The **FOOT** Calorimeter: a summary

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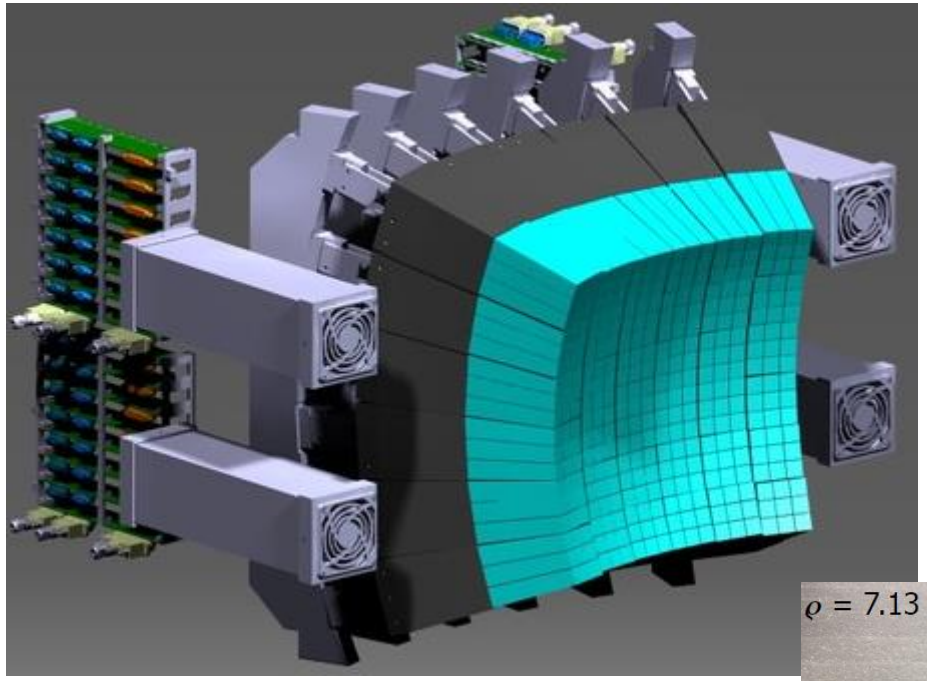
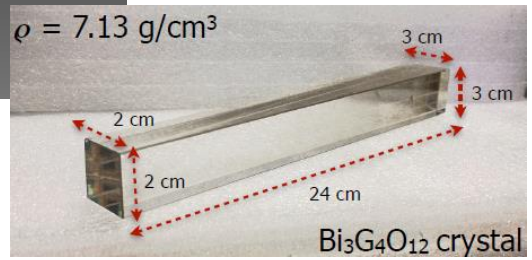
The Detector

- ✓ 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 and temperature-calibrated



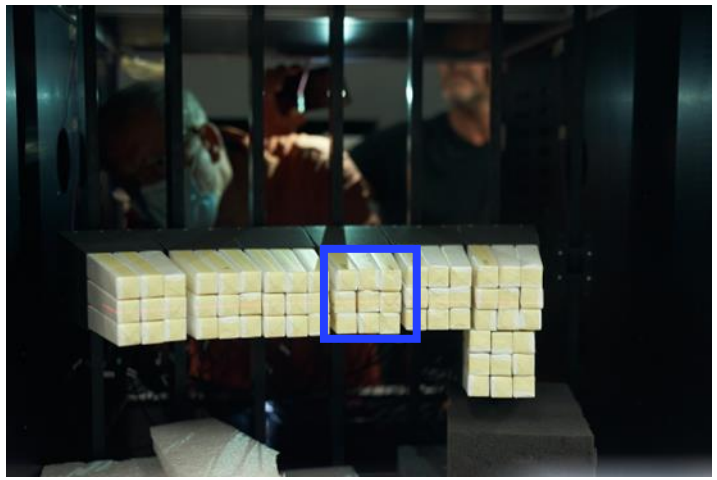


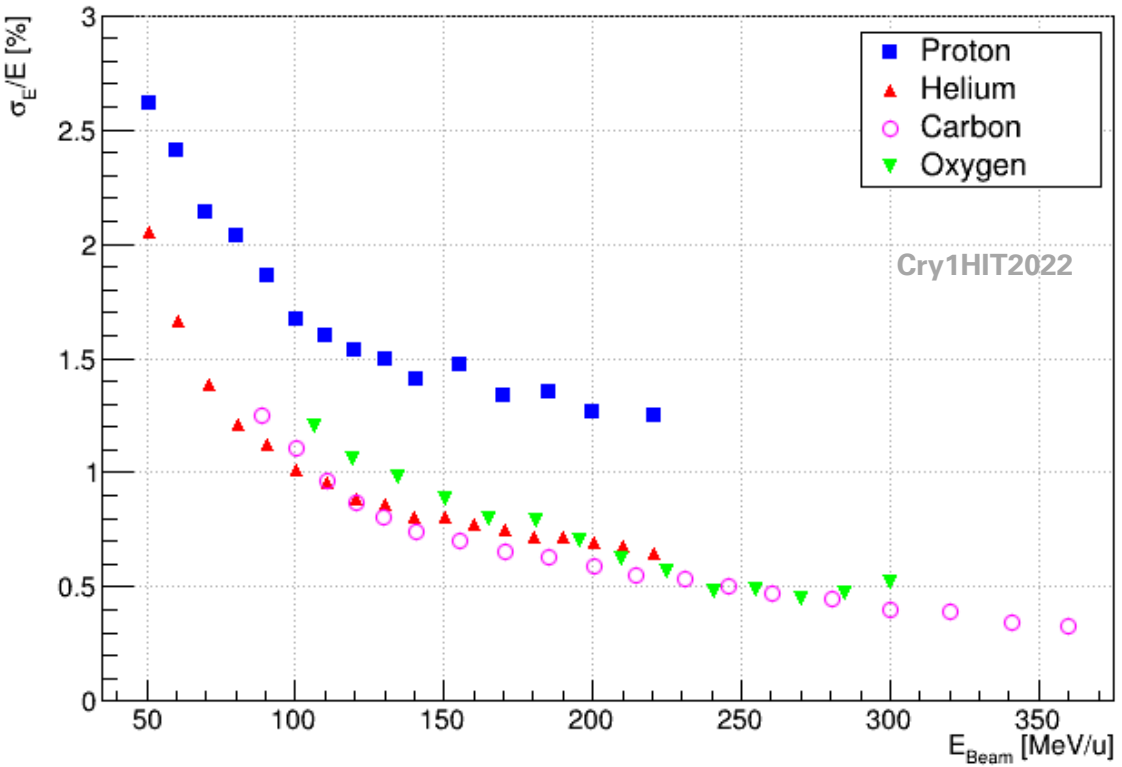
Multiple data acquisition campaigns for calibration and equalisation at:

