Nuclear fragmentation cross section measurement with the FOOT experiment

Riccardo Ridolfi

on behalf of the FOOT collaboration

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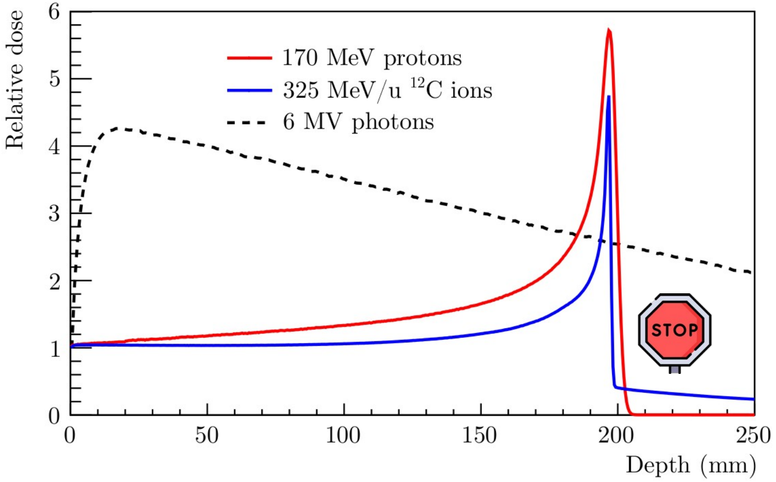
Hadrontherapy

Space radioprotection

The FOOT experiment

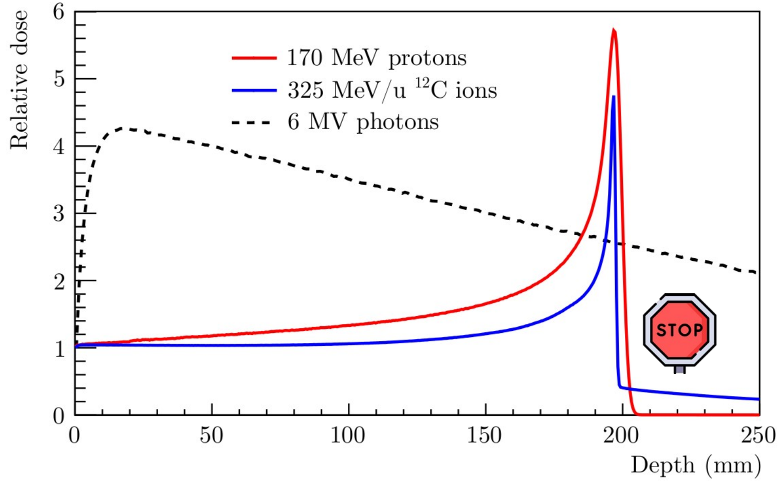
First analysis of GSI2021 data

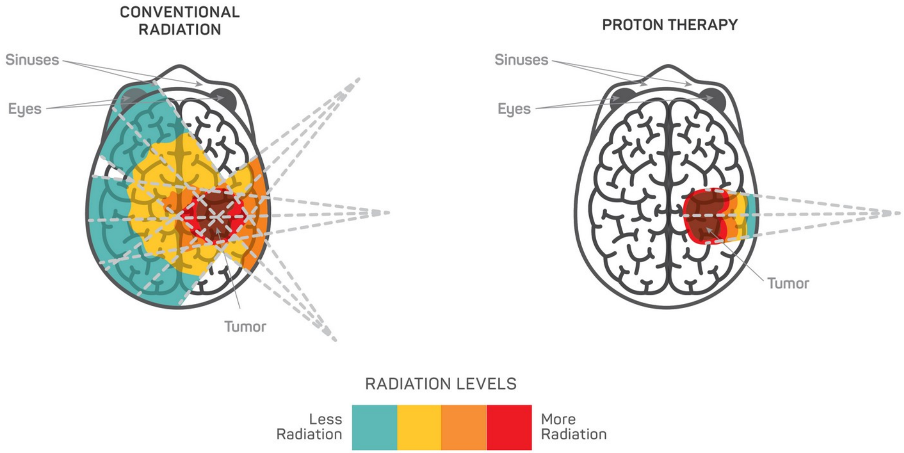
Hadrontherapy



-**low dose** in the entrance channel
-**Bragg peak**
-**range** can be **adjusted** with incident ion energy

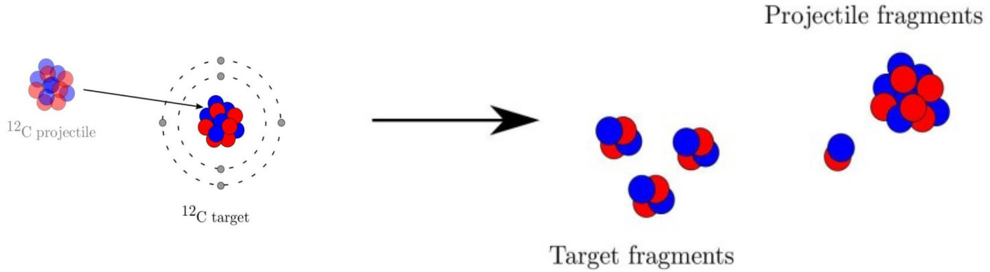
Hadrontherapy





-**low dose** in the entrance channel
-**Bragg peak**
-**range** can be **adjusted** with incident ion energy
-powerful for treatment **near organs at risk**

Nuclear fragmentation



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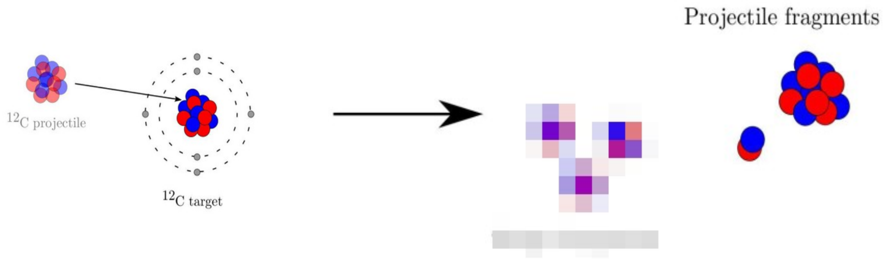
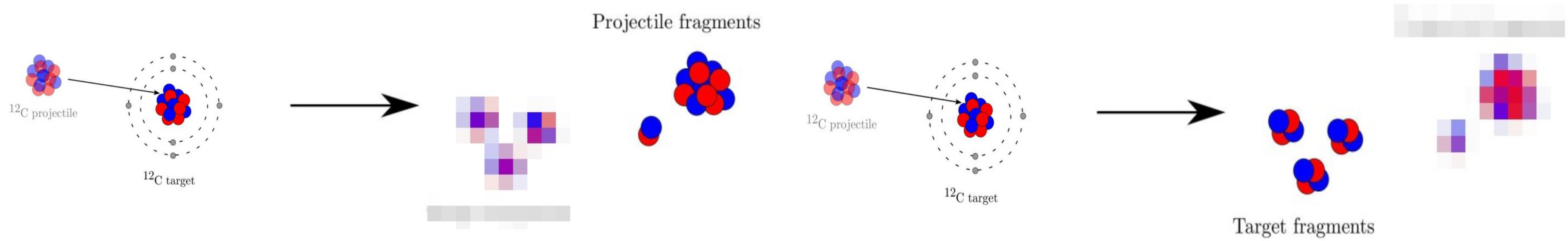


-projectile fragments have a **longer range**
-**non-zero dose** beyond the Bragg peak to address
-**not present** in protontherapy

Nuclear fragmentation



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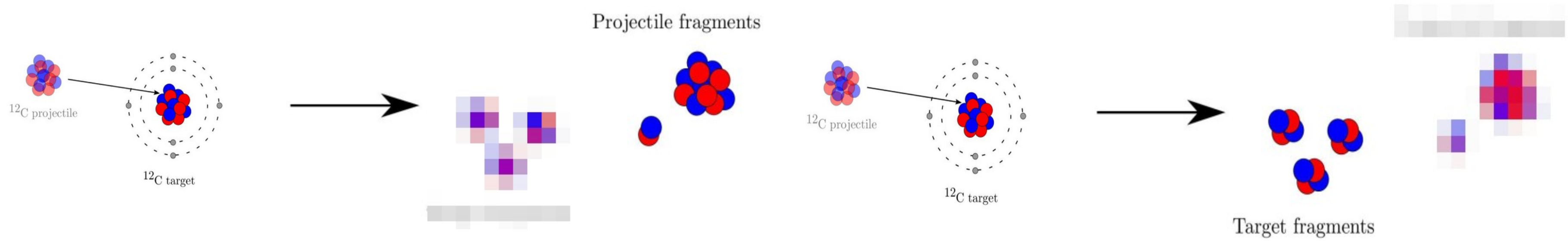
-target fragments have very **low energies** (short range, hundreds of μm)
-**difficult to detect**
-their **damage** can be more important in **healthy tissues**
-biological **effectiveness of protons** still in question

Nuclear fragmentation

Nuclear fragmentation cross section measurement with the FOOT experiment

R.Ridolfi



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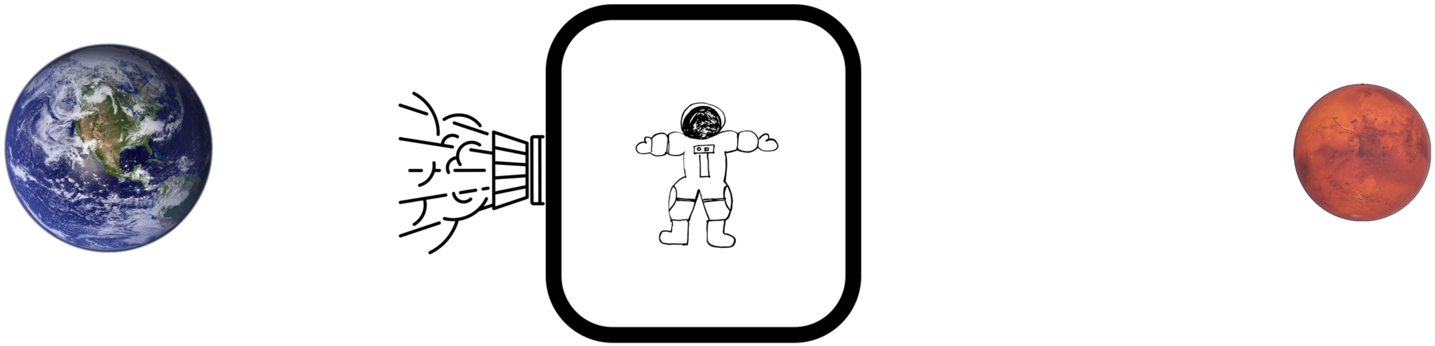
$$\sigma_R = \int_0^{\Omega} \int_0^{\infty} \frac{d^2\sigma}{dE_K d\Omega} dE_K d\Omega$$

Space radioprotection



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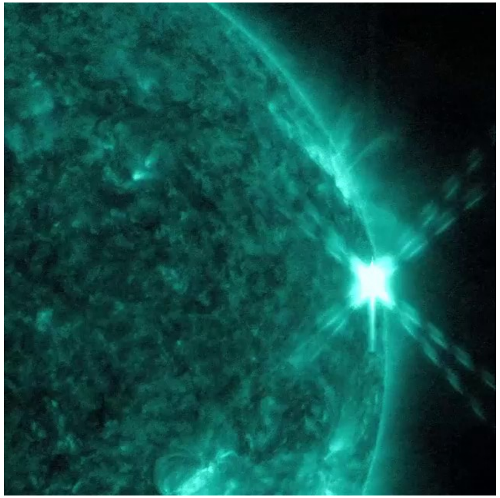


Solar Particle Events (SPEs)

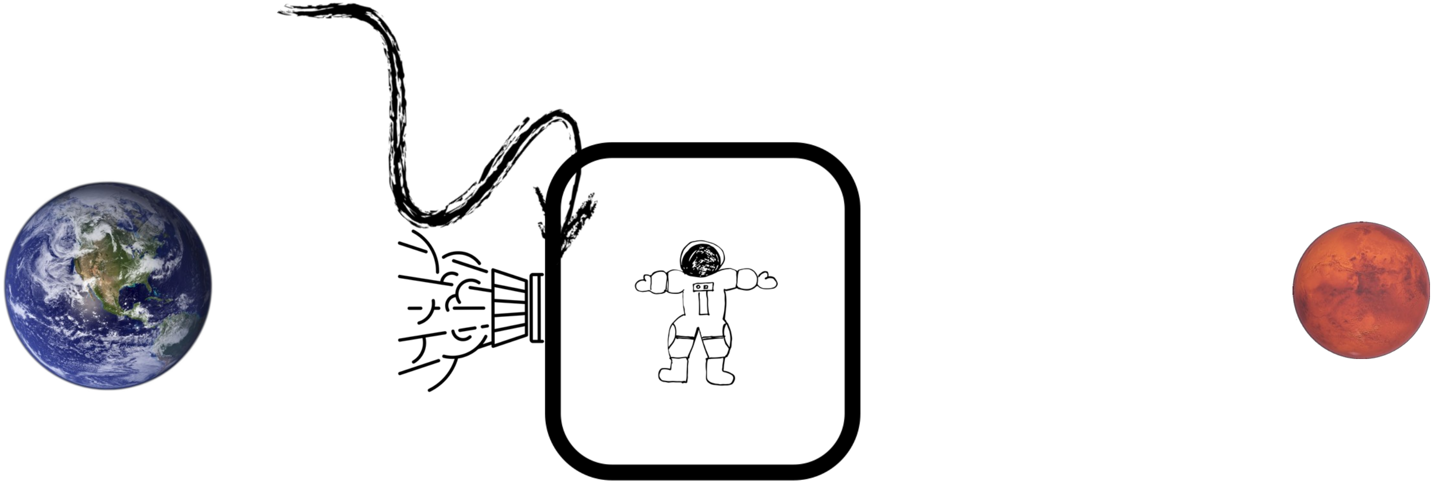
suddenly

92% p

6% He

2% HZE

<1 GeV/n



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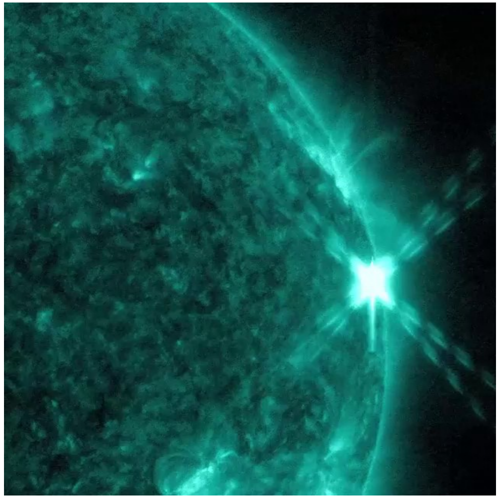

