

Response of a nitrogen-filled Spherical Proportional Counter to MeV-energy neutrons

T. Avgitas¹, M. Axiotis², Z. Balmforth¹, P. Gadow¹, I. Giomataris⁵, D. Fassouliotis³, J. Fock¹, P. Knights⁴, A. Lagoyannis², **I. Manthos¹**, L. Millins¹, K. Nikolopoulos^{1,4}, I. Oceano¹, K. Prodromou³, L. Schweder¹, E. Taimpiri², C. Toukmenidis¹, R. Ward¹, A. Ziagkova²

¹University of Hamburg, Institute for Experimental Physics, Hamburg, 22761, Germany

³National and Kapodistrian University of Athens, Department of Physics, 157 84, Athens, Greece

²NCSR "Demokritos, Institute of Nuclear and Particle Physics, Athens, 153 10, Greece

⁴University of Birmingham, School of Physics and Astronomy, B15 2TT, UK

⁵IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, F-91191, France

Introduction

Underground Dark Matter searches: MeV-scale neutrons are a critical background that can **mimic WIMP signals** through elastic scattering with target nuclei.

Main sources: natural radioactivity and **muon-induced showers** in the underground environment and detector materials.

Neutron rejection: shielding and the use of **high-purity materials** help minimise neutron backgrounds.

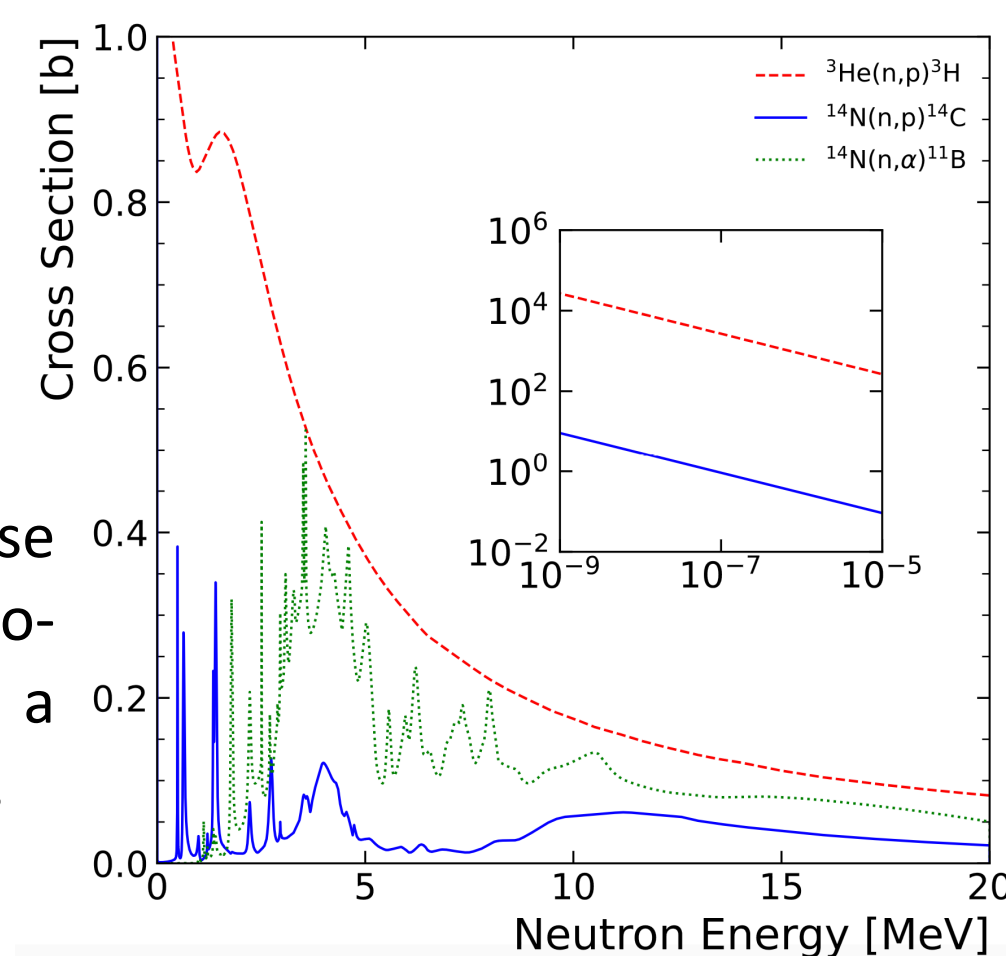
An N_2 -filled SPC enables neutron spectroscopy through the following nuclear reactions:

- $^{14}\text{N} + n \rightarrow ^{14}\text{C} + p + 625 \text{ keV}$
- $^{14}\text{N} + n \rightarrow ^{11}\text{B} + \alpha - 159 \text{ keV}$

