2018 European Nuclear Physics Conference

September 2nd-7th, 2018: Bologna, Italy
San Domenico Center

Istituto Nazionale di Fisica Nucleare
Sezione di Bologna

FOOT: FragmentatiOn Of Target Experiment


Bologna, San Domenico, 6/9/2018

- ***Hadrontherapy, Radio Protection***
  - ***Main concepts***
- ***FOOT***
  - ***Main goals***
  - ***Detector***
  - ***Performances***
- ***FUTURE PERSPECTIVE***

Roberto Spighi (INFN Bologna), on behalf of the FOOT Collaboration

spighi@bo.infn.it

FOOT goals

Hadrontherapy

Target fragmentation

- dσ/dE and dσ/dω with 5% precision of the fragment production X sections in inverse kinematics
- p, C, O beams
- Hadrontherapy energies (200-400 *MeV/u*)

Projectile fragmentation

- same but in direct kinematics

Radiobiology request: to have a more precise **TPS** Treatment Planning System

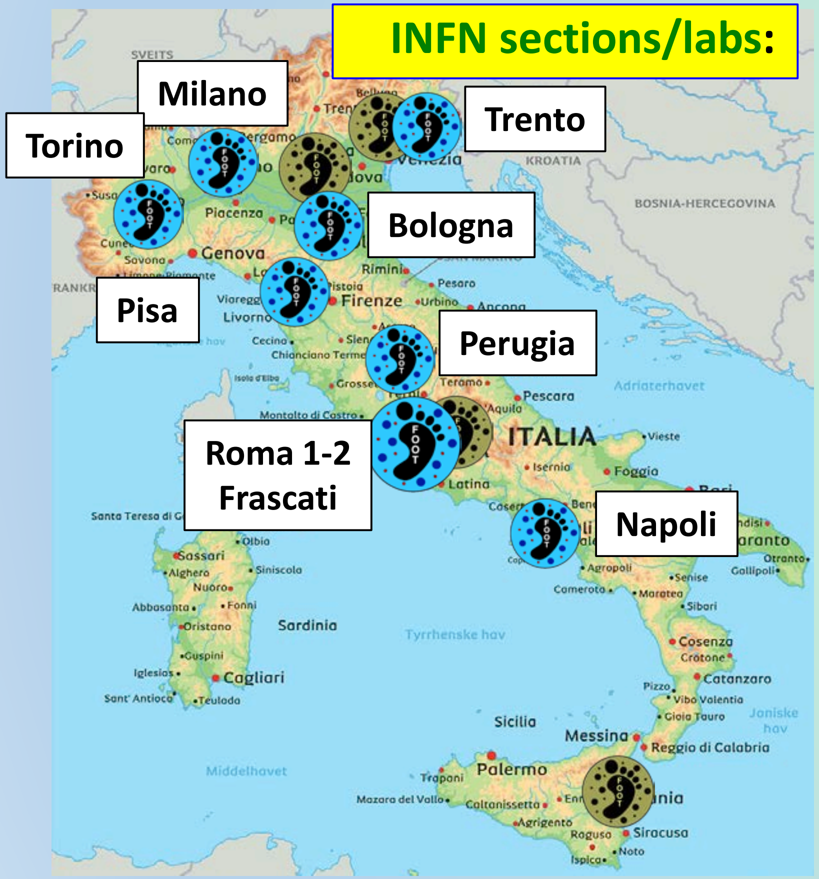
Radioprotection in space

detailed knowledge of the fragmentation processes to optimize the spacecraft shielding (long term mission)

- dσ/dE and dσ/dω with 5% precision of the fragment production X sections in direct and inverse kinematics
- p, He, Li, C, O beams (the most common in space)
- Radioprotection energies (around 700 *MeV/u*)

FOOT Collaboration

FOOT approved by the INFN on September 2017 (CSN3)



92 members (60% staff):

- **10 INFN Sections**
- **5 laboratories: Frascati, CNAO, Trento, GSI,IPHC (Strasbourg)**
- **12 Italian Universities**
- **2 foreign Universities:** Aachen, Nagoya
- **Centro Fermi**

Physics program:

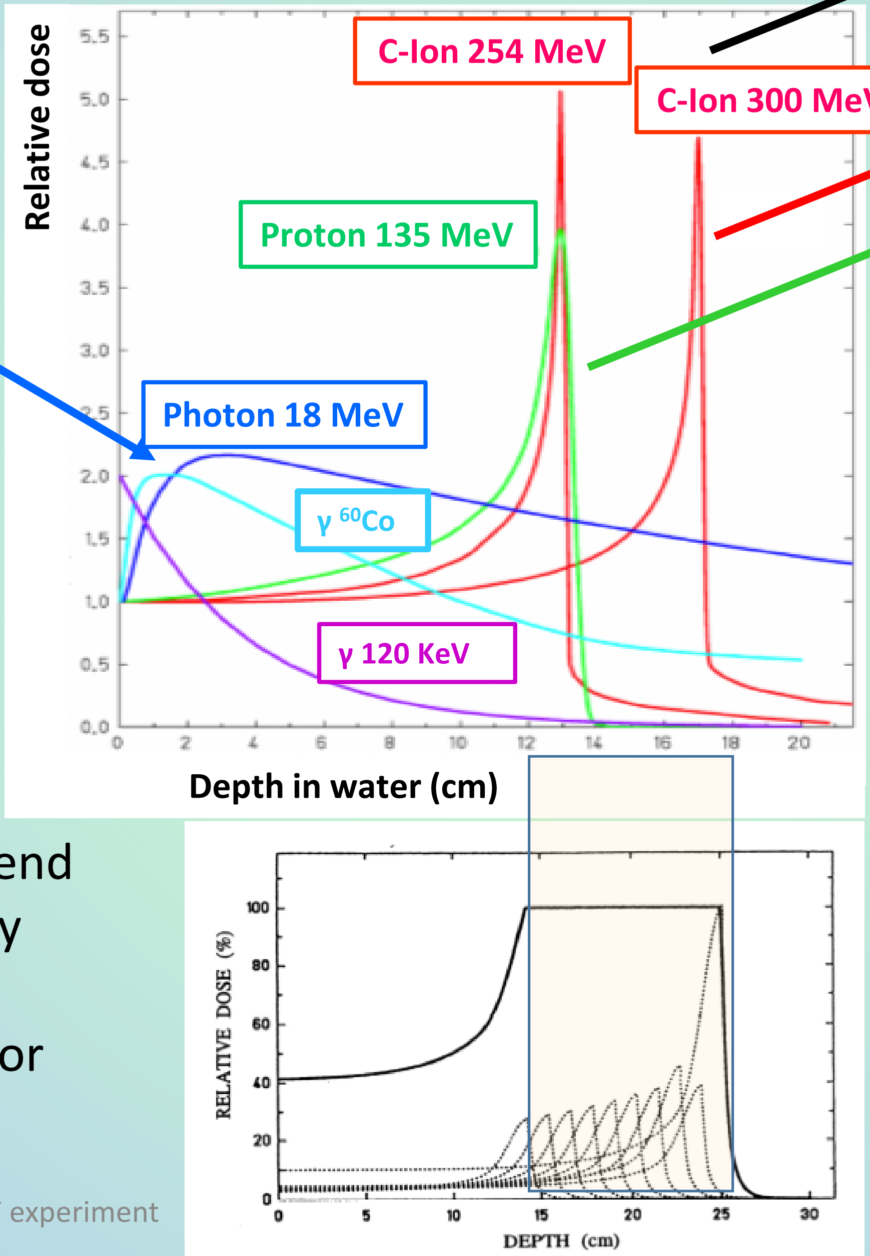
- **Hadrontherapy:**
  - **Nuclear fragmentation @ 200 MeV/u**
- **Radioprotection in Space:**
  - **Nuclear fragmentation @ 700 MeV/u**

Hadrontherapy vs Radiotherapy

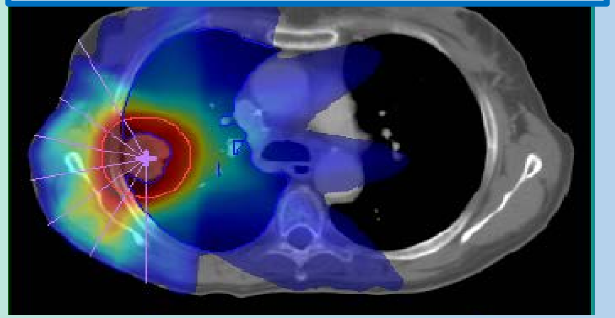
Bragg Peak

Proton/charged ion
- Ionization
- Excitation
- Bremsstrahlung
- Fragmentation

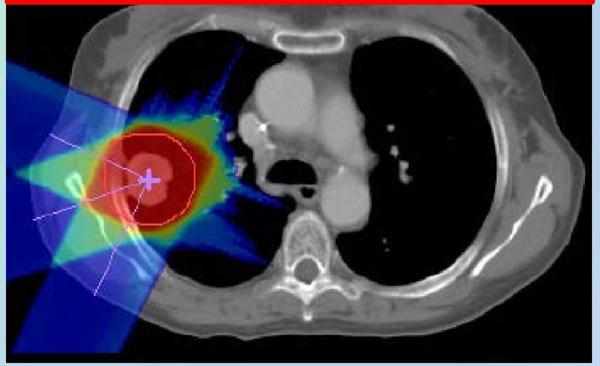
Gamma
- Photoelectric ($\sim Z^4/E^3$)
- Compton ($\sim Z/E$)
- Pair prod ($\sim Z^2/\ln E$)



Radiotherapy, IMRT 7 fields



Hadrontherapy, proton

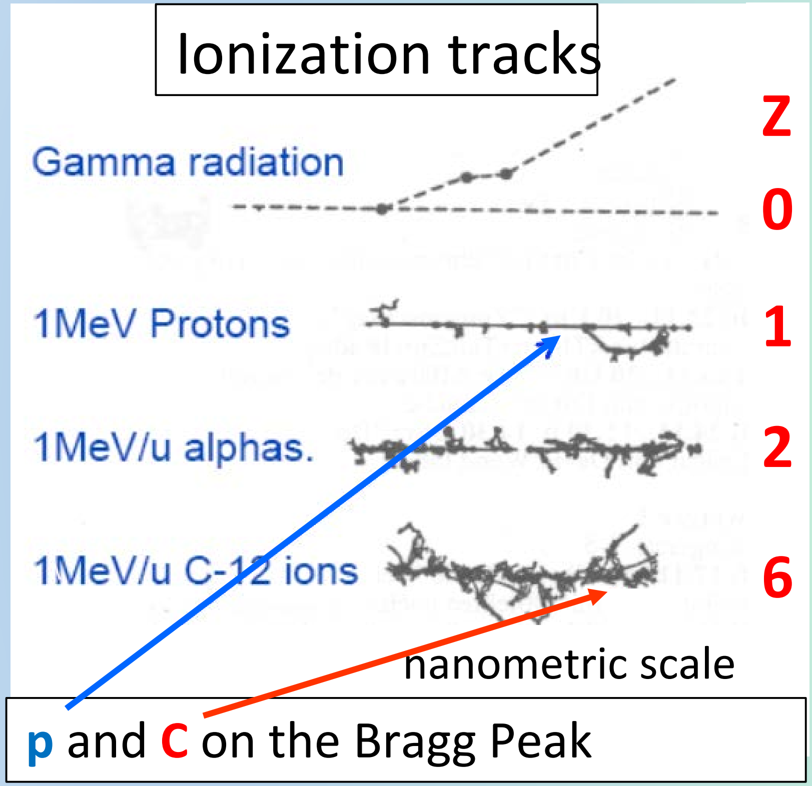


Pros and cons

- dose release maximum at the end
- Penetration depends on energy
- Hadron > efficient than γ
- Hadron < damage outside tumor
- MORE expensive than γ

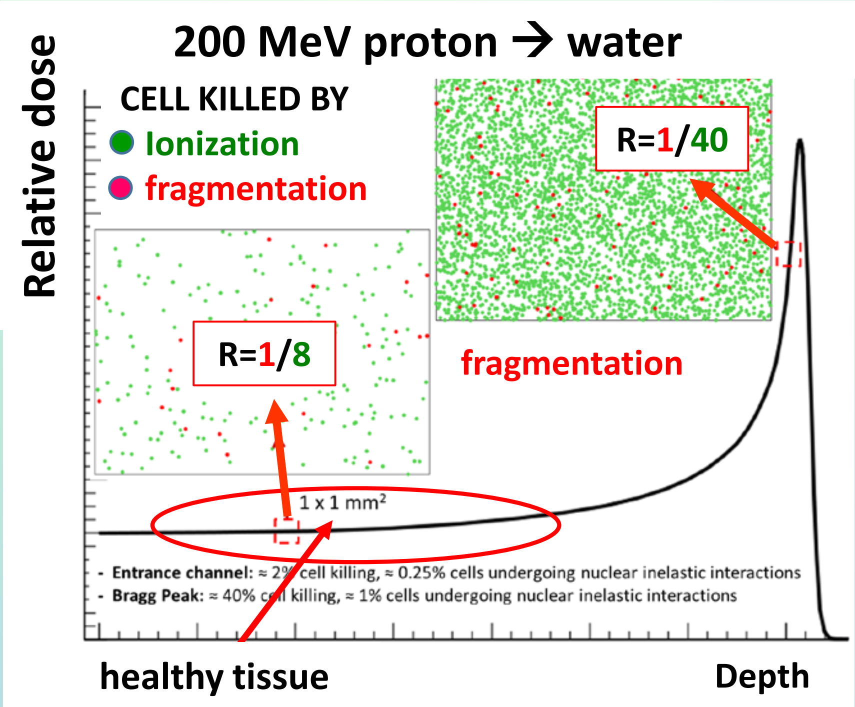
Damage on DNA

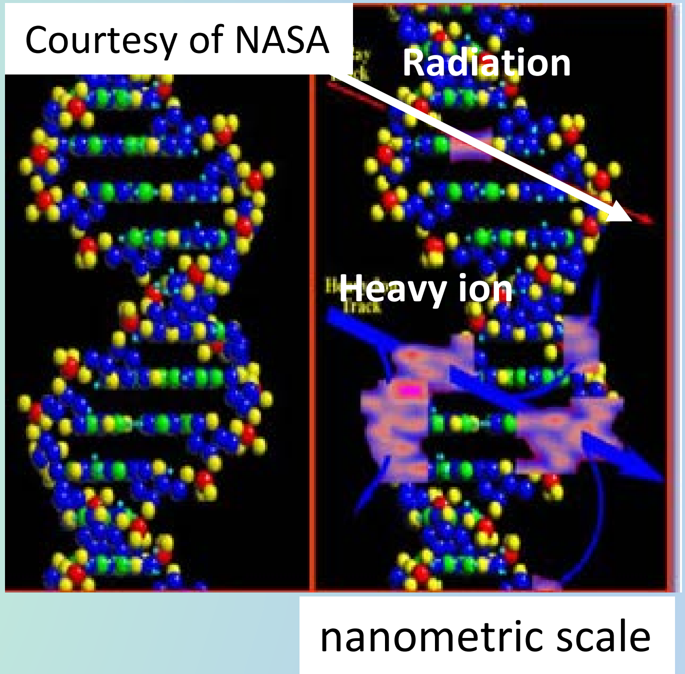
Tumor is a cellular alteration → not controlled proliferation → stop the proliferation → damage on DNA



Higher Z → Higher damage

but, necessary to know the
Nuclear fragmentation cross sections





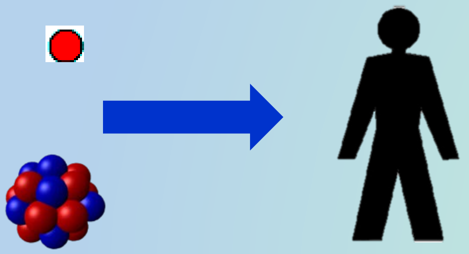
Double strand break →
irreparable damage

Target-Projectile fragmentation

beam

p

C



H, C, O (95%)

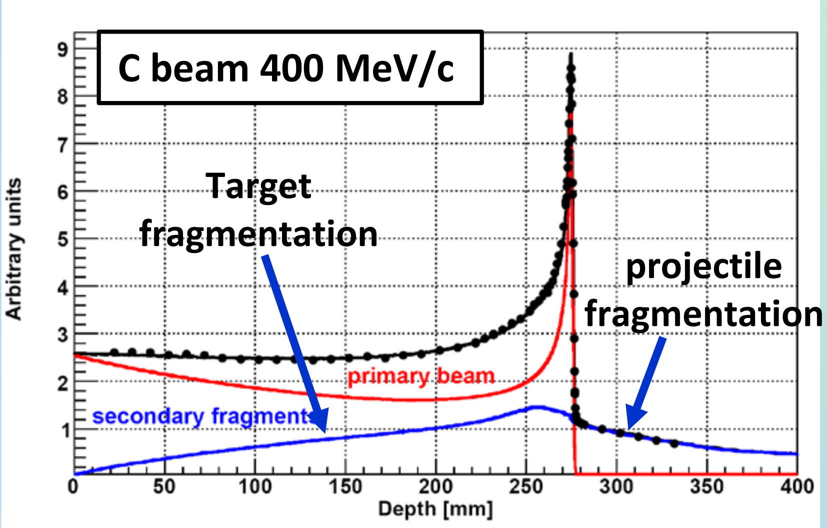
Proton therapy

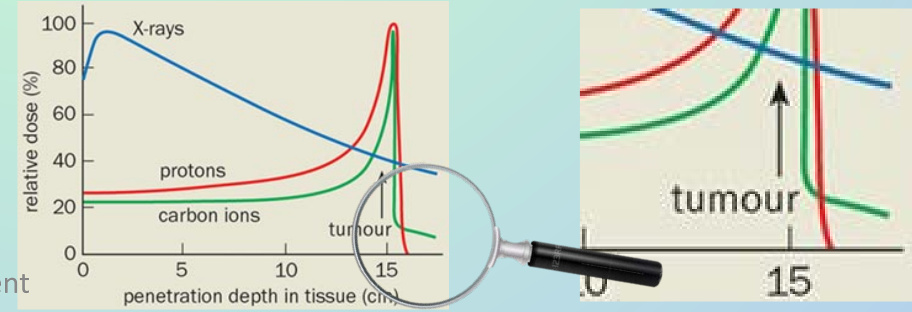
- **p** + H → No fragmentation
- **p** + C,O → target fragments
  low Energy → **low range** → Target fragmentation

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

Ion therapy

- **C** + H → projectile fragments
  High Energy → **Long range** → Projectile fragmentation
- **C** + C,O → target/projectile fragments → both





Tail present only when using Carbon

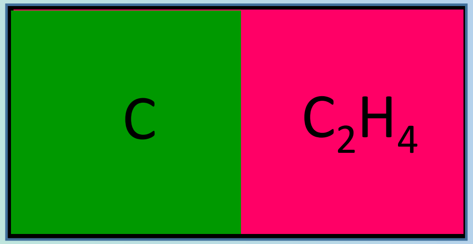
FOOT MAIN GOAL: Target fragmentation in proton therapy

p + C,O → fragments

Target fragments remain in the target

Impossible to detect fragments

Target (2mm)