- ✓ 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 the center of the 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

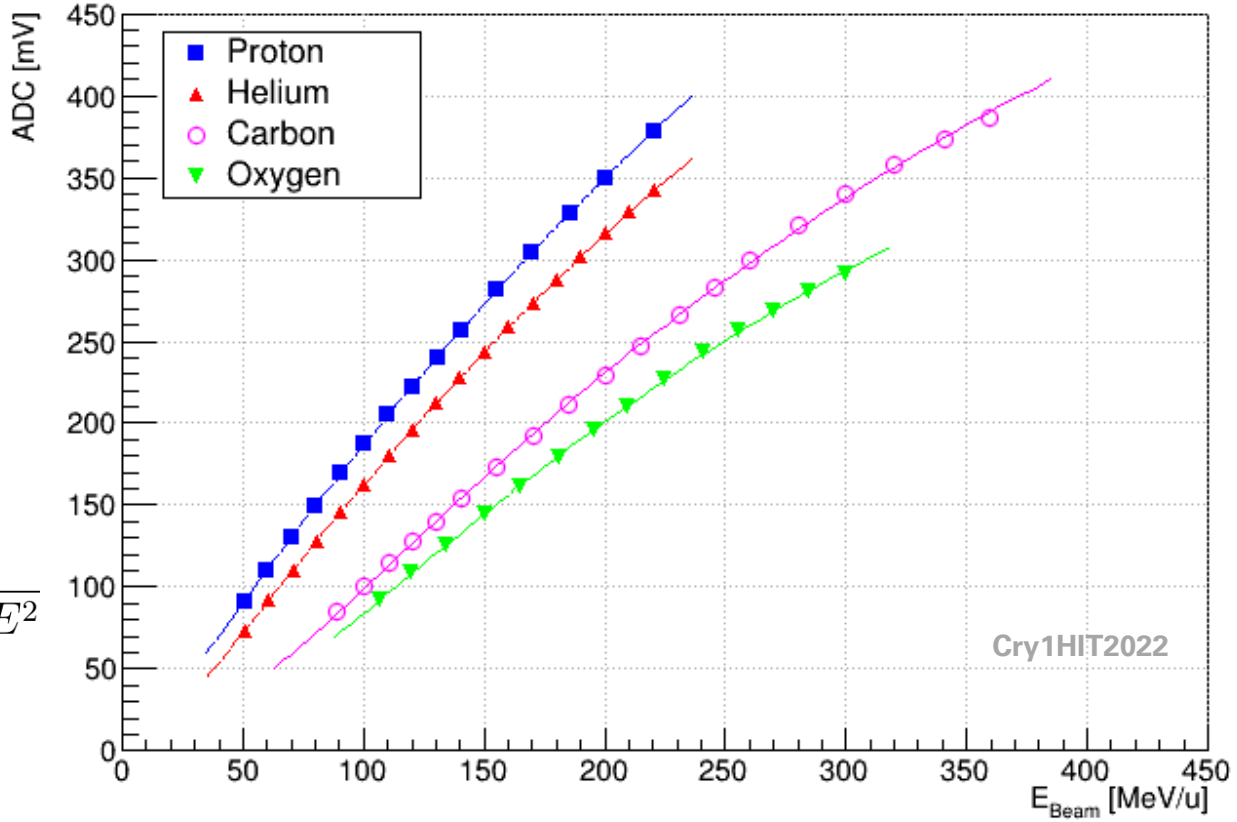
Energy Calibration Curves

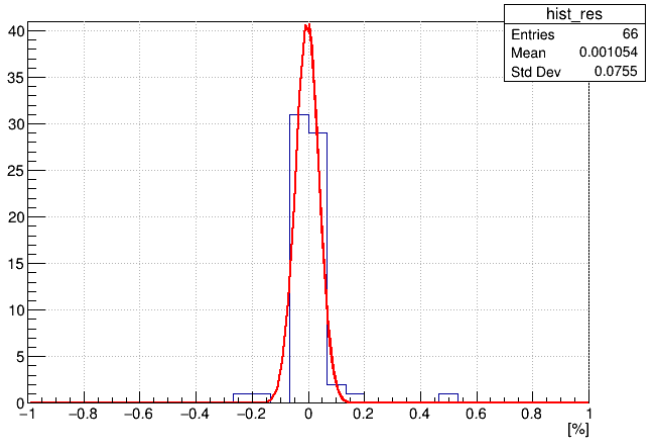
- ✓ The calorimeter linearity is affected by the Birks effect

