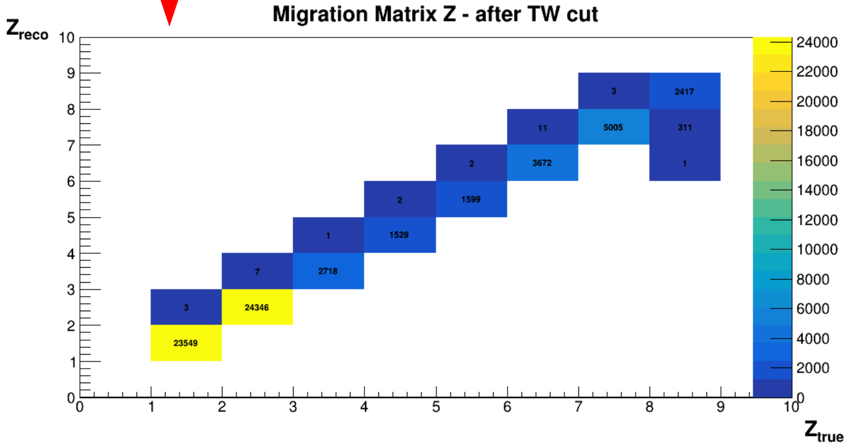
- It is possible that every bar layer of the TW is hitted by more than a fragment at the same time: **multiple hits / ghost hits systematics**



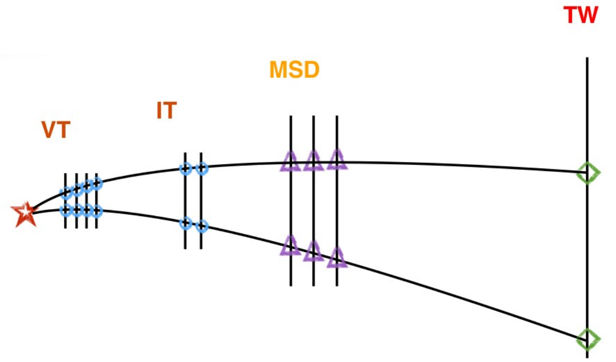


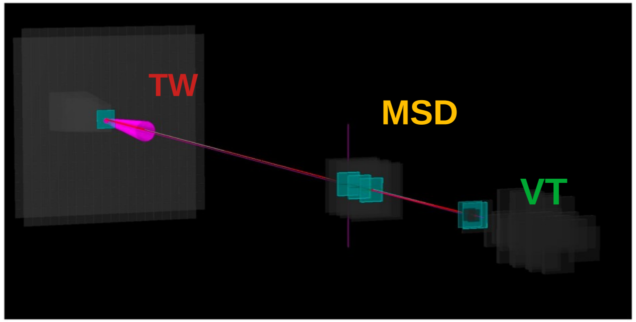


Applying TW cut:

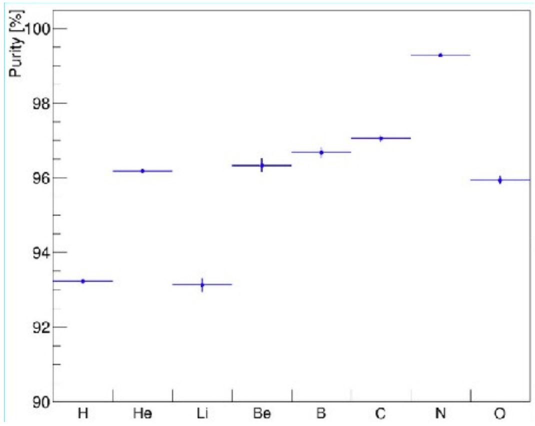


Track reconstruction





- track reconstruction on GSI 2021 data
  No B field present



Kalman Filter reconstruction of a track

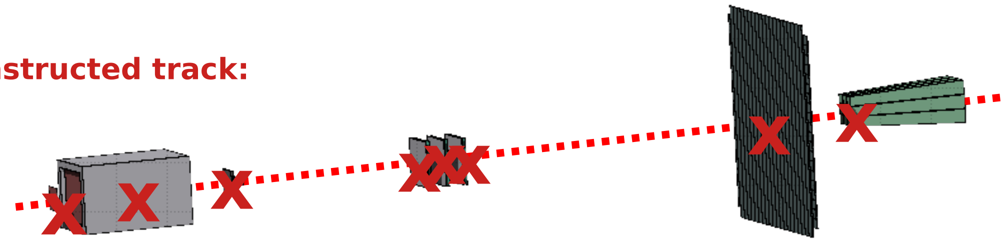
- Start from VT tracklets
- Projection to possible planes of IT
- KF extrapolation to MSD
- KF extrapolation to TW
- Fit the track candidates and extract reconstructed quantities: **Z**, **momentum** ...

