Antiproton-Nucleus Annihilations at Low Energies

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in collaboration with AEgIS

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ÖAW Austrian Academy of Sciences
MBI
FWF Austrian Science Fund [P 34438] [W 1252-N27]
universität wien Vienna Doctoral School in Physics
CERN
medipix collaboration
Nikhef

1. Antiproton-Nucleus Annihilation
2. Annihilation Studies Project
3. Detection System
4. Vertex Reconstruction
5. Status & First Results

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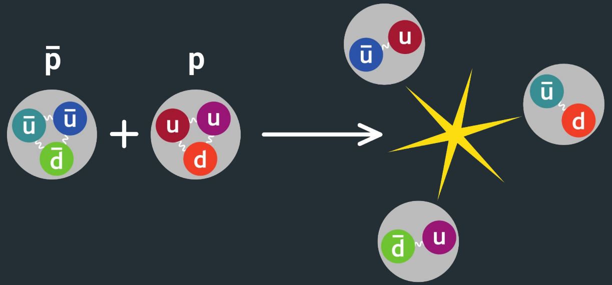
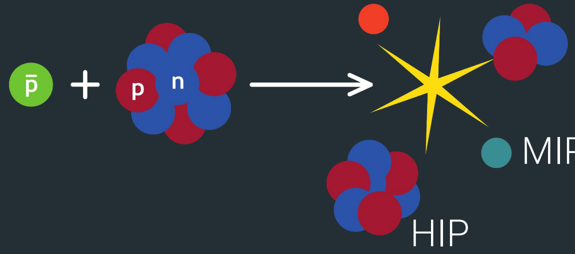
Antiproton-Nucleus ($\bar{p}$A) Annihilation

Most antimatter experiments detect annihilation products, not antimatter directly!





Annihilation happens on quark level
Creates charged and neutral mesons
- 3.0 ± 0.2 charged pions
- 2.0 ± 0.2 neutral pions
- ~ 230 MeV kinetic energies

Possible final state interactions (FSIs) of pions with nucleus
- Inelastic scattering
- Direct Emission of fast π, p, d, …
- Break-up of nucleus

Amsler et al., Rev. Mod. Phys. (1998),
Klempt et al., Physics Reports (2005)

Hofmann et al., Nuclear Physics A (1990)

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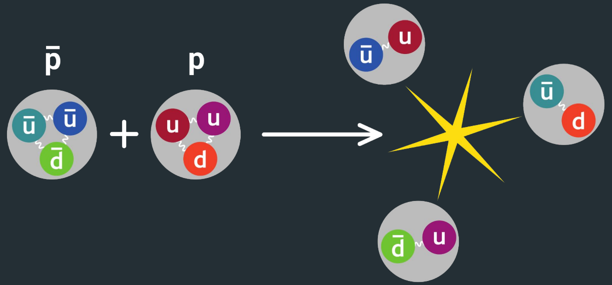

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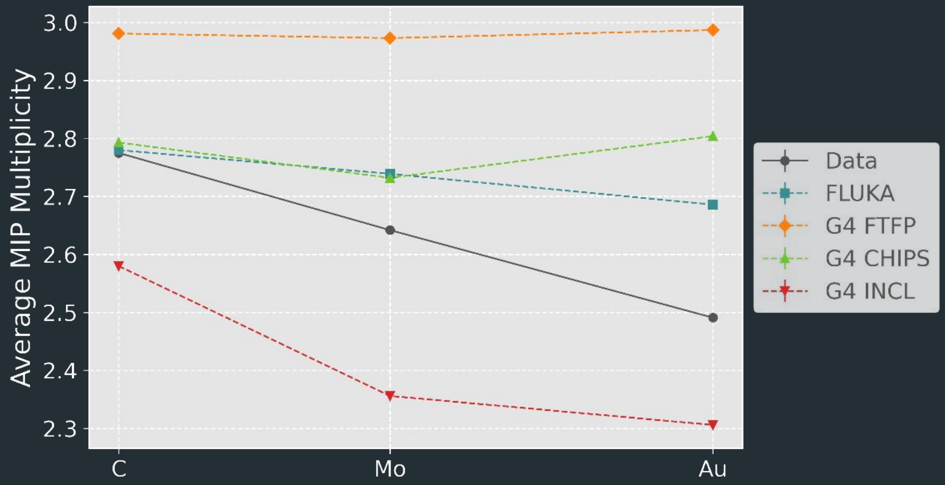
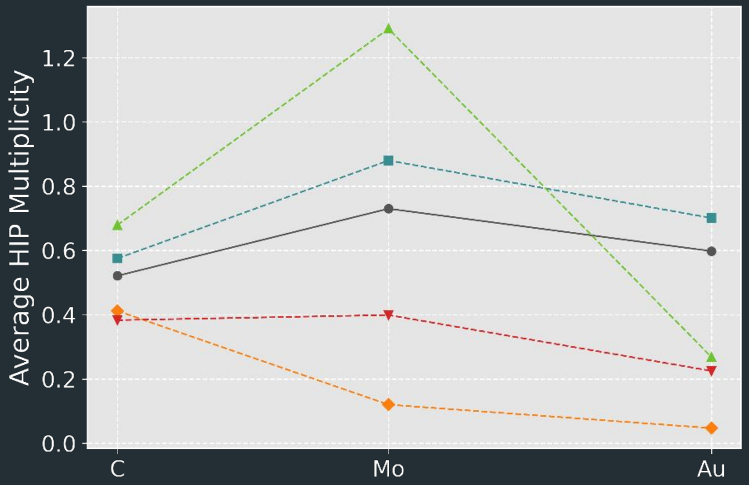
Hofmann et al., Nuclear Physics A (1990)

Prong Multiplicities

Minimum Ionising Particles (MIPs)



Heavily Ionising Particles (HIPs)



Amsler et al., Antiproton annihilation at rest in thin solid targets and comparison with Monte Carlo simulations, EPJ A (2024)

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$\bar{p}$A Annihilation Studies

~ 100 eV to 6 keV antiprotons annihilating on thin target foils of 1-3 µm

- Different target foils/nuclei to study dependence on nuclear size
- Thin foil allows also heavy particles to reach the detector

