Equalizing the response of the **FOOT** Calorimeter as a function of the ion energy and charge

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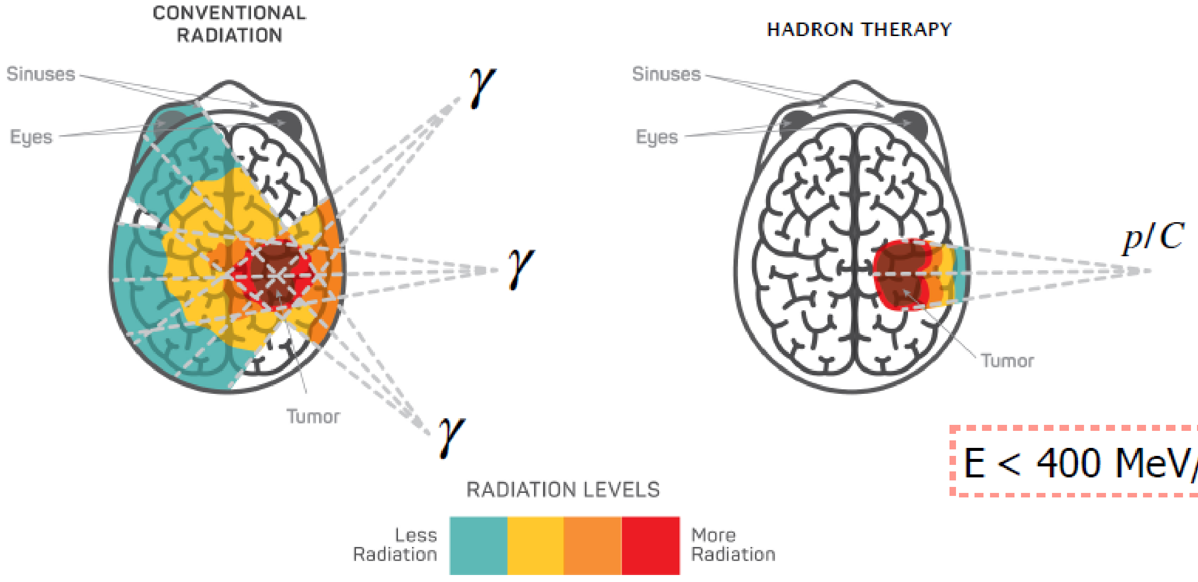
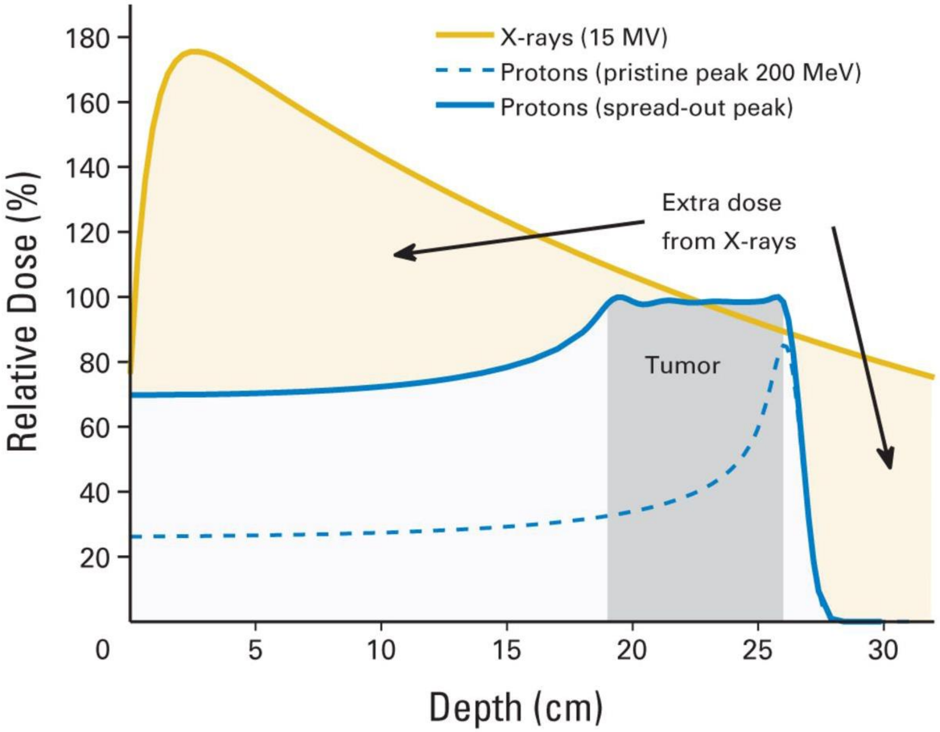
on behalf of the FOOT collaboration

Particle Therapy

- ✓ Particle therapy is performed with p or C ions
- ✓ The Bragg peak is very effective in minimizing the dose delivered to healthy tissues



E < 400 MeV/A



Secondary fragments are created in the interaction between treatment beams and tissues

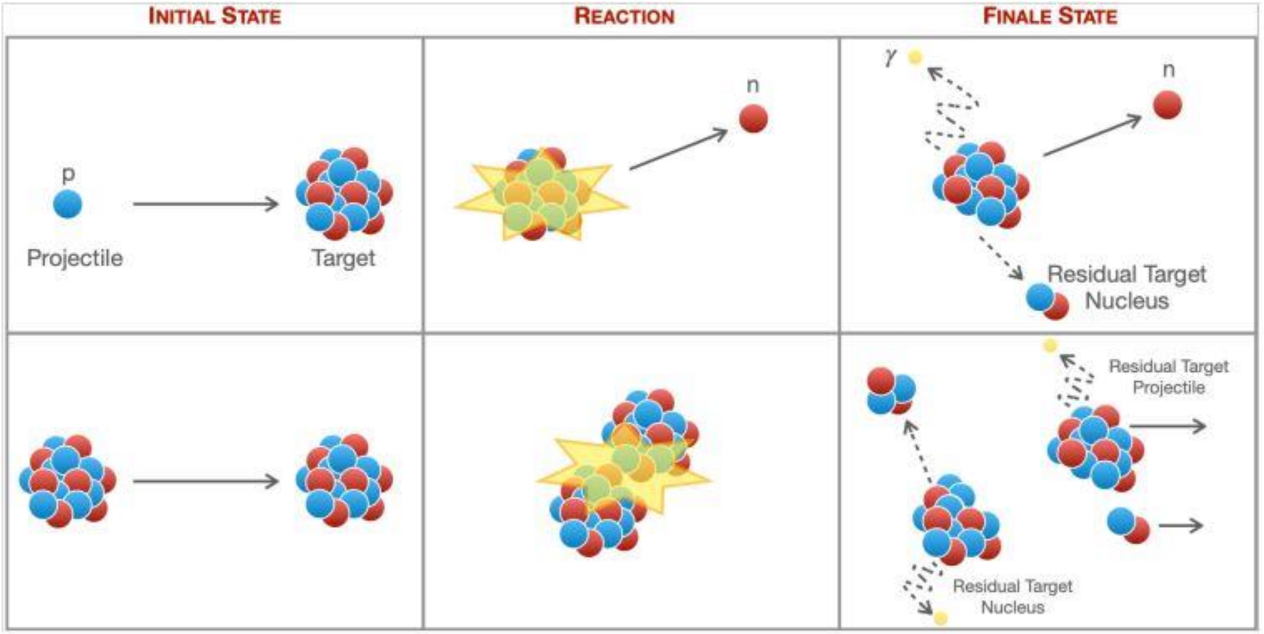
Nuclear Fragmentation

Target Fragmentation:

- ✓ Target fragments are produced with low energies (short range, hundreds of μm)
- ✓ Difficult to detect

