FramentatiOn Of Target

Measurements of ^{16}O fragmentation cross sections on C target with the FOOT apparatus

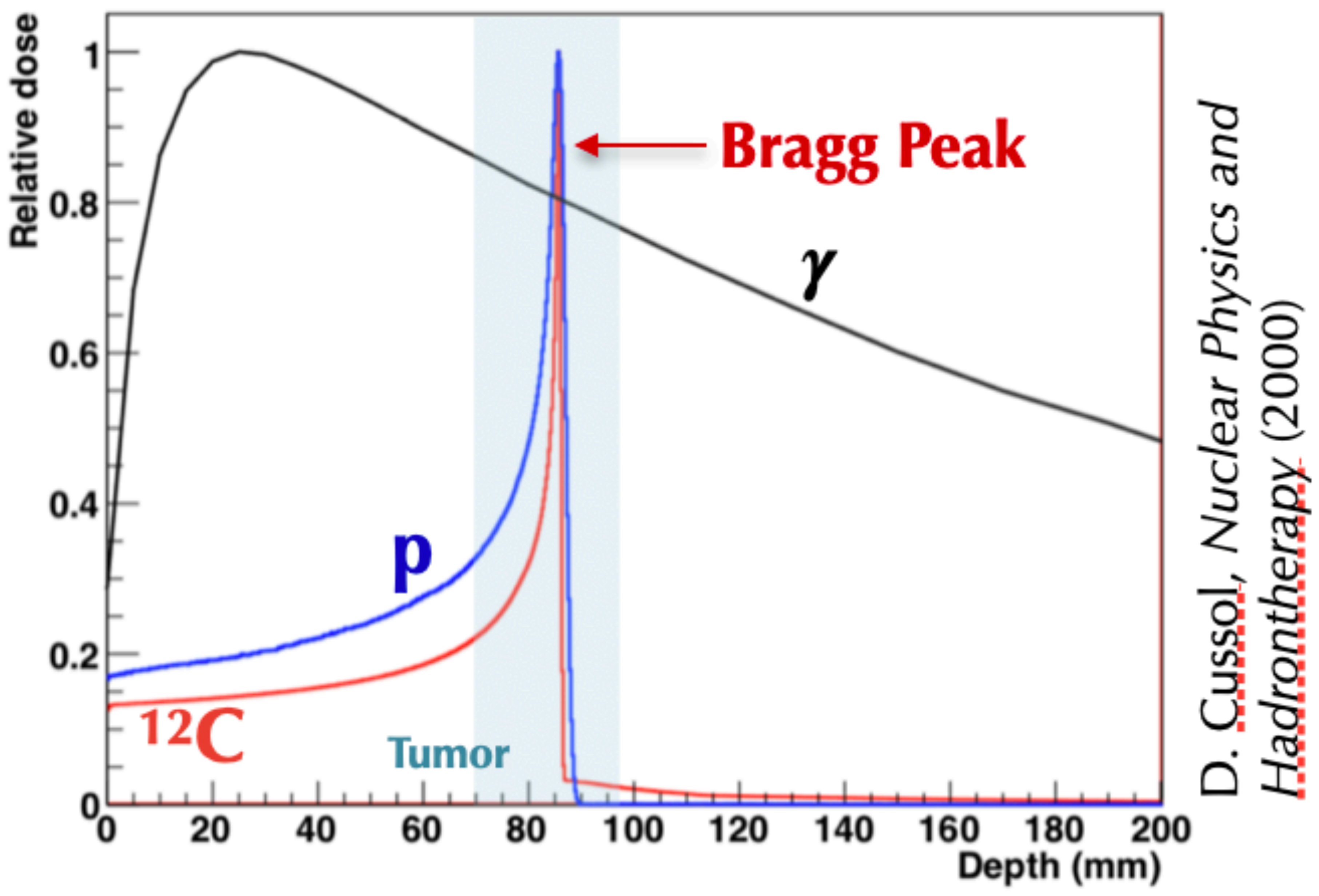
Marco Toppi, on behalf of the FOOT collaboration

Outline

FramentatiOn
Of Target

- **FOOT (FragmentatiOn Of Target) experiment:**
  - **Motivations**: Particle Therapy and Radioprotection in space
  - **Strategy** for fragmentation cross section measurements
  - **Experimental set-up**
  - **Preliminary cross section measurement for the process $^{16}O+C$ @ 400 MeV/u**
  - **Conclusions**

Particle Therapy



D. Cussol, *Nuclear Physics and Hadrontherapy* (2000)

- Particle Therapy (**PT**) uses **proton or heavy ions** beams to treat **deep-seated solid tumors.**

- Advantages wrt conventional radiotherapy:

    1. Maximum dose released inside the tumor: **Bragg Peak**
    2. High **RBE**

$$\mathrm{RBE} = \frac{D_\gamma}{D_{part}}$$

- Disadvantages: **fragmentation** of **projectile** and **target** nuclei

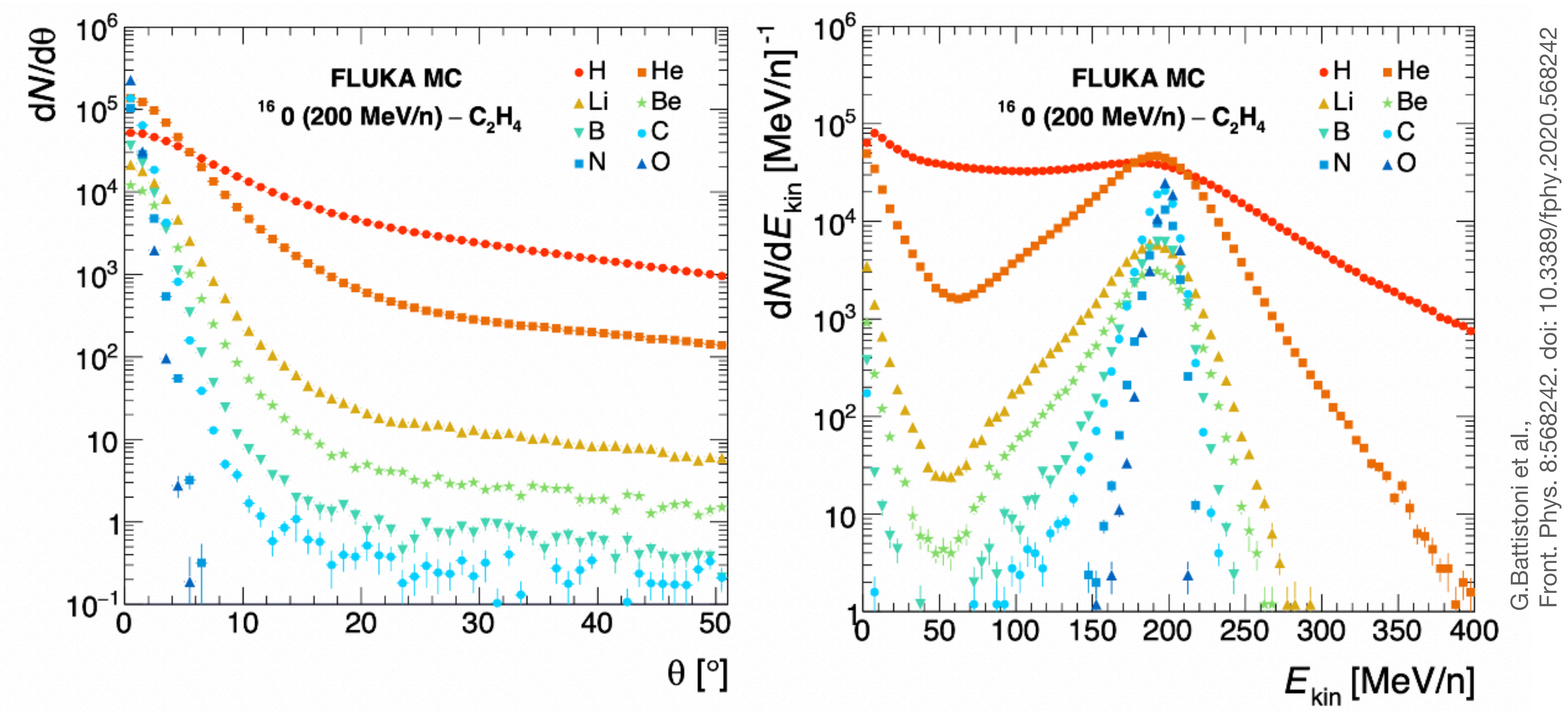
Projectile fragments:
lower Z and higher range ($\beta_{frag} \sim \beta_{beam}$)

FRAGMENTATION TAIL

Target fragments:
Low kinetic energy and low range

LOCAL RELEASE

Fragments angular and energetic distributions



- Z>2 fragments ~ same velocity of the ^{16}O ions. Emitted in forward direction
- Protons & neutrons are the most abundant fragments: wide kinetic energy and angular distributions

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lower Z and higher range ($\beta_{frag} \sim \beta_{beam}$)

FRAGMENTATION TAIL

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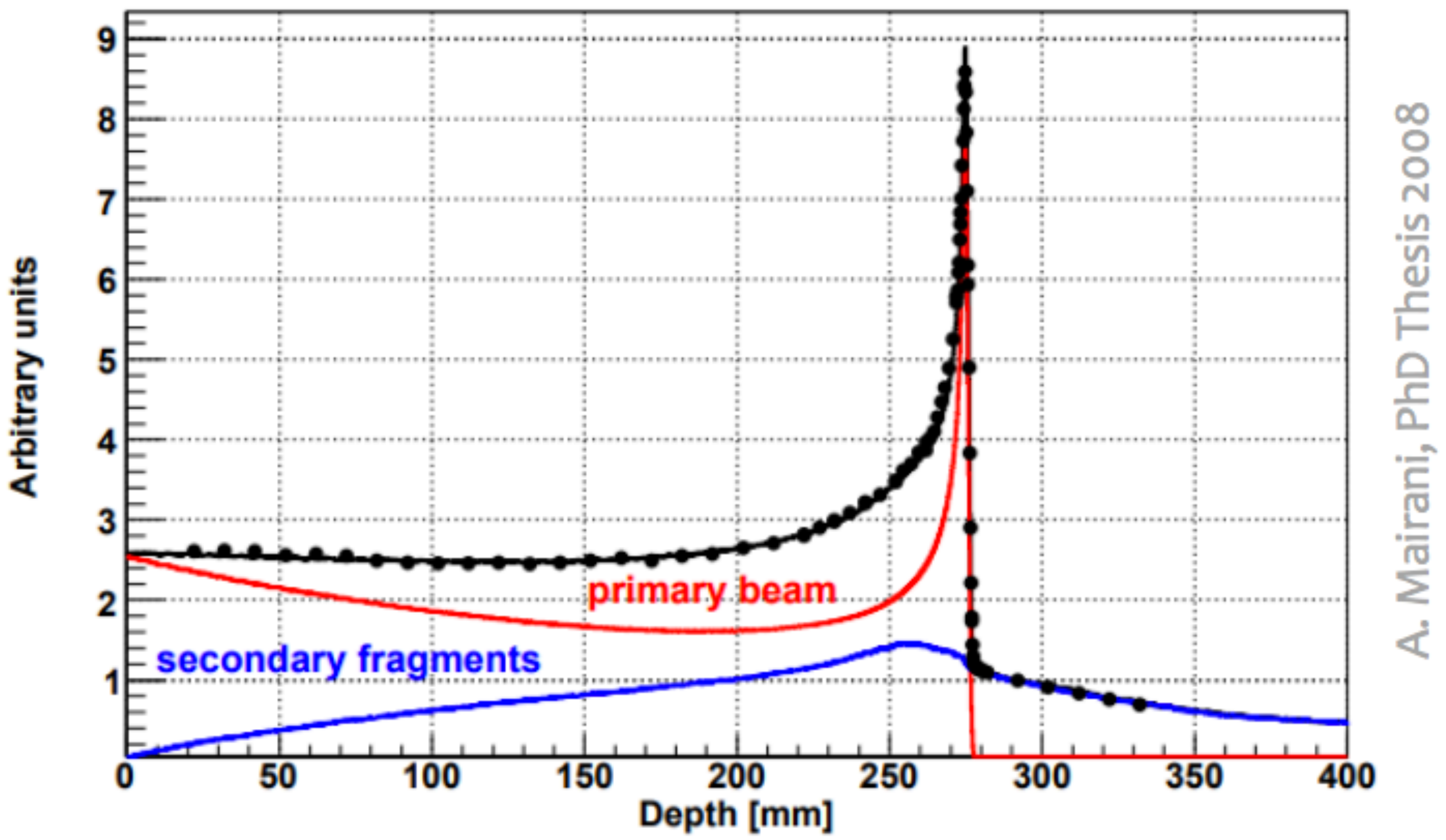
Fragmentation consequences



- Fragmentation processes modify the delivered dose map
- This effect strongly depends on the **mass** and the **energy** of the ion beam and on the **target** involved in the interaction

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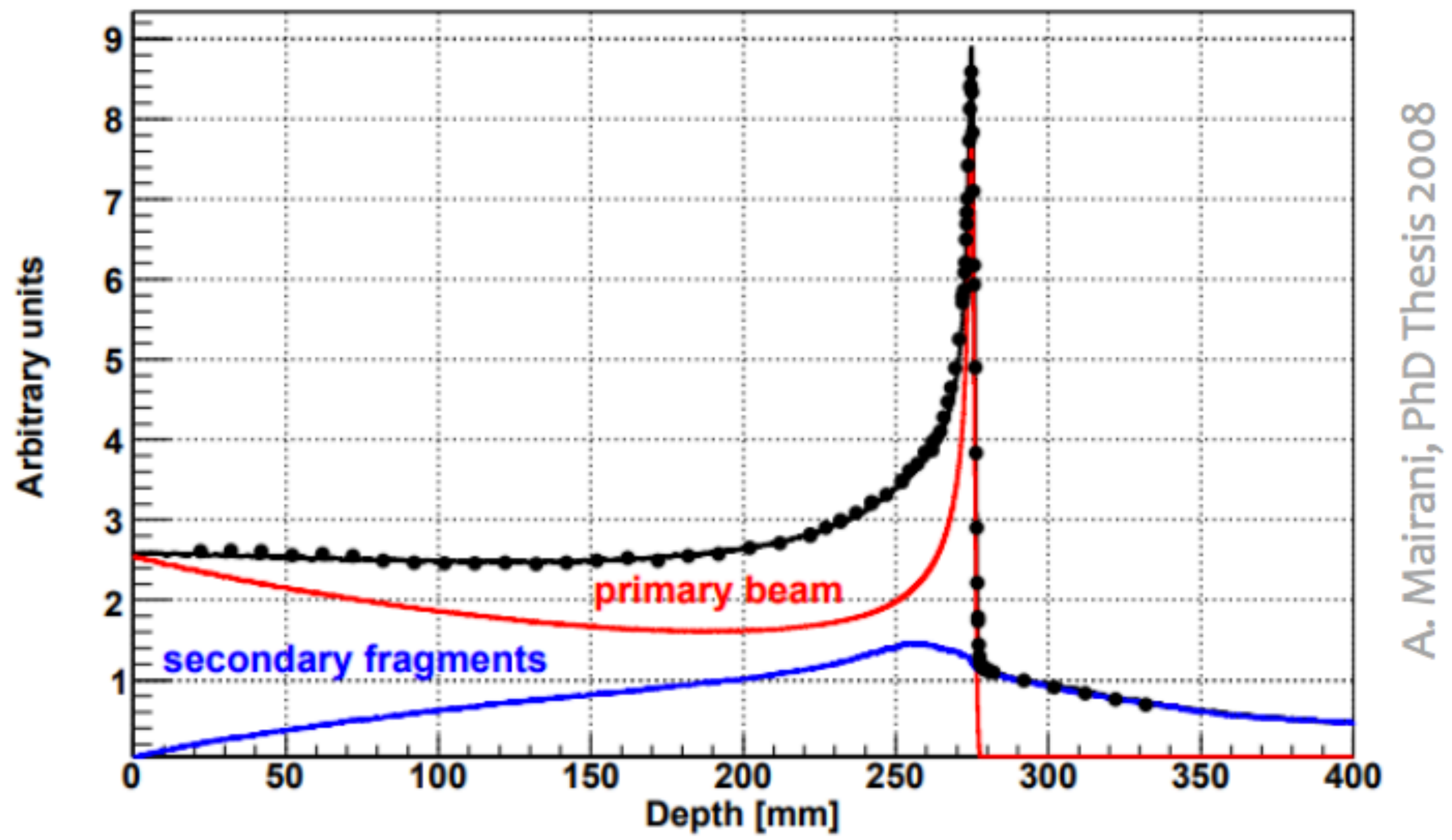

