Development and Characterization of Time Projection Chamber Prototype for HIBEAM Experiment at the European Spallation Source

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HIBEAM Programme at ESS: Searching for New Physics

Why Particle Physics at ESS:

- ESS is designed to be the world's most powerful neutron source that can provide intense cold-neutron beams
- Opportunity for a beamline for a scientifically excellent research program to tackle **important open questions in particle physics**

The HIBEAM Approach:

Blue-sky exploration

- For the past 50 years, colliders kept confirming the Standard Model, but dark matter and the matter–antimatter asymmetry are still unexplained, so we must look in new places with new tools
- Design the beamline in flexible way to explore new ideas as they come

Targeted searches

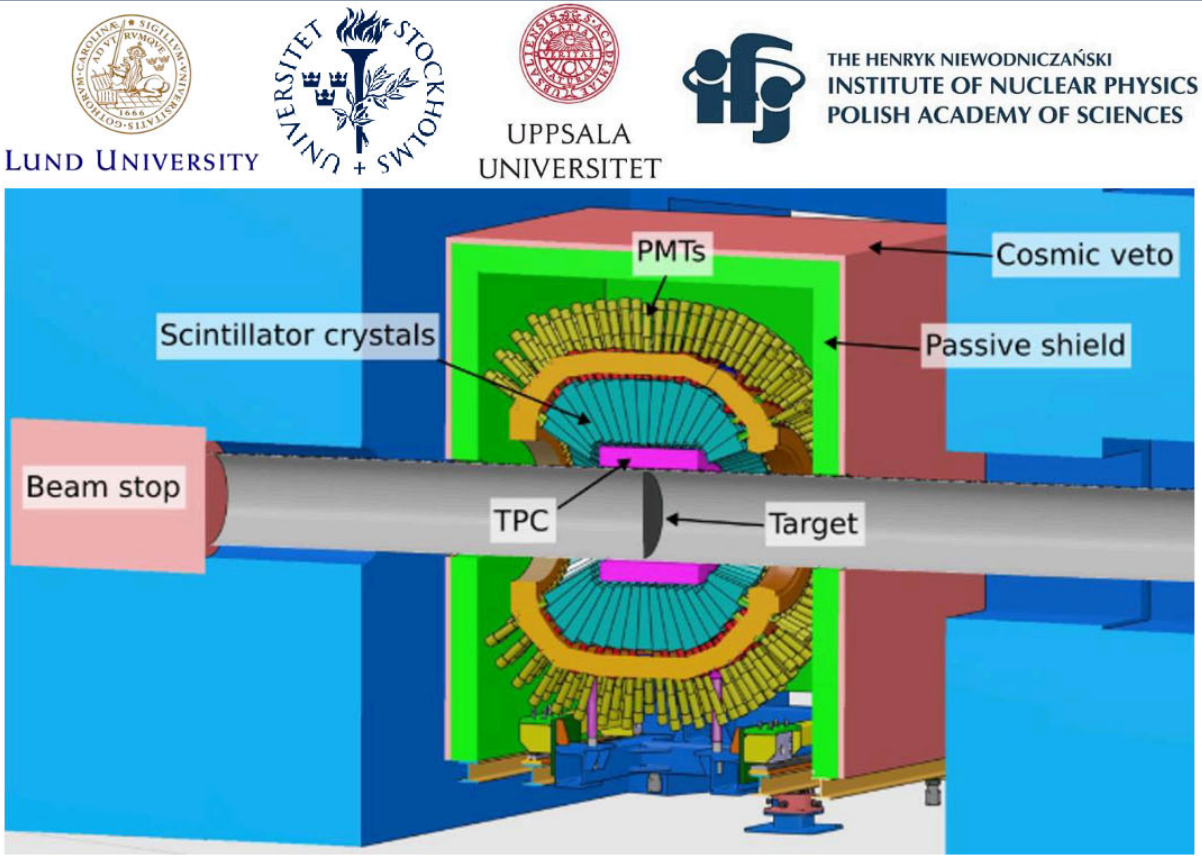
- Neutron → antineutron conversions (ΔB = 2)
- Neutron → sterile neutron conversions (ΔB = 1)
- Axion-like particles and other light, weakly coupled states
- Electromagnetic properties of the neutron (EDM, tiny electric charge)

Santoro, Valentina, et al. "The HIBEAM instrument at the European spallation source." *Journal of Physics G: Nuclear and Particle Physics* 52.4 (2025): 040501.

