The FOOT experiment:

enhancing the understanding of fragmentation processes in hadrontherapy and space radiation protection

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TIFPA Trento Institute for Fundamental Physics and Applications

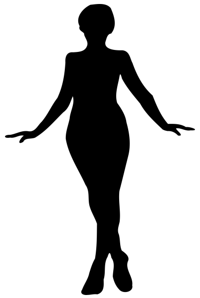
UNIVERSITÀ DEGLI STUDI DI TRENTO

INFN Istituto Nazionale di Fisica Nucleare

OUTLINE

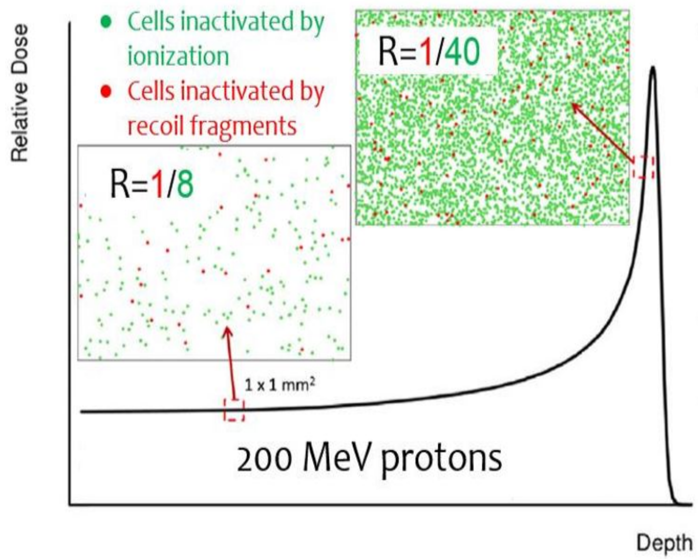
- Nuclear fragmentation in proton therapy
- FOOT
  - Main goals
  - Experimental approaches
  - Experimental setups
  - Performances: charge and mass identification, isotopes separation
- Conclusion and future perspectives

NUCLEAR FRAGMENTATION IN PROTON THERAPY

p ● →  → p + C,O   Target fragmentation ⚠

H, C, O (95%)

- **Target fragmentation** gives **higher contribution in healthy tissue** where beam is still energetic (~200MeV)
- Low energy fragments: **short range** (~tens of μm)
- The contribution to biological effects of the fragmentation of target is **not considered in treatment planning**



Tommasino and Durante, *Cancers* (2015)

FOOT GOAL

Characterization of the fragments generated in the target
to improve the knowledge of the p -> patient (p -> H,C,O) interaction
at therapeutic energies (200 – 400 MeV/u)

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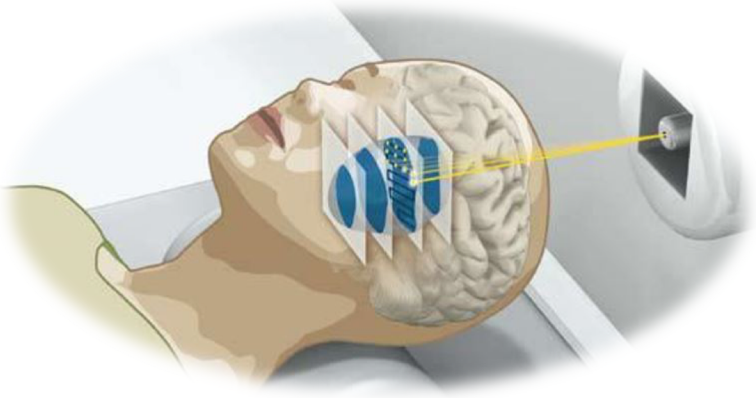
Fragmentation double differential cross-section (5% precision)

$$\frac{d^2\sigma}{d\Omega dE}$$

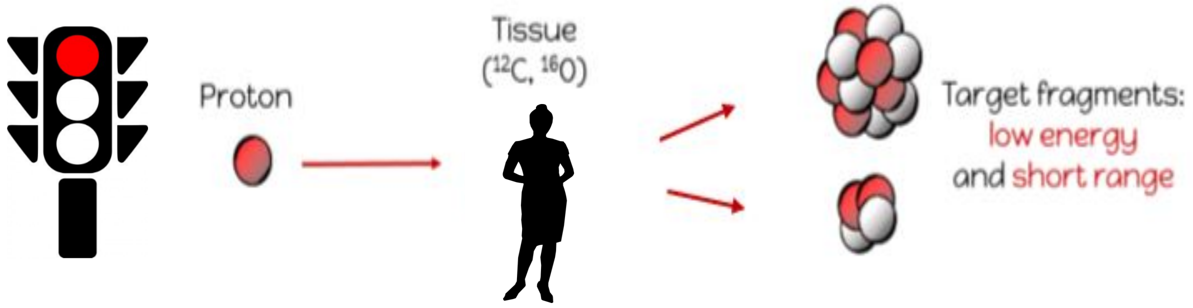
- Charge ID
- Mass ID
- Fragment momentum
- Fragment generation angle

Particle therapy
Data used to improve the accuracy of the TPS (Treatment Planning System)

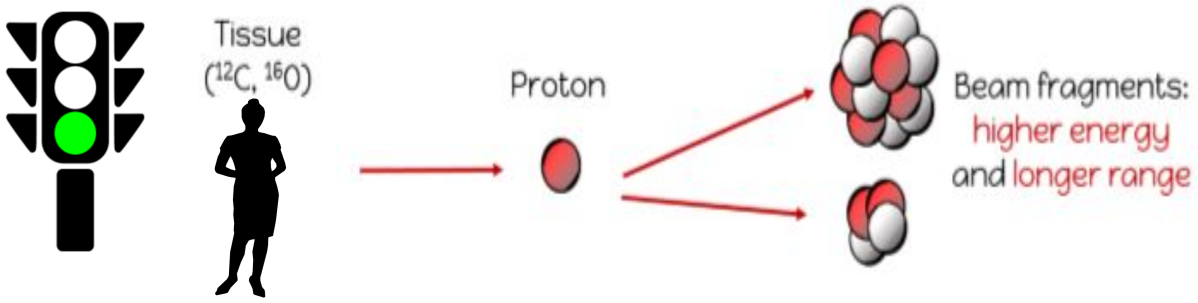


EXPERIMENTAL APPROACHES

Direct kinematics



Inverse kinematics



EXPERIMENTAL APPROACHES

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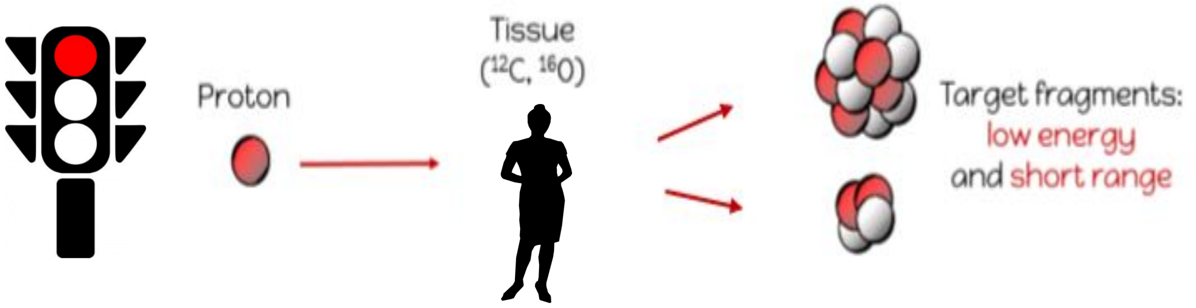
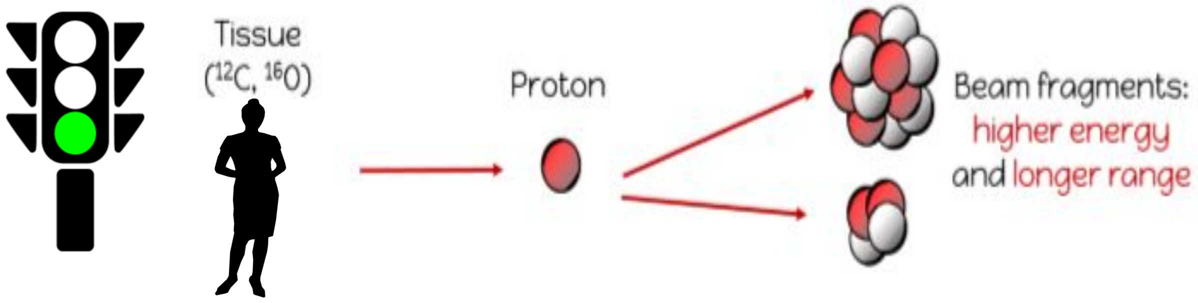


Inverse kinematics

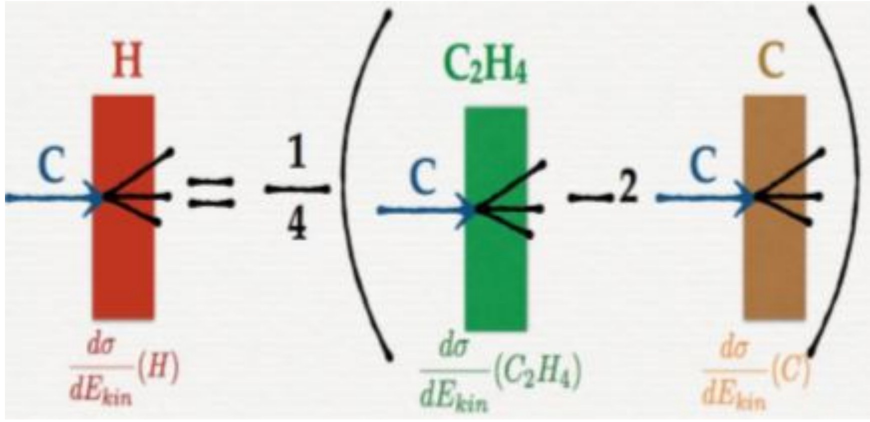


Ideal target choice
Hydrogen gas target

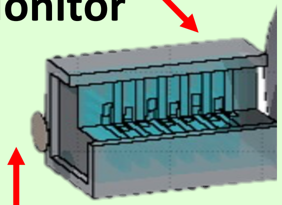
→

Hydrogenated target $(C_2H_4)_n$
&
Graphite target (C)

Fragmentation cross sections on H can be measured by subtracting the cross sections of $(C_2H_4)_n$ and C



