Energy response function and calibration of the **FOOT** calorimeter

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on behalf of the FOOT collaboration

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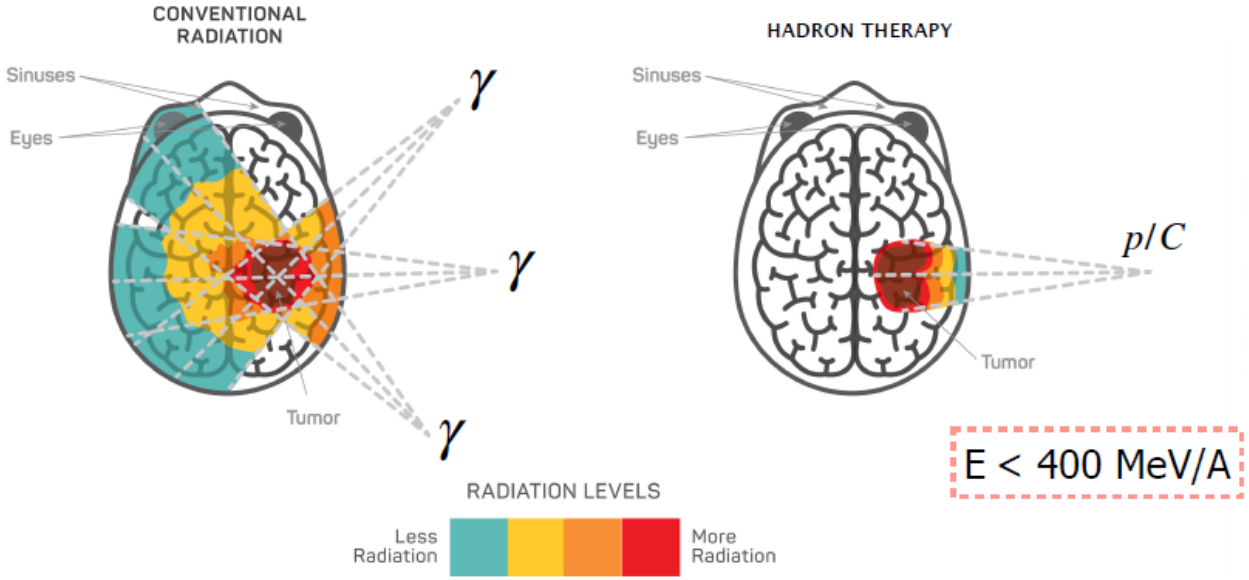
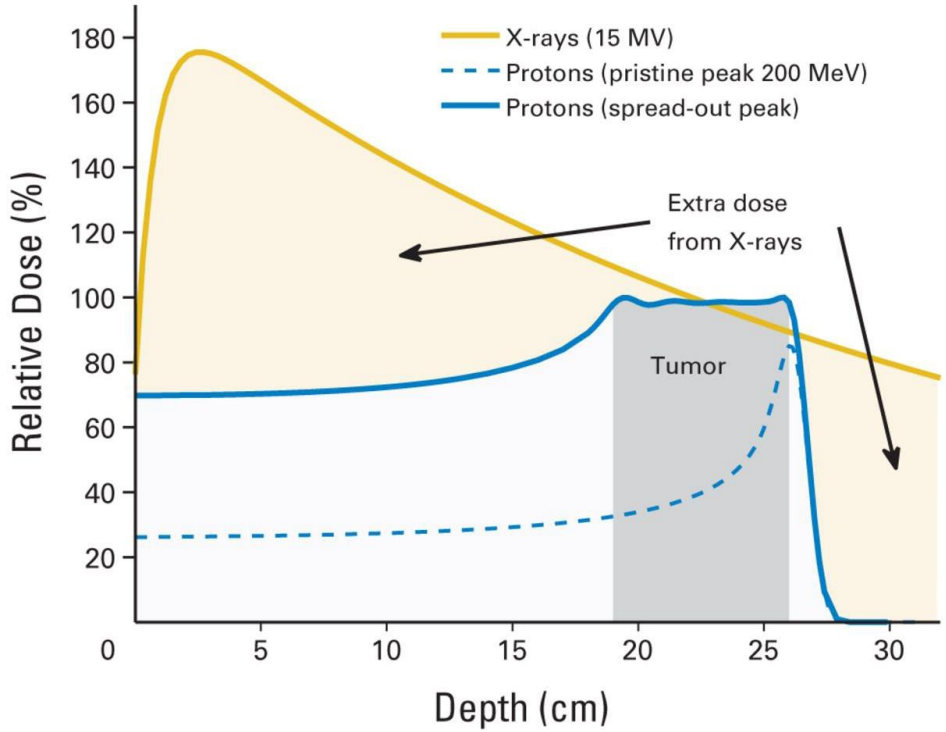
Particle Therapy

- ✓ 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

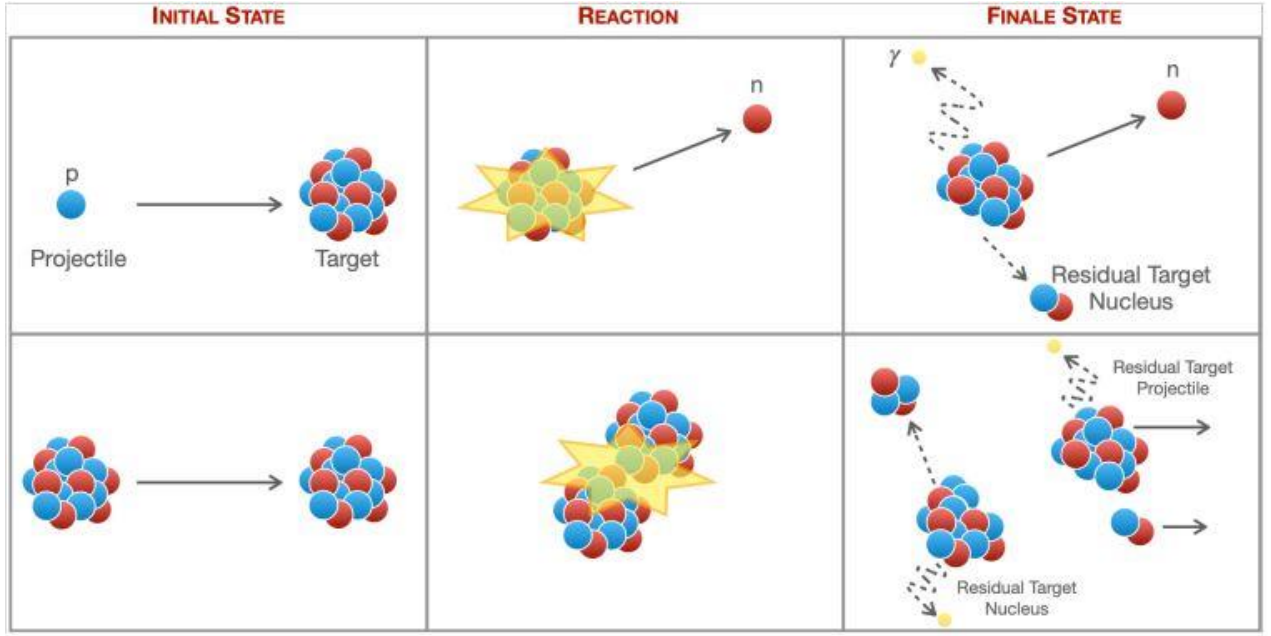
Nuclear Fragmentation

Target Fragmentation:

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

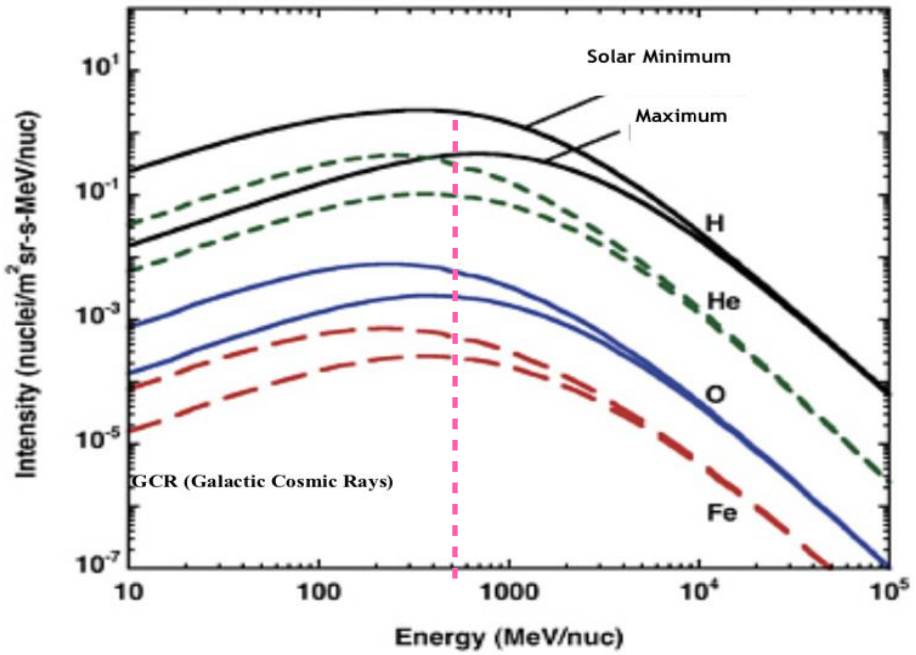
Beam Fragmentation:

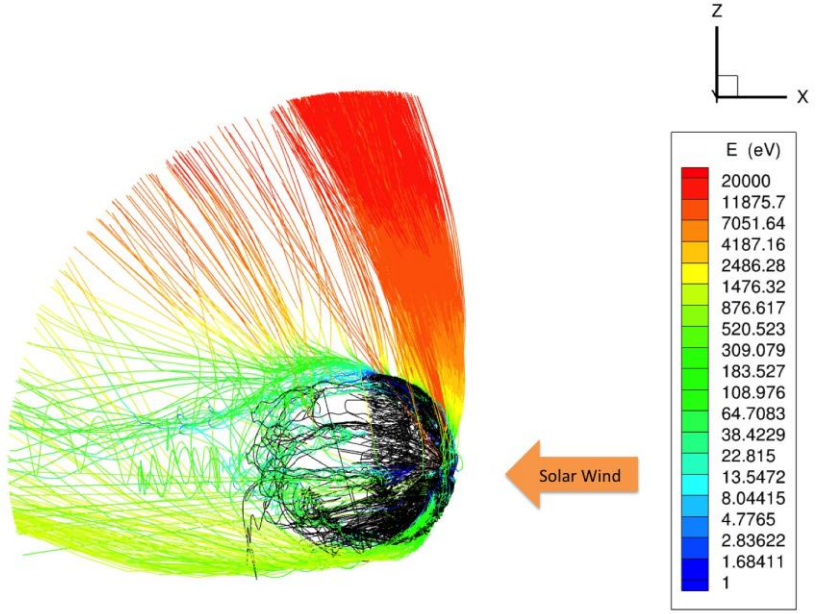
- ✓ Projectile fragments (longer range)
- ✓ Non-zero dose beyond the Bragg peak to address
- ✓ Not present in protontherapy



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

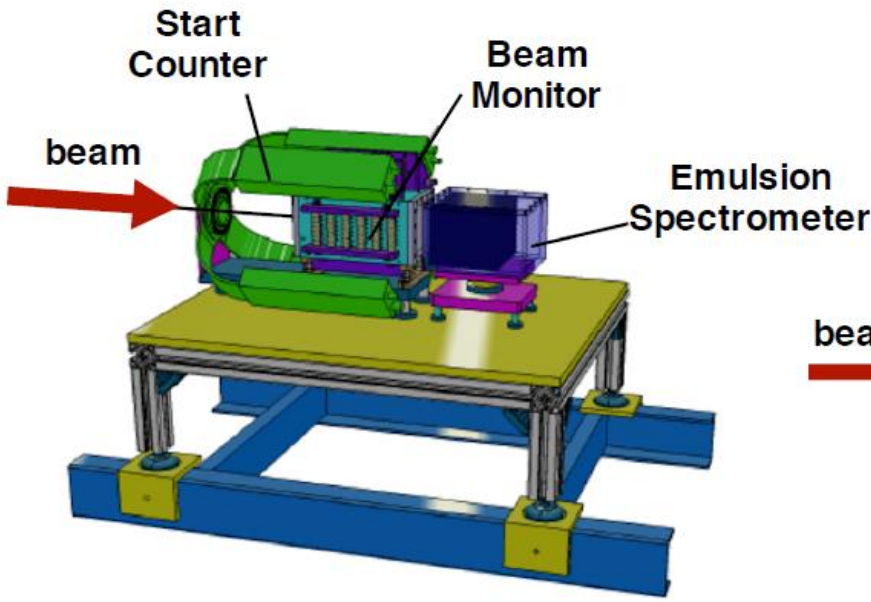
- ✓ Aim: measurement of beam and target fragmentation cross sections with 5% accuracy
- ✓ Experiment design to perform charge and mass identification at 2-3% and 5% accuracy
- ✓ Inverse kinematics approaches
- ✓ ^{4}He, ^{12}C, ^{16}O beams of 200-400 MeV/u on ^{12}C, C_2H_4 and $C_5O_2H_8$ targets (Hadronterapy)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

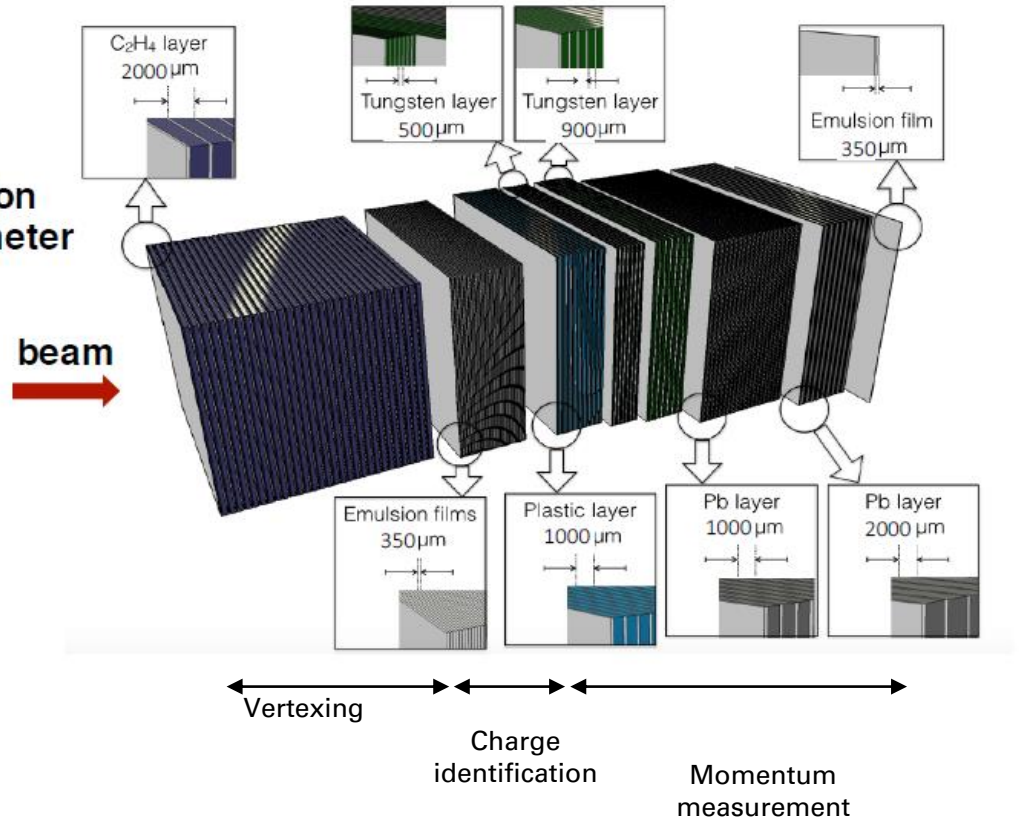
FOOT is a collaboration with about 100 members coming from