H target

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

DIRECT KINEMATIC

proton
200 MeV

C,O at rest

p + C,O → fragments

INVERSE KINEMATIC

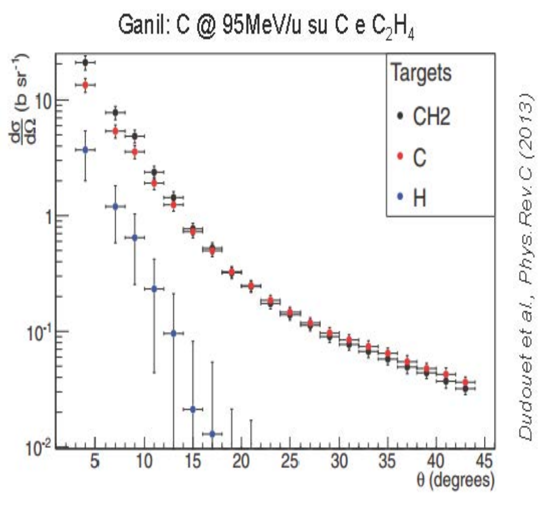
C,O 200 MeV/A

C,O + p → fragments

Proton (H)
at rest

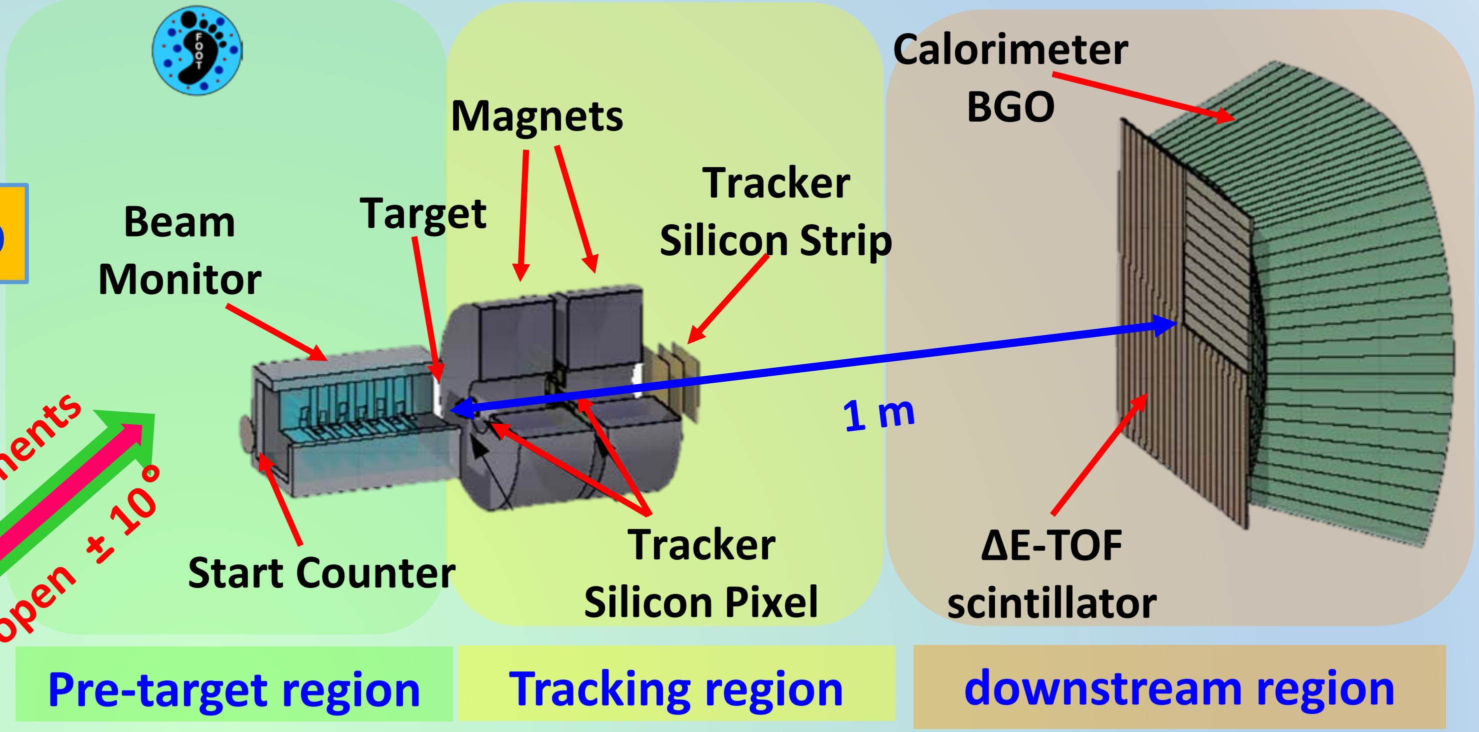
A the end
Lorentz boost

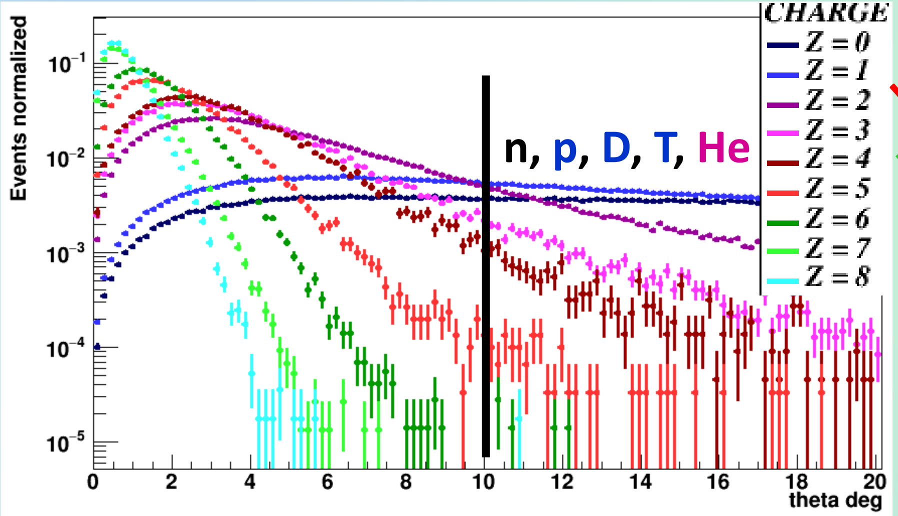
Ganil experimental data



FOOT Detector (in construction)

Electronic Setup





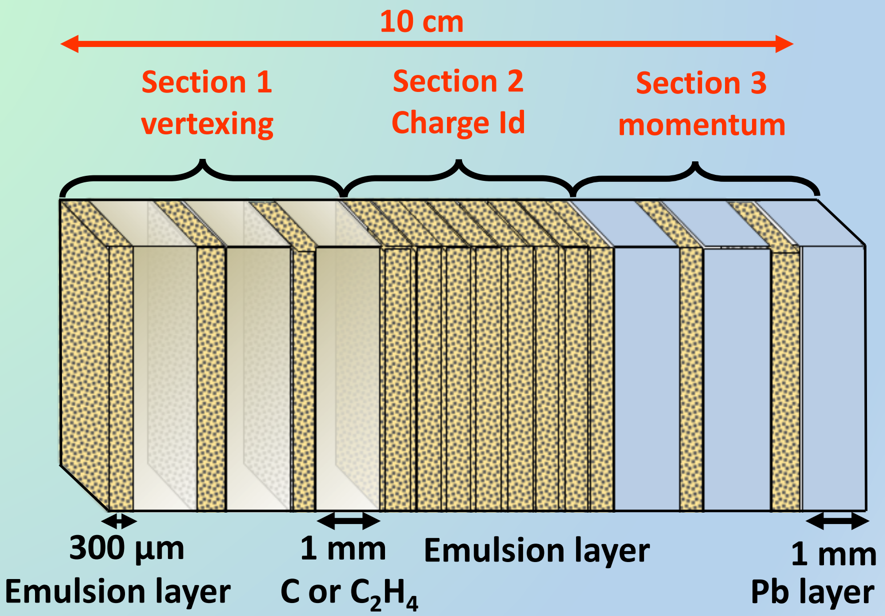
Heavy fragments

Angular open ± 10°

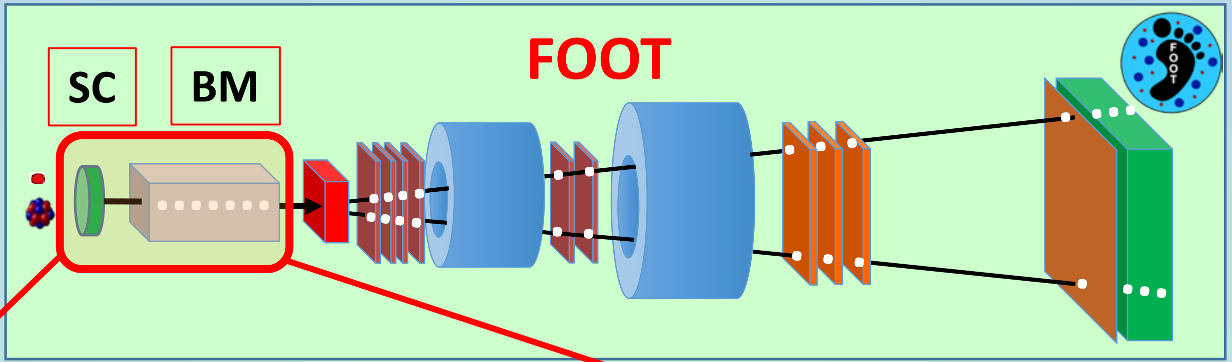
Light fragments

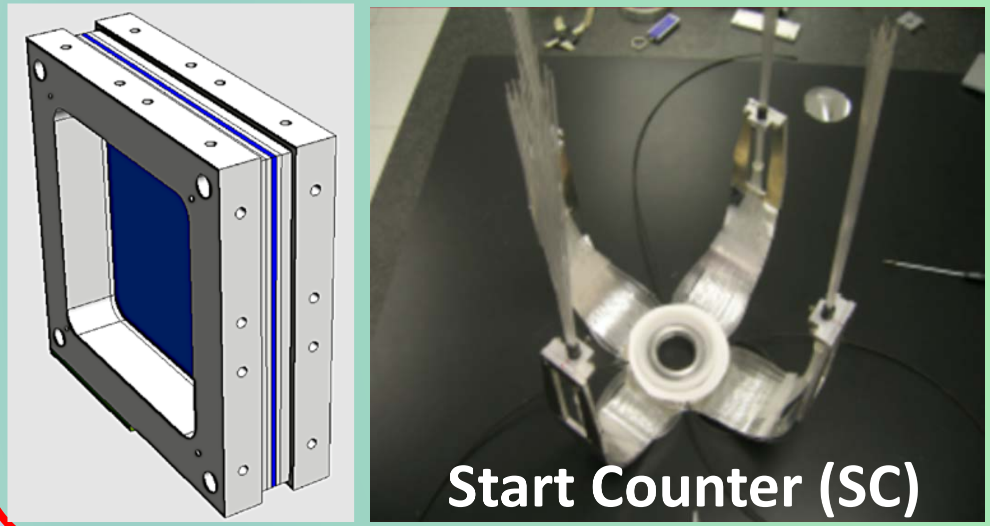
Angular open ± 70°

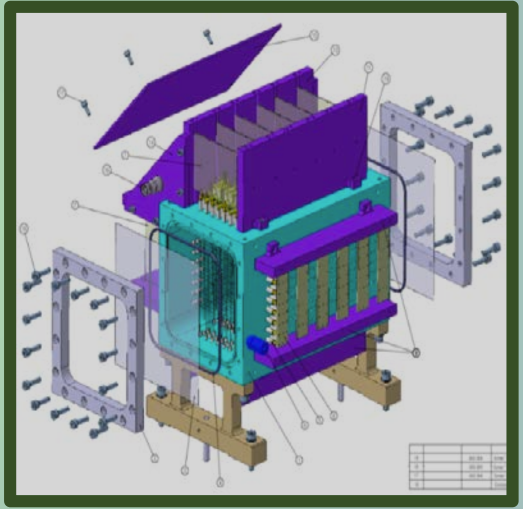
Emulsion Chamber Setup

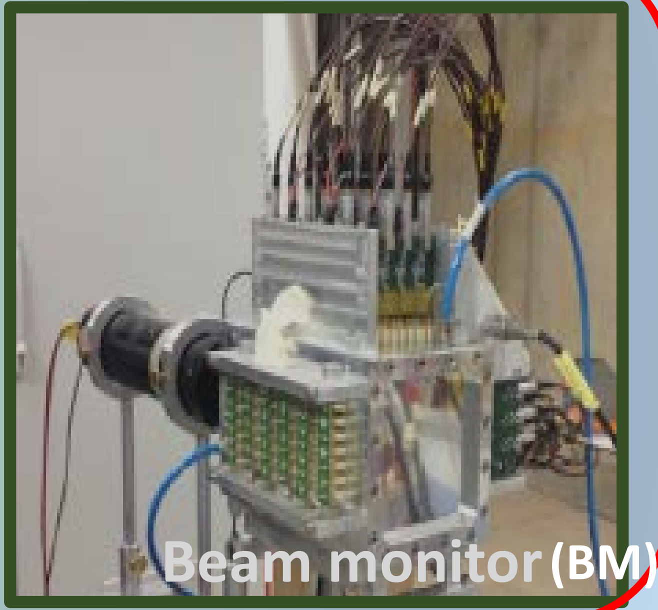


Pre target region









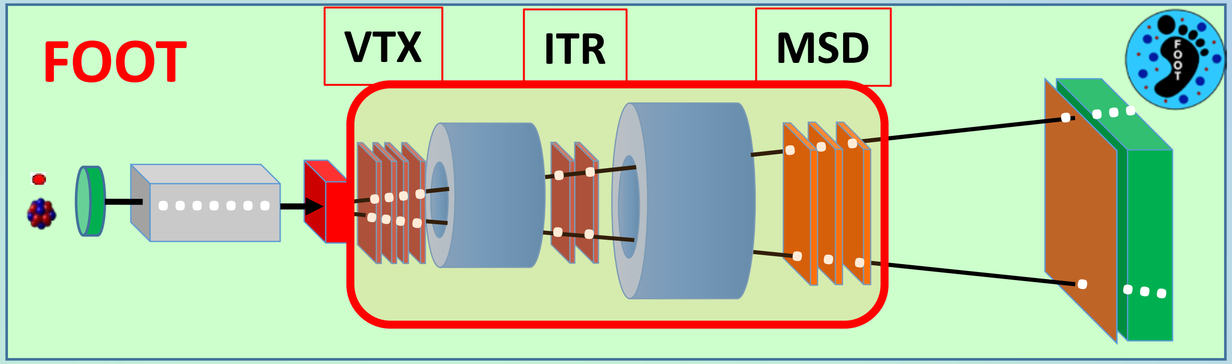
Trigger and ToF start

250 µm–1 mm thick plastic scintillator (depending on E beam)
50 mm radius
~ 400 optical fibers → 4 boundles to 4 PMTs
Test beam in september in Trento

Beam momentum/direction & fragmentation in SC

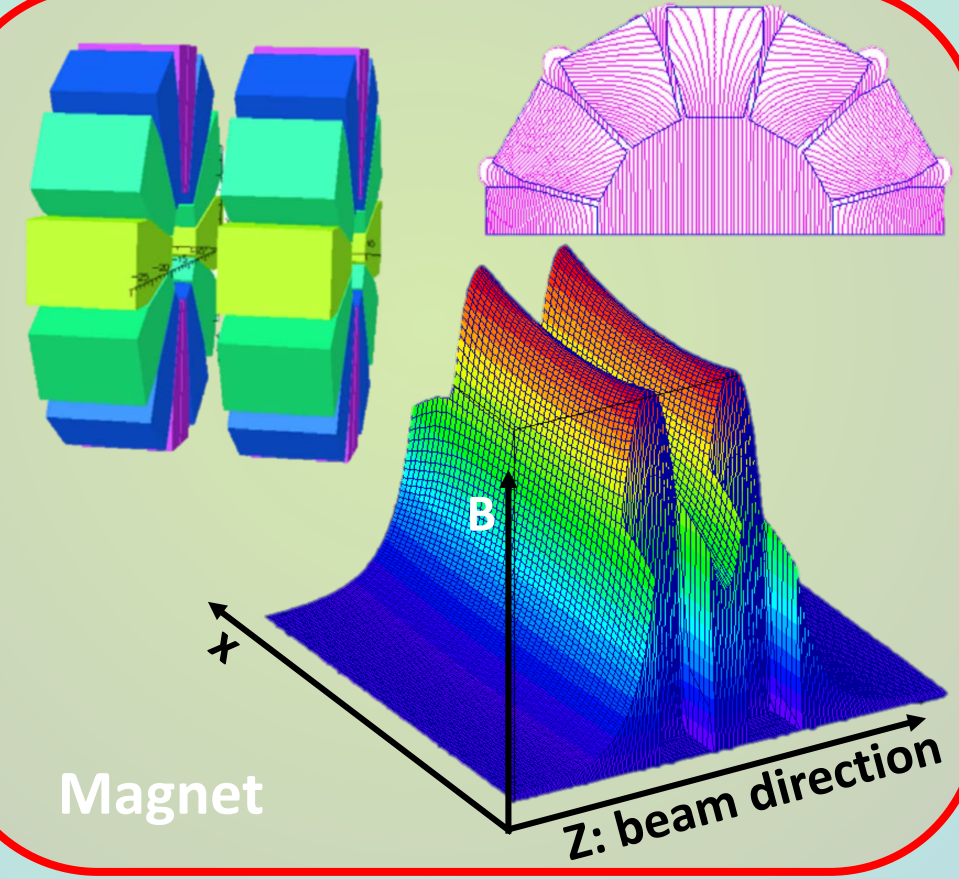
Drift chamber
Gas: Ar/Co_2 (80/20%)
Test beam in september in Trento

Tracking region

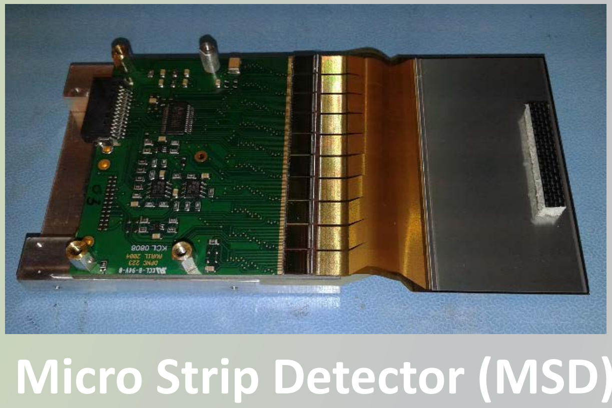


VTX: 4 layers of Si pixel (20 x 20 µm)

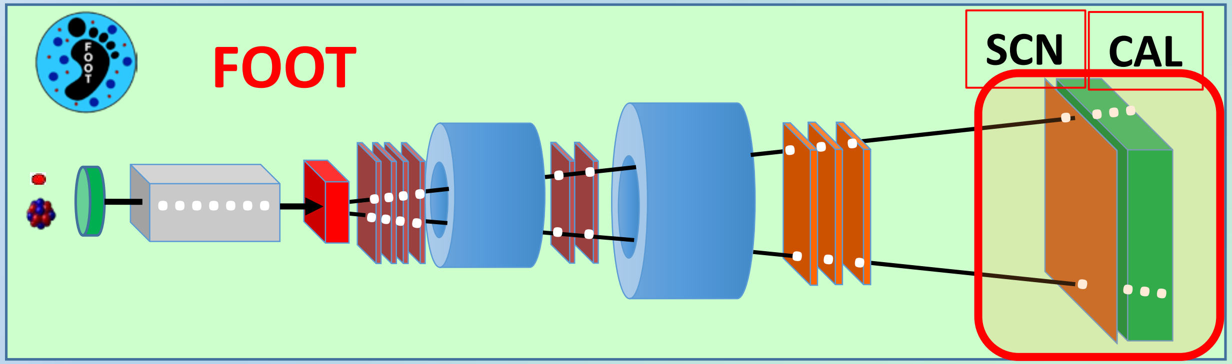
ITR: 2 layers of Si pixel (20 x 20 µm)



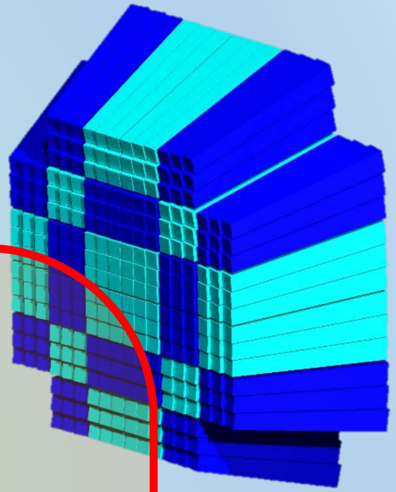
2 permanent magnets
Hallbach geometry
B field in y direction (max 0.8 T)

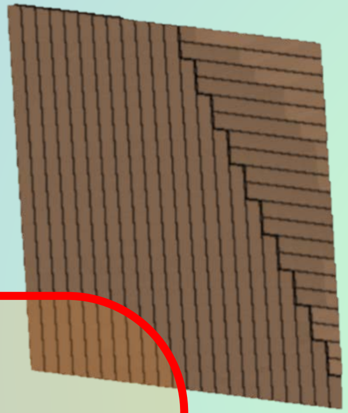


MSD:
3 layers of Si strips (120 µm x 9 cm)



downstream region





Scintillator (SCN)

40 x 2 cm plastic scintillator bars
3 mm thickness
2 layers of 20 bars
Silicon PhotoMultiplier (SiPM)

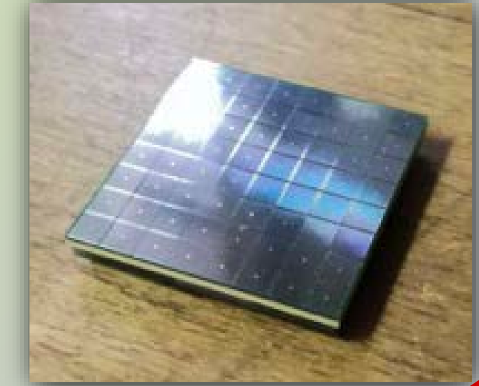
ΔE-Tof

Calorimeter (CAL)

BGO – ($Bi_4Ge_3O_{12}$)
Inorganic scintillator

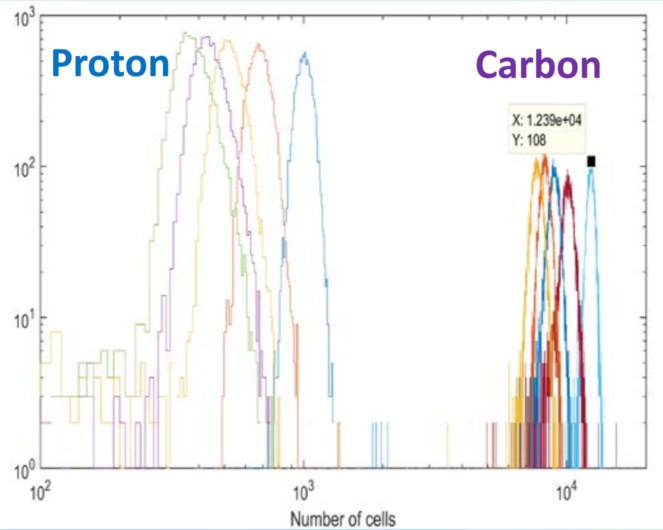
$Z_{Bi} = 83$
$P_{BGO} = 7.13\ g/cm^3$
Weight = 1.027 kg
Total weight 330 Kg

