Cross sections update from GSI 2021 data

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XIII FOOT Collaboration Meeting, Perugia

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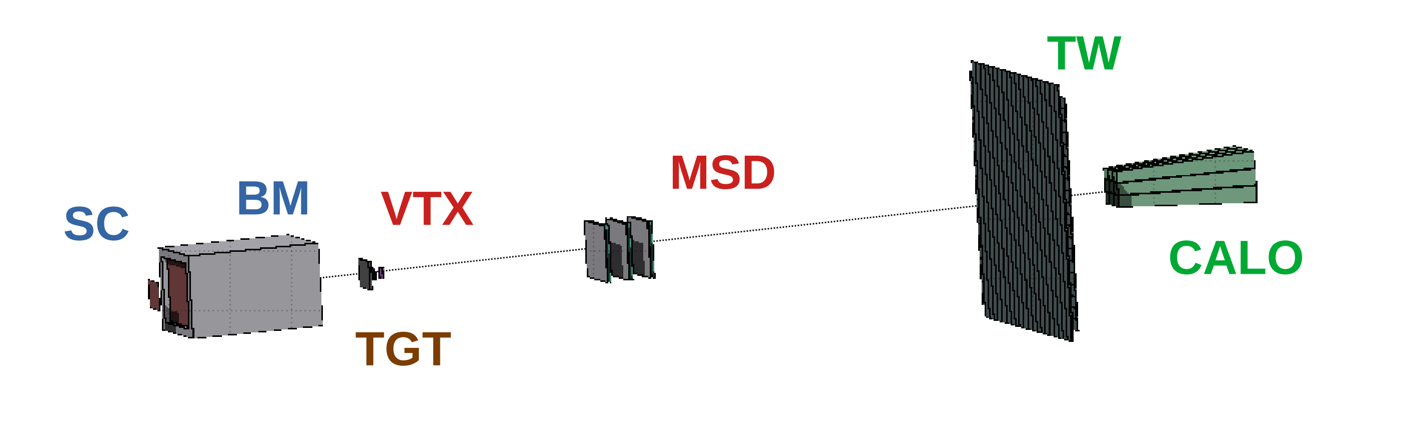
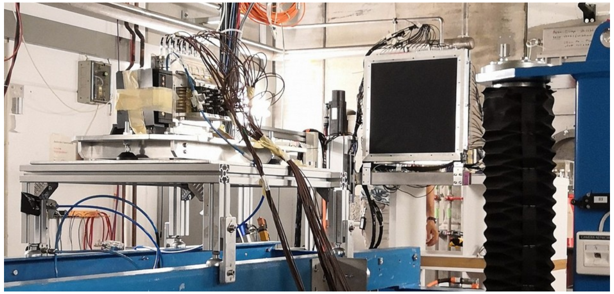
GSI 2021 Analysis

- 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





My analysis goal:

- Elemental fragmentation cross section measurements
- Angular differential cross section measurements for every charge

Analysis procedure

To compute elemental cross section and angular differential cross section:

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

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

Y: fragment counts

Bkg: background source counts

N_{beam}: n° of primary events

N_{target}: n° of scattering centers per unit area

ε: efficiency

Ω_ϑ: angular phase space

- Event reconstruction in **SHOE** with ***Global Tracking***
- Analysis procedure in **Python** code

Analysis procedure

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

1) Starting from a **MC dataset** of 10^6 events generated by FLUKA to simulate detectors and beams of GSI 2021 campaign.

Analysis procedure

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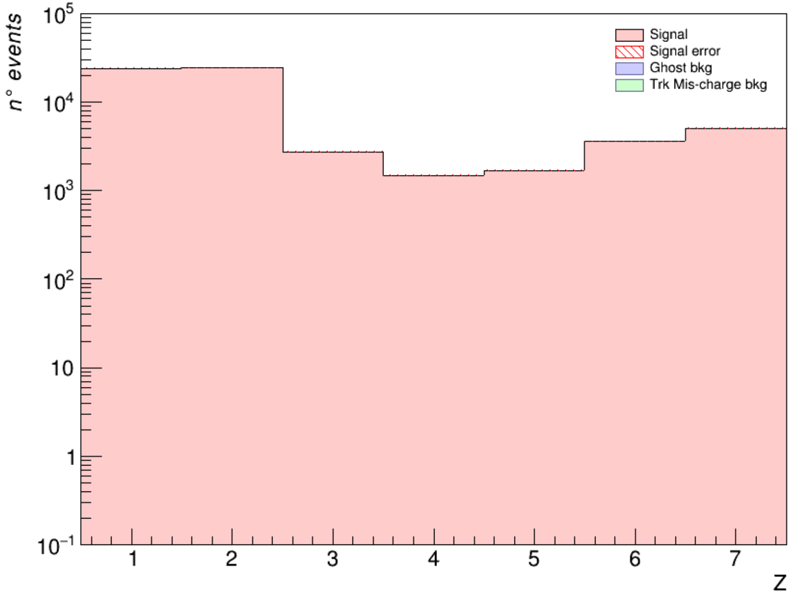
1) Starting from a **MC dataset** of 10^6 events generated by FLUKA to simulate detectors and beams of GSI 2021 campaign.

2) **Yield of Z** obtained from **reconstructed tracks**
   - Exploiting **tracking** reconstruction algorithm
   - Simulating a **"trigger"** in order to consider only fragments

Z yield and Bkg sources



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2) **Yield of Z** obtained from **reconstructed tracks**
   - Exploiting **tracking** reconstruction algorithm
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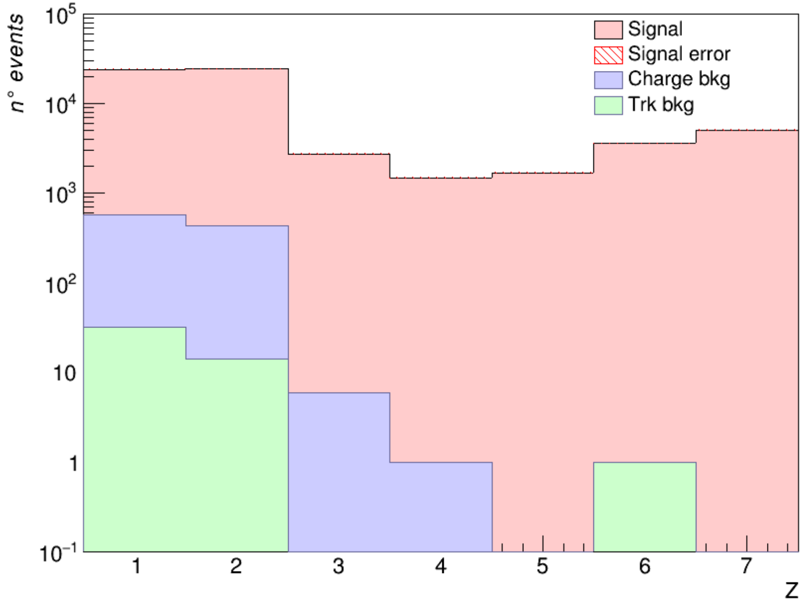
3) **Background** obtained from MC cuts on:
   - **Charge** algorithm mis-reconstruction
   - **Tracking** algorithm mis-reconstruction

Z yield and Bkg sources



Implementation of Unfolding

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

- Unfolding accomplish for events migration effect between bins and total efficiency correction.

$$y_i = M_{ij}\, x_j$$

Reconstructed distribution

Migration matrix

Unspoiled distribution

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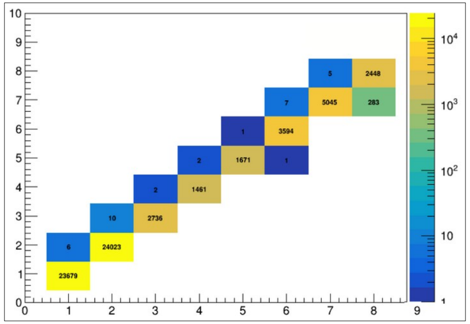
Reconstructed distribution

Unspoiled distribution



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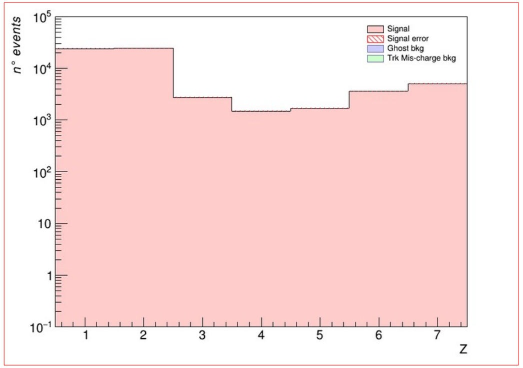

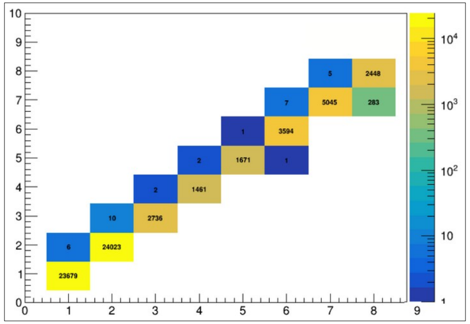

Unspoiled distribution

Implementation of Unfolding

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

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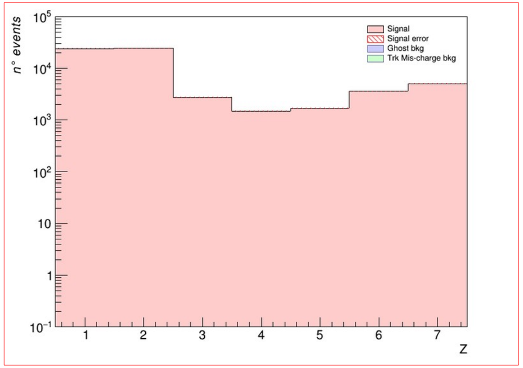
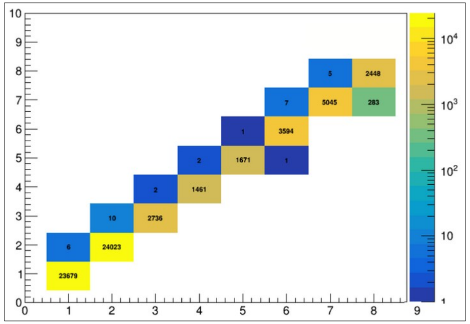




Unspoiled distribution

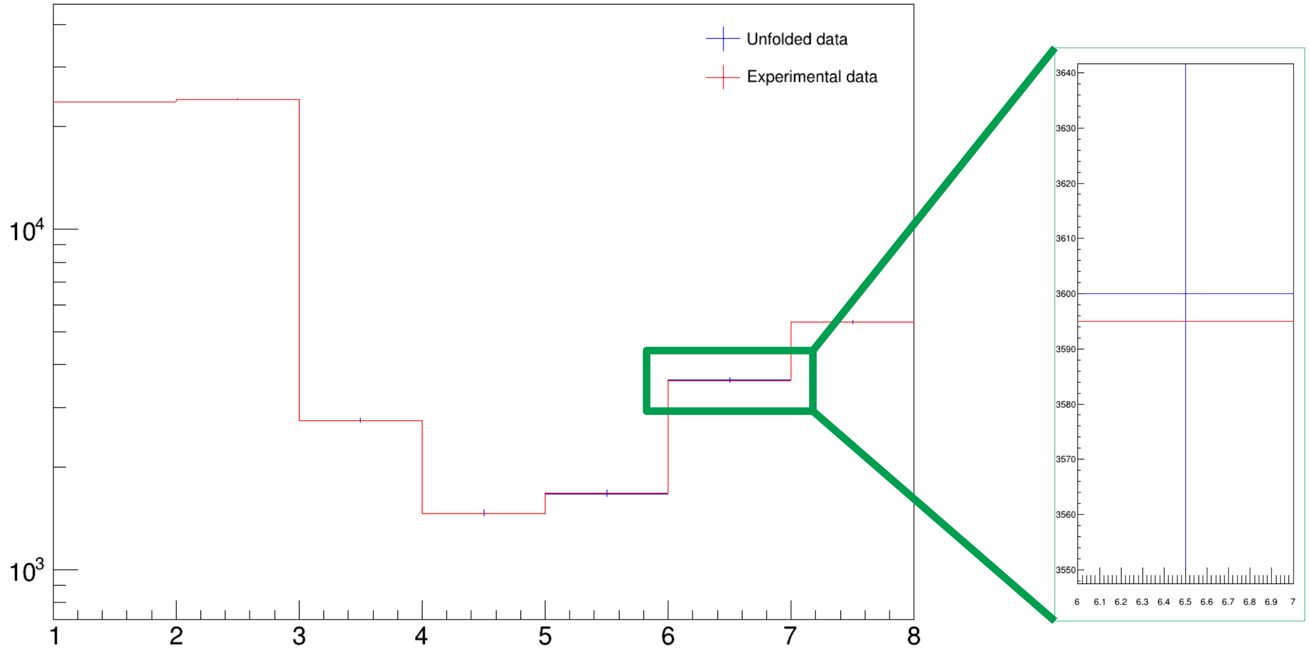
Then:

$$x_j = M_{ij}^{-1}\, y_i$$

- Application of **RooUnfold** library

Implementation of Unfolding

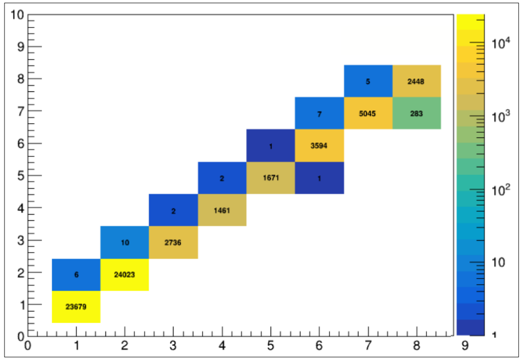
$$\sigma(Z) = \frac{\left(Y(Z) - B(Z) \right)^{U}}{N_{beam}\, N_{target}\, \epsilon(Z)}$$



$$y_i = M_{ij}\, x_j$$

$$x_j = M_{ij}^{-1}\, y_i$$

- Little variation because the migration matrix is very diagonal

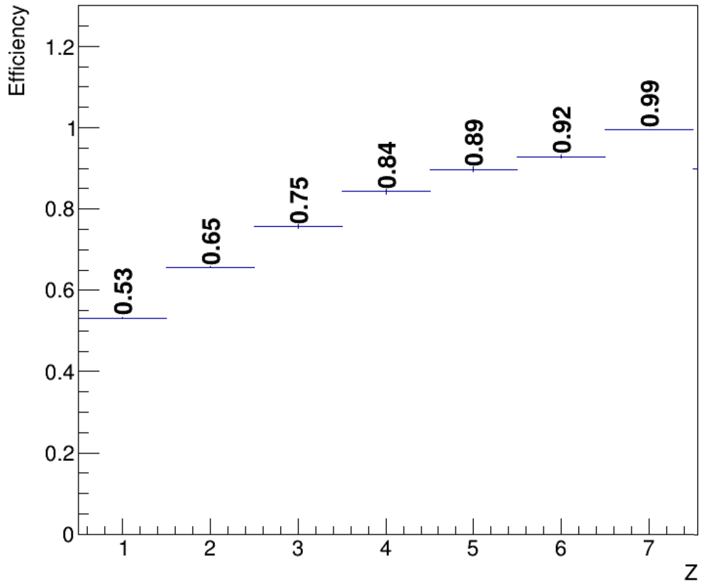


Analysis procedure

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

4) Track efficiency obtained as:

$$\boxed{\epsilon(Z) = \frac{N_{track}(Z)}{N_{true}(Z)}}$$



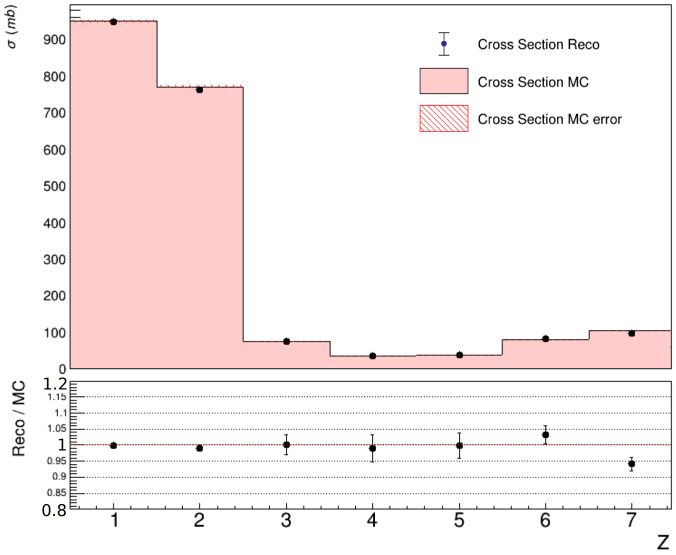
where

- N_{track} is obtained by tracking algorithm
- N_{true} are generated particles from the simulation with angular acceptance **θ≤8°**

MC Closure test - elemental cross section

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

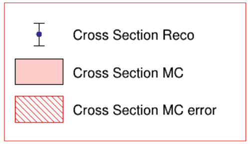
- **Fiducial** (**θ≤8°**) elemental cross section
- Only statistical errors
- comparing the MC data-like cross sections with the MC generated ones.
- understand the **reliability** of the analysis chain and algorithms ➔ **solid analysis**

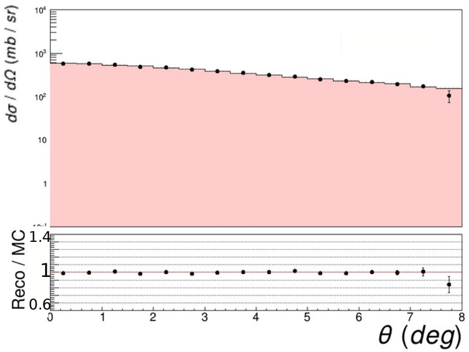


Charge	σ_{reco}(mb)	σ_{MC}(mb)
Z = 1	946 ± 9	949 ± 4
Z = 2	762 ± 7	770 ± 4
Z = 3	74.1 ± 1.3	74.1 ± 1.2
Z = 4	35.3 ± 1.5	35.2 ± 1.2
Z = 5	37.4 ± 1.6	37.2 ± 1.7
Z = 6	82.8 ± 1.7	79.3 ± 1.2
Z = 7	97.3 ± 1.4	103.0 ± 1.5

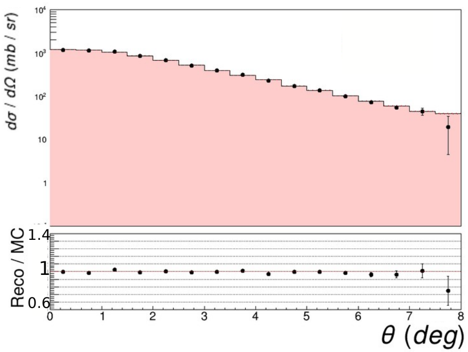
MC Closure test - angular differential cross section

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\theta} \cdot \frac{1}{sen(\theta) \cdot 2\pi}$$