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- **Treatment plans for PT are not yet able to include the fragmentation contribution with the accuracy (3%) required for radiotherapy**
- This is due to the lack of experimental data, and in particular of fragmentation cross section

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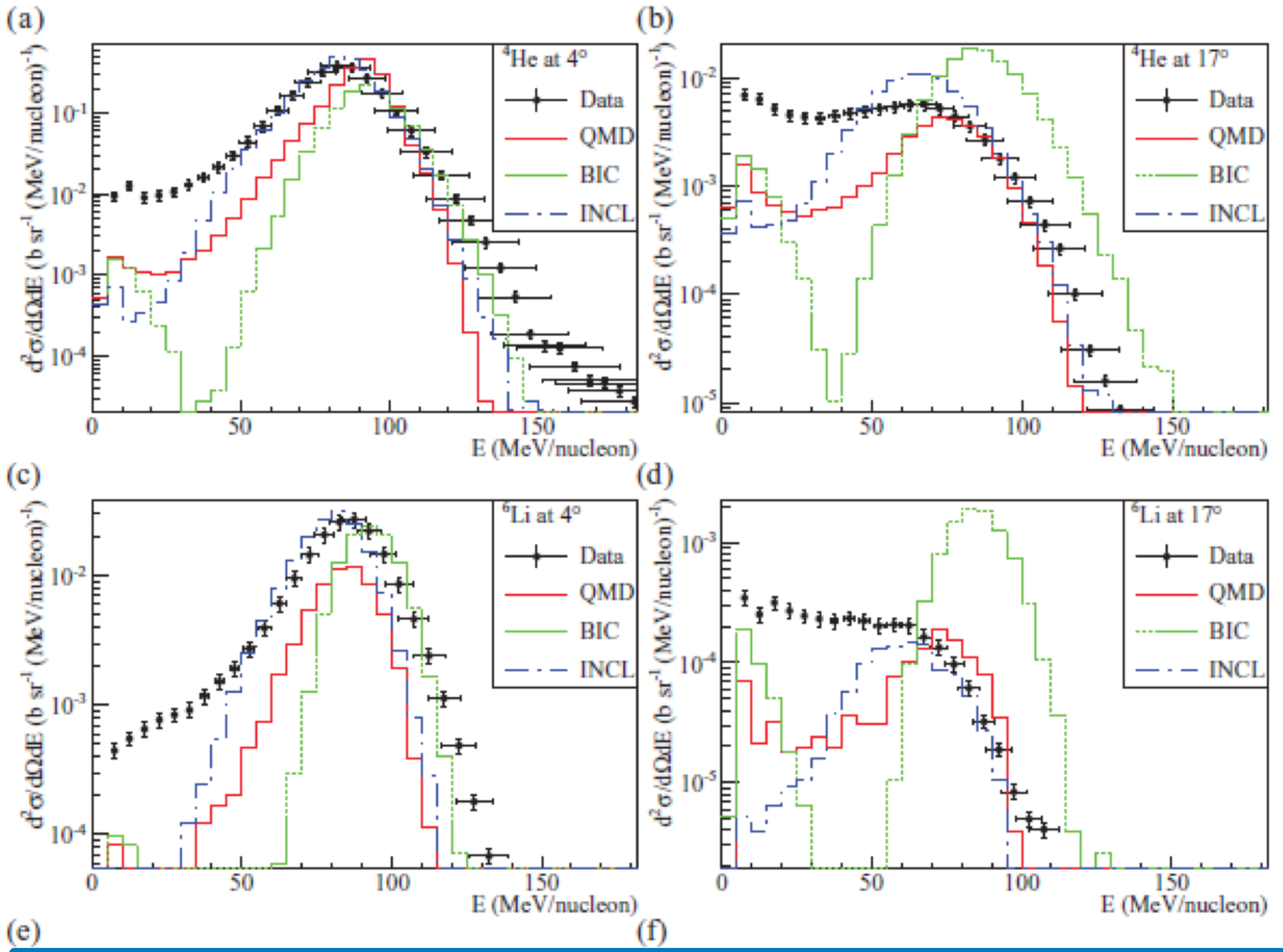

J. Dudouet et al., PHYSICAL REVIEW C **89**, 054616 (2014)

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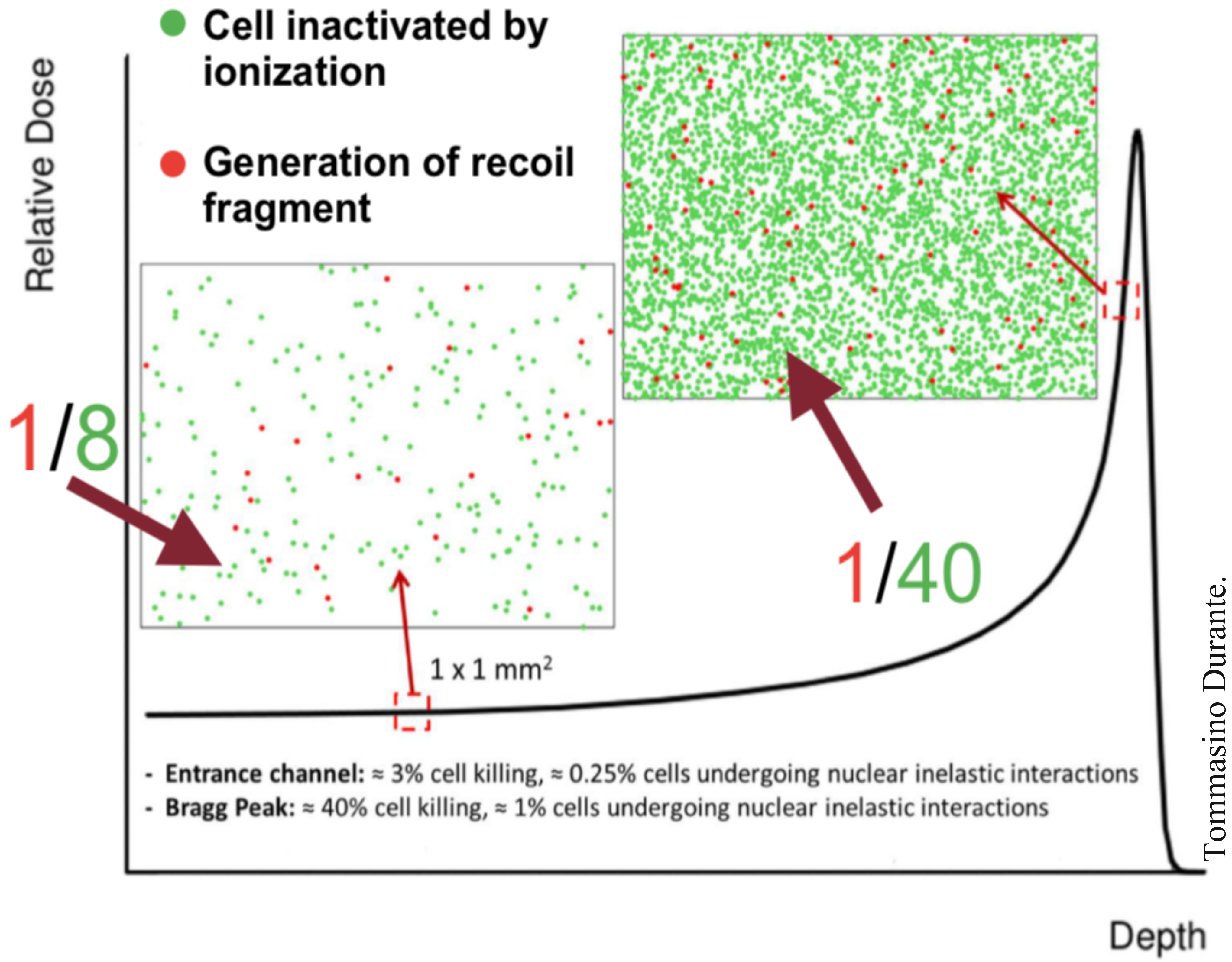
Target fragmentation contribution



Tommasino Durante. Cancers 2015, 7, 353-381; doi:10.3390/cancers7010353

Can be of interest in proton-therapy:

$$p + x \rightarrow p + \sum_i x_i$$

$$T_{x_i} << T_p$$

$$\left(\frac{dE}{dx}\right)_x >> \left(\frac{dE}{dx}\right)_p$$

→ Target fragments have **high RBE** values

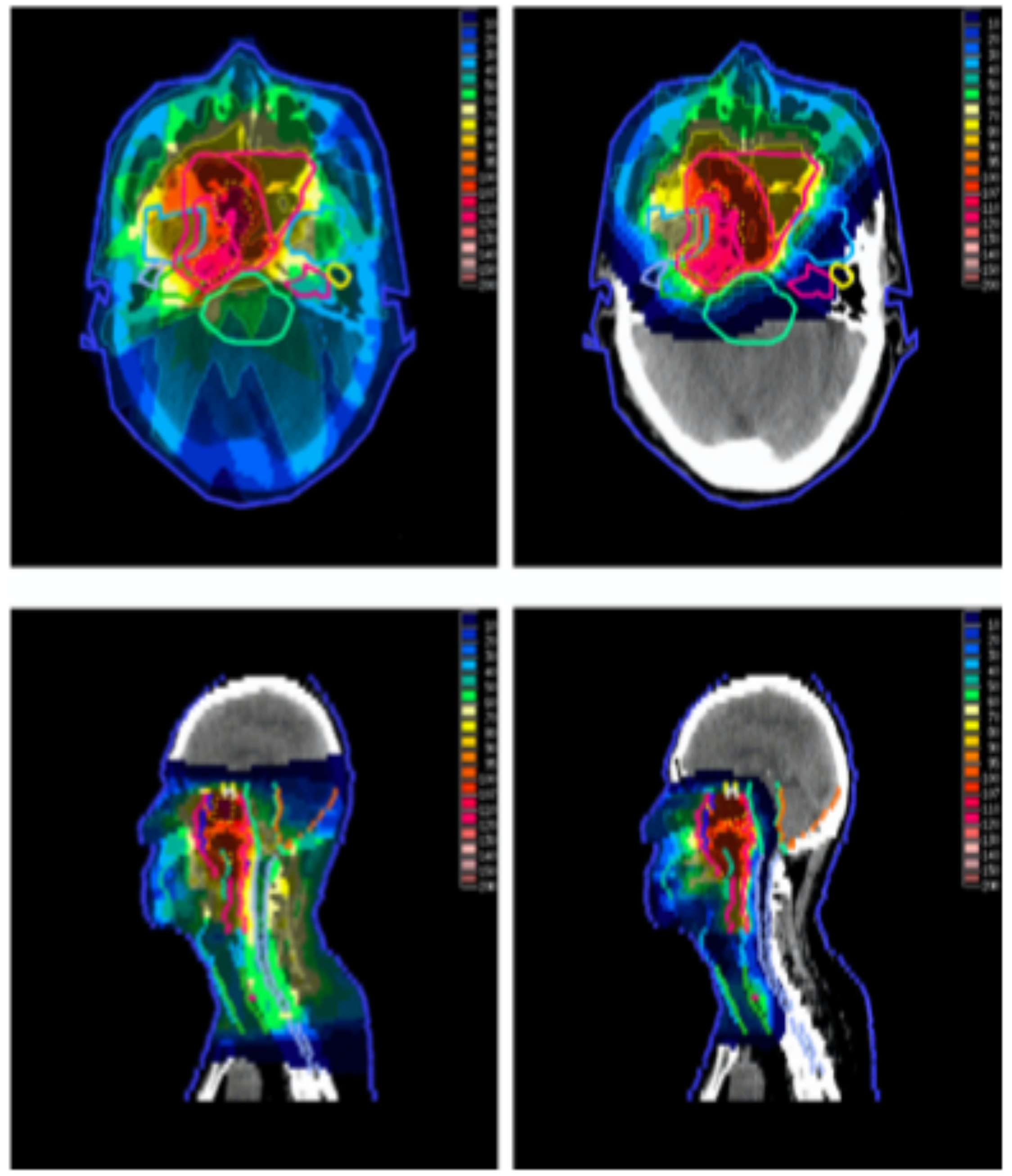
In clinical practice protons RBE = 1.1

- The particles produced in target **fragmentation** are one of the causes contributing **(~10%)** to the increase of proton RBE

FragmentatiOn Of Target (FOOT) experiment

Measurements of target and projectile fragmentation cross section relevant for **PT** and for **Radio Protection in Space** applications.

Particle Therapy



- Projectile fragmentation of ^{4}He, ^{12}C, ^{16}O beams in the energy range 100÷500 MeV/u interaction with main constituent of human body (H, C, O, Ca)
- ^{12}C and ^{16}O target fragmentation induced by 50÷250 MeV proton beams

Radioprotection in space

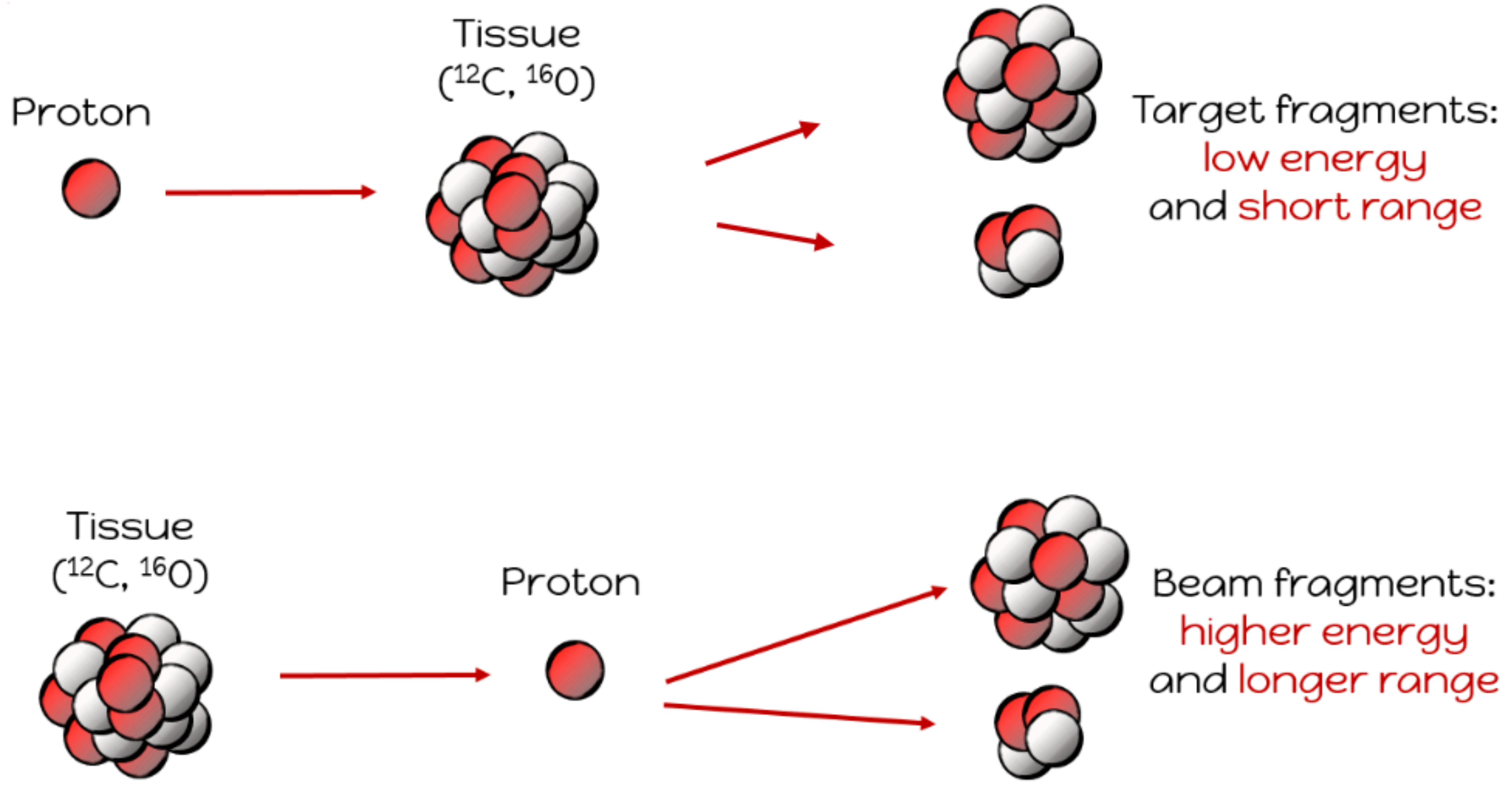
- Same PT ions (plus ions up to ^{56}Fe) interacting with hydrogen-rich targets, of interest for shieldings, at the increased energy range of 100÷800 MeV/u

Strategy for target fragmentation measurement

Target fragments have a very **low energy** and so a very **low range** that make the detection really difficult.

