

Antiproton-Nucleus Annihilations at Low Energies

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in collaboration with AEgIS

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1 Antiproton-Nucleus Annihilation

2 Annihilation Studies Project

3 Detection System

4 Vertex Reconstruction

5 Status & First Results

1 Antiproton-Nucleus Annihilation

2 Annihilation Studies Project

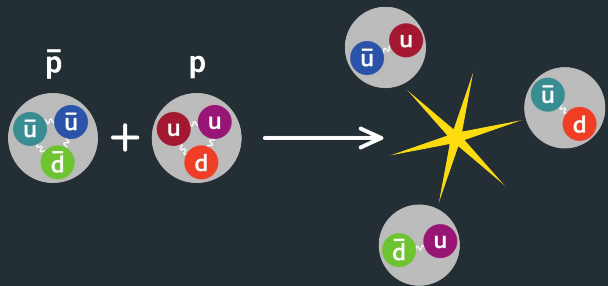
3 Detection System

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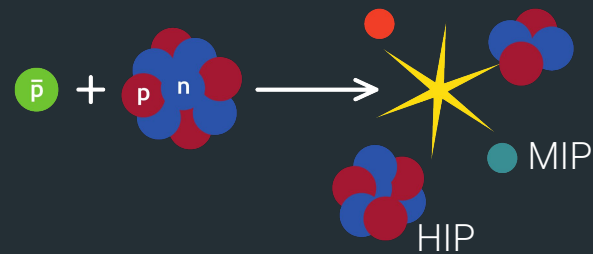
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Antiproton-Nucleus ($\bar{p}A$) Annihilation

Most antimatter experiments detect annihilation products, not antimatter directly!



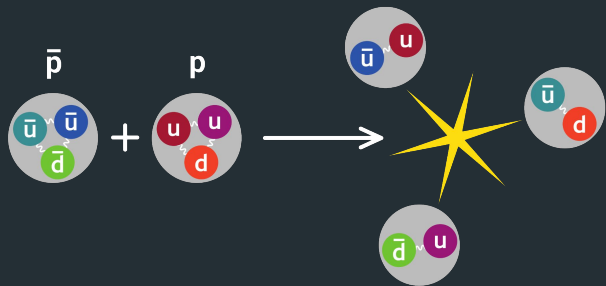
Annihilation happens on quark level
Creates charged and neutral mesons
 3.0 ± 0.2 charged pions
 2.0 ± 0.2 neutral pions
 ~ 230 MeV kinetic energies



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

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

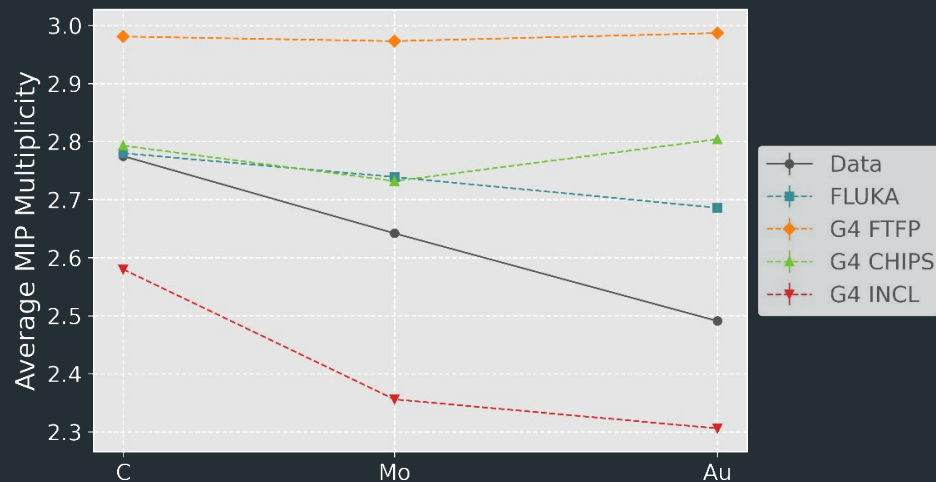


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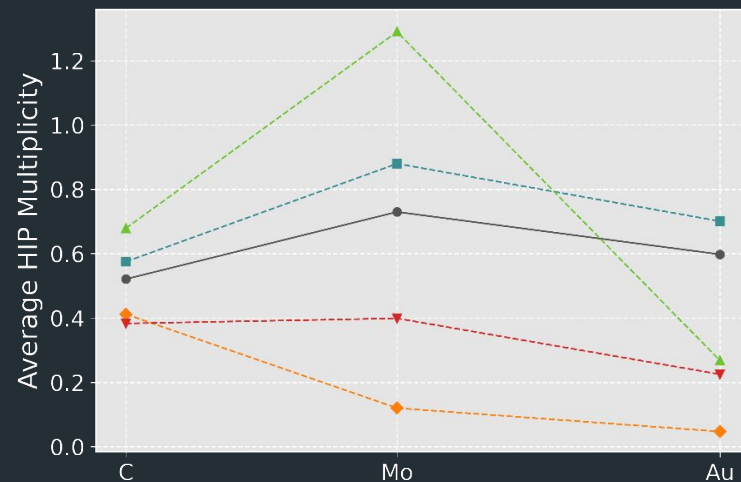
Hofmann et al., Nuclear Physics A (1990)