DIFFERENT EXPERIMENTAL SETUPS



Pre-target region

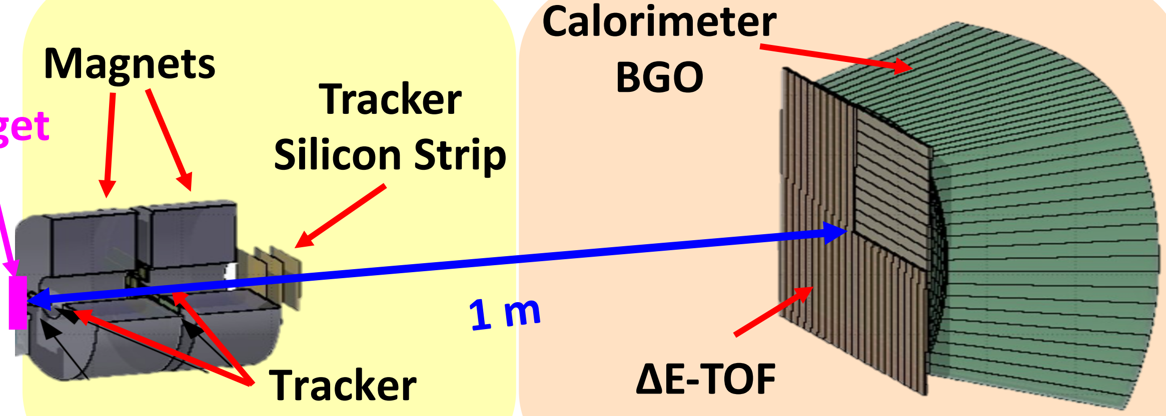
Heavy fragments

Angular open ± 10°

Light fragments

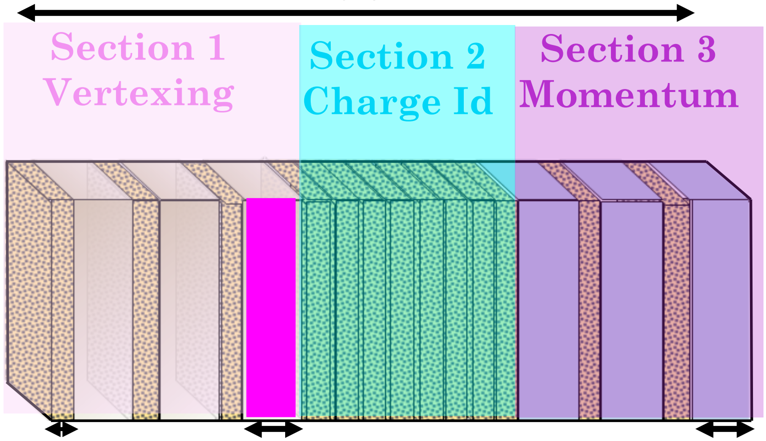
Angular open ± 70°

Electronic Setup



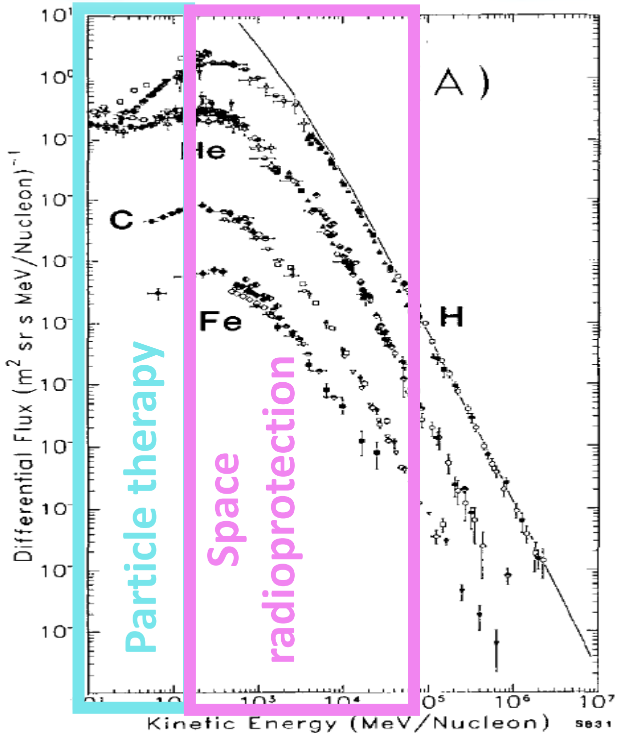
Tracking region

Downstream region



Emulsion Chamber Setup

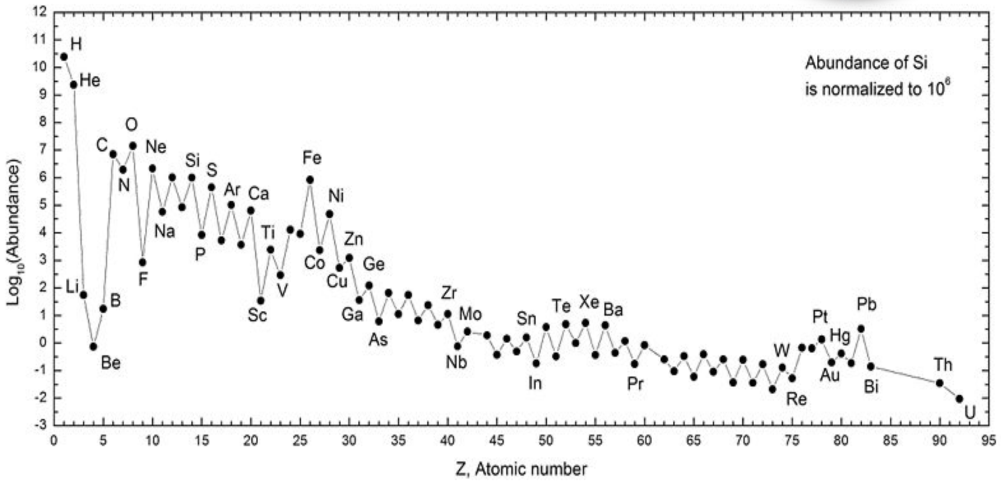
… ONE MORE GOAL



Galactic cosmic rays
Simpson et al., 1983

Background radiation in space:

- 2% electrons and positrons
- 98% nuclei
  - **87% protons**
  - 12% helium
  - 1% of heavier ions



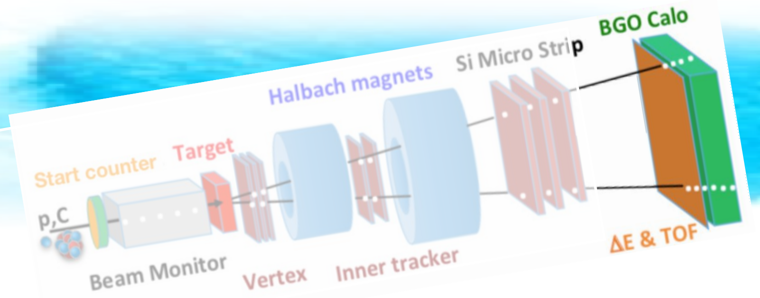
Fragmentation of GCR can occur in:

- spacecraft structure
- shielding materials
- astronaut's body

Changing in the composition of the radiation field and thus in the dose

Radioprotecion in space

700 MeV/u for p, He, Li, C, O beams : detailed knowledge of the fragmentation processes to optimize the spacecraft shielding (long term mission)



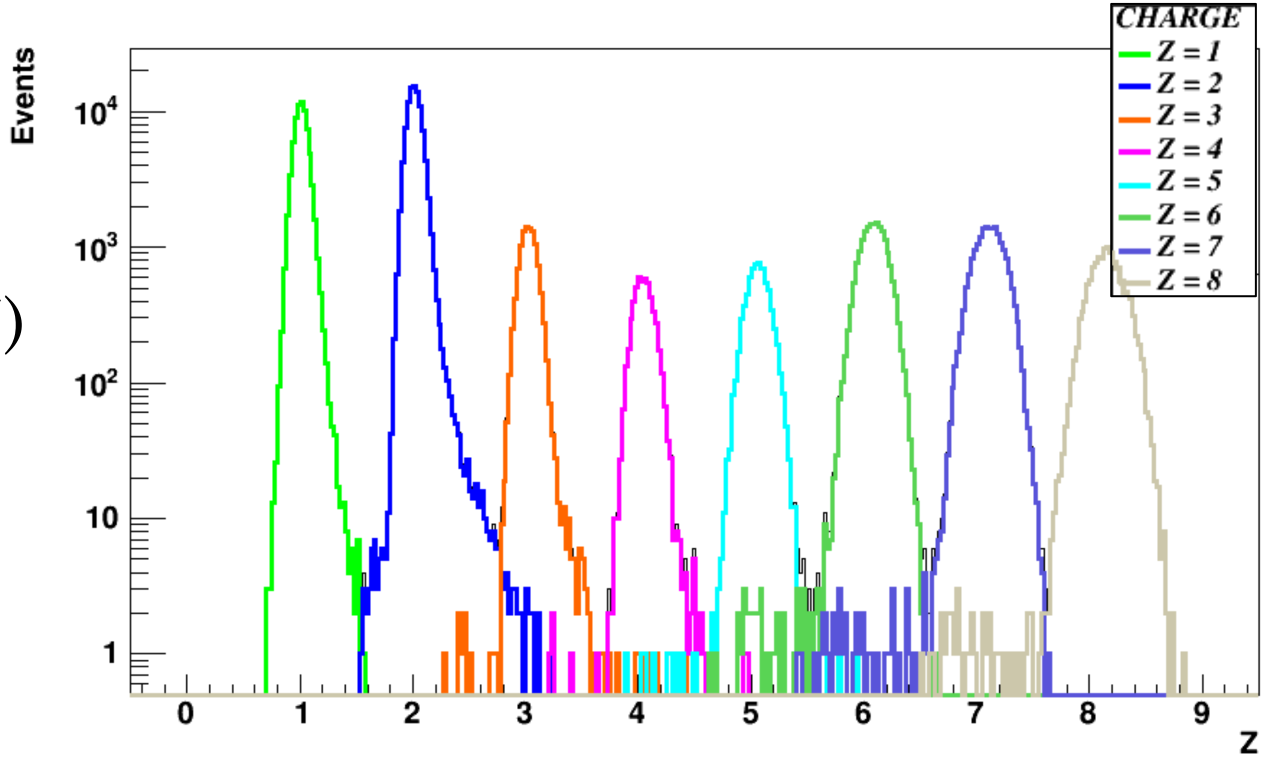
CHARGE IDENTIFICATION

The Z determination is obtained by the mean **energy loss** of charged particle deposited in the **plastic scintillator (SCN)** and by the TOF measurement (Start Counter – SCN)

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

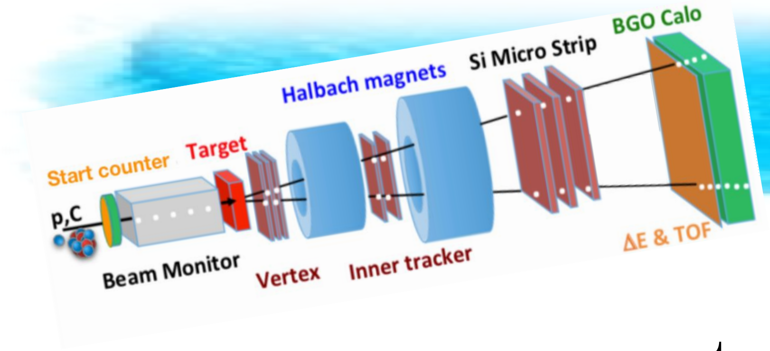
Charge and velocity of the fragment (divided by c)

- Resolution: **2%** (^{16}O) – **6%** (^{1}H)
- Wrong charge assignment < 1%



Fluka simulation

^{16}O (200 MeV/u) → C_2H_4



MASS IDENTIFICATION

Combination of reconstructed quantities:

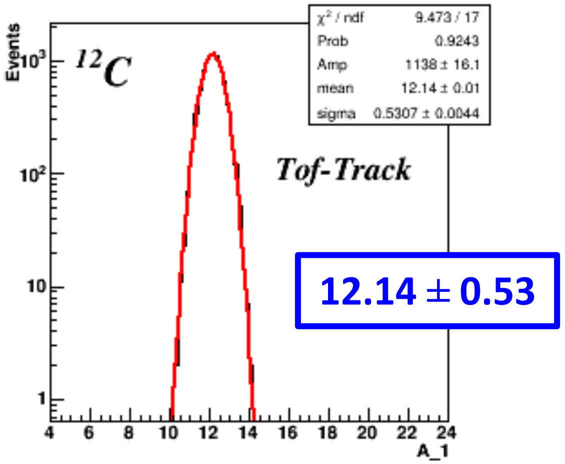
- Momentum (**magnetic spectrometer**)
- ToF (**scintillator**)
- Kinetic energy (**calorimeter**)

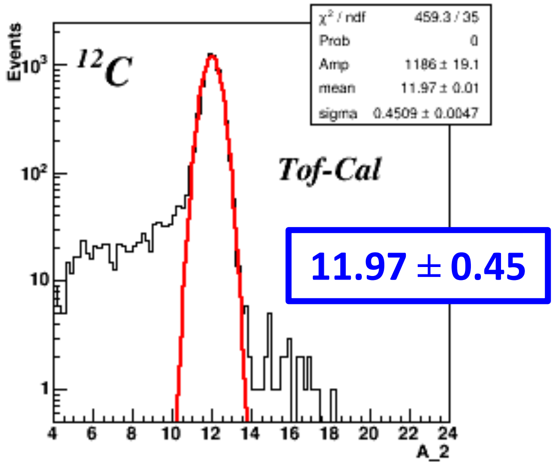
$$A_1 = \frac{p}{U\beta\gamma c} \qquad A_2 = \frac{E_k}{Uc^2(1-\gamma)} \qquad A_3 = \frac{pc^2 - E_k{}^2}{2Uc^2 E_k}$$