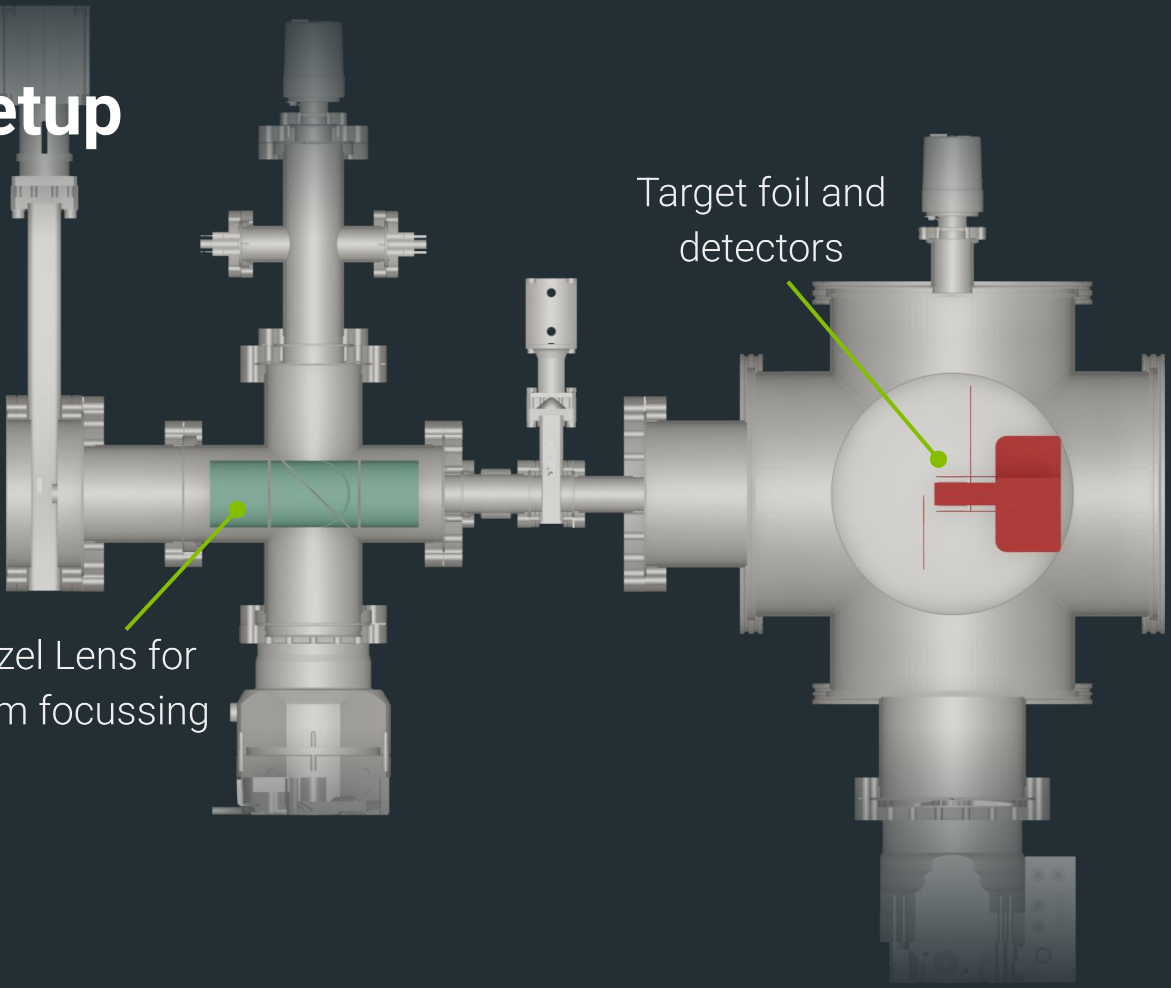
Detector covering large solid angle

- Particle identification
- Total multiplicities
- Energy deposit
- Angular distribution

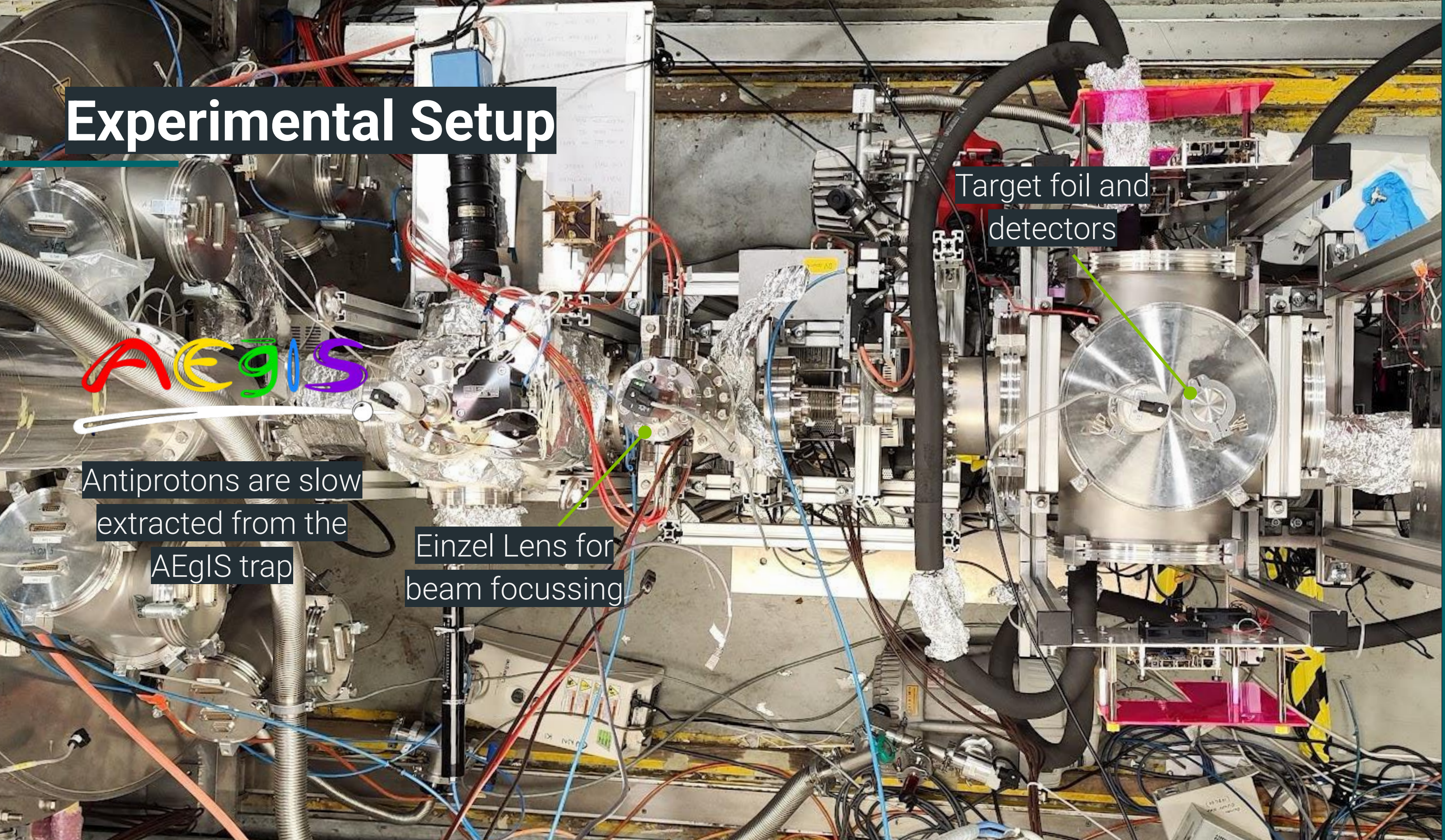
Vertex reconstruction important to tag individual events

Experimental Setup

Antiprotons are slow extracted from the AEgIS trap



Experimental Setup



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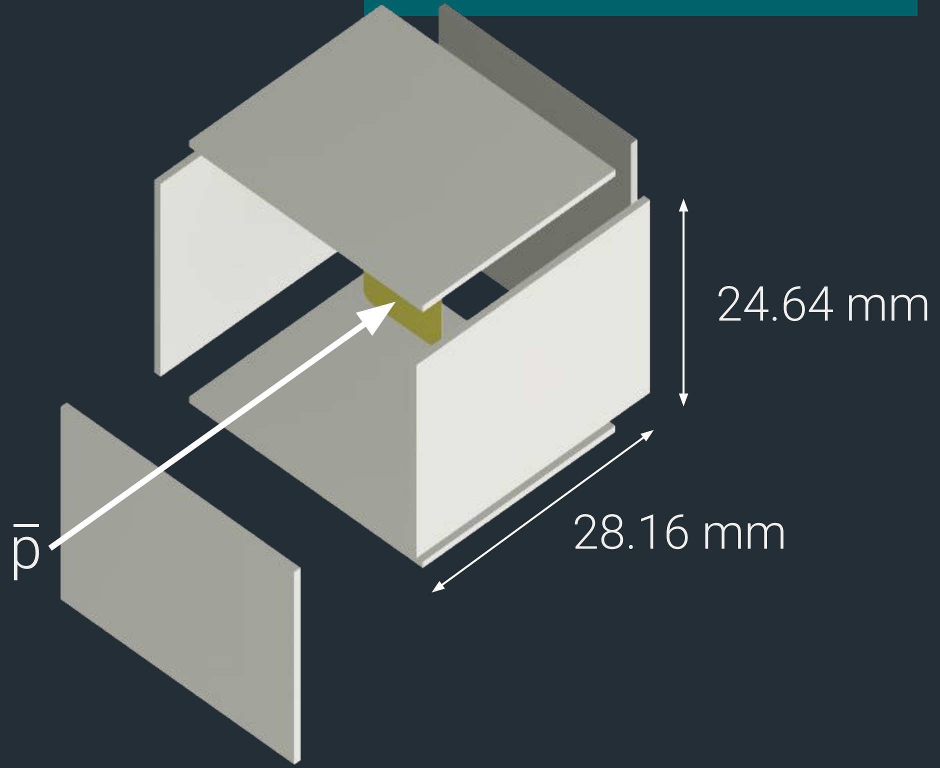
Detector Geometry

