Alma Mater Studiorum - Università di Bologna

ANALYSIS OF FRAGMENTATION CROSS SECTIONS OF GSI 2021 DATA FOR THE FOOT EXPERIMENT

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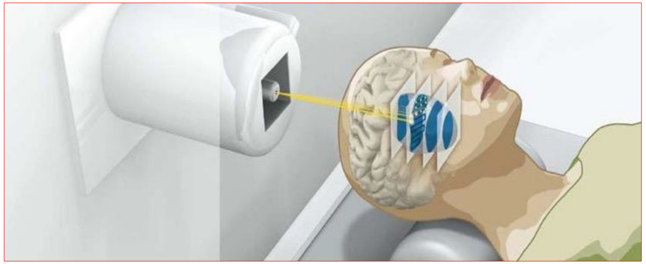
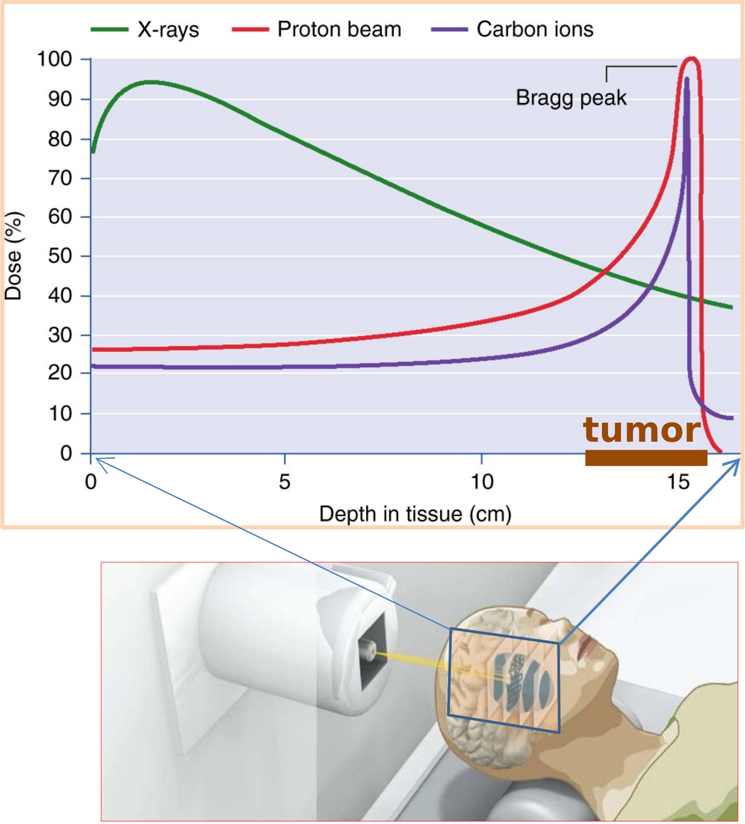
28/10/2022

Hadrontherapy



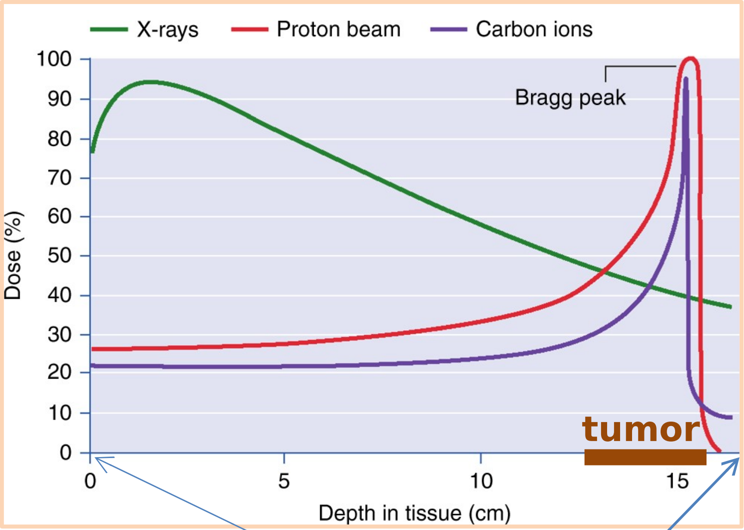
Hadrontherapy

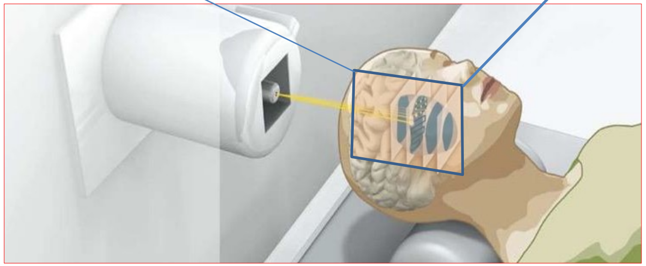


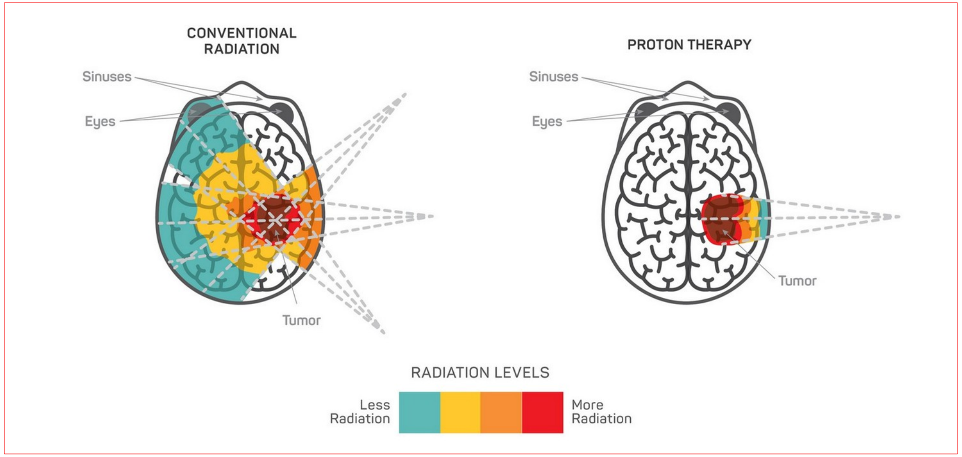
Hadrontherapy vs radiotherapy:

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

Hadrontherapy







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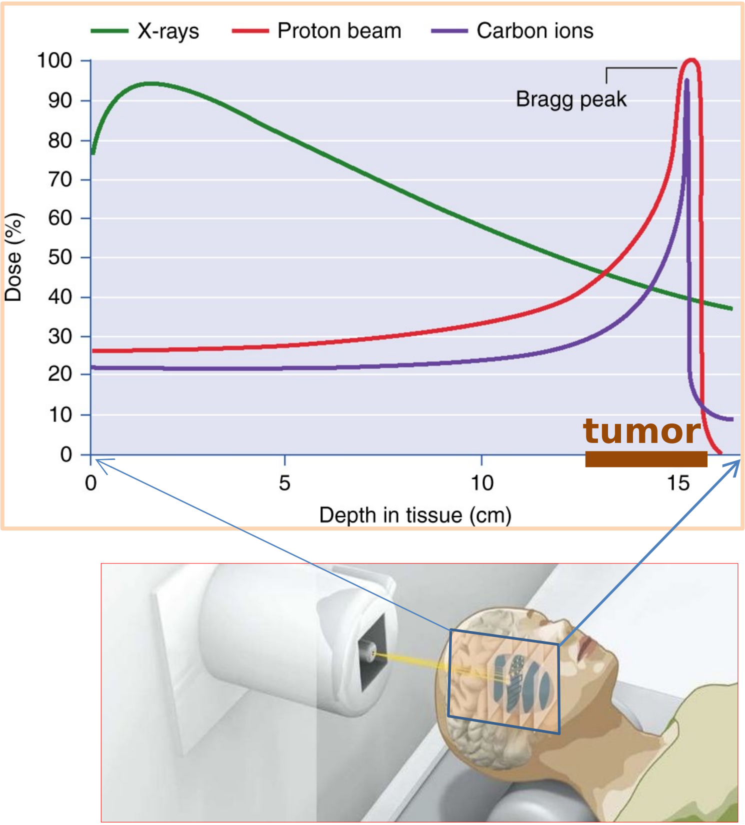
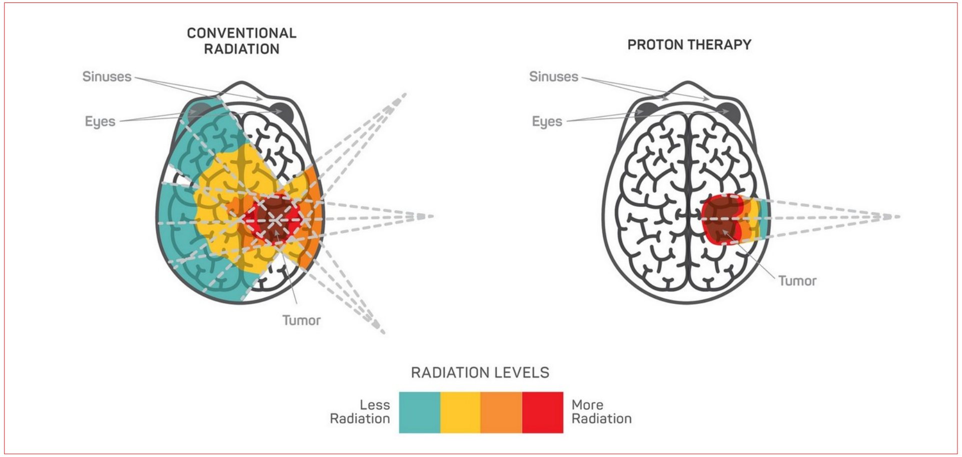
Hadrontherapy





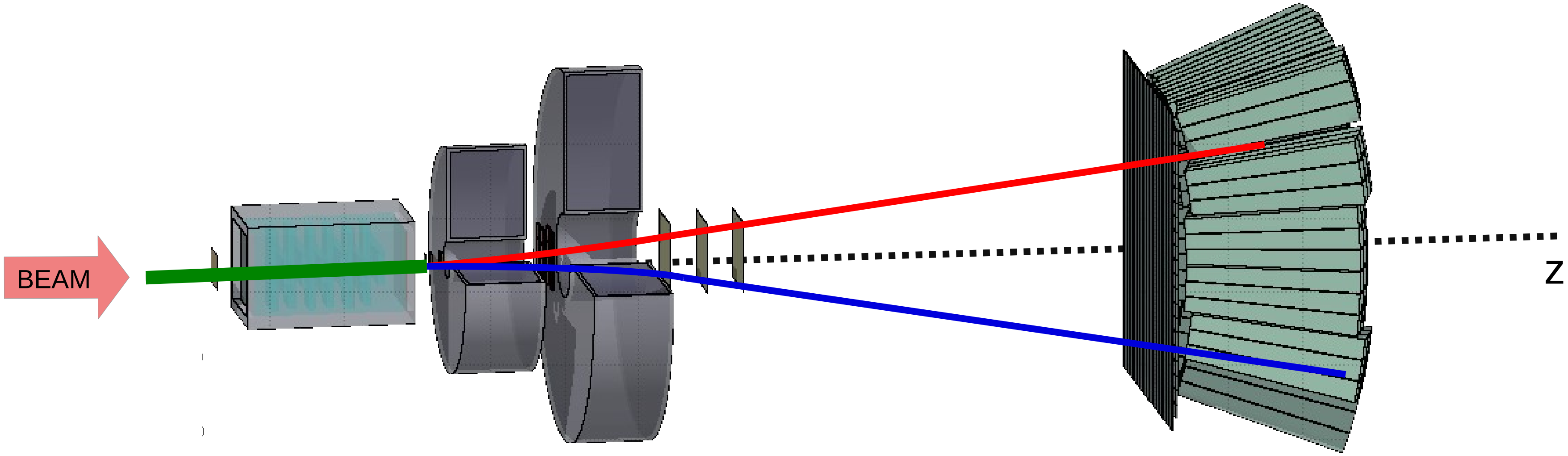
Hadrontherapy vs radiotherapy:

- ✔ **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



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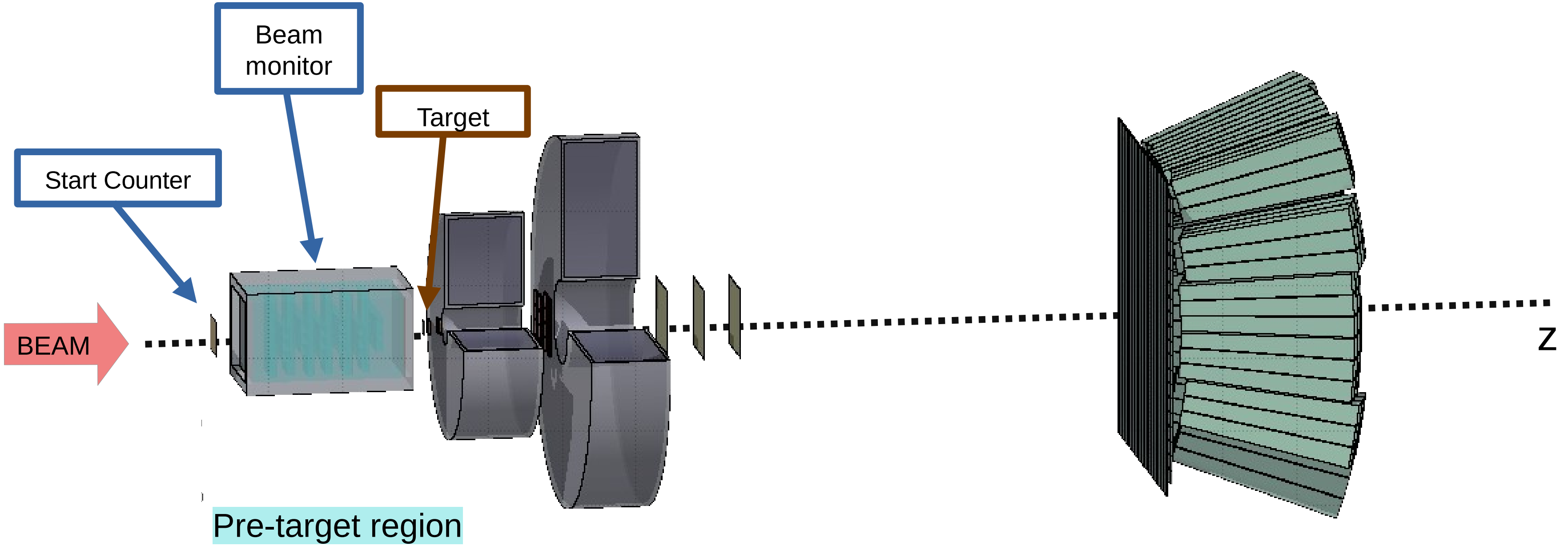
The FOOT experiment

Goal:

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

- Particle identification by measuring all kinematic quantities



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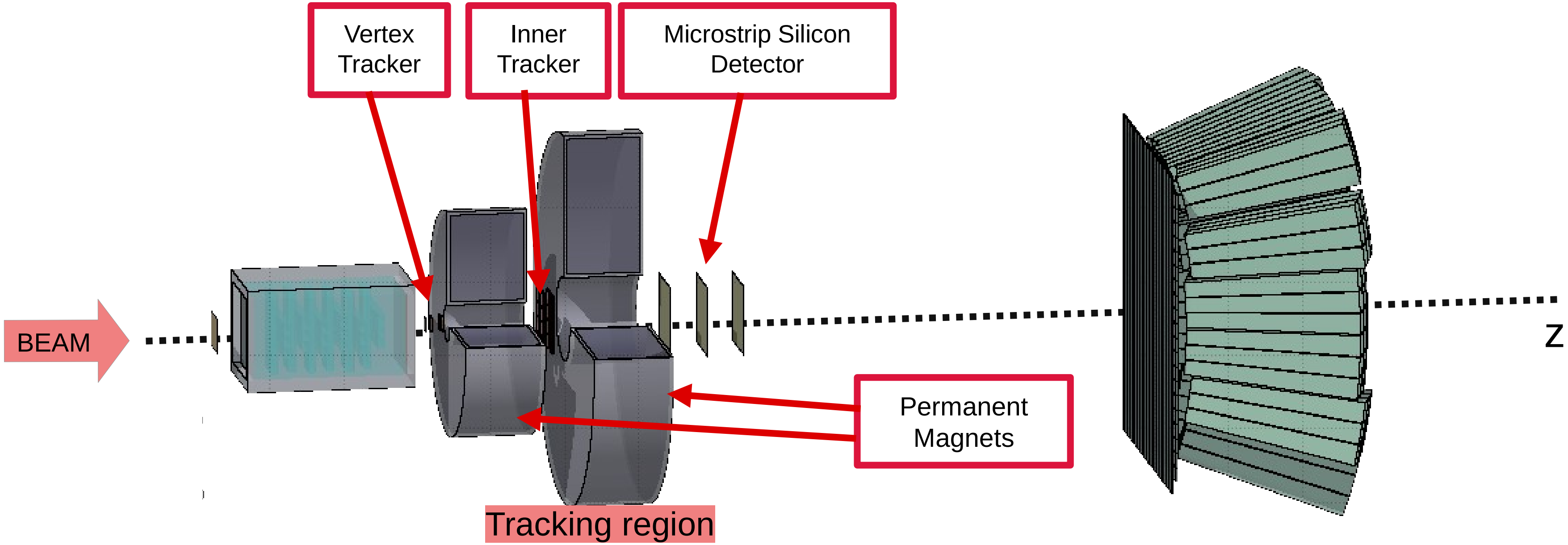

