FRAGMENTATION MEASUREMENTS WITH THE EMULSION SPECTROMETER OF THE FOOT EXPERIMENT

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on behalf of the FOOT Collaboration

OUTLOOK

Particle therapy

- Particle therapy vs. radiotherapy
- Target fragmentation

FOOT experiment

- Inverse kinematic approach
- Double target strategy
- The detector

The emulsion detector

- Nuclear emulsions
- Controlled fading

The data analysis for charge identification of the fragments

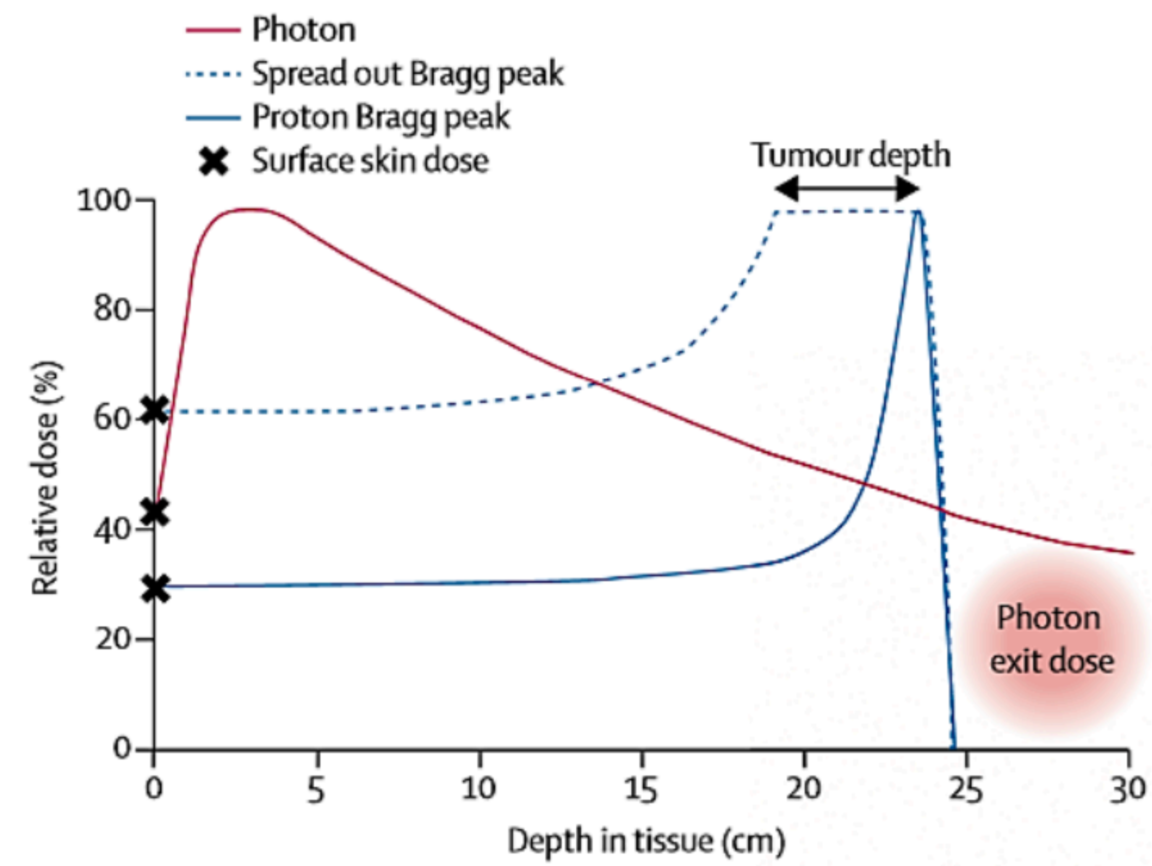
- Cut based analysis
- Principal component analysis
- Results

Particle therapy: why?

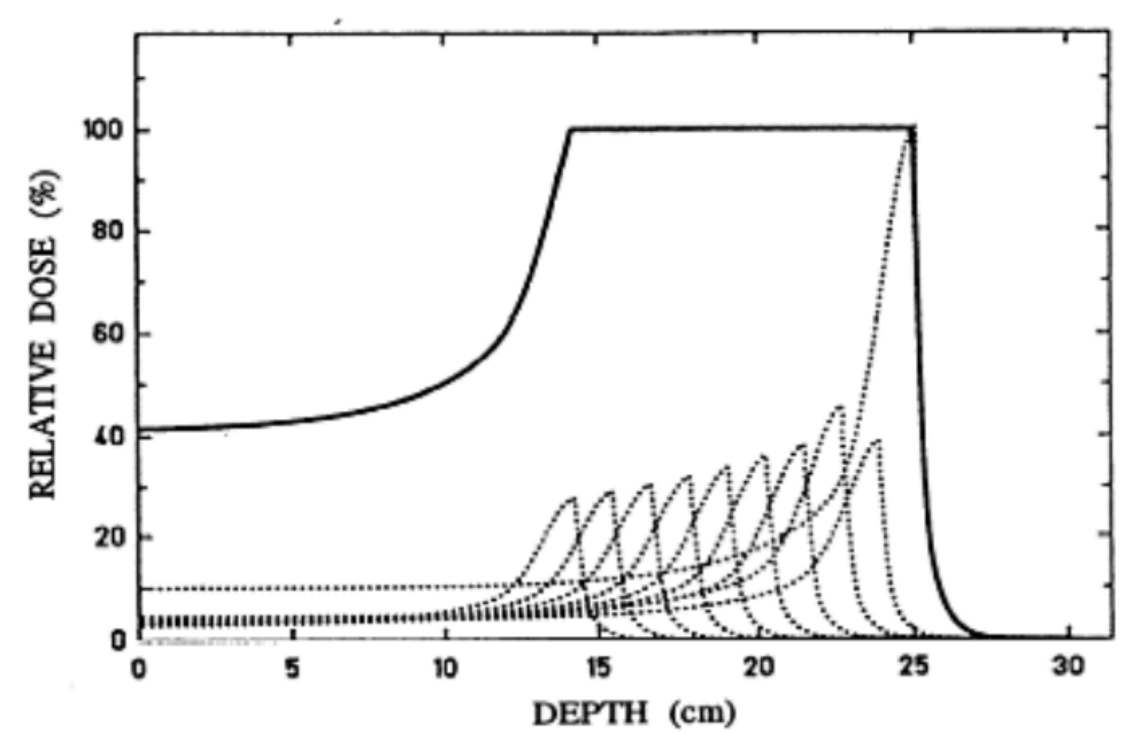
Comparison ions vs. photon:

- ✓ Maximum dose release at the end, in the Bragg peak
- ✓ Possibility to control the depth dose release according to the beam energy
- ✓ Depth tumors
- ✓ Large areas
- ✓ Lower dose to healthy tissues

but…



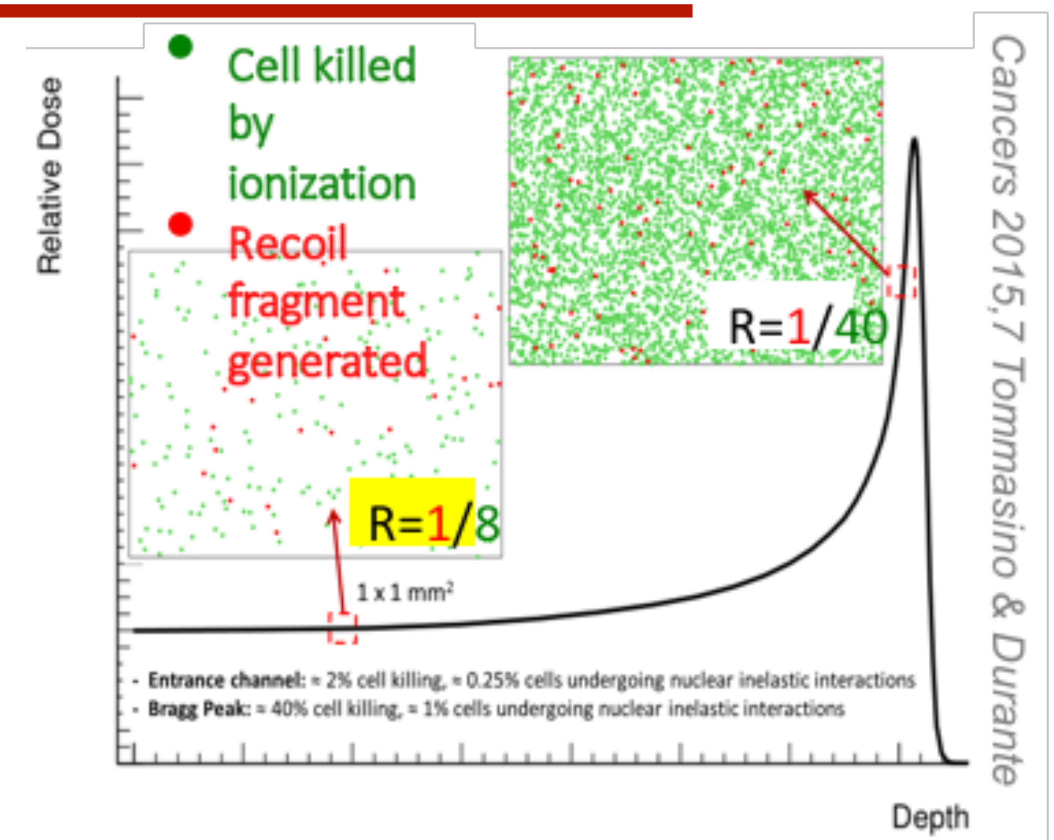
J. E. Leeman et al. The Lancet Oncology, 18(5):254–265, 2017.