Solar Particle Events (SPEs)
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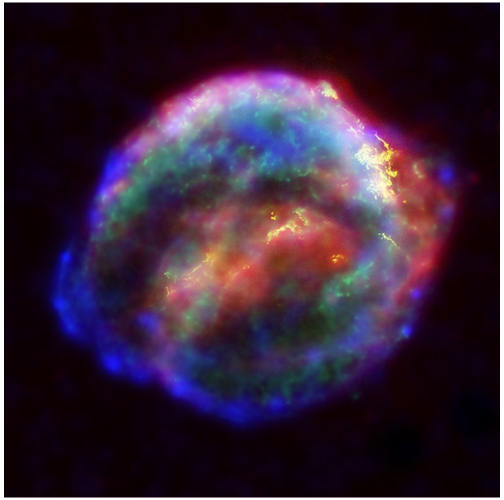
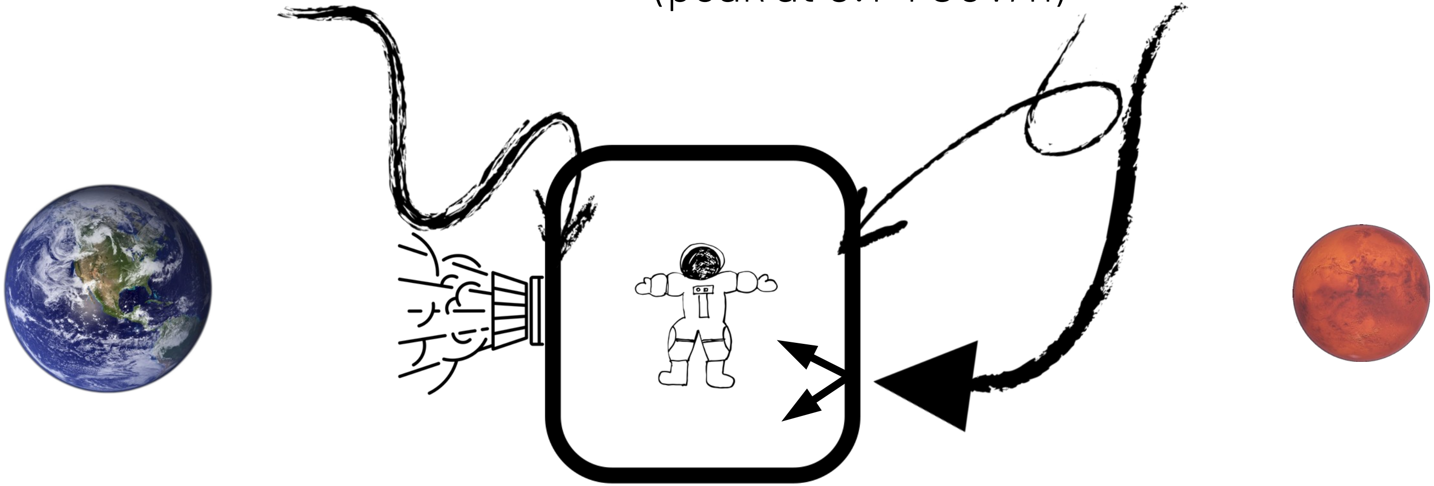
6% He
2% HZE

<1 GeV/n

Galactic Cosmic Rays (GCRs)
constantly
90% p
9% He
1% HZE

0.001-10^{14} GeV/n
(peak at 0.1-1 GeV/n)





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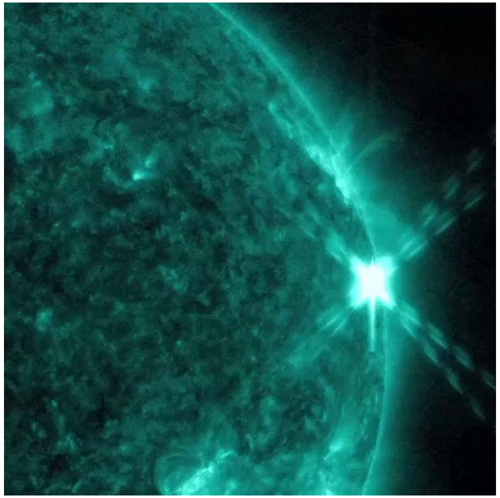

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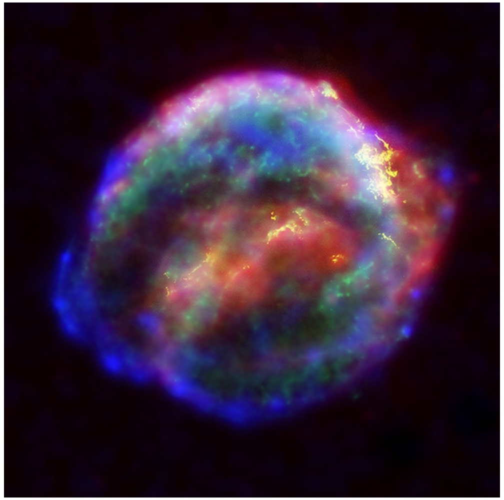
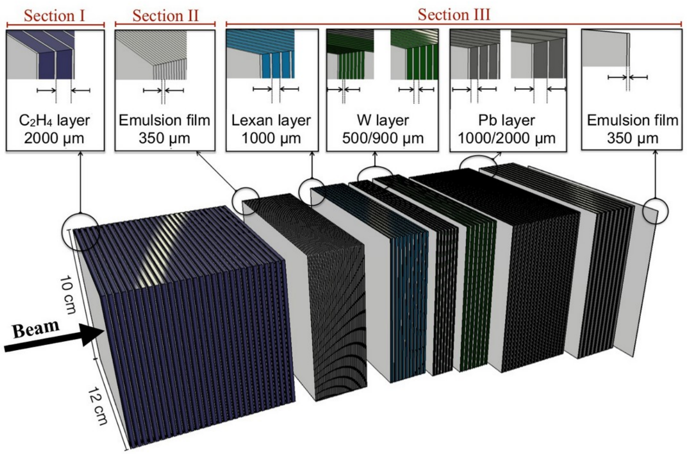
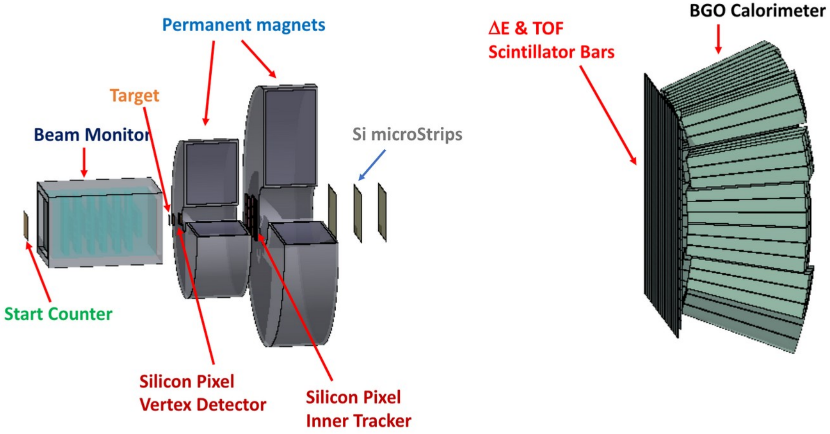


$$\sigma_R = \int_0^\Omega \int_0^\infty \frac{d^2\sigma}{dE_K d\Omega} dE_K d\Omega$$

The FOOT (FragmentatiOn Of Target) experiment





measurement of **double differential cross sections** in angle and kinetic energy with a maximum uncertainty of 5%

direct/inverse kinematics and cross section subtraction

isotopic identification by measuring all kinematic quantities

table top setup to be moved according to beam availability

the **core program** can be **extended** thanks to its flexibility

The FOOT experiment: core program

Physics	Application field	Beam	Target	Upper Energy (MeV/nucleon)	Kinematic approach
Target fragmentation	Hadrontherapy	^{12}C	C, C_2H_4	200	inverse
Target fragmentation		^{16}O	C, C_2H_4	200	inverse
Beam fragmentation	Hadrontherapy	^{4}He	C, C_2H_4, PMMA	250	direct
Beam fragmentation		^{12}C	C, C_2H_4, PMMA	400	direct
Beam fragmentation		^{16}O	C, C_2H_4, PMMA	500	direct
Beam fragmentation	Space	^{4}He	C, C_2H_4, PMMA	800	direct
Beam fragmentation		^{12}C	C, C_2H_4, PMMA	800	direct
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Beam fragmentation		^{12}C	C, C_2H_4, PMMA	800	direct
Beam fragmentation		^{16}O	C, C_2H_4, PMMA	800	direct

more beam-target settings **to explore...**

The FOOT experiment: emulsion setup

Nuclear fragmentation cross section measurement with the FOOT experiment

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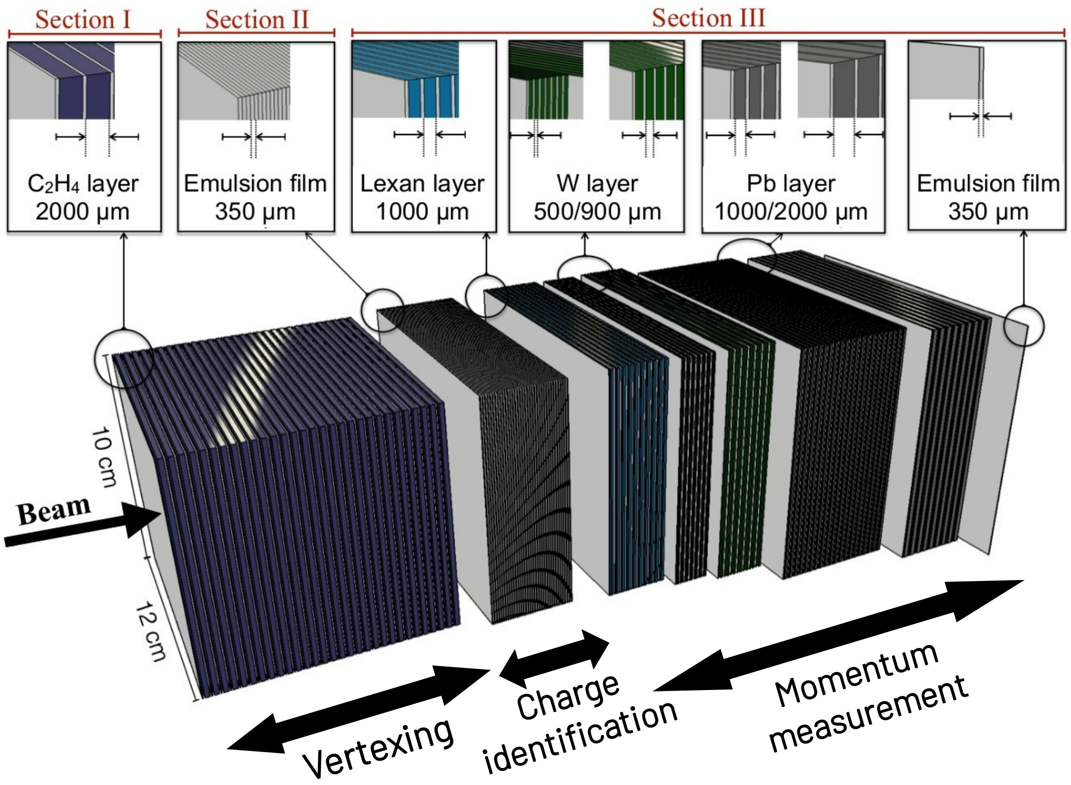


Emulsion Cloud Chamber setup

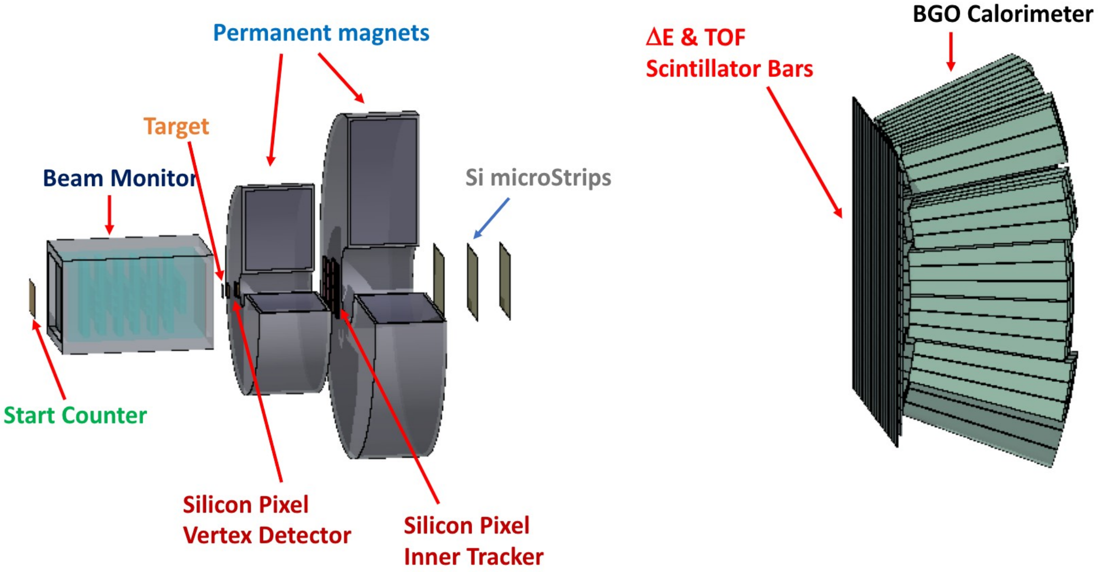
designed for **light fragments** ($Z \leq 3$)

high angular acceptance (70°)

no need of **real time data acquisition**

emulsions have to be **developed** after the irradiation

The FOOT experiment: electronic setup



large variety of detectors

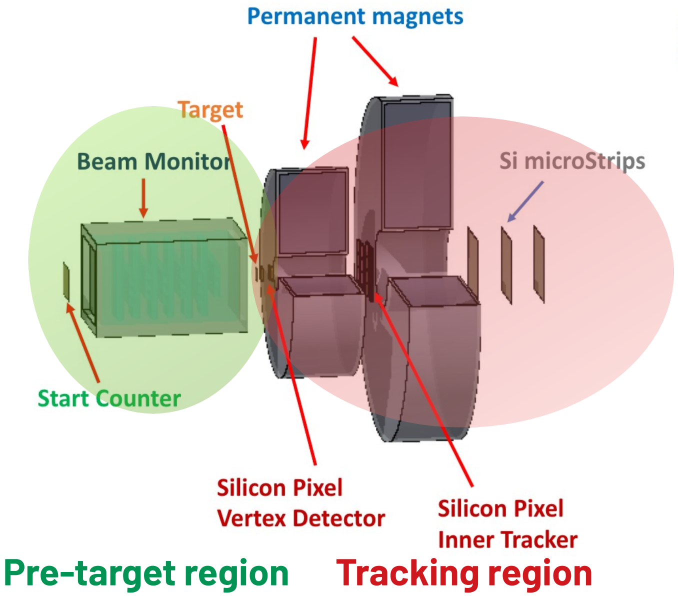
highly distributed data acquisition system

