10TH BEAM TELESCOPES & TEST BEAMS WORKSHOP

Future perspective of the FOOT experiment for neutrons identification

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on behalf of the FOOT collaboration

Istituto Nazionale di Fisica Nucleare

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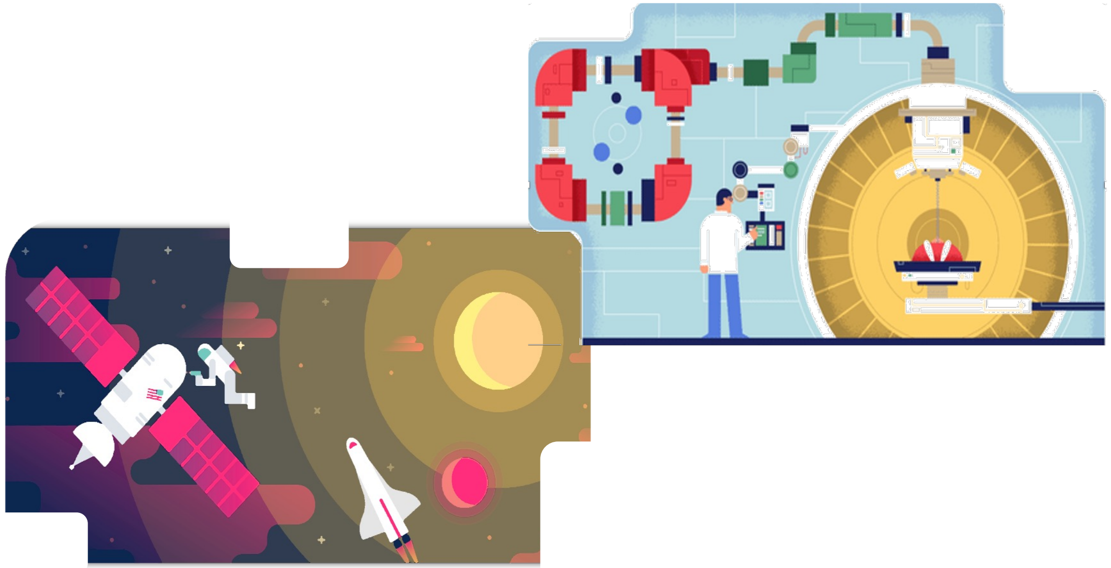
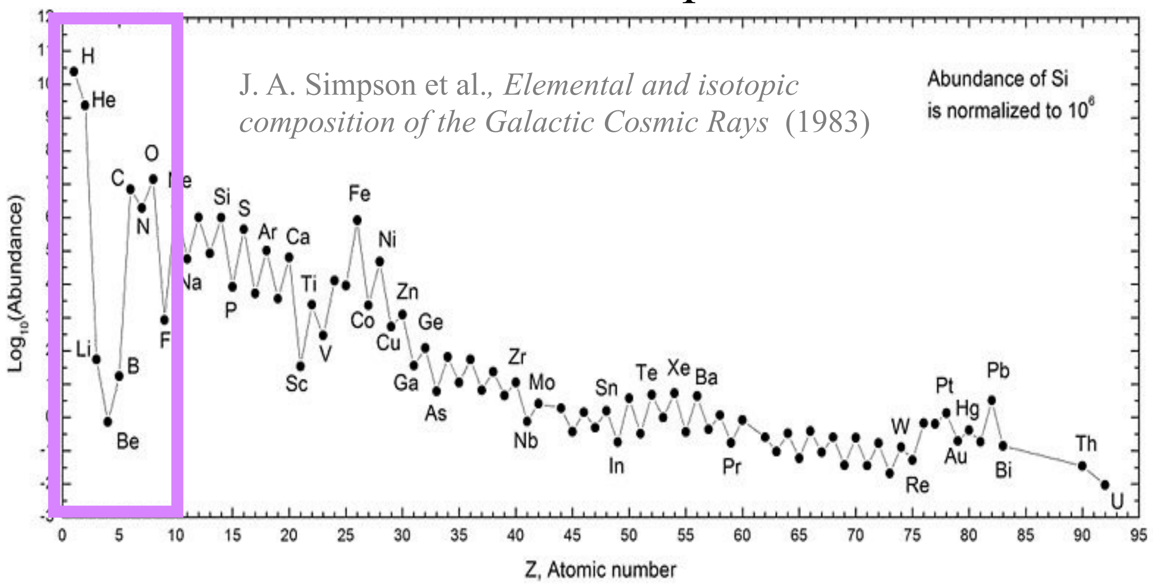
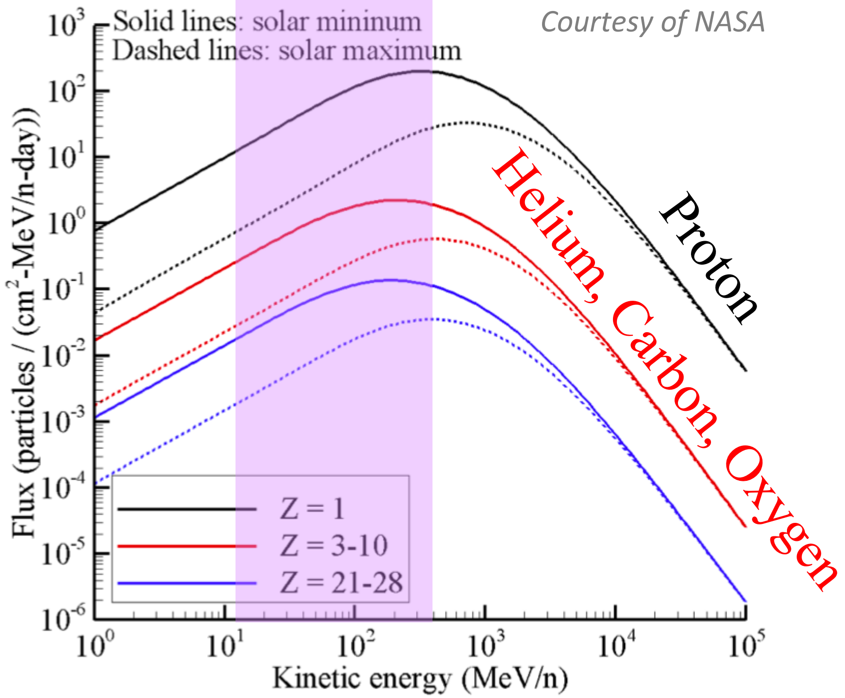
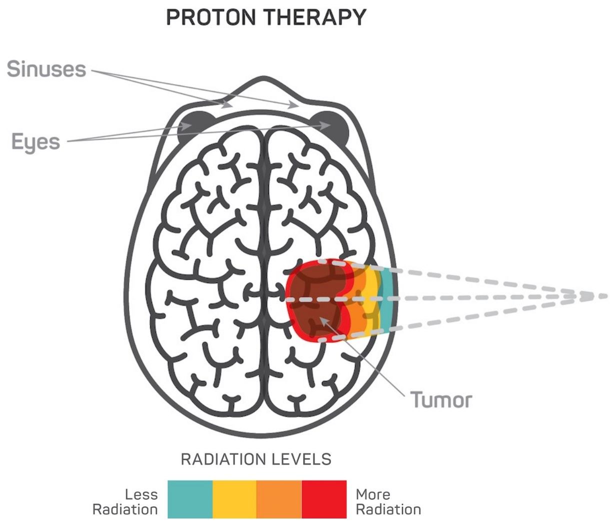


What do particle therapy and space radiation have in common?

Elemental abundance & annual space radiation fluence



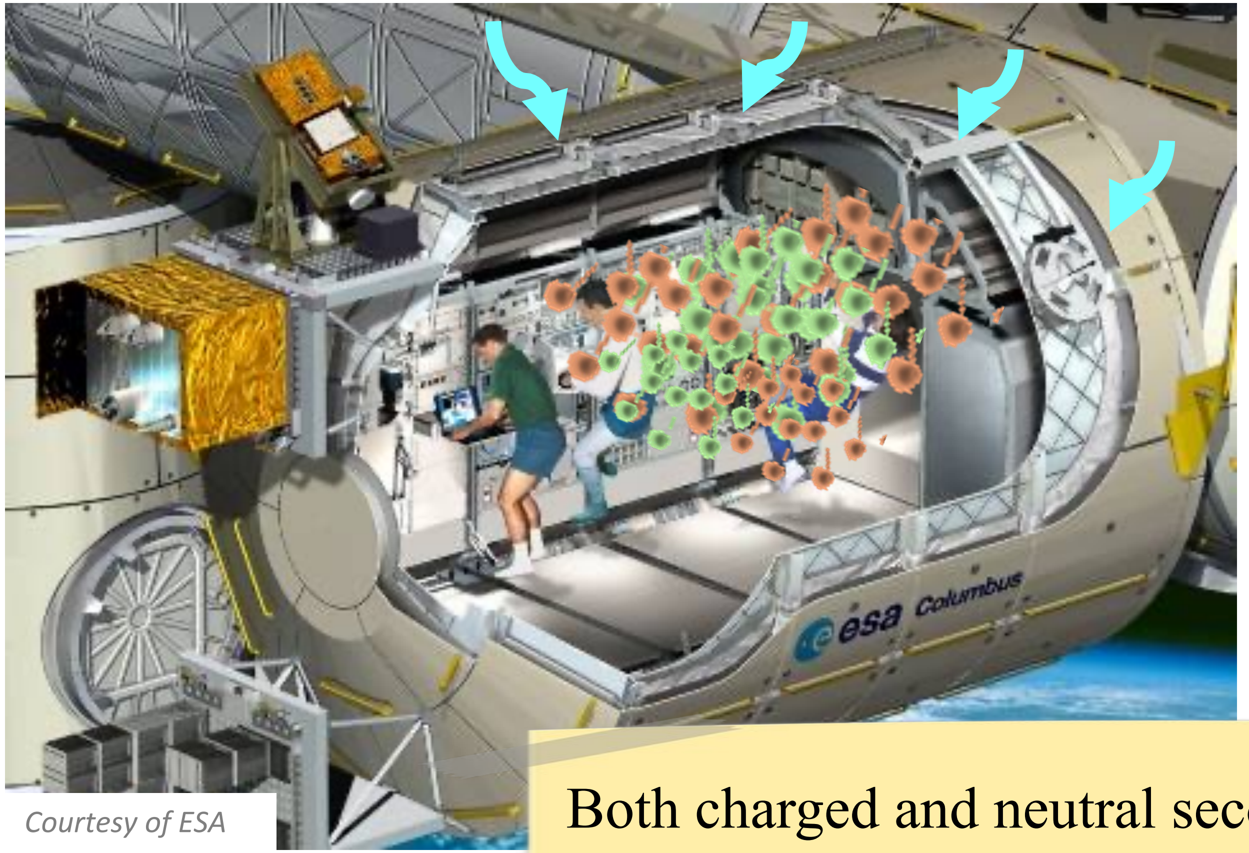




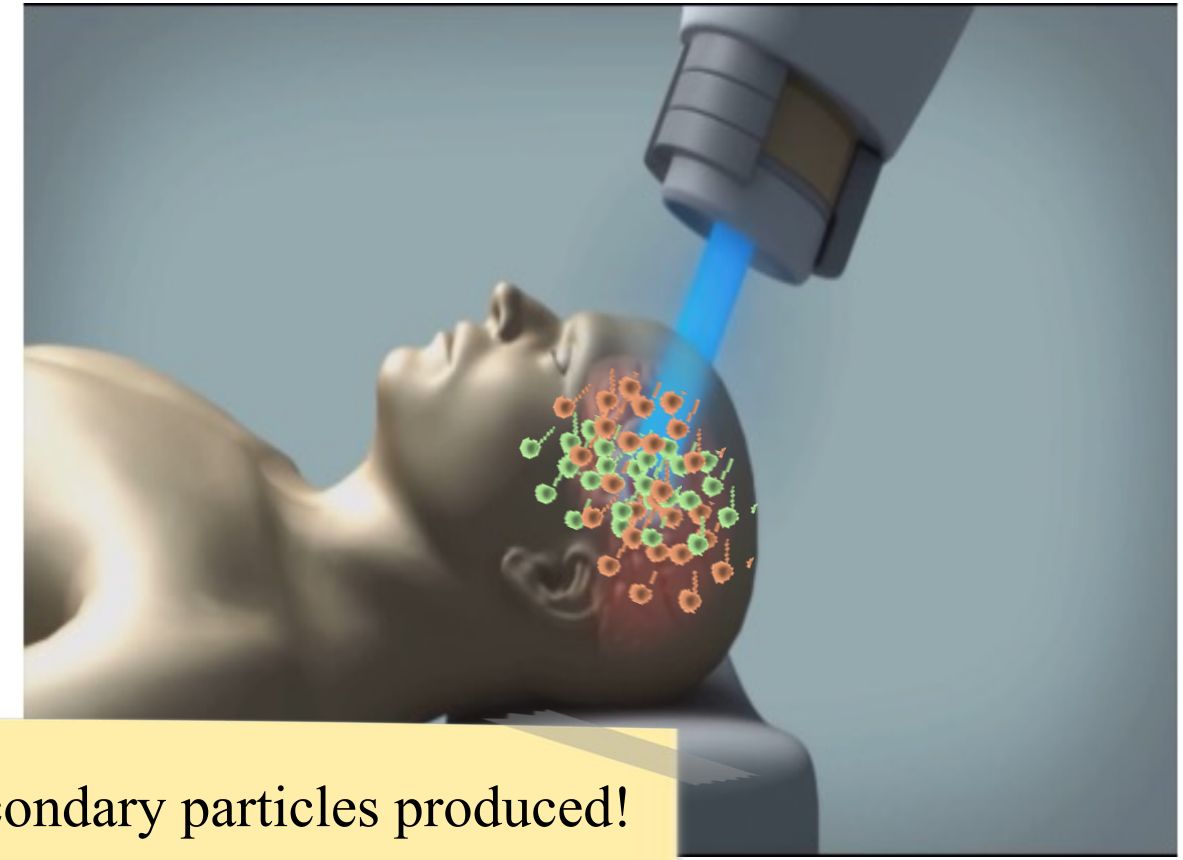
- Pool of particles currently used in particle therapy or considered promising alternative
- Particle therapy energy range: 60 – 400 MeV/u

What do particle therapy and space radiation have in common?

Same radiation-matter interactions can occur in



Courtesy of ESA

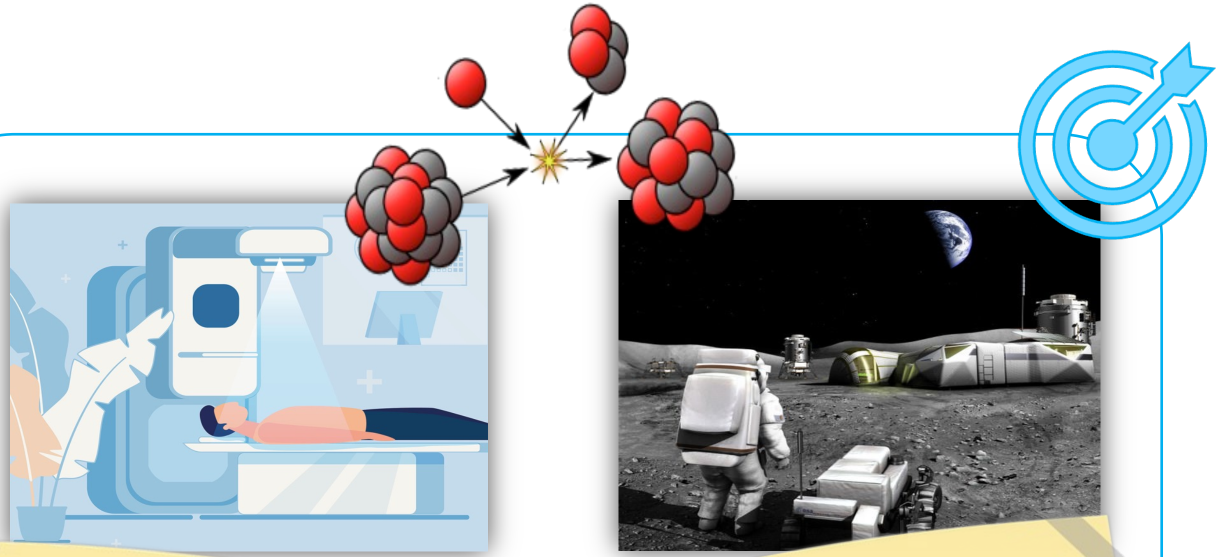


Both charged and neutral secondary particles produced!