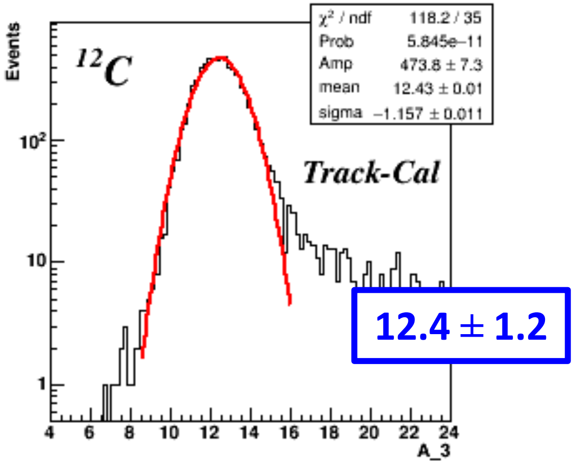
Fluka simulation

^{16}O (200 MeV/u) → C_2H_4

(Example of ^{12}C)







Best determination of A throught:

- Standard χ^2 fit
- Augmented Lagrangian Method (ALM)

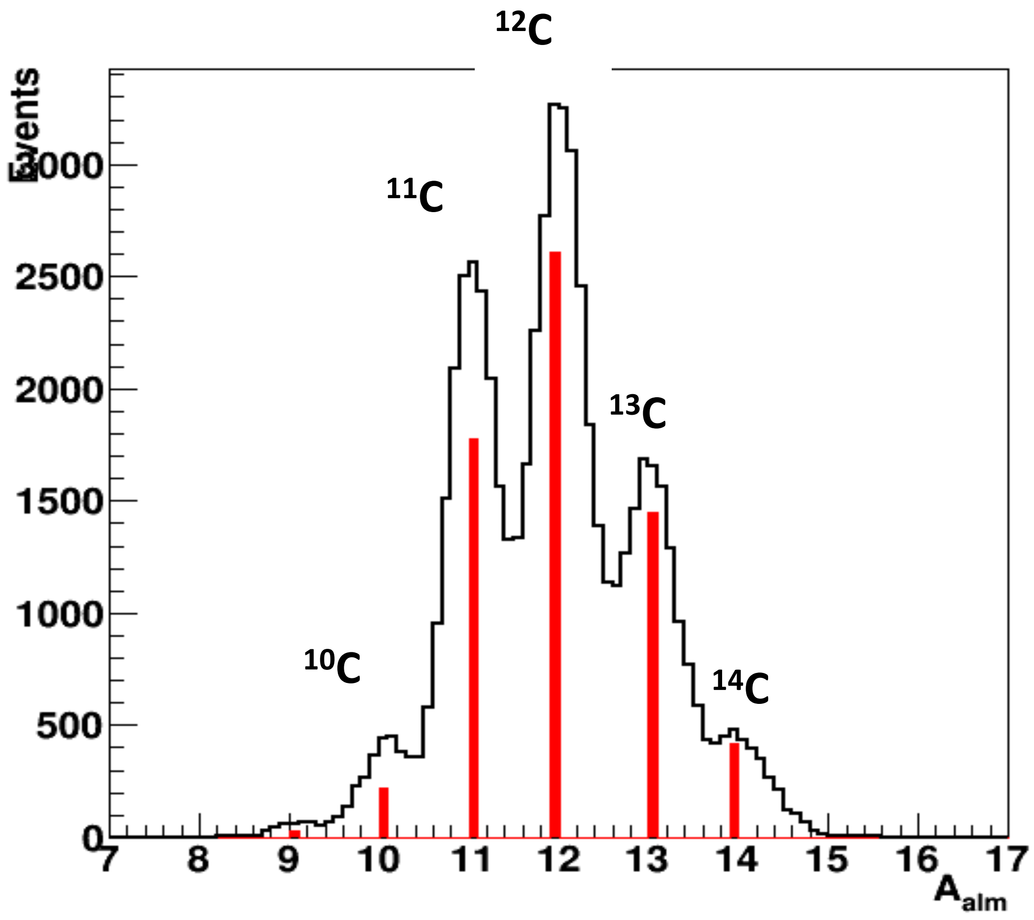
- Peak position centered around the expected values
- Resolution: **4%** (^{16}O) – **6%** (^{1}H)

ISOTOPES SEPARATION

Fluka simulation

^{16}O (200 MeV/u) → C_2H_4

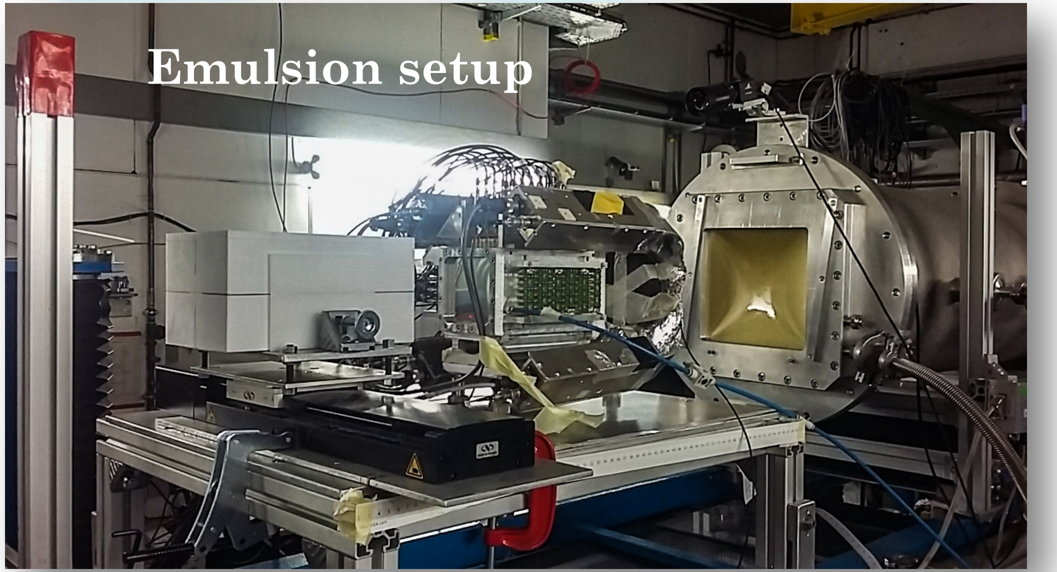
(Example of ^{12}C)

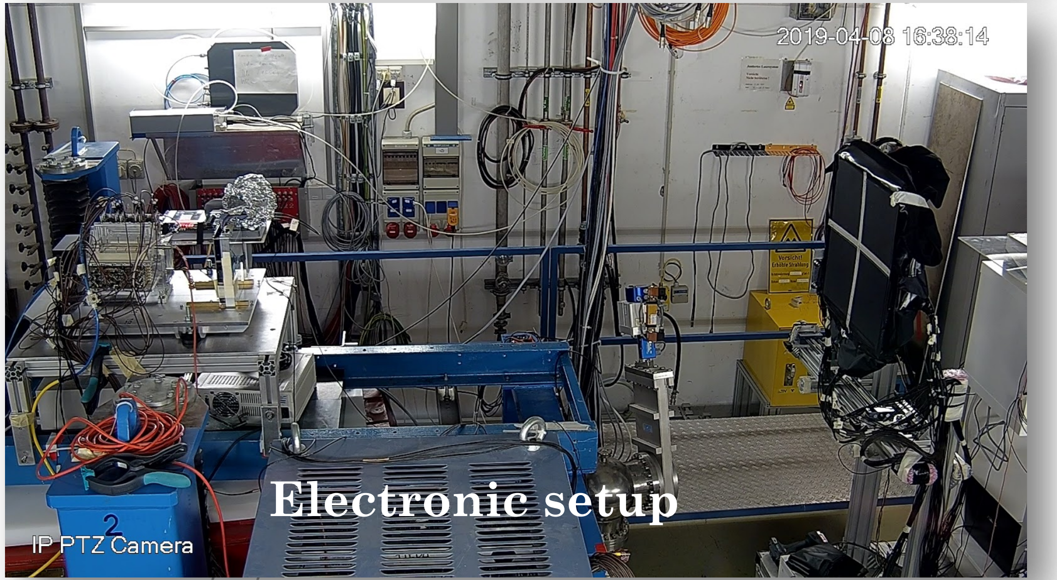


Resolutions from Test Beam

- $\Delta p/p$ → 4%
- $\Delta E_{kin}/E_{kin}$ → 1.0%
- Δtof → 50 – 100 ps
- $\Delta(dE)/dE$ → 3-10%

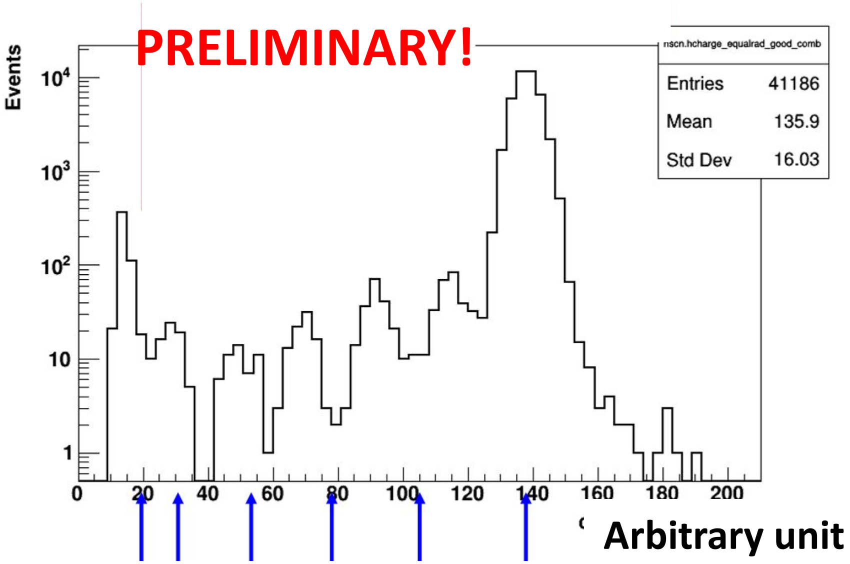
1^{ST} GLOBAL DATA TAKING @ GSI (Darmstadt, Germany)





Beam: ^{16}O @ 200 MeV/u & 400 MeV/u
Target: C & C_2H_4

- Emulsion data taking -> emulsion layers have been developed and are currently under analysis
- Global data acquisition test beam (no MSD, no calorimeter, no magnets)



CONCLUSIONS & FUTURE WORK

- The FOOT goal is the **experimental characterization of target fragment** production cross sections for beams, energy and targets relevant in hadrontherapy and radioprotection in space

- Simulation phase is done. **First emulsion setup data taking and first FOOT global data acquisition test beam** performed at GSI in March 2019. Data are still under analysis, but performances as expected