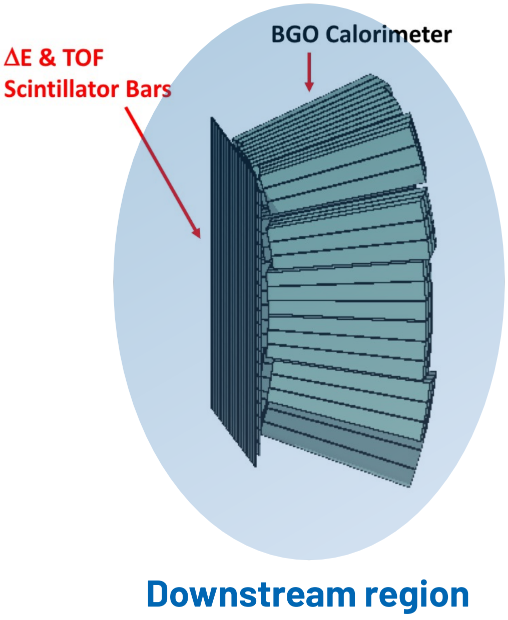
designed for **heavier fragments** $(3 \leq Z \leq 8)$

angular acceptance of **10°**

to be completed in **2023**

The FOOT experiment: electronic setup





large variety of detectors

highly distributed data acquisition system

designed for **heavier fragments** $(3 \leq Z \leq 8)$

angular acceptance of **10°**

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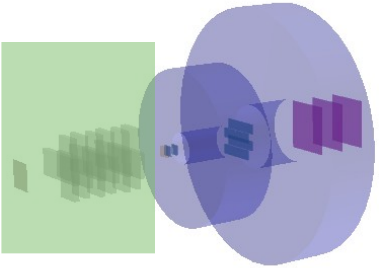
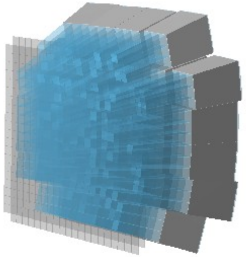
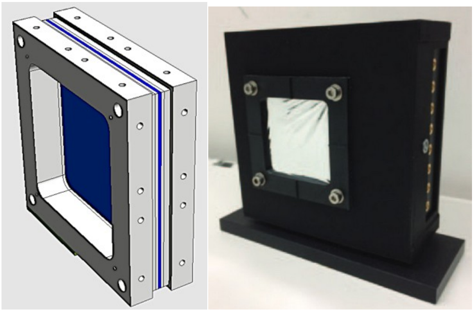
Electronic setup: pre-target region





beam characterization

Start Counter (SC)



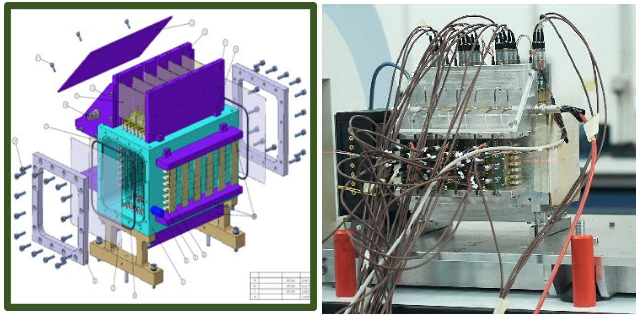
Trigger and ToF start

250 μm thick plastic scintillator

5x5 cm^2 active area

48 SiPM → 8 channels

Beam Monitor (BM)



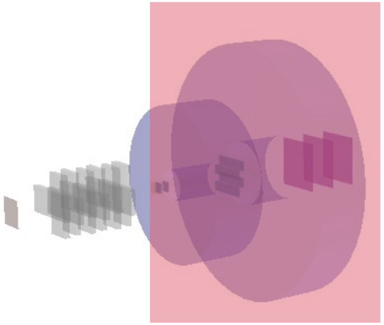
Beam momentum and direction

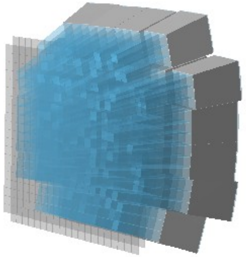
Rejection of pre-target fragmentation

Drift chamber Ar/CO_2 (80%/20%)

12 layers with 3 cells each (orthogonal views)

Electronic setup: tracking region



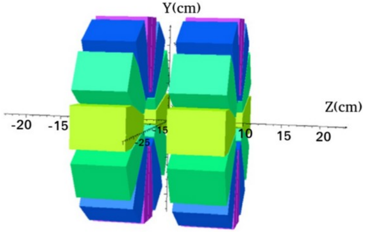


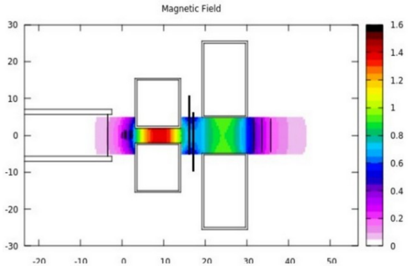
fragment tracking
momentum measurement

Vertex (VTX) & Inner Tracker (IT)

Mimosa-28 Si pixel
20 μm pitch
VTX→4 layers   IT→2 layers

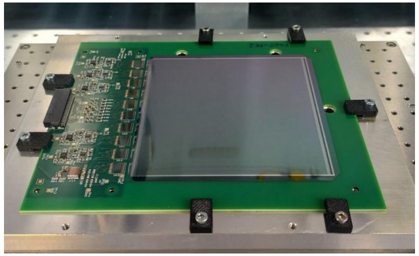
Magnets





2 permanent magnets Halbach configuration
B field in y axis up to 1.2 T

Microstrip detector (MSD)



3 pairs of X-Y layers
9 x 9 cm^2 active area
150 μm readout pitch

Electronic setup: downstream region

Nuclear fragmentation cross section measurement with the FOOT experiment

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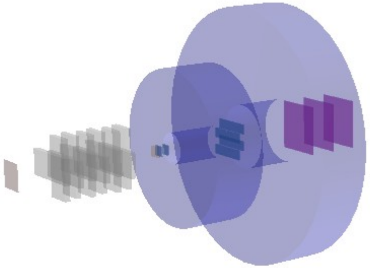
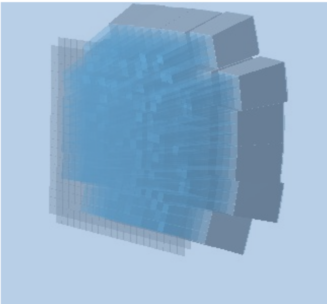
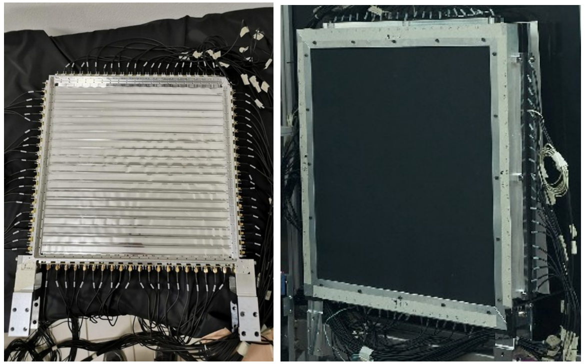



fragment identification

TOF Wall (TW)



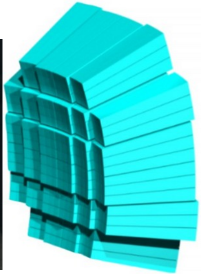
ΔE – TOF

44 cm x 2 cm x 3 mm plastic scintillator bars

2 layers of 20 bars each

SiPM readout

Calorimeter (CALO)

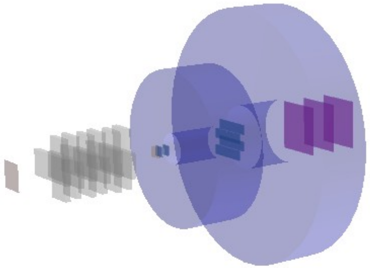



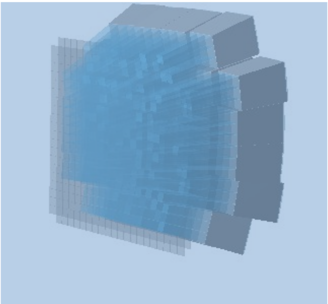
Kinetic energy

BGO scintillator

320 crystals 2 (3) x 2 (3) x 24 cm^3

Electronic setup: downstream region





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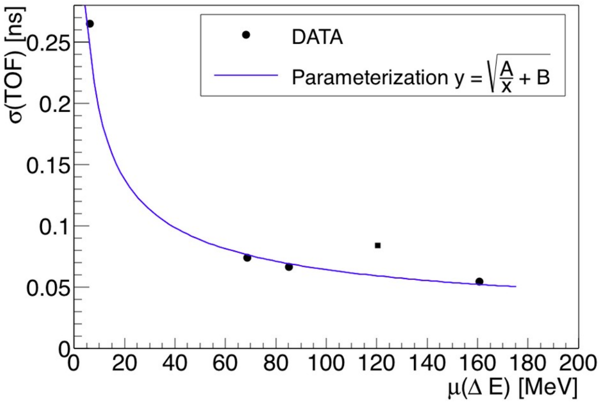
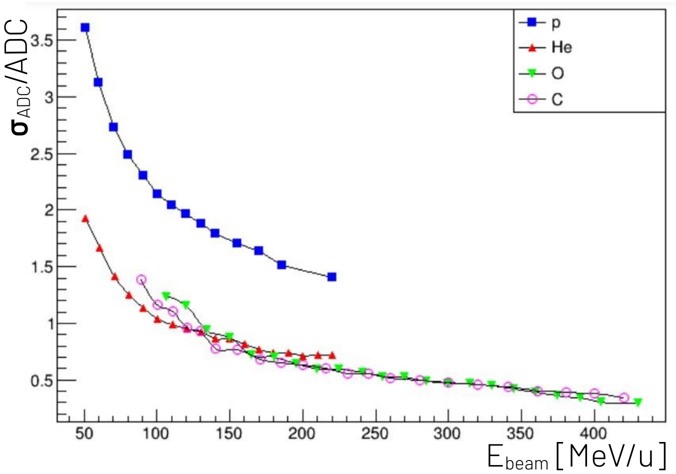
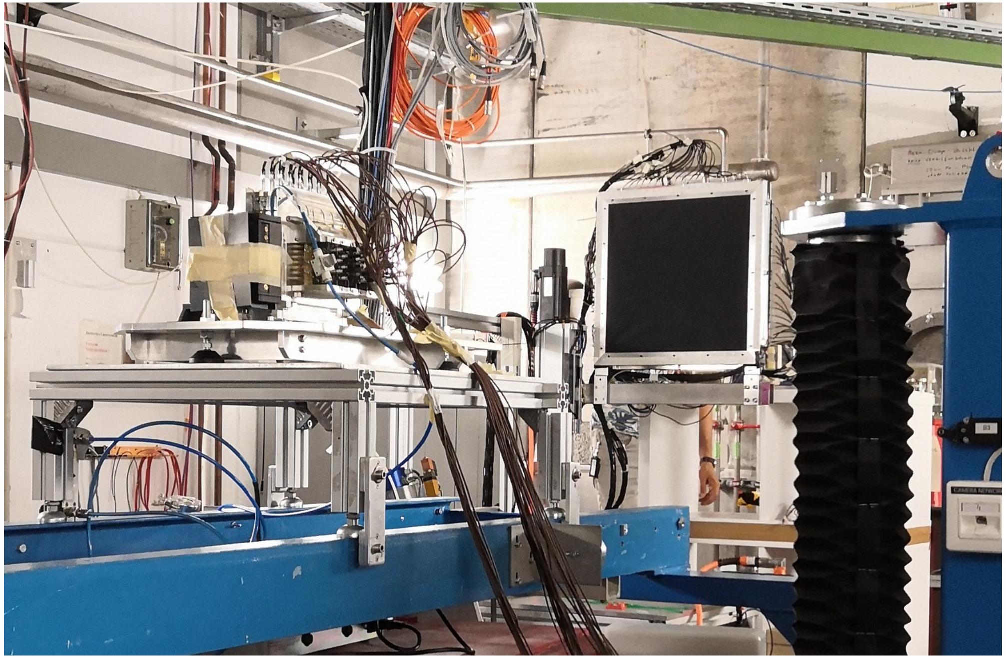