They can influence the dose delivered by radiation and thus its biological effects

The FOOT (*F*ragmentati*O*n *O*f *T*arget) experiment

- Projectile and target fragments identification
- $\frac{d^2\sigma_{frag}}{d\Omega dE}$ with great accuracy



Accuracy of the TPS & data for the implementation of “new ions” in PT

Optimization of the spacecraft shielding

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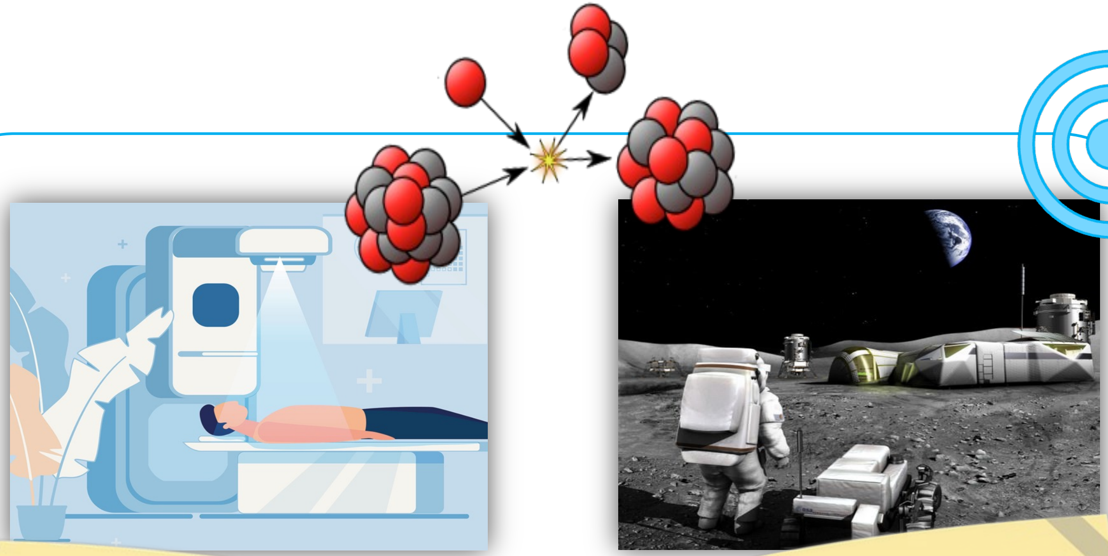
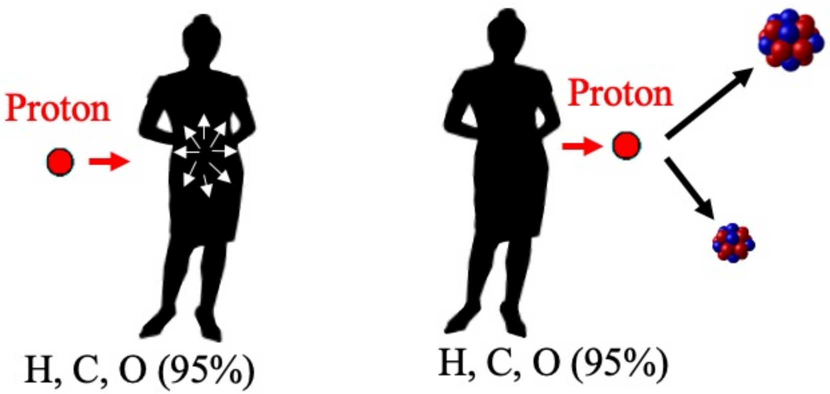
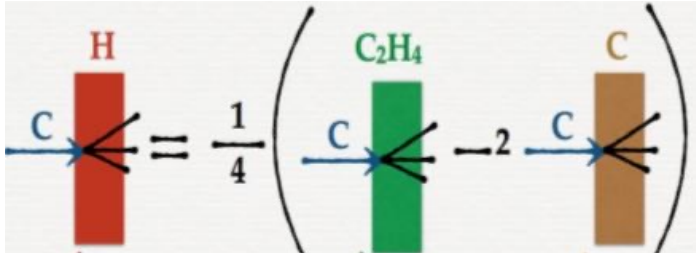


Accuracy of the TPS & data for the implementation of "new ions" in PT

Optimization of the spacecraft shielding

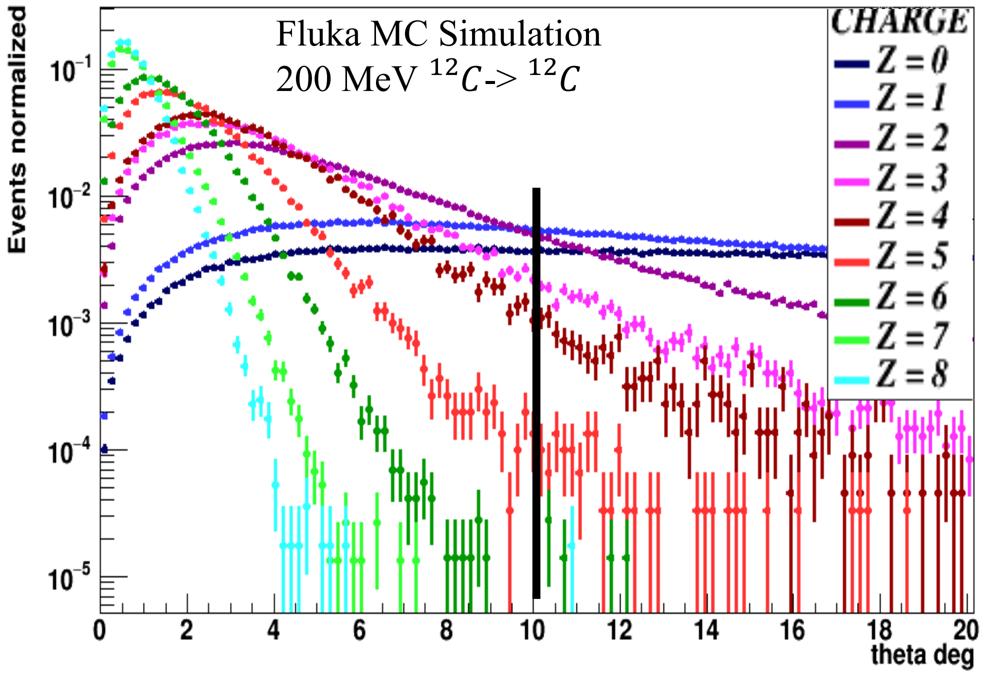
Direct kinematics **Inverse kinematics**





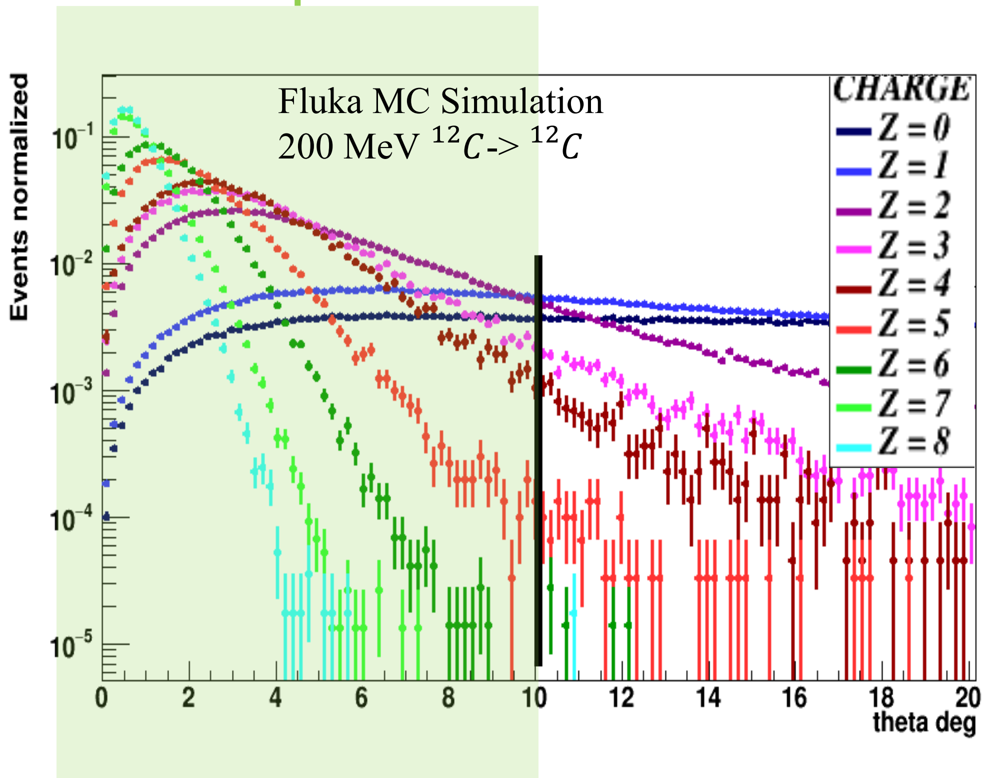
$$\frac{d\sigma}{dE_{kin}}(H) = \frac{1}{4}\left(\frac{d\sigma}{dE_{kin}}(C_2H_4) - 2\frac{d\sigma}{dE_{kin}}(C)\right)$$

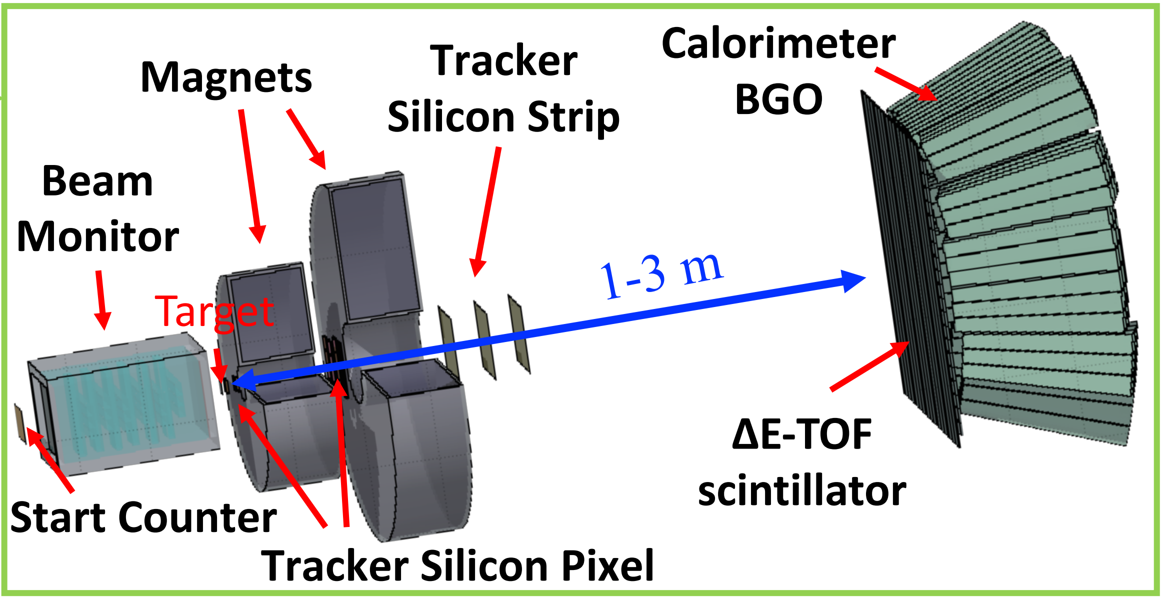
FOOT experimental setups



FOOT experimental setups

Electronic Setup: heavy fragments





FOOT experimental setups

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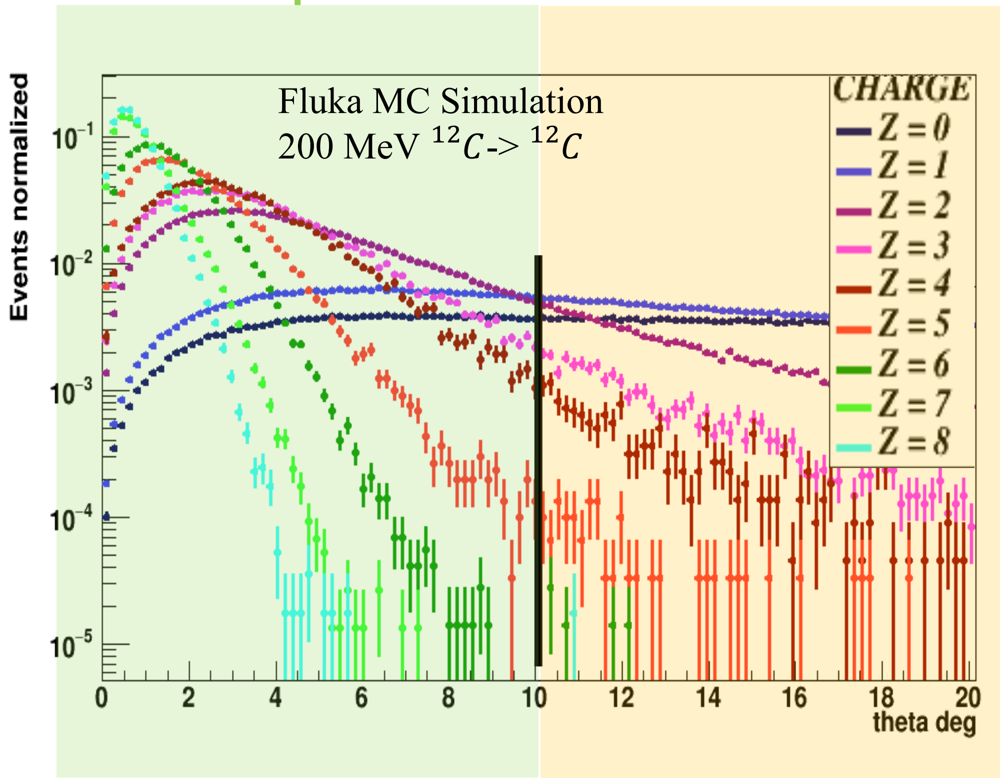
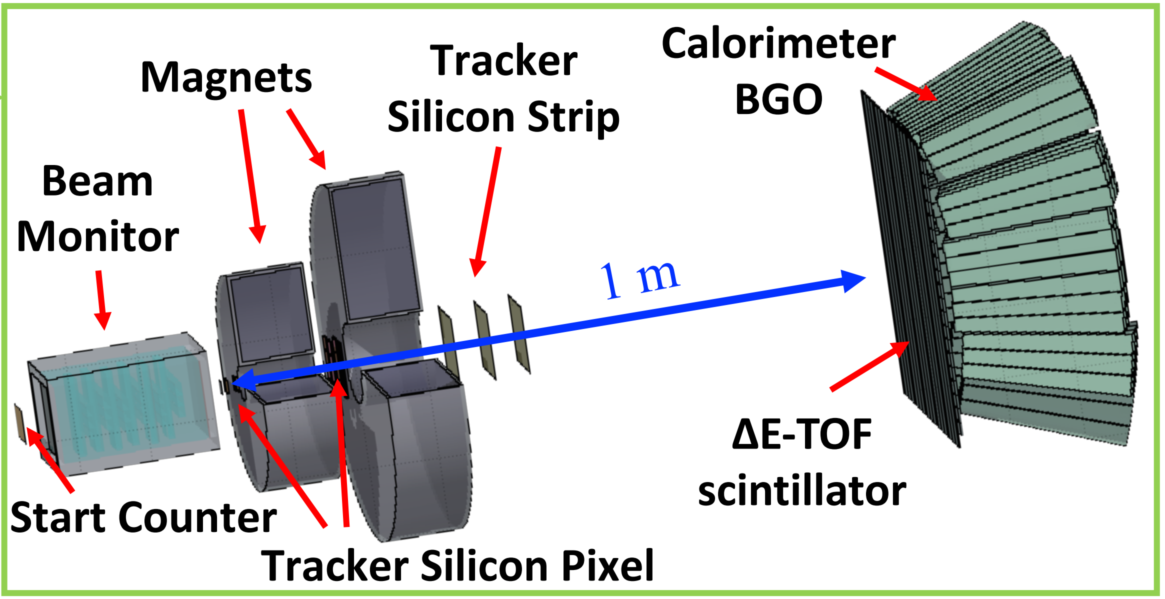
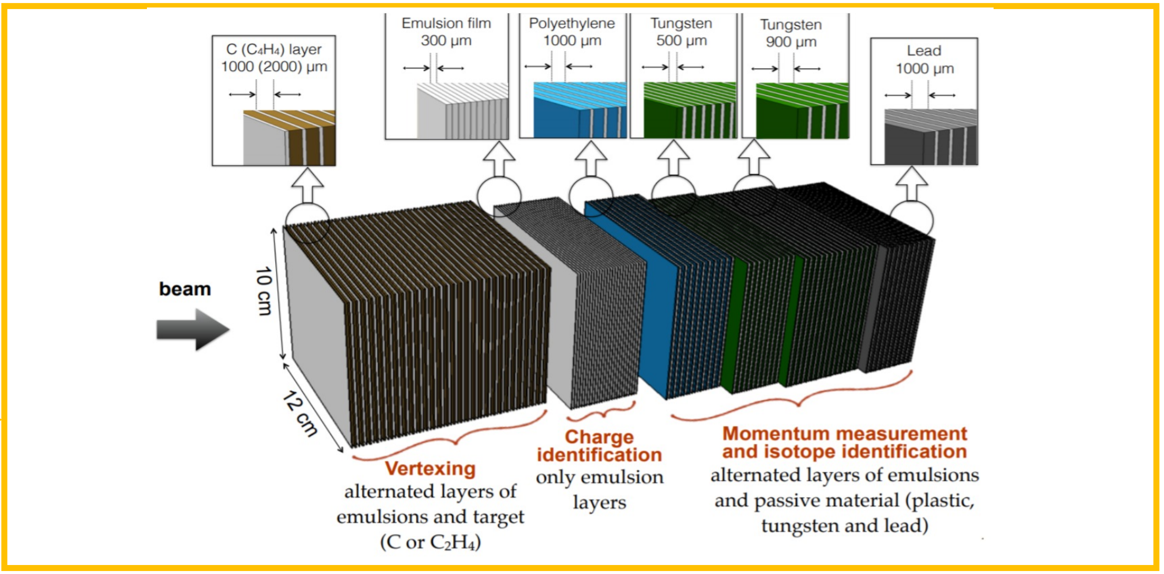


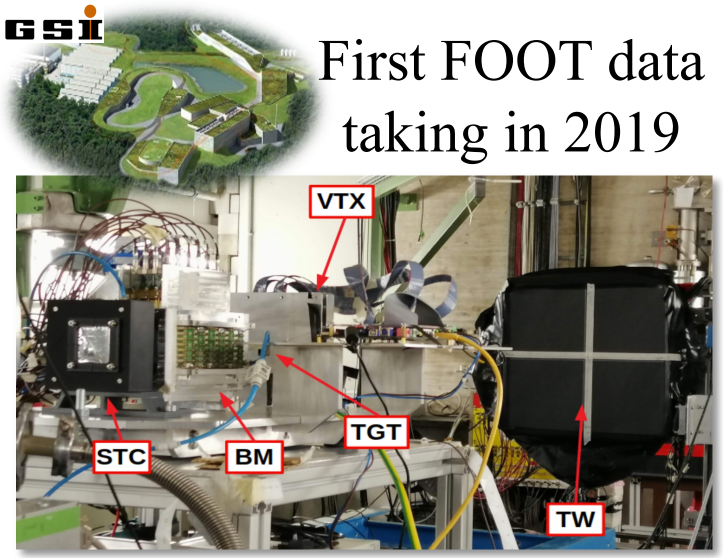




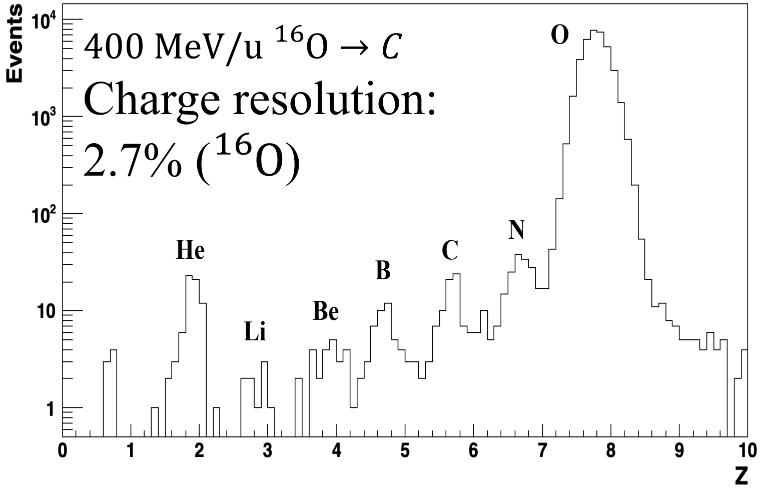
Emulsion Setup: light fragments

Last steps of FOOT

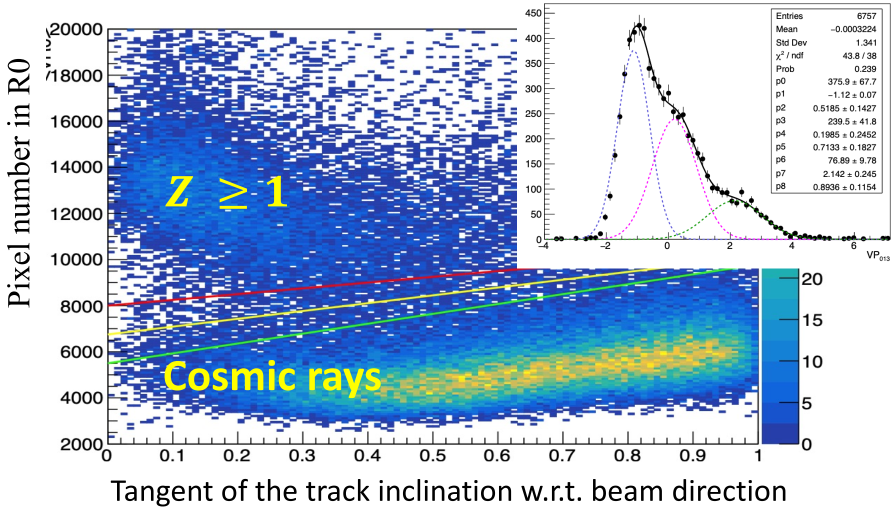
First FOOT data taking in 2019



Electronic spectrometer



Emulsion chamber 2019 + 2020

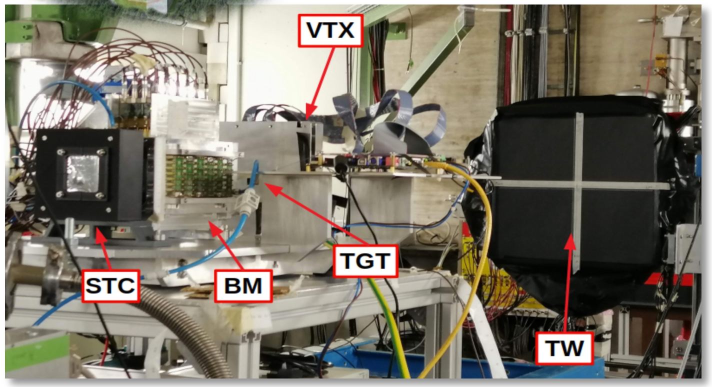


G. Galati et al., Charge identification of fragments with the emulsion spectrometer of the FOOT experiment, Open Physics (2021)