Prong Multiplicities

Minimum Ionising Particles (MIPs)



Heavily Ionising Particles (HIPs)



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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

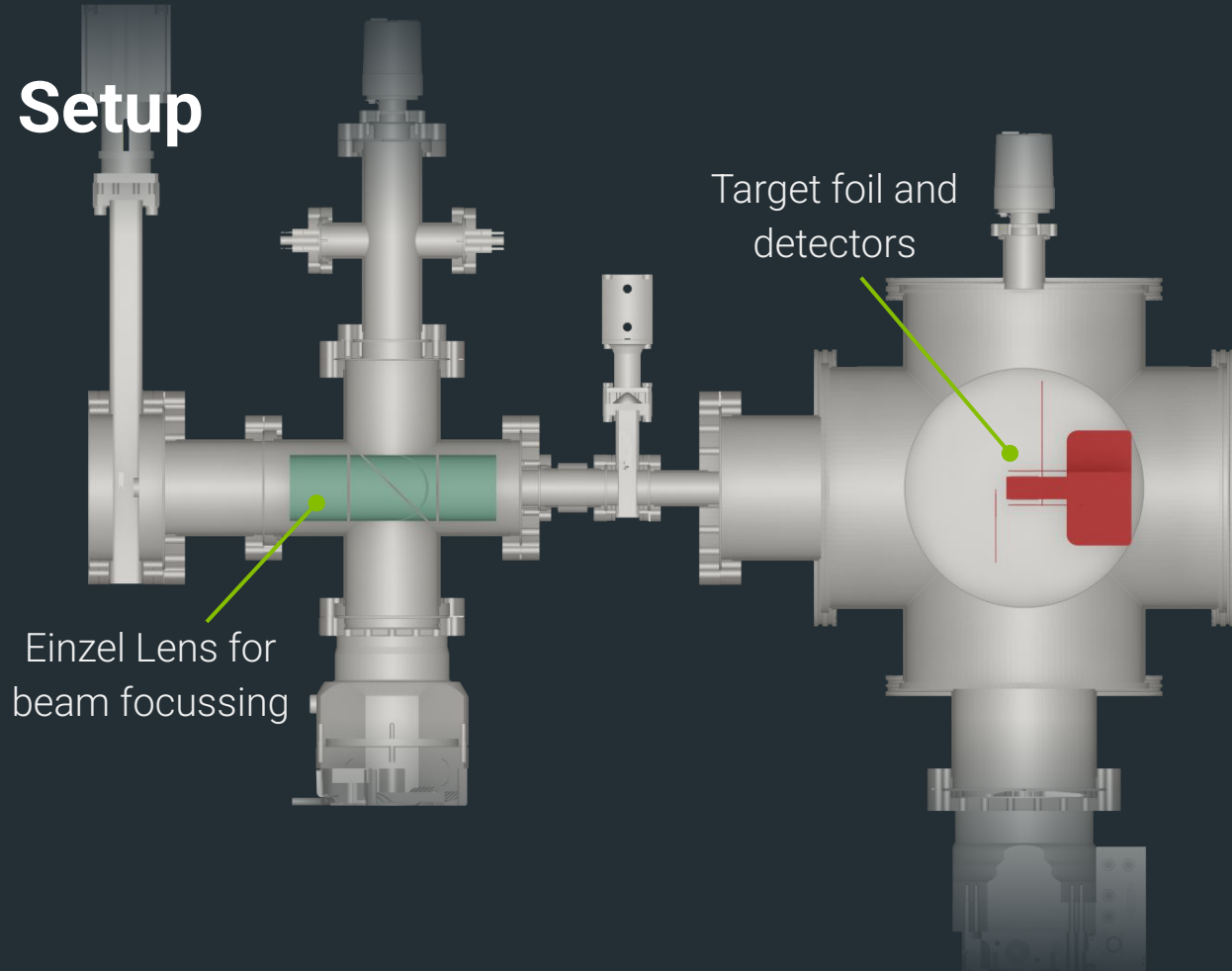
- Particle identification
- Total multiplicities
- Energy deposit
- Angular distribution

Vertex reconstruction important to tag individual events

Experimental Setup



Antiprotons are slow
extracted from the
AEgIS trap



Experimental Setup

AEGIS

Antiprotons are slow
extracted from the
AEGIS trap

Einzel Lens for
beam focussing

Target foil and
detectors

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Detector Geometry

Target foil surrounded by detectors

Six Si sensors coupled to
Timepix4 ASICs:

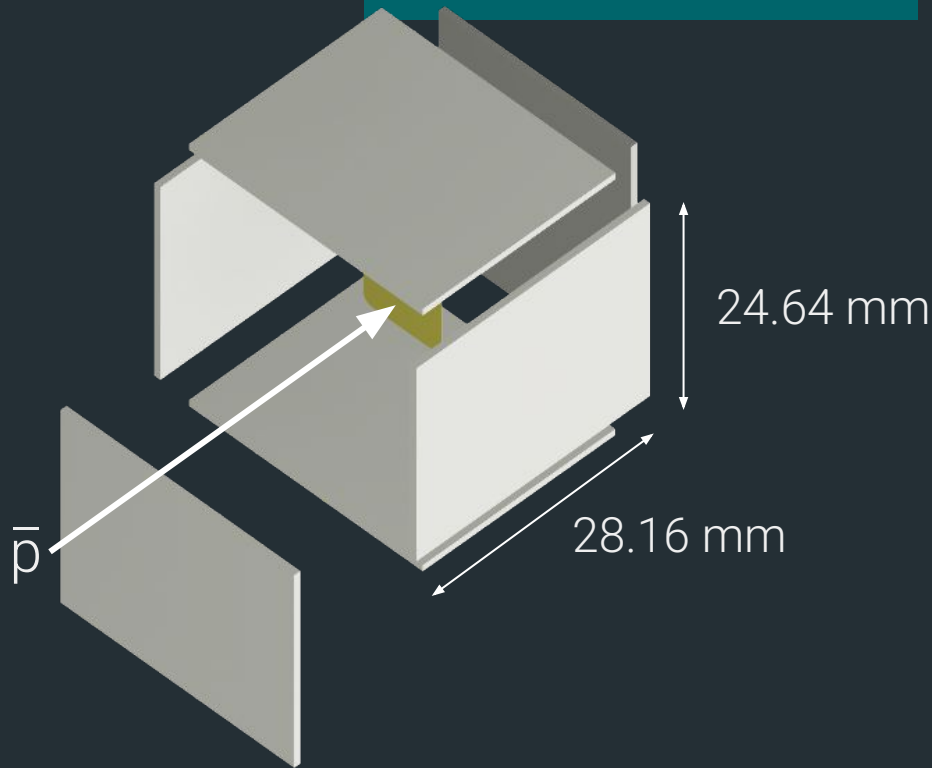
- $5 \times 500 \mu\text{m}$ $1 \times 625 \mu\text{m}$
- 1 sensor in the back with offset allows beam to enter
- 5 sensors cover the other planes of the cube-like geometry
- $\sim 64\%$ of solid angle coverage