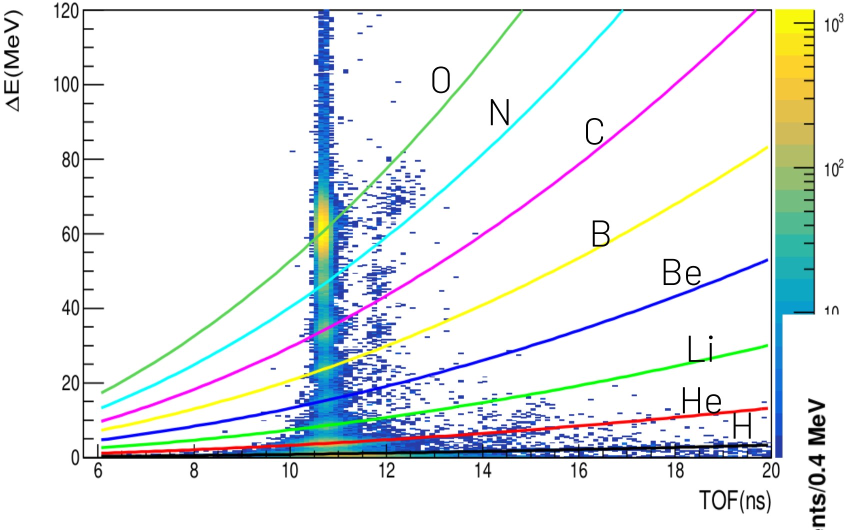
GSI2021 campaign

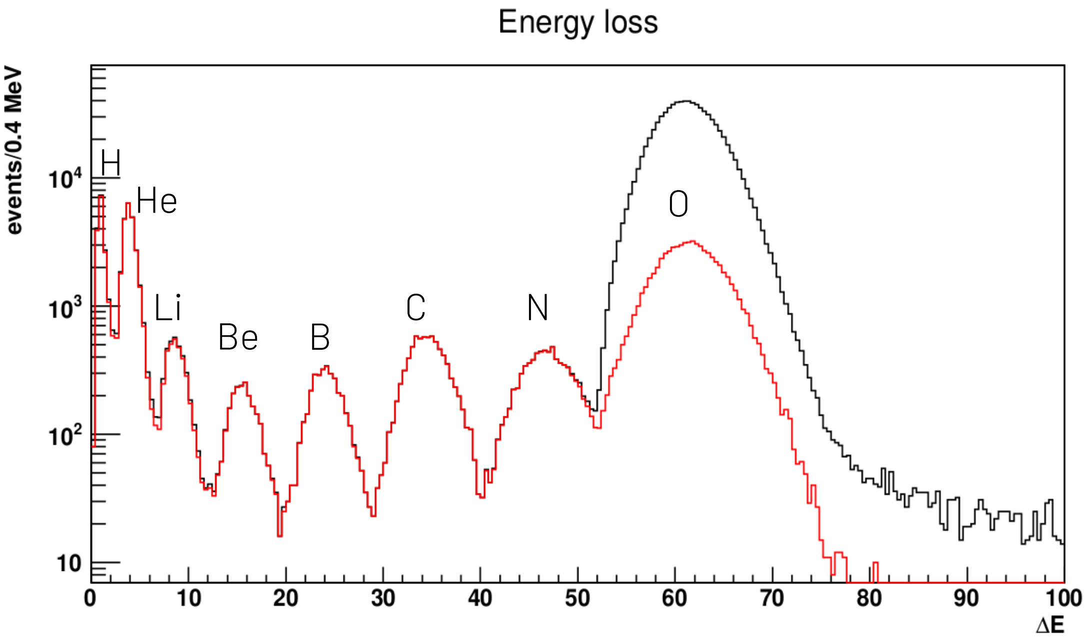
400 MeV/u ^{16}O beam on 5mm Carbon target
angular acceptance of 4.85°



1.3 Mevents Minimum Bias with target
2 Mevents Minimum Bias + frag with target
57 kevents Minimum Bias without target

Analysis





excellent charge separation!

Cross sections

Nuclear fragmentation cross section measurement with the FOOT experiment

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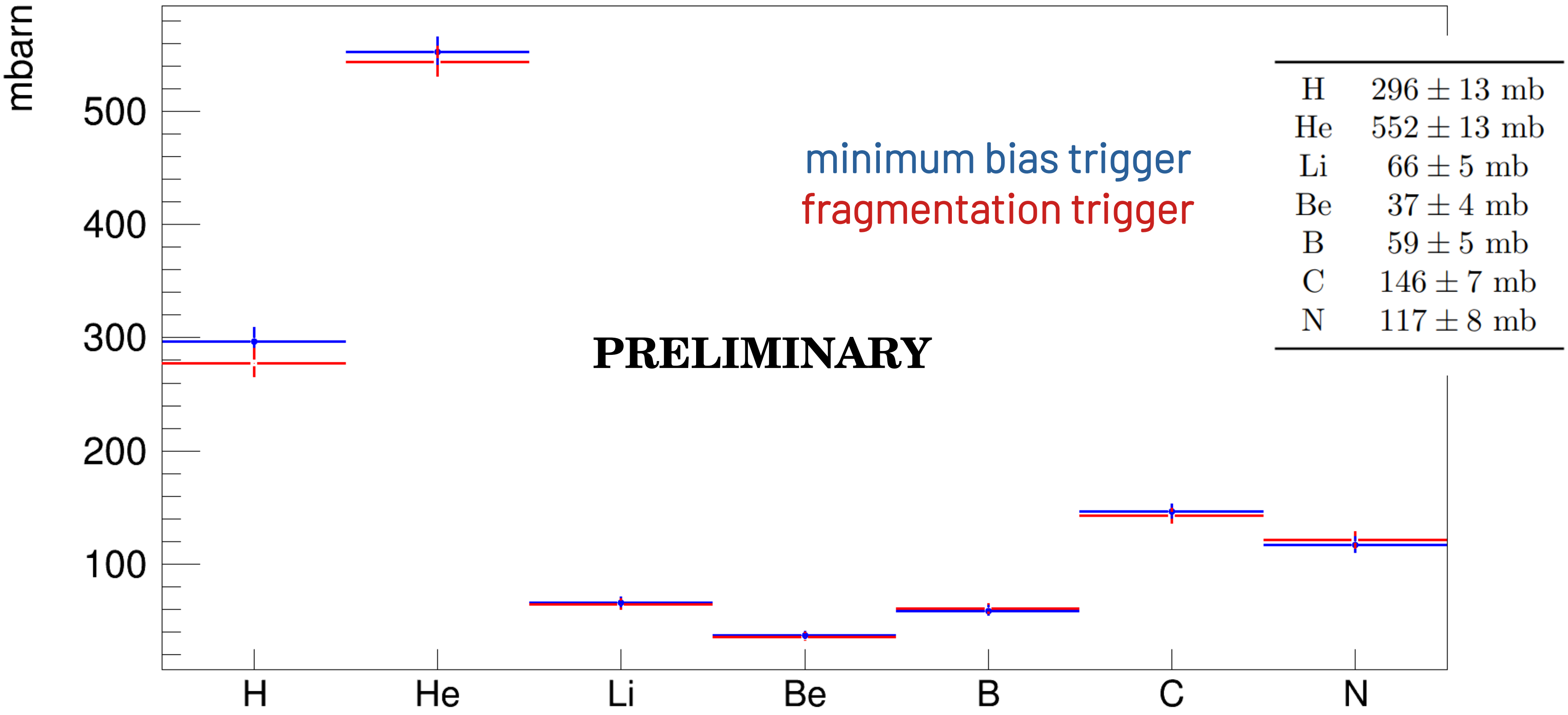

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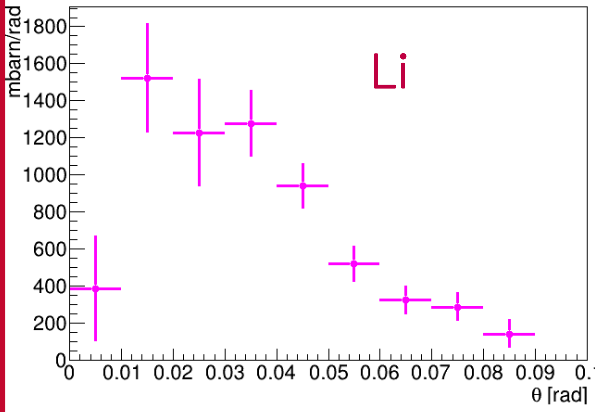
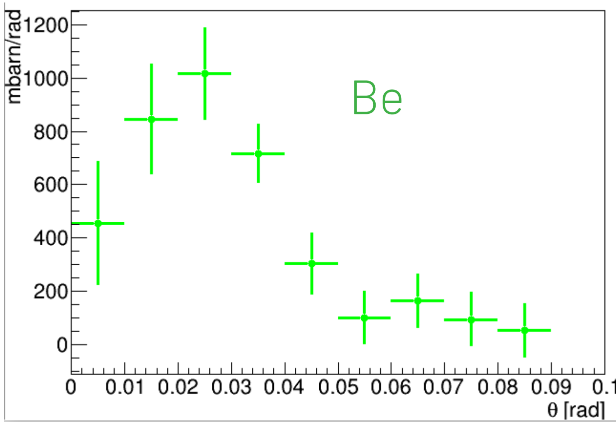
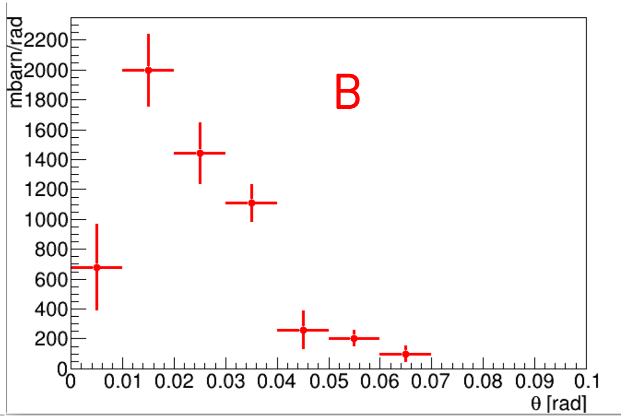
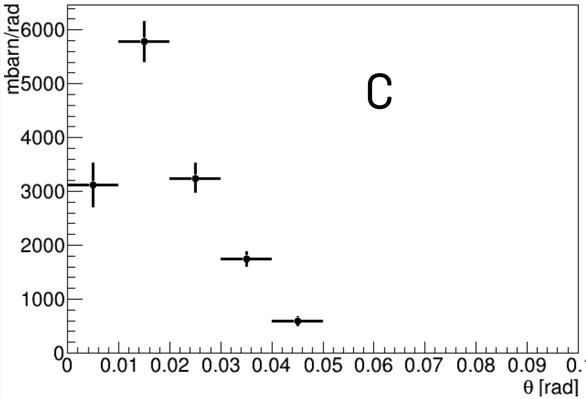
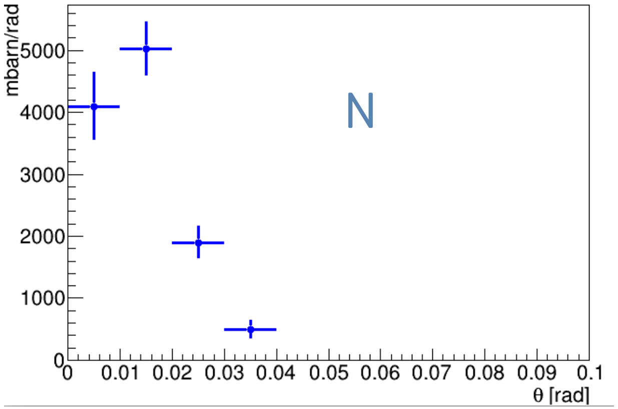






PRELIMINARY



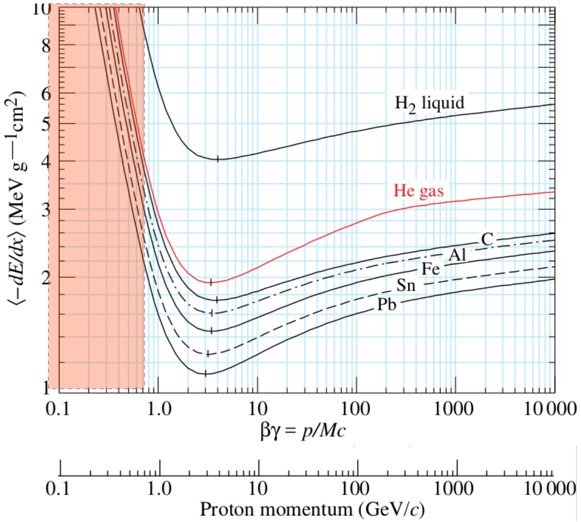


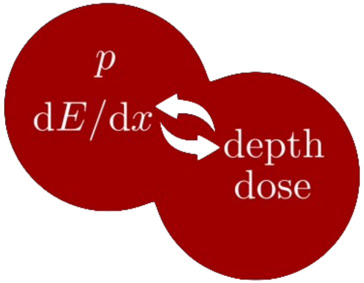
First available measurements!

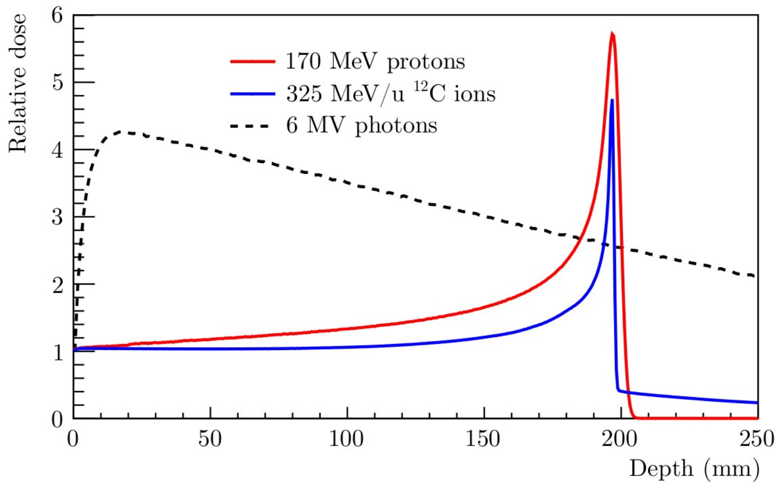
Conclusions

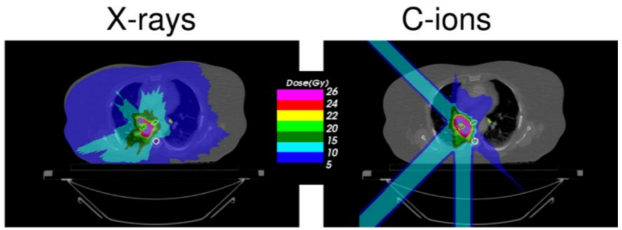
-several fields can profit from **double differential cross section** measurement (hadrontherapy, space radioprotection...)
-the FOOT experiment aims to **measure double differential cross sections in angle and kinetic energy** for various beam-target settings
-**data taking campaigns are ongoing** (GSI2019, GSI2020, GSI2021, HIT2022) with different beams and energies
-electronic setup to be completed in **2023**
-more than **40M events** acquired at GSI in July 2021 with Oxygen beam
-more than **90M events** acquired at HIT in July 2022 with Helium beam
-**first cross section measurements** from GSI2021 show good capabilities to fulfill FOOT program
-a **continuous** data taking **activity** will be carried out (CNAO2022, beam request @GSI)

Thanks for listening!