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

Emulsion Setup

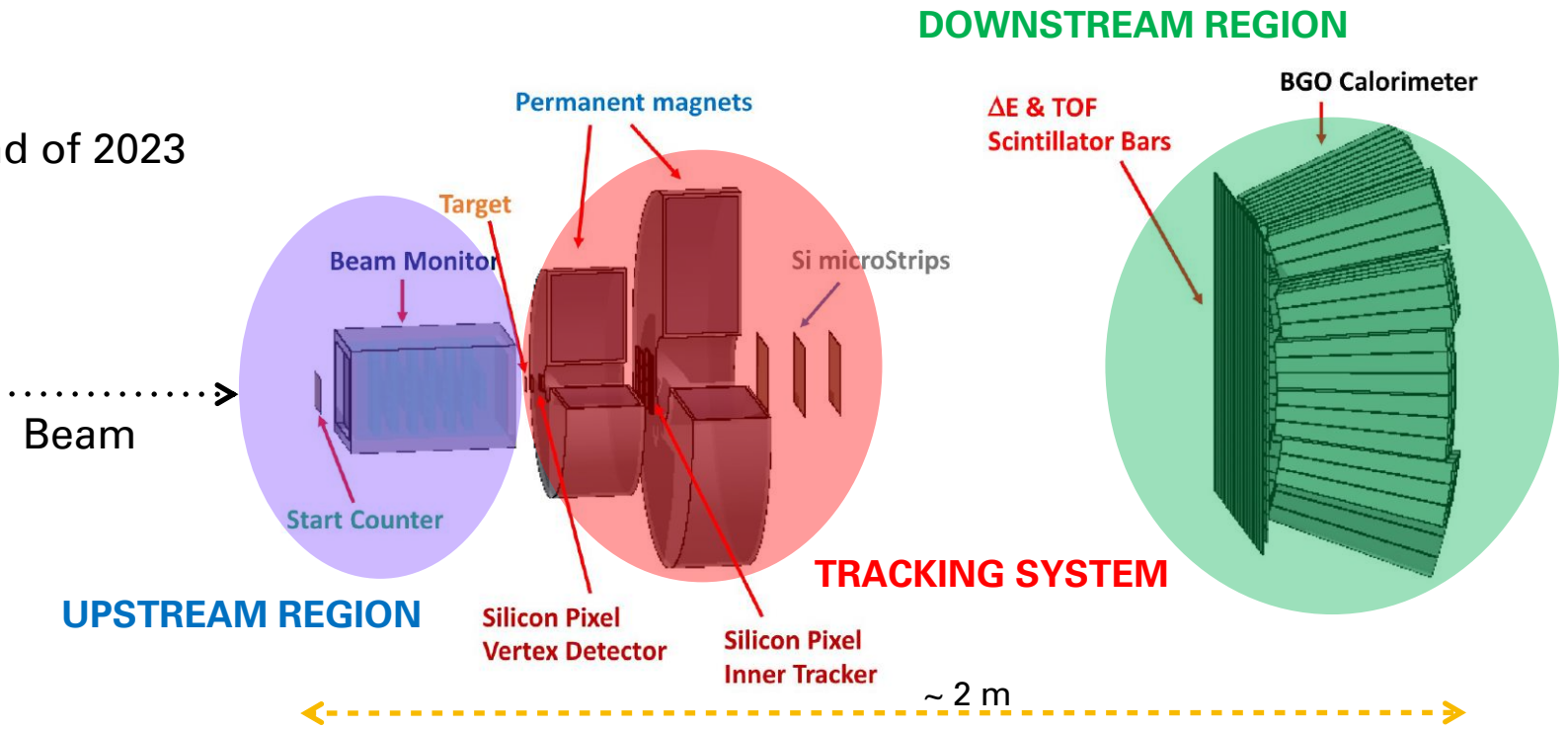
- ✓ Designed for light fragments (Z ≤ 3)
- ✓ Large angular acceptance (70°)
- ✓ Emulsions must be developed after irradiation
- ✓ Isotope identification





Electronic Setup

- ✓ Large variety of detectors
- ✓ Designed for heavier fragments ($3 \leq Z \leq 8$)
- ✓ Angular acceptance of 10°
- ✓ Will be completed by the end of 2023



Mass Reconstuction

TOF (β) – TRACKER (p)

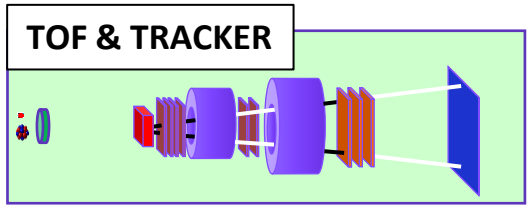
$$A_1 = \frac{m}{u} = \frac{p\sqrt{1-\beta^2}}{u\,\beta}$$

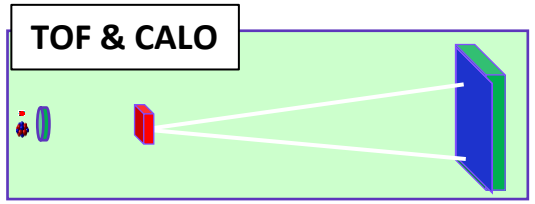
TOF (β) – CALO (E_{kin})

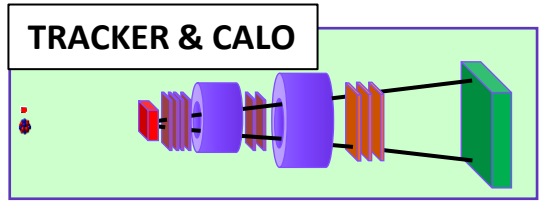
$$A_2 = \frac{m}{u} = \frac{E_{kin}}{u(\gamma - 1)}$$

TRACKER (p) – CALO (E_{kin})

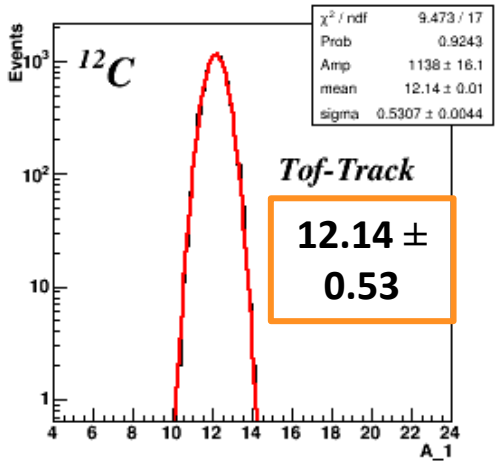
$$A_3 = \frac{m}{u} = \frac{p^2 - {E_{kin}}^2}{2E_{kin}}$$