Timepix4

55 μm pixel size

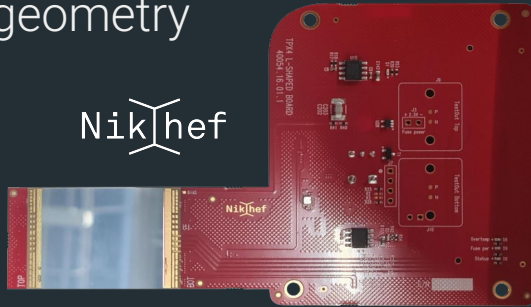
512 x 448 pixels

Time resolution < 200 ps



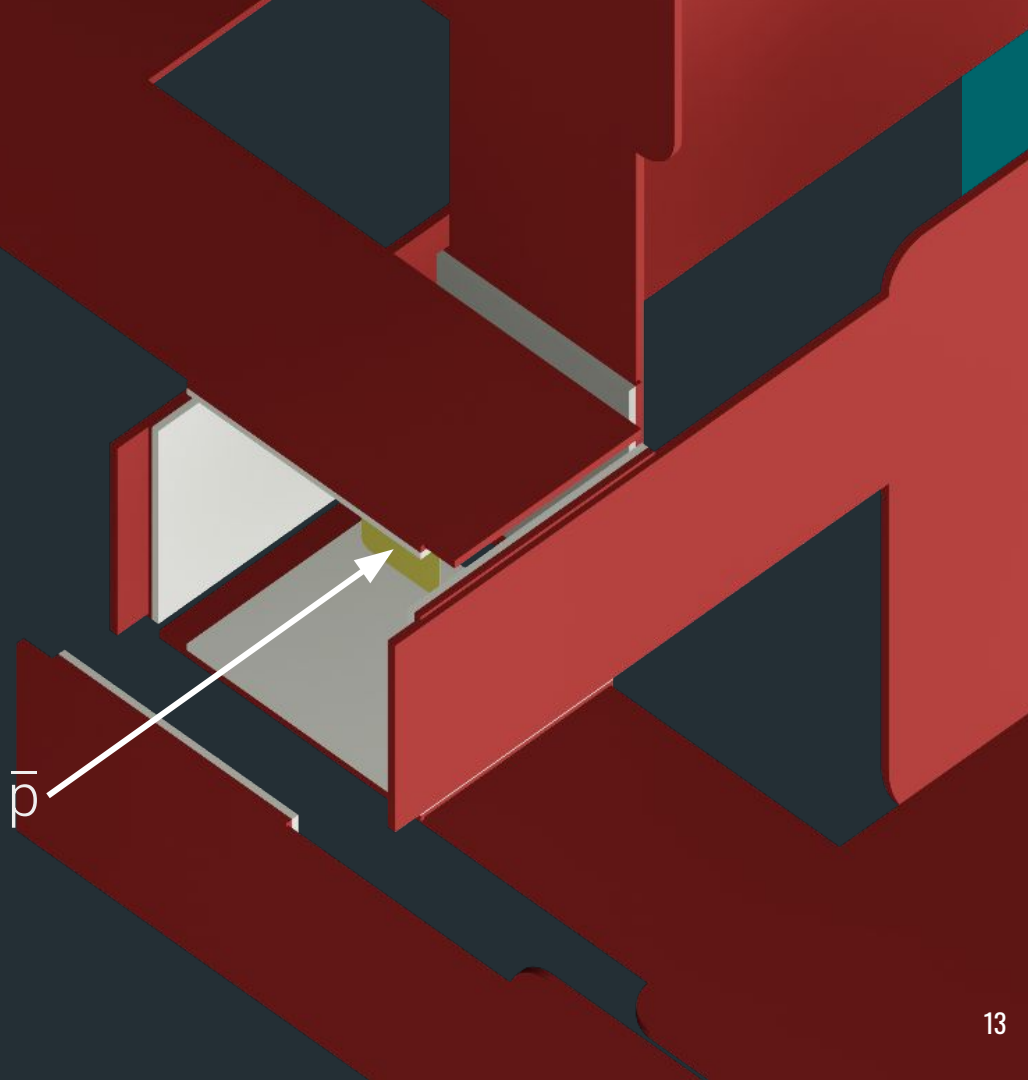
Annihilation Chamber

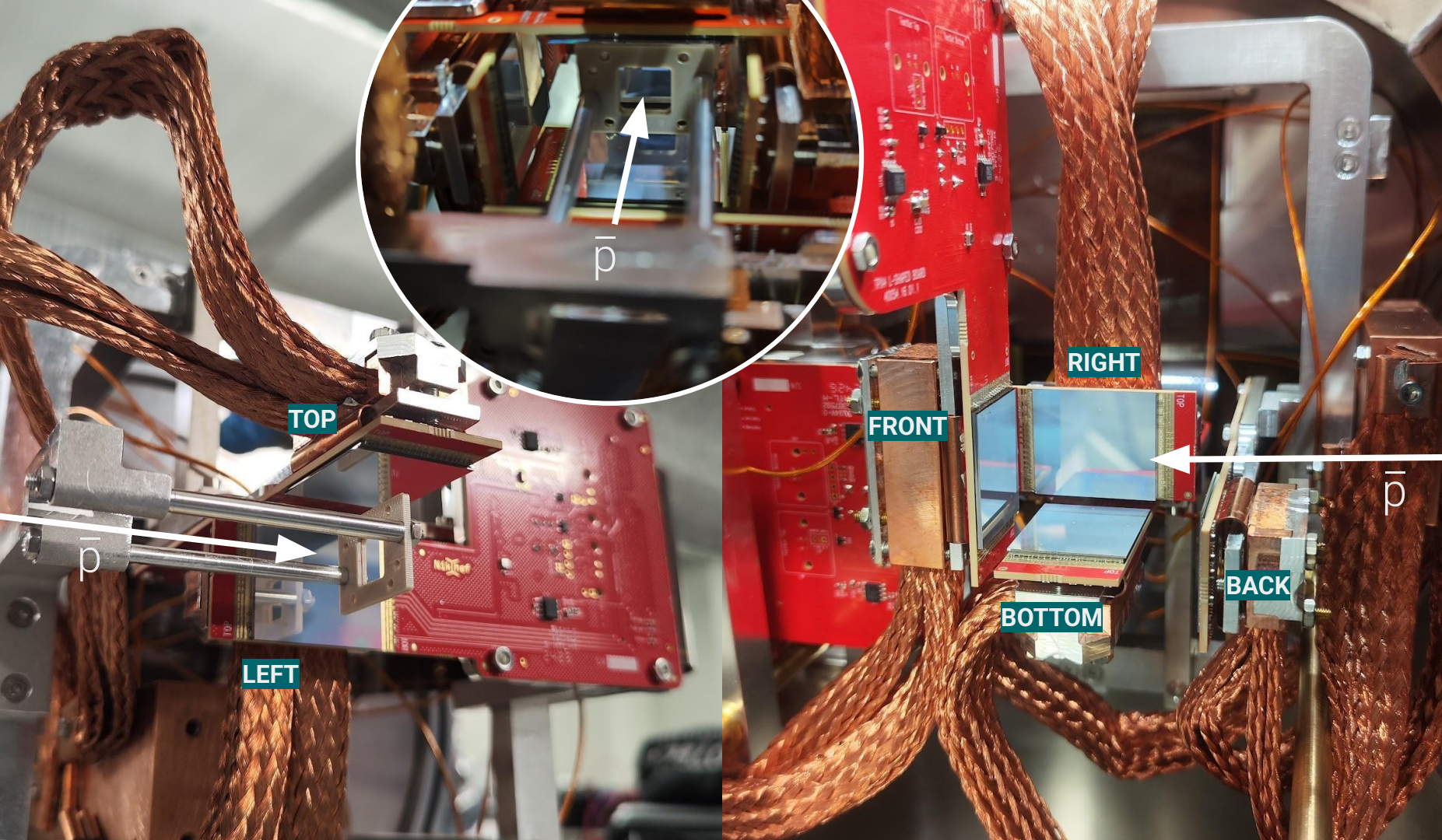
PCB boards specifically designed for our geometry