- Mass and charge of the fragments well reconstructed in almost all the events

- Next test beam with emulsion setup at GSI in February 2020

FOOTERS AROUND THE WORLD

INFN & University of Milano

CNAO

TIFPA & University of Trento

INFN & University of Torino

INFN & University of Bologna

INFN & University of Pisa

INFN & University of Perugia

INFN & Roma 1 & Roma 2 University

INFN & University of Napoli

INFN Bari

Centro Fermi

LNS

FOOTERS AROUND THE WORLD

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University of

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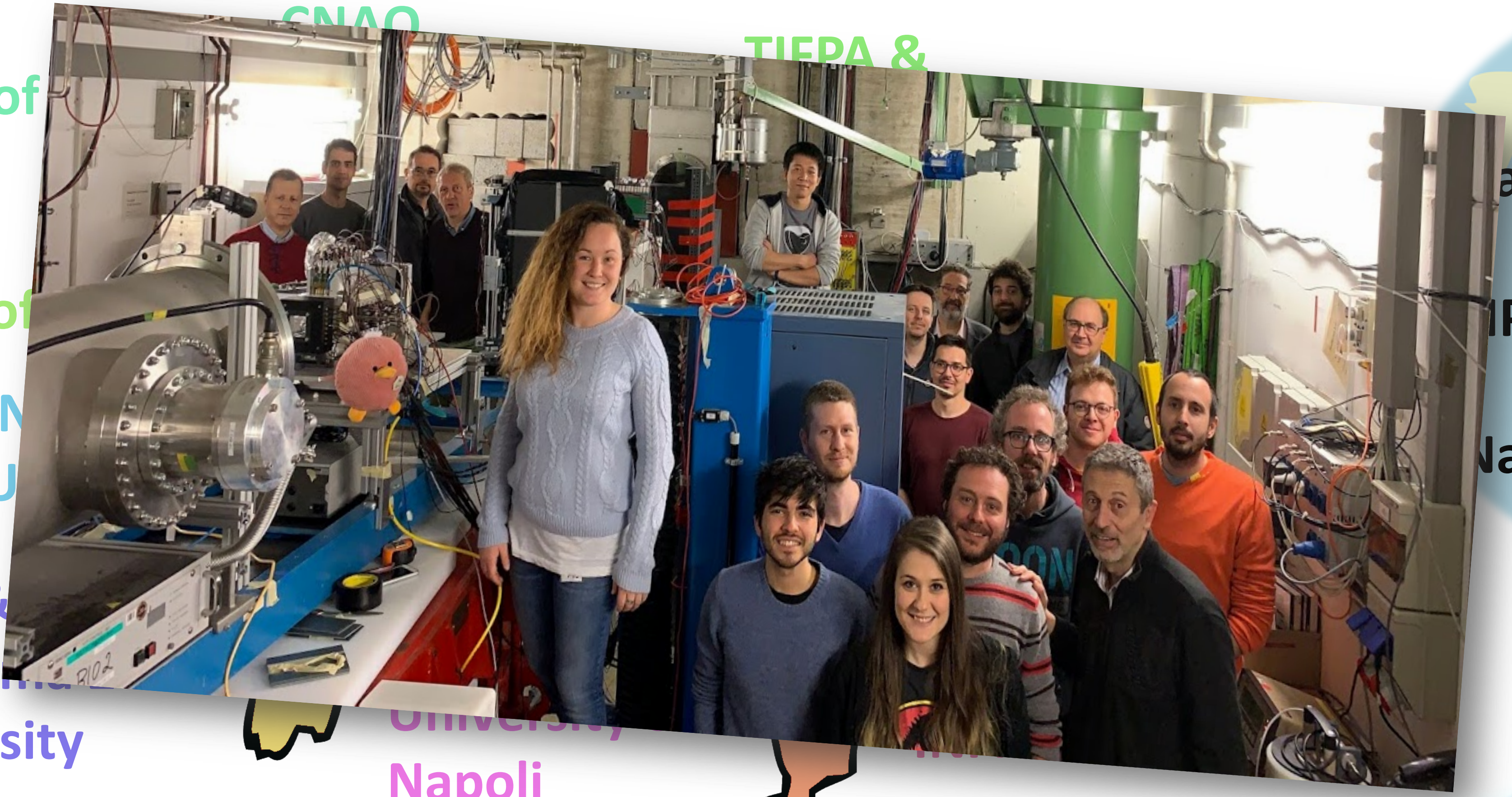
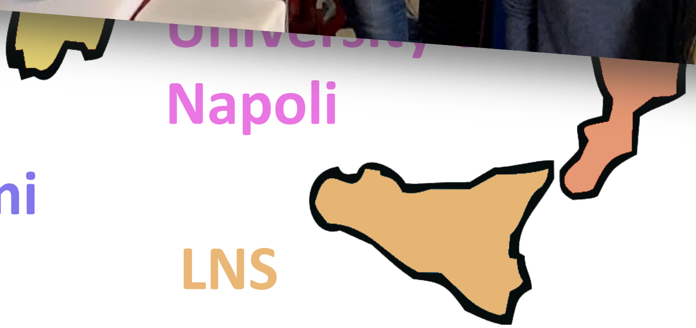
University





Napoli

Centro Fermi

LNS

GSI

achen University

IPHC Strasbourg

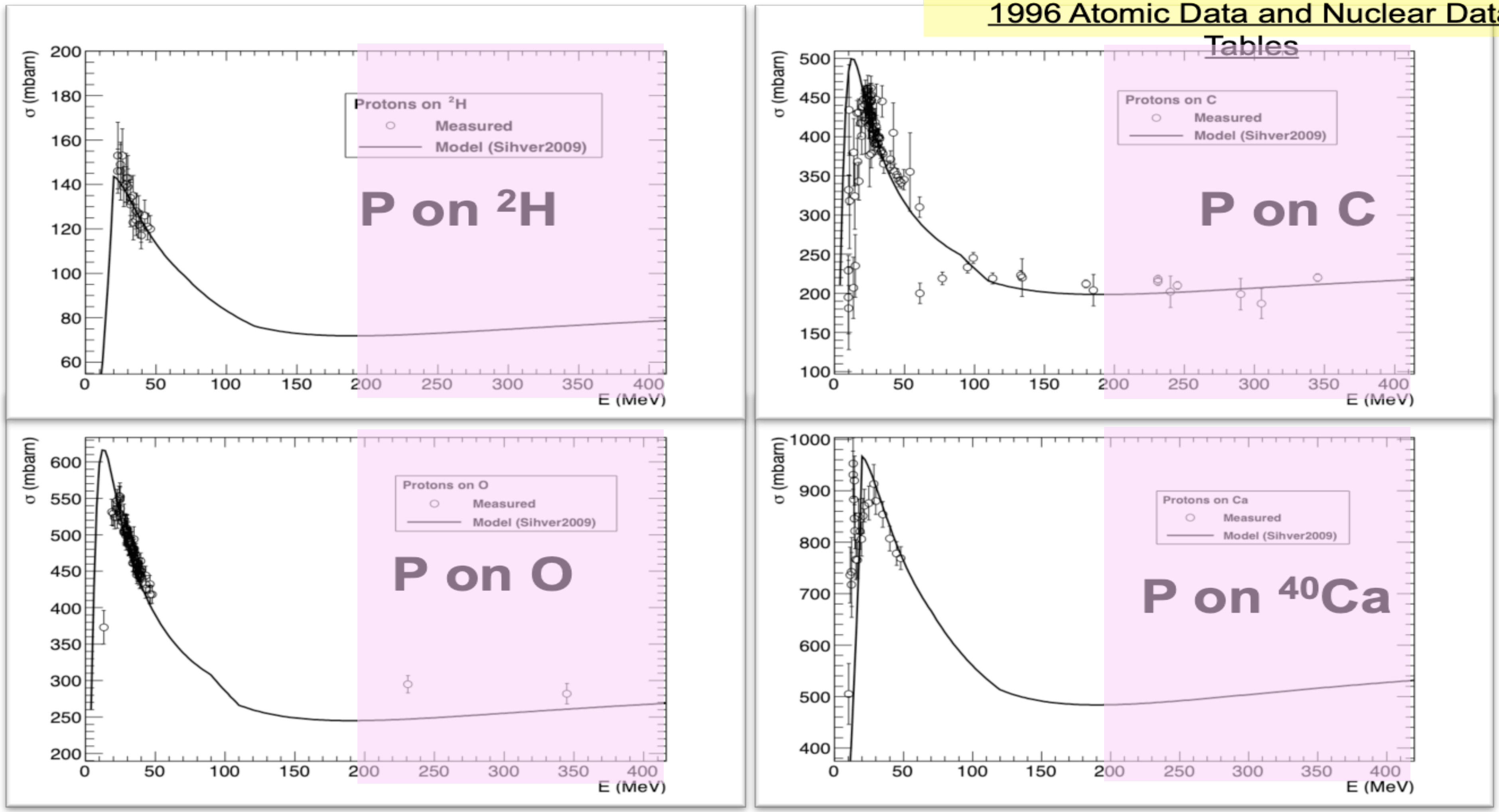
Nagoya University

Thank you!

BACKUP SLIDES

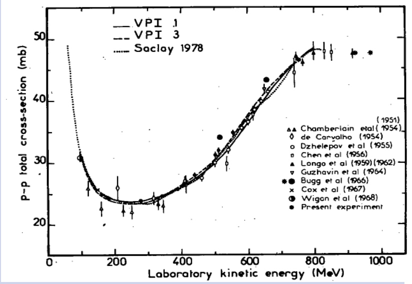
PROTON CROSS SECTION: WHAT'S ON THE MARKET

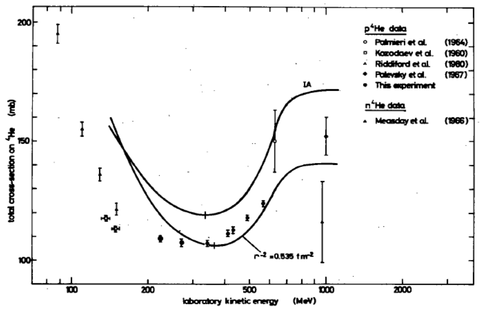
Experimental data taken from Carlson 1996 Atomic Data and Nuclear Data Tables

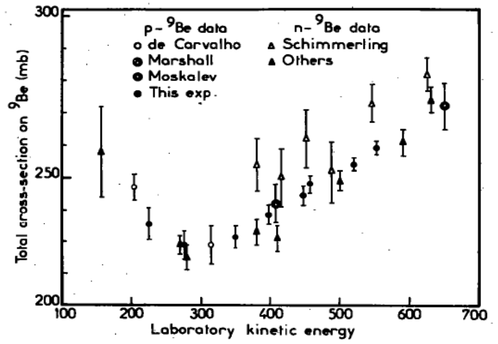


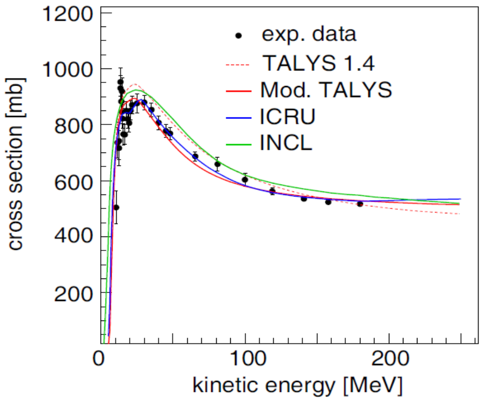
PROTON CROSS SECTION: WHAT'S ON THE MARKET

Reaction	E_{Kin} MeV	σ_{TOT} (mb)	
p → p	10	300	
	100	30	
	180-500	25-35	
	600-2000	45-50	
P → ^{4}He	150-600	110-120	
P → ^{9}Be	200-600	230-250	
P → ^{12}C	50	450	
	100-200	230	
	200-1000	280-350	
P → ^{16}O	20	550	
	50	400	
	200	350	
	200-600	350-400	
P → ^{40}Ca	30	900	
	100-200	500	