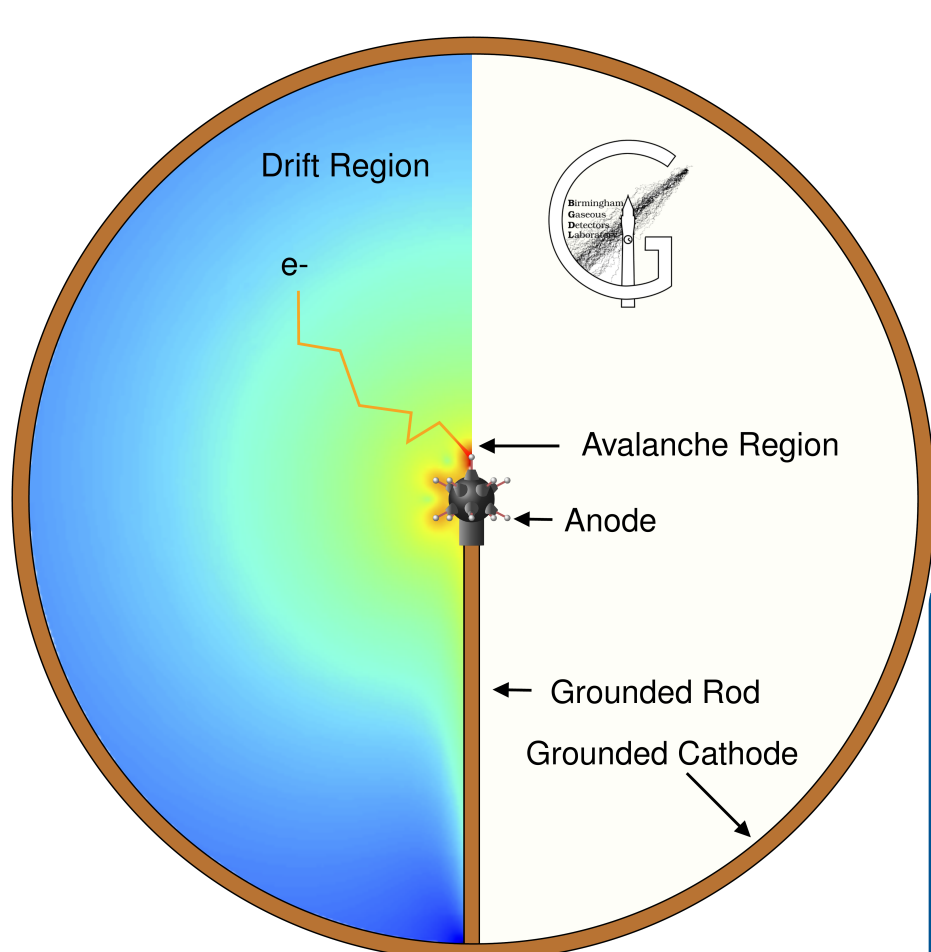
Following the demonstration of the method [1] and detector response measurements with broad-spectrum neutron sources [2,3], mono-energetic neutron beams are required to characterise the SPC as a neutron spectrometer. This work presents such a characterisation [4].

Neutron spectroscopy: key technique for Dark Matter, neutrinoless double-beta decay, medical imaging, and materials analysis.

Background estimation: accurate prediction of the expected neutron background is essential to **compare with the observed number of events**.



Spherical Proportional Counter



The SPC is a novel gaseous detector with several advantages, including low capacitance.

$$C = 4\pi\epsilon\epsilon_0 \frac{r_a r_c}{r_c - r_a} \approx 4\pi\epsilon\epsilon_0 r_a$$

$$\vec{E}(r) = \frac{V_0}{r^2} \frac{r_a r_c}{r_c - r_a} \hat{r} \sim V_0 r_a \frac{1}{r^2} \hat{r}$$

r_a : Anode radius
 r_c : Cathode radius
 ϵ_0 : Electric permittivity of the vacuum
 ϵ : Electric permittivity of the gas used

Separates the detector volume into:

- A large drift region $\rightarrow$ primary ionisations e^- are drifting towards the anode
- A small avalanche region near the anode surface $\rightarrow$ the field is sufficiently strong to induce charge multiplication and provide signal amplification