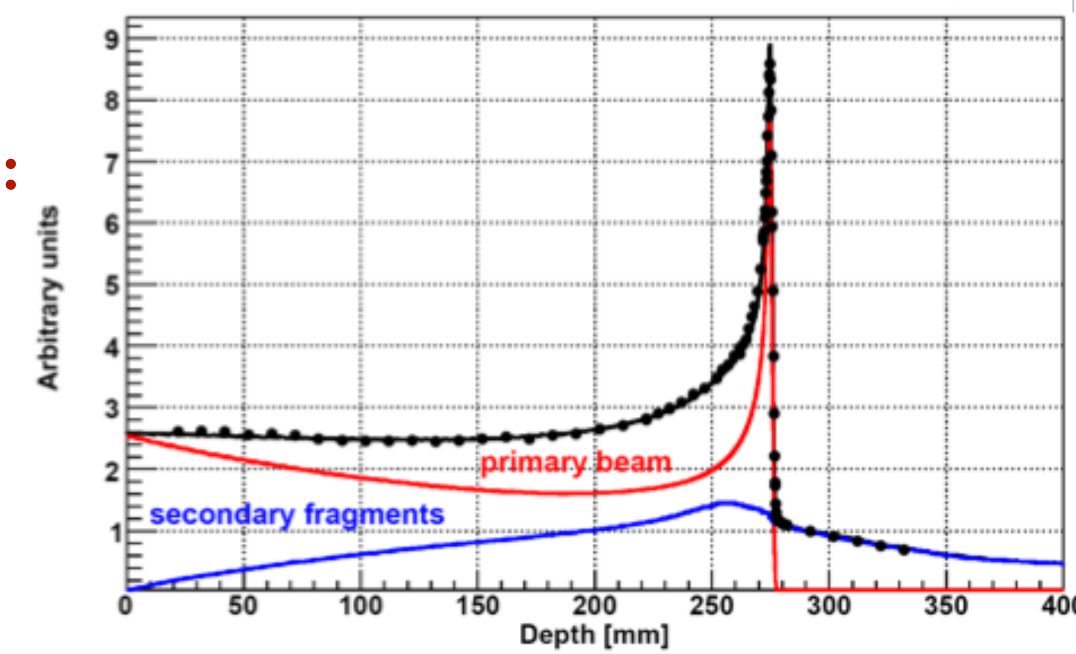


Particle therapy: fragmentation of the target

The nuclear fragmentation of the target and beam particles is an open issue.

- **Proton beam (Target fragmentation):**
  - Small range fragments (~tens of μm)
  - Missing experimental data for heavy fragments having the greatest contribution to the dose
  - Increase of biological damage (~10%) in the entrance channel
- **Charged particles (Beam and target fragmentation):**
  - Fragments have the same velocity of the beam, but the lower mass allows longer range producing tail beyond the Bragg peak
  - Scarce validation data for ^{12}C clinical beam
  - New beams (^{4}He and ^{16}O) to be studied





Exp. Data (points) from Haettner et al, Rad. Prot. Dos. 2006
Simulation: A. Mairani PhD Thesis, 2007, Nuovo Cimento C, 31, 2008

Measurements of nuclear fragmentation cross sections useful to develop a new generation of biologically oriented Treatment Planning Systems for ions therapy

FOOT EXPERIMENT: TARGET FRAGMENTATION

- **The experiment:**
  - FragmentatiOn Of the Target
  - Funded by INFN since 2017
  - https://pandora.infn.it/public/3d8535: FOOT Conceptual Design Report (June 2017)

- **AIM: characterize the target fragmentation in terms of**
  - Fragments production **cross sections** (at level of 5%)
  - Fragments **energy spectra** dσ/dE (energy resolution ~1 MeV/u)
  - **Charge ID** (at the level of 2-3%)
  - **Isotopic ID** (at the level of 5%)

- **HOW:**
  - **Data taking** for beams at therapeutic energies and for space radioprotection:
    - 250 MeV/n (700 MeV/n) for He ions
    - 350 MeV/n (700 MeV/n) for C ions
    - 400 MeV/n (700 MeV/n) for O ion
  - Target simulating the human tissue (H, C, O)

- **EXPERIMENTAL STRATEGY**
  - Inverse kinematic geometry
  - Experimental apparatus: electronic detector and emulsion spectrometer

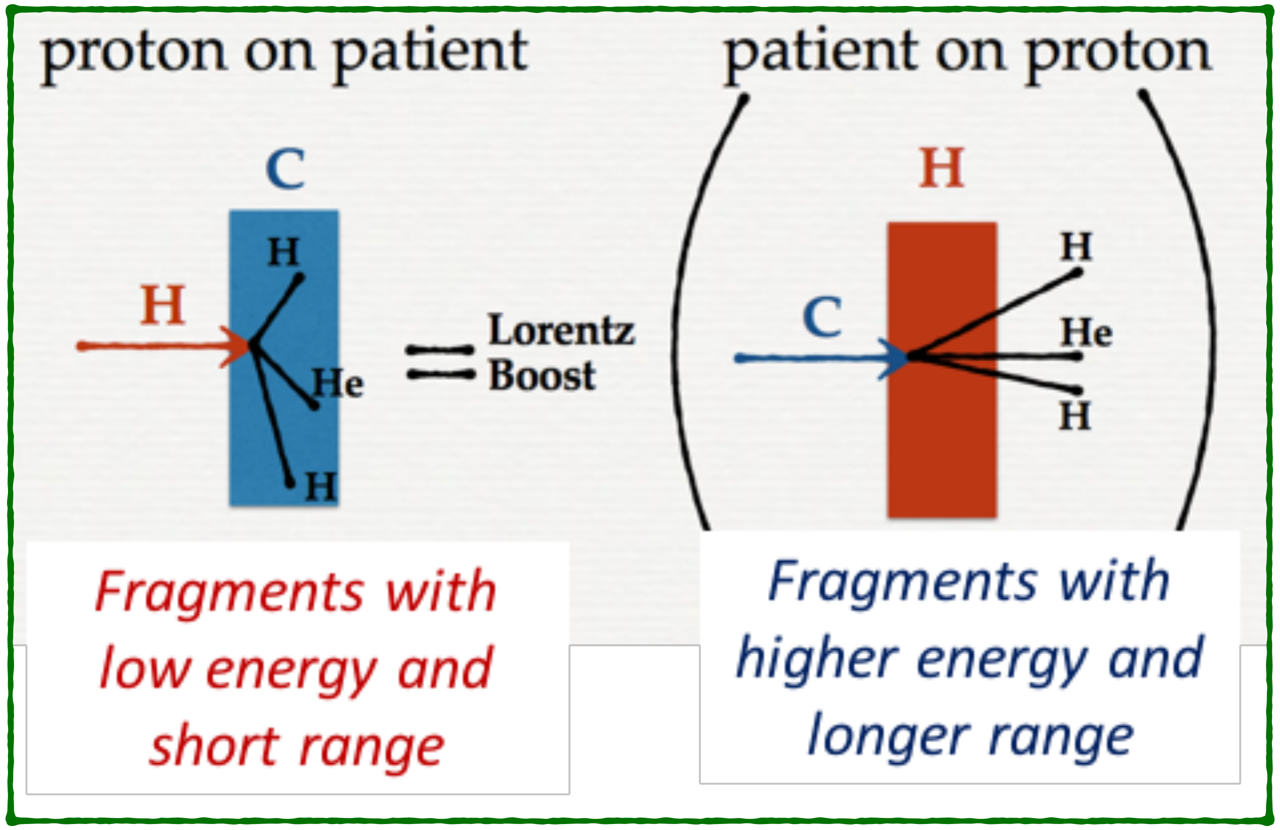
INVERSE KINEMATIC GEOMETRY

- Protons @ E_{kin}= 200 MeV (β~0.6) on a "patient" (98% C, O, and H nucleus) can be replaced by ^{16}O, ^{12}C ion beams (E_{kin} ~ 200 MeV/n β~0.6) impinging on a **target made of protons** (C → H)
- by applying the Lorentz transformation (well known β) it is possible **to switch from the laboratory to the patient frame**

P (200 MeV) on O_2: range of fragments

Tommasino and Durante *Cancers* - 2015

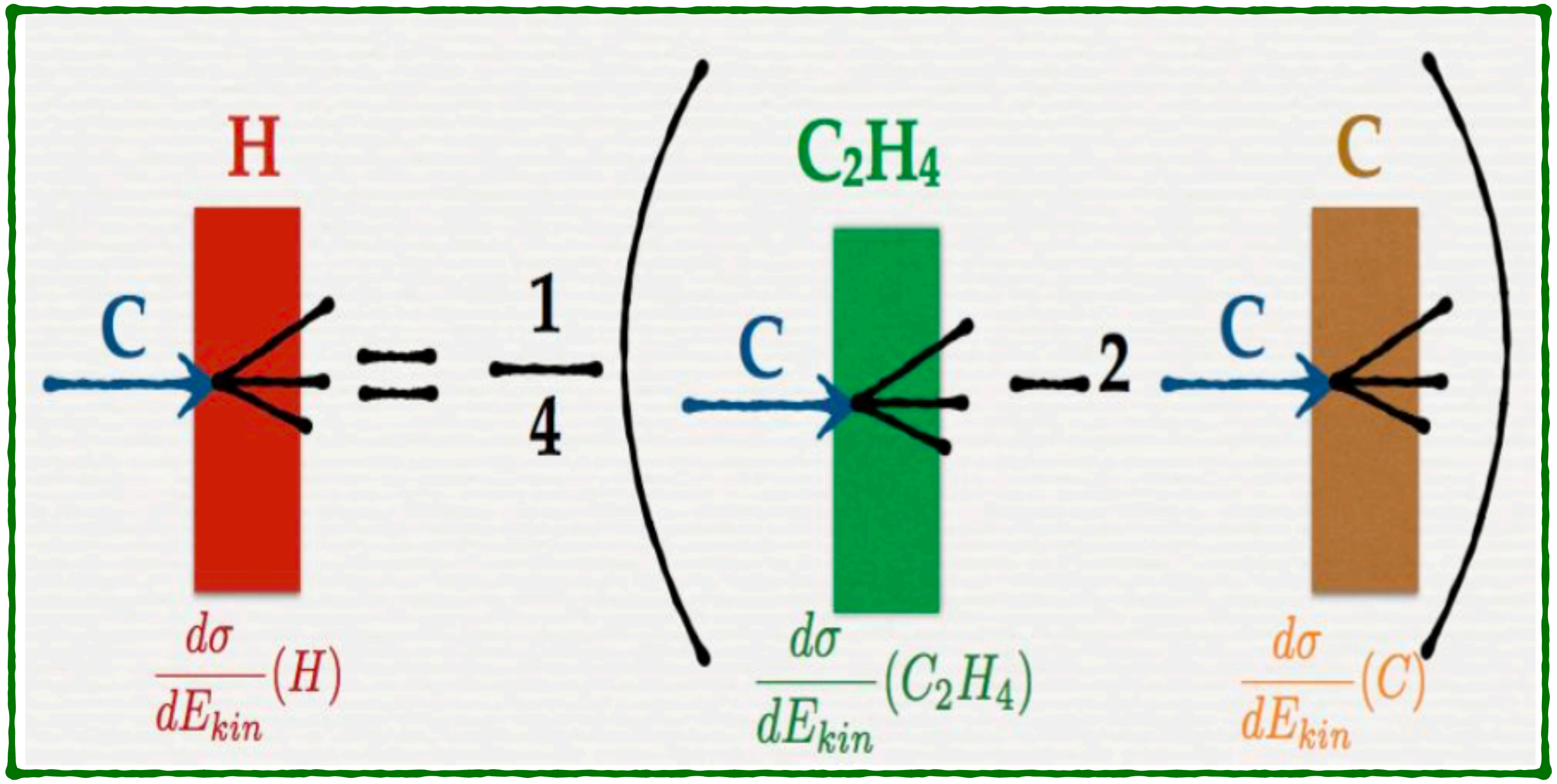
Fragment	E (MeV)	LET (keV/μm)	Range (μm)
^{15}O	1.0	983	2.3
^{15}N	1.0	925	2.5
^{14}N	2.0	1137	3.6
^{13}C	3.0	951	5.4
^{12}C	3.8	912	6.2
^{11}C	4.6	878	7.0
^{10}B	5.4	643	9.9
^{8}Be	6.4	400	15.7
^{6}Li	6.8	215	26.7
^{4}He	6.0	77	48.5
^{3}He	4.7	89	38.8
^{2}H	2.5	14	68.9