Target foil surrounded by detectors

Six Si sensors coupled to Timepix4 ASICs:

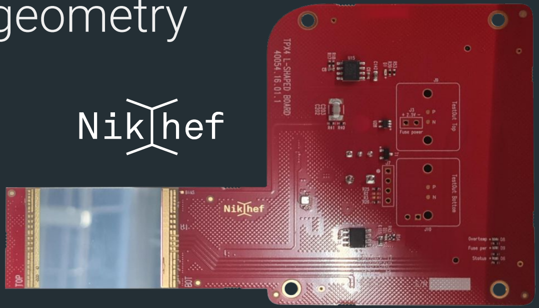
- 5 x 500 µm 1 x 625 µm
- 1 sensor in the back with offset allows beam to enter
- 5 sensors cover the other planes of the cube-like geometry
- ~ 64 % of solid angle coverage

Timepix4
55 µm pixel size
512 x 448 pixels
Time resolution < 200 ps

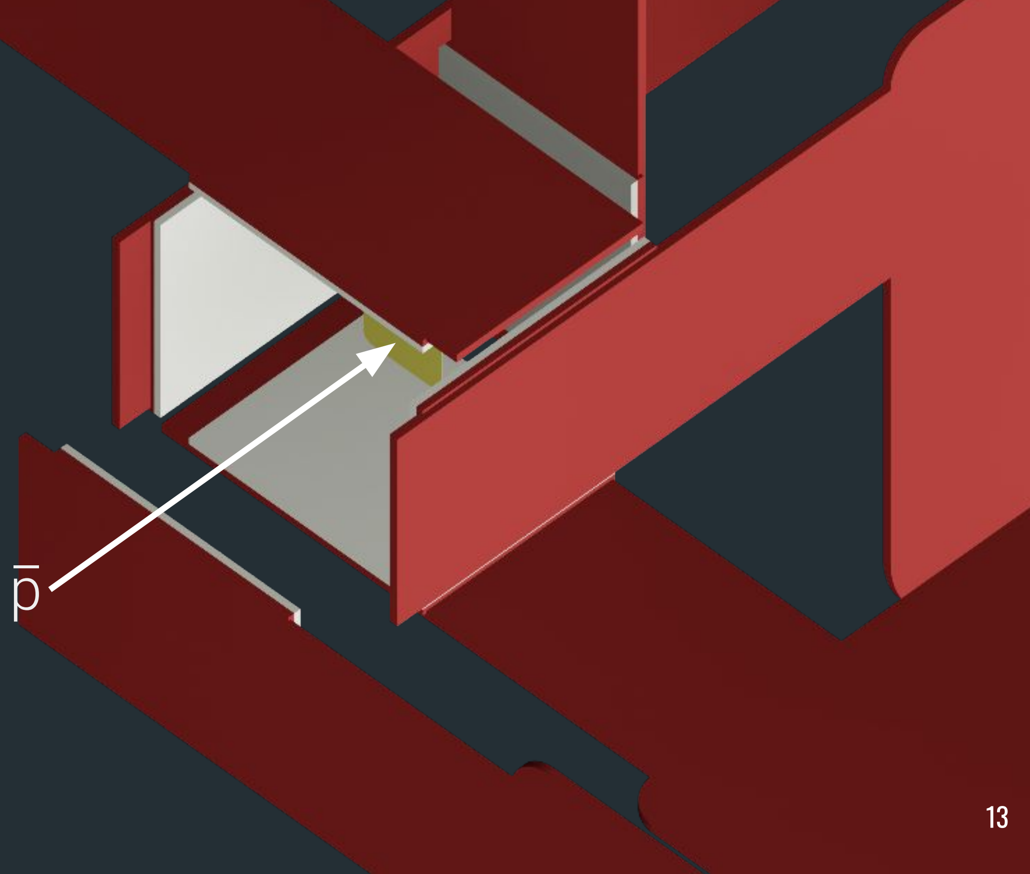


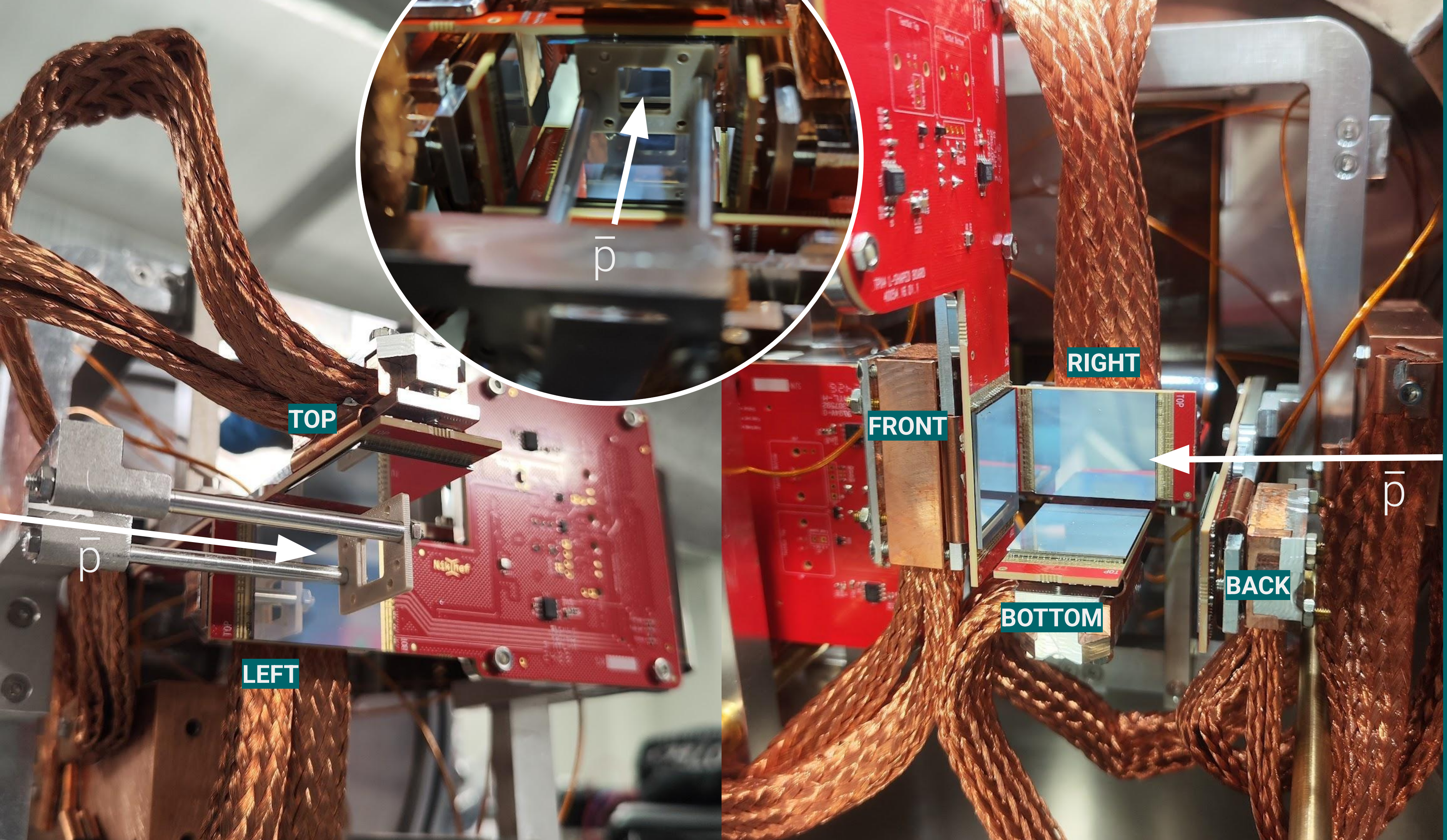
Annihilation Chamber

PCB boards specifically designed for our geometry



Cooling the detectors with water through copper pipes/blocks




$\bar{p}$
TOP