Direct kinematic

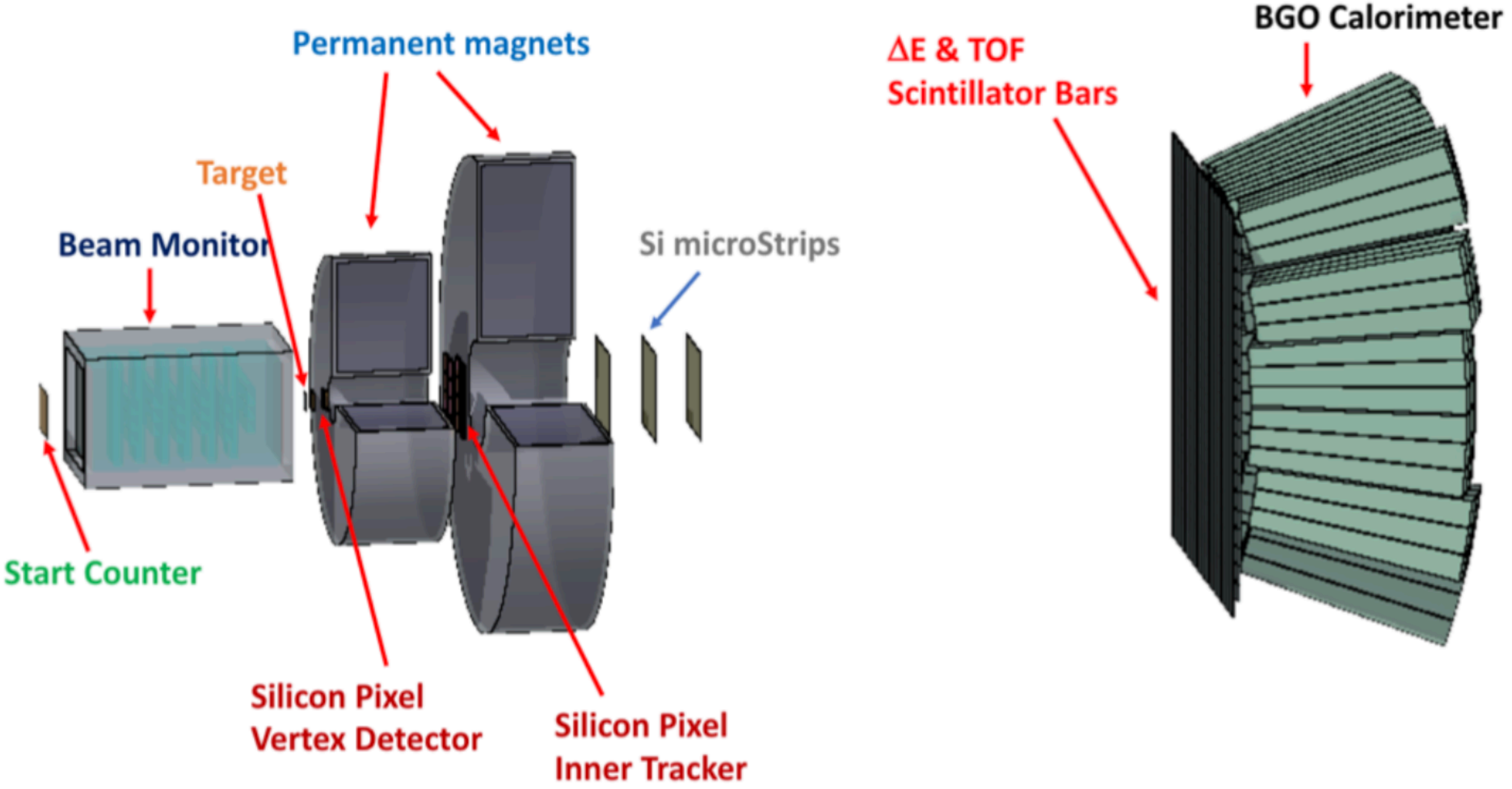
Inverse kinematic



By applying a Lorentz boost it is possible to switch from the laboratory frame to the “patient frame”

With this strategy the fragmentation of **tissue-like ion beams** (mainly C and O) impinging on a **hydrogen enriched target** are studied moving from the challenging measurement of target fragmentation to the easier case of projectile fragmentation

FOOT detector



- **Fixed target** experiment with magnetic spectrometer for the identification of fragments, optimitezed fot Z>2 fragments
- **Emulsion setup**: another setup exploiting emusion chambers is optimized for Z<3 fragments → see **Adele Lauria 's talk**

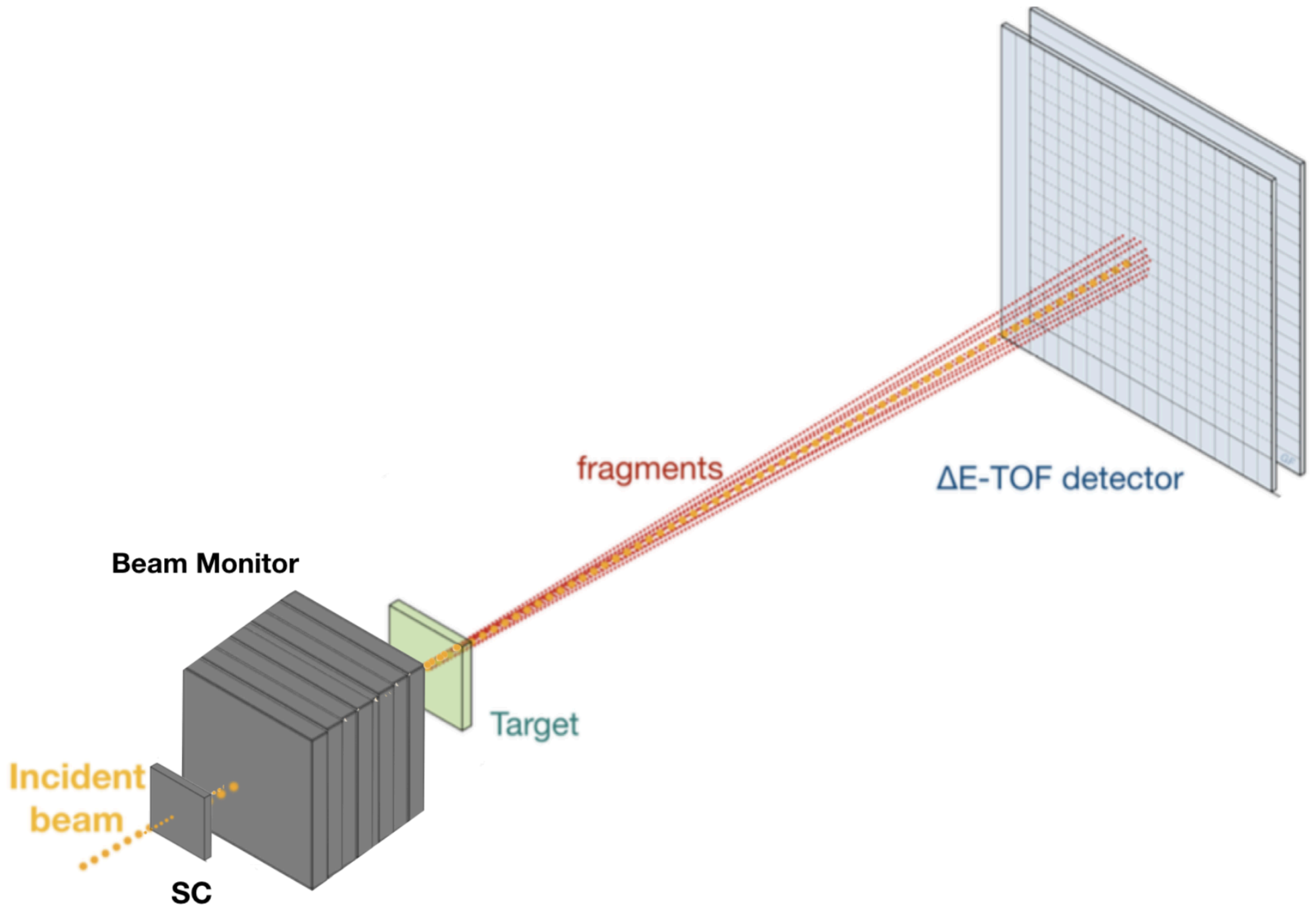
Required performances for cross section precision < 10%

- $\sigma(p)/p \sim 5\%$
- $\sigma(E_k)/E_k \sim 2\%$
- $\sigma(\Delta E)/\Delta E \sim 3-10\%$
- $\sigma(TOF)/TOF \sim 100ps$

The FOOT detector is a movable set-up to fit the experimental rooms dimensions of different PT treatment centers / experimental facility (CNAO, HIT, GSI) with ions beams.

Data acquisition at GSI in 2019

- Preliminary data taking @ GSI in 2019 with a partial FOOT experimental set-up composed of Start Counter, Beam Monitor and Tof-Wall detector with a beam of ^{16}O at 400 MeV/u meant for calibration



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- Very few statistics (~67k events) collected for physics runs with fragmentation of the ^{16}O beam of 400 MeV/u on a C target
- Preliminary charge-changing cross sections integrated over the angular TW acceptance for the process ^{16}O (400 MeV/u)+C

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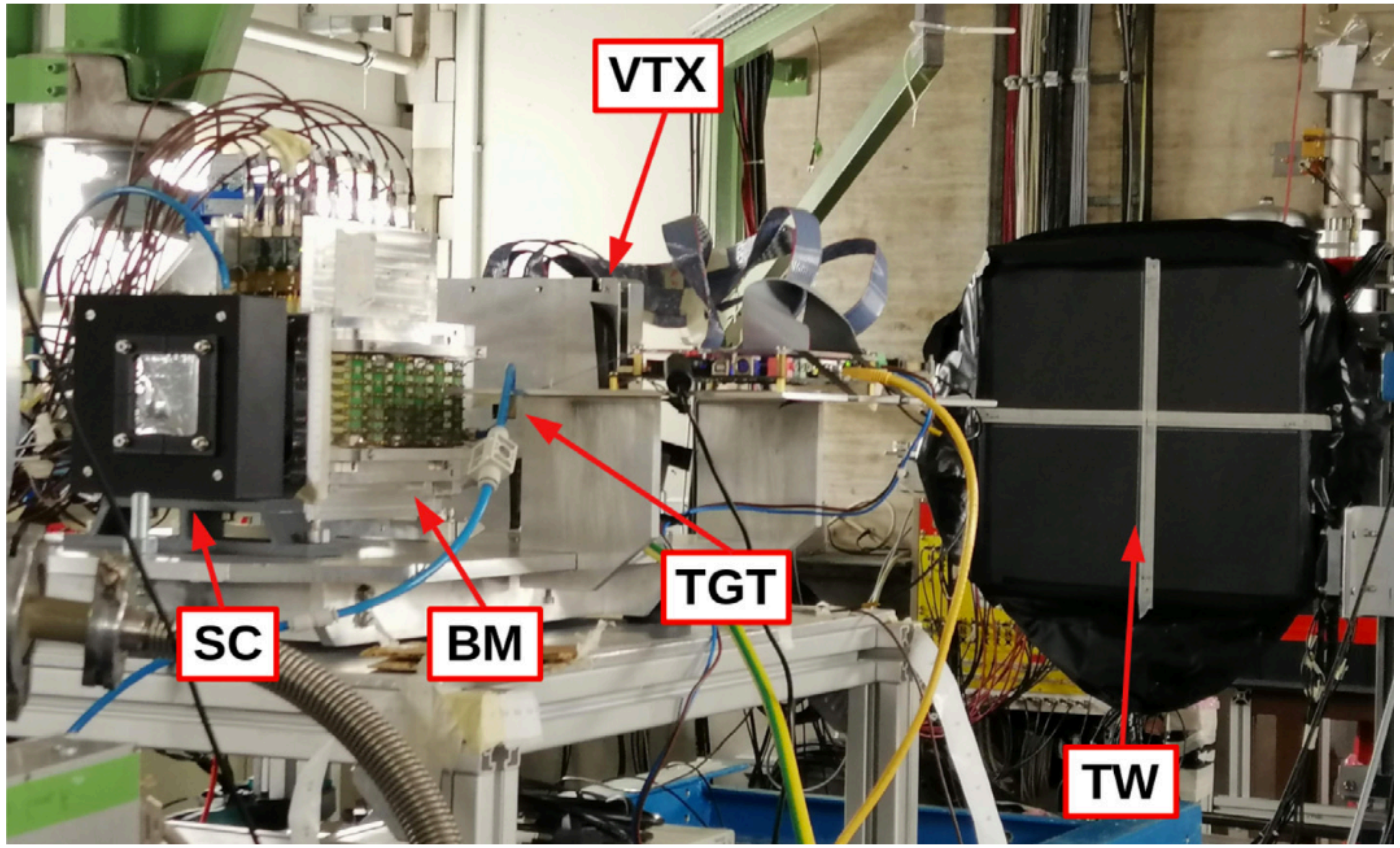