The moving charges induce the signal in the detector

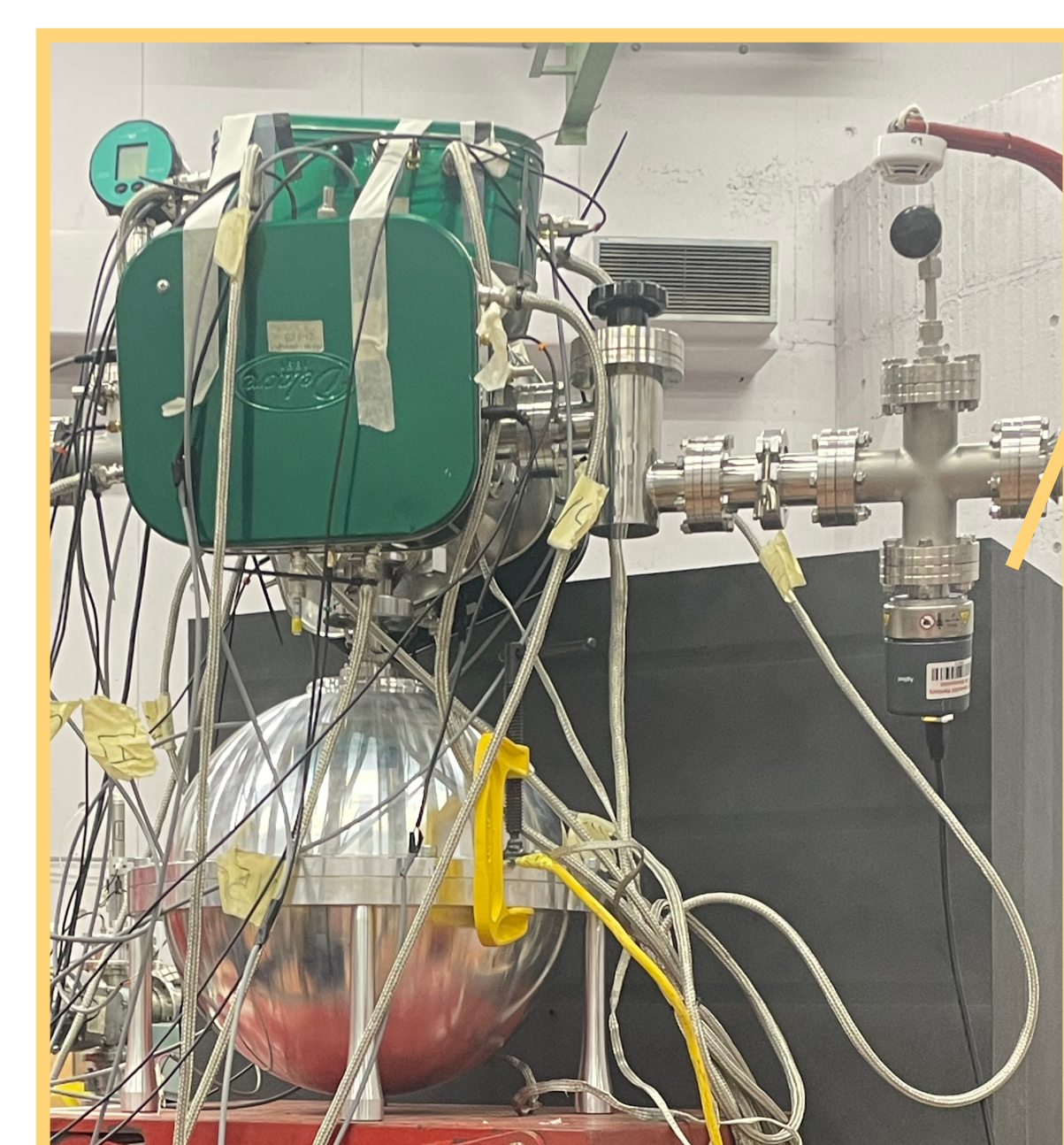
- Electrons drift toward the anode
- Positive ions drift toward the grounded shell

[1] 10.1016/j.nima.2016.11.007 [3] 10.1016/j.nima.2022.167590
[2] 10.1016/j.nima.2023.168124 [4] arXiv:2609.07541

Experimental setup - NCSR Demokritos

The Tandem Accelerator Laboratory is the major research facility of the Institute of Nuclear and Particle Physics of the National Centre for Scientific Research "Demokritos" in Athens [7]. It features a 5.5 MV T11/25 Van de Graaff Tandem accelerator manufactured by the High Voltage Engineering Corporation (HVEC).

The facility provides monoenergetic neutron beams with fluxes of approximately $10^5 - 10^6 \text{ cm}^{-2}\text{s}^{-1}$ neutrons in the energy ranges from thermal to 450 keV, 4 – 11.5 MeV and 16 – 20.5 MeV by using the $^7\text{Li}(p, n)$, $^2\text{H}(d, n)$ and $^3\text{H}(d, n)$ reactions.



Shielding: High density polyethylene containing 10% Boron



- A 30 cm diameter, nitrogen-filled, spherical proportional counter made of aluminium
- Equipped with an 11-anode ACHINOS sensor
- Mono-energetic neutrons were produced via the $^7\text{Li}(p, n)^7\text{Be}$ reaction, with protons of energy E_p impinging on a LiF target

[7] 10.1140/epjp/s13360-021-01596-5

Conclusion

- First detection and spectroscopic measurement of mono-energetic neutrons with a N_2 -filled SPC at an accelerator facility have been presented
- The linearity of the detector in the probed energy range has been demonstrated
- Future measurements exploring a broader range of neutron energies will allow the unfolding of the detector response and the reconstruction of the incoming neutron energy spectrum.

This work has been supported by the DFG under Germany's Excellence Strategy — EXC 2121 "Quantum Universe" — 390833306.