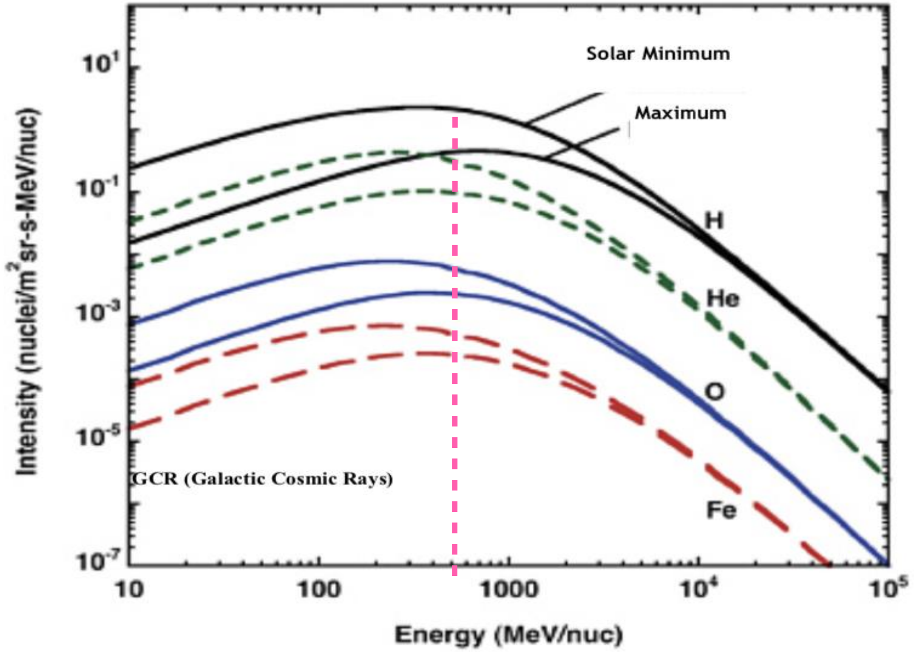
Beam Fragmentation:

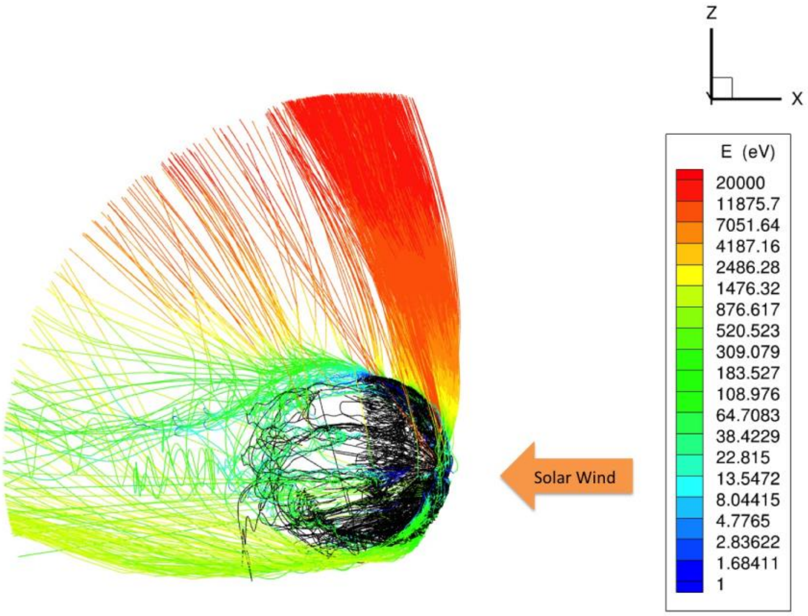
- ✓ Projectile fragments (longer range)
- ✓ Non-zero dose beyond the Bragg peak to address
- ✓ Not present in protontherapy



Spacecraft Shielding

- ✓ Charged particles in space: Solar Particles Events (SPEs), Galactic Cosmic Rays (GCRs), geomagnetically trapped particles
- ✓ Interaction with walls/shielding of spacecraft produce secondary fragments





FragmentatiOn Of Target: FOOT

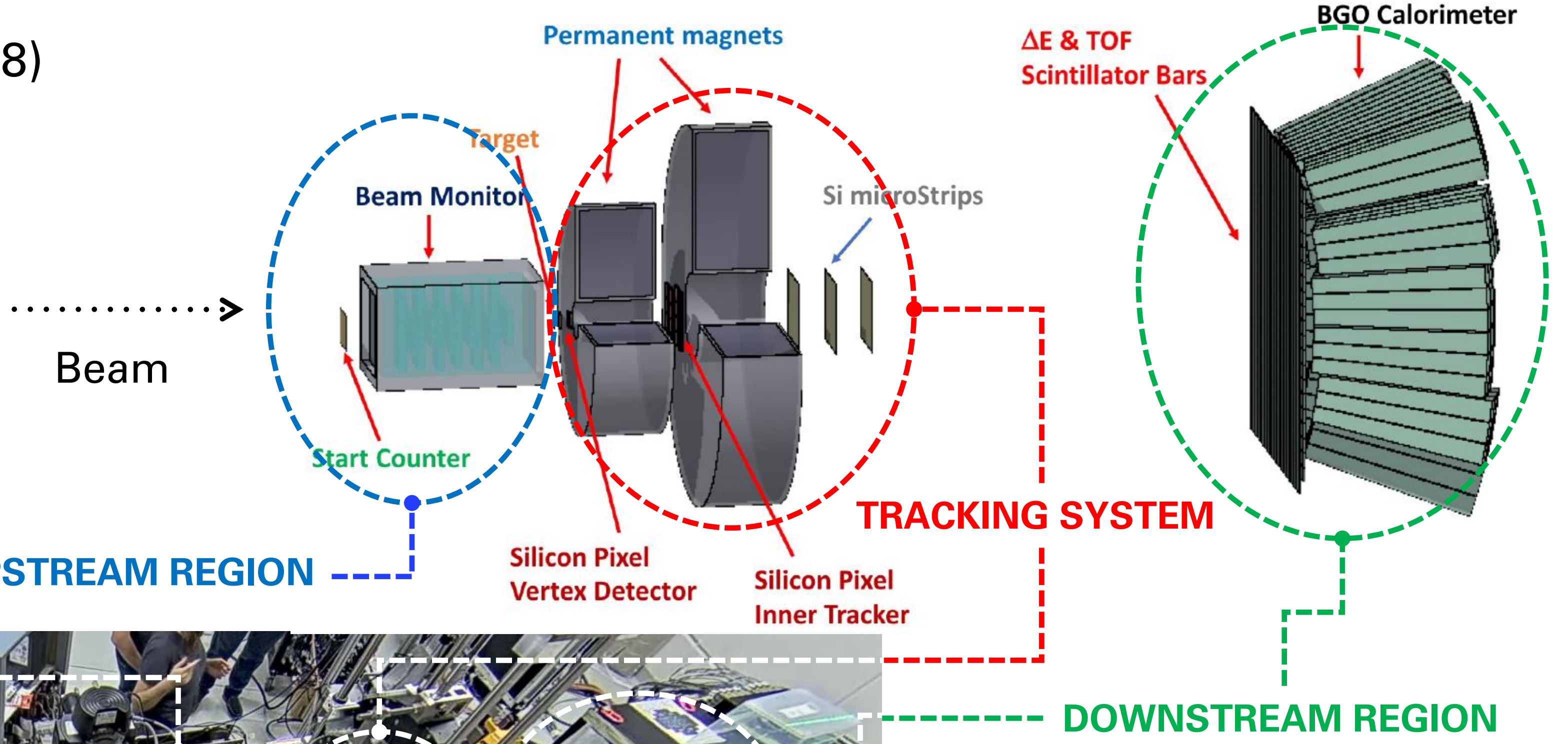
- ✓ Aim: measurement of beam and target fragmentation differential cross sections with 5% accuracy
- ✓ Goal: charge and mass identification at 2-3% and 5% accuracy, respectively
- ✓ Inverse kinematics approaches
- ✓ ^{4}He, ^{12}C, ^{16}O beams of 200-400 MeV/u on ^{12}C, C_2H_4 and $C_5O_2H_8$ targets (Hadronterapy)
- ✓ ^{12}C, ^{16}O beams of 800 MeV/u on ^{12}C, C_2H_4 and $C_5O_2H_8$ targets (Radioprotection)