Requirements: the fragments direction must be well measured in the lab frame to obtain the correct energy in the patient frame

DOUBLE TARGET STRATEGY

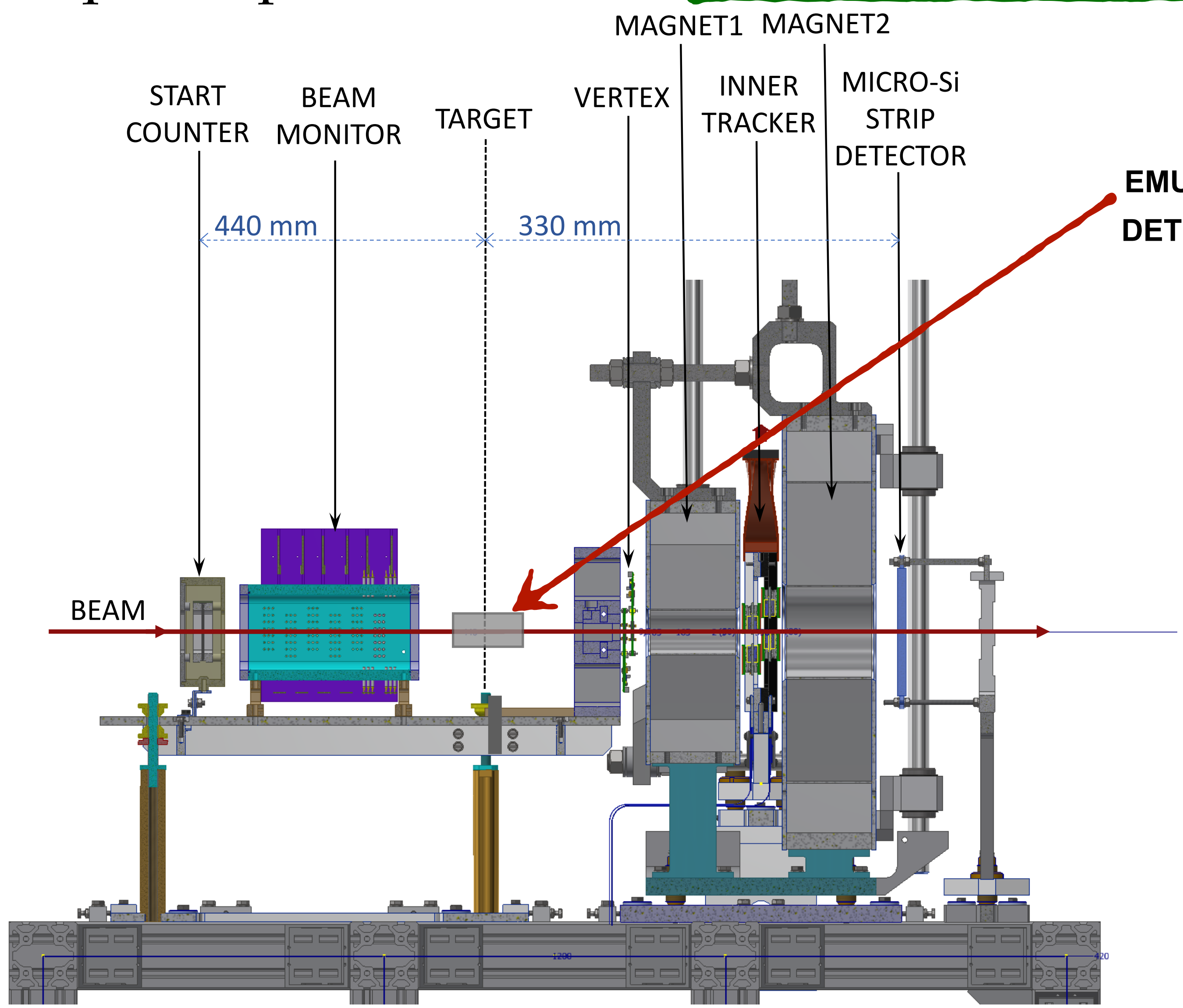
- H target: very difficult to realize
- Use **twin targets** of **C** and **polyethylene** $(C_2H_4)_n$
- Obtain the fragmentation results on H target from the **difference**

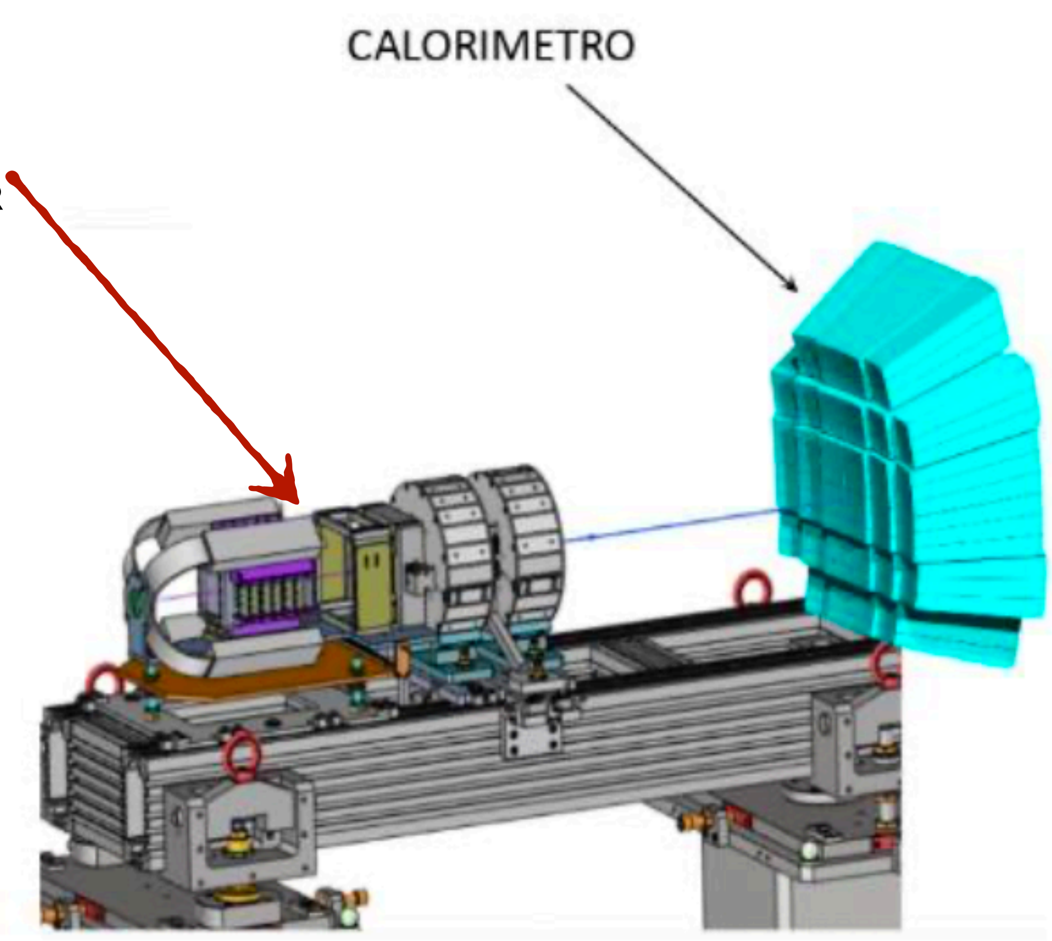


FOOT EXPERIMENT: THE DETECTOR

- A table top detector (<2 m long)
- **Electronic detector**[1] optimized for fragments with **Z ≥ 3** and angular acceptance **±10°**
- **Emulsion detector** for the detection of **light charged fragments** at large angle (**up to 70°**)
- Required performances:

$$\frac{\Delta p}{p} \approx 5\,\% \qquad \Delta TOF \approx 100ps \qquad \frac{\Delta(dE)}{dE} \approx 2\,\% \qquad \frac{\Delta Ekin}{Ekin} \approx 2\,\%$$





(1) See Marco Toppi's talk: "Measurements of ^{16}O fragmentation cross sections on C target with the FOOT apparatus"