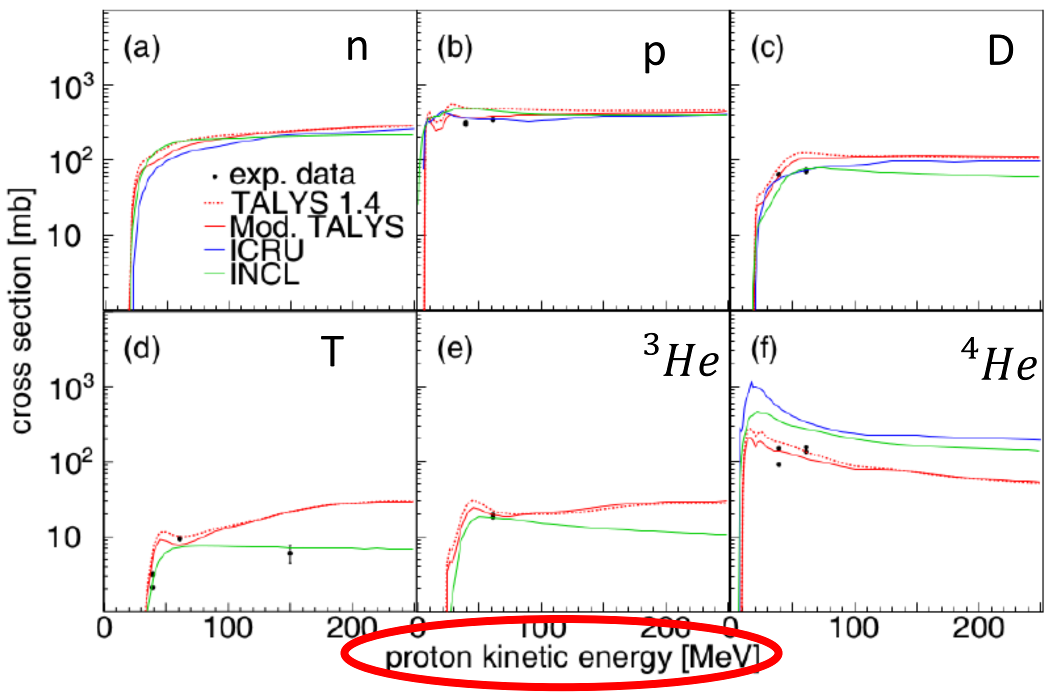




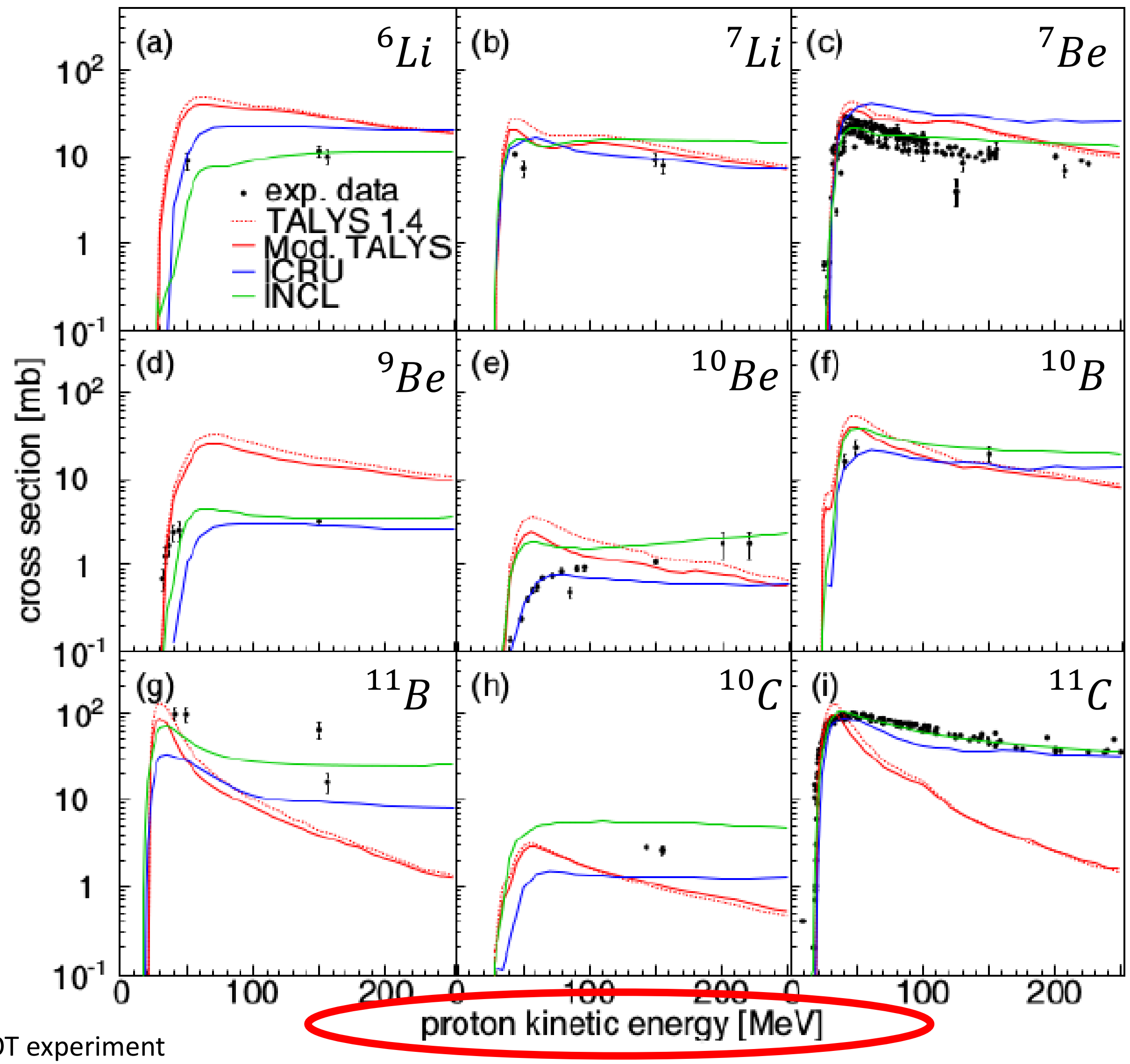




PROTON CROSS SECTION: WHAT'S ON THE MARKET

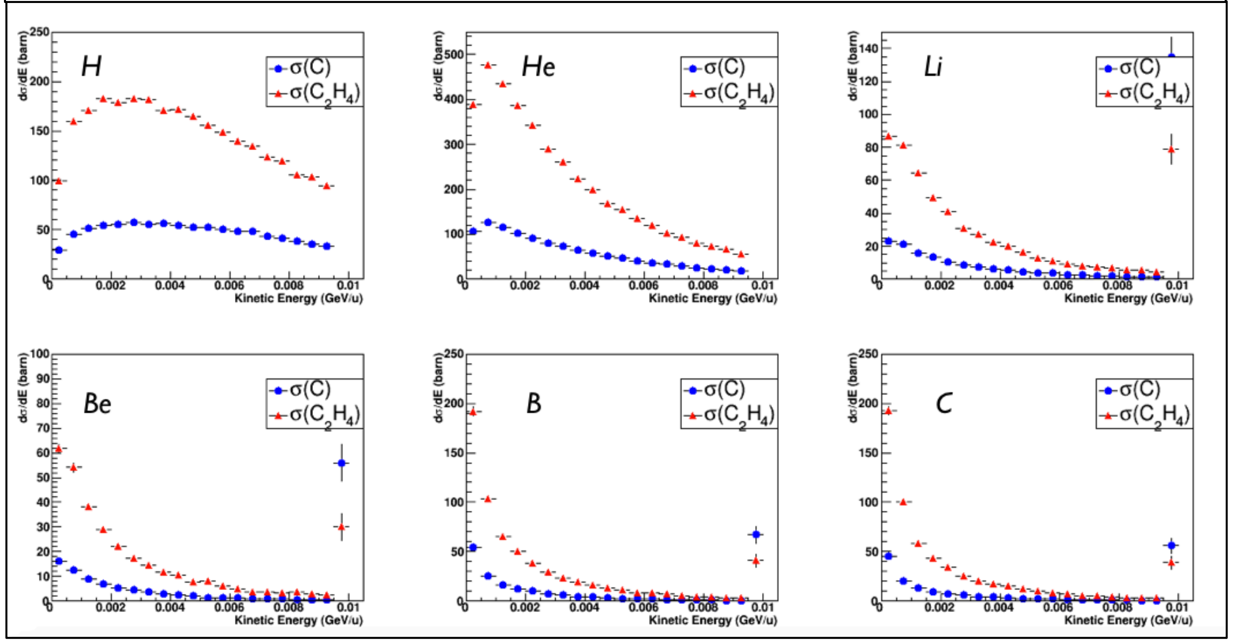


p → ^{12}C differential cross section



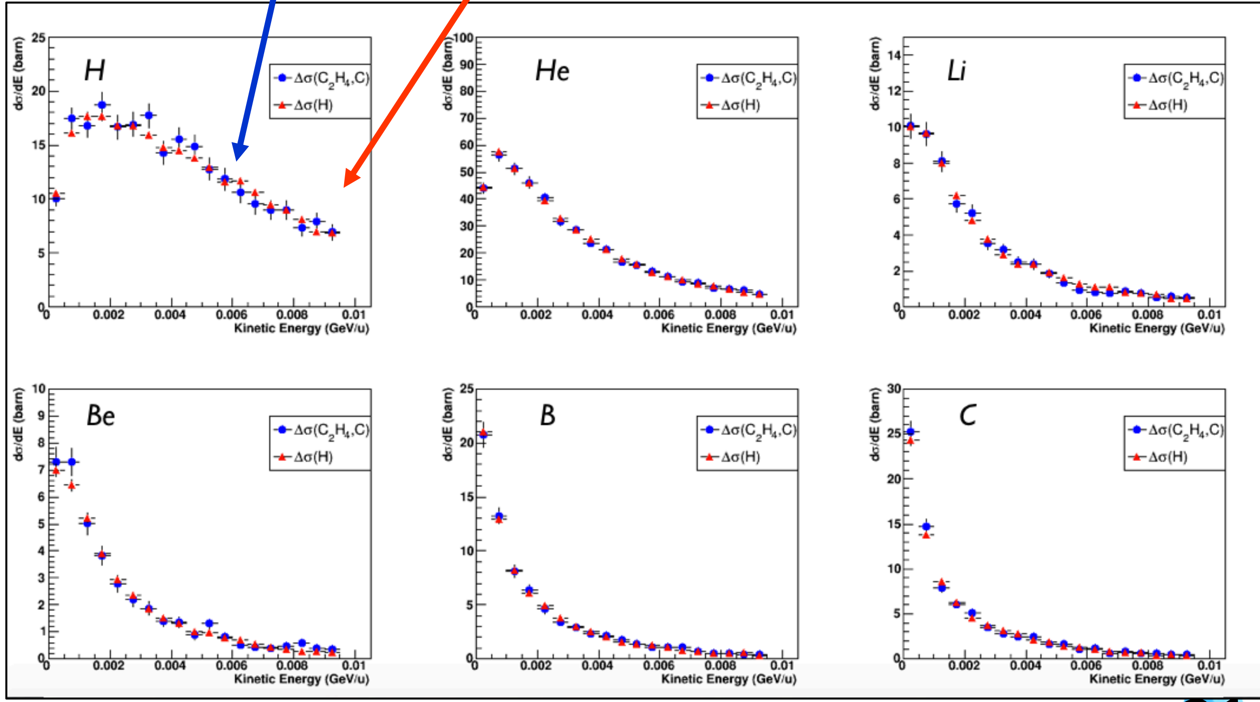
TARGET FRAGMENTATION CROSS-SECTIONS: INVERSE KINEMATICS

dσ/dE$_{kin}$(fragment) in C & C_2H_4 targets (inverse kinematic)



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

$$\frac{d\sigma}{dE_{kin}}(H)$$



Fluka simulation

^{16}O (200 MeV/u) → C_2H_4

ELECTRONIC SETUP

- ✓ Measures primaries position and direction
- ✓ Reject events fragmentated before the target