Reconstruction, Track Algo

- Another source of systematics can be the way points are collected in a track

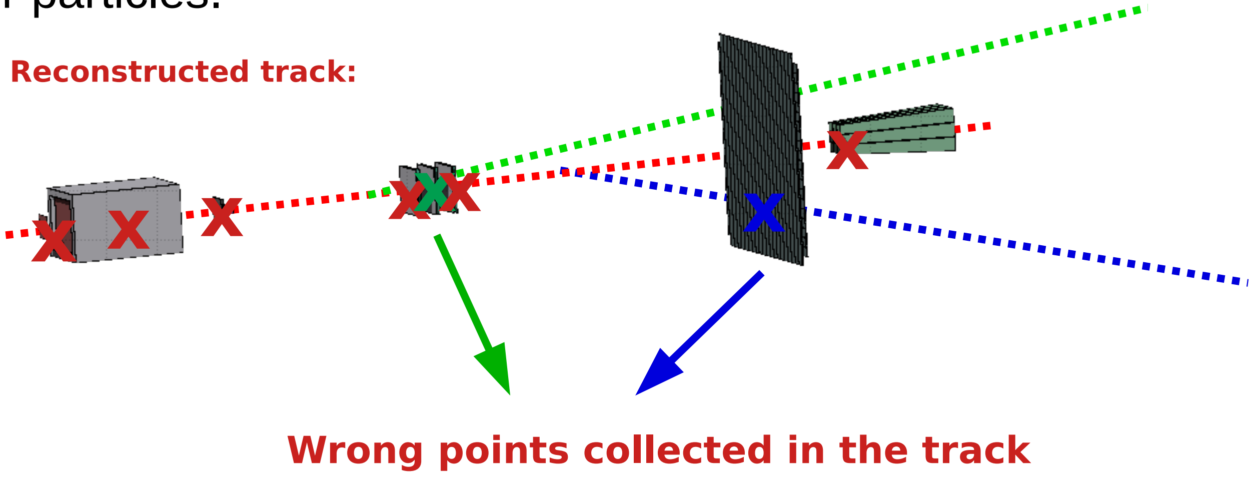
- In the best scenario, all points belong to the same particle:

Reconstructed track:



Reconstruction, Track Algo

- However, due to the presence of a lot of secondary fragmentation, some points can belong to other particles.

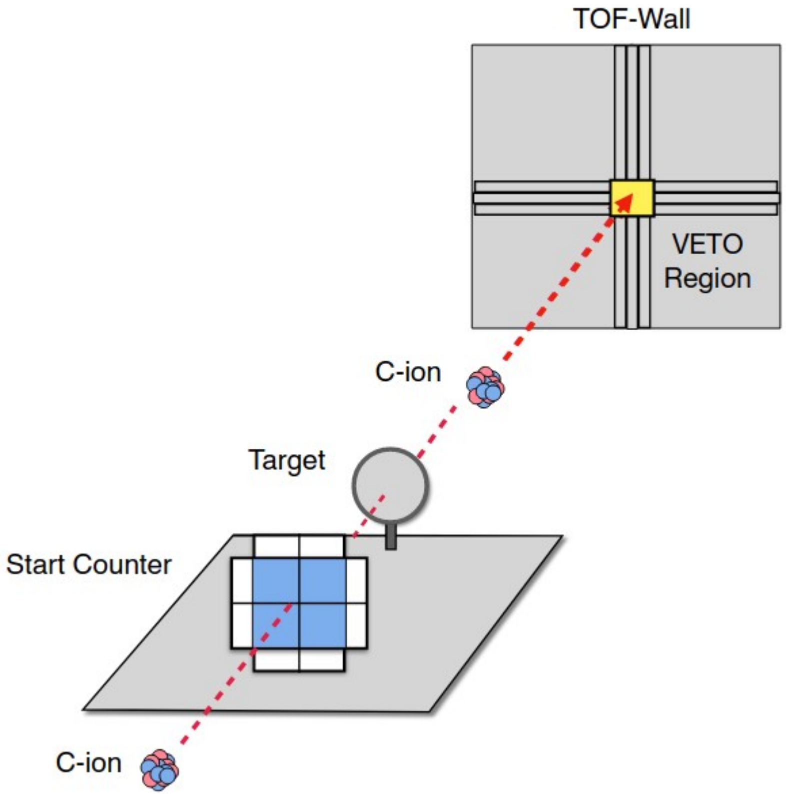


- The McId of the track is given by the most present particle in the collection
- However, if the TWPoint is of another particle → **its McId is different**
- → filter out all the tracks in which **$McId_{track} \neq McId_{TWPoint}$**

Trigger Simulation

It is a **Minimum Bias** trigger based on **SC signals** in **anticoincidence** with a signal from one of the **TW central bars** compatible with the energy of the primary.

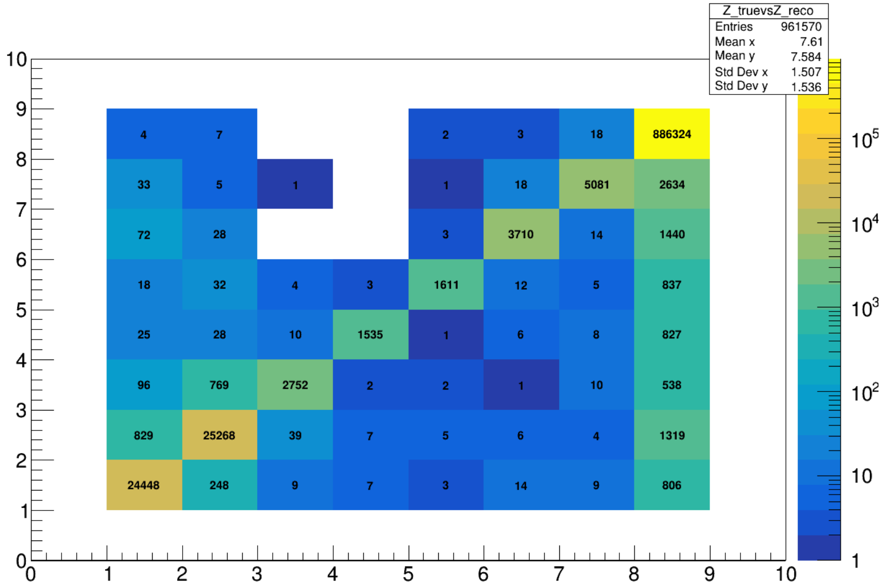
Minimum Bias is fired whenever the number of SC channels above a certain threshold exceeds a programmable value (aka *majority*).