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

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

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



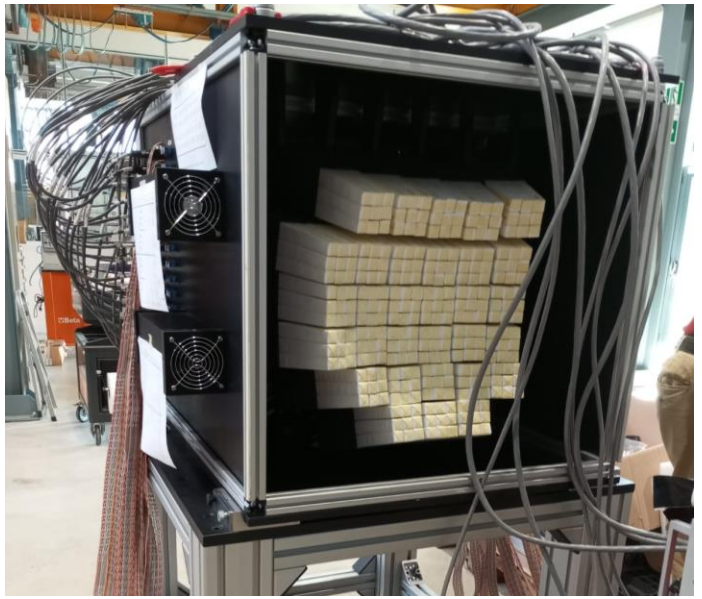


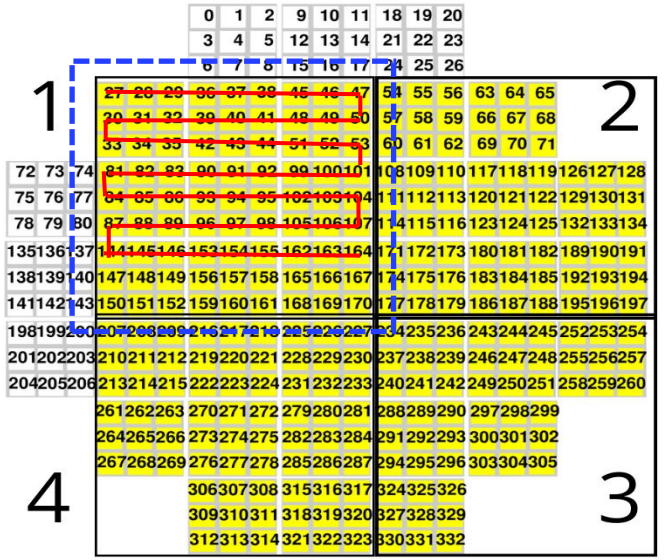
- ✓ Good fitting of experimental data

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

CNAO – Calibration Validation

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



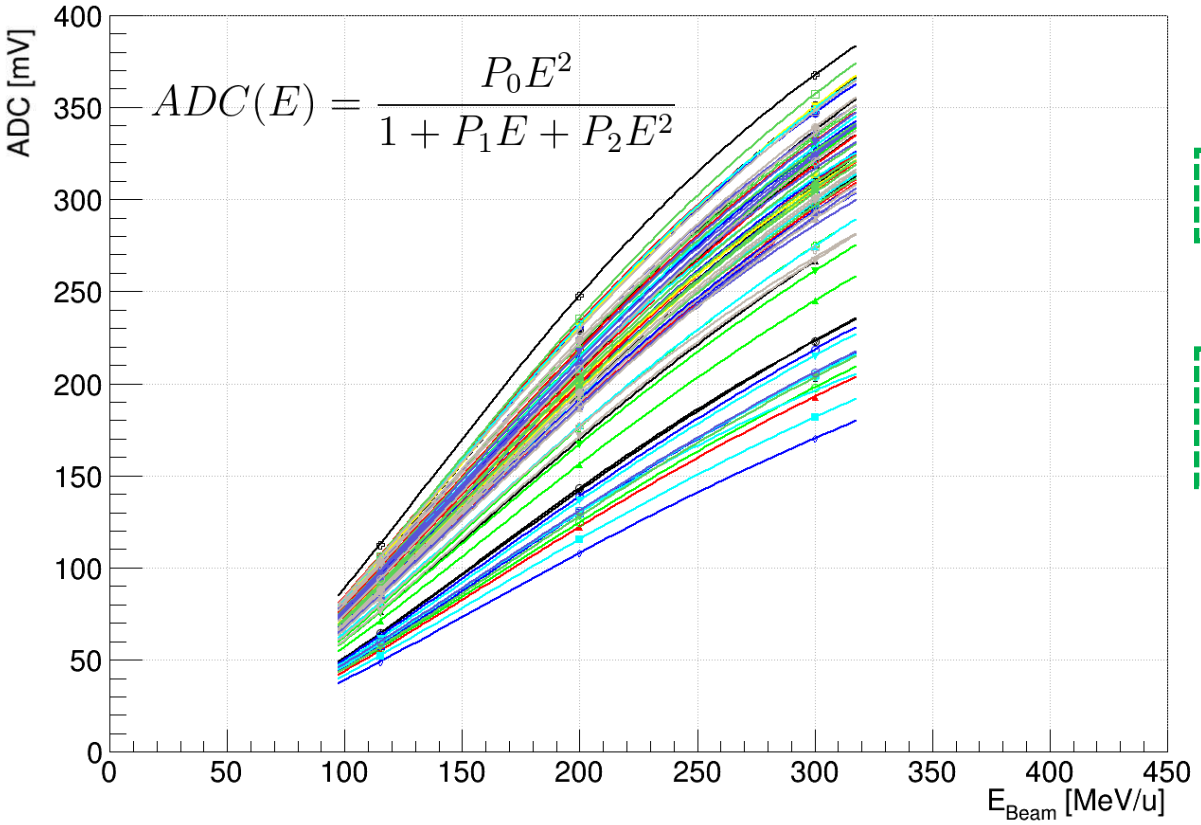


Crystal intercalibration is performed using the Modified Birks function

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

Intercalibration Strategy

How to test whether screensaver run achieve the performance needed?