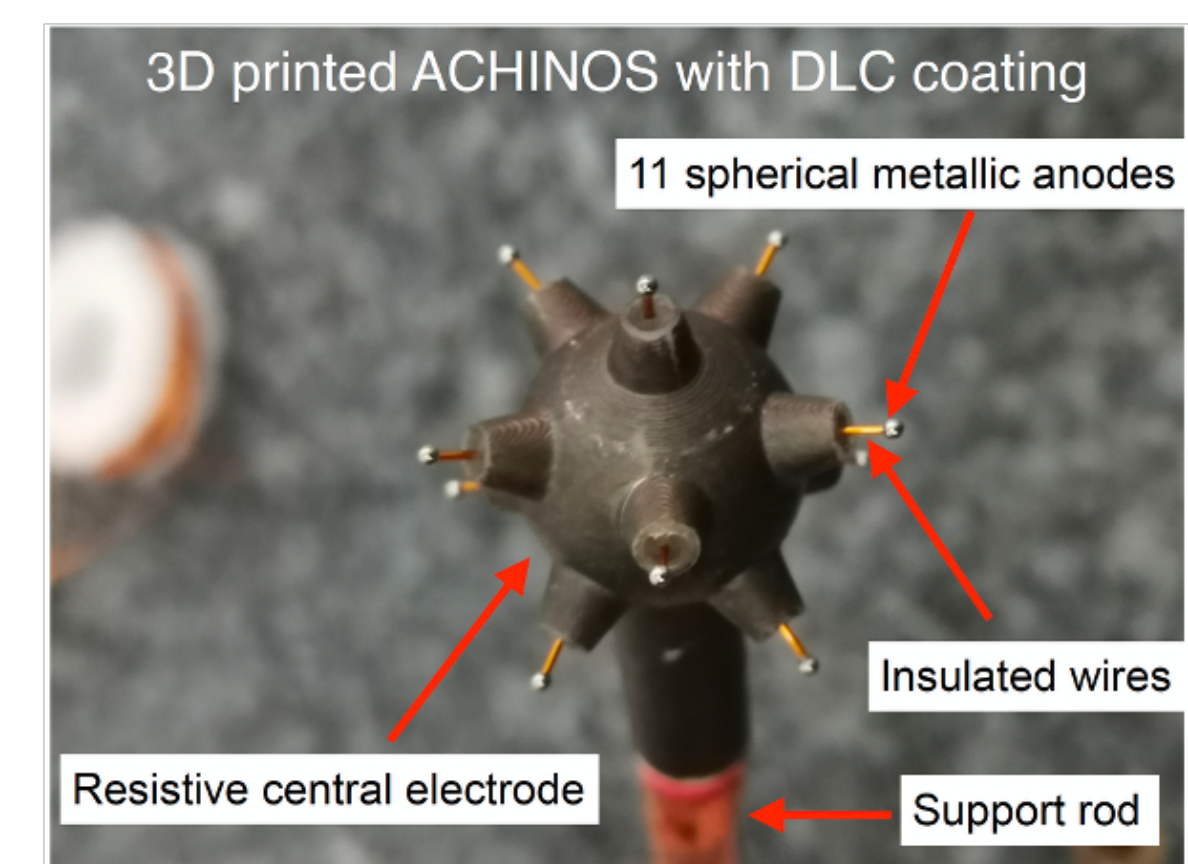
ACHINOS multi-anode sensor

A single-anode read-out $\rightarrow$ the anode voltage and radius control both the drift and the amplification fields.



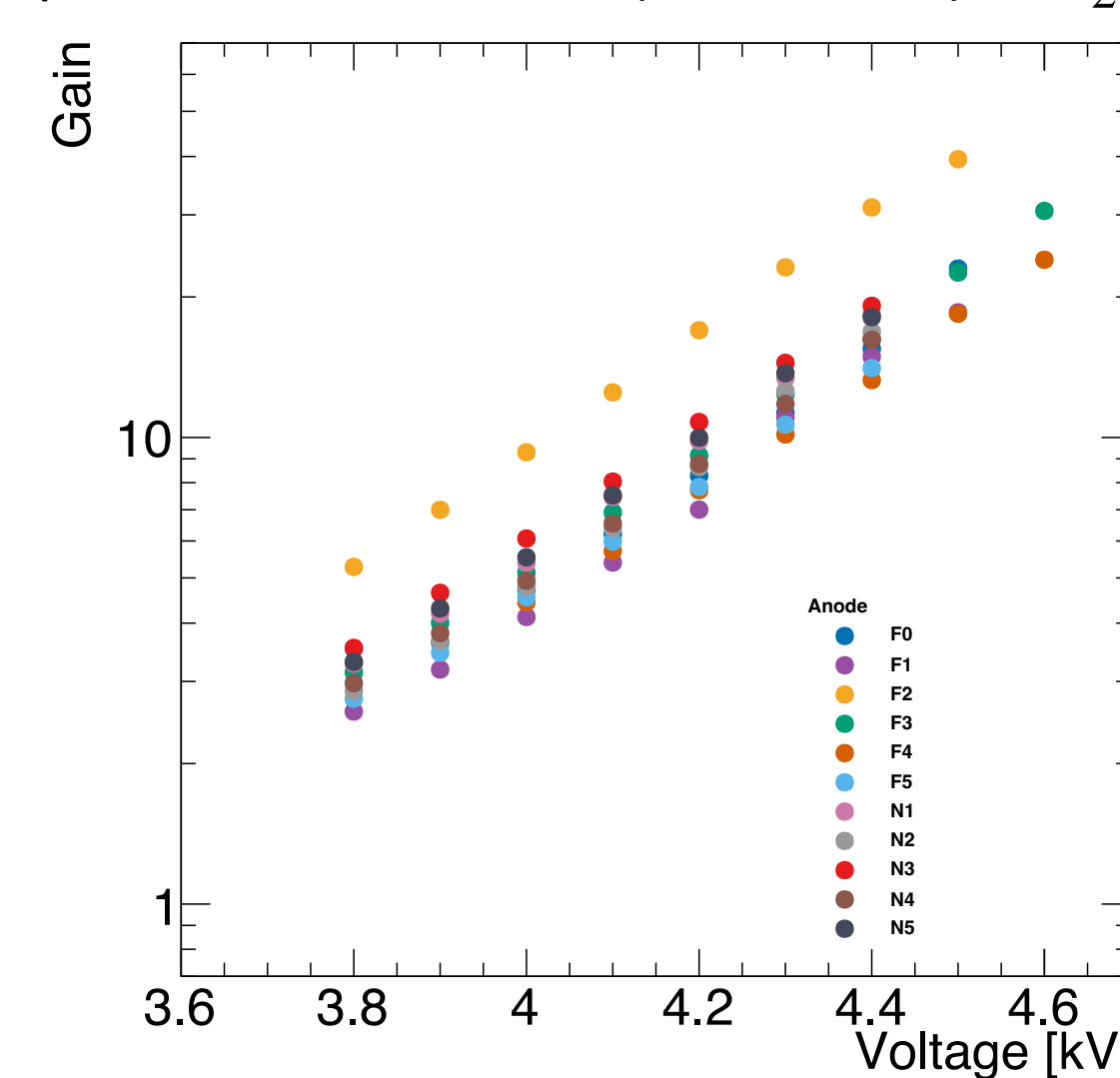
The **ACHINOS multi-anode sensor** [5, 6] overcomes this limitation by placing several anodes

- The drift field in the detector bulk is the collective contribution of all anodes
- The radius and voltage of each individual anode locally determine the amplification field.