LEFT
$\bar{p}$
RIGHT
FRONT
BOTTOM
BACK
$\bar{p}$

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4. **Vertex Reconstruction**
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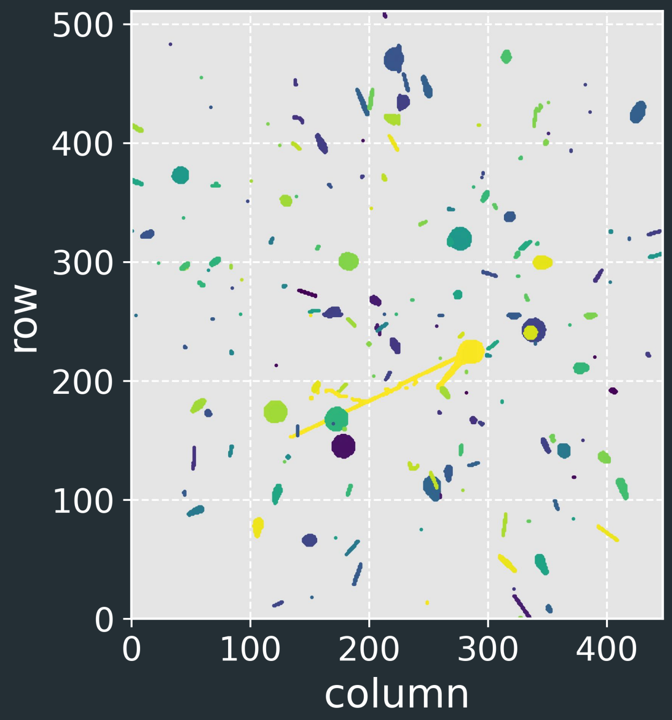
Data Structure

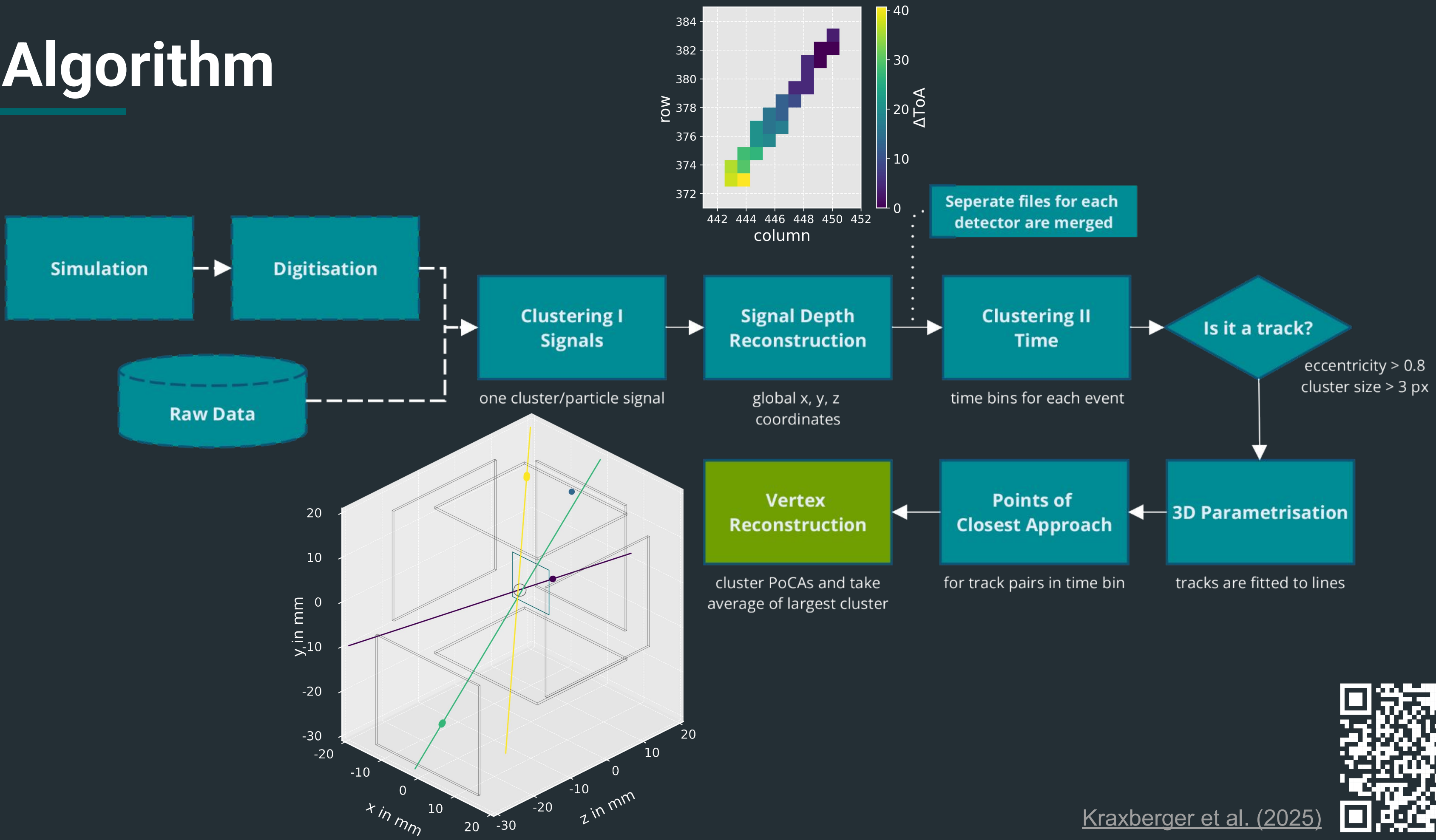
- Pixel (column, row)
  Time-of-Arrival
  Time-over-Threshold

- Minimum ionising particles MIPs:
  Leave track when traversing the sensor

- Heavily ionising particles HIPs:
  Rounder clusters stopping in sensor
  or thick tracks (protons)



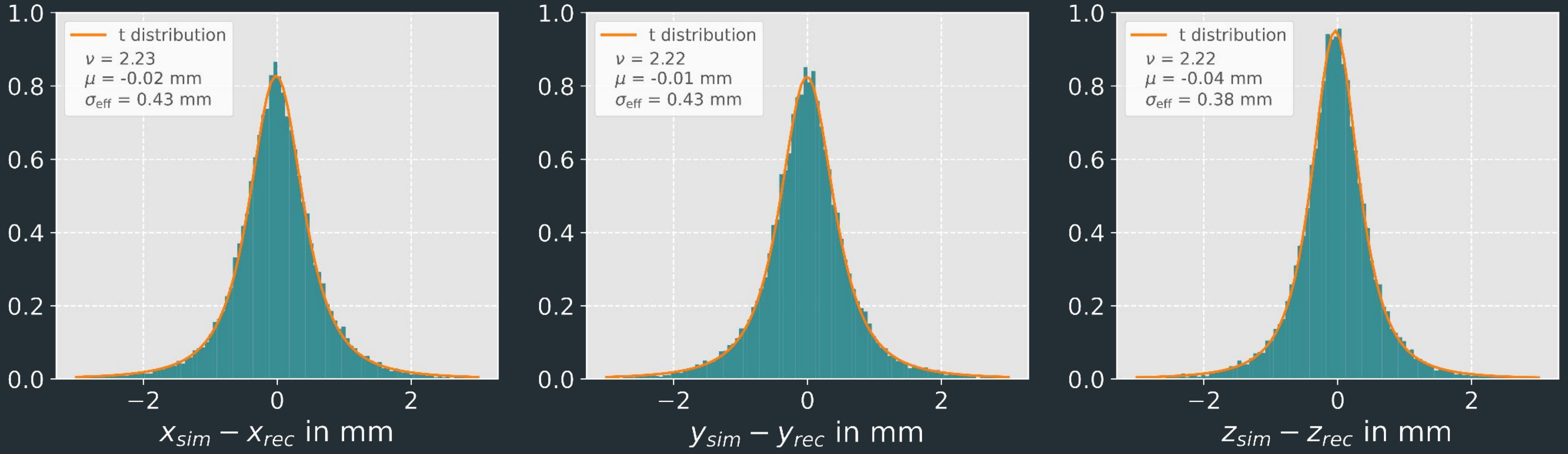
Algorithm



Kraxberger et al. (2025)