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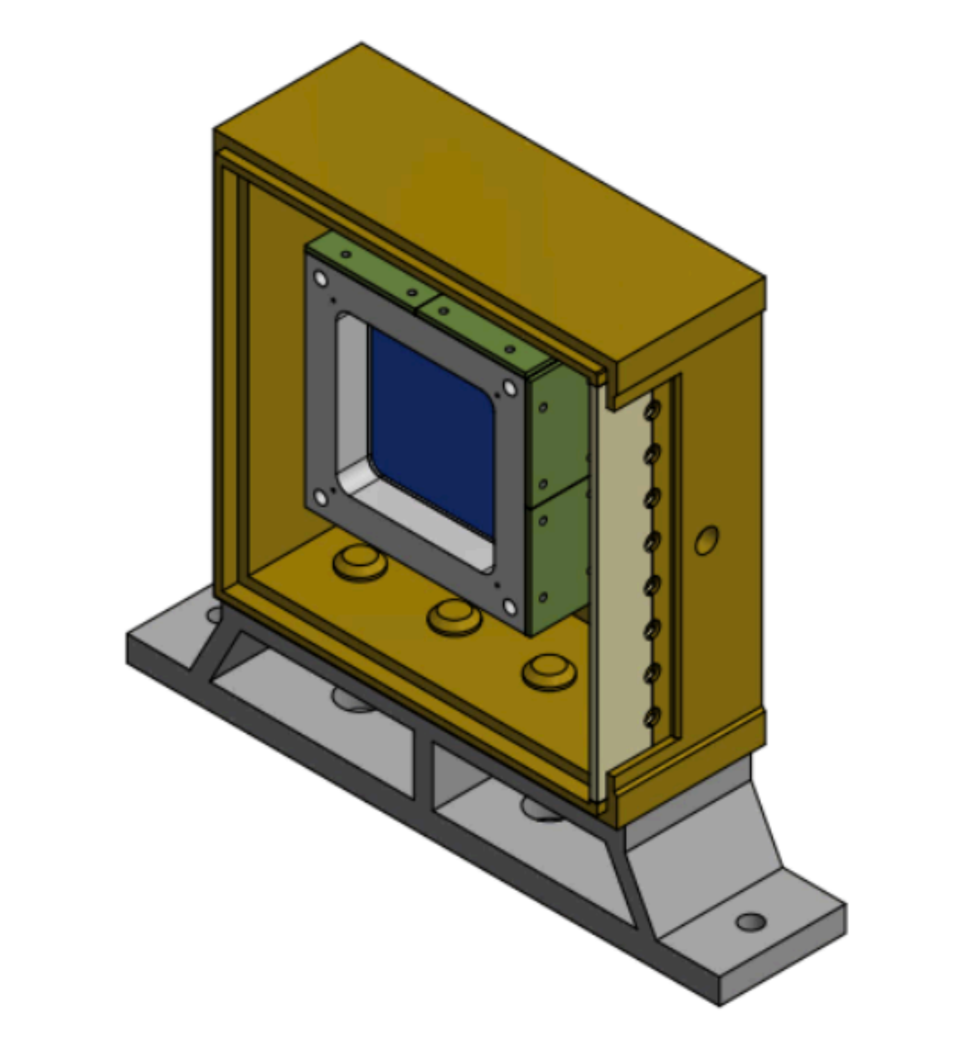
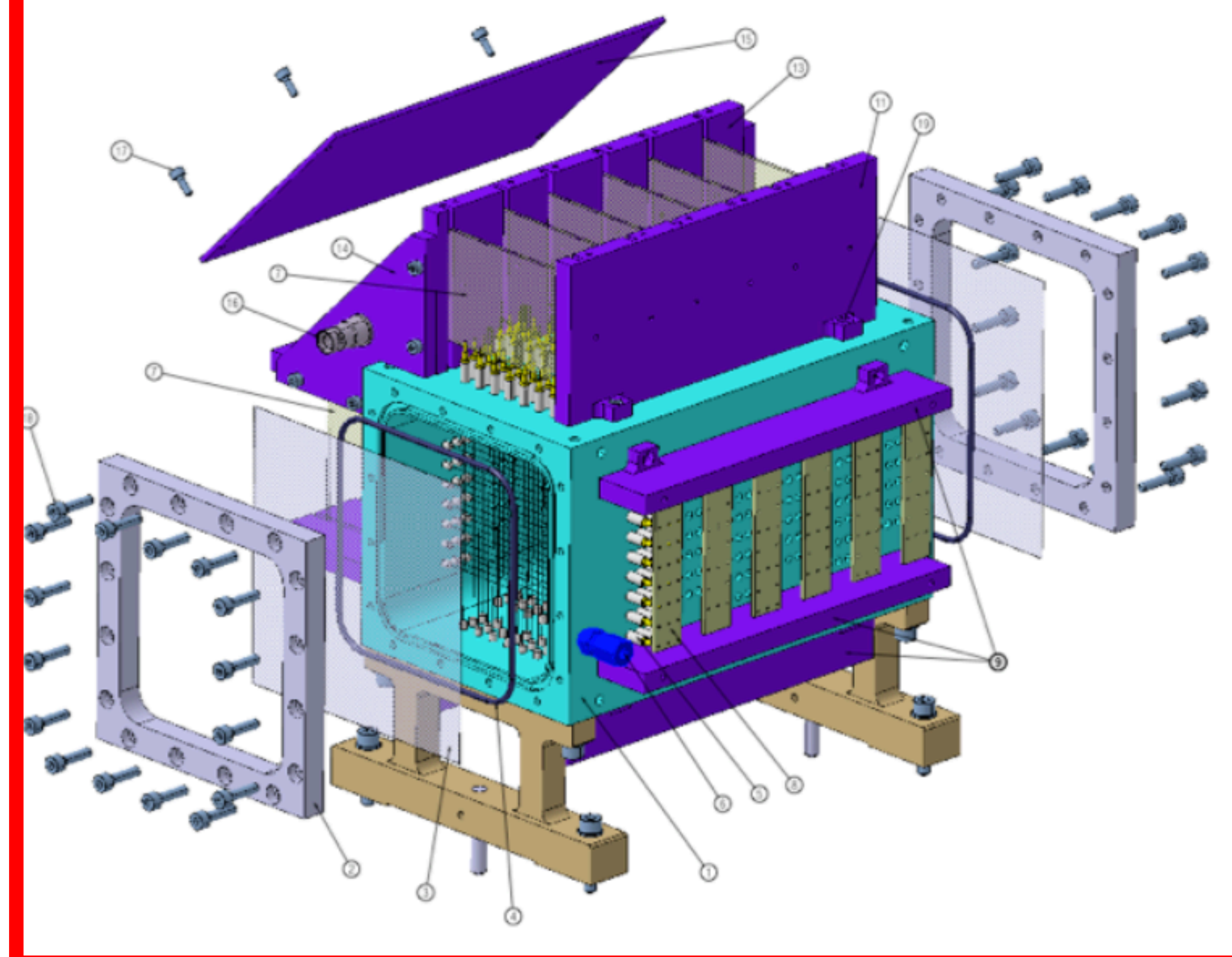
Start Counter and Beam monitor





- The Beam Monitor (BM) is a **drift chamber** of 12 wire layers (3 drift cells per layer)
- Wire layers alternated in x and y view
- Rectangular cell: 16 mm × 10 mm
- The BM operates at ≃ 0.9 bar with a 80/20% gas mixture of Ar/CO2
- It provide the **direction** and **impinging point** of the beam ions on the target

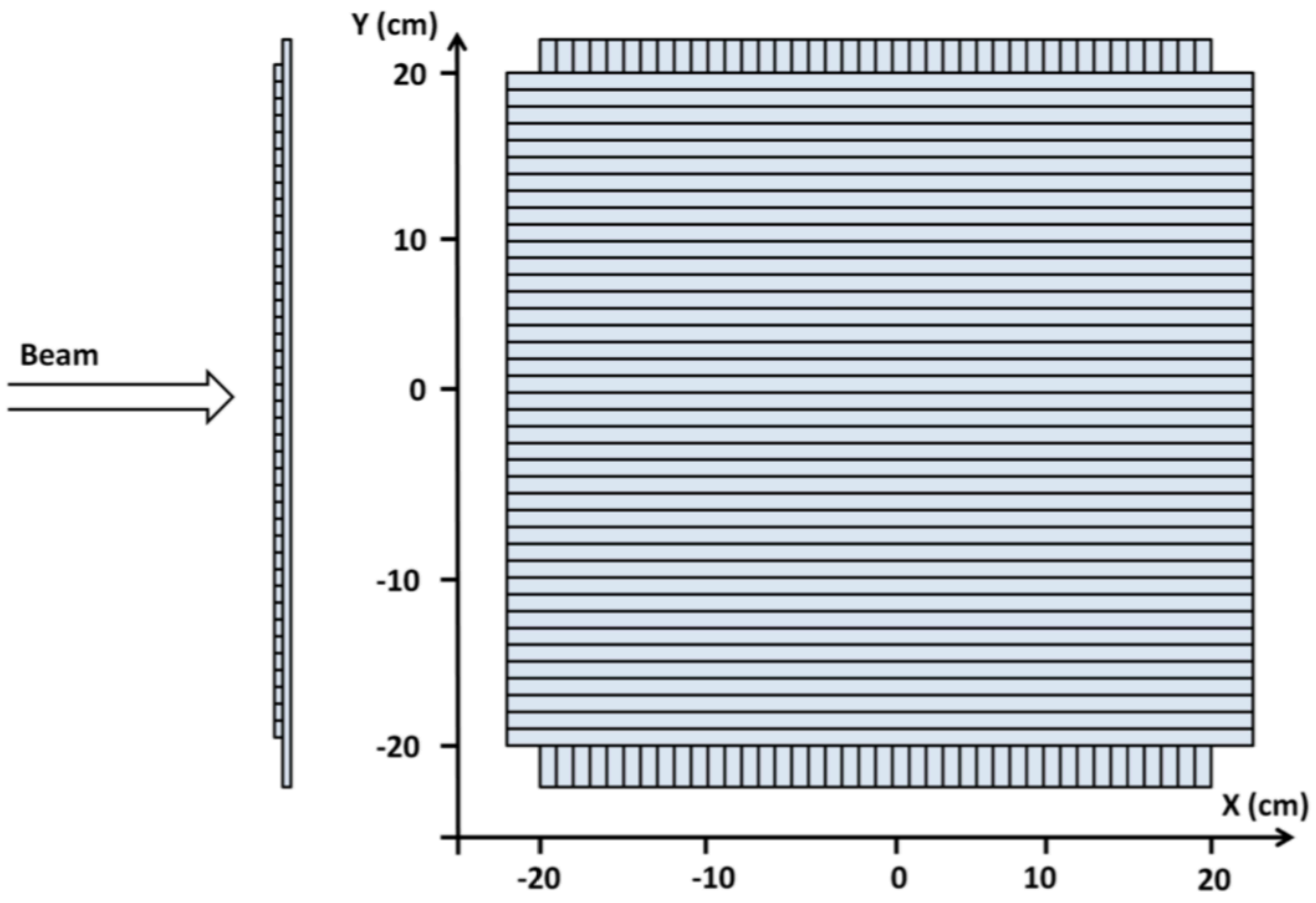
- The Start Counter (SC) is a **thin plastic scintillator layer** (EJ-204 – [250 μm, 1mm] thick) placed about 30 cm before the target with an active surface of $5\ x\ 5\ cm^2$
- Coupled to **48 SiPM** (8 channel readout)
- Layout optimized to **maximize the light collection**

It provides:

1. The **start of the TOF** masurements
2. The **trigger signal**
3. The measurement of the incoming **ion flux**

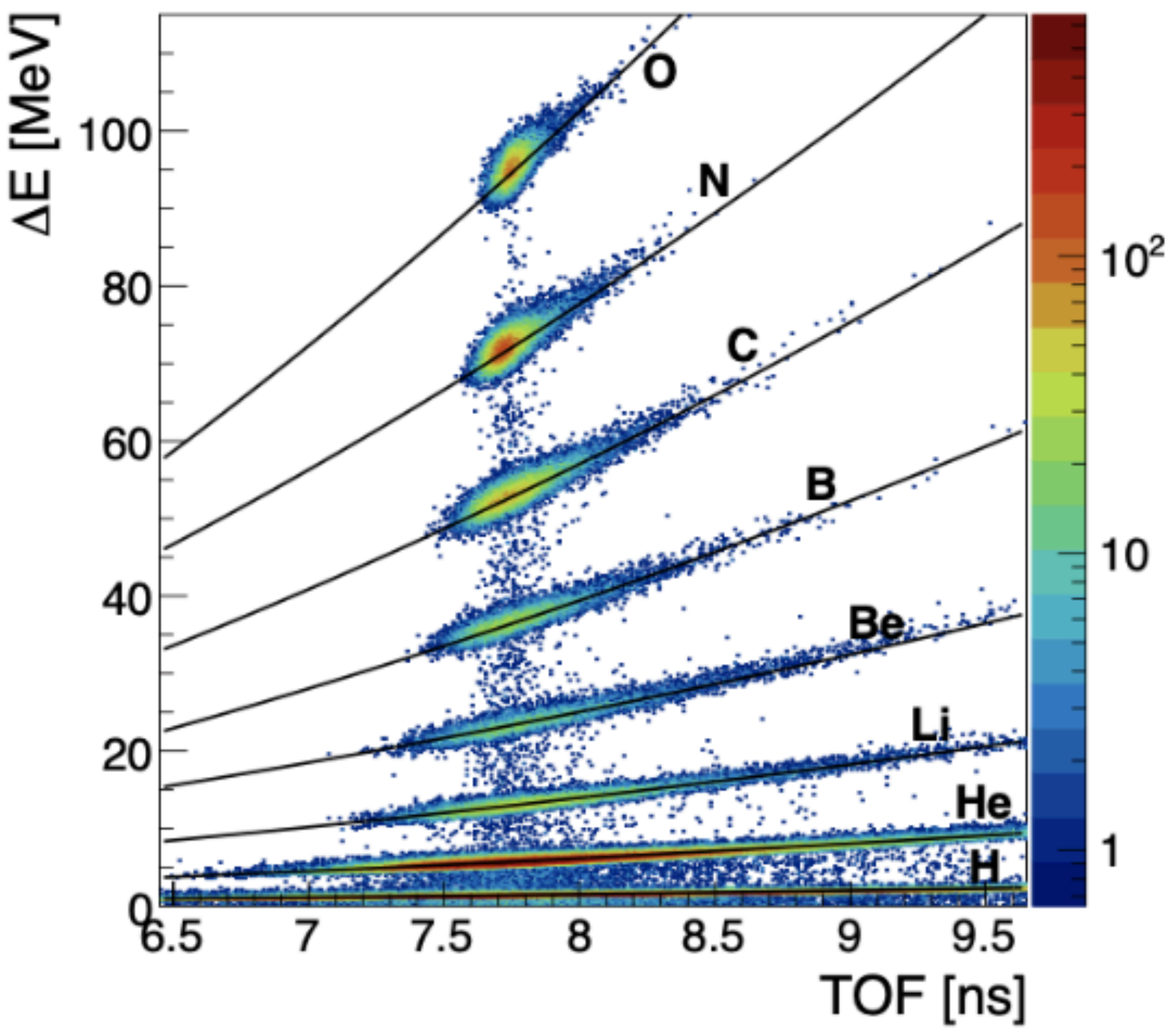
Both detector projected to minimize the out of target fragmentation probability

Tof-Wall detector: charge ID of the fragments



TW provides:

1. Deposited energy ΔE
2. Time of flight **TOF** (using the t_0 provides by ST)
3. Hit **positions**



- The **Tof-Wall** detector (TW) is composed of **two layers of 20 scintillator bars** (0.3 cm thick, 2 cm wide, 44 cm long) arranged orthogonally with a $40\ x\ 40\ cm^2$ active area
- Each of two edges of the TW bars is coupled to **4 SiPM** with a $3\ x\ 3\ cm^2$ active area and 25 μm microcell pitch.

Fragment charge Z identification performed using a Bethe-Bloch parametrization as a function of TOF for each Z

Cross section measurement strategy

^{16}O beam @ 400 MeV/nucleon on a 5 mm Carbon TG

$$\sigma(Z) = \int_{E_{min}}^{E_{max}} \int_0^{\Delta\theta} \left(\frac{\partial^2 \sigma}{\partial\theta \partial E_{kin}}\right) d\theta dE_{kin} = \frac{N_{frag}(Z)}{N_{prim} \cdot N_{TG} \cdot \epsilon(Z)}$$

$$N_{TG} = \frac{\rho \cdot dx \cdot N_A}{A}$$

$$\begin{cases} \rho = 1.83\ g/cm^3 \\ dx = 0.5\ cm \\ A = 12.0107 \end{cases}$$

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1. **Align FOOT detector** at GSI and select angular acceptance for cross section integration;
2. Compute **MC efficiencies** for each fragment;
3. Estimate **fragmentation out of target** for background subtraction;
4. Extract the **fragments yields** from Z identification TW algorithms;
5. **Systematics** study.