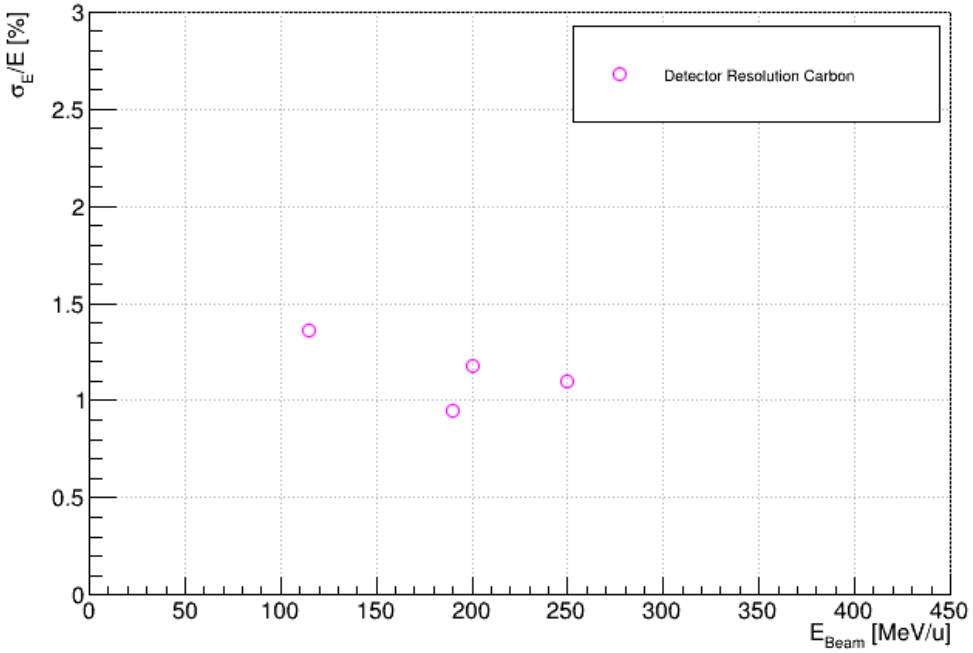
Four Carbon energy screensaver points

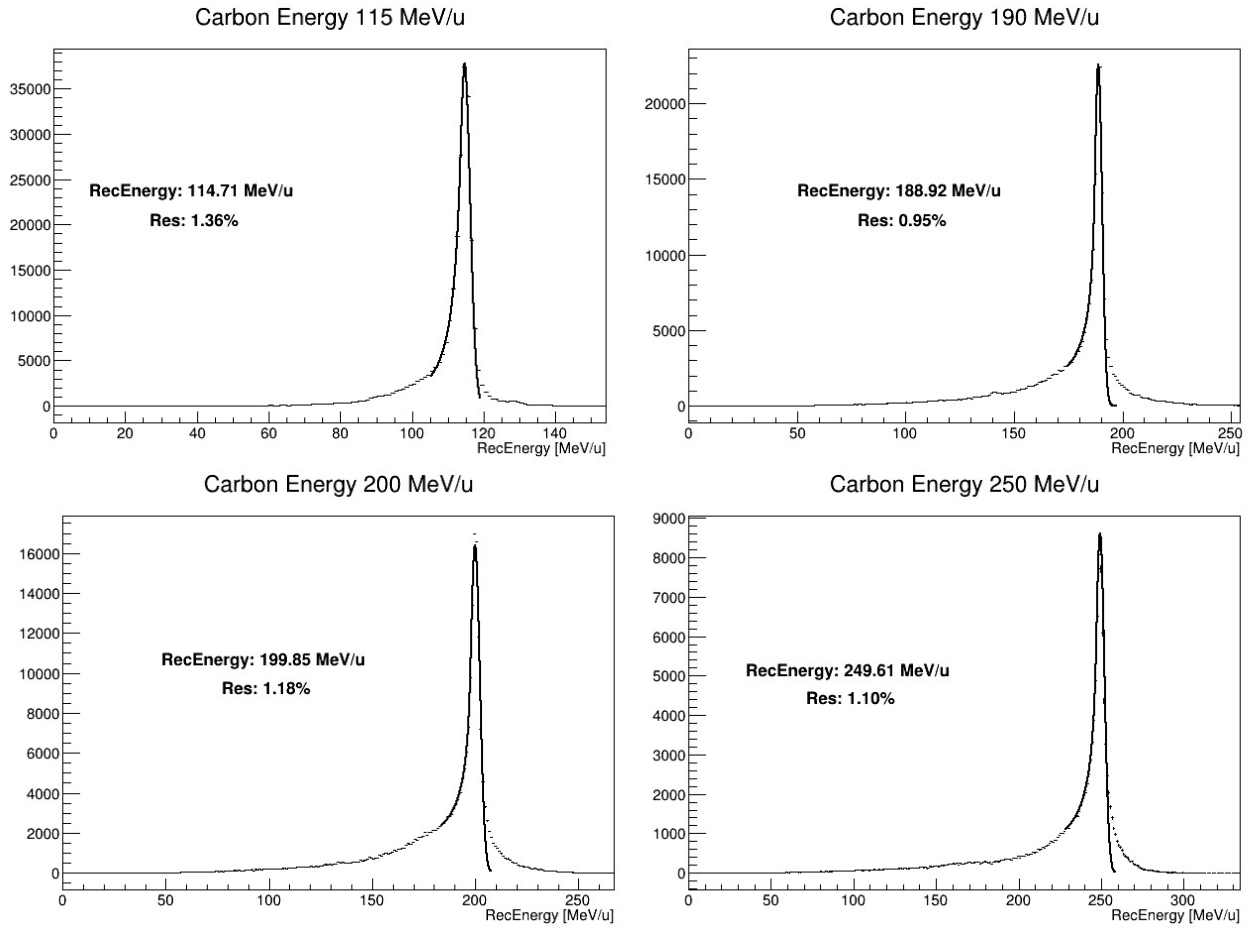
For each crystal we obtain p0, p1 and p2