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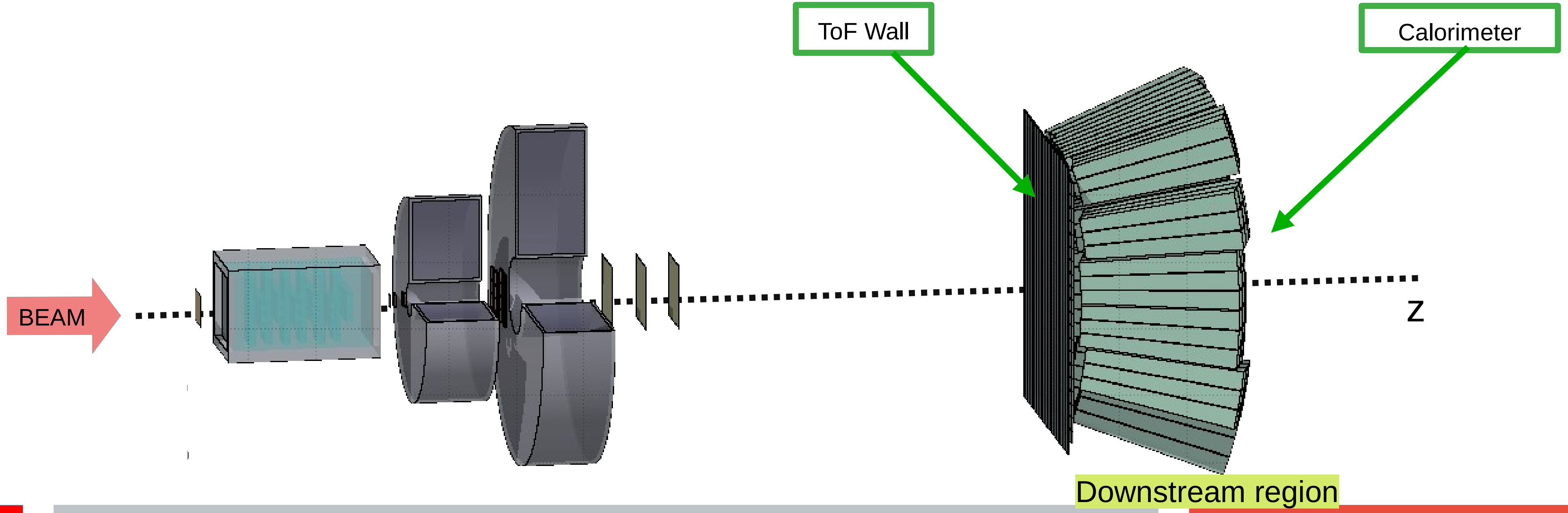
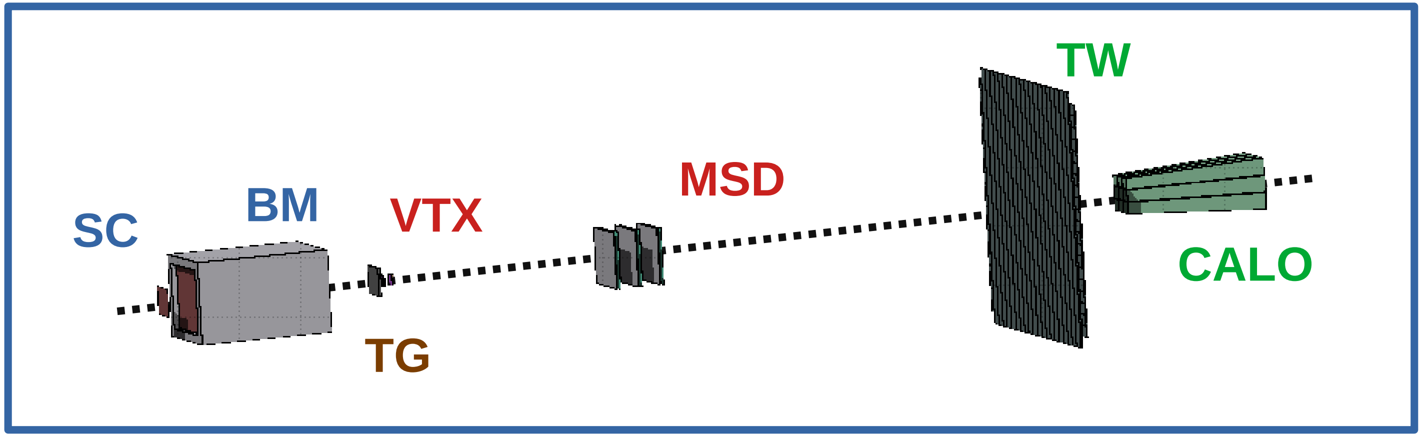
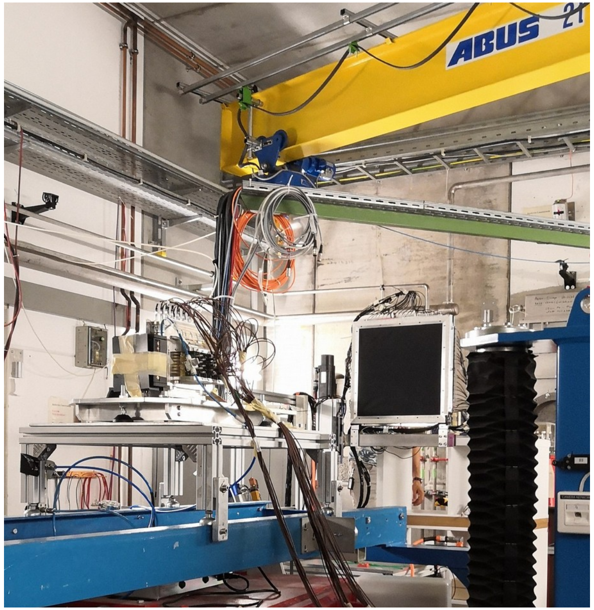


GSI 2021 Analysis

- 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 and angular differential cross section:

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

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

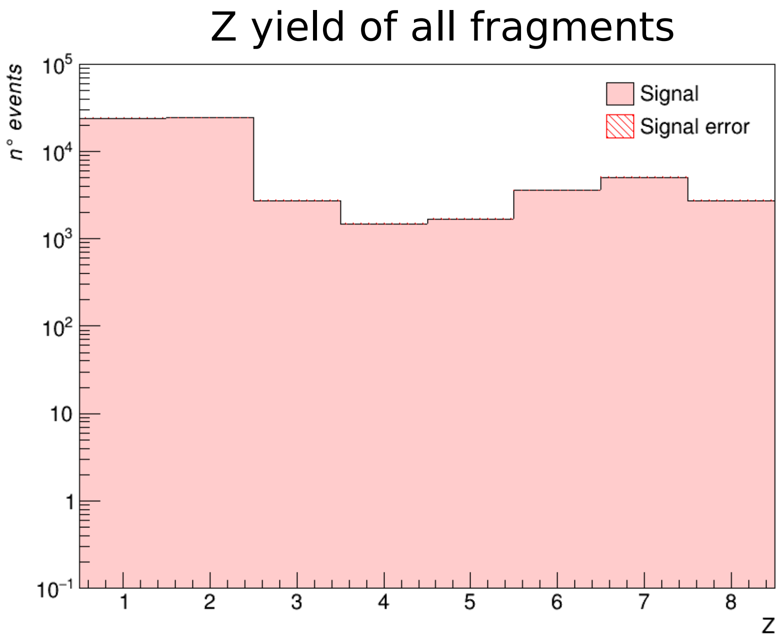
1) Starting from a **MC dataset** of 10^6 events generated by FLUKA to simulate detectors and beams of GSI 2021 campaign.

Analysis procedure

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

2) Yield of Z obtained from reconstructed tracks

- Exploiting **charge** reconstruction algorithm
- Exploiting **tracking** reconstruction algorithm
- Simulating a **"trigger"** in order to consider only fragments



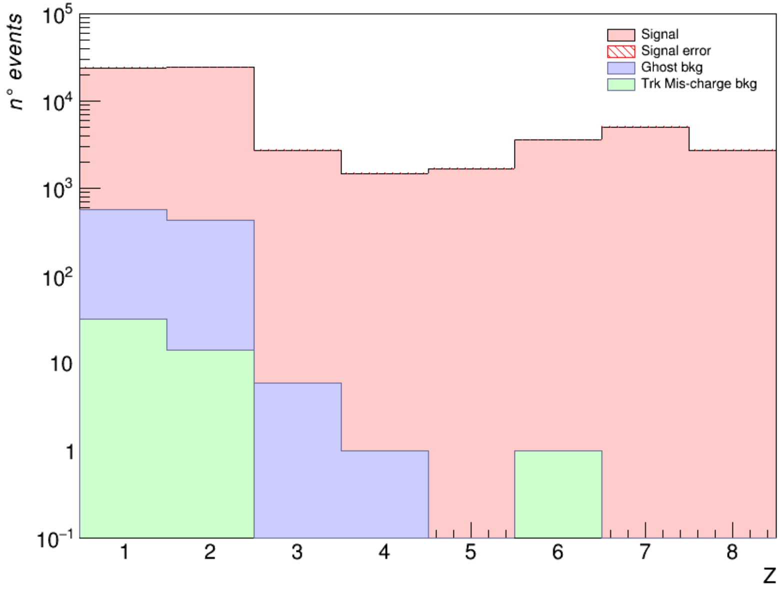
Analysis procedure

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

3) Background obtained from MC cuts on:

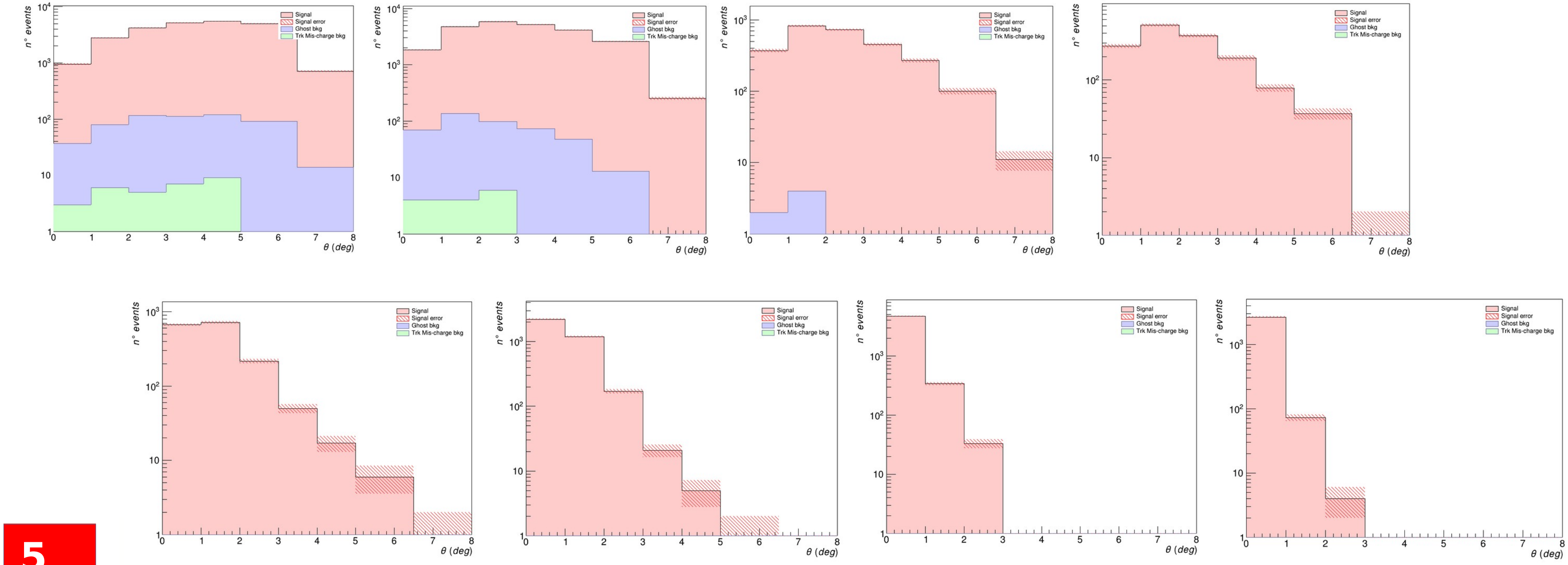
- **Charge** algorithm mis-reconstruction
- **Tracking** algorithm mis-reconstructio

Z yield and Bkg sources



Analysis procedure

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



Analysis procedure

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

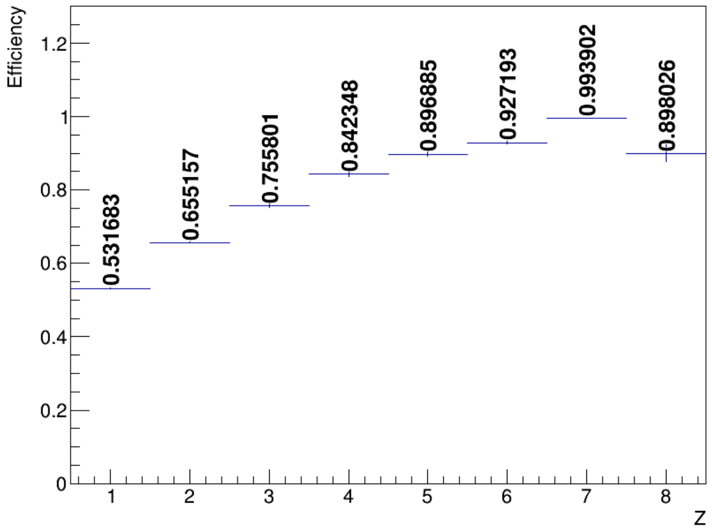
4) Track efficiency obtained as:

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

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

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

Fiducial Track efficiency



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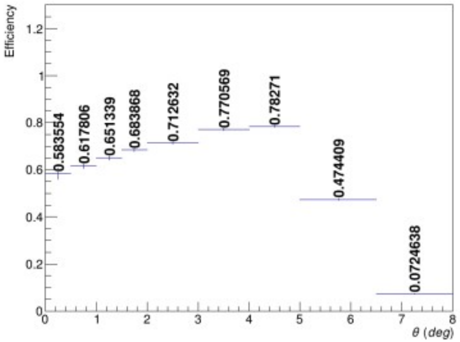
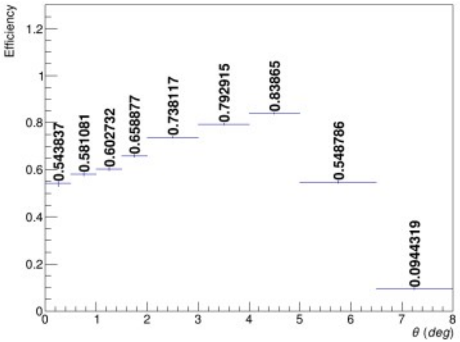
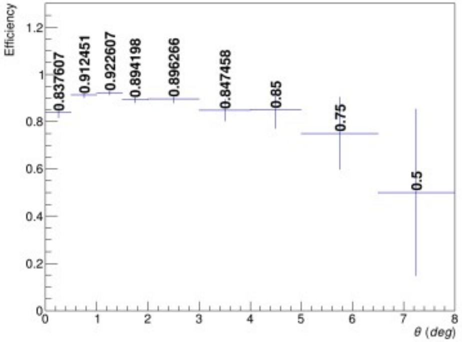
Angular efficiencies