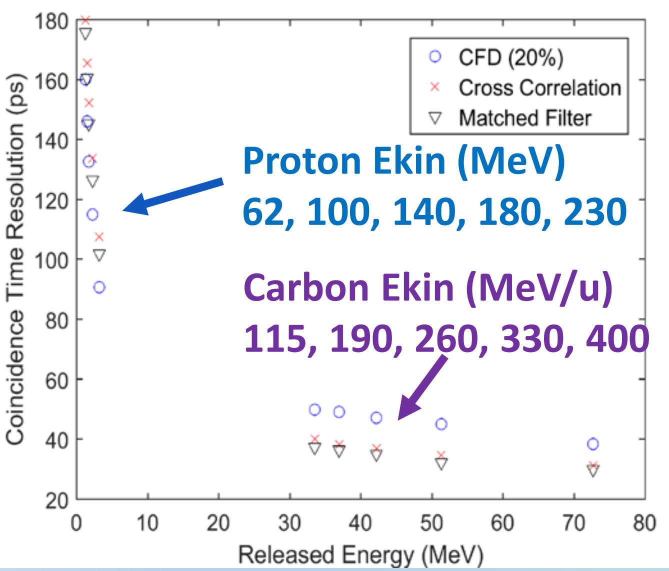
SiPM
Pitch 50 µm
Voltage breakdown 53 V



Test beam results

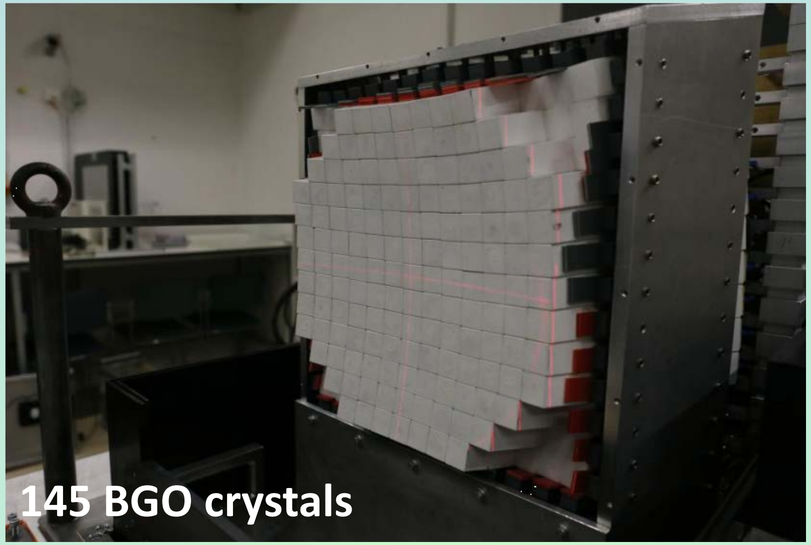
ΔE-Tof test beam @CNAO

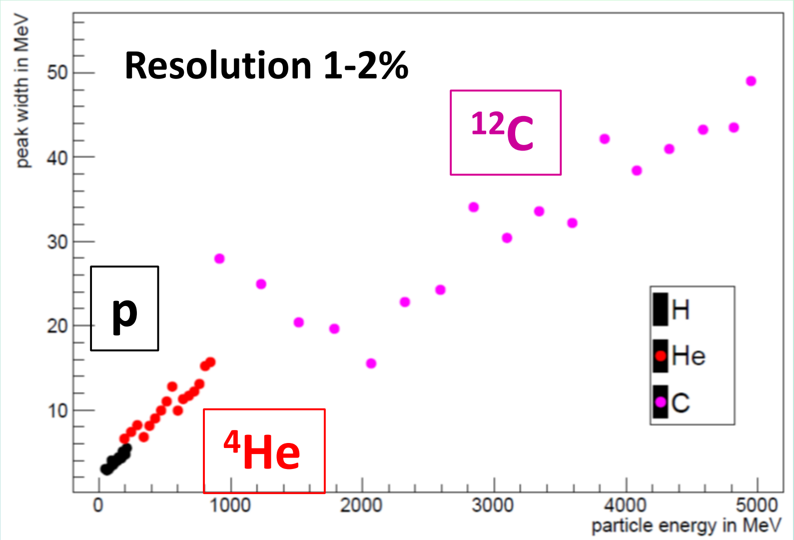




Tof resolution (C) better 40 ps

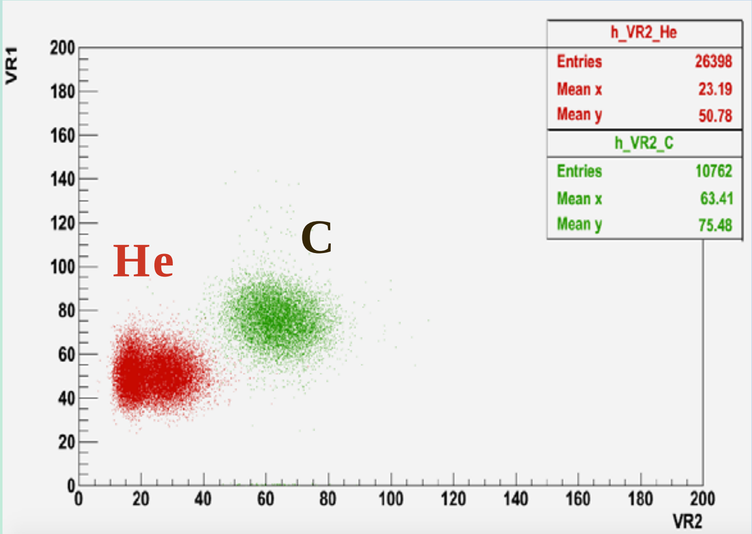
Calorimeter: test beam @HIT





Kinetic energy resolution at 1-2%

Emulsion test beam @LNS and Trento



ECC: charge separation

Conservative Resolutions

- $\Delta p/p$ → 4%
- $\Delta E_{kin}/E_{kin}$ → 1.5%
- Δtof → 70-140 ps
- $\Delta(dE)/dE$ → 3-10%

Performances: charge Z reconstruction

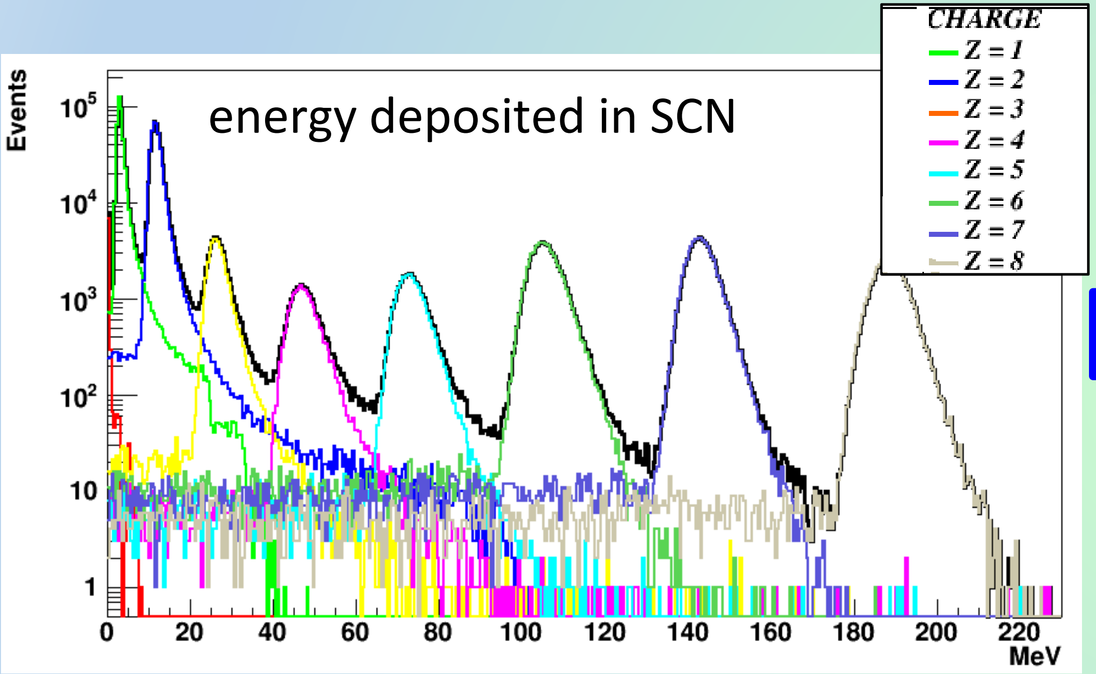
^{16}O (200 MeV/u) → C_2H_4

Fragment univocally defined by Z and A

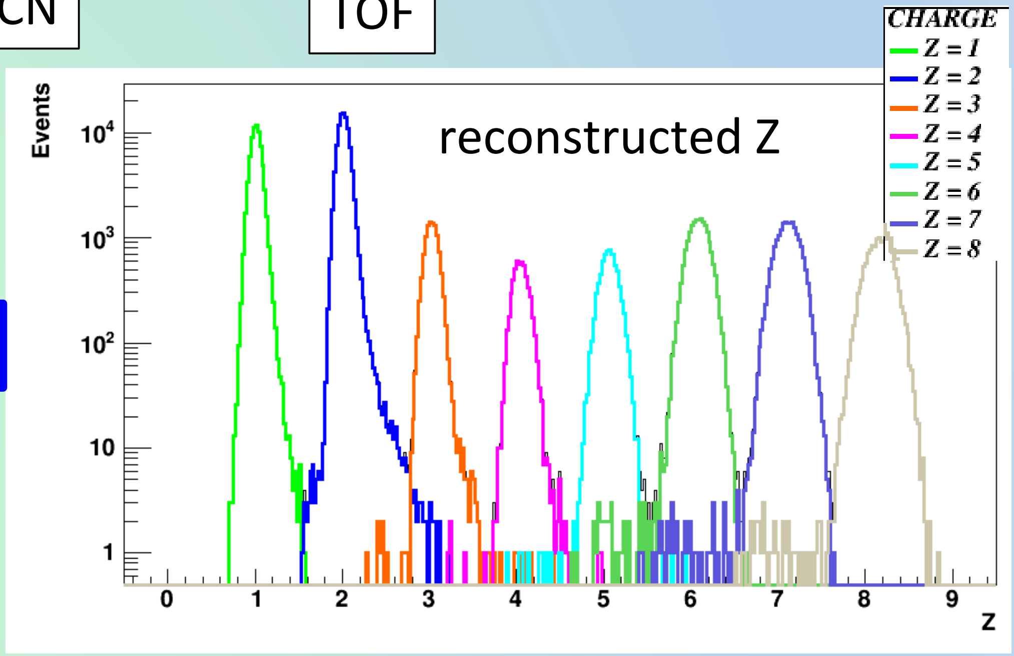
$$-\frac{dE}{dx} = \frac{\rho \cdot Z}{A} \frac{4\pi\, N_A\, m_e c^2}{M_U} \left(\frac{e^2}{4\pi\epsilon_0\, m_e c^2} \right)^2 \frac{z^2}{\beta^2} \left[\ln \left(\frac{2 m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right]$$

SCN

TOF



Fluka simulation



^{1}H	^{4}He	^{7}Li	^{9}Be	^{11}B	^{12}C	^{14}N	^{16}O
1	2	3	4	5	6	7	8
1.01±0.09	2.01±0.06	3.03±0.08	4.05±0.09	5.06±0.10	6.09±0.12	7.11±0.14	8.15±0.15

Z Resolution : **9%** **3%** **2.0%**

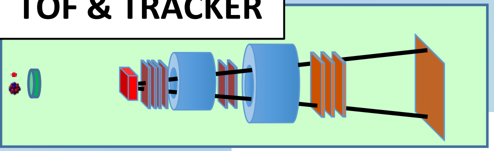
wrong charge assignment < 1%

Performances: Number of mass A (ex of ^{12}C)

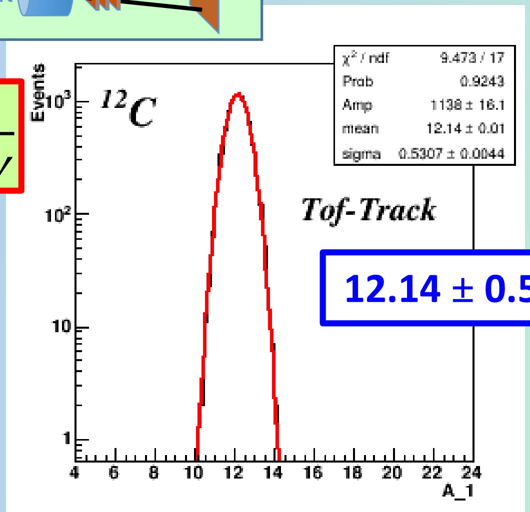
Fluka simul ^{16}O (200 MeV/u) → C_2H_4

REDUNDANT Detector → different ways to determine A

TOF & TRACKER

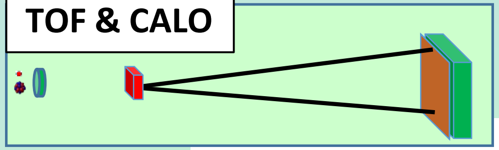


$$A_1 = \frac{p}{U\,\beta\,\gamma}$$

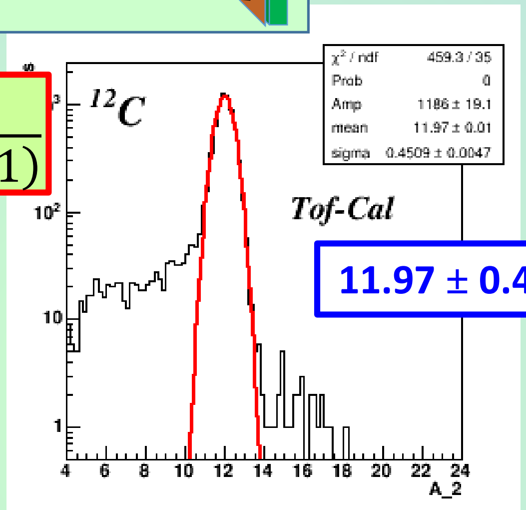


12.14 ± 0.53

TOF & CALO

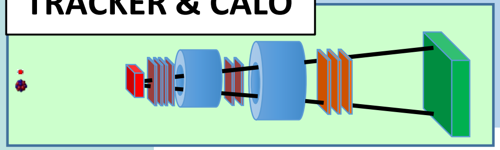


$$A_2 = \frac{E_{kin}}{U(\gamma - 1)}$$

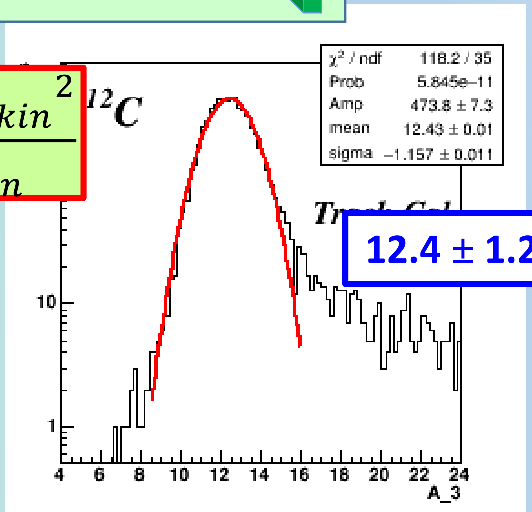


11.97 ± 0.45

TRACKER & CALO



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

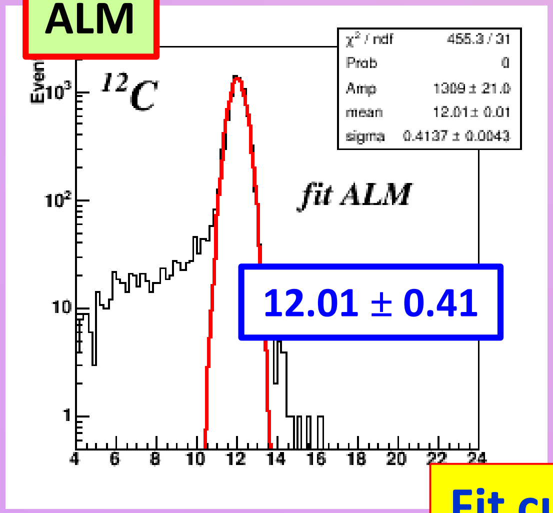


12.4 ± 1.2

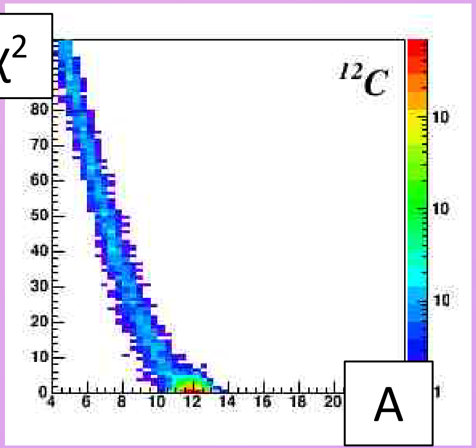
FIT Methods:

- **Standard χ^2**
- **Augmented Lagrangian (ALM)**

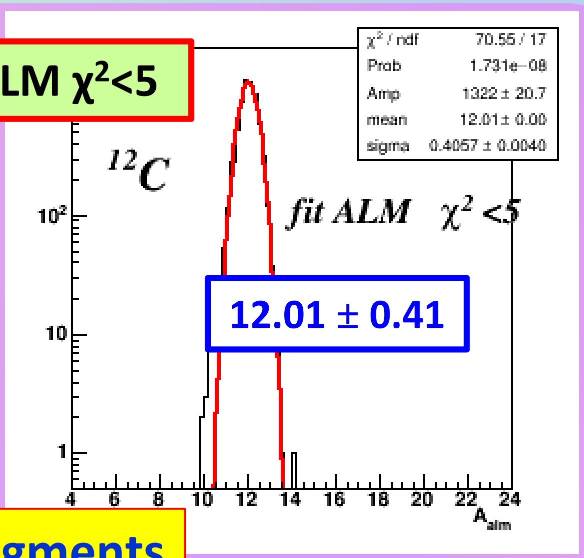
ALM



12.01 ± 0.41



ALM χ^2<5



12.01 ± 0.41

Fit cut the wrong reconstructed fragments

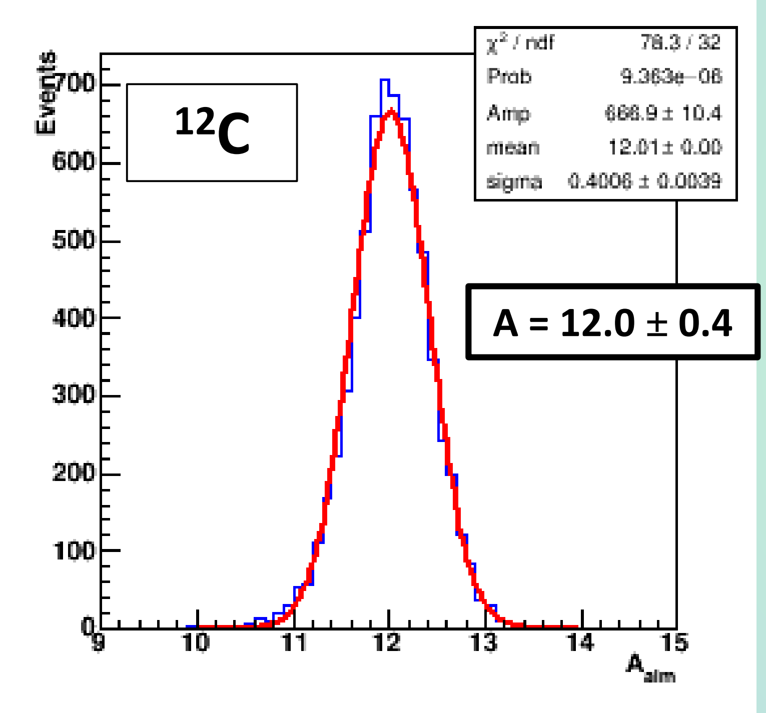
FOOT Performances: Number of mass reconstruction

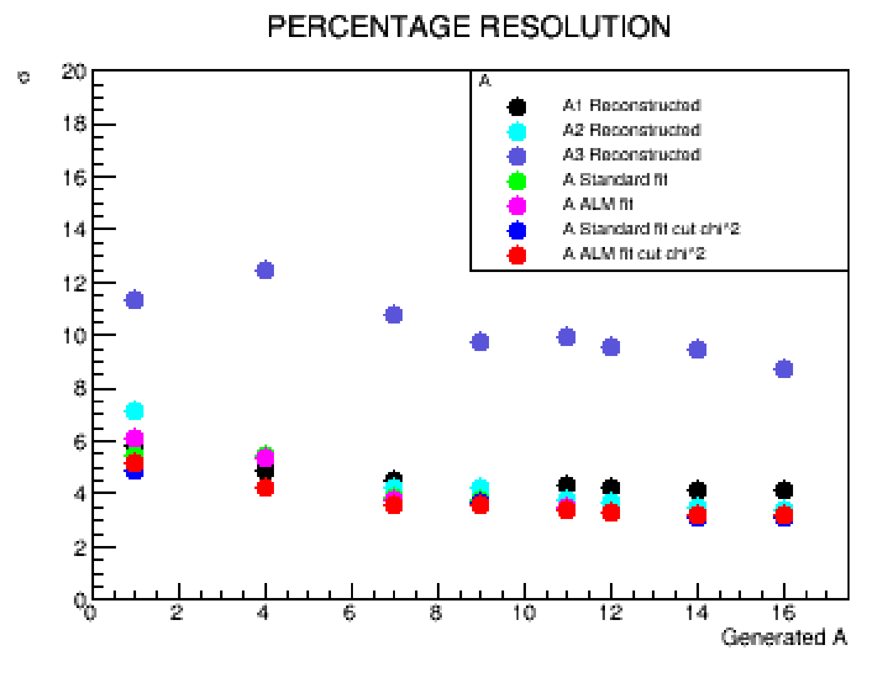
^{16}O (200 MeV/u)→ C_2H_4

Conservative Resolutions

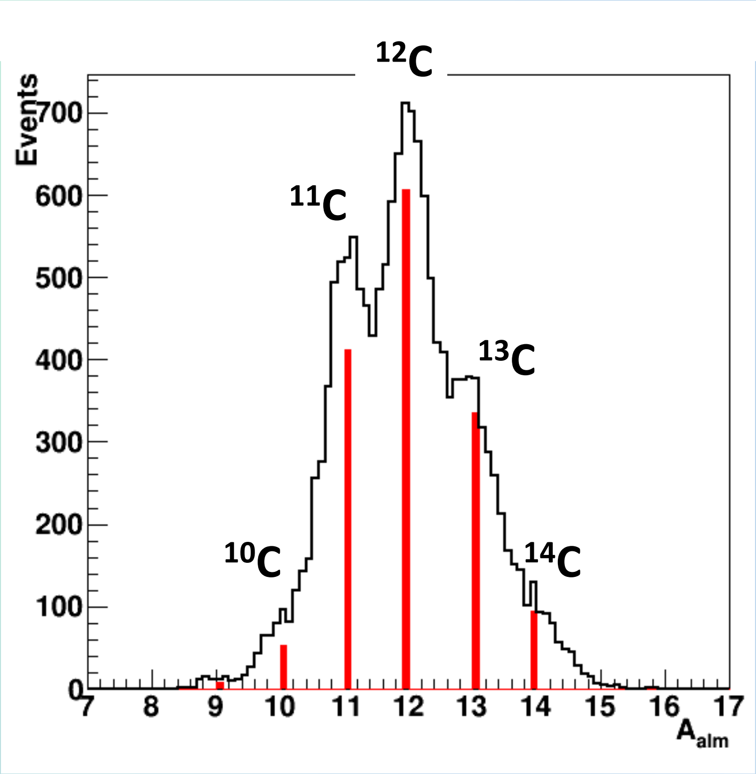
- $\Delta p/p$ → 4%
- $\Delta E_{kin}/E_{kin}$ → 1.5%
- Δtof → 70 – 140 ps
- $\Delta(dE)/dE$ → 3 -10%