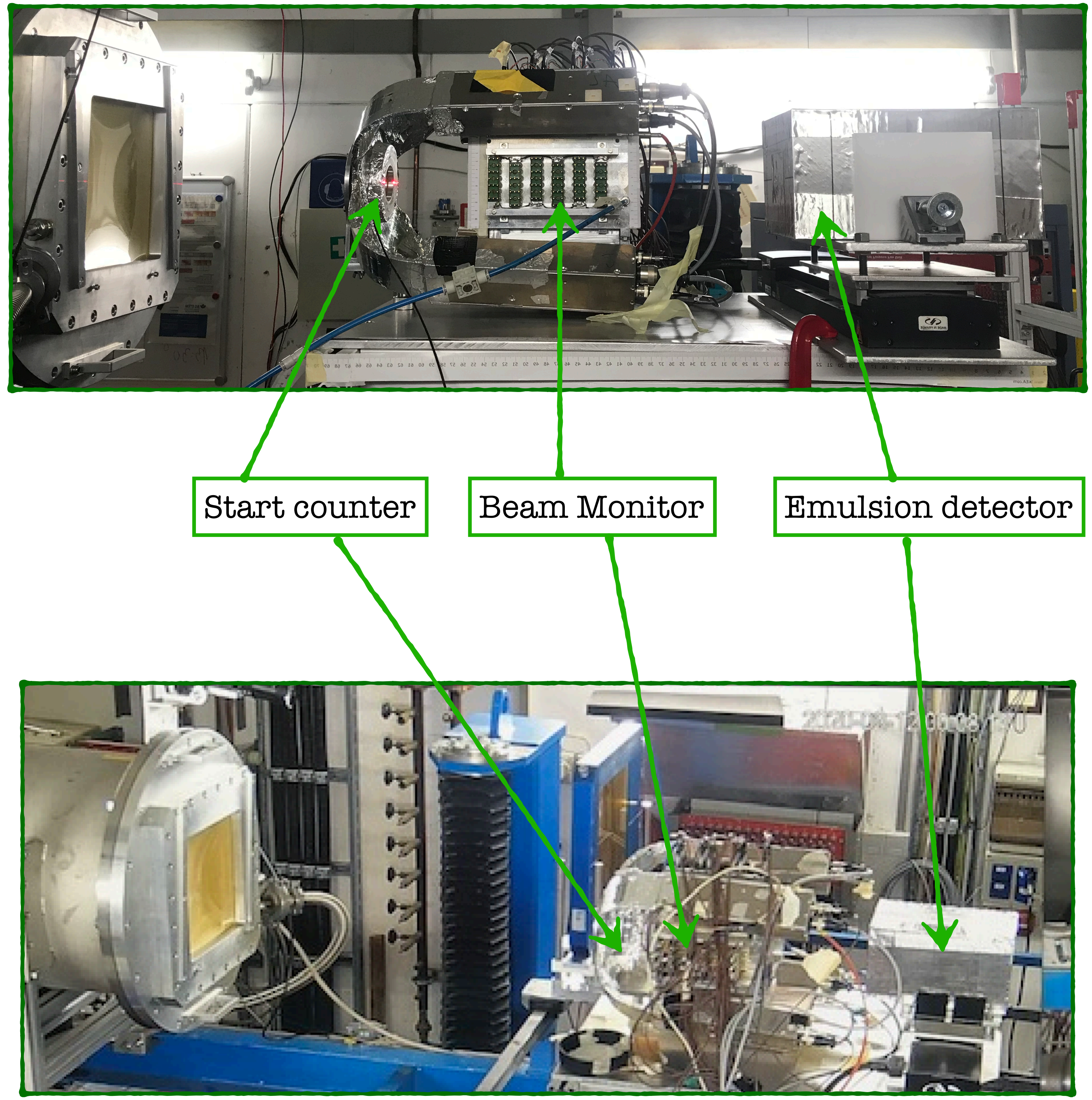
THE EMULSION SPECTROMETER: DATA TAKING

✓ **GSI (March 2019):**

- First data taking with ^{16}O (200, 400 MeV/n)
- 4 emulsion detectors exposed (C and C_2H_4 target)
- Data analysis presented on ^{16}O @200 MeV/n beam on C and C_2H_4 target

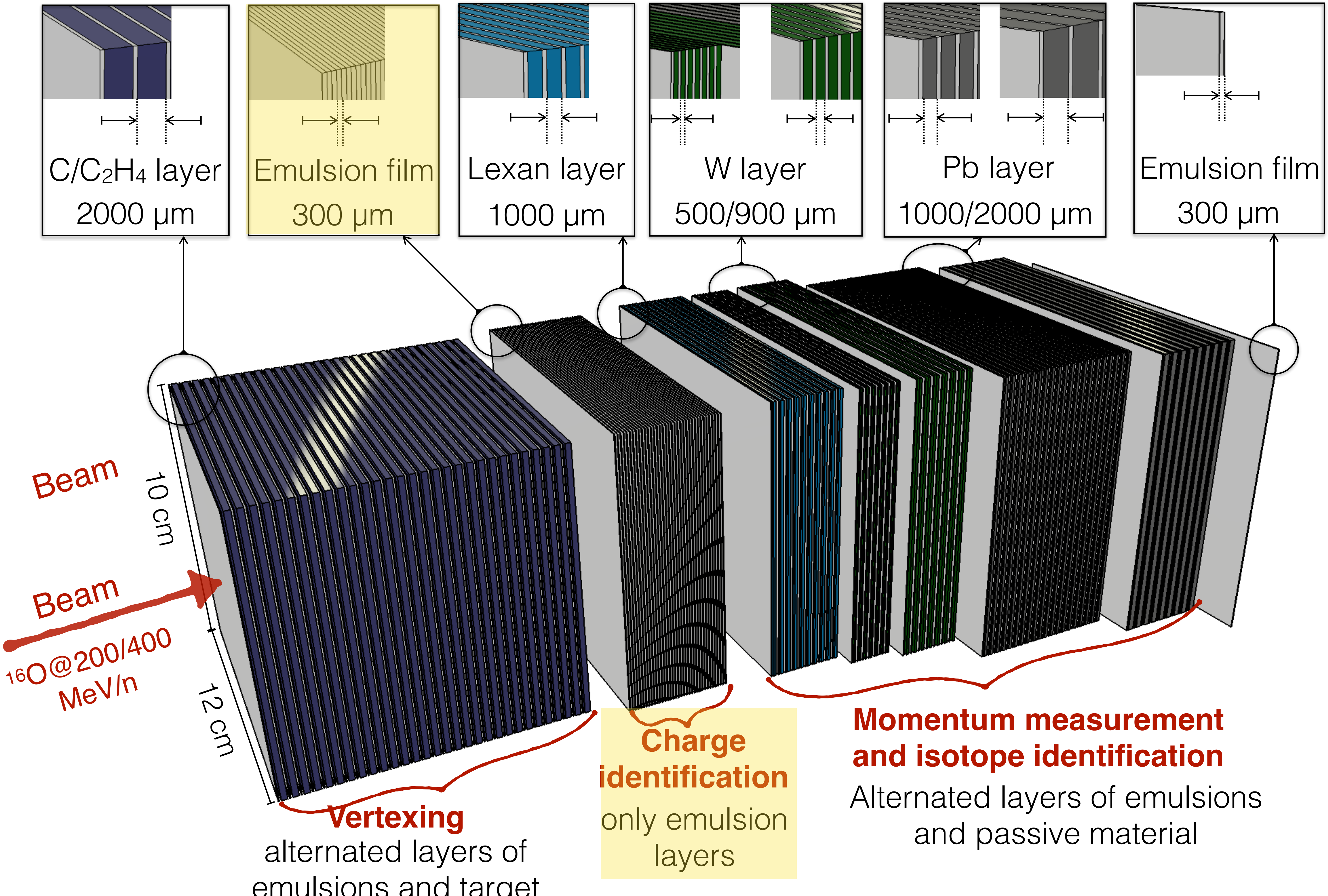
✓ **GSI (February 2020):**

- Second data taking with ^{12}C (700 MeV/n)
- 2 emulsion detectors exposed (C and C_2H_4 target)