Sensor characterisation:

α particles from ^{241}Am (5.49 MeV) in N_2 at 1 bar



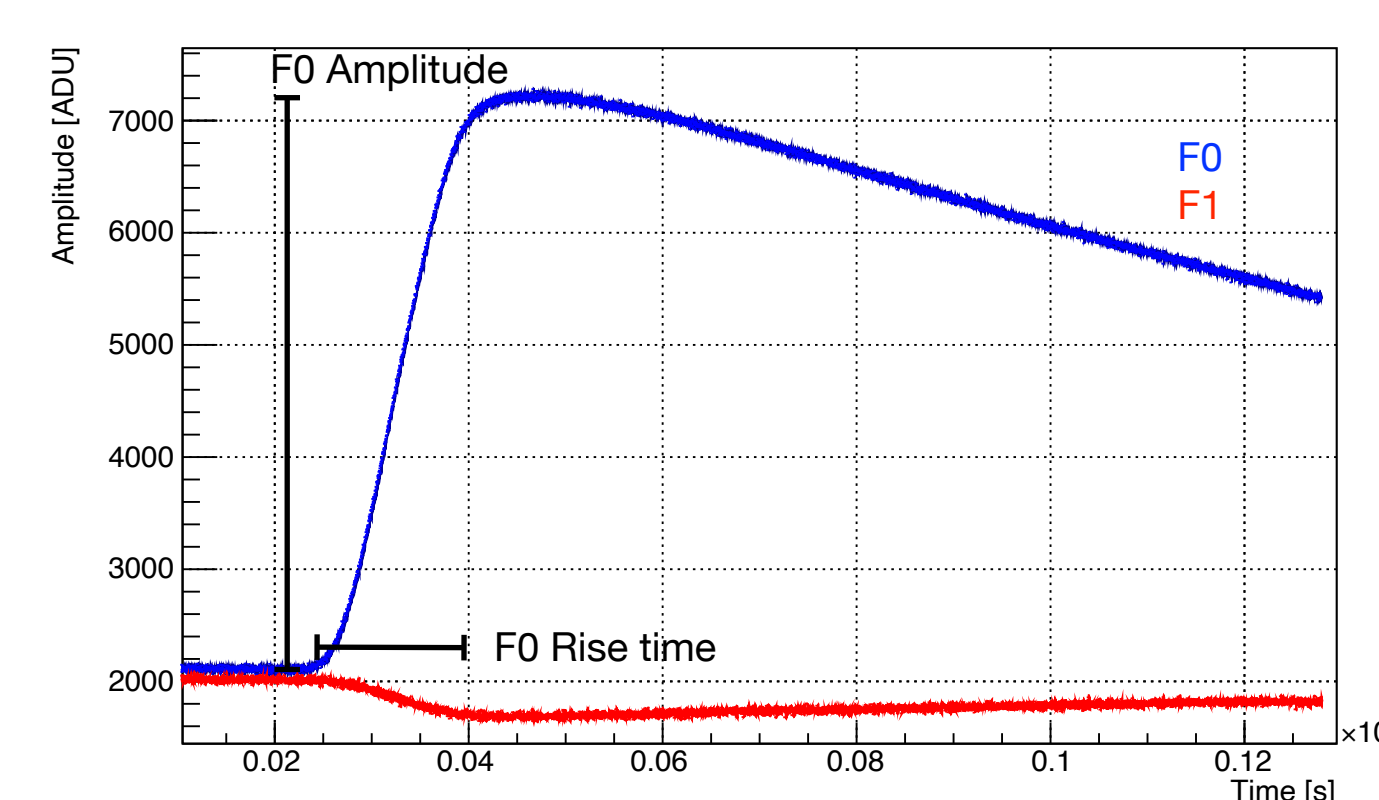
11-anode ACHINOS

- Spherical stainless steel anodes
- $r_a = 1 \text{ mm}$
- DLC coated central structure

- Individual anode bias and readout
- Increased target mass allowed
- Improved detector energy resolution
- TPC-like capabilities