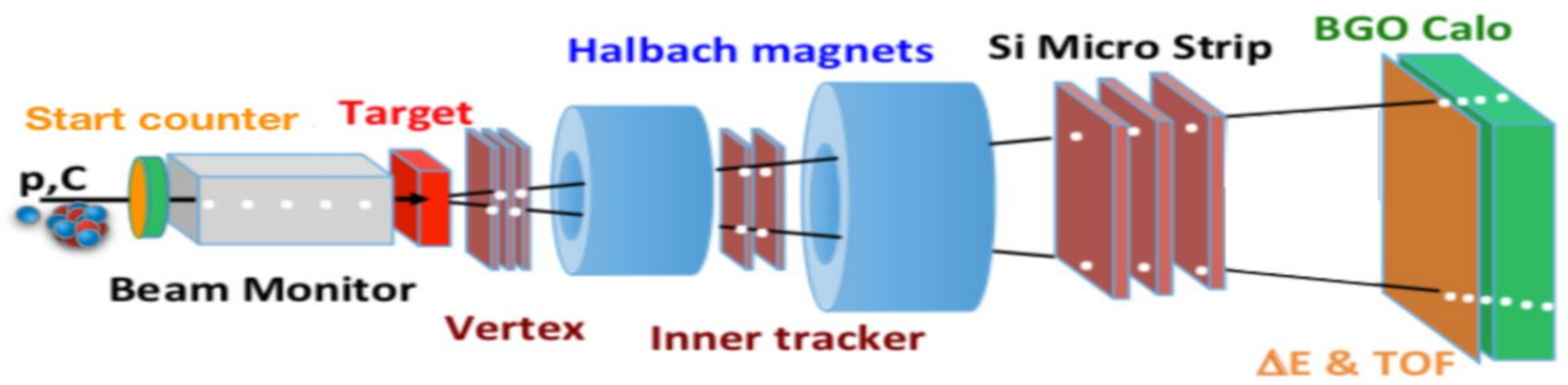
MOMENTUM

- ✓ Magnets to separate fragments of different charges

KINETIC ENERGY

ToF & CHARGE

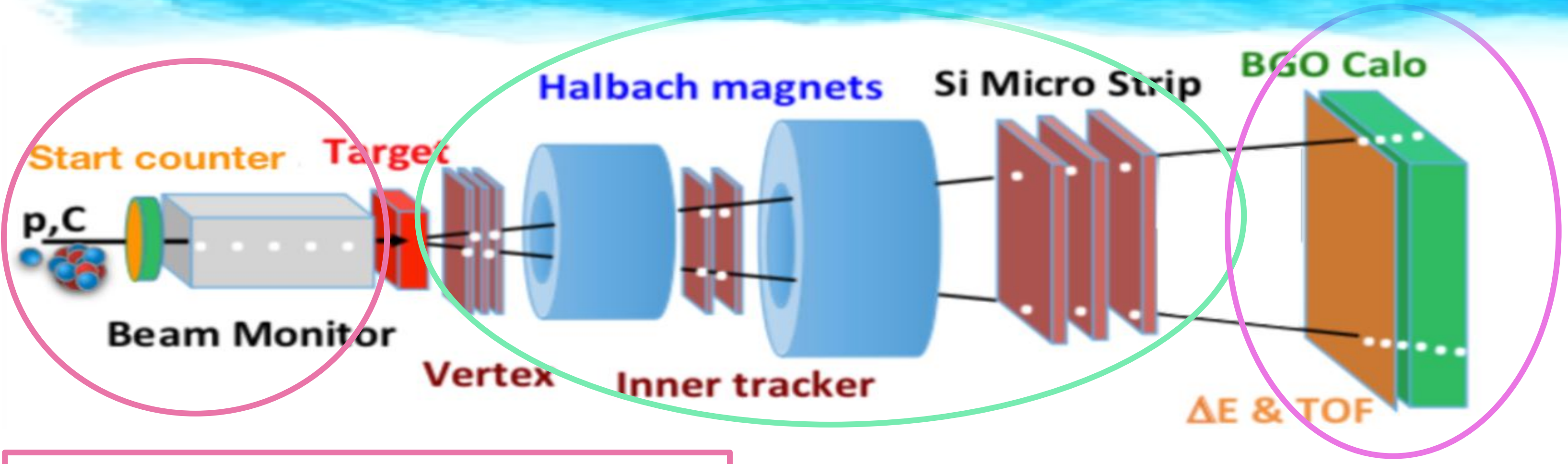
- ✓ ToF and energy release measurement



- ✓ Reconstruction of the particles track inside and outside the magnetic field

- ✓ Fragments kinetic energy measurement

ELECTRONIC SETUP



Calorimeter region

- **Scintillator**
  - ❖ 2 layers of 3 mm thick plastic scintillator bars orthogonally oriented
  - ✓ Measures ToF
  - ✓ Measures energy release
- **Calorimeter**
  - ❖ 360 BGO crystals 24 cm long
  - ✓ Measures kinetic energy

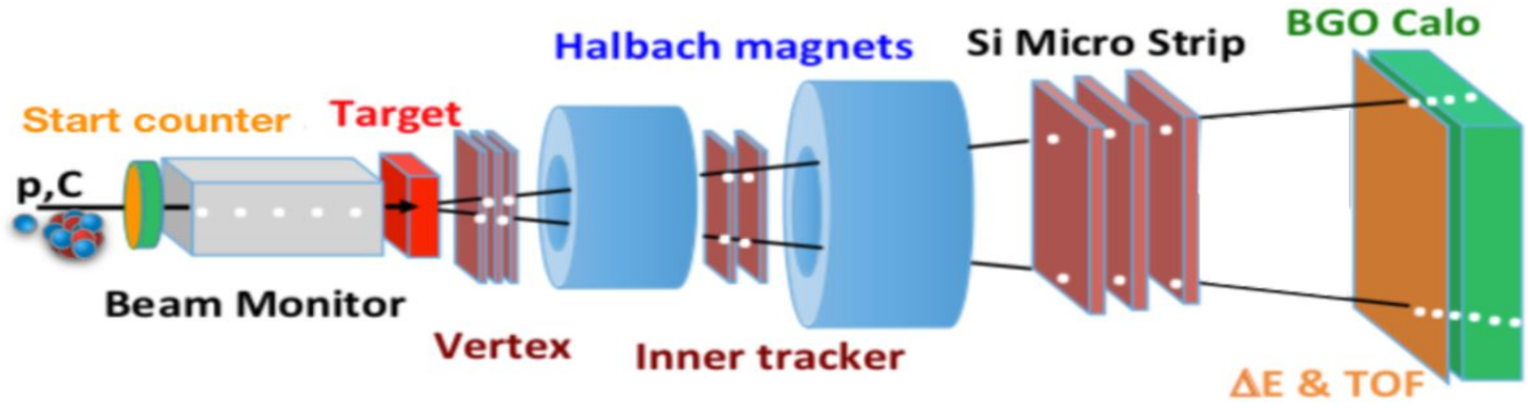
Pre-target region

- **Start counter**
  - ❖ Plastic scintillator 250 µm
  - ✓ Counts primaries
  - ✓ Starts ToF measurement
- **Beam monitor**
  - ❖ Ar-CO2 drift chamber
  - ❖ 3 cells x 12 XY planes
  - ✓ Measures primaries position and direction

Magnetic spectrometer

- **Vertex**
  - ❖ 4 layers of silicon pixel detectors 50 µm
  - ✓ Reconstructs vertex position
- **Inner tracker**
  - ❖ 2 layers of silicon pixel detectors 50 µm
  - ✓ Tracking in magnetic field
- **Microstrip detector**
  - ❖ 3 layers of silicon microstrips 150 µm
  - ✓ Tracking in magnetic field
- **Magnets**
  - ❖ 2 magnets in Hallback configuration
  - ❖ Max field 0.8 T

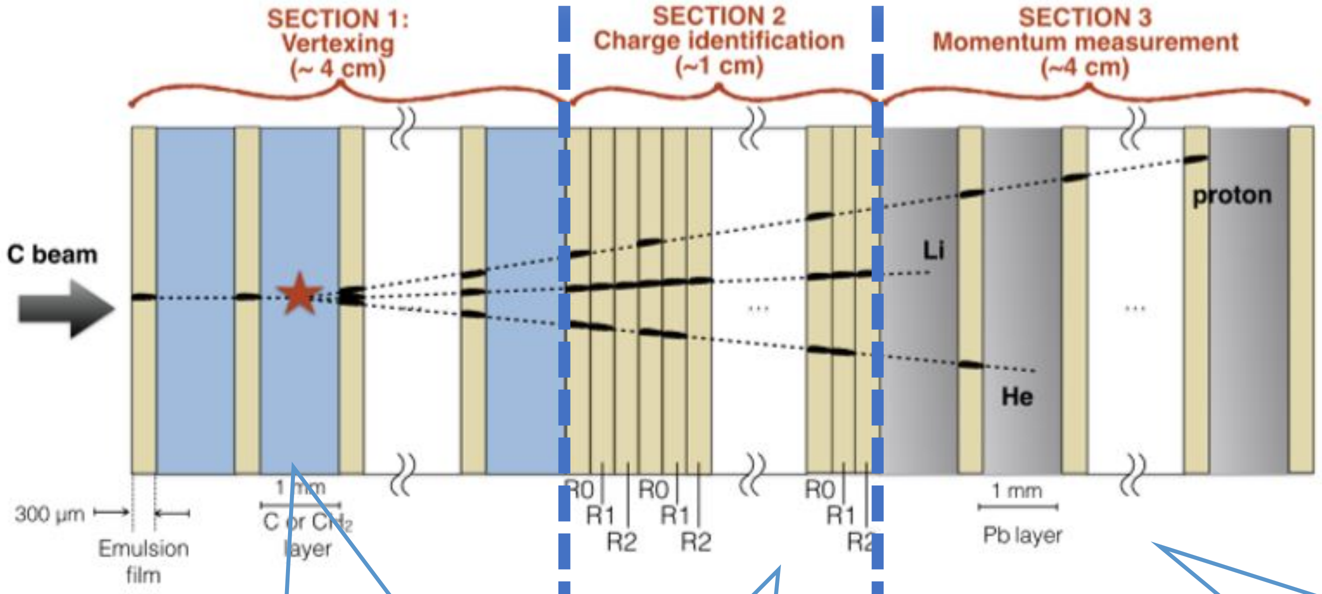
ELECTRONIC SETUP



Minimum required performances:

- 10° polar angle (optimized for $Z > 2$ fragments)
- **σ(TOF)** ~ 100ps
- **σ(p)/p** ~ 5%
- **σ(Ek)/Ek** ~ 2%
- **σ(ΔE)/ΔE** ~ 2%

EMULSION SETUP

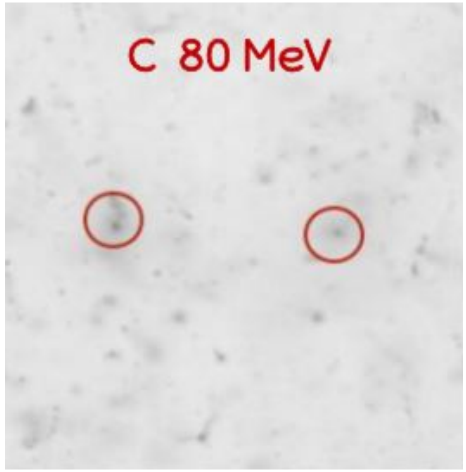


- Z<3 fragments emitted at large angles (up to 75° wrt the beam direction)
- The developed emulsions are scanned by an automated microscope
- Images are analyzed by a dedicated software to recognize tracks produced by ionizing particles

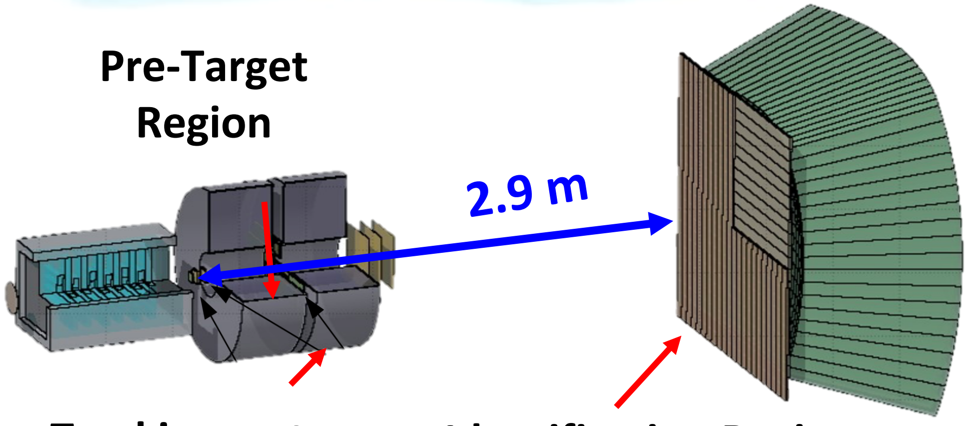
Target plates (C/C_2H_4) interleaved with emulsion films

Emulsion films only -> Charge identification for low Z fragments (H, He, Li)

Lead planes interleaved with emulsion films -> Momentum measurement and isotopic ID

