# FOOT: FragmentatiOn of Target Experiment

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*on behalf of the FOOT Collaboration*

57th International Winter Meeting on Nuclear Physics



INFN
Istituto Nazionale di Fisica Nucleare
Sezione di Bologna

# FOOT goal

## 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 Treatment Planning System (TPS)

## 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)


## 101 members (60% staff):

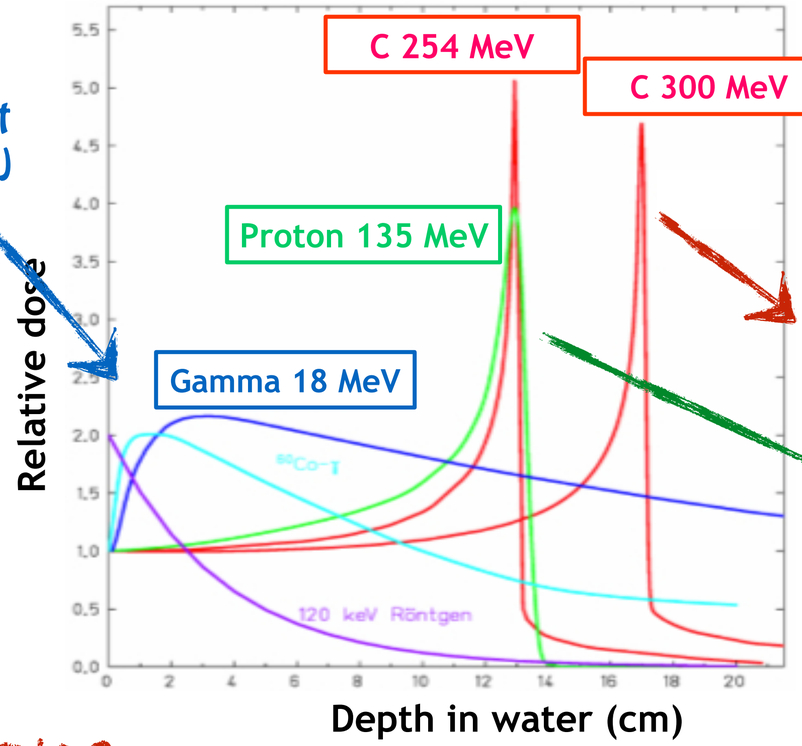
- 10 INFN Sections
- 5 laboratories: Frascati, CNAO, Trento, GSI,IPHC (Strasbourg)
- 12 Italian Universities
- 2 foreign Universities: Aachen, Nagoya
- Centro Fermi

## Physics program:

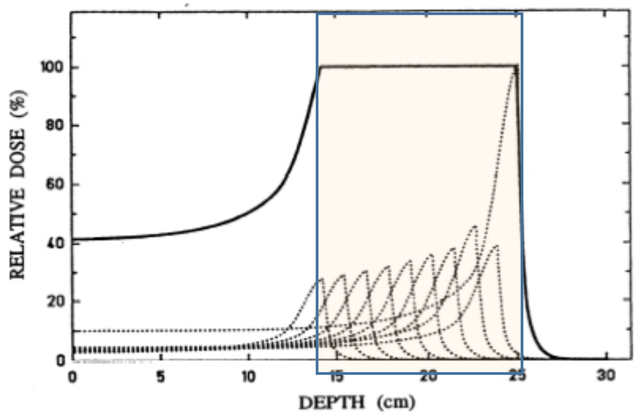
- Hadrontherapy:
- Nuclear fragmentation @ 200 MeV/u
- Radioprotection in Space:
- Nuclear fragmentation @ 700 MeV/u

# Hadrontherapy VS Radiotherapy

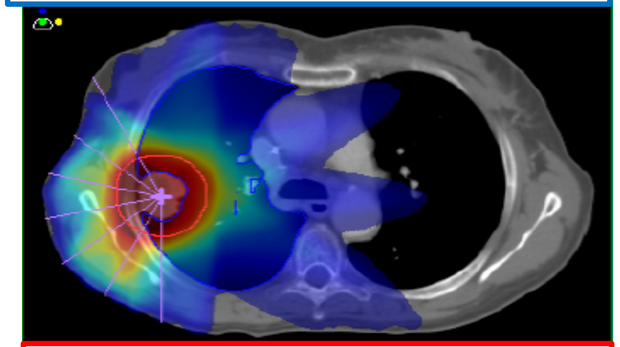
**Gamma**
Superficial Energy deposit
Ionization (Compton, pair)



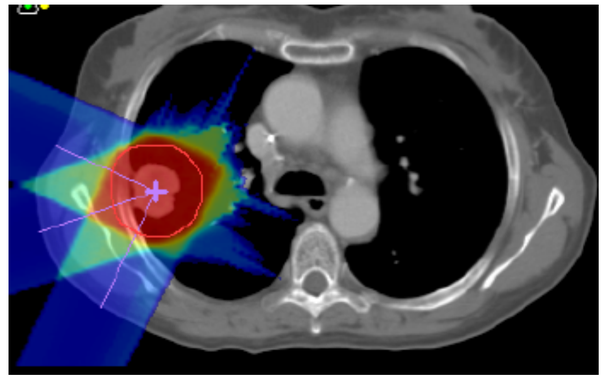

**Proton/charged ion**
Brag Peek
Long Range
Fragmentation




Radiotherapy, IMRT 7 fields



Hadrontherapy, proton



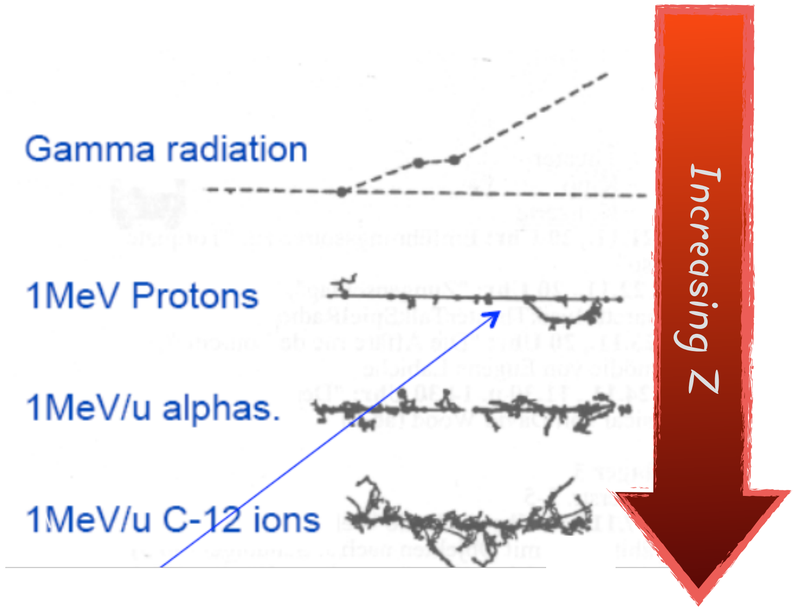
## Pros and cons

- Dose release maximum at the end
- Penetration depends on energy
- More efficient than γ
- Less damage outside tumour
- MORE expensive than γ

# Damage on DNA

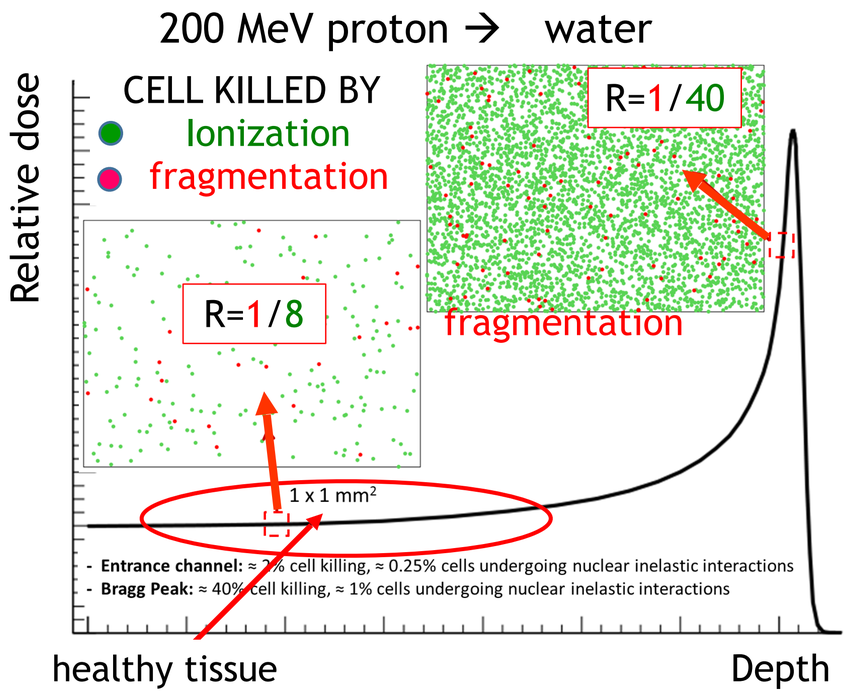
Tumor is a cellular alteration → not controlled proliferation → stop the proliferation → damage on DNA

Ionising tracks @ nanoscale

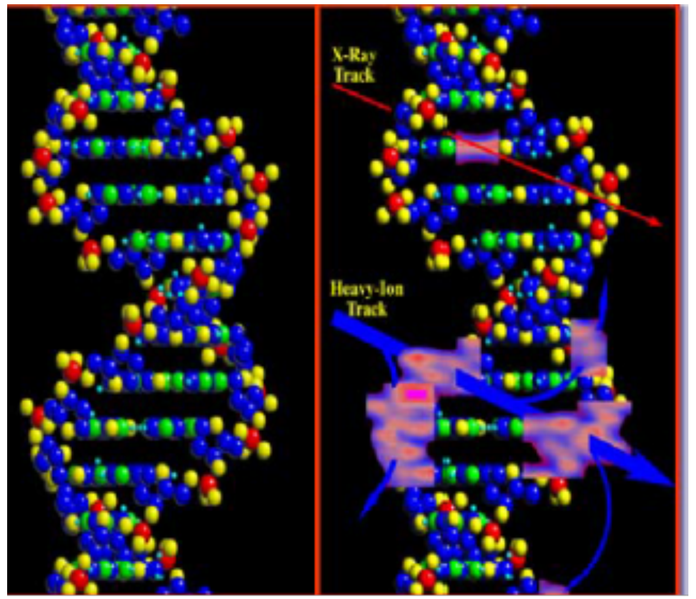



Higher Z → Higher damage

... but necessary to know the Nuclear fragmentation cross sections



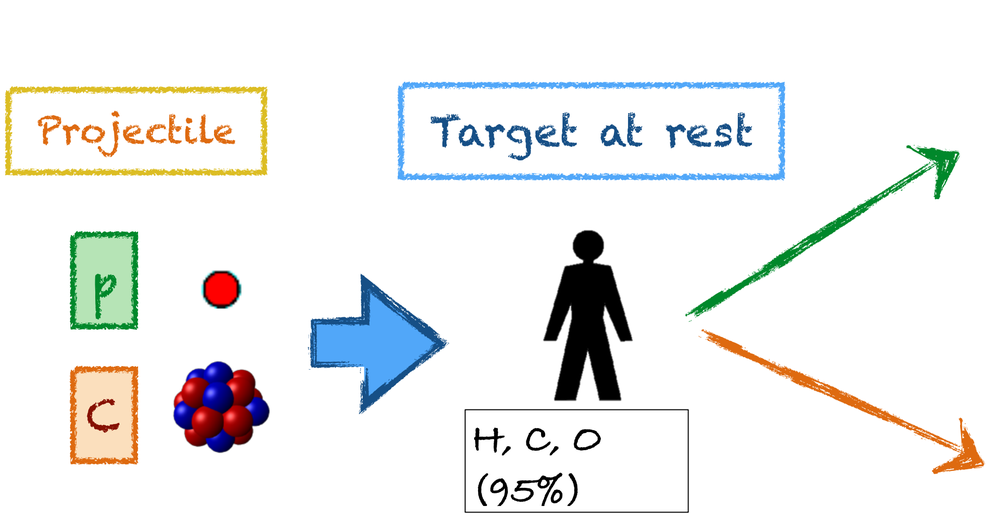

Courtesy of NASA




Double strand break

irreparable damage

# Target-Projectile fragmentation

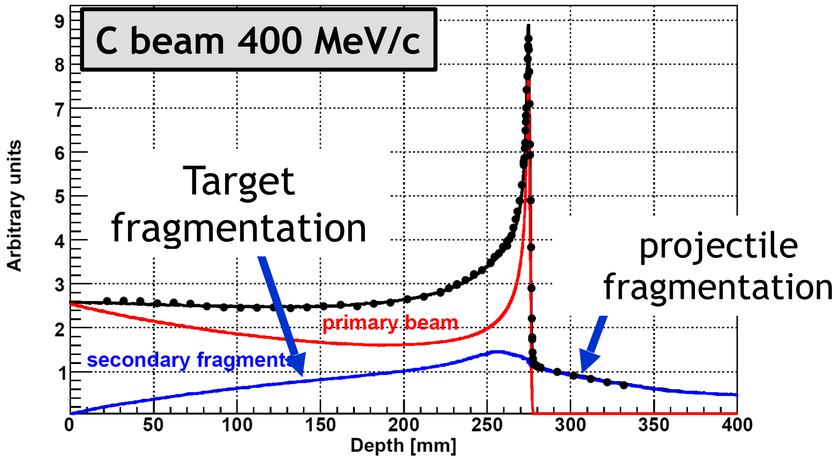


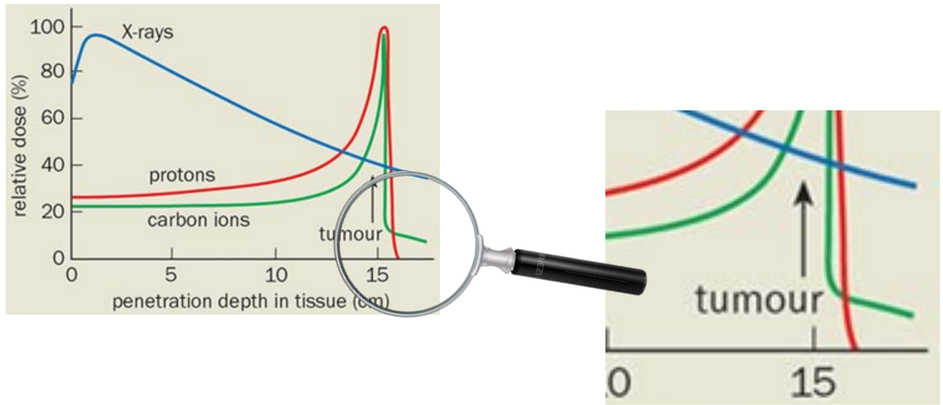

p + H → No fragmentation

p + C,O → Target fragmentation → Low Energy and Range

C + H → Projectile Fragmentation → high energy and long range

C + C,O → Both fragmentation

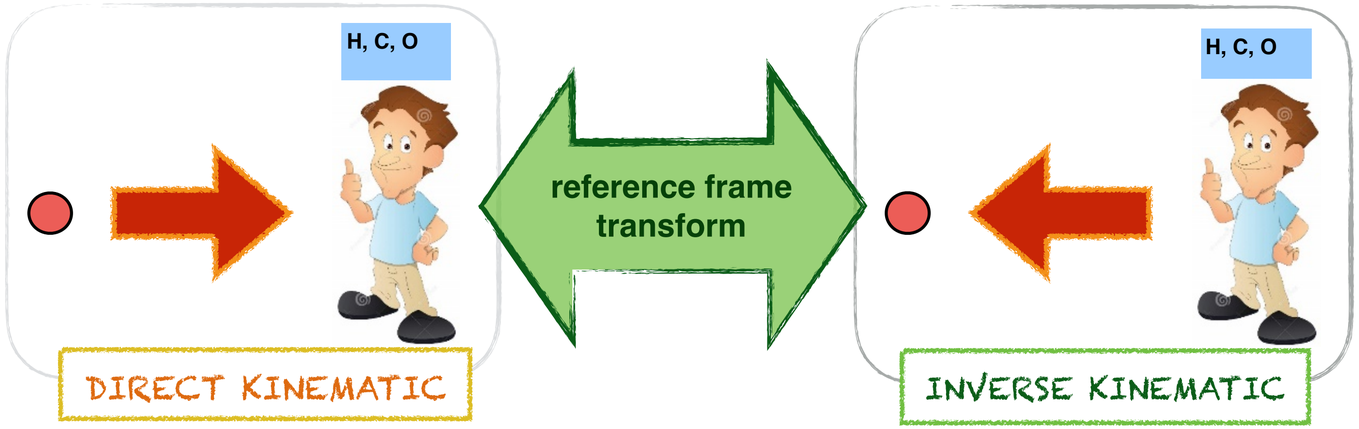



Tail present only when using Carbon

# Target fragmentation measurement

**Problem:** Need to measure target fragments
**BUT** fragments remain in target

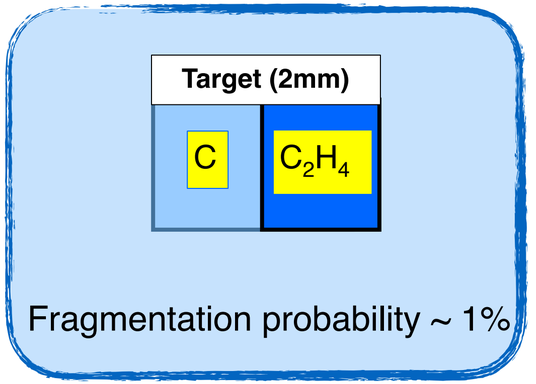



Shoot C,O (,H) on proton beam

**Reference frame back-transformation** = **Lorentz boost** to the final products (subtract the projectile momentum).

**Problem (again):** Hydrogen target

Solution

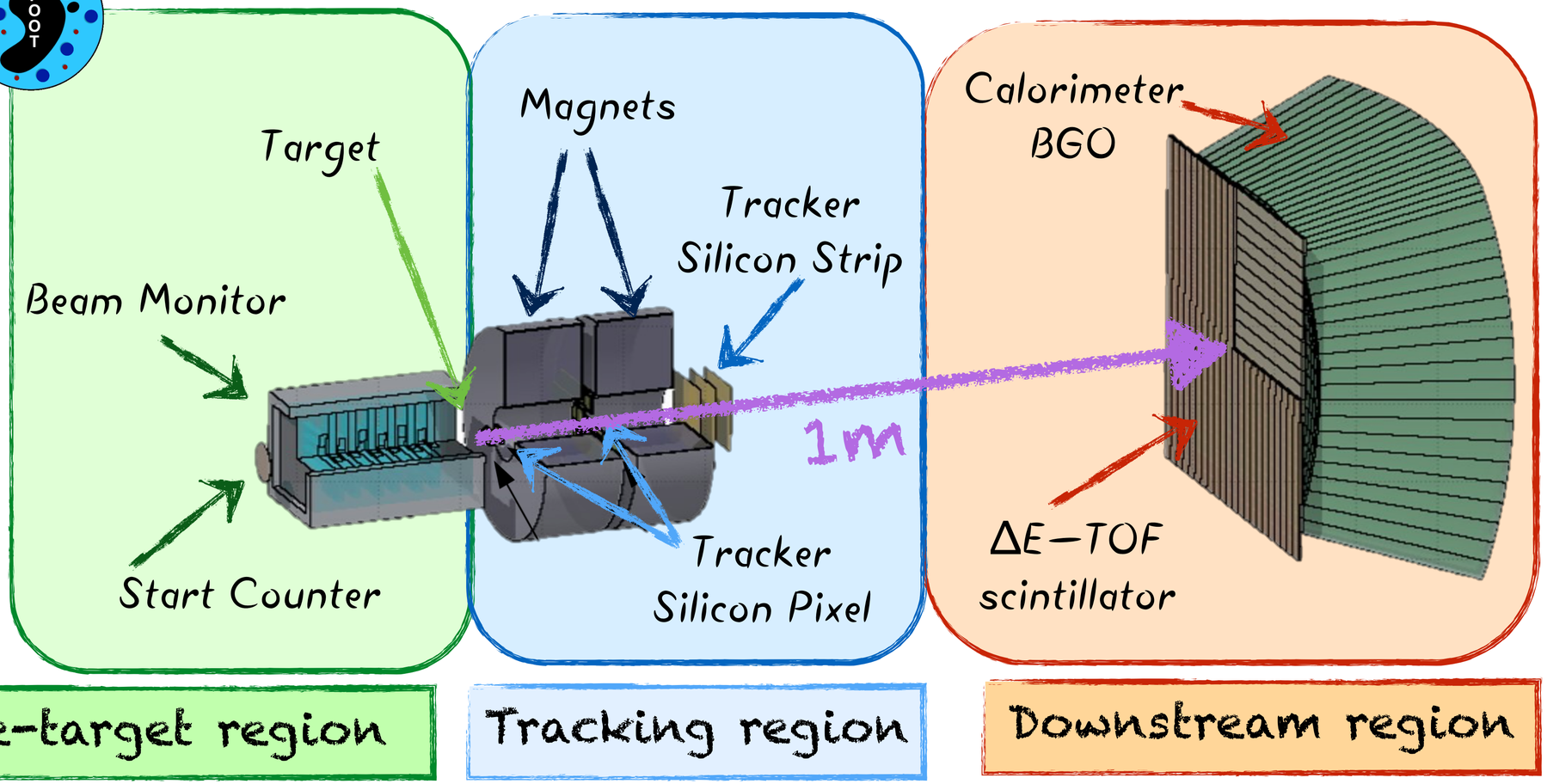



- Polyethylene target $C_2H_4$ + carbon target (graphite)
- Subtract the cross section on carbon to the one on polyethylene