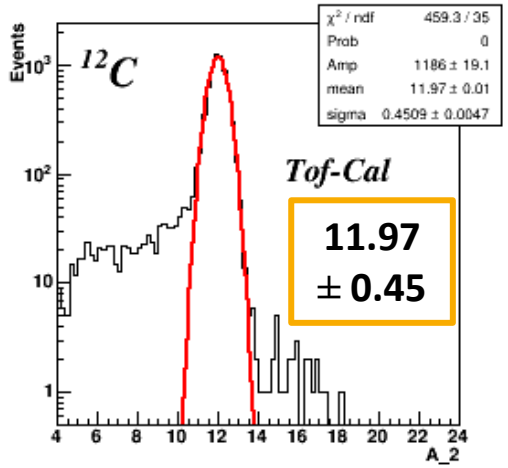


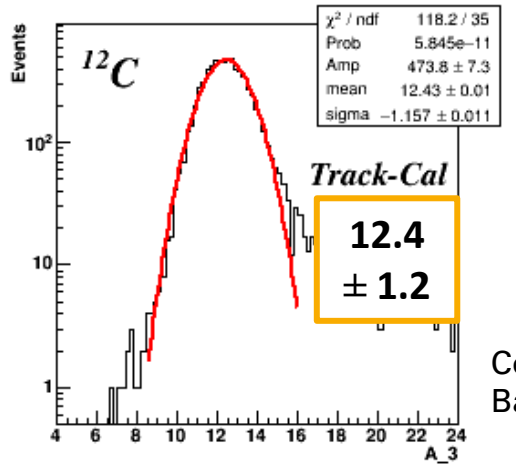




Fluka simulation ^{16}O (200 MeV/u) + C_2H_4



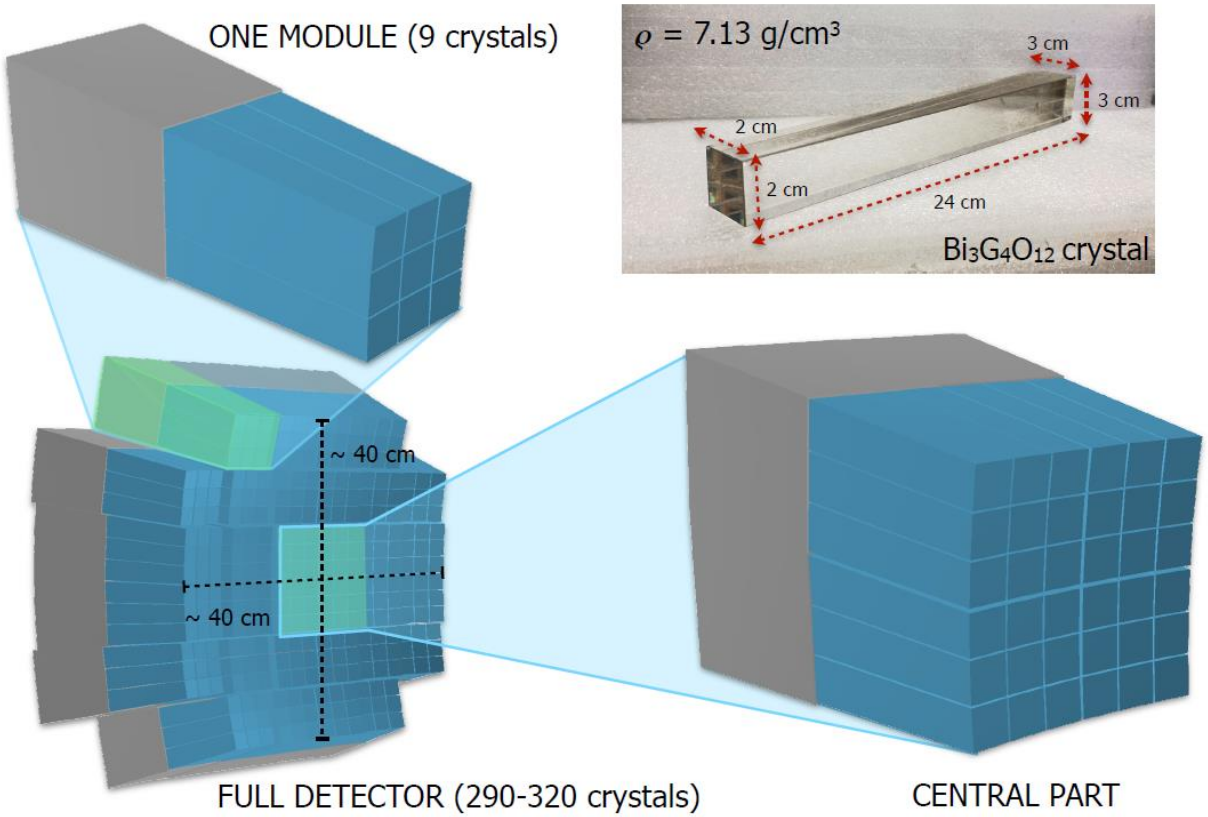




Courtesy of G. Battistoni

Calorimeter

- ✓ 320 BGO crystals grouped in modules (9 crystals for each module)
- ✓ Crystals dimension: 2x2 cm2 (front) 3x3 cm2 (back) 24 cm (lenght)
- ✓ SiPM based readout
- ✓ 31/37 modules fully assembled (glueing completed)
- ✓ Measurement of the kinetic energy

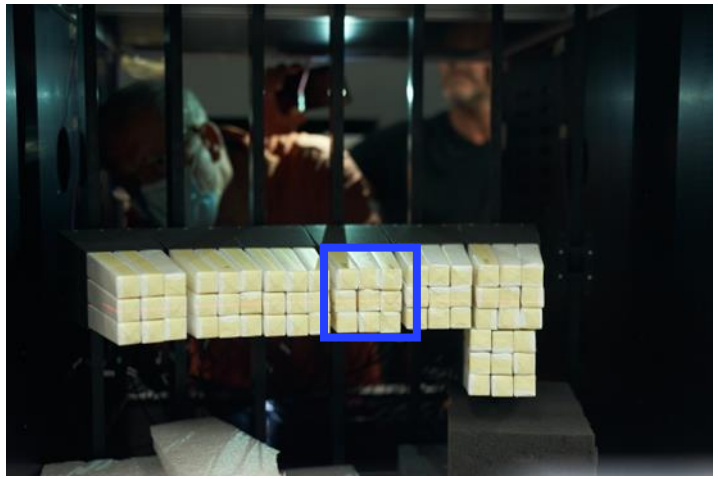


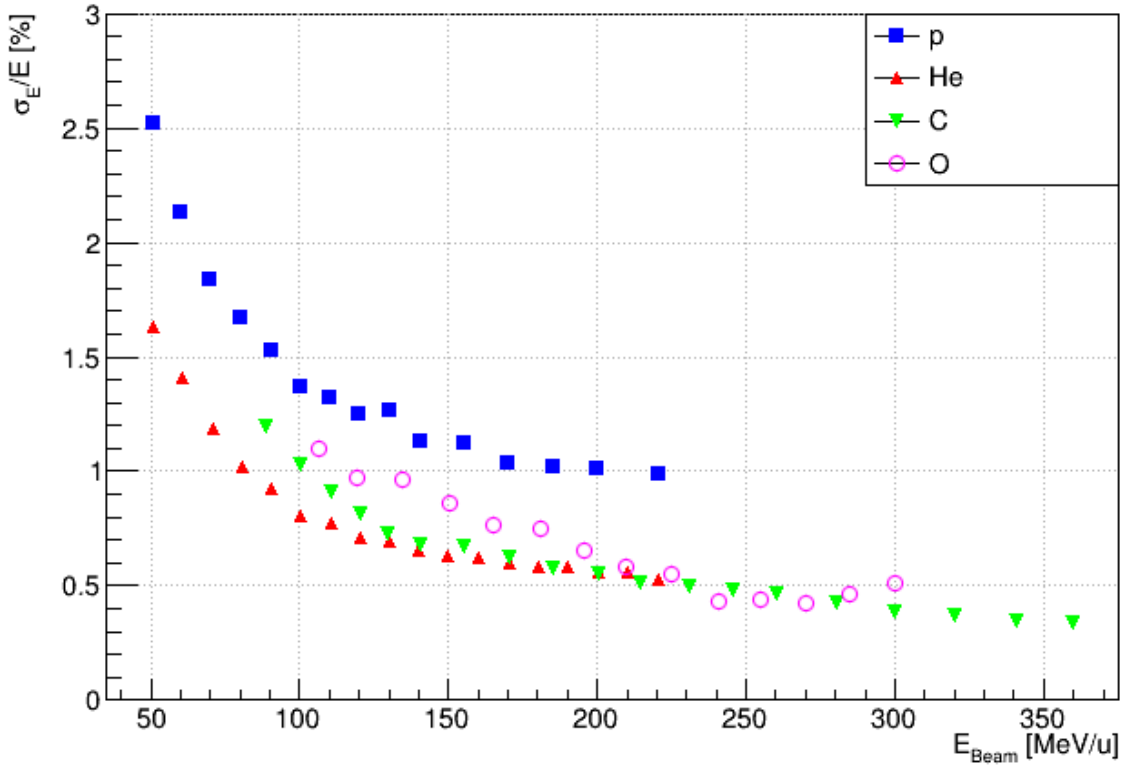
Two different data acquisition campaigns for calibration and equalisation:

- ✓ Heidelberg Ion Therapy center (HIT) in July 2022
- ✓ CNAO in November 2022

HIT Setup

- ✓ 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 per different ions

Energy Calibration Curves

- ✓ The calorimeter linearity is affected by the Birks effect

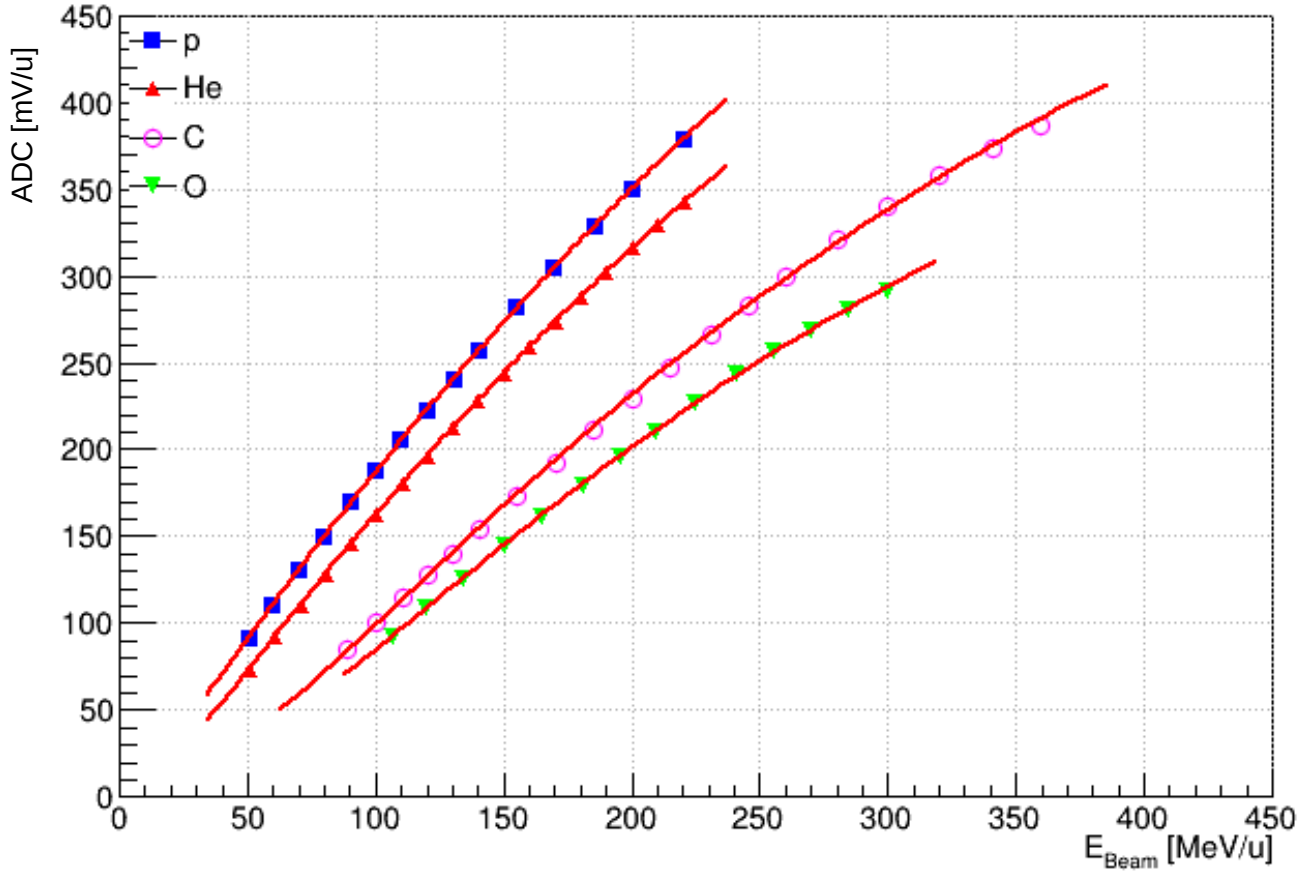
$$\frac{dS}{dx} = \frac{A \cdot dE/dx}{1 + k \cdot B \cdot dE/dx}$$

- ✓ There is clear dependence on Z
- ✓ The chosen fit function is a modified Birks function with three free parameter

$$ADC(E) = \frac{p_0 x^2}{1 + p_1 x + p_2 x^2}$$

- ✓ Good fitting of experimental data

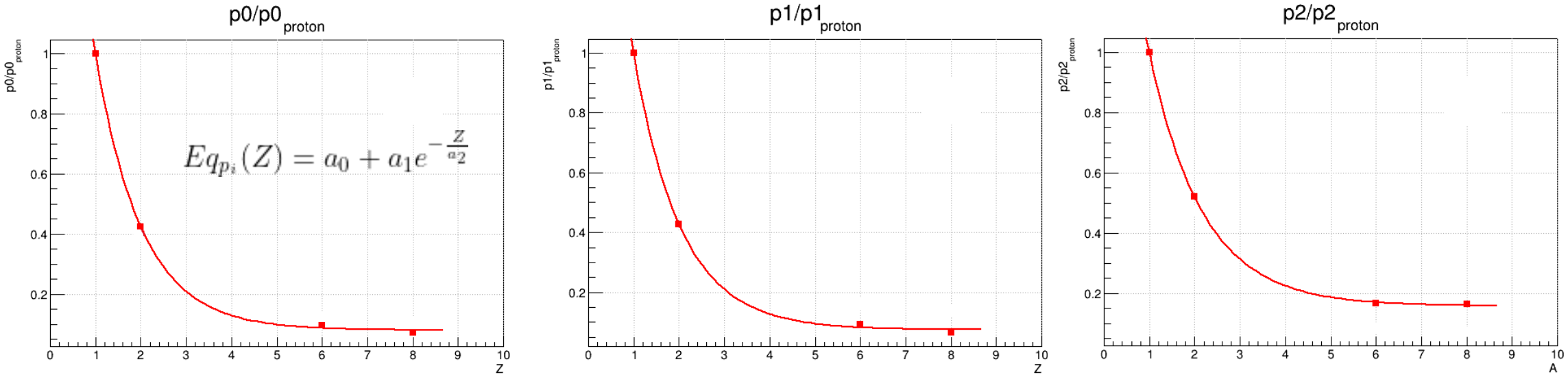
$$\frac{|E_{fit} - E_{ADC}|}{E_{fit}} < 1\%$$



Atomic Number Dependance

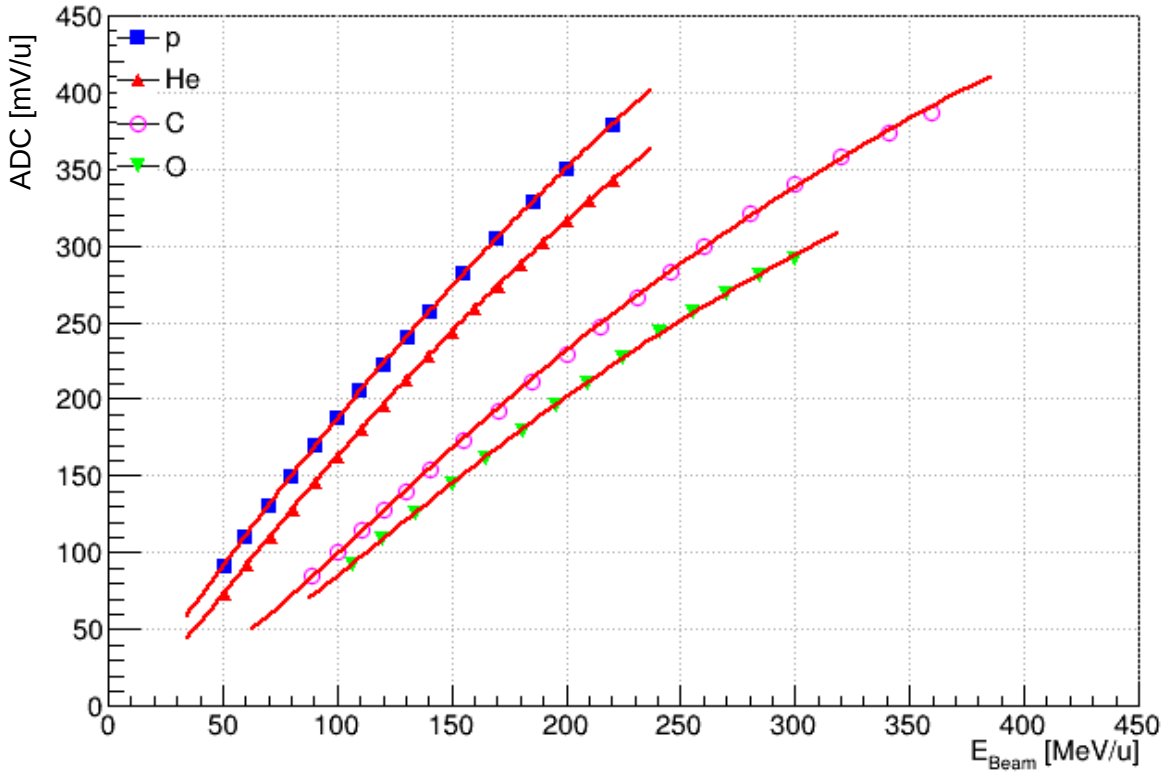
Is it possible to adress the Z dependence problem?