Cooling the detectors with water through copper pipes/blocks

\bar{p}





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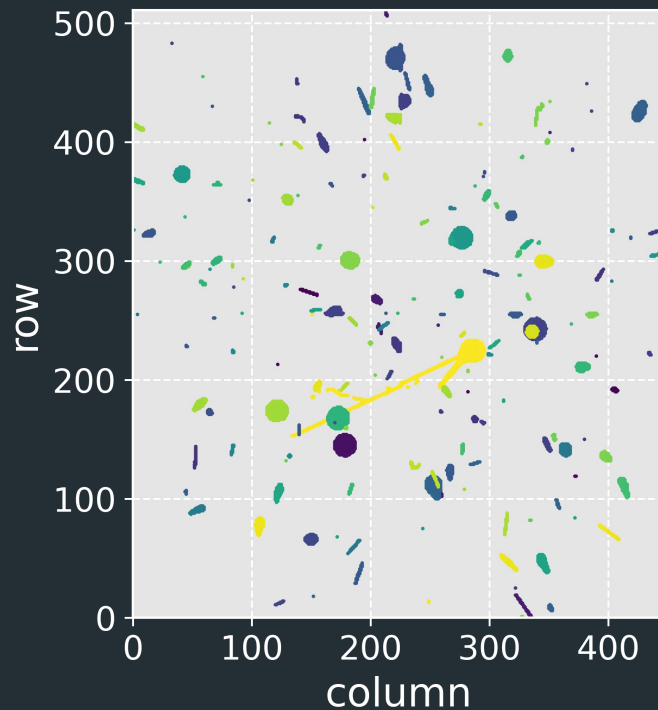
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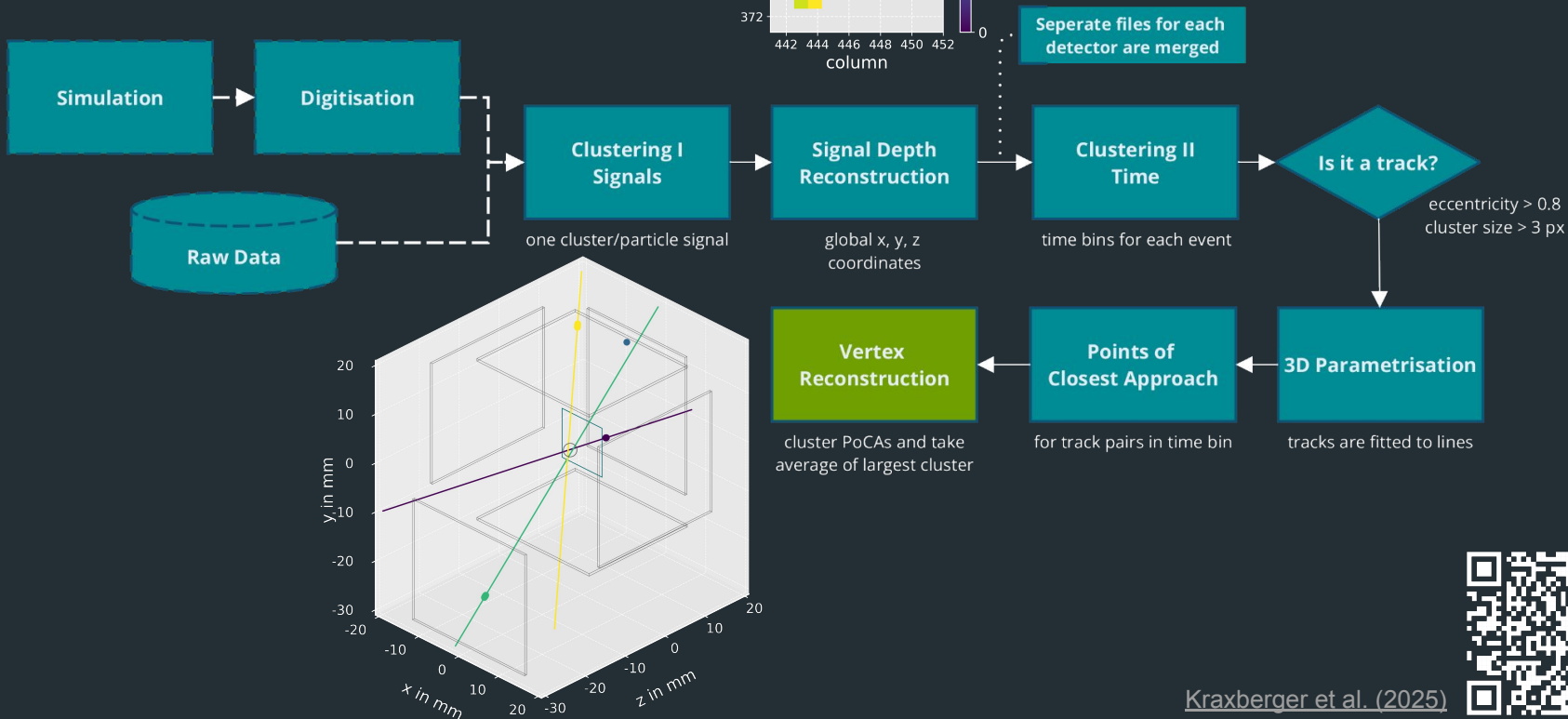
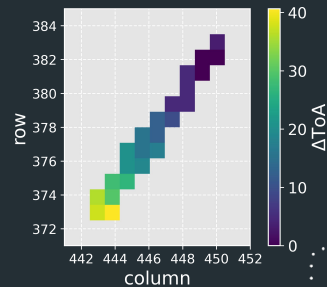
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Data Structure