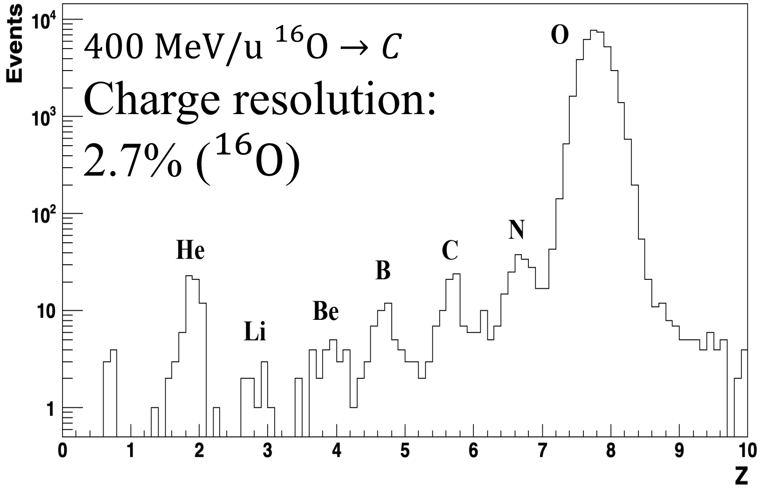
M. Toppi et al., *Elemental fragmentation cross sections for a 16O beam of 400 MeV/nucleon kinetic energy interacting with a graphite target using the FOOT ΔE- TOF detectors,* submitted

Last steps of FOOT

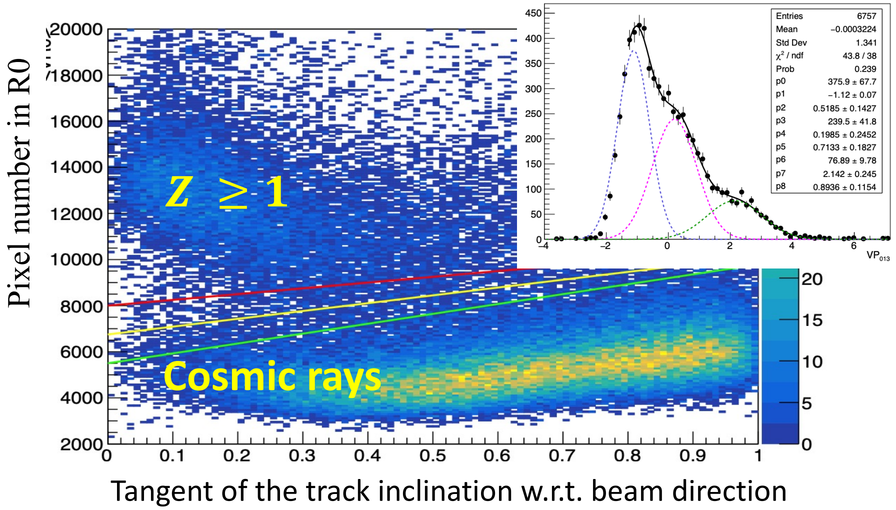
First FOOT data taking in 2019



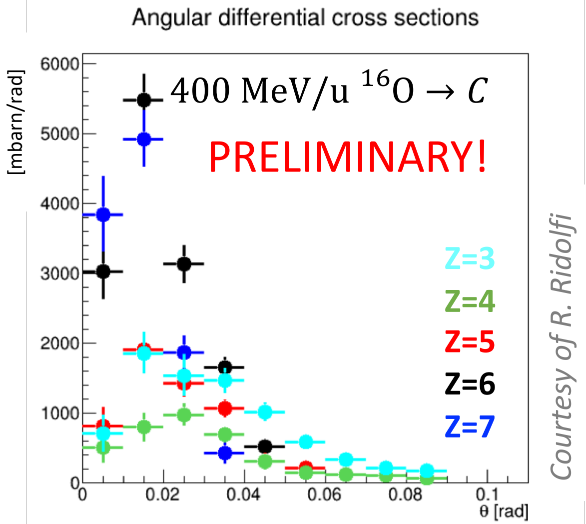
Electronic spectrometer



Emulsion chamber 2019 + 2020



Data taking in 2021



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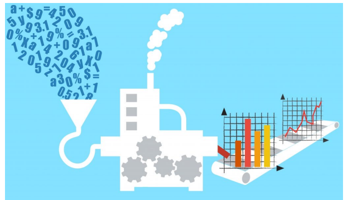
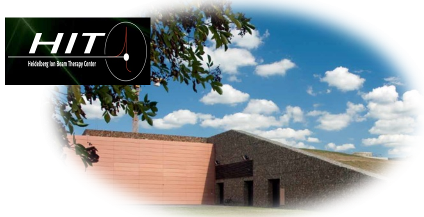


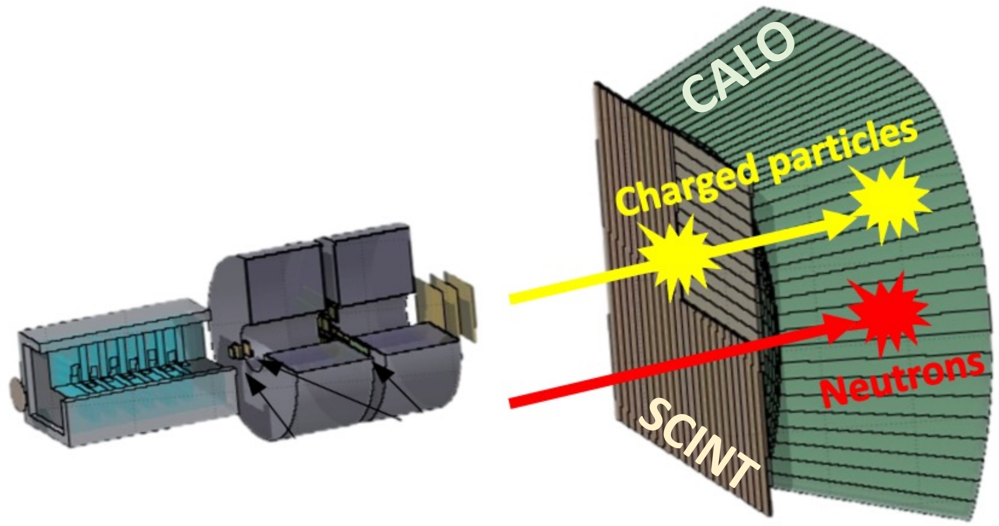
Many data analysis ongoing!



New data taking in July 2022

Future perspective: FOOT for neutrons

Detecting neutrons with the existing setup:



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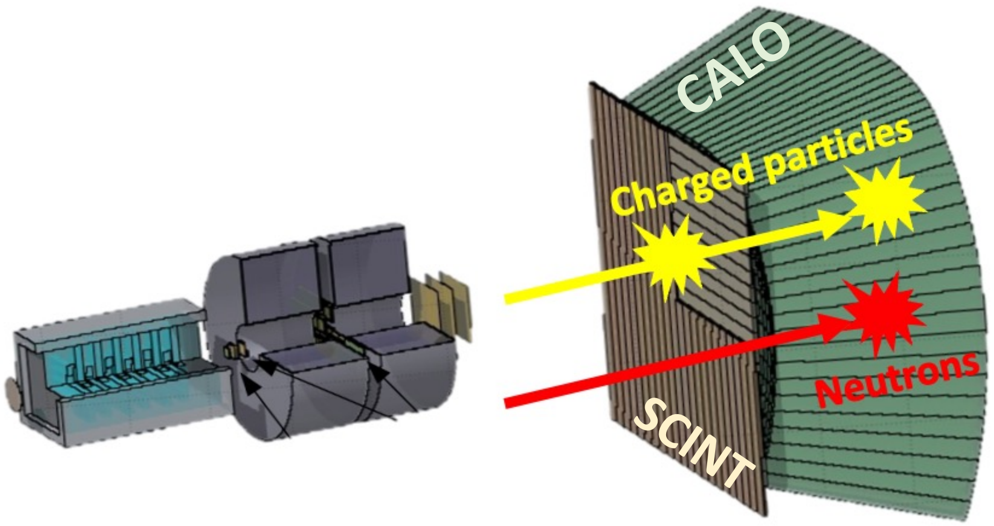
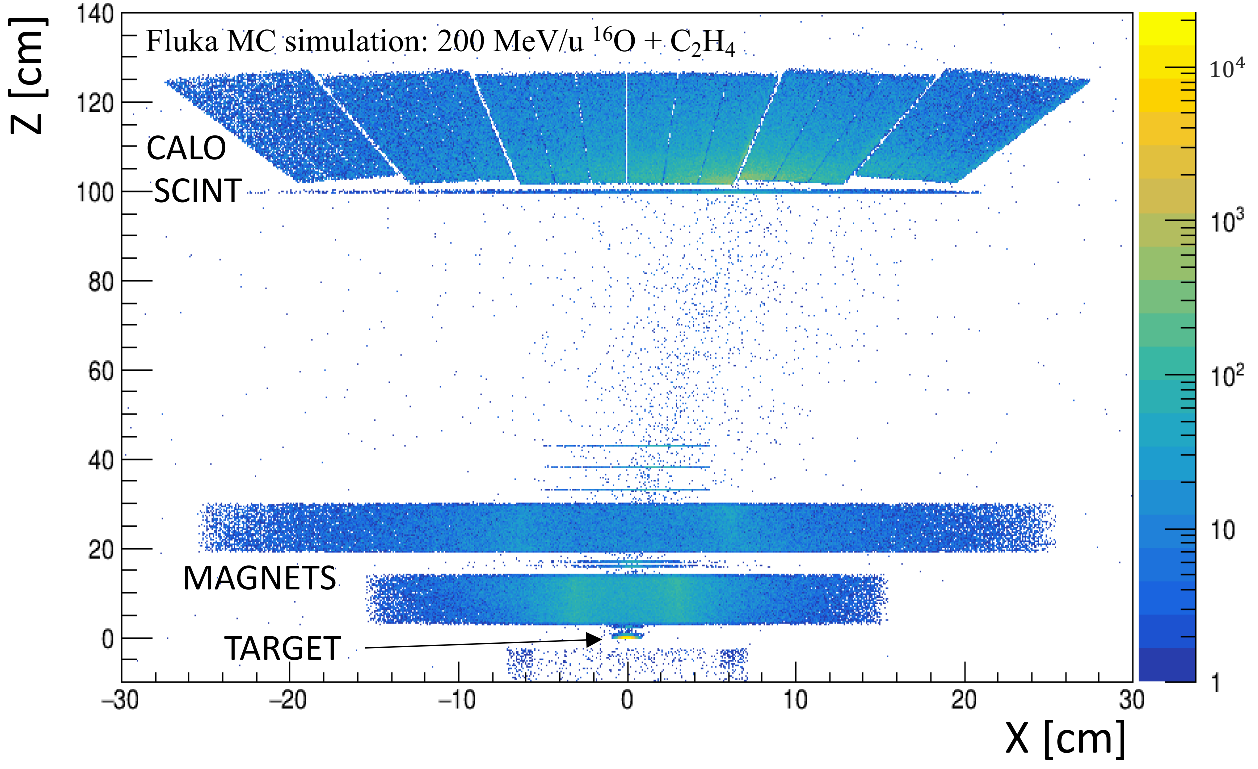


Birth position of all neutrons



Neutrons generated outside the target:

- magnets / target ~ 2
- calorimeter / target ~ 4

Future perspective: FOOT for neutrons

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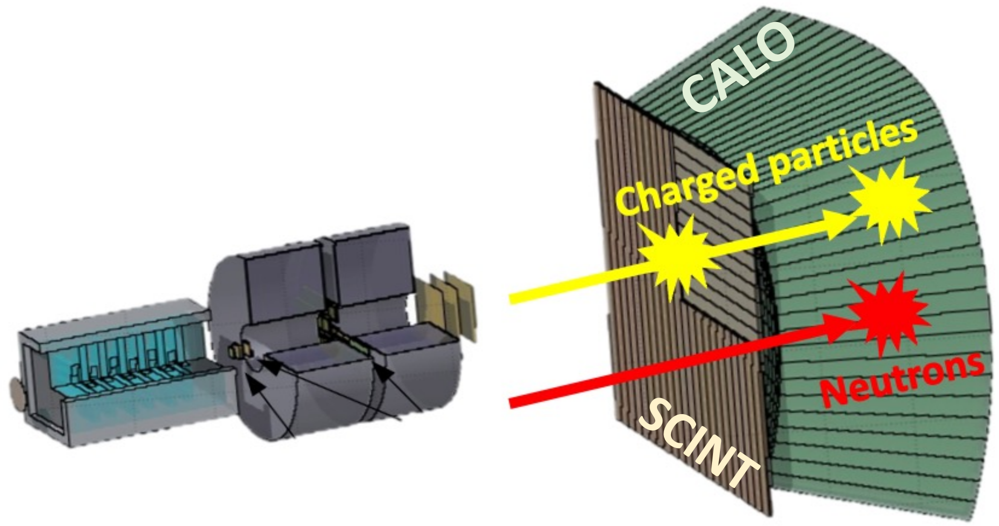

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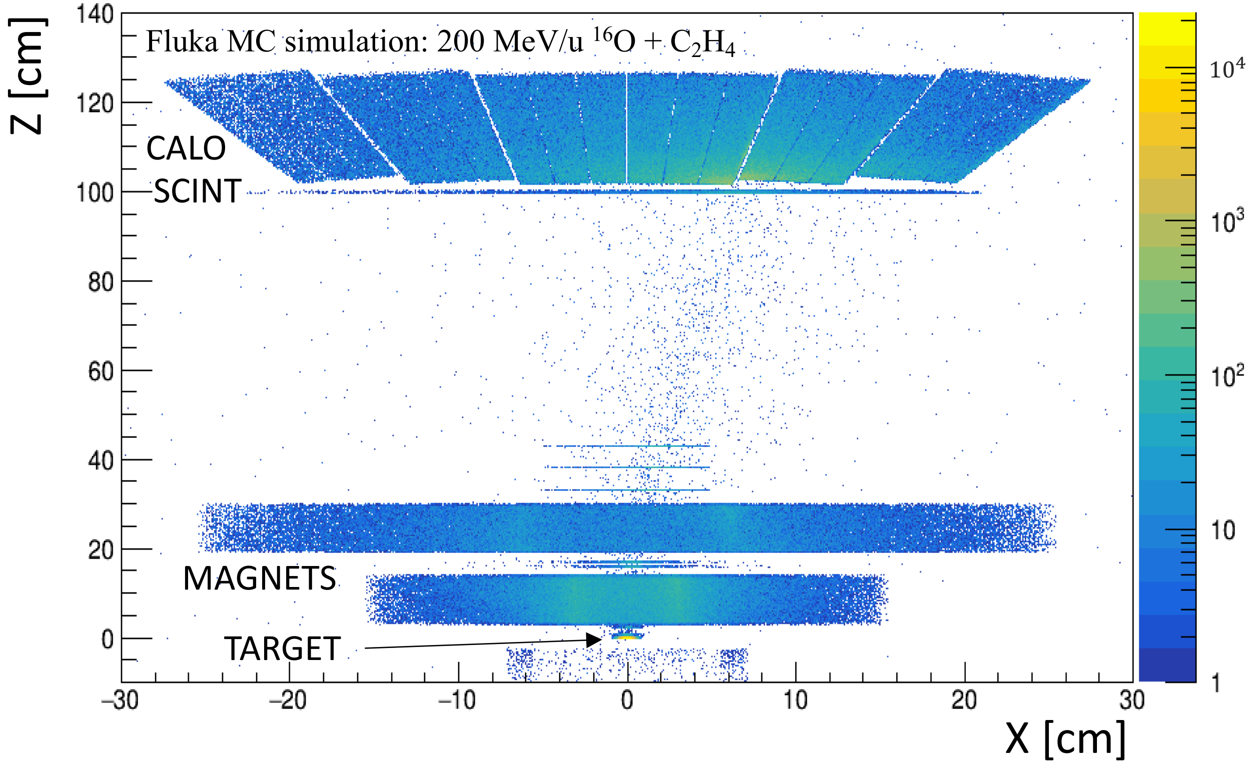


Neutrons generated outside the target:

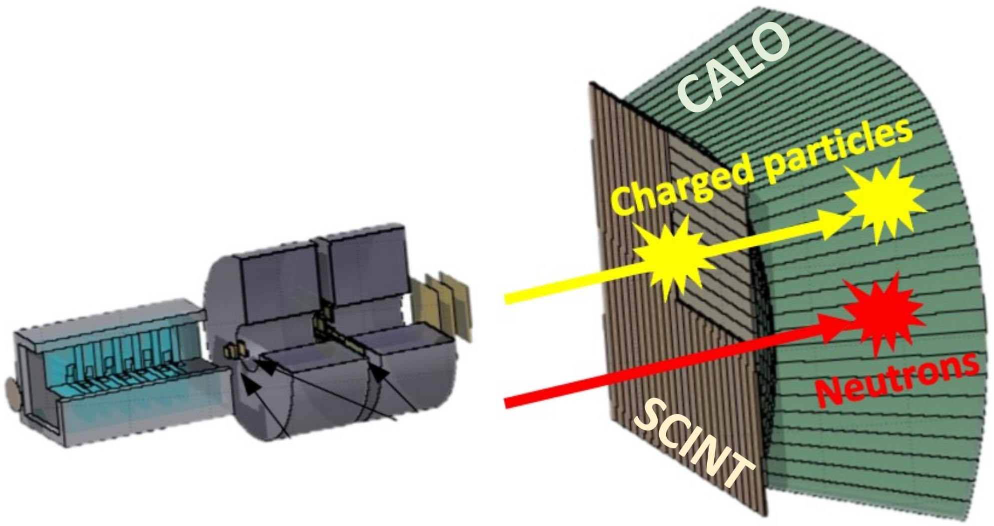
- magnets / target ~ 2
- calorimeter / target ~ 4