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

# FOOT Detector (in construction)

## Electronic Setup




**Heavy fragments**

n, p, D, T, He

**Angular open**

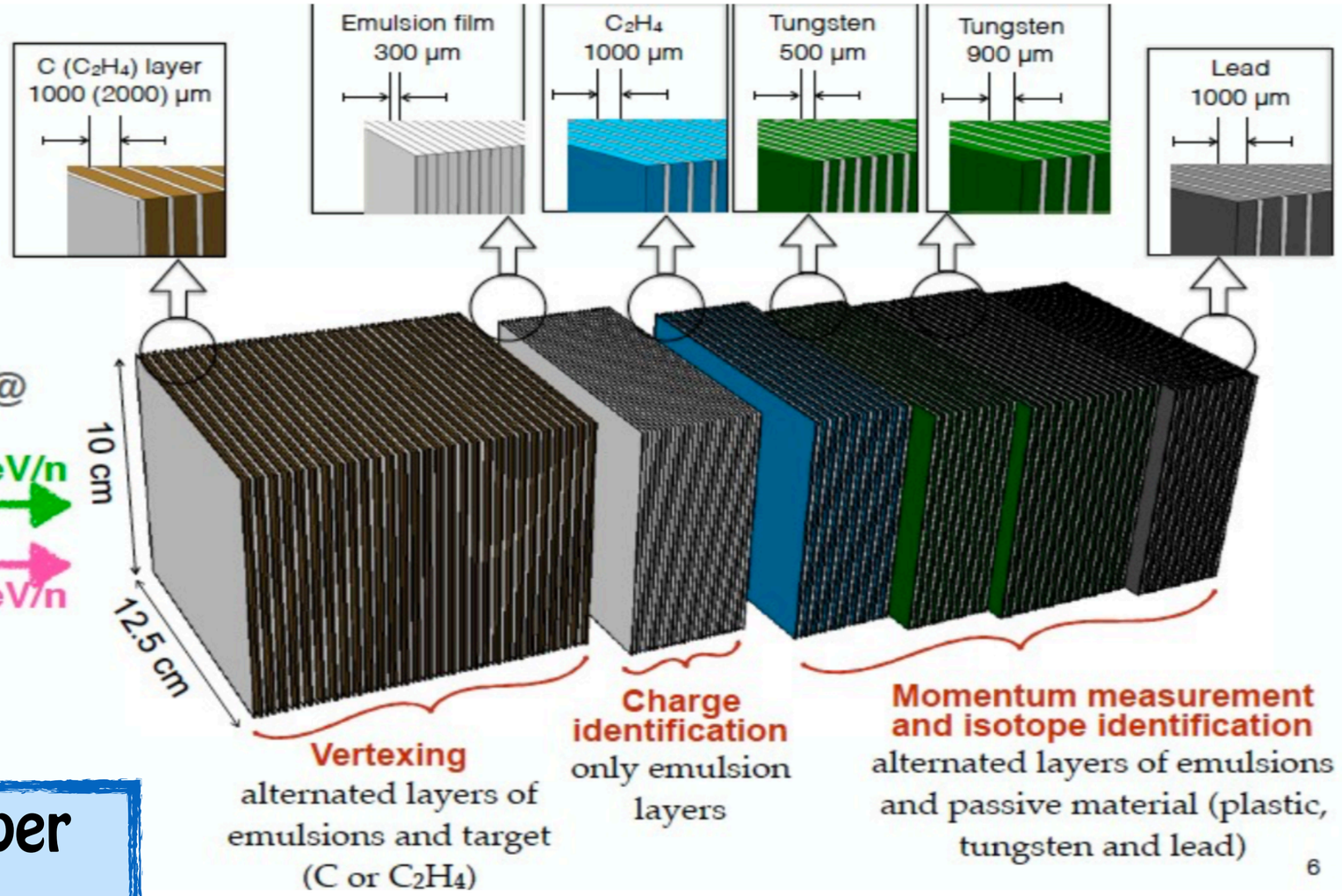
± 10°

# FOOT Detector (in construction)

**Light fragments**
(p, He)

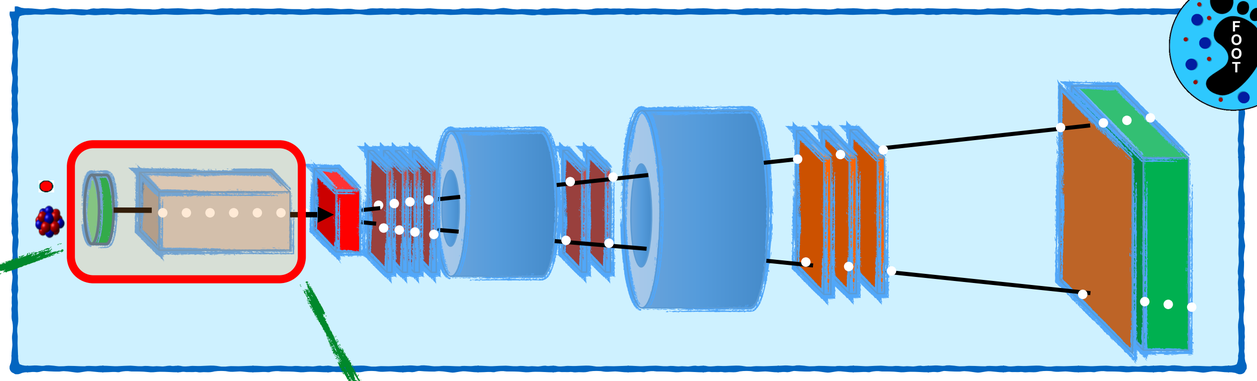
**Angular open**
± 70°

$^{16}O$@
200 MeV/n
400 MeV/n

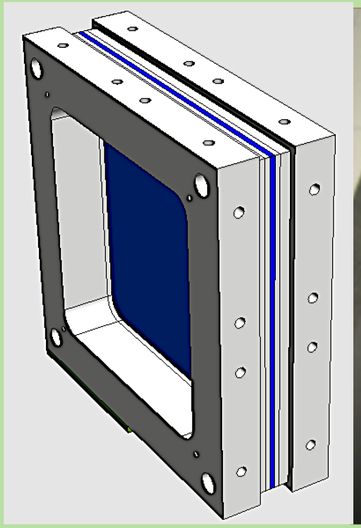


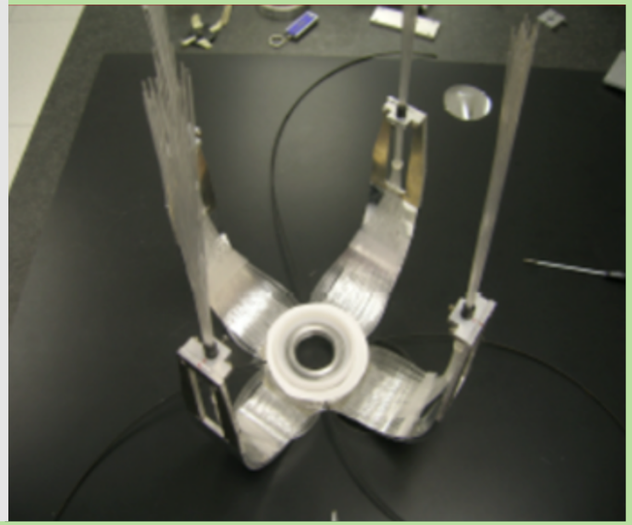

**Emulsion Chamber Setup**

# Pre-target region



## Start Counter (SC)

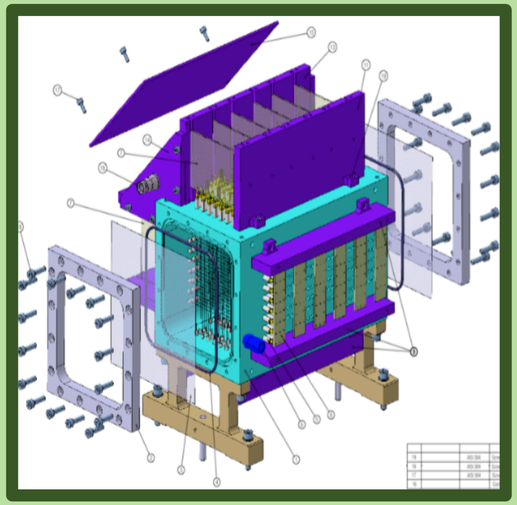


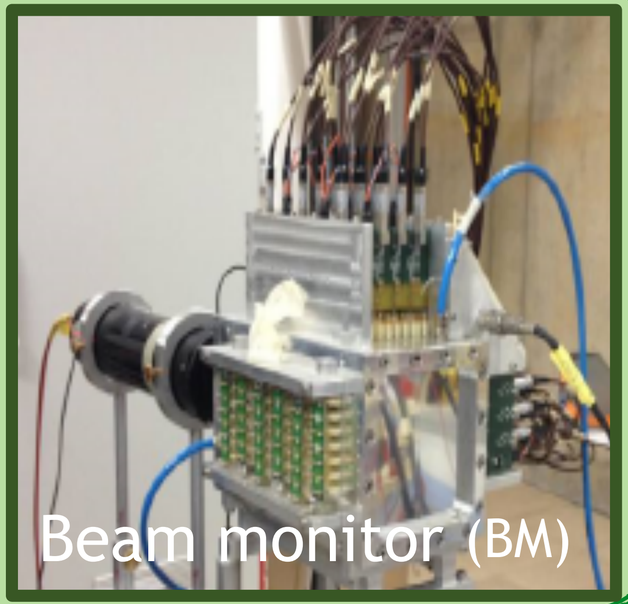


**Trigger and ToF start**

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

## Beam Monitor (BM)

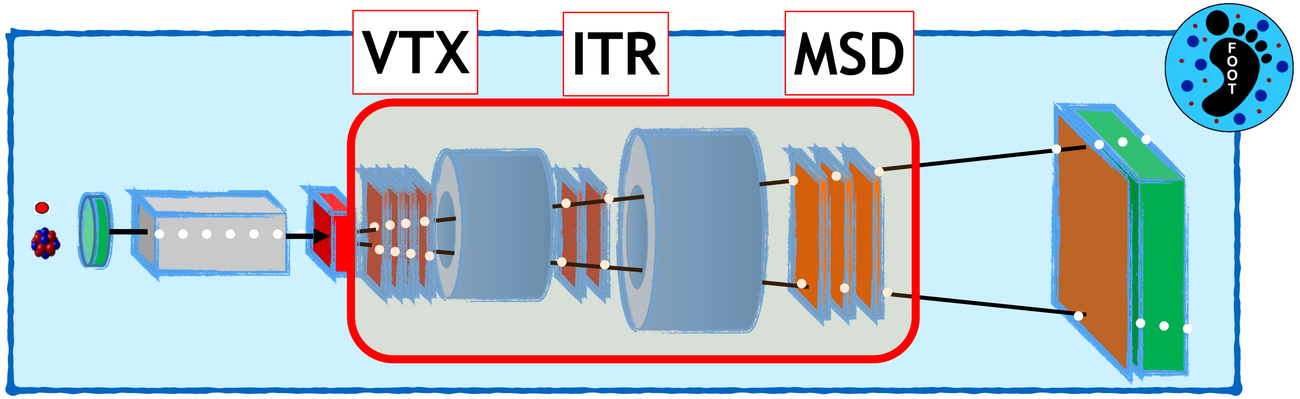


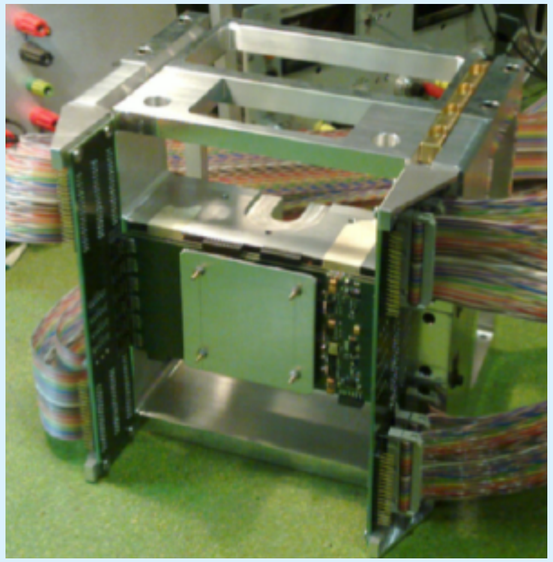



**Beam momentum/direction & fragmentation**

Drift chamber
Gas: Ar/$CO_2$ (80/20%)

# Tracking region

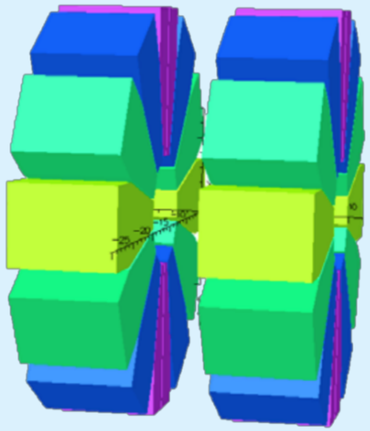


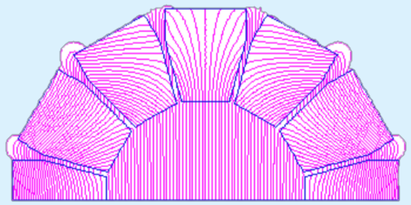



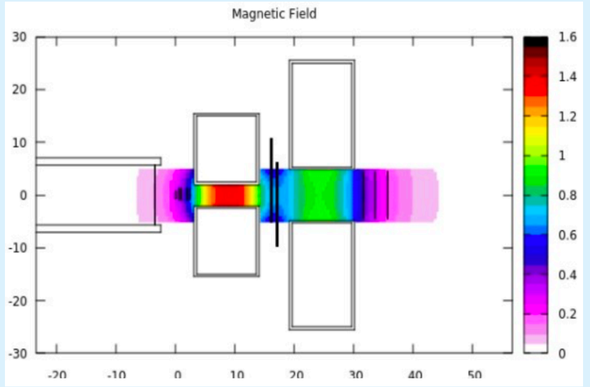
VTX: 4 layers of Si pixel (20 x 20 μm)
ITR: 2 layers of Si pixel (20 x 20 μm)

## Vertex & Inner Tracker

## Magnet

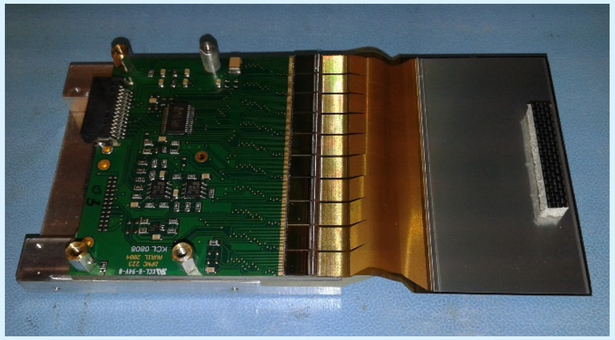







2 permanent Hallbach magnets

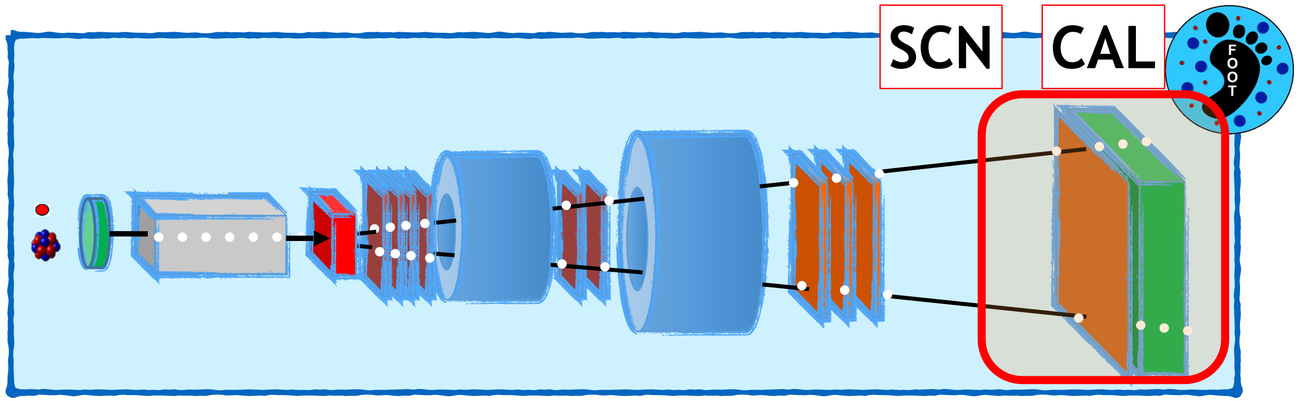
B field in y axis (max 0,9 and 1.1 T respectively)



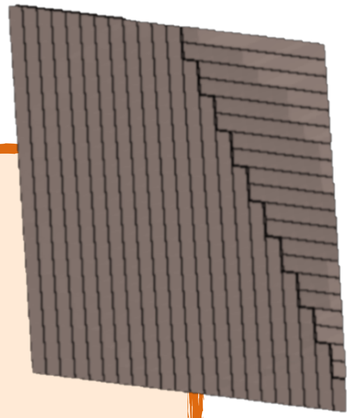
3 layers of Si strips
(120 μm x 9 cm)

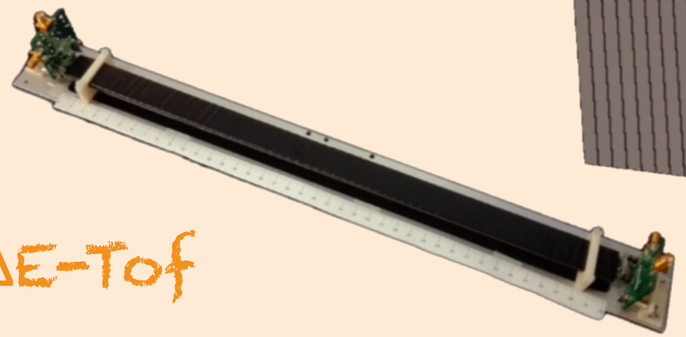
## Micro Strip Detector (MSD)

# Downstream region




## Scintillator (SCN)

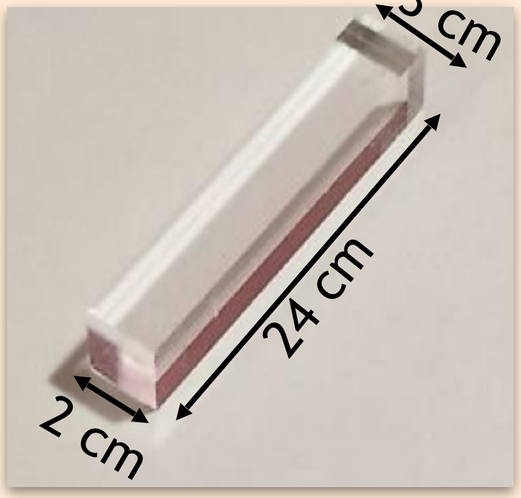




### ΔE-Tof

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

## Calorimeter (CAL)



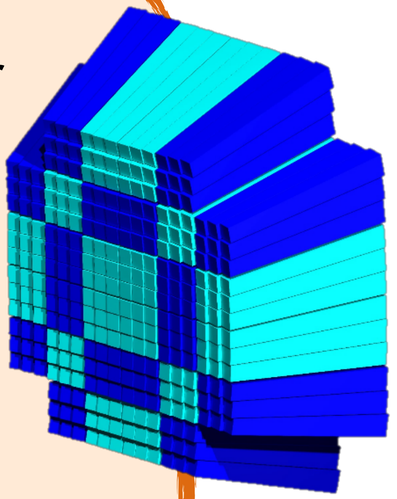

**BGO - ($Bi_4Ge_3O_{12}$)**
**Inorganic scintillator**

$Z_{Bi} = 83$

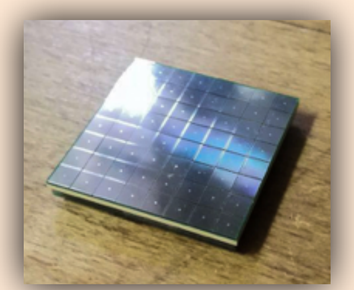
$P_{BGO} = 7.13\ g/cm^3$

*Weight = 1.027 kg*

*Total weight 330 Kg*

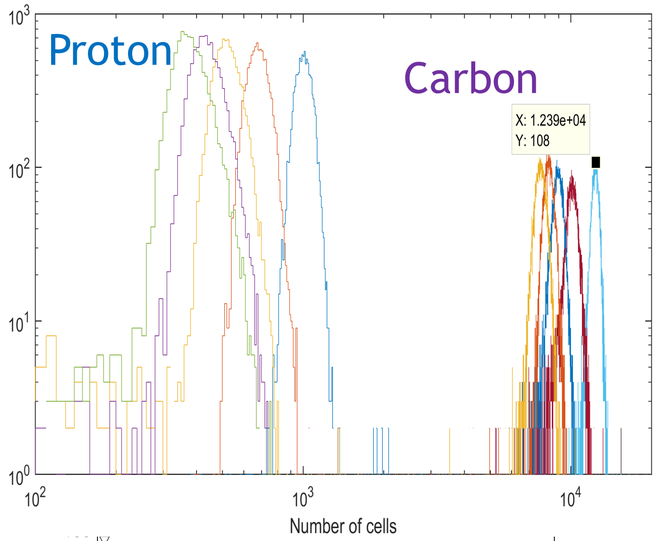


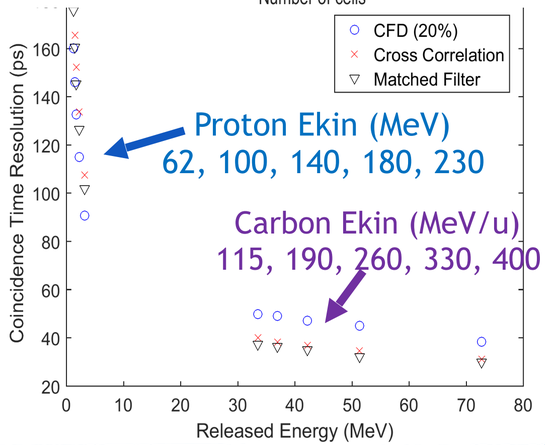
SiPM. Pitch 50 μm
Voltage breakdown 53 V