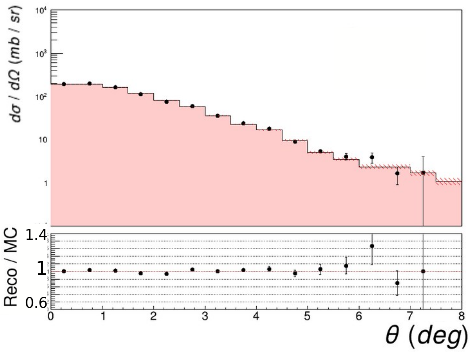




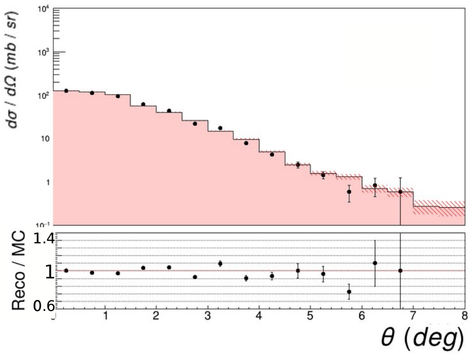
Z=1



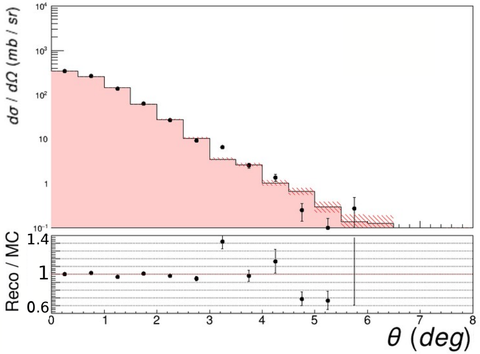
Z=2



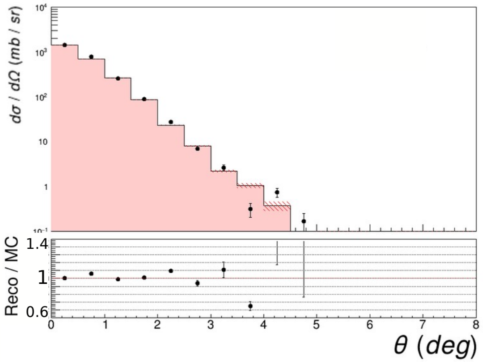
Z=3



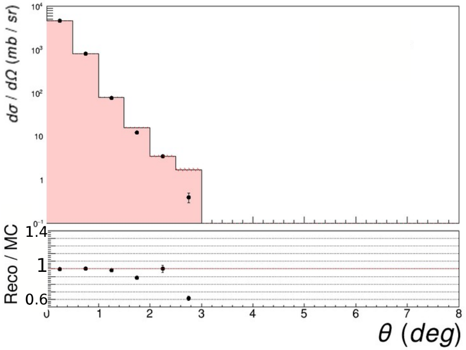
Z=4



Z=5



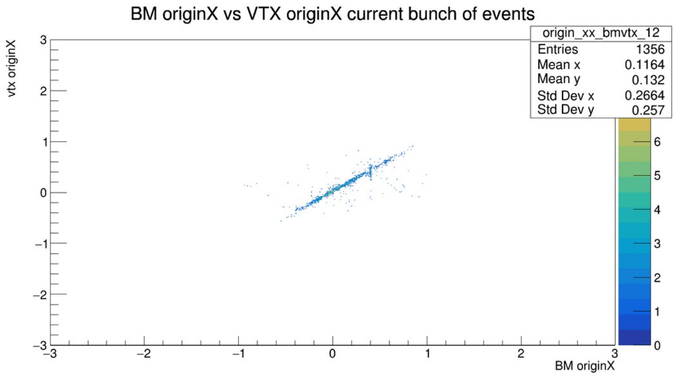
Z=6



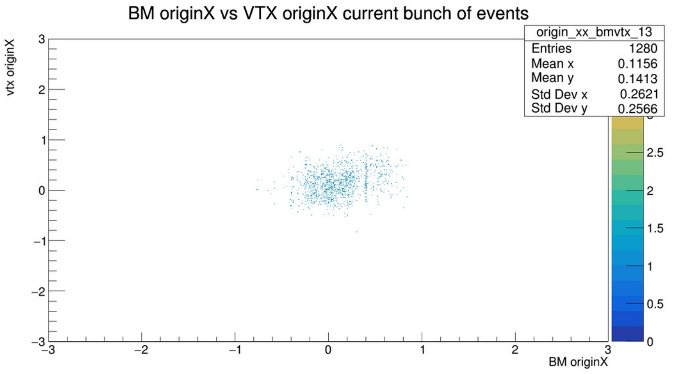
Z=7

Experimental data

- **run 4306 (Minimum Bias)**
- **Vertex synchronization up to 65k events:**



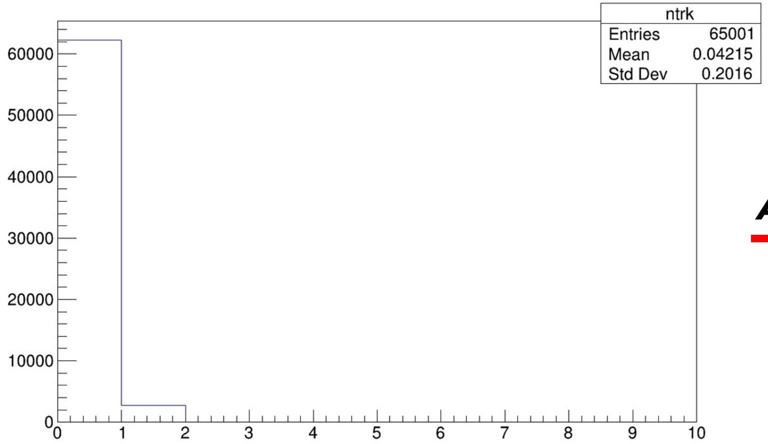
Bm-vtx correlation up to 65 k evts



Bm-vtx correlation from 65k to 75 k evts

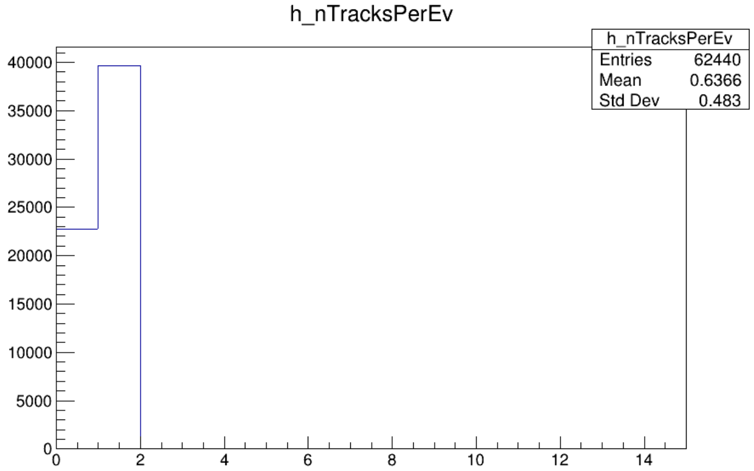
Alignment

- Very low inefficiency in tracking reconstruction



Only **3%** of events reconstructed with > 1 track

AlignFOOTMain.C



More than **60%** of events reconstructed with > 1 track

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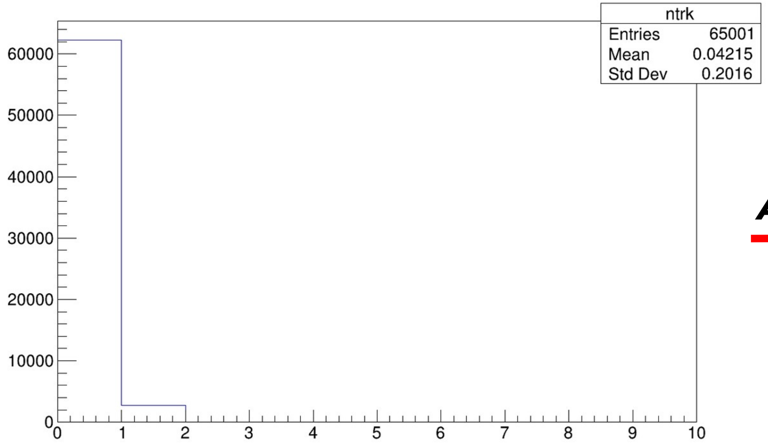

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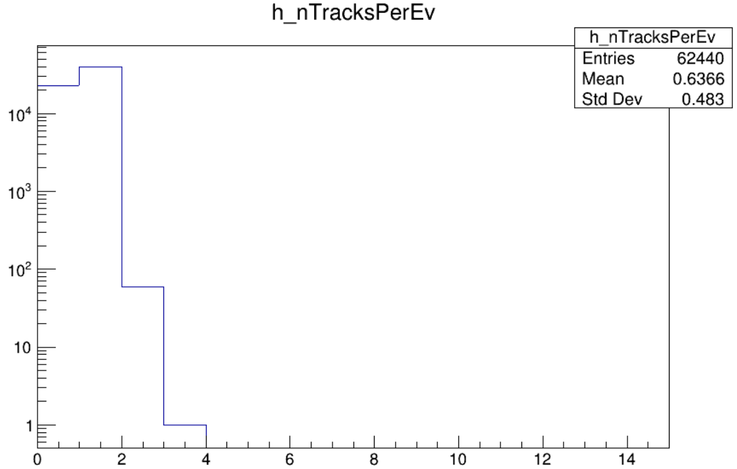
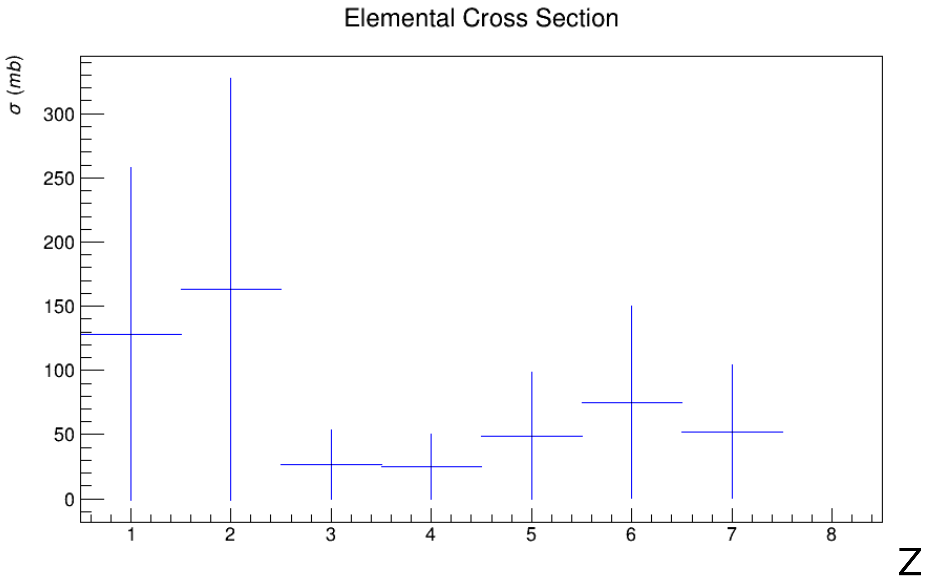


More than **60%** of events reconstructed with > 1 track

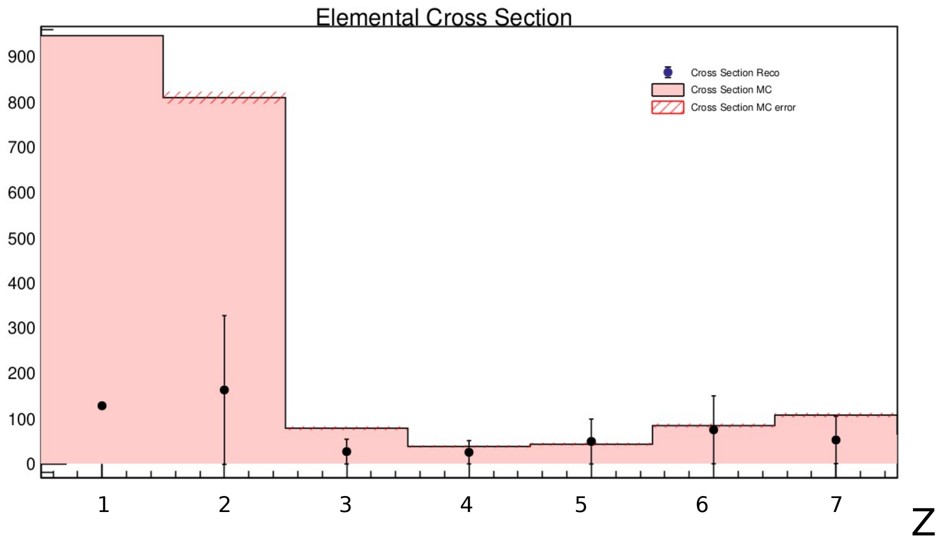
Experimental results - elemental cross section

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

- experimental results



- experimental results and comparison with MC

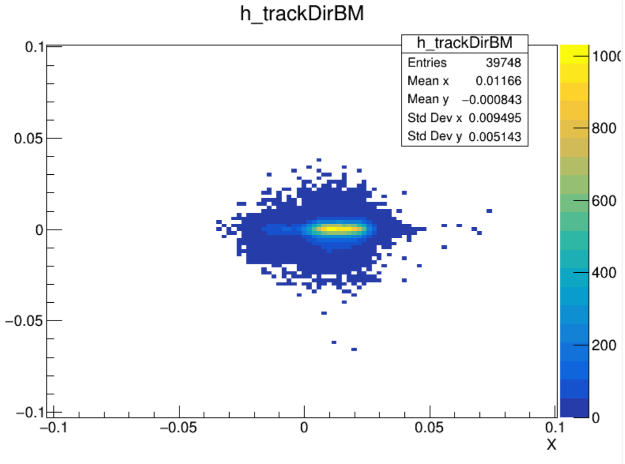


Highest discrepancy for elements with high angular distribution (see next)

Alignment – global track

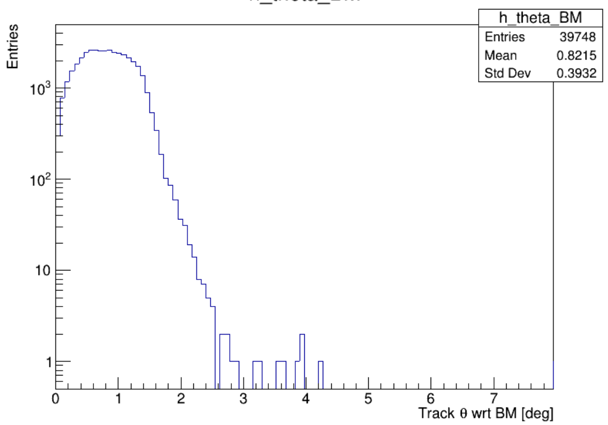
Reference system with beam (X,Y) in (0,0)

- Global tracks XY profile



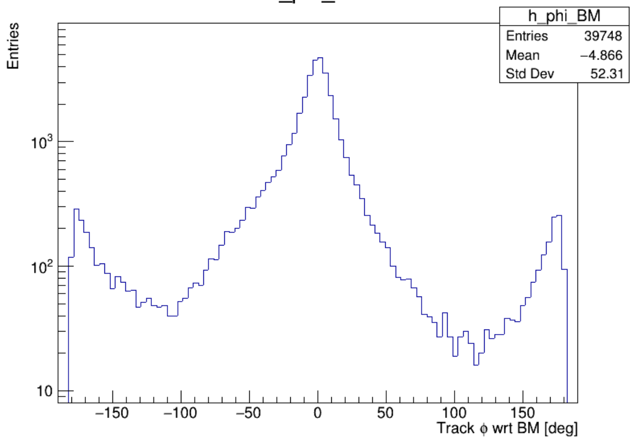
Shifted on X axis

- Global tracks theta angle



It seems only “straight” tracks are reconstructed

- Global tracks phi angle



Due to profile shape → favored direction

Experimental results - angular differential cross section

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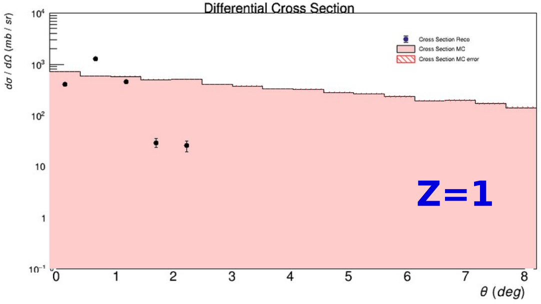
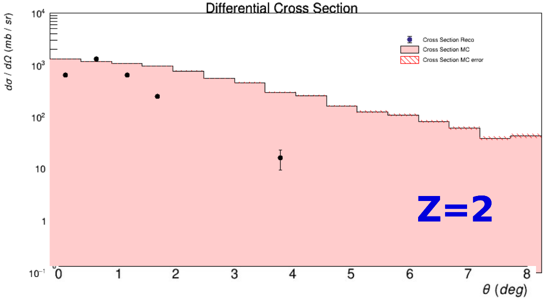
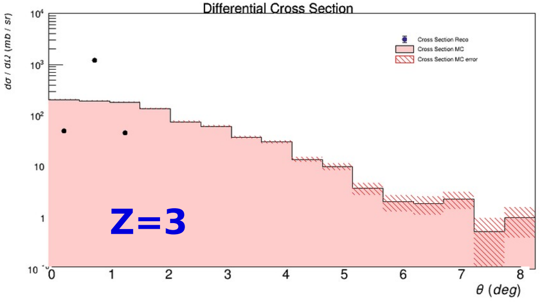
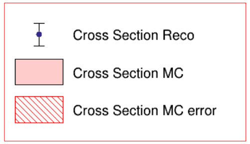
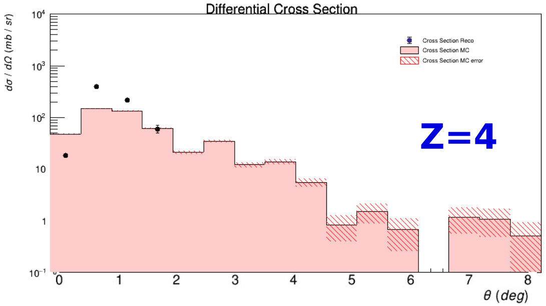
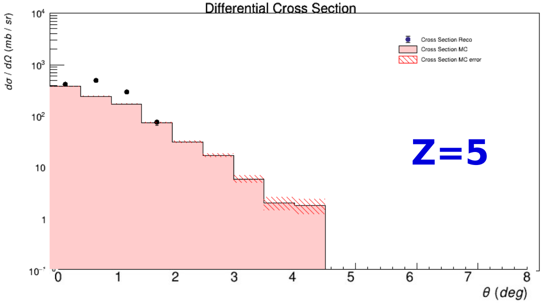


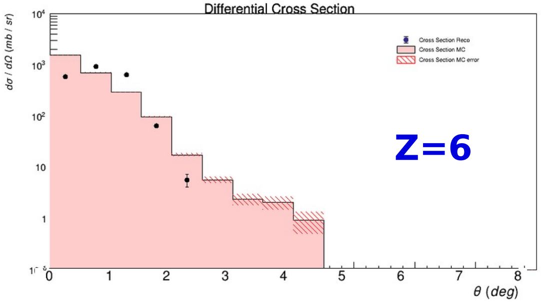


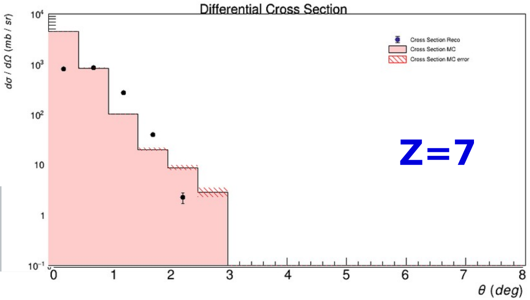












- **Highest agreement with high Z, whose angular distribution is more focalized around low angles**

Conclusions

- Analysis strategy checked by **MC** events with a **solid closure test**
- First preliminary results of **experimental** cross sections with full reconstruction algorithm

Future perspectives:

- **For the analysis:**

Increase the statistics

Including systematic uncertainties

Including unfolding to correct for migrations

- **For the global tracking reconstruction:**

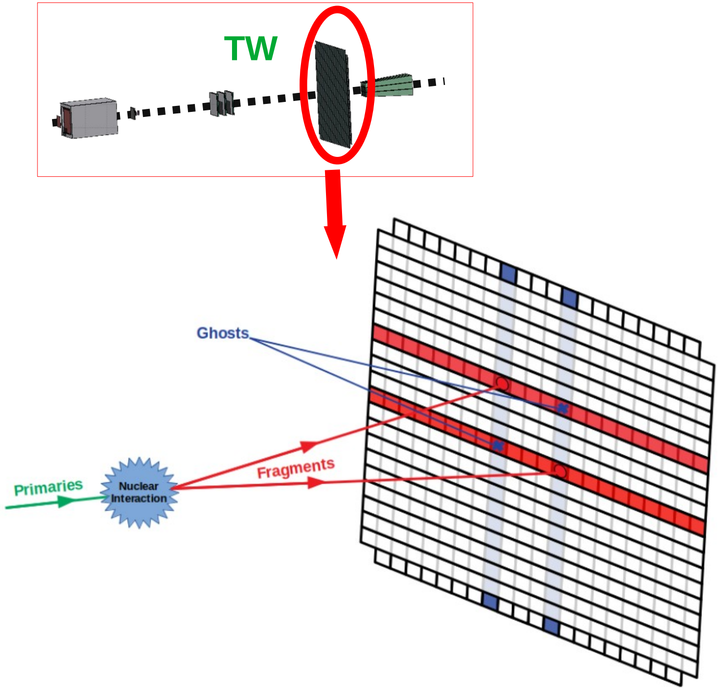
Deeper studies about alignment and detector components