HIBEAM Experiment: Search for Baryon Number Violation at ESS

- The observable Universe is made almost entirely of matter
  - almost no antimatter is observed
- This matter–antimatter asymmetry needs process that violates baryon number
- One clean possibility: neutron → antineutron (n → n̄) conversions
  - The HIBEAM experiment at ESS aims to searches for these conversions
  - This requires a sensitive **annihilation detector** at the end of a long cold-neutron beamline

Annihilation Detector to Search for $n \rightarrow \bar{n}$

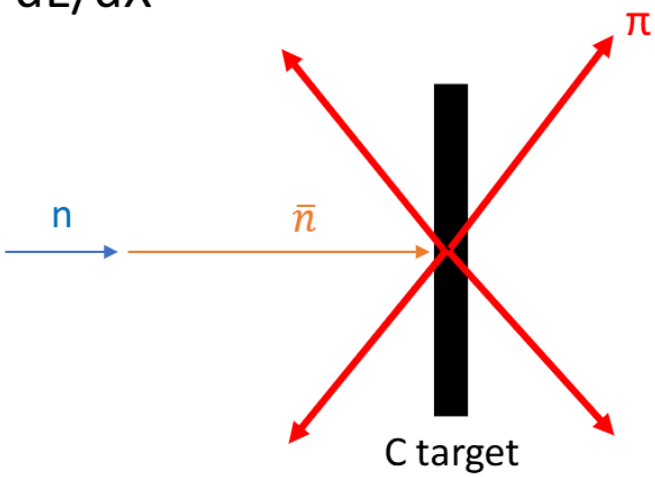


Annihilation detector for HIBEAM

Adapted from Persson, L. (2024). "*Design of an experiment to search for neutron oscillations at the European Spallation Source*" Master's thesis, Lund University.

Why TPC Detector

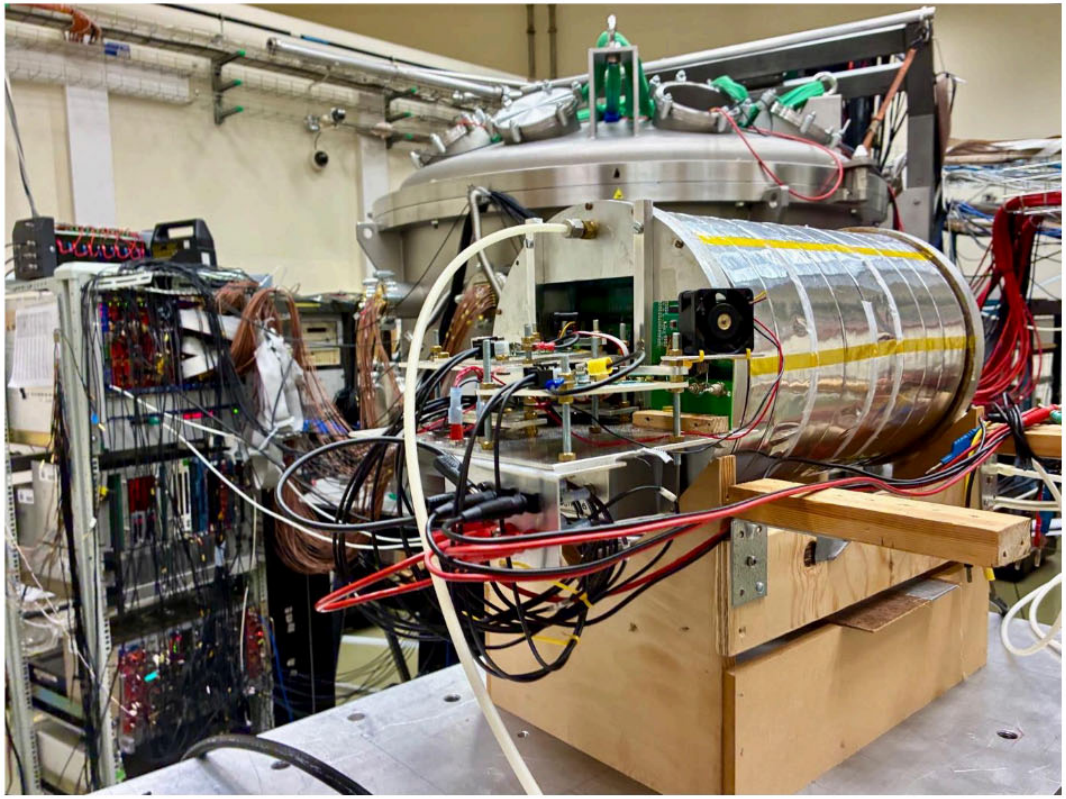
- Allows tracking of charged particles in 3D over wide angular coverage
- Suited well for the HIBEAM annihilation detector
  - Short drift lengths in the gas -> low diffusion
    - Enables precise tracking towards the vertex (point of annihilation) and into the calorimeter
  - May allow particle identification (PID) from dE/dX