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



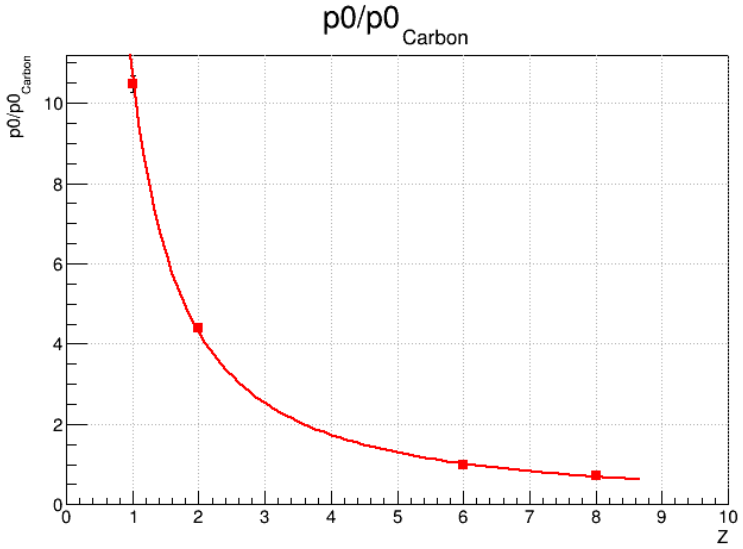


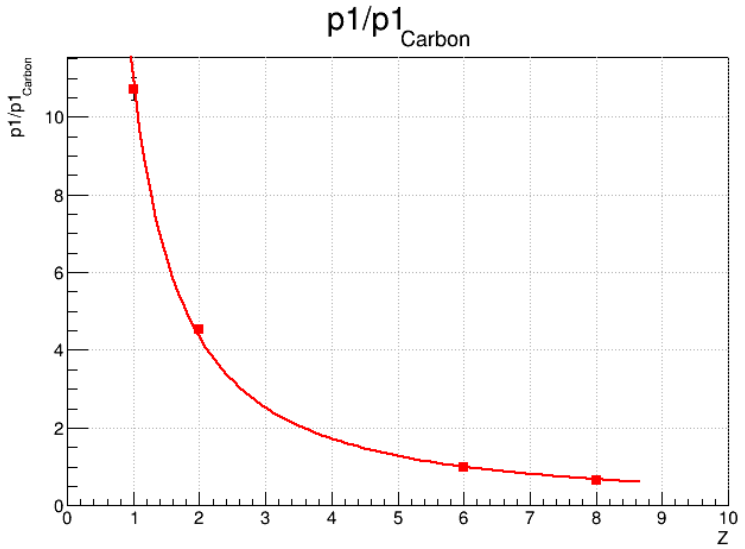
After equalization the integrated energy resolution is ~1%

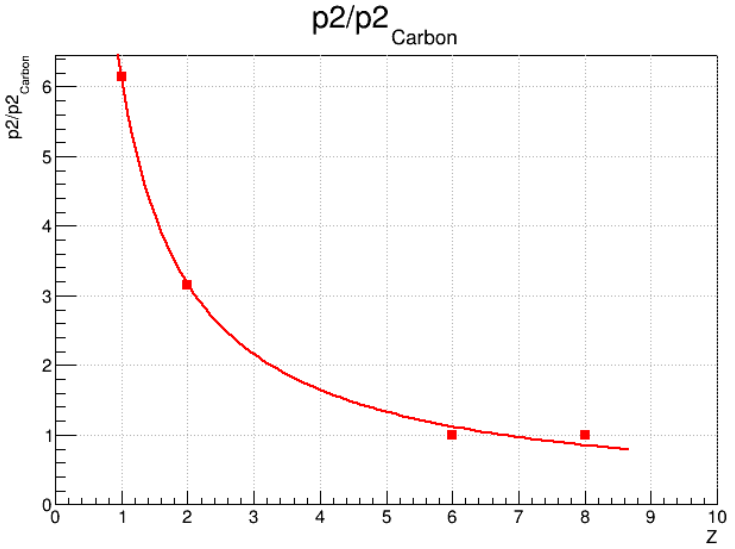
Atomic Number Dependance

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 an exponential law

$$\frac{P_x}{P_{x_{carbon}}} = a_0 + a_1 e^{-\frac{Z}{a_2}}$$

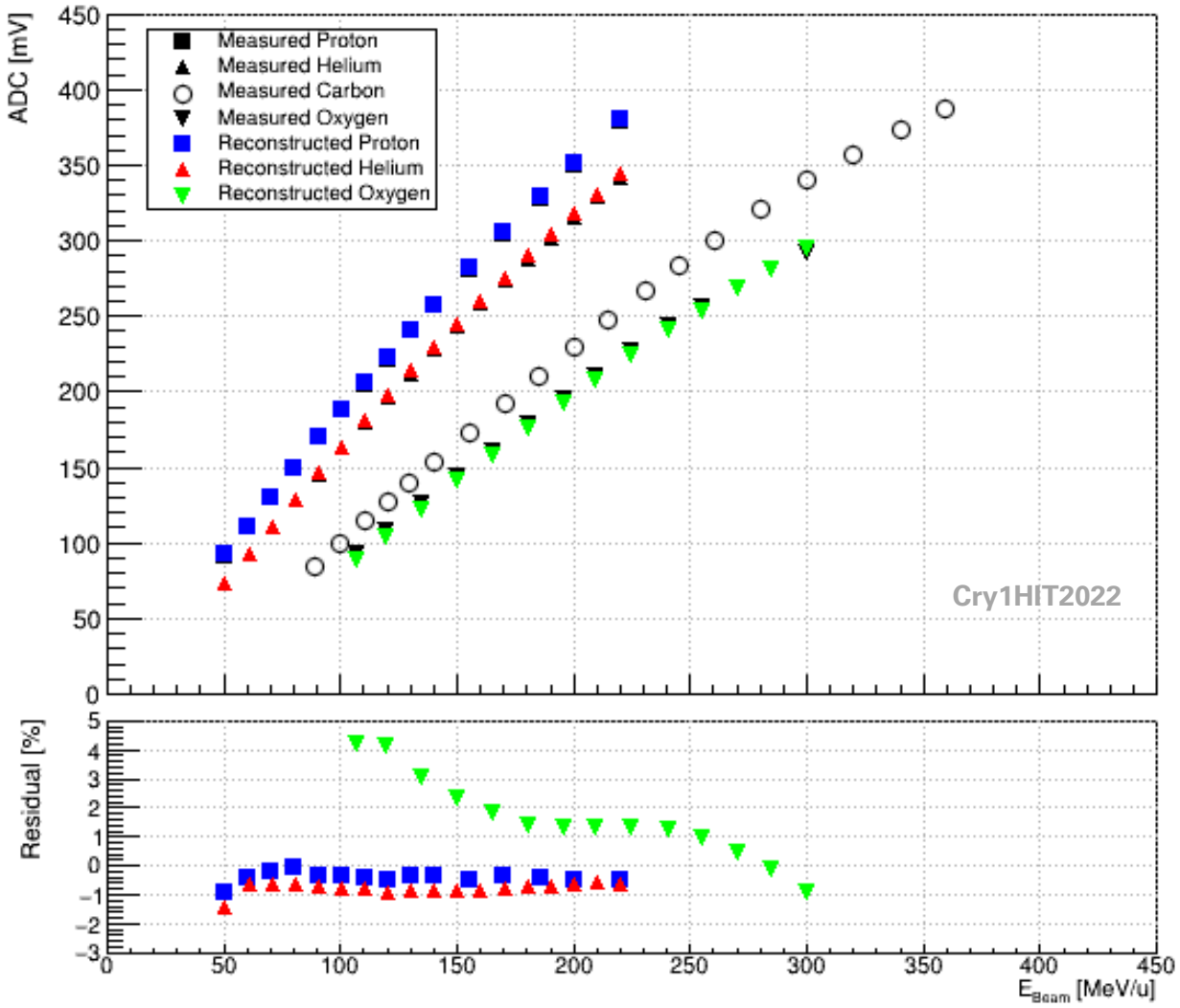
By measuring Z we can convert the ADC response to Energy for all the possible fragments