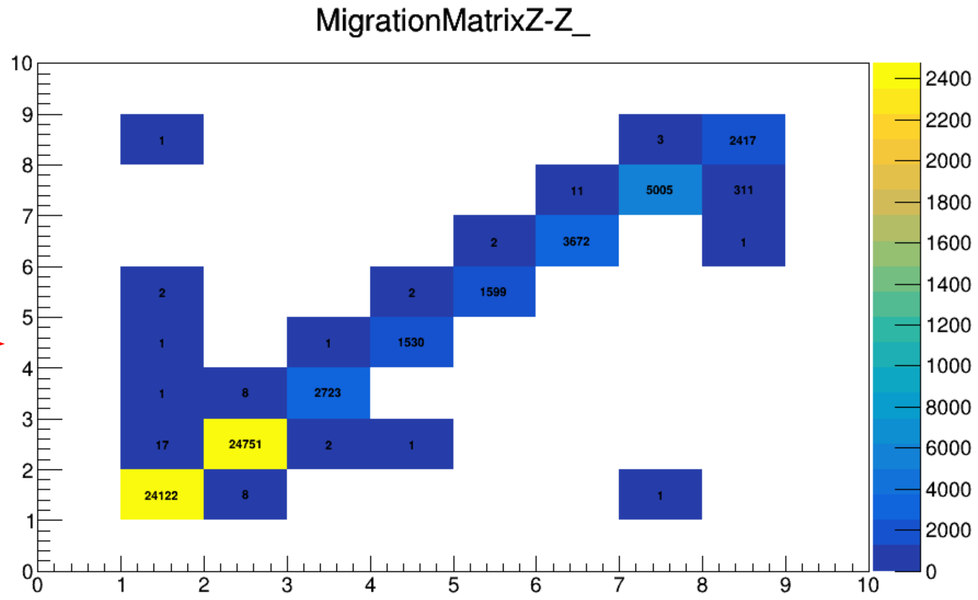


- **Fragment Trigger** is fired every time Minimum Bias condition on TW is not verified

Trigger Simulation

Applying Trigger cut:

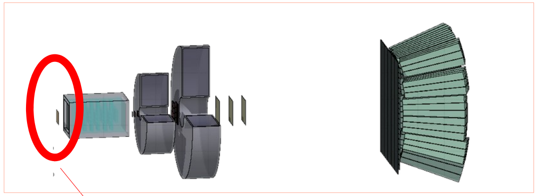


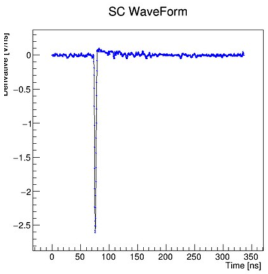


- Main source of mis-reconstruction is given by O due to its high statistics

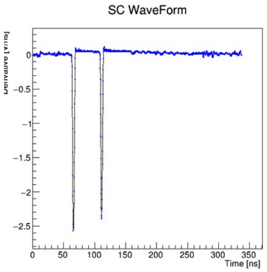
Pile-up removal

- What it was seen in the last data taking (GSI - CNAO 2021) is that the **beam flux is not constant** → **pile-up events**



