PhD Programme in Physics of the University of Bologna
38th Cycle

“Measurements of nuclear **fragmentation** differential **cross section** of a ^{16}O beam in an energy range between 200 MeV/n and 400 MeV/n at the FOOT experiment”

Thesis description presentation

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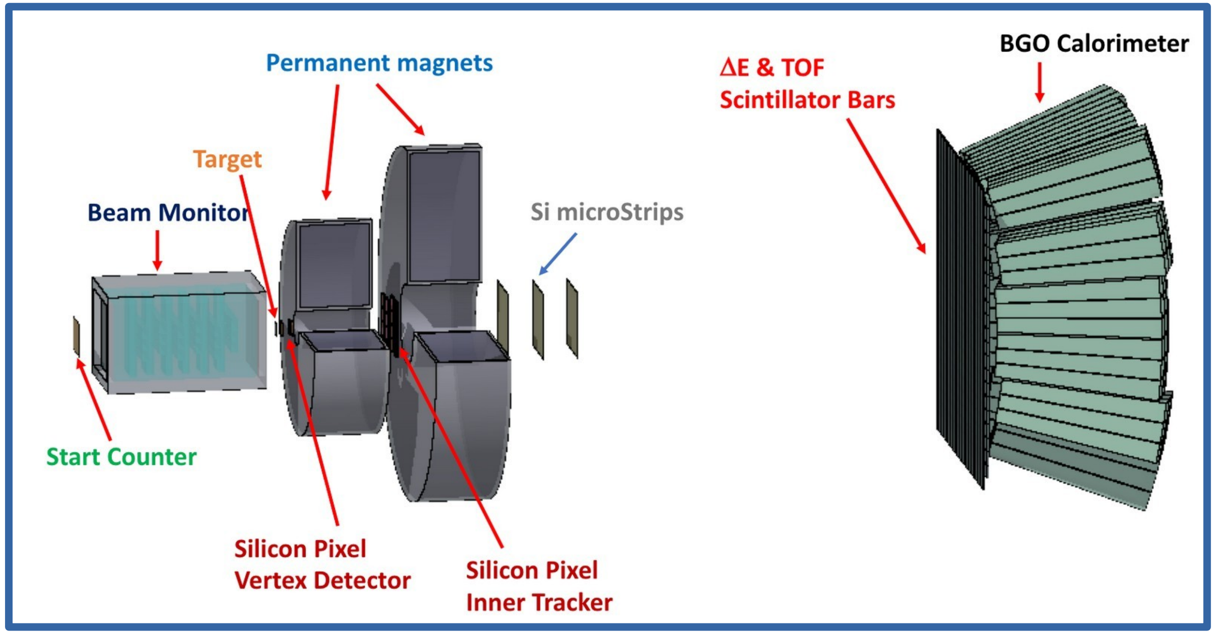
The FOOT experiment

Fixed target experiment with **scintillators**, **magnetic spectrometer**, **calorimeter**

- Beams of p,C,O between 200 MeV/u and 700 MeV/u for **hadrontherapy** and **space radioprotection** topics
- Particle identification by measuring all kinematic quantities



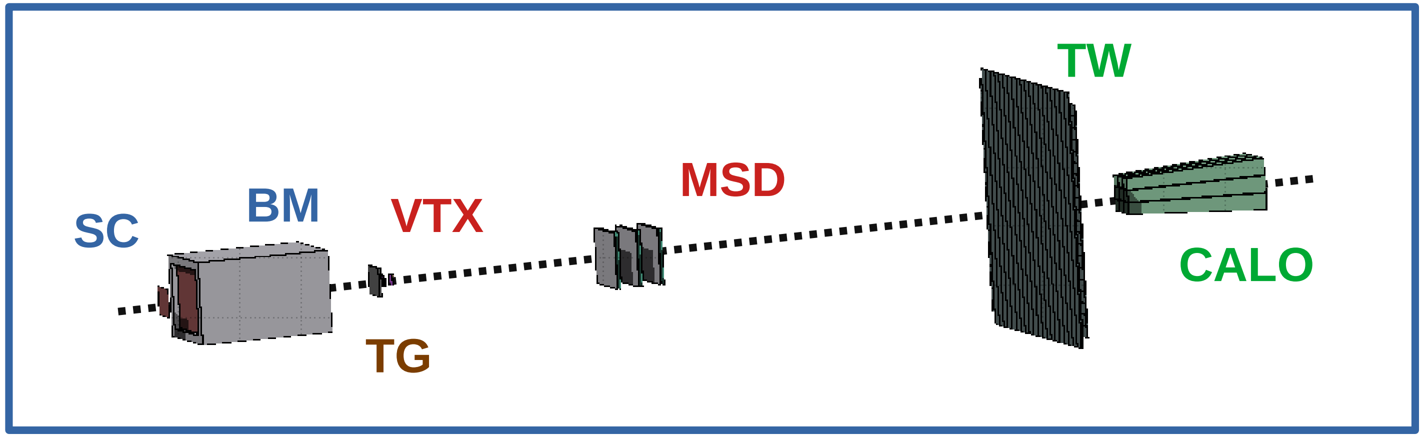
Goal:
Diffential **fragmentation cross sections** mesurements:

$$\frac{d^2\sigma}{d\Omega \cdot dE_{kin}}$$

My work

- Analysis of data taken at GSI in 2021 of ^{16}**O 400 MeV/u** and **200 MeV/u** against **C** as target
- Analysis integrated in **SHOE** and optimization for specific data

- Partial setup: no tracker, only one module of calorimeter



Specific goal:

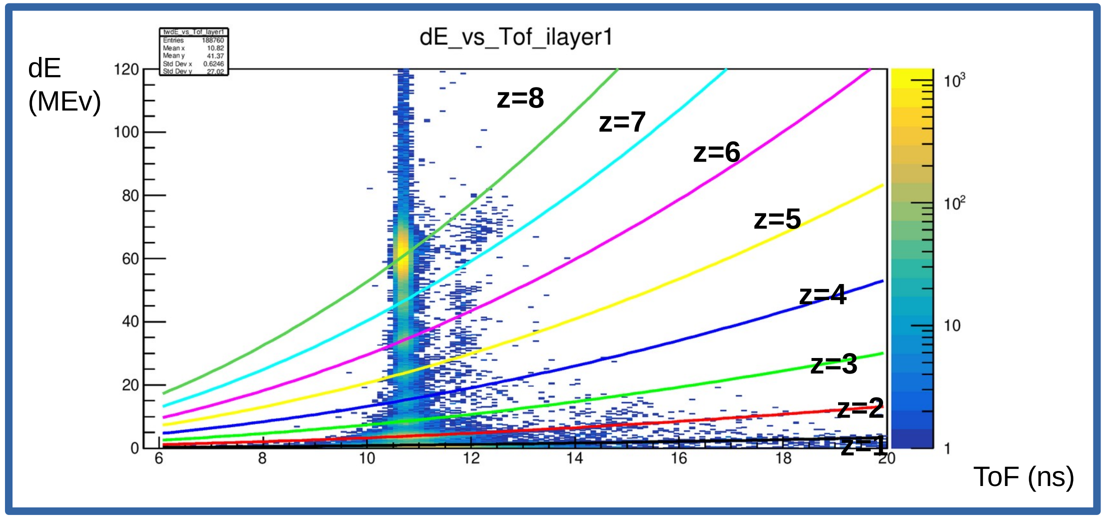
Differential fragment cross section:

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

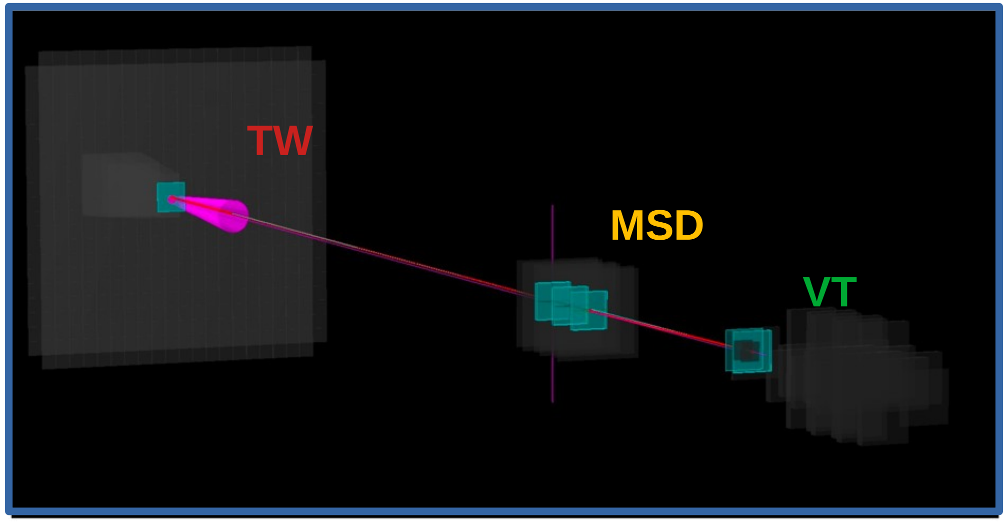
Event reconstruction

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

TW ***charge reconstruction*** *algorithm*



Kalman Filter reconstruction *of a track*

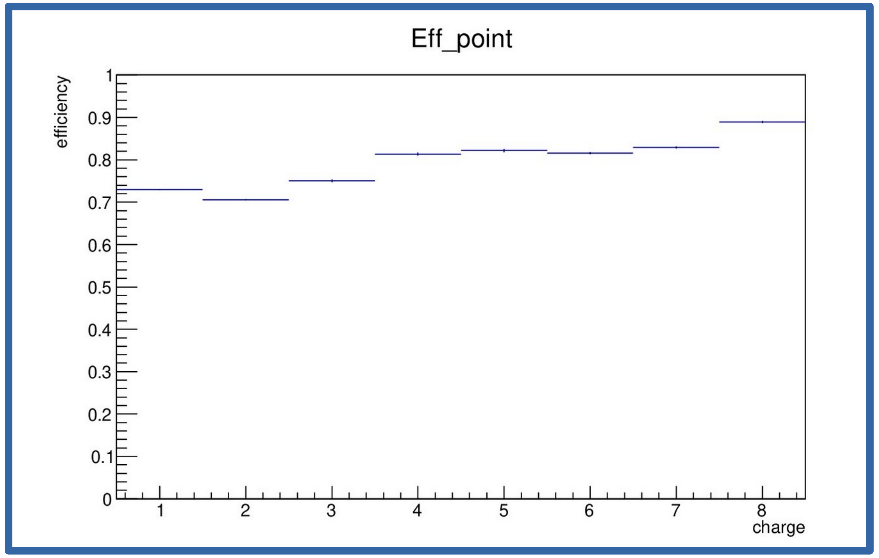


Efficiencies

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

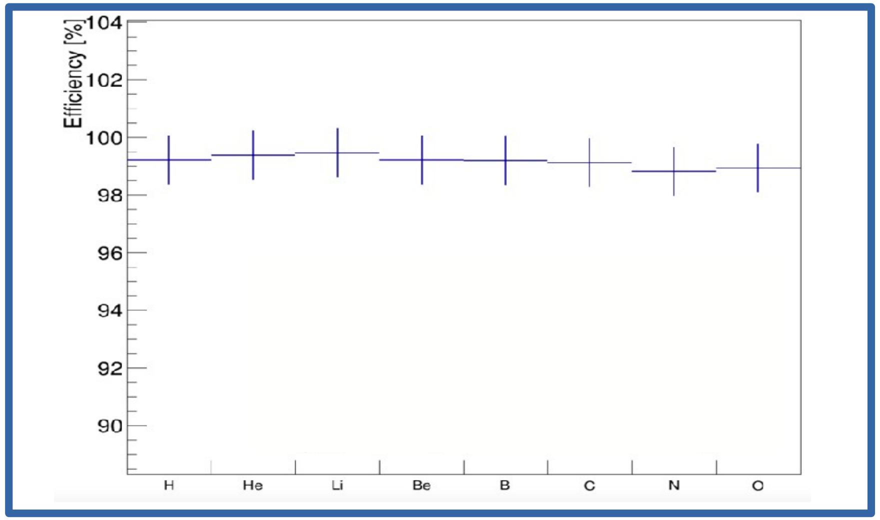
charge reconstruction *efficiency*

$$\varepsilon(Z) = \frac{N_{\mathrm{TW}}(Z) + 1}{N_{\mathrm{track}}(Z) + 2}$$



***Track reconstruction** efficiency*

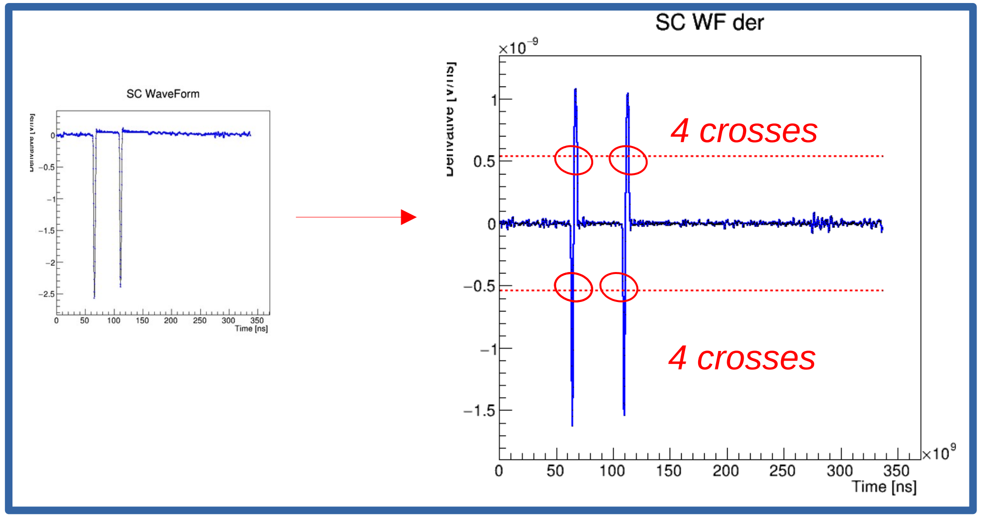
$$\varepsilon(Z) = \frac{N_{Z,conv}}{N_{Z,tot}}$$



Pile-up removal

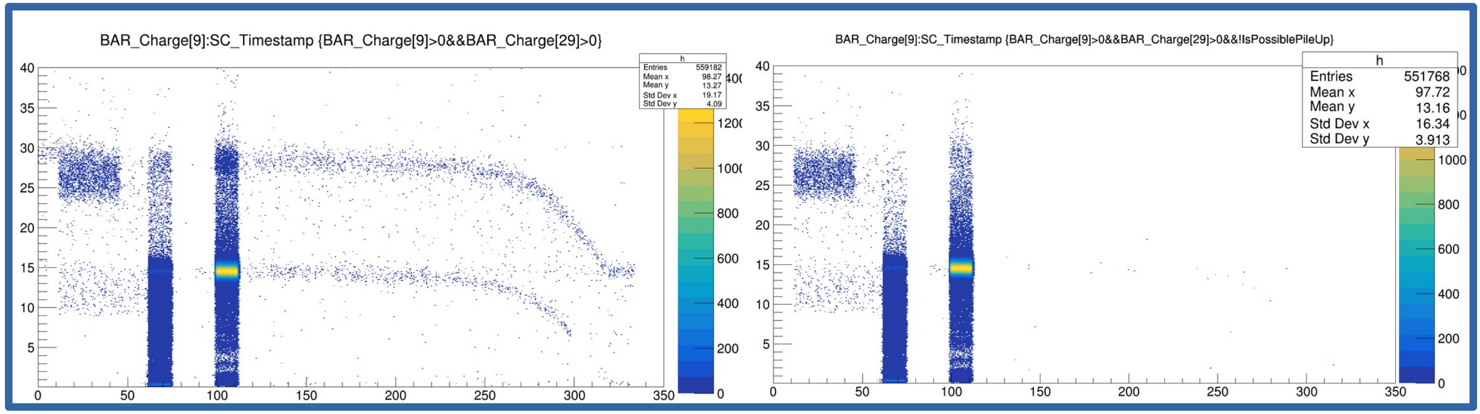
$$\frac{d\sigma}{d\theta} = \frac{(Y_f - B_f)^u}{N_{beam} \cdot N_{target} \cdot \Delta\theta \cdot \epsilon}$$