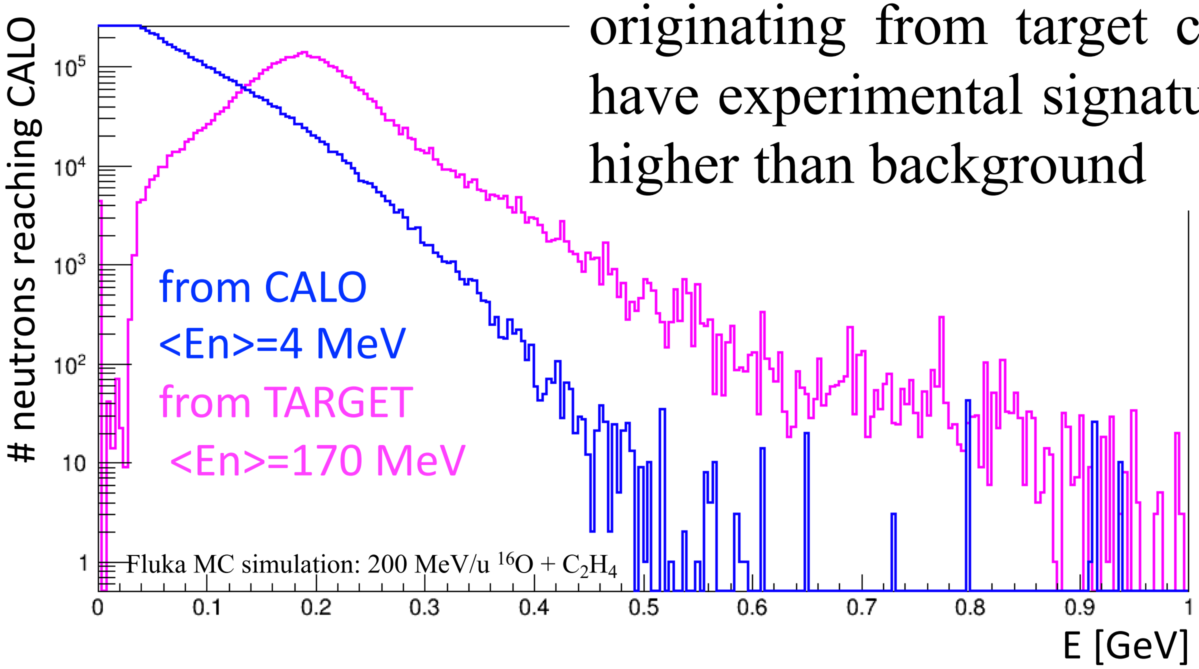
Only 1/5 reach the calorimeter for detection

- # in target / # in magnets ~ 7
- # in calorimeter / # in target ~ 8

Future perspective: FOOT for neutrons

Detecting neutrons with the existing setup:





Only high-energy neutrons originating from target can have experimental signature higher than background

Neutrons generated outside the target:

- magnets / target ~ 2
- calorimeter / target ~ 4

Only 1/5 reach the calorimeter for detection

- # in target / # in magnets ~ 7
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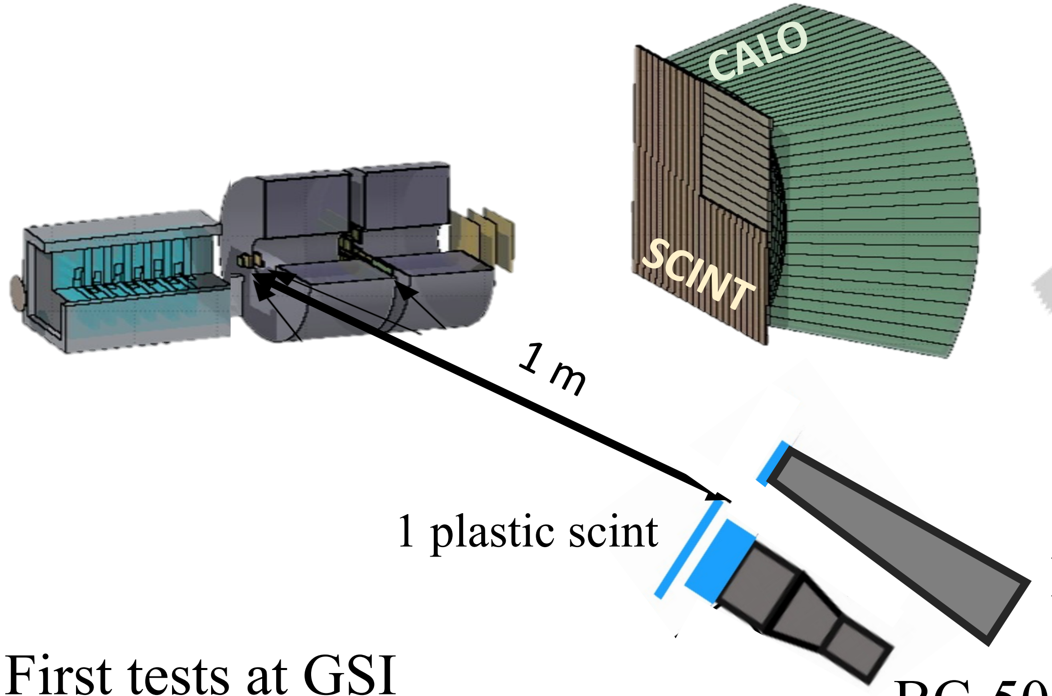
Neutrons produced in CALO ≈ main contribution to background

Possible FOOT upgrades for neutrons detection

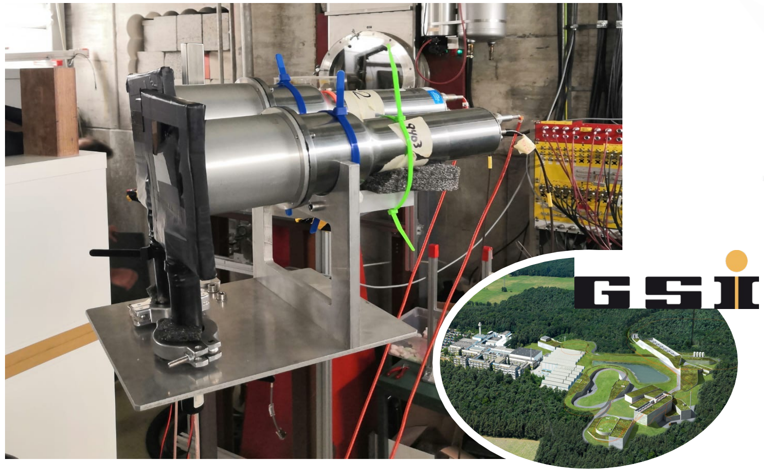


Possible calorimeter upgrade

- BGO crystal
- Thin plastic EJ232 scintillator foil on the front

- Liquid scintillator
- Excellent PSD properties for neutron-gamma discrimination

First tests at GSI



Nov 2022

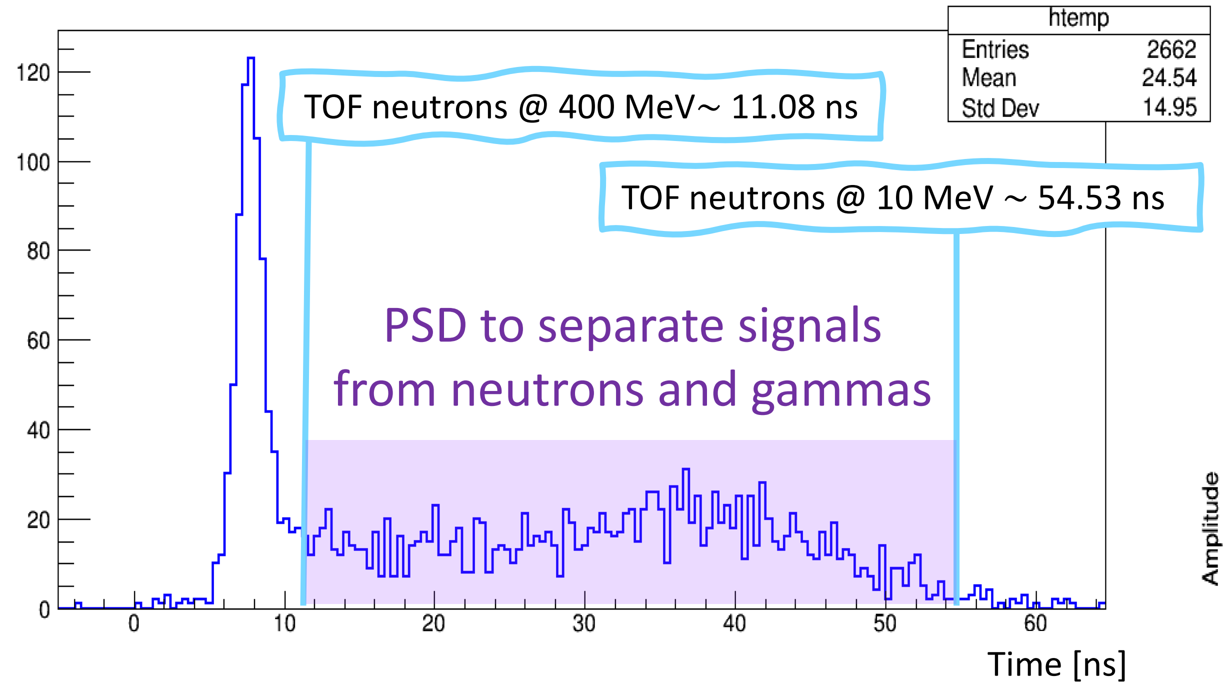
12C+12C reactions

@ 30, 80 and 5 deg

@ 135 and 290 MeV/u

to compare with literature

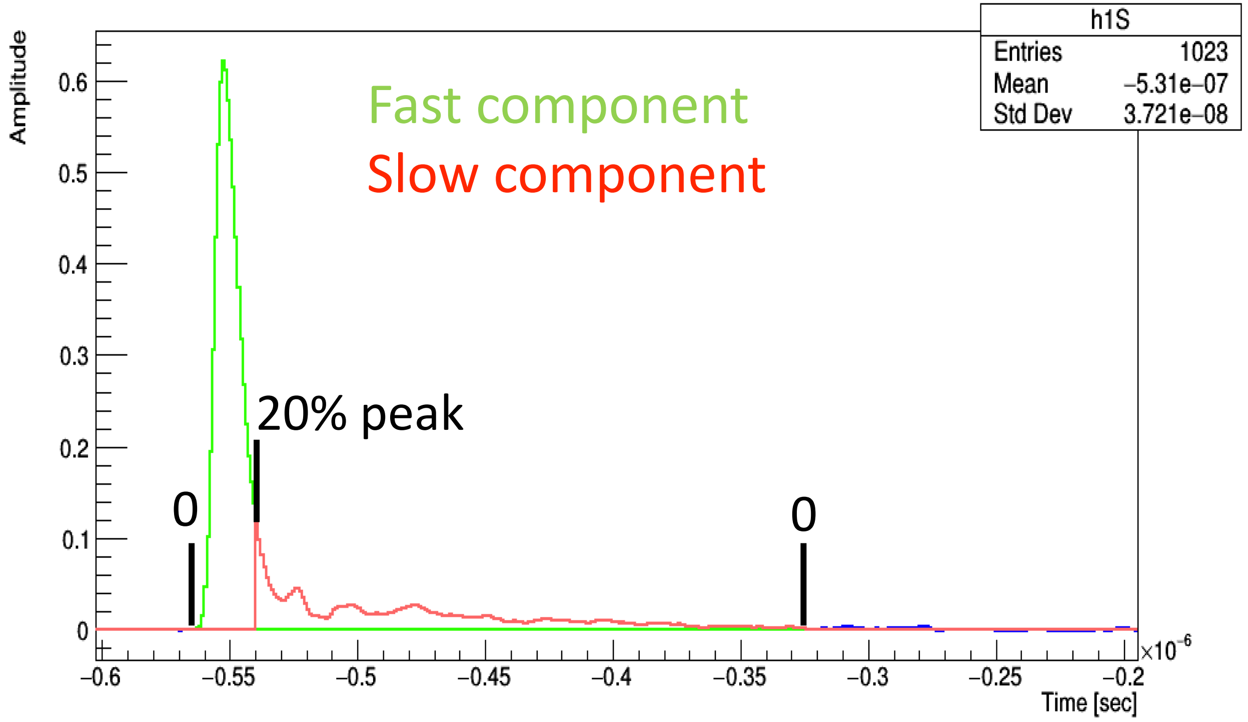
Neutrons and gammas separation



NEUTRONS

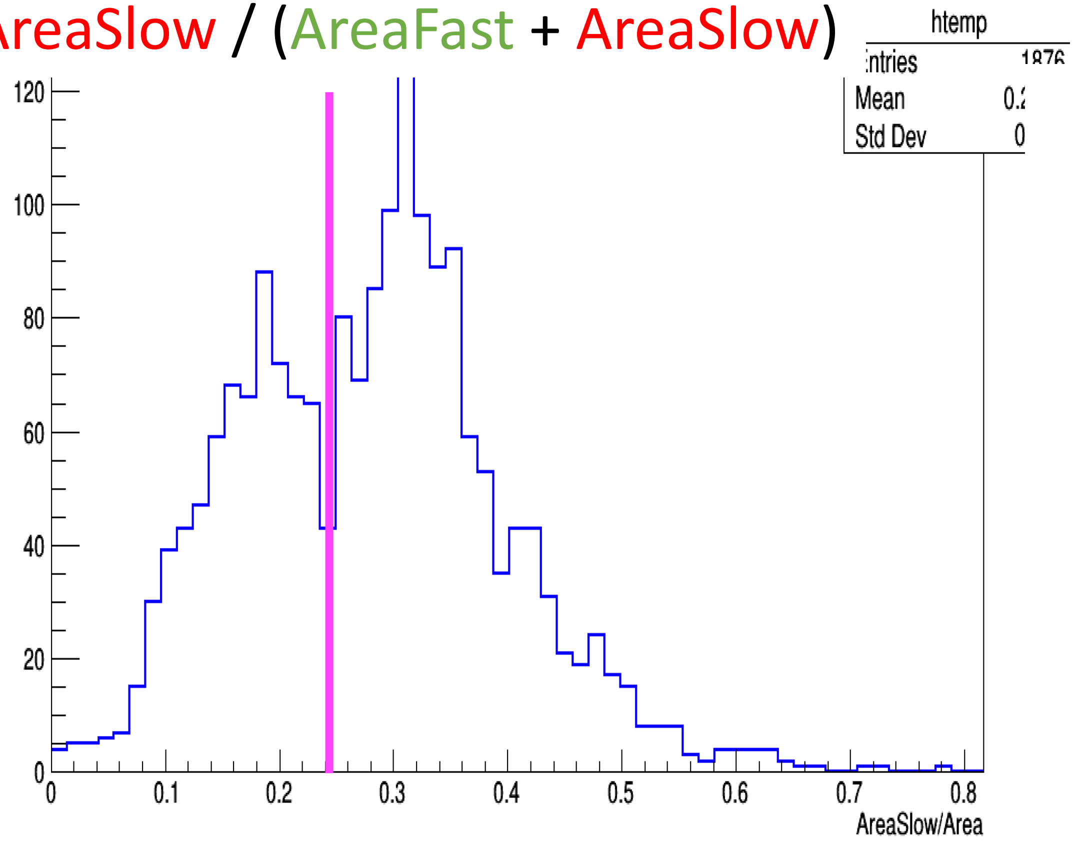
TOF > $\mu_{gamma\ peak} + 2\sigma_{gamma\ peak} \sim$ **9.7 ns**

- γ generate a fast signal described by $\tau_{FAST} \sim$ **3.2 ns**
- **Neutrons** generate a longer tail described by $\tau_{SLOW} \sim$ **32.2 ns**

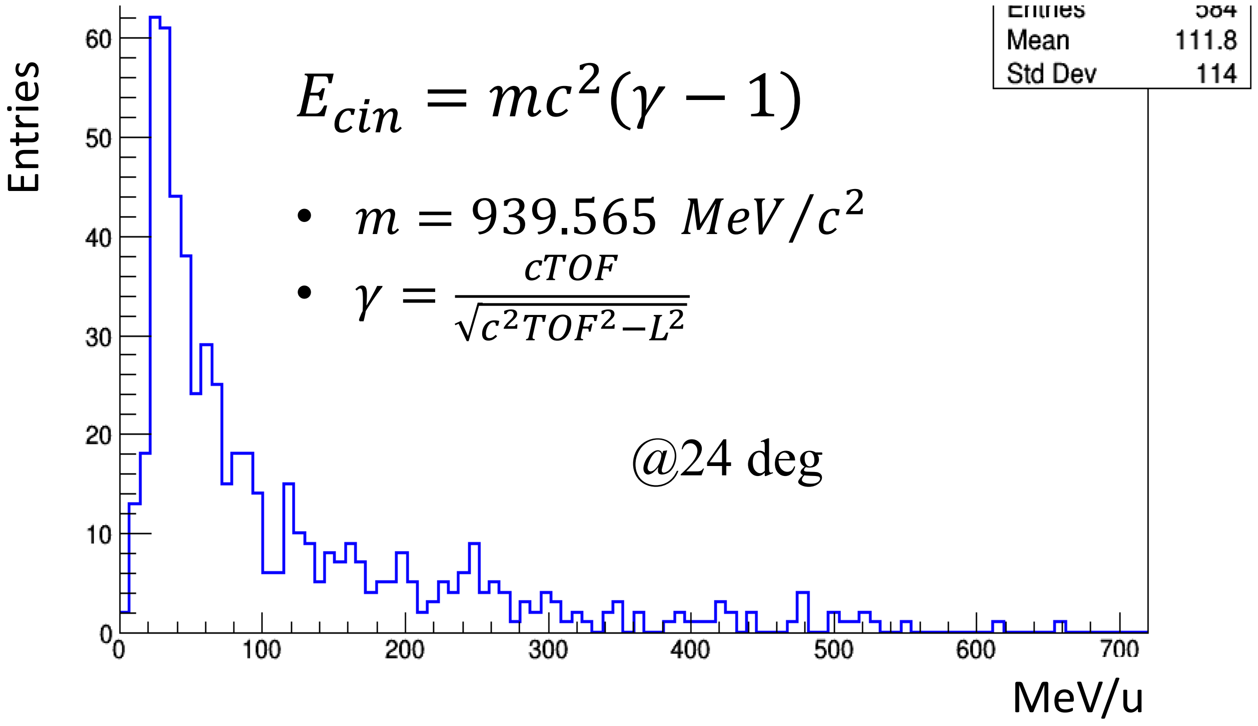


Neutrons and gammas separation

AreaSlow / (AreaFast + AreaSlow)