Simulation by Fluka





Resolution for heavy fragments ~ 3-4%



Possibility to disentangle isotopes

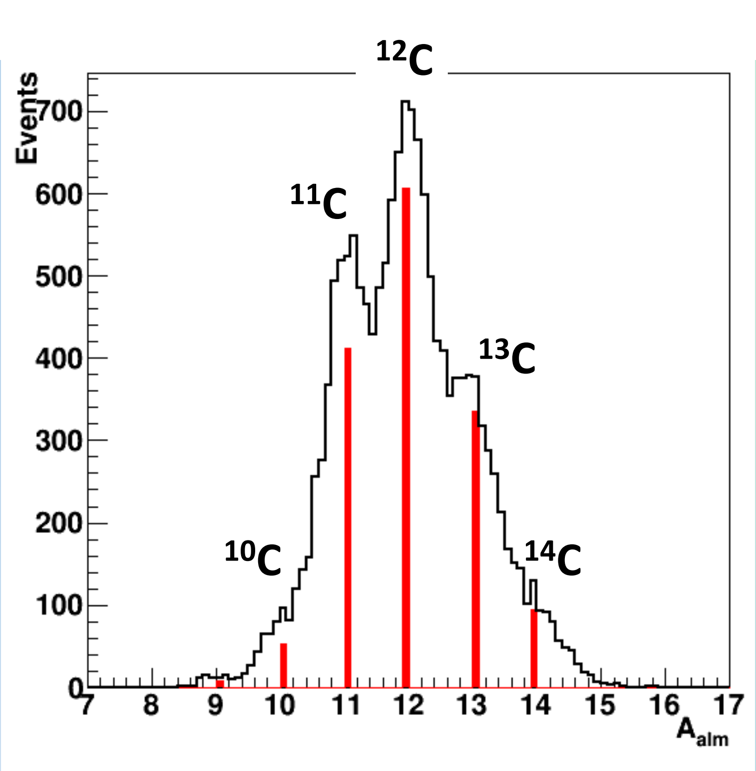
FOOT Performances: Isotopes separation (example of C)

Data simulated by Fluka

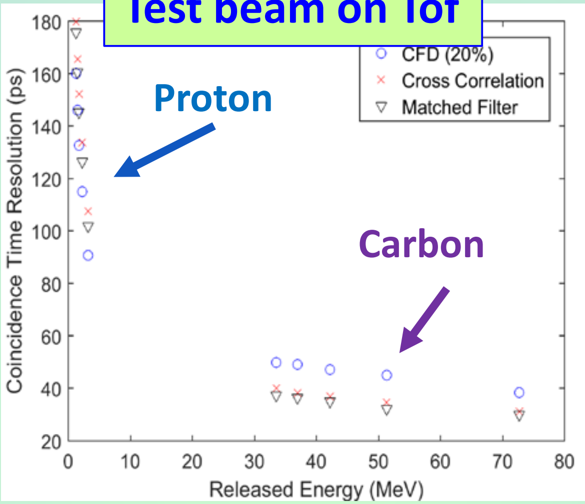
^{16}O (200 MeV/u) → C_2H_4

Conservative Resolutions

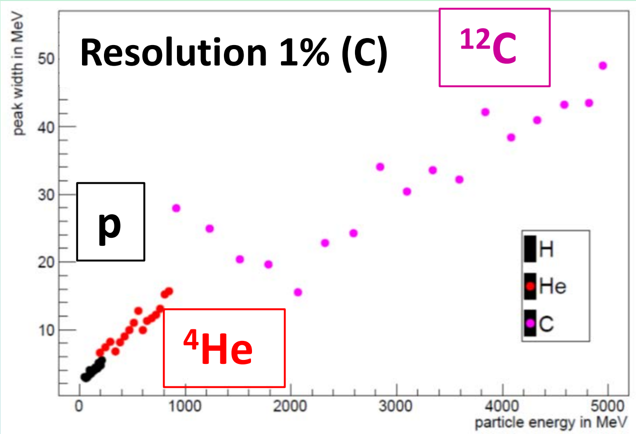
- $\Delta p/p$ → 4%
- $\Delta E_{kin}/E_{kin}$ → 1.5%
- Δtof → 70 -140 ps
- $\Delta(dE)/dE$ → 3-10 %



Test beam on Tof

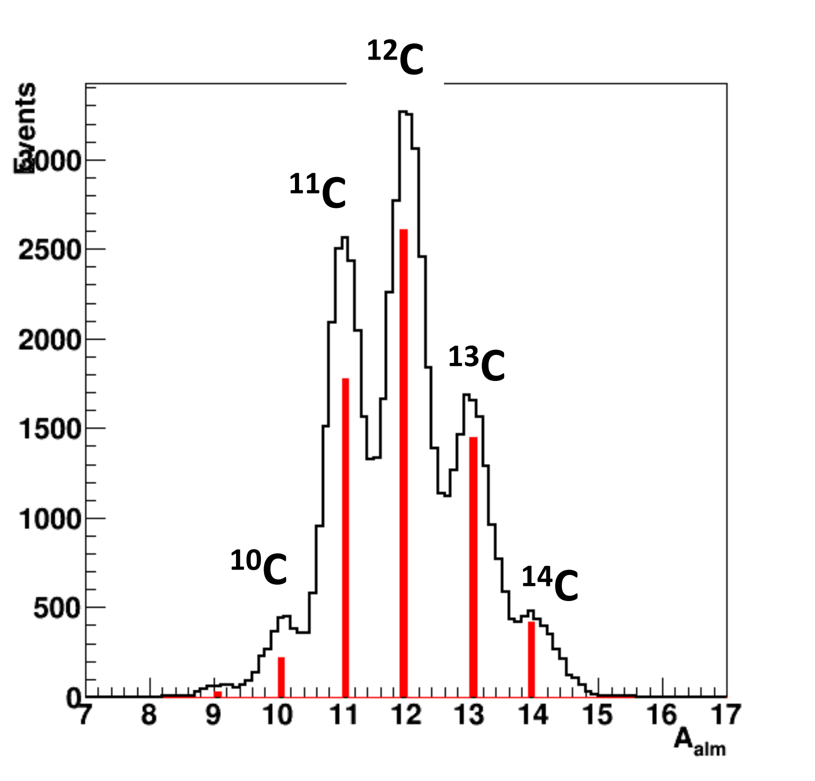


Test beam on Calorimeter

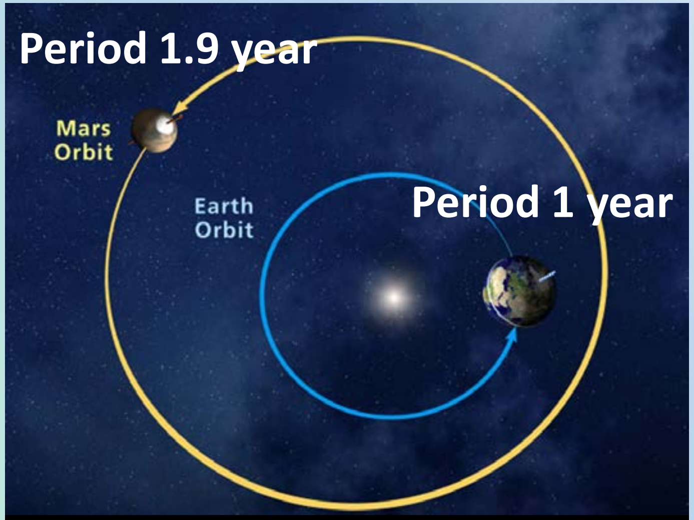


Resolutions from Test Beam

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



Mars mission: radio protection in space



<Travel time> ~ 270 days

Mars: NO magnetosphere and very thin atmosphere → no protection from GCR and SPE

Radiation:

- Travel: 1.8 mSv/day (GCR + SPE)
- On Mars: 0.64 mSv/day

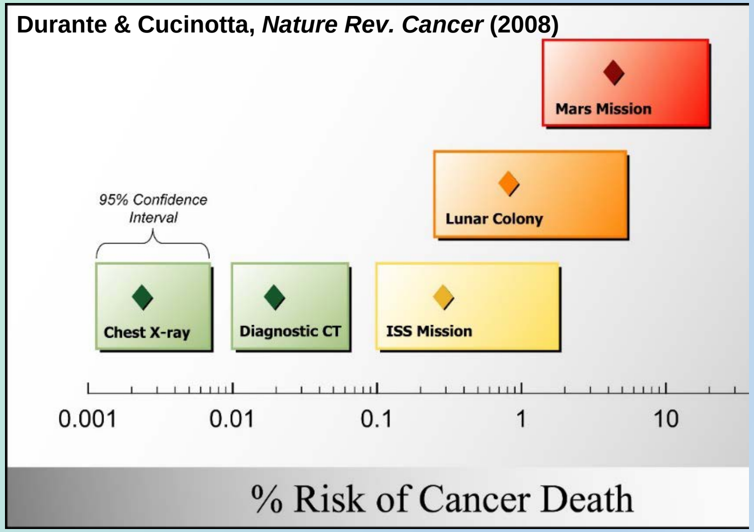
} ~ 1 Sv (increase the cancer probability of ~3%)

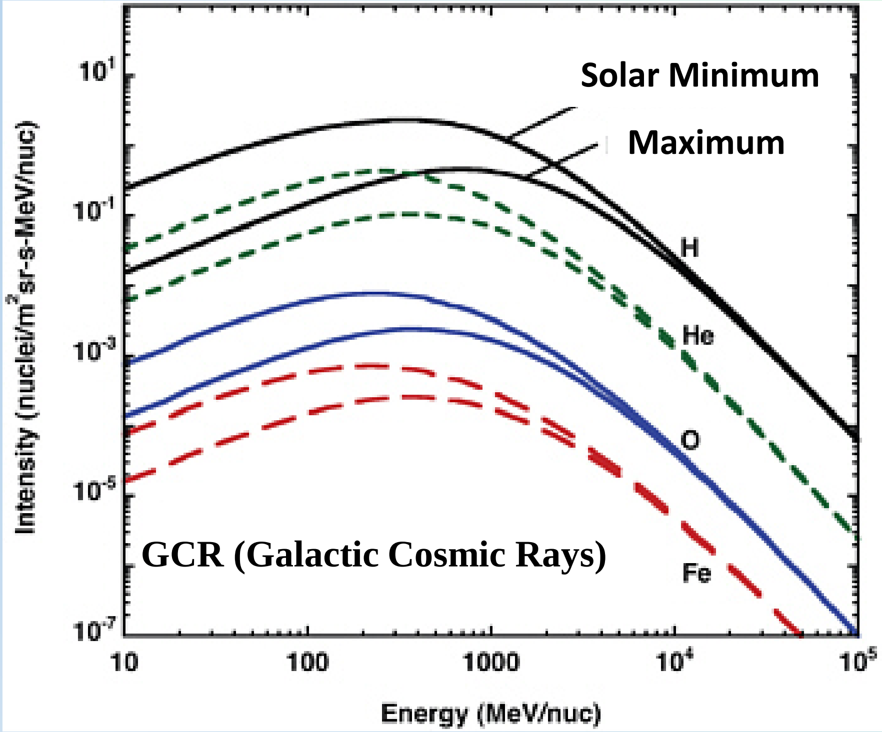
- On earth: 2.64 mSv/year

$$\frac{Rad\ \ on\ Mars}{Rad\ on\ Earth} = \sim 280$$

shielding is needed (interaction on it?)

→ 90% of particles are proton (9% ^{4}He, ...)



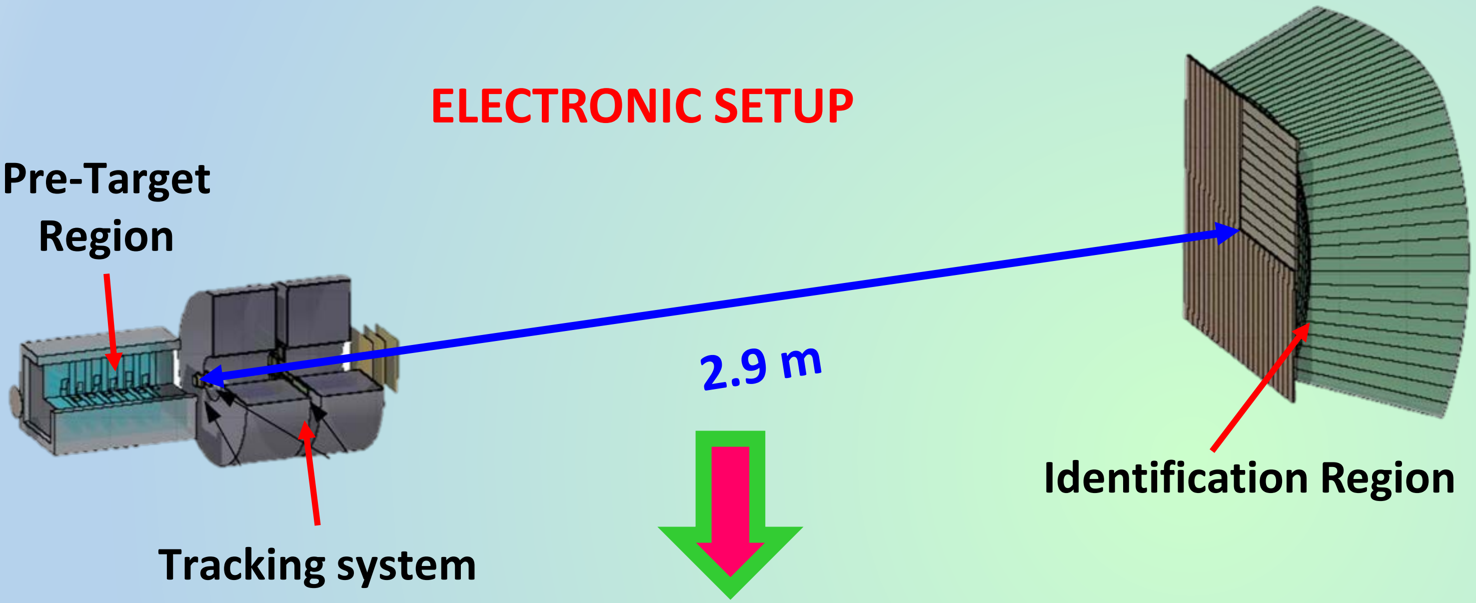


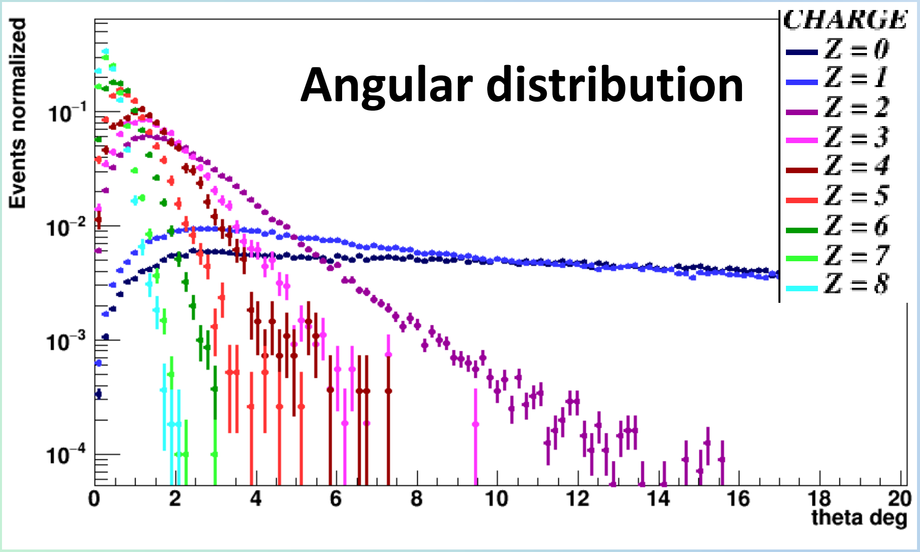
Large Intersection with the hadrontherapy measures but higher energy

FOOT Setup for higher energy

Fluka Simulation: ^{16}O (700 MeV/u) on C2H4

ELECTRONIC SETUP



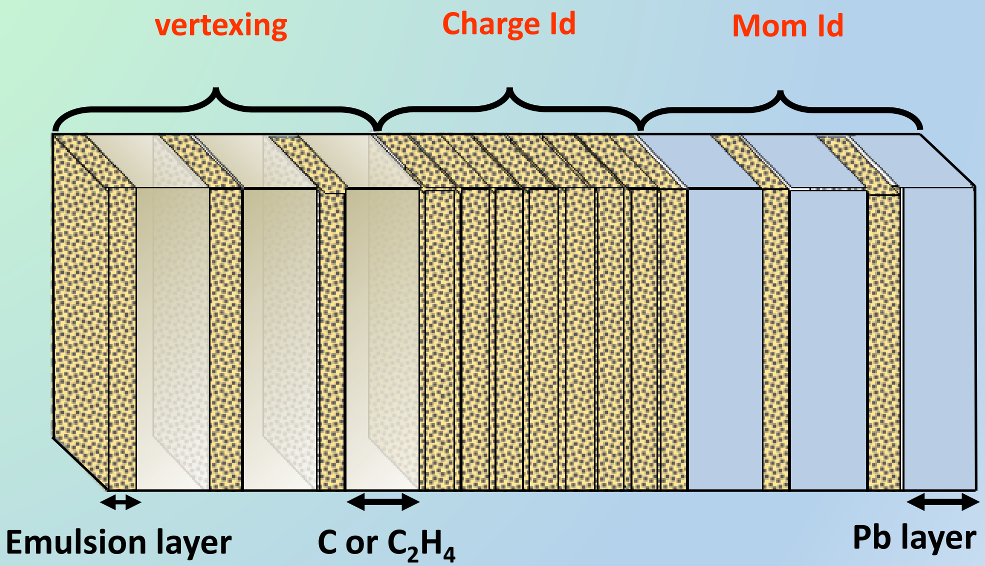


Z>2 fragments inside 4°

- Same acceptance as @ 200 MeV/u
- high resolution on β
- crucial for Z & A determination