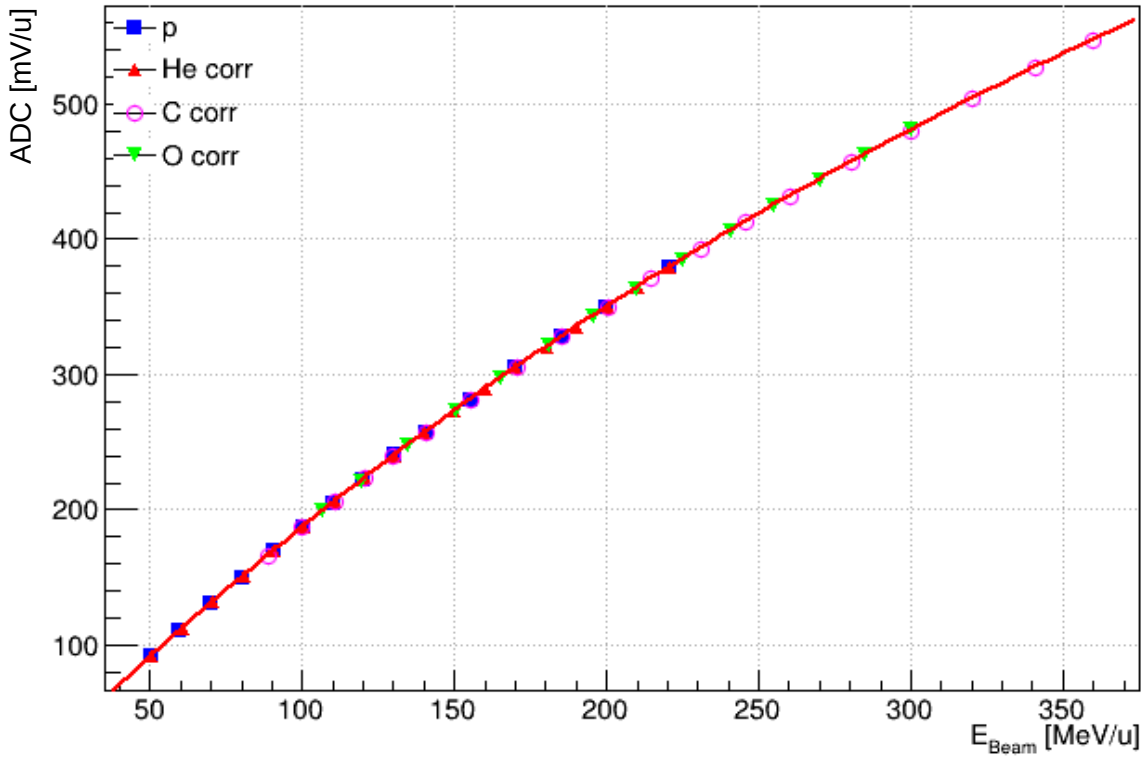
$$ADC(E) = \frac{p_0 x^2}{1 + p_1 x + p_2 x^2}$$



Ratio of energy calibration curve parameters to proton curve parameters follow an exponential law → By measuring Z we can equalize the ADC response for different particle

Energy Equalization





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

CNAO Setup

- ✓ Setup with twelve fully assembled modules
- ✓ TofWall on beam line
- ✓ Beam in "Screensaver Mode": sweeping 72 crystal during each run in about 15 minutes
- ✓ Scan at three different energies 115, 200, 300 MeV/u with Carbon ions

Two different strategies have been used in order to equalize crystal response, both using the modified Birks function

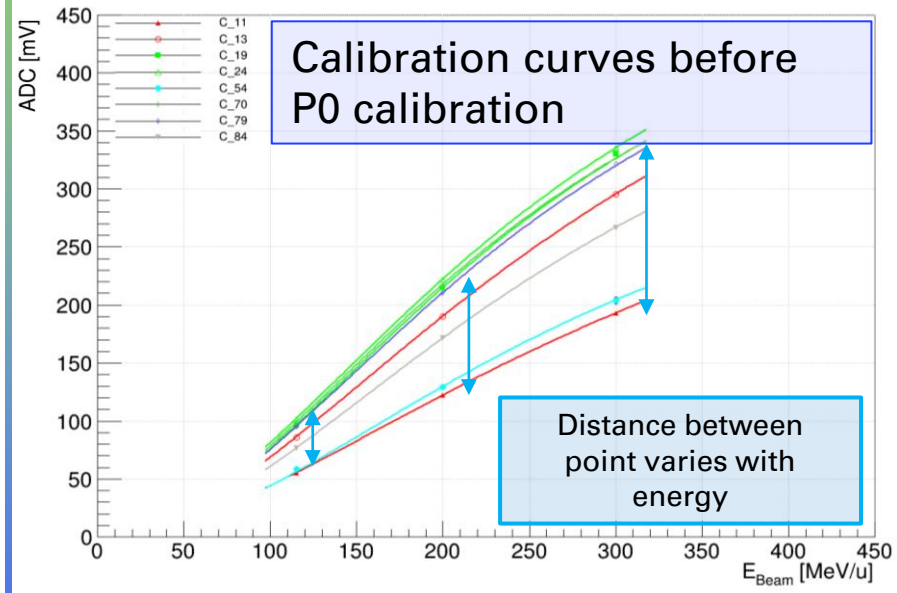
$$ADC(E) = \frac{p_0 x^2}{1 + p_1 x + p_2 x^2}$$

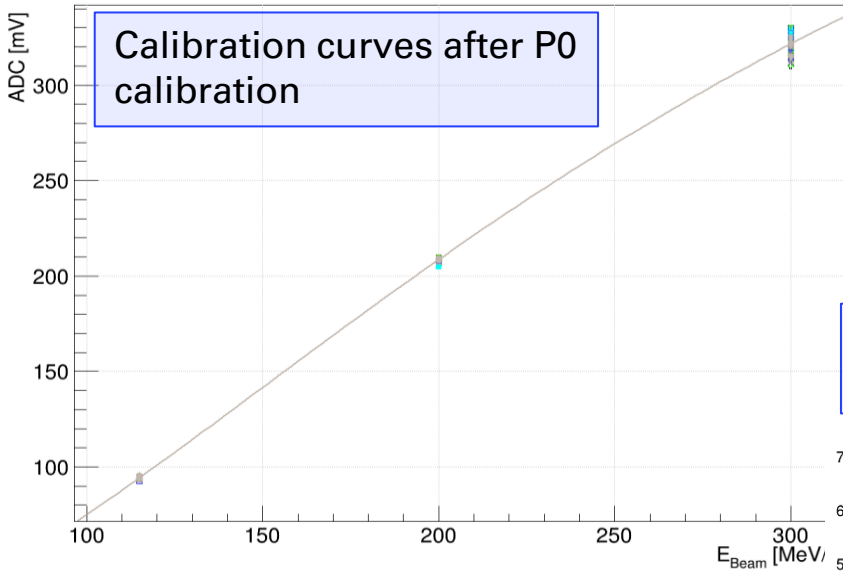
Equalization with a single multiplying factor

Equalization done by calculate energy response curve for each crystal

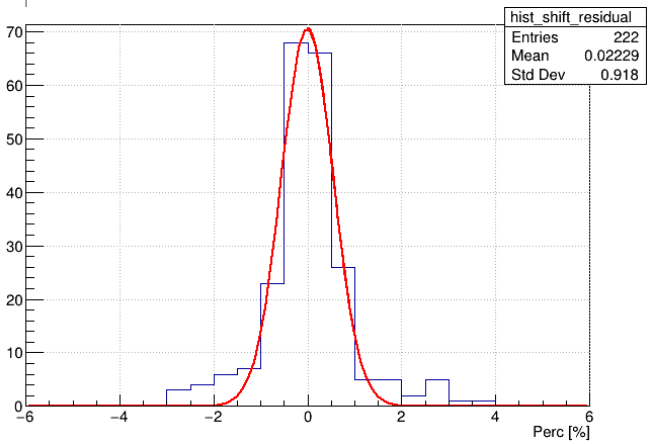
Single Factor

Fit reference crystal with free parameter → Fit all other crystals with P1 and P2 fixed → $P0_{23}/P0_{cry}$ is the intercalibration factor