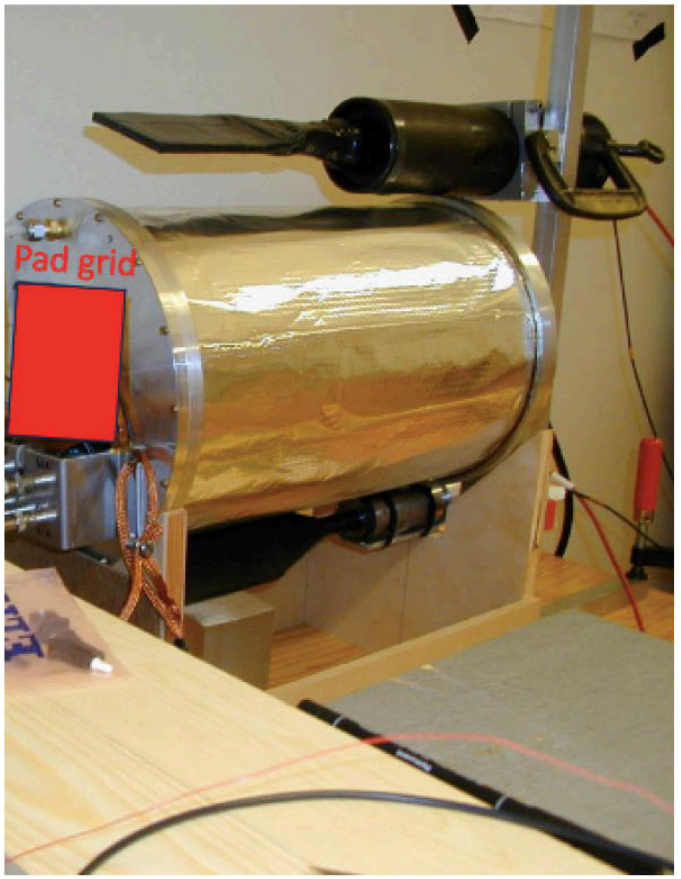


Signal: 3 – 5 Charged Pions at 1.8 GeV

Small TPC Prototype

- In-house development at Lund University

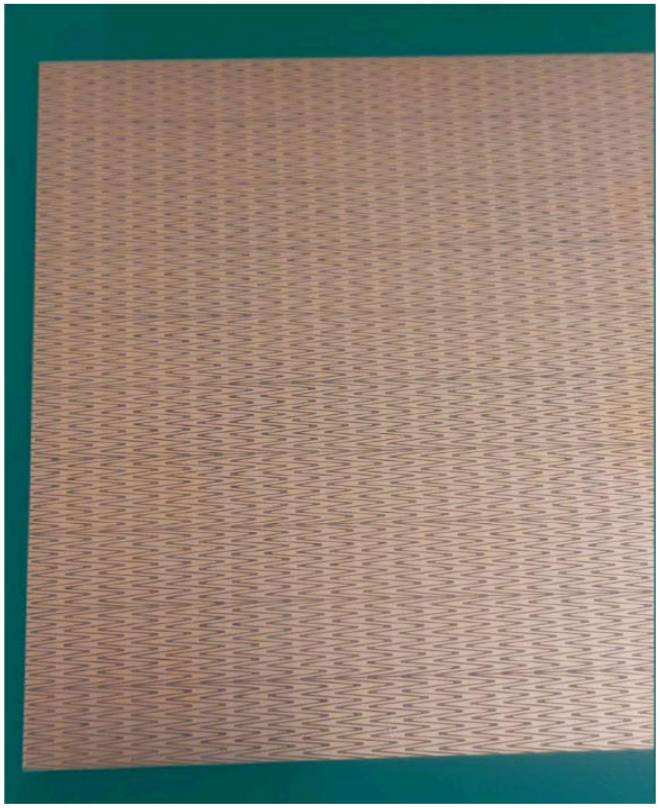




Small TPC Prototype

- Cylindric shaped gas chamber (Ar/CO_2 80/20 %)
- Triple GEM stack for electron amplification
- Pad plane (10 x 10 cm^2):
  - zig-zag shape of pads for charge sharing (250 pads/dm^2; rectangular 4 x 10 mm^2 eq.)
- Track lengths ≈ 10 cm
- Drift lengths ≈ 25 cm

- This prototype closely **matches** the future HIBEAM TPC in size, track length and drift length
  - makes it suitable for testing



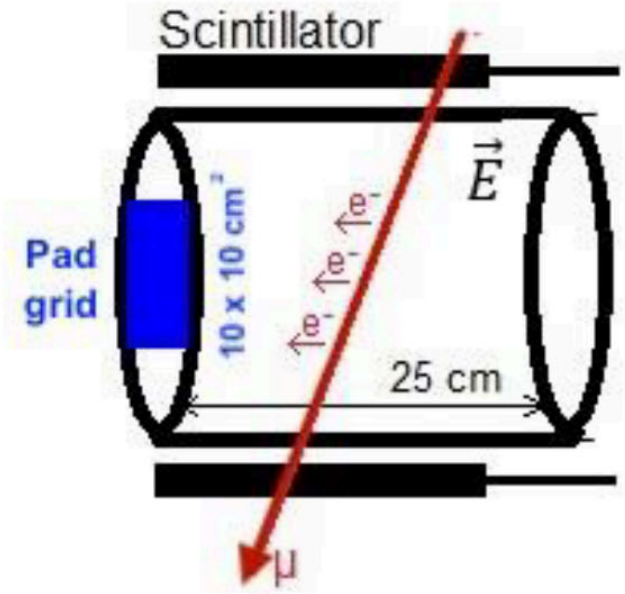
Anode zig-zag pad plane (grid)