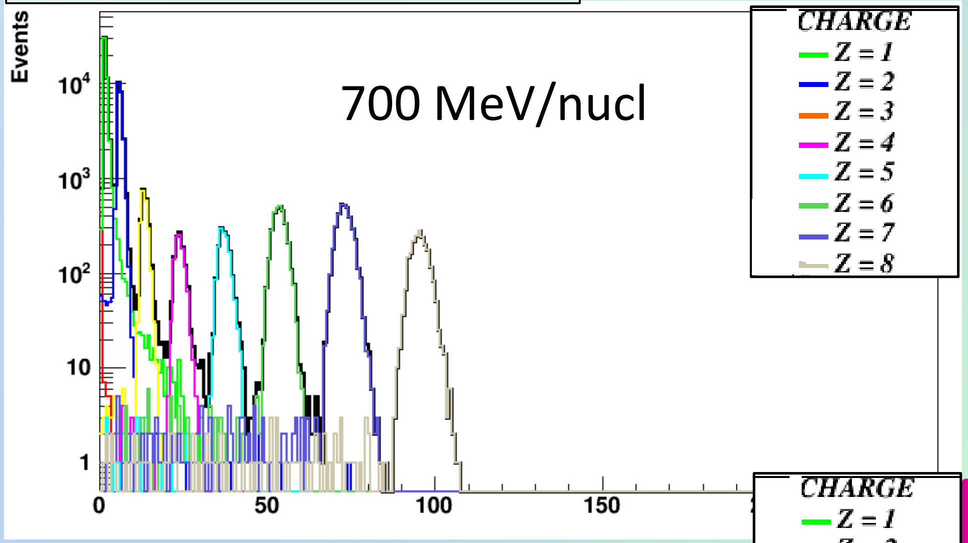
EMULSION CHAMBER

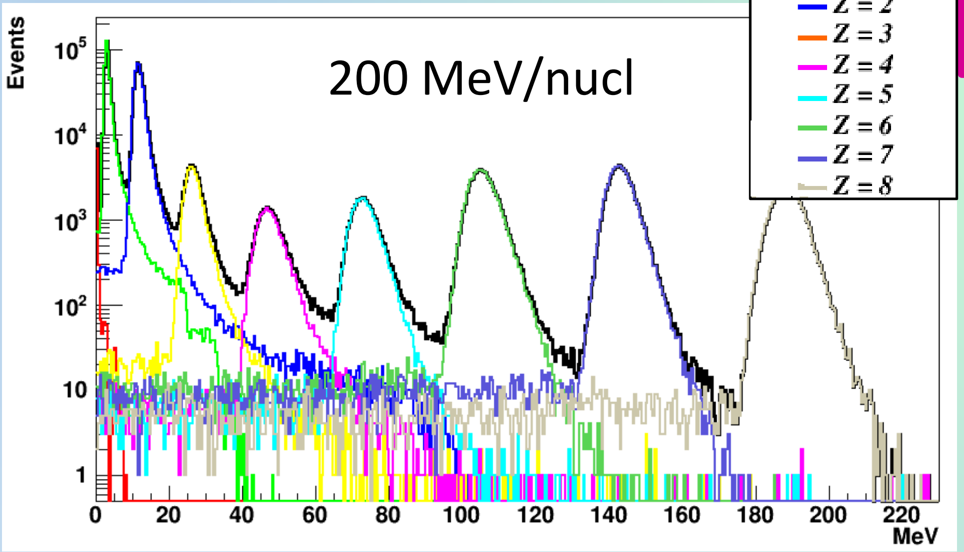
Different geometry and number of layers



Z reconstruction performance @700 MeV/u

energy deposited in SCN



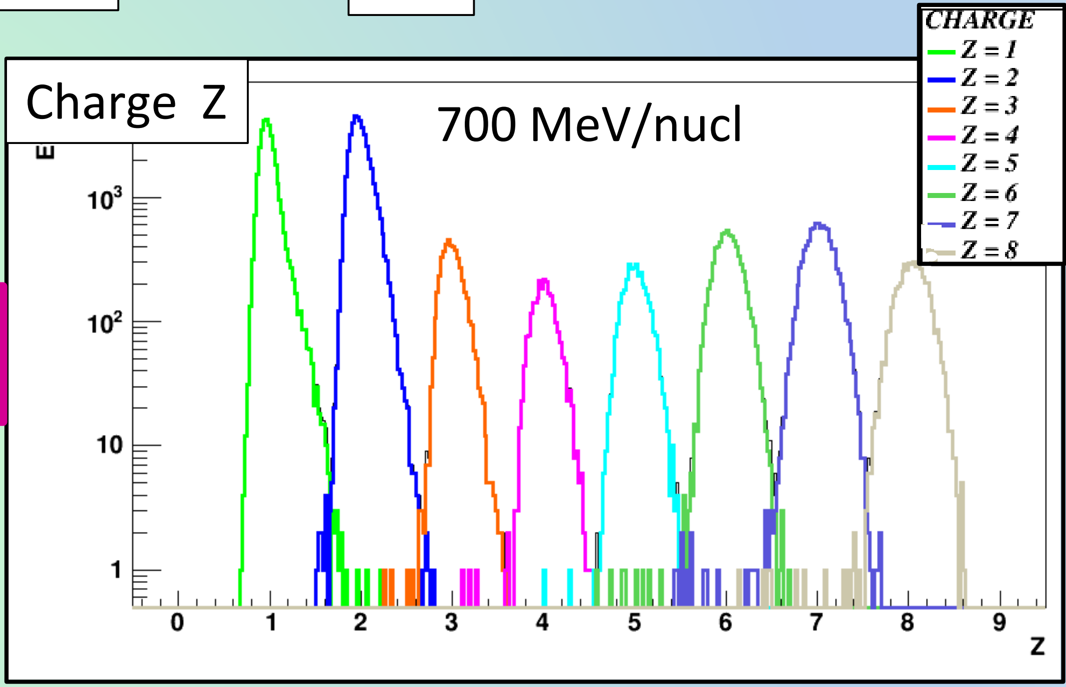


$$-\frac{dE}{dx} = \frac{\rho \cdot Z}{A}\,\frac{4\pi N_A m_e c^2}{M_U}\left(\frac{e^2}{4\pi\epsilon_0 m_e c^2}\right)^2 \frac{z^2}{\beta^2}\left[\ln\left(\frac{2m_e c^2\beta^2}{I\cdot(1-\beta^2)}\right)-\beta^2\right]$$

SCN

TOF

Fluka Simulation
^{16}O (700 MeV/u) → C_2H_4



Z:	1	2	3	4	8
Resol (200 MeV):	9%	3.0%	2.0%	2.0%	2.0%
Resol (700 MeV):	9%	4.5%	3.6%	3.0%	2.1%

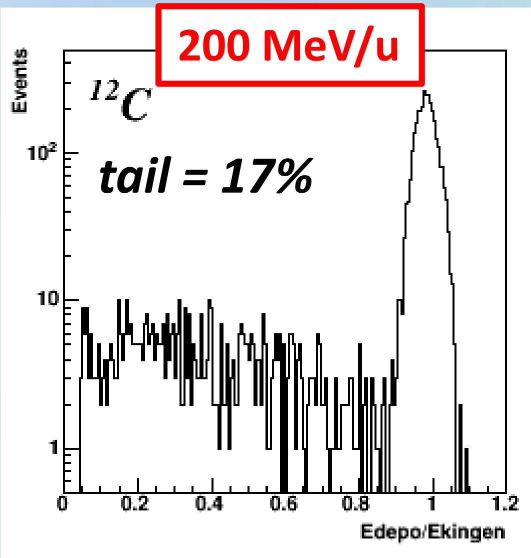
^{1}H	^{4}He	^{7}Li	^{9}Be	^{11}B	^{12}C	^{14}N	^{16}O
1	2	3	4	5	6	7	8
0.97±0.08	1.99±0.09	3.00±0.11	4.01±0.12	5.01±0.13	6.03±0.14	7.03±0.16	8.04±0.17

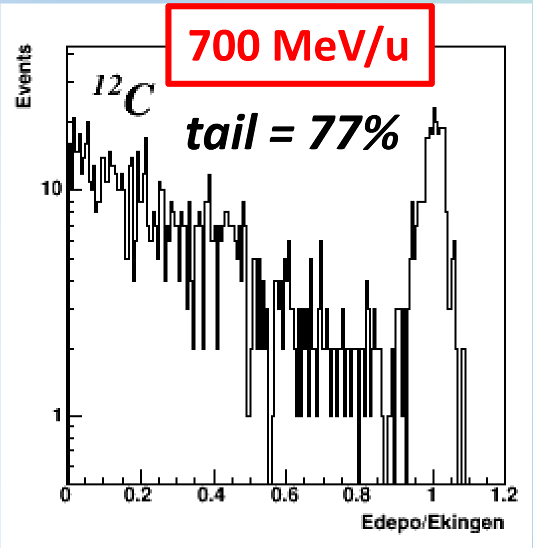
wrong charge assignment < 1%

Problems with higher energy: example of ^{12}C

Fragments with larger energy → higher probability to fragment in CALO

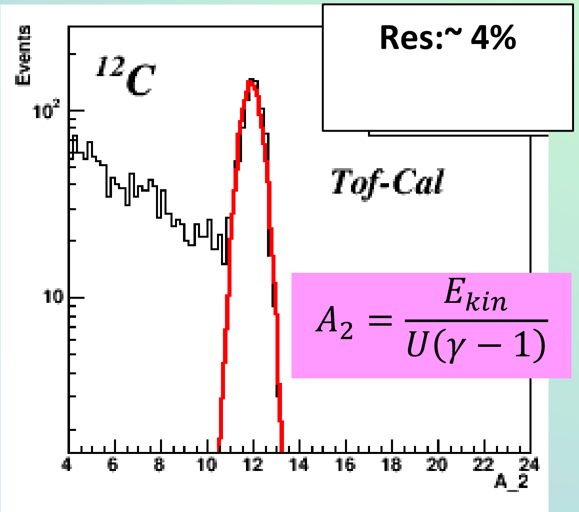
Fraction of deposited energy



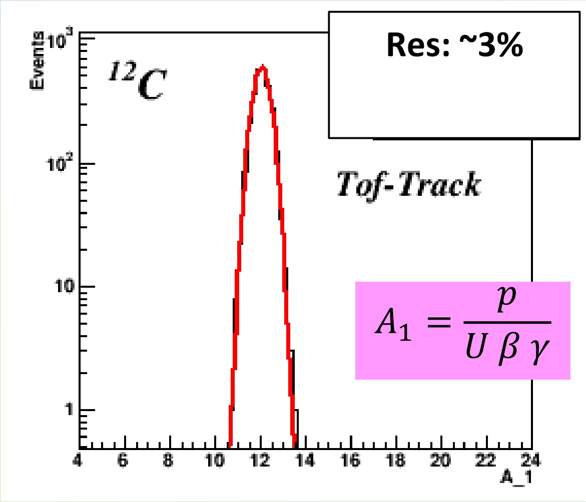


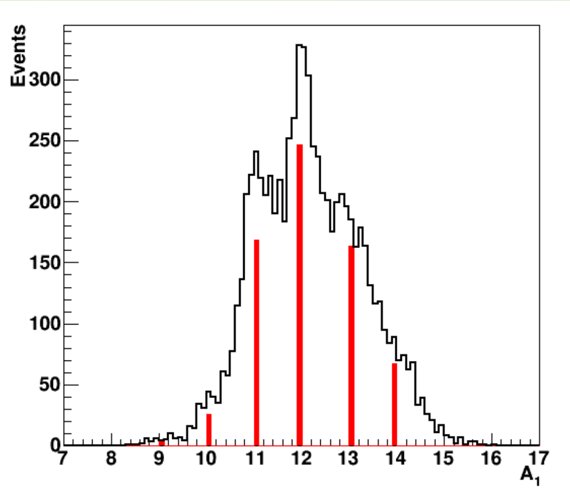
Larger neutrons production

missed energy in CAL



A with Tof & Tracker

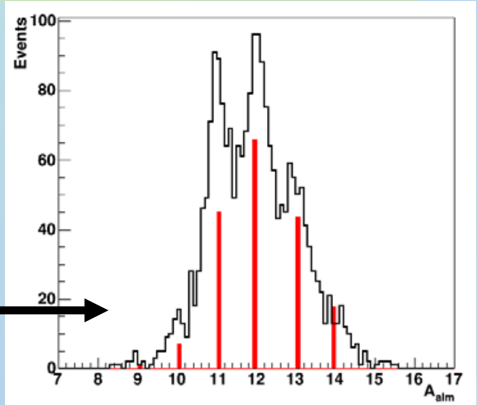




FOOT redundancy

~ performance @ 700 MeV/u

20% of well reconstructed



Future perspective

Test Beam / Data Taking

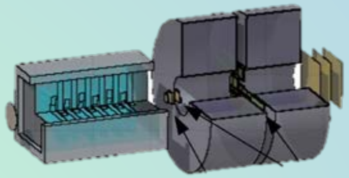
- Test beam during 2018-2019 at CNAO, Trento, Catania to finalize the detector
- GSI: FOOT approved for the IBER-2017 ESA program
  - Last week 11/2018: 16 h beam (He or C)
    - test of EMC
    - Electronic setup: BM, SC, prototype of MSD, SCN
  - GSI: 12/2019 Data taking with almost complete apparatus (~ first data taking)
- 2020-21 Data taking with the complete apparatus

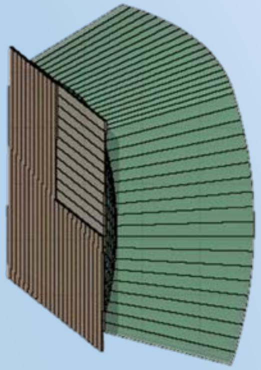
Publications

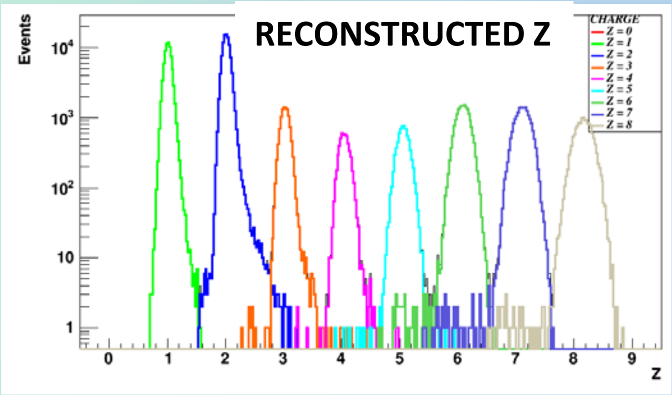
- SCN detector (NIM): in publication
- General Apparatus Paper: in preparation
- dσ/dE for light fragments (p, d, T, He) at 4 angles (34°, 52°, 60°. 90°): in preparation
  - Data taking at CNAO: C beam from 115-352 MeV/u on H, C, O targets
  - Setup: SCNs for Tof & charge and CAL (LYSO 8 cm) for Energy

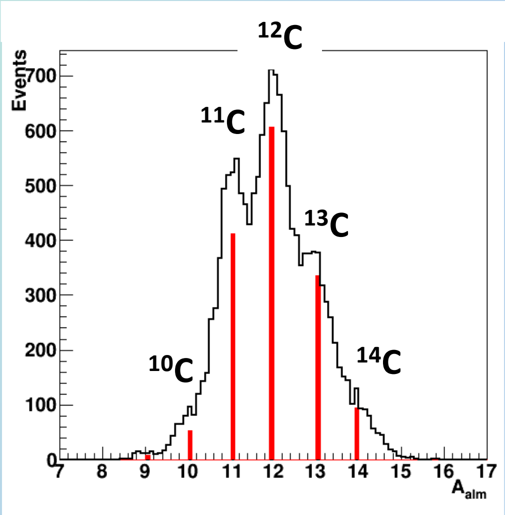
Conclusion

- Approved on September 2017
- Wide physics panorama
  - Hadrontherapy
    - Target fragmentation
    - Projectile fragmentation
  - Radioprotection in space
- Detector Status:
  - Simulation phase is well advanced
  - Setup almost established
  - Many tests on beam already made
  - Performance as expected
- Future perspective
  - Scheduled Test Beam on 2018-2019
  - Data taking in 2020-1
  - 3 papers in publication/preparation





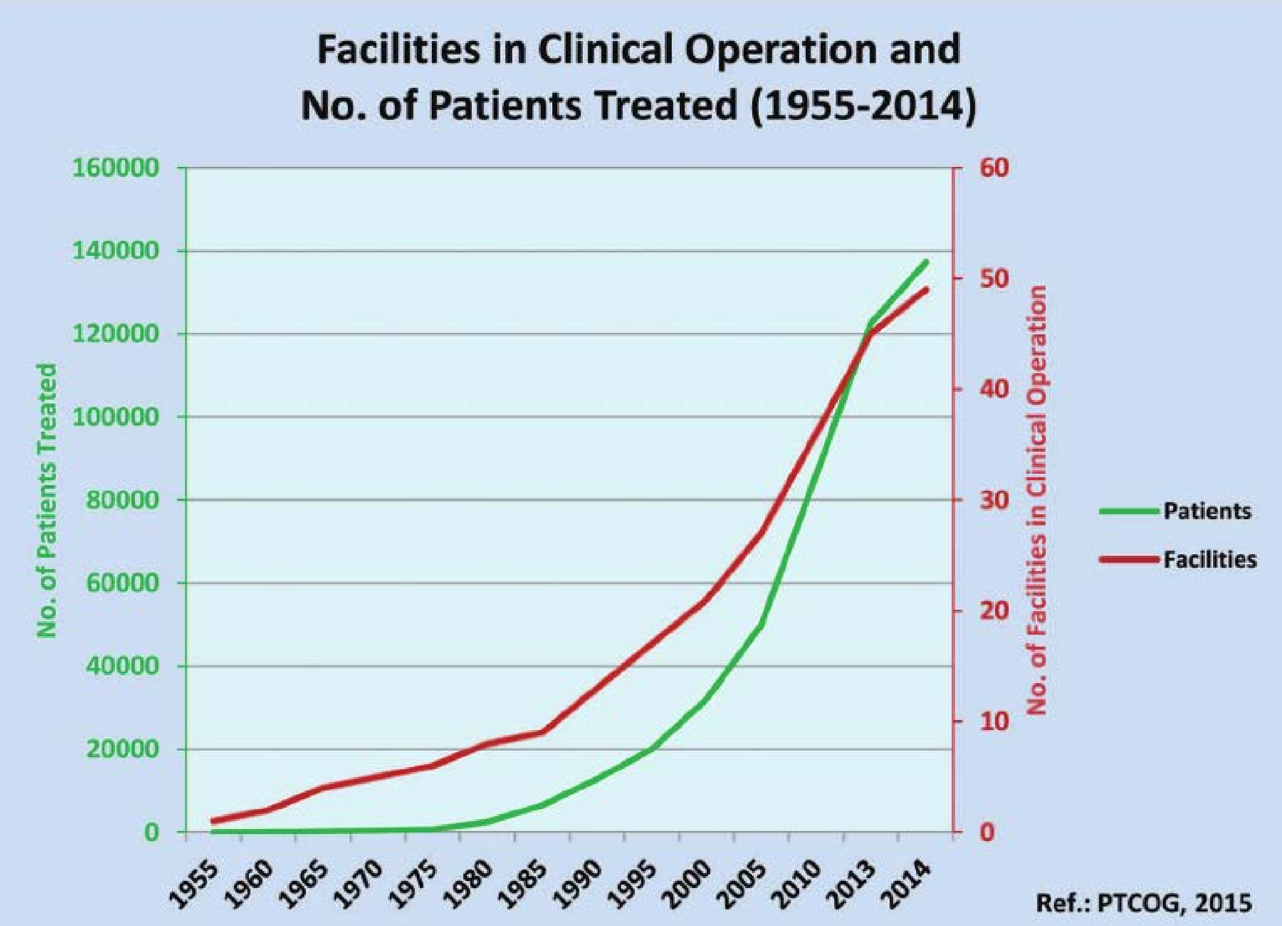




Backup slides

Hadrontherapy in the world

Continuous expansion in the last 50 years



Facility (2014):

- operative
  - 44 proton/7 heavy ion centers
- Under construction
  - 25 proton/4 heavy ion centers

Treated patients (2014):

- 120000
  - 107000 with p (in USA 54000)
  - 13000 with 12C (in Japan 11000

From 2010: 10000 patients per year

In Italy on 18/3/2017 hadrontherapy entered in LEA (Livelli Essenziali di Assistenza) allowing the treatment to 10 tumour pathologies

Hadrontherapy in Italy

CATANA Proton Therapy beam line

- Proton beam (till 60 MeV)
- Active since 2002
- Eye tumour: 363 patients (98% survived)

CNAO Pavia
Centro Nazionale Terapia Oncologica

- proton beam till 250 MeV
- Carbon beam till 400 MeV
- Active since 2011
- First 5 years → 828 patients (70-90% success)
- Till now 1200 patients

Proton therapy Center - Trento

- Active since 2015
- Proton beam (60-230 MeV)
- Full body treatment
- Experimental halls