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)

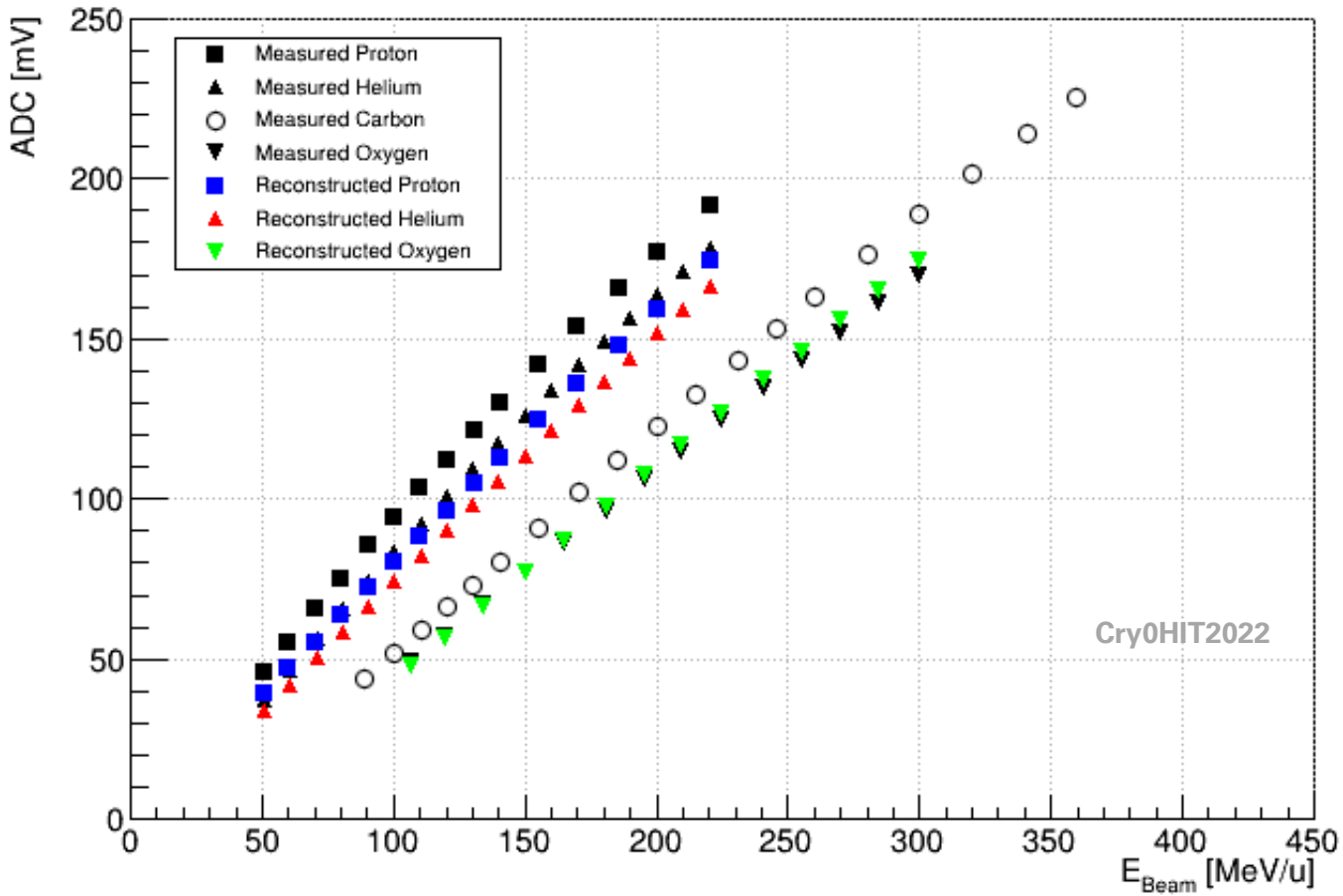


Applicability

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 exponential law parameters

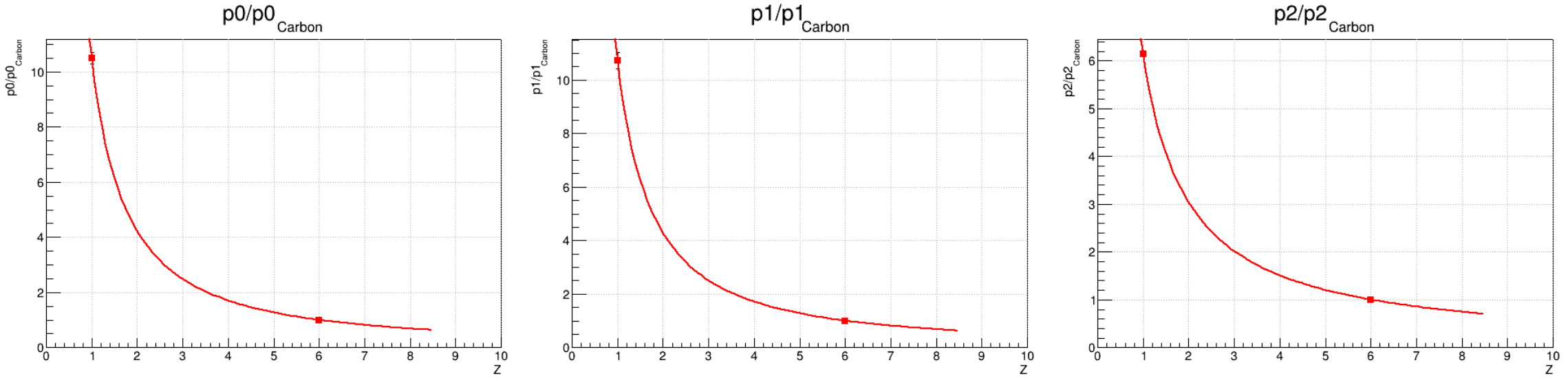


Energy Calibration – CNAO feasibility