constant threshold ***discrimination method***



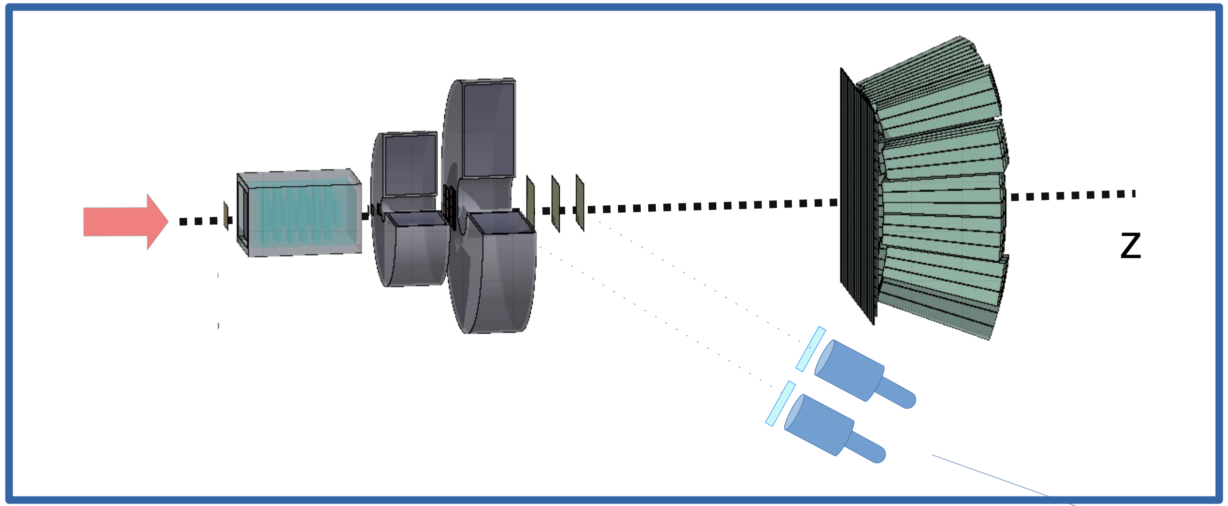
pileup projectile: >4 crosses

Pile-up rejection ~ 1%



Future prospects

Foreseen:
- New data taking with beam of ^{4}He, ^{12}C, ^{16}O at energies of 200 MeV/u, 400 MeV/n, 800 MeV/n



- Analysis optimization for all the setup
- Implementation of neutron detectors in analysis software
- Inverse kinematic application