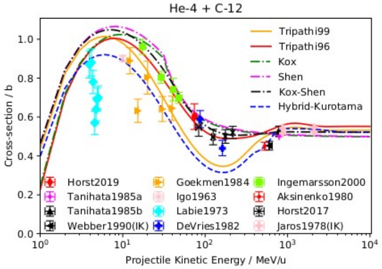


$$-\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle = \frac{2\pi N_a e^4 \rho}{m_e} \frac{Z}{A} \frac{z^2}{v^2} \left[\ln\left(\frac{2 m_e \gamma^2 v^2 W_{\max}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right]$$

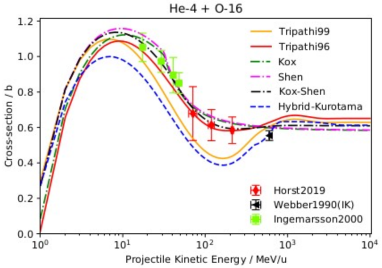
$$p = \frac{\sqrt{E_k\,(E_k + 2m_0c^2)}}{c} \qquad \mathcal{E} = \frac{E_k}{m_0c^2}. \qquad \beta\gamma = \sqrt{\mathcal{E}(\mathcal{E}+2)}.$$

$$R_{m_x} \approx \frac{m_x}{m_p}\frac{z_p^2}{z_x^2} R_{m_p} \qquad \frac{\sigma_{R1}}{\sigma_{R2}} \approx \sqrt{\frac{m_2}{m_1}}.$$

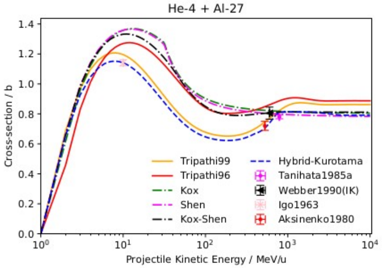
$$\sigma_R = \pi r_0^2 c_1(E) \left(A_p^{1/3} + A_t^{1/3} - c_2(E) \right)^2$$



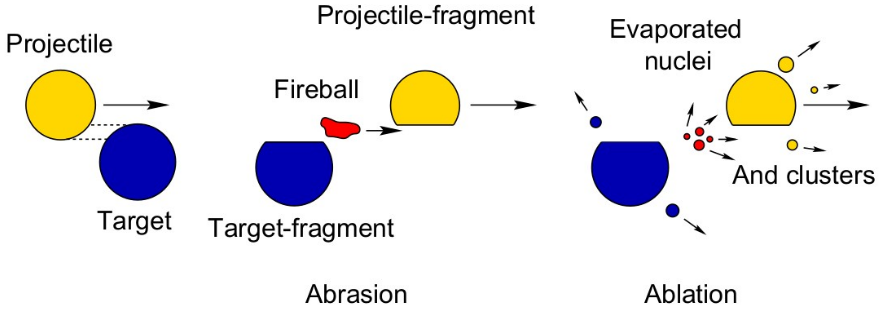
(a)

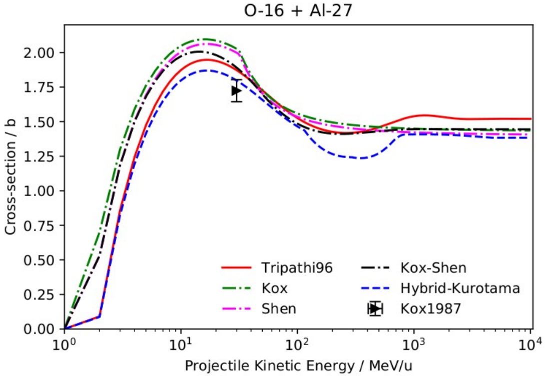


(b)

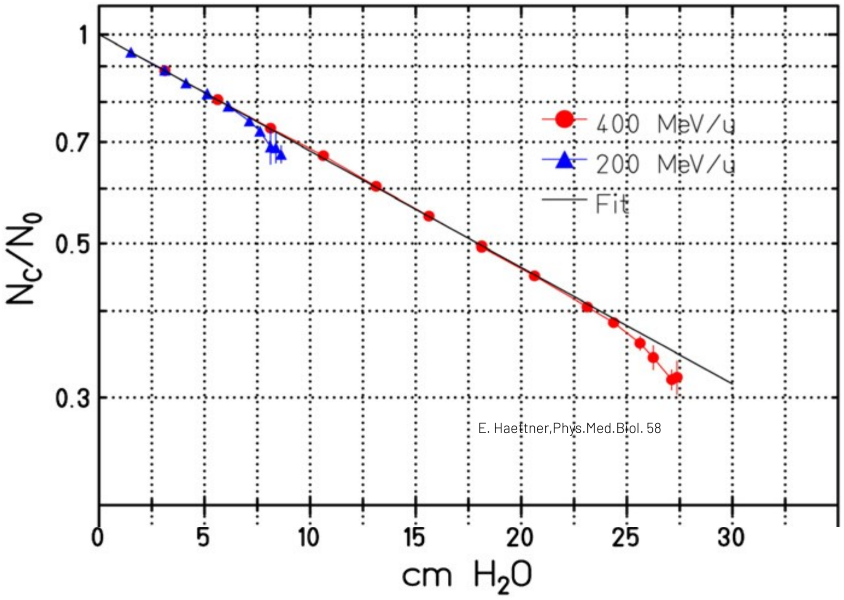


(c)





Nuclear fragmentation



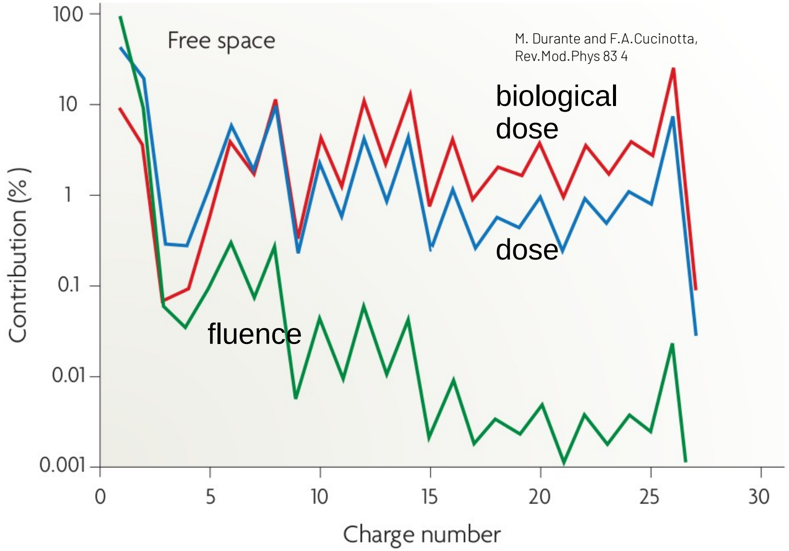
-**attenuation** of primary beam can be important at **large** penetration **depths**
-**surviving ions** can be counted and **related to total reaction cross sections**

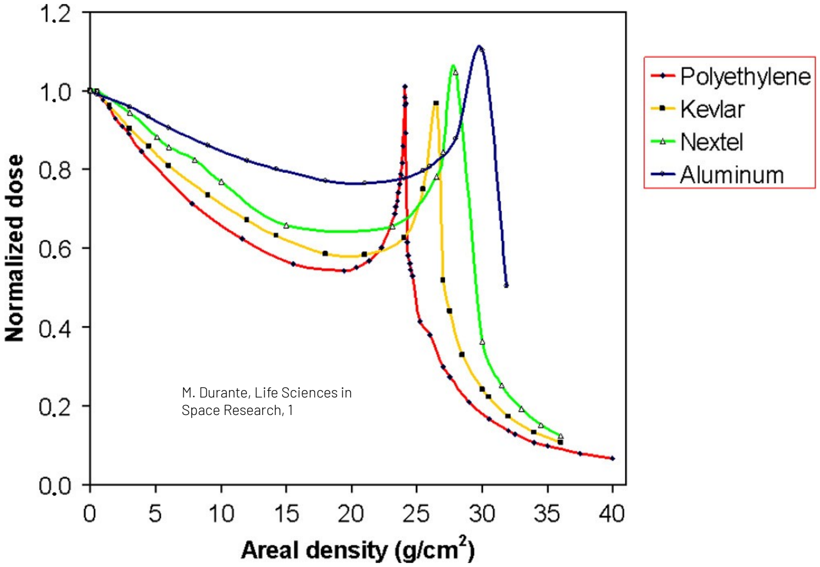
$$P(x) = \frac{N(x)}{N(0)} = \exp(-x/\lambda_{\rm int})$$

$$\sigma_R = \int_0^{\Omega}\int_0^{\infty} \frac{d^2\sigma}{dE_K d\Omega} dE_K d\Omega$$

$$\lambda_{\rm int} = \frac{A_t}{N_a \sigma_R \rho}$$

Space radioprotection





measurement of Bragg curves in different materials of different thicknesses

$$\sigma_R = \int_0^{\Omega} \int_0^{\infty} \frac{d^2\sigma}{dE_K d\Omega} dE_K d\Omega$$

Cross sections

400 MeV/u ^{16}O beam on 5mm Carbon target

With available data **total integrated** and angle differential cross section are achievable (no kinetic energy)

$$\Delta\sigma(Z) = \int_{E_{\text{min}}}^{E_{\text{max}}} \int_{0}^{\theta_{\text{max}}} \left(\frac{\partial^2 \sigma}{\partial\theta \partial E_{\text{kin}}} \right) \mathrm{d}\theta \mathrm{d}E_{\text{kin}} = \frac{Y(Z)}{N_{\text{prim}} \cdot N_{\text{TG}} \cdot \varepsilon(Z)}$$

Align FOOT detectors and estimate **angular acceptance**

Extract fragment yields from TW

Calculate MC efficiencies for fragments

Cross sections

400 MeV/u ^{16}O beam on 5mm Carbon target

With available data total integrated and **angle differential** cross section are achievable (no kinetic energy)

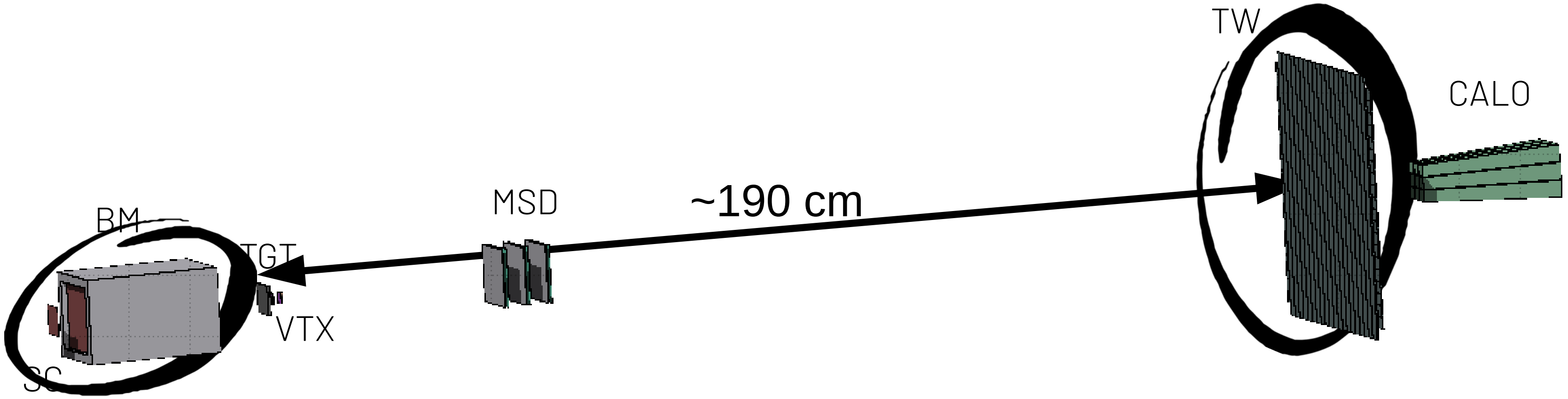
$$\frac{d\sigma}{d\theta}(Z) = \frac{Y(Z,\theta)}{N_{\text{prim}} \cdot N_{\text{TG}} \cdot \Delta\theta \cdot \varepsilon(Z,\theta)}$$