Thank you for the attention

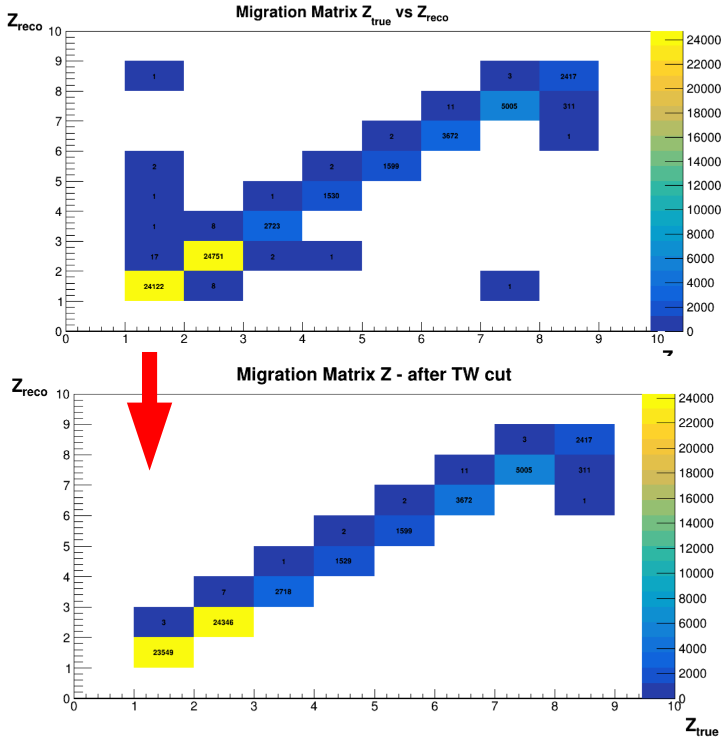
Backup slides

Example: Track reconstruction

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



Applying TW cut:
Matrix more diagonal

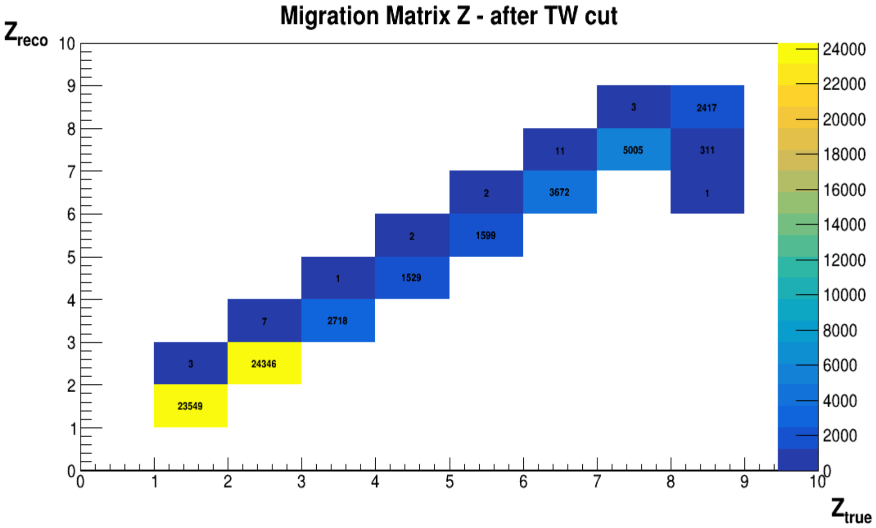


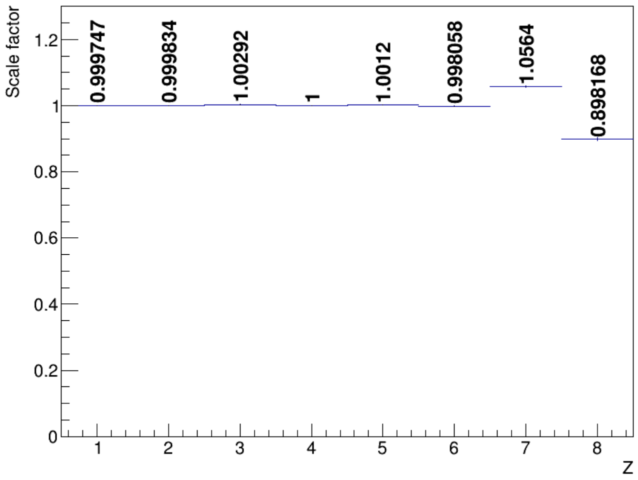
Analysis procedure

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

Migration matrix correction as scale factor:

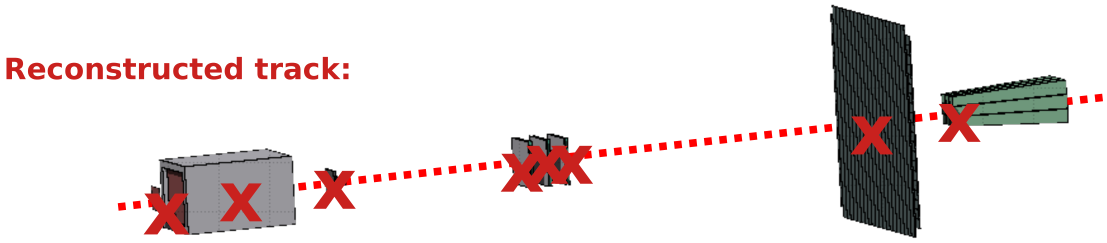
$$\gamma(Z) = \frac{Y(Z)_{reco} - Y(Z)^{mis}_{reco} + Y(Z)^{mis}_{gen}}{Y(Z)_{reco}}$$





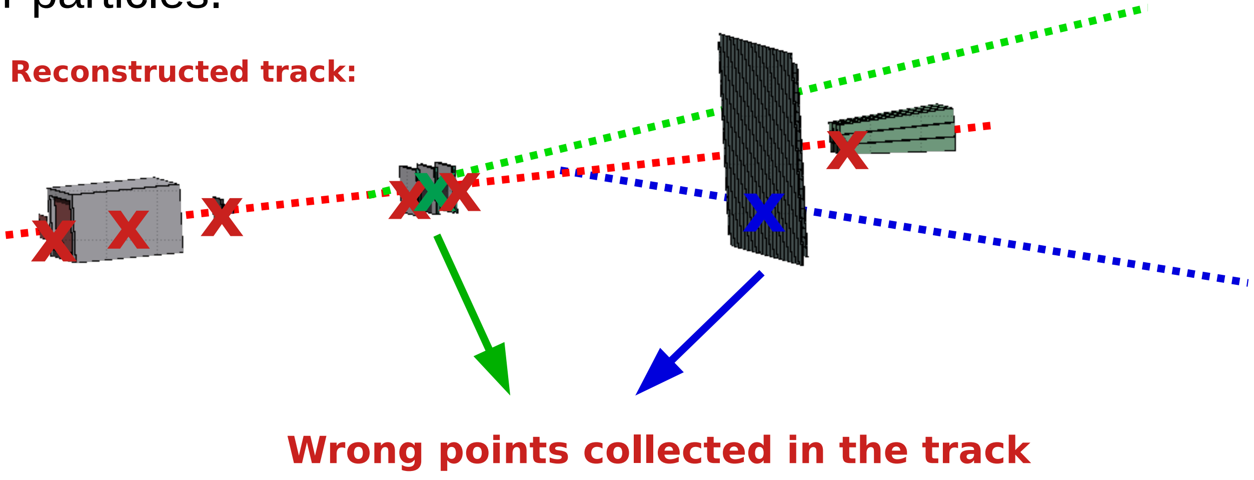
Reconstruction, Track Algo

- 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:



Reconstruction, Track Algo

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

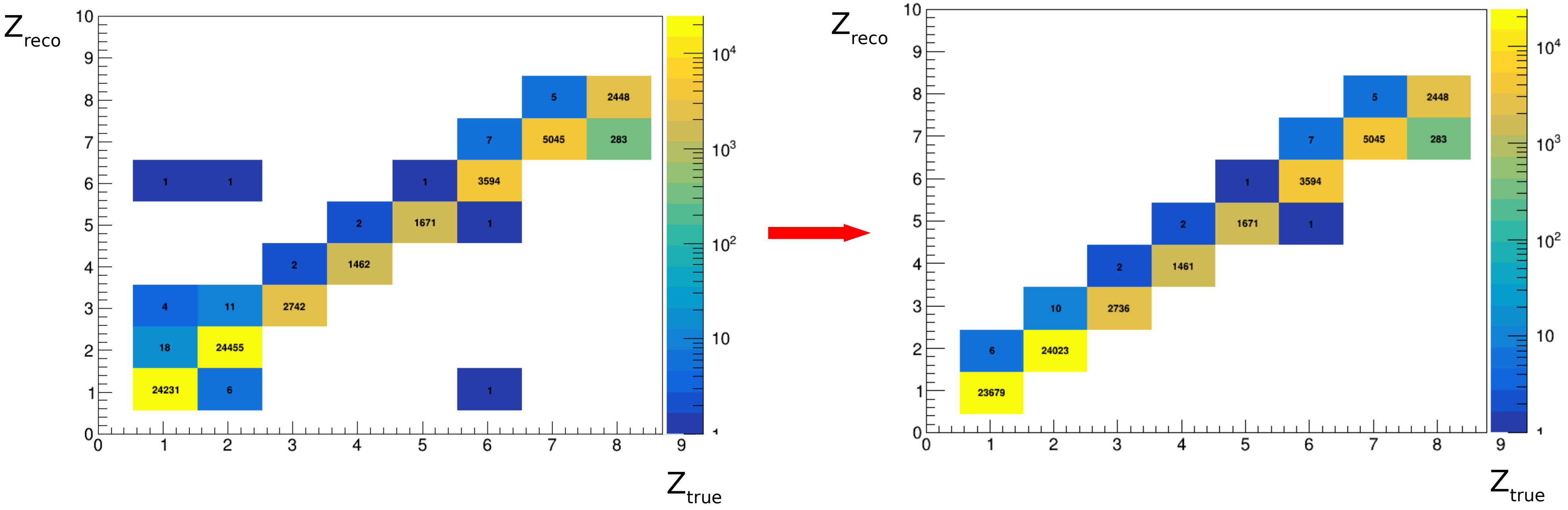


- The McId of the track is given by the most present particle in the collection
- However, if the TWPoint is of another particle → **its McId is different**
- → filter out all the tracks in which **$McId_{track} \neq McId_{TWPoint}$**

Analysis procedure

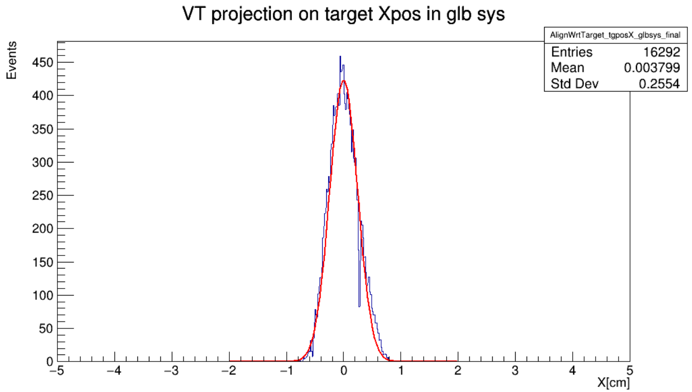
$$\sigma(Z) = \frac{Y(Z) - B(Z)}{N_{beam}\ N_{target}\ \epsilon(Z)}$$

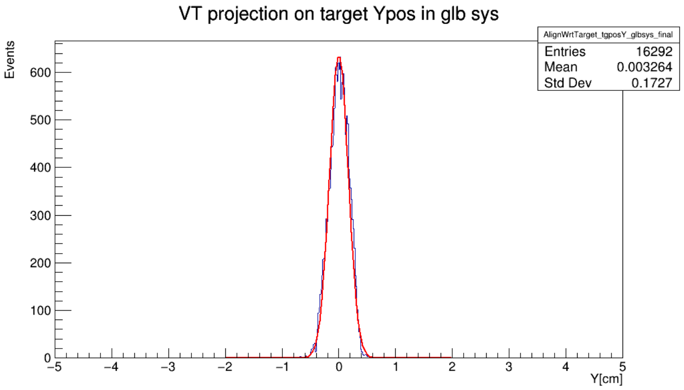
Before and after background removal: more diagonal migration matrix → **less noise sources**



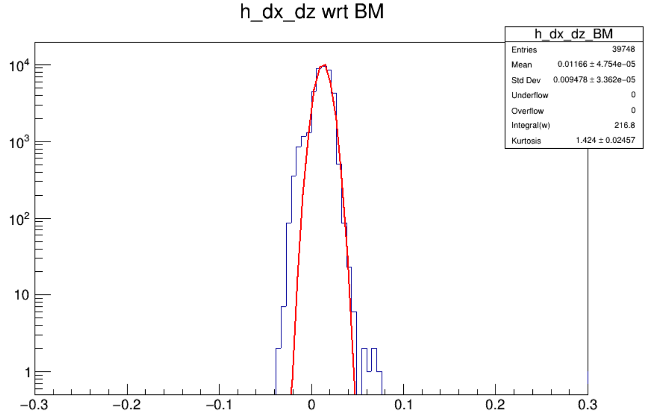
Backup slides

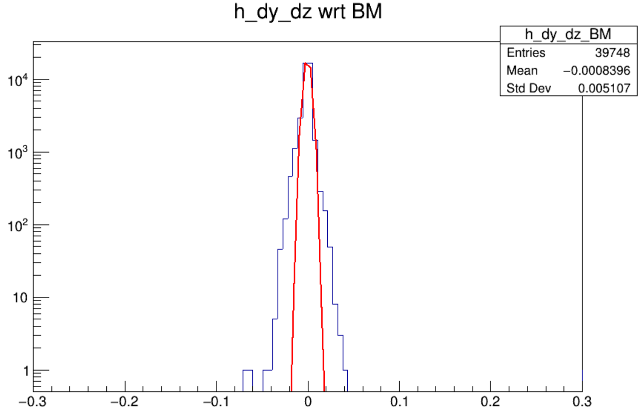
Alignment





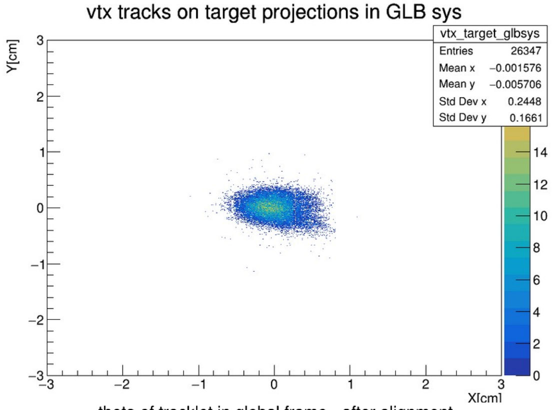
- VTX tracklets position wrt X,Y

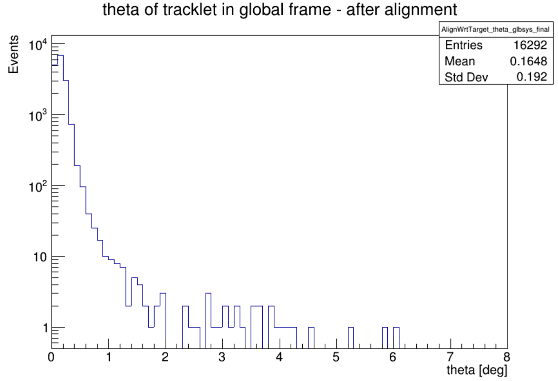


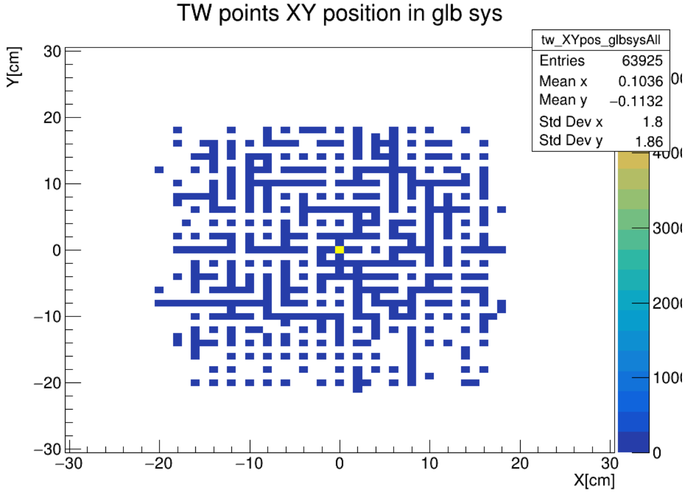


- Global tracks position wrt X,Y
  - Shift on X of 0.01 cm

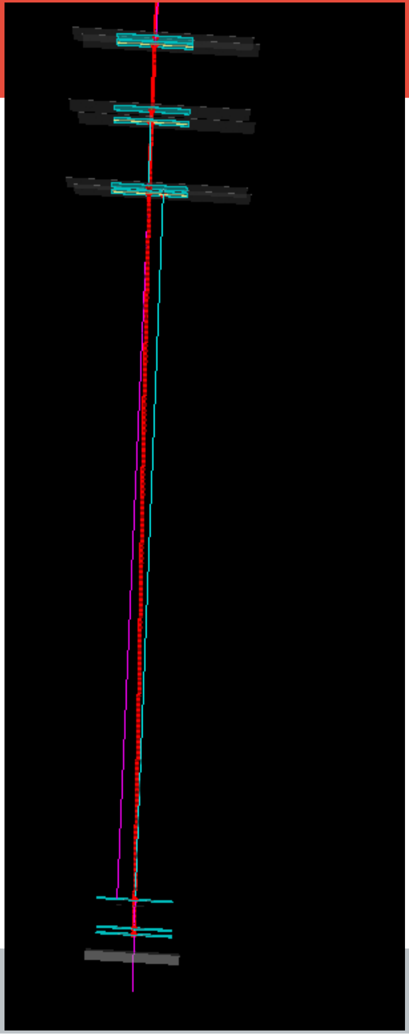
Alignment


vtx tracks on target projections in GLB sys
vtx_target_glbsys
Entries 26347
Mean x −0.001576
Mean y −0.005706
Std Dev x 0.2448
Std Dev y 0.1661
Y[cm]
X[cm]


theta of tracklet in global frame - after alignment
AlignWrtTarget_theta_glbsys_final
Entries 16292
Mean 0.1648
Std Dev 0.192
Events
theta [deg]


TW points XY position in glb sys
tw_XYpos_glbsysAll
Entries 63925
Mean x 0.1036
Mean y −0.1132
Std Dev x 1.8
Std Dev y 1.86
Y[cm]
X[cm]

Alignment events

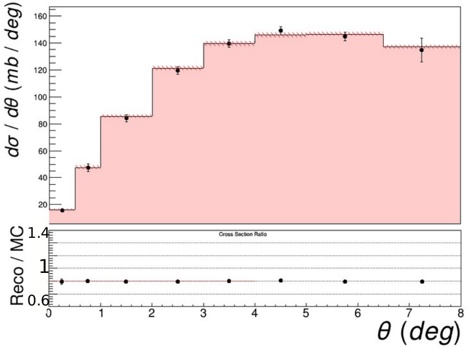


VTX and MSD are reciprocally tilted

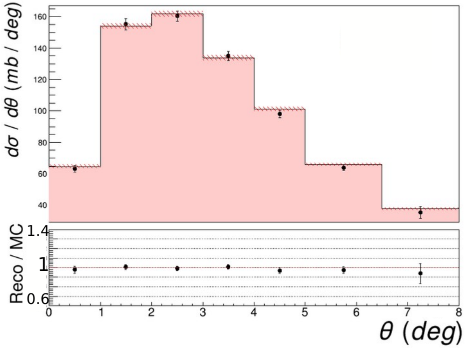
Backup slides

MC Closure test - angular differential cross section

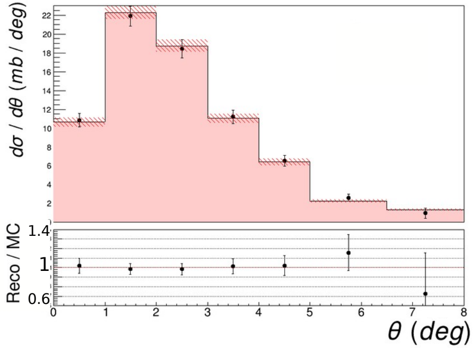
$$\frac{d\sigma}{d\theta}(Z,\theta) = \frac{Y(Z,\theta) - B(Z,\theta)}{N_{beam}\, N_{target}\, \Omega_\theta\, \epsilon(Z,\theta)}$$