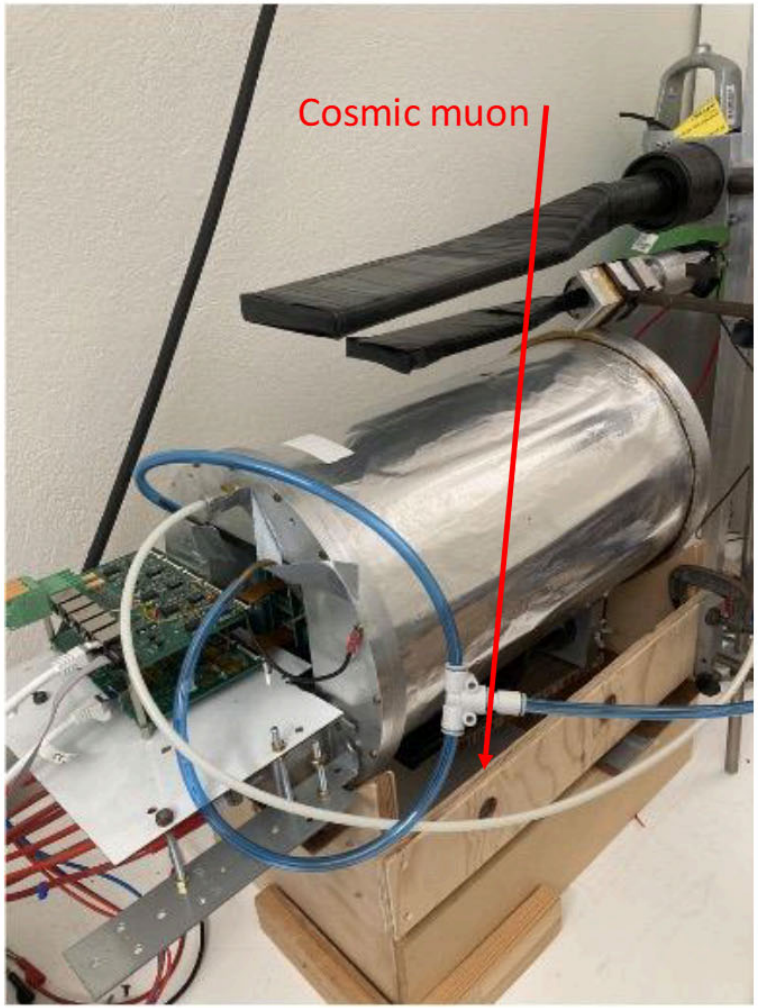
Aims of the characterization of Small TPC prototype

- Test basic detector concepts such as pad shape for signal readout, optimal drift field and gas flow & study their impact on performance.
- Develop and test code to perform data analysis and reconstruct tracks based on the TPC signal readout

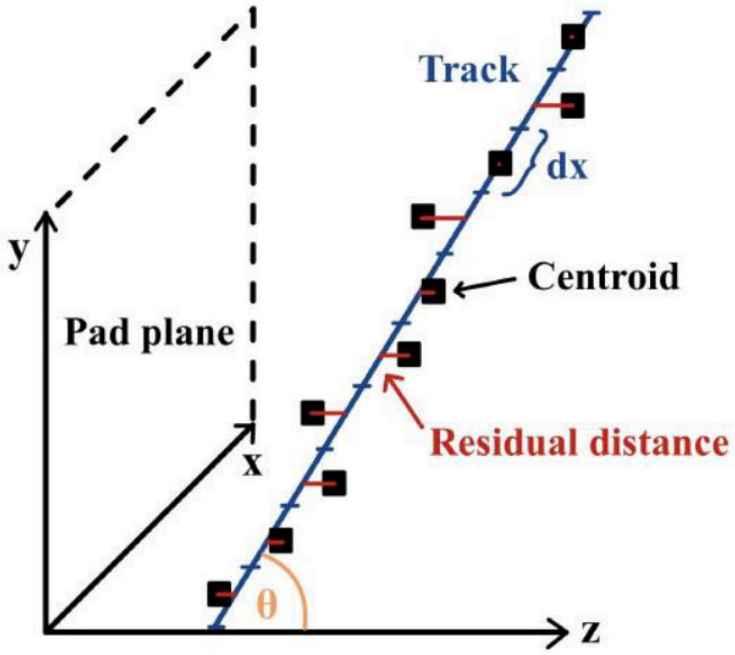
Experimental Test with Cosmic Muon Triggers