Align FOOT detectors and estimate **angular acceptance**

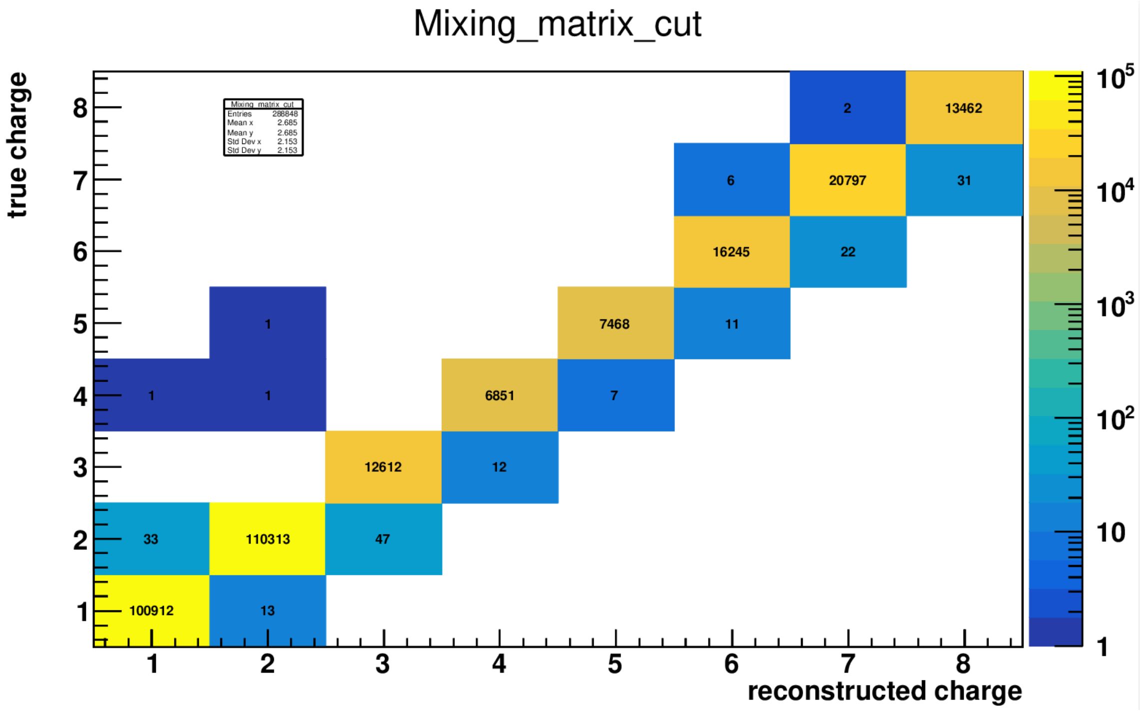
Extract fragment yields from TW

Calculate MC efficiencies for fragments

GSI2021 MC setup



Charge identification performances



Only particles with cut in E_{kin}, produced in target by primary beam inside TW acceptance

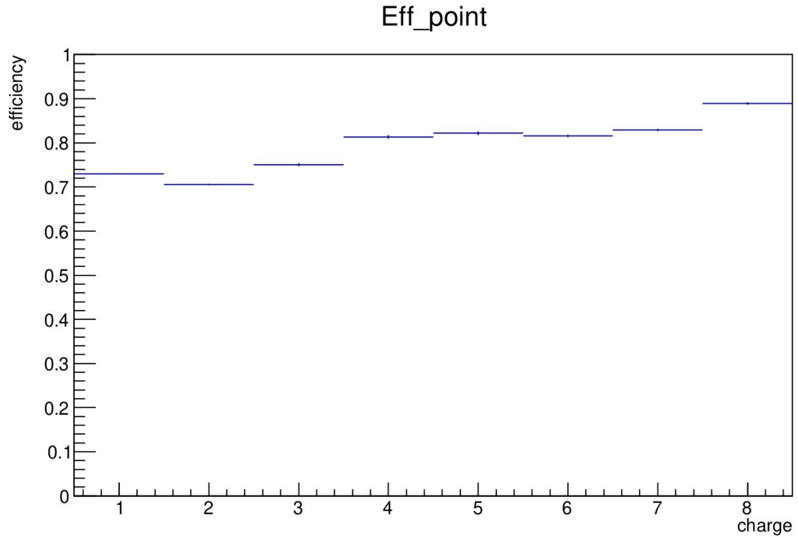
Efficiency

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

asking for a good TW point matched to a fragment produced in TG and kinetic energy between [100,600] MeV/u

asking for a fragment produced in TG within TW acceptance and kinetic energy between [100,600] MeV/u

$$\epsilon_{\varepsilon}(Z) = \sqrt{\varepsilon(Z)\frac{1-\varepsilon(Z)}{N_{\mathrm{track}}(Z)}}$$

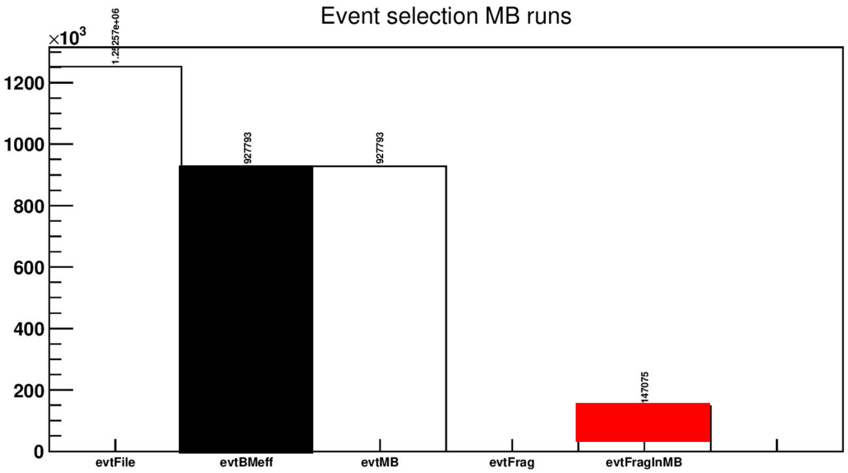


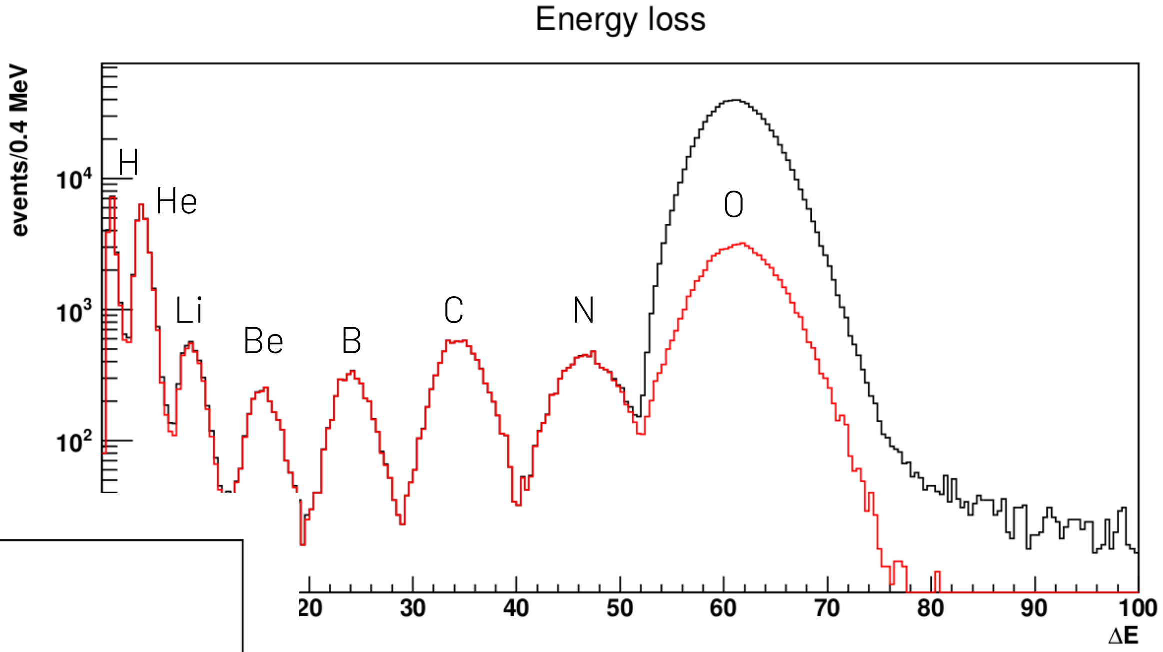
Number of primaries estimation

$$R = \frac{N_{\mathrm{evtFragInMB}}}{N_{\mathrm{evtMB}}} \approx 0.1585$$

$$\varepsilon_{\mathrm{frag}}(Z) = \frac{N_{\mathrm{evtFragInMB}}(Z)}{N_{\mathrm{evtMB}}(Z)}.$$

H	He	Li	Be
95.7 ± 0.2	98.2 ± 0.1	99.1 ± 0.2	99.3 ± 0.2
B	C	N	O
99.6 ± 0.1	99.8 ± 0.1	98.2 ± 0.1	8.46 ± 0.03

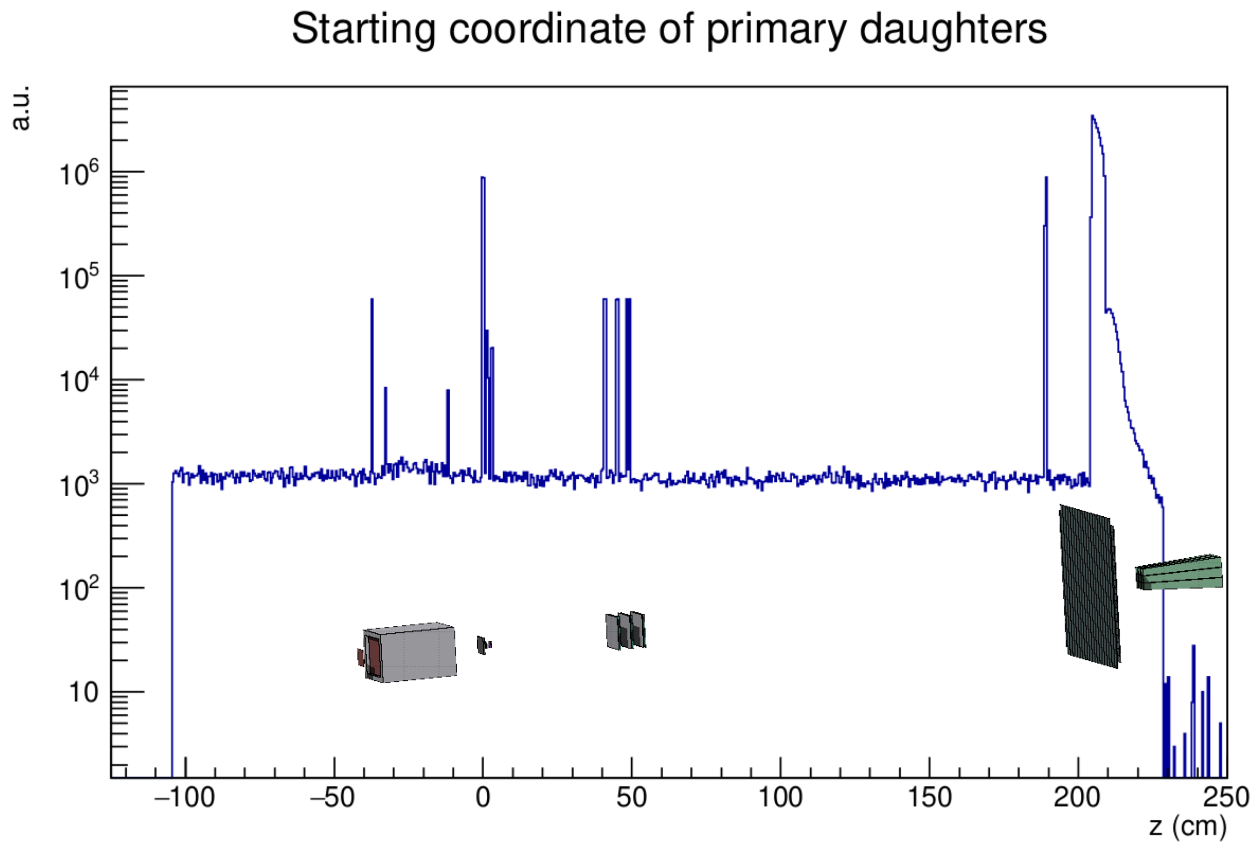




$$N_{\mathrm{prim}} = N_{\mathrm{frag}}/R$$

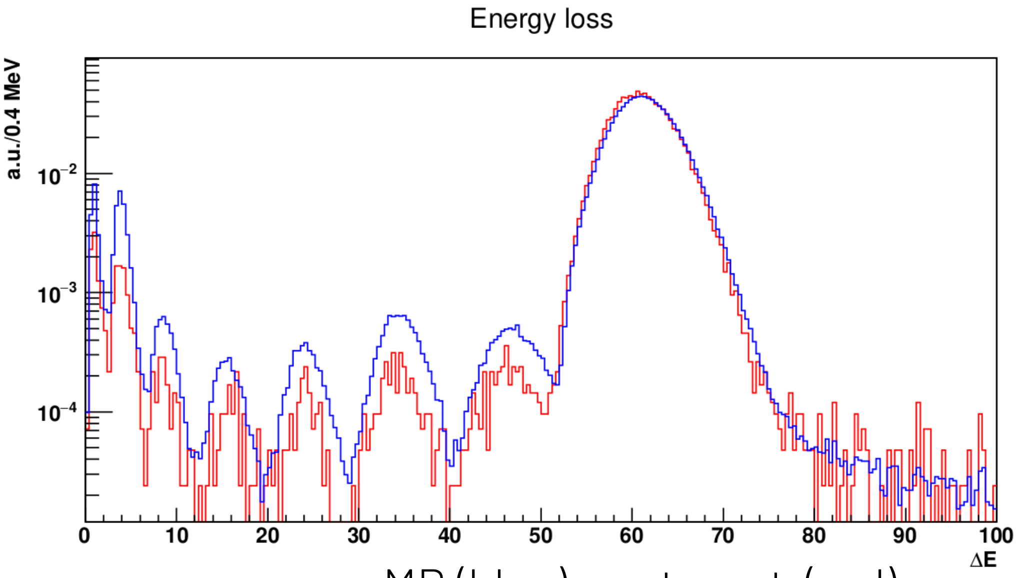
$$Y(Z) \to Y(Z)/\varepsilon_{\mathrm{frag}}(Z).$$

Out of target fragmentation from MC



Out of target fragmentation from data

Fragment	Y^{sig}	Y^{bkg}
H	16696 ± 129	339 ± 18
He	24213 ± 156	350 ± 19
Li	3591 ± 60	56 ± 8
Be	2242 ± 47	48 ± 7
B	3497 ± 59	61 ± 8
C	7944 ± 89	131 ± 11
N	8004 ± 89	179 ± 13
O	846504 ± 920	40603 ± 202