BC-501A **liquid scintillator**

Back up slides

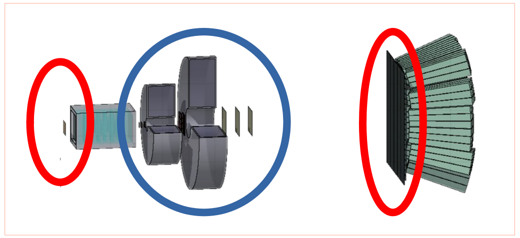
Isotopic identification

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

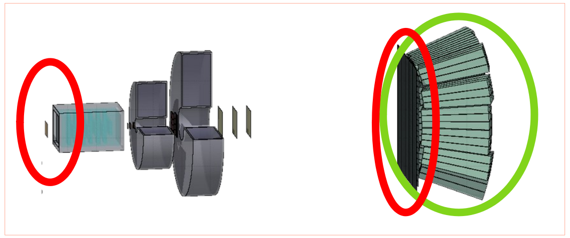
- MC data

Mass reconstruction *using all FOOT subdetectors:*

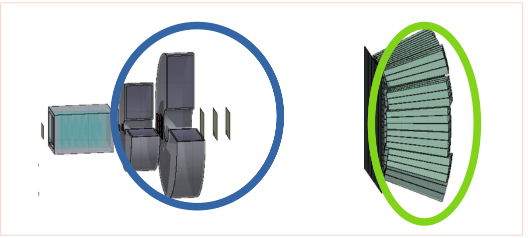
$$A_1 = \frac{p}{U\beta c\gamma}$$



$$A_2 = \frac{E_k}{Uc^2(\gamma - 1)}$$



$$A_3 = \frac{p^2c^2 - E_k^2}{2Uc^2E_k}$$



Isotopic identification

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

- MC data

Augmented Lagrangian Method

- *Minimization of*

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

where

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

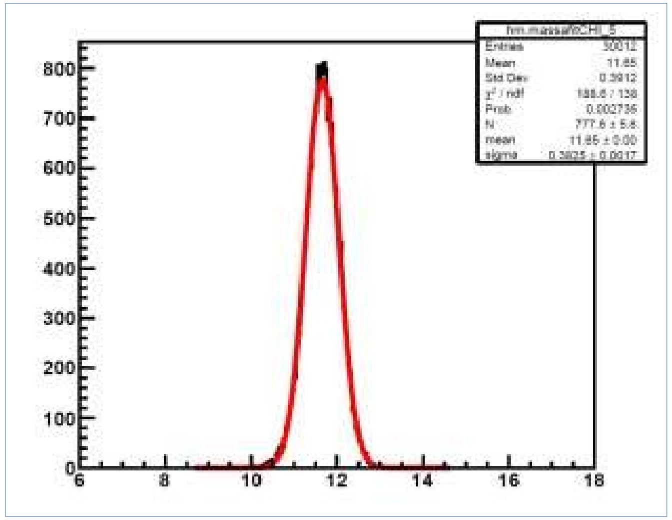
$$c_a(\vec{x}) = A - A_a$$

Es. **A = 12**

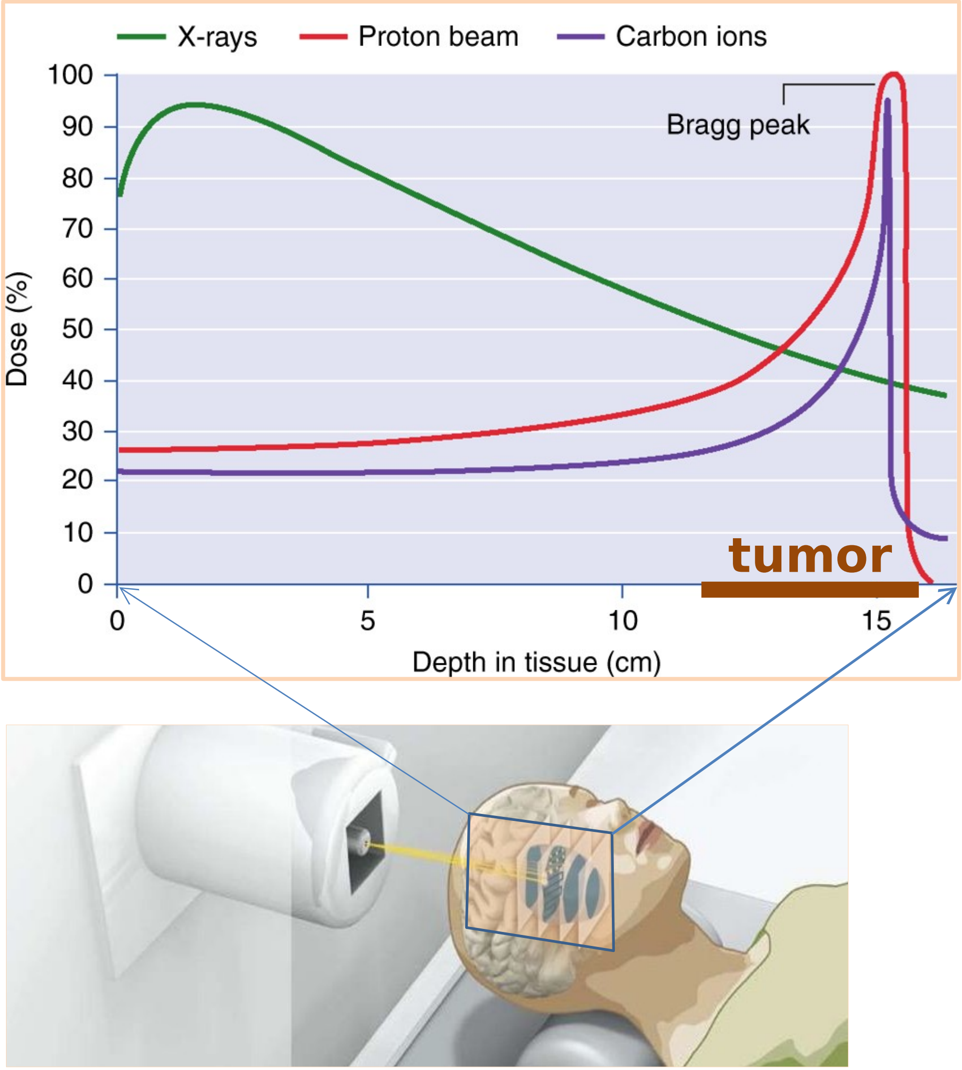
$A_{ALM} = 11.66 \pm 0.38$

$A/\sigma_A = 3.2$ %

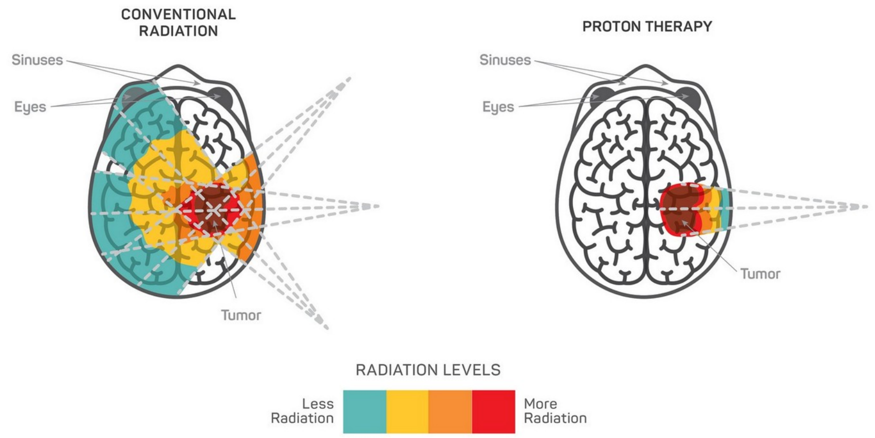
χ 2 < 5



Hadrontherapy



depth- dose profile for X-rays and charged particles as a beam

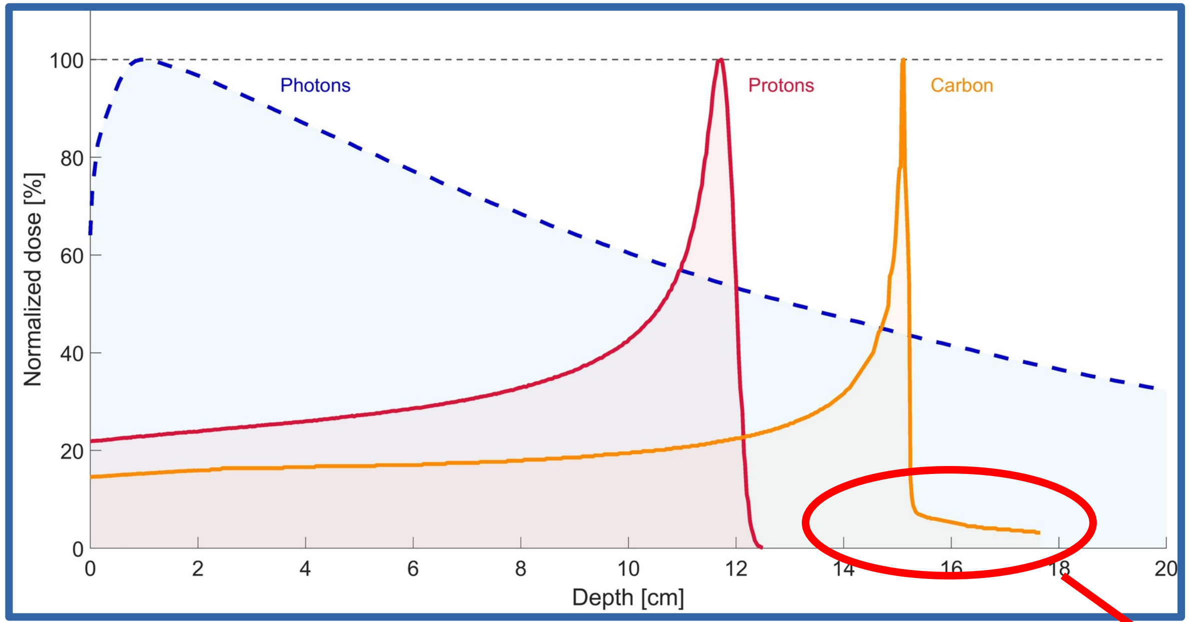


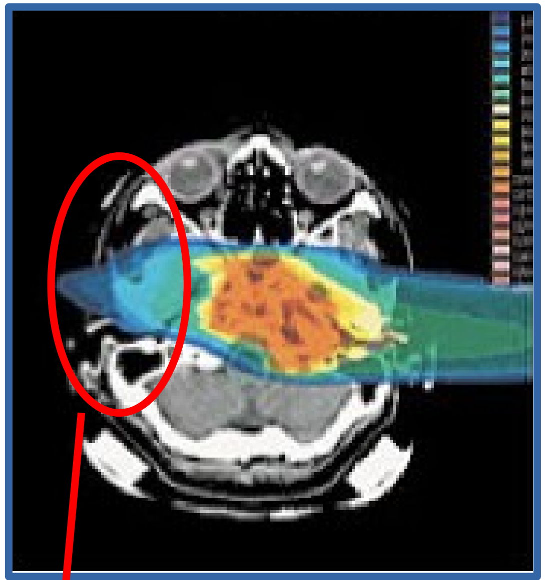
Sketch of a treatment planning system on brain-located tumor

Hadrontherapy vs radiotherapy:

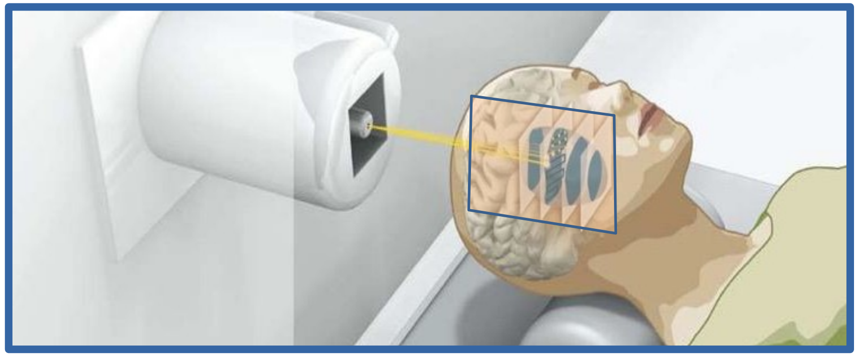
- **Finite range**
- **Localized dose profile**
- **Nuclear fragmentation**