# Beam tests results

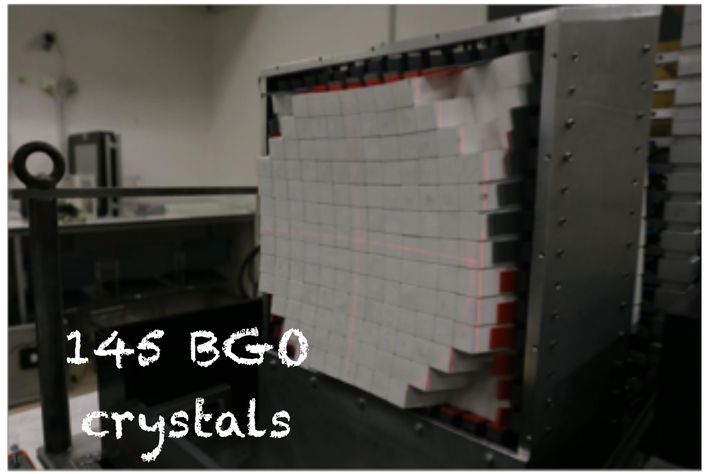
## ΔE-Tof test beam @CNAO

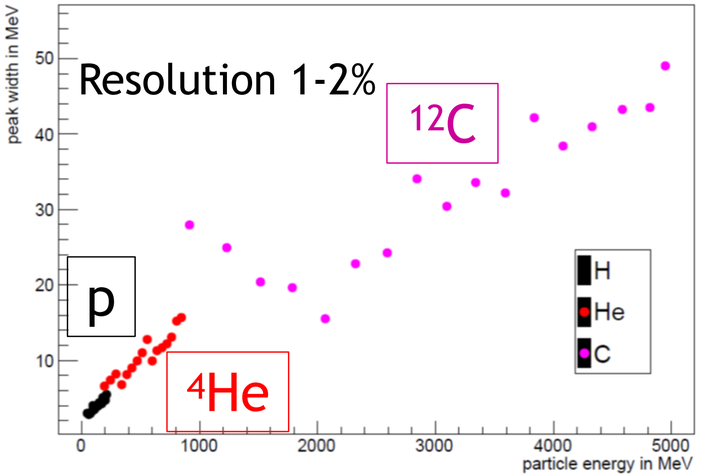



**Tof resolution (C) better 40 ps**

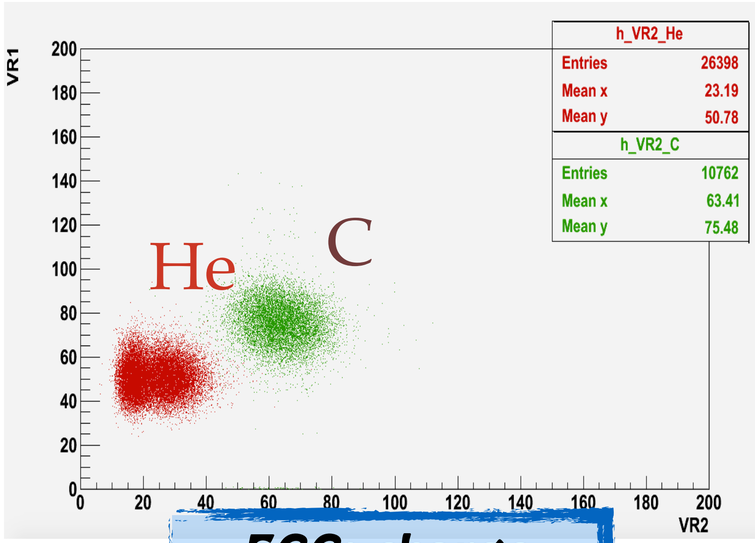
## Calorimeter: test beam @HIT




**Kinetic energy resolution at 1-2%**

## Emulsion test beam @LNS and Trento




**ECC: charge separation**

# Performances: charge Z reconstruction

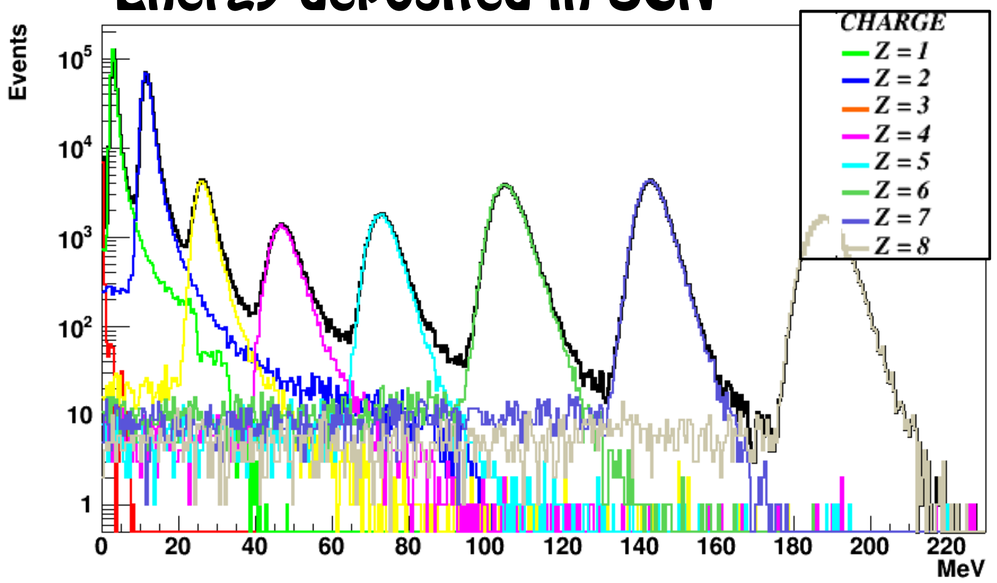
$^{16}O$ (200 MeV/u)→ $C_2H_4$

Fluka simulation

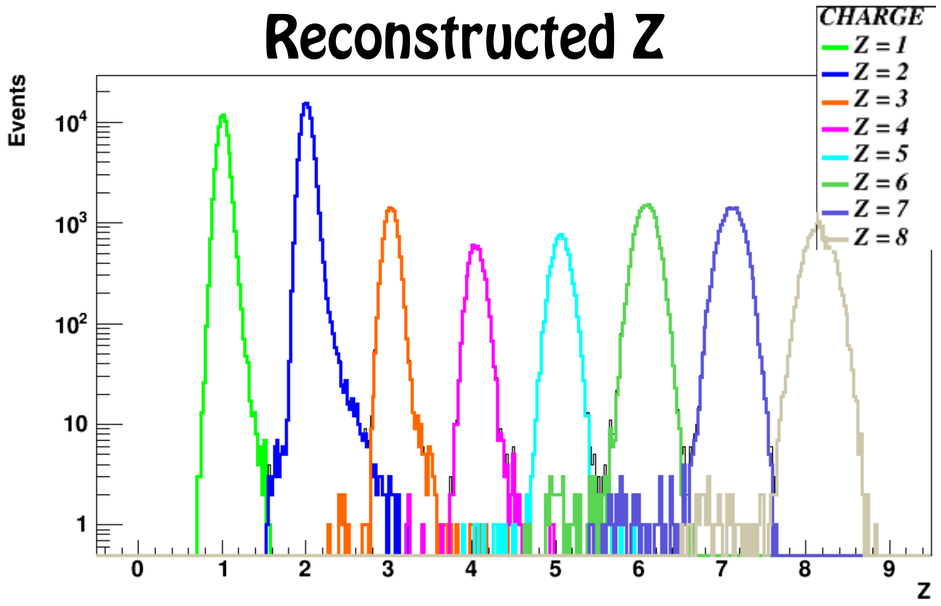
SCN ← $-\frac{dE}{dx} = \frac{\rho \cdot Z}{A} \frac{4\pi N_A m_e c^2}{M_U} \left(\frac{e^2}{4\pi\epsilon_0 m_e c^2}\right)^2 \frac{z^2}{\beta^2} \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$

TOF

## Energy deposited in SCN




## Reconstructed Z




Z resolution = 2.0% (9% p, 6% He)

| $^{1}H$ | $^{4}He$ | $^{7}Li$ | $^{9}Be$ | $^{11}B$ | $^{12}C$ | $^{14}N$ | $^{16}O$ |
|---|---|---|---|---|---|---|---|
| 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 |

Charge misidentification < 1%

# Number of mass A

REDUNDANT Detector

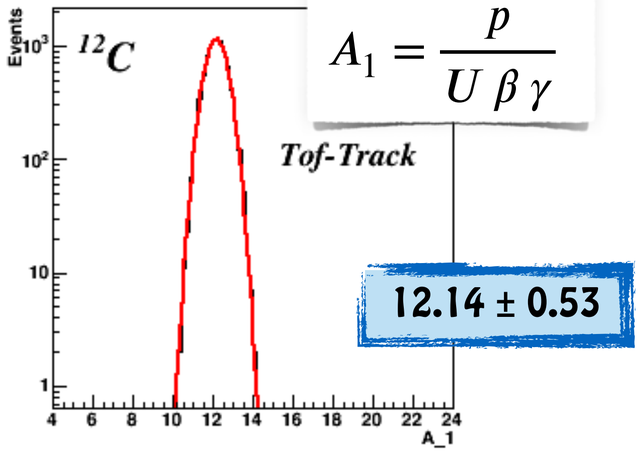
different ways to determine A

$^{16}O$ (200 MeV/u)→ $C_2H_4$

Fluka simulation

TOF & TRACKER

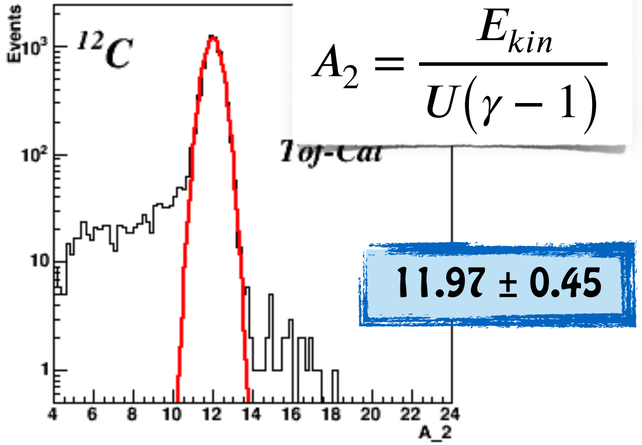
$$A_1 = \frac{p}{U\,\beta\,\gamma}$$




12.14 ± 0.53

TOF & CALO

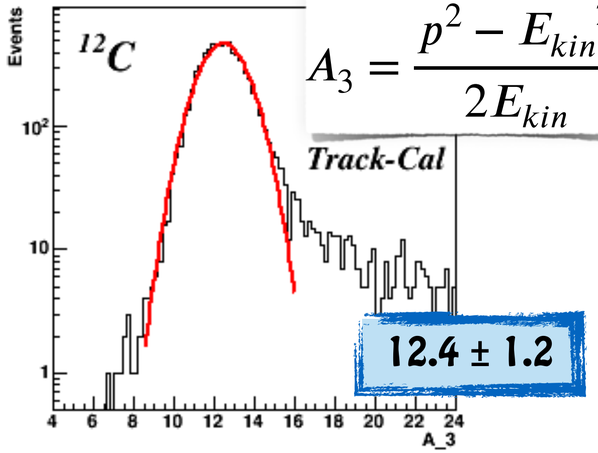
$$A_2 = \frac{E_{kin}}{U(\gamma - 1)}$$




11.97 ± 0.45

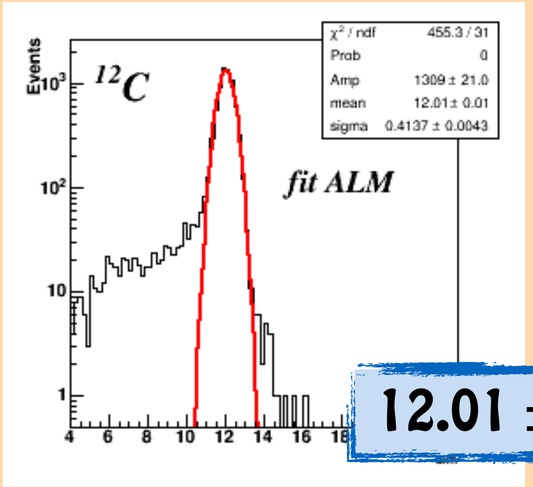
TRACKER & CALO

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



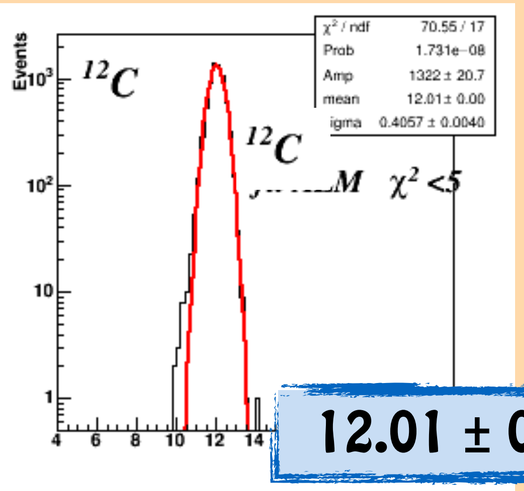

12.4 ± 1.2

Final result with Augmented Lagrangian Fit (ALM)




12.01 ± 0.41

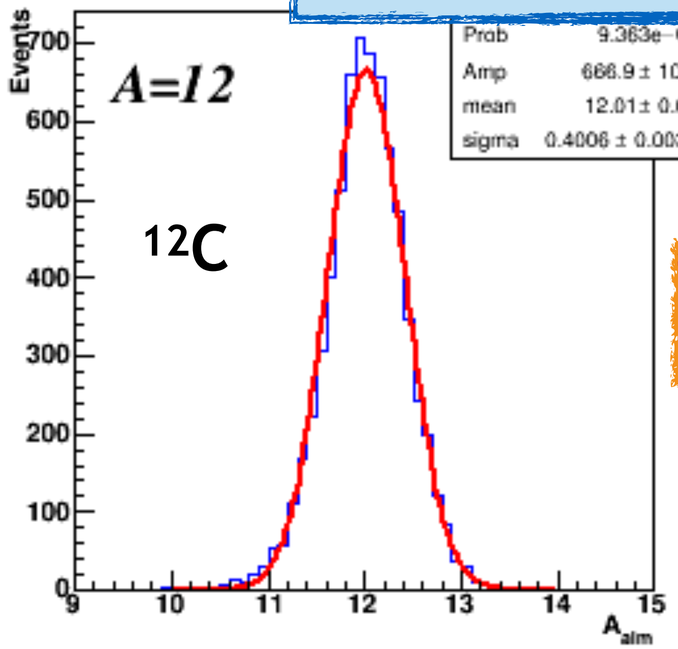
$\chi^2$ cut

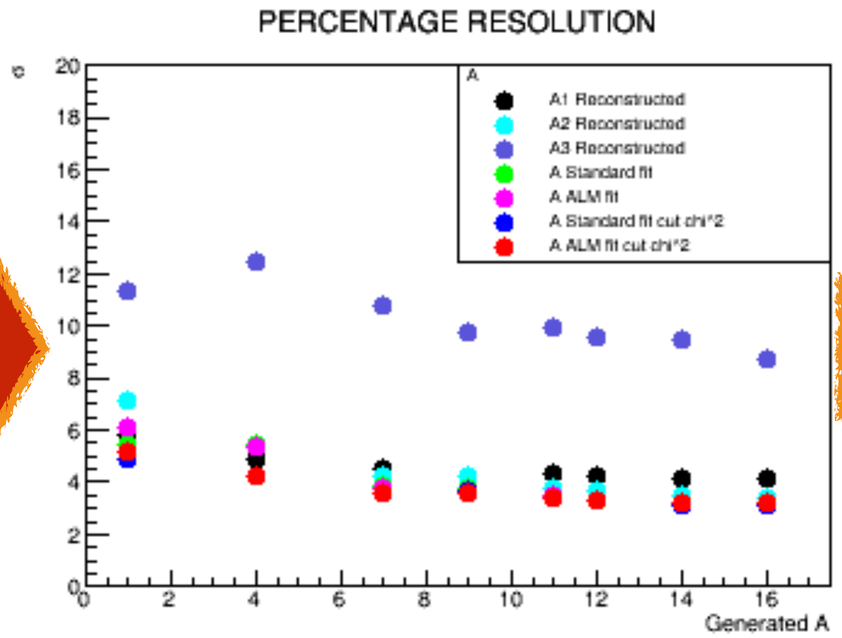


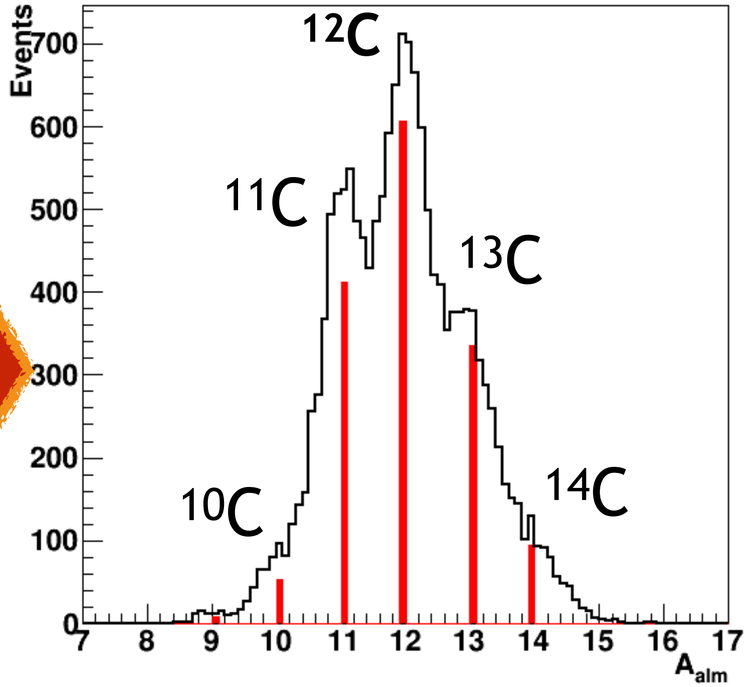

12.01 ± 0.41

# Mass reconstruction

**A = 12.0 ± 0.4**




## Conservative Resolutions

$\Delta p/p$ → 4%

$\Delta E_{kin}/E_{kin}$ → 1.5%

$\Delta TOF$ → 70-140 ps

$\Delta(dE)/dE$ → 3-10%

Resolution for heavy fragments ~ 3–4%

Possibility to disentangle isotopes!!!
(C most difficult)

# Isotopes separation

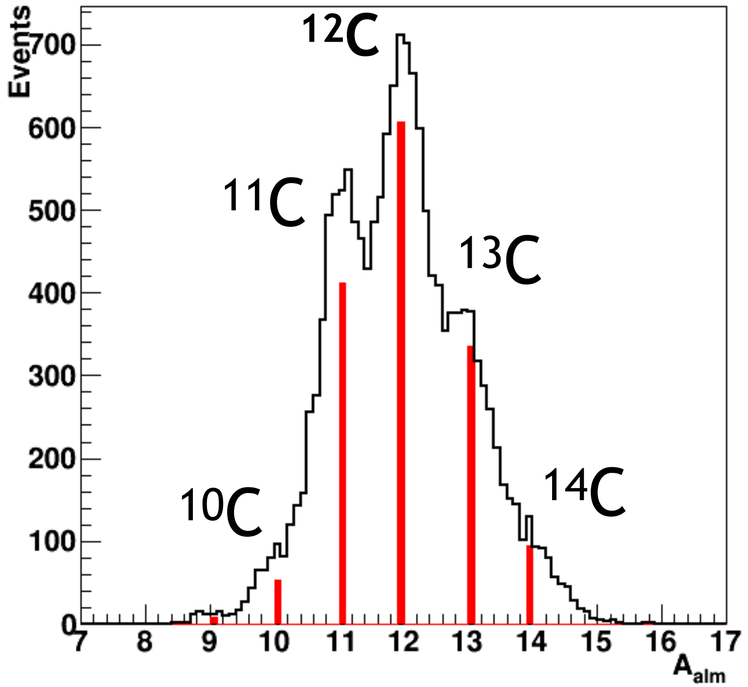
**Conservative Resolutions**

$\Delta p/p$ → 4%

$\Delta E_{kin}/E_{kin}$ → 1.5%

$\Delta TOF$ → 70-140 ps

$\Delta(dE)/dE$ → 3-10%




**Test Beam updates**

ΔE-Tof test beam @CNAO

**Tof resolution (C) better 40 ps**

Calorimeter: test beam @HIT

**Kinetic energy resolution at 1-2%**

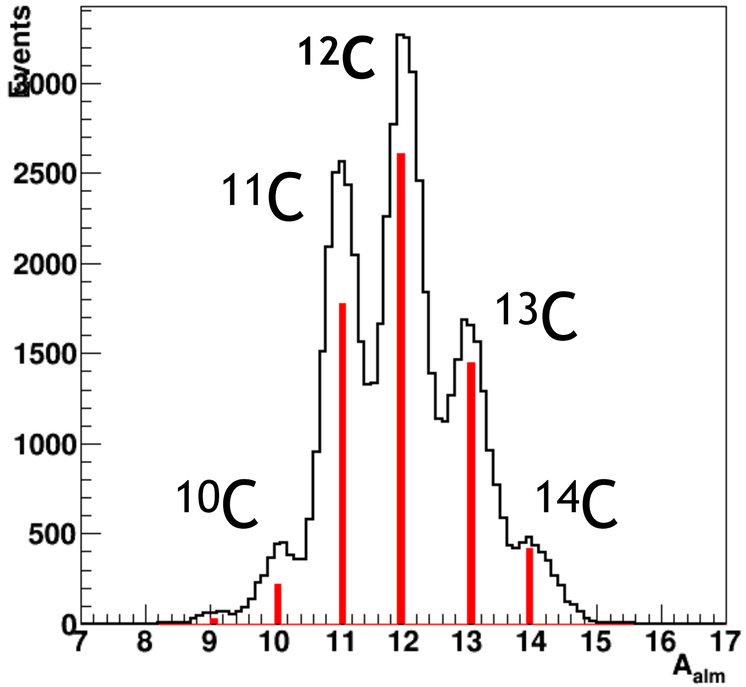
**Test Beam Resolutions**

$\Delta p/p$ → 4%

$\Delta E_{kin}/E_{kin}$ → 1.0%

$\Delta TOF$ → 100 ps

$\Delta(dE)/dE$ → 3-10%



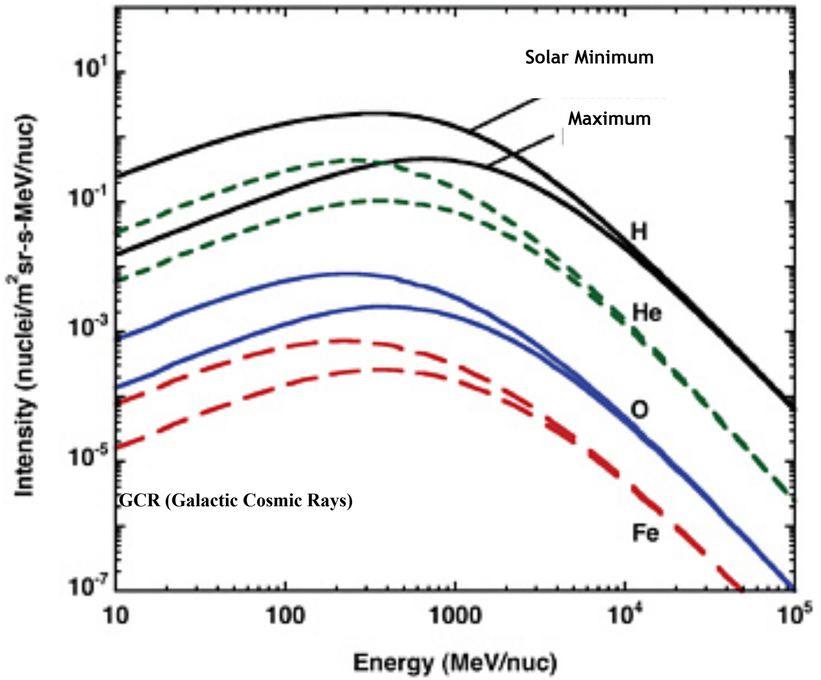
# Space radio-protection

## Mission to Mars!

Since 1 Sv
(increase the cancer probability of ~3%)
**astronauts need shielding !**