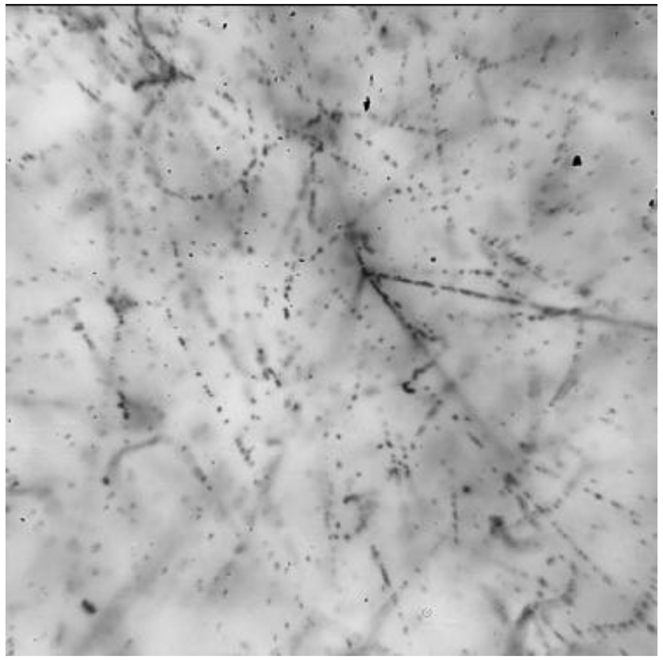


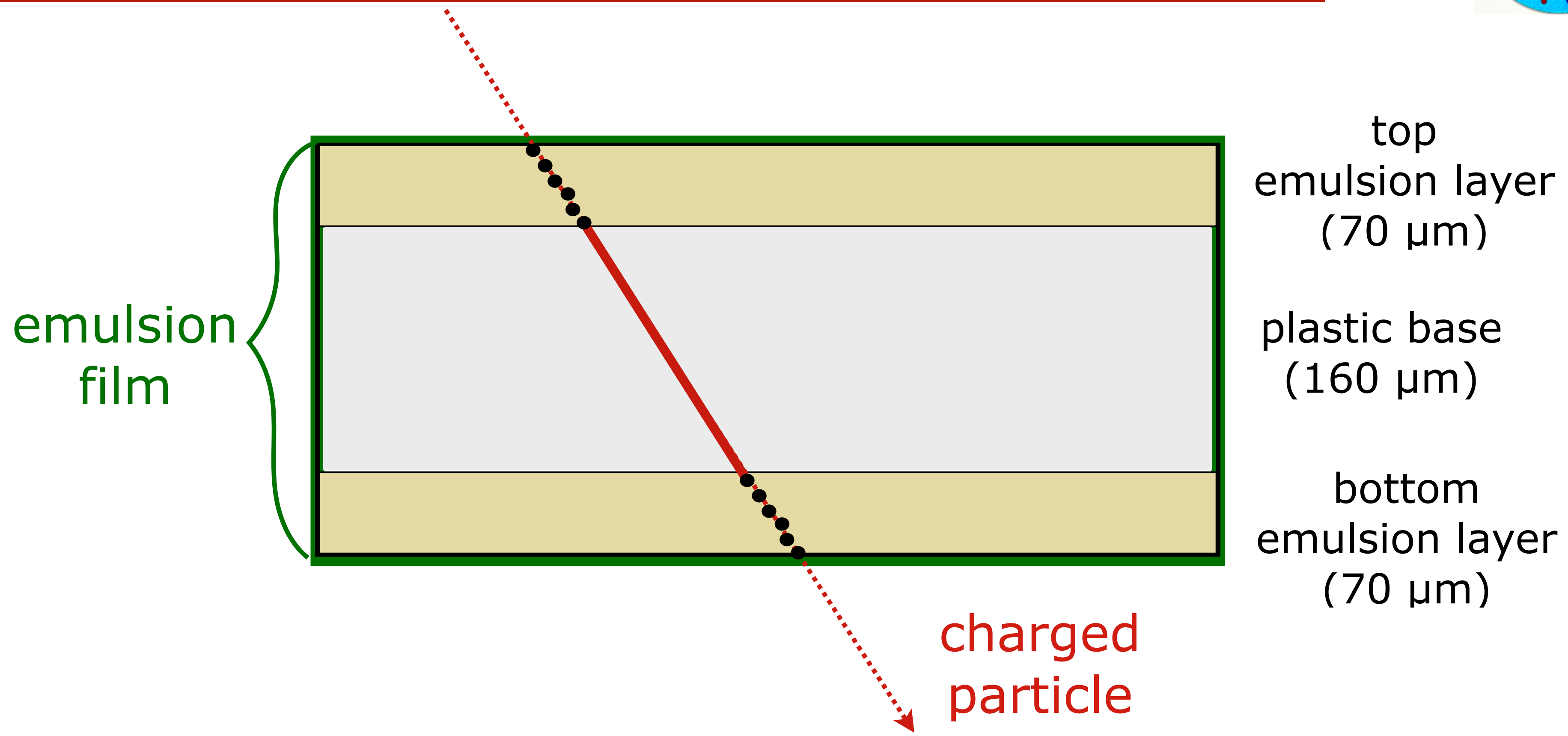
THE EMULSION SPECTROMETER: OVERALL

- Detector based on the concept of **Emulsion Cloud Chamber** (ECC)

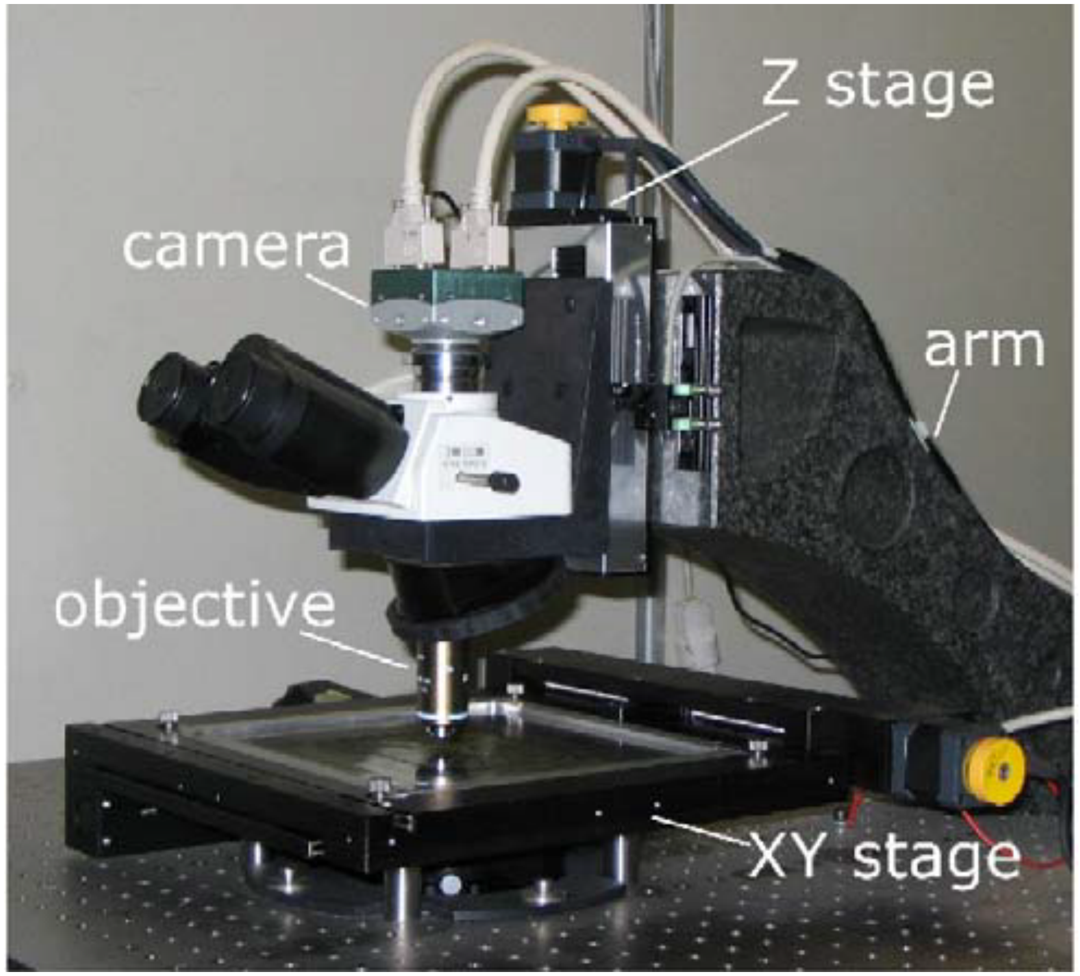


PARTICLE TRAJECTORY RECONSTRUCTION



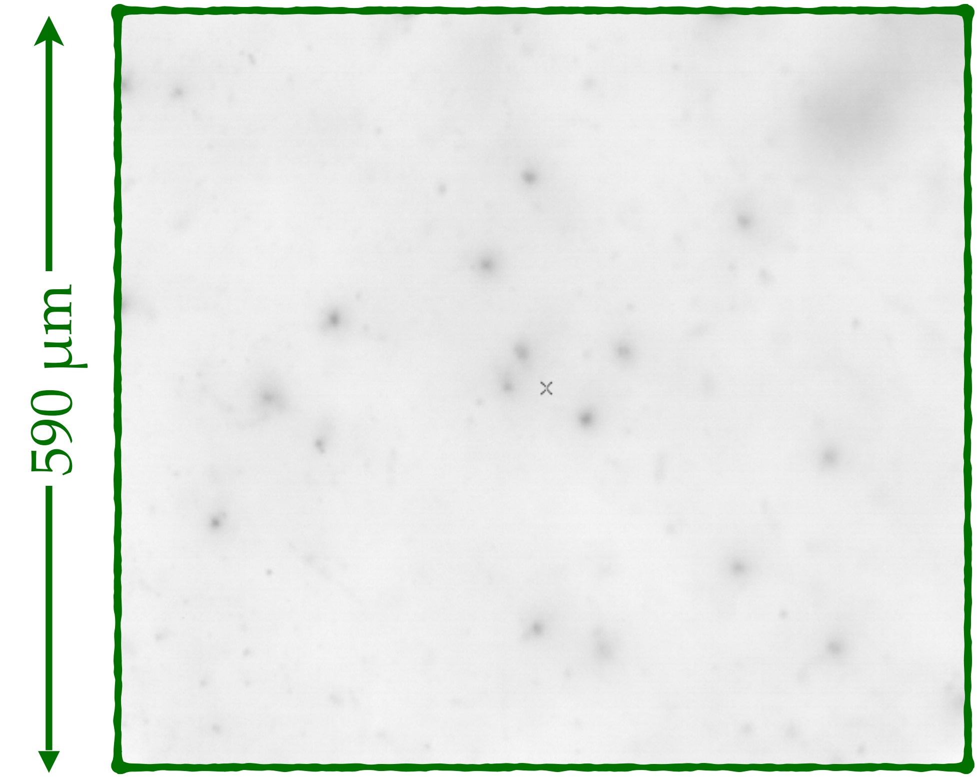


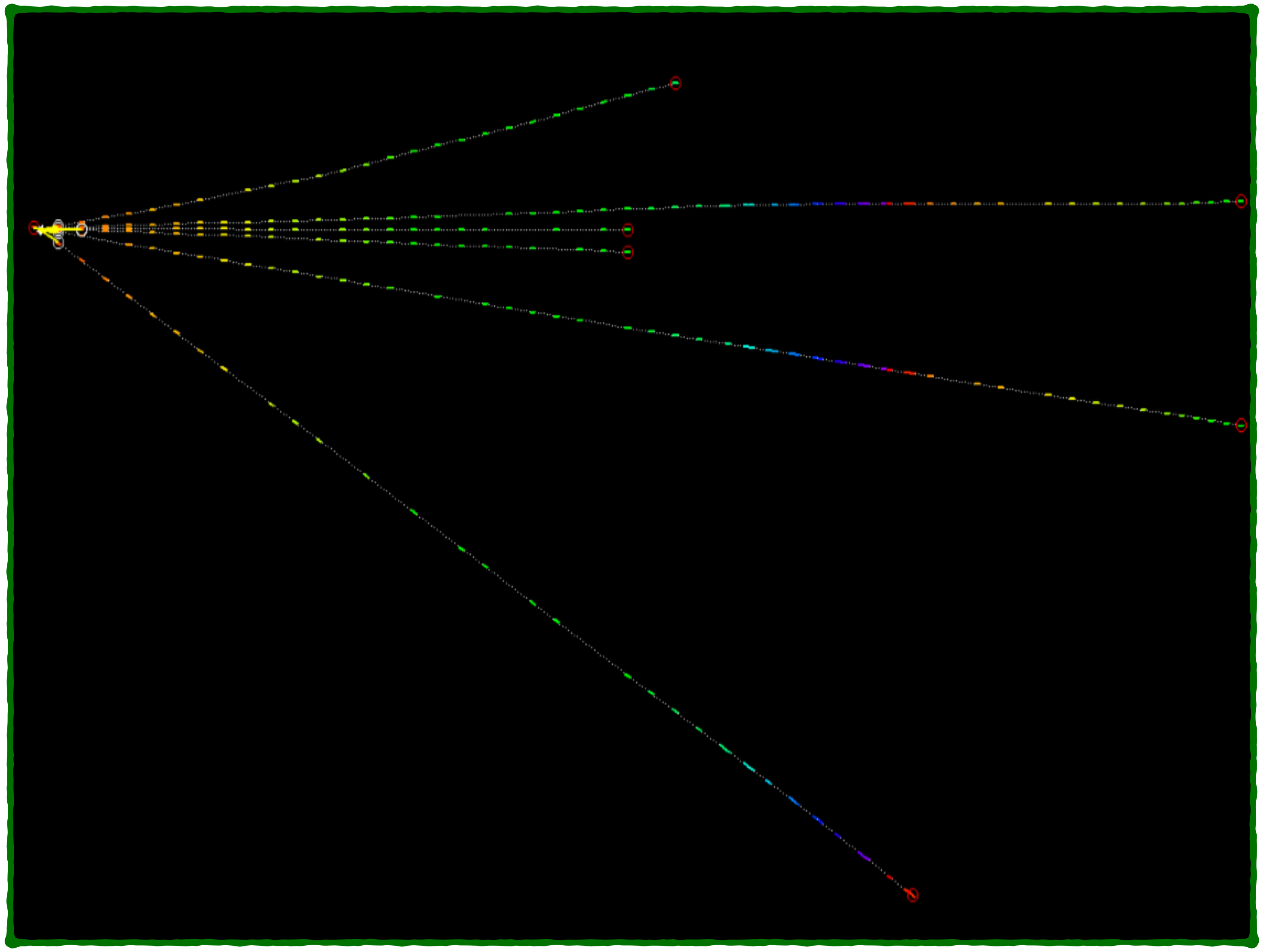
Silver grains produced by charged particles are recognised by automated microscopes as aligned clusters of dark pixels and associated to reconstruct the particle trajectory