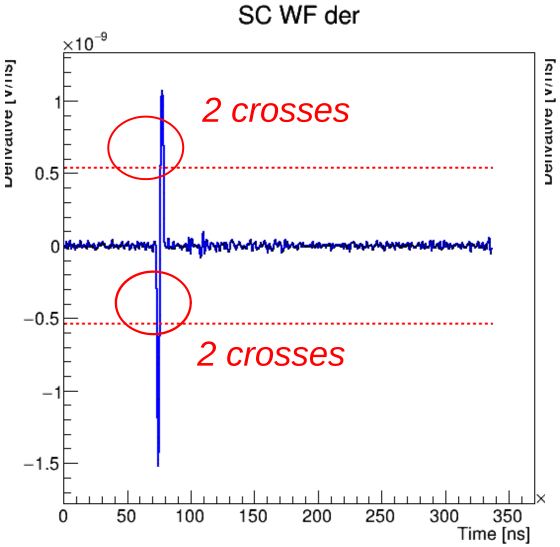


Single projectile

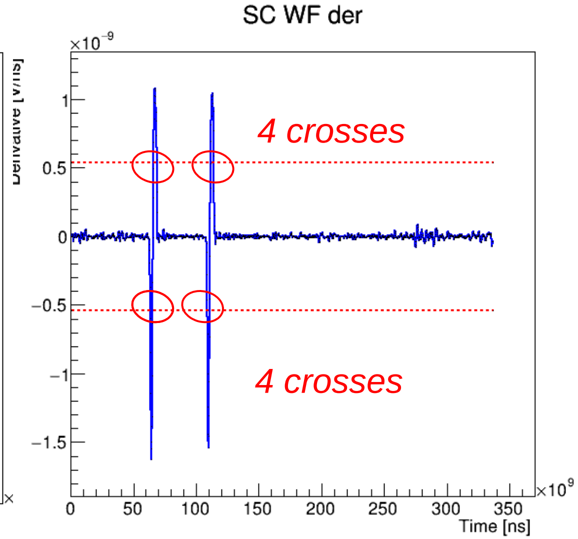


Pileup projectile

constant threshold discrimination method



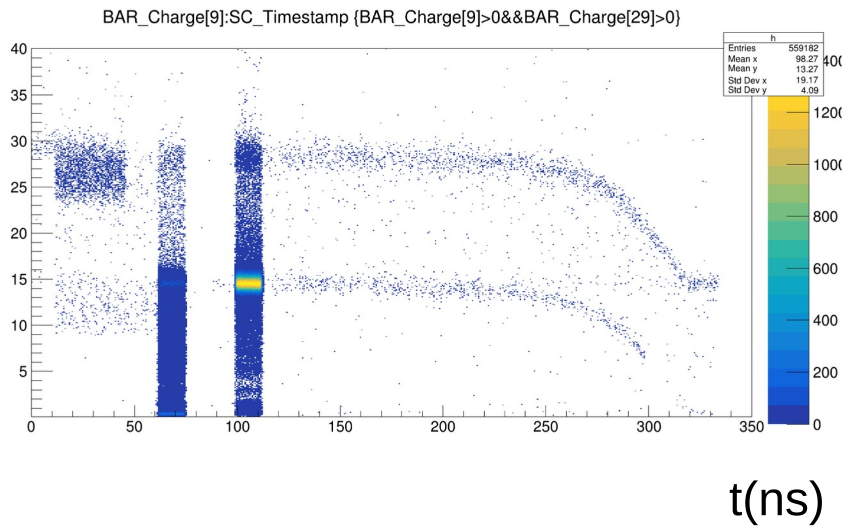
Single projectile: 4 crosses

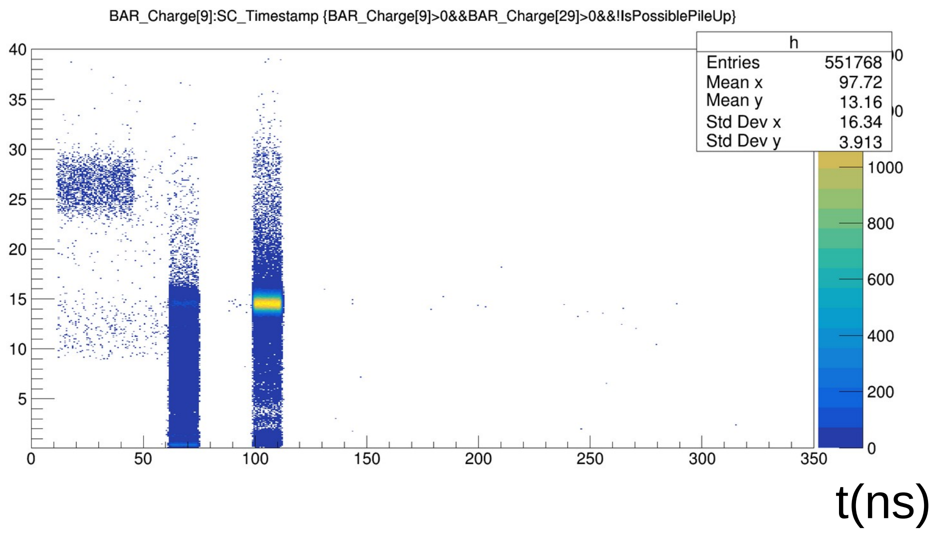


pileup projectile: >4 crosses

Pile-up removal

Both ***minimum bias trigger*** and ***trigger fragmentation***



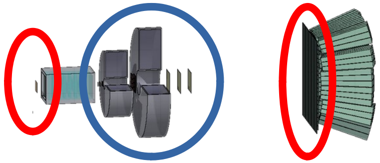


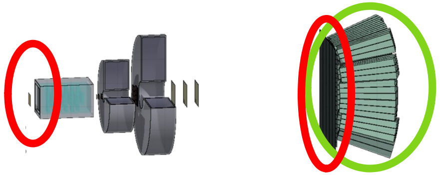
PileUp on 600.000 events ~ 1%

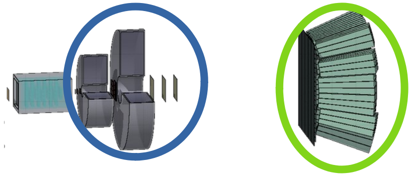
Isotopes identification

- Mass reconstruction using all FOOT subdetectors:

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





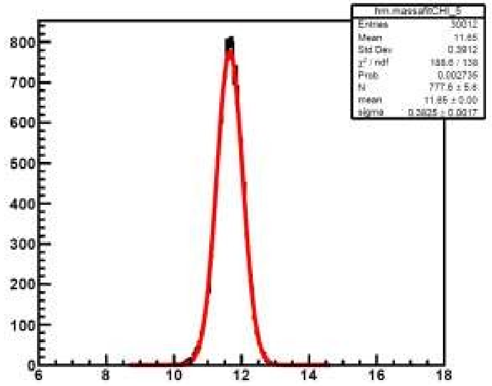


- In our data no tracker and calorimeter → mass measurement only in MC data!
- Augmented Lagrangian

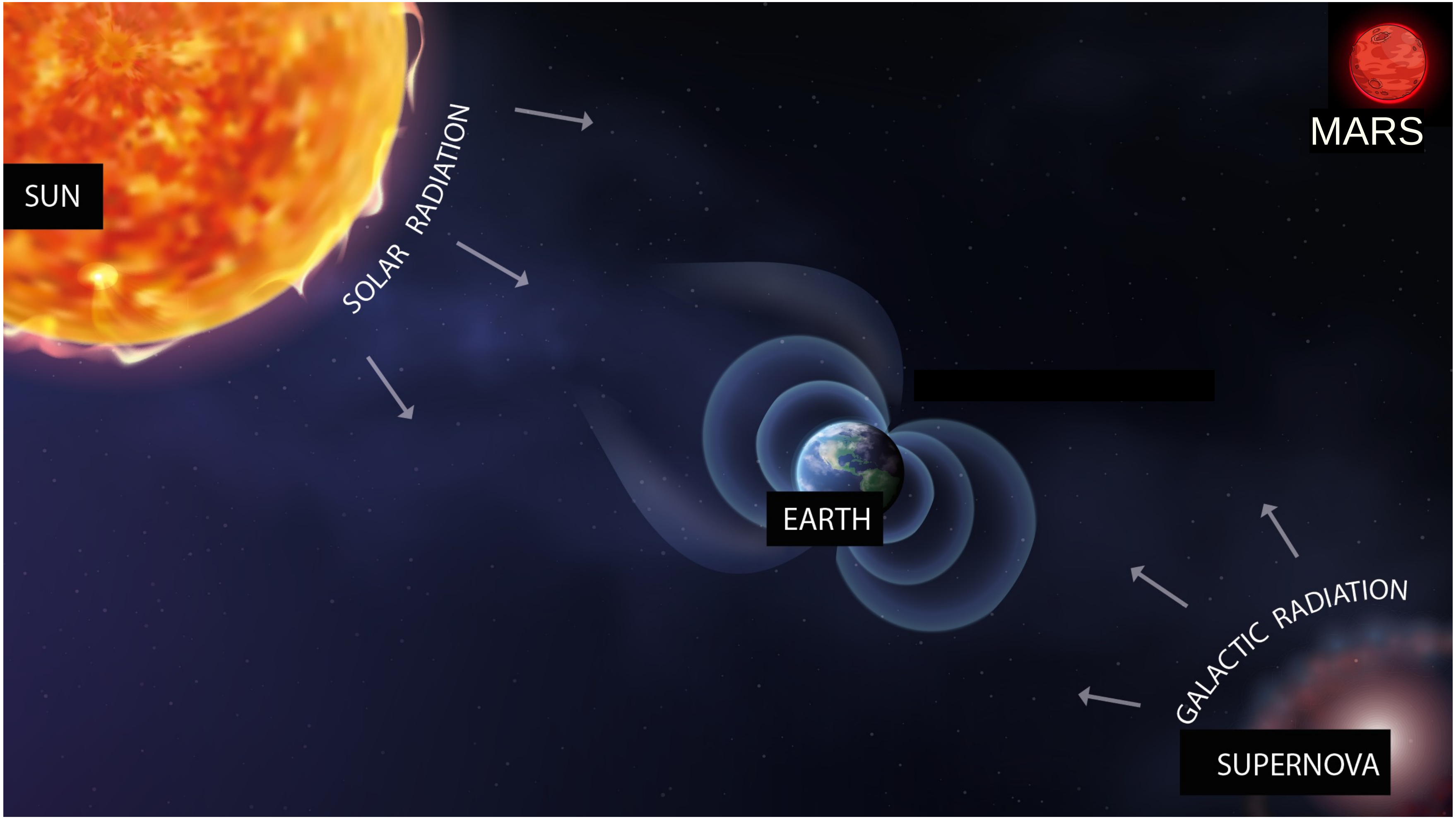
$$L(\vec{x}, \lambda, \mu) \equiv f(\vec{x}) - \sum \lambda_a c_a(\vec{x}) + \frac{1}{2\mu} \sum c_a^2(\vec{x})$$