Hadrontherapy



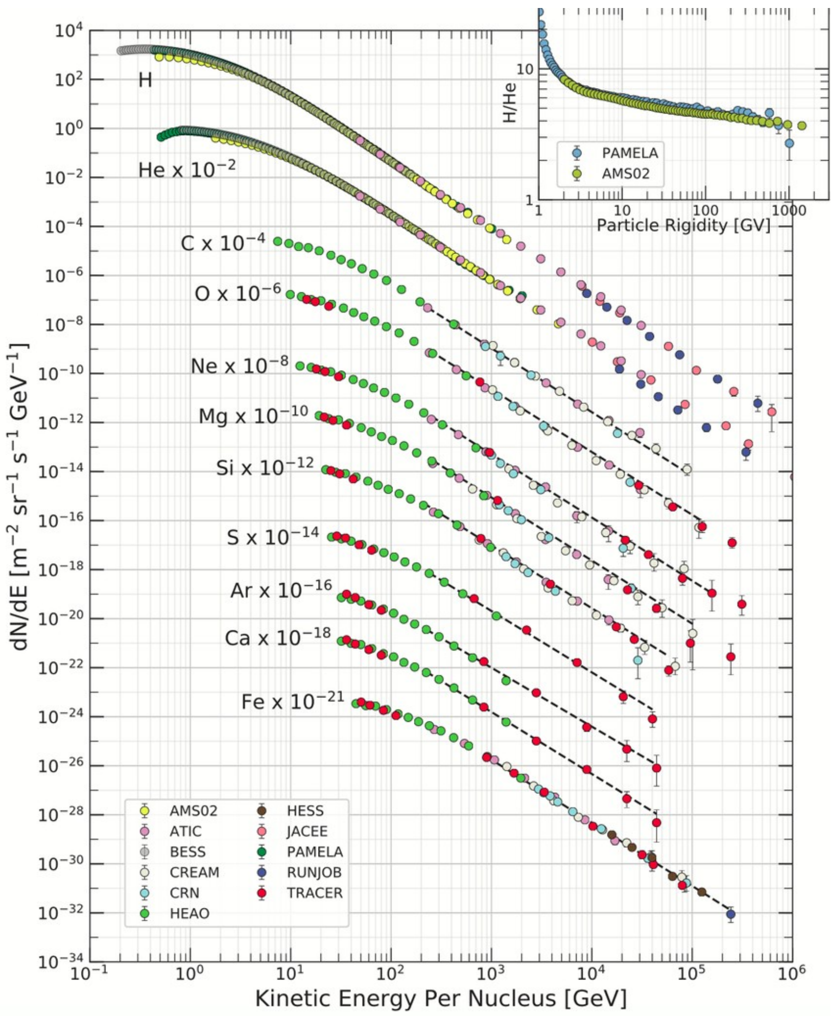


^{12}C

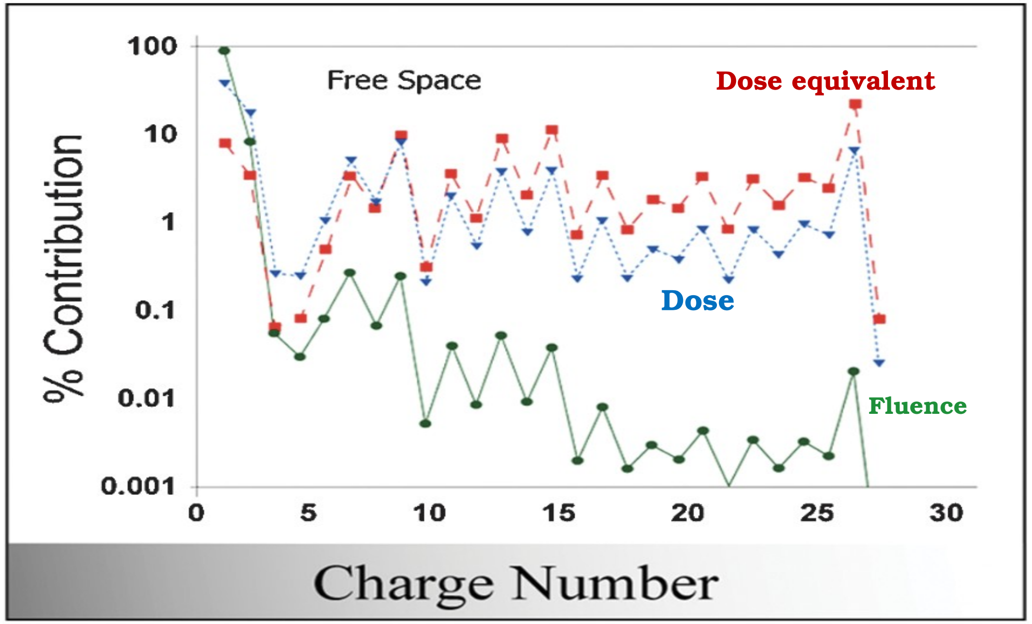


Tail after Bragg peak: nuclear fragmentation!

Space radioprotection



GCR fluence



Particles contribution in
Fluence, dose and equivalent dose

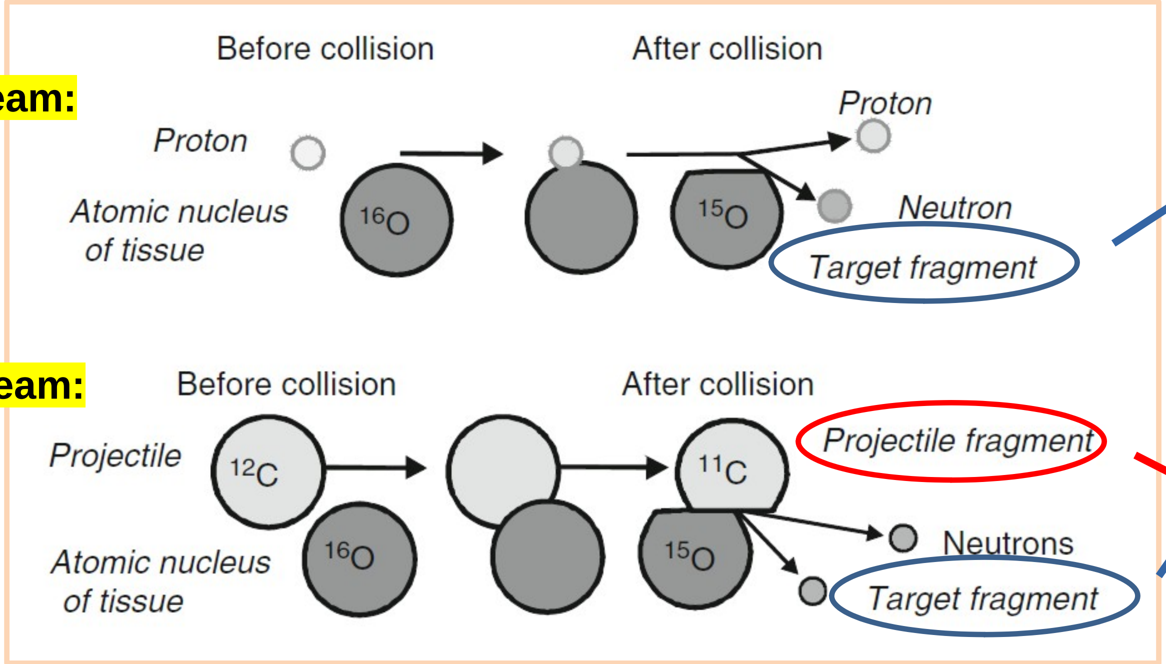
Nuclear Fragmentation

Proton beam:

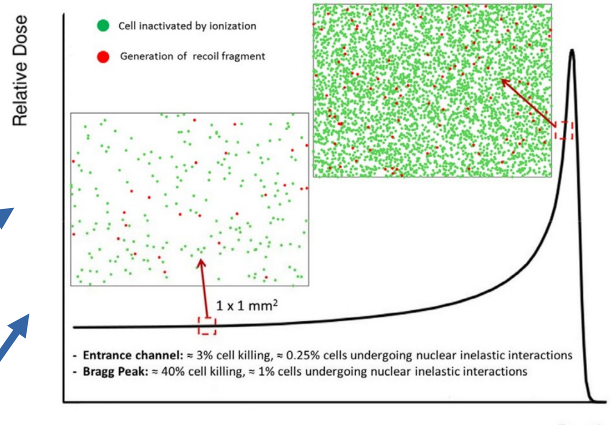
~ 200 MeV

Carbon beam:

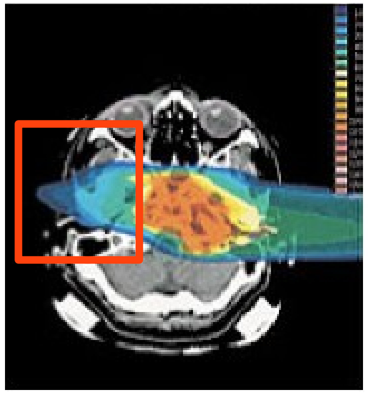
~ 400 MeV/u



Sketch of Nuclear fragmentation



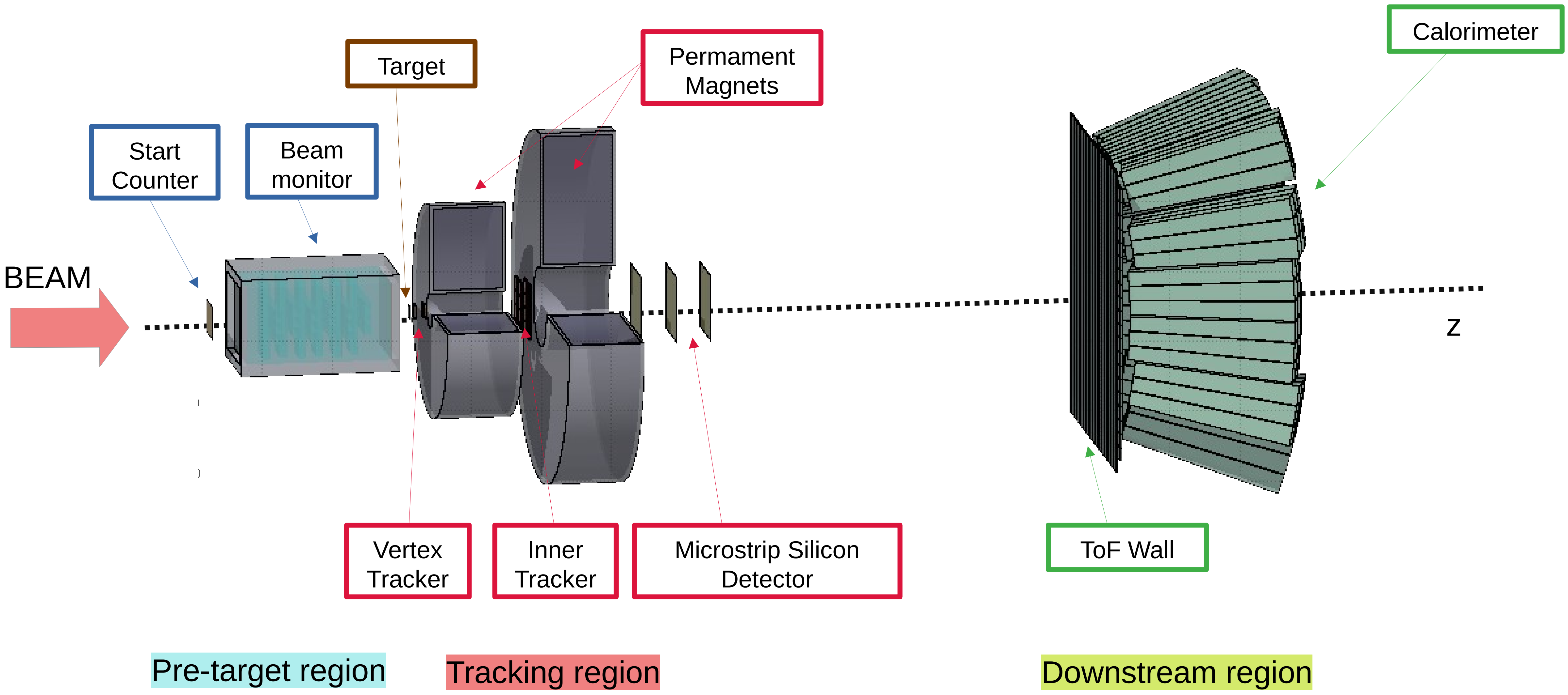
Damage in all the path



BEAM

Damage after the BP

The FOOT detector



Differential Cross section

Yield of all fragments

Background

unfolding

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

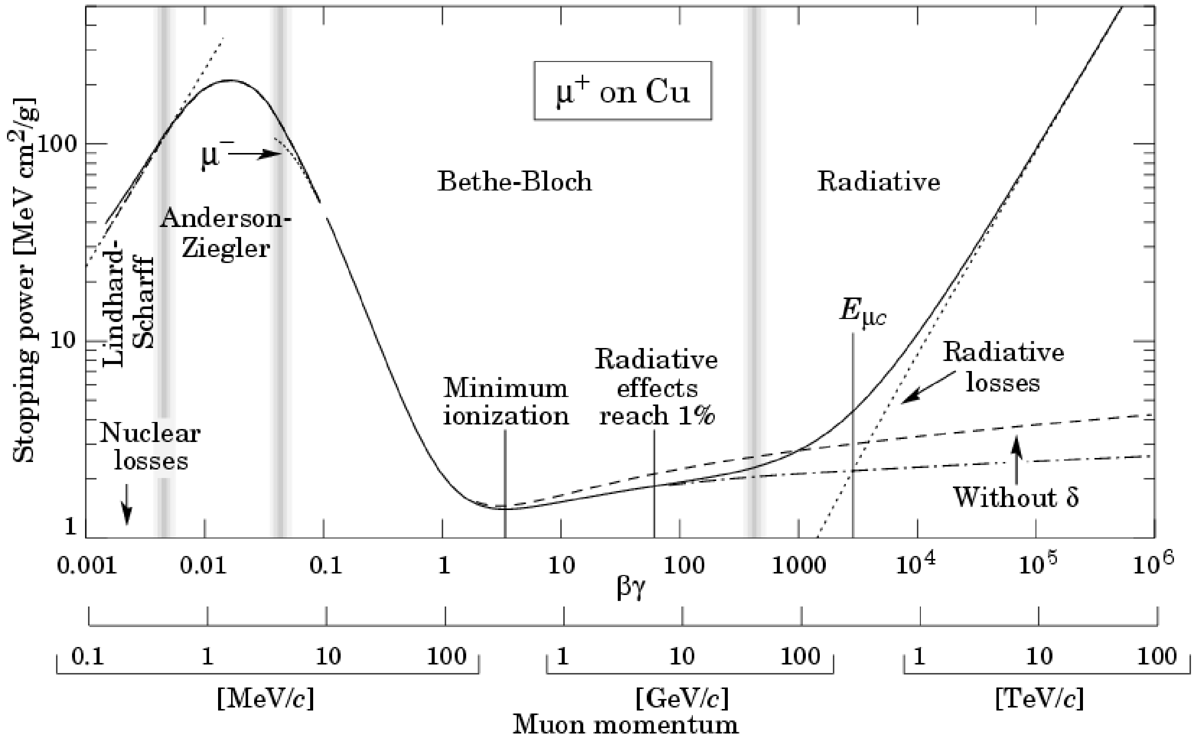
efficiency