Very low statistics and no detectors for mass identification → cross section integrated in angular and kinetic energy interval is feasible

MC studies: efficiencies and background rejection

Developed a detailed FLUKA simulation with the geometry of the set-up used at GSI 2019 data taking

$$\epsilon(Z) = \frac{N(Z)_{TW}}{N(Z)_{prod}}$$

Numerator: asking for a reconstructed and Z identified fragment with TW matched to primary fragments with origin in target with production angle < 5.7° and E_{kin} production in the range [100, 800] MeV/u

Denominator: asking for primary fragments produced in target with an angle < 5.7° and E_{kin} production in the range [100, 800] MeV/u

Element	Efficiency(%)
He	91.92 ± 0.05
Li	85.38 ± 0.20
Be	88.32 ± 0.26
B	88.75 ± 0.24
C	91.13 ± 0.15
N	95.88 ± 0.09

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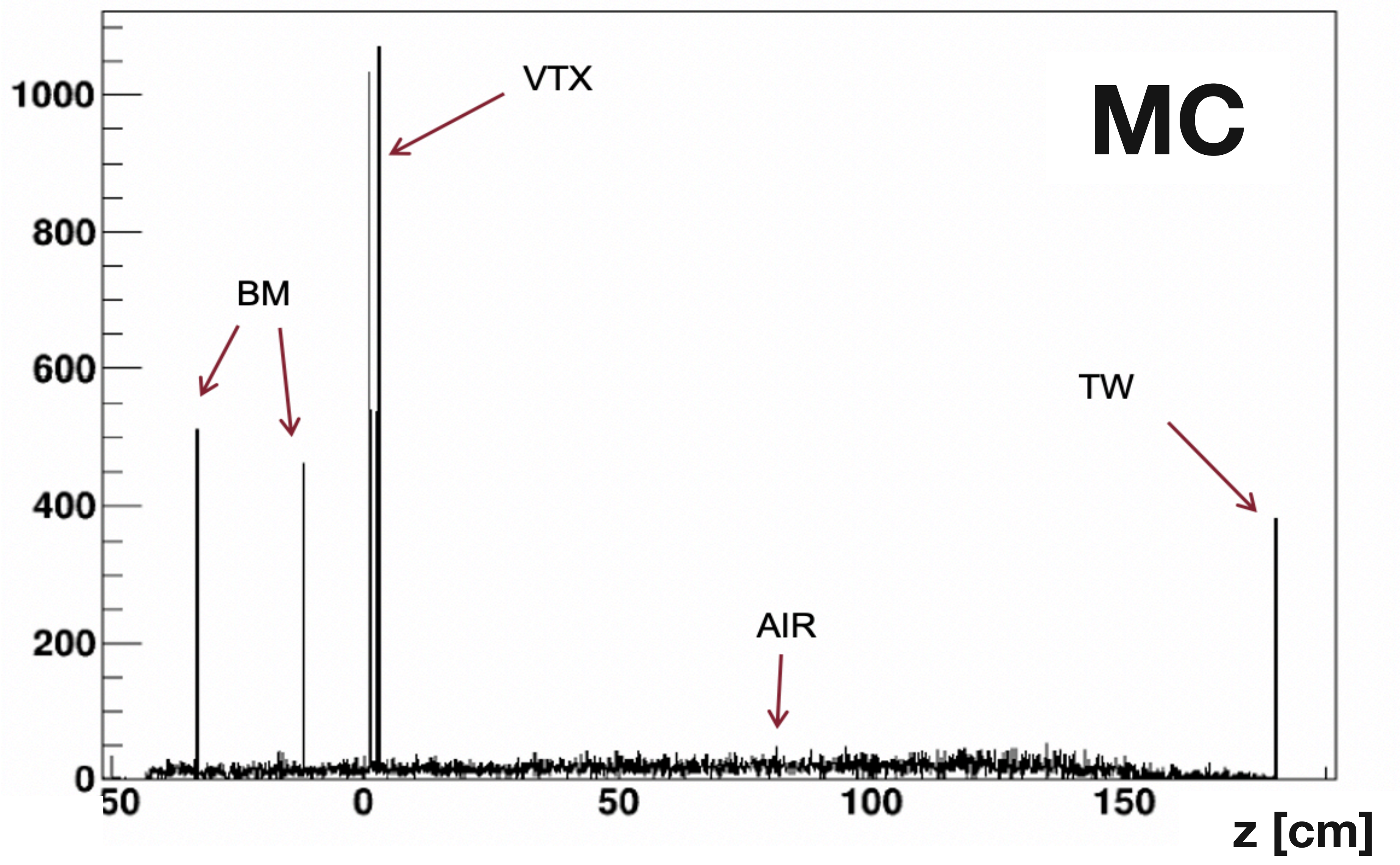
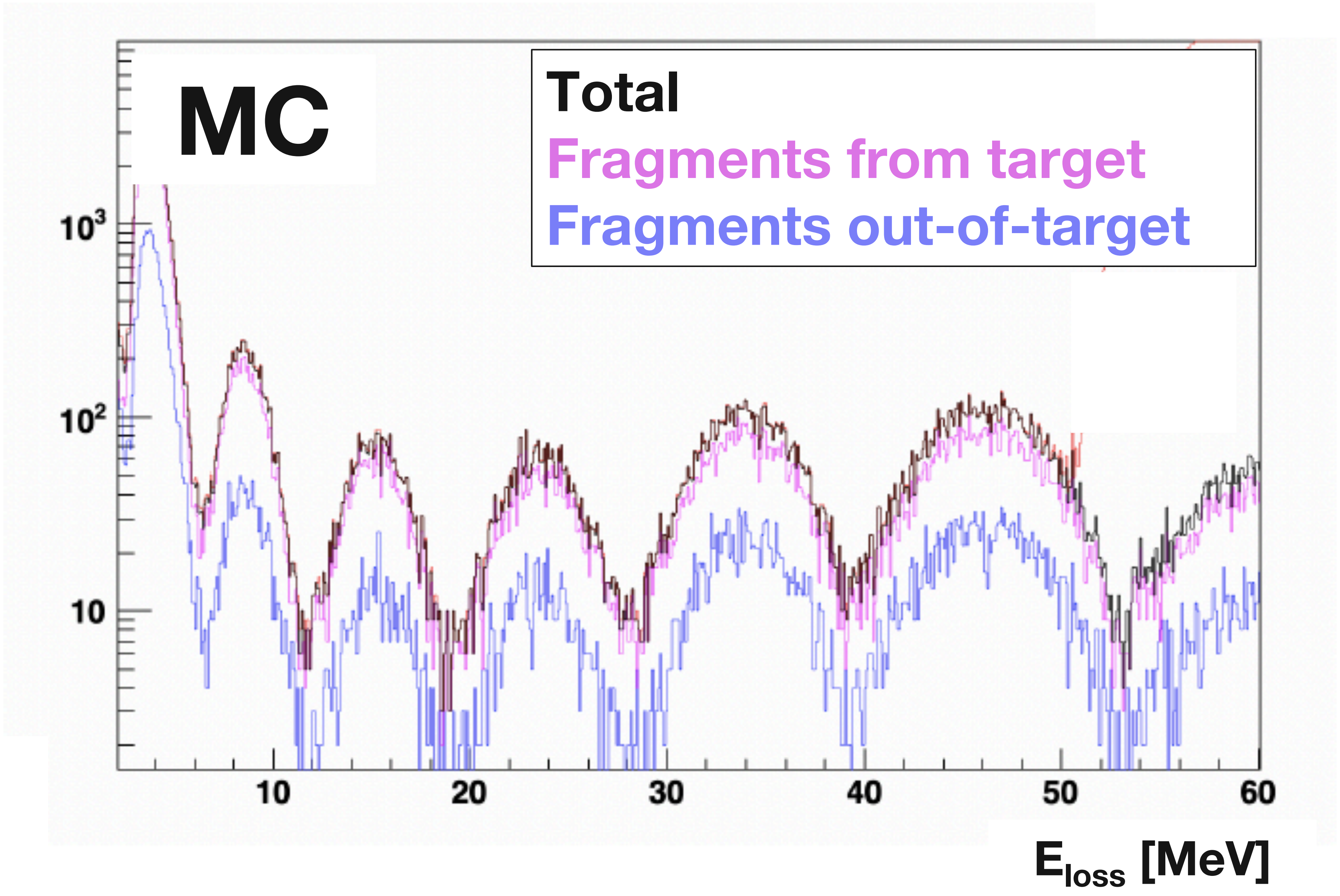
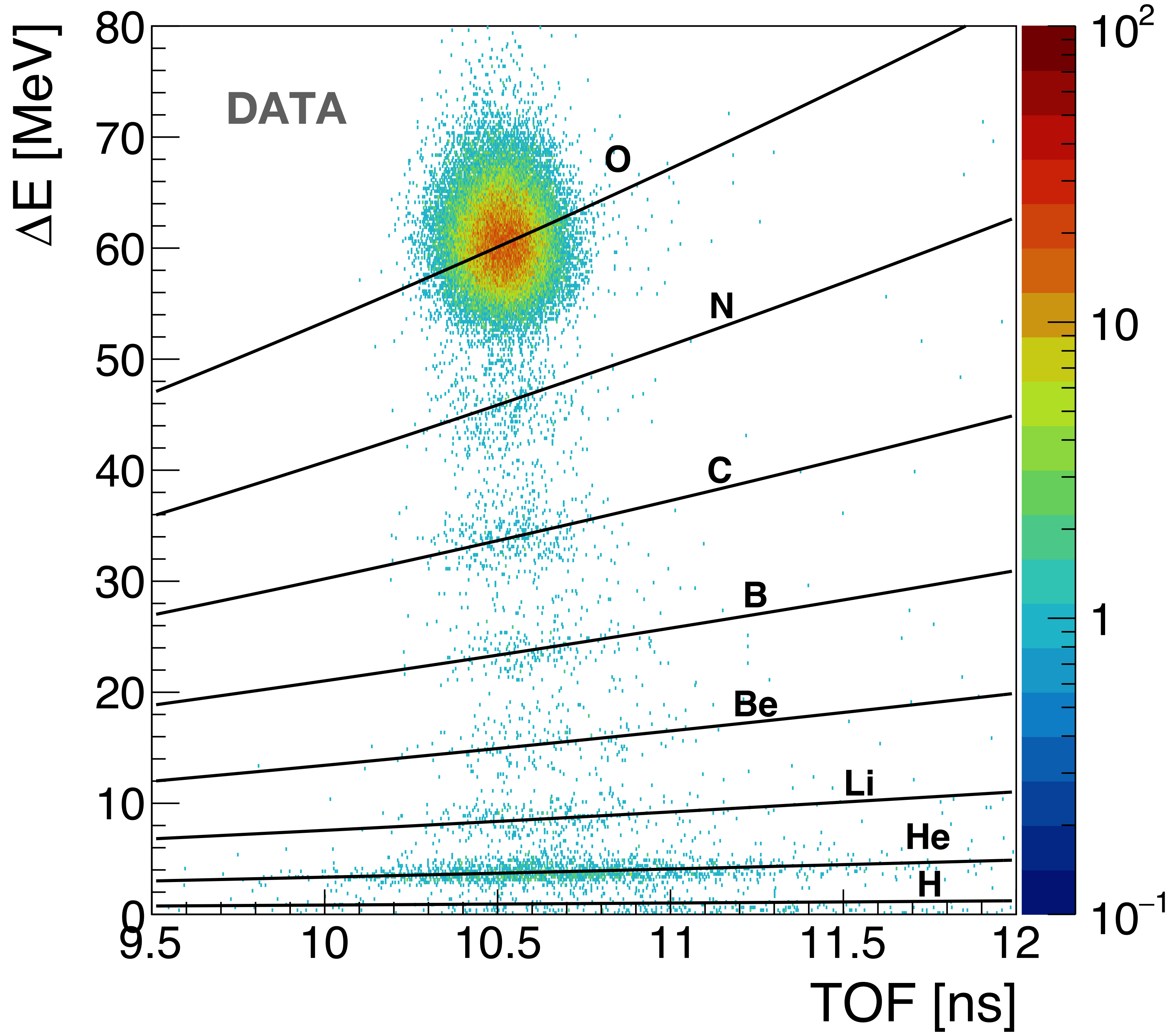
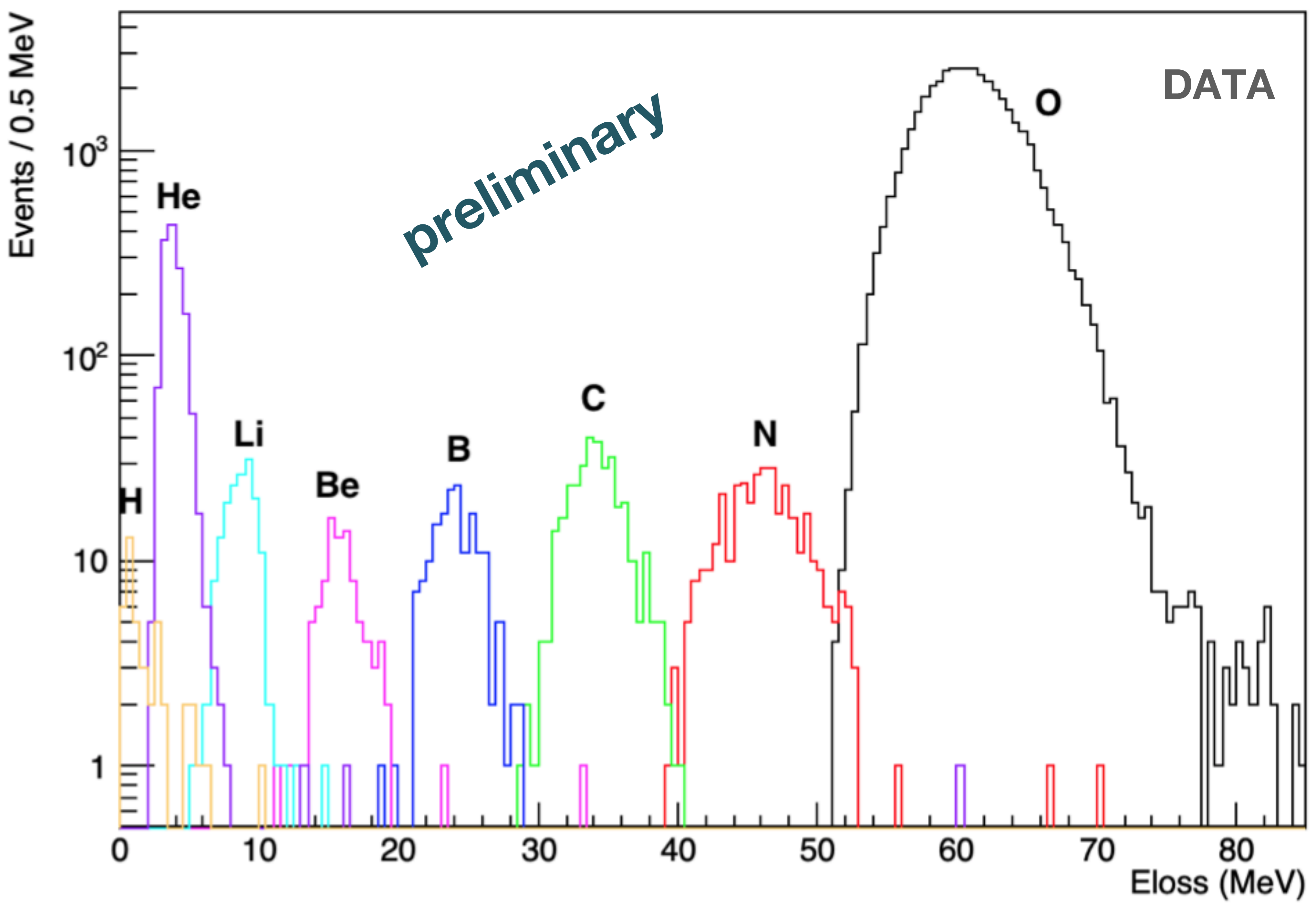




Out of target primary fragmentation is a not negligible background to be subtracted (~30% of the signal from MC studies). Most of it coming from air