A 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

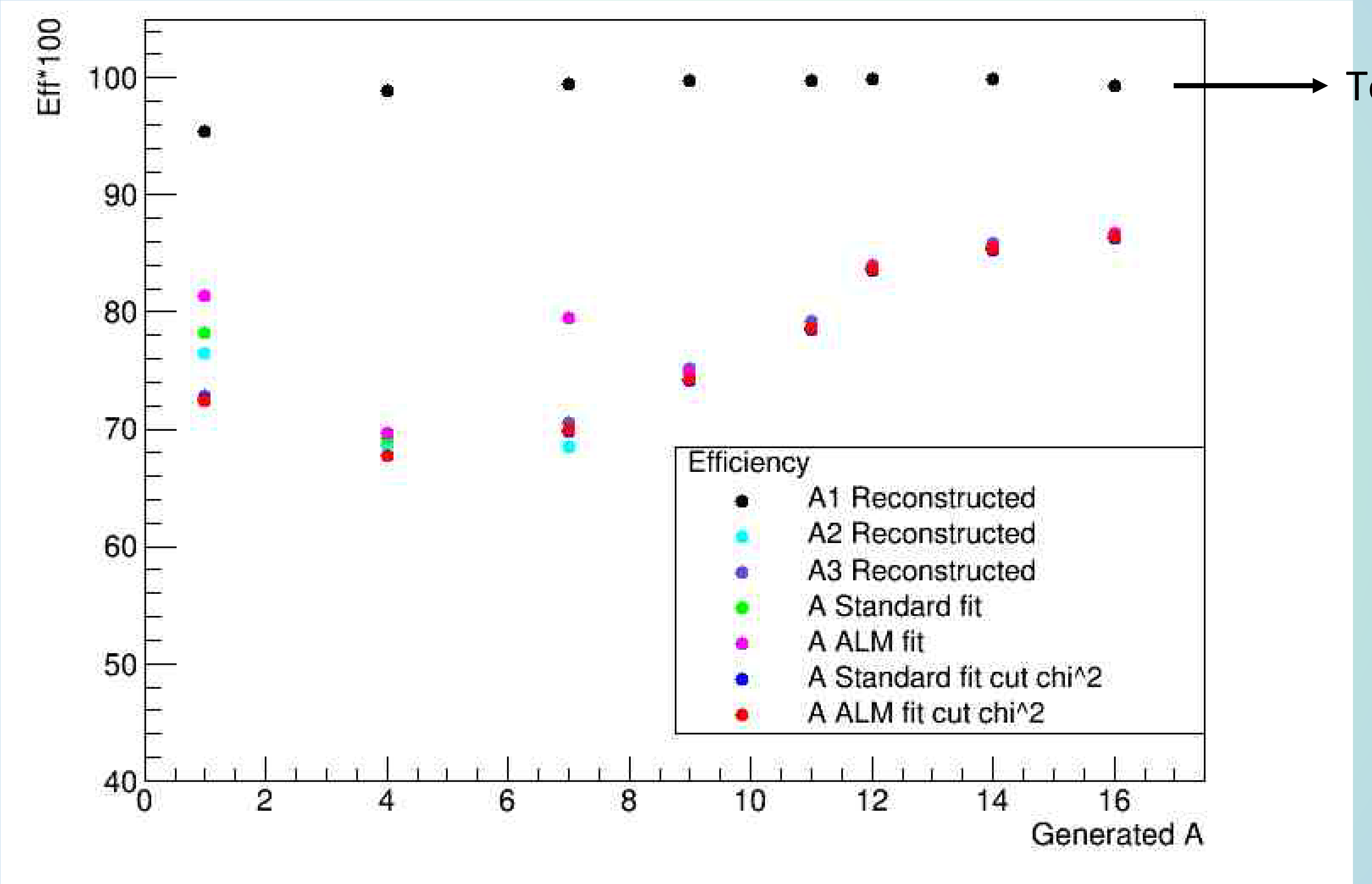
$$f = \left(\frac{(tof_{reco} - t)}{\sigma tof_{reco}}\right)^2 + \left(\frac{(p_{reco} - p)}{\sigma p_{reco}}\right)^2 + \left(\frac{(E_{kin,reco} - E_{kin})}{\sigma E_{kin,reco}}\right)^2 + (A_1 - A \quad A_2 - A \quad A_3 - A)\begin{pmatrix} C_{00} & C_{01} & C_{02} \\ C_{10} & C_{11} & C_{12} \\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

$$C = (A \cdot A^T)^{-1} \qquad A = \begin{pmatrix} \frac{\partial A_1}{\partial t} dt & \frac{\partial A_1}{\partial p} dp & 0 \\ \frac{\partial A_2}{\partial t} dt & 0 & \frac{\partial A_2}{\partial E_{kin}} dE_{kin} \\ 0 & \frac{\partial A_3}{\partial p} dp & \frac{\partial A_3}{\partial E_{kin}} dE_{kin} \end{pmatrix}$$

- **Augmented LagrangianFit (ALM)**

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

A reconstruction efficiency



Tof +Tracker

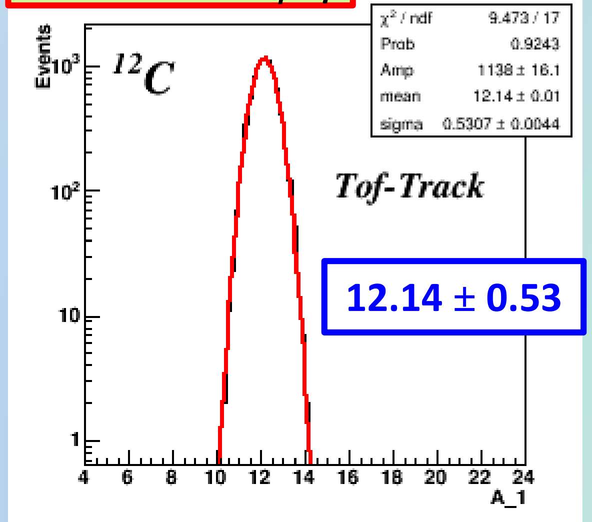
Reconstruction efficiency ~ 70-80 % depending on the fragment

Number of mass reconstruction: example of ^{12}C

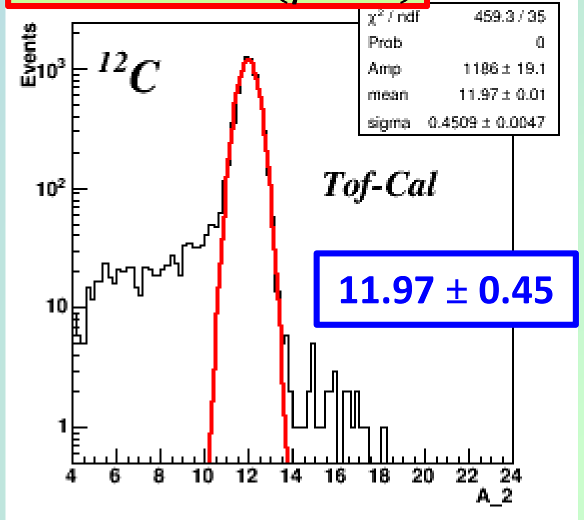
^{16}O (200 MeV/u) → C_2H_4

Data simulated by Fluka

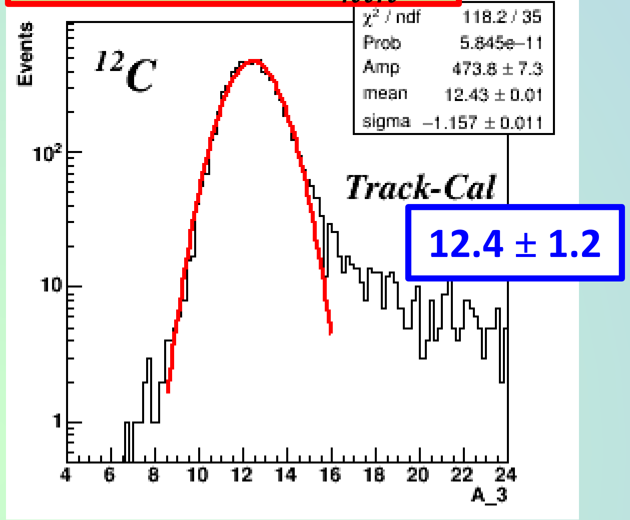
$$A_1 = \frac{m}{U} = \frac{p}{U\,\beta\,\gamma}$$



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

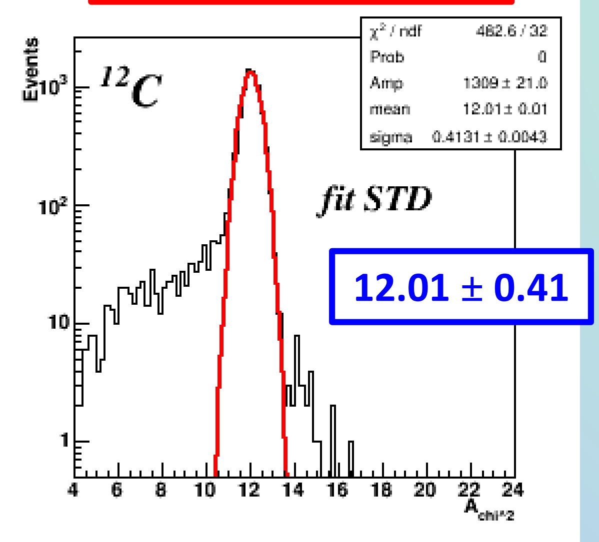


$$A_3 = \frac{m}{U} = \frac{p^2 - {E_{kin}}^2}{2E_{kin}}$$

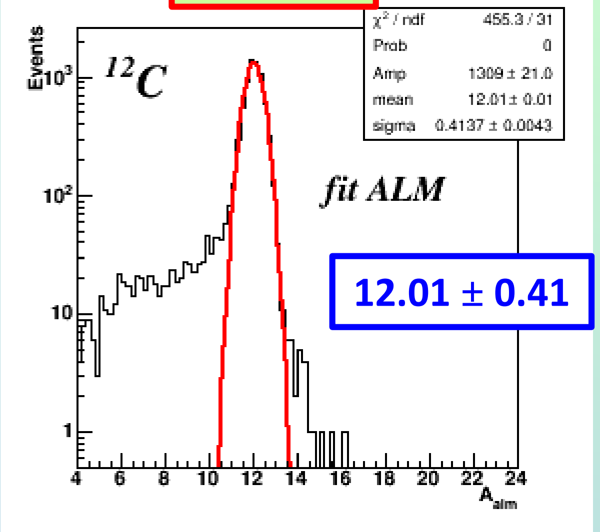


Tail: nuclear interaction on BGO of calorimeter

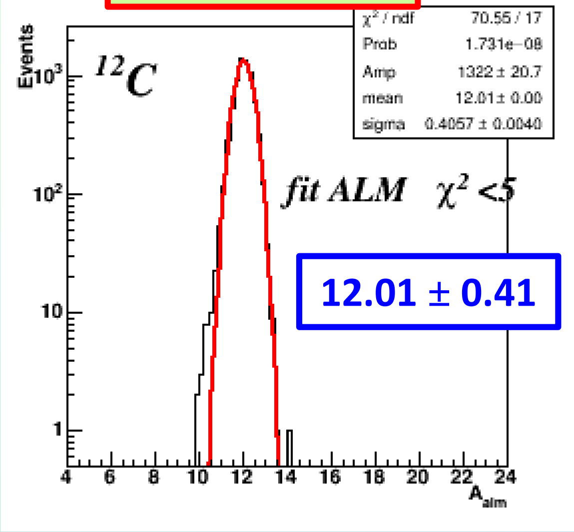
STANDARD χ^2 Fit

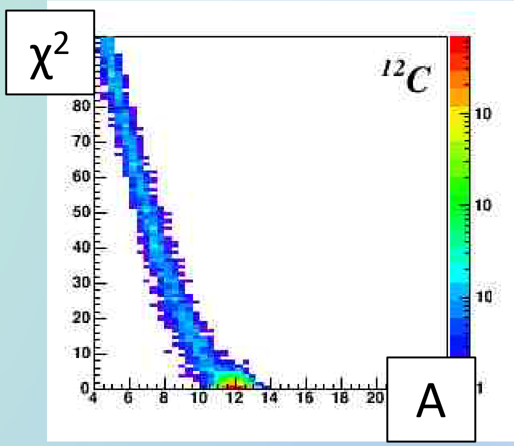


ALM Fit



ALM Fit χ^2<5





Fit allows to cut the wrong reconstructed fragments

FOOT Performances: Number of mass reconstruction

- Reconstruction

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

TRACKER (p), TOF ($\beta\gamma$)

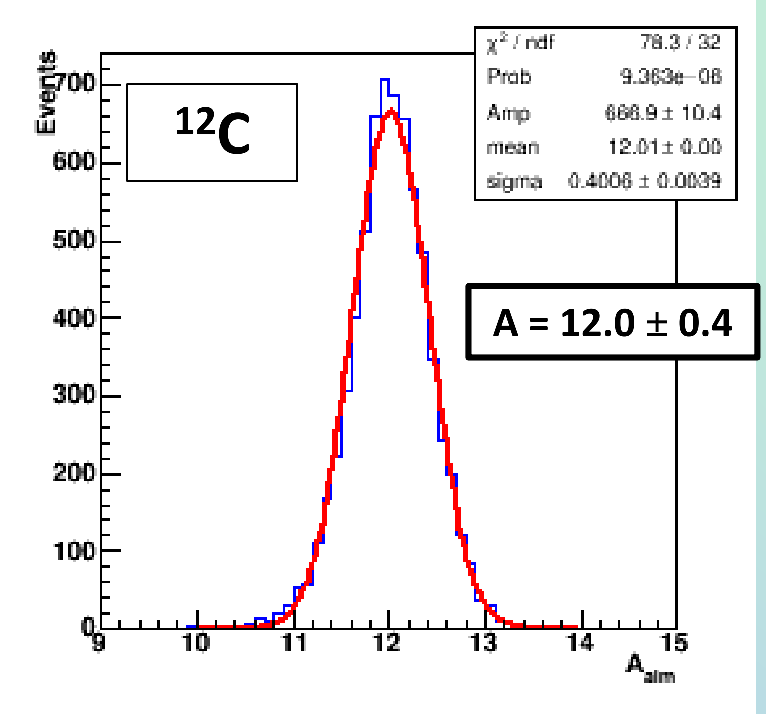
$$A_2 = \frac{m}{U} = \frac{E_{kin}}{U(\gamma - 1)}$$

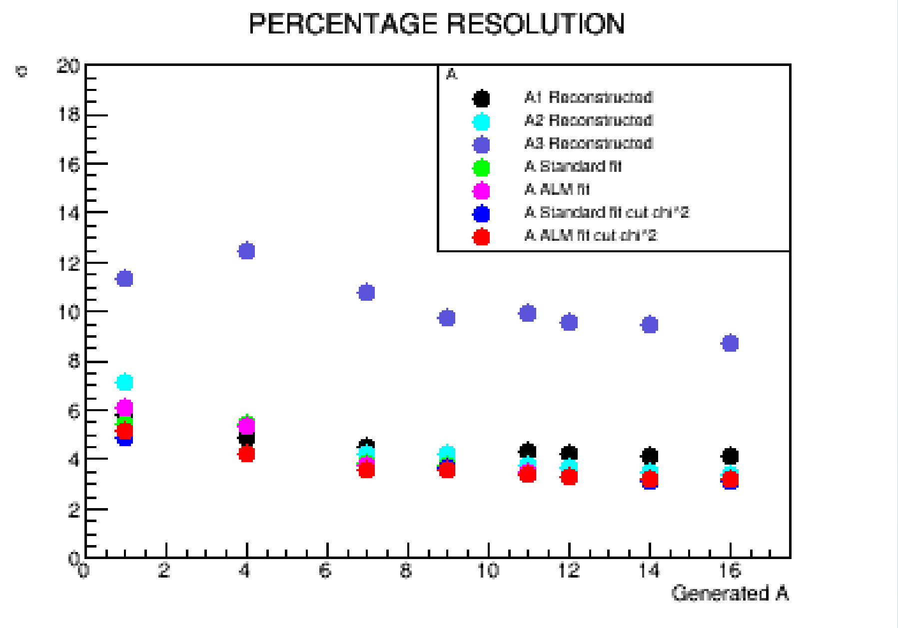
CALO (E_{kin}), TOF (γ)

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

TRACKER (p), CALO (E_{kin})

- Fit Methods: **STANDARD** χ^2 and **ALM**





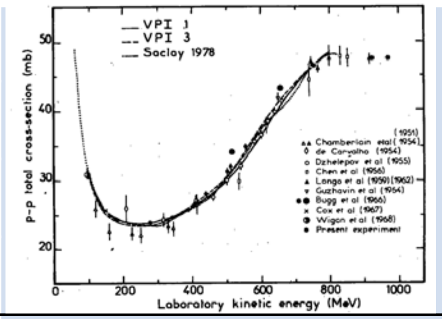
^{16}O (200 MeV/u) → C_2H_4

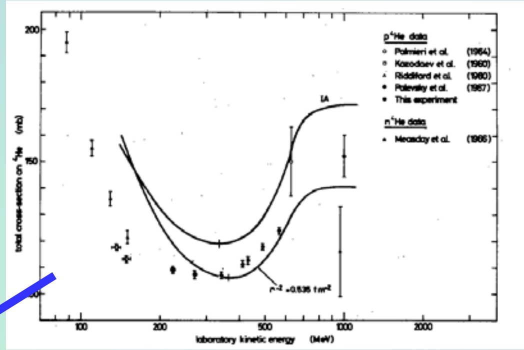
Data simulated by Fluka

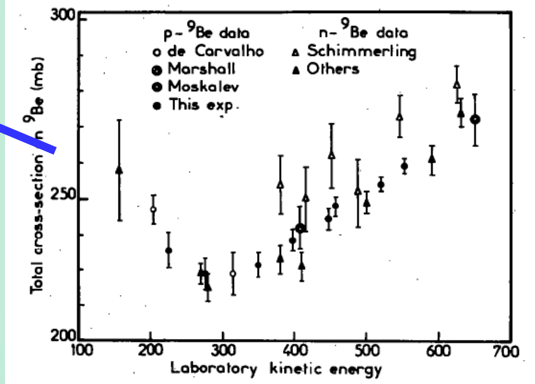
Resolution for heavy fragments ~ 3-4%

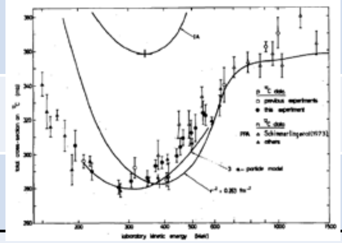
brief experimental panorama on proton cross section

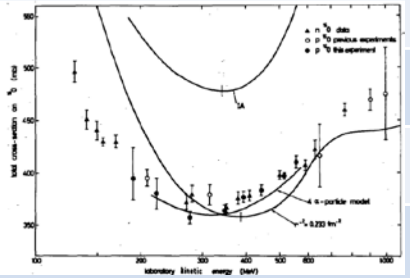
Reaction	E_{Kin} MeV	σ_{TOT} (mb)	
p → p	10	300	
	100	30	
	180-500	25-35	
	600-2000	45-50	
P → ^{4}He	150-600	110-120	
P → ^{9}Be	200-600	230-250	
P → ^{12}C	50	450	
	100-200	230	
	200-1000	280-350	
P → ^{16}O	20	550	
	50	400	
	200	350	
	200-600	350-400	
P → ^{40}Ca	30	900	
	100-200	500	