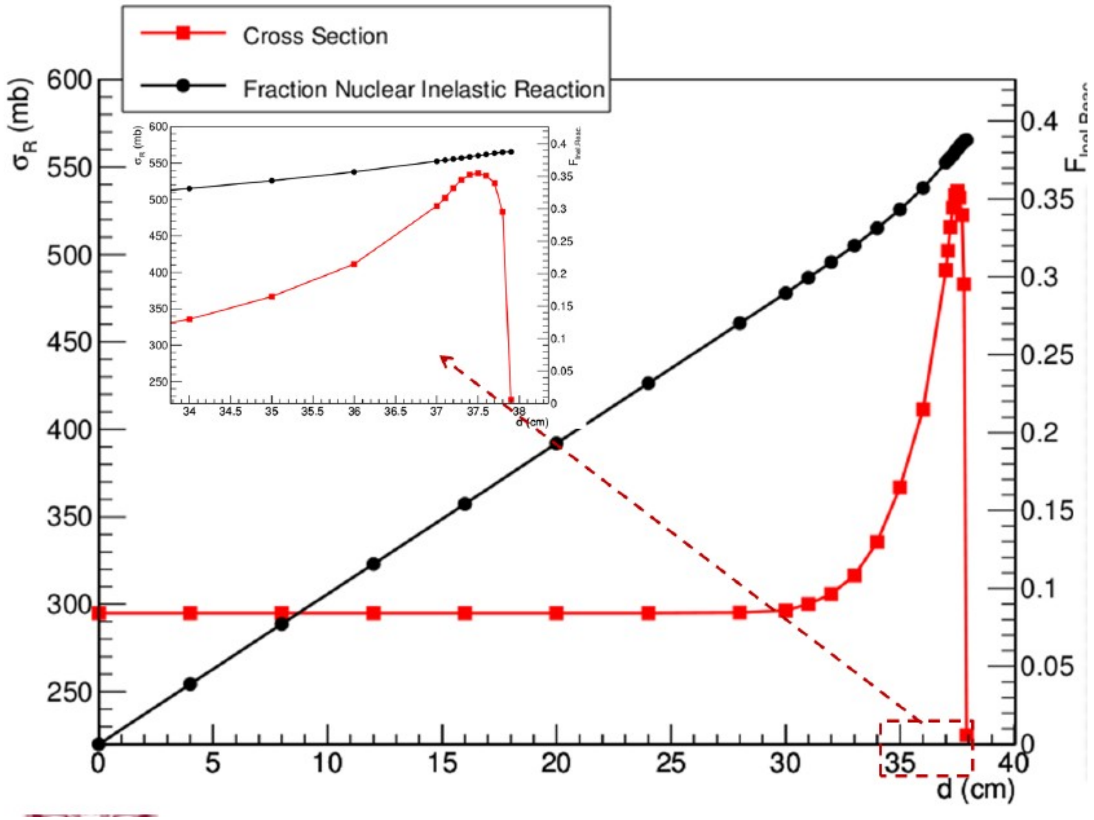
N° of primary events

N° of scattered centers

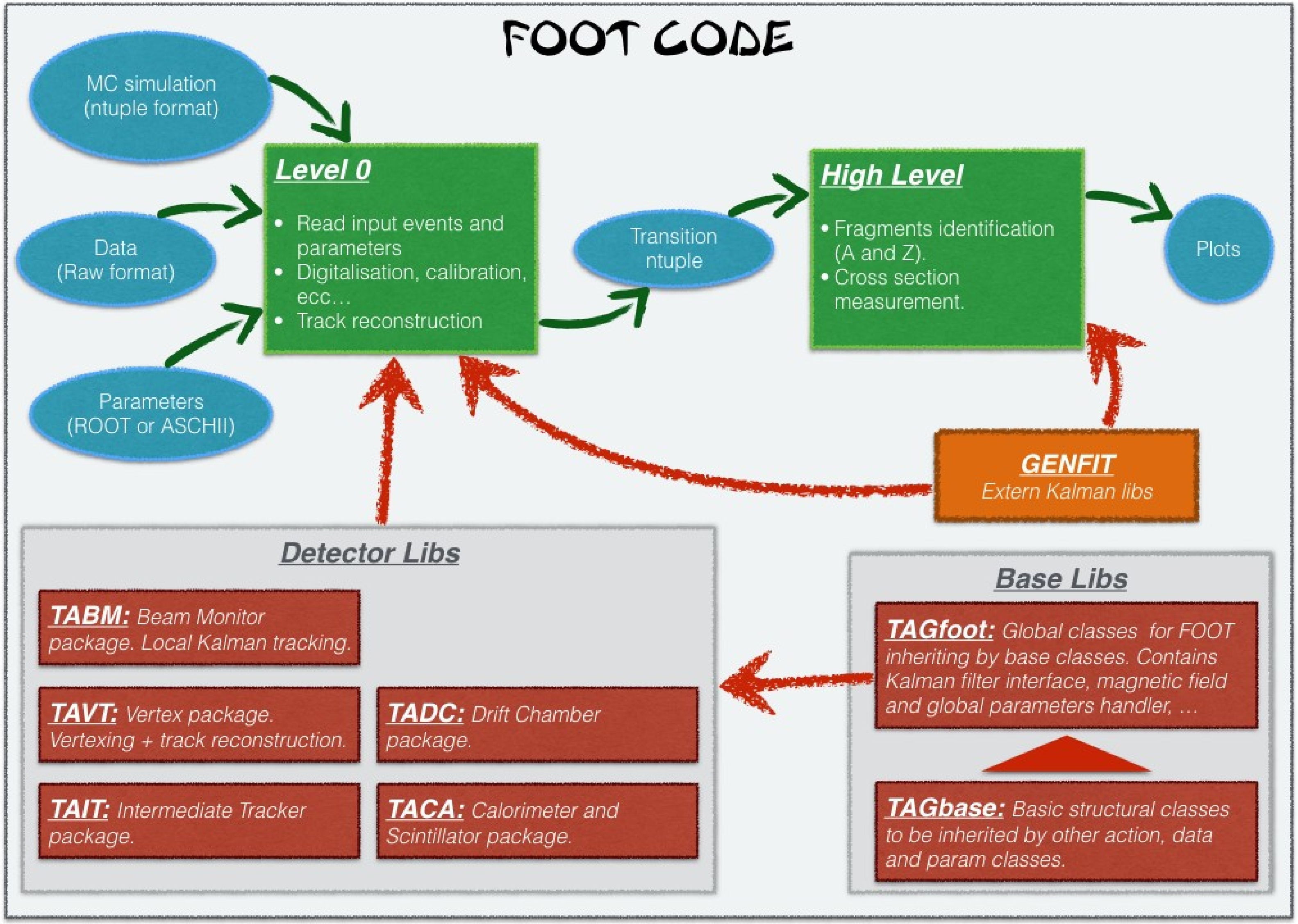
Phase space

Bethe Bloch vs nuclear cross section





SHOE organization



Kalman filter in pills

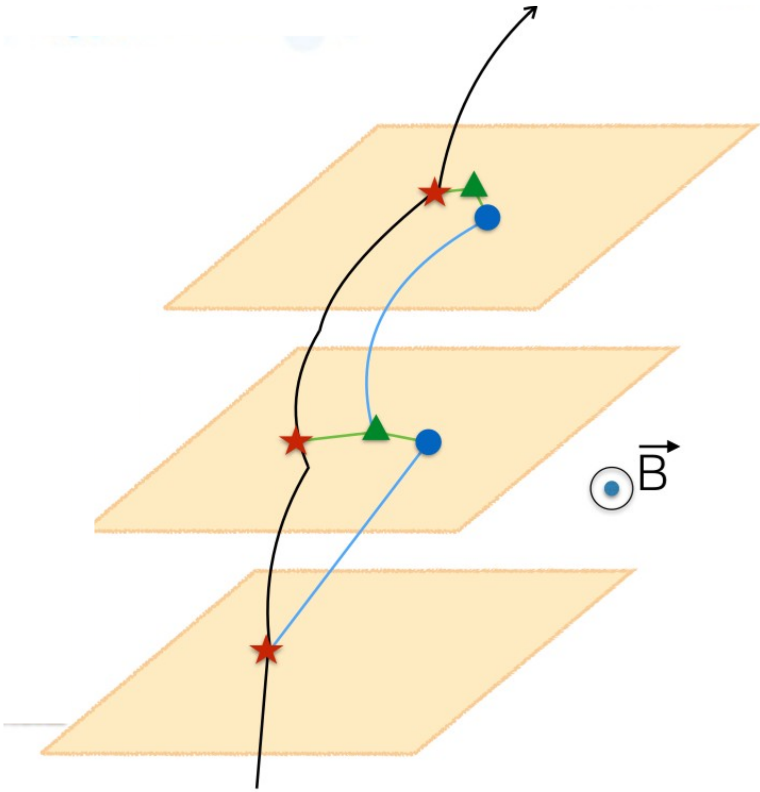
1. Take an ideal particle in vacuum. If we add air + detector layers, trajectory changes due to M.S. and energy loss.