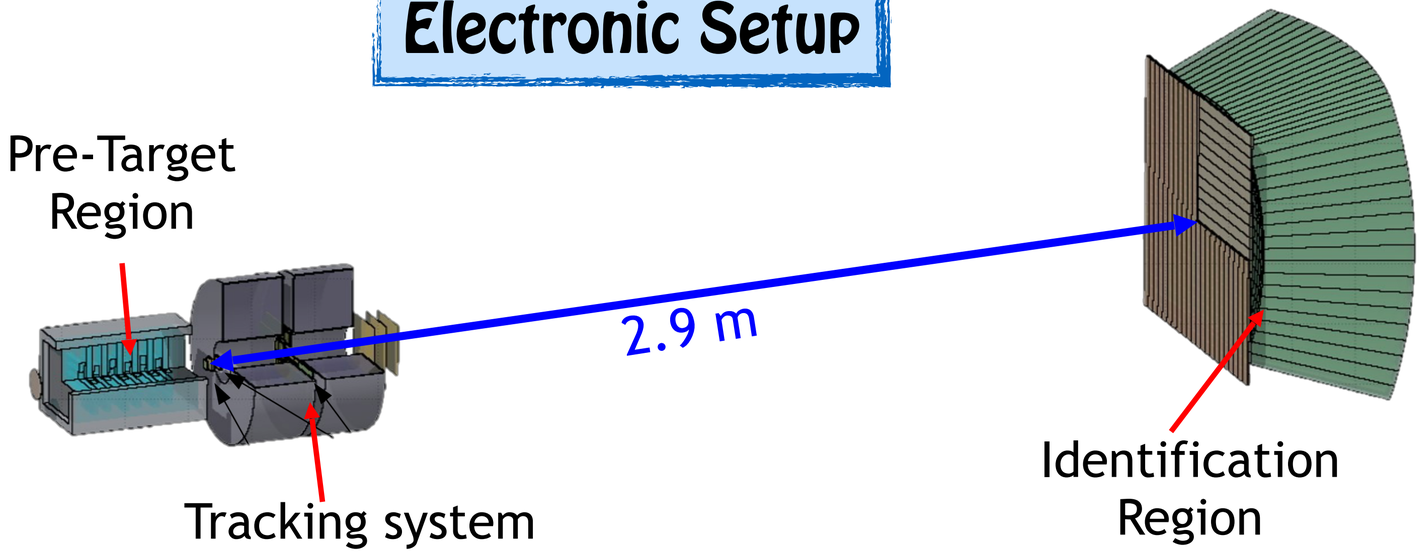
- Long cruise (180 days each way), no natural protection from radiation
- Mars has thin atmosphere and no magnetosphere
  - ☆ no protection against CR and Solar Particle Events (SPE)
- Mars exploration constrained by Mars–Earth periods relation (270 days, best guess )

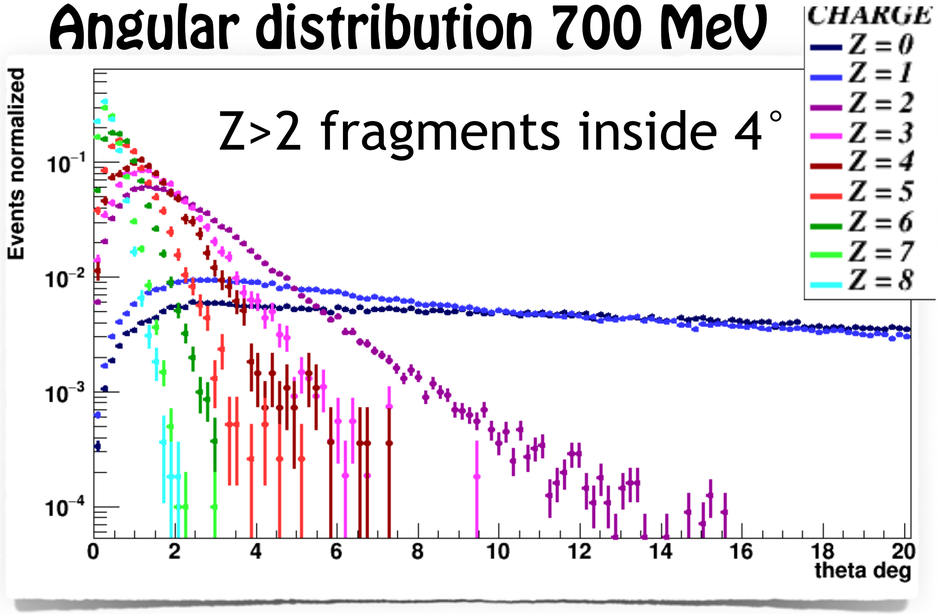
- Mars voyage total radiation: > 1Sv/y
  - Travel: 1.8 mSv/day (GCR + SPE)
  - On Mars: 0.64 mSv/day (base) + ~1 Sv (surface walk)
- On earth: 2.64 mSv/year



# FOOT Setup for higher energy

## Electronic Setup

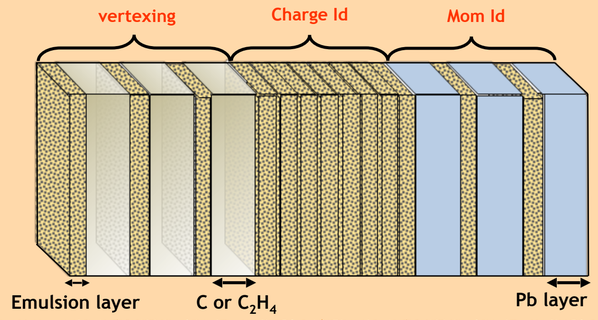



- Same acceptance as @ 200 MeV/u
- High resolution on β
- Crucial for Z & A determination

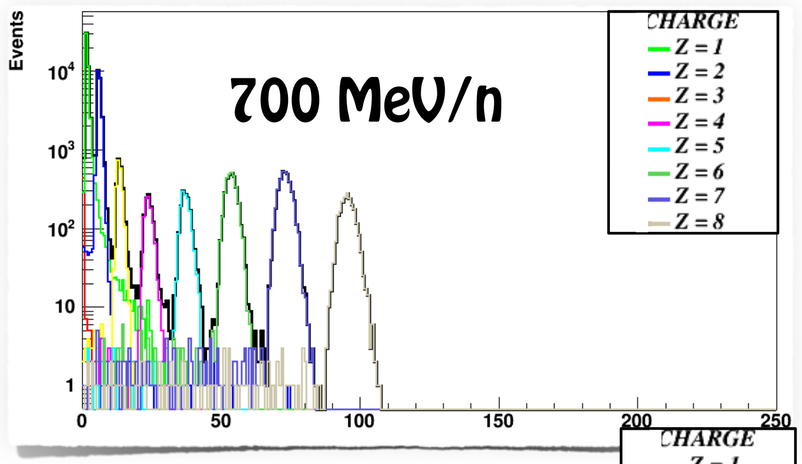
**EMULSION CHAMBER**

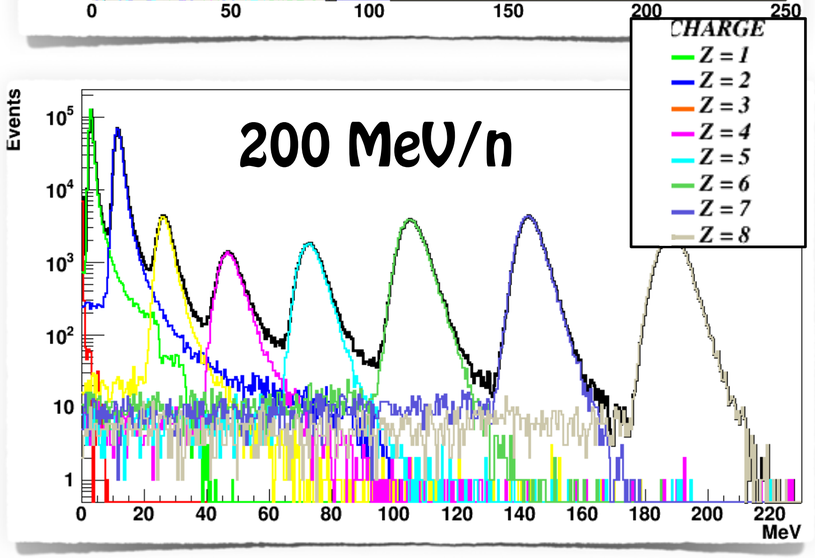
Different geometry and number of layers



# Z reconstruction performance @700 MeV/u

## Energy deposited in SCN

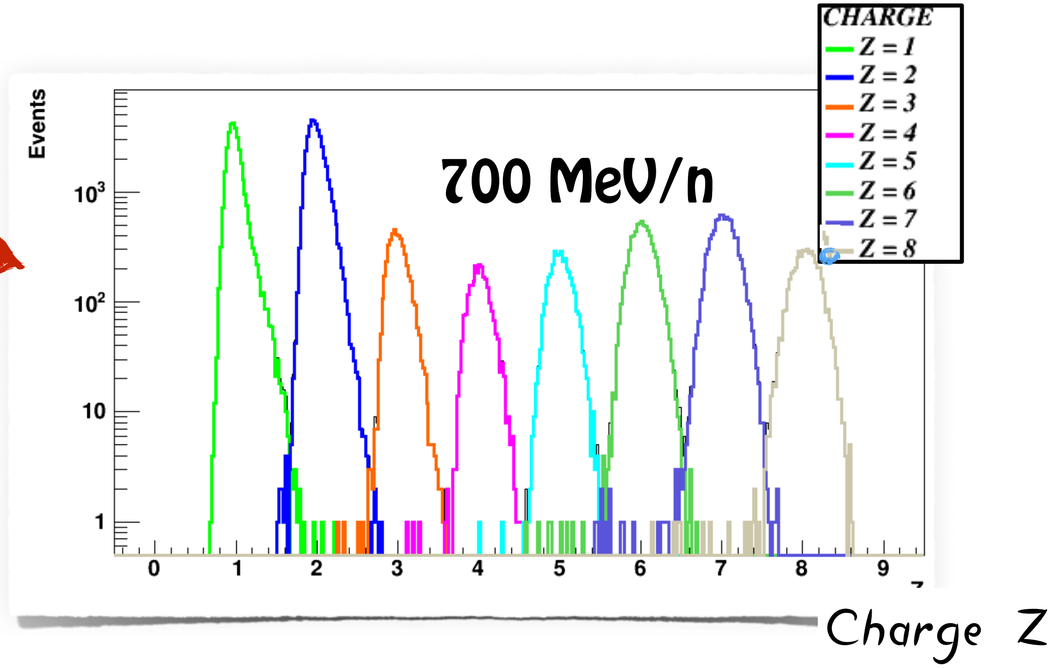



SCN

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

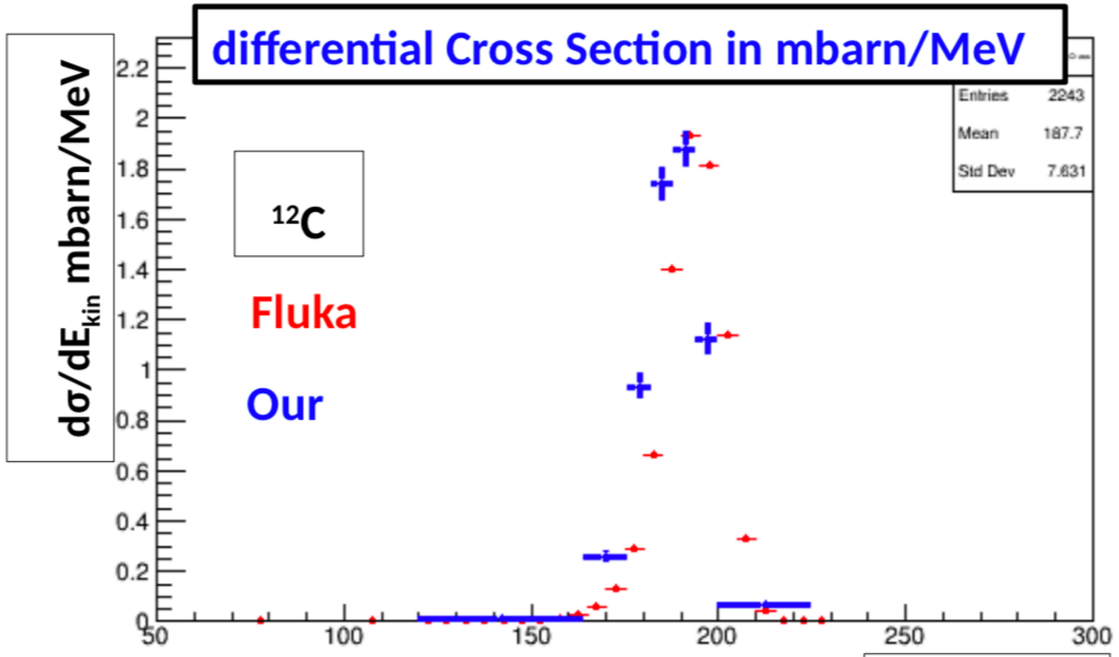
TOF




| 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% |

# Cross Section Closure test

- Set up the full machinery to evaluate the differential (in energy, Z, A) cross section
- Unfolding technique used to recover bin migrations of events
- Performed a closure test comparing the reconstructed cross section (from MC events) with the expected one!




$$\frac{d\sigma_f}{dE_{kin}} = \frac{(Y_f - Bkg_f)^U}{N_{Prim} \cdot N_t \cdot \Omega_{Ekin}\, \epsilon_f}$$

| Total σ mbarn | FLUKA | OUR |
|---|---|---|
| $^{16}$O +C-> $^{12}$C+X | 39.3 ± 0.2% | 39.4 ± 0.5 |

- $f$ fragment: all Carbon Isotopes
- $(Y_f - Bkg_f)^u$ Unfolded (Yield – Bkg) of the fragment
- $N_{prim}$ number of primary events
- $N_t$ number of scattered center per unit area $N_t = \frac{\rho \cdot N_A \cdot depth}{A}$
- $\epsilon_f$ efficiency
- $\Omega_{Ekin}$ phase space $\Omega_{Ekin} = Ekin^f_{max} - Ekin^f_{min}$

# Conclusion and Future

- Wide physic program on both Hadrontherapy and Space Radioprotection
  - Both projectile and target fragmentation
  - Fragment ID in both Z and A!
  - Differential fragmentation Xsec (in angle and energy) with < 5% precision!
- Many encouraging MC studies & successful beam tests
- 🚧 Detector under construction 🚧

- Scheduled data taking (partial detector setup) in April 2019, with Oxygen beam @ GSI
- Full data taking foreseen in 2020, with Carbon, Oxygen and Helium beams.

# Thanks

... e Buon Appetito!

# Backup

# 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



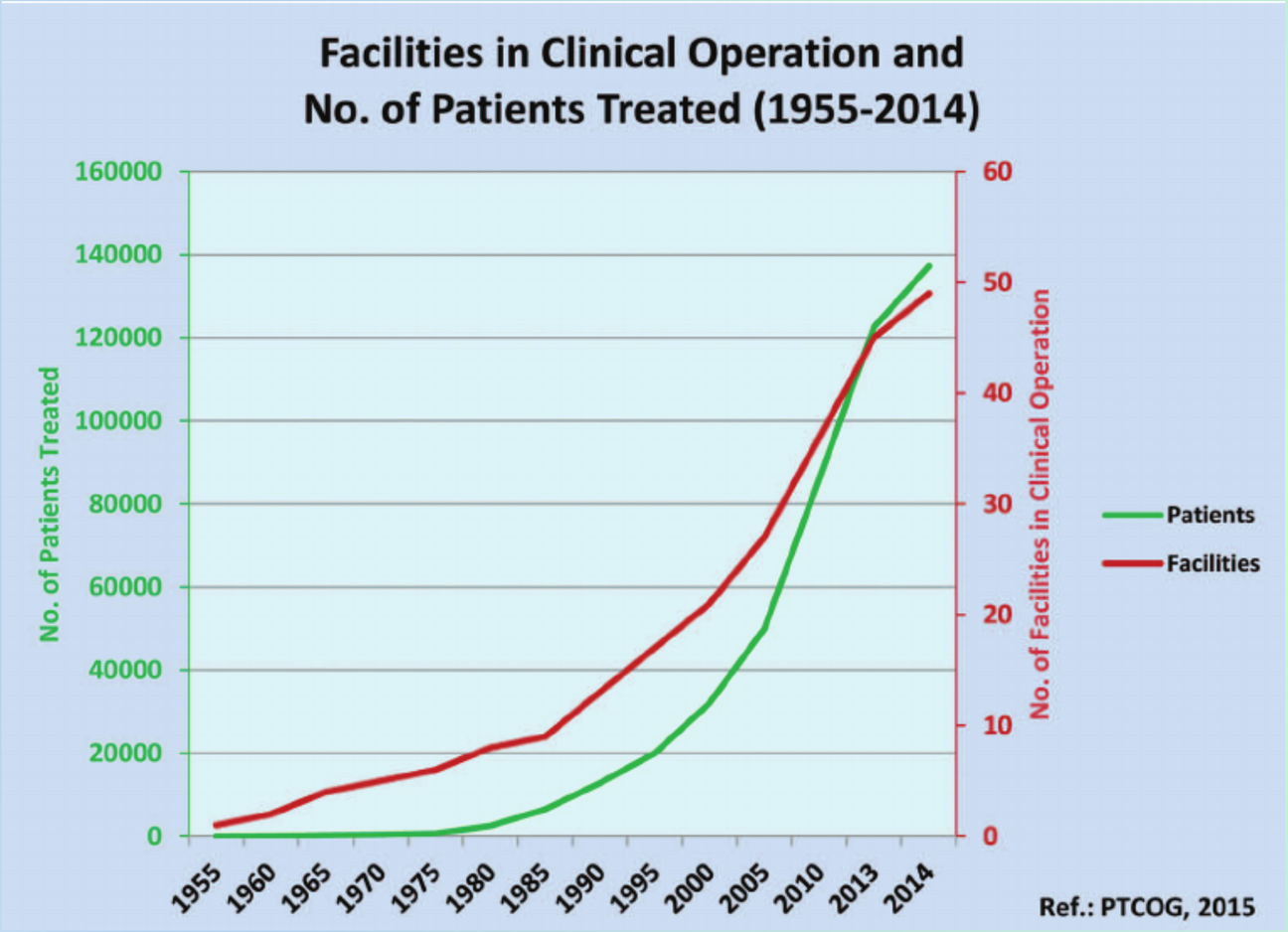

## Publications

- 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

Trento Proton Therapy Center

# *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

# Hadrontherapy in Italy

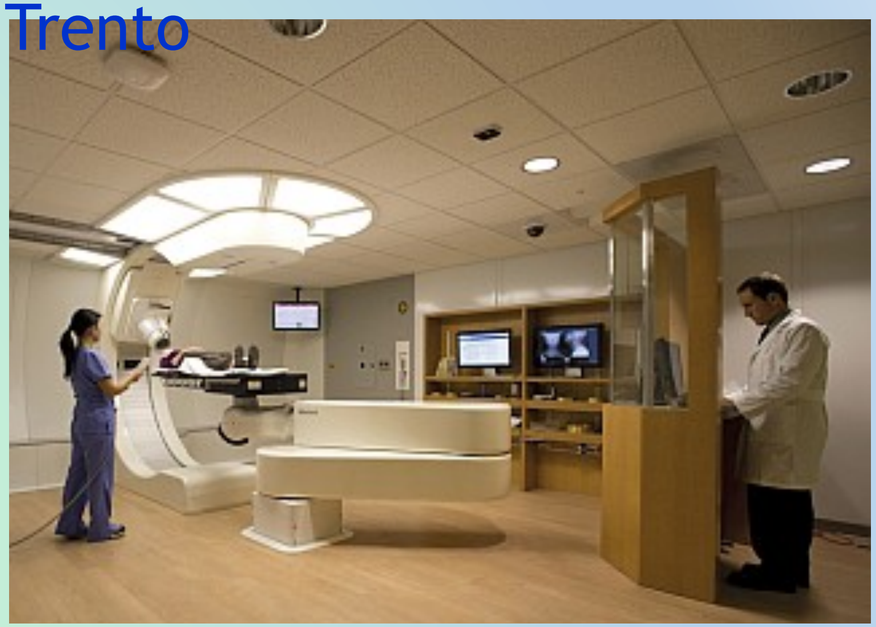
## CATANA Proton Therapy beam line

- 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

| 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 |

# 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 $x^2$ Fit**
  - Taking into account the correlation between $A_1$, $A_2$ and $A_3$

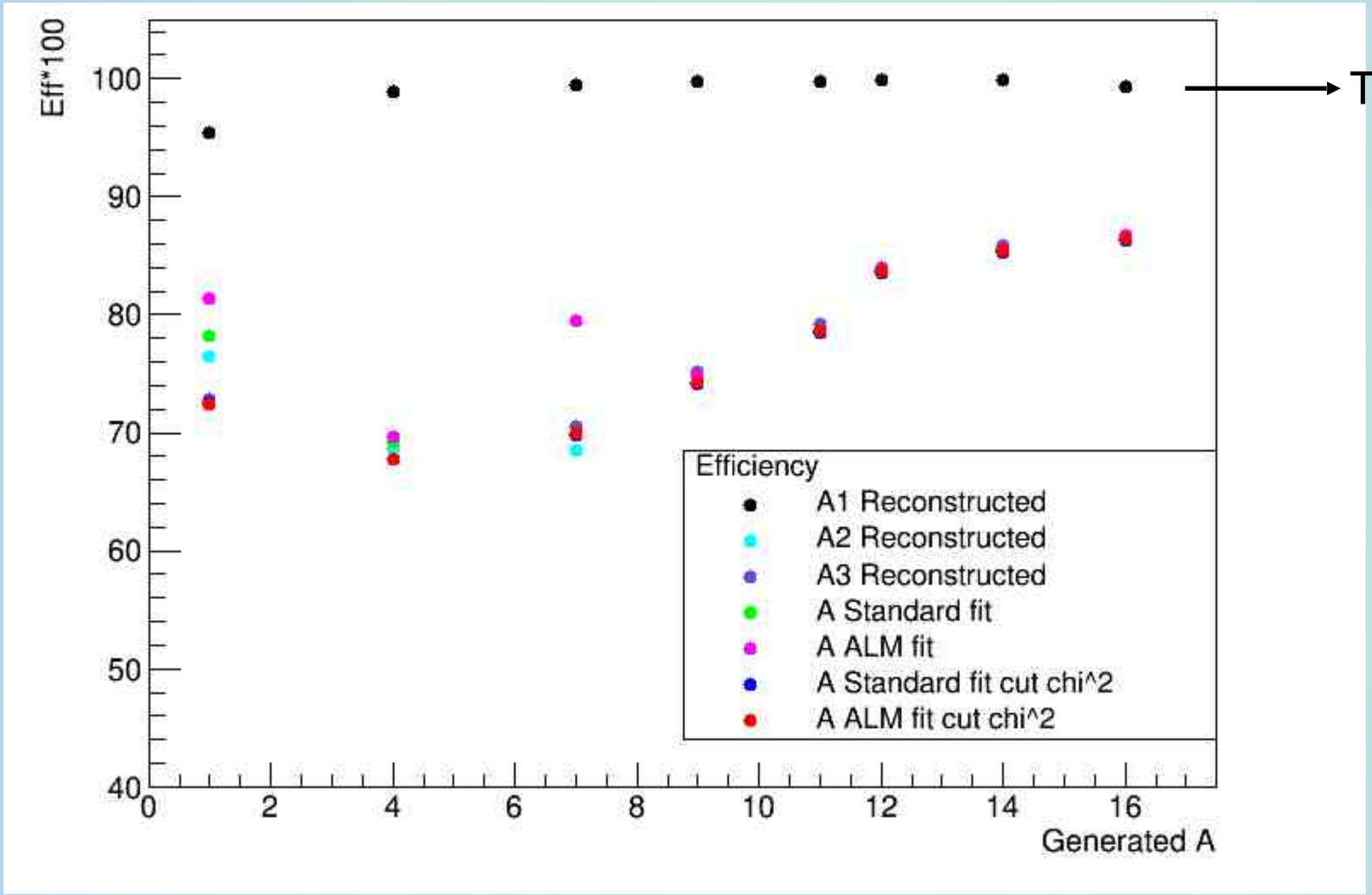
$$f = \left(\frac{(tof_{reco} - t)}{\sigma tof_{reco}}\right)^2 + \left(\frac{(p_{reco} - p)}{\sigma p_{reco}}\right)^2 + \left(\frac{(E_{kin,reco} - E_{kin})}{\sigma E_{kin,reco}}\right)^2 + \begin{pmatrix} A_1 - A & A_2 - A & A_3 - A \end{pmatrix} \begin{pmatrix} C_{00} & C_{01} & C_{02} \\ C_{10}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