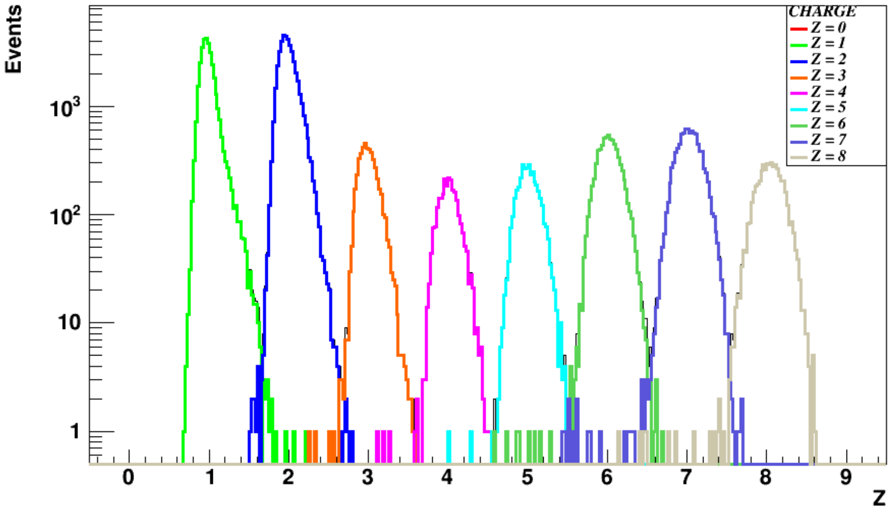


FOOT AT HIGHER ENERGIES



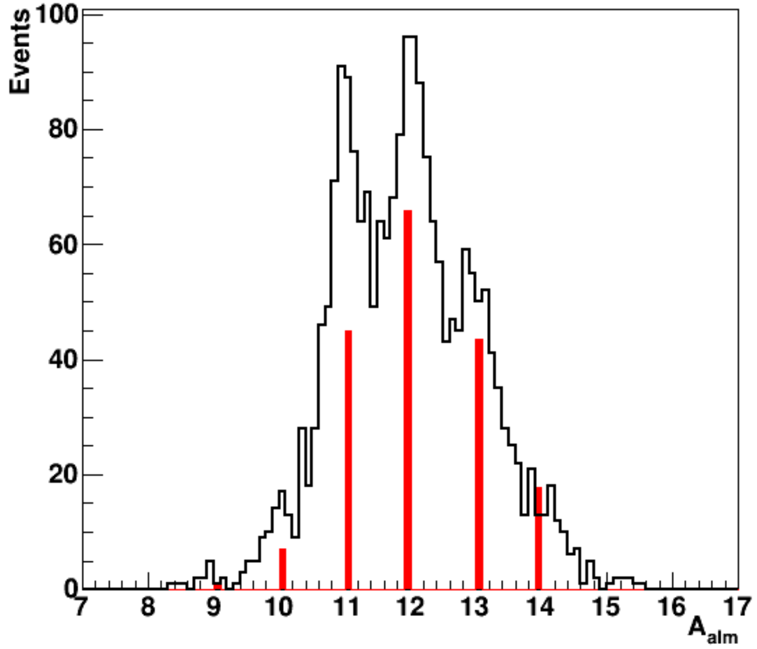
- Z>2 fragments inside 4°
- Same acceptance as @ 200 MeV/u
- Fragments with larger energy
  - higher probability to fragment in the calorimeter
  - larger neutrons production

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



Fluka simulation

^{16}O (700 MeV/u) → C_2H_4



- Resolution: **2.1%** (^{16}O) – **8%** (^{1}H)
- Wrong charge assignment < 1%

MASS RECONSTRUCTION AND FIT

TOF (β) – TRACKER (p)

$$A_1 = \frac{m}{U} = \frac{p}{U\,\beta\,\gamma}$$

TOF (β)– CALO (E_{kin})

$$A_2 = \frac{m}{U} = \frac{E_{kin}}{U(\gamma - 1)}$$

TRACKER (p) – CALO (E_{kin})

$$A_3 = \frac{m}{U} = \frac{p^2 - {E_{kin}}^2}{2E_{kin}}$$

- **Standard χ^2 Fit**
  - Taking into account the correlation between A_1, A_2 and A_3 (reconstructed quantities)
  - Minimization method based on a function *f* defined by:

$$f = \left(\frac{(tof_{reco} - t)}{\sigma tof_{reco}}\right)^2 + \left(\frac{(p_{reco} - p)}{\sigma p_{reco}}\right)^2 + \left(\frac{(E_{kin,reco} - E_{kin})}{\sigma E_{kin,reco}}\right)^2 + (A_1 - A \quad A_2 - A \quad A_3 - A)\begin{pmatrix} C_{00} & C_{01} & C_{02} \\ C_{10} & C_{11} & C_{12} \\ C_{20} & C_{21} & C_{22} \end{pmatrix}\begin{pmatrix} A_1 - A \\ A_2 - A \\ A_3 - A \end{pmatrix}$$

$$C = (A \cdot A^T)^{-1}$$ Correlation matrix

$$A = \begin{pmatrix} \frac{\partial A_1}{\partial t} dt & \frac{\partial A_1}{\partial p} dp & 0 \\ \frac{\partial A_2}{\partial t} dt & 0 & \frac{\partial A_2}{\partial E_{kin}} dE_{kin} \\ 0 & \frac{\partial A_3}{\partial p} dp & \frac{\partial A_3}{\partial E_{kin}} dE_{kin} \end{pmatrix}$$

MASS RECONSTRUCTION AND FIT

TOF (β) – TRACKER (p)

$$A_1 = \frac{m}{U} = \frac{p}{U\,\beta\,\gamma}$$

TOF (β)– CALO (E_{kin})

$$A_2 = \frac{m}{U} = \frac{E_{kin}}{U(\gamma - 1)}$$

TRACKER (p) – CALO (E_{kin})

$$A_3 = \frac{m}{U} = \frac{p^2 - {E_{kin}}^2}{2E_{kin}}$$

- **Augmented LagrangianFit (ALM)**
  - The method minimizes a Lagrangian function *L* expressed by:

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

  - *f* is the analog of χ^2 fit

$$f = \left(\frac{(tof_{reco} - t)}{\sigma tof_{reco}}\right)^2 + \left(\frac{(p_{reco} - p)}{\sigma p_{reco}}\right)^2 + \left(\frac{(E_{kin,reco} - E_{kin})}{\sigma E_{kin,reco}}\right)^2$$

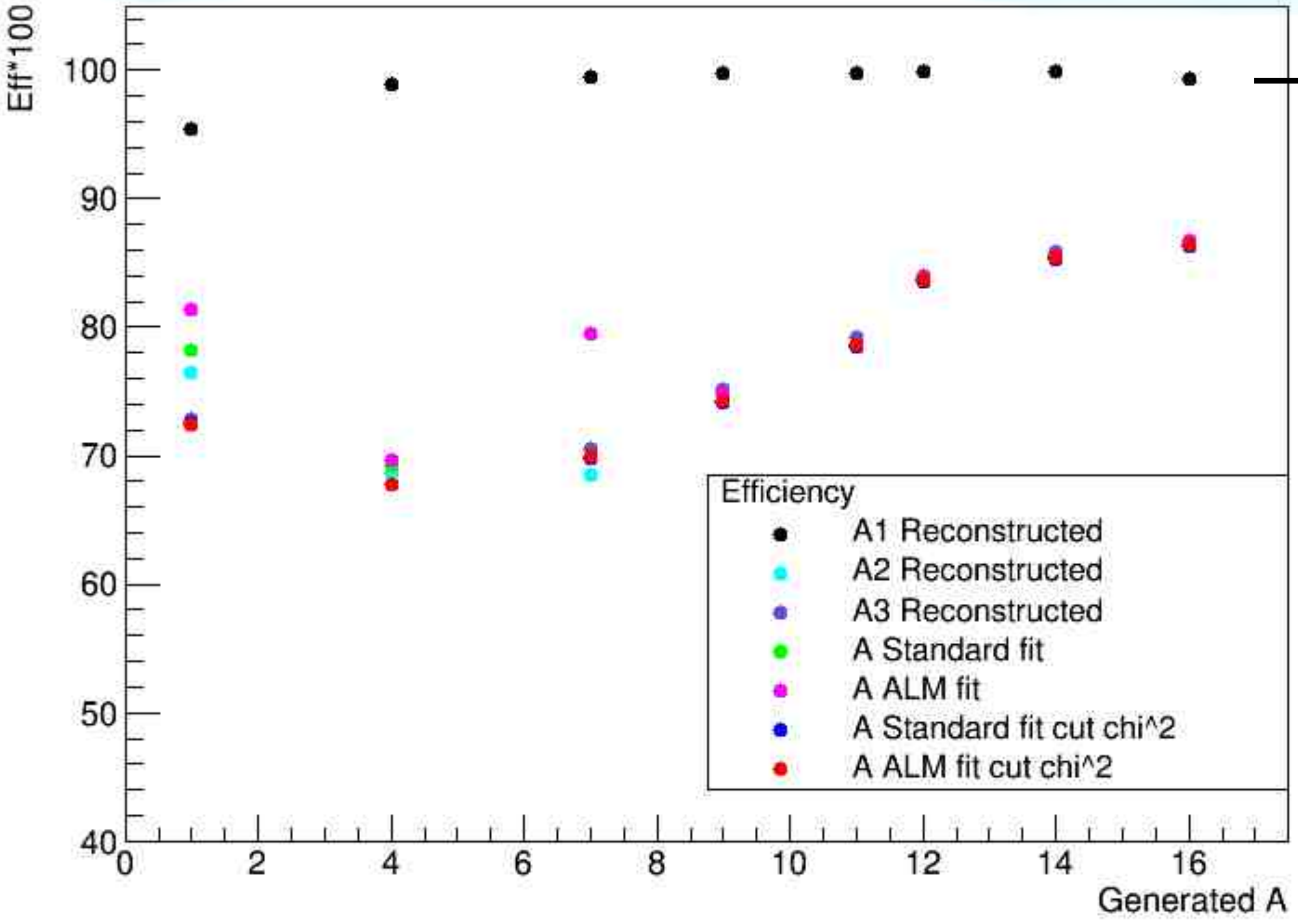
  - Summations run over A_1, A_2 and A_3 with the relation

$$\sum_a \lambda_a c_a(\vec{x}) + \frac{1}{2\mu}\sum_a c_a^2(\vec{x}) = (\lambda_1(A_1 - \mathrm{A}) + \lambda_2(A_2 - \mathrm{A}) + \lambda_3(A_3 - \mathrm{A}) + \frac{1}{2\mu}\,((A_1 - \mathrm{A})^2 + (A_2 - \mathrm{A})^2 + (A_3 - \mathrm{A})^2)^2$$

λ = variable Lagrangian multiplier parameters

μ = penalty term fixed at 0.1 -> the lower is μ the greater is the effect of A_1, A_2 and A_3 (reconstructed quantities)