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

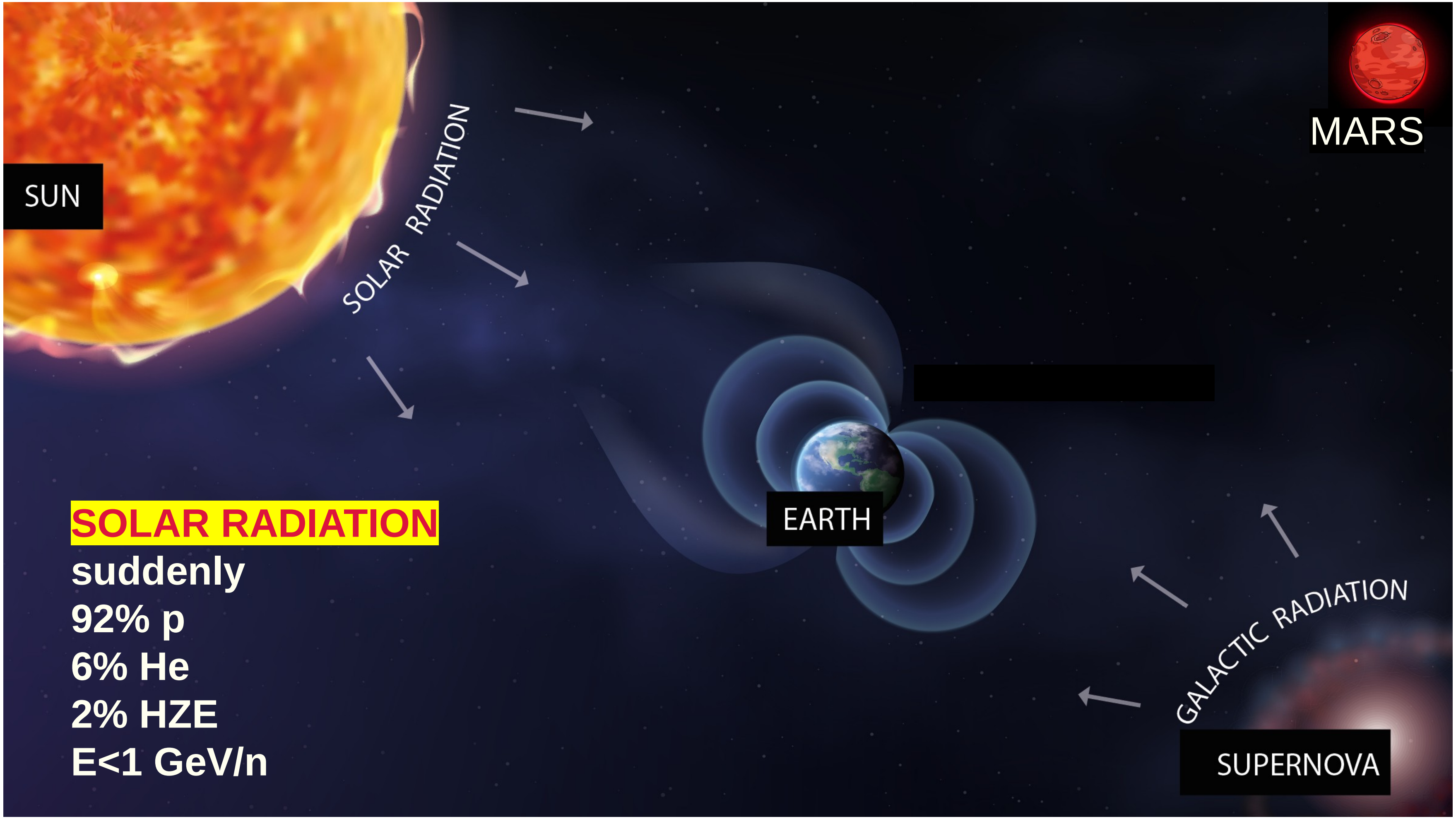
$A\chi 2$ = 11.66 ± 0.38
risoluz. 3.2 %
$\chi 2 < 5$