Neutrons energy (400 MeV/u ^{16}O - 10 mm C_2H_4)



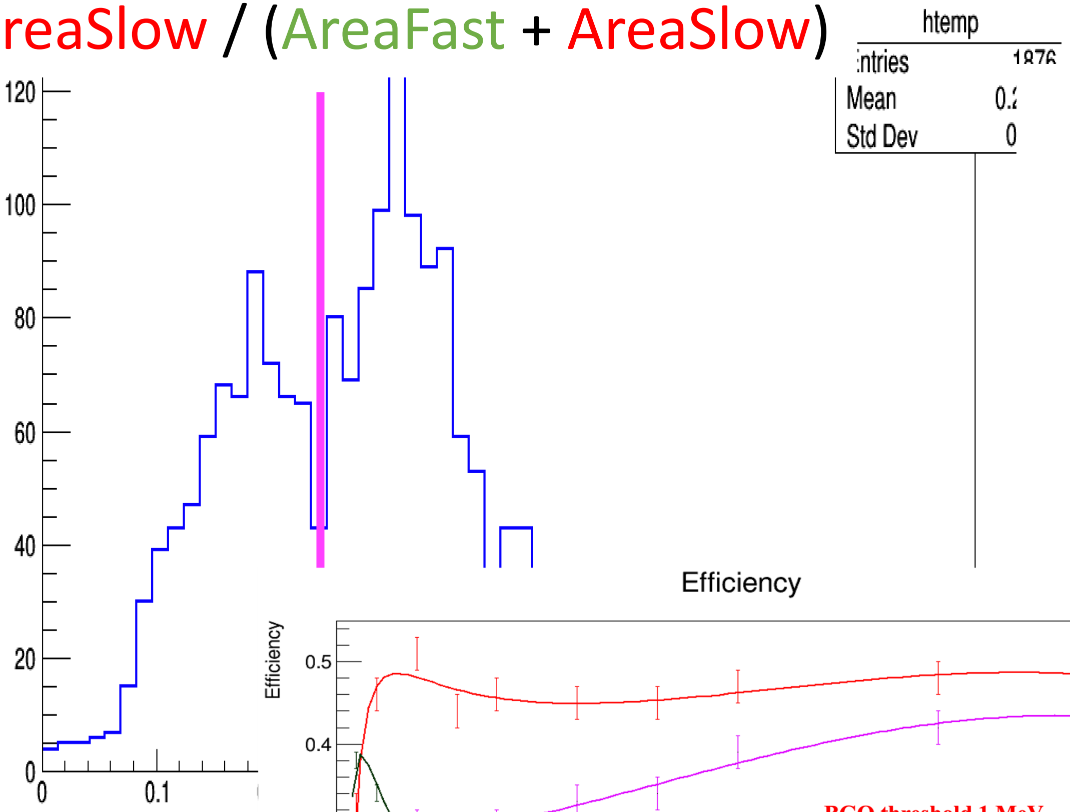
$$E_{cin} = mc^2(\gamma - 1)$$

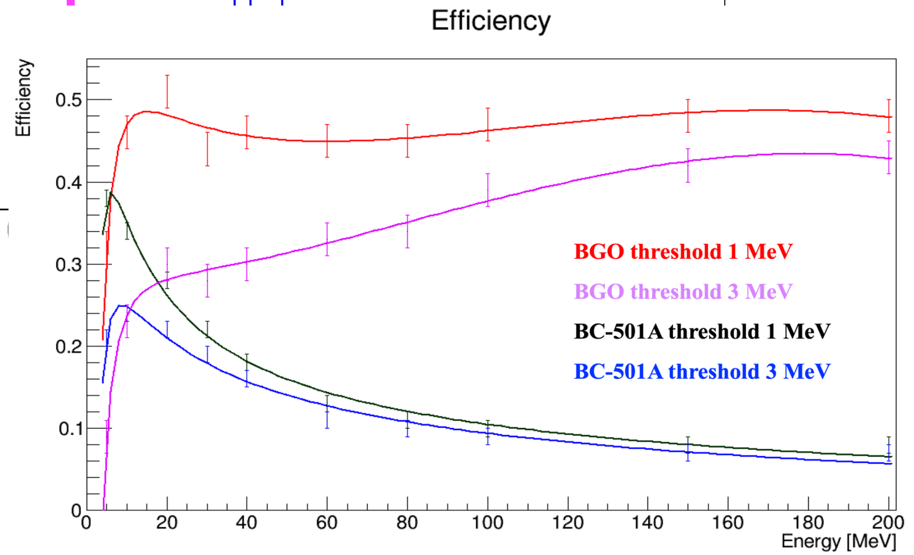
- $m = 939.565\ MeV/c^2$
- $\gamma = \frac{cTOF}{\sqrt{c^2TOF^2 - L^2}}$

@24 deg

Neutrons and gammas separation

AreaSlow / (AreaFast + AreaSlow)





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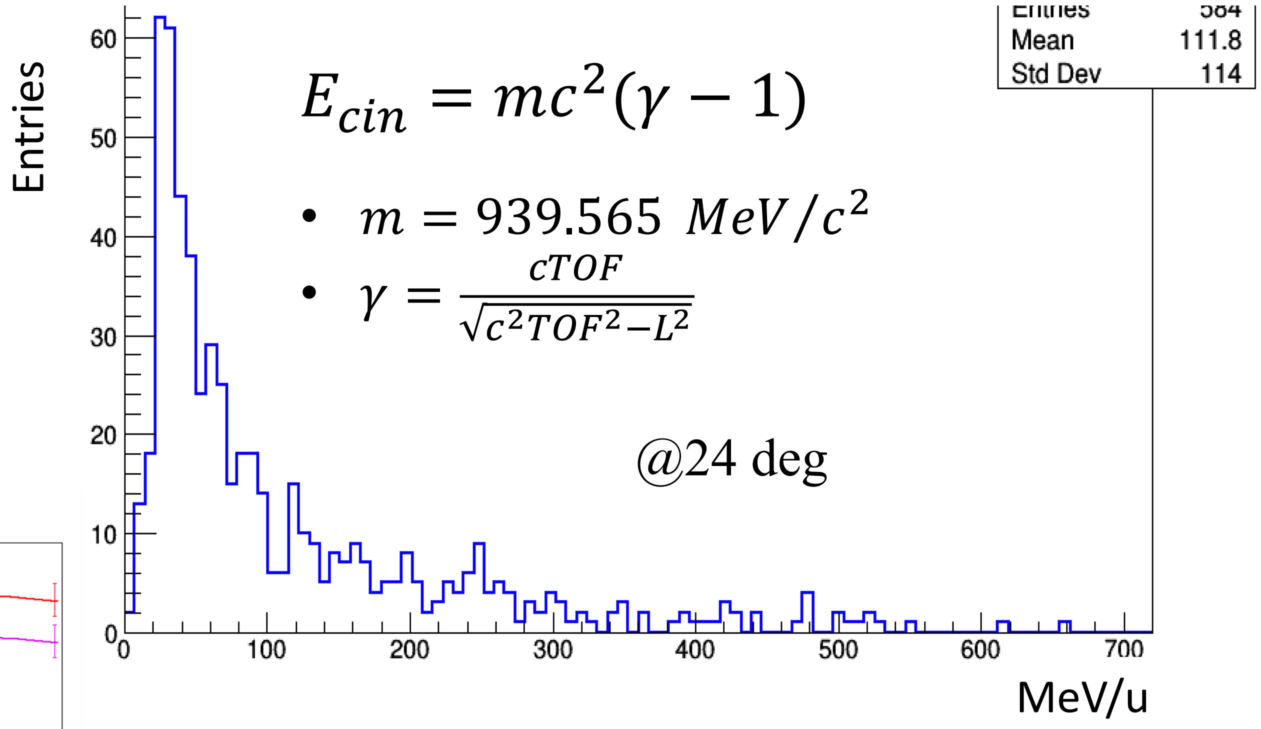

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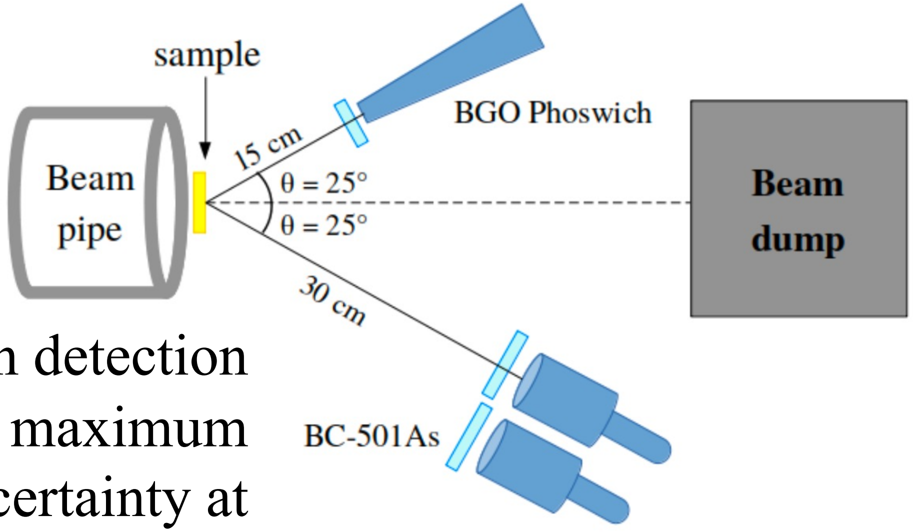
- $m = 939.565\ MeV/c^2$
- $\gamma = \frac{cTOF}{\sqrt{c^2TOF^2 - L^2}}$

$$\frac{d\sigma_f}{d\Omega\, dEkin} = \frac{N_{neutrons}}{N_{events}\, \Omega\, \epsilon_f\, \Delta E_{kin}}$$

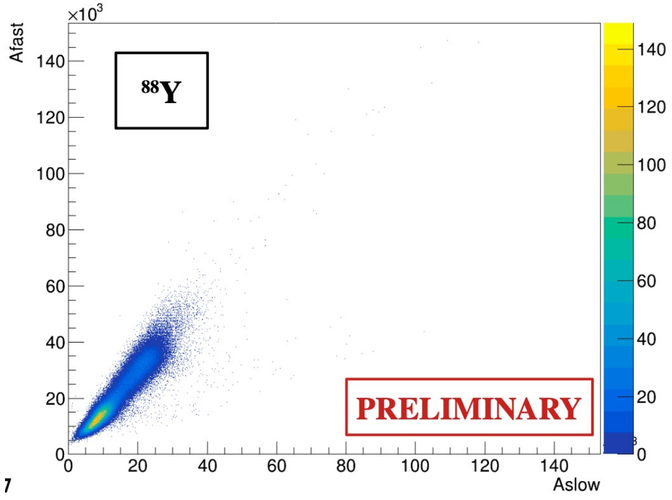
Detectors calibration @ n_TOF

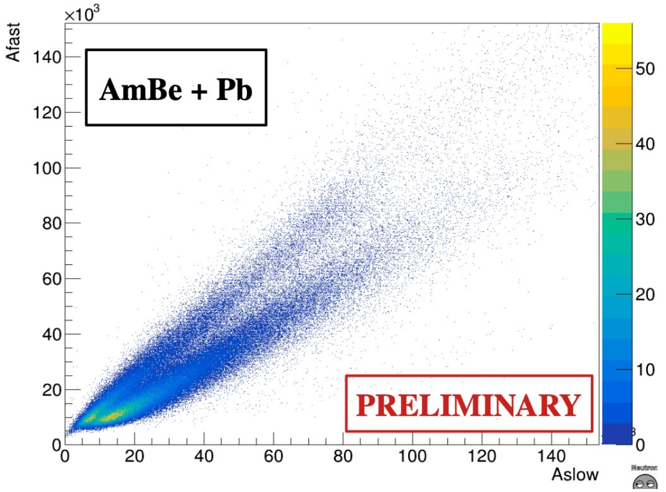


Neutron detection efficiency with maximum statistical uncertainty at the level of 5%

1) Am-Be/^{88}Y sources for preliminary particle identification (n-γ) studies

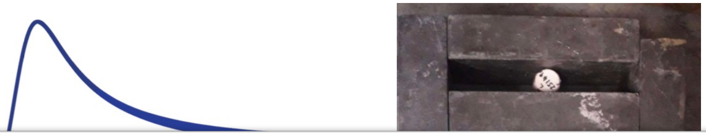
1) Neutron efficiency studied with neutron beam

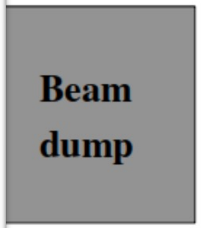


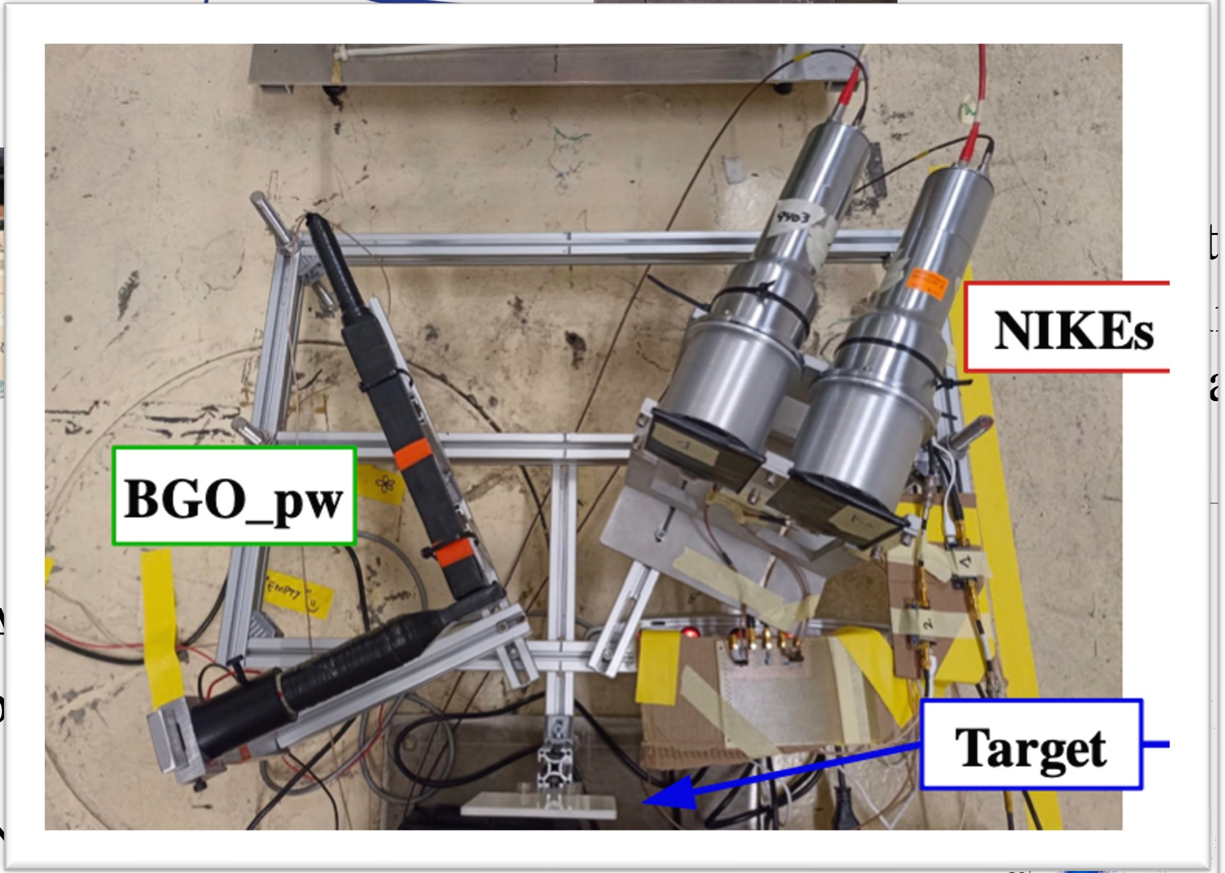


Courtesy of A. Manna and R. Zarrella

Detectors calibration @ n_TOF

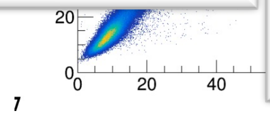


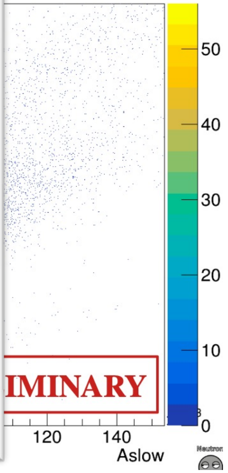




1) A
p

1) N
neutron beam





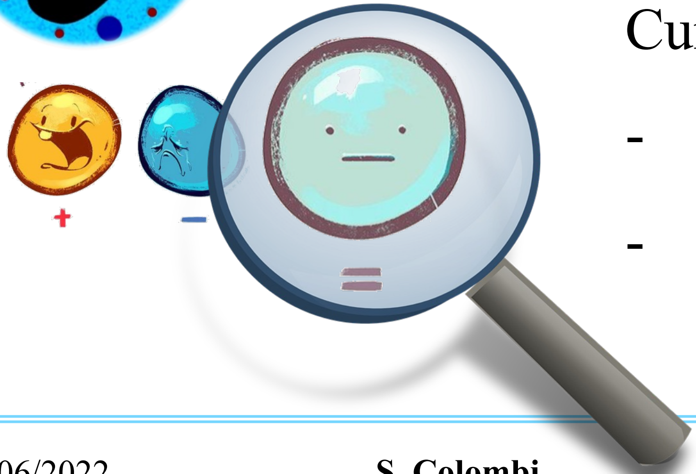
Courtesy of A. Manna and R. Zarrella

Conclusions

Analysis based on real data collected in the past 3 years have been published or are being performed.