- 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)

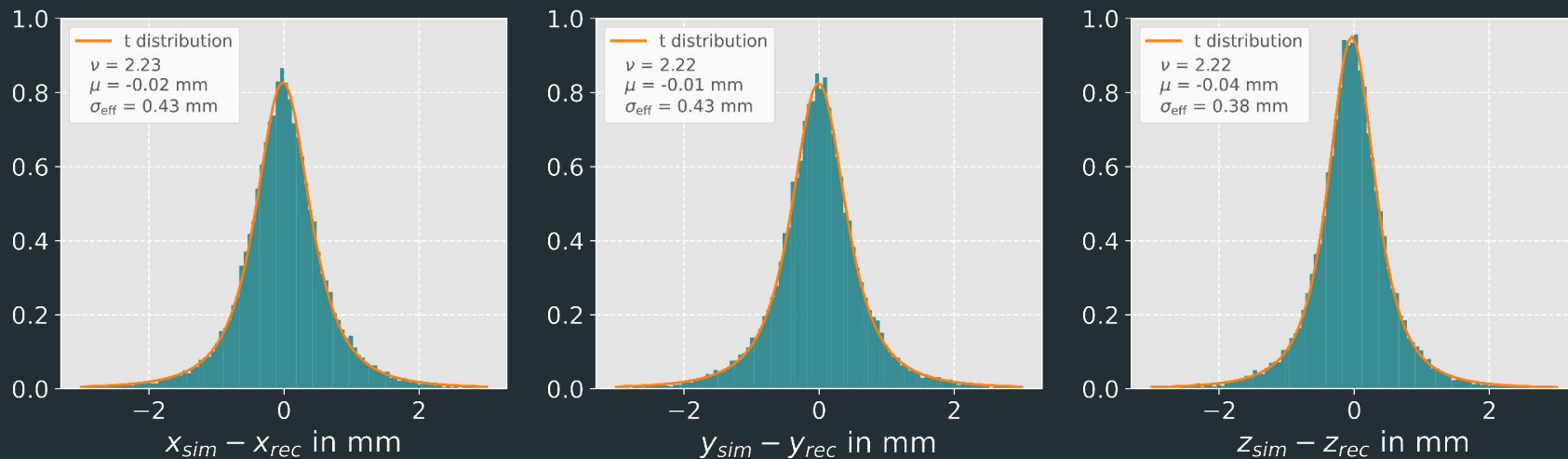


Algorithm



Vertex Reconstruction Resolution

Comparison of simulated annihilation position to reconstructed vertex:



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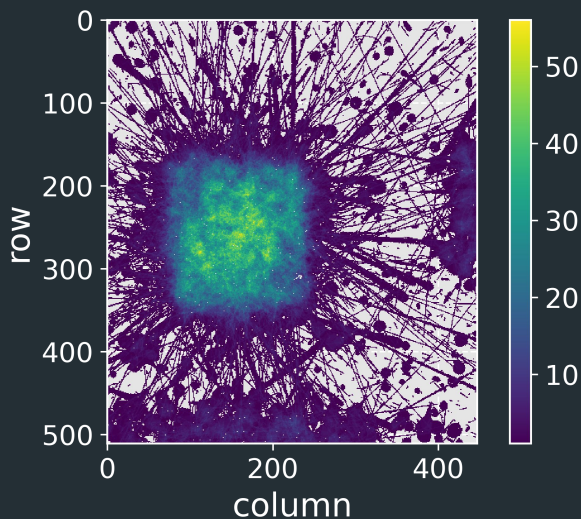
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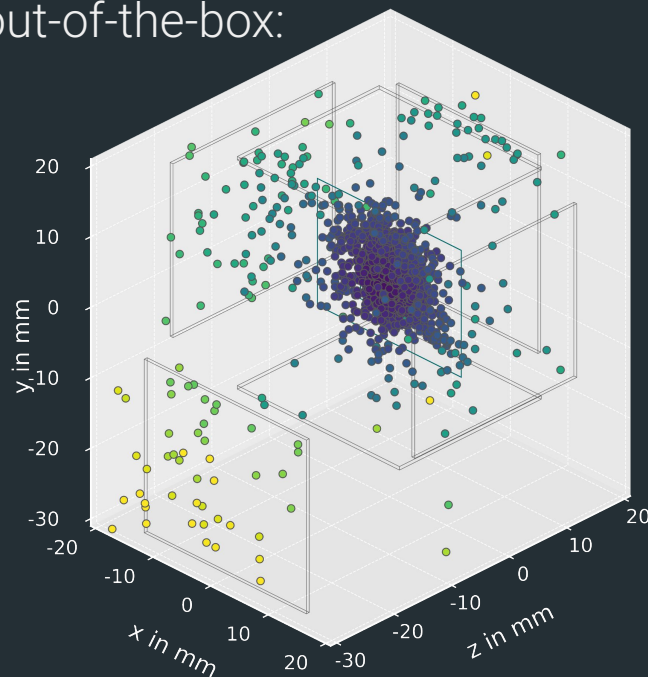
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Beam Campaign in August 2025