[5] JINST 15 P11023
[6] JINST 19 P01018

Experimental results

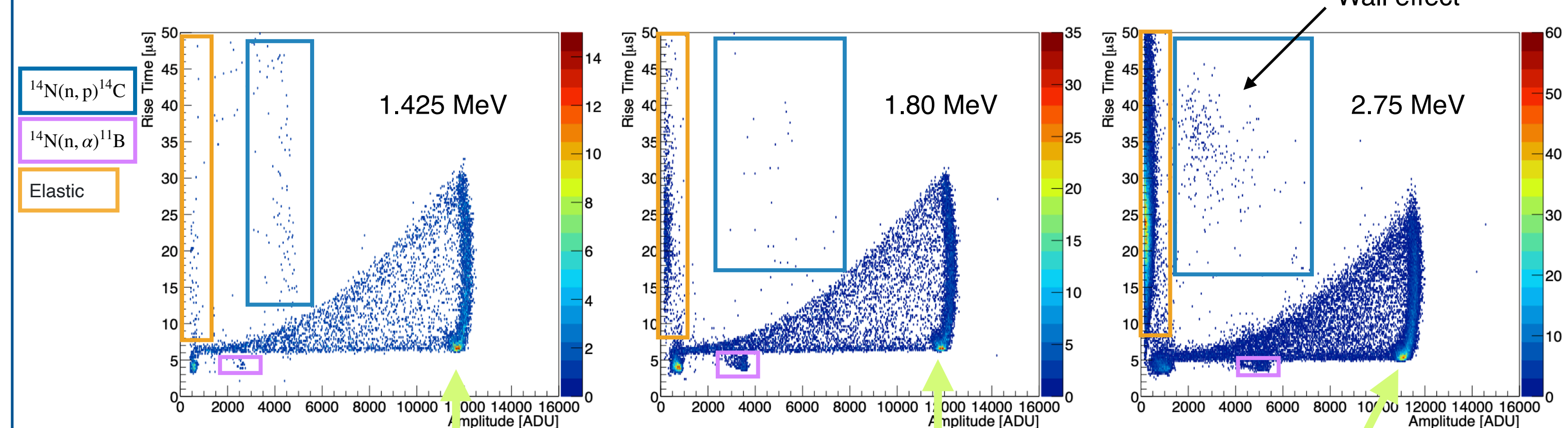


Neutron beam directed onto F0

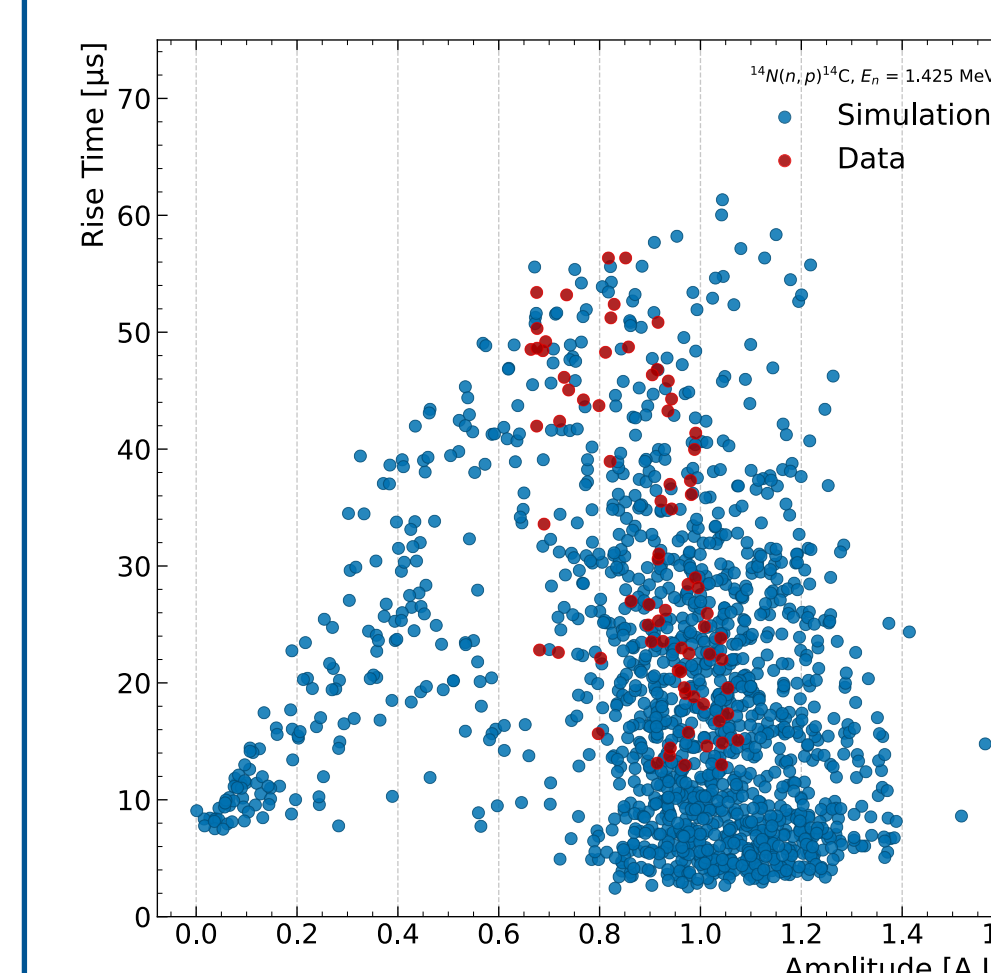
- Trigger was based on F0
- Analysis restricted to events with a positive signal in F0
- Lower threshold of the rise time set to 2 μs

Pulse shaper analysis parameters:

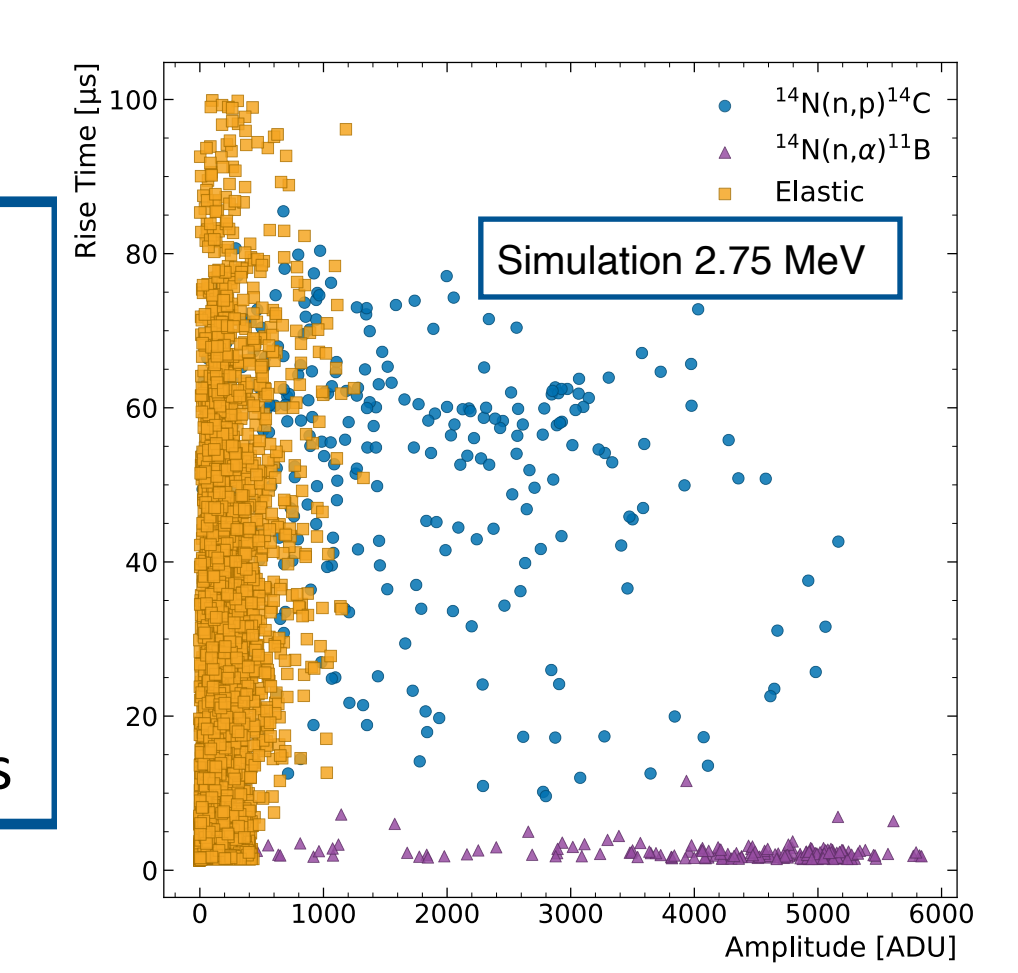
- Amplitude
- Rise time (10-90%)
- Negative signal to non-triggered channels (Shockley-Ramo theorem)



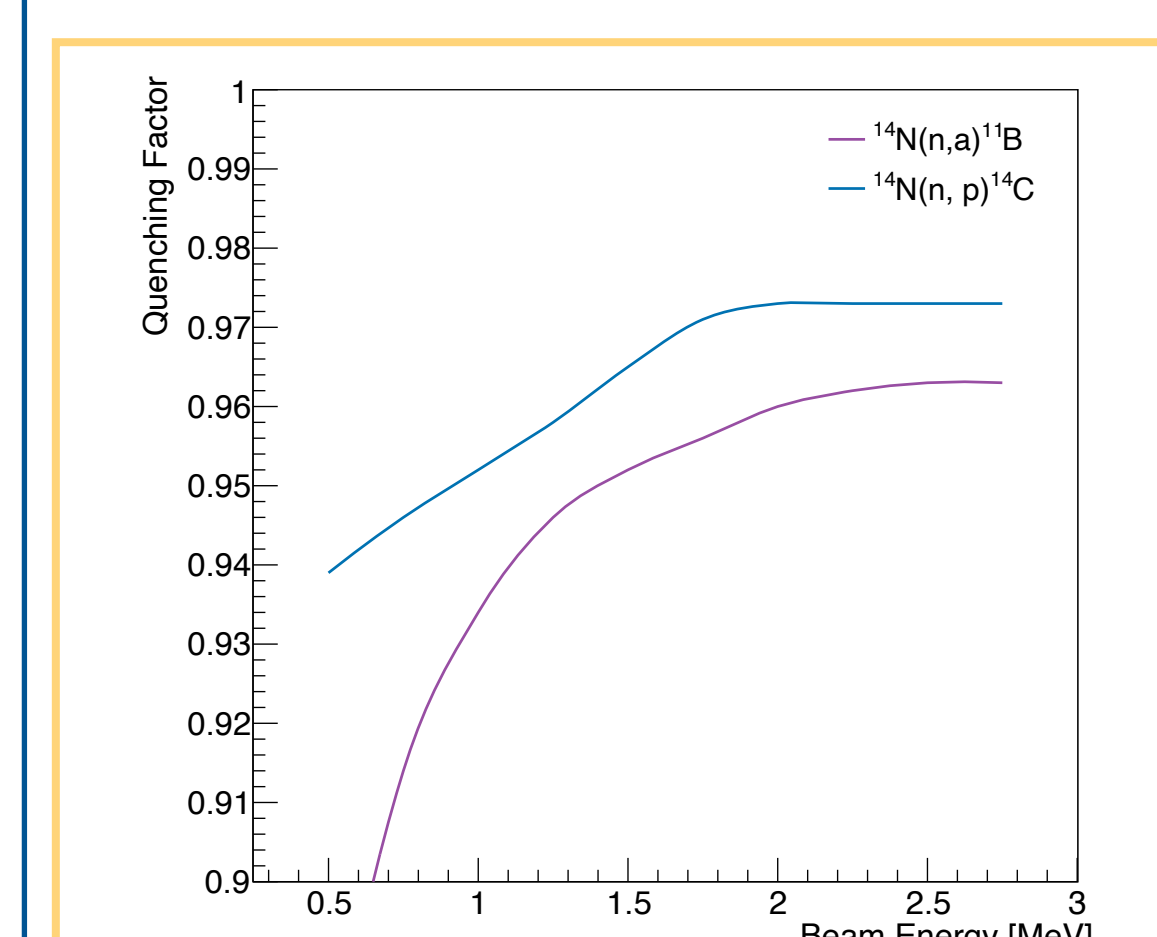
^{241}Am α source (5.49 MeV) used to provide a reference for the calibration between runs