- Detectors performances
- Fragments identification
- Charge-changing cross sections

Infos for high-energy neutrons by benefiting from the current FOOT configuration



Current studies and experimental tests to investigate

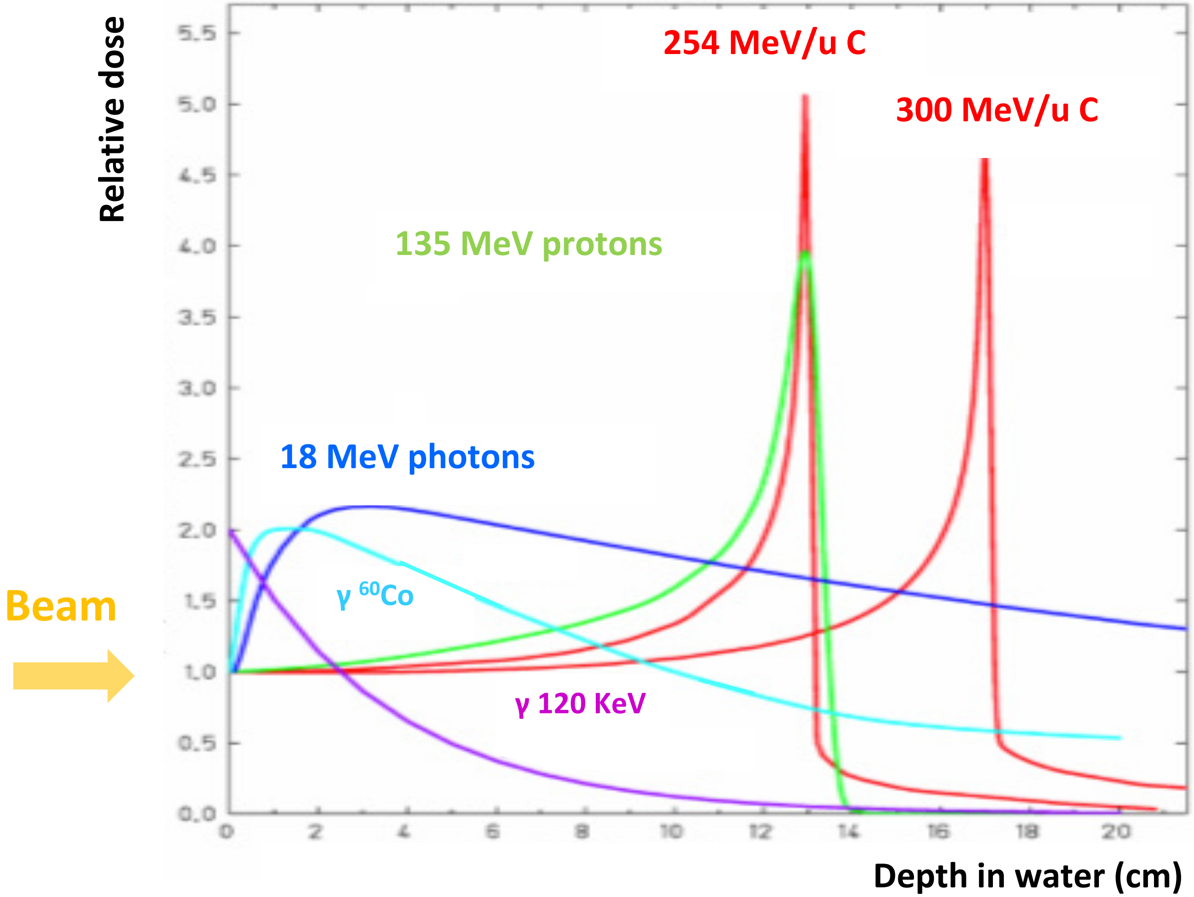
- the present setup
- additional liquid e solid scintillators

THANK YOU!

Backup

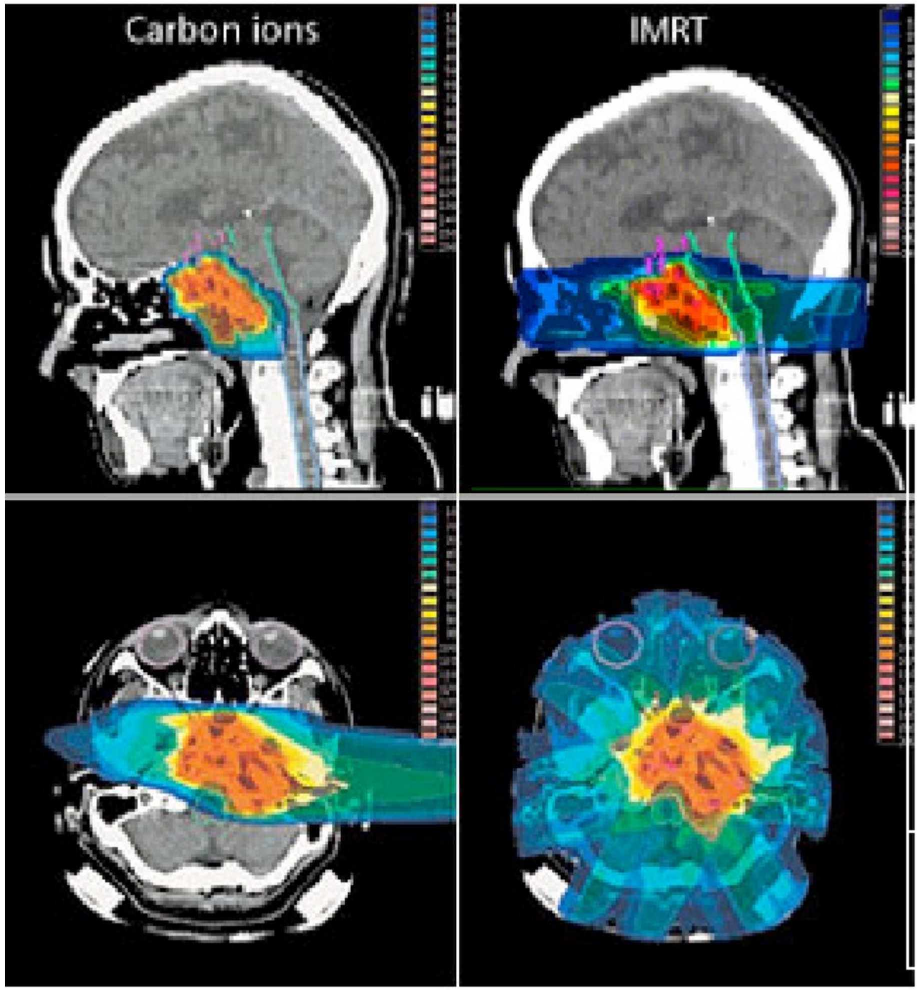
Advantages of particle therapy

Better sparing of normal tissues



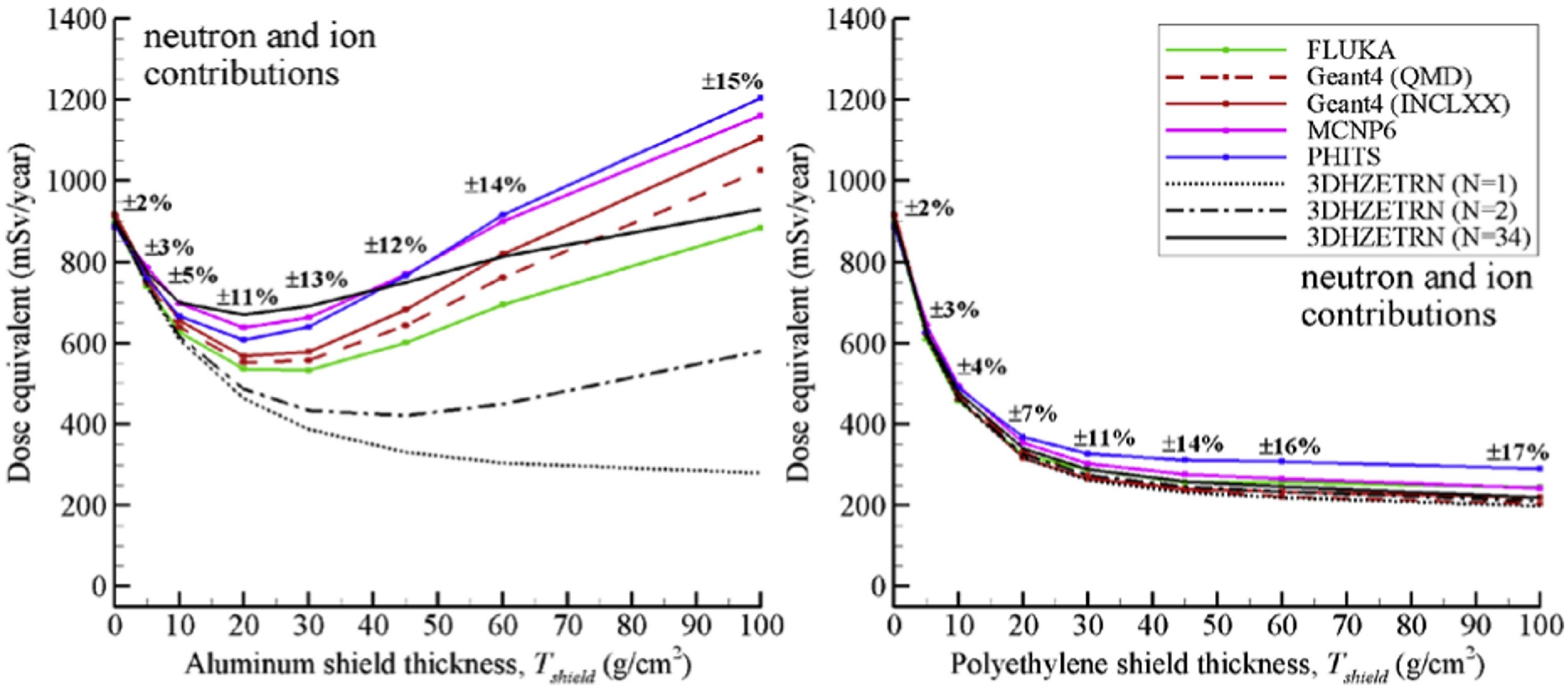
Courtesy of GSI

Particle therapy | Conventional radiotherapy



W. Chu, *Heavy Ion Radiotherapy: Yesterday , Today and Tomorrow (2010)*

Shielding in deep space



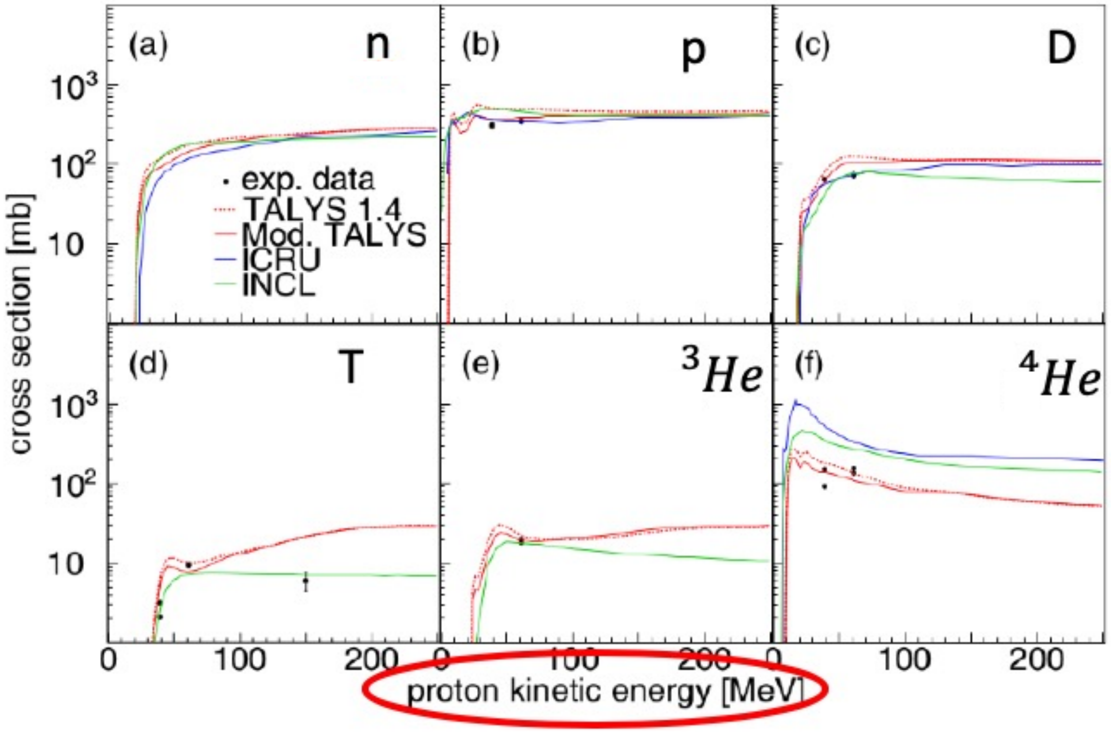
The more the better is **not always** the best strategy in space!

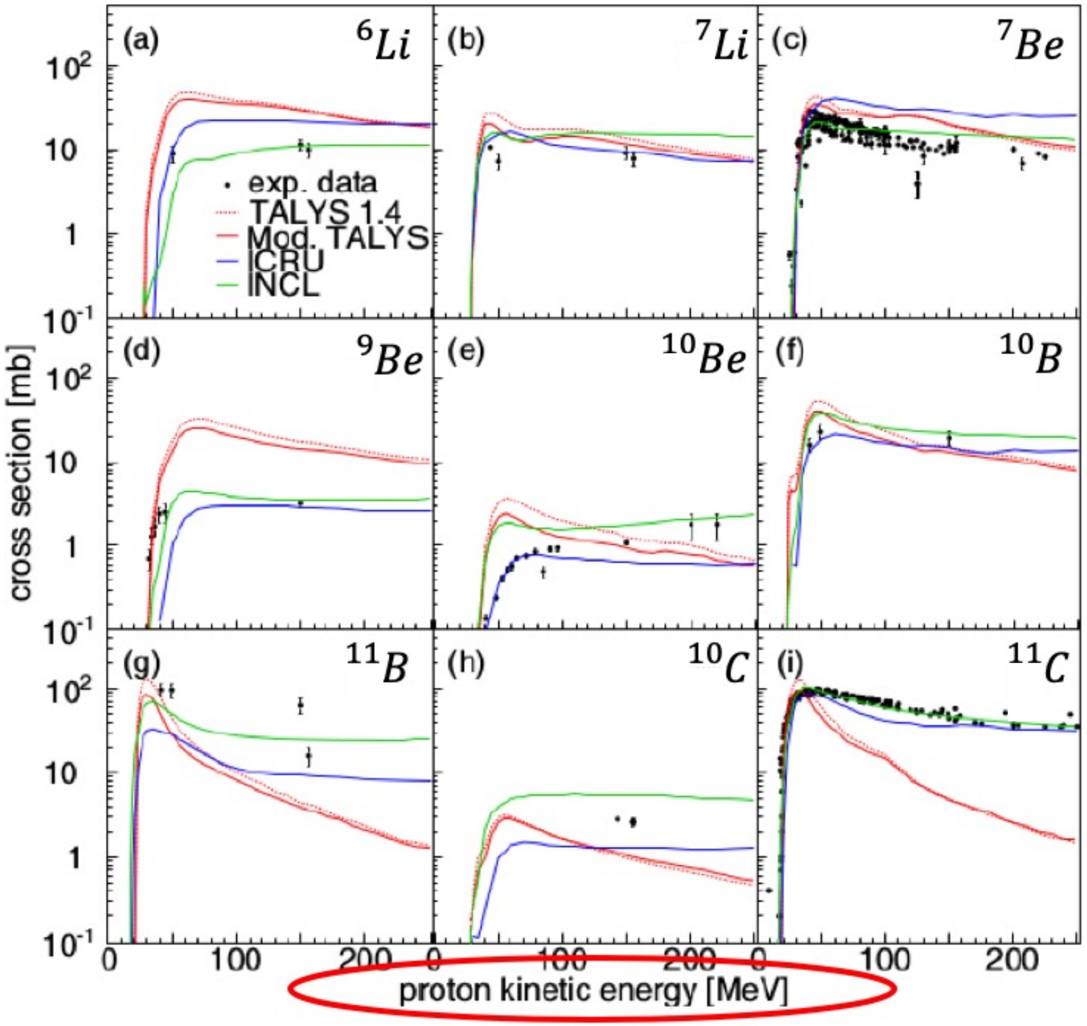
Slaba *et al.*, *Life Sci. Space Res.* (2017)

Fragmentation cross-sections: what is available on the market

Particle therapy

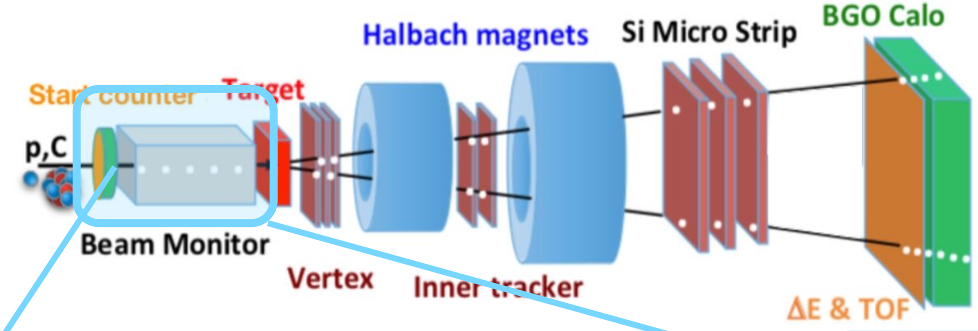
p → ^{12}C Fragments production cross section



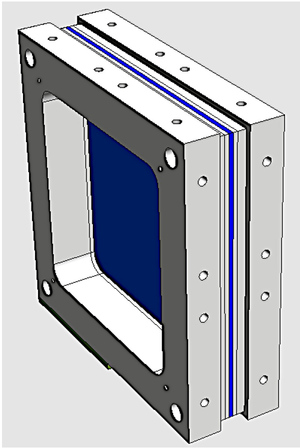


B. Braunn et al., *Assessment of nuclear-reaction codes for proton-induced reactions on light nuclei below 250 MeV* (2015)

Pre-target region



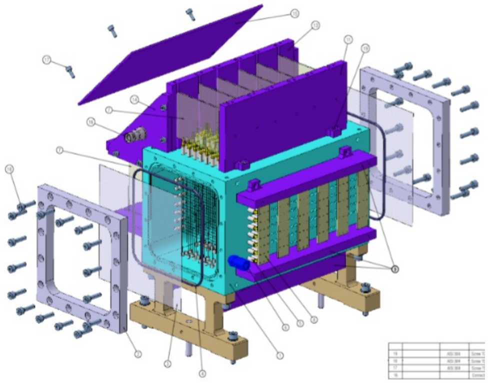
Start Counter (SC)



ToF start

- Plastic scintillator
- 250 µm thick
- 5 x 5 cm2 surface
- 60 ps res

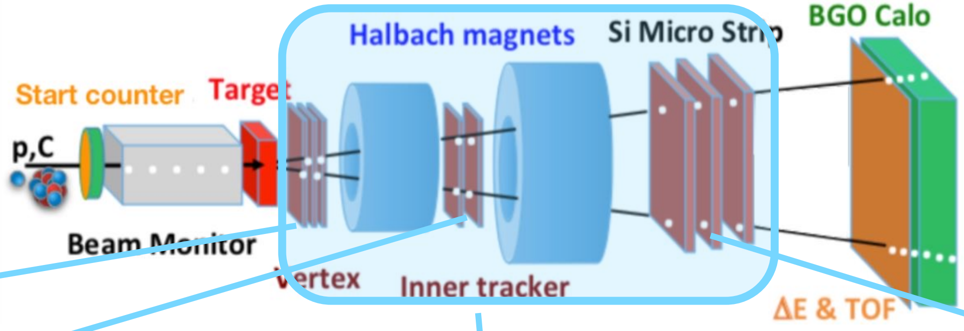
Beam Monitor (BM)