Data: fragment yields and background subtraction





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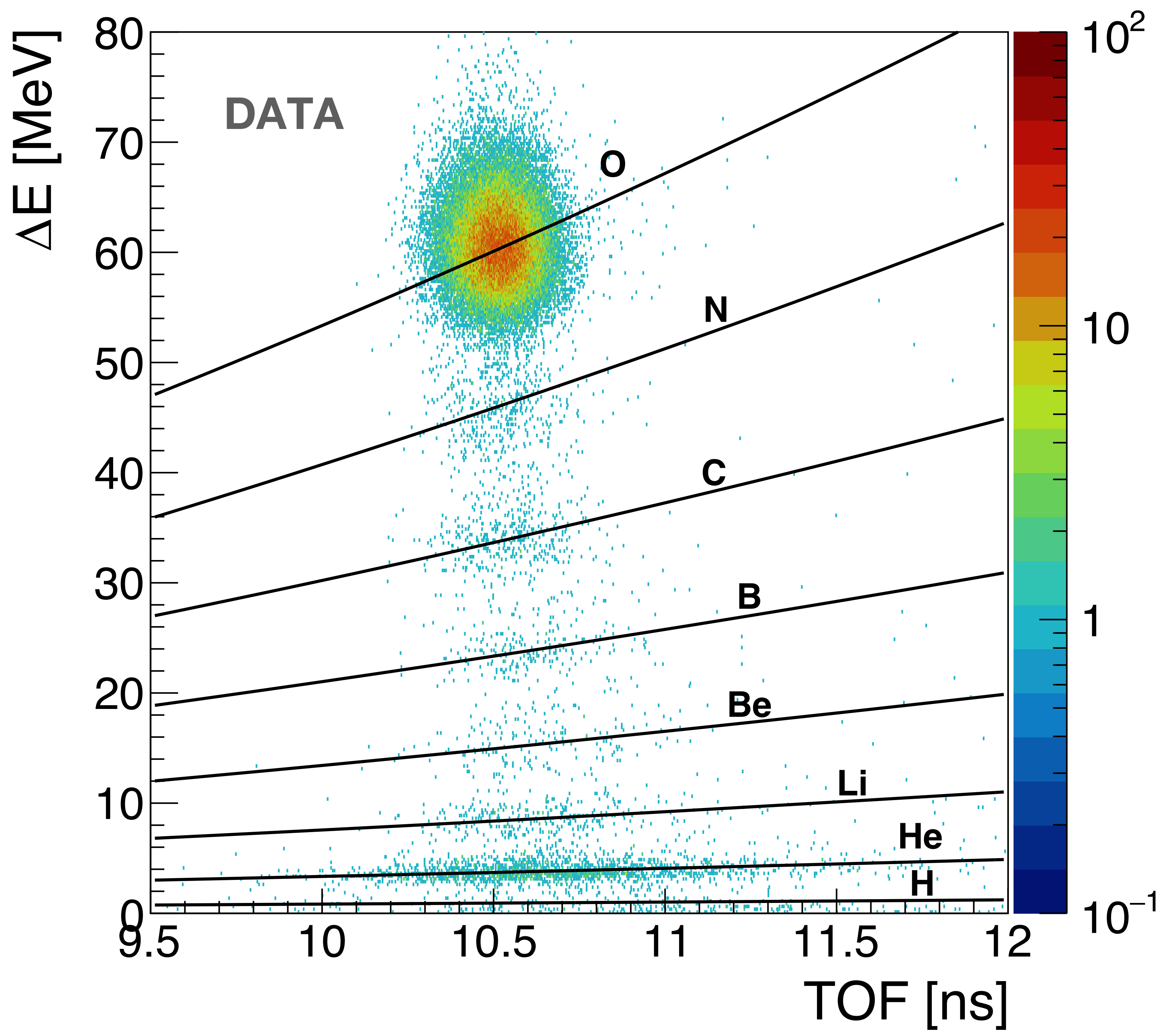

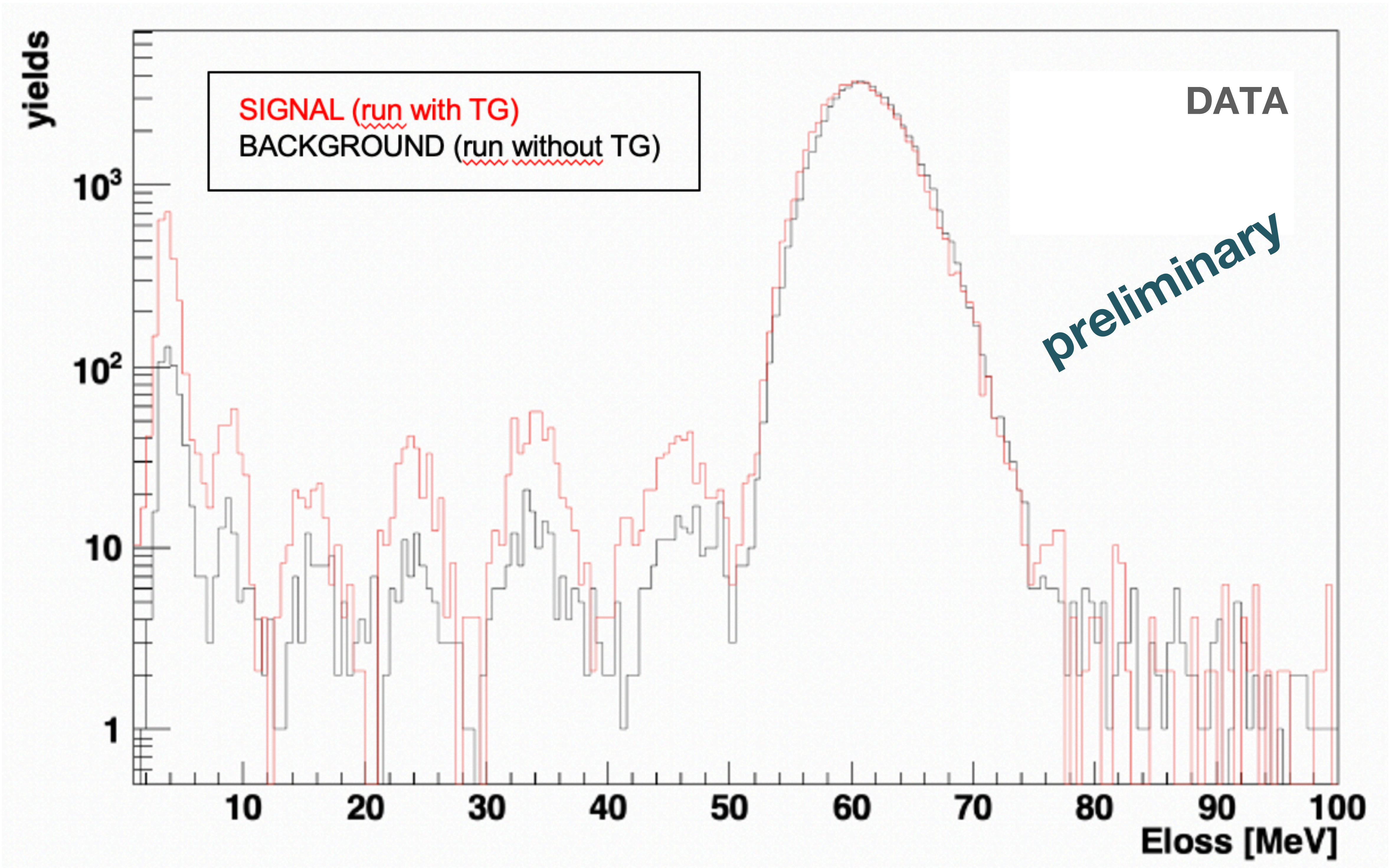

$$\sigma(Z) = \frac{1}{N_{TG} \cdot \epsilon(Z)} \left[\frac{N_{TG}(Z)}{N_{TG}^{prim}} - \frac{N_{noTG}(Z)}{N_{noTG}^{prim}} \right]$$

$$N_{TG} = \frac{\rho \cdot dx \cdot N_A}{A}$$

$\rho = 1.83\ g/cm^3$
dx = 0.5 cm
A = 12.0107

Element	$Yields_{bkg}$	$Yields_{signal}$
N_{prim}	31660	61516
He	484 ± 22	1087 ± 33
Li	89 ± 9	152 ± 12
Be	73 ± 9	77 ± 9
B	88 ± 9	136 ± 12
C	156 ± 13	231 ± 16
N	207 ± 14	248 ± 16

The **count of the primary ions** of the beam interacting with the target is provided by the **Start Counter**

Data: fragment yields and background subtraction

Results for the charge-changing cross section for the interaction of a beam of ^{16}O at 400 MeV/u on a 0.5 cm C target:

Element	$\sigma_{frag} \pm \Delta_{stat} \pm \Delta_{sys}[mbarn]$	$\Delta_{stat}/\sigma_{frag}$	$\Delta_{sys}/\sigma_{frag}$	$\sigma_{MC}[mbarn]$
He	$625 \pm 22 \pm 21$	3.6%	3.6%	621
Li	$85 \pm 10 \pm 5$	11.9%	5.6%	67
Be	$31 \pm 10 \pm 3$	31.8%	8.8%	33
B	$70 \pm 10 \pm 5$	14.9%	7.3%	38
C	$113 \pm 12 \pm 3$	10.9%	2.7%	81
N	$101 \pm 14 \pm 5$	13.7%	4.8%	105

As expected the statistical error is dominant wrt the systematic uncertainty and it is around 10%

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Systematic uncertanties estimated from:

1. Different **selection criteria of the projection** of the beam direction **on TG**;
2. Quality of the **BM reconstructed tracks**;
3. Charge **reconstruction algorithm** in the TW fragments' identification

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Nice agreement between the measured cross section and the ones reconstructed with the same algorithms in the MC simulation developed in FLUKA

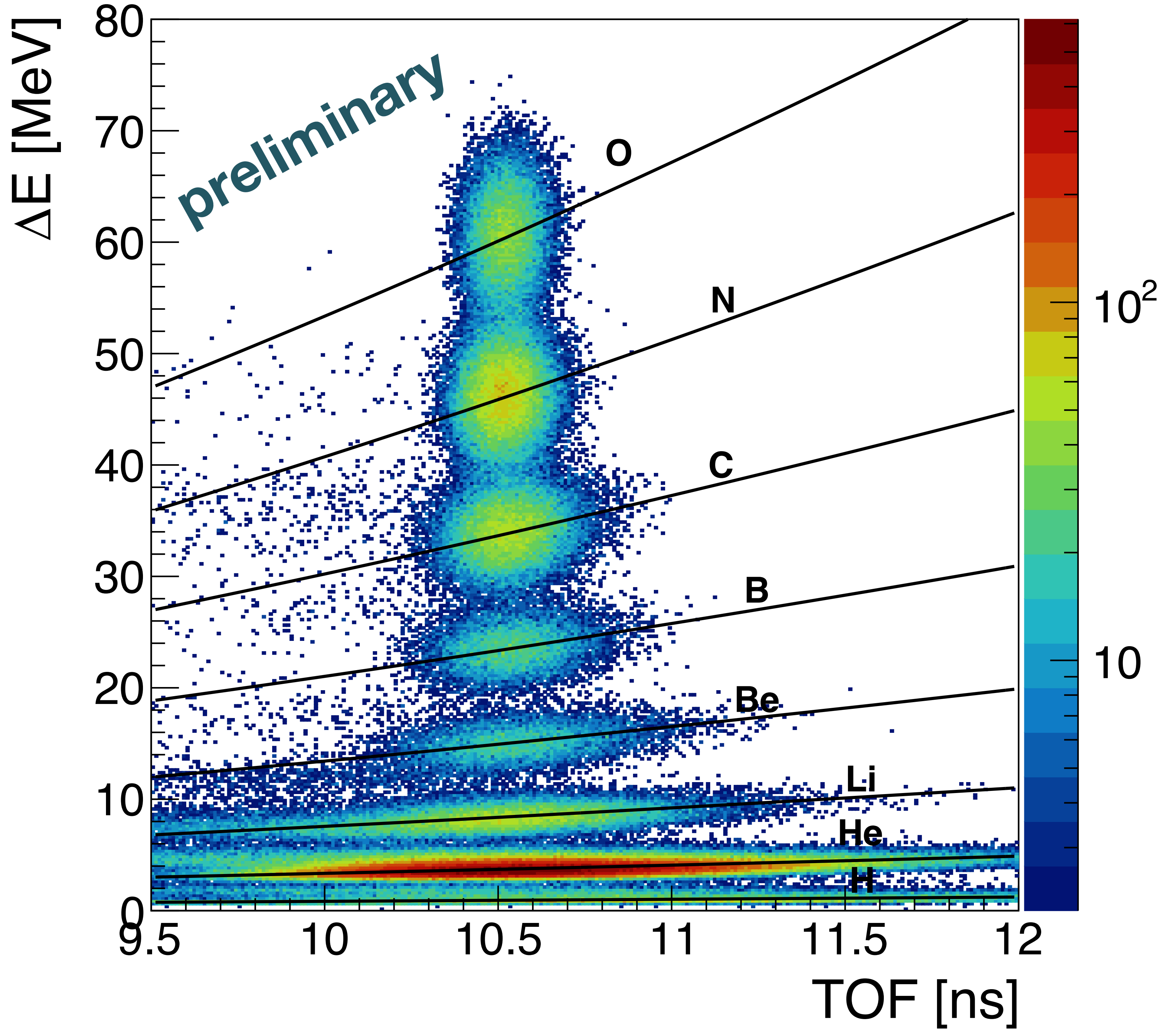
Conclusions

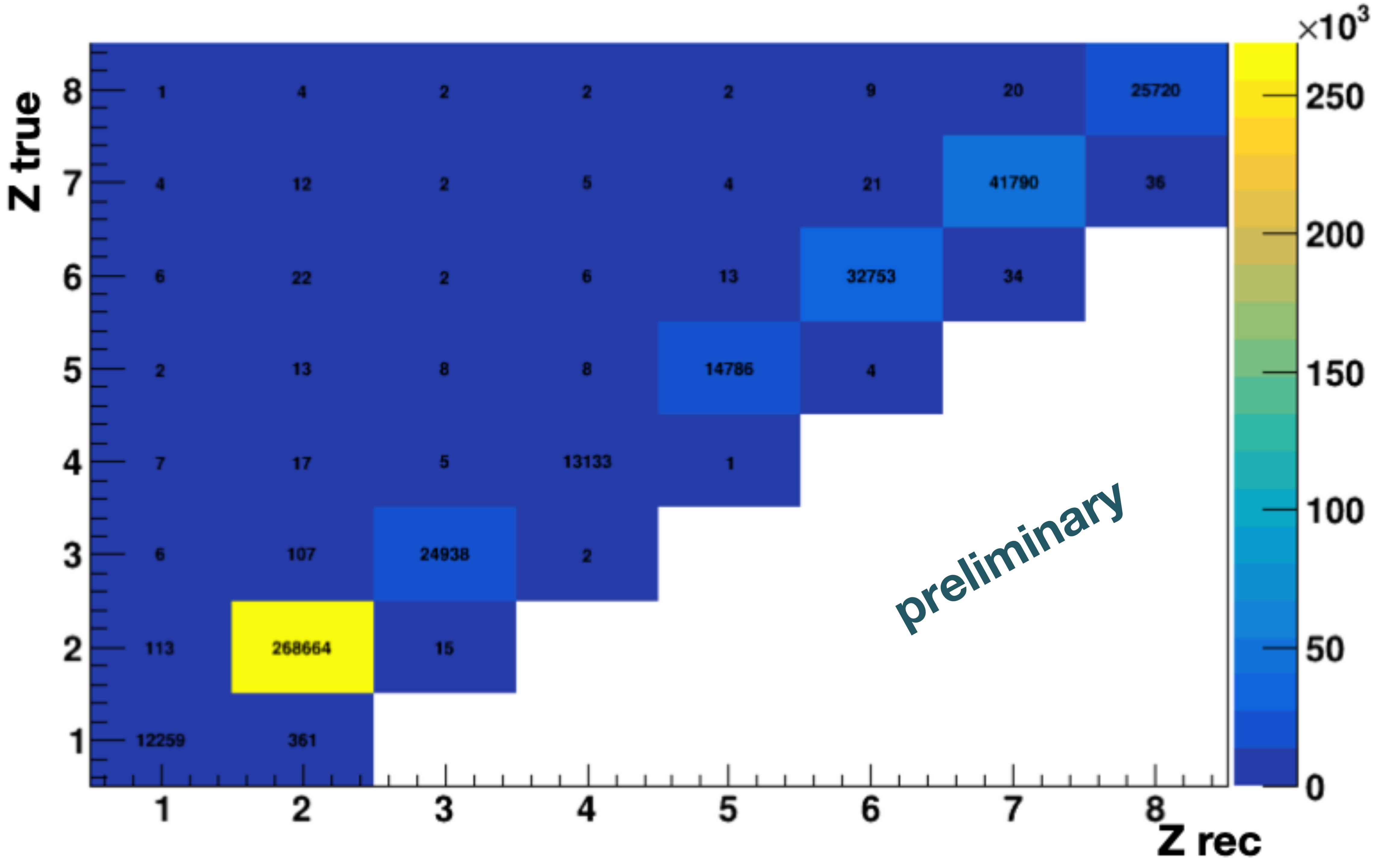
- The **FOOT experiment** is designed for the measurement of **the fragmentation differential cross sections** of interest in Particle Therapy and radio protection in space with an accuracy better than 10%
- The **final set up** is almost completed (Inner Tracker (IT) + Magnet + Calo still in development)
- **First preliminary cross section measu rement** of a ^{16}O beam at 400 MeV/u with a partial setup, integrated in the detector acceptance
- A data taking performed in july 2021 in GSI provided 40 M events for ^{16}O beam at 200 and 400 MeV/u impinging on C and C_2H_4
- A new data taking will be performed at CNAO (Centro Nazionale di Adroterapia Oncologica) in November 2021 witha beam of ^{12}C at 200 and 400 MeV/u impinging on targets of C and C_2H_4

Spare Slides

Charge identification and mixing

It is possible to **correlate** in a charge mixing matrix the **reconstructed charge to the real one** (for MC truth), thanks to which it is possible to observe when the charge identification algorithm assigns a fragment to a wrong Z.