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

- **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**

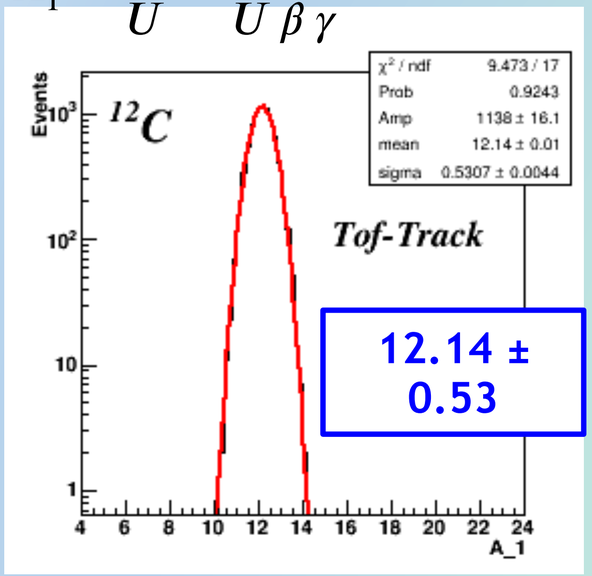
# Number of mass reconstruction: example of $^{12}C$

$^{16}O$ (200 MeV/u)→ $C_2H_4$

**Data simulated by Fluka**

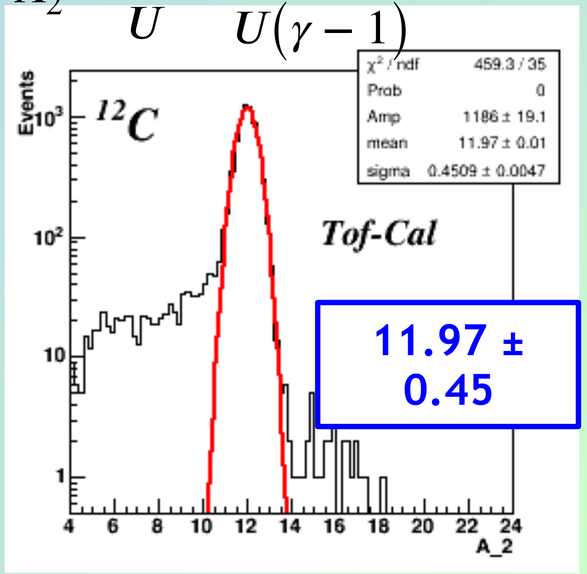
**Tail: nuclear interaction on BGO of calorimeter**

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



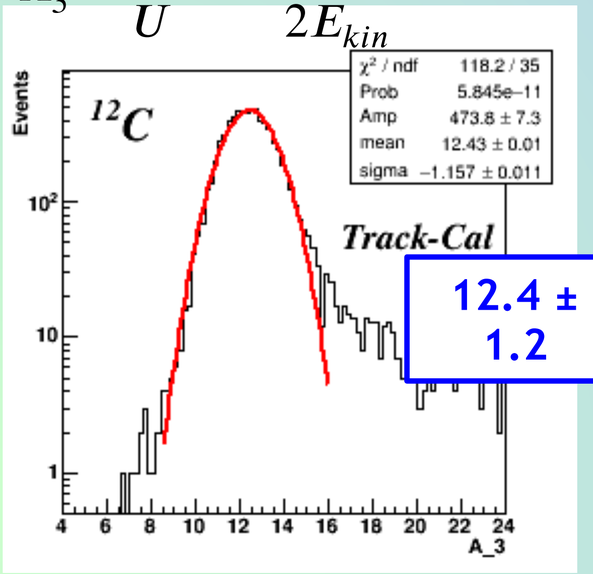

**12.14 ± 0.53**

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



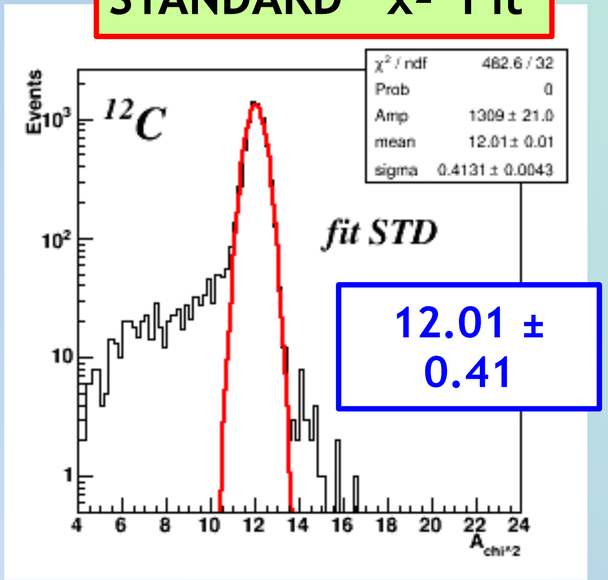

**11.97 ± 0.45**

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



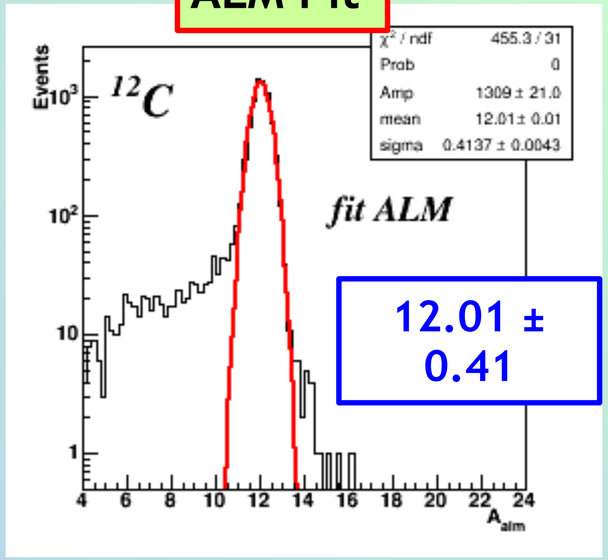

**12.4 ± 1.2**

**STANDARD $x^2$ Fit**



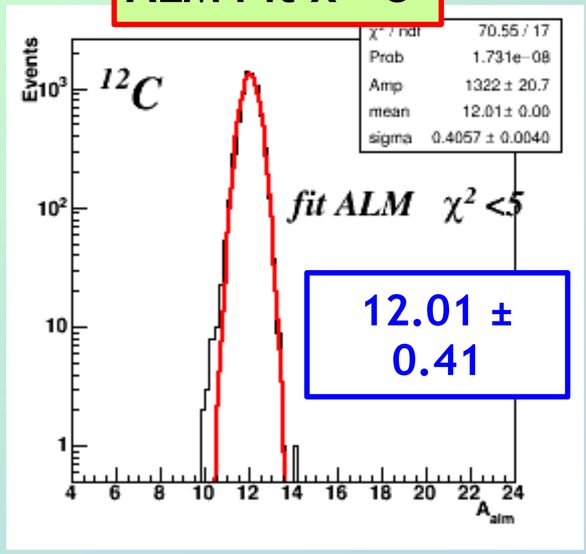

**12.01 ± 0.41**

**ALM Fit**

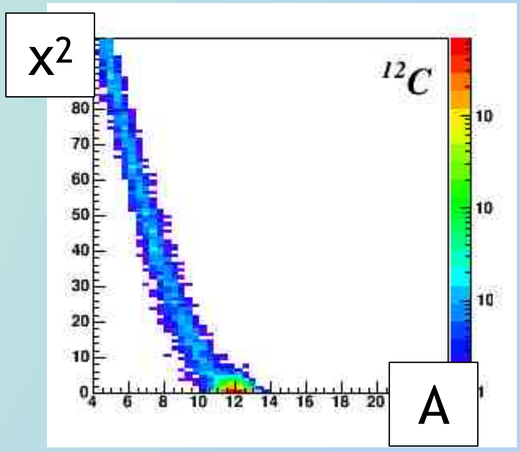



**12.01 ± 0.41**

**ALM Fit $x^2$<5**




**12.01 ± 0.41**




**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 → $\beta\,\gamma$

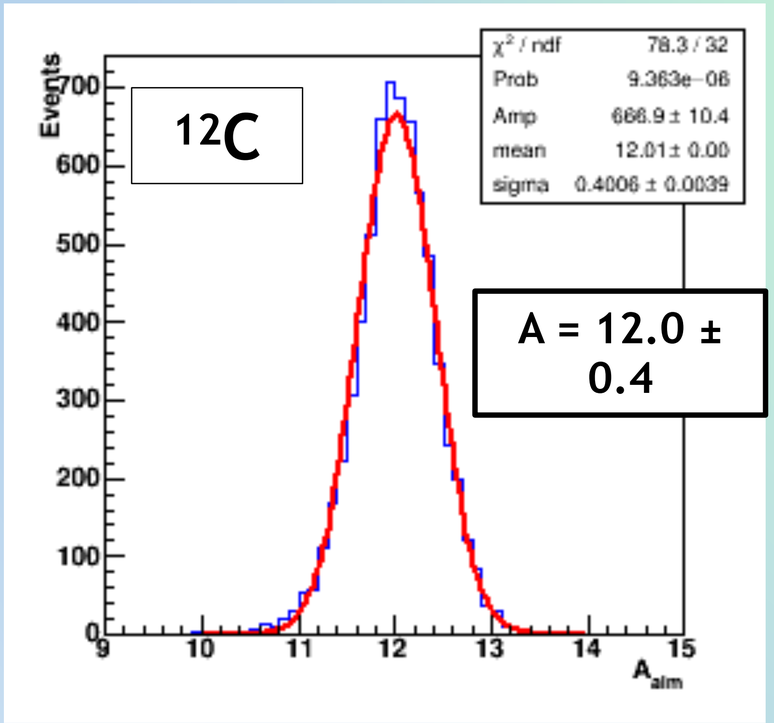
$$A_2 = \frac{m}{U} = \frac{E_{kin}}{U(\gamma - 1)}$$

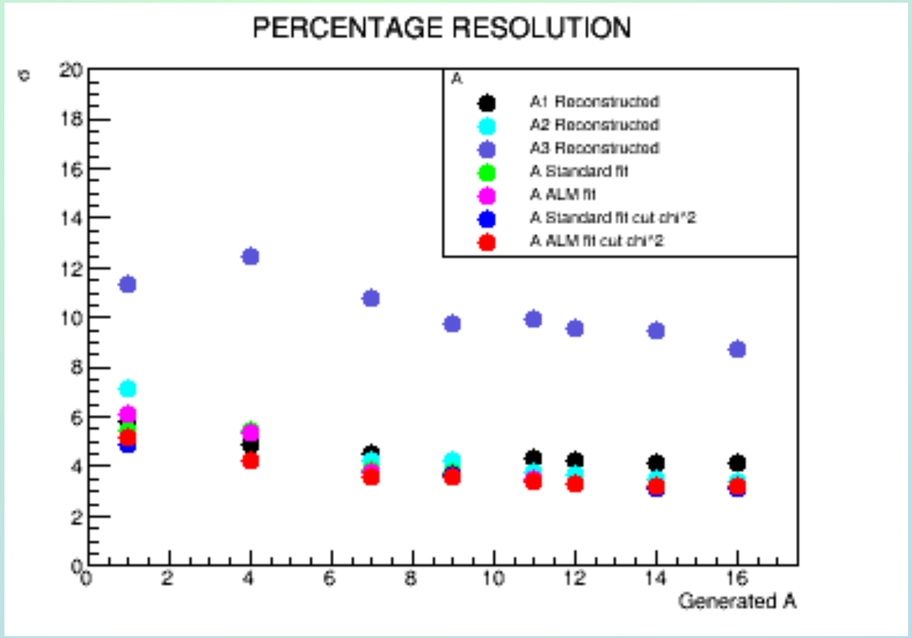
CALO → $E_{kin}$; TOF → $\gamma$

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

TRACKER → $p$; CALO → $E_{kin}$

- Fit Methods: **STANDARD** $x^2$ and **ALM**



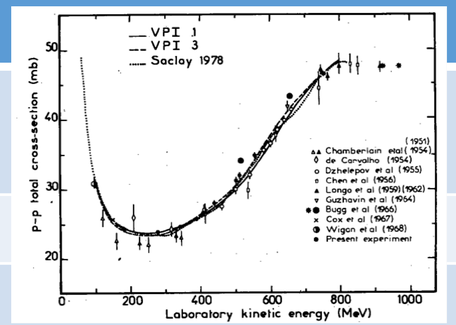

$^{16}O$ (200 MeV/u)→ $C_2H_4$

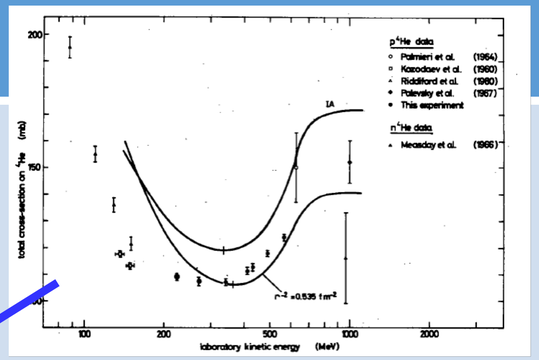
**Data simulated by Fluka**

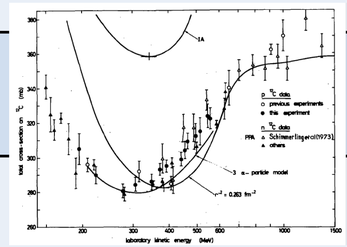
**Resolution for heavy fragments ~ 3-4%**

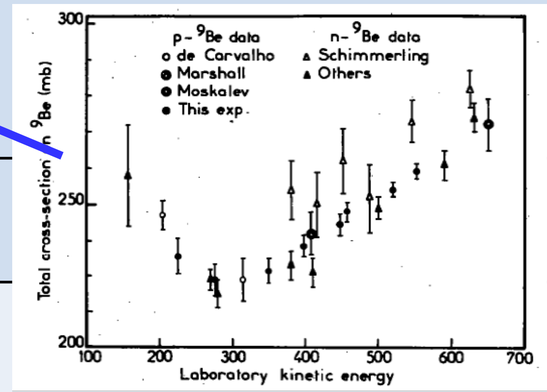
# *brief experimental panorama on proton cross section*

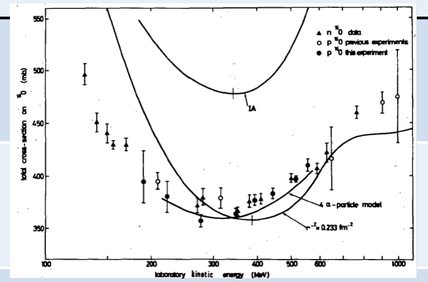
| Reaction | $E_{Kin}$ MeV | $\sigma_{TOT}$ (mb) |
|---|---|---|
| p → p | 10 | |
| | 100 | |
| | 180-500 | |
| | 600-2000 | 45-50 |
| P → $^{4}$He | 150-600 | |
| P → $^{9}$Be | 200-600 | |
| P → $^{12}$C | 50 | |
| | 100-200 | |
| | 200-1000 | 280-350 |
| P → $^{16}$O | 20 | 550 |