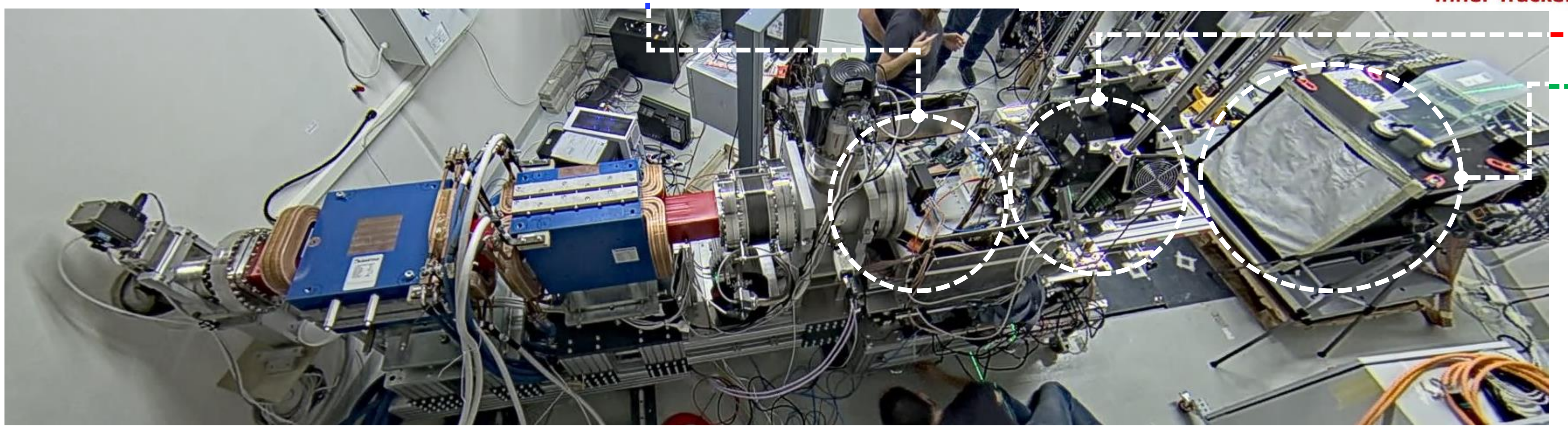
FOOT is a collaboration with about 100 members coming from

- INFN: 10 sections
- 3 laboratories: CNAO, GSI, IPHC
- 15 universities: France, Italy, Japan, Germany

Electronic Setup

- ✓ Designed for fragments (3 ≤ Z ≤ 8)
- ✓ Angular acceptance < 10°

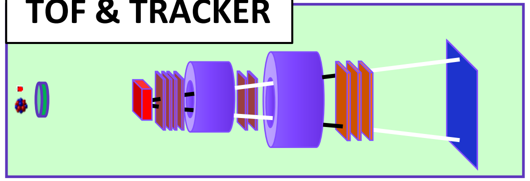




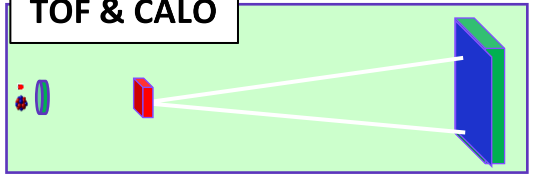
Mass Reconstruction

TOF (β) – TRACKER (p)	TOF (β) – CALO (E_{kin})	TRACKER (p) – CALO (E_{kin})
$A_1 = \frac{m}{u} = \frac{p\sqrt{1-\beta^2}}{u\,\beta}$	$A_2 = \frac{m}{u} = \frac{E_{kin}}{u(\gamma - 1)}$	$A_3 = \frac{m}{u} = \frac{p^2 - {E_{kin}}^2}{2E_{kin}}$

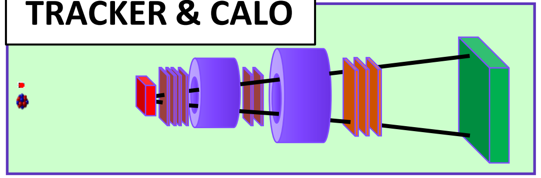
TOF & TRACKER



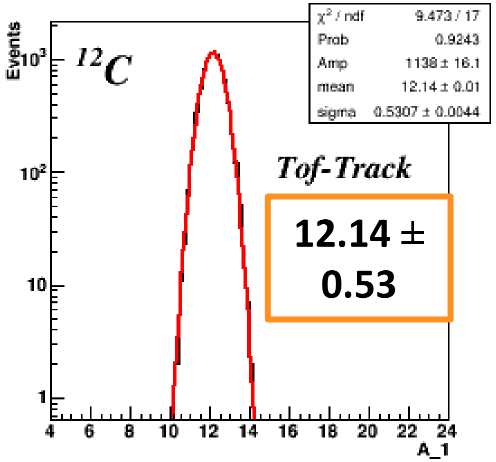
TOF & CALO

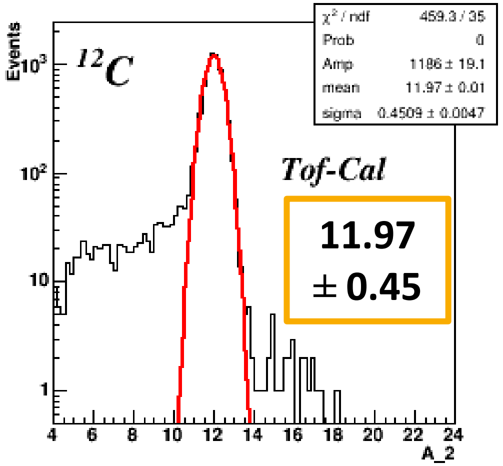


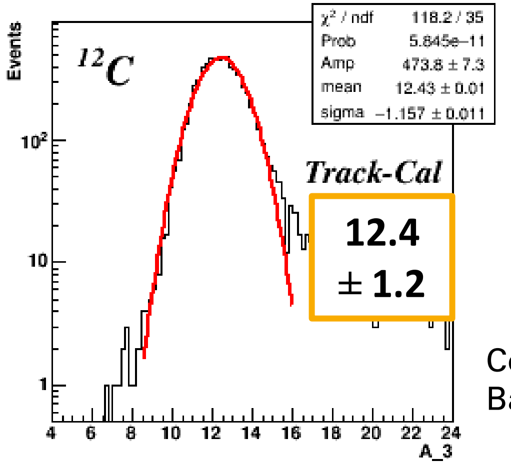
TRACKER & CALO



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



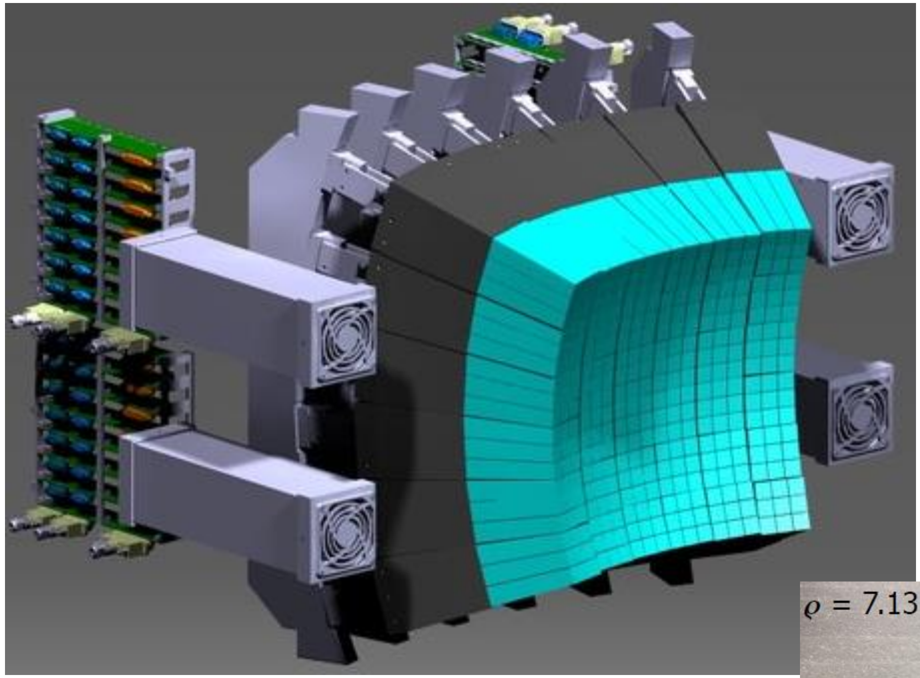


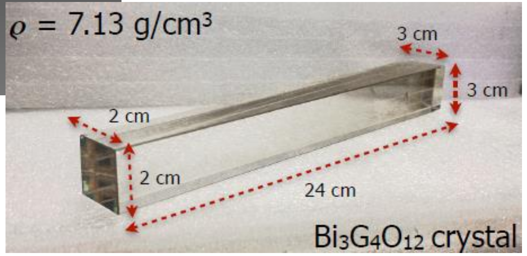


Courtesy of G. Battistoni

Calorimeter

- ✓ 320 BGO crystals grouped in modules (9 crystals for each module)
- ✓ Crystals dimension: 2x2 cm2 (front) 3x3 cm2 (back) 24 cm (length)
- ✓ SiPM based readout
- ✓ 36/36 modules fully assembled
- ✓ Measurement of the kinetic energy