Available statistics and event selection

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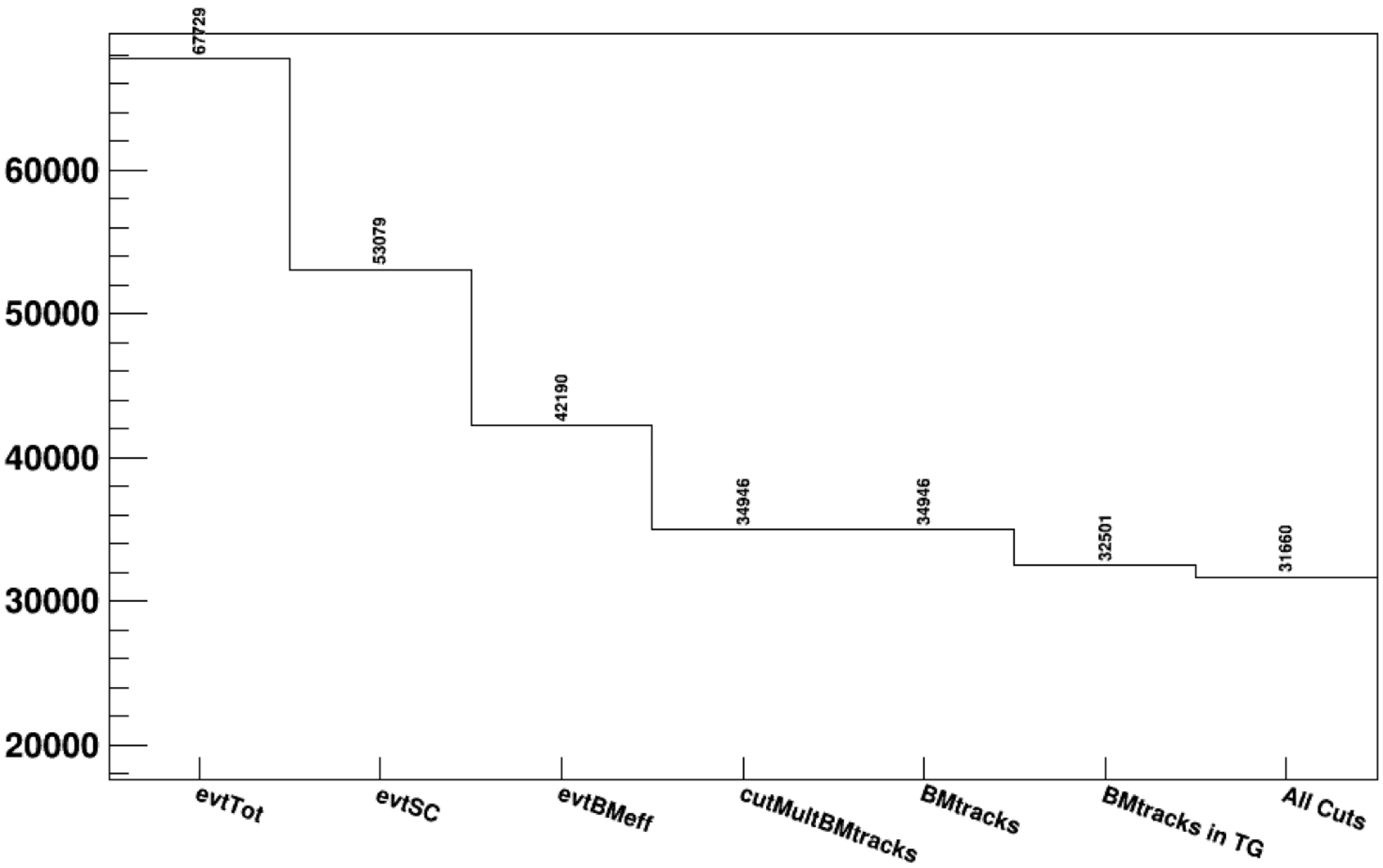
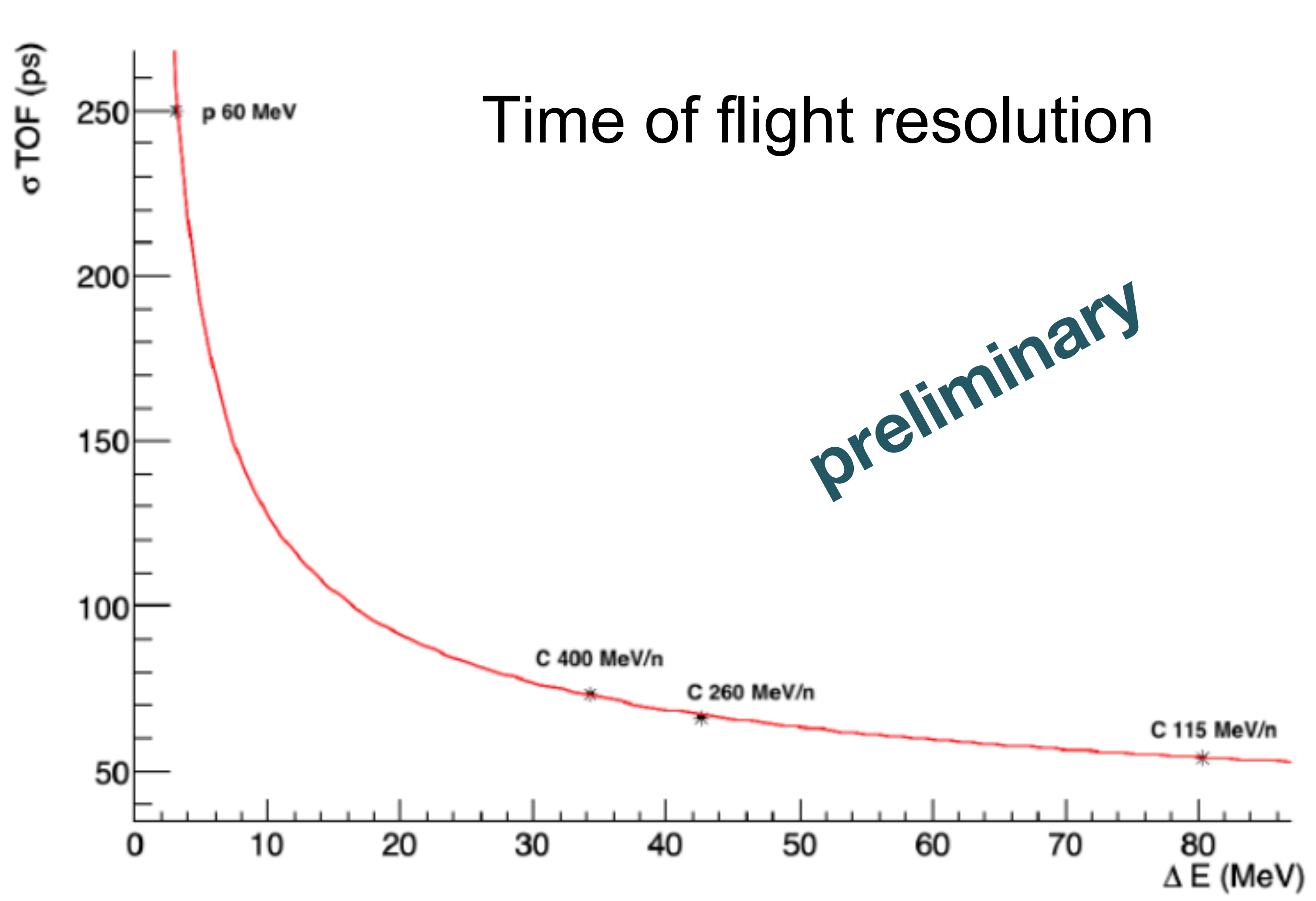
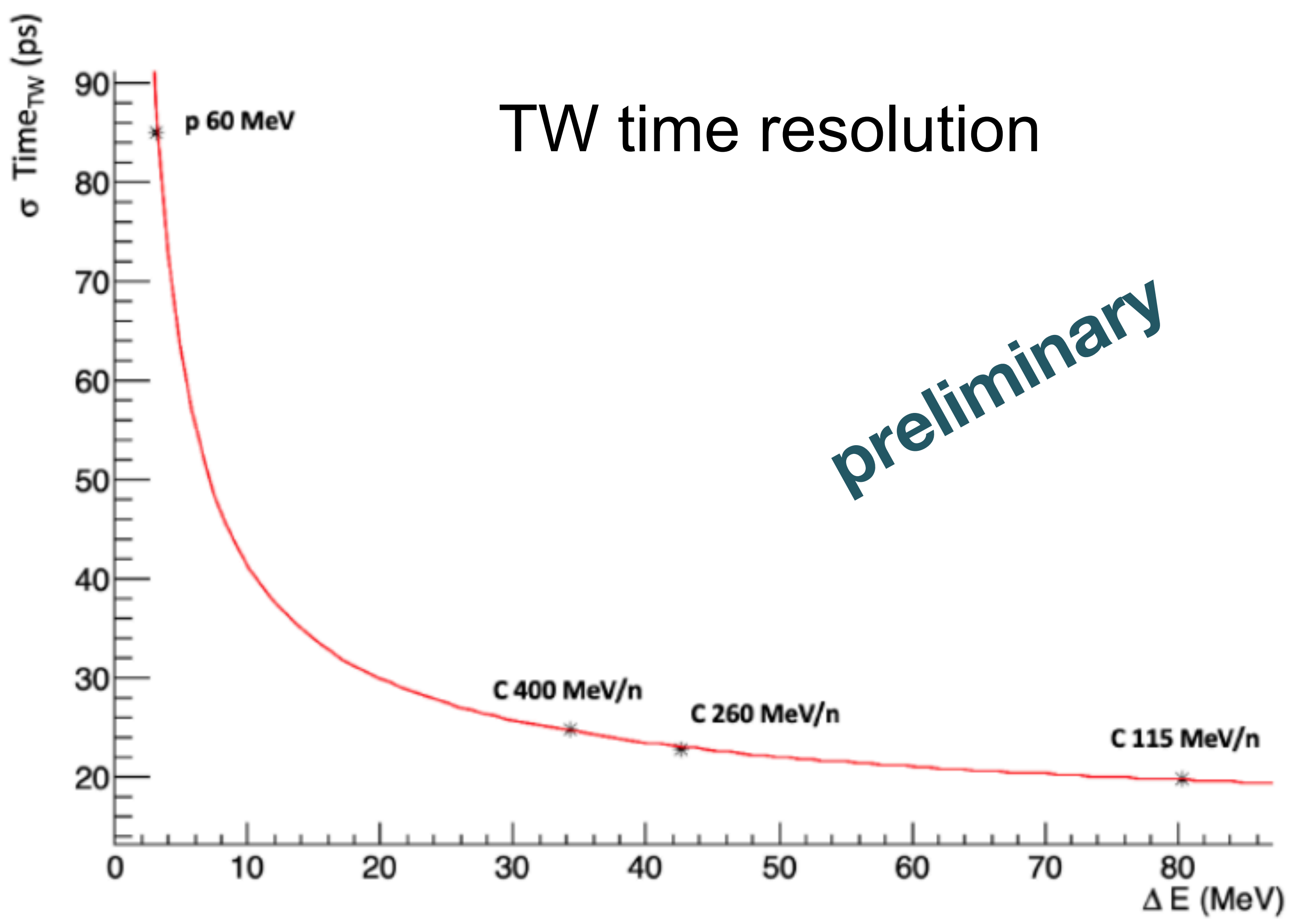
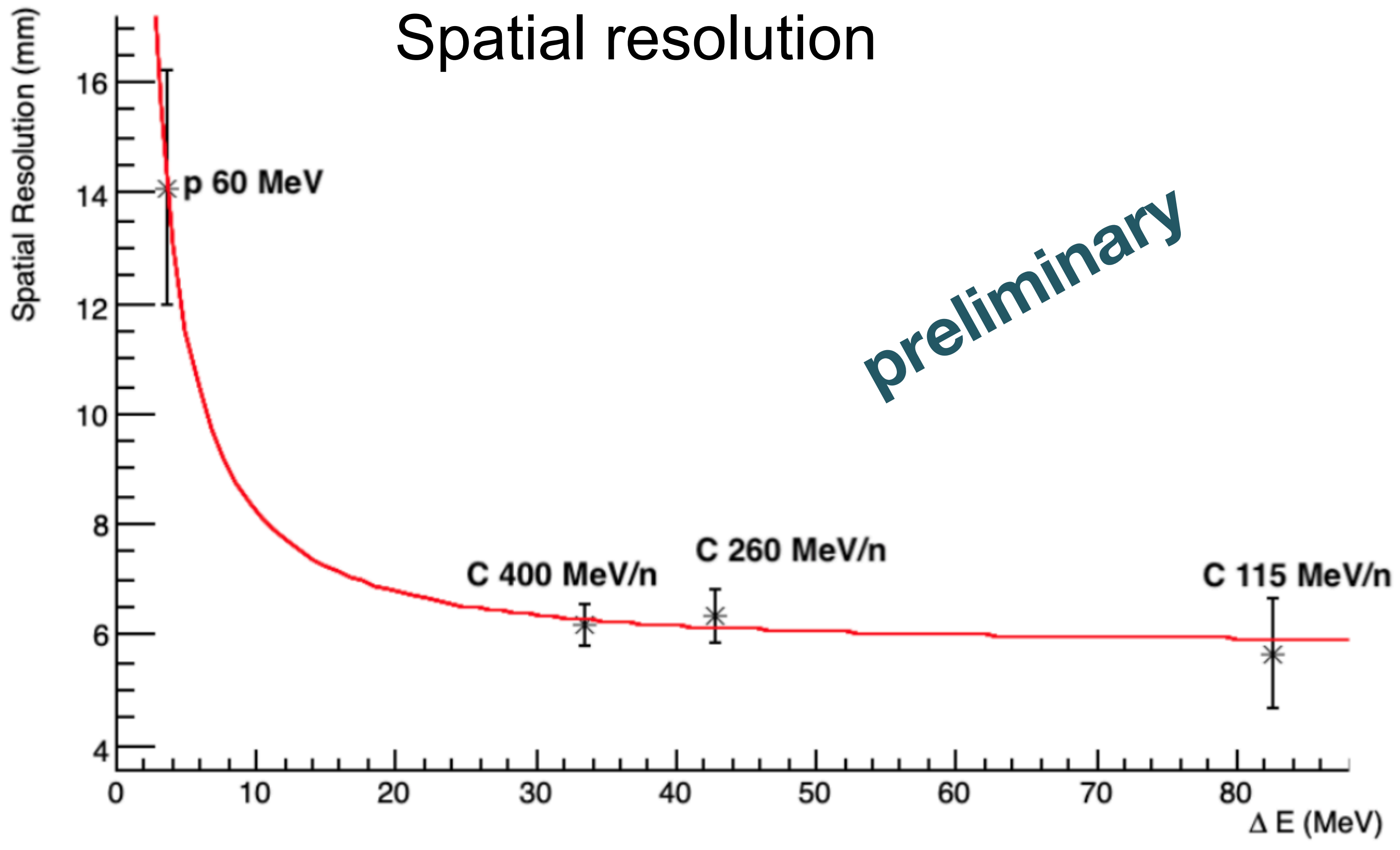