Particle Trajectory Reconstruction

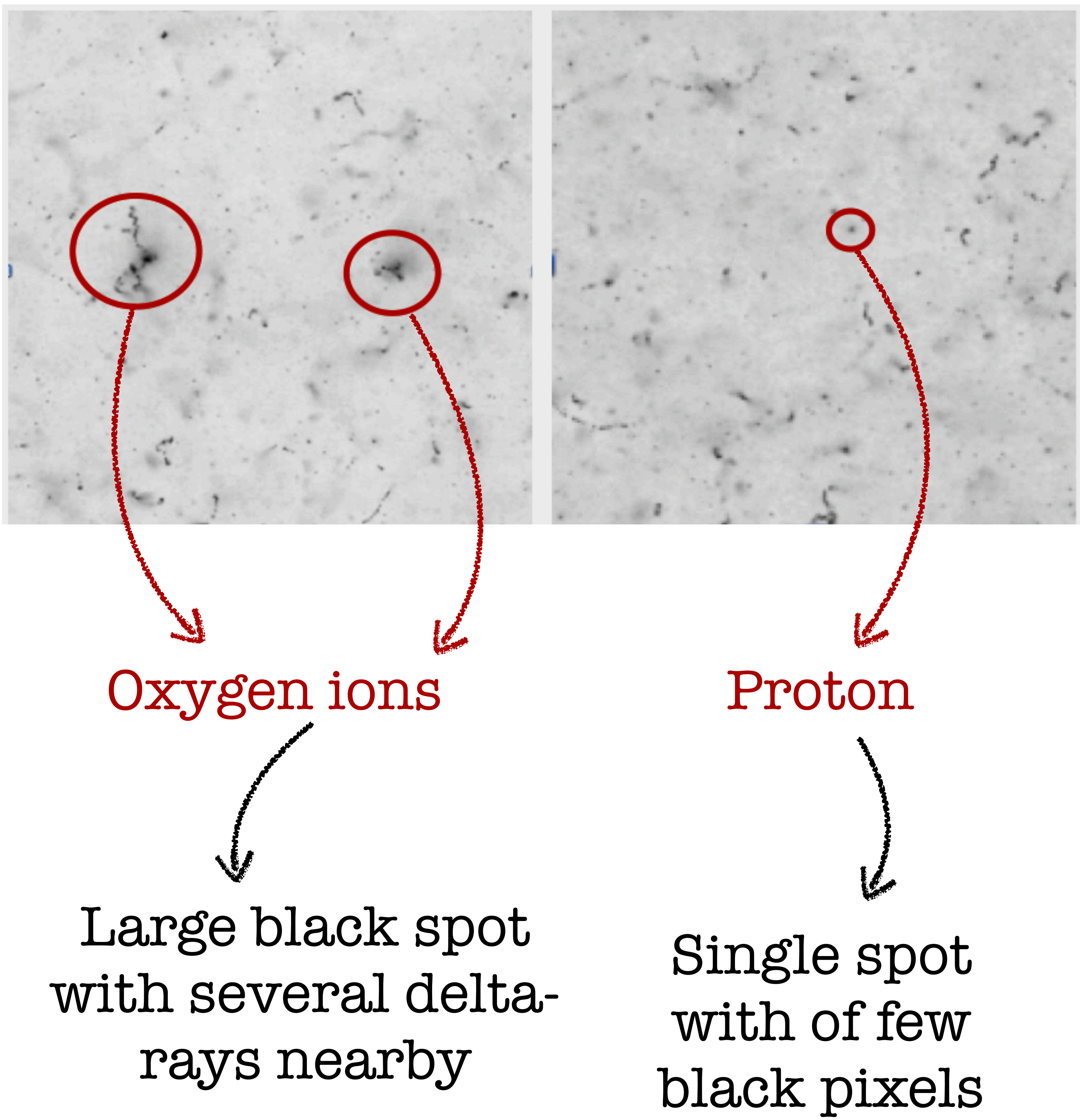
^{16}O (200 MeV/n) passing through the nuclear emulsion





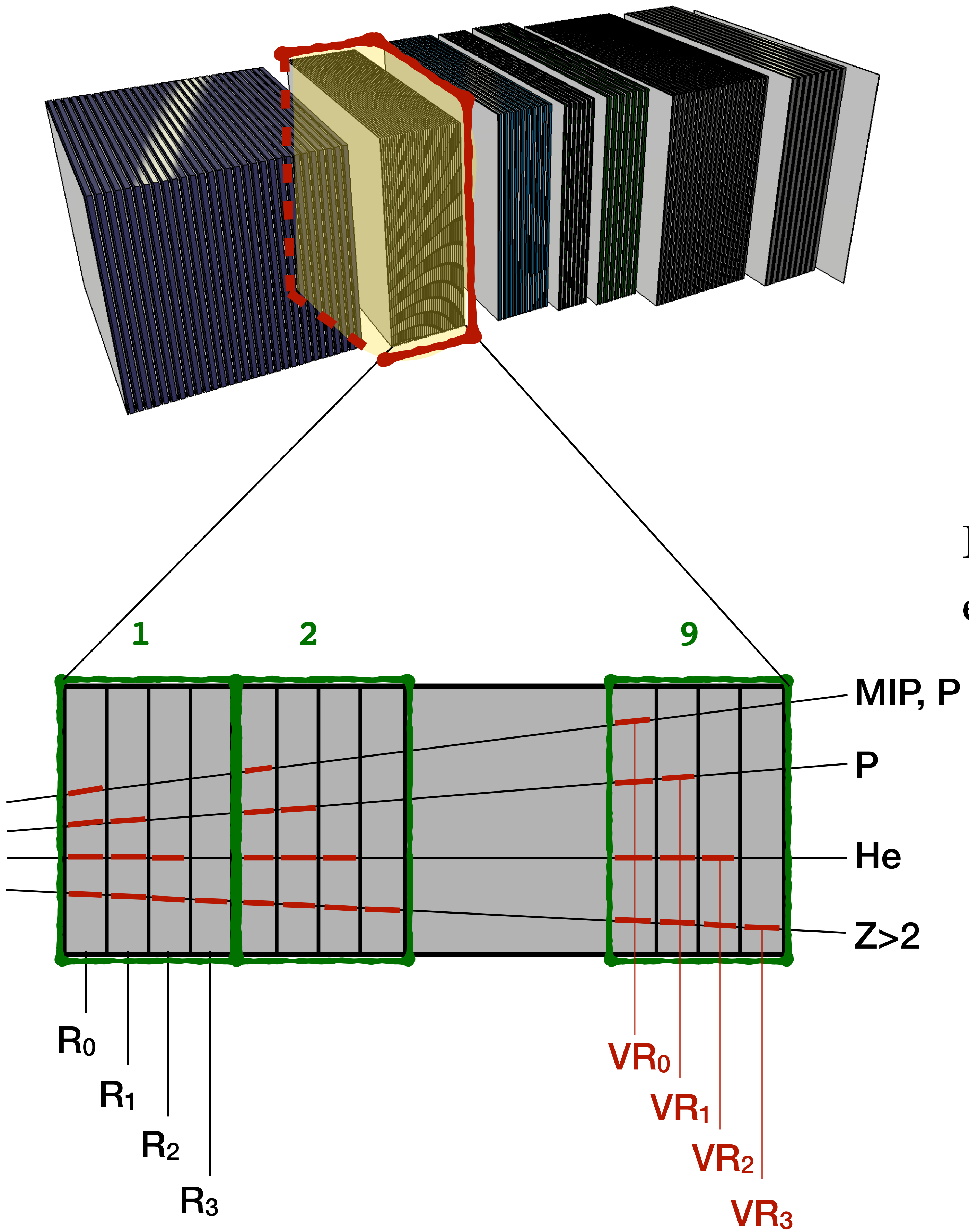
^{16}O (200 MeV/n) on C_2H_4 target: Vertexing reconstruction

NUCLEAR EMULSIONS CONTROLLED FADING



- The grain density is proportional to the energy loss by primary ionization
- For highly ionizing particles, a saturation effect occurs due to the limited range of the grain density, thus preventing the charge measurement
- It is possible to extend the dynamical range of the emulsion response with a controlled fading that partially or totally erase the tracks, depending on their ionization.