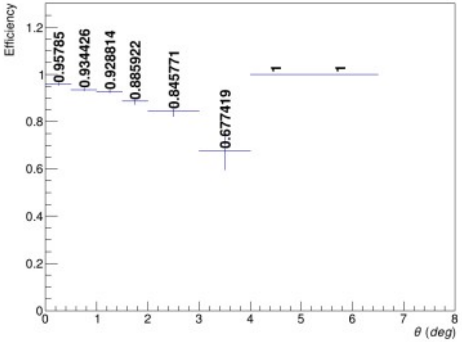
(a) Z=1



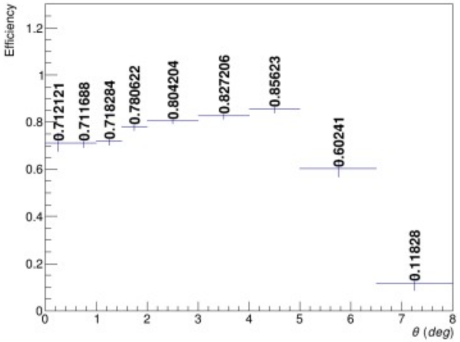
(b) Z=2



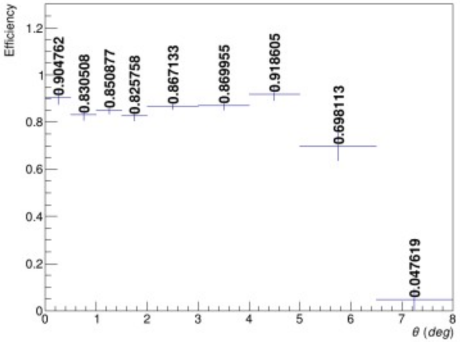
(e) Z=5



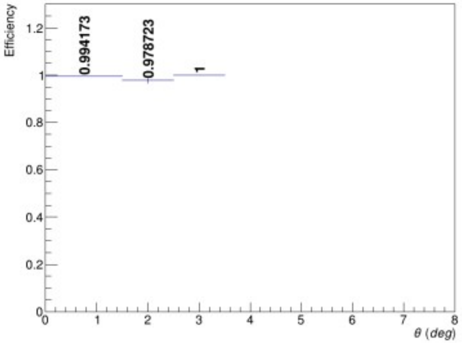
(f) Z=6



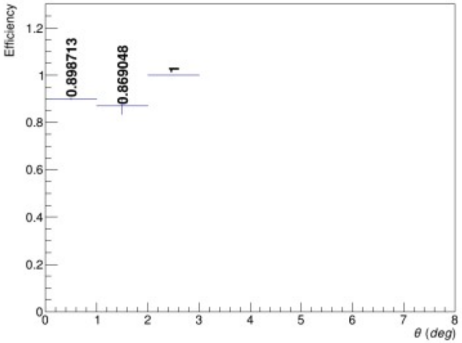
(c) Z=3



(d) Z=4



(g) Z=7



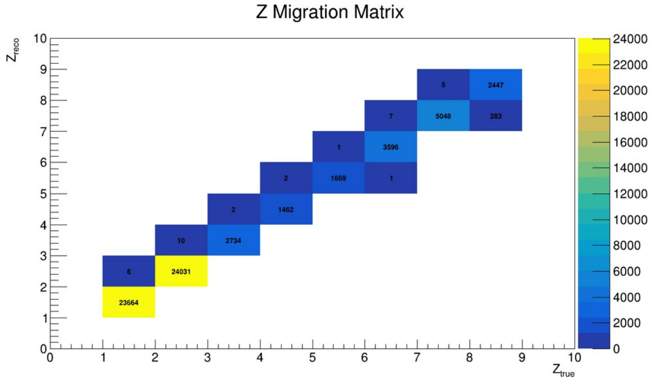
(h) Z=8

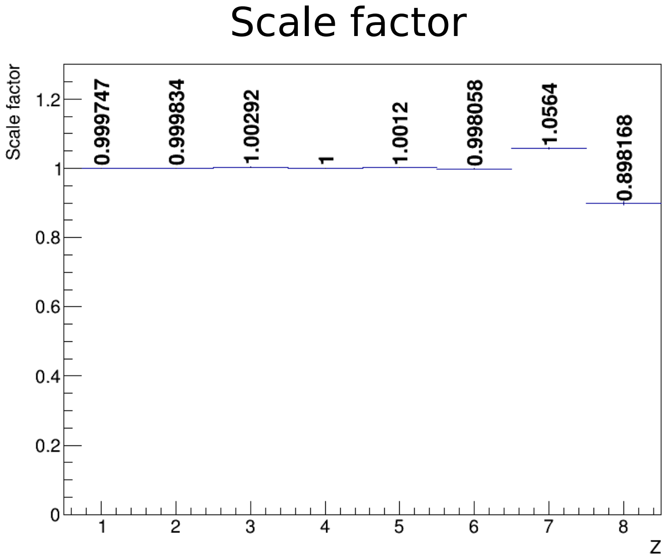
Analysis procedure

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

4) Migration matrix correction as scale factor:

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

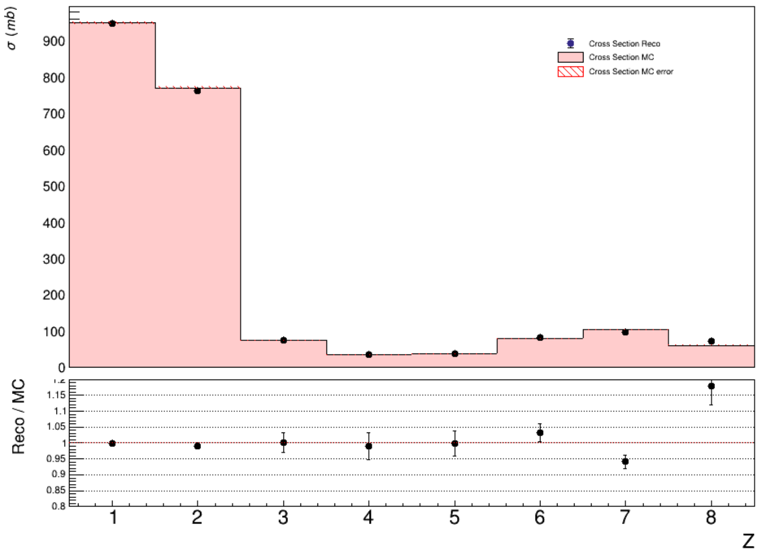




Analysis procedure

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

4) MC cross section measurement (fiducial θ<8°)

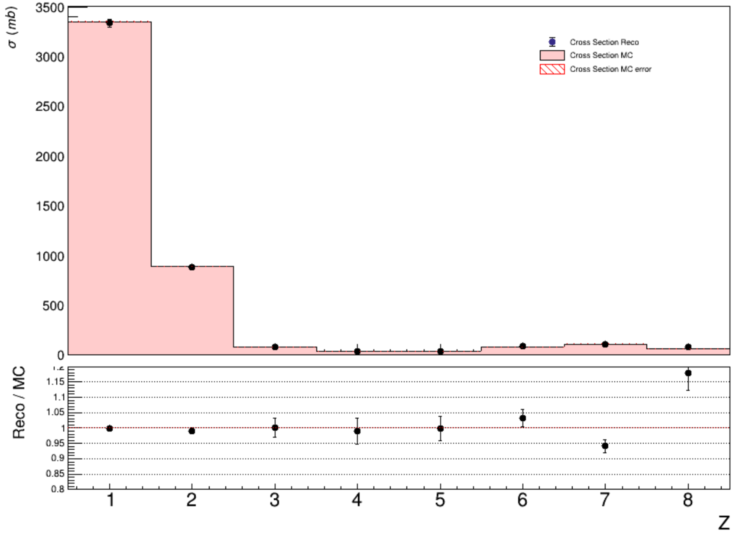


Charge	σ_{meas}(mb)	σ_{MC}(mb)
Z = 1	946 ± 9	949 ± 4
Z = 2	762 ± 7	770 ± 4
Z = 3	74.1 ± 1.3	74.1 ± 1.2
Z = 4	35.3 ± 1.5	35.2 ± 1.2
Z = 5	37.4 ± 1.6	37.2 ± 1.7
Z = 6	82.8 ± 1.7	79.3 ± 1.2
Z = 7	97.3 ± 1.4	103.0 ± 1.5
Z = 8	72.2 ± 3	61.3 ± 1.3

Analysis procedure

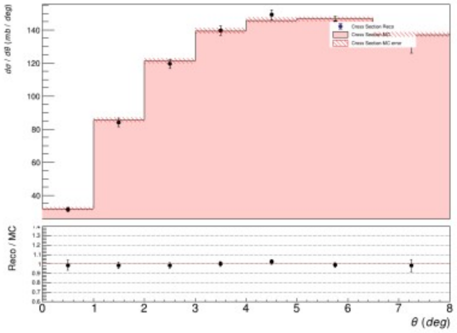
$$\sigma(Z) = \frac{Y(Z) - B(Z)}{N_{beam}\ N_{target}\ \epsilon(Z)} \qquad \frac{d\sigma}{d\theta}(Z) = \frac{Y(Z,\theta)\ -\ B}{N_{beam}\ N_{target}\ \Omega_{\theta}\ \epsilon(Z,\theta)}$$

4) MC cross section measurement (total)

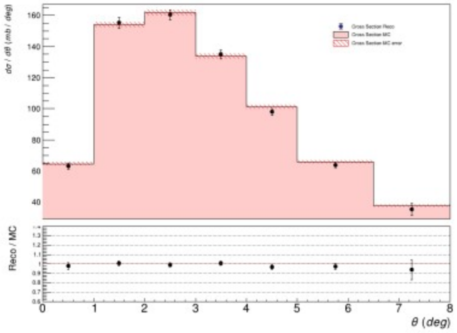


Charge	σ_{meas}(mb)	σ_{MC}(mb)
Z = 1	3340 ± 40	3346 ± 9
Z = 2	880 ± 9	888 ± 4
Z = 3	80 ± 2	80.2 ± 1.3
Z = 4	37.8 ± 1.3	38.2 ± 0.9
Z = 5	40.5 ± 1.3	40.6 ± 0.9
Z = 6	87.5 ± 1.9	84.7 ± 1.4
Z = 7	104.2 ± 1.9	110.8 ± 1.6
Z = 8	78 ± 4	66 ± 2

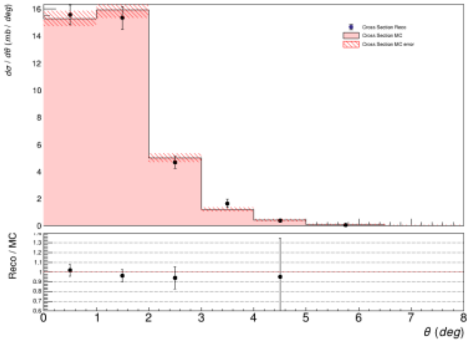
Angular differential XS



(a) Z=1



(b) Z=2



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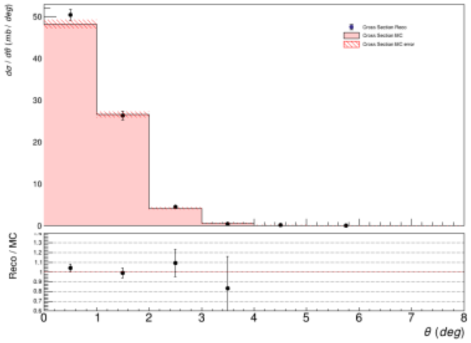

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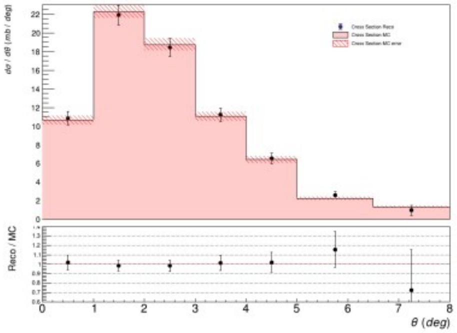
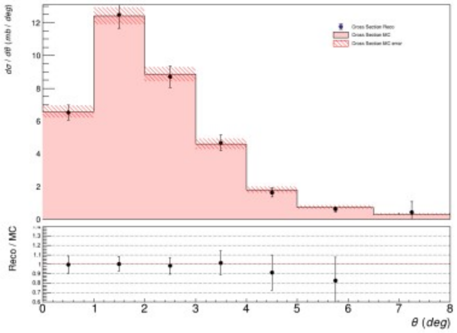
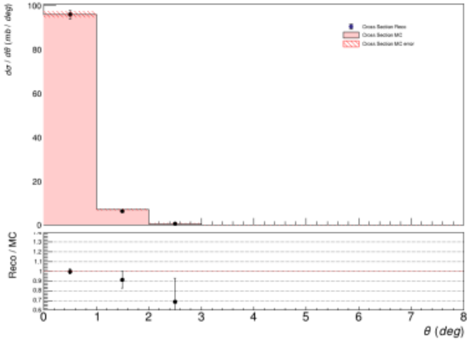


(c) Z=3



(d) Z=4



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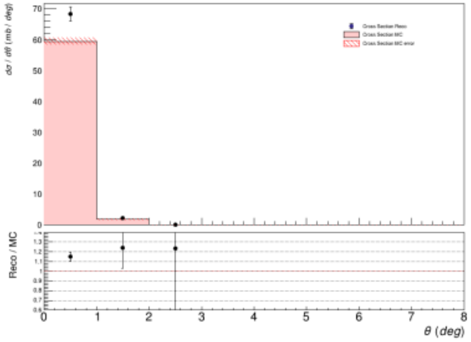
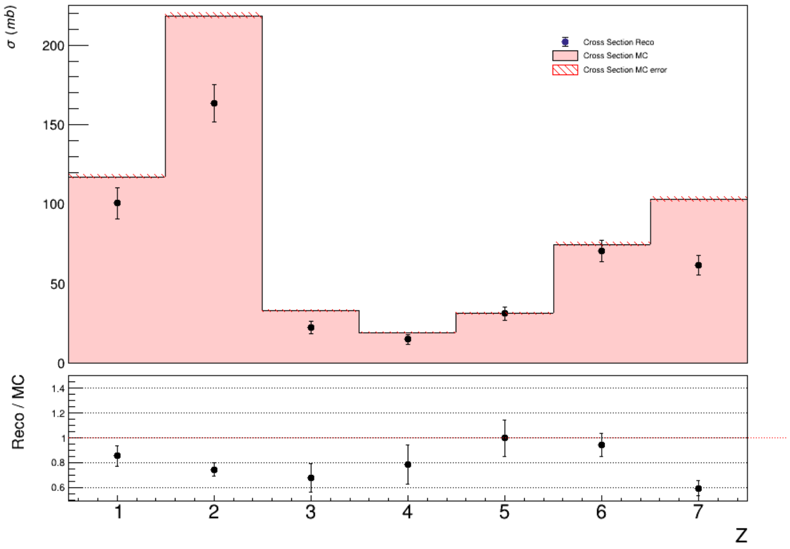


(h) Z=8

Analysis procedure

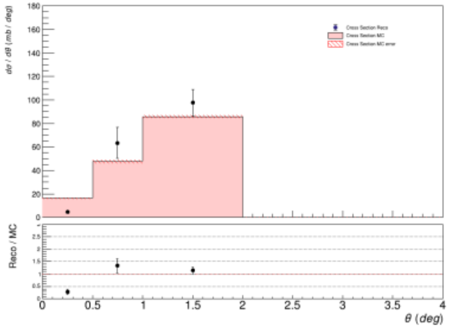
$$\sigma(Z) = \frac{Y(Z) - B(Z)}{N_{beam}\ N_{target}\ \epsilon(Z)} \qquad \frac{d\sigma}{d\theta}(Z) = \frac{Y(Z,\theta)\ -\ B}{N_{beam}\ N_{target}\ \Omega_\theta\ \epsilon(Z,\theta)}$$

4) experimental cross section measurement (fiducial θ<2.5°)

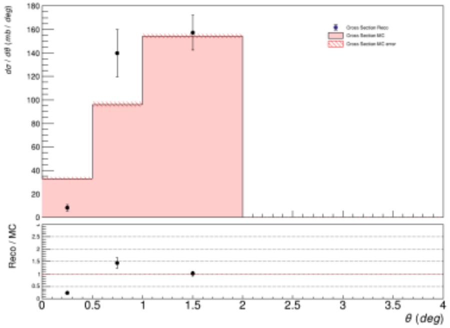


Charge	σ_{meas}(mb)	σ_{MC}(mb)
Z = 1	100 ± 9	117.4 ± 1.3
Z = 2	163 ± 11	218 ± 2
Z = 3	22 ± 3	32.3 ± 1.2
Z = 4	14 ± 2	18.4 ± 1.3
Z = 5	31 ± 4	31.1 ± 1.7
Z = 6	70 ± 6	74.3 ± 1.2
Z = 7	61 ± 6	103 ± 2