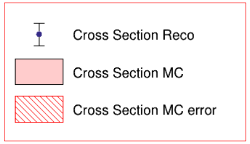
Z=1

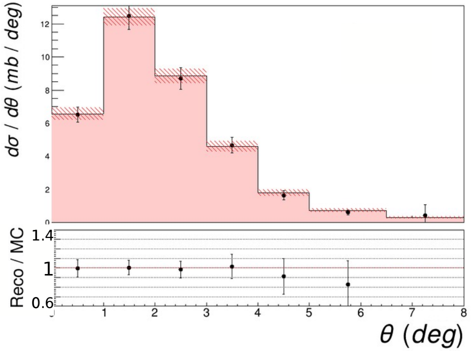


Z=2

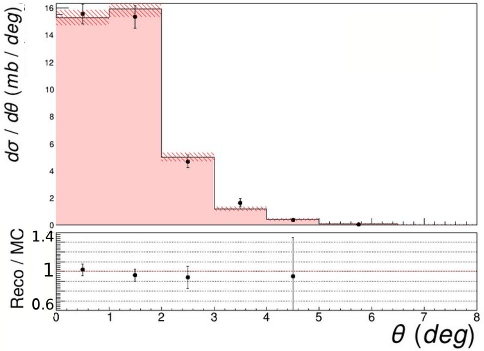


Z=3

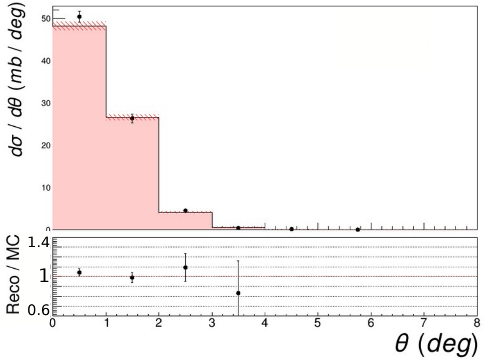




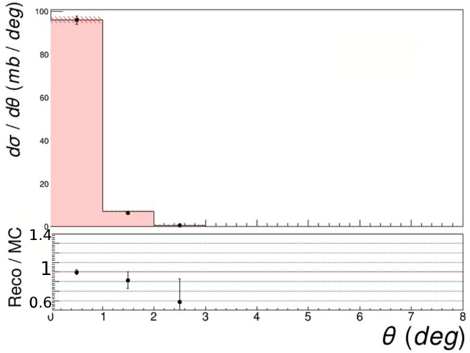
Z=4



Z=5

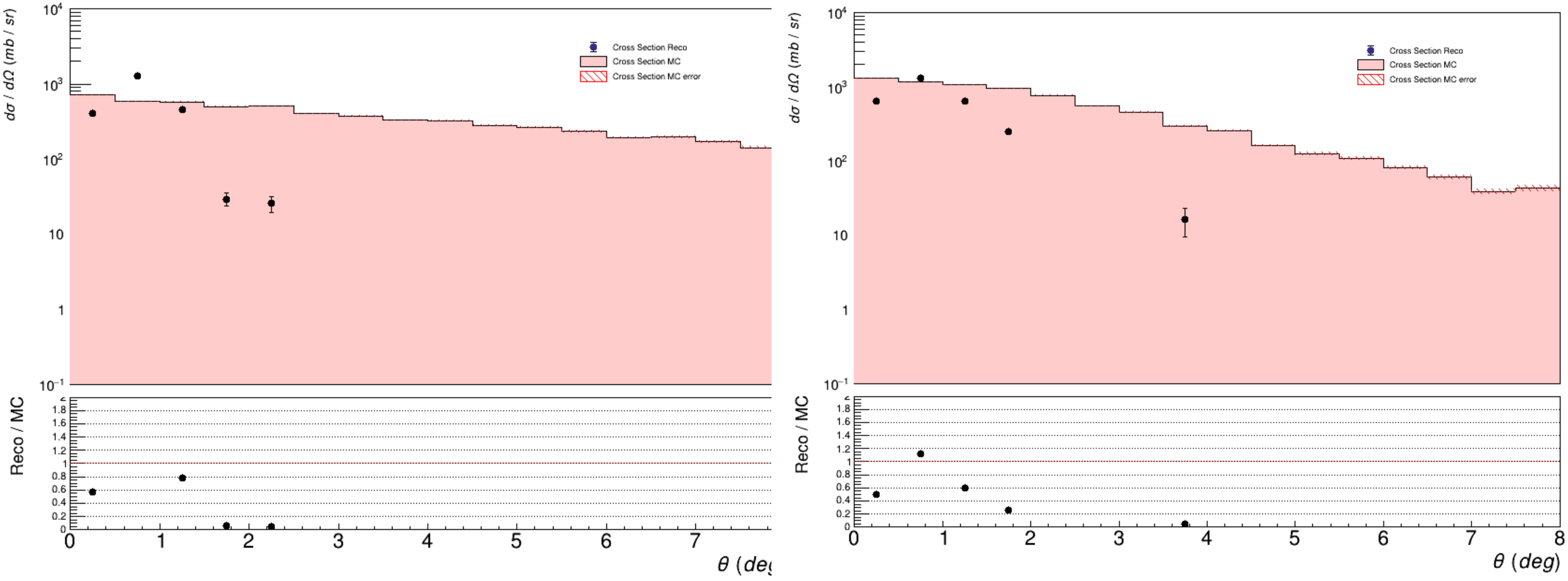


Z=6

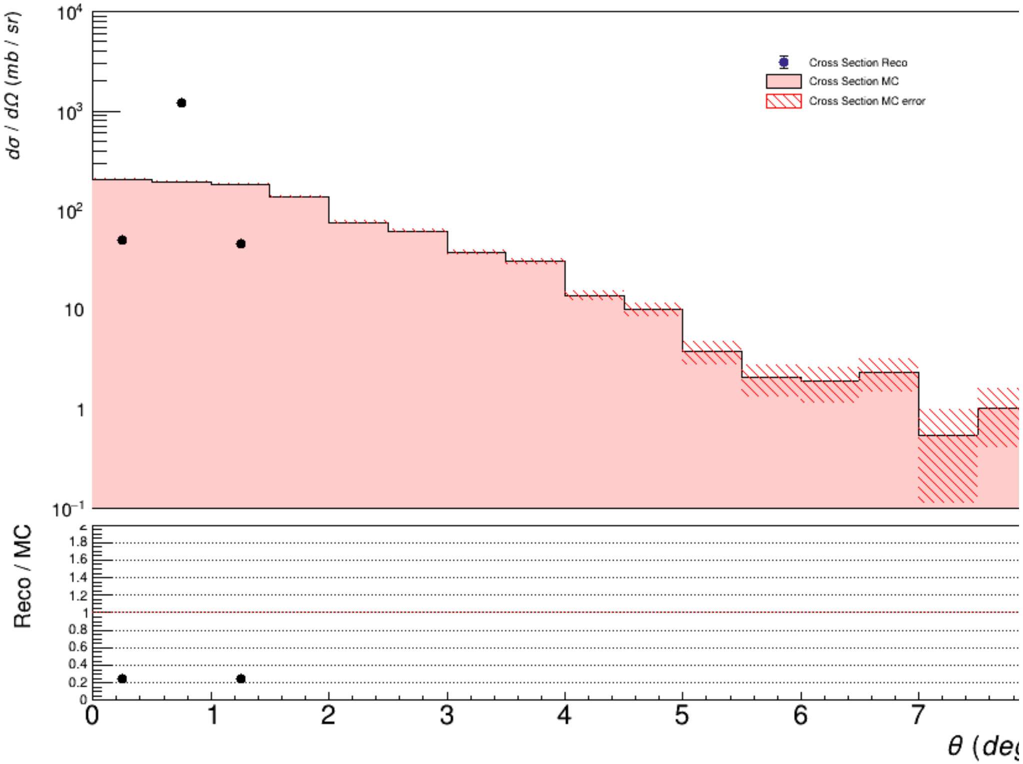


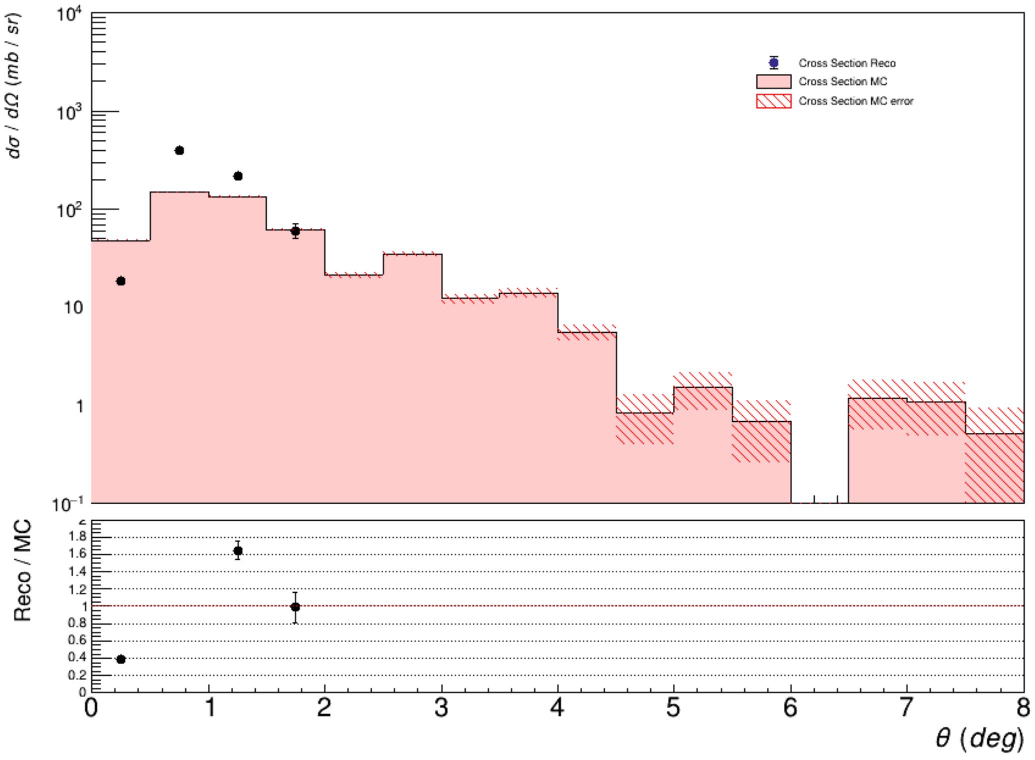
Z=7

Angular xsec, Z=1,2

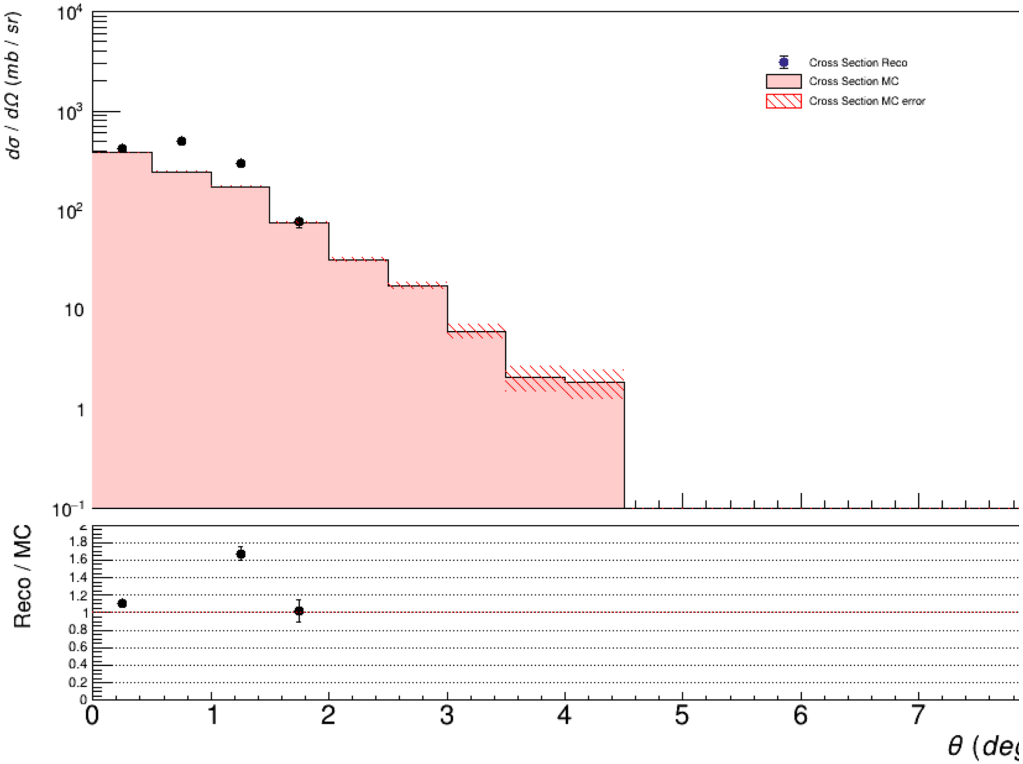


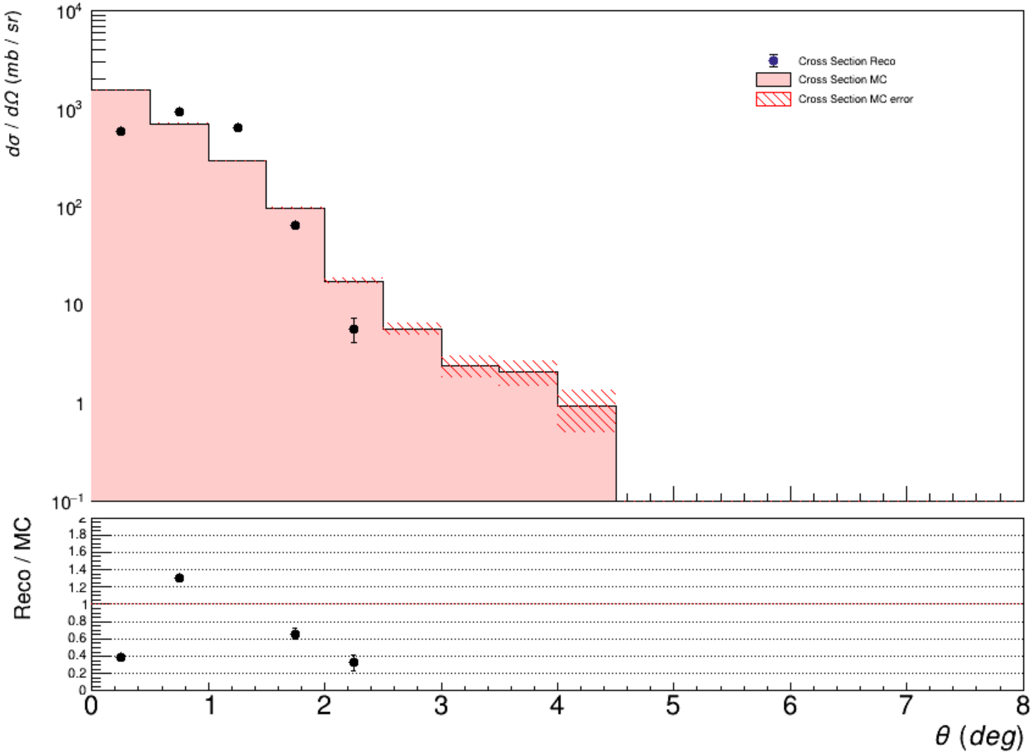
Angular xsec, Z=3,4



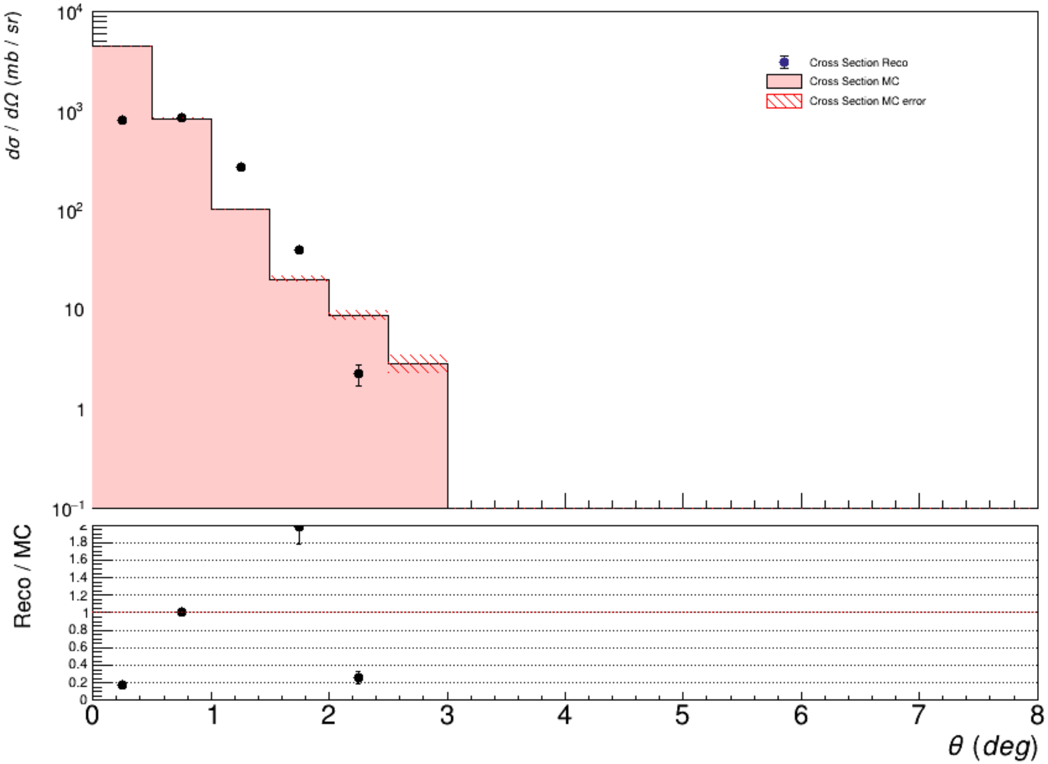


Angular xsec, Z=5,6



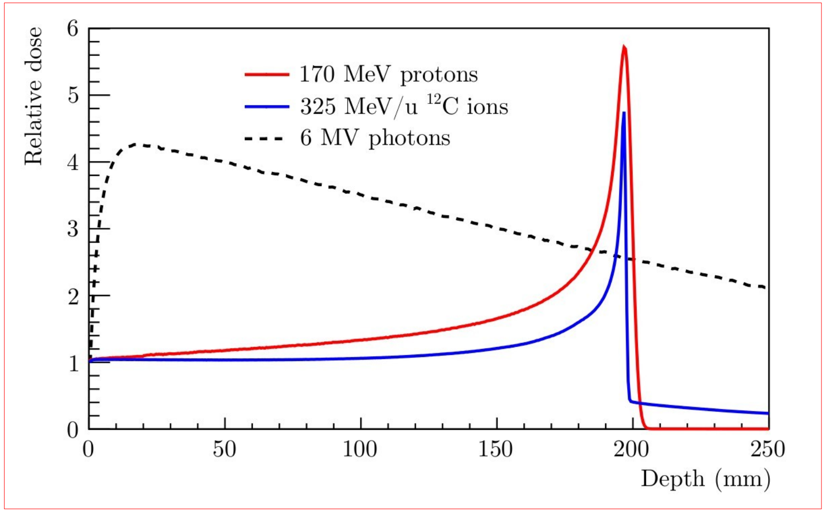


Angular xsec, Z=7

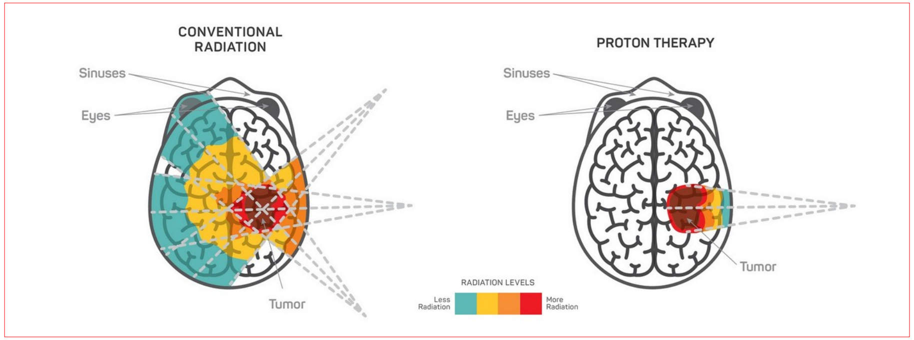


Backup slides

FOOT Applications



- **Hadrontherapy** treatments: *up to 400 MeV/n*
  sparing of healthy tissues

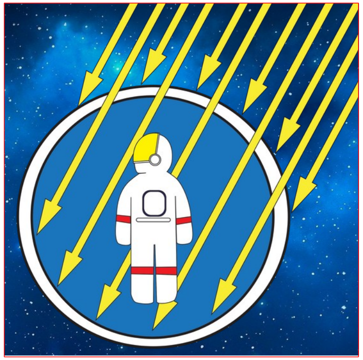


Charged particles interaction with matter:

✓ **Localized dose profile**

✗ **Nuclear Fragmentation**

- **Space radioprotection**:
  up to 800 MeV/n
  shielding from charged fragments in space