Vertex Reconstruction Resolution

Comparison of simulated annihilation position to reconstructed vertex:



Kraxberger et al. (2025)

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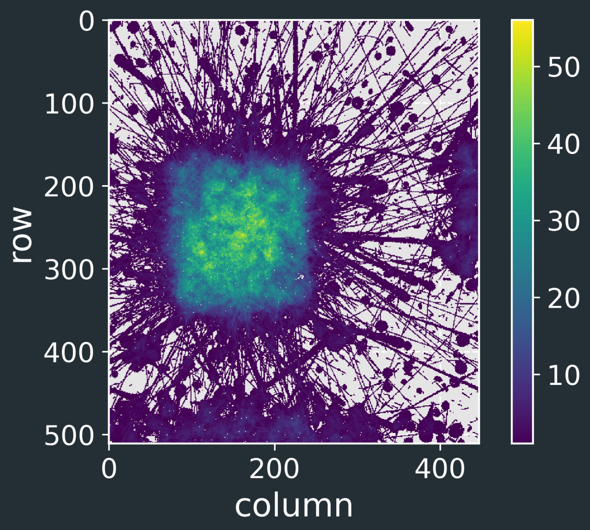
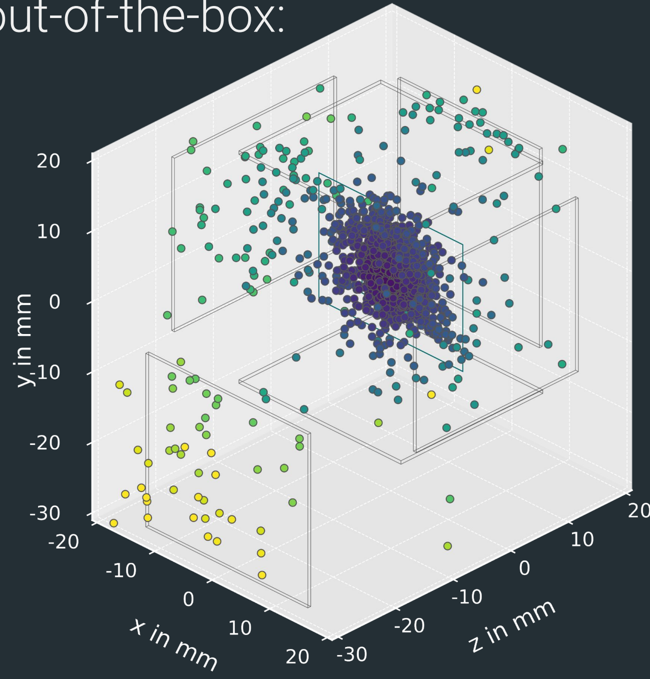
Beam Campaign in August 2025

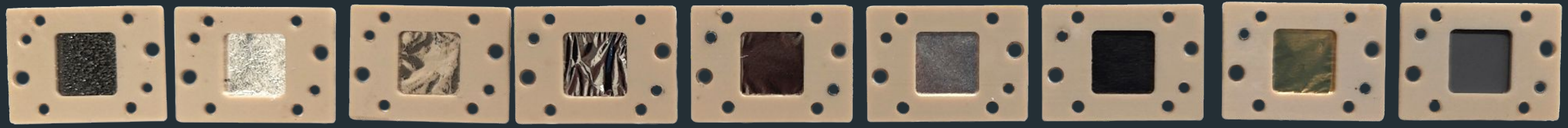
- Estimated over 700 antiprotons on the foil every 2 minutes
  Data with empty foil holder:



- Vertex reconstruction worked out-of-the-box:



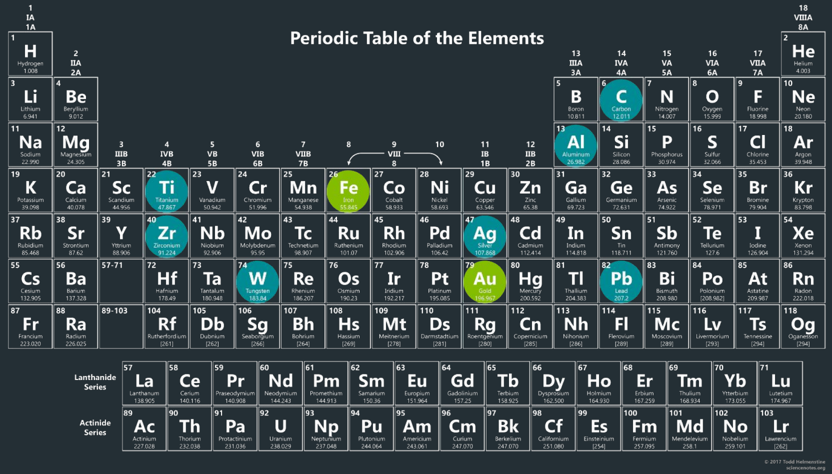
Measured Targets



C	Al	Ti	Fe	Zr	Ag	W	Au	Pb
12 u	27 u	48 u	56 u	91 u	108 u	184 u	197 u	207 u

In total 9 foils measured

7 under perfect conditions,
Fe and Au with only 5/6 detectors

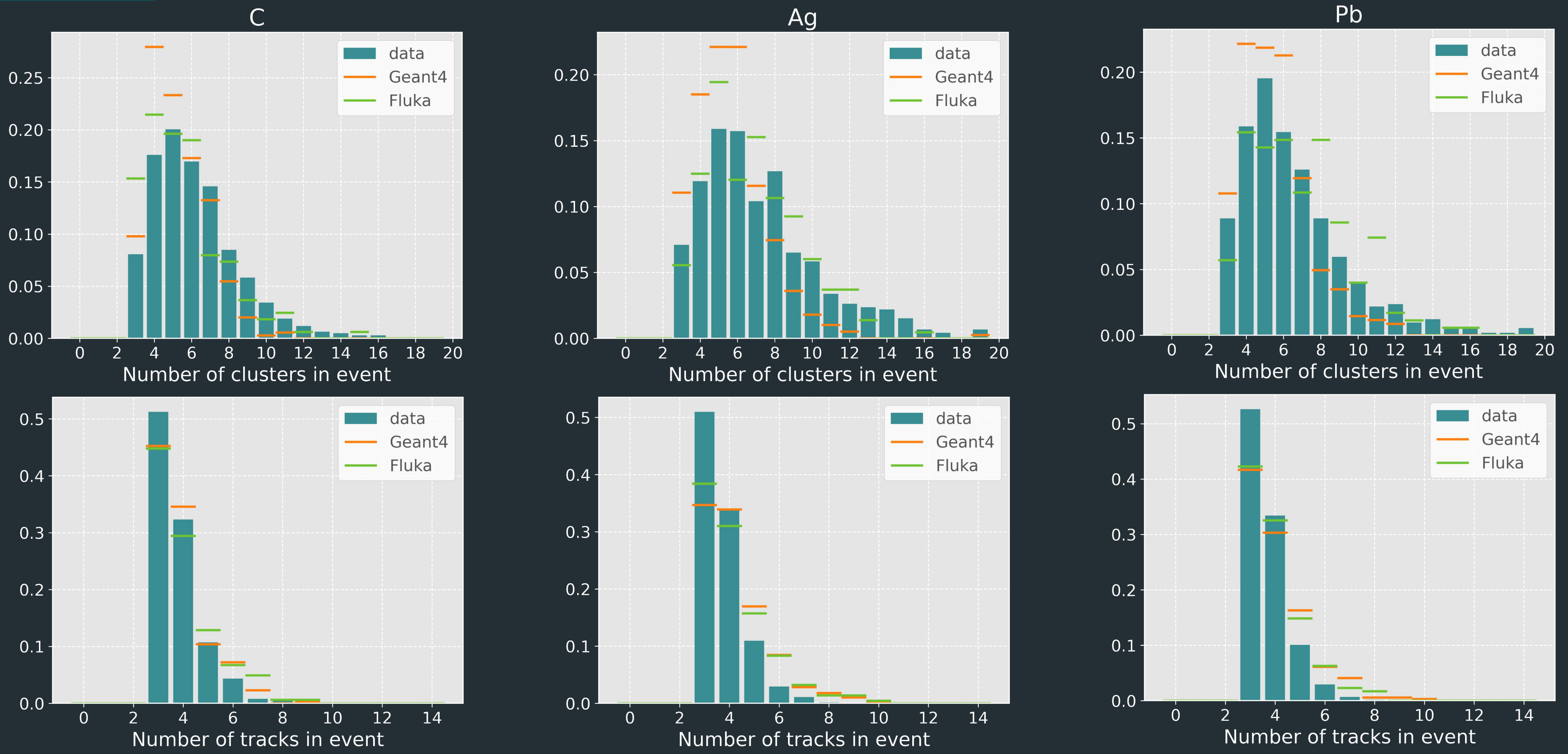


Data analysis just started…

- The following data contains only 3 runs per foil (very limited statistics).
- Only events where the reconstructed vertex lies within ((-5, 5), (-5, 5), (-2, 2)) are taken into account.
- Iron and gold have not been analysed yet since they need more adjustments.

Cluster Multiplicities

Data from only 3 runs per foil
Events where Vrec in ((-5, 5), (-5, 5), (-2, 2))



Cluster Multiplicities

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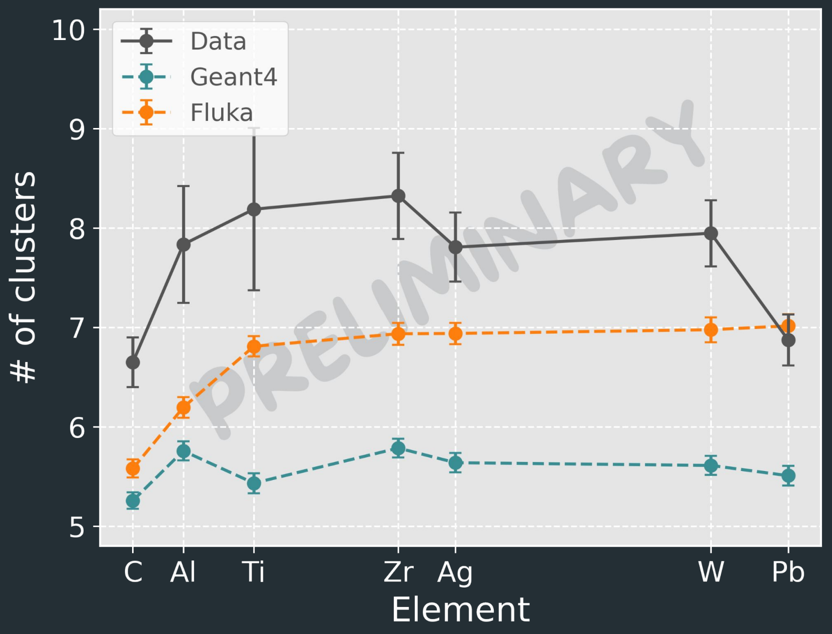
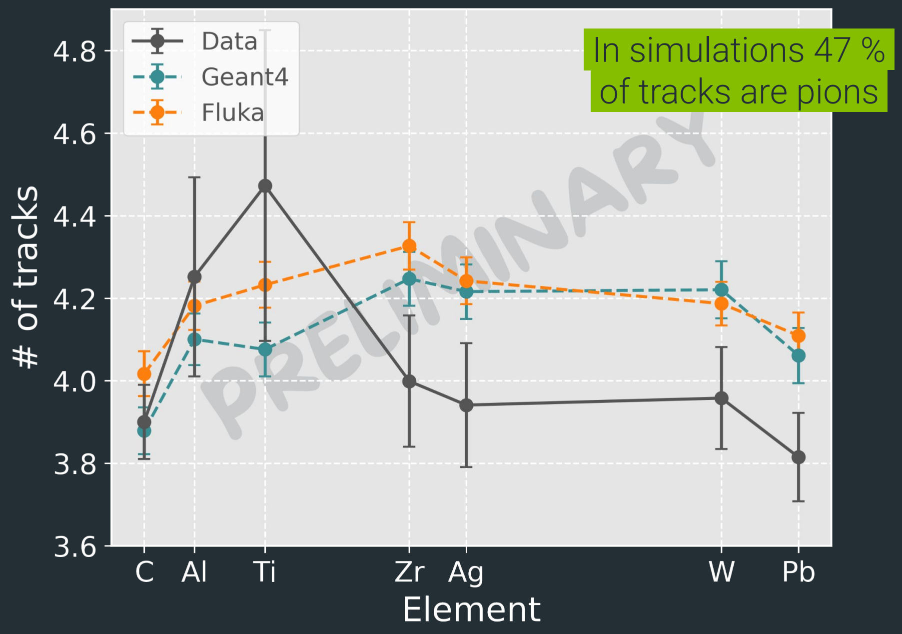
Total number of clusters per event