- ✓ 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

We need a different function

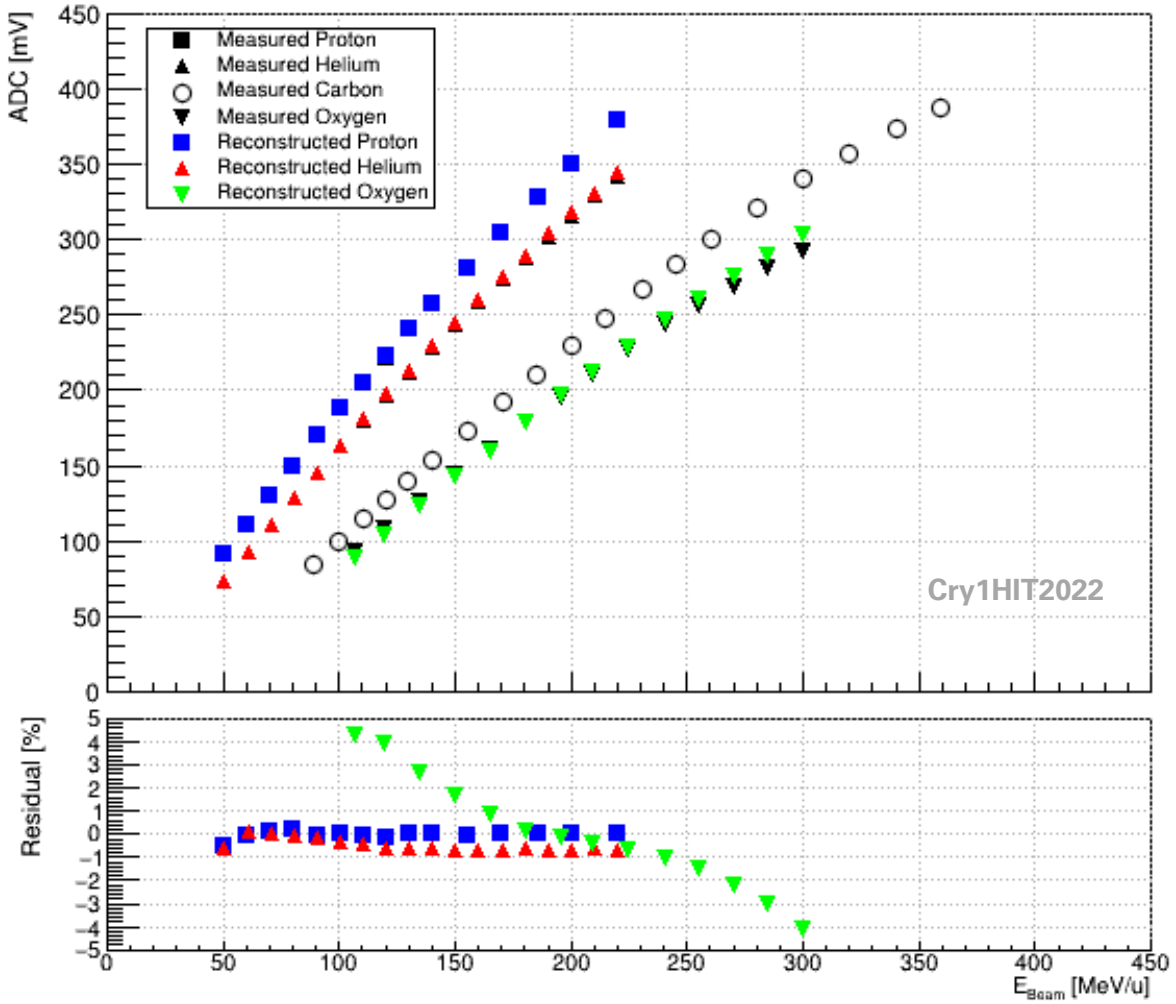
$$\frac{P_x}{P_{x_{carbon}}} = a_0 Z^{a_1}$$



Energy Calibration – CNAO feasibility

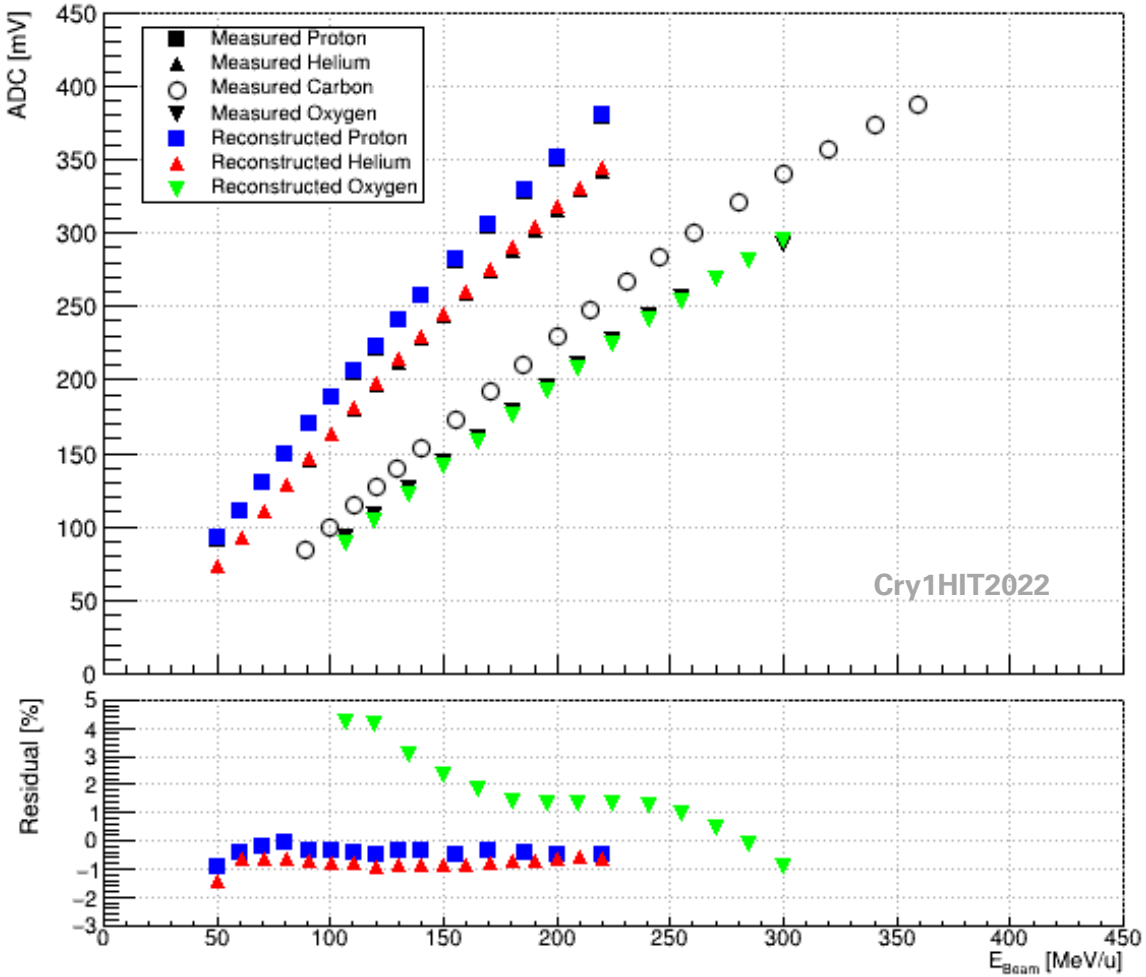
Same validation procedure used with 4-ions-power law