Residual distribution after P0 calibration

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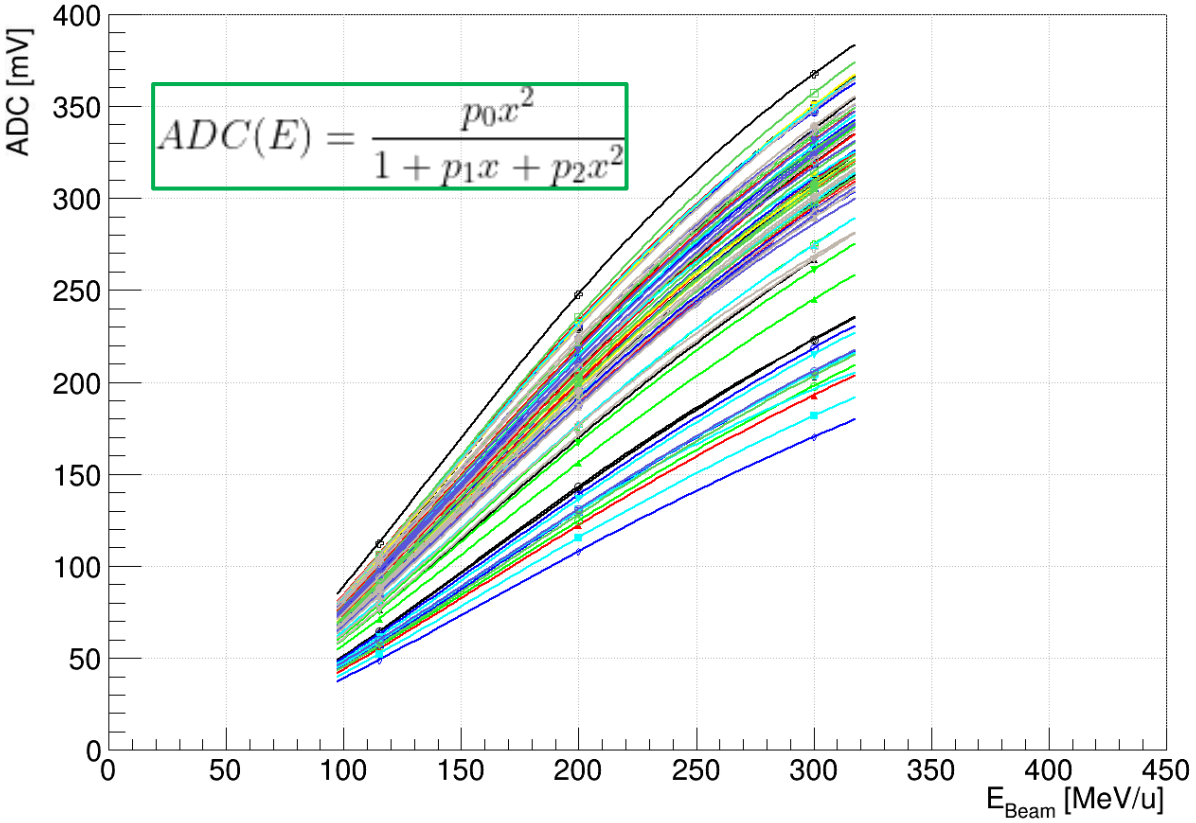
                     EDM=4.16105e-09    STRATEGY= 1      ERROR MATRIX ACCURATE
 EXT PARAMETER                                   STEP         FIRST
 NO.   NAME      VALUE            ERROR          SIZE      DERIVATIVE
  1  Constant     7.06857e+01   7.06111e+00   1.31198e-02   1.14155e-05
  2  Mean         2.19694e-03   3.96364e-02   1.02058e-04  -6.93488e-04
  3  Sigma        5.49849e-01   3.82597e-02   3.18030e-05   6.88296e-03
```

Response Curves



Three Carbon energy screensaver points

↓

For each crystal we obtain p0, p1 and p2

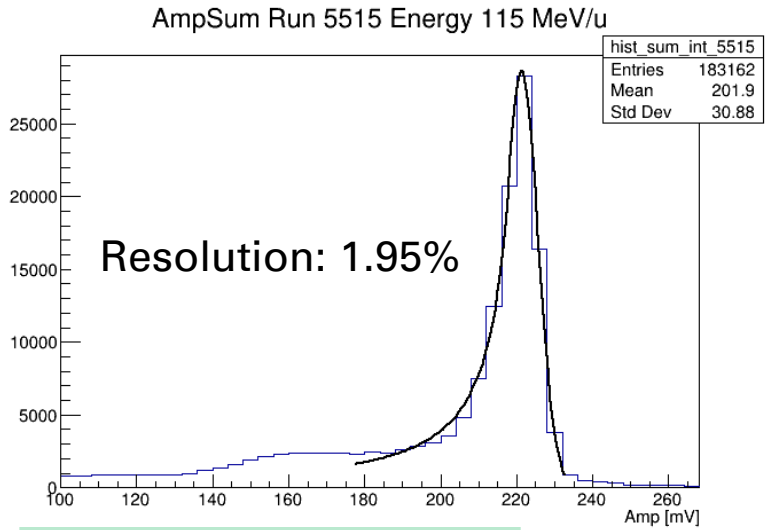
↓

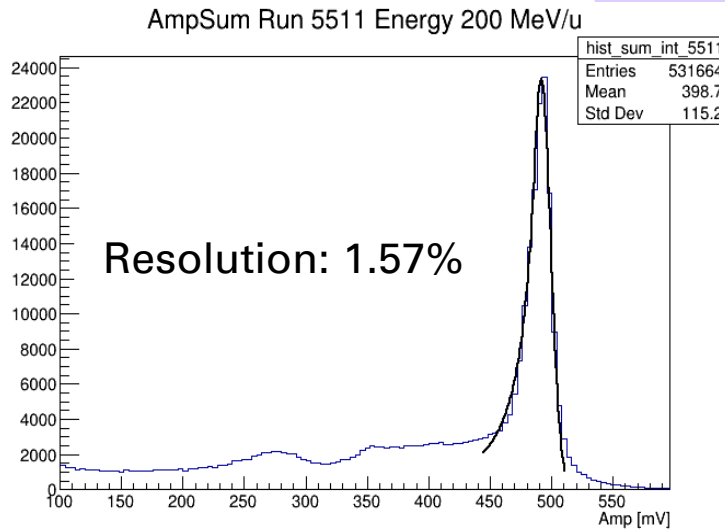
Energy esteemed as inverse modified Birks

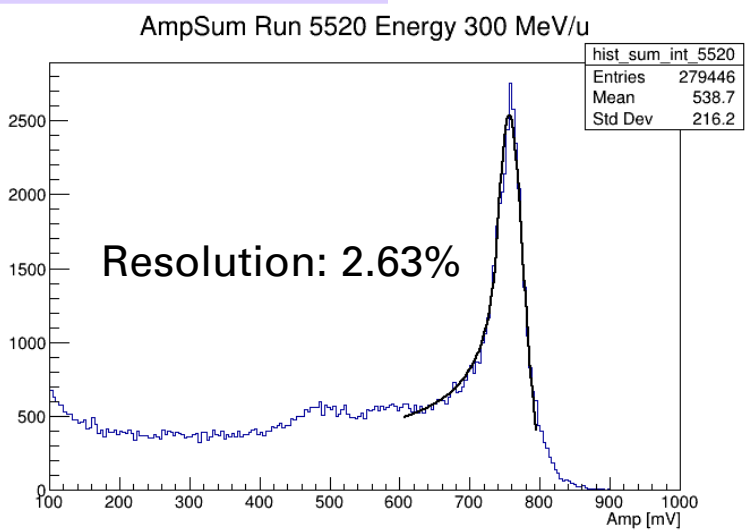
$$E(ADC) = \frac{-p_1 ADC - \sqrt{(p_1 ADC)^2 - 4ADC(p_2 ADC - p_0)}}{2(p_2 ADC - p_0)}$$

Method Comparison

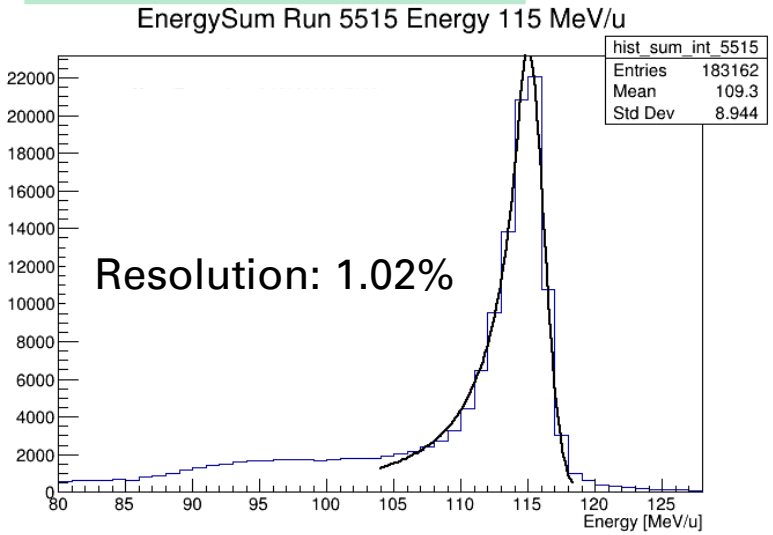
Single multiplying factor