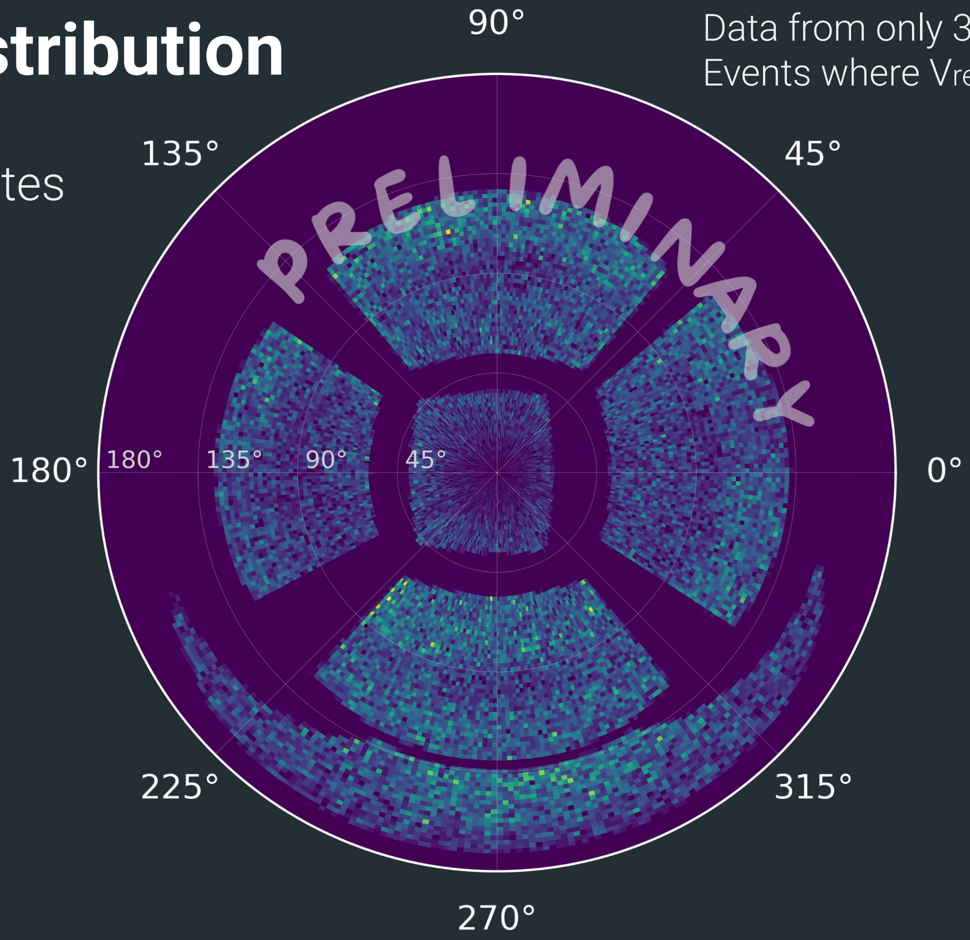


Number of clusters classified as track



Angular Distribution

Average coordinates of each cluster in polar distribution



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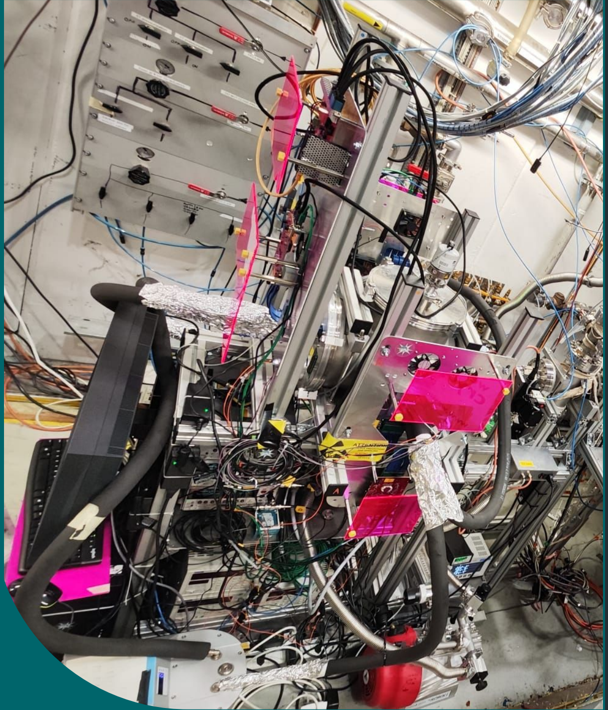
Events where Vrec in ((-5, 5), (-5, 5), (-2, 2))

Summary

- Antiproton annihilations with nine different nuclei using Timepix4 detectors with high solid angle coverage were measured
- Data analysis is starting now and will reveal:
  - Multiplicities of MIPs and HIPs
  - Deposited energy
  - Angular distribution
- Results will allow the study of final state interactions and assessment of models such as the Liège Intranuclear Cascade model

Thank you!



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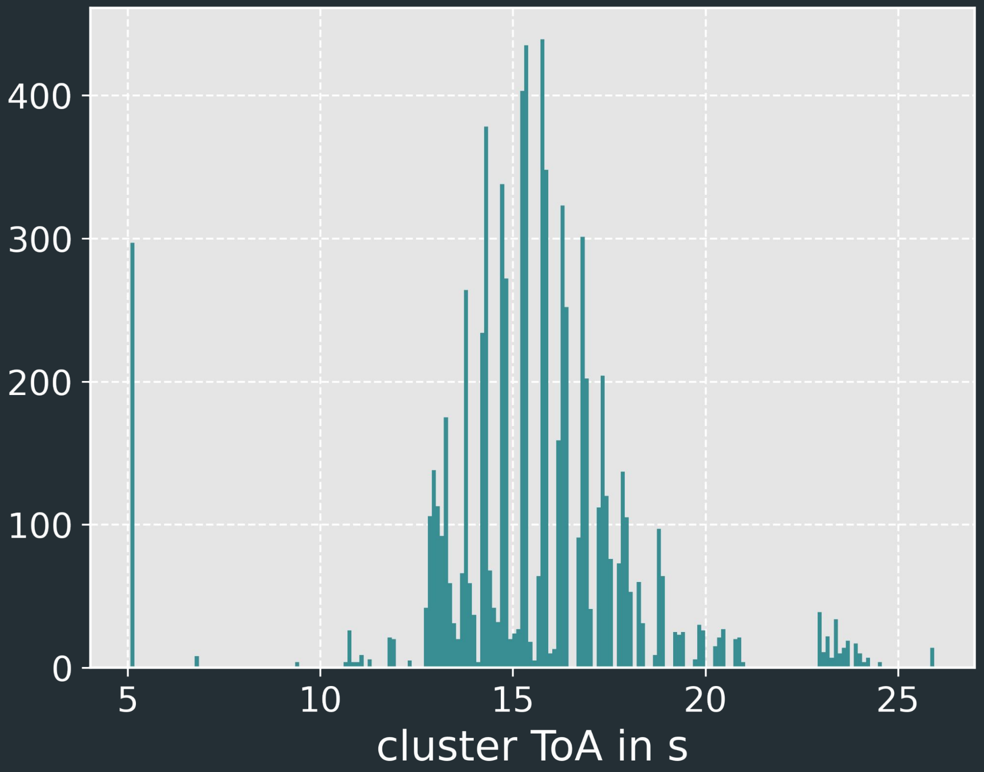
Backup

Beam Energies

Trapping potential in AEgIS is lowered in steps.

→ Steps seen in ToA structure
→ Correlation possible via timestamps in data
→ Annihilation process or possibly reflection can be studied depending on initial kinetic energy