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



Summary and Results (before CNAO2024)

- ✓ 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



Next steps (After CNAO2024)

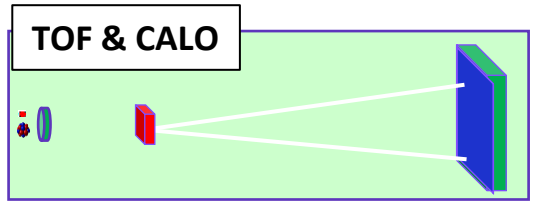
- ✓ Measure Proton and Carbon MBF for all the crystals
- ✓ Measure the total resolution of the detector (integral resolution)
- ✓ Verify how the extrapolation of Proton MBF performs using HIT parameters (4 ions, single reference crystal)
- ✓ Verify how the extrapolation of Proton MBF performs using CNAO2024 parameters (2 ions measured with all crystals)
- ✓ Mass reconstruction of Helium fragments

Crucial to evaluate MBF parameter transformation strategy

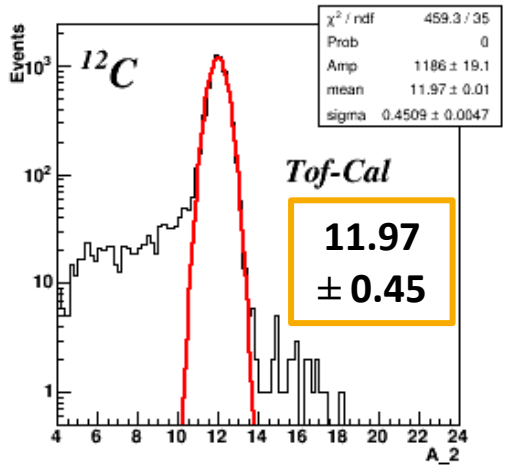
Helium should also be the less "clustering dependent" fragment

TOF (β) – CALO (E_{kin})

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

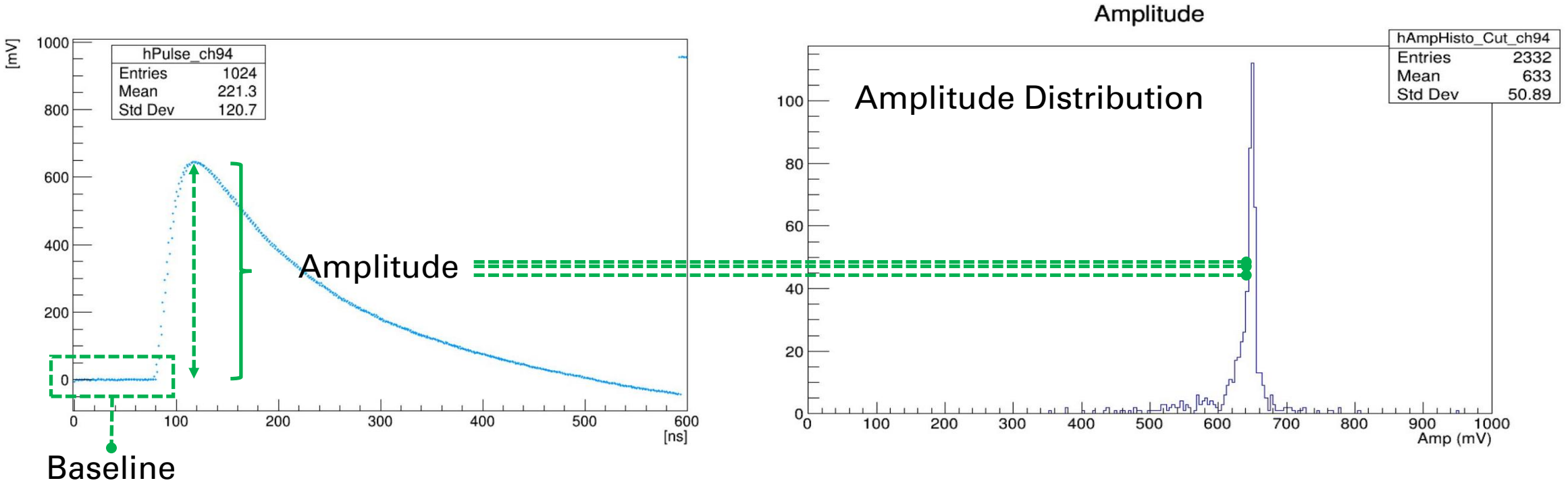


Fluka simulation ^{16}O (200 MeV/u) + C_2H_4



... Then we can say how well our detector is working!!!

Amplitude distribution



Energy Point: (E_{beam}, $Amplitude_{peak}$)