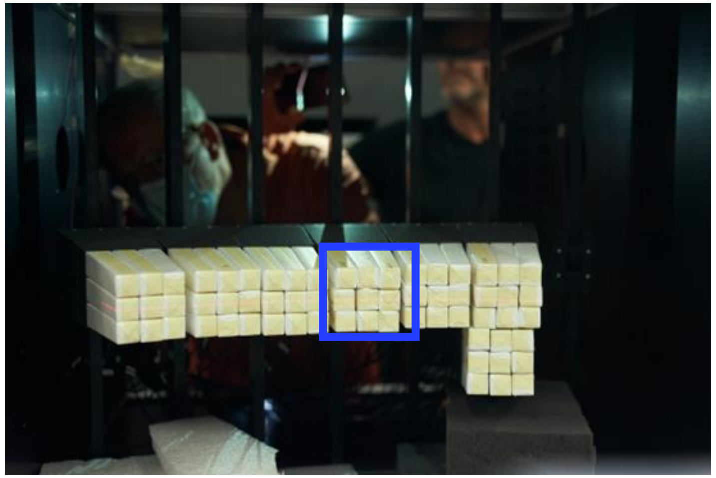


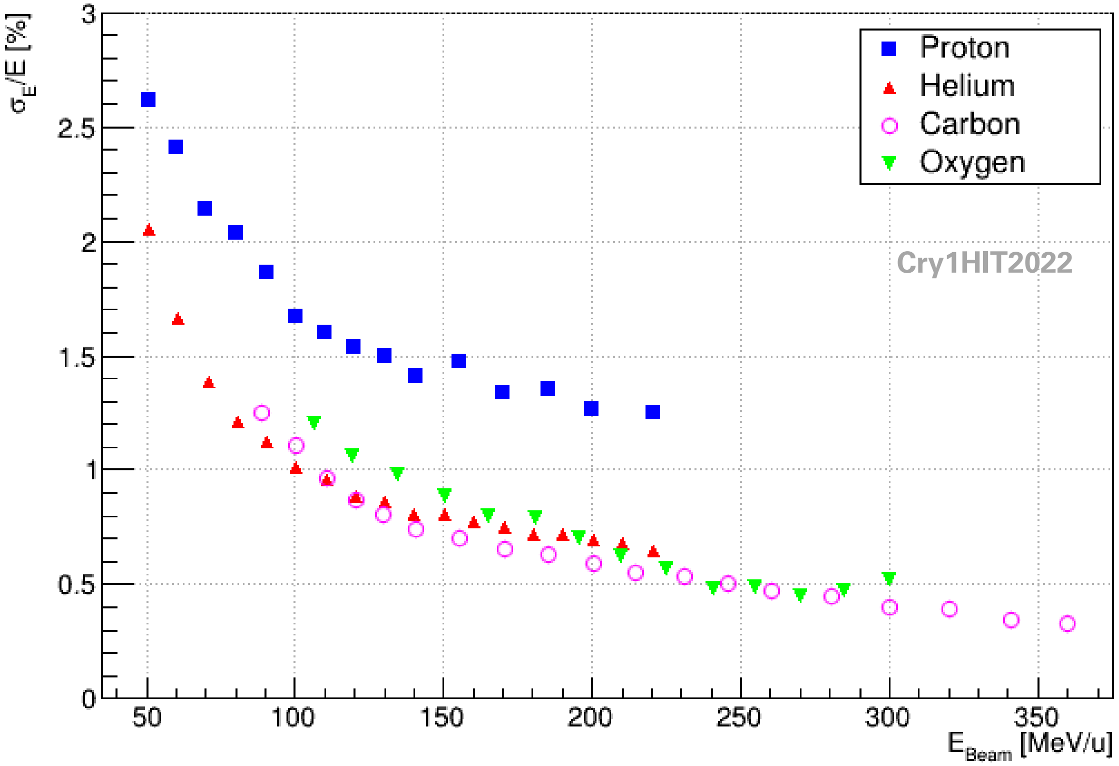
Multiple data acquisition campaigns for calibration and equalisation at:

- ✓ Heidelberg Ion Therapy Center (HIT)
- ✓ Centro Nazionale di Adroterapia Oncologica (CNAO)

HIT – First Energy Calibration Study

- ✓ Simple setup with just one fully assembled module
- ✓ Beam focused on central crystal
- ✓ No other detector between Calorimeter and beam nozzle (autotrigger)
- ✓ Energy scan from 50 to 400 MeV/u with Proton, Helium, Carbon and Oxygen ions