- Cosmic muon:
  - Minimum ionizing in Ar/CO_2
  - 10 – 100 GeV

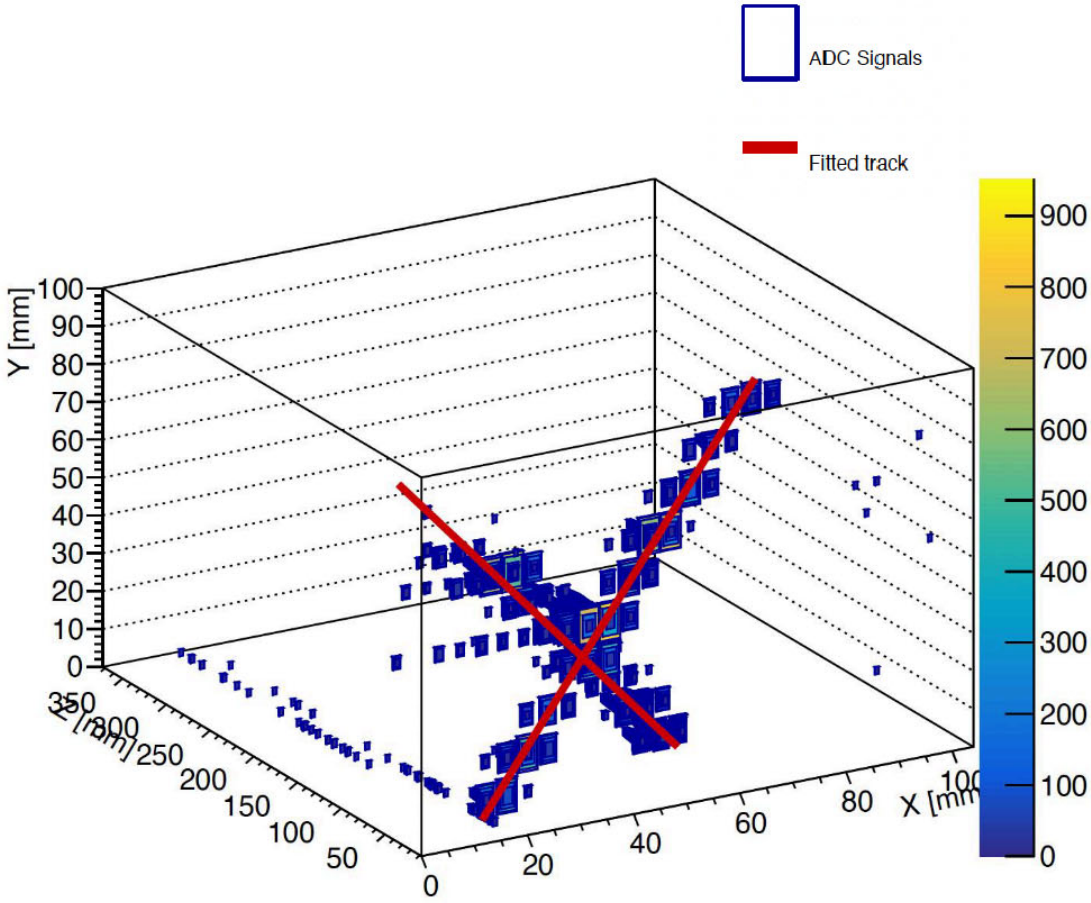




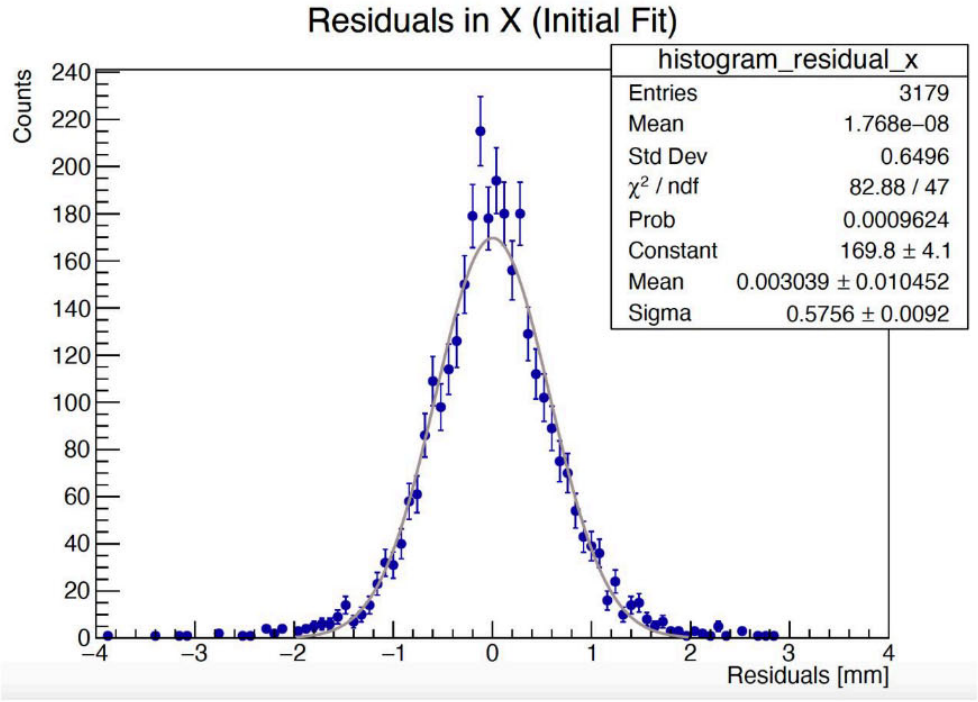
Track Reconstructions Based on the TPC Readout