STRUCTURE OF THE SECTION 2 (S2)



Emulsions will have a **different thermal treatment** according to its position in the elementary cell:

- **R0**: not thermally treated, sensitive to all particles
- **R1@28°C**, sensitive to $Z > 1$
- **R2@34°C**, sensitive to $Z > 2$
- **R3@36°C**, sensitive to $Z > 3$

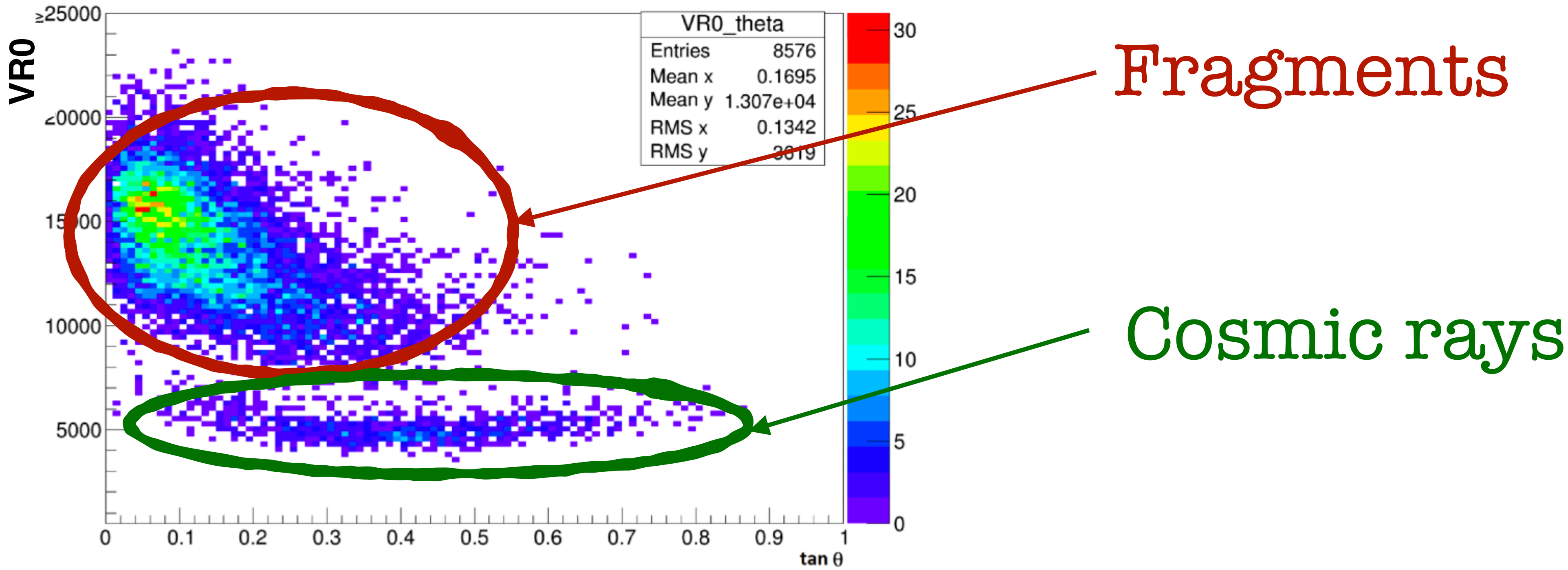
For each track the following variables are evaluated:

$\tan\theta$: tangent of the track inclination w.r.t. the Z axis

NRx: number of base-tracks belonging to the volume-track for each thermal treatment Rx, $x \in \{0,1,2,3\}$

Volume VRx: for each base-track, a variable named “volume” is defined as the sum of the pixel brightness

ANALYSIS FOR CHARGE ID

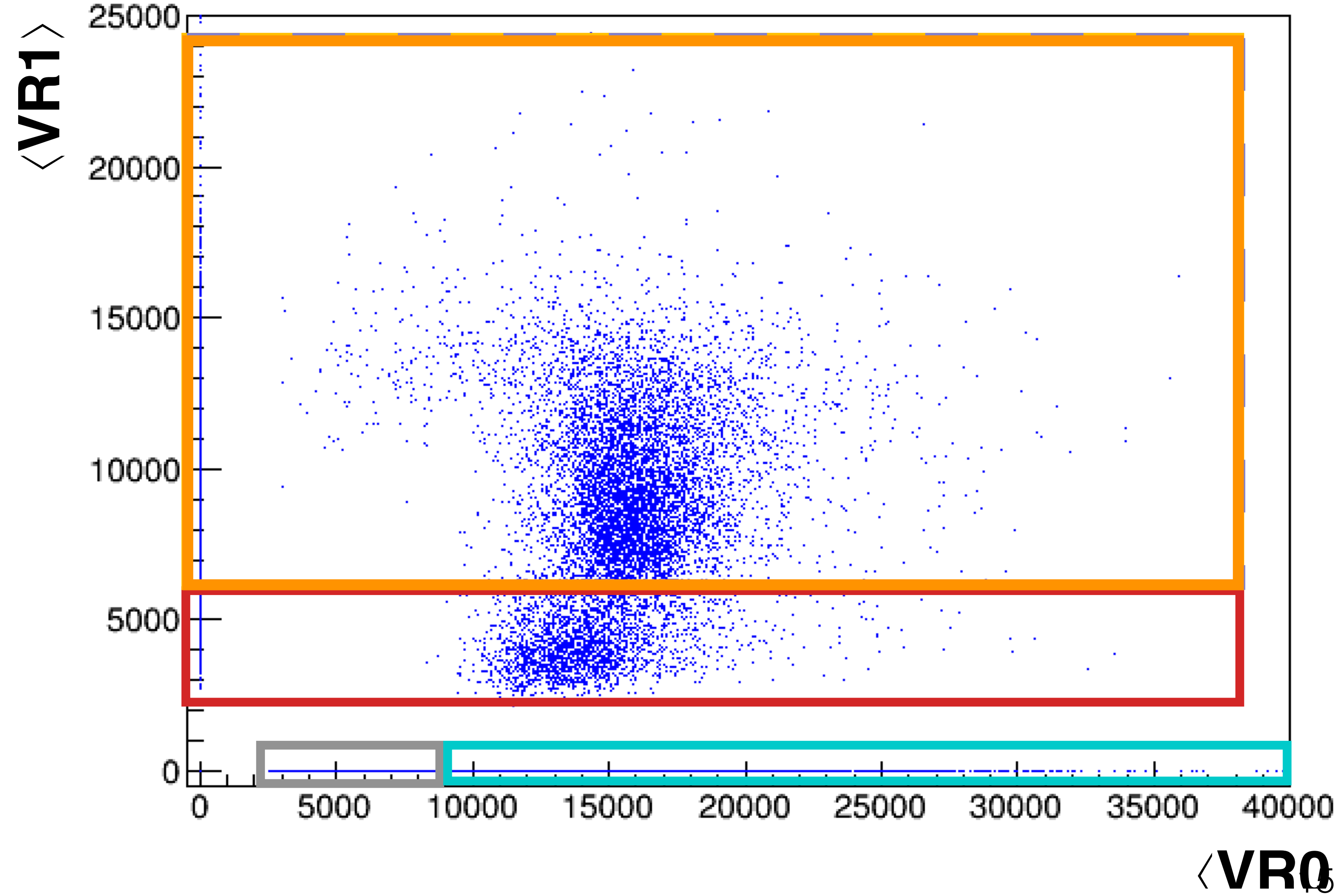


CUT BASED ANALYSIS:

- Z=0: Cosmic rays
- Z=1: High energy Proton
- Z=1: Low energy Proton

PRINCIPAL COMPONENTS ANALYSIS:

- Z ≥ 2



Principal Component Analysis

- A multidimensional technique, well known in the field of pattern recognition

- Four different variables are created: VP_xyz = a·⟨VRx⟩ + b·⟨VRy⟩ + c·⟨VRz⟩ (x, y, z ∈ {0, 1, 2, 3})

- The variable VP_123 is used if ⟨VR1⟩, ⟨VR2⟩ and ⟨VR3⟩ are available. Otherwise one of the others VP_xyz applies

$$VR01 = \alpha_{01} VR0 + \beta_{01} VR1$$

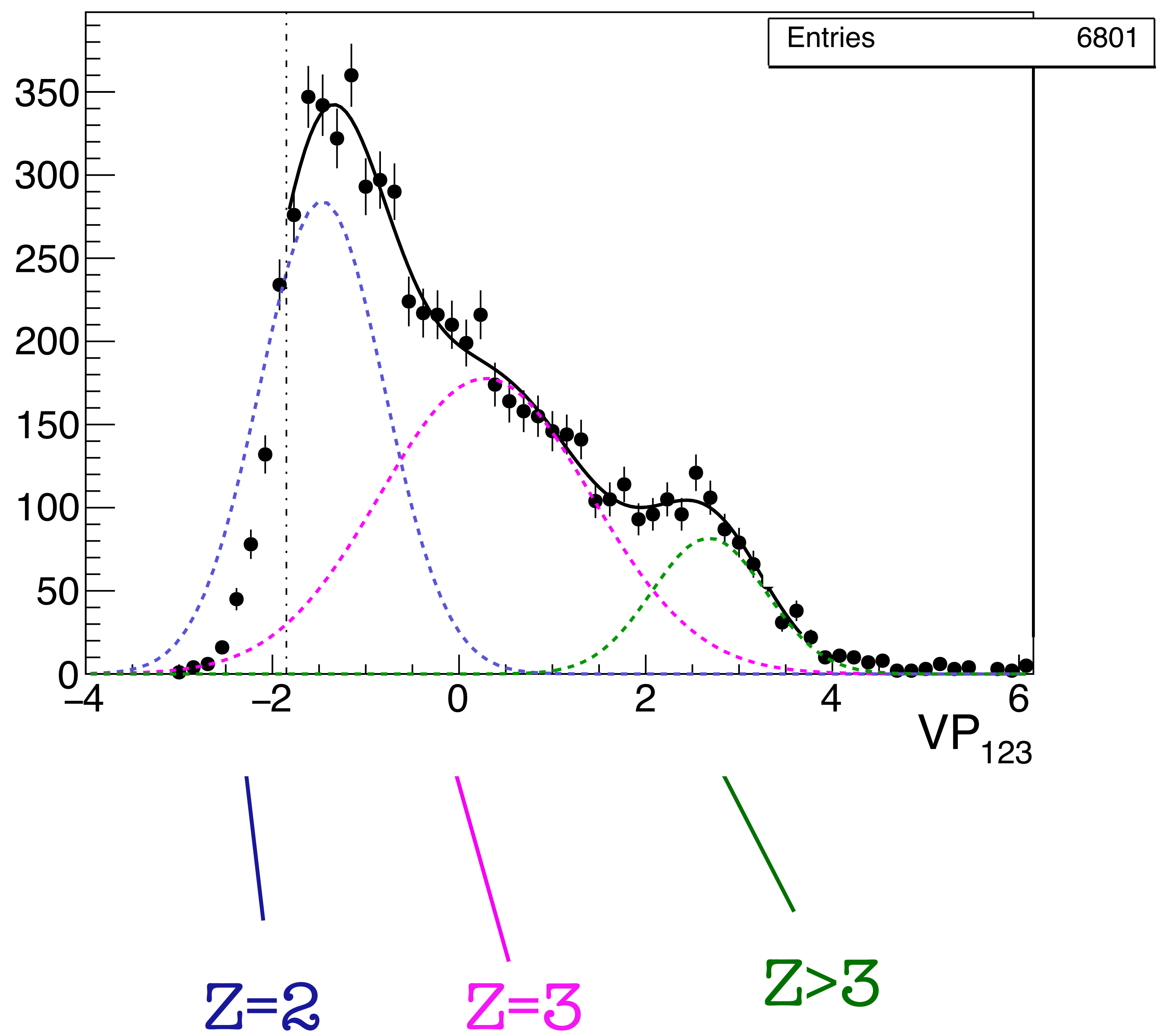
$$VR012 = \alpha_{012} VR0 + \beta_{012} VR1 + \gamma_{012} VR2$$

$$VR123 = \alpha_{123} VR1 + \beta_{123} VR2 + \gamma_{123} VR3$$

$$VR0123 = \alpha_{0123} VR0 + \beta_{0123} VR1 + \gamma_{0123} VR2 + \delta_{01234} VR2$$