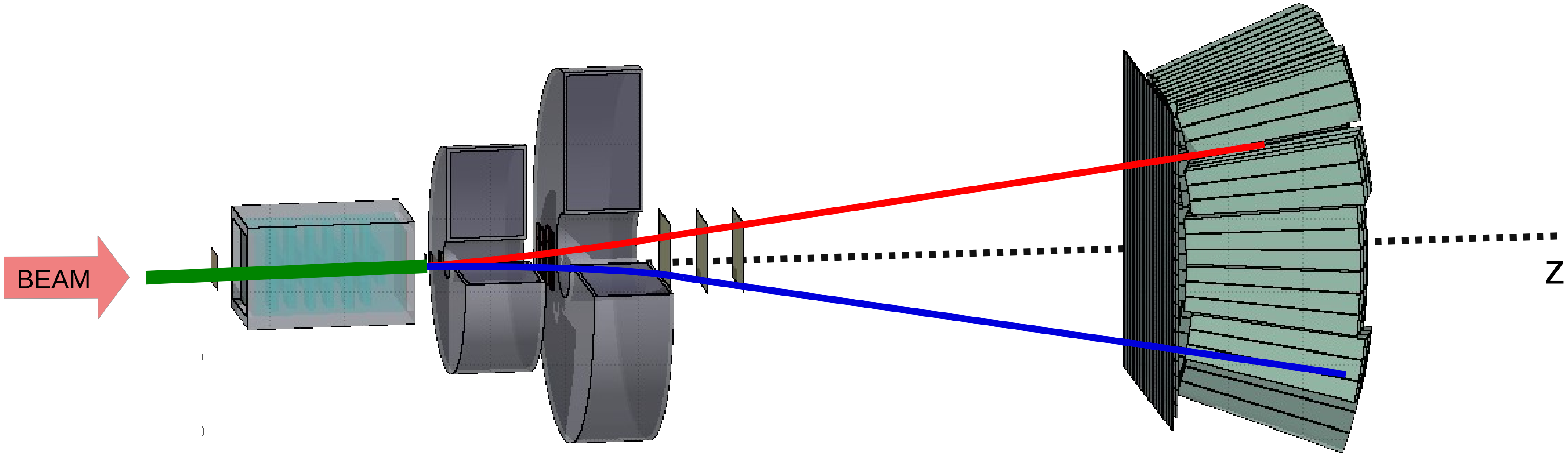


The FOOT experiment

Goal:

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

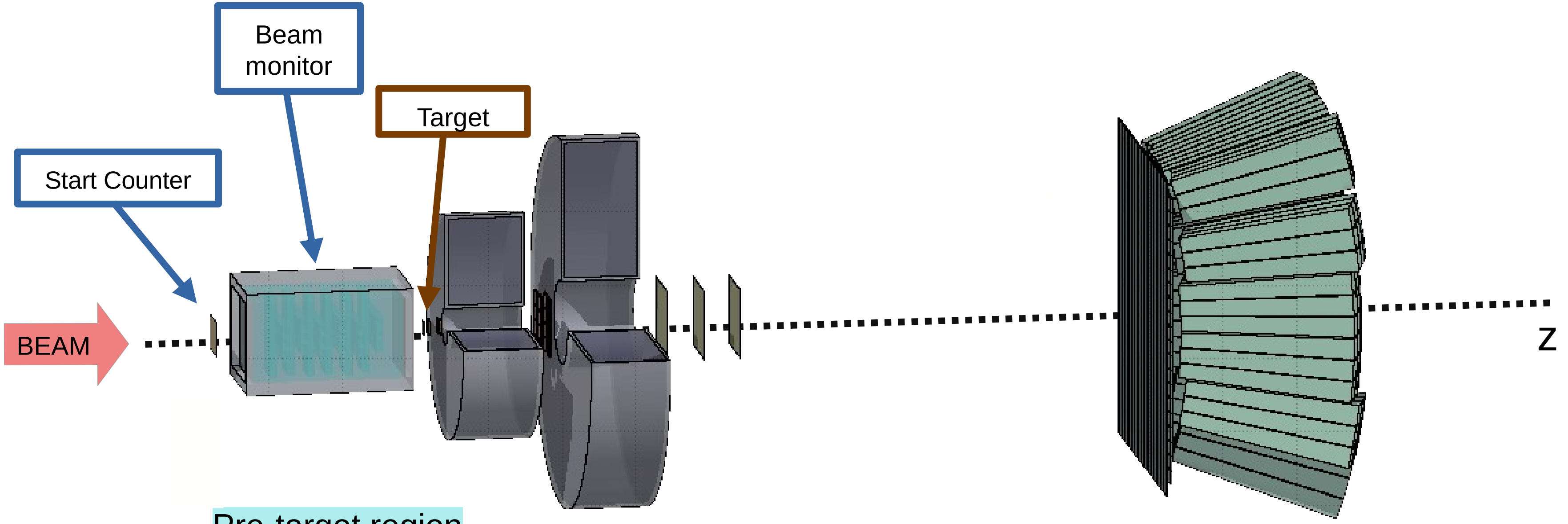
- Fixed target collisions
- Beam energies between 200 MeV/u and 800 MeV/u for **hadrontherapy** and **space radioprotection** topics
- **table top setup** to be moved according to beam facility availability



The FOOT experiment

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

- Particle identification by measuring all kinematic quantities

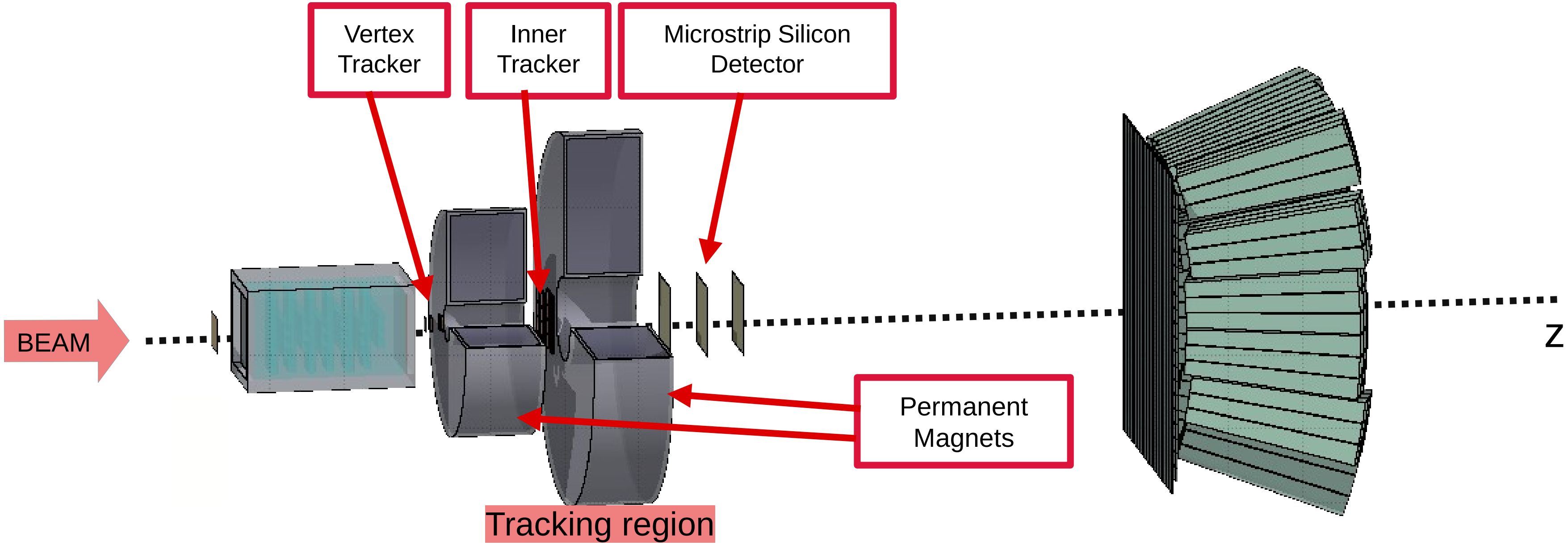


Pre-target region

The FOOT experiment

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

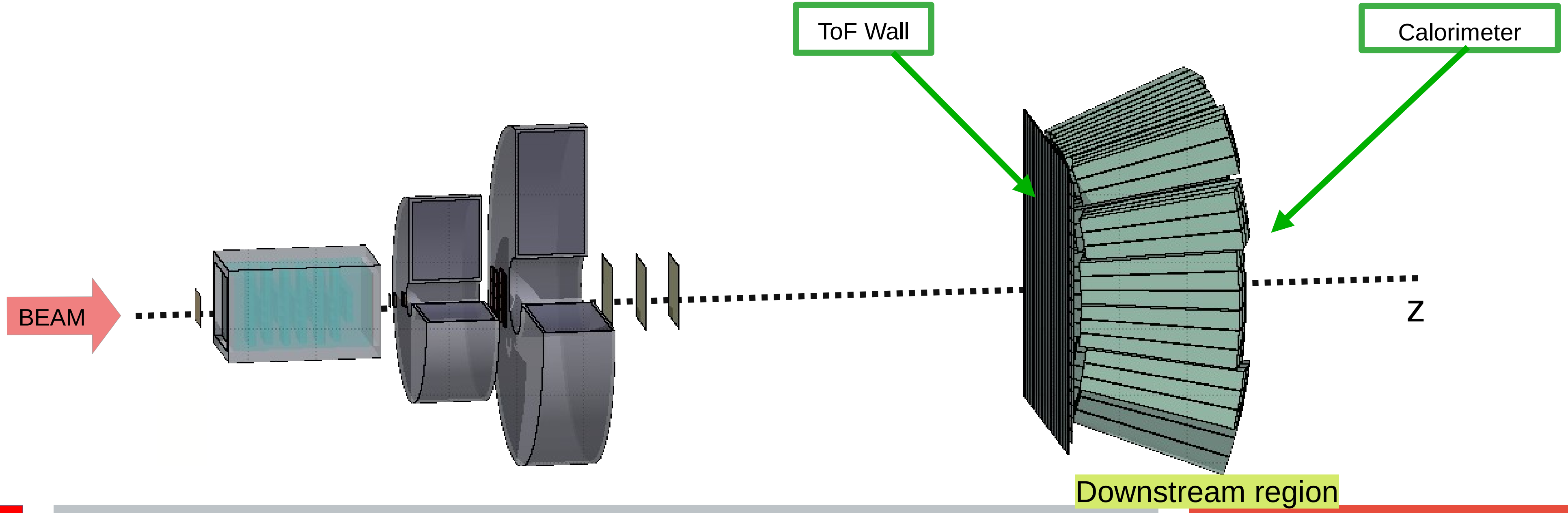
- Particle identification by measuring all kinematic quantities



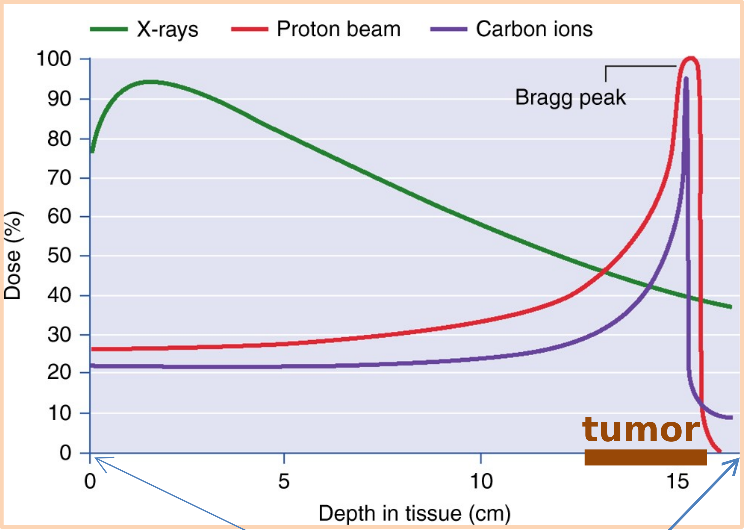
The FOOT experiment

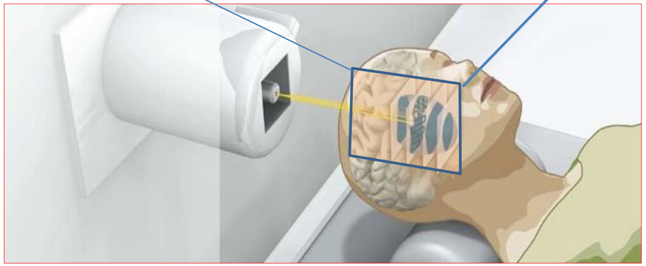
Goal:
Double differential nuclear fragmentation cross section $$\frac{d^2\sigma}{d\Omega\, dE_{kin}}$$ with resolution better than 5%

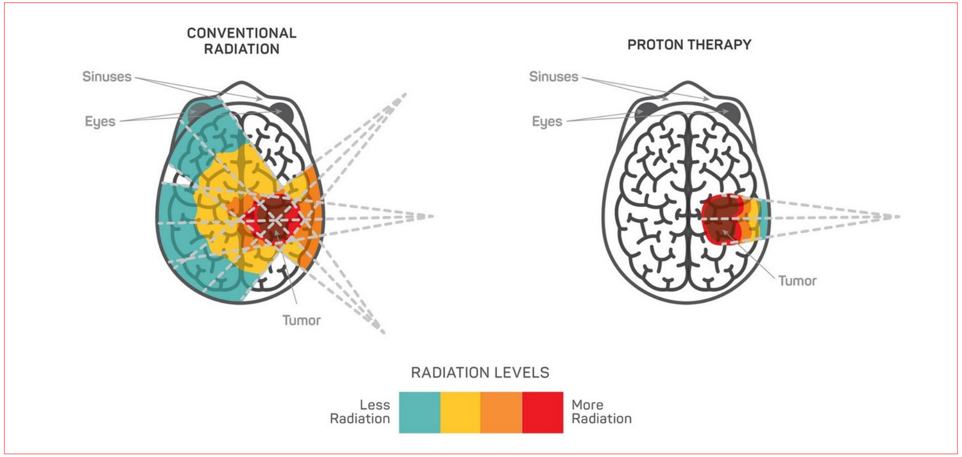
- Particle identification by measuring all kinematic quantities



Hadrontherapy



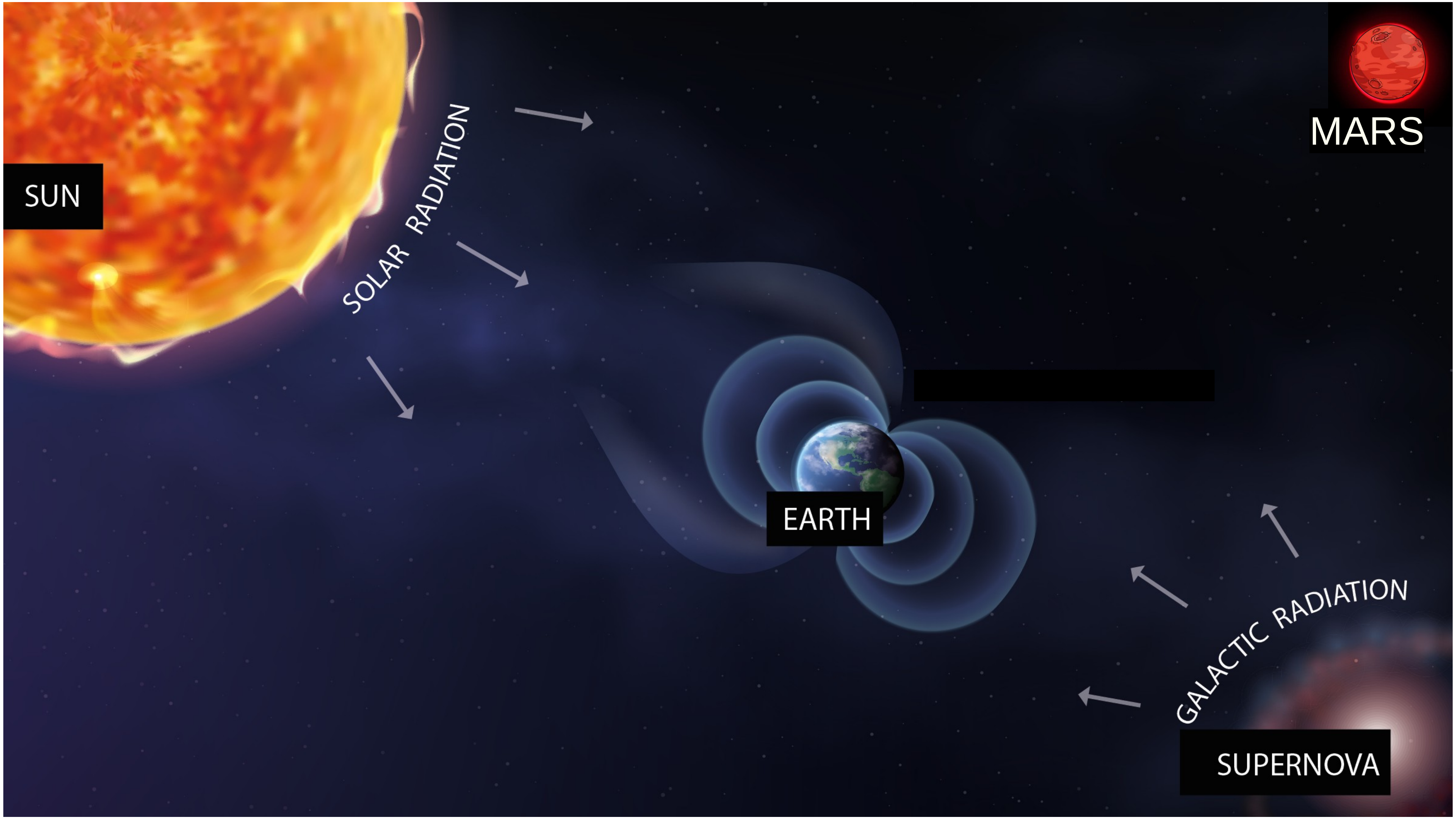




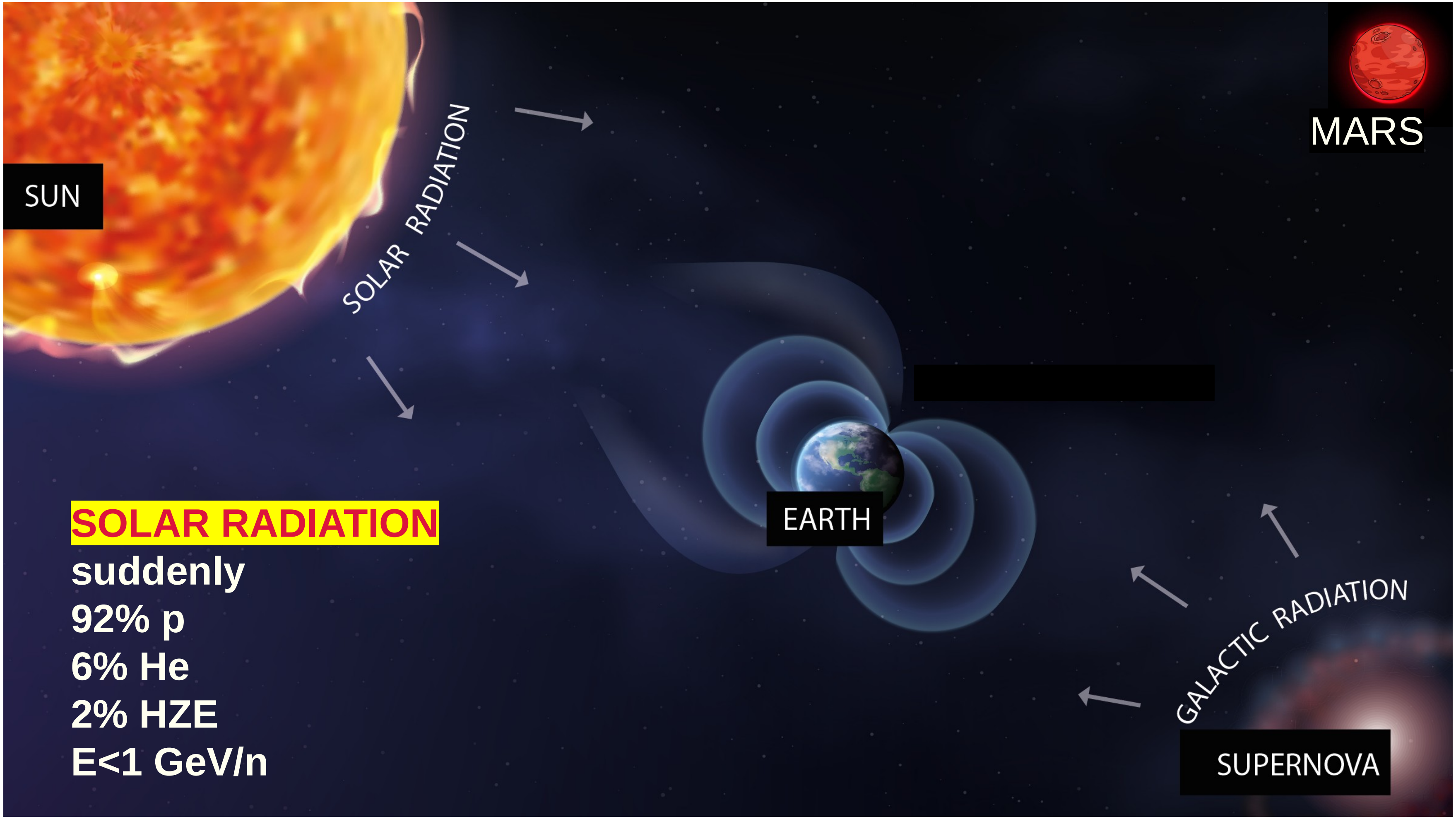
Hadrontherapy vs radiotherapy:

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

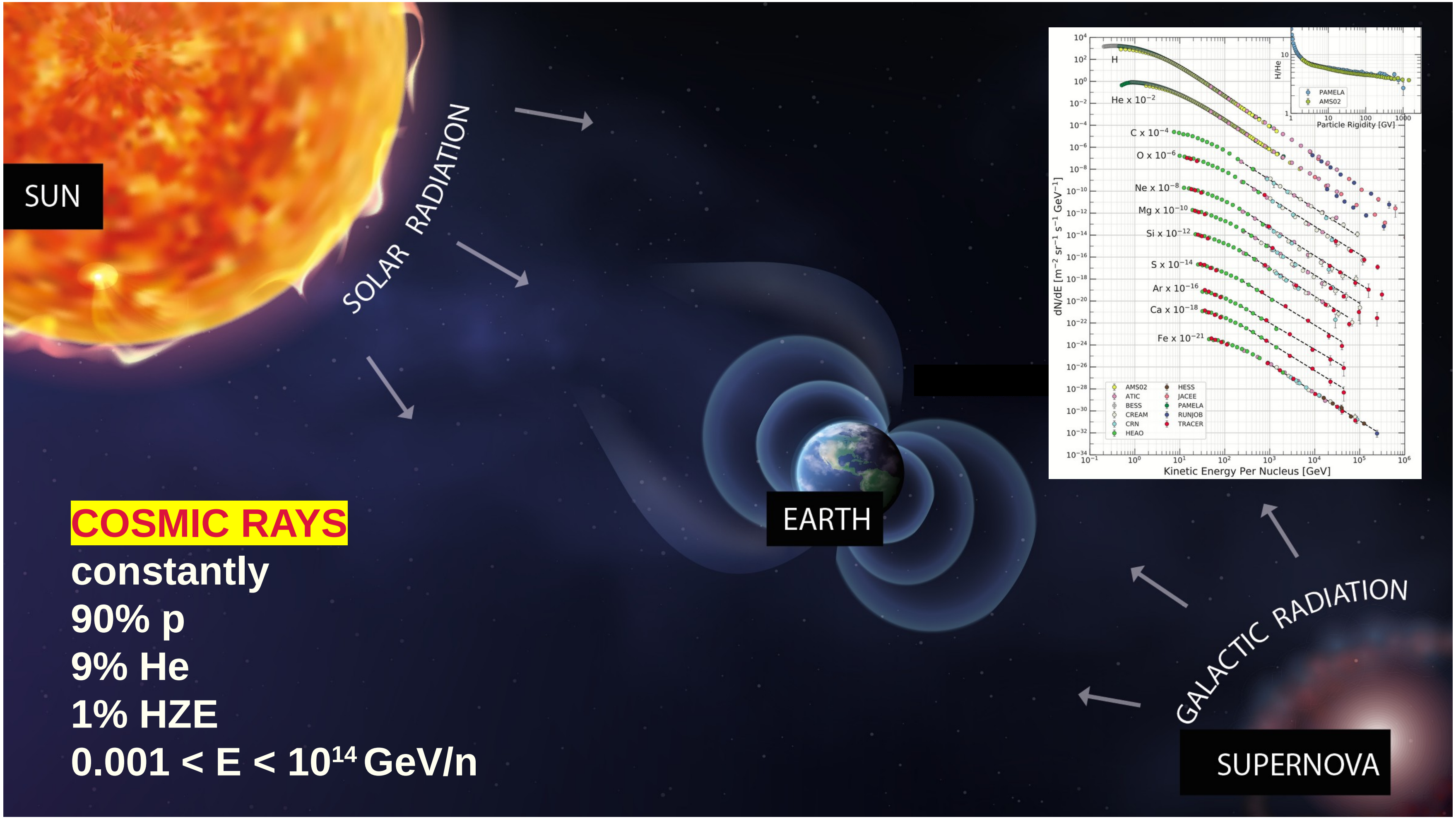
Space radioprotection



Space radioprotection



Space radioprotection



COSMIC RAYS

constantly

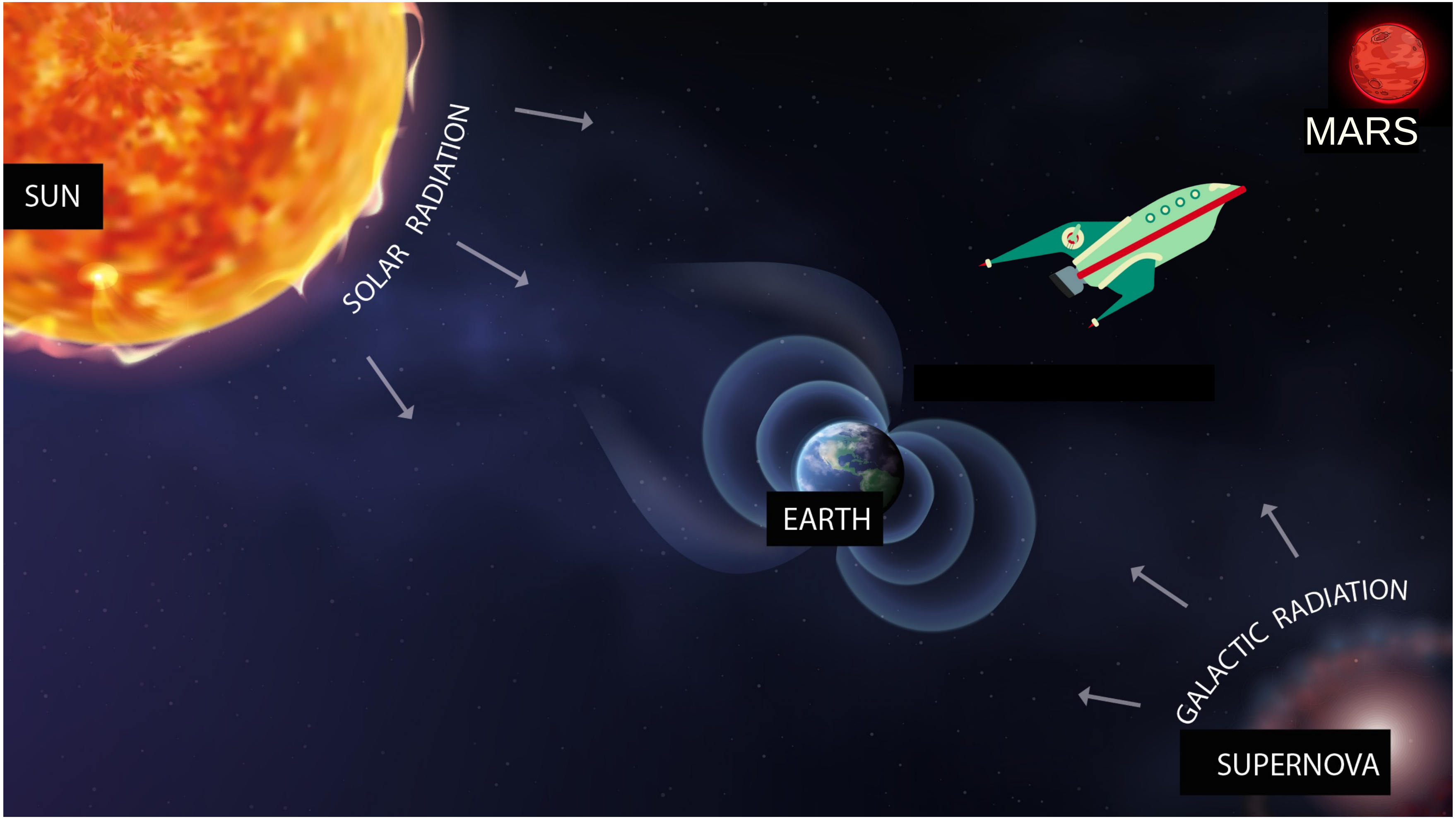
90% p

9% He

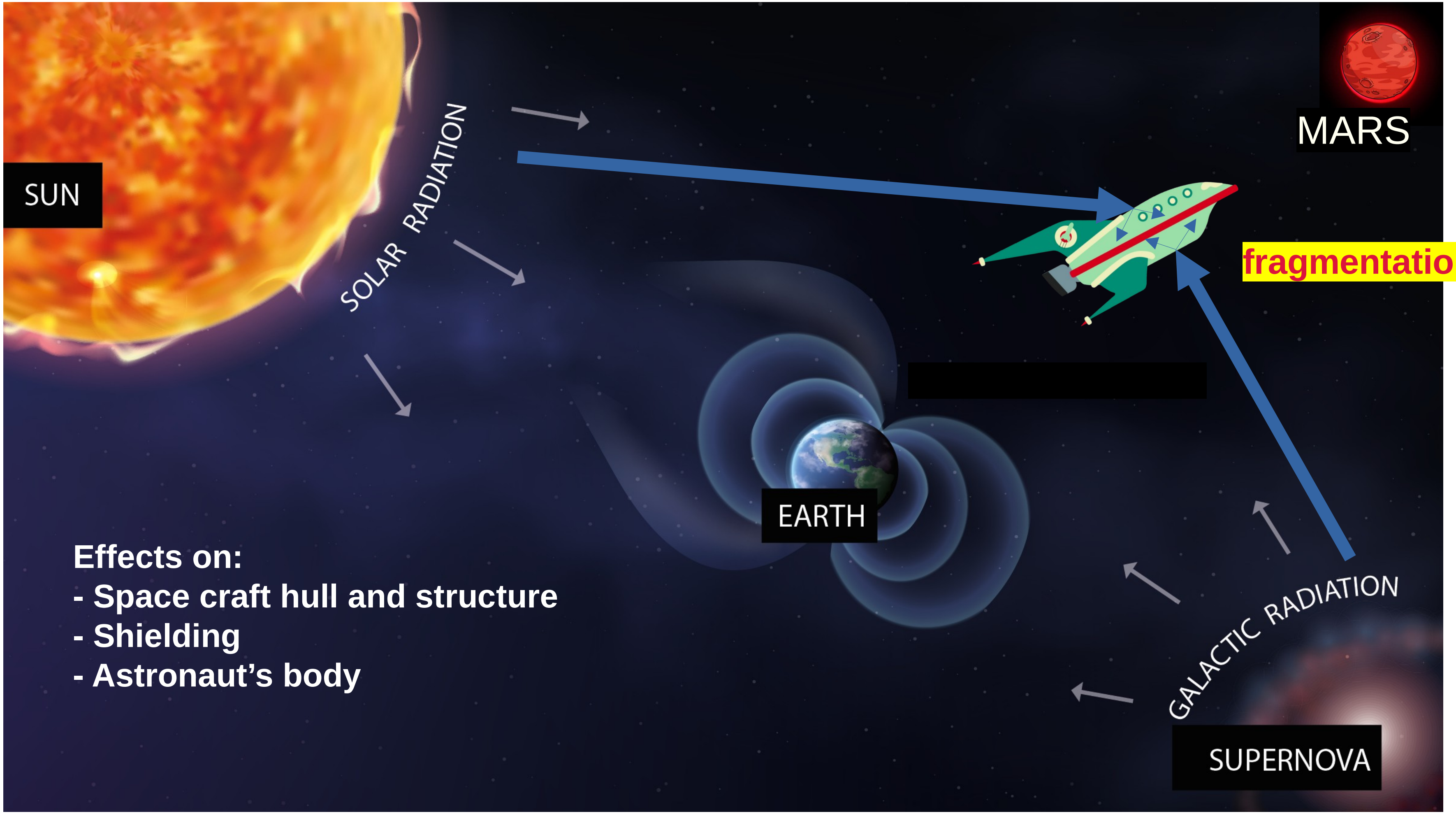
1% HZE

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

Space radioprotection

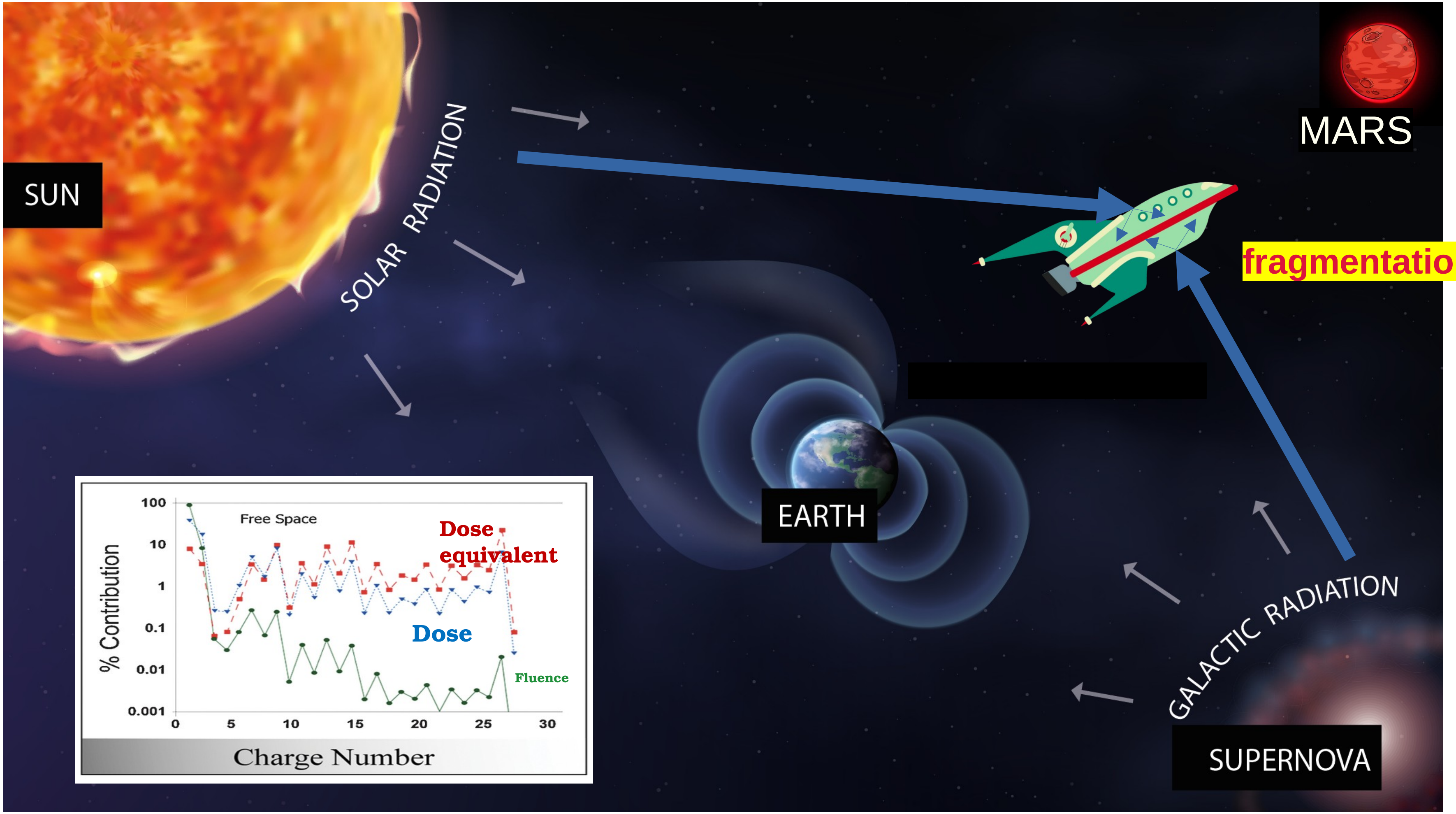


Space radioprotection



Effects on:
- **Space craft hull and structure**
- **Shielding**
- **Astronaut’s body**

Space radioprotection



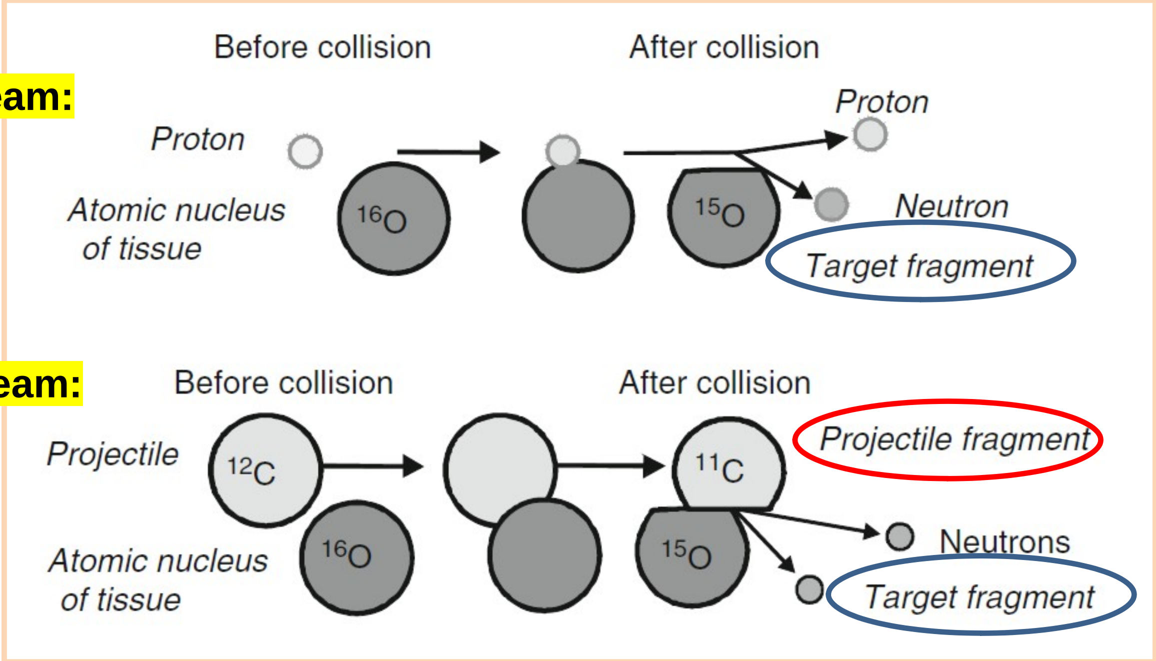
Nuclear fragmentation

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

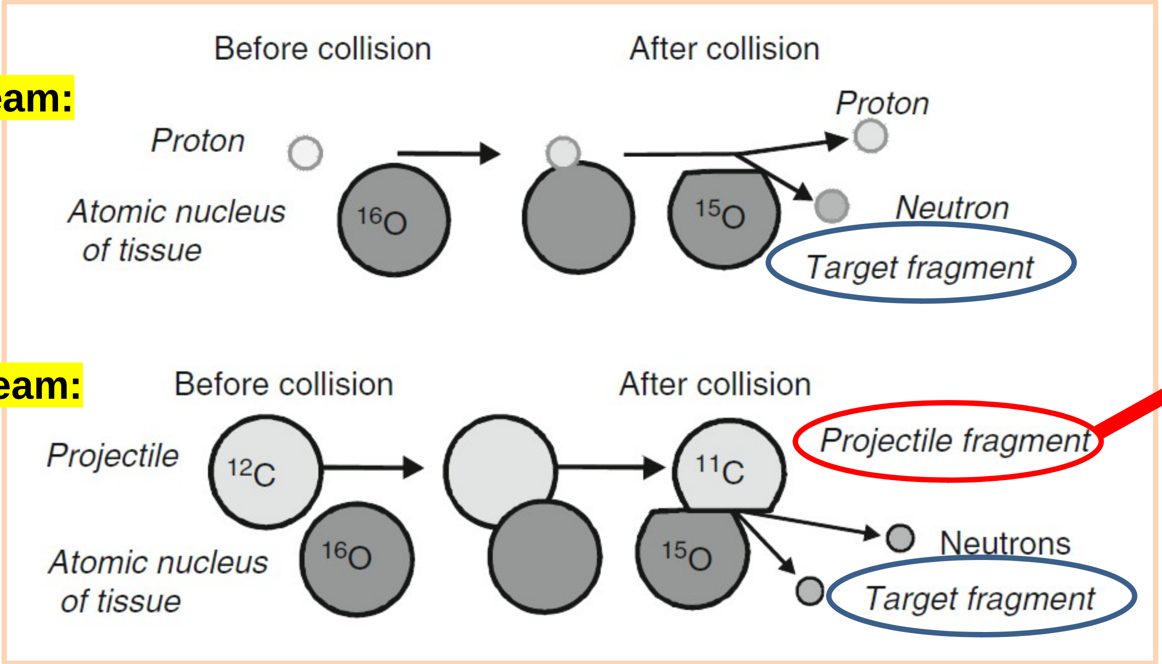
Nuclear fragmentation

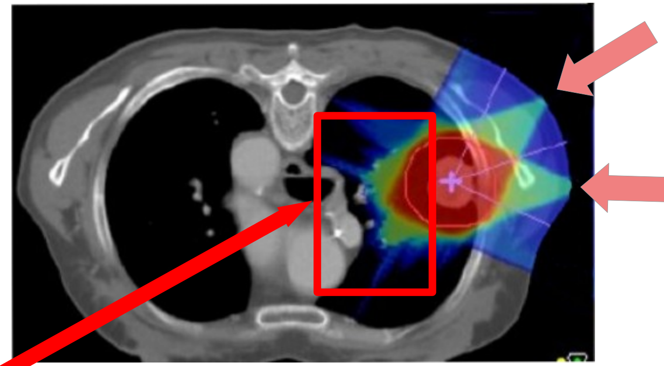
Proton beam:

~ 200 MeV

Carbon beam:

~ 400 MeV/u





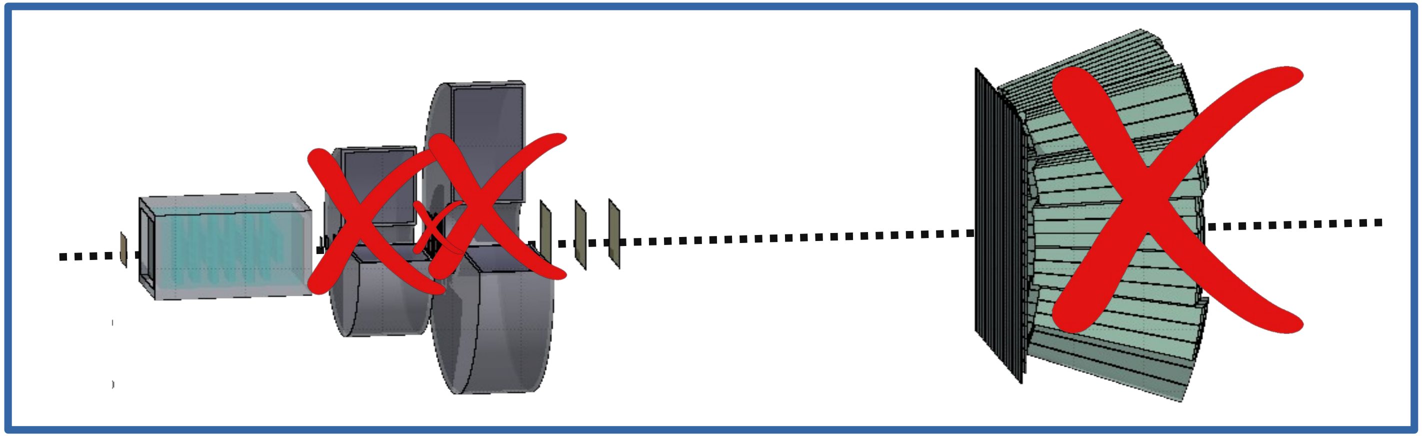
Projectile fragments:

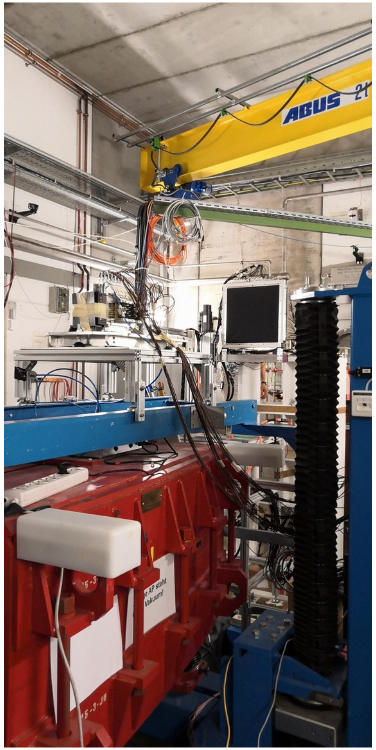
- Longer range than beam
- Dose beyond the Bragg peak

nuclear cross section
mesurements needed

GSI 2021 Analysis

- Data-taking at GSI (Darmstadt, Germany) in 2021
- ^{16}O 400 MeV/u and 200 MeV/u on 5 mm C target
- Partial setup: no tracker, only one module of calorimeter





Specific goal:

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

Differential Cross section

Yield of all fragments

Background

unfolding

$$\frac{d\sigma}{d\theta} = \frac{(Y_f - B_f)^u}{N_{beam} \cdot N_{target} \cdot \Delta\theta \cdot \epsilon}$$

efficiency

N° of primary events

N° of scattered centers

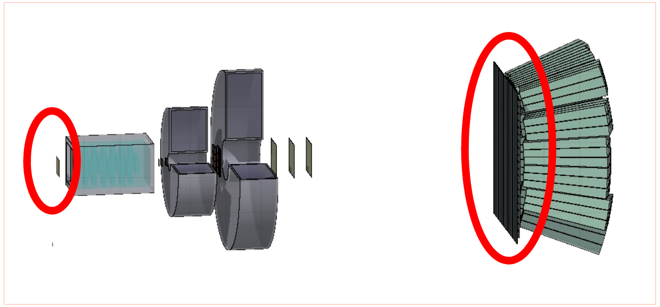
Phase space

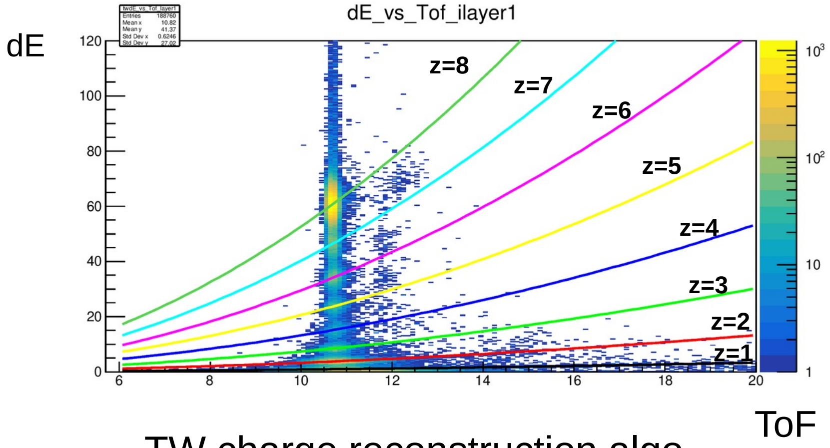
Fragments identification

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

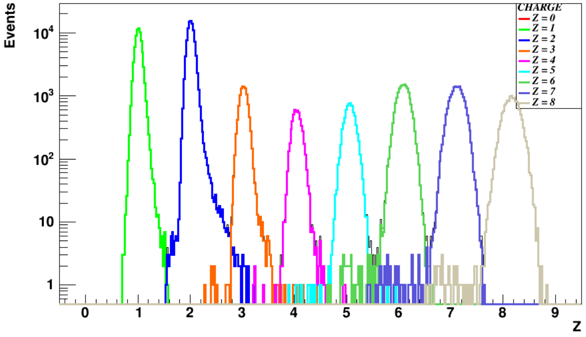
$$-\boxed{\frac{dE}{dx}} = 4\pi N_e r_e^2 m_e c^2 \frac{z^2}{\boxed{\beta^2}}\left(\ln\frac{2m_e c^2 \boxed{\beta^2}\gamma^2}{I} - \boxed{\beta^2} - \frac{\delta(\gamma)}{2}\right)$$

- **Infos taken from SC and TW**





TW charge reconstruction algo



Charge discrimination

Analysis procedure

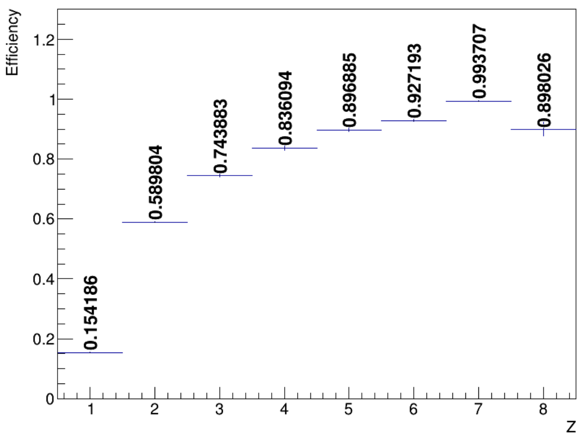
$$\sigma(Z) = \frac{Y(Z) - B(Z)}{N_{beam}\, N_{target}\, \epsilon(Z)}$$

4) Track efficiency obtained as:

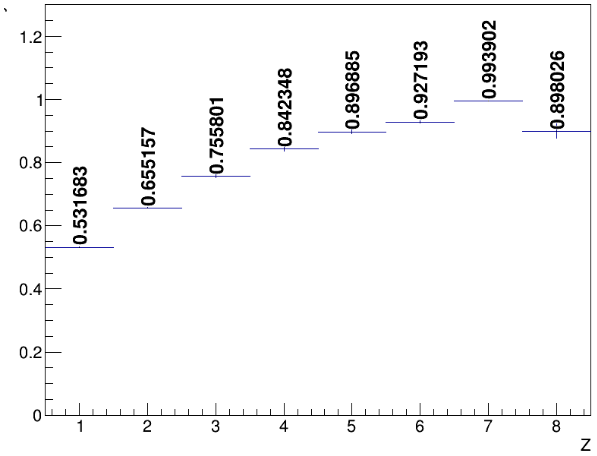
$$\epsilon(Z) = \frac{N_{track}(Z)}{N_{true}(Z)}$$

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

Total Track efficiency



Fiducial Track efficiency

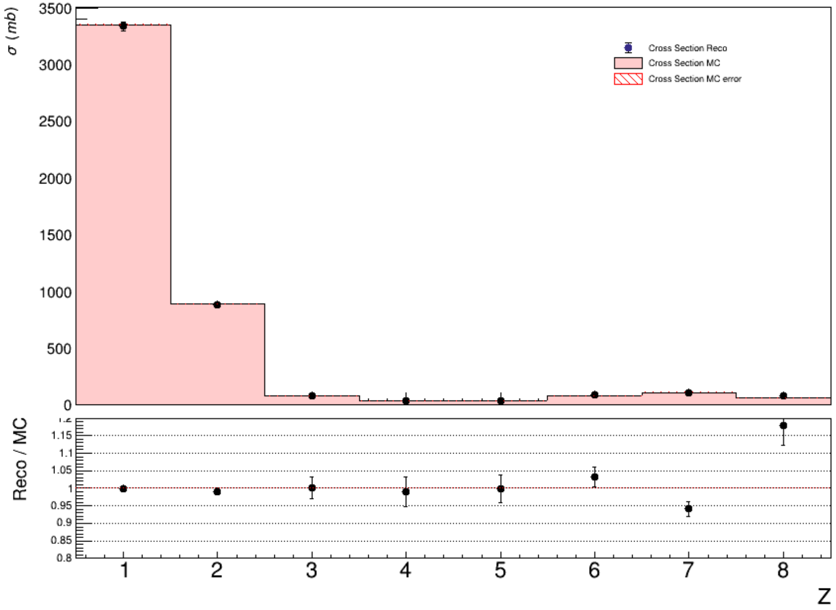


MC Closure test
elemental cross section

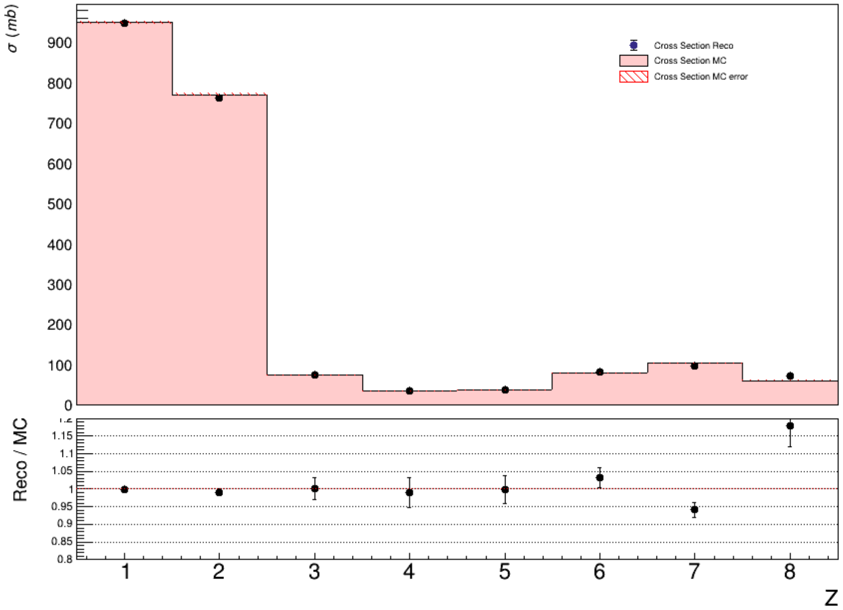
$$\sigma(Z) = \frac{Y(Z) - B(Z)}{N_{beam}\, N_{target}\, \epsilon(Z)}$$

- understand the **reliability** of the analysis chain and algorithms
- comparing the MC data-like cross sections with the MC generated ones.

Total cross section

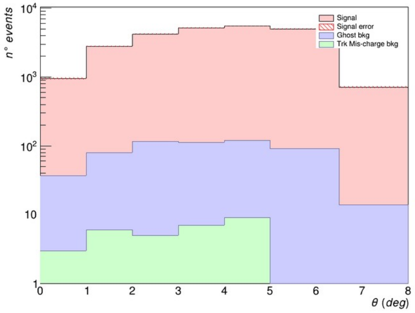


Fiducial cross section

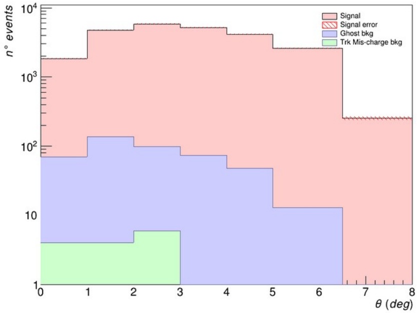


MC – Angular yields and Bkg

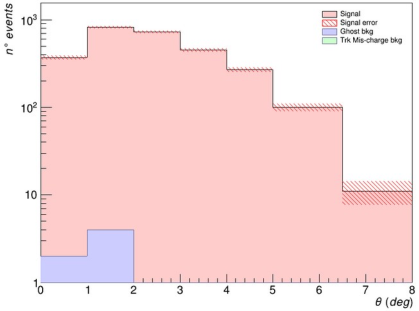
$$\frac{d\sigma}{d\theta}(Z) = \frac{Y(Z,\theta) - B}{N_{beam}\; N_{target}\; \Omega_\theta\; \epsilon(Z,\theta)}$$



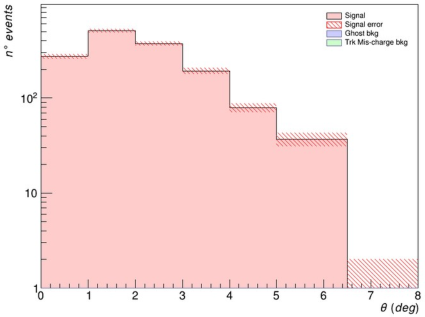
z=1



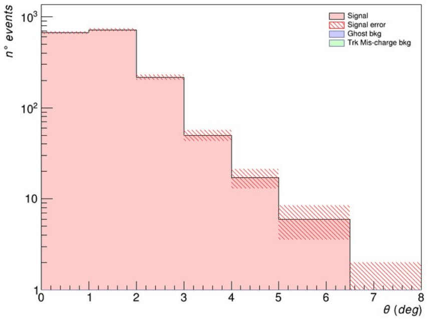
z=2



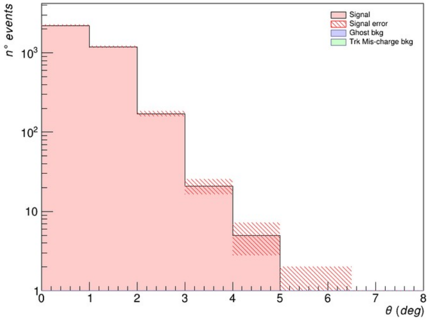
z=3



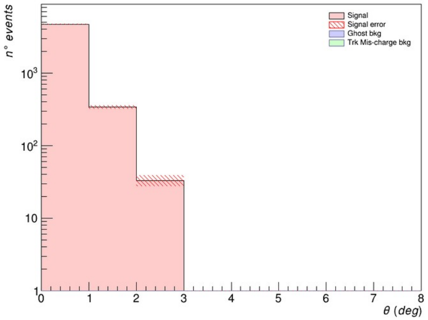
z=4



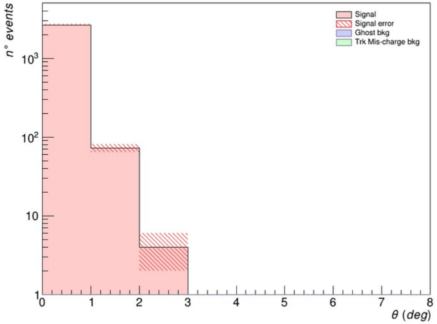
z=5



z=6



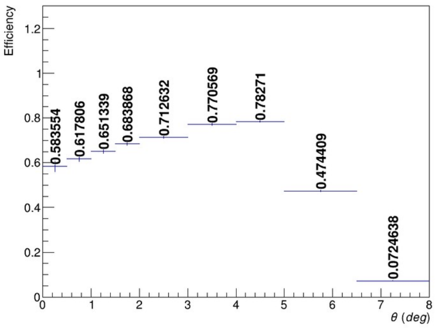
z=7



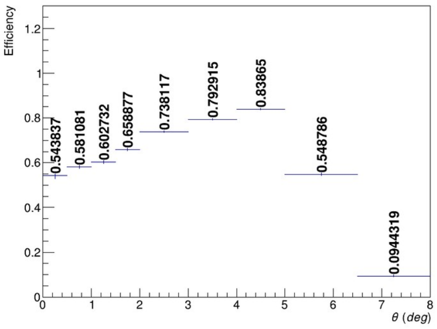
z=8

MC - Angular efficiencies

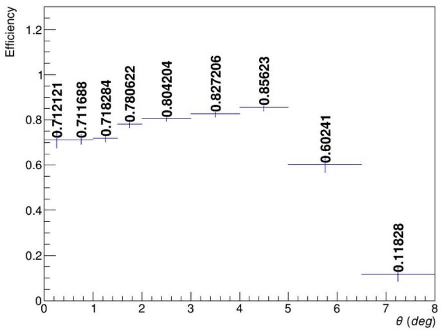
$$\frac{d\sigma}{d\theta}(Z) = \frac{Y(Z,\theta)\ -\ B}{N_{beam}\ N_{target}\ \Omega_\theta\ \epsilon(Z,\theta)}$$