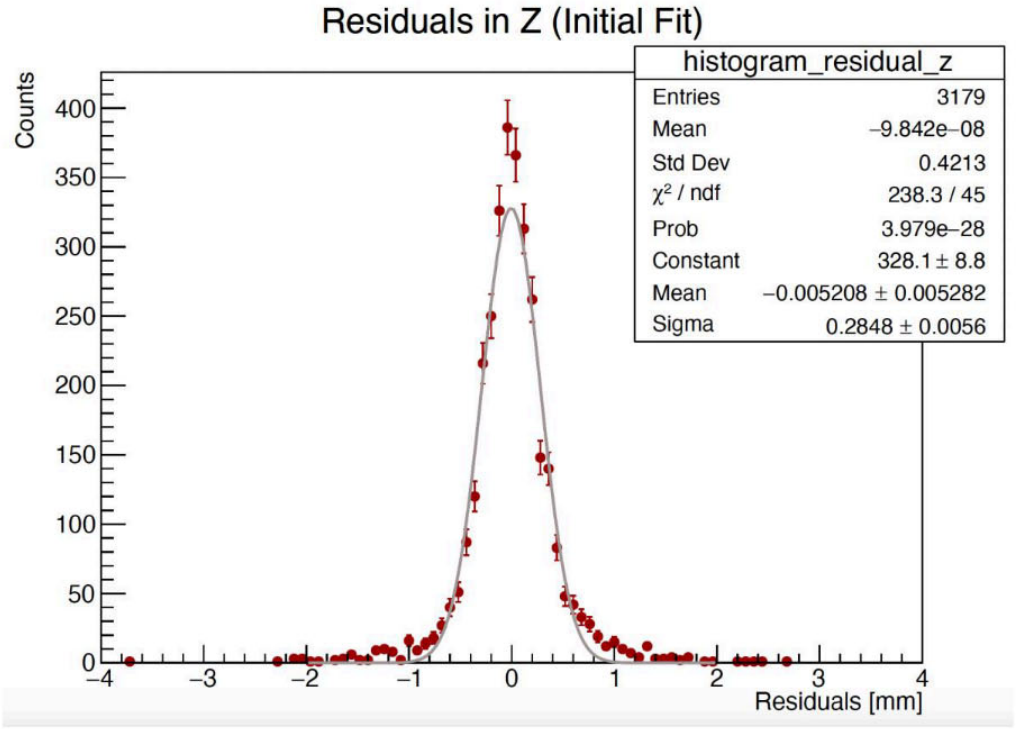


Adapted from Hehl, Verena. "Characterization of the HIBEAM time projection chamber prototype." (2025).