MASS RECONSTRUCTION EFFICENCY



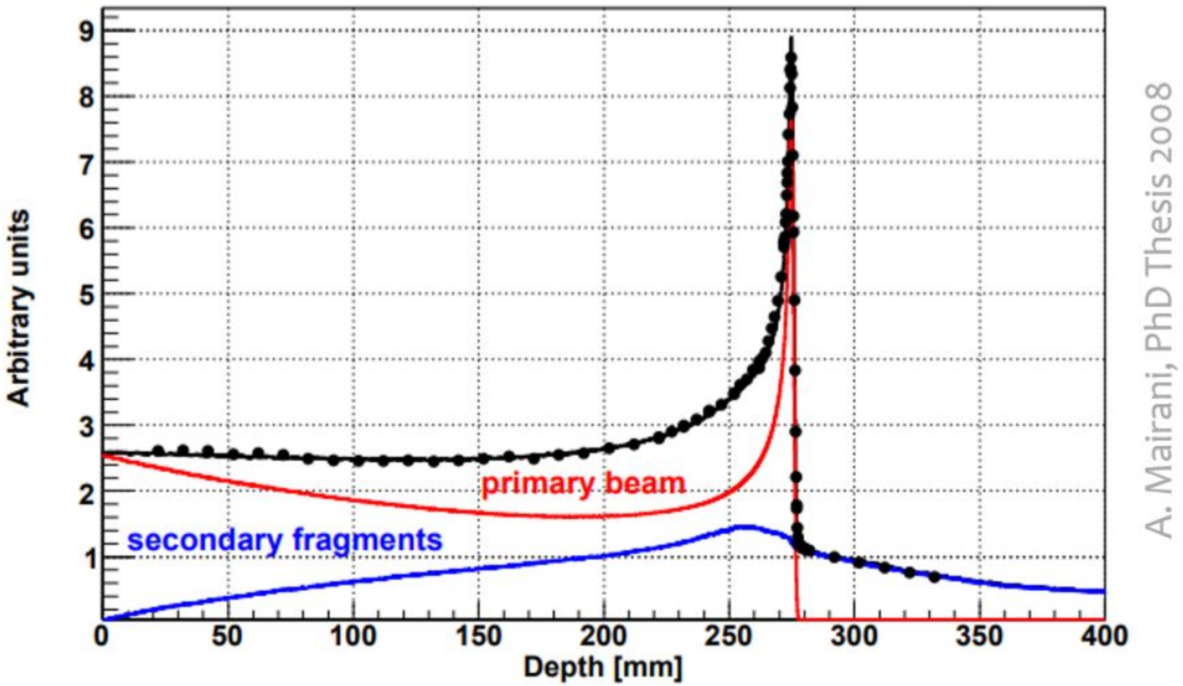
→ Tof +Tracker

Reconstruction efficiency ~ 70-80 % depending on the fragment

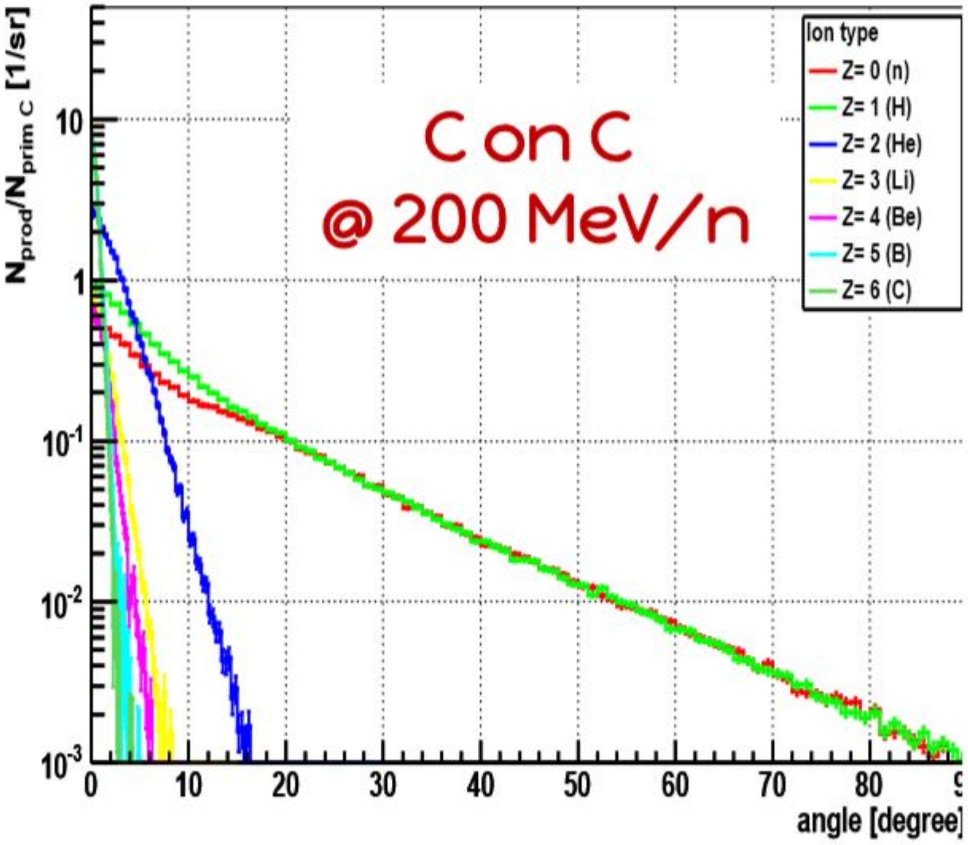
NUCLEAR FRAGMENTATION IN HADRONTHERAPY

Ion Therapy

- **Both projectile and target nuclei fragmentation**
- Same velocity but lower mass wrt primary particles: **long range**
- **Mixed particle field** of different cell killing effectiveness: considered in 12C treatment, but still scarce validation data



STUDY OF TARGET FRAGMENTATION



- Heavy (Z>2) fragments produced at small angle (<10°)
- Light fragments produced in a broader angle

STUDY OF TARGET FRAGMENTATION

200 MeV/u p on Oxygen

Estimation of the energy and range of target fragments obtained with an analytical model

No experimental data

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

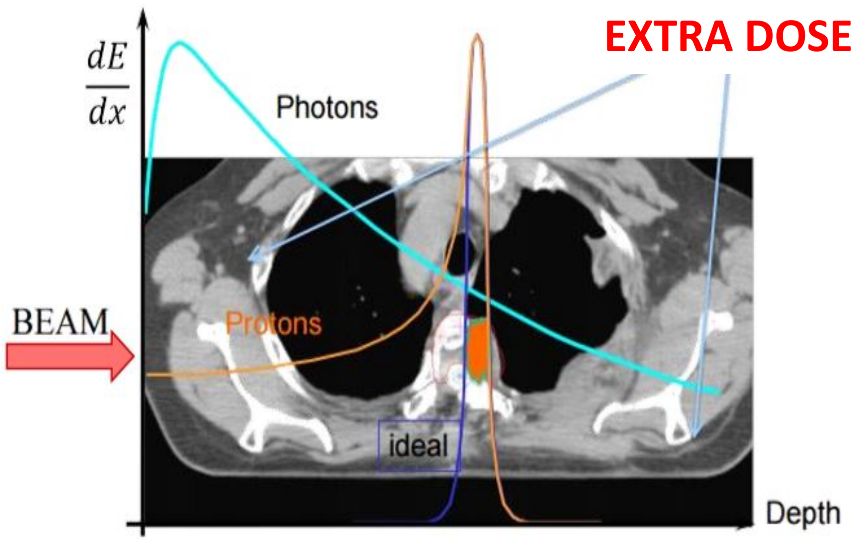
Tommasino and Durante, *Cancers* (2015)

HADRONTHERAPY

Radiotherapy employs different kinds of radiation to destroy cancer cells, by damaging their DNA and thus invalidating their duplicating capability

Radiotherapy concern ~50% of all cancer patients

Particle Therapy (p & C)



Spatial selectivity

- higher conformity of dose to the target volume (Bragg Peak)
- smaller lateral scattering

Better sparing of normal tissues

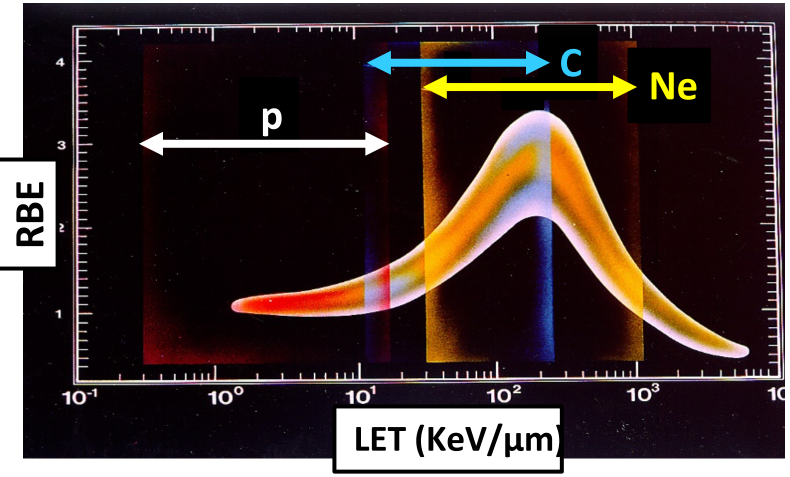
Biological effectiveness

- greater biological effectiveness (increases with the charge)

Radioresistant tumors

- Sensitive to target motion

RELATIVE BIOLOGICAL EFFECTIVENESS (RBE)



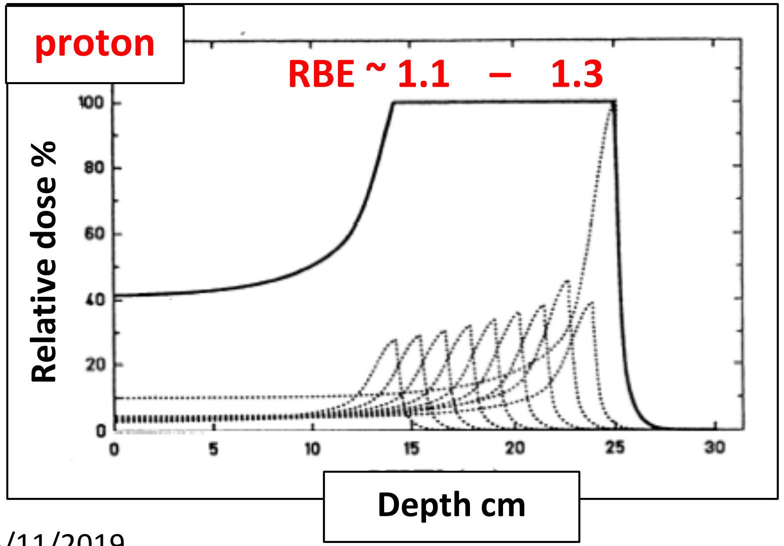
$$R.B.E = \left(\frac{D_{X-ray}}{D_H}\right)_{Same\ effect}$$

- Quantify the strength of different radiation types
- High RBE → high effect wrt radiation

RBE depends on

- LET
- Dose
- Depth in the body
- Beam energy
- Vivo/vitro
- Tissue type …
- **Nuclear interaction**

not considered



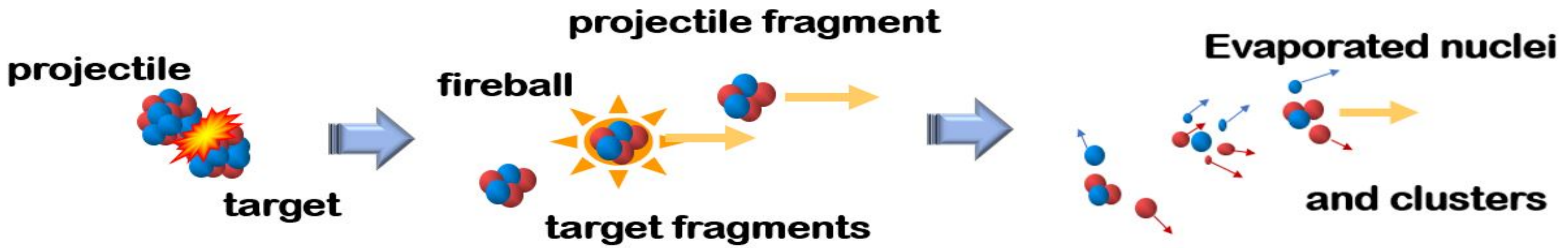
proton RBE = 1.1

NUCLEAR FRAGMENTATION IN HADRONTHERAPY

Hadrontherapy energies:
p → 200 MeV
^{12}C → 400 MeV/u

Most probable nuclear process: fragmentation ->peripheral interaction between projectile (p, ^{12}C,…) and target (H, C, O, …)

Protons ≠ photons * 1.1 due to Nuclear interaction → **No Standard Treatment Planning for hadrontherapy** → Study of the Target-Projectile fragmentation



ABRASION PHASE

Creation of **prefragments** : lower mass but same velocity of the primary beam

ABLATION PHASE

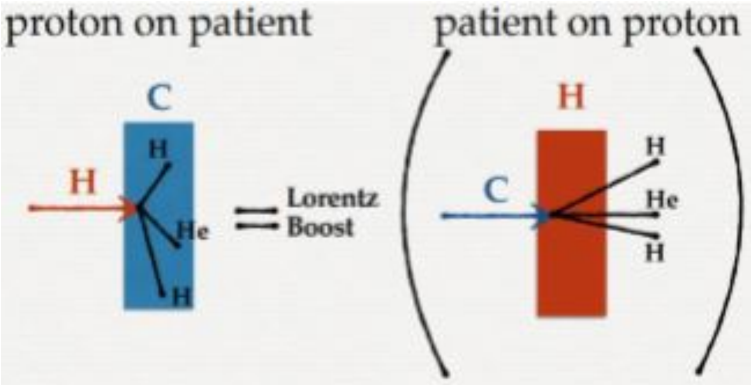
Evaporation process: isotropic distribution of particles

EXPERIMENTAL STRATEGIES

Shooting a proton on a patient (i.e., at 98% a C, O, H nucleus) could not be the right choice. A possible work around is to **shoot a patient** (i.e., 0, C beam) **on** a target made of **protons** and measure the fragments

Direct kinematics

Inverse kinematics



By applying the Lorentz transformation it is possible to switch from *the laboratory frame* to the *patient frame*

MASS IDENTIFICATION