Space radioprotection

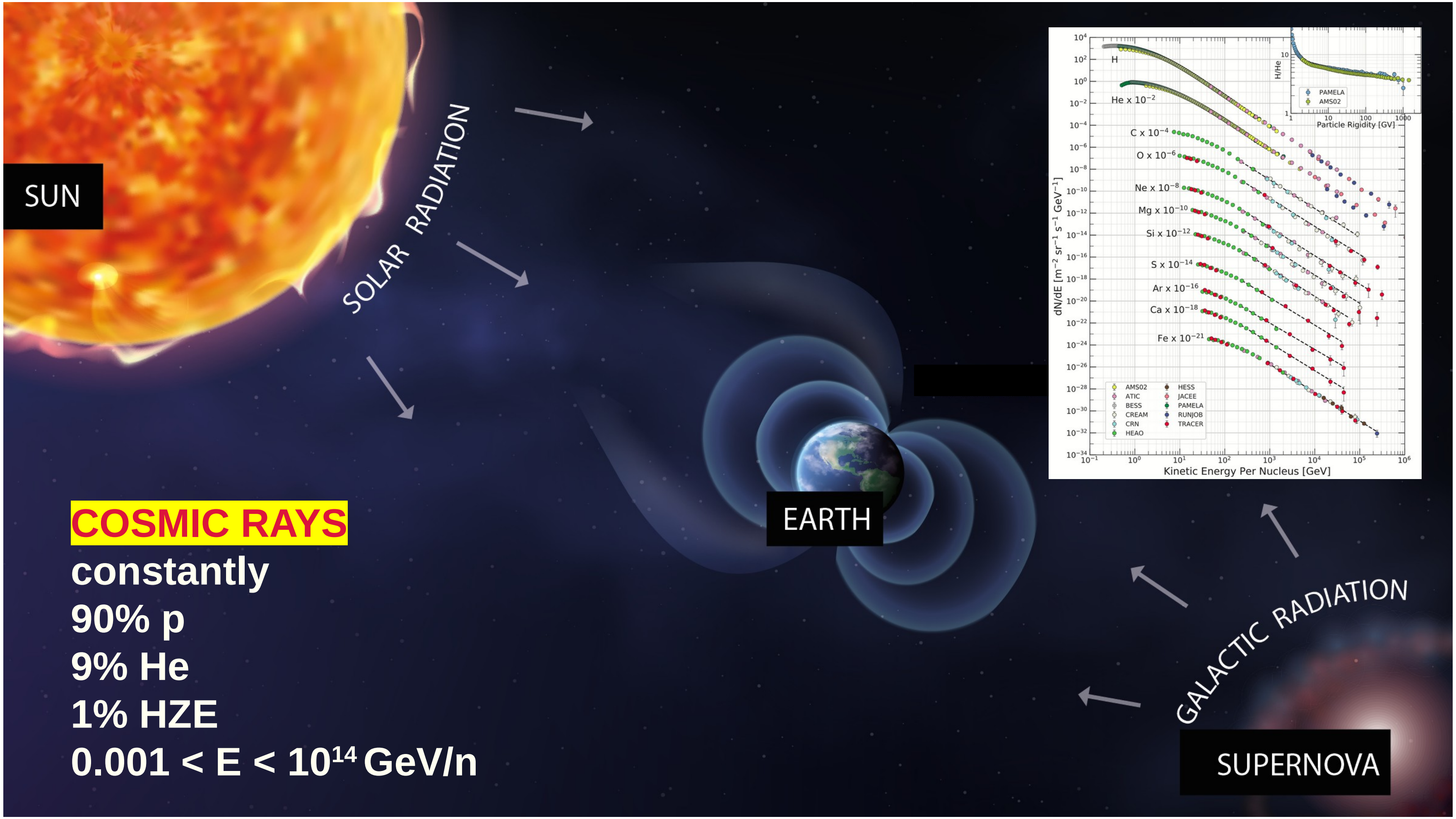


Space radioprotection



SOLAR RADIATION
suddenly
92% p
6% He
2% HZE
E<1 GeV/n

Space radioprotection



COSMIC RAYS

constantly