MB (blue), no-target (red)

$$\Delta\sigma(Z) = \frac{1}{N_{TG} \cdot \varepsilon(Z)} \left(\frac{Y^{sig}(Z)}{N^{sig}_{prim}(Z)} - \frac{Y^{bkg}(Z)}{N^{bkg}_{prim}(Z)} \right)$$

Comparison with literature

PHYSICAL REVIEW C **83**, 034909 (2011)

Fragmentation of ^{14}N, ^{16}O, ^{20}Ne, and ^{24}Mg nuclei at 290 to 1000 MeV/nucleon

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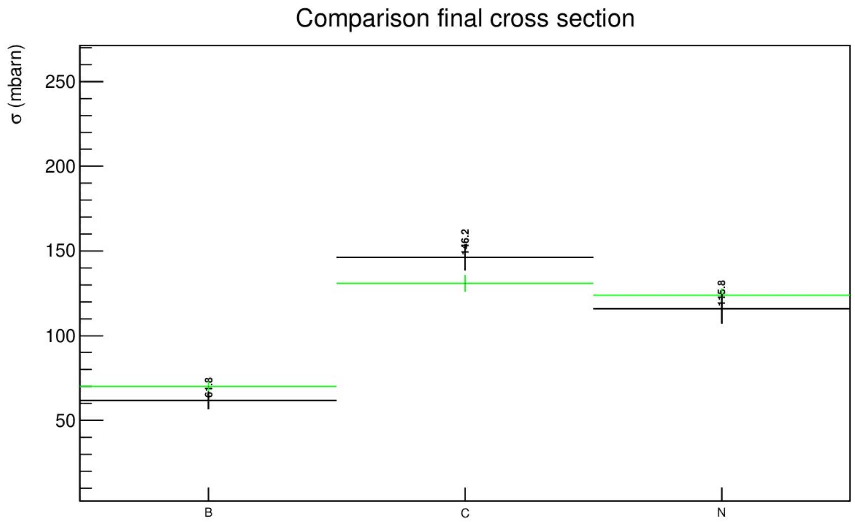
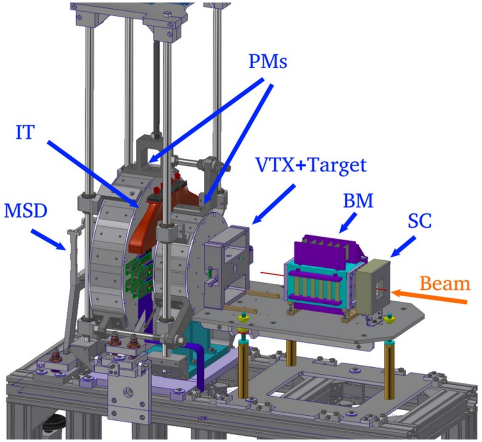
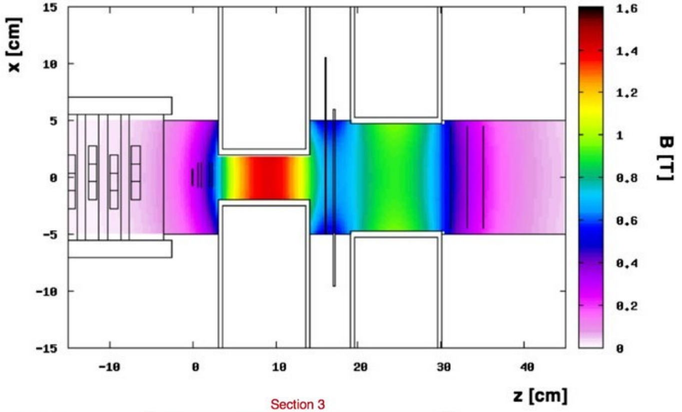
10.1103/PhysRevC.83.034909

We report fragmentation cross sections measured at 0° for beams of ^{14}N, ^{16}O, ^{20}Ne, and ^{24}Mg ions, at energies ranging from 290 MeV/nucleon to 1000 MeV/nucleon. Beams were incident on targets of C, CH_2, Al, Cu, Sn, and Pb, with the C and CH_2 target data used to obtain hydrogen-target cross sections. Using methods established in earlier work, cross sections obtained with both large-acceptance and small-acceptance detectors are extracted from the data and, when necessary, corrected for acceptance effects. The large-acceptance data yield cross sections for fragments with charges approximately half of the beam charge and above, with minimal corrections. Cross sections for lighter fragments are obtained from small-acceptance spectra, with more significant, model-dependent corrections that account for the fragment angular distributions. Results for both charge-changing and fragment production cross sections are compared to the predictions of the Los Alamos version of the quark gluon string model (LAQGSM) as well as the NASA Nuclear Fragmentation (NUCFRG2) model and the Particle and Heavy Ion Transport System (PHITS) model. For all beams and targets, cross sections for fragments as light as He are compared to the models. Estimates of multiplicity-weighted helium production cross sections are obtained from the data and compared to PHITS and LAQGSM predictions. Summary statistics show that the level of agreement between data and predictions is slightly better for PHITS than for either NUCFRG2 or LAQGSM.

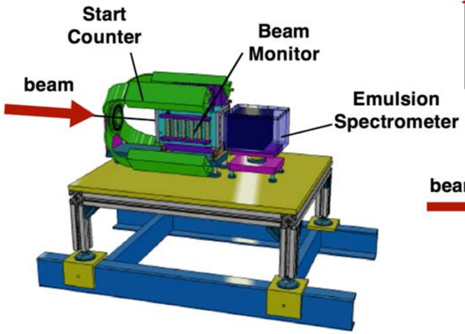


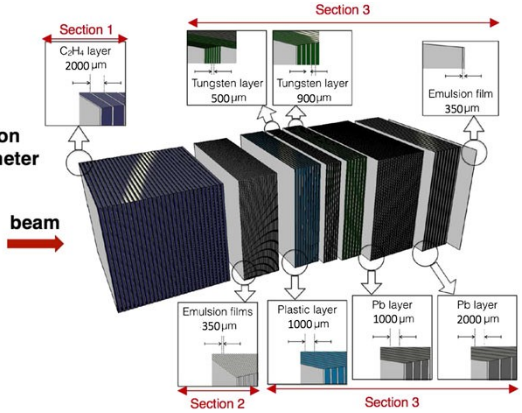
	This work	Ref.[69]	Weighted average	t
B	62 ± 5	70 ± 3	68.0 ± 2.6	-1.37
C	146 ± 8	131 ± 5	135.5 ± 4.2	1.66
N	116 ± 9	124 ± 4	122.6 ± 3.6	-0.86





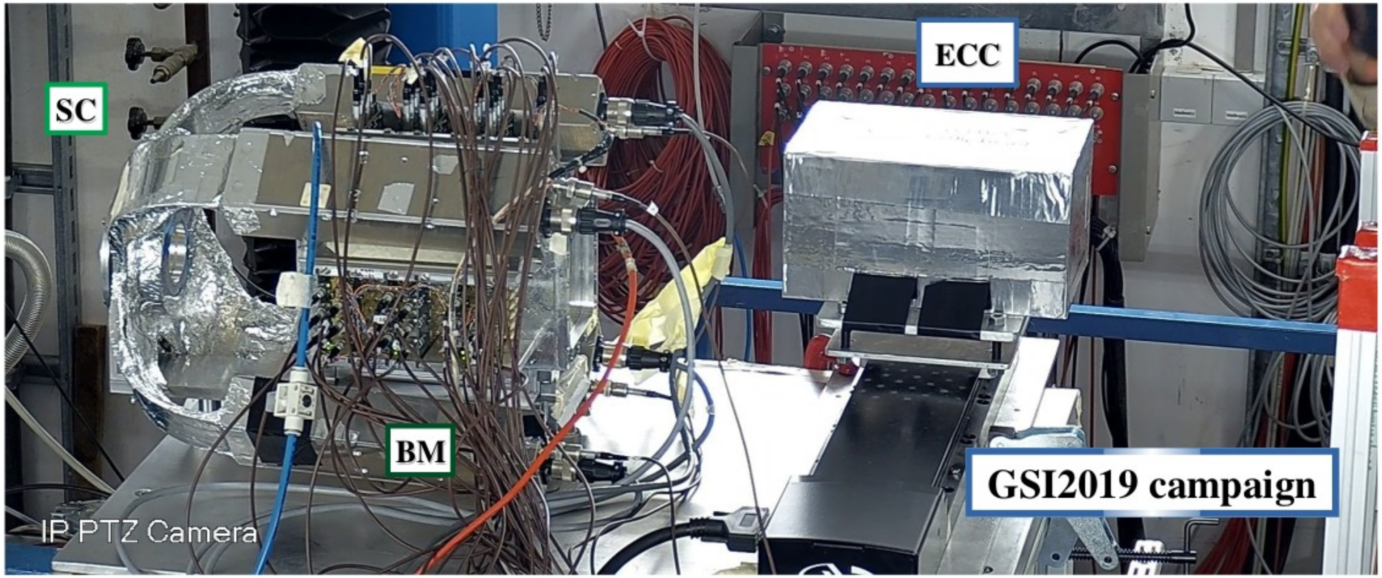
$$p = mc\beta\gamma$$
$$E_{\mathrm{kin}} = mc^2(\gamma - 1)$$
$$E_{\mathrm{kin}} = \sqrt{p^2c^2 + m^2c^4} - mc^2$$





- $\sigma(p)/p$ at level of $4-5\%$;
- $\sigma(T_{\mathrm{tof}})$ at level of 100 ps;
- $\sigma(E_{\mathrm{kin}})/E_{\mathrm{kin}}$ at level of $1-2\%$;
- $\sigma(\Delta E)/\Delta E$ at level of 5%;

Emulsion setup: first results



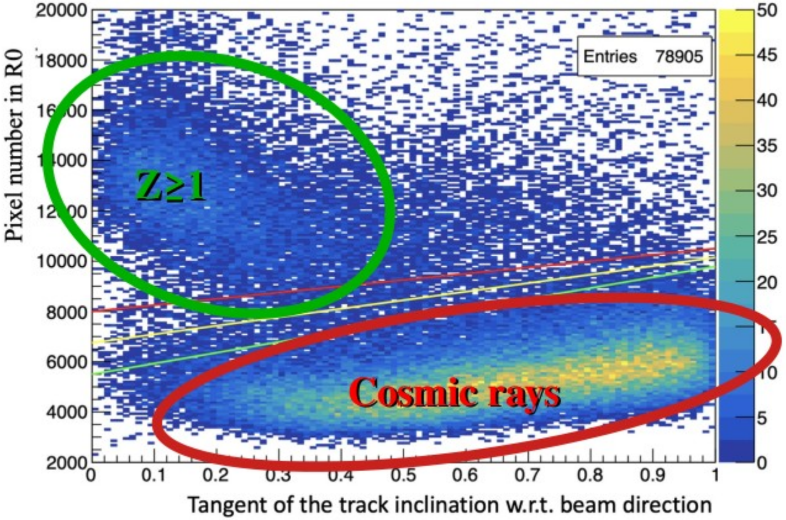
- Data acquisitions started in 2019
- SC + BM for primary beam monitoring
- Only charge identification up to now

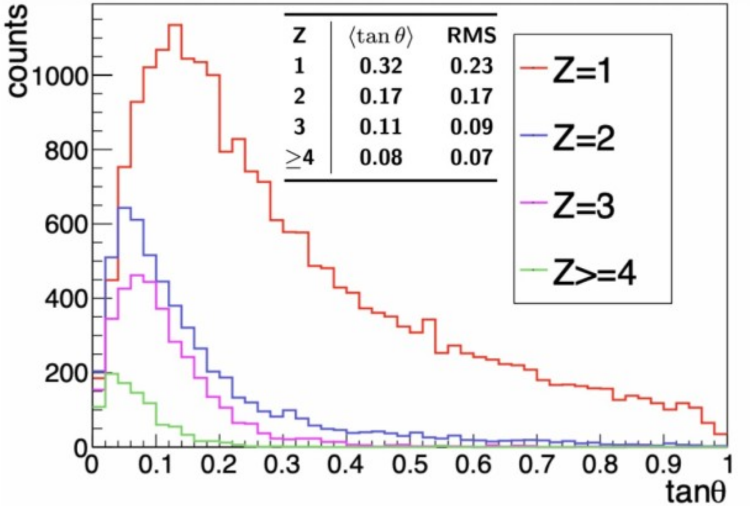
$^{16}O + C/C_2H_4$ @ 200 MeV/u

Emulsion setup: first results

Charge identification in Section2:

- Different thermal treatment for track etching
- Cosmic rays cut-based rejection
- Principal Component Analysis for Z ≥ 1





Z	⟨tan θ⟩	RMS
1	0.32	0.23
2	0.17	0.17
3	0.11	0.09
≥4	0.08	0.07

$^{16}O + C/C_2H_4$ @ 200 MeV/u

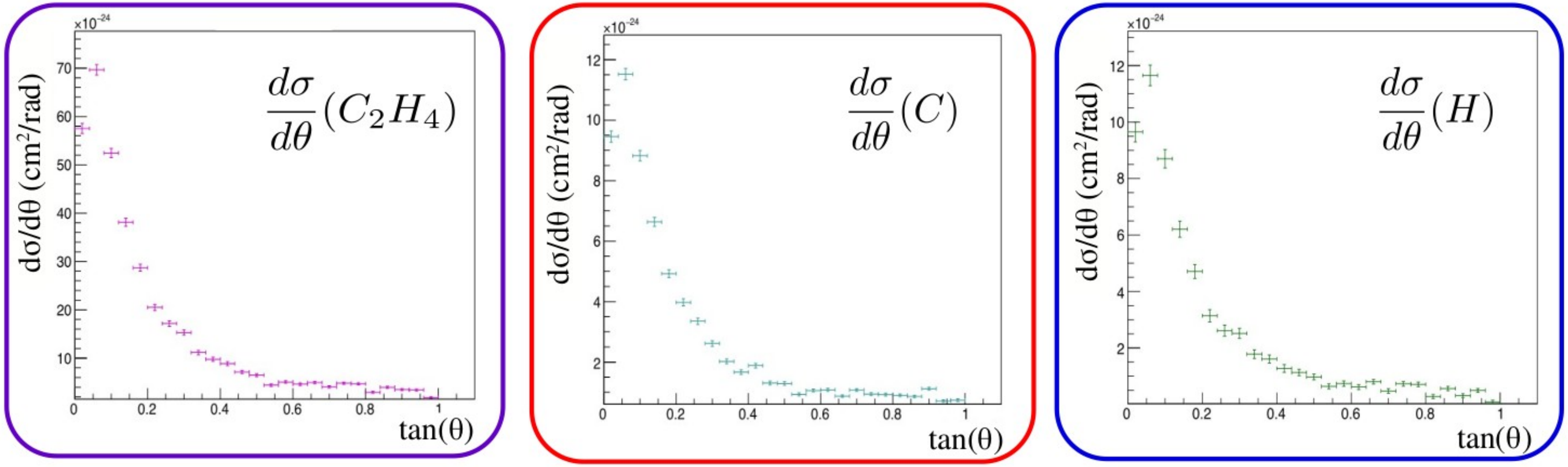
Emulsion setup: first results

$$\left.\frac{d\sigma(\theta)}{d\theta}\right|_{C\ or\ C_2H_4} = \frac{Y_i(\theta)}{N_B N_{TG} \Delta\theta \epsilon^i_{reco}(\theta)}$$