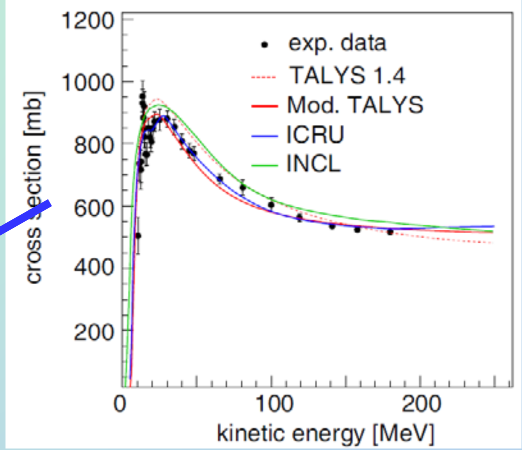




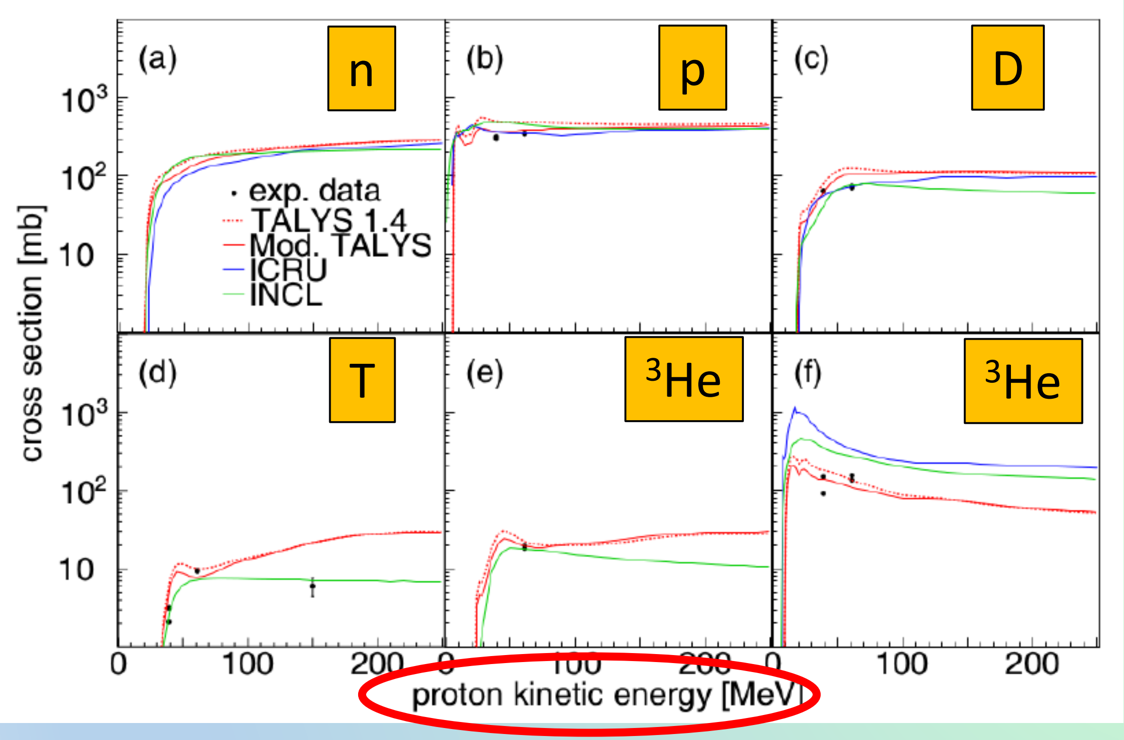


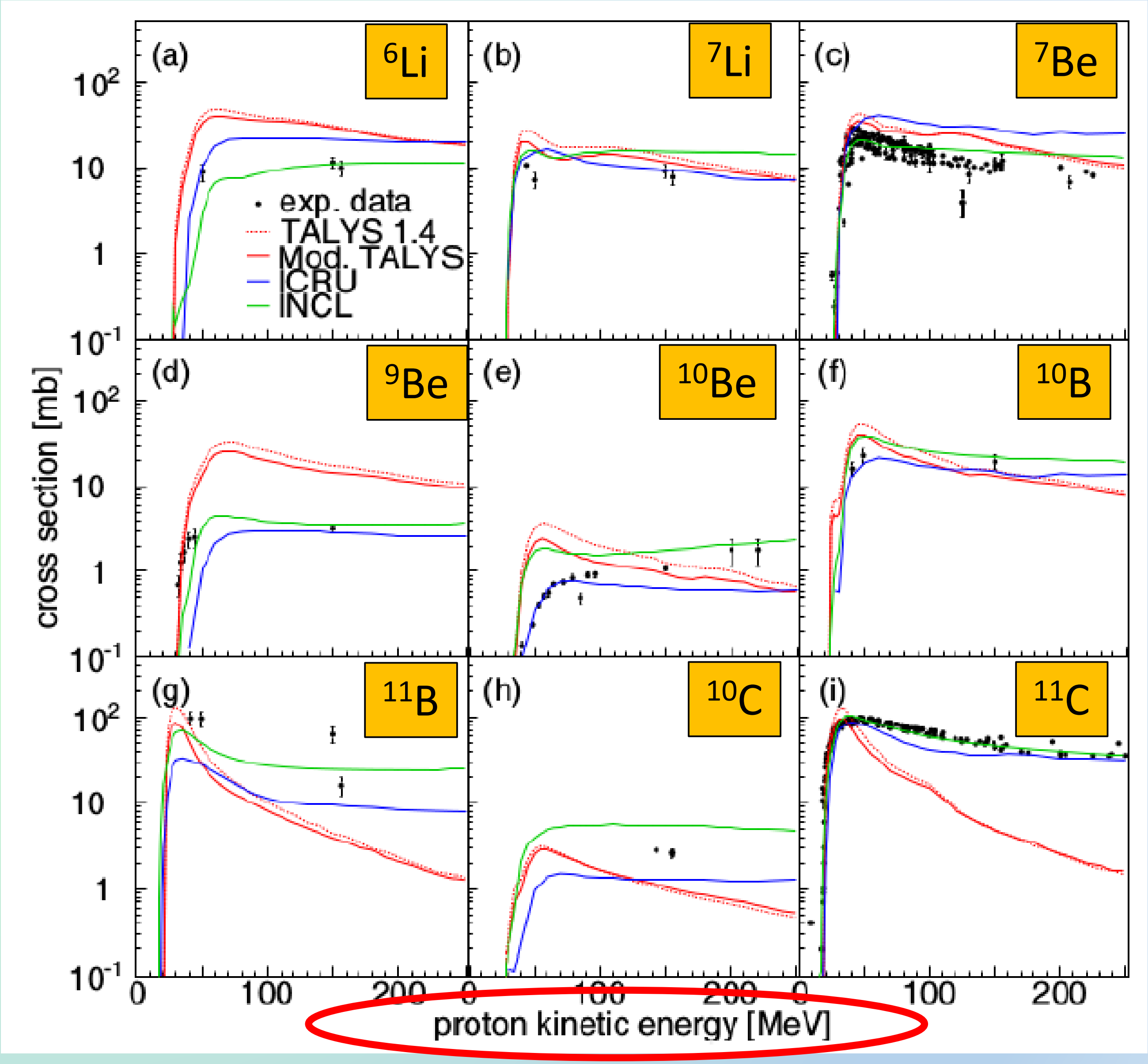






brief experimental panorama on p → ^{12}C differential cross section



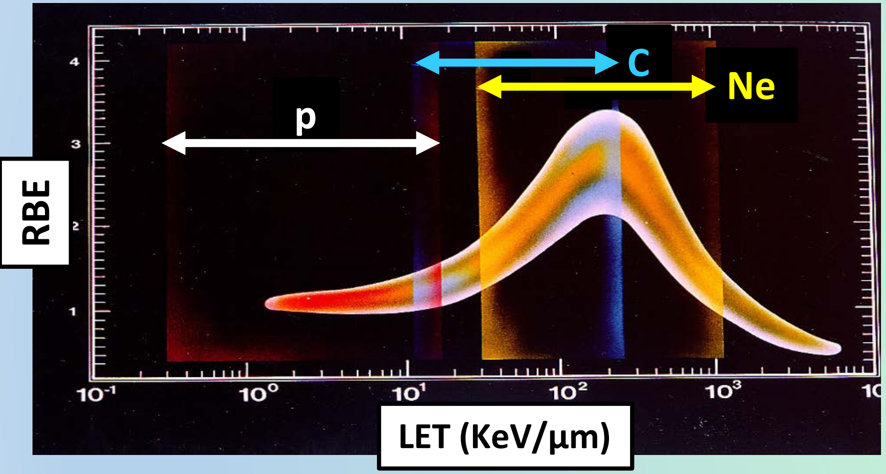


Relative Biological Effectiveness (RBE)

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

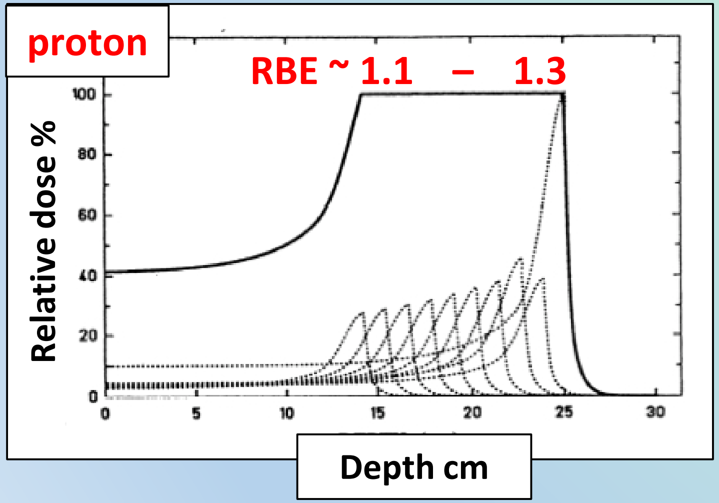
quantify the strength of different radiation types

High RBE → high effect wrt radiation

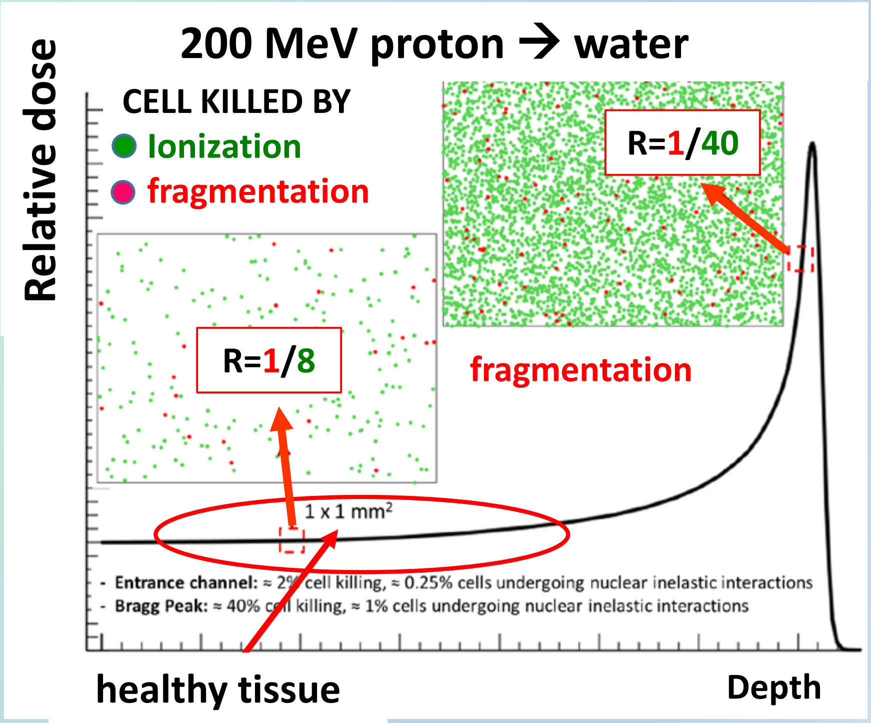


RBE depends on
- LET
- Dose
- Depth in the body
- Beam energy
- Vivo/vitro
- Tissue type …
- **Nuclear interaction**

not considered



proton RBE = 1.1



Nuclear interaction

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

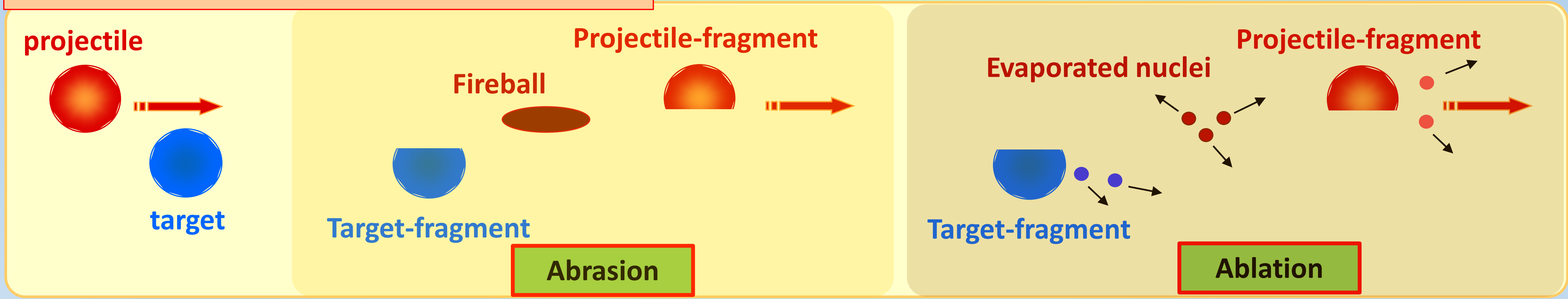
Most probable nuclear process: Fragmentation
peripheral interaction between projectile (p, ^{12}C,...) and target (H, C, O, ...)

Protons ≠ photons * 1.1
due to Nuclear interaction

No Standard Treatment Planning for hadrontherapy

Study of the Target-Projectile fragmentation

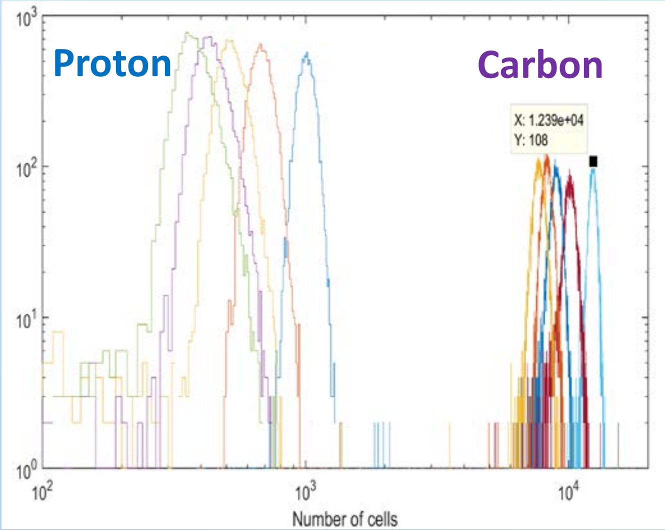
Abrasion-Ablasion model → 2 stages

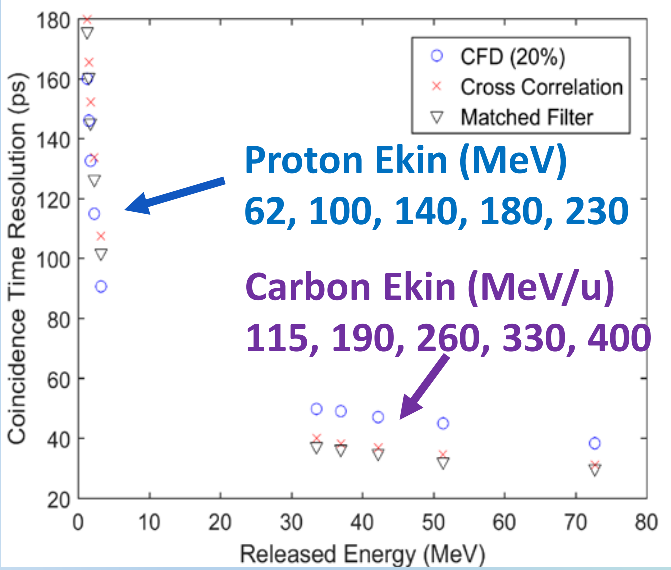


No quarks interaction

Test beam results

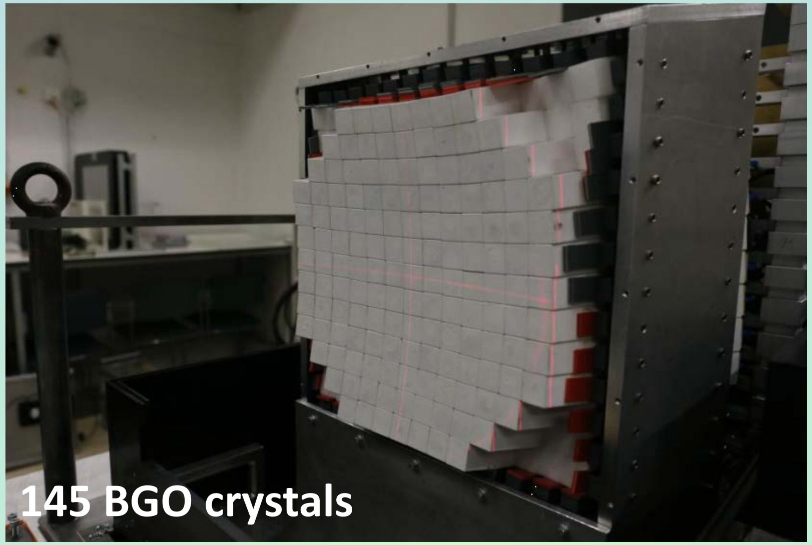
ΔE-Tof test beam @CNAO

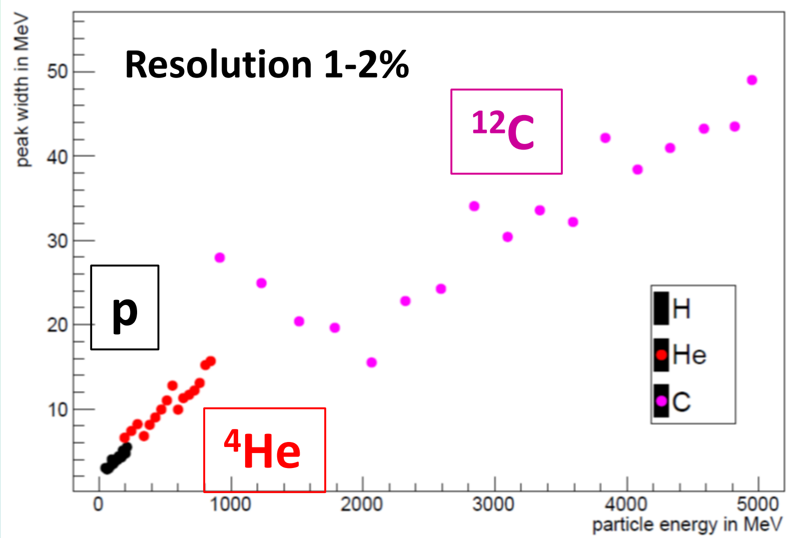




Tof resolution (C) better 40 ps

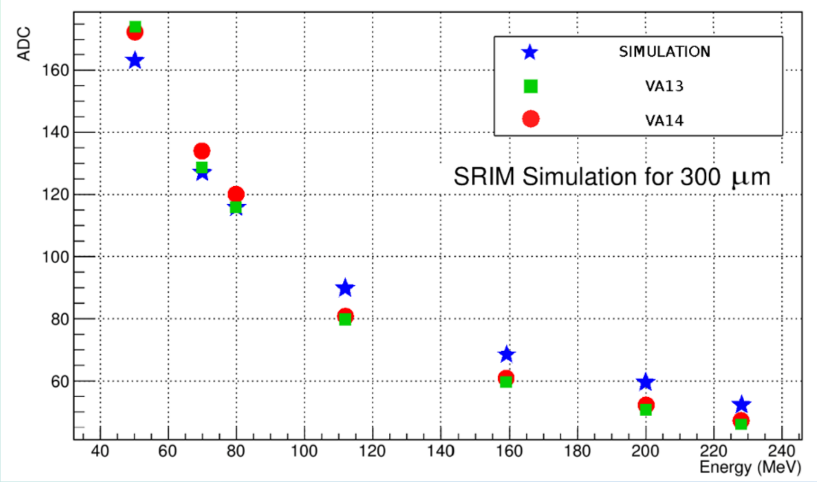
Calorimeter: test beam @HIT





Kinetic energy resolution at 1-2%

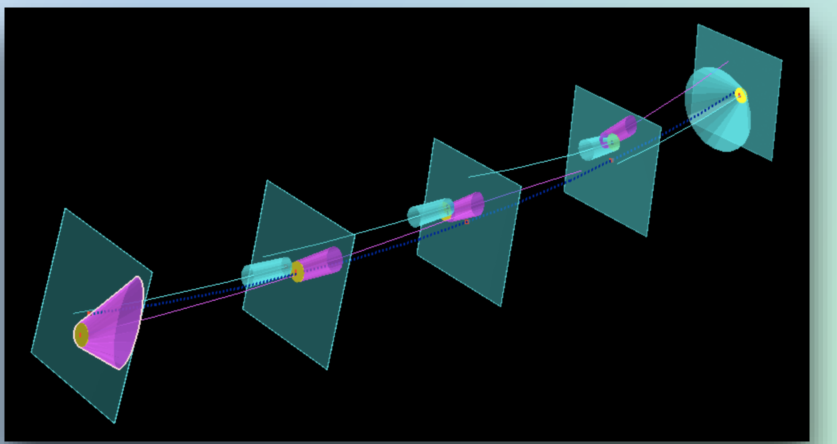
MSD: test @ Trento (proton)

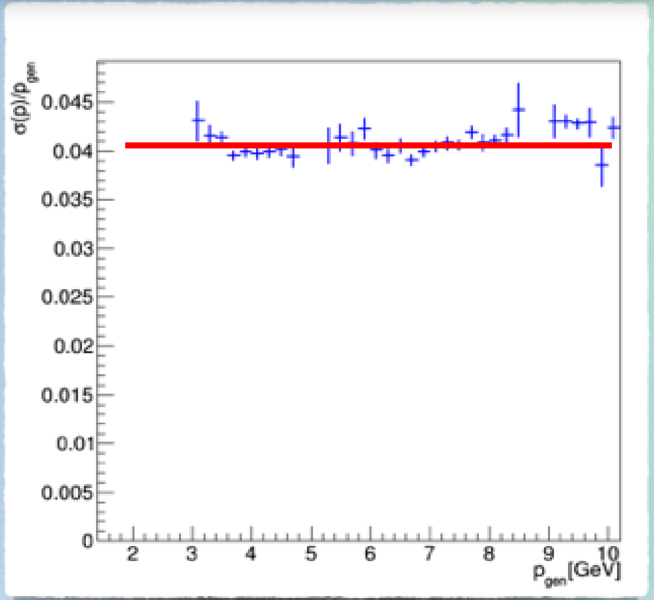


Agreement simulation data in few %

Test beam and simulation results

Tracking Kalman Filter (simulation)

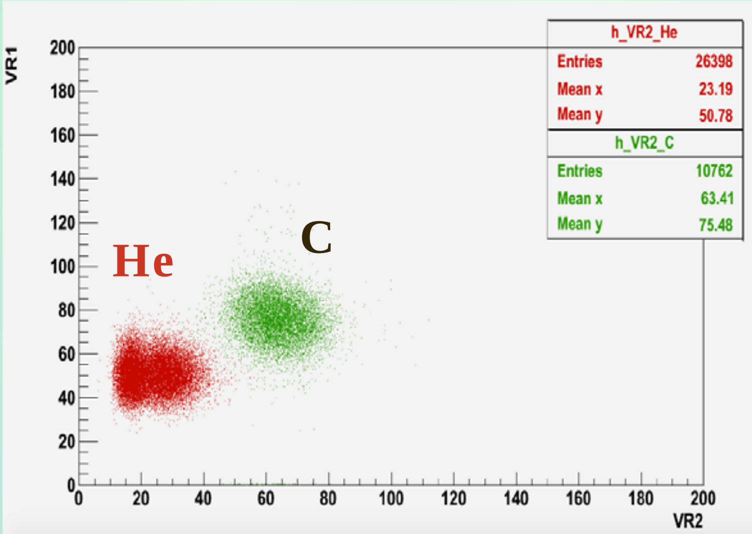




p resolution at level of 4%

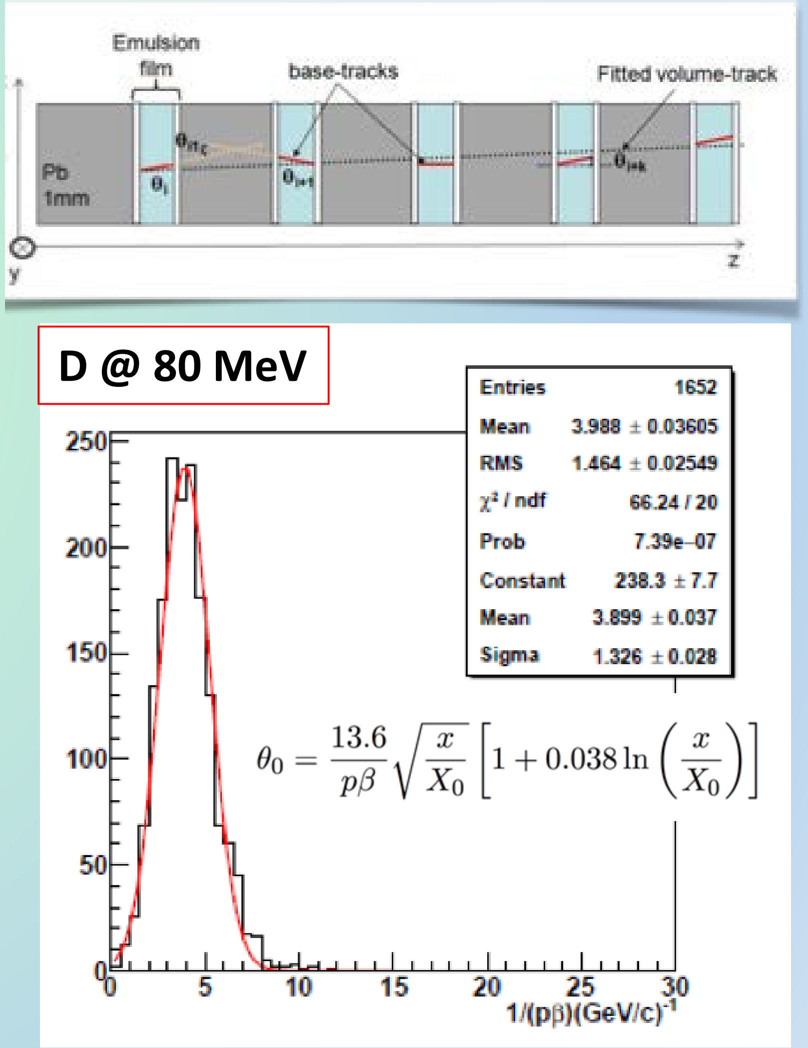
Emulsion chamber test beam @LNS (p, D, He, C) and Trento (p at 50, 80, 200 MeV)