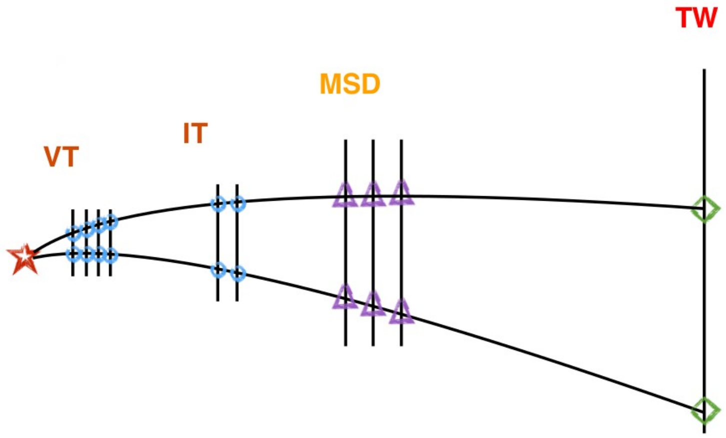
2. We'll see some measurement hits on the detector layers (considering finite detector uncertainty).

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.



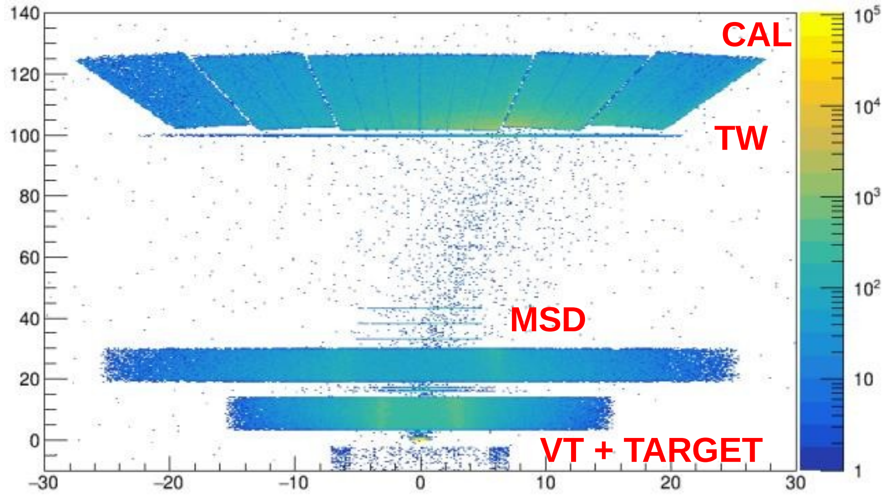


Kalman Filter reconstruction of a track

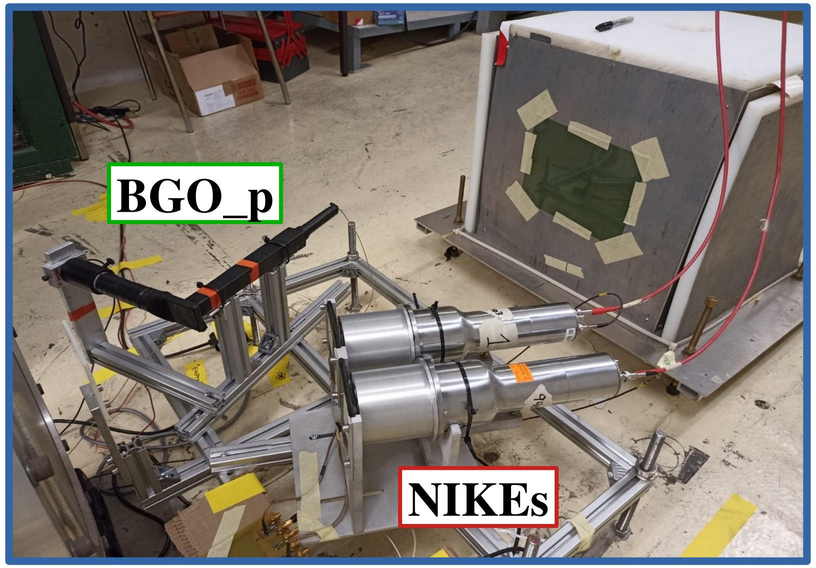
- Start from VT tracklets
- Projection to possible planes of IT
- KF extrapolation to MSD
- KF extrapolation to TW
- Fit the track candidates and extract reconstructed quantities: es. **momentum**

Fast neutrons detectors

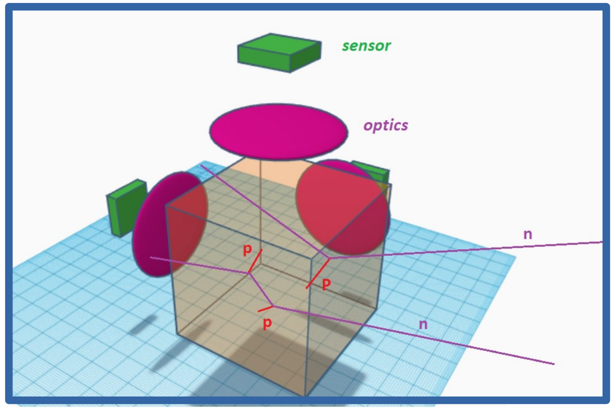
High **neutron production** as a consequence of fragmentation with detectors



Purpose to Add neutron detectors:

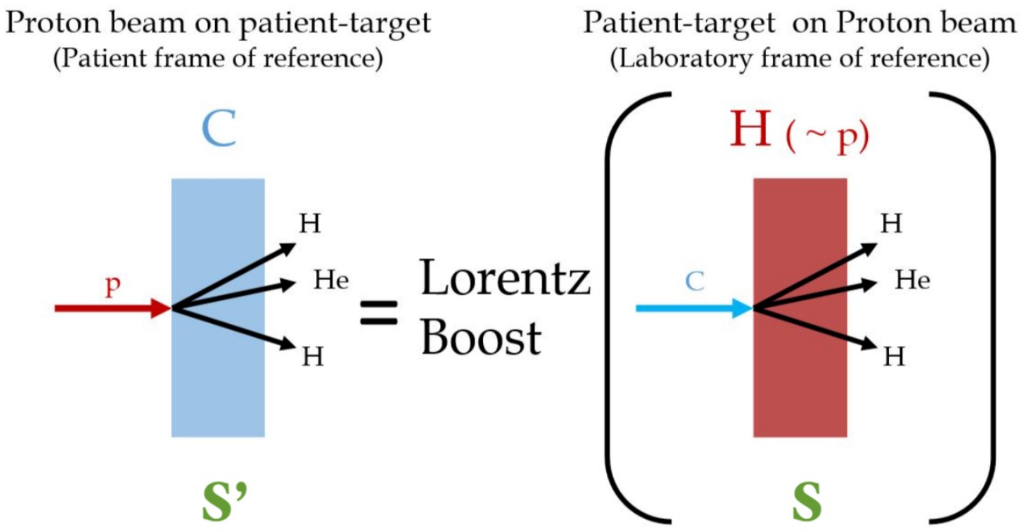


- BC-501A **liquid scintillator**
- **BGO Phoswich**



- recoil-proton track **imaging detector**

Inverse kinematics



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

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