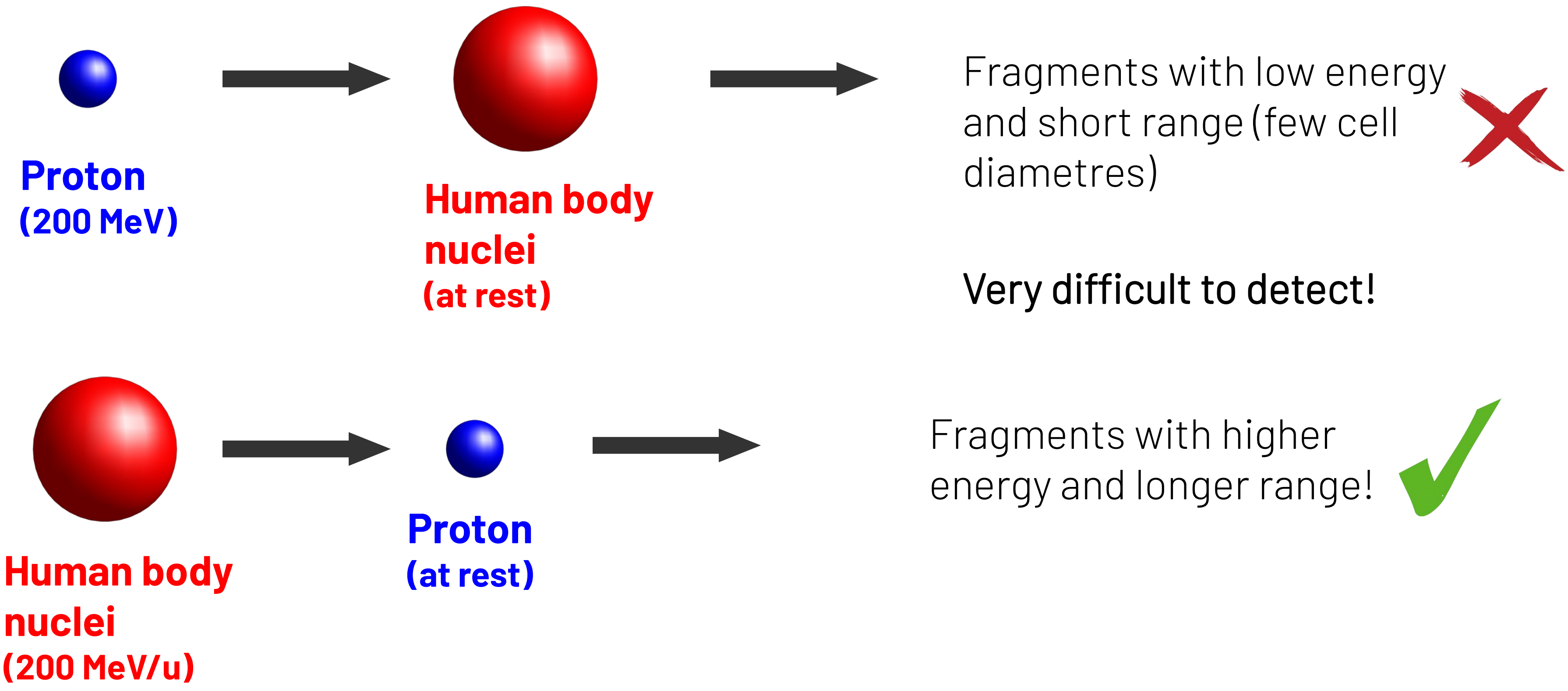
^{16}O (200 MeV/u) + C/C_2H_4

PRELIMINARY

Differential Cross Sections



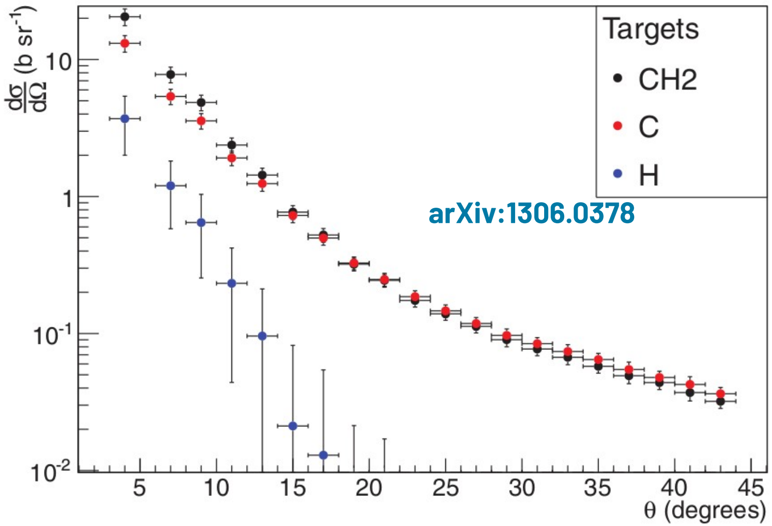
Courtesy of G. Galati


Proton
(200 MeV)
Human body
nuclei
(at rest)
Fragments with low energy and short range (few cell diametres)
Very difficult to detect!
Human body
nuclei
(200 MeV/u)
Proton
(at rest)
Fragments with higher energy and longer range!

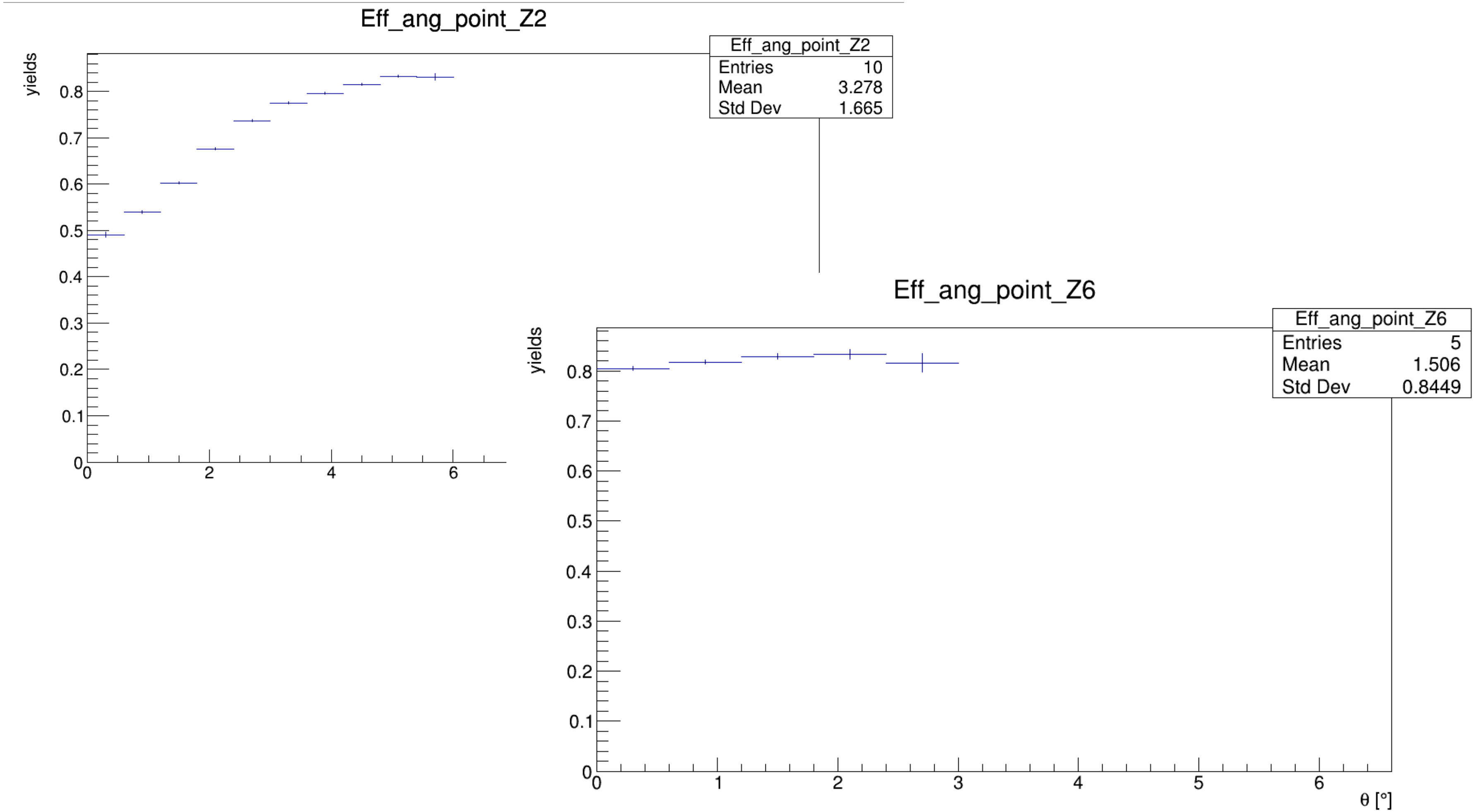
Problem: hydrogen target

- gas is not allowed in all experimental rooms
- gas is too sparse (low interaction probability)

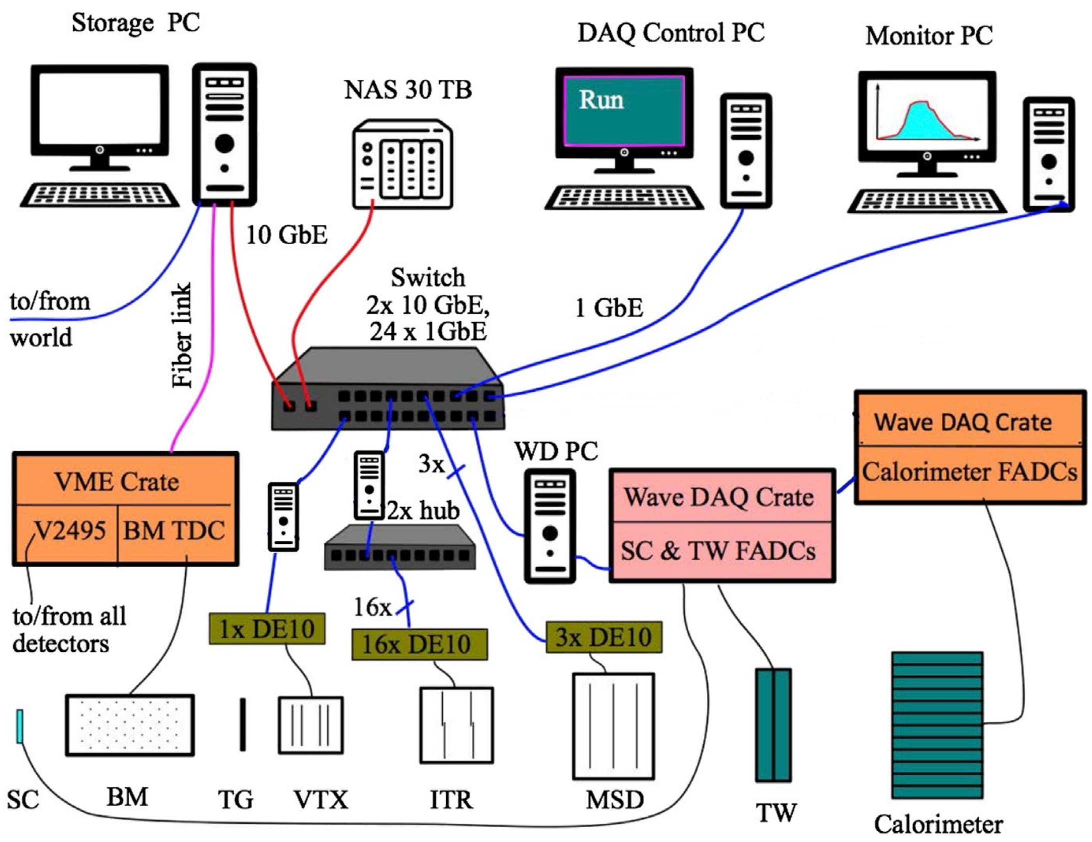
Polyethylene target $(C_2H_4)_n$ and Carbon target



$$\frac{d\sigma}{d\Omega}(H) = \frac{1}{4} \cdot \left(\frac{d\sigma}{d\Omega}(\mathrm{C_2H_4}) - 2 \cdot \frac{d\sigma}{d\Omega}(\mathrm{C}) \right)$$


Eff_ang_point_Z2
Eff_ang_point_Z2
Entries 10
Mean 3.278
Std Dev 1.665
yields
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
0 2 4 6
Eff_ang_point_Z6
Eff_ang_point_Z6
Entries 5
Mean 1.506
Std Dev 0.8449
yields
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
0 1 2 3 4 5 6
θ [°]

TDAQ infrastructure



-**flexible and distributed** system
VME, Linux PC, custom boards, Ethernet, optical fibers
-**70 kB/event**
1 kHz acquisition rate
2 TB/day
-V2495 handles **trigger and busy signals**
-data path is not signal path