Calibrated crystal resolution for different ions

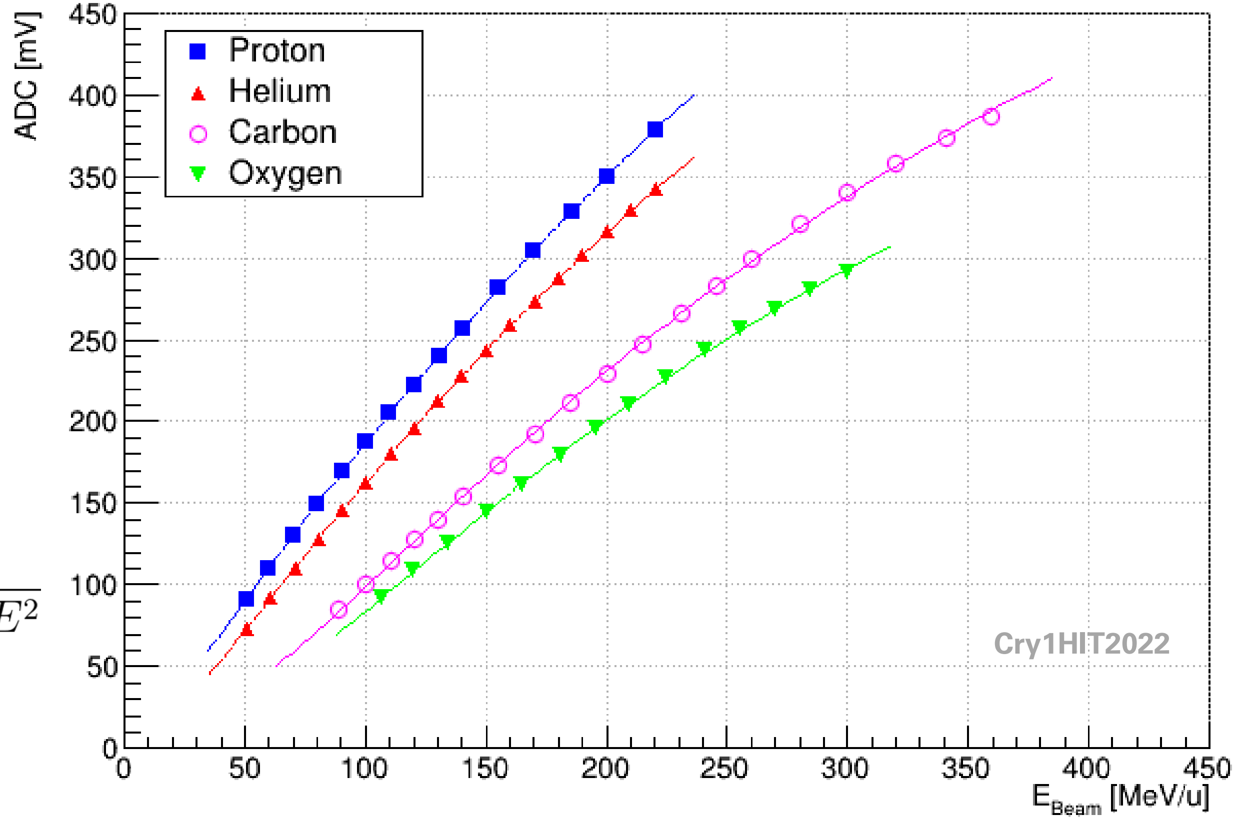
Energy Calibration Curves

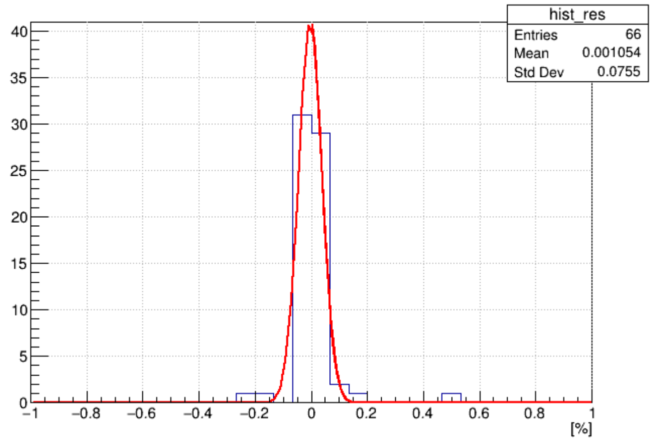
- ✓ The calorimeter linearity is affected by the Birks effect

$$\frac{dS}{dx} = \frac{A \cdot dE/dx}{1 + k \cdot B \cdot dE/dx}$$

- ✓ There is clear dependence on Z
- ✓ The chosen fit function is derived from Birks formula, we call it modified Birks function (MBF)

$$ADC(E) = \frac{P_0 E^2}{1 + P_1 E + P_2 E^2}$$





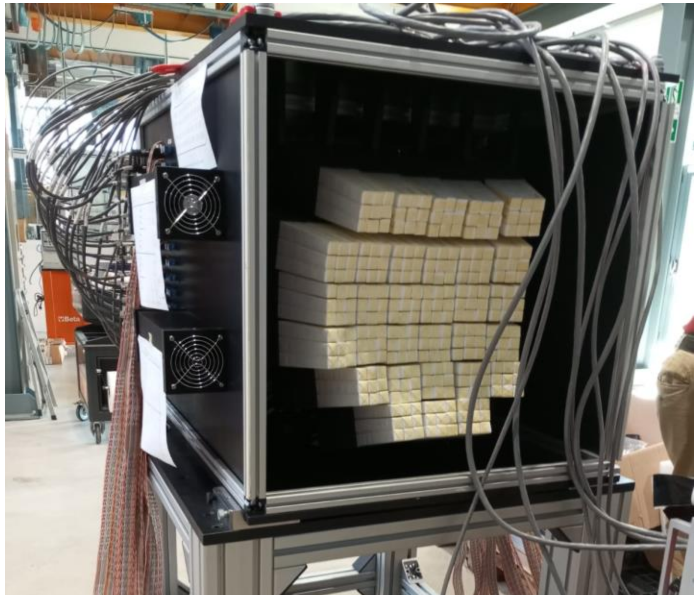
- ✓ Good fitting of experimental data

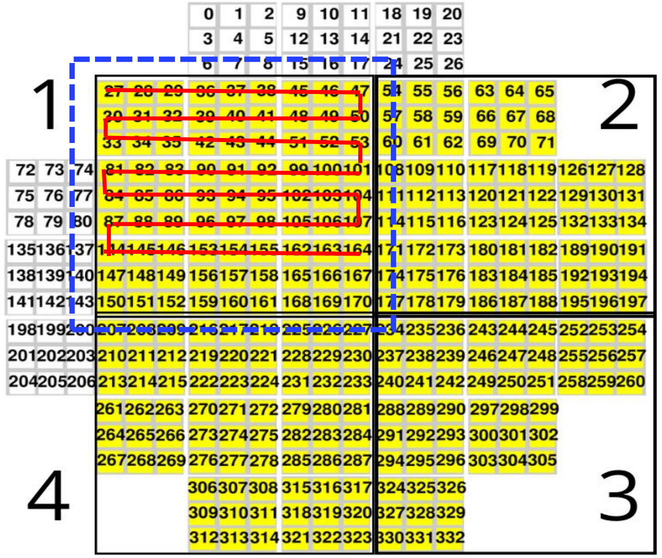
$$\frac{|E_{fit} - E_{ADC}|}{E_{fit}} < 1\%$$

CNAO – Calibration Validation

- ✓ Beam in "Screensaver Mode": sweeping a quarter of the modules at a time during each run greatly reducing data acquisition time
- ✓ Setup with 31 fully assembled modules
- ✓ Scan at four different energies 115, 190*, 200, 250 MeV/u with Carbon ions

Crystal intercalibration is performed using the Modified Birks function

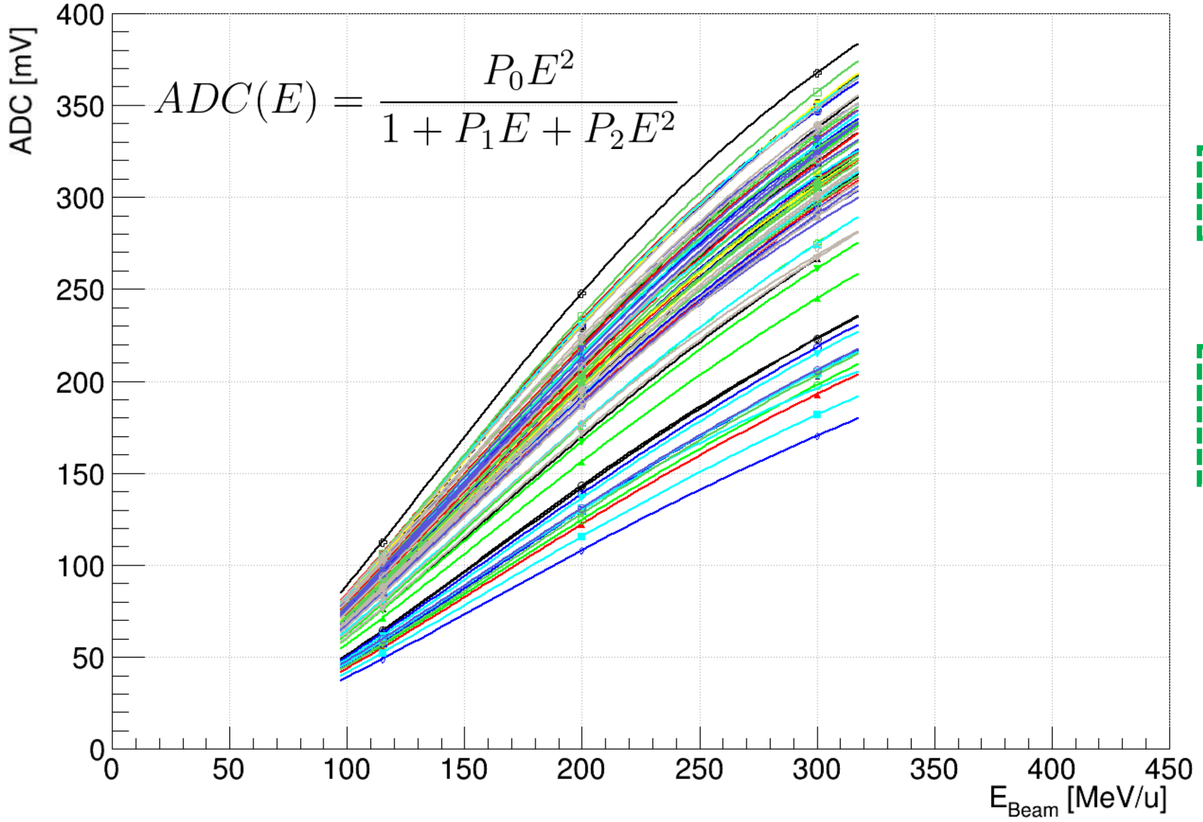




* *foreseen at 150 MeV, issue with beam delivery*

Intercalibration Strategy

How to test whether screensaver run achieve the performance needed?