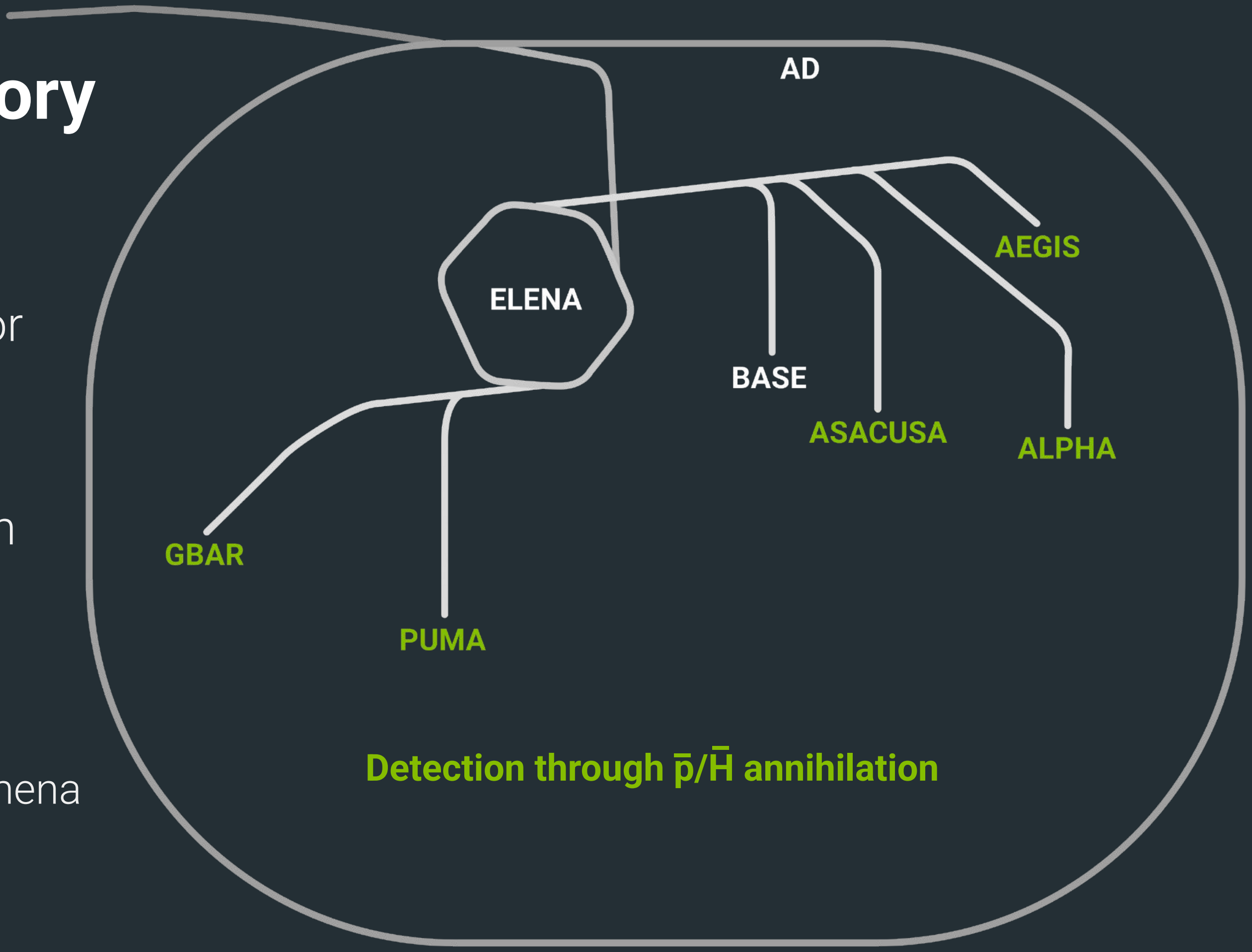
Antimatter Factory

@ CERN

Antiproton Decelerator
ELENA
100 keV $\bar{p}$

Study antimatter through

- Spectroscopy
- Gravitational behavior
- Magnetic moments
- Exotic nuclear phenomena



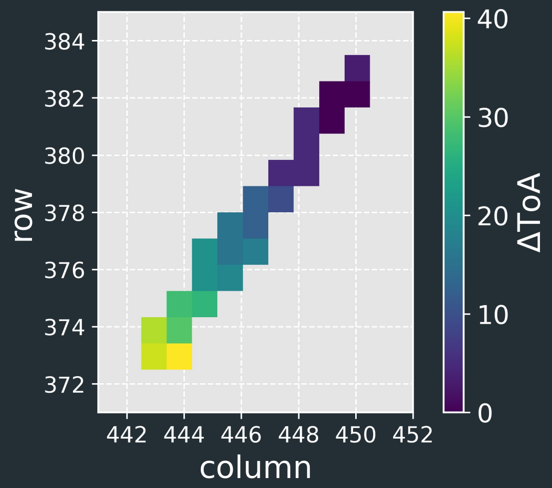
Bergmann, B. et al, EPJ C (2017)

Signal Depth Reconstruction from ToA

Each sensor is used similar to a time projection chamber :

Difference in drift time along particle trajectory (*ΔToA*) to get the signal depth *z* within the sensor

$$z(t) = \frac{d}{2U_D} \cdot (U_D + U_B) \cdot \left(1 - \exp\left(\frac{2U_D \mu_h t}{d^2}\right)\right)$$



d	sensor thickness
U_D	depletion voltage
U_B	bias voltage
μ_h	hole mobility
t	drift time = ΔToA

Simulation Models

- Geant4
  - FTFP_BERT with EM option 4
    Fritiof annihilation model
  - FTFP_INCLXX with EM option 4
    Model for low energy antiproton annihilation New in Geant4 11.2
- FLUKA
- Digitisation with Allpix²
  Converts simulation to hits in the detector

Particle Identification (PID)

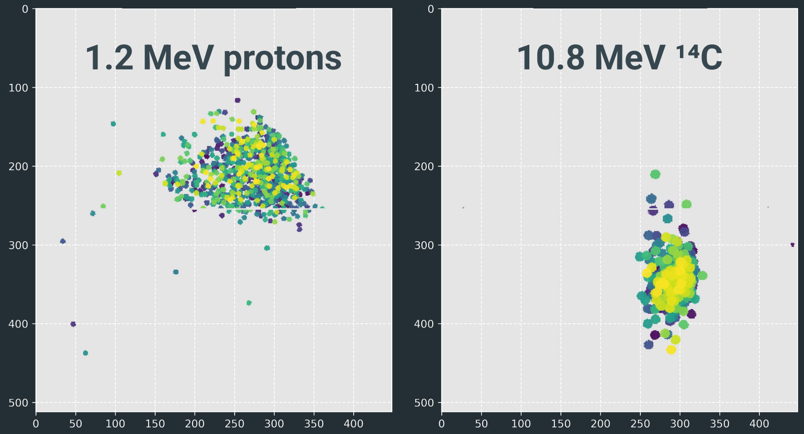
Differentiation by energy deposit, dE/dx and cluster morphology

Test beams with different particles and energies

- Gather data sets for typical annihilation products
- Machine learning can be used to refine classical PID methods

Ruffenach et al., IEEE Transactions on Nuclear Science (2021)

Example of different cluster sizes from test beam at VERA



Refined identification of particle types

Previously only distinguished between minimum ionizing (MIPs) and heavily ionizing particles (HIPs)

Track Fitting

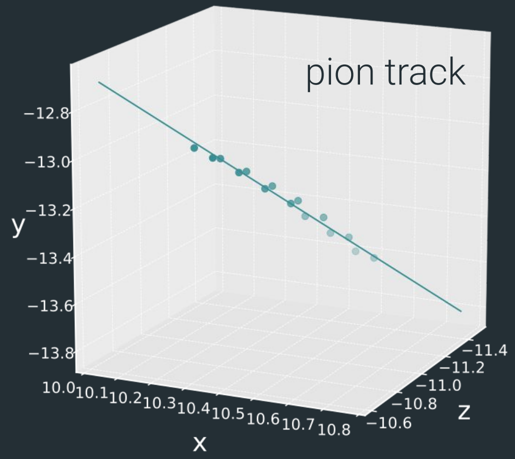
[row, col, z(ToA)] in each sensor → [x, y, z] global coordinates

Tracks are defined as clusters with eccentricity > 0.9

Finding the direction vector *v* is done using SVD (singular value decomposition)

$$\vec{p}_0 = \begin{pmatrix} \overline{x_i} & \overline{y_i} & \overline{z_i} \end{pmatrix}$$

$$A = \begin{pmatrix} \vdots & \vdots & \vdots \\ x_i & y_i & z_i \\ \vdots & \vdots & \vdots \end{pmatrix} - \vec{p}_0 = U \Sigma V^T \qquad V^T[0,:] = \vec{v}$$



Parametric equation for each track: $\vec{p}_0 + t \cdot \vec{v}$

Vertex Reconstruction

No trigger → Clustering of the tracks by their first ToA

Finding the closest point of all tracks within one "time bin":

- I take all possible combinations of two tracks, for each one I find their intersection point:

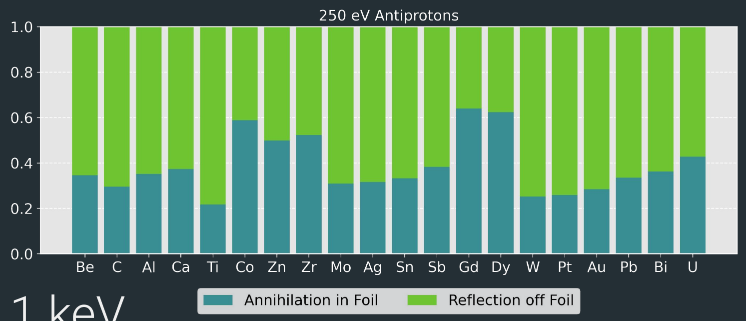
$$I = \vec{p_0} \pm \frac{||\vec{v} \times \overrightarrow{p_0 q_0}||}{||\vec{v} \times \vec{u}||}\vec{u}$$

average points p_0, q_0
direction vectors u, v

- The reconstructed vertex is taken as the mean of all found intersections

Annihilation vs. Reflection

- Experimental evidence that significant amount of antiprotons at few keV actually are reflected by a solid wall
  Sub-keV it's possible that ~ 50 % reflect and don't annihilate
  Bianconi et. al. Phys Rev A 78 (2008)



- Geant4 simulation shows 40 - 80 % reflections depending on nucleus
- Fluka does not calculate stopping powers < 1 keV
- Stopping power (of antiprotons) around 1 keV hard to model:
  - Contributions from multi-electron and molecular effects
  - Nuclear stopping power becomes more relevant than electronic