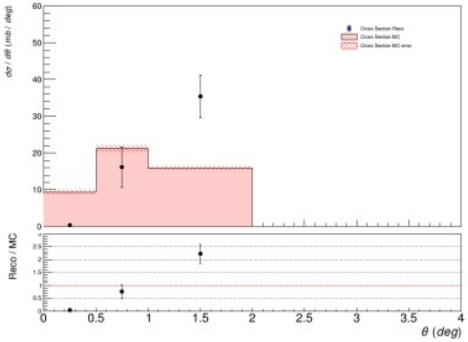
Experimental differential XS



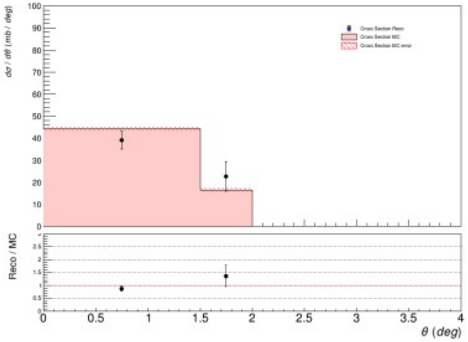
(a) Z=1



(b) Z=2



(e) Z=5



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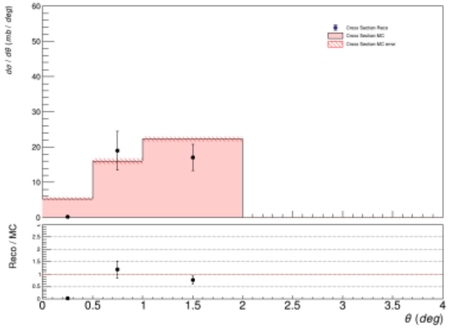

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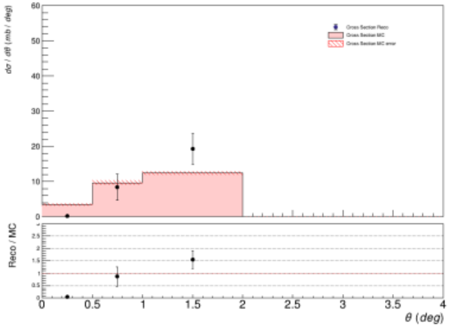

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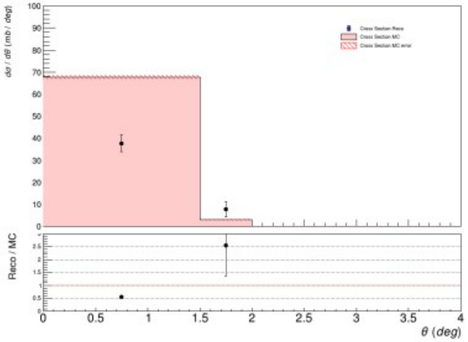
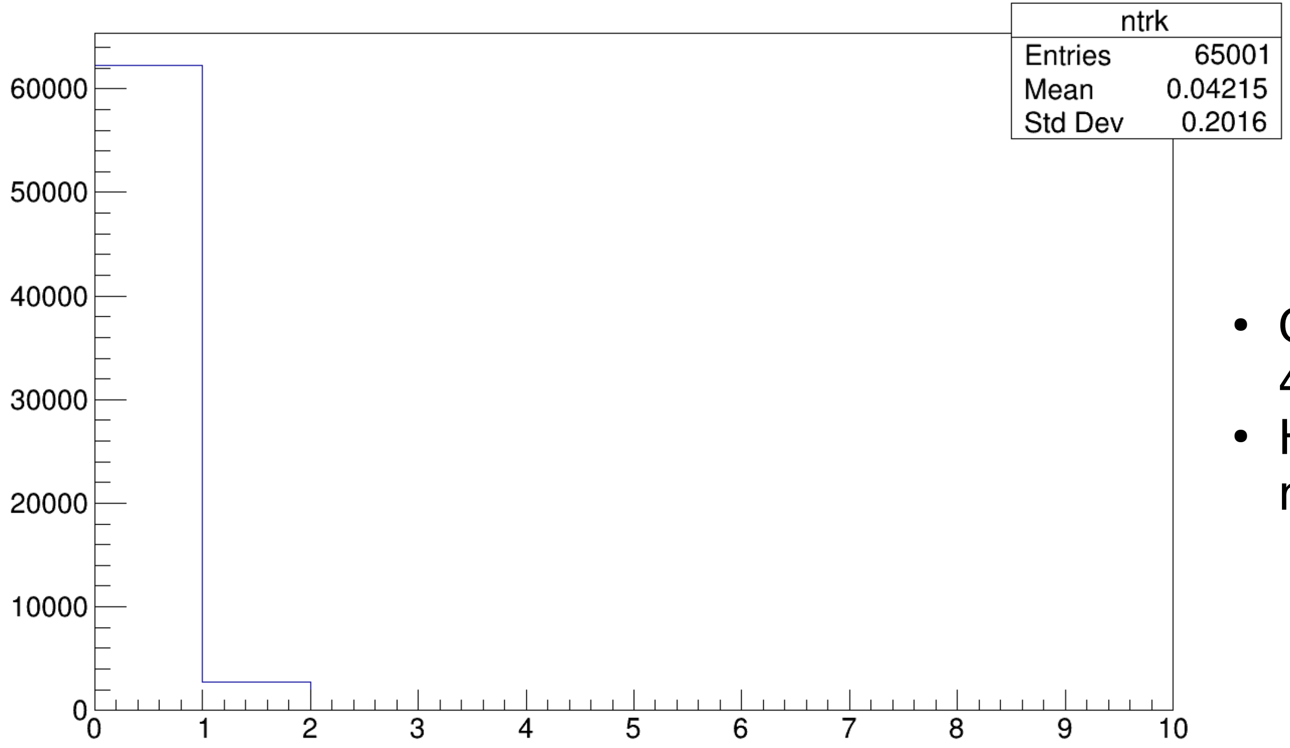


(g) Z=7

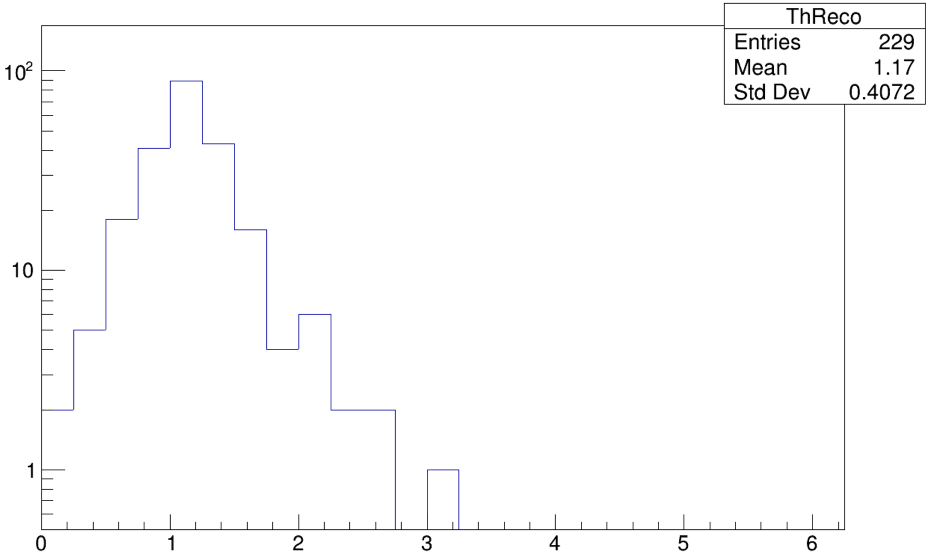
Experimental data issues



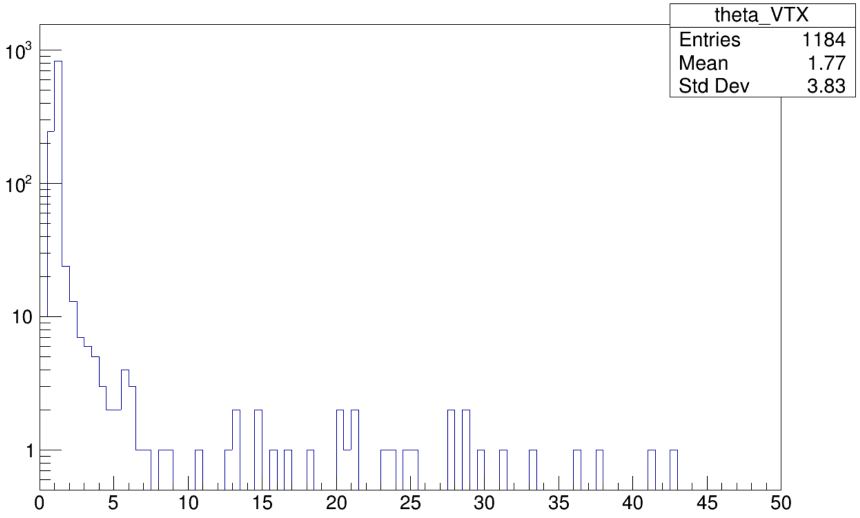
- GLB tracking
  4 points (**VT**) + 1 (**TW**)
- High inefficiency in track reconstruction

Is it a problem of VT?

Global vs VT theta



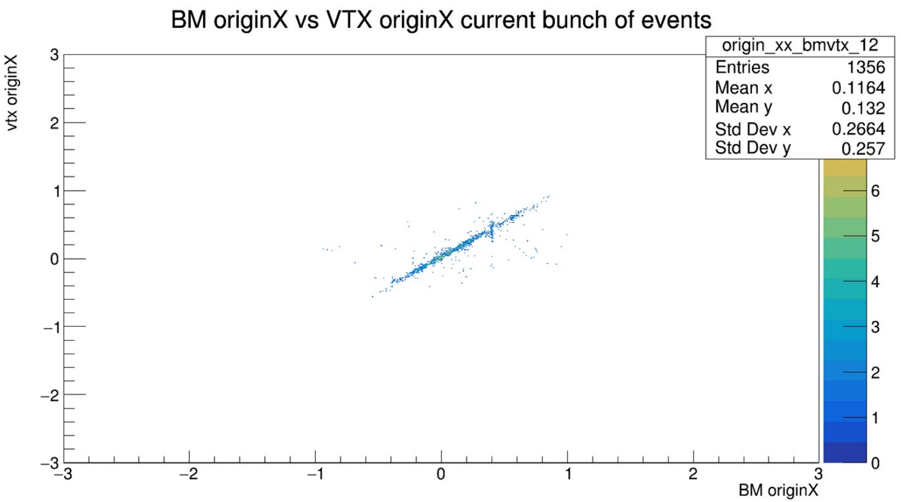
Global theta



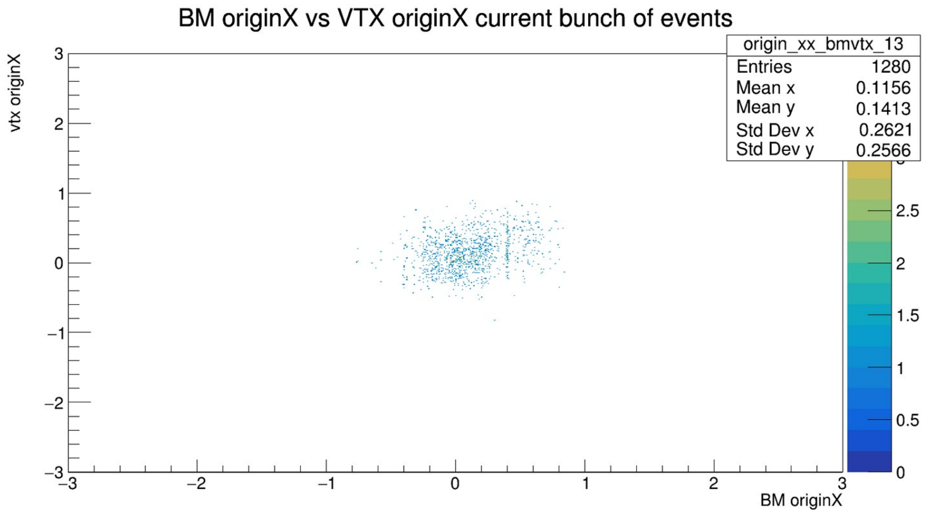
VT theta

It seems tracks with wider angle aperture are not reconstructed

VT synch



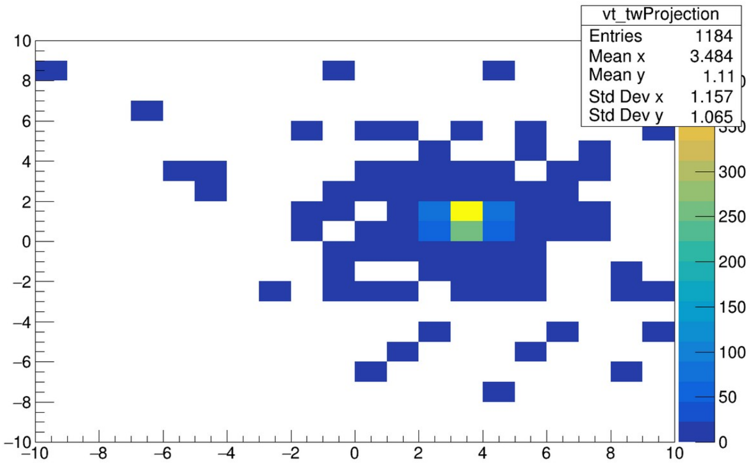
correlazione tracce bm-vtx per eventi fino a 60 k



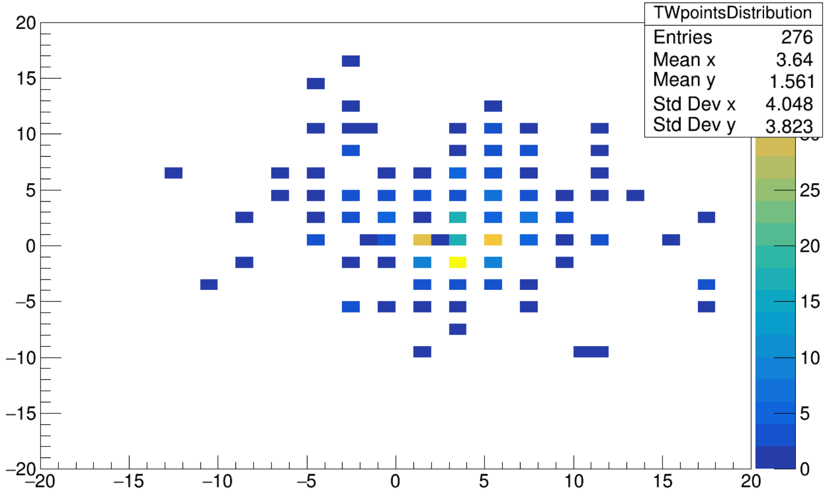
correlazione tracce bm-vtx per eventi da 60k a 65k

→ events up to 65000 are synchronized

fragments



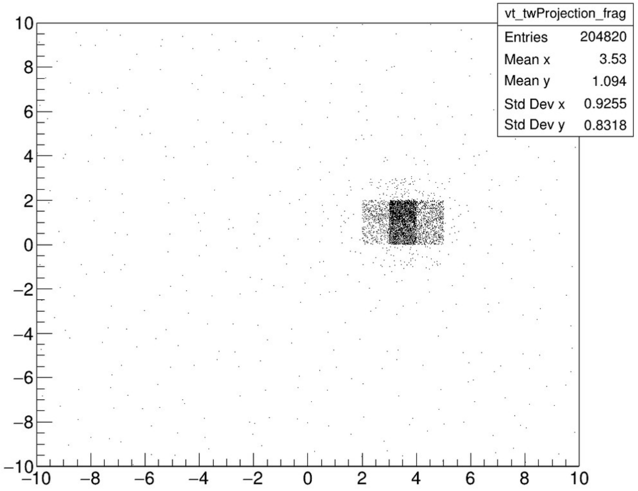
Projection of the tracklet in
the TW in global frame