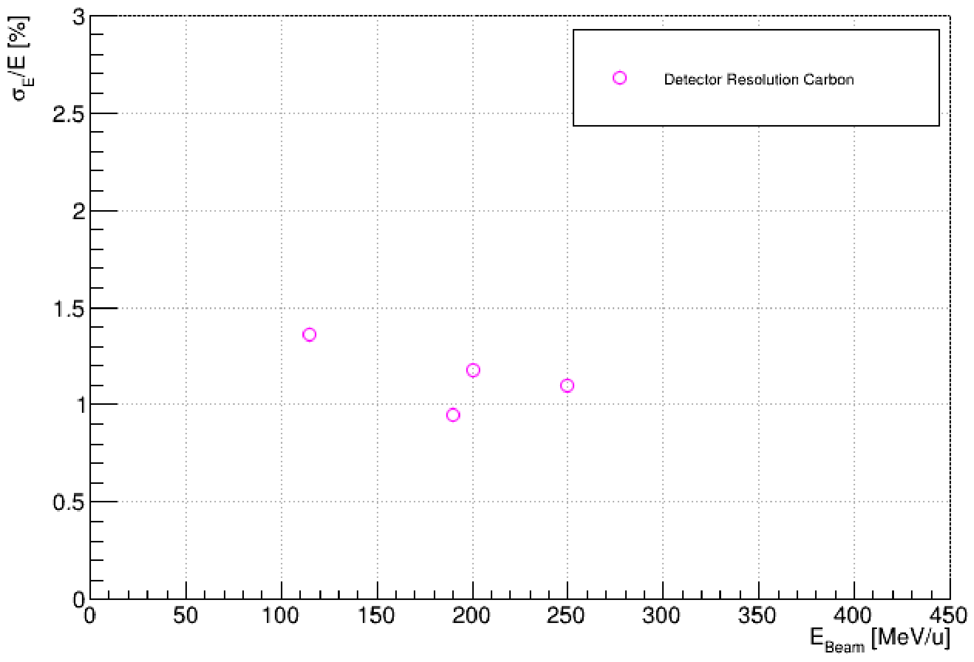
Four Carbon energy screensaver points

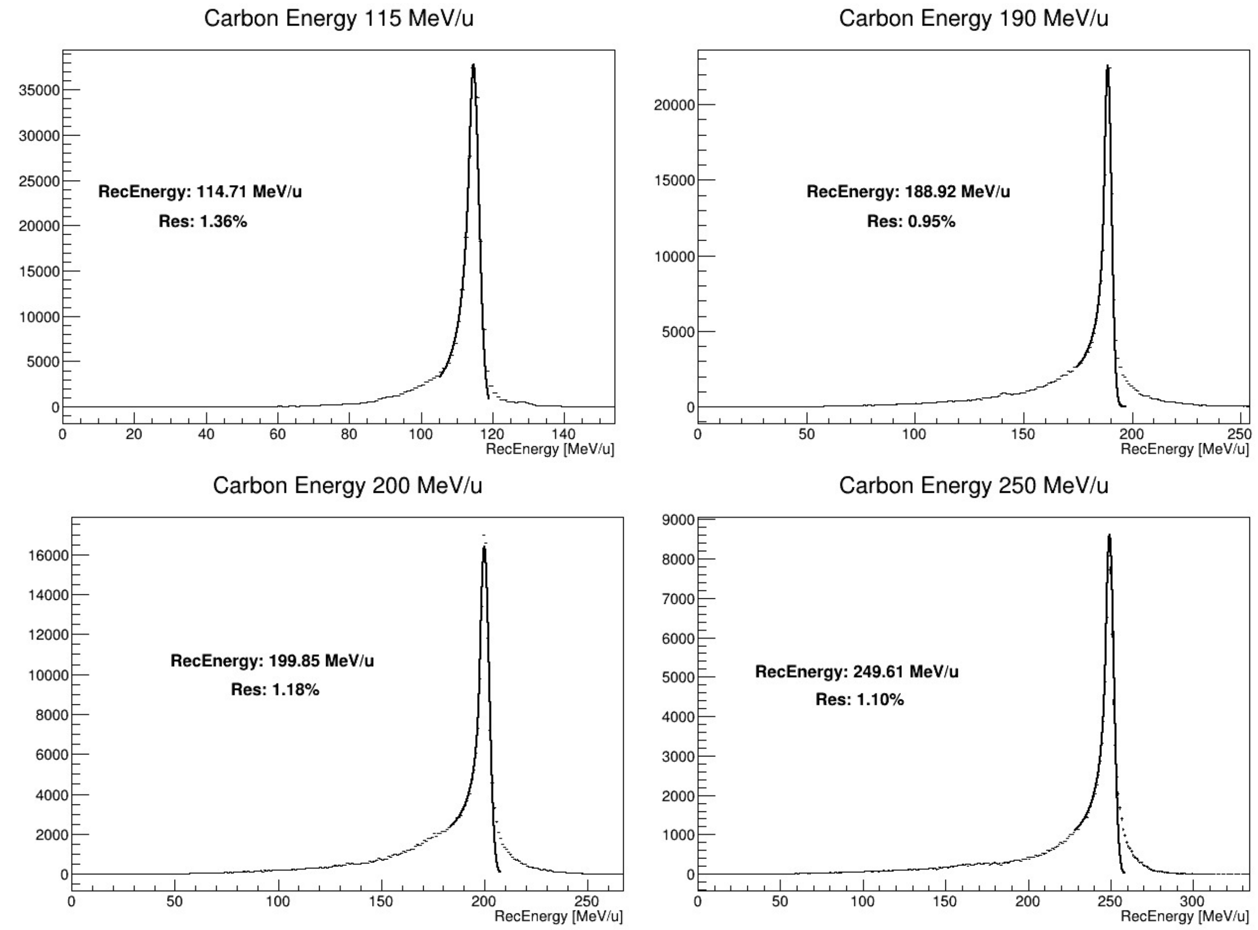
For each crystal we obtain p0, p1 and p2

Energy calculated as inverse modified Birks

$$E(ADC) = \frac{-P_1 ADC - \sqrt{(P_1 ADC)^2 - 4ADC(P_2 ADC - P_0)}}{2(P_2 ADC - P_0)}$$

Calorimeter Resolution



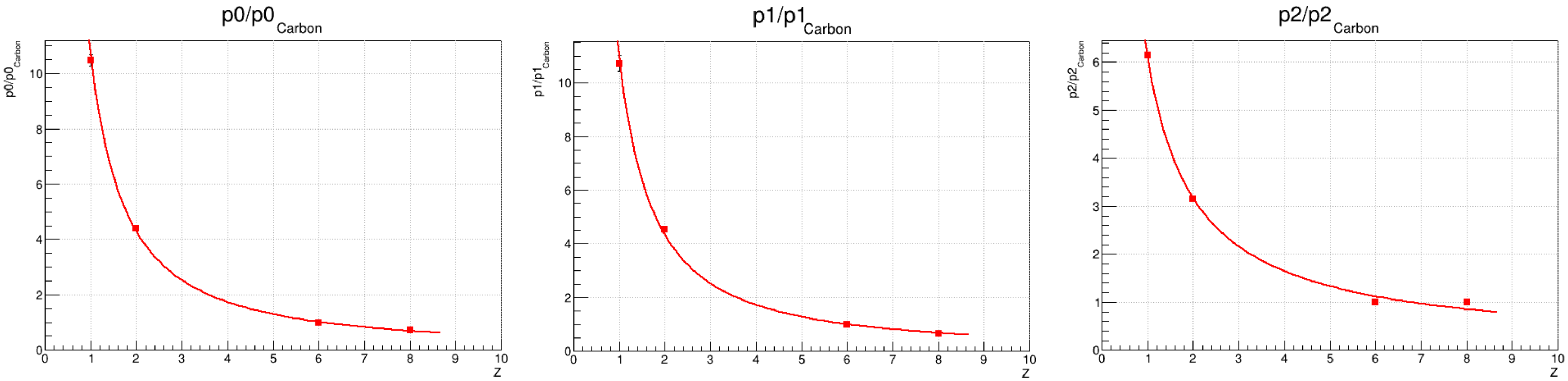


After equalization the integrated energy resolution is ~1%

Atomic Number Dependance

Is it possible to address the Z dependence problem?