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



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



Measured Targets



In total 9 foils measured

7 under perfect conditions,

Fe and Au with only 5/6 detectors

Periodic Table of the Elements

1 1A H Hydrogen 1.008	2 2A He Helium 4.003	3 3A B Boron 10.81	4 4A C Carbon 12.011	5 5A N Nitrogen 14.007	6 6A O Oxygen 15.999	7 7A F Fluorine 18.998	8 8A Ne Neon 20.180	9 9A Na Sodium 22.990	10 10A Mg Magnesium 24.305	11 11A Al Aluminum 26.982	12 12A Si Silicon 28.086	13 13A P Phosphorus 30.974	14 14A S Sulfur 32.06	15 15A Cl Chlorine 35.45	16 16A Ar Argon 39.948	17 17A K Potassium 39.098	18 18A Ca Calcium 40.078	19 19A Sc Scandium 44.956	20 20A Ti Titanium 47.88	21 21A V Vanadium 50.942	22 22A Cr Chromium 51.996	23 23A Mn Manganese 54.938	24 24A Fe Iron 55.845	25 25A Co Cobalt 58.933	26 26A Ni Nickel 58.69	27 27A Cu Copper 63.546	28 28A Zn Zinc 65.38	29 29A Ga Gallium 69.723	30 30A Ge Germanium 72.63	31 31A As Arsenic 74.922	32 32A Se Selenium 78.96	33 33A Br Bromine 79.904	34 34A Kr Krypton 83.8	35 35A Rb Rubidium 85.468	36 36A Sr Strontium 87.62	37 37A Y Yttrium 88.906	38 38A Zr Zirconium 91.224	39 39A Nb Niobium 92.906	40 40A Mo Molybdenum 95.94	41 41A Tc Technetium 98	42 42A Ru Ruthenium 101.07	43 43A Rh Rhodium 102.905	44 44A Pd Palladium 106.42	45 45A Ag Silver 107.868	46 46A Cd Cadmium 112.411	47 47A In Indium 114.818	48 48A Sn Tin 118.710	49 49A Sb Antimony 121.757	50 50A Te Tellurium 127.6	51 51A I Iodine 126.905	52 52A Xe Xenon 131.29	53 53A Cs Cesium 132.905	54 54A Ba Barium 137.327	55 55A La Lanthanum 138.905	56 56A Ce Cerium 140.12	57 57A Pr Praseodymium 140.908	58 58A Nd Neodymium 144.24	59 59A Pm Promethium 145	60 60A Sm Samarium 150.36	61 61A Eu Europium 151.964	62 62A Gd Gadolinium 157.25	63 63A Tb Terbium 158.925	64 64A Dy Dysprosium 162.50	65 65A Ho Holmium 164.930	66 66A Er Erbium 167.259	67 67A Tm Thulium 168.934	68 68A Yb Ytterbium 173.054	69 69A Lu Lutetium 174.967	70 70A Hf Hafnium 178.49	71 71A Ta Tantalum 180.948	72 72A W Tungsten 183.84	73 73A Re Rhenium 186.207	74 74A Os Osmium 190.23	75 75A Ir Iridium 192.222	76 76A Pt Platinum 195.084	77 77A Au Gold 196.967	78 78A Hg Mercury 200.59	79 79A Tl Thallium 204.38	80 80A Pb Lead 207.2	81 81A Bi Bismuth 208.98	82 82A Po Polonium 209	83 83A At Astatine 210	84 84A Rn Radon 222	85 85A Fr Francium 223	86 86A Ra Radium 226	87 87A Ac Actinium 227	88 88A Th Thorium 232	89 89A Pa Protactinium 231	90 90A U Uranium 238.029	91 91A Np Neptunium 237	92 92A Pu Plutonium 244	93 93A Am Americium 243	94 94A Cm Curium 247	95 95A Bk Berkelium 247	96 96A Cf Californium 251	97 97A Es Einsteinium 252	98 98A Fm Fermium 257	99 99A Md Mendelevium 258	100 100A No Nobelium 259	101 101A Lr Lawrencium 262	102 102A 103 103A
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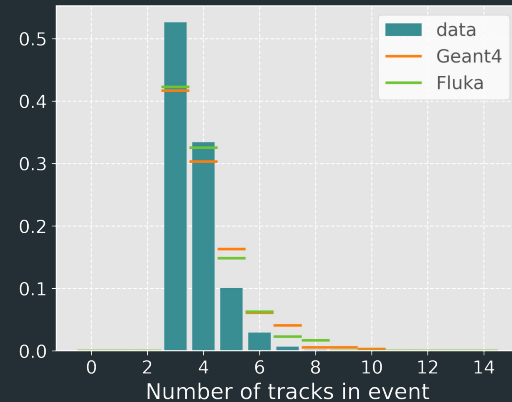
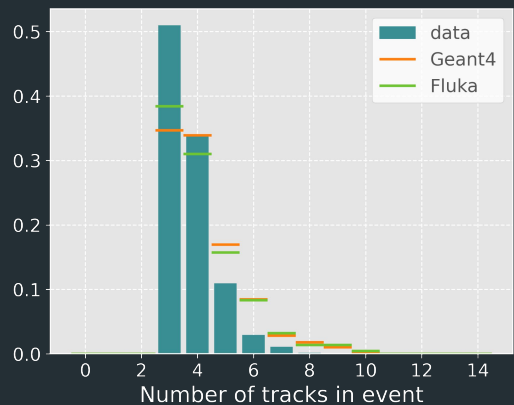
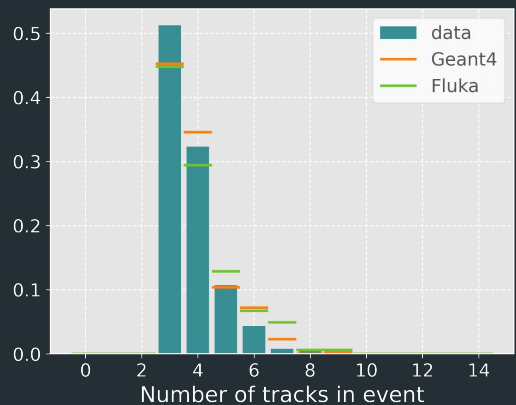
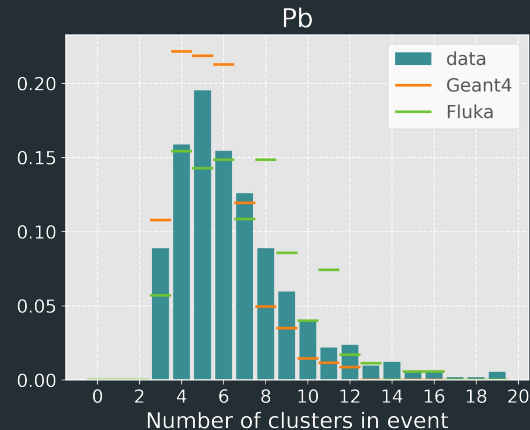
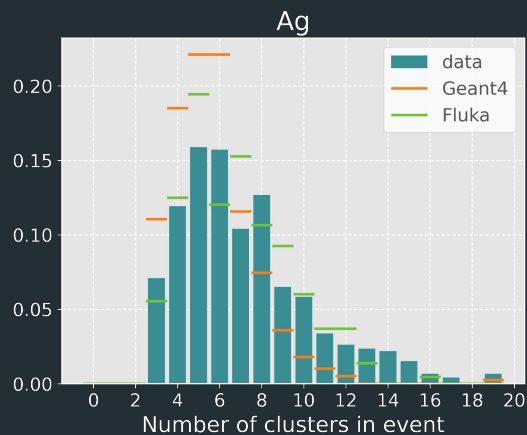
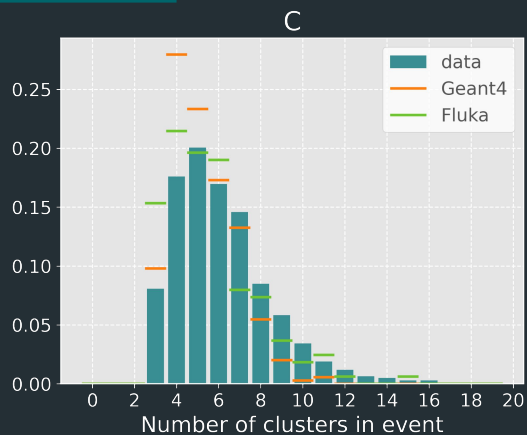
Data analysis just started...



- 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