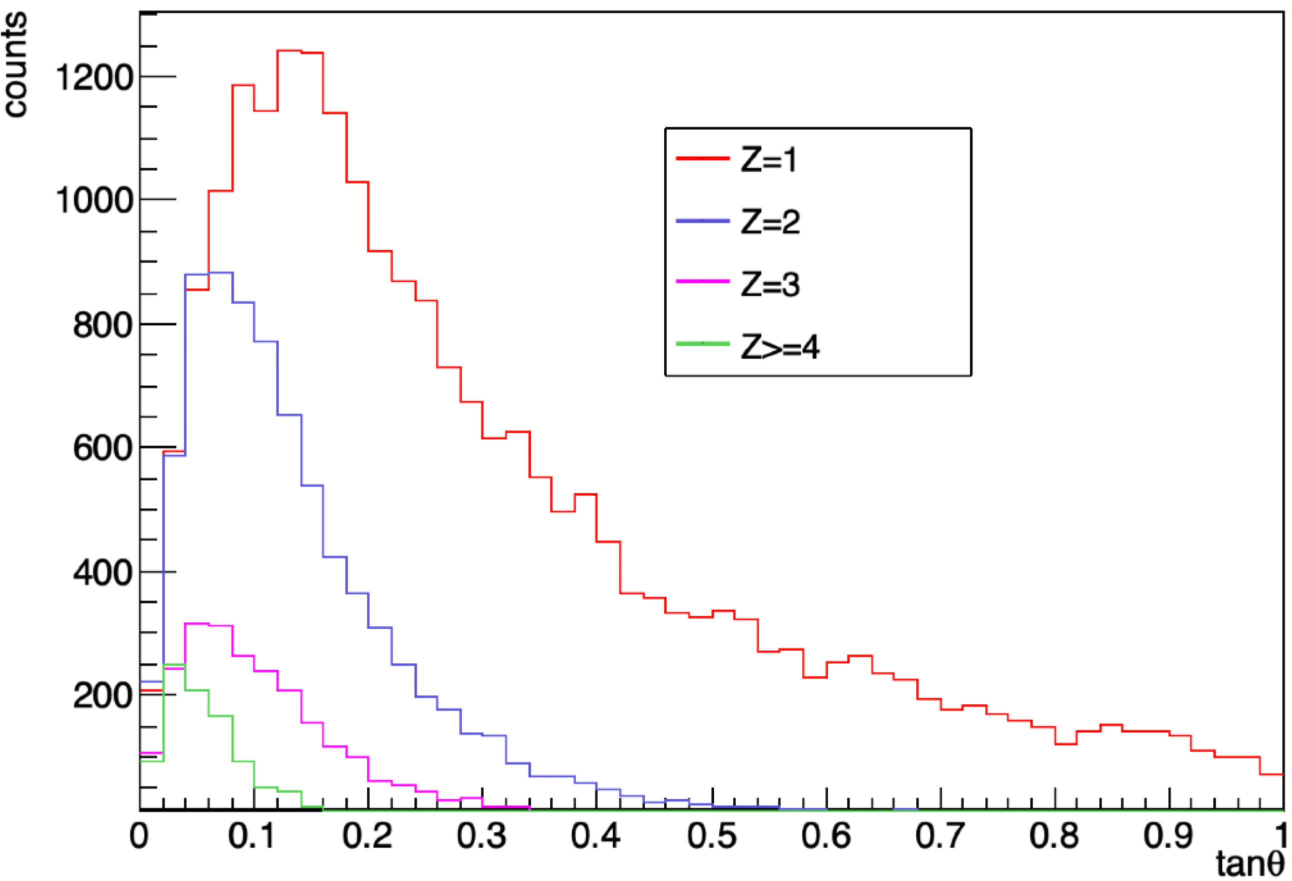
Charge Assignment for Z≥2

$$VR123 = \alpha_{123}VR1 + \beta_{123}VR2 + \gamma_{123}VR3$$



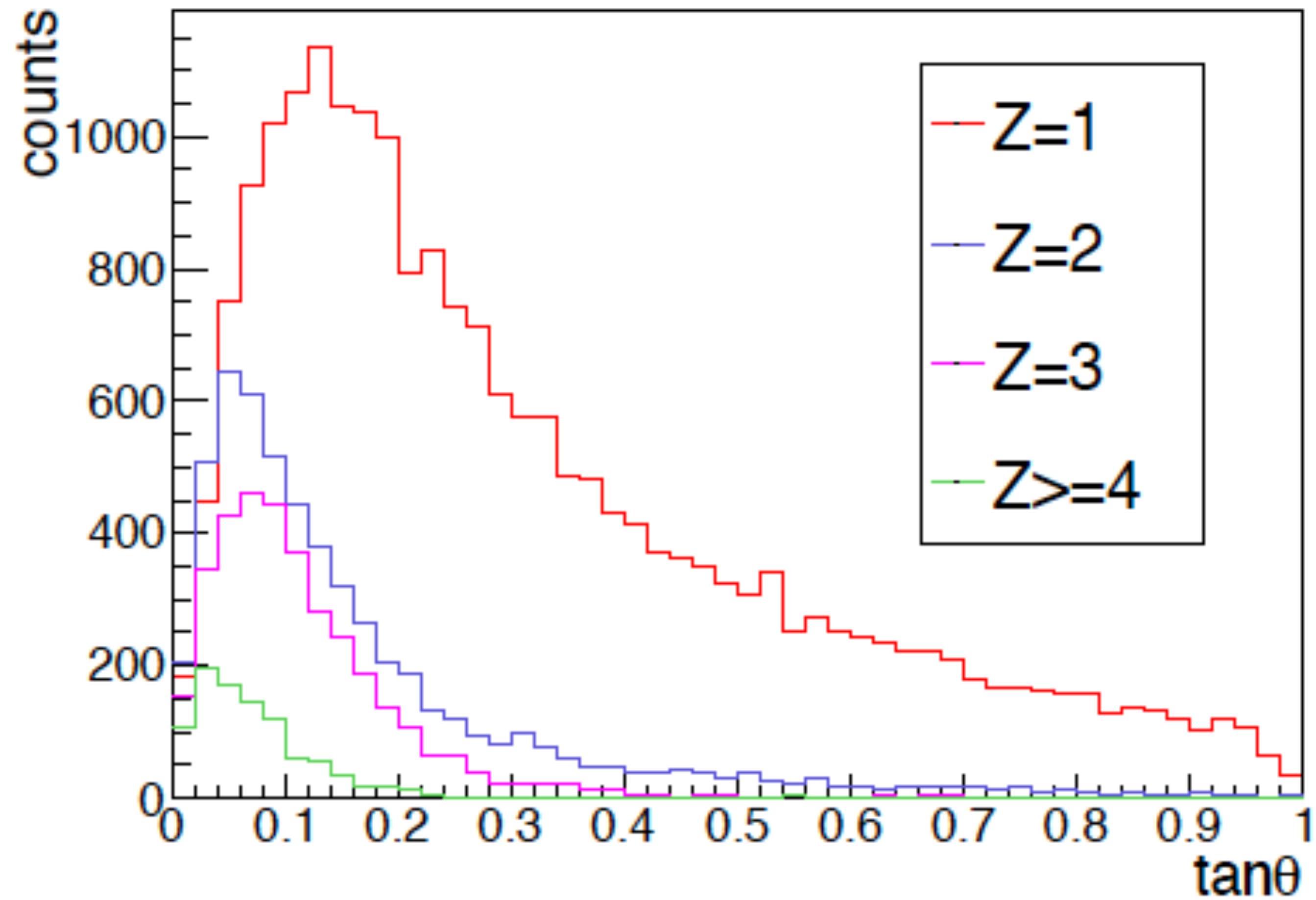
ANALYSIS BY THE PRINCIPAL COMPONENTS METHOD

^{16}O (200 MeV/n) on C target



Z	% in total charged			
	Result	Systematic err	Gauss Param err	Statistic err
1	67%	2%	/	1%
2	22%	3%	0%	1%
3	8%	2%	0%	2%
>3	3%	0%	0%	3%

^{16}O (200 MeV/n) on C_2H_4 target



Z	% in total charged			
	Result	Systematic err	Gauss Param err	Statistic err
1	70%	5%	/	1%
2	16%	2%	0%	1%
3	10%	2%	0%	2%
>3	4%	1%	0%	3%

Overview

- An overview of the FOOT experiment to investigate on target fragmentation in particle therapy is given

- Description of the controlled fading technique, based on different thermal treatments, adopted for the nuclear emulsion detector to extend the dynamical range of the emulsions to distinguish fragments charge (Z=1, Z=2, Z=3, Z≥4 and cosmic rays)

- The charge of the fragments obtained by the exposing a C and C_2H_4 target to a ^{16}O (200 MeV/n) beam are measured by two complementary methods: a cut-based analysis and the Principal Component Analysis

- The charge was assigned for 99.4% of tracks reconstructed in section 2, dedicated to the charge id

Thank you