$$ADC(E) = \frac{P_0 E^2}{1 + P_1 E + P_2 E^2}$$



Ratio of energy calibration curve parameters to carbon curve parameters follow a power law

$$\frac{P_x}{P_{x_{carbon}}} = a_0 Z^{a_1}$$

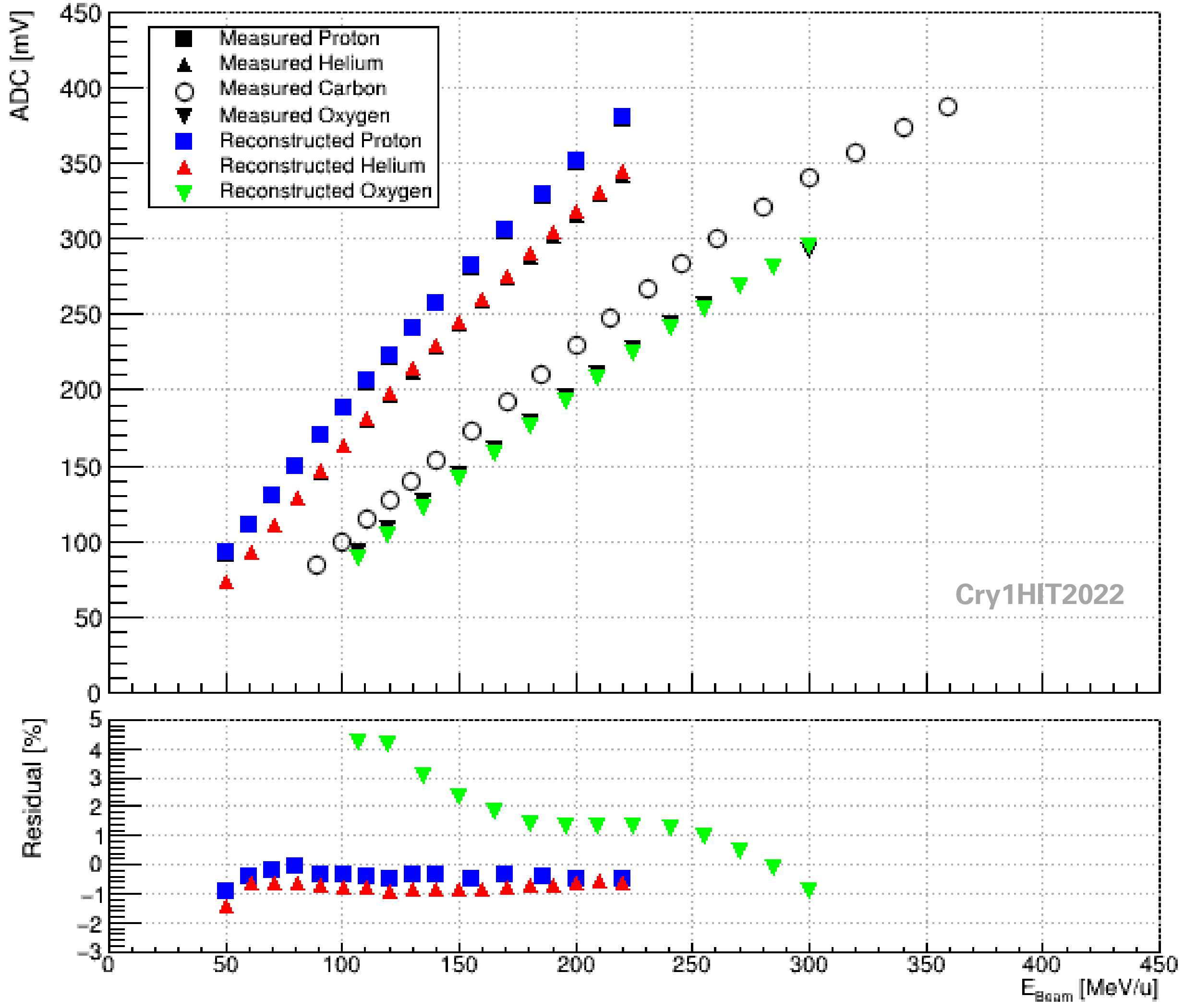
By measuring Z we can convert the ADC response to Energy for all the possible fragments

Energy Calibration

With the power law function from previous slide, it is possible to calculate proton, helium and oxygen point starting from carbon MBF parameter

Superimposition and residual to verify the performance of this method

It is now possible to measure the kinetic energy by knowing the charge of the ion (TW)

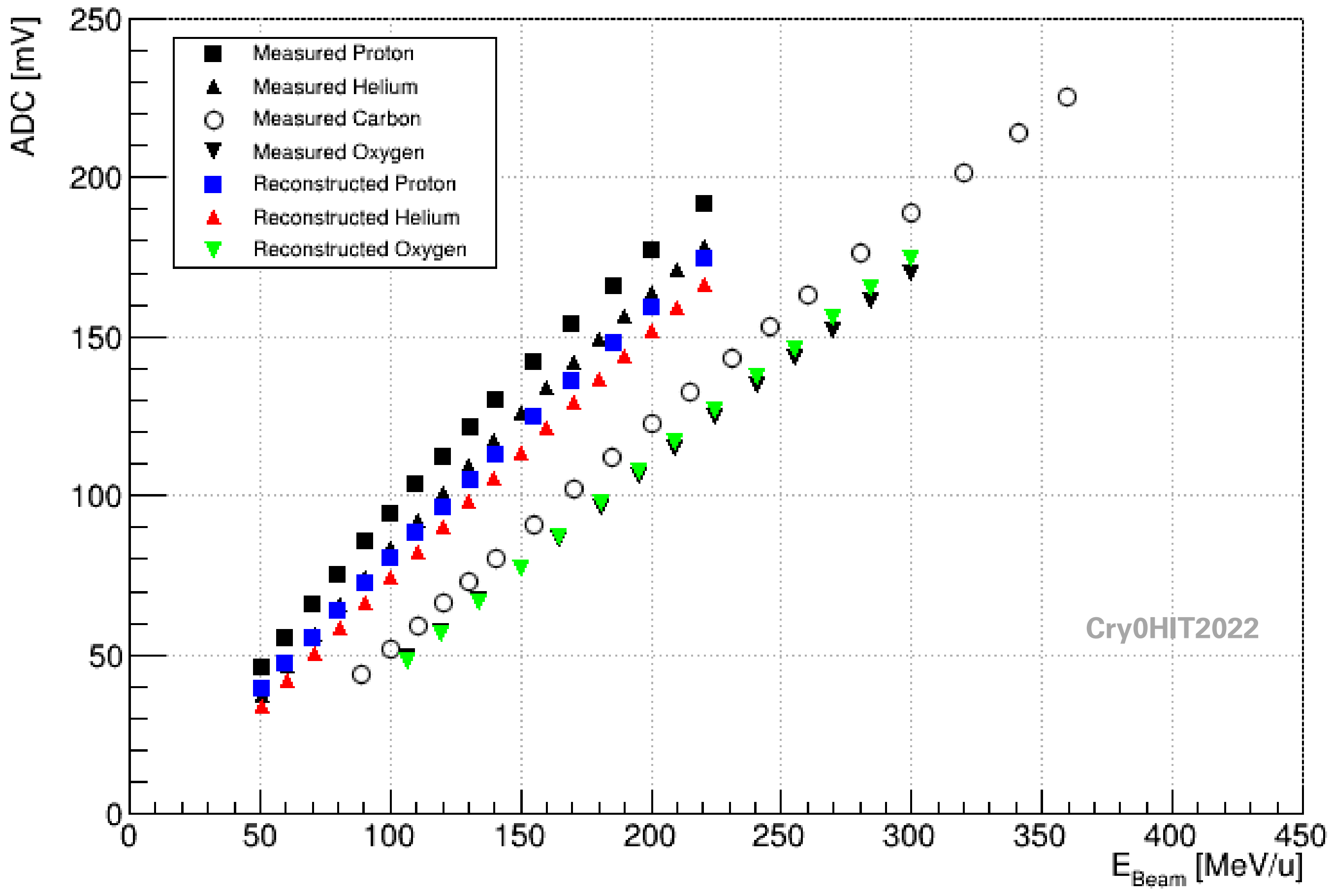


Applicability

Are the power law parameters the same for every crystal?