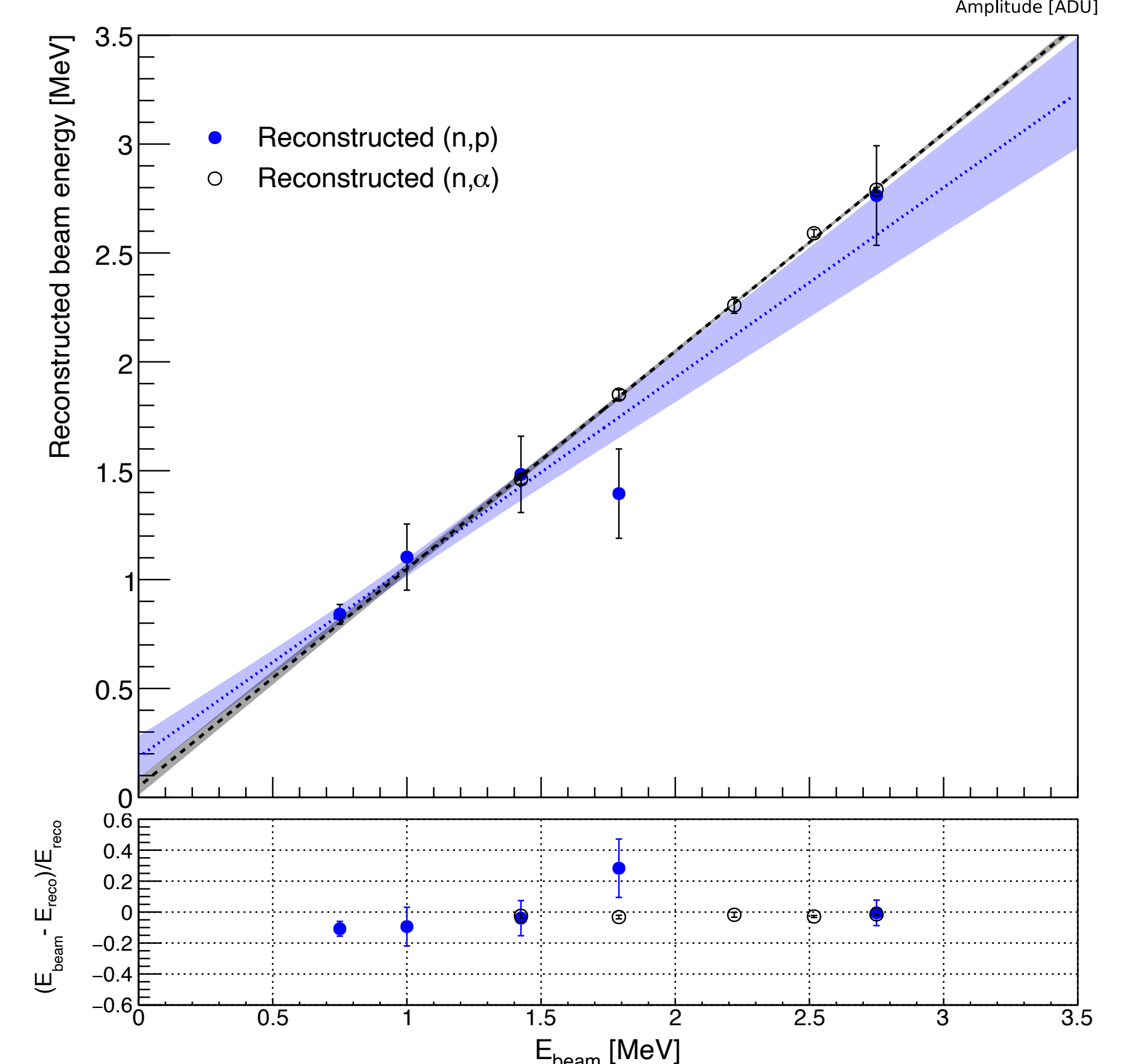
- The simulation framework combines
- Geant4 $\rightarrow$ interaction of particles with matter
 - Garfield++ $\rightarrow e^-$ transport and signal induction
 - Gmsh/Elmer $\rightarrow$ finite element calculation of the electric fields



Ballistic deficit due to electronics demonstrated with simulation - evaluated using LTSpice



Quenching factors estimated from SRIM, accounting for the fraction of energy that goes to each species based on kinematics



Neutron energy reconstructed from the measured pulse amplitude associated with the $^{14}\text{N}(n, p)^{14}\text{C}$ and $^{14}\text{N}(n, \alpha)^{11}\text{B}$ reactions