Resolution TOF and Eloss





(b)



Energy resolution flat ∽ 5%

MC studies: efficiencies and background rejection

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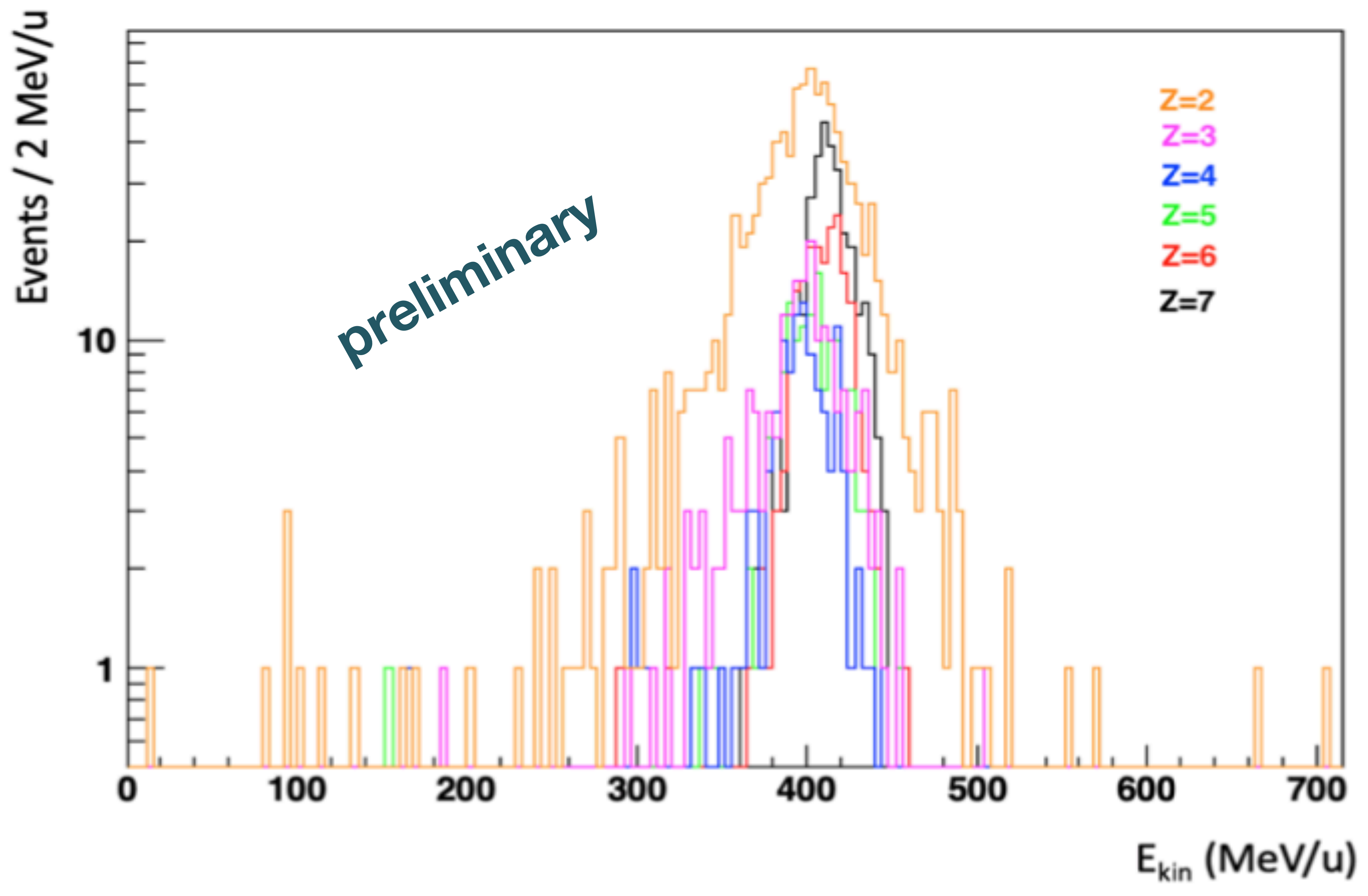

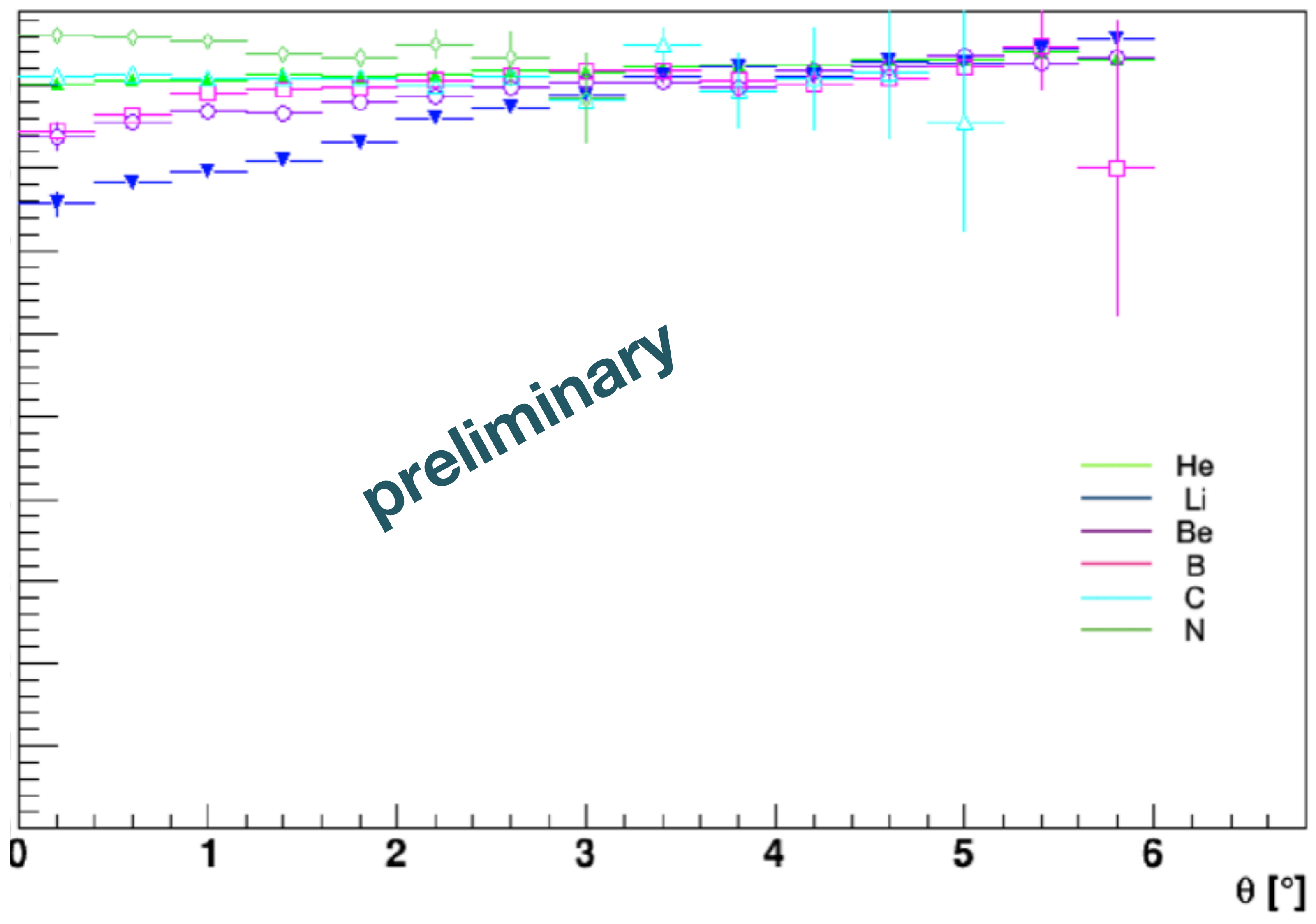

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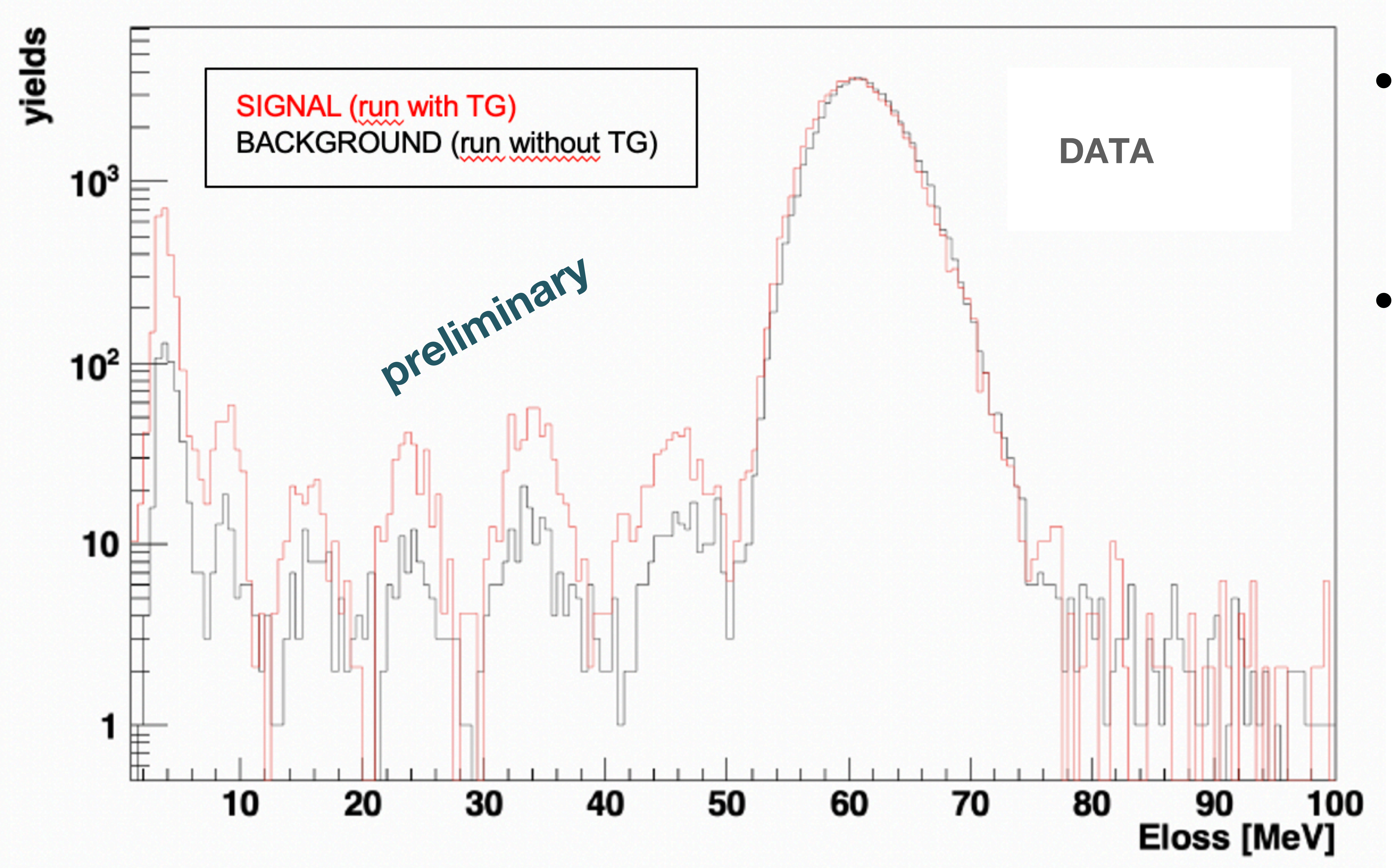
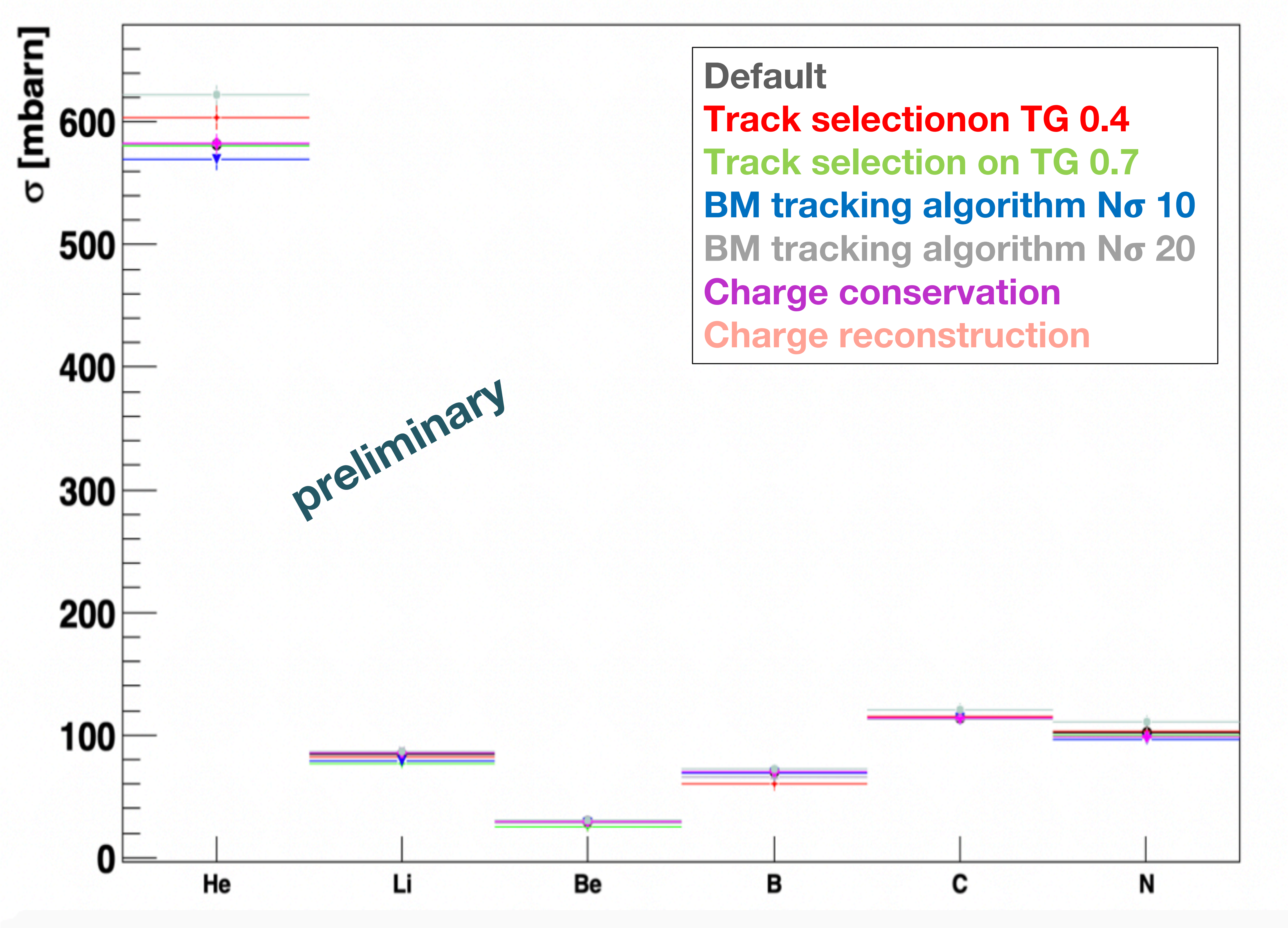
Data: background subtraction

- The fragments yields extracted by the TW detector mix **primary fragmentation produced in the TG** (signal) and **primary fragmentation out of target** (background)



- The **count of primary ions** of the beam interacting with the target is provided by the **Start Counter (minimum bias trigger)**
- Requiring events with single tracks in BM with projection on the target within [-1,1] cm and $\theta < 5.7°$ for all the emitted fragments we got the **total number of primaries selected** for the cross section measurement.

Systematic uncertainties



1. Different **selection criteria of the projection** of the beam direction **on TG**;
2. Quality of the **BM reconstructed tracks**;
3. Charge **reconstruction algorithm** in the fragments' identification