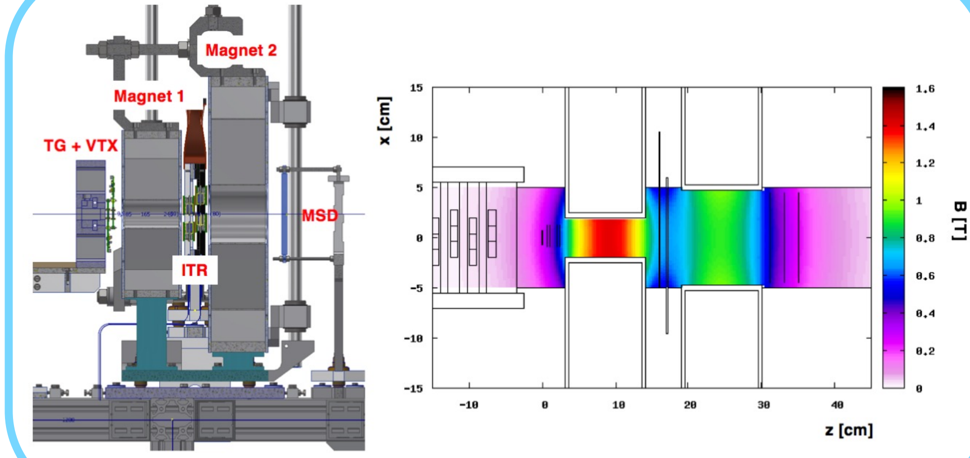
Beam direction & fragmentation in SC

- Drift chamber
- Gas: Ar/Co_2 (80/20**%**)
- spatial resolution of 100 µm

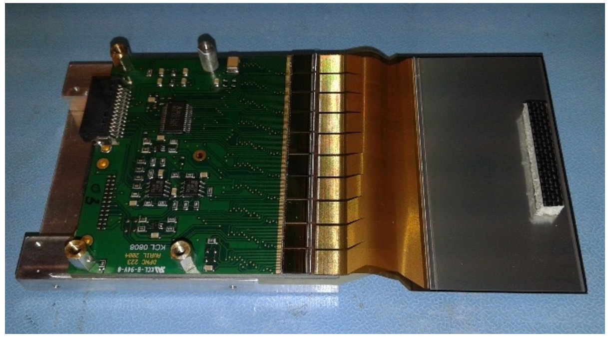
Tracking region



Vertex (VTX) &
Inner Tracker (ITR)



Micro Strip Detector (MSD)

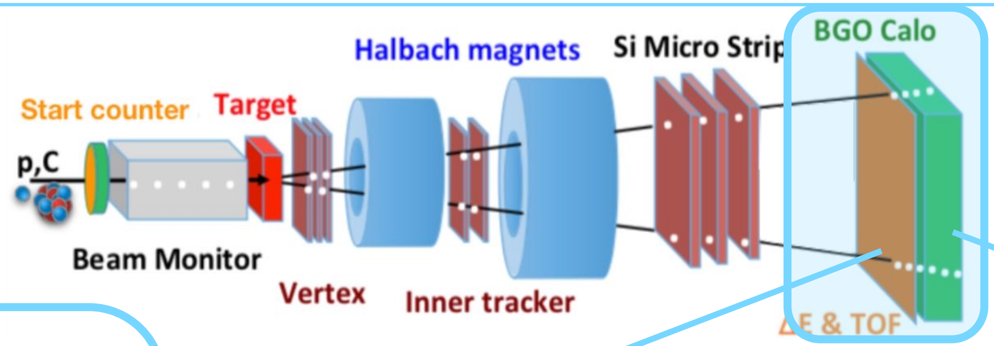


- 4 layers of Si pixel (2 cm x 2 cm)
- 2 layers of Si pixel (8 cm x cm)
- spatial resolution of 5 μm

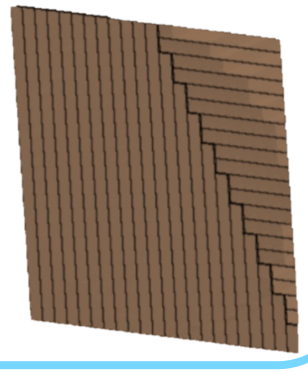
- 2 permanent magnets
- Hallbach geometry
- B field in y direction (1.4 T & 0.9 T)

- 3 layers of Si strips (9cm x 9 cm)
- spatial resolution of 40 μm

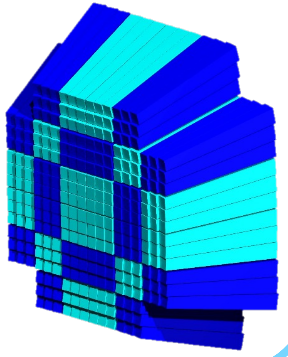
Downstream region



Scintillator (xSCN)



Calorimeter (CAL)



ToF stop and ΔE signal

- 40 cm x 2 cm plastic scintillator bars
- 3 mm thickness
- 2 layers of 20 bars
- TOF resolution better than 70 ps
- energy loss resolution better than 5%

E signal

- BGO – ($Bi_4Ge_3O_{12}$)
- Inorganic scintillator
- Total weight 330 Kg
- energy resolution better than 2%

Resolutions: test beam results

Dedicated test beam have been performed in order to estimate the resolution of each subdetector:

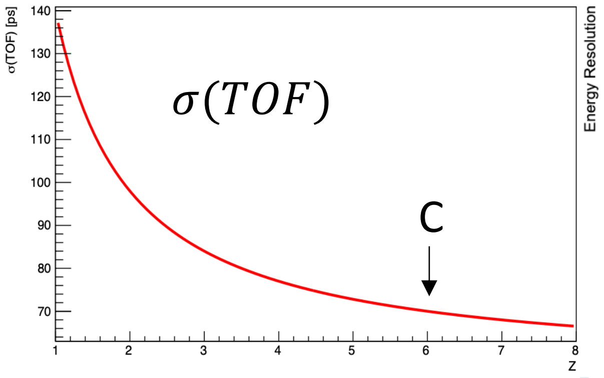
$\sigma(p)/p$ → 3.7 %

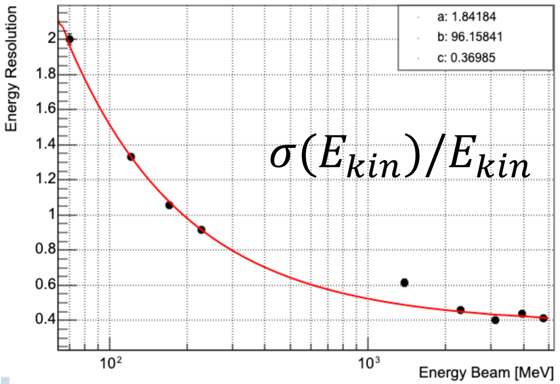
$\sigma(E_{kin})/E_{kin}$ → 1.5 %

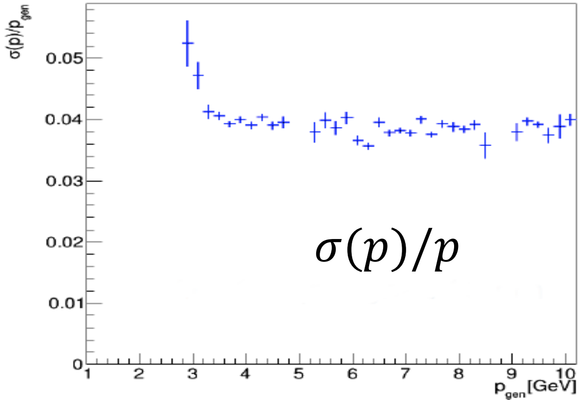
$\sigma(TOF)$ → 70 ps

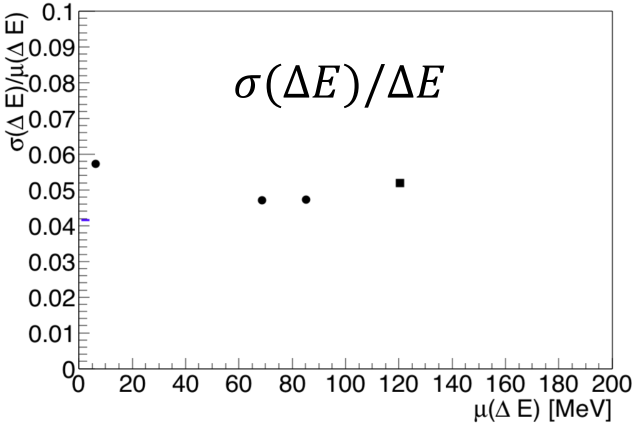
$\sigma(\Delta E)/\Delta E$ → 4.5 %

→ Applied to Monte Carlo data in order to reproduce an experimental-like data sample









Courtesy of L. Scavarda, R. Ridolfi, R. Zarrella

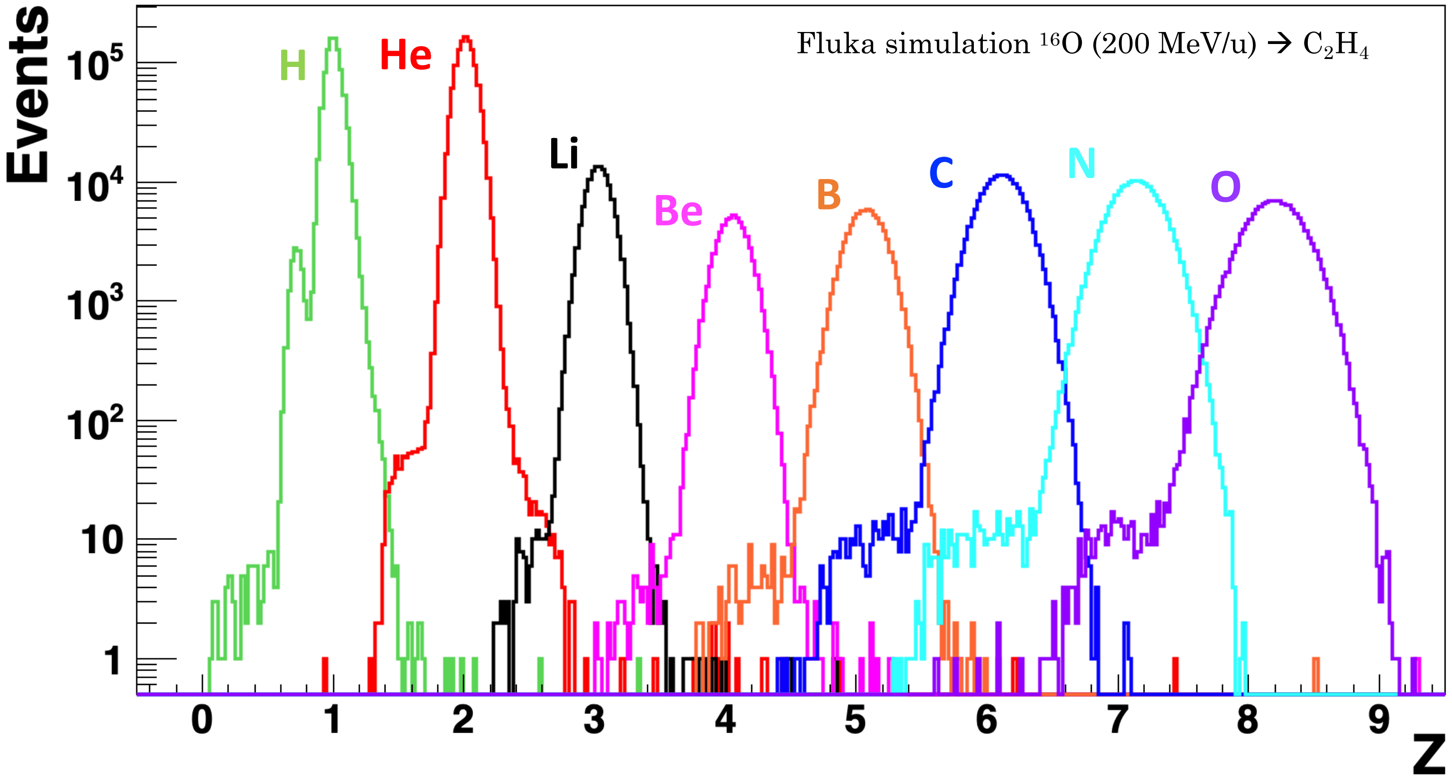
Charge reconstruction

Energy loss in SCN

Time-of-Flight via β
(Start Counter – SCN)

Bethe-Bloch equation

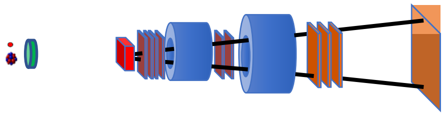
$$-\frac{dE}{dx} = \frac{\rho \cdot Z}{A} \frac{4\pi N_A m_e c^2}{M_U} \left(\frac{e^2}{4\pi\epsilon_0 m_e c^2}\right)^2 \frac{z^2}{\beta^2} \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$



Charge resolution:
2% (^{16}O) – **6%** (^{1}H)

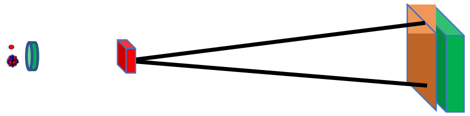
Mass identification

TOF & TRACKER



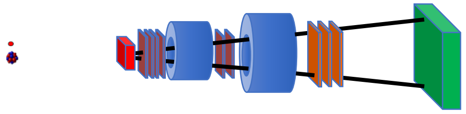
$$A_1 = \frac{p}{U\beta\gamma c}$$

TOF & CALO



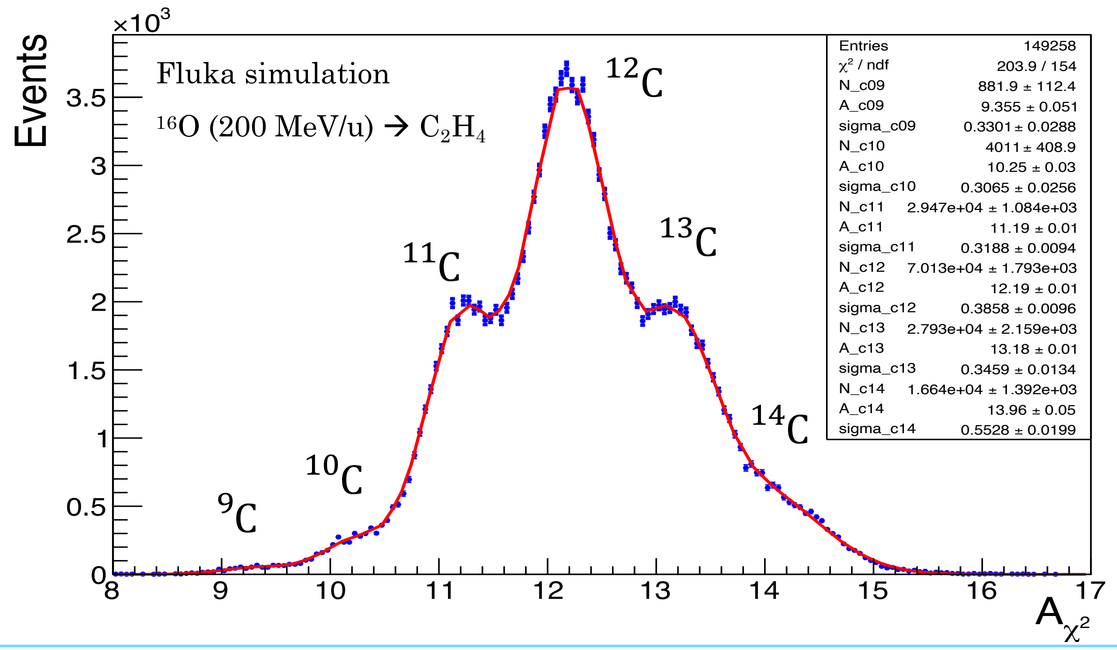
$$A_2 = \frac{E_k}{Uc^2(1-\gamma)}$$

TRACKER & CALO



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

Best determination of A through a standard χ^2 minimization



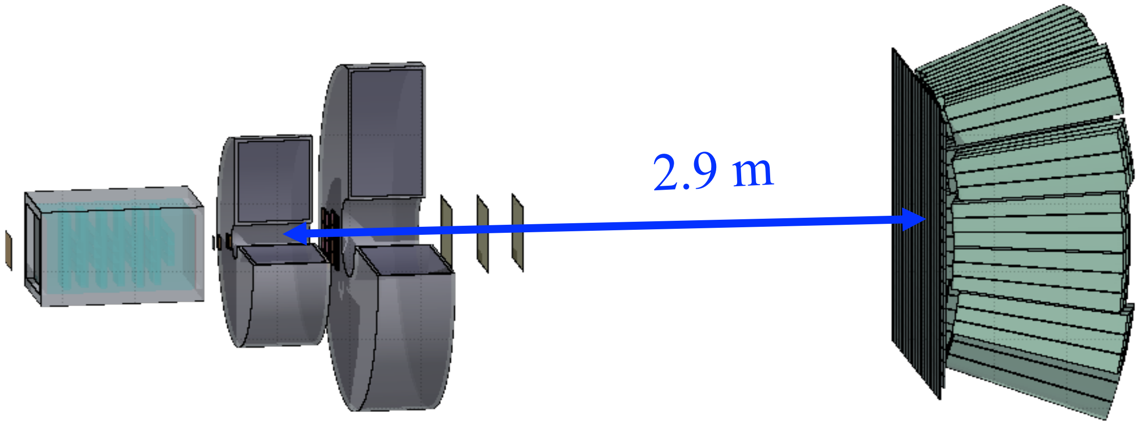
Mass resolution:

4% (^{16}O) – **6%** (^{1}H)

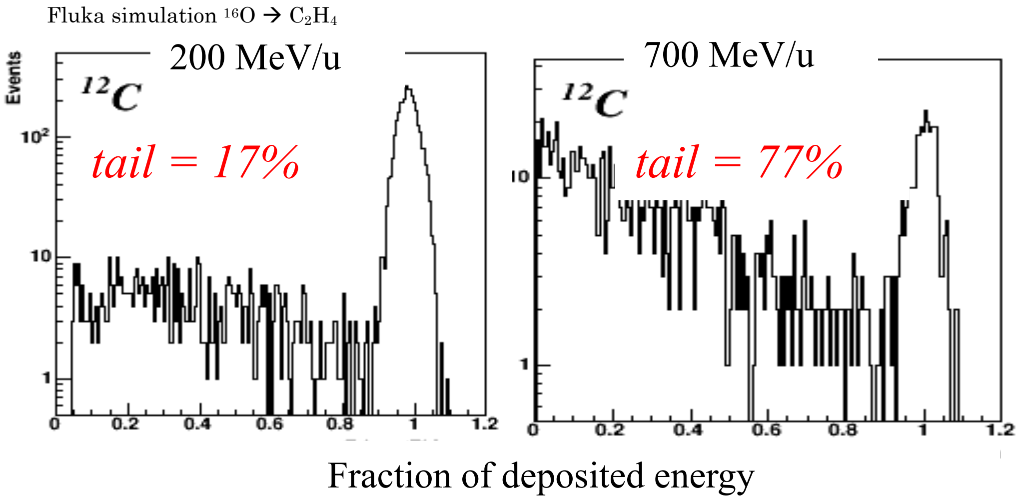
Mass identification @ 700 MeV/u

- Downstream region moved to $\sim 3\ m$:

  same TOF resolution as @ 200 MeV/u



Fragments with larger energy have a higher probability to fragment in **CALO:** larger neutrons production!