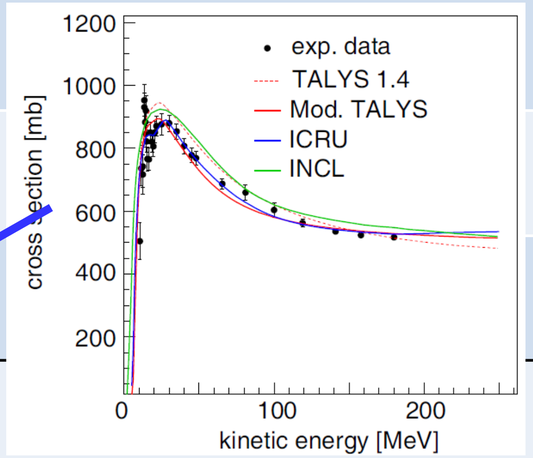


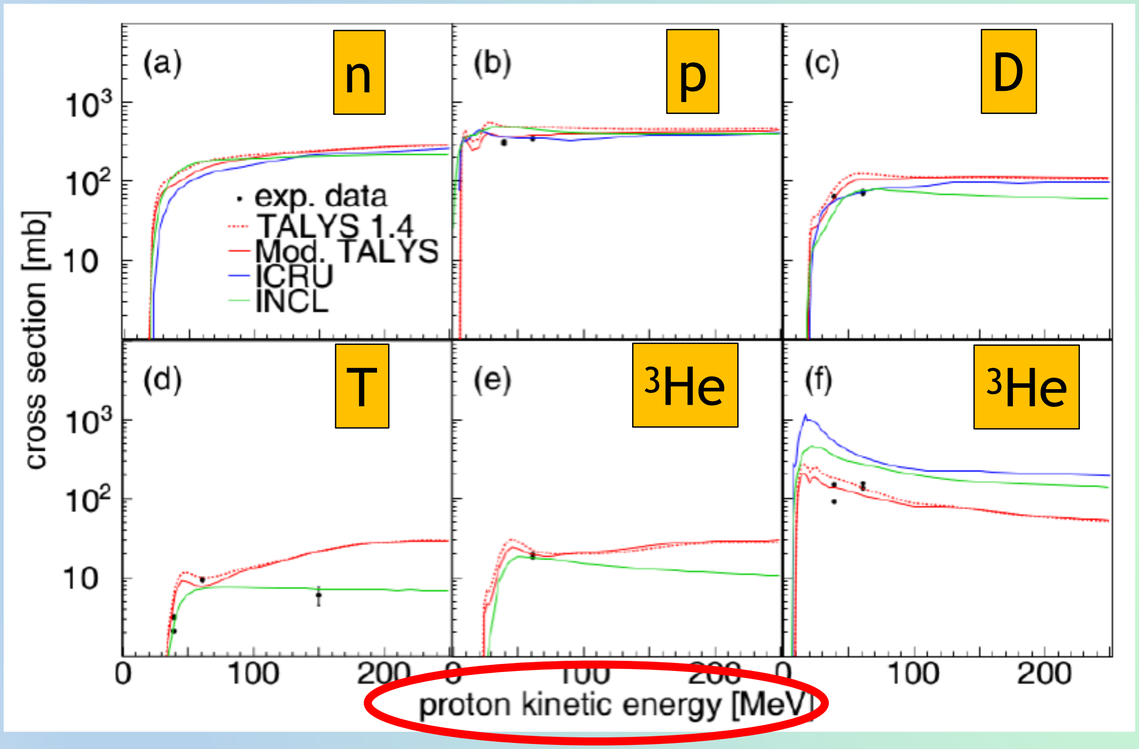



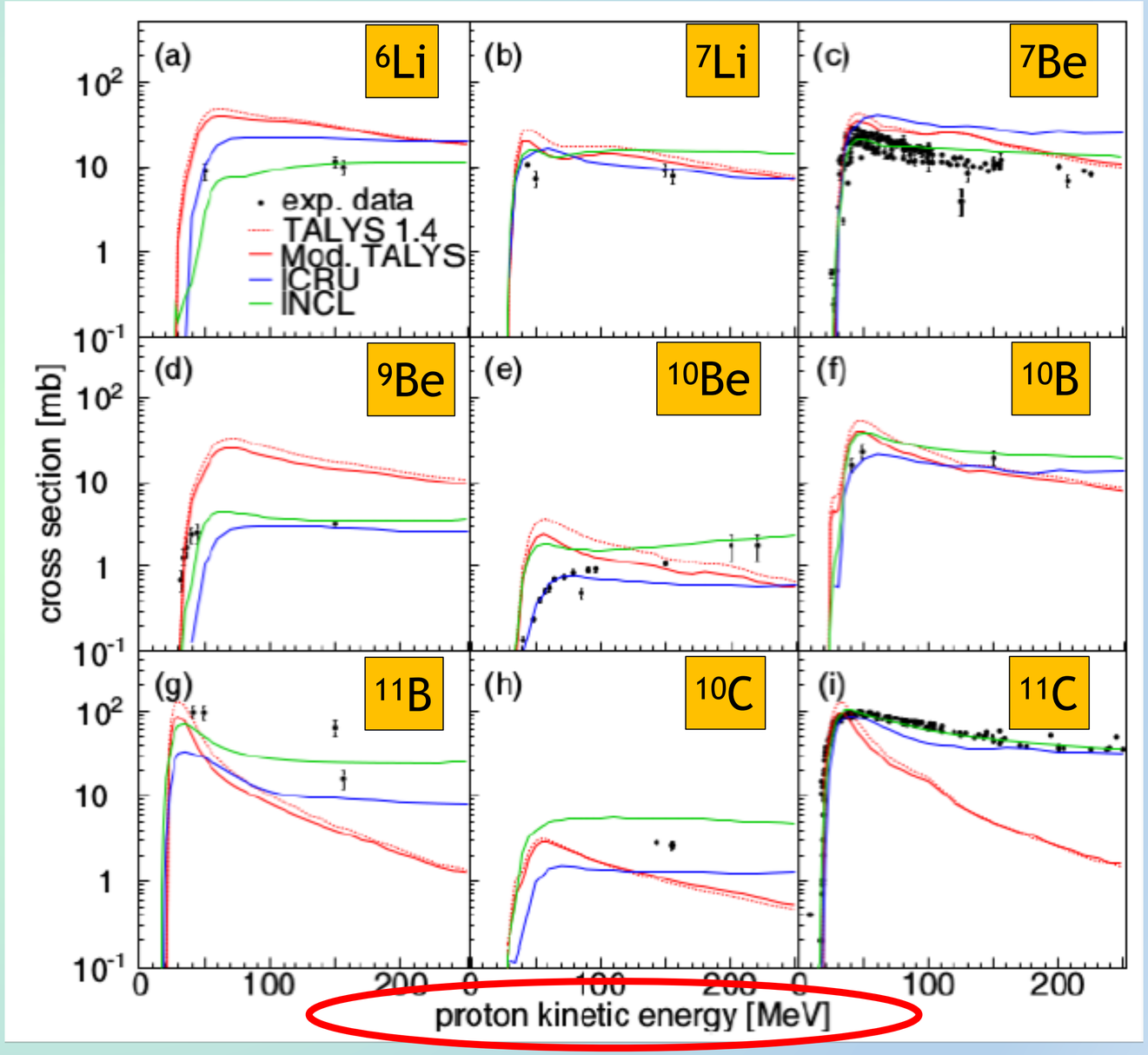



# brief experimental panorama on p → $^{12}C$ differential cross secti



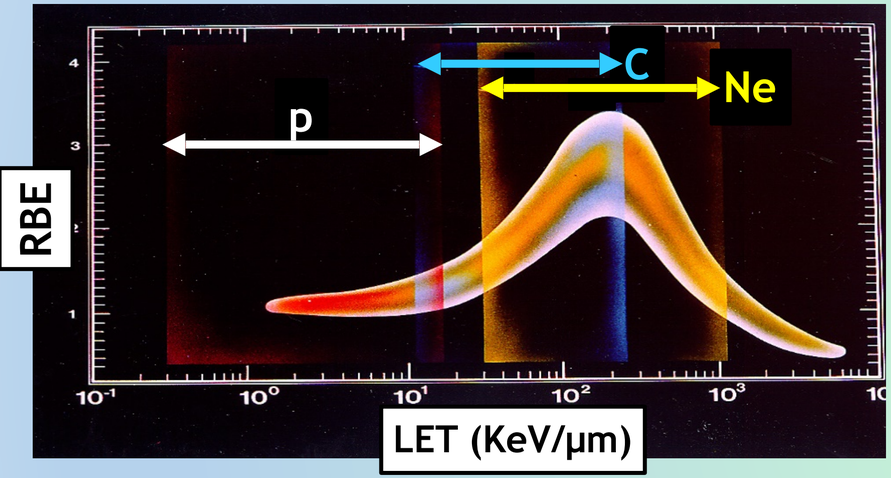



# Relative Biological Effectiveness (RBE

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

quantify the strength of different radiation types

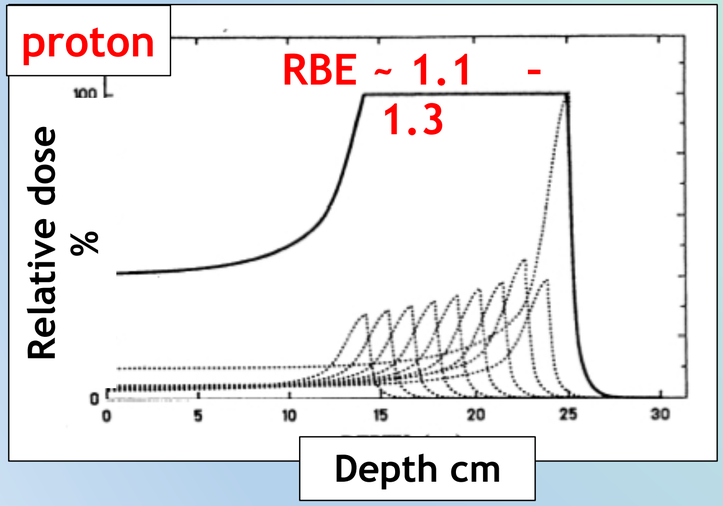
High RBE → high effect wrt radiation



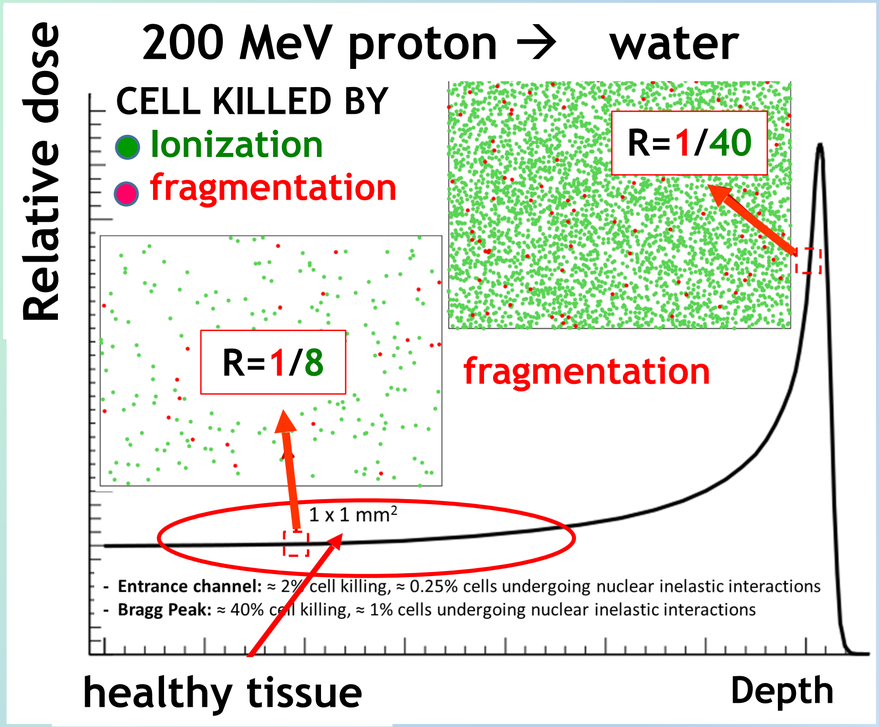

RBE depends on

- 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

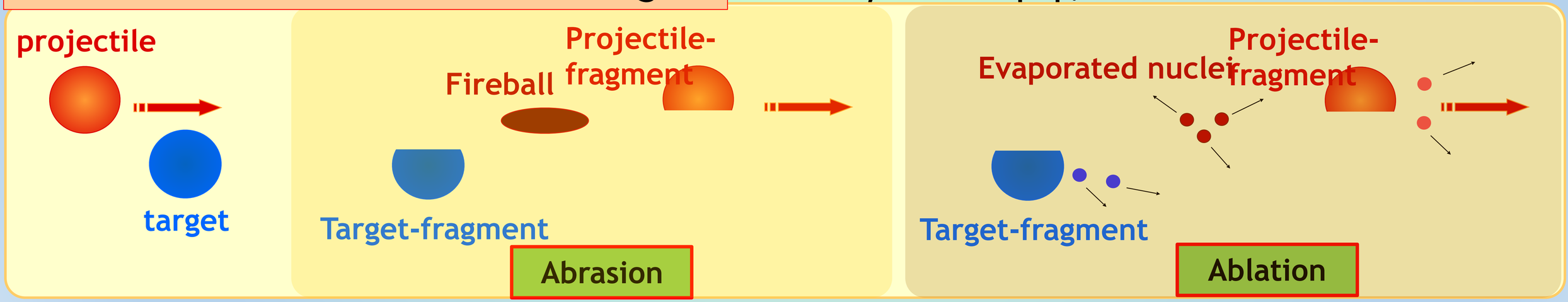
Protons ≠ photons * 1.1 due to Nuclear interaction

**No Standard Treatment Planning for hadrontherapy**

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

Abrasion-Ablasion model → 2 stages

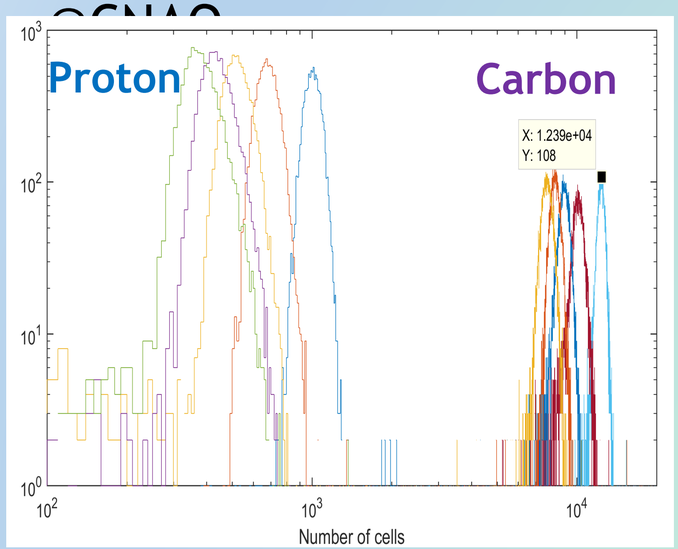
Study of the Target-Projectile



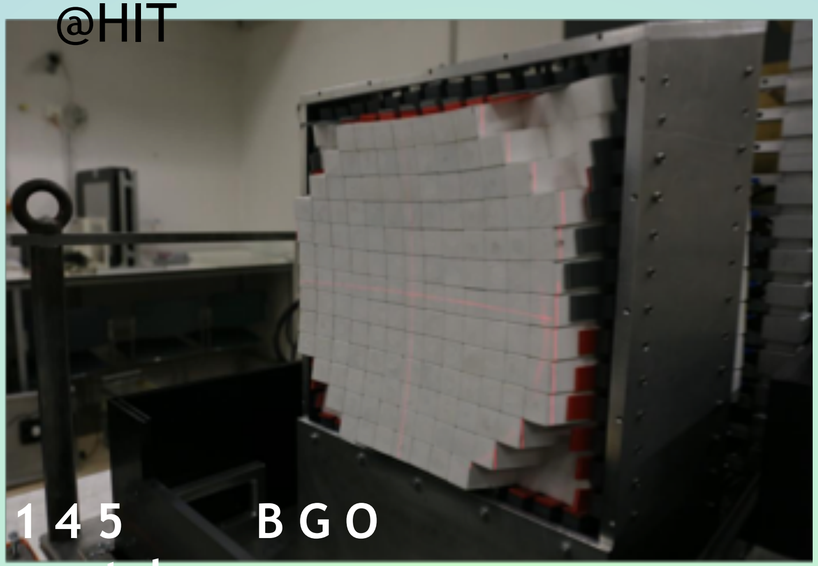

No quarks

# Test beam results

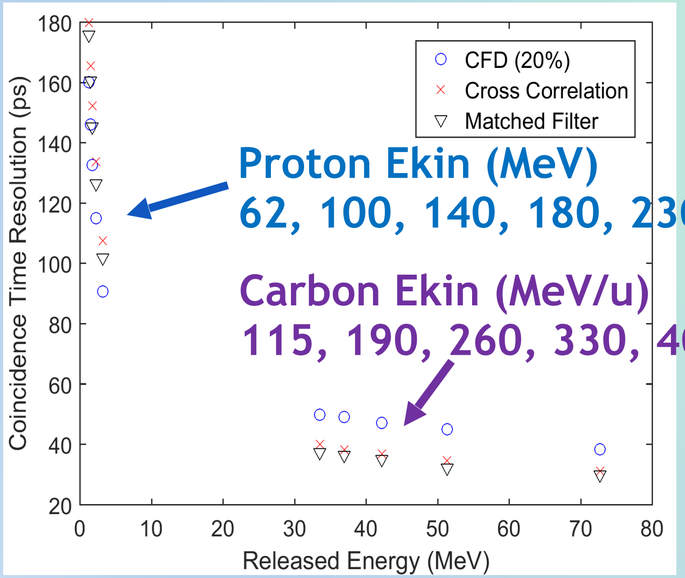
**ΔE-Tof** test beam @GNAO

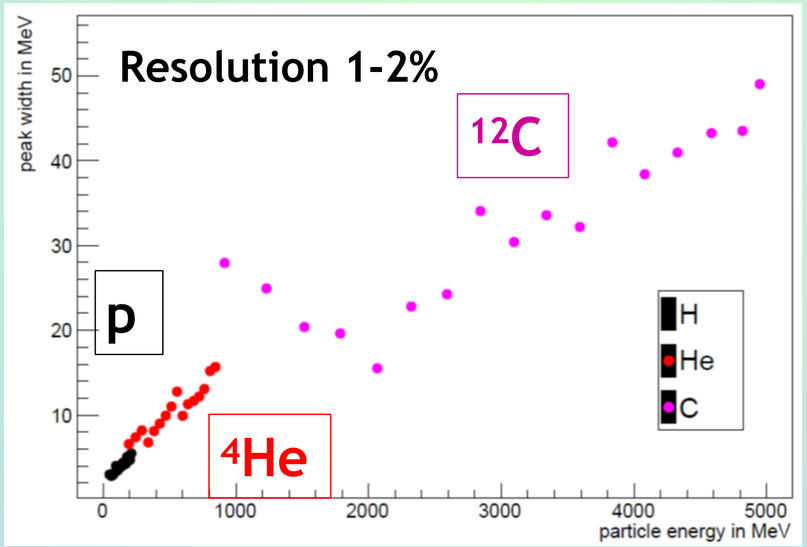


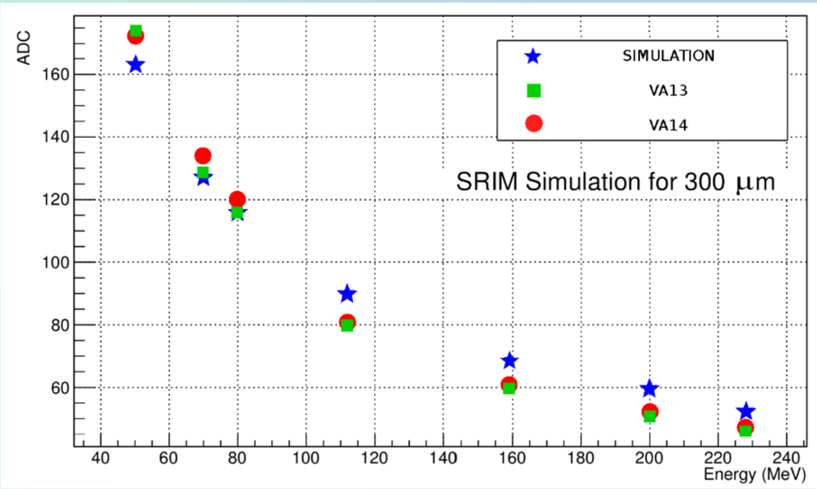

**Calorimeter**: test beam @HIT




**MSD**: test @ Trento (proton)



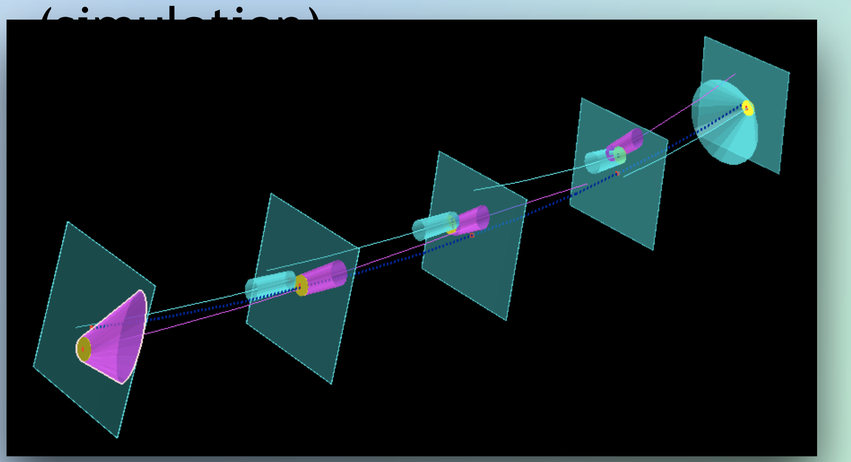

Tof resolution (C) better 40 ps

Kinetic energy resolution at 1-2%

Agreement simulation data in few %

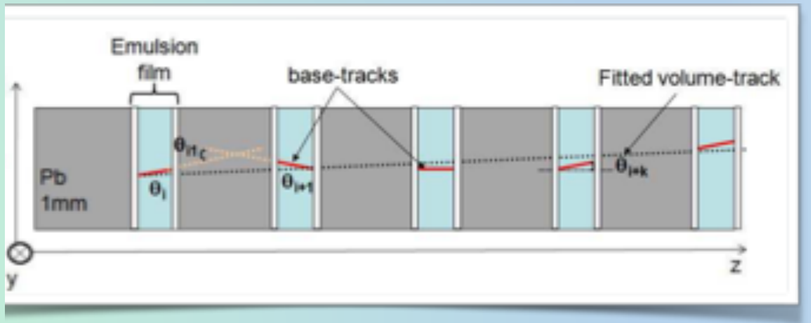
# *Test beam and simulation results*

**Tracking** Kalman Filter (simulation)

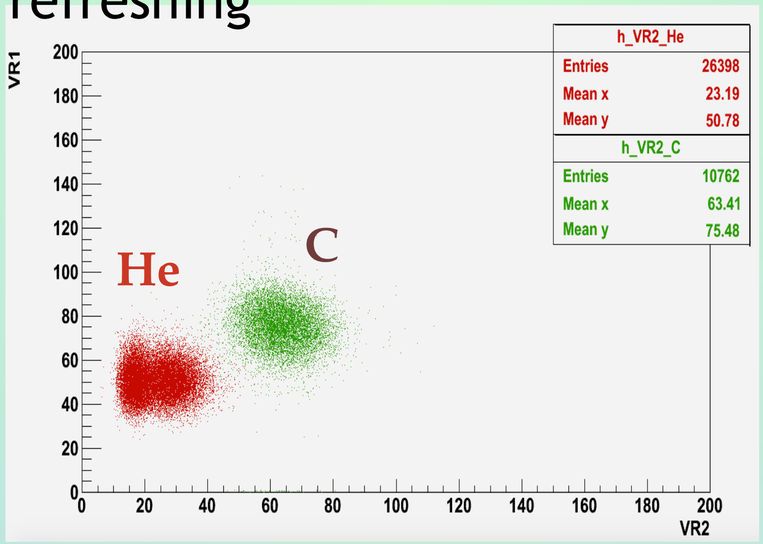


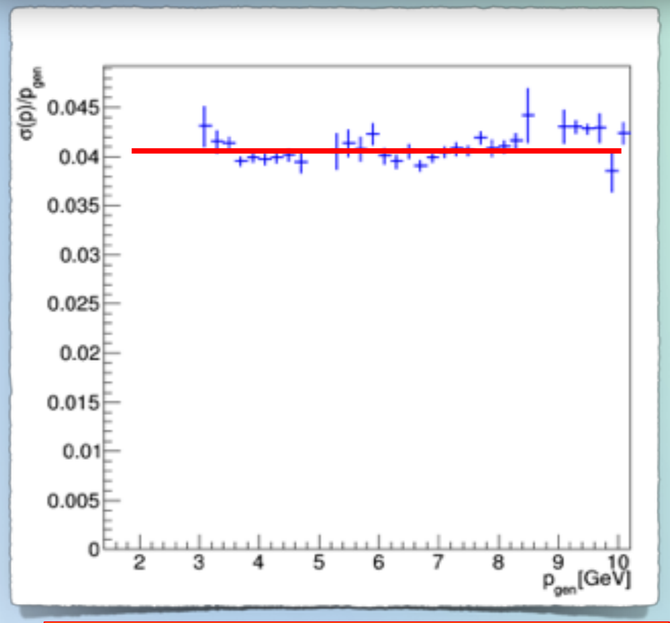
**Emulsion chamber** test beam @LNS (p, D, He, C) and Trento (p at 50, 80, 200 MeV)