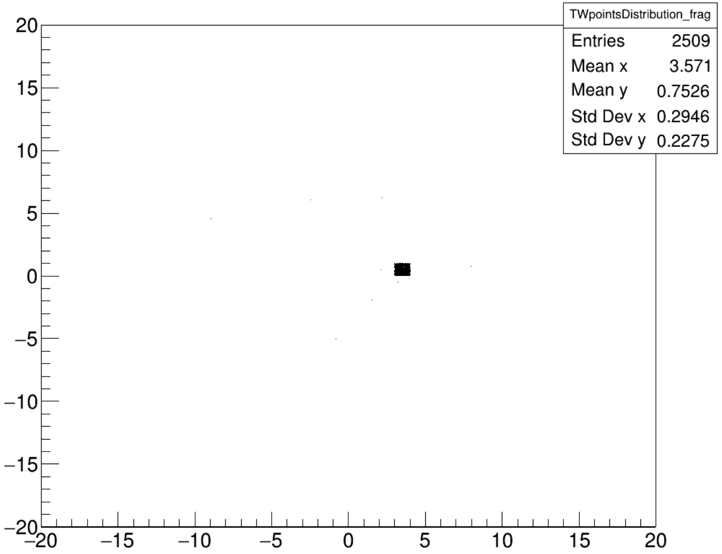


TW points (global frame)

→ TW is shifted wrt to vtx

beam

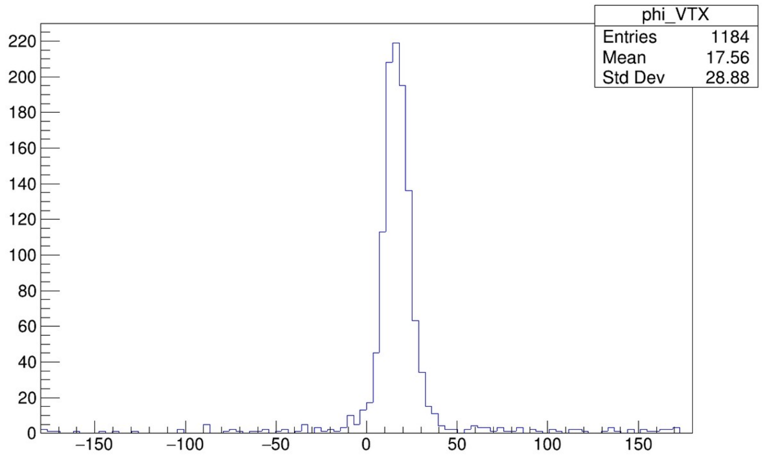




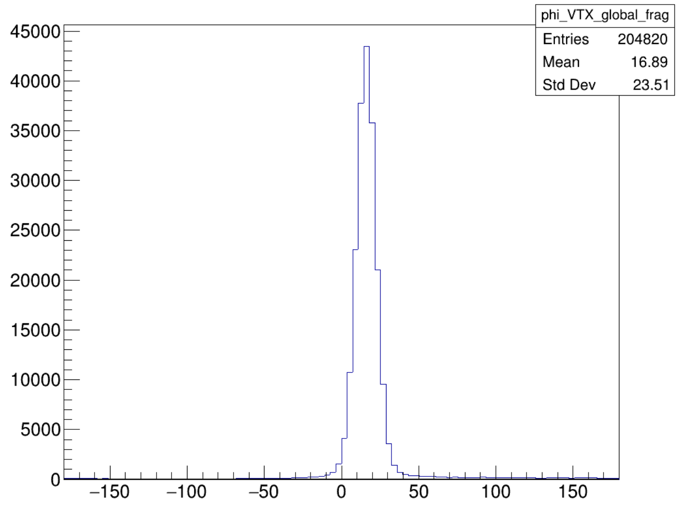
TW points (global frame)

Projection of the tracklet in
the TW in global frame

→ TW is shifted wrt to vtx



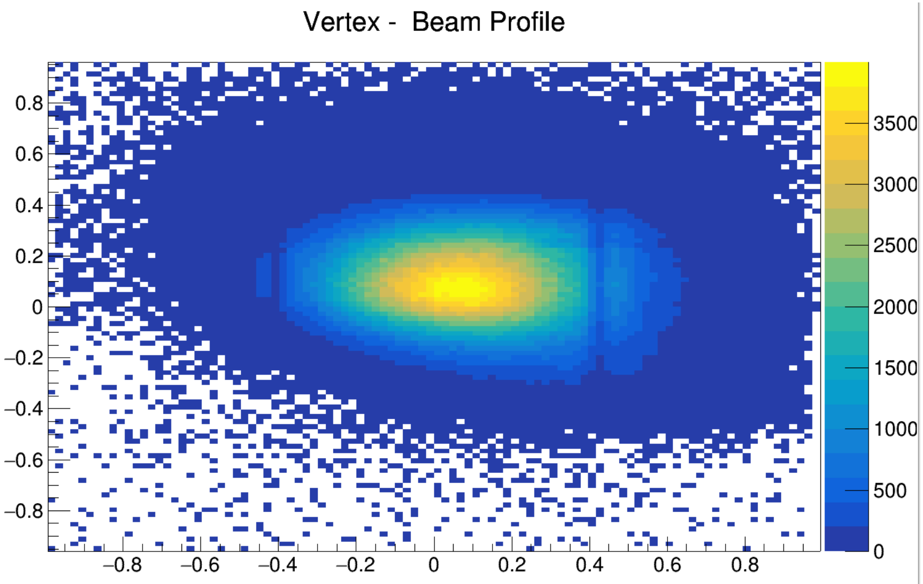
frags

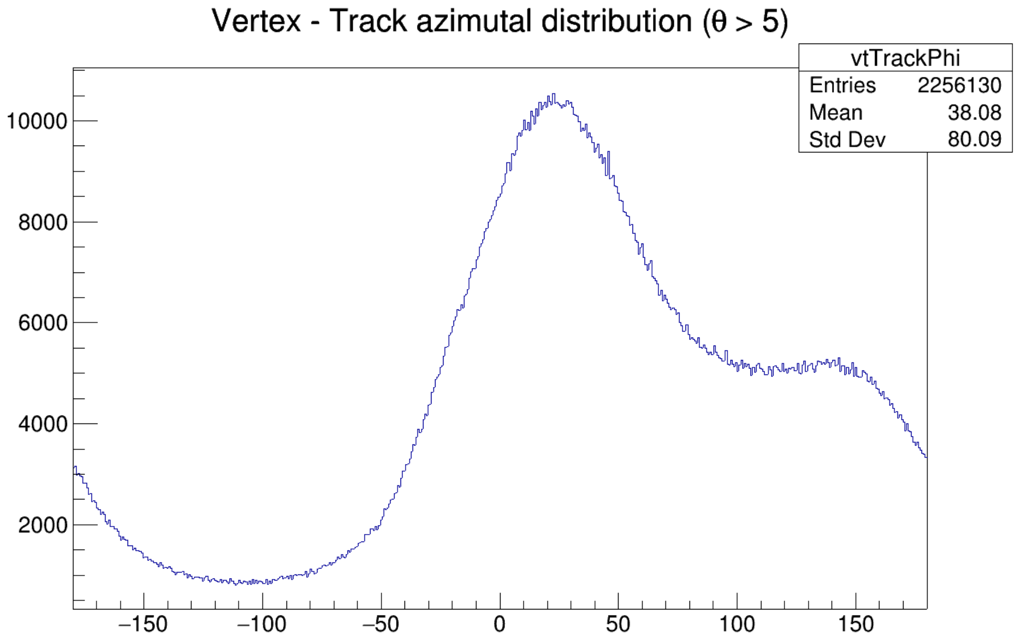


oxygen

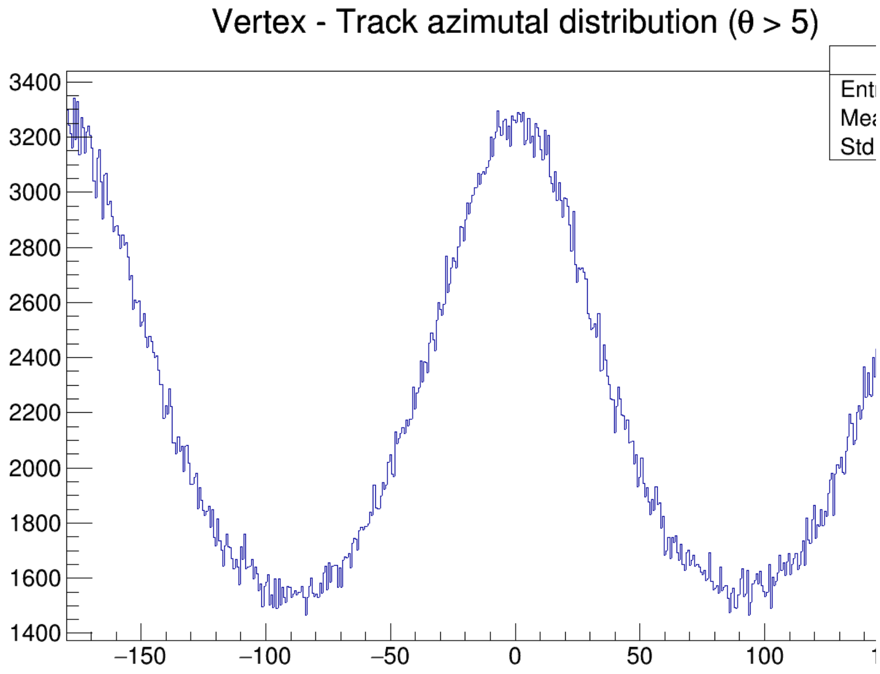
- Azimutal distribution peaked around 18° → is the VT tilted?

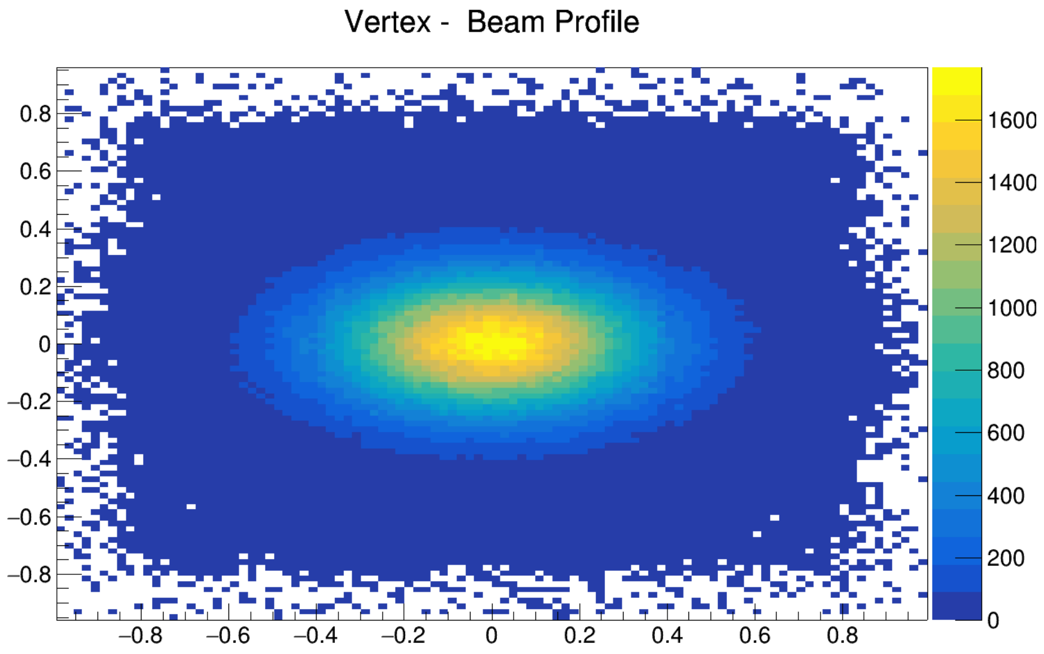
Phi distribution of ORIGIN of tracklets





MC Phi distribution of ORIGIN of tracklets





```
//_____________________________________________________________________________
//! Get theta angle in deg
Float_t TAGbaseTrack::GetTheta() const
{
   TVector3 direction = fSlope->Unit();
   Float_t theta      = direction.Theta()*TMath::RadToDeg();

   return theta;
}

//_____________________________________________________________________________
//! Get phi angle in deg
Float_t TAGbaseTrack::GetPhi() const
{
   TVector3 origin = fOrigin->Unit();
   Float_t phi     = origin.Phi()*TMath::RadToDeg();

   return phi;
}
```

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

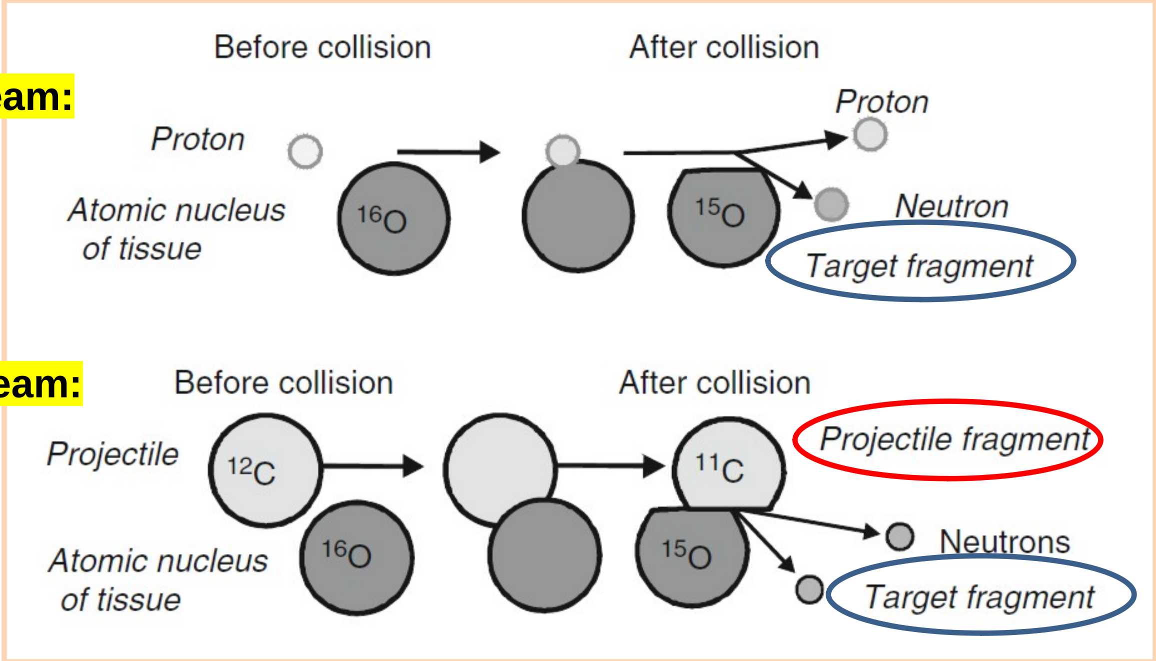
Nuclear fragmentation

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

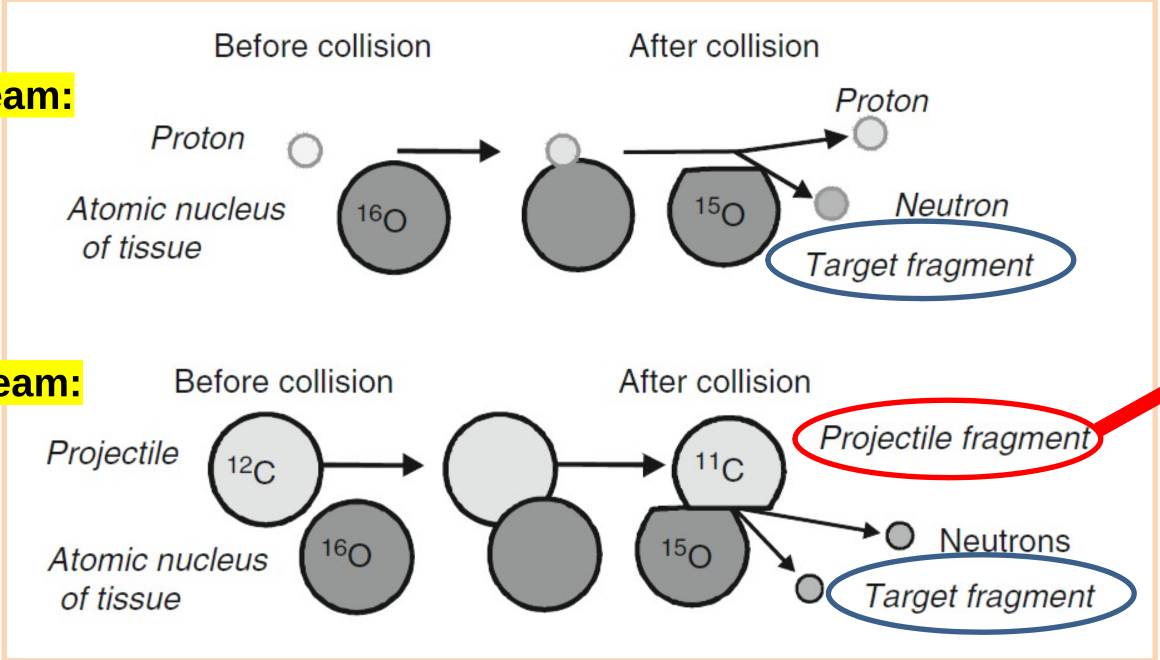
Nuclear fragmentation

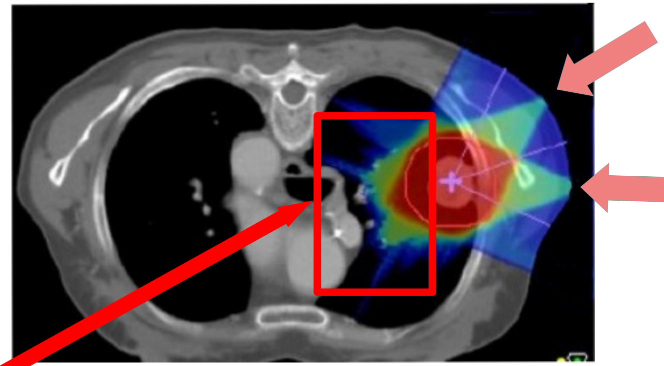
Proton beam:

~ 200 MeV

Carbon beam:

~ 400 MeV/u



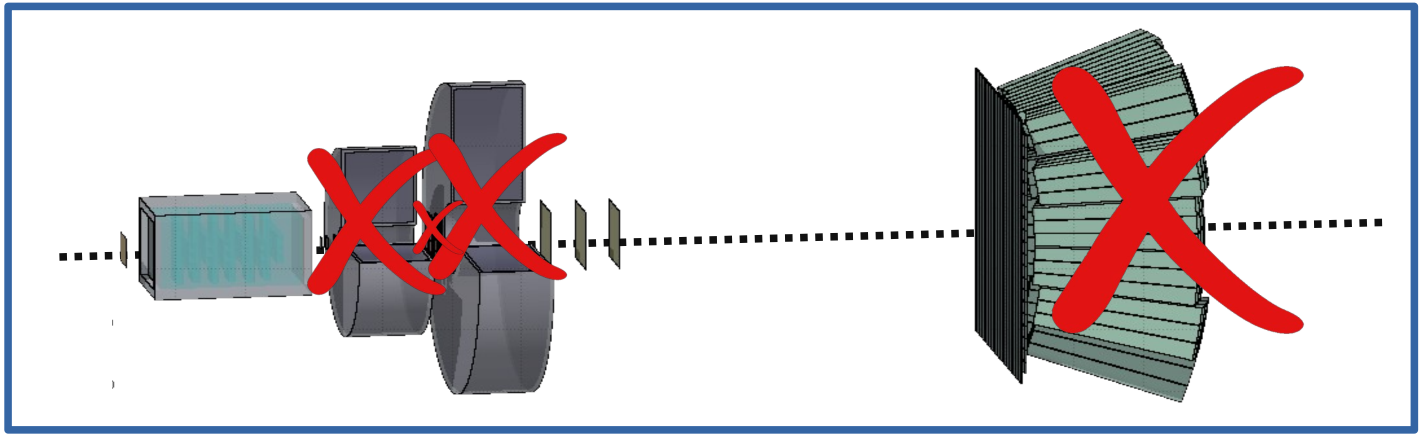


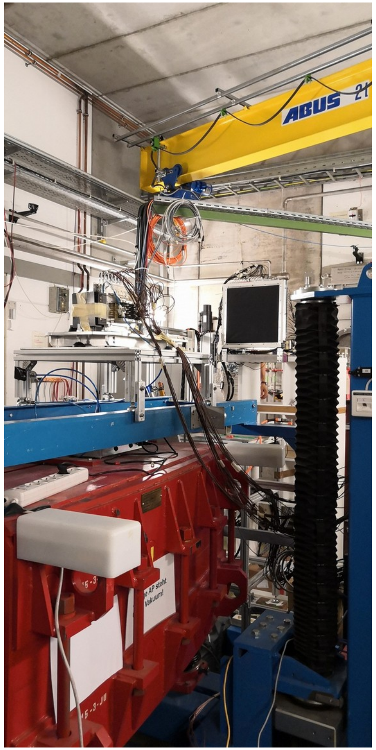
Projectile fragments:
- Longer range than beam
- Dose beyond the Bragg peak

nuclear cross section
mesurements needed

GSI 2021 Analysis

- 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:

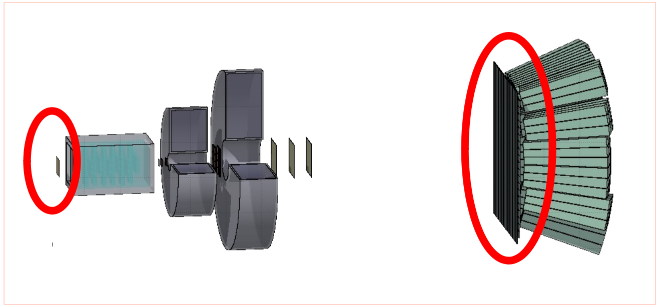
- Elemental (charge differential) fragmentation cross section
- Angular charge double differential cross section

Fragments identification

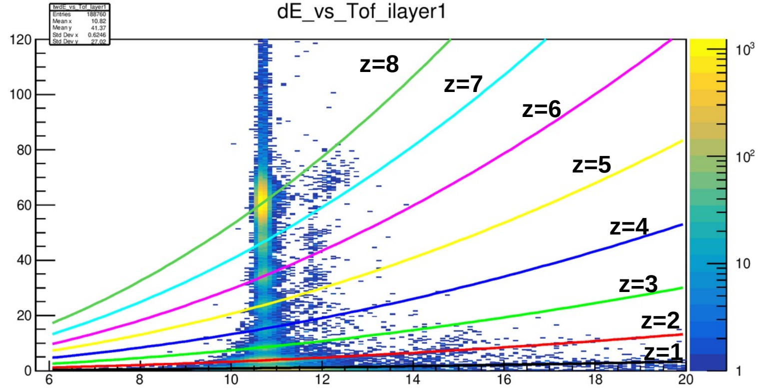
- From Bethe – Bloch formula I can get **z**:

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

- **Infos taken from SC and TW**

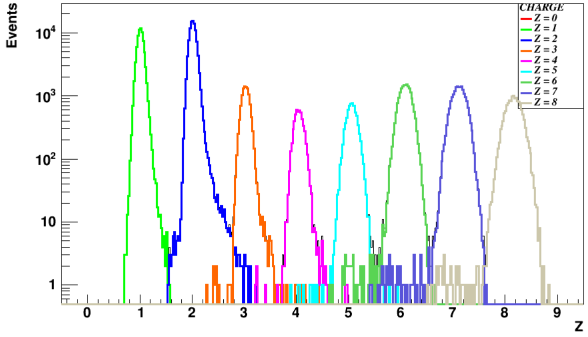


dE



ToF

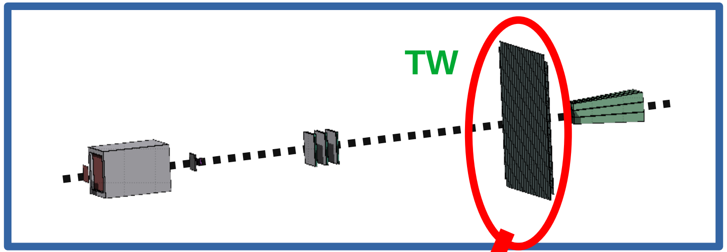
TW charge reconstruction algo

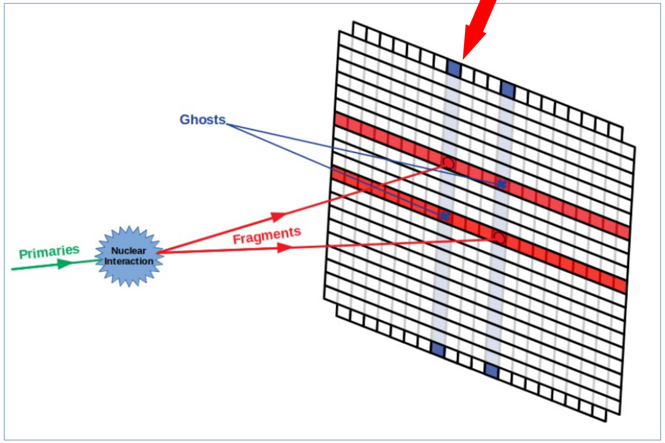


Charge discrimination

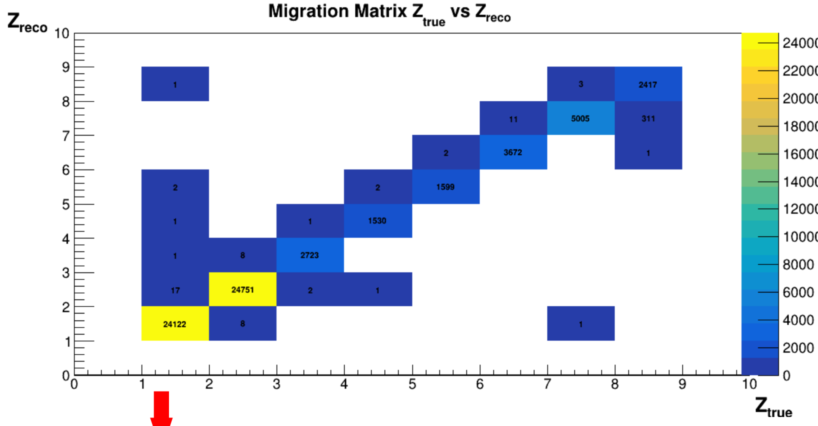
Track reconstruction, TW systematics

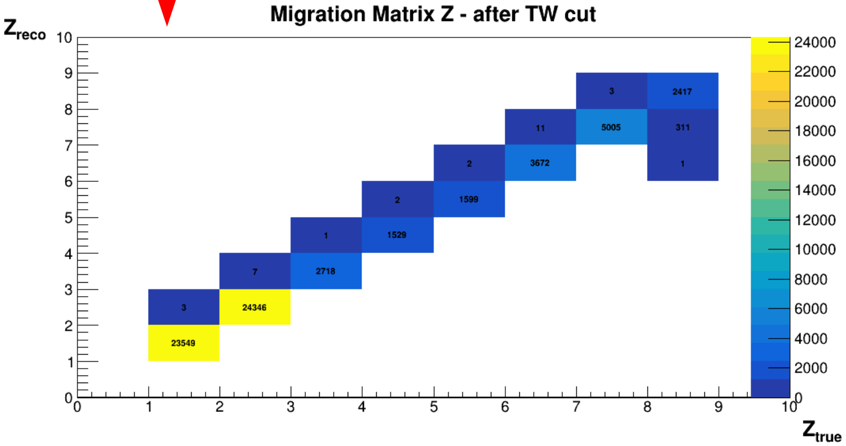
- It is possible that every bar layer of the TW is hitted by more than a fragment at the same time: **multiple hits / ghost hits systematics**



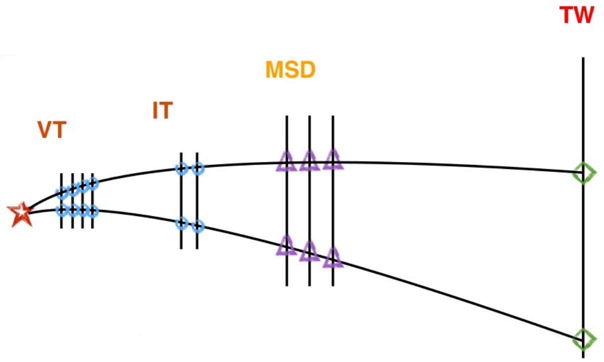


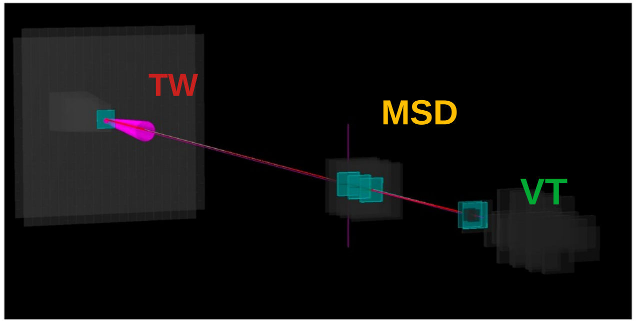
Applying TW cut:



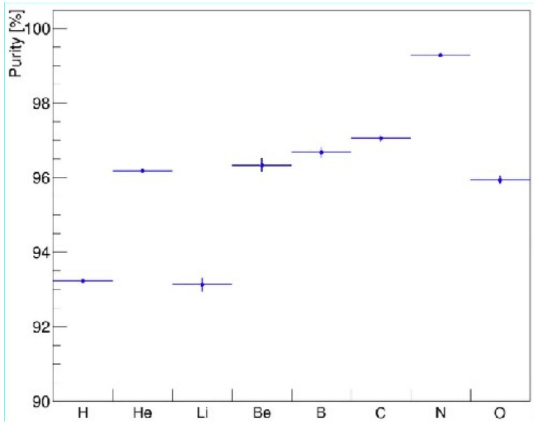


Track reconstruction





- track reconstruction on GSI 2021 data
  No B field present



Kalman Filter reconstruction of a track

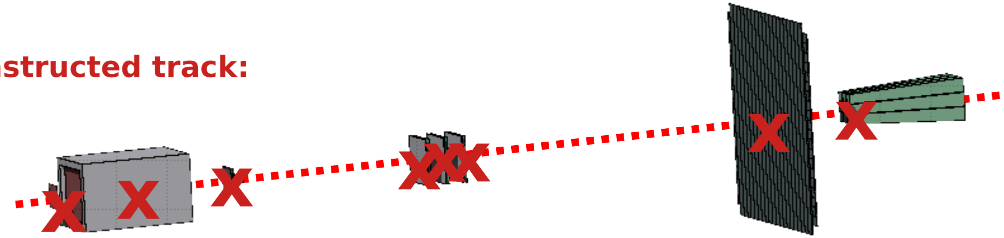
- Start from VT tracklets
- Projection to possible planes of IT
- KF extrapolation to MSD
- KF extrapolation to TW
- Fit the track candidates and extract reconstructed quantities: **Z**, **momentum** ...

Reconstruction, Track Algo

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

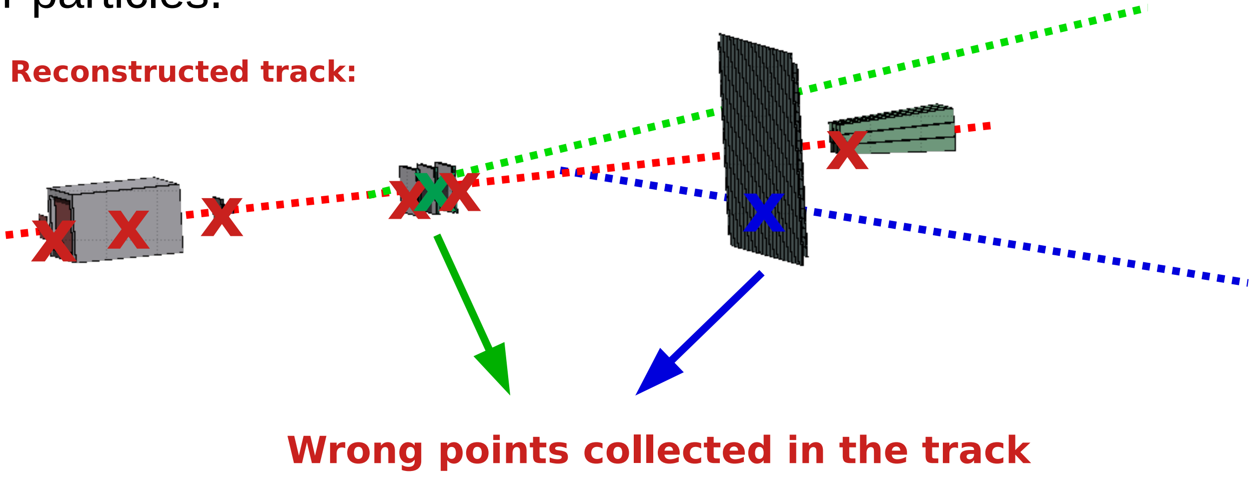
- In the best scenario, all points belong to the same particle:

Reconstructed track:



Reconstruction, Track Algo

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

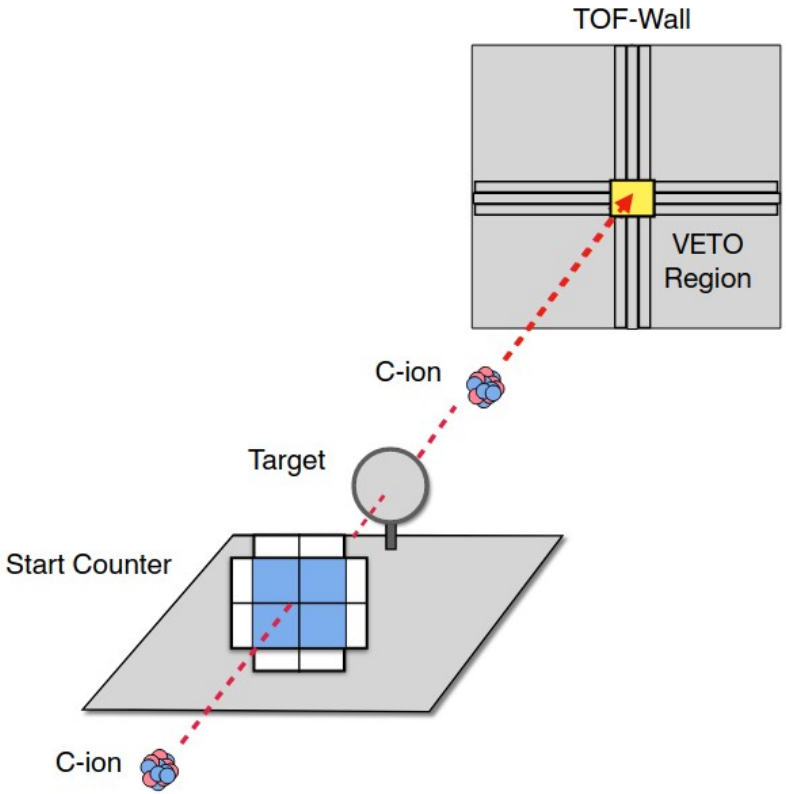


- The McId of the track is given by the most present particle in the collection
- However, if the TWPoint is of another particle → **its McId is different**
- → filter out all the tracks in which **$\mathbf{McId_{track} \neq McId_{TWPoint}}$**

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.