Reconstruct proton, helium and oxygen point of Cry0HIT2022 with power law parameter calculated from Cry1HIT2022

Each crystal has its own power law parameter

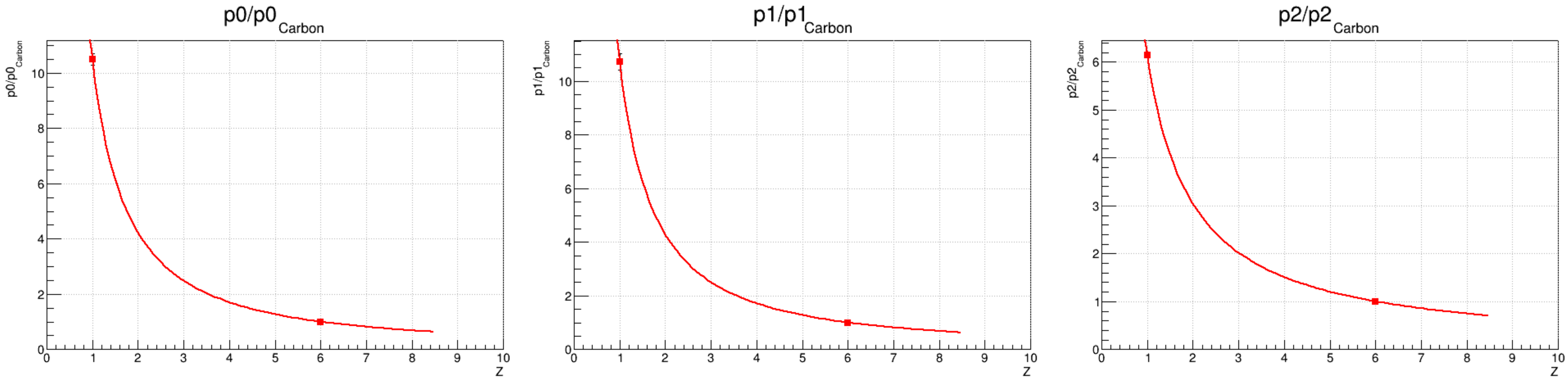


Energy Calibration – CNAO feasibility

- ✓ Taking data at HIT is a challenging task: not enough beam time available to us to measure the response of all the crystals
- ✓ Performing calibration procedure at CNAO is possible but CNAO provides only Proton and Carbon ions

$$\frac{P_x}{P_{x_{carbon}}} = a_0 Z^{a_1}$$

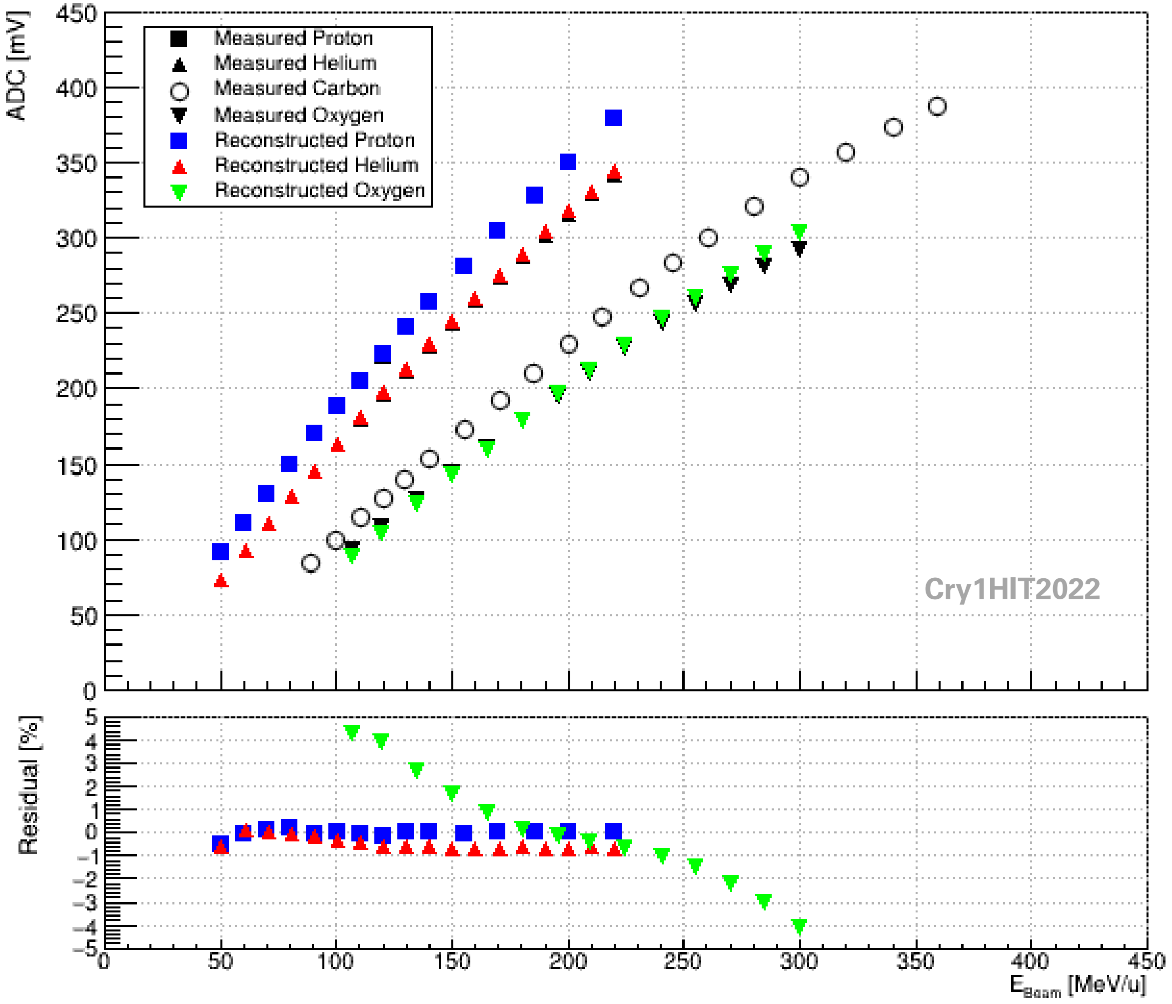
What equalization strategy at CNAO?



Energy Calibration – CNAO feasibility

Same validation procedure used with 4-ions-power law

Seems possible to calibrate all crystals at CNAO with the provided ions



Summary and Results

- ✓ Calibration run at HIT with proton, helium, carbon and oxygen ions
- ✓ BGO calorimeter is affected by Birks effect (Modified Birks function achieve <1% residual distribution)
- ✓ Modified-Birks-Parameter-function based Energy Calibration method has been identified, tested and validated on a single crystal
- ✓ Each crystal has different power-law parameters
- ✓ CNAO allows calibration for all crystals with only two ions (proton and carbon) using screensaver run
- ✓ Screensaver run meets experimental requirement: resolution is well below < 2%
- ✓ Next step: full calorimeter calibration