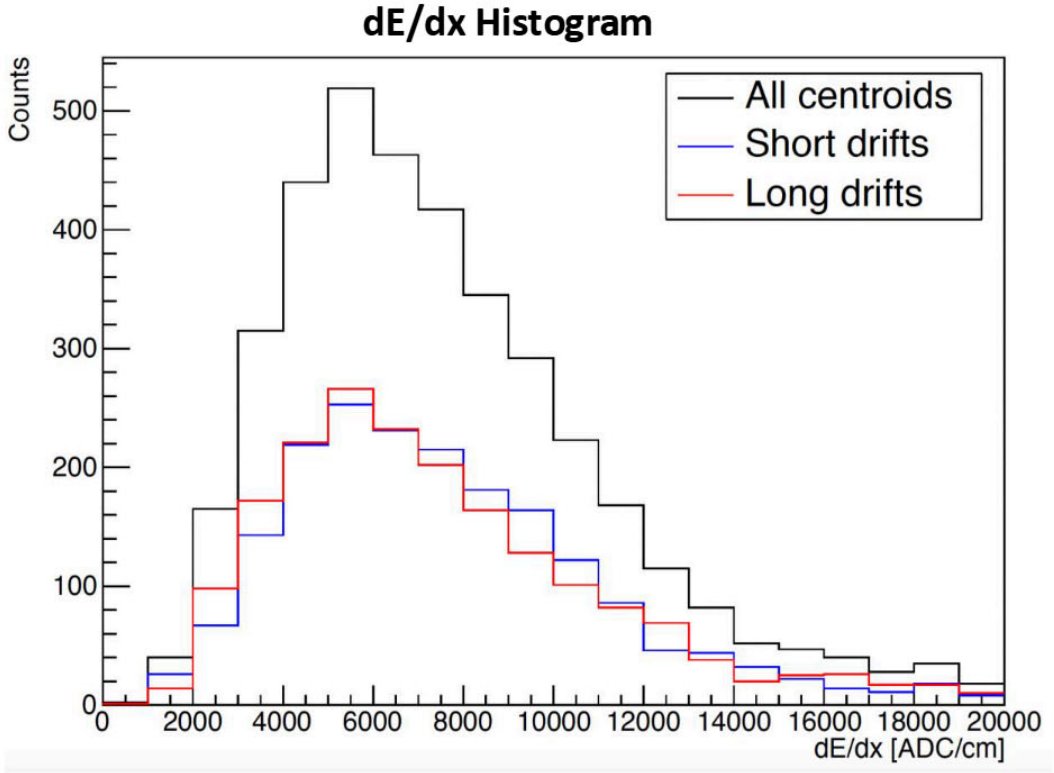


Residual Analysis





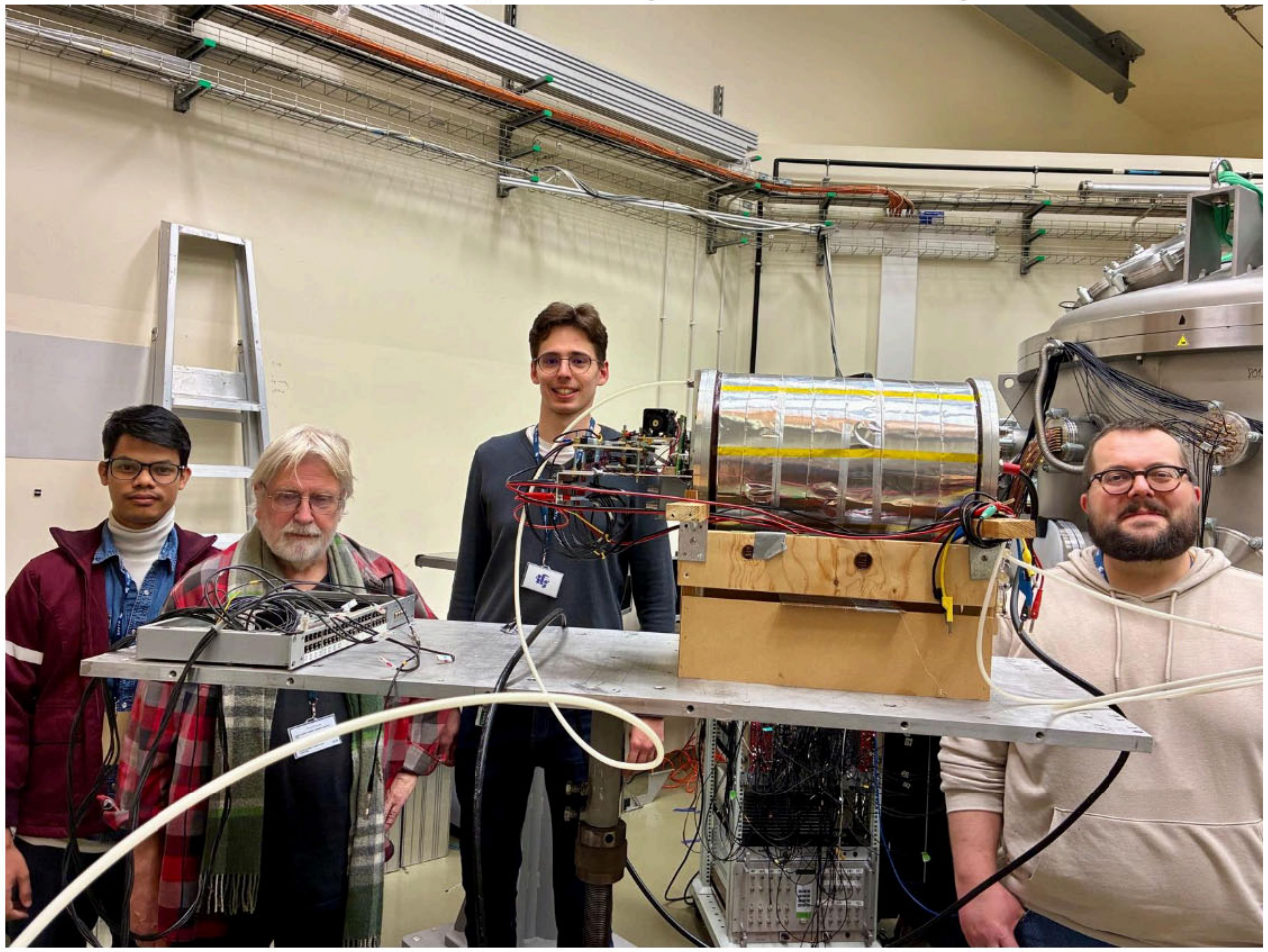
dE/dx Analysis



500 V/cm; 12 l/h

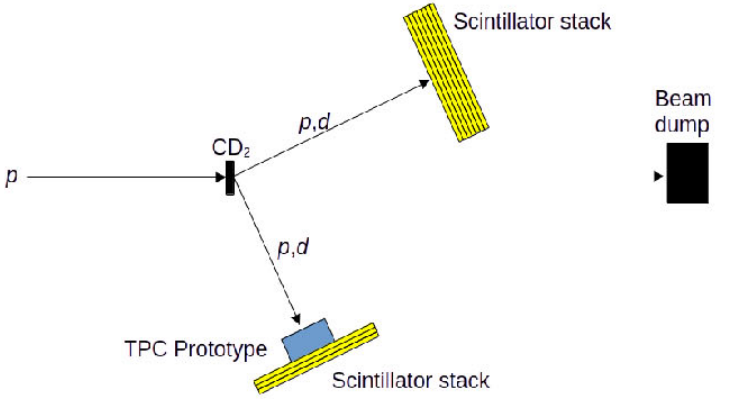
First In-Beam Test at CCB

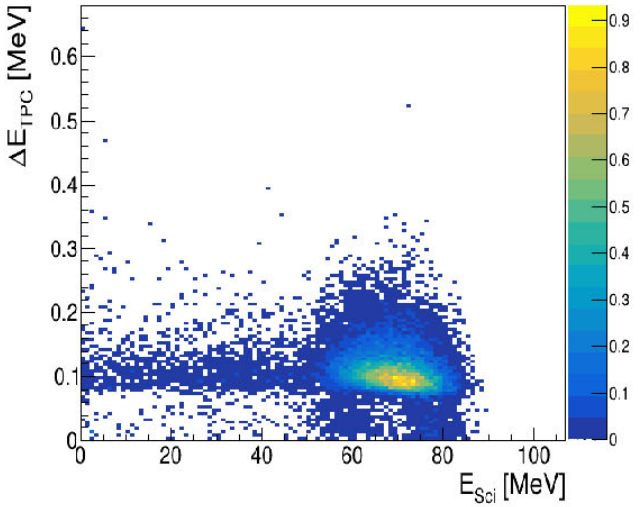
- **Small TPC Prototype at CCB, Krakow (1 December 2025)**



First In-Beam Test at CCB

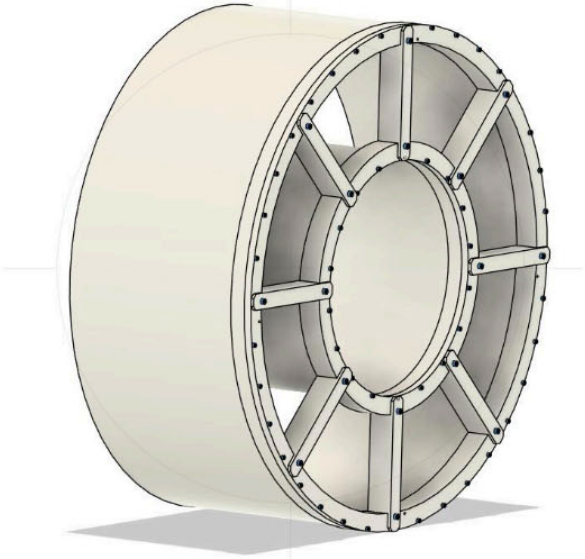
- Test of TPC prototype together with scintillator prototype bars
- Measuring elastic scattering of proton beam on a CD_2 target
- Experimental goals
  - Investigate capability of TPC and scintillators to provide particle identification
  - Investigate TPC performance at high track density/high ion backflow
  - Validation of Geant4 simulations and tracking algorithm