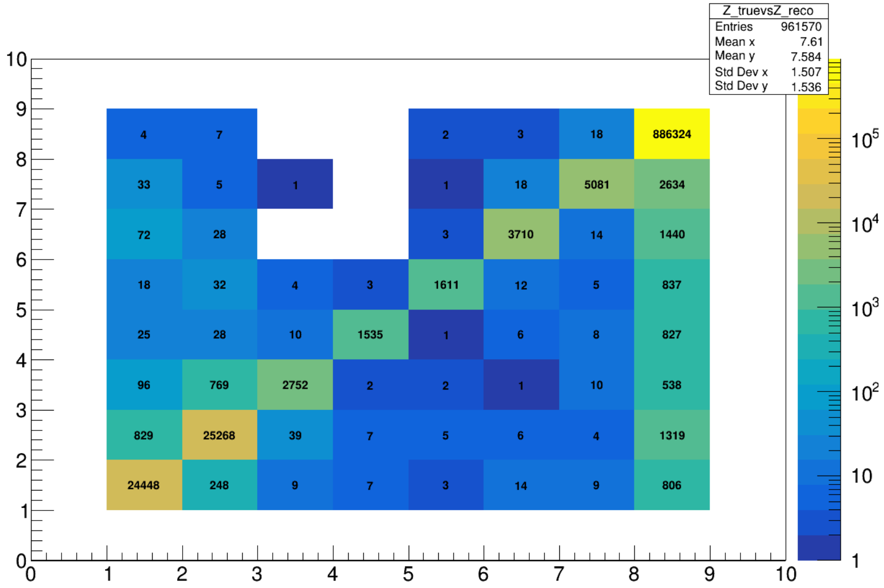
Minimum Bias is fired whenever the number of SC channels above a certain threshold exceeds a programmable value (aka *majority*).

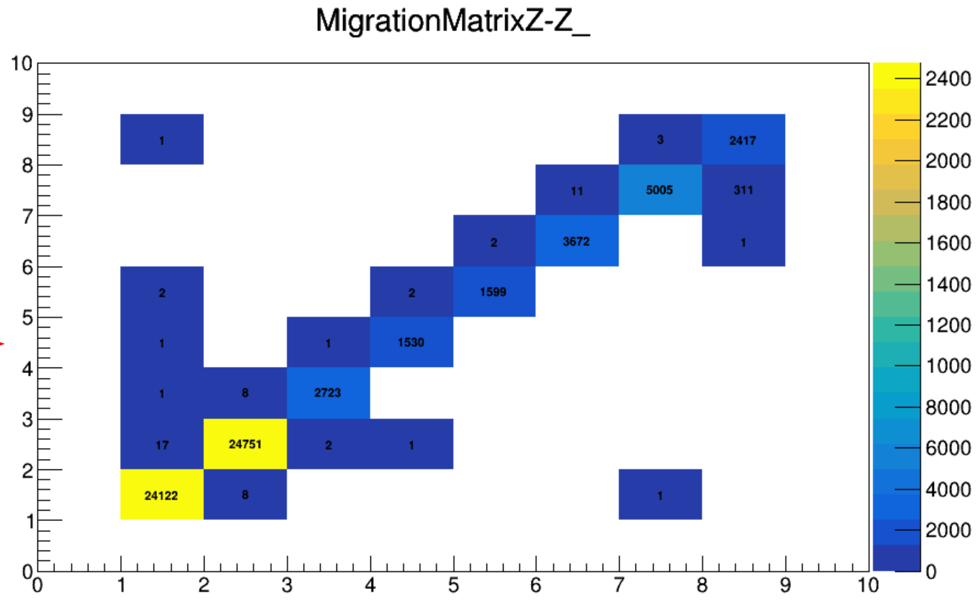


- **Fragment Trigger** is fired every time Minimum Bias condition on TW is not verified

Trigger Simulation

Applying Trigger cut:

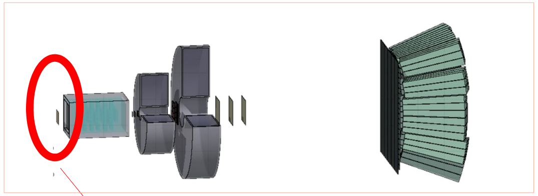


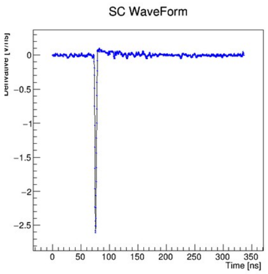


- Main source of mis-reconstruction is given by O due to its high statistics

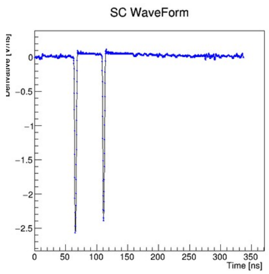
Pile-up removal

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



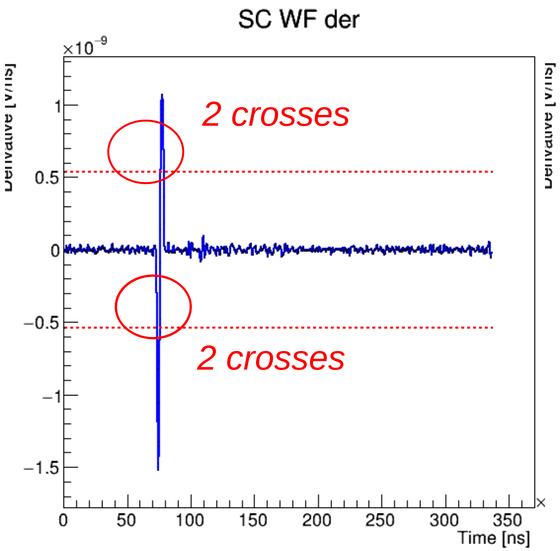


Single projectile

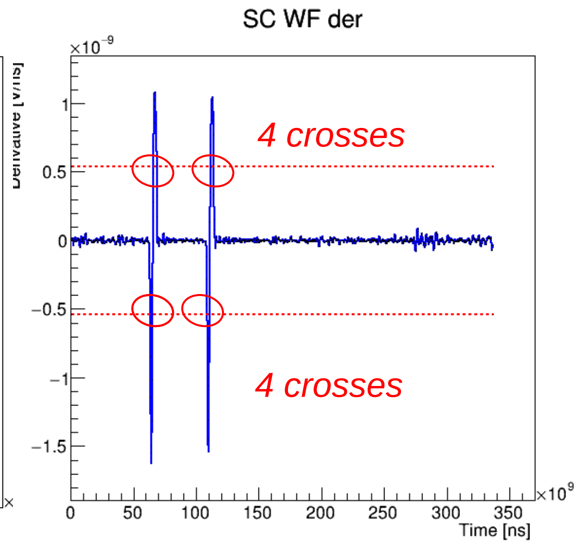


Pileup projectile

constant threshold discrimination method



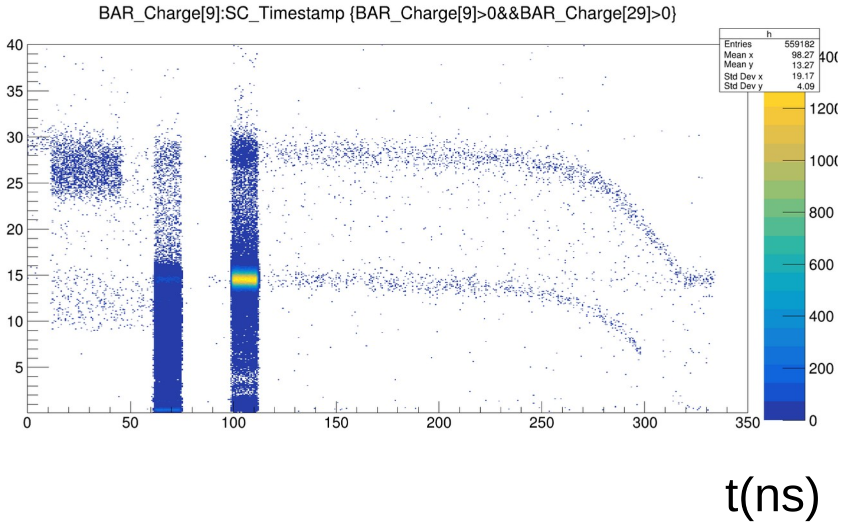
Single projectile: 4 crosses

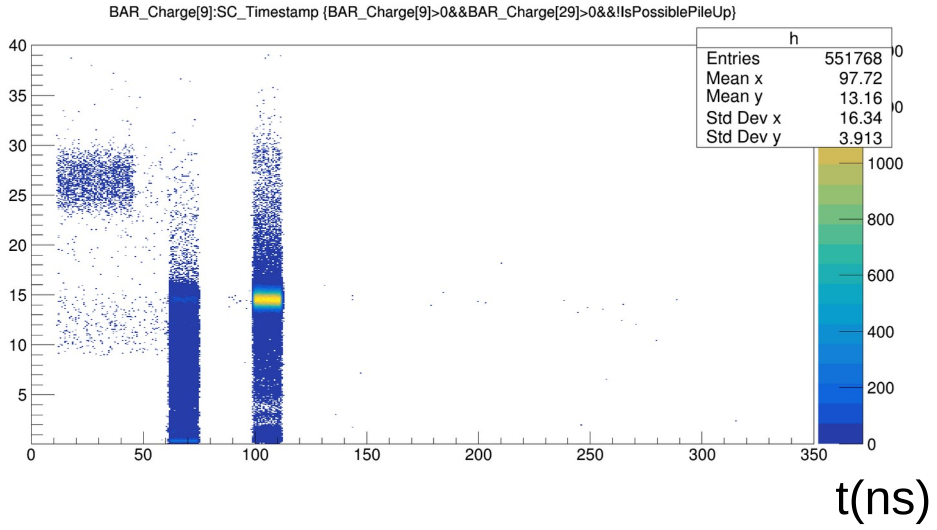


pileup projectile: >4 crosses

Pile-up removal

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



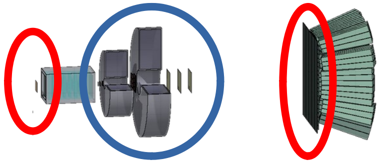


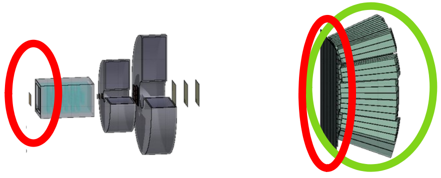
PileUp on 600.000 events ~ 1%

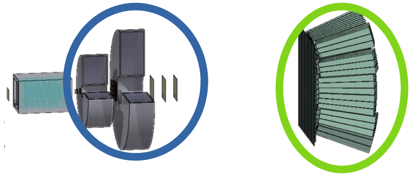
Isotopes identification

- Mass reconstruction using all FOOT subdetectors:

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





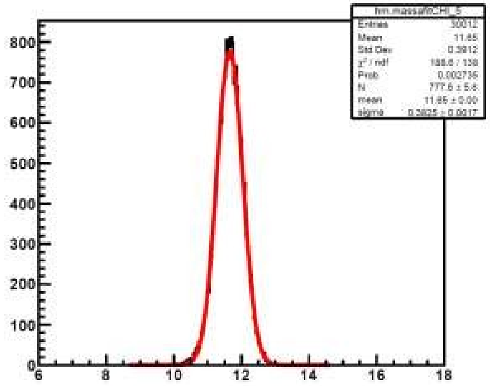


- In our data no tracker and calorimeter → mass measurement only in MC data!
- Augmented Lagrangian

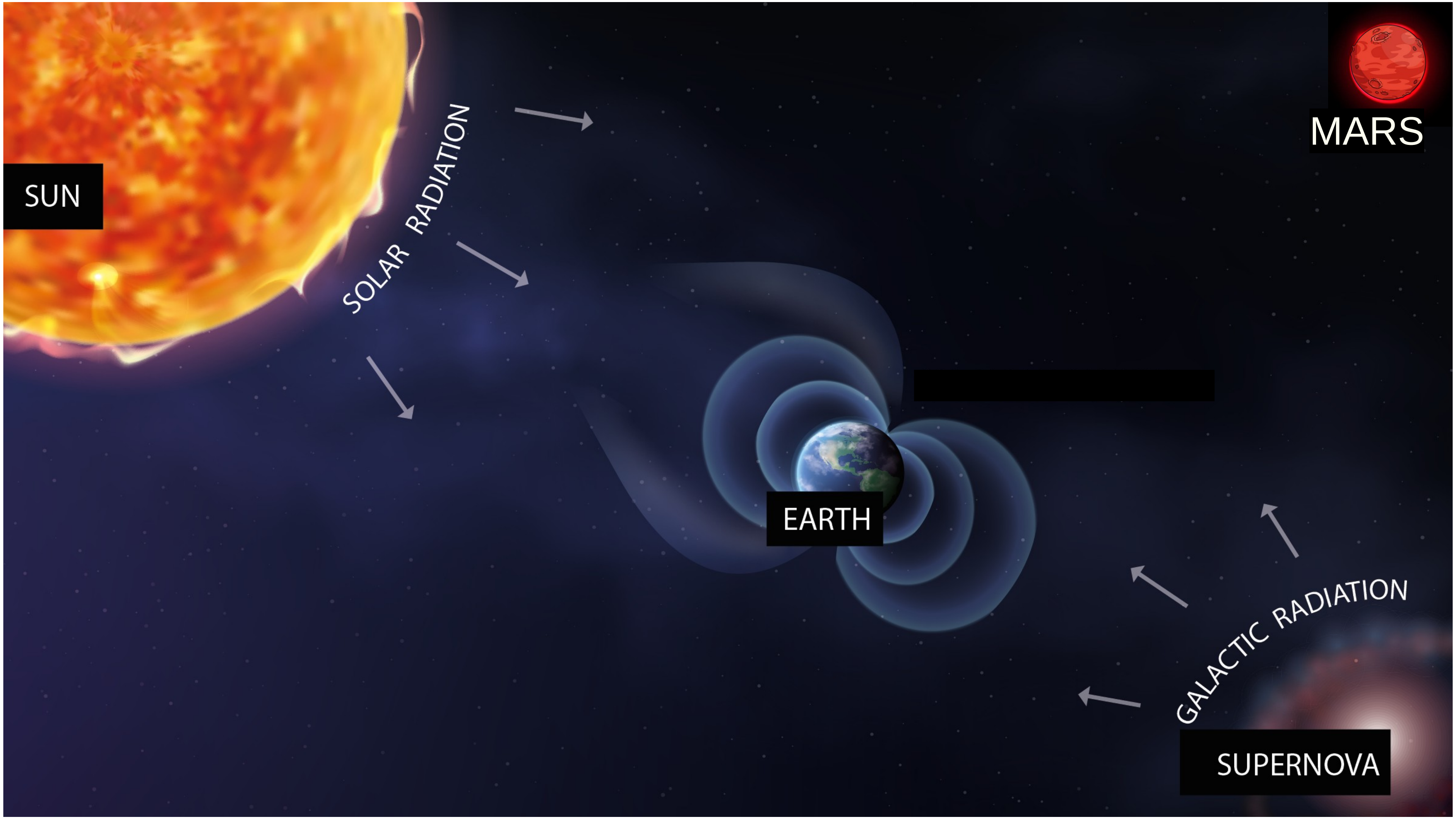
$$L(\vec{x}, \lambda, \mu) \equiv f(\vec{x}) - \sum \lambda_a c_a(\vec{x}) + \frac{1}{2\mu}\sum c_a^2(\vec{x})$$