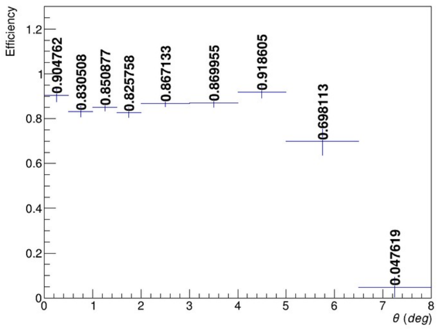
z=1



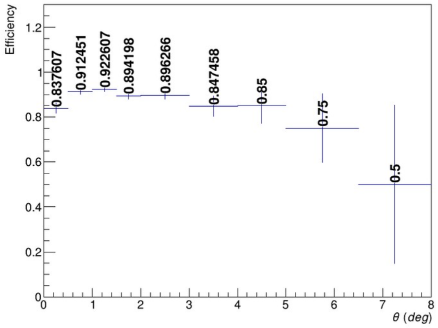
z=2



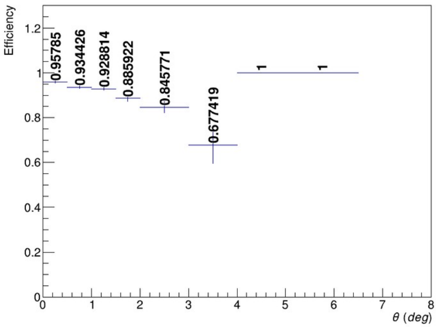
z=3



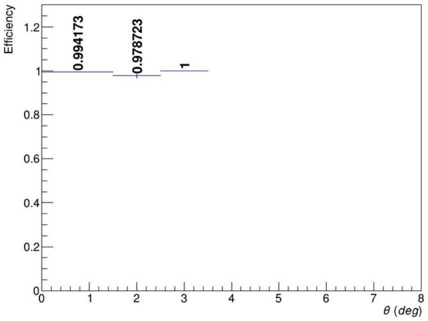
z=4



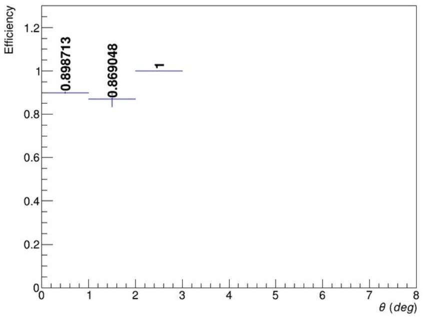
z=5



z=6

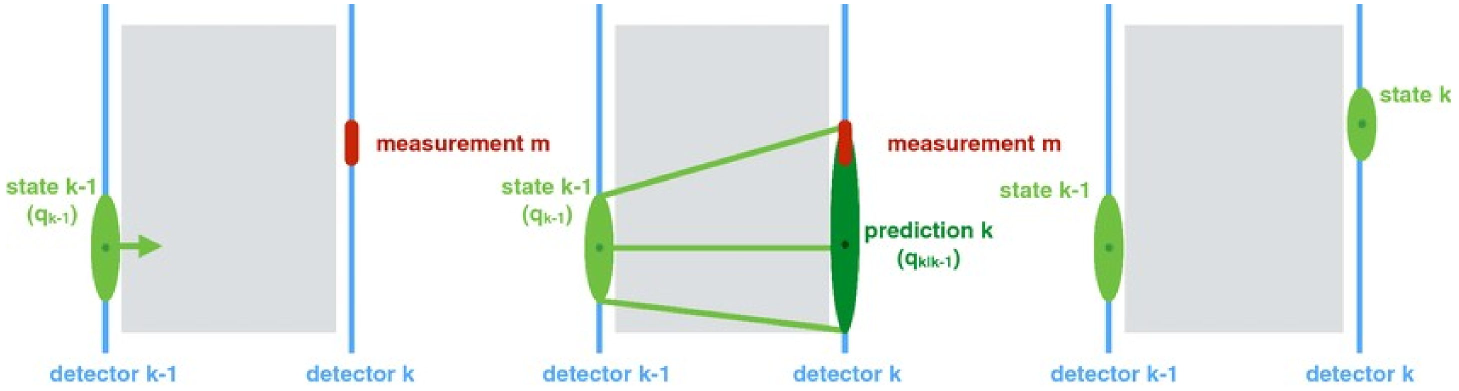


z=7



z=8

Kalman Filter



1. Take an ideal particle in vacuum. If we add air + detector layers, trajectory changes due to M.S. and energy loss.

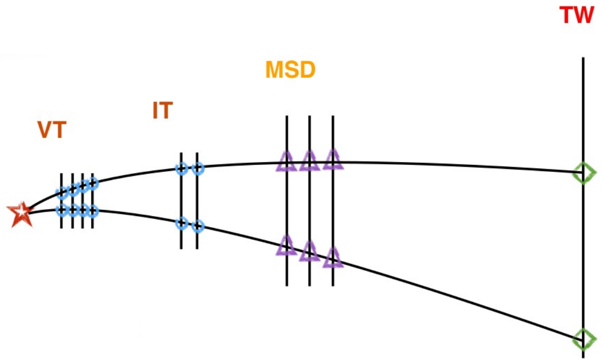
2. We'll see some measurement hits on the detector layers (considering finite detector uncertainty).

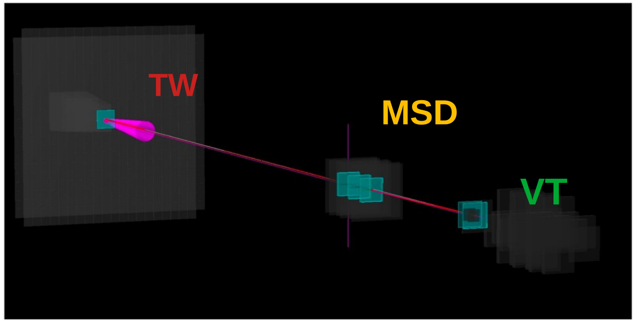
3. Propagate the first hit to the next layer. Propagator Matrix F.

4. Find the best compromise between the propagated point and the closest hit on the 2 nd layer. Use a Chi2 and a Projection Matrix H.

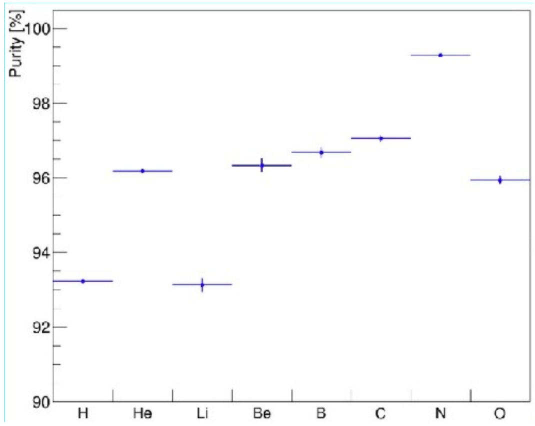
5. Iterate 3 and 4 for the next layers.

Track reconstruction





- track reconstruction on GSI 2021 data
  No B field present



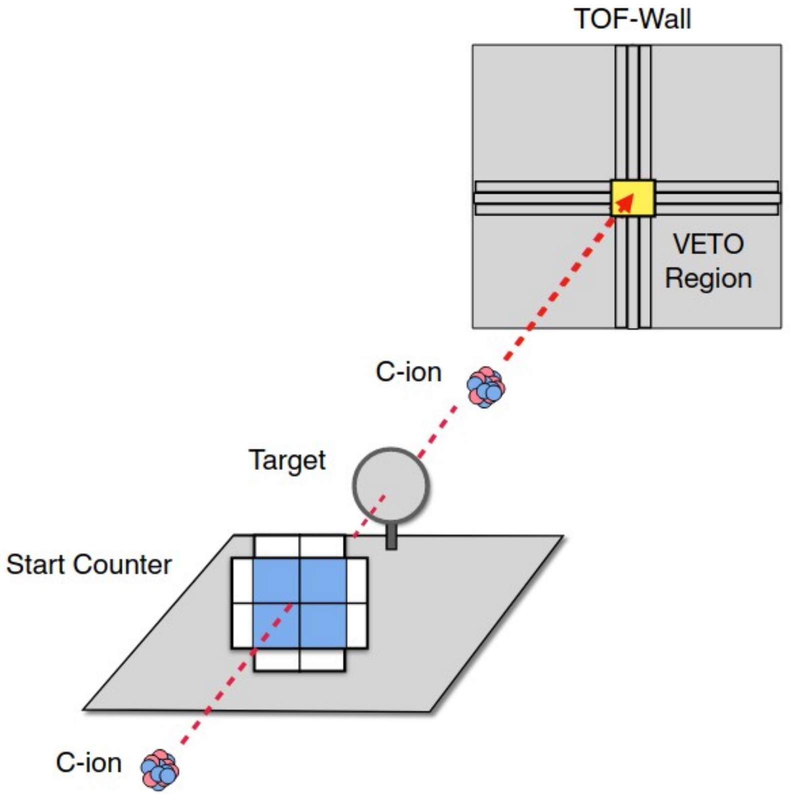
Kalman Filter reconstruction of a track

- 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** ...

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.

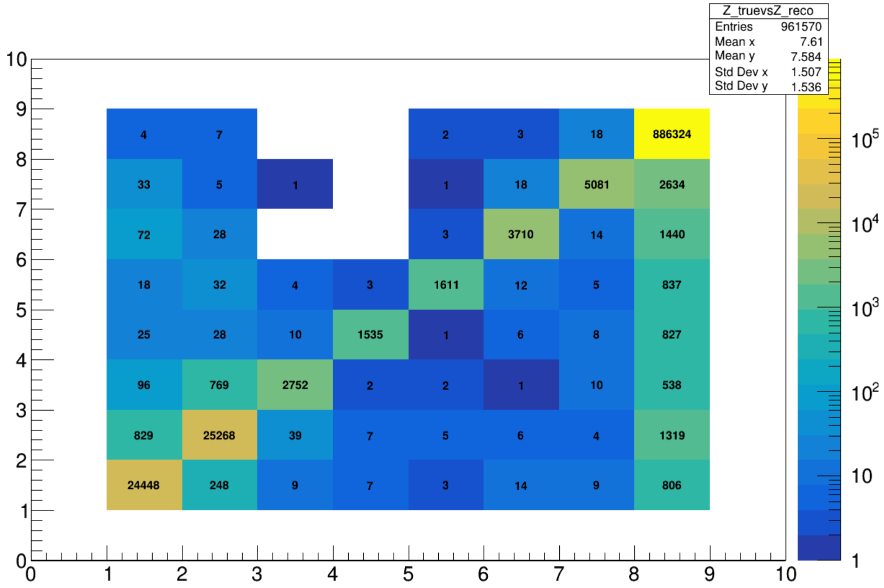
Minimum Bias is fired whenever the number of SC channels above a certain threshold exceeds a programmable value (aka *majority*).

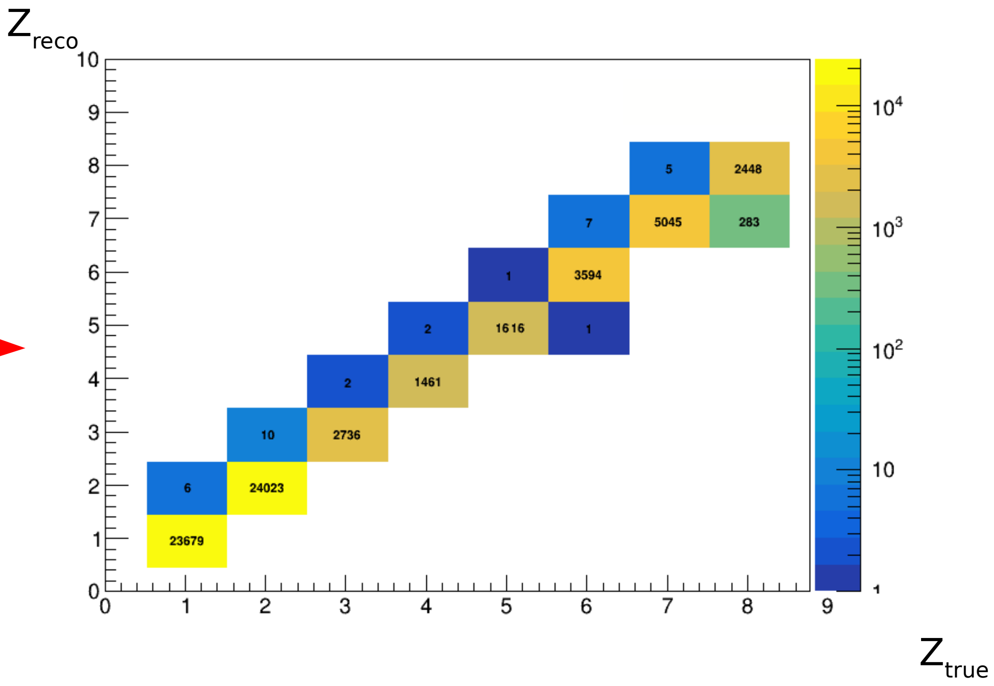


- **Fragment Trigger** is fired every time Minimum Bias condition on TW is not verified

Trigger Simulation

Applying Trigger cut:

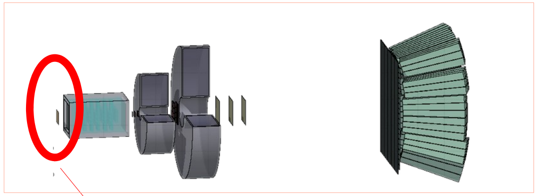


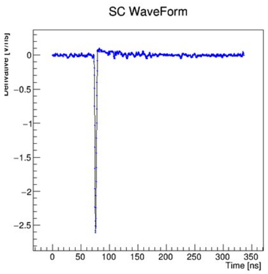


- Main source of mis-reconstruction is given by O due to its high statistics

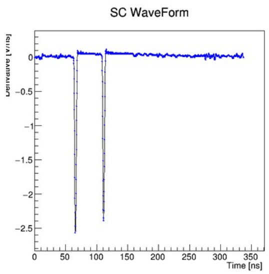
Pile-up removal

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



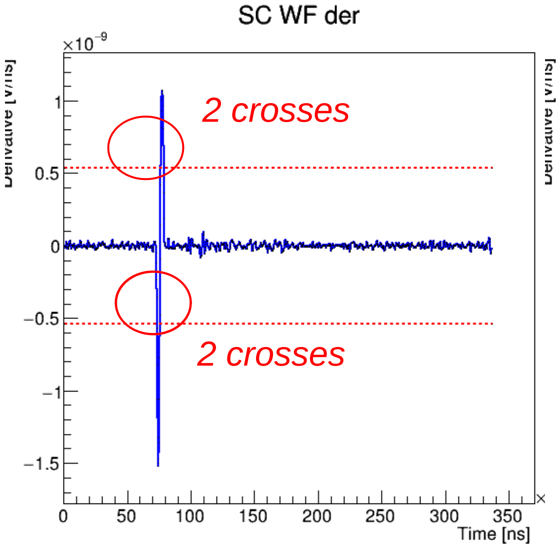


Single projectile

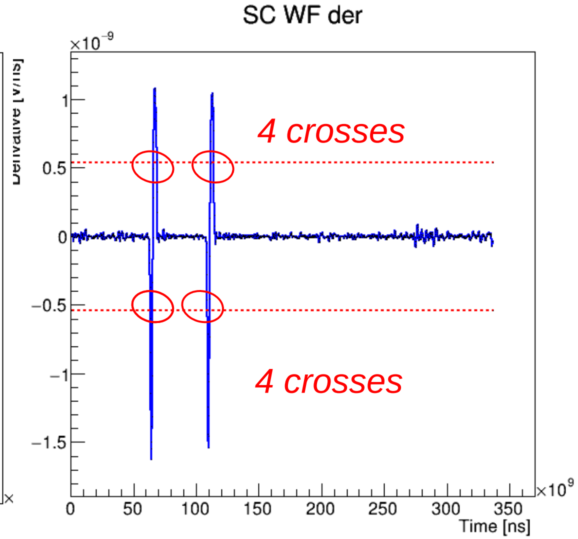


Pileup projectile

constant threshold discrimination method



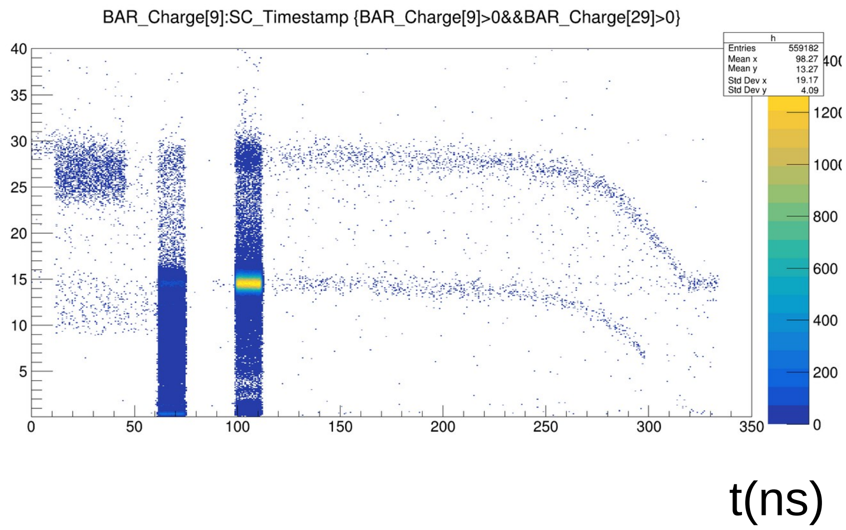
Single projectile: 4 crosses

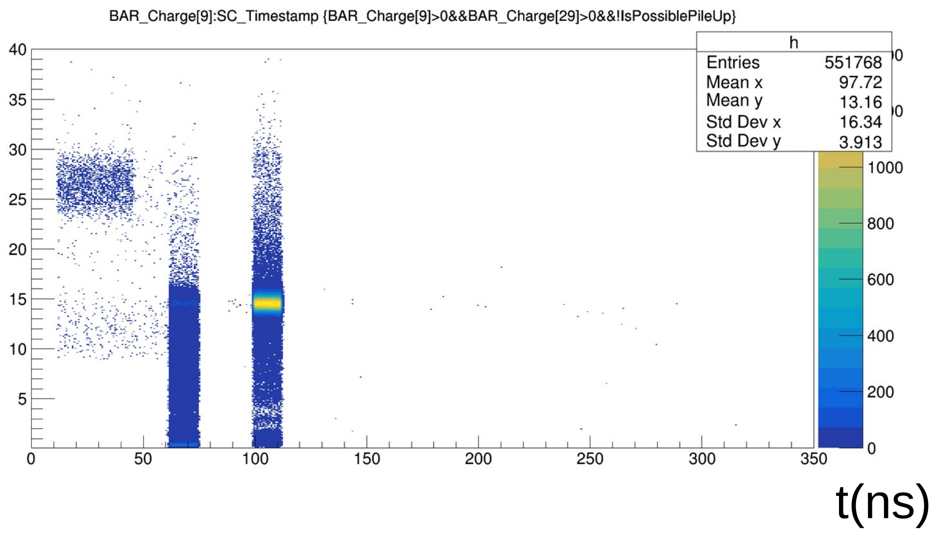


pileup projectile: >4 crosses

Pile-up removal

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



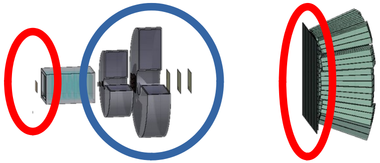


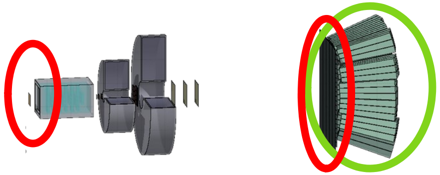
PileUp on 600.000 events ~ 1%

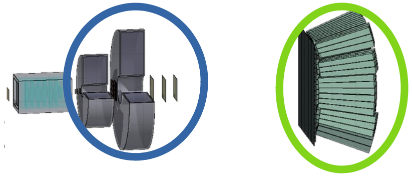
Isotopes identification

- Mass reconstruction using all FOOT subdetectors:

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





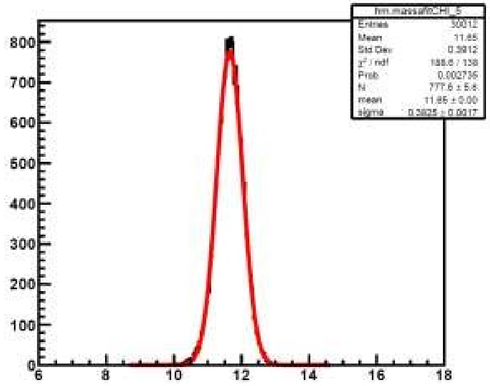


- In our data no tracker and calorimeter → mass measurement only in MC data!
- Augmented Lagrangian

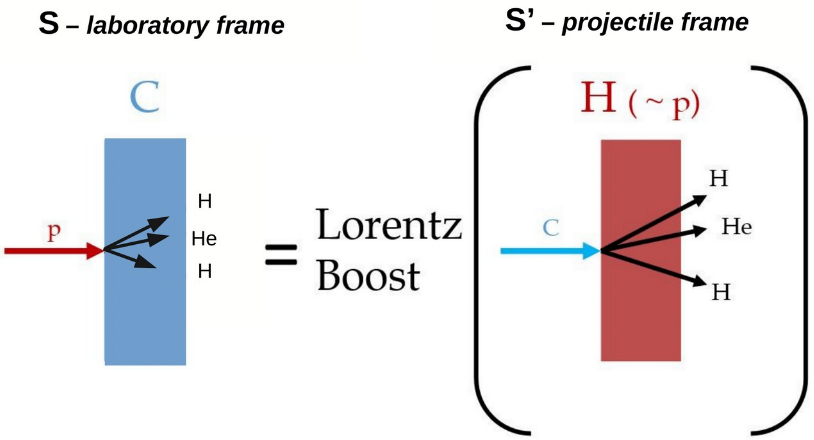
$$L(\vec{x}, \lambda, \mu) \equiv f(\vec{x}) - \sum \lambda_a c_a(\vec{x}) + \frac{1}{2\mu} \sum c_a^2(\vec{x})$$

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

Aχ 2 = 11.66 ± 0.38
risoluz. 3.2 %
χ 2 < 5



Inverse kinematics



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

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