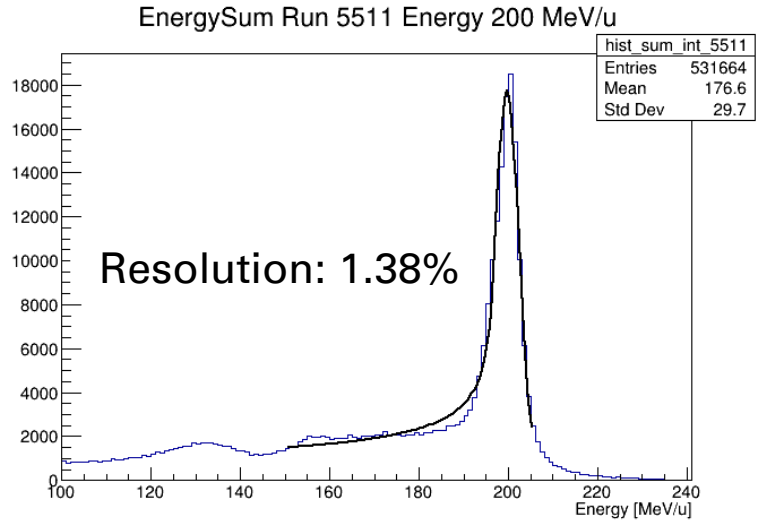


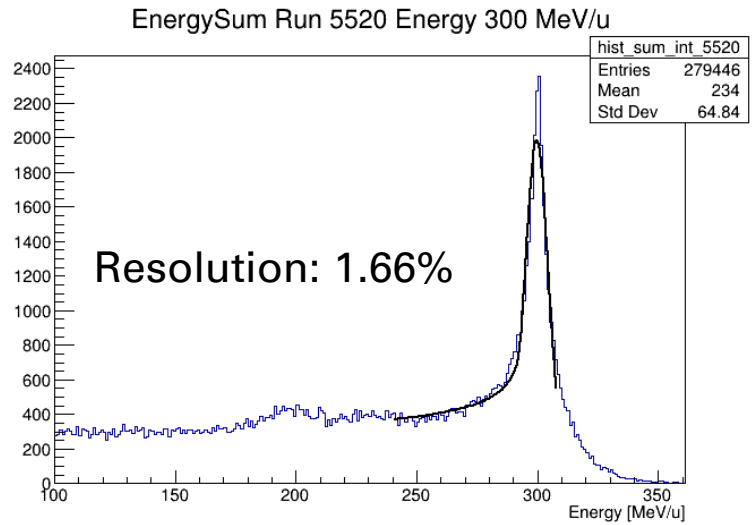




Energy response curve

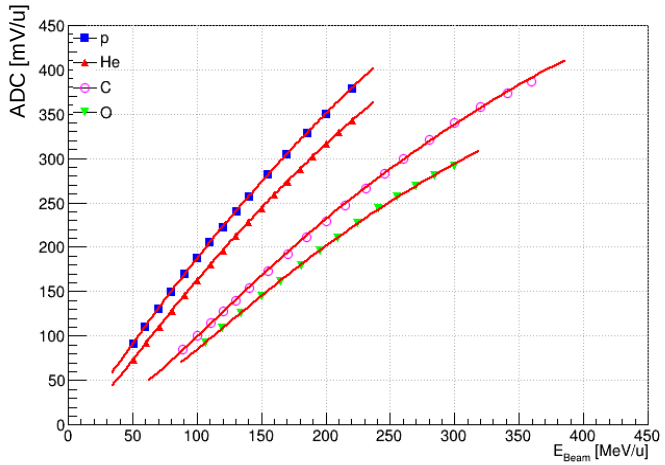


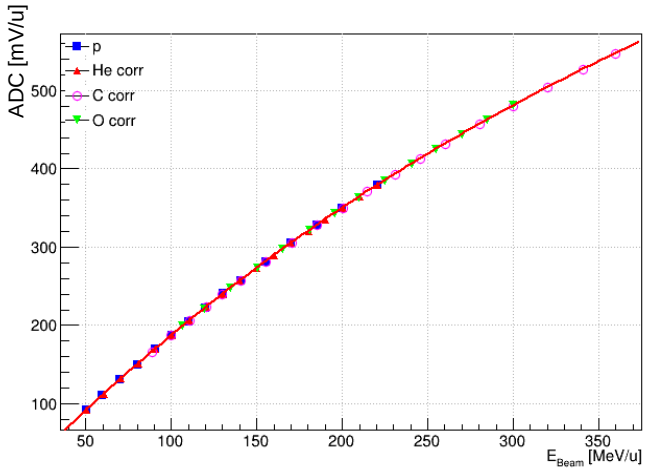


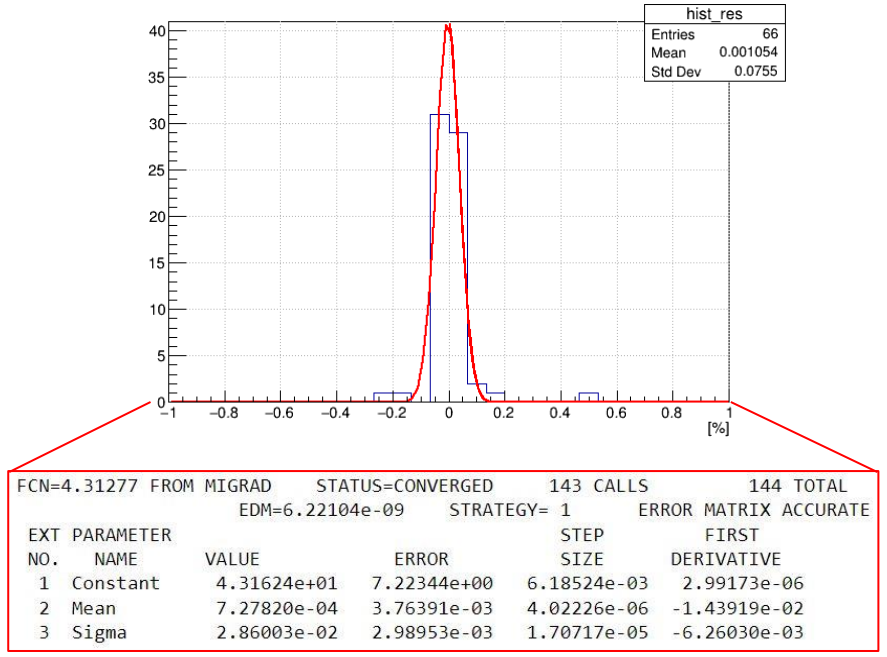


Conclusions

- ✓ Energy Calibration is under control: particle equalization leads to a < 1% residual distribution
- ✓ Fast Equalization strategy founded: worst case scenario still meets experimental requirement resolution < 2%








```
FCN=4.31277 FROM MIGRAD    STATUS=CONVERGED      143 CALLS          144 TOTAL
                     EDM=6.22104e-09    STRATEGY= 1      ERROR MATRIX ACCURATE
 EXT PARAMETER                                   STEP         FIRST
 NO.   NAME      VALUE            ERROR          SIZE      DERIVATIVE
  1  Constant     4.31624e+01   7.22344e+00   6.18524e-03   2.99173e-06
  2  Mean         7.27820e-04   3.76391e-03   4.02226e-06  -1.43919e-02
  3  Sigma        2.86003e-02   2.98953e-03   1.70717e-05  -6.26030e-03
```

Timeline: first data taking with the full detector @ CNAO in 2023