p•β by Multiple Coulomb Scatt




Fragments charge determined by volume of points after refreshing

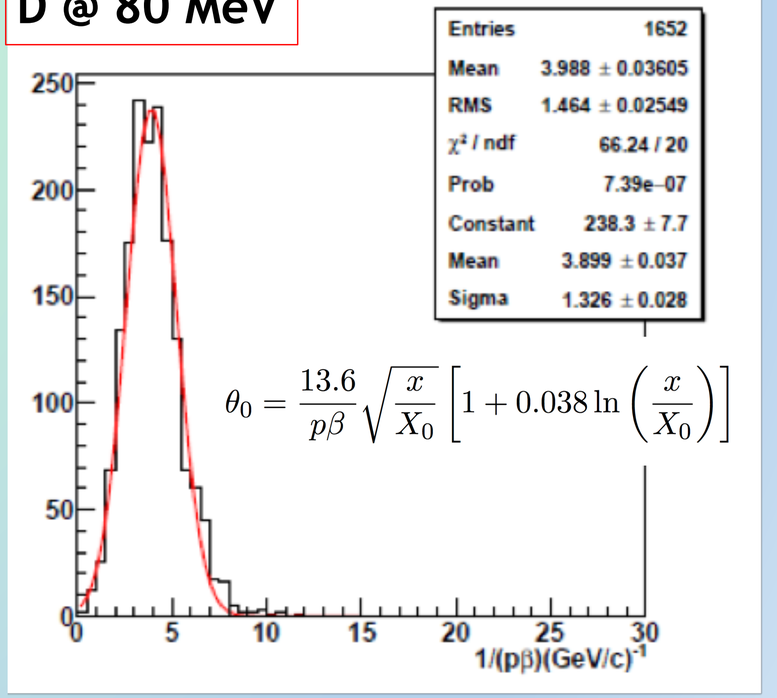



p resolution at level of

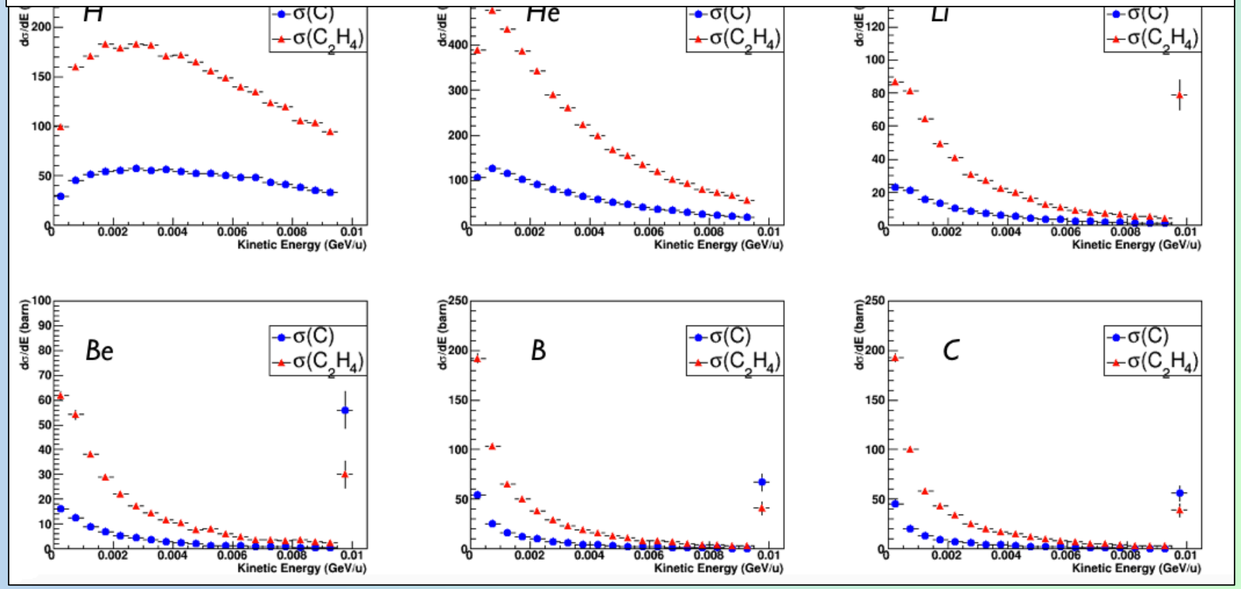
ECC: charge separation

**D @ 80 MeV**

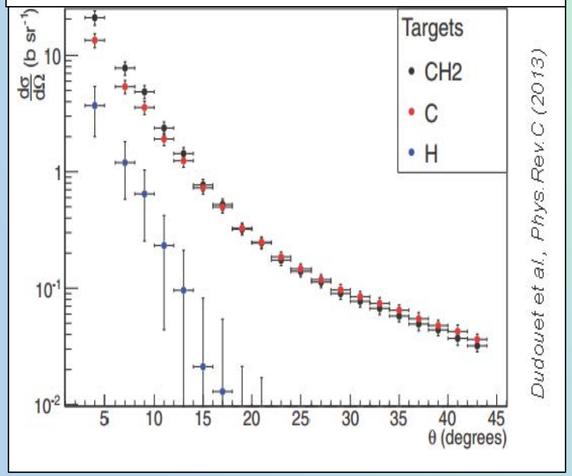


# Target Fragmentation cross sections

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

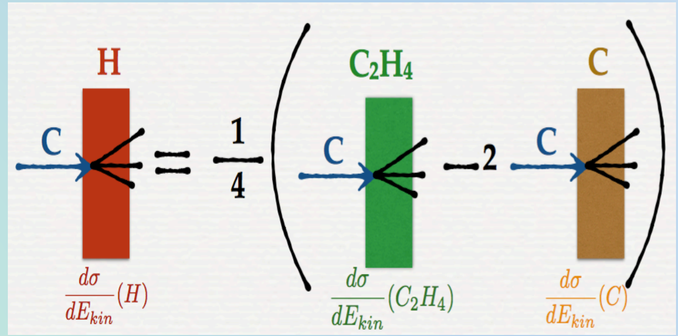



## Ganil experimental data



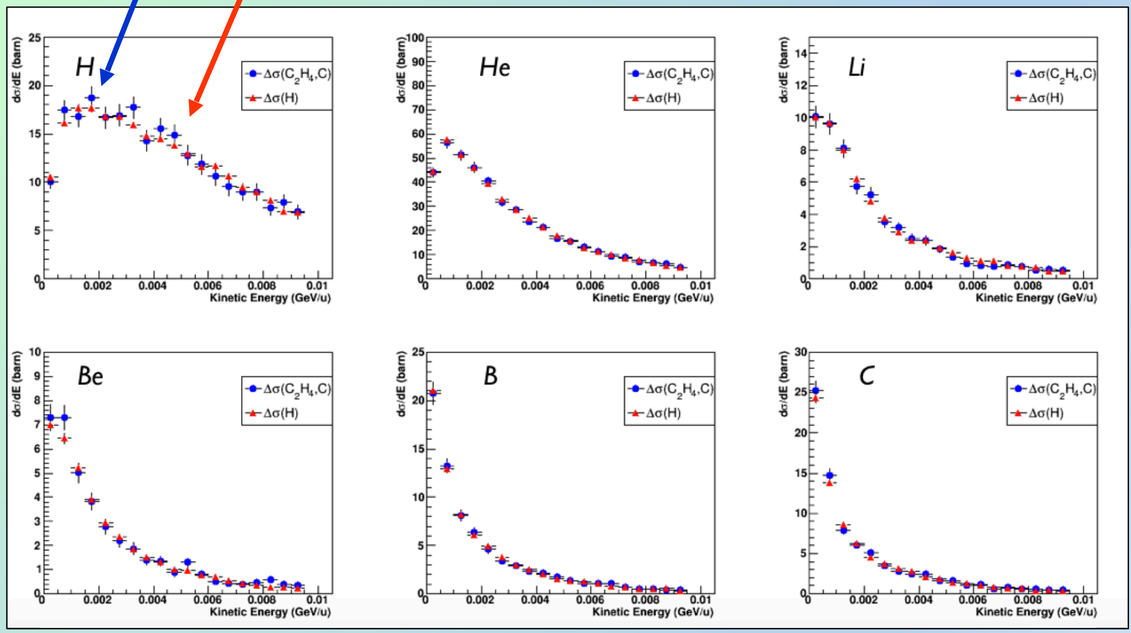

## Fluka Simulation

$^{12}C$ (200 MeV/u)→ $C_2H_4$ & H




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

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

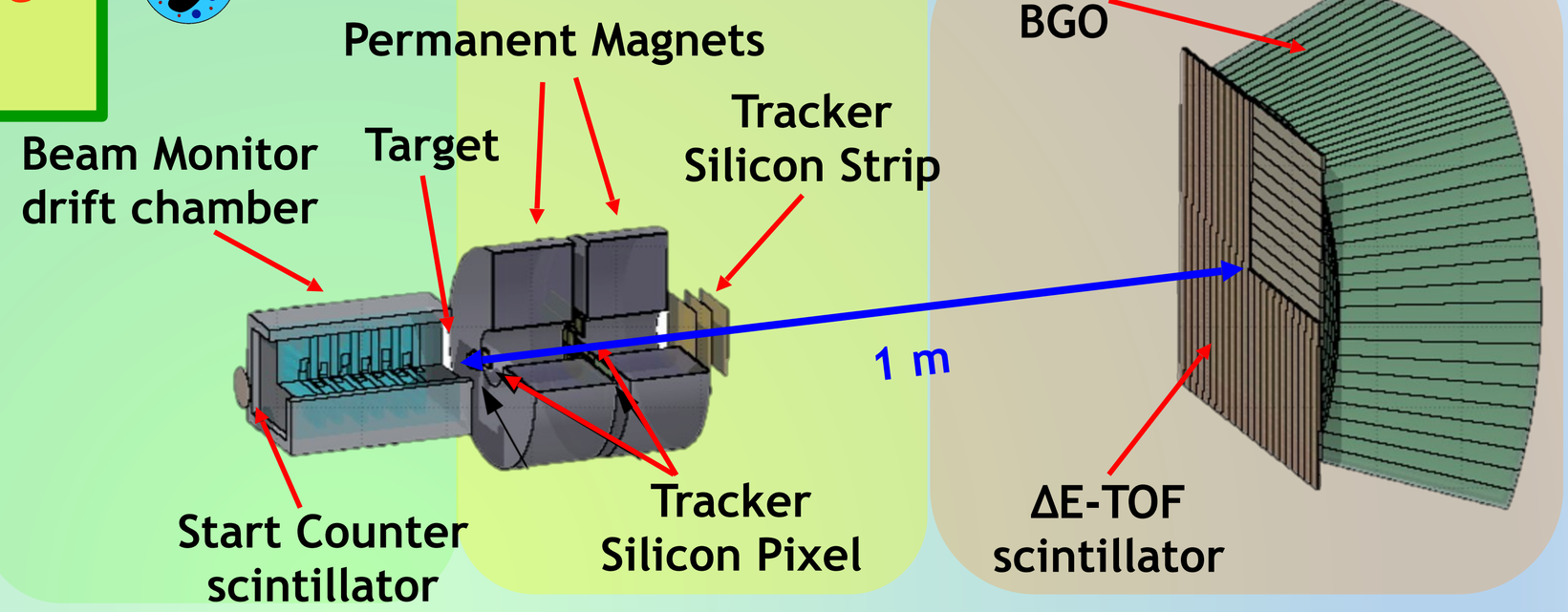



Agreement between the two methods

# 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°

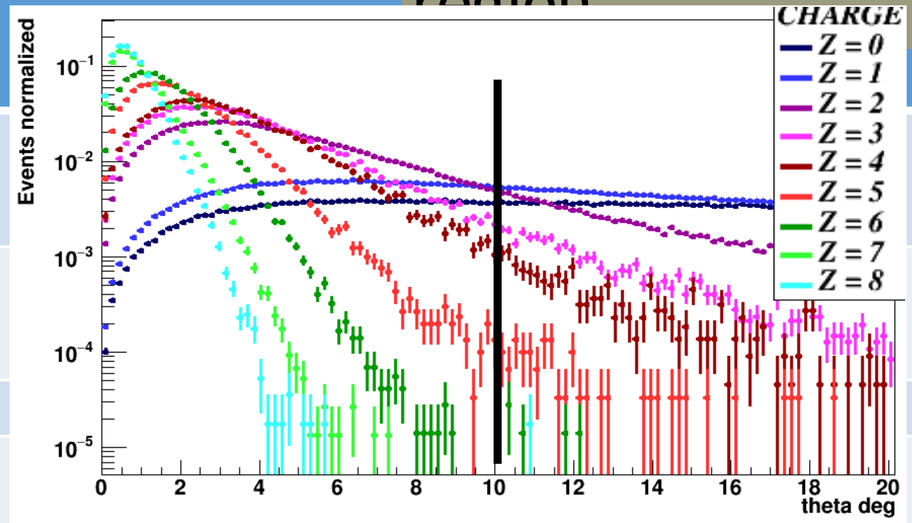



Pre-target region

Tracking region

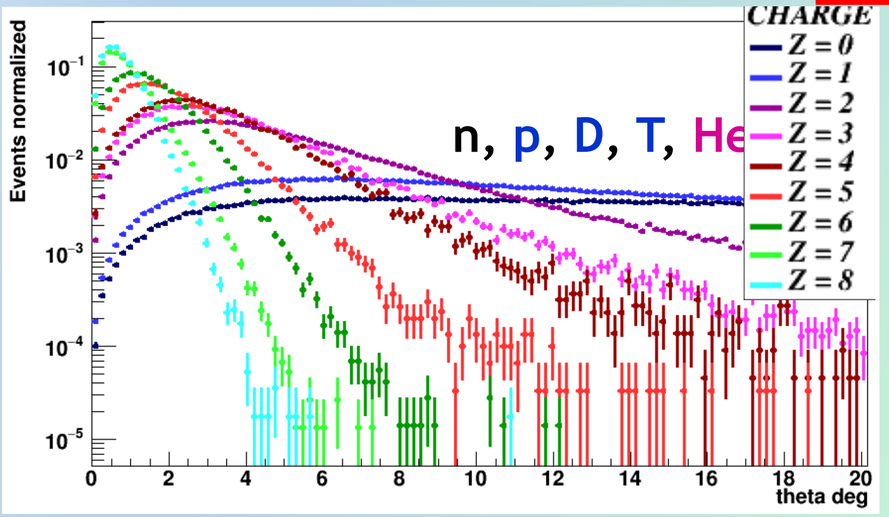
Identification region

| 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) |

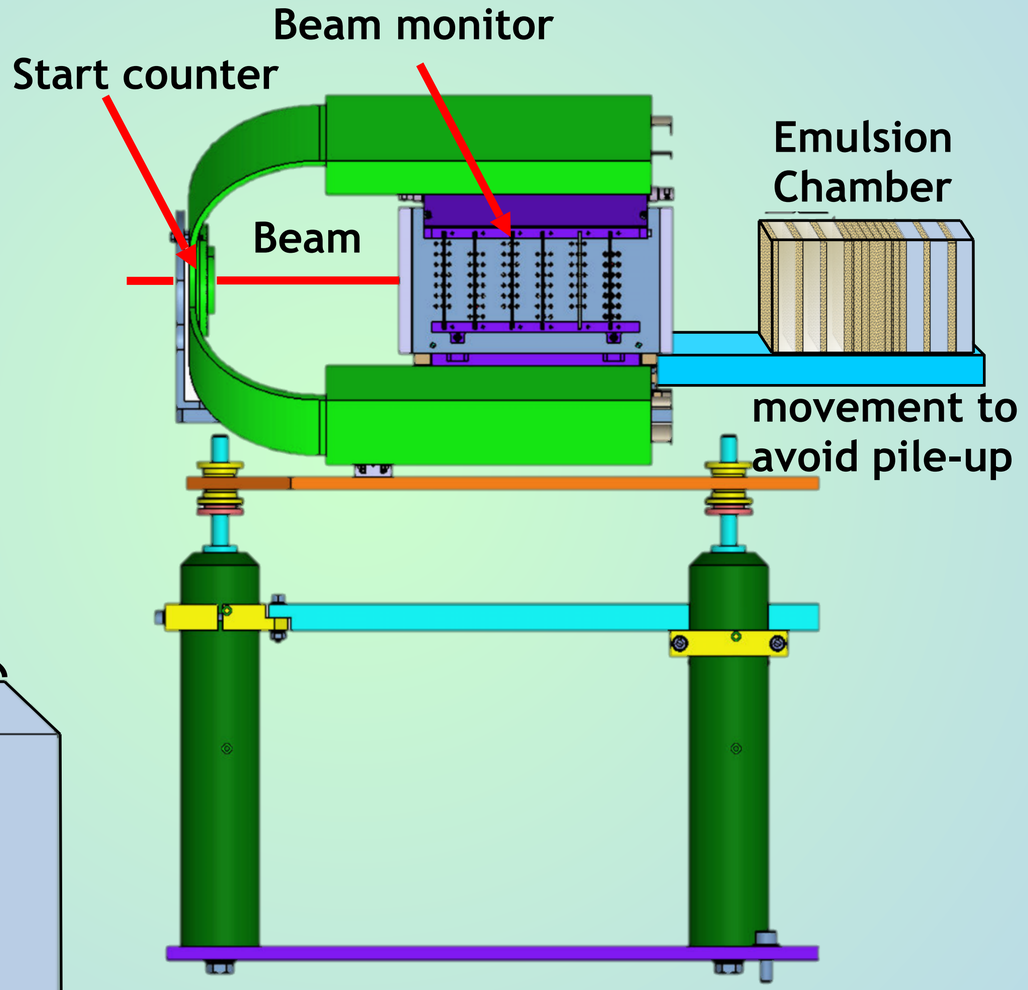


# FOOT: Emulsion chamber setup

C on C @ 200 MeV/nucl




Light fragments (Z<3) produced at wide angle (~75°)