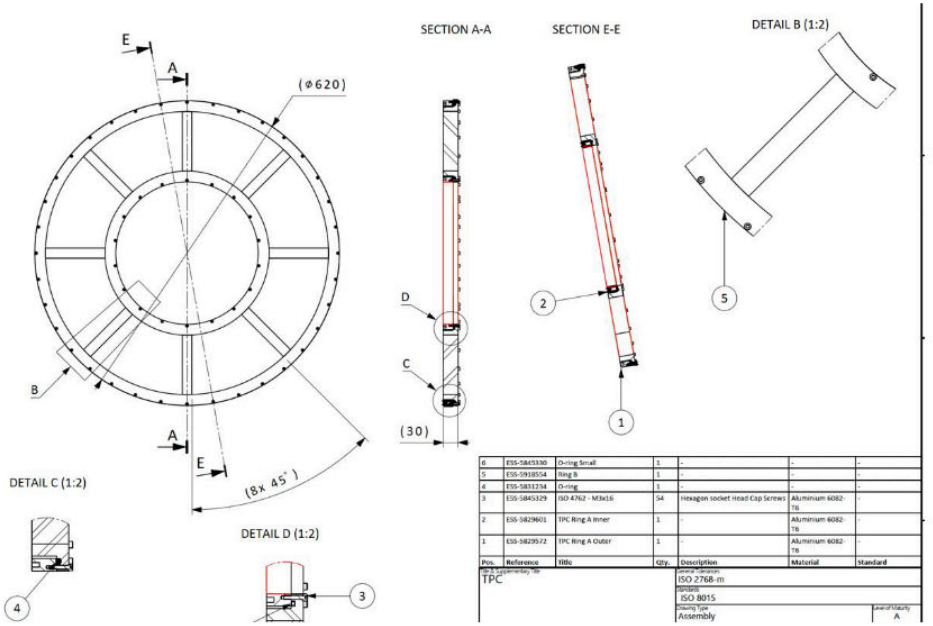




Outlook: Building More Realistic HIBEAM TPC Prototype

- More realistic field boundaries (curved field cage)
  - ≈ 10 cm wide E-field formed by cylindrical-shaped edges
  - Can study distortions near the boundary
- Supported by the Royal Physiographic Society of Lund (Fysiografen)





Cocnlusion

- The HIBEAM annihilation detector requires high-resolution event reconstruction.
- Small TPC prototype tested over the last two years at Lund University with cosmic muons.
- This week experimental test at CCB, Krakow
- Final TPC ready for construction in 2028
- Polish (IFJ) contribution to HIBEAM programme including design of polarizer and cosmic veto and arranging the prototype test