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

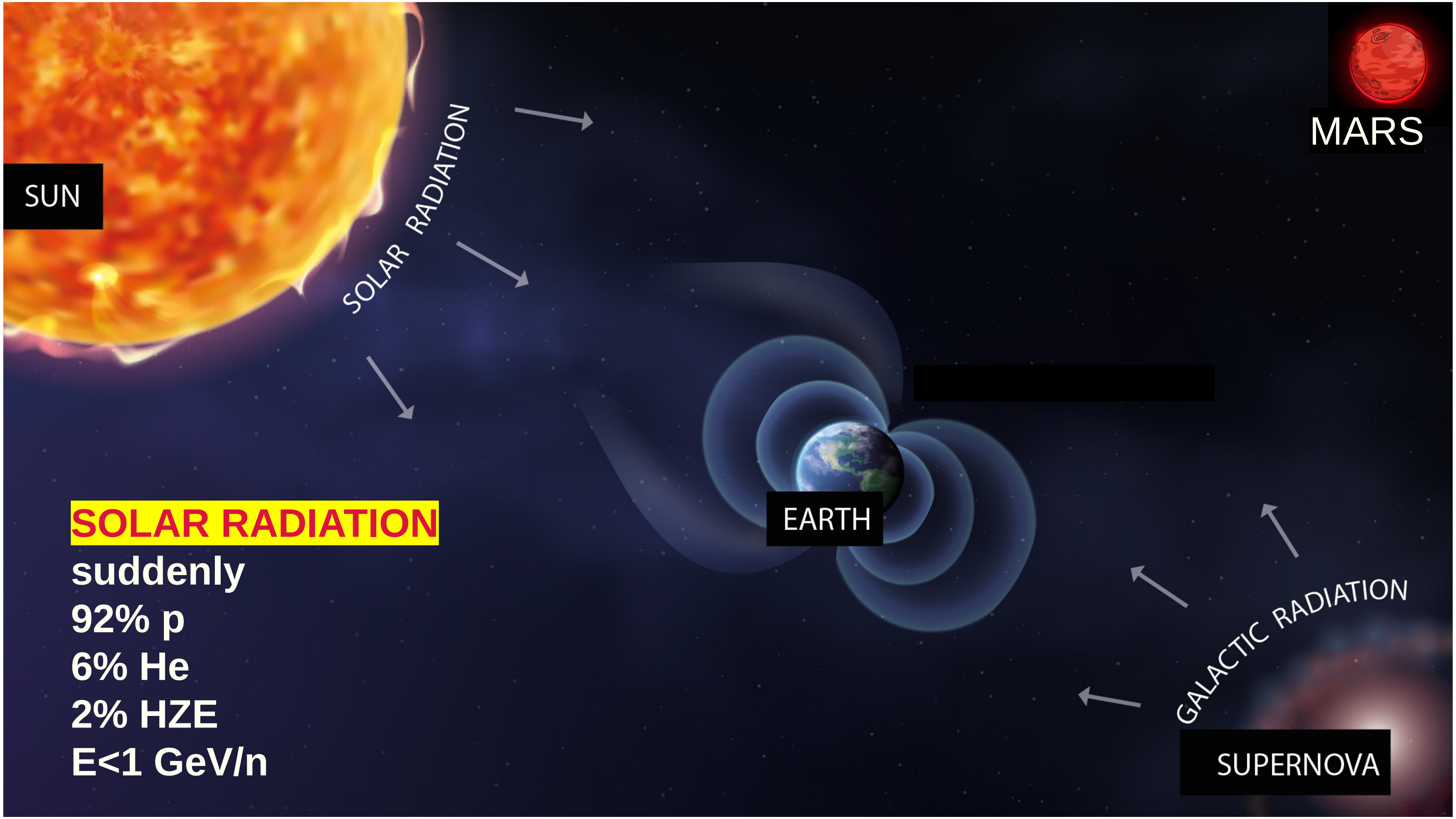
$A\chi 2 = 11.66 \pm 0.38$
risoluz. 3.2 %
$\chi 2 < 5$



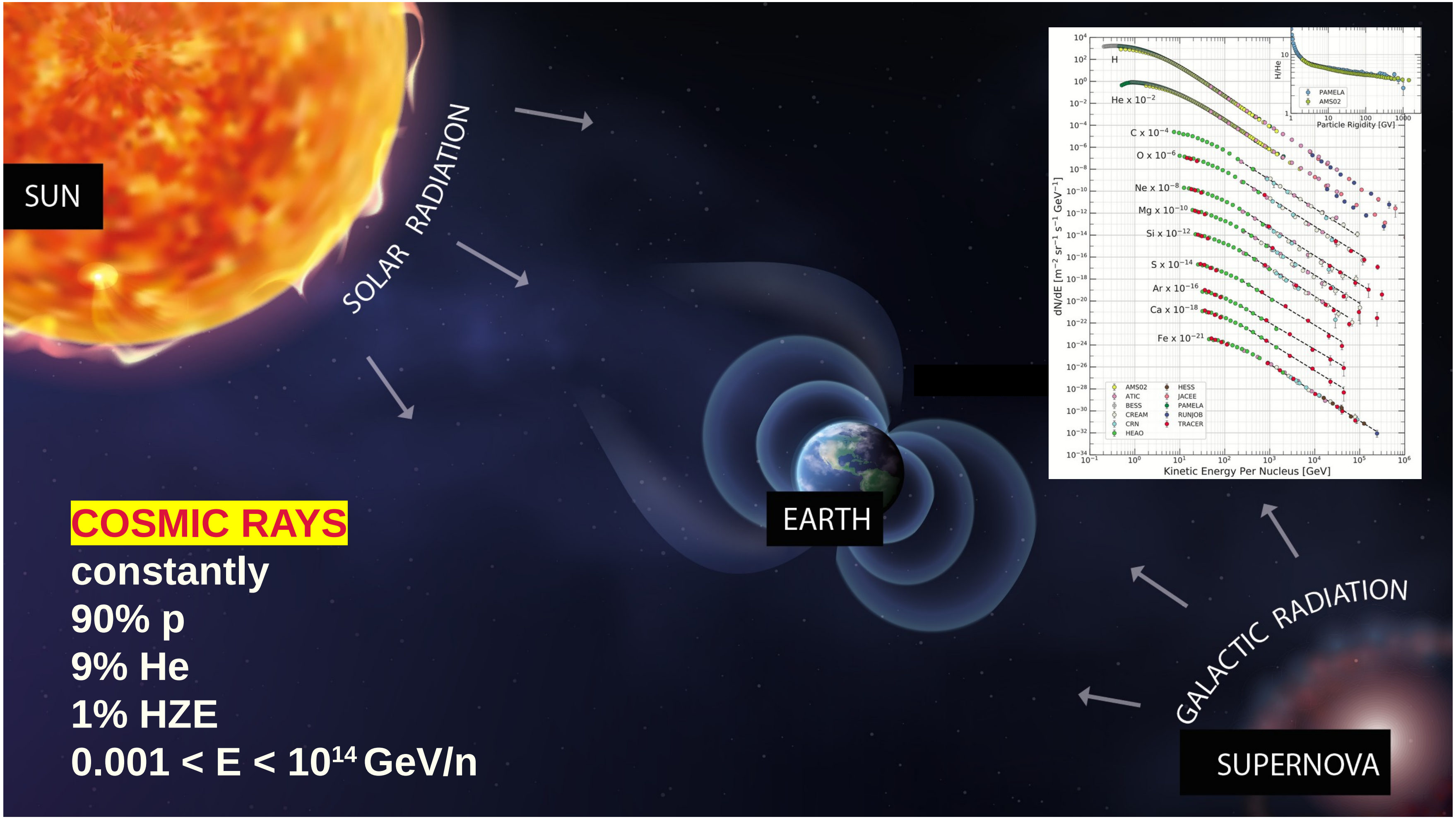
Space radioprotection



Space radioprotection



Space radioprotection



COSMIC RAYS

constantly

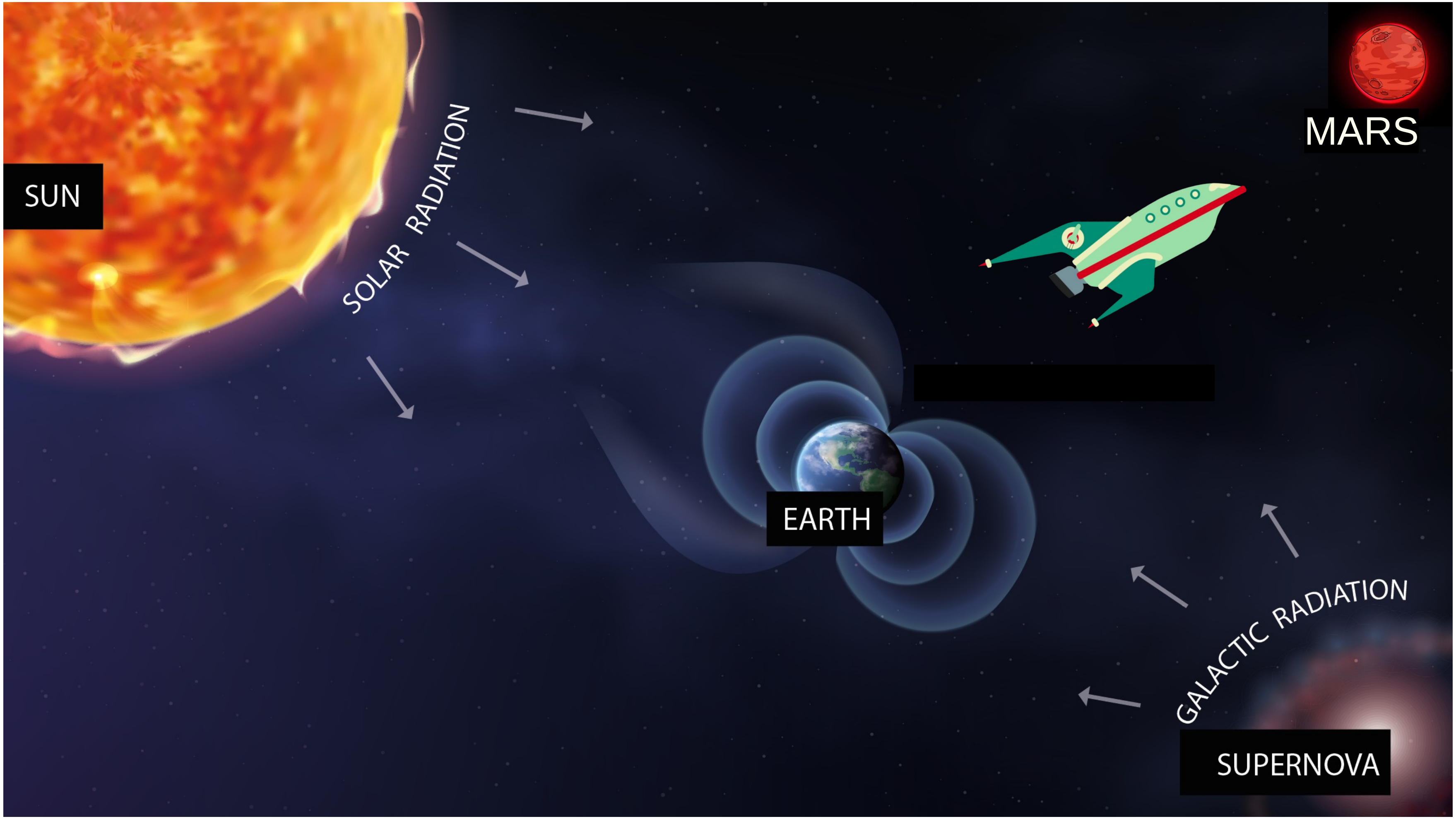
90% p

9% He

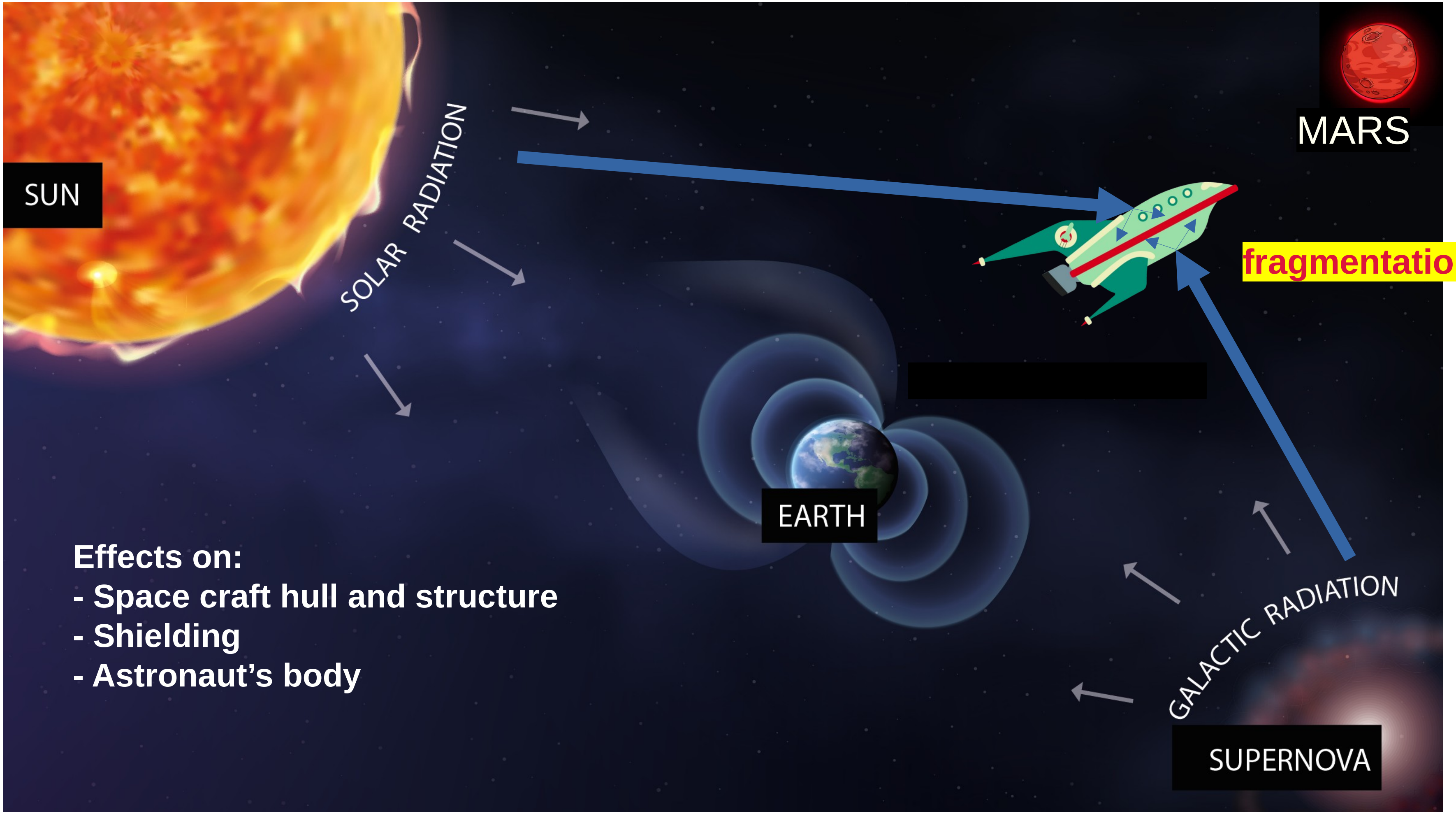
1% HZE

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

Space radioprotection



Space radioprotection



Space radioprotection