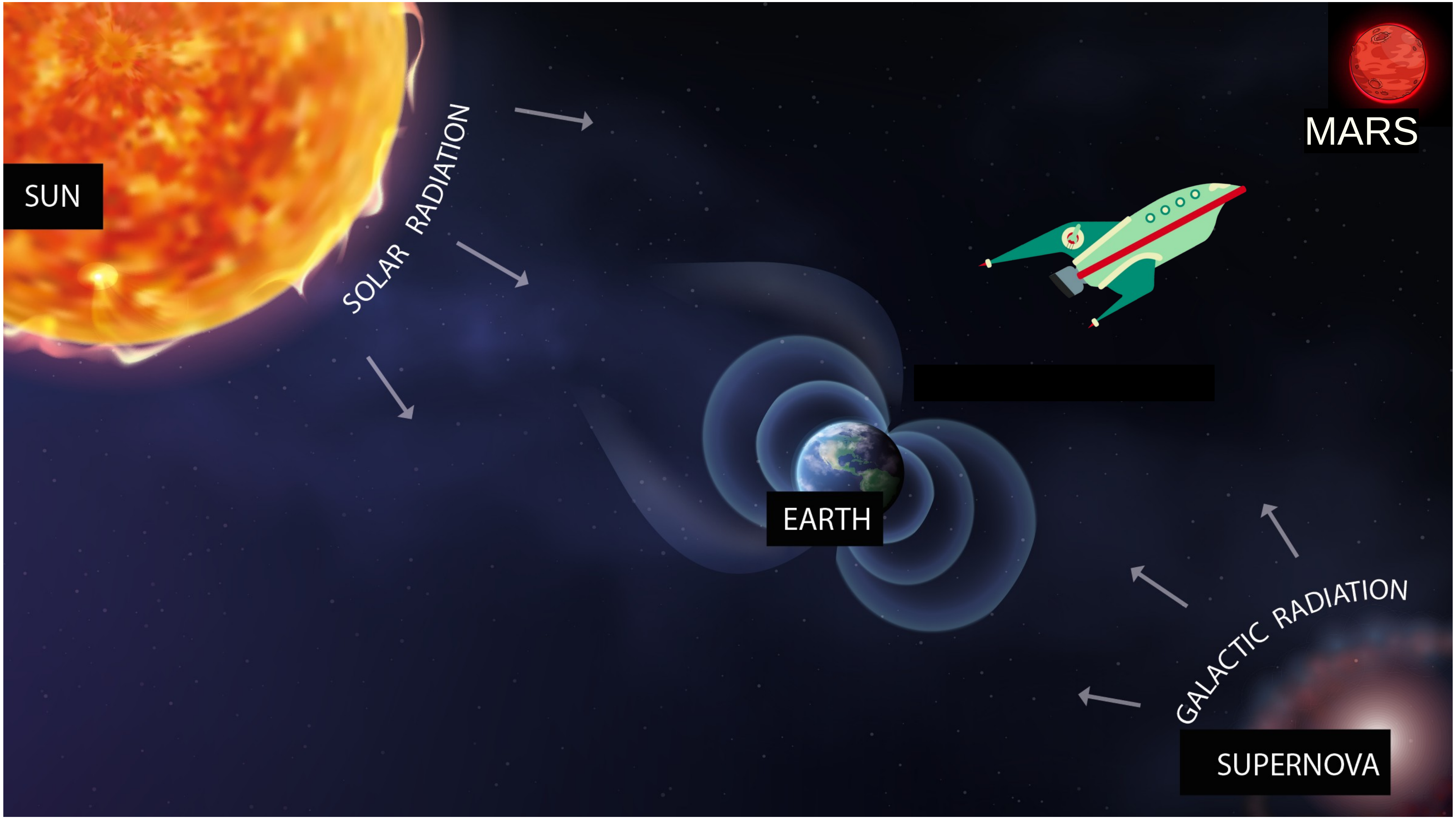
90% p

9% He

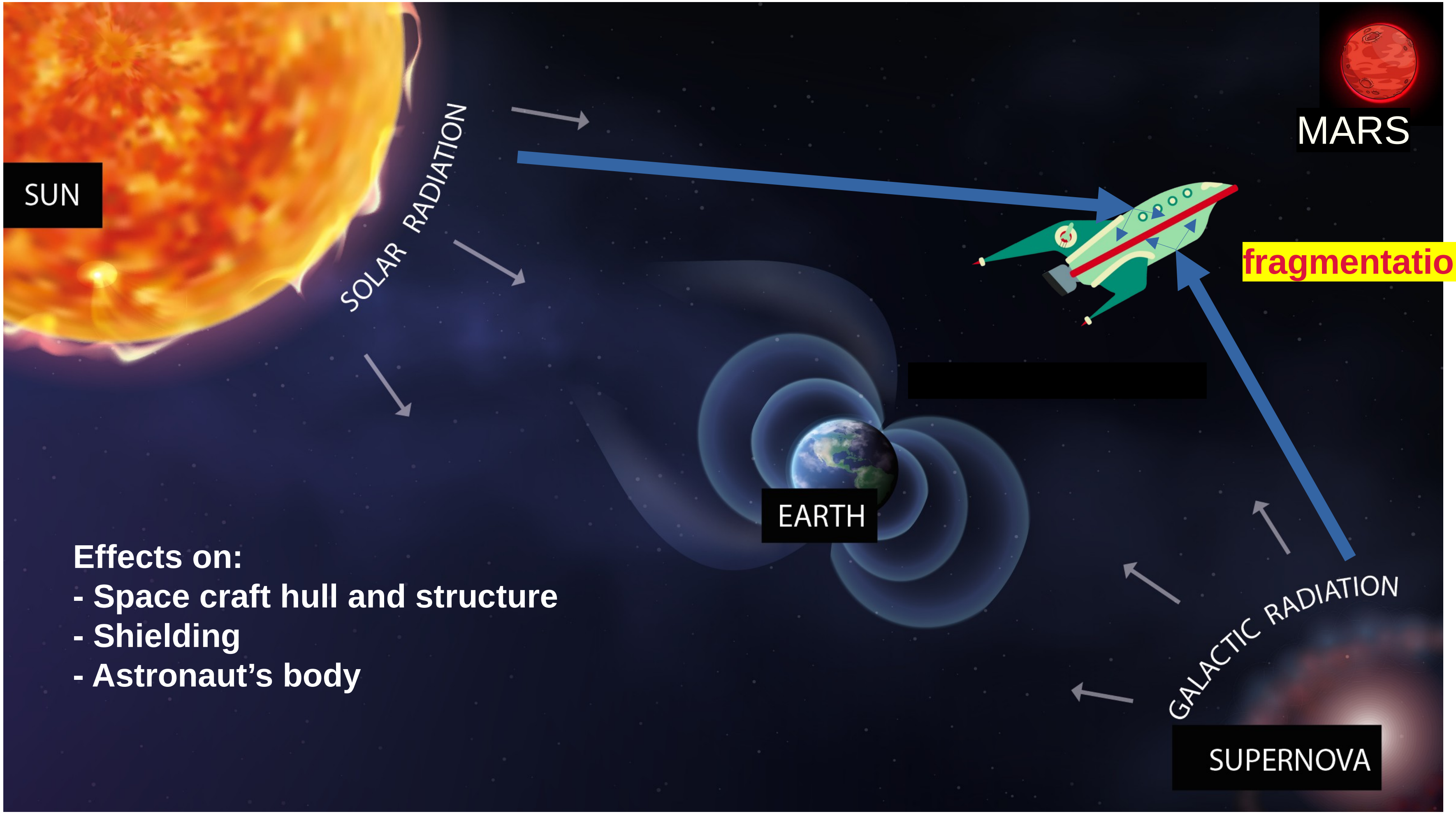
1% HZE

$0.001 < E < 10^{14}$ GeV/n

Space radioprotection



Space radioprotection



Space radioprotection