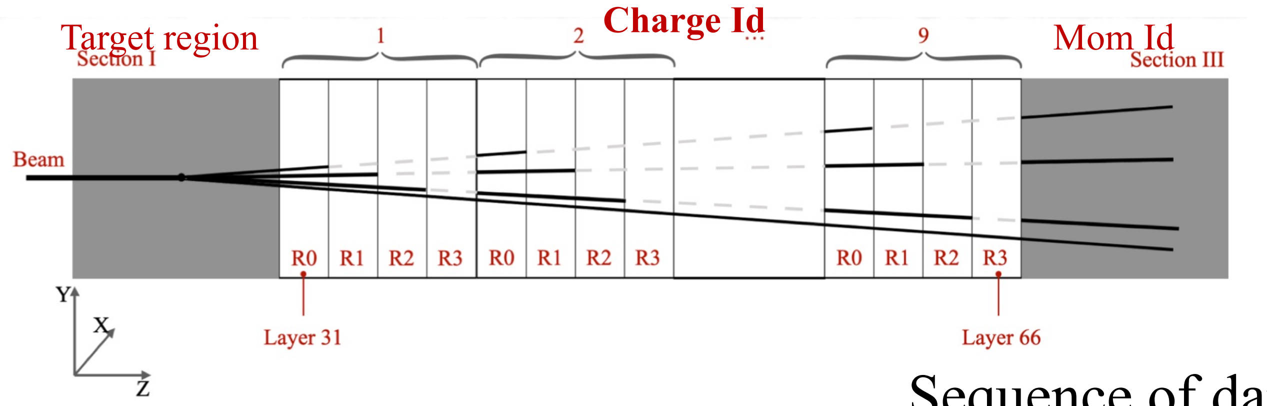
$$A_2 = \frac{E_k}{Uc^2(1-\gamma)}$$

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

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

FOOT redundancy allow to correctly reconstruct ~ 20% of the events @ 700 MeV!

Light charge (Z<4) identification for 200 MeV/u $^{16}O \rightarrow C_2H_4$

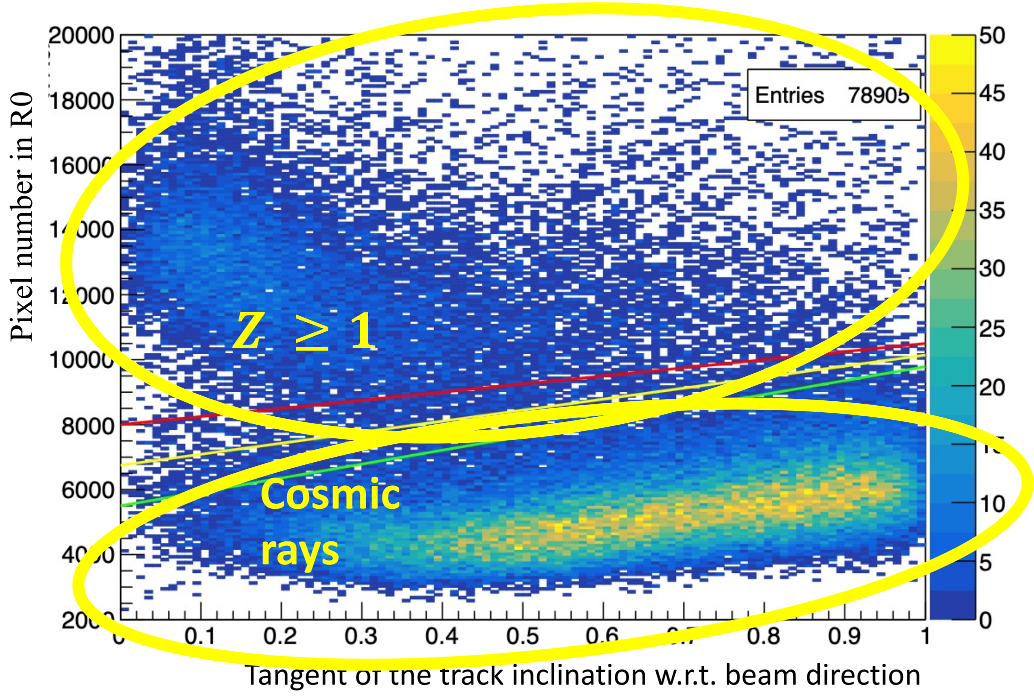


Section II -> divided into 9 cells, each one consisting of 4 emulsion films which underwent different thermal treatments (R0, R1, R2, R3).

⇩

Sequence of dark silver grains along the crossing particle trajectory: grain density almost proportional to $E_{particle}$

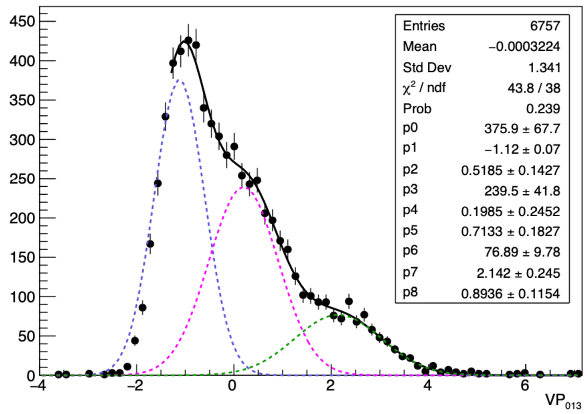
Real data!



Fragments charge from the experiment ⇨ Charge assigned for 99.4% of the tracks

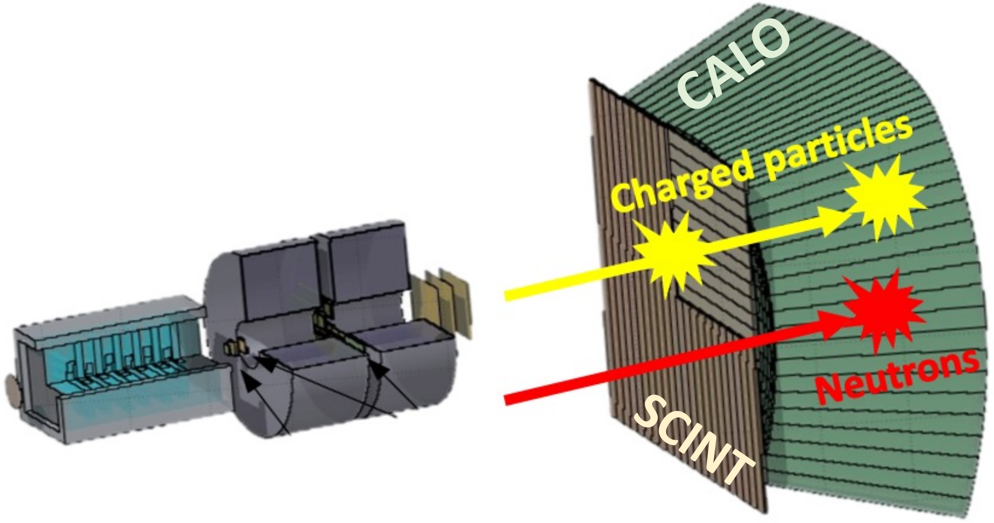
Z=1	67 % ± 5%
Z=2	19 % ± 2%
Z=3	10 % ± 2%
$Z \geq 4$	4 % ± 1%

Integrated over the detector lifetime

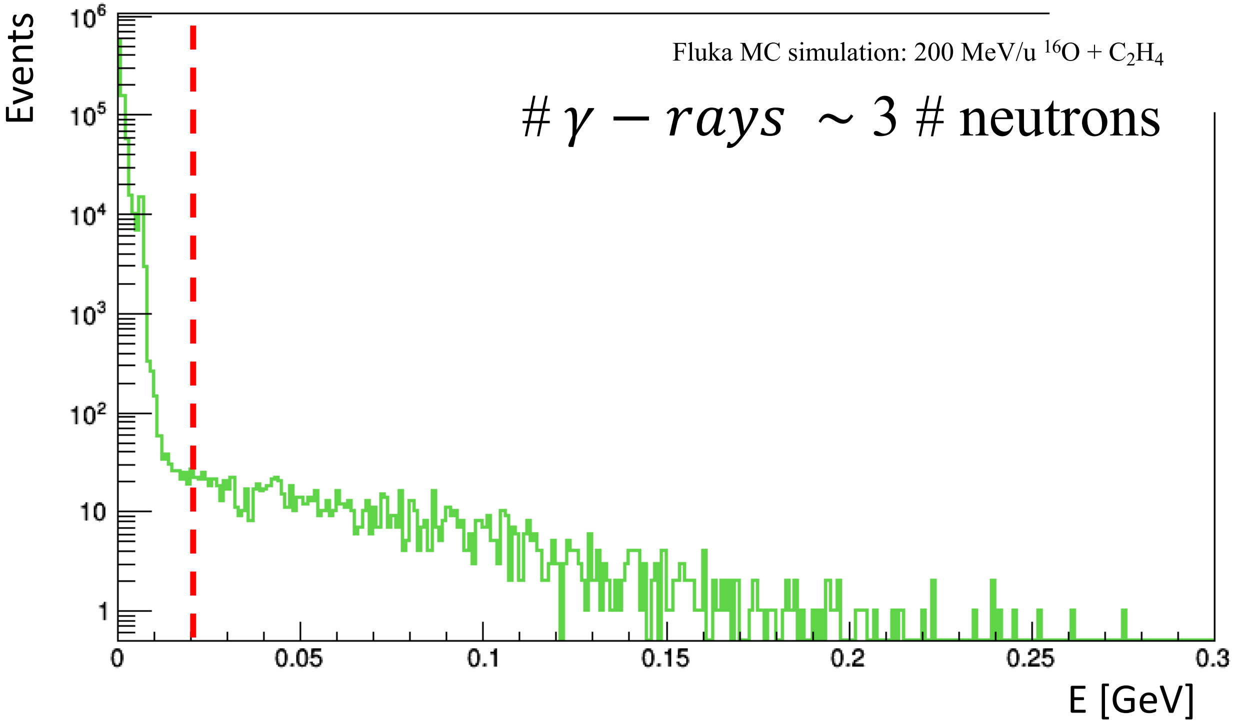


Future perspective: FOOT for neutrons

Detecting neutrons with the existing setup:



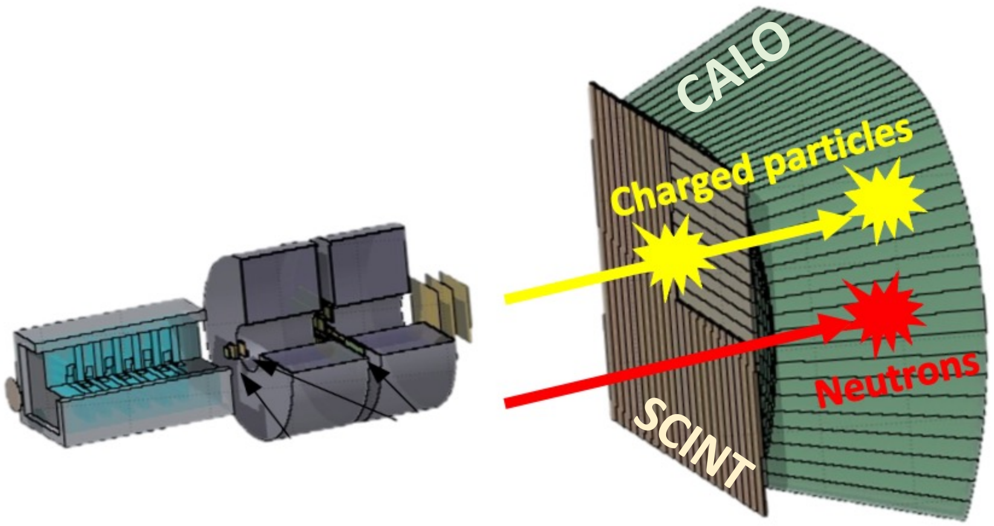
$\gamma - rays$ contribution from everywhere



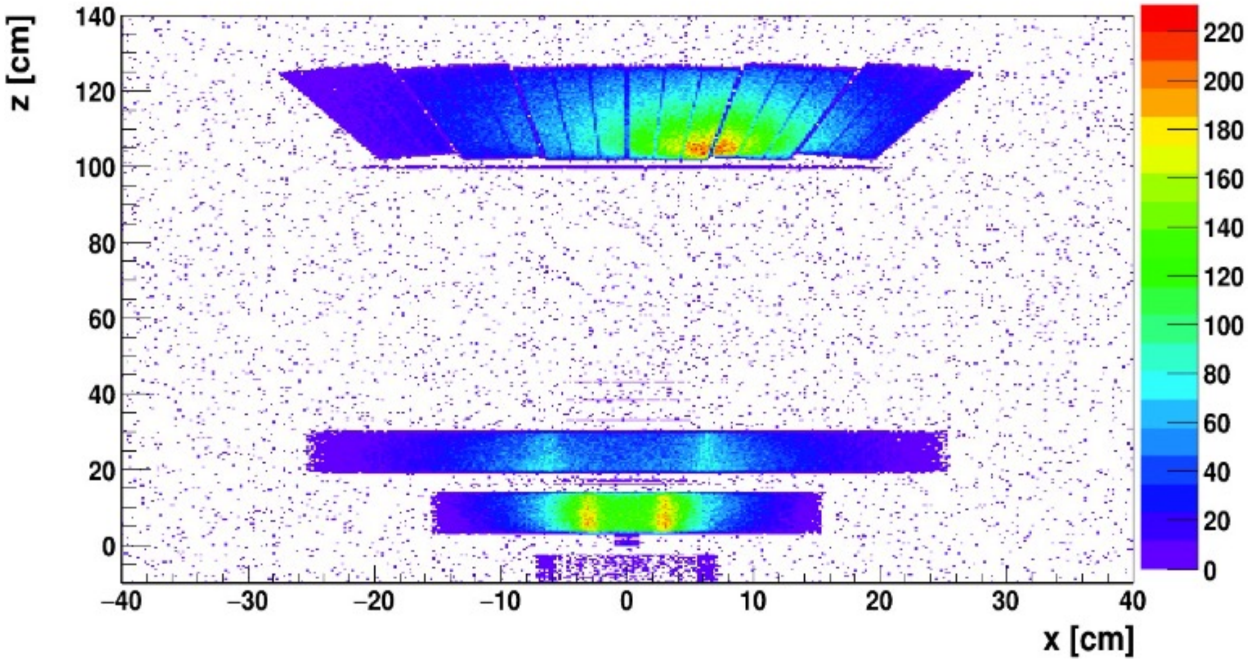
A discrimination level of 20 MeV makes the gamma-rays background negligible

Future perspective: FOOT for neutrons

Detecting neutrons with the existing setup:



Interaction position of all neutrons



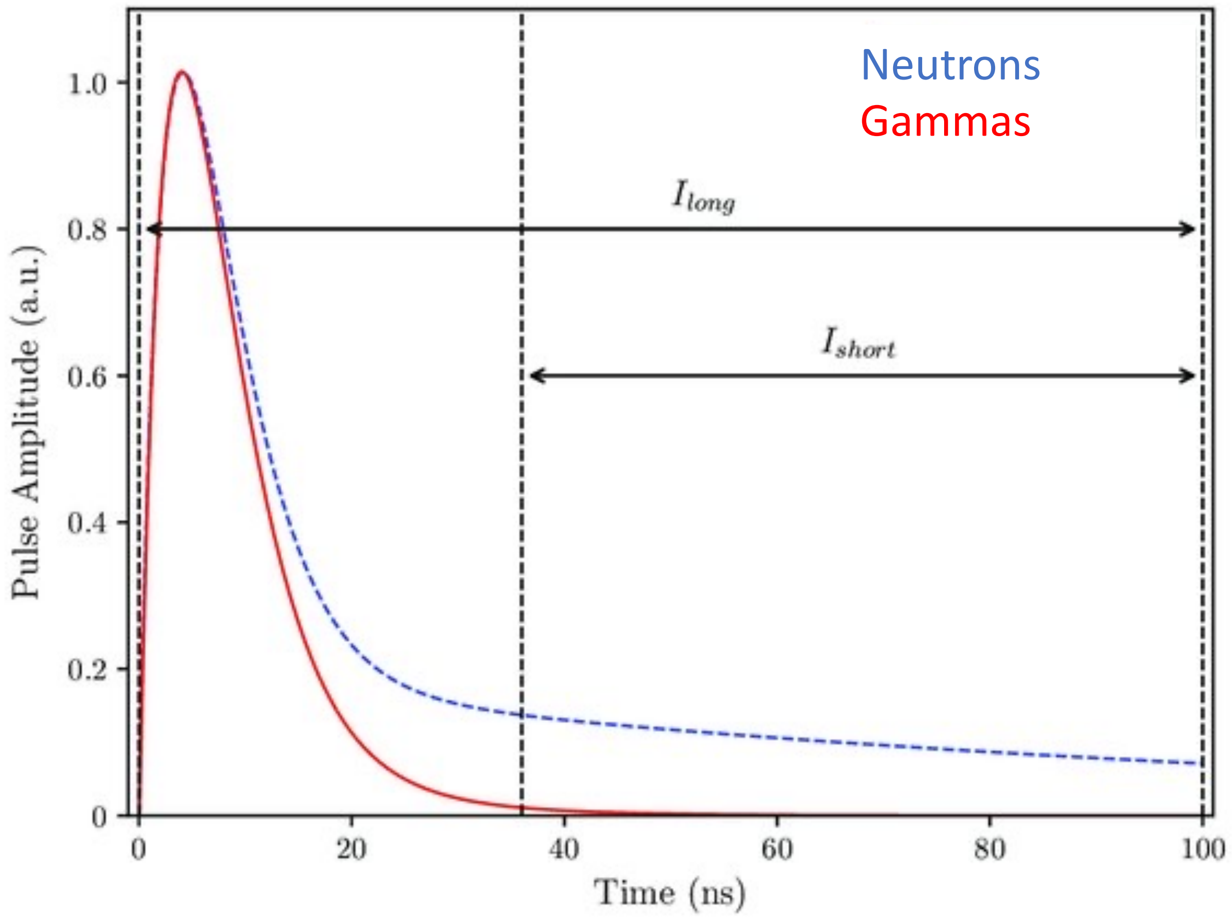
Neutrons generated outside the target:

- magnets / target ~ 2
- calorimeter / target ~ 4

Only 1/5 reach the calorimeter for detection

Pulse Shape Discrimination

Signal from a scintillating crystal



A different signal shape is expected:

- $\boldsymbol{\gamma}$ generate a fast signal described by an exponential decay with $\boldsymbol{\tau_{FAST}} \sim$ **3.2 ns**
- **Neutrons** generate a longer tail described by the convolution of two exponential decays with $\tau_{FAST} \sim$ 3.2 ns and $\boldsymbol{\tau_{SLOW}} \sim$ **32.2 ns**

⬇

Separating the short and long components of the signal
is the key to identify neutrons from γ