Fragments charge determined by volume of points after refreshing



ECC: charge separation

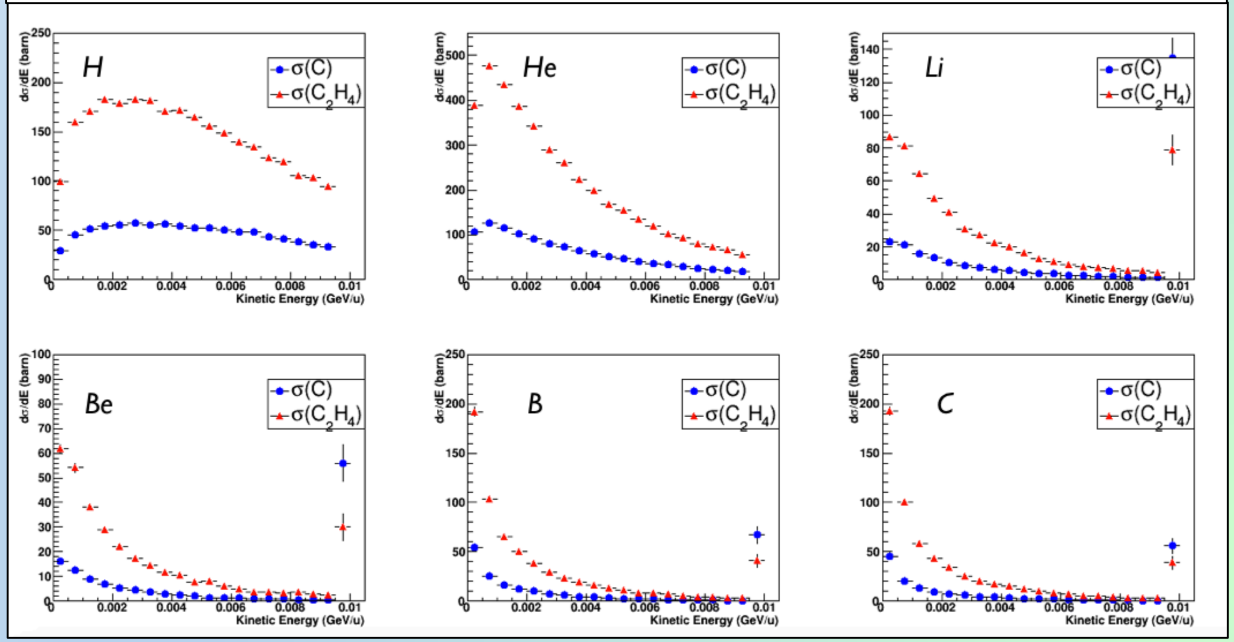
p•β by Multiple Coulomb Scatt



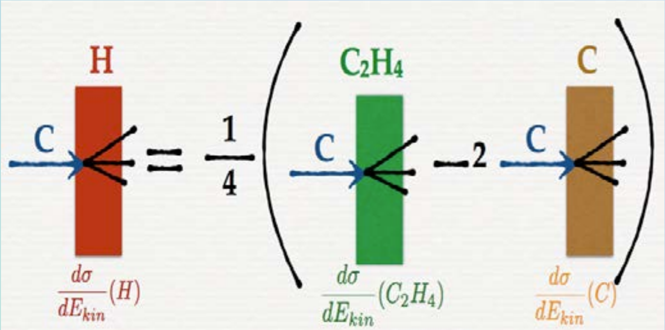
$$\theta_0 = \frac{13.6}{p\beta}\sqrt{\frac{x}{X_0}}\left[1 + 0.038\ln\left(\frac{x}{X_0}\right)\right]$$

Target Fragmentation cross sections

$d\sigma/dE_{kin}$(fragment) in C & C_2H_4 targets (inverse kinematic)

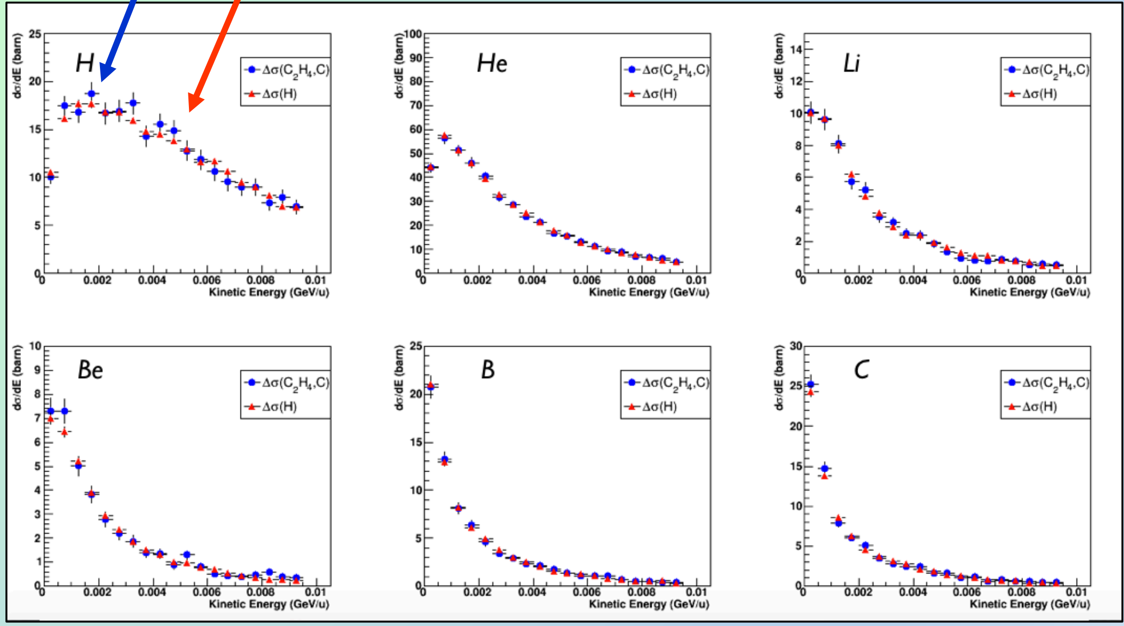


Fluka Simulation
^{12}C (200 MeV/u)→ C_2H_4 & H

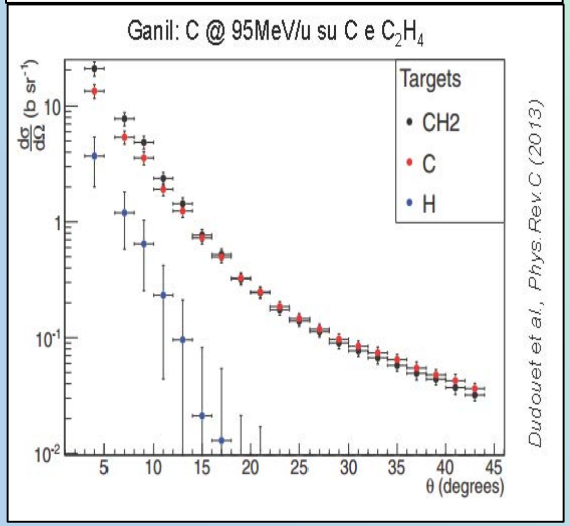


$$\frac{d\sigma}{dE_{kin}}(H) = \frac{1}{4}\left(\frac{d\sigma}{dE_{kin}}(C_2H_4) - 2\frac{d\sigma}{dE_{kin}}(C)\right)$$

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



Ganil experimental data

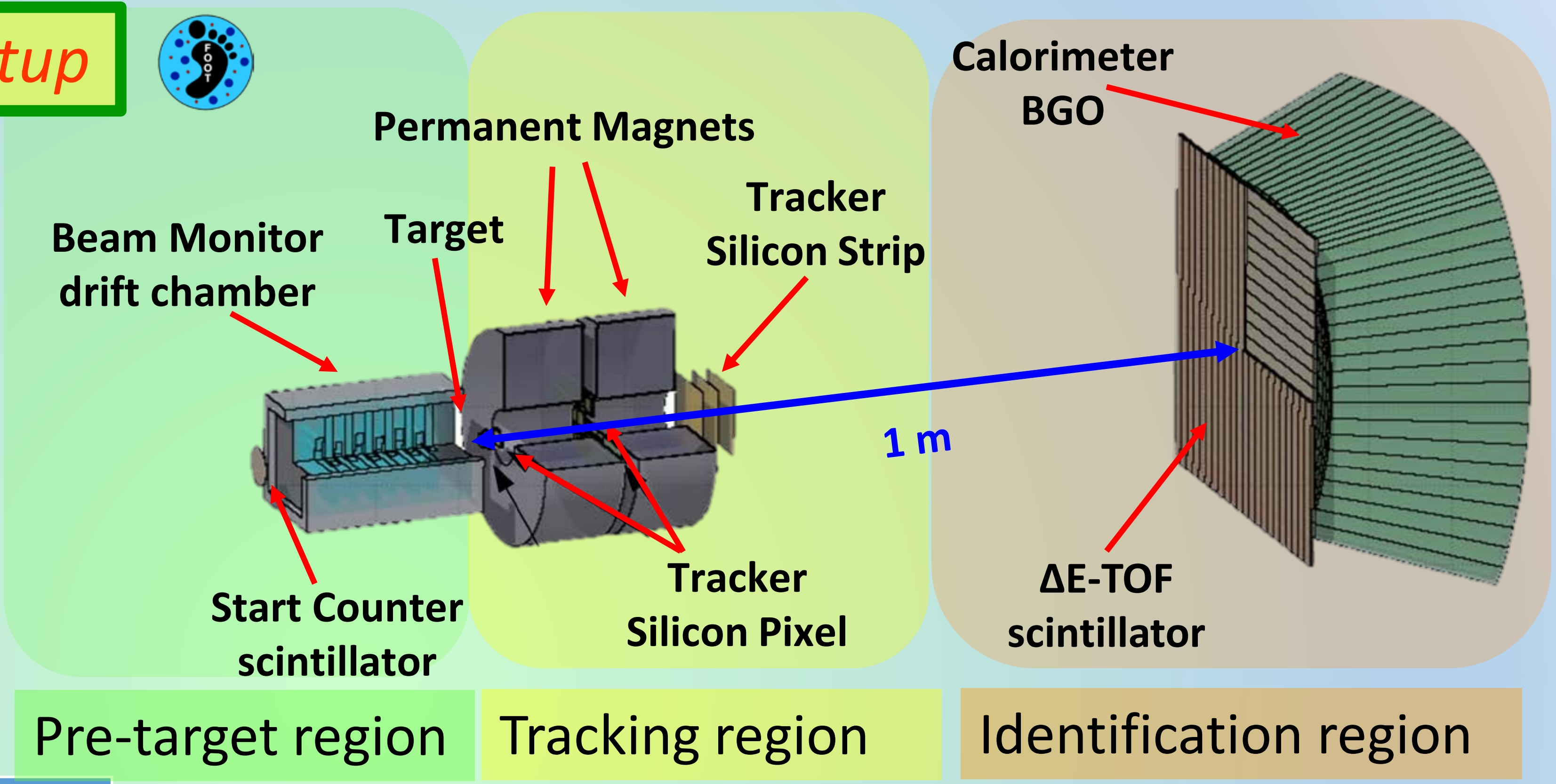


Agreement between the two methods

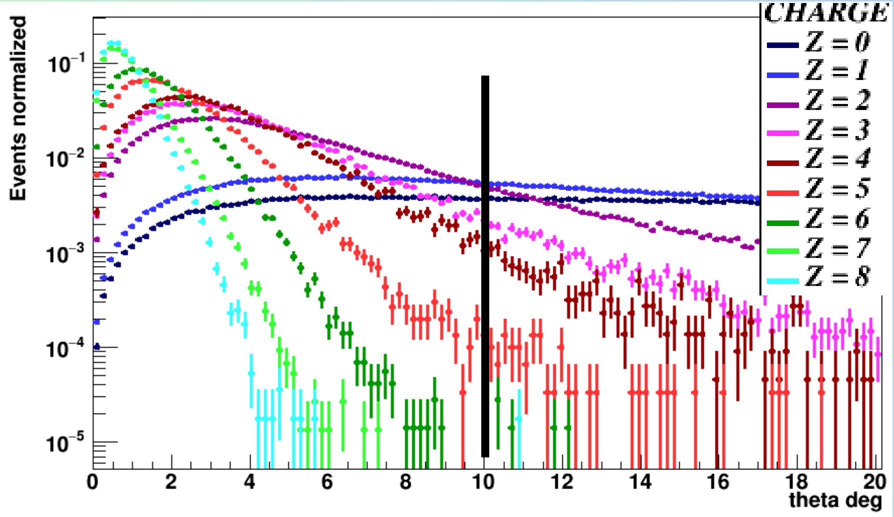
FOOT Detector: electronic Setup

Detector in construction and test beam phase

- **Optimized for heavy (Z≥3) fragments**
- **< 2 m (@200 MeV/u)→ portability**
- **Angular acceptance → ± 10°**

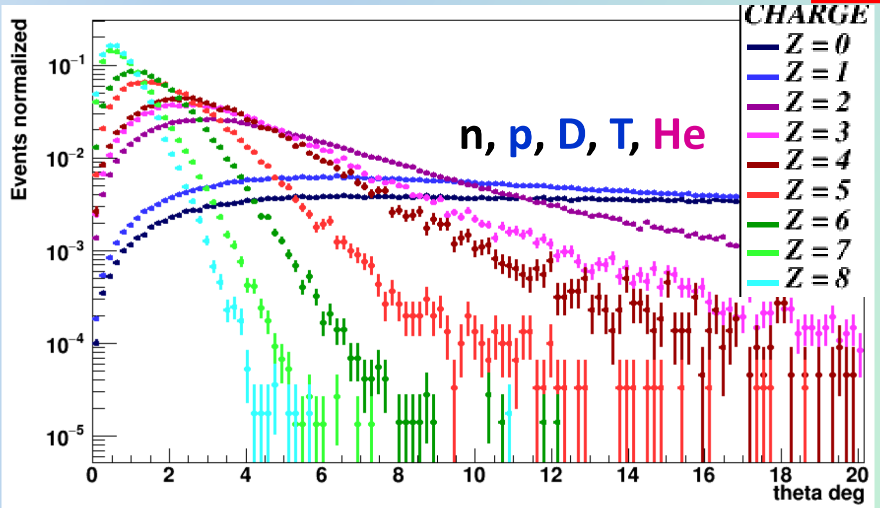


Sub-detector	Main Characteristics
Start Counter	Plastic scintillator 250 µm
Beam monitor	Drift chamber (12 layers of wires)
Target	C + C_2H_4 (2 mm)
Vertex	4 layers silicon pixel (20x20 µm)
Magnet	2 permanent dipoles (Halbach geometry 0.8 T)
Inner Tracker	2 layers silicon pixel (20x20 µm)
Outer Tracker	3 layers of Silicon strip (125 µm pitch)
Scintillator	2 layers of 20 barrels (2x40x0.3 cm)
Calorimeter	360 BGO crystals (2x2x14 cm)



FOOT: Emulsion chamber setup

C on C @ 200 MeV/nucl FLUKA → Light fragments (Z<3) produced at wide angle (~75°)

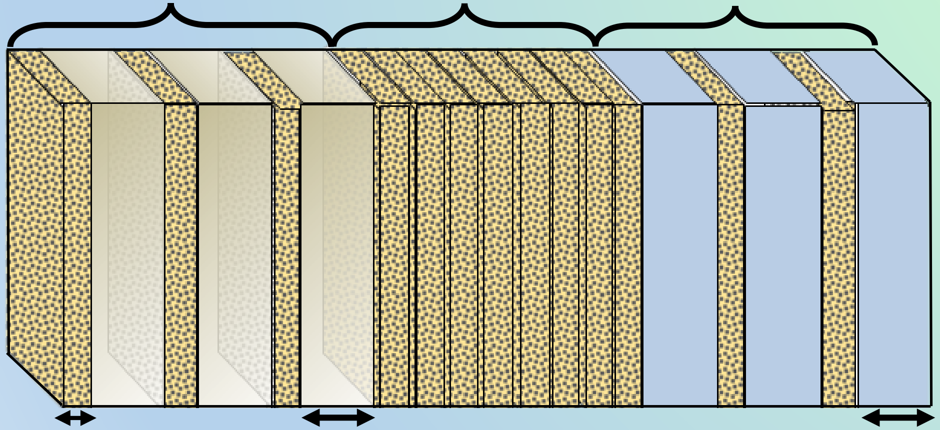


10 cm

Section 1 vertexing

Section 2 Charge Identification

Section 3 momentum

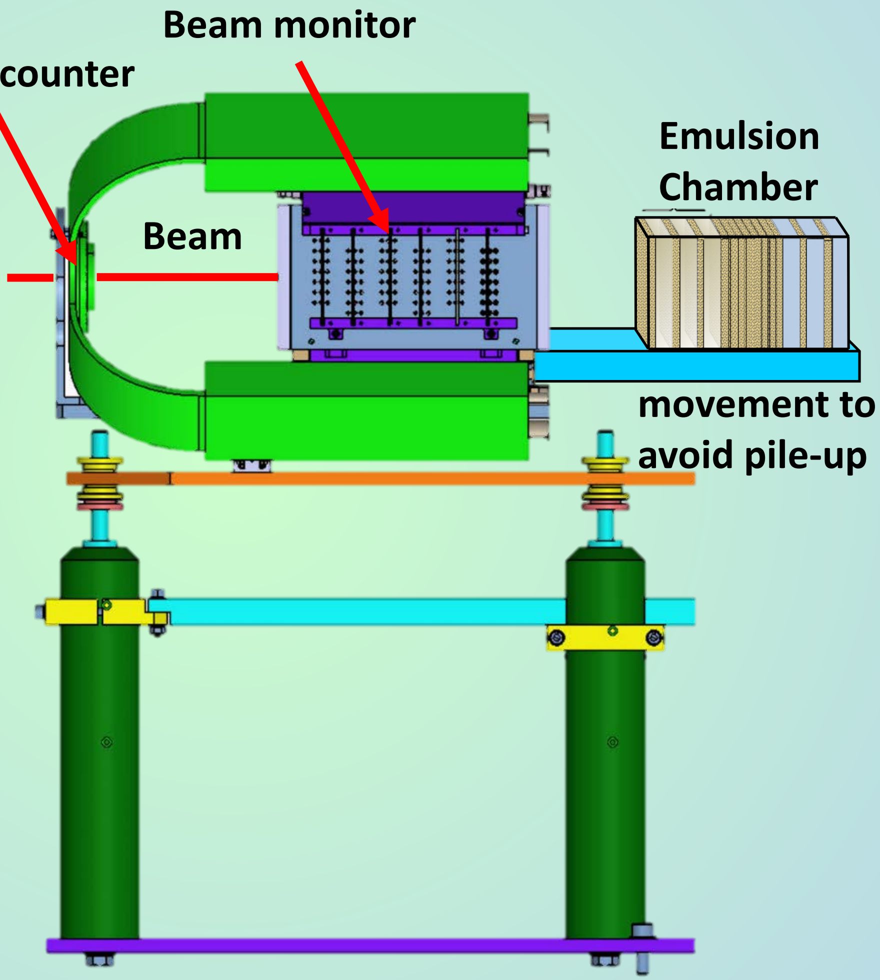


300 µm Emulsion layer

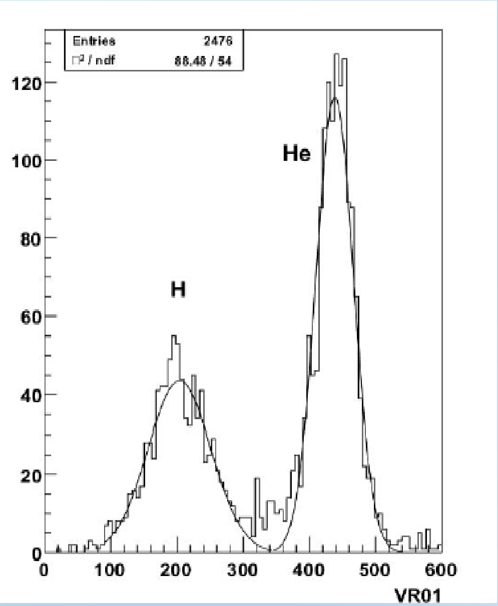
1 mm C or C_2H_4

Emulsion layer

1 mm Pb layer



High speed automated scanning



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