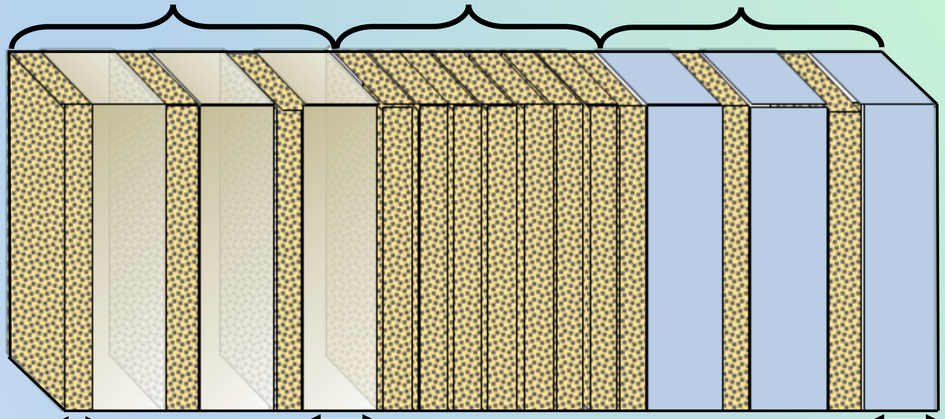

High speed automated scanning

10 cm

Section 1 vertexing

Section 2 Charge Identification

Section 3 momentum

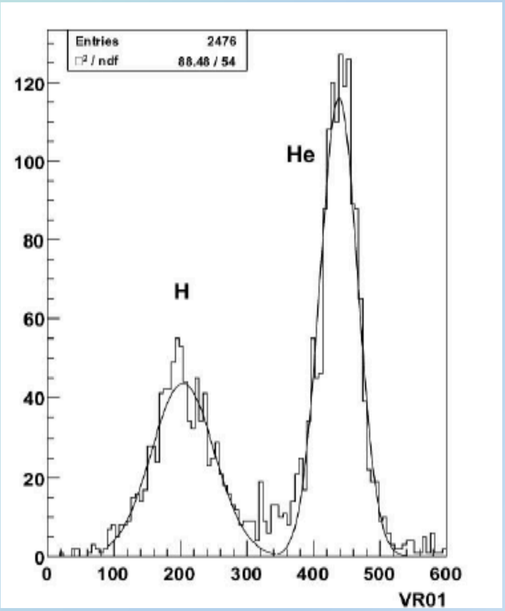


300 μm Emulsion layer

1 mm C or $C_2H_4$

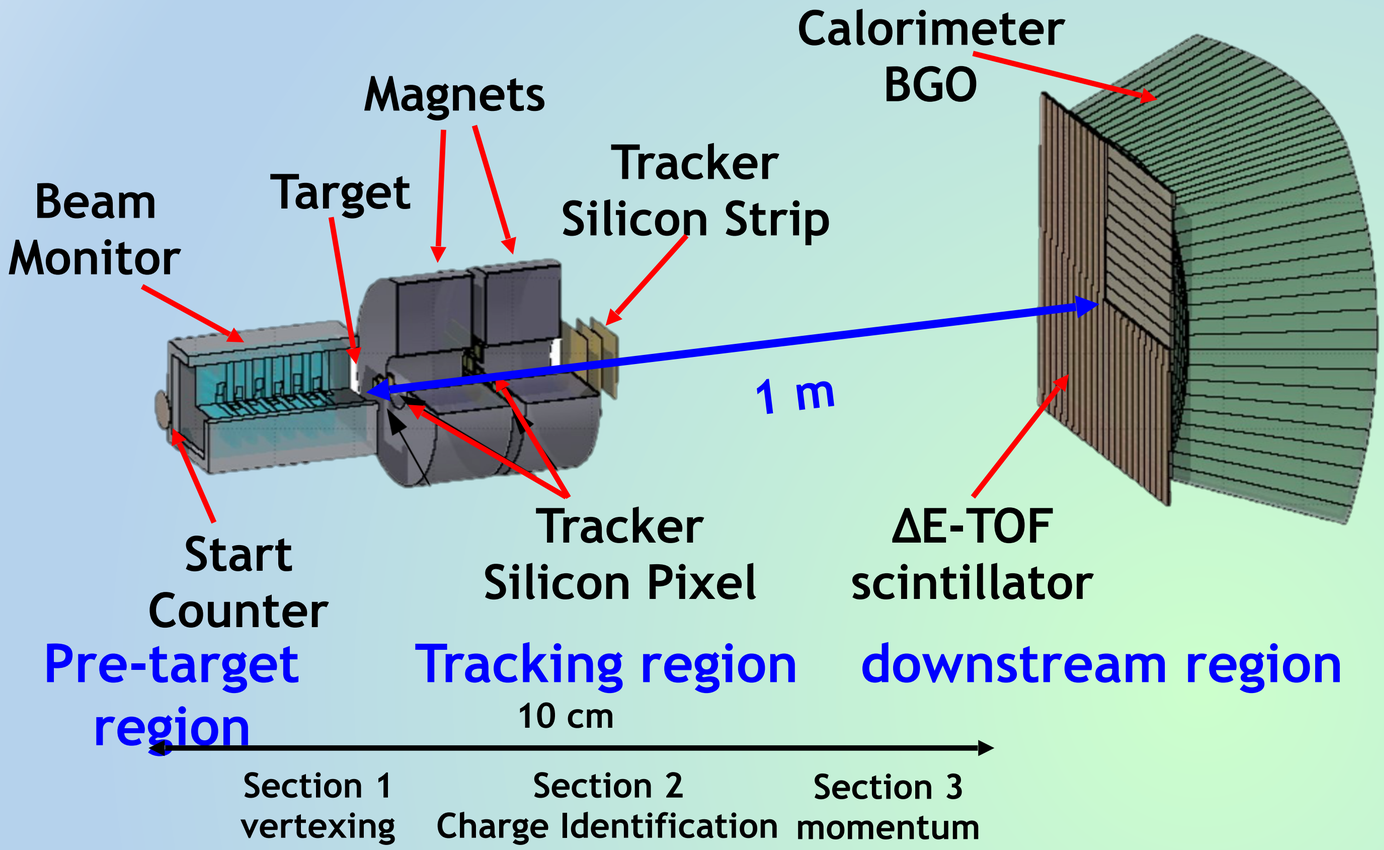
Emulsion layer

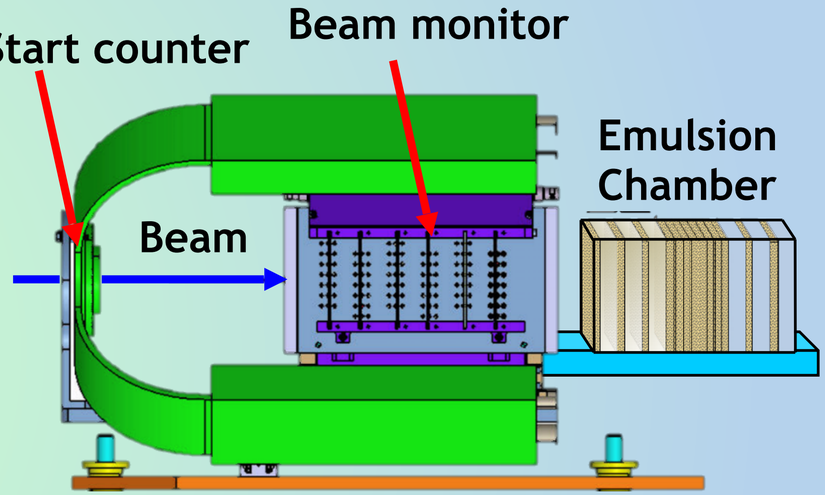
1 mm Pb layer

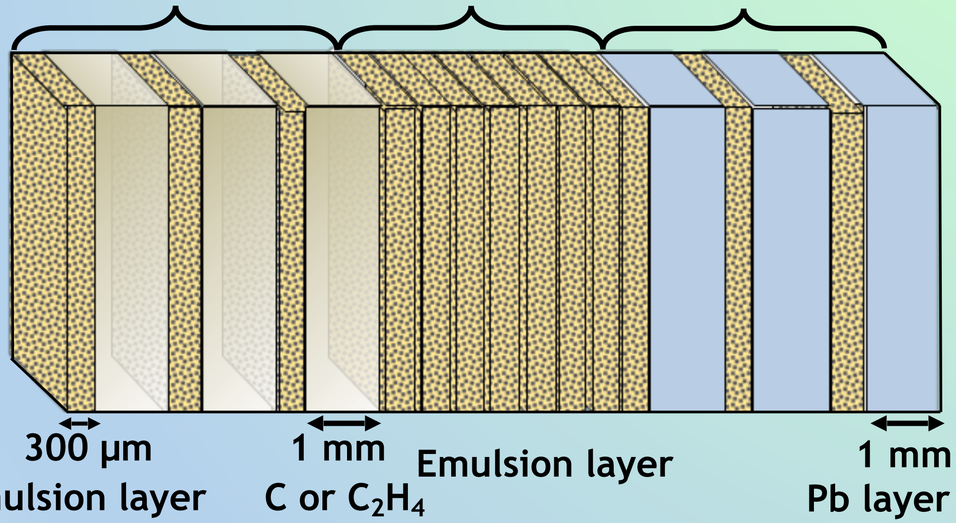


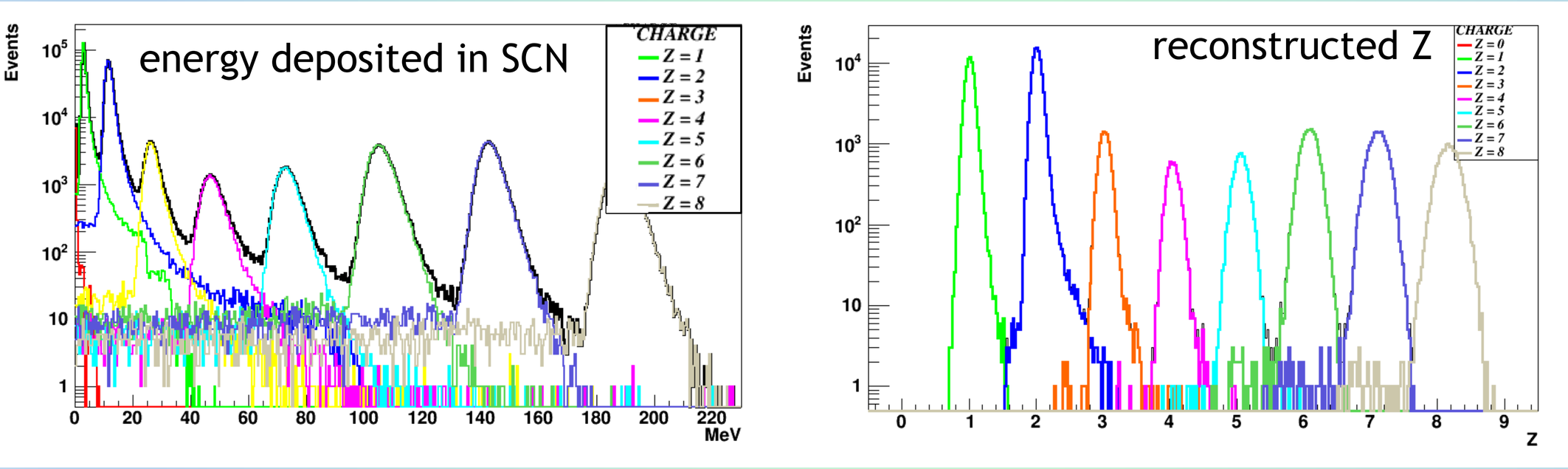


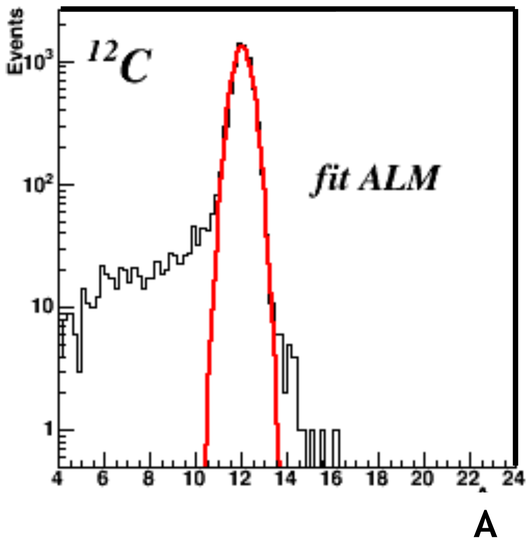

G. De Lellis et al. JINST 2, 2007,

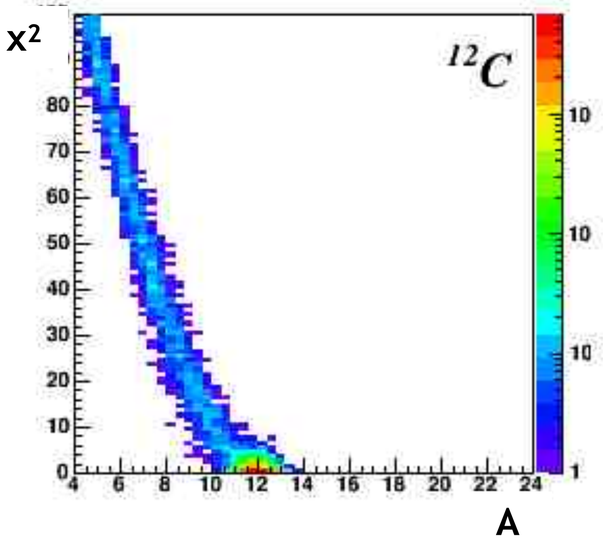

Calorimeter
BGO
Magnets
Tracker
Silicon Strip
Target
Beam
Monitor
1 m
Start
Counter
Tracker
Silicon Pixel
ΔE-TOF
scintillator
Pre-target
region
Tracking region
downstream region
10 cm
Section 1
vertexing
Section 2
Charge Identification
Section 3
momentum

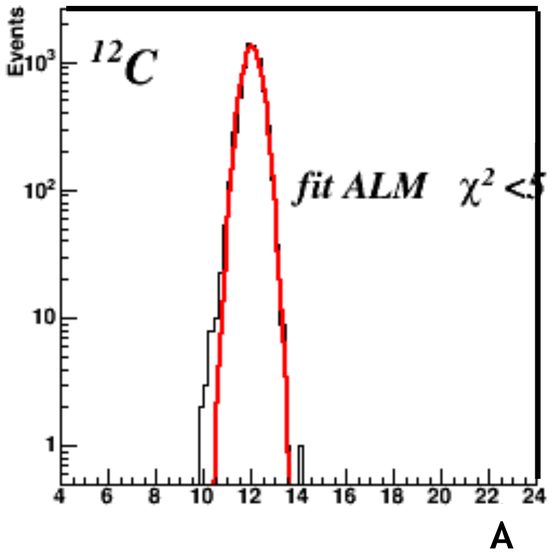

Start counter
Beam monitor
Emulsion
Chamber
Beam

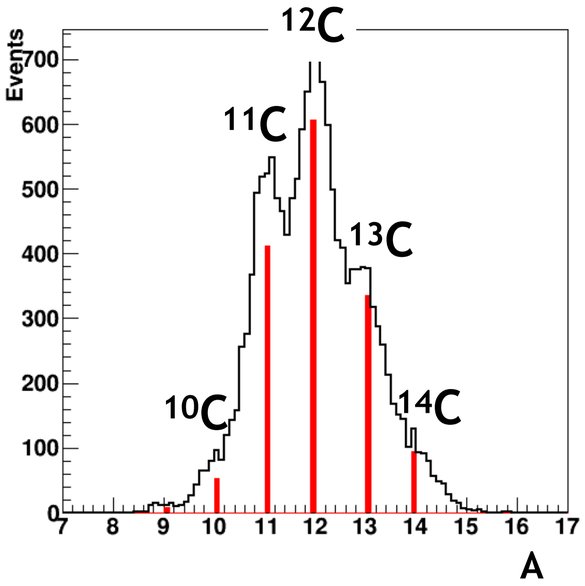

300 μm
Emulsion layer
1 mm
C or $C_2H_4$
Emulsion layer
1 mm
Pb layer

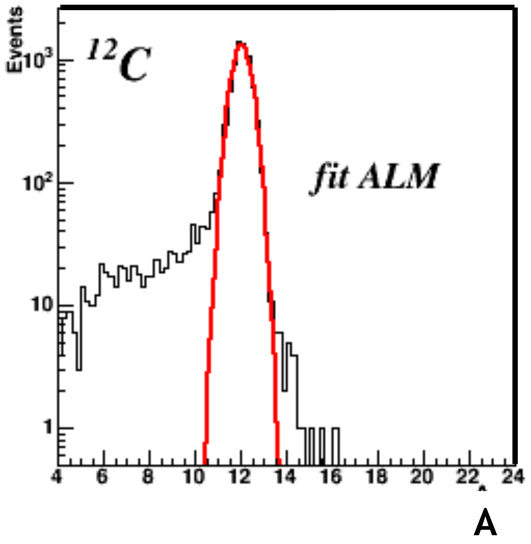

energy deposited in SCN
Events
MeV
CHARGE
Z = 1
Z = 2
Z = 3
Z = 4
Z = 5
Z = 6
Z = 7
Z = 8
reconstructed Z
Events
Z
CHARGE
Z = 0
Z = 1
Z = 2
Z = 3
Z = 4
Z = 5
Z = 6
Z = 7
Z = 8

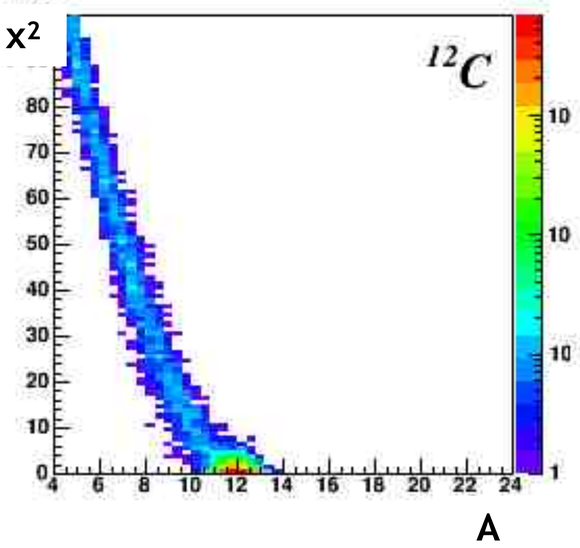

Events
$^{12}C$
fit ALM
A

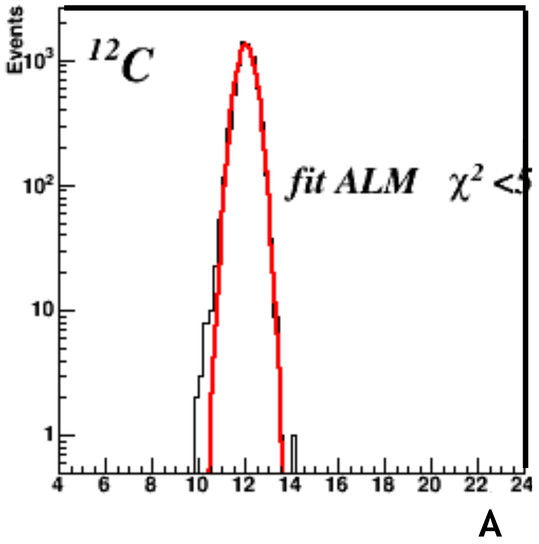

$x^2$
$^{12}C$
A

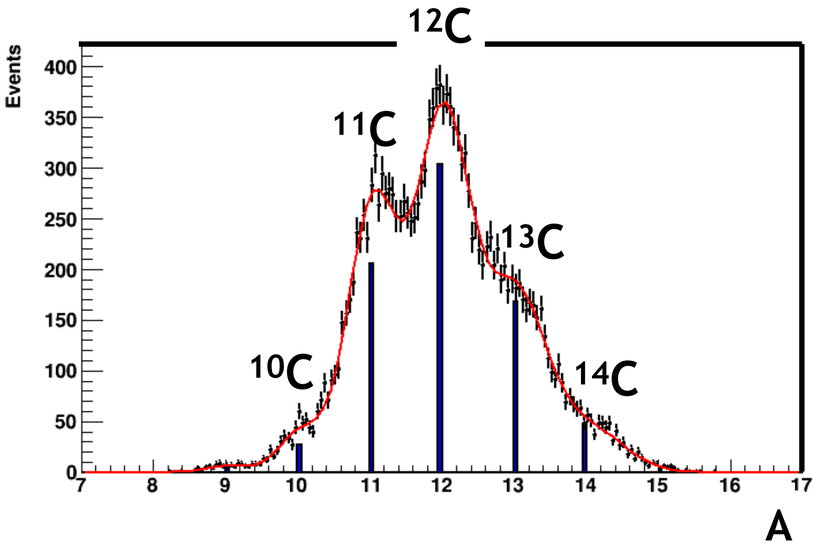

Events
$^{12}C$
fit ALM $\chi^2$ <5
A

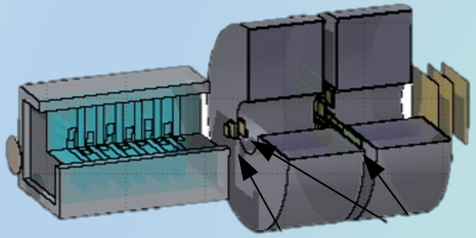

$^{12}C$
$^{11}C$
$^{13}C$
$^{10}C$
$^{14}C$
Events
A

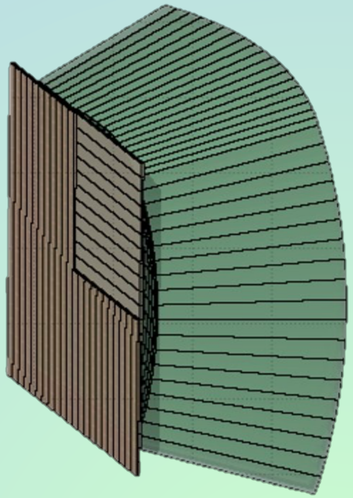

Events
$^{12}C$
fit ALM
A

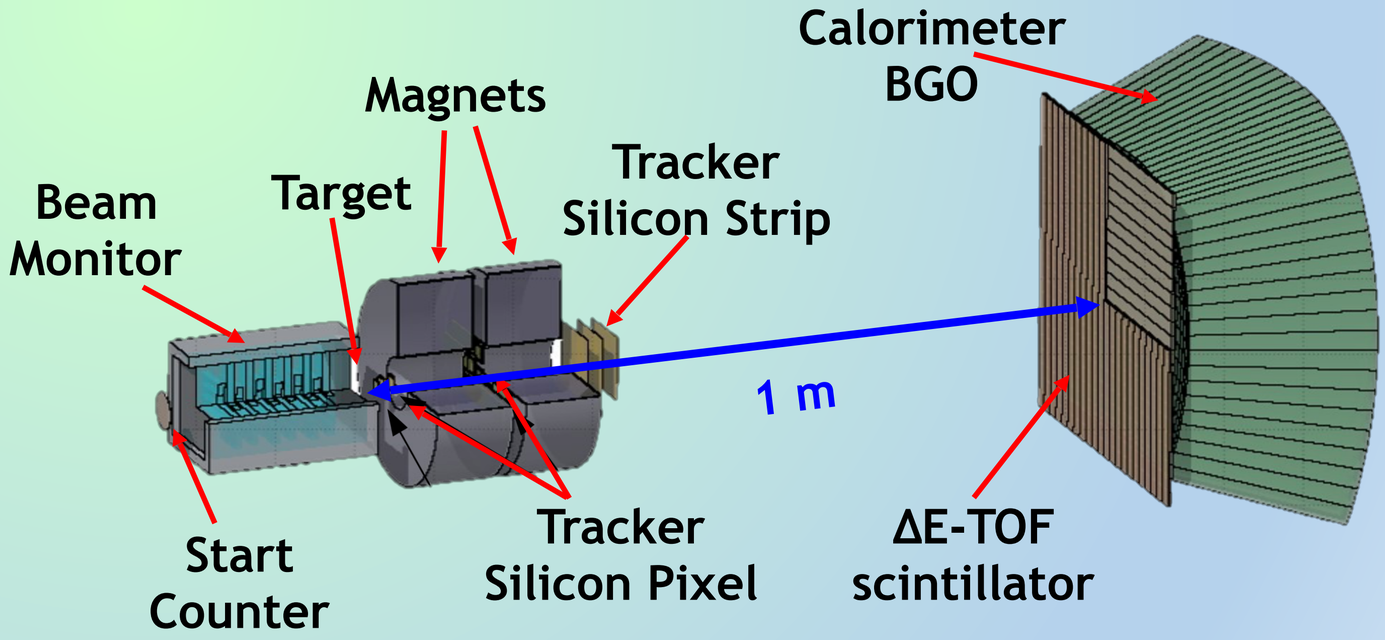

$x^2$
$^{12}C$
A


Events
$^{12}C$
fit ALM $\chi^2$ <5
A


$^{12}C$
$^{11}C$
$^{13}C$
$^{10}C$
$^{14}C$
Events
A



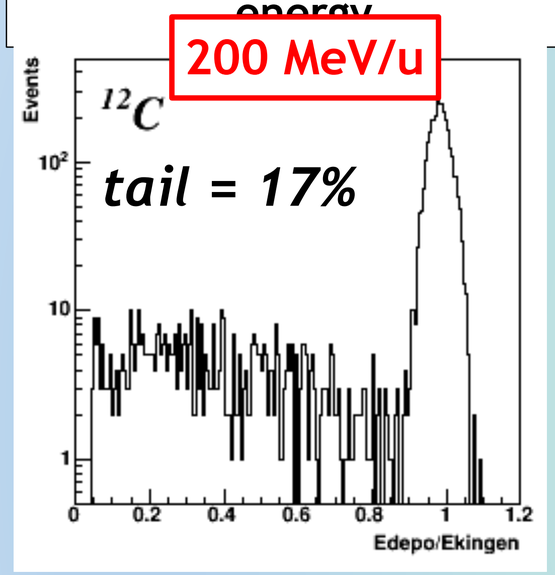



Calorimeter
BGO
Magnets
Tracker
Silicon Strip
Target
Beam
Monitor
1 m
Start
Counter
Tracker
Silicon Pixel
ΔE-TOF
scintillator
Pre-target
region
Tracking region
downstream region

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

Fragments with larger energy → higher probability to fragment in CALO

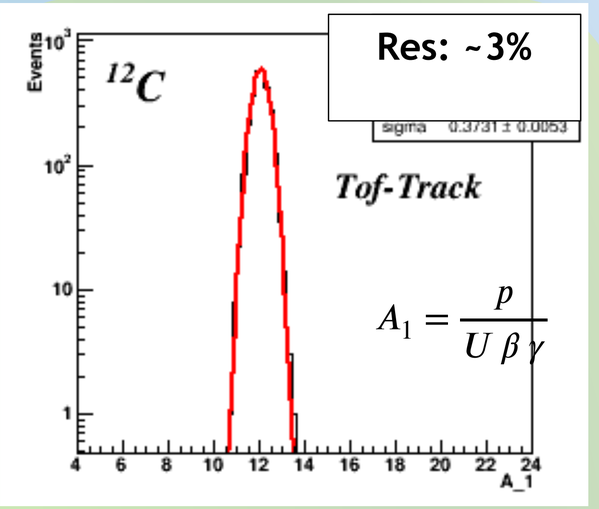
Fraction of deposited energy

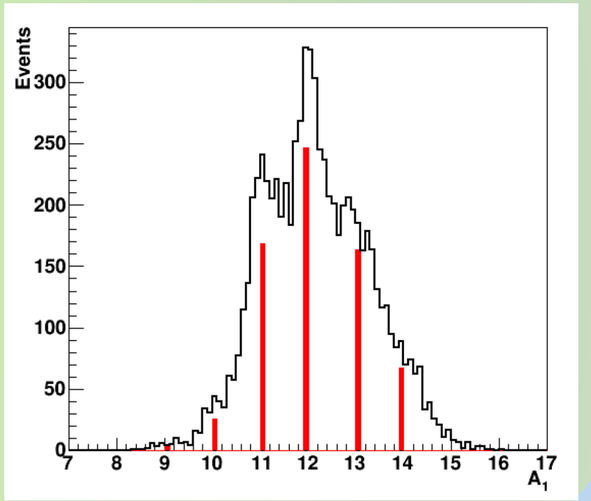



Larger neutrons production

missed energy in CAL

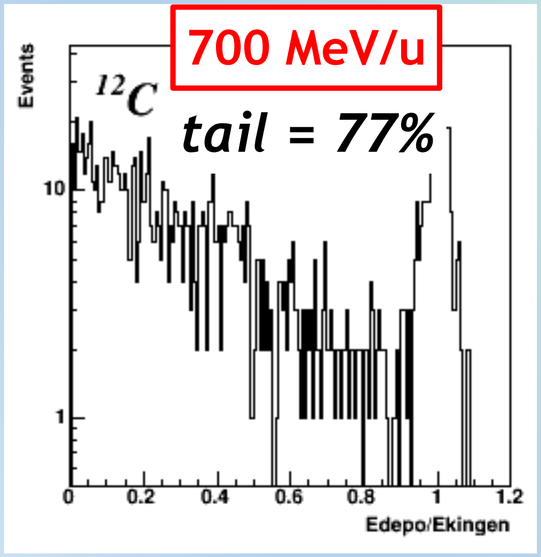
A with Tof & Tracker

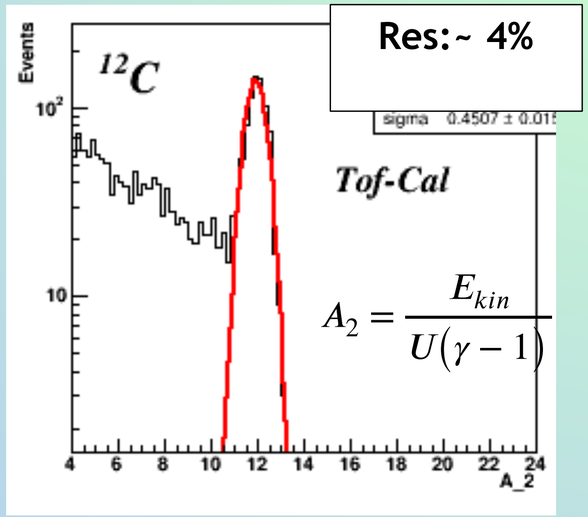



FOOT redundancy

~ performance @ 700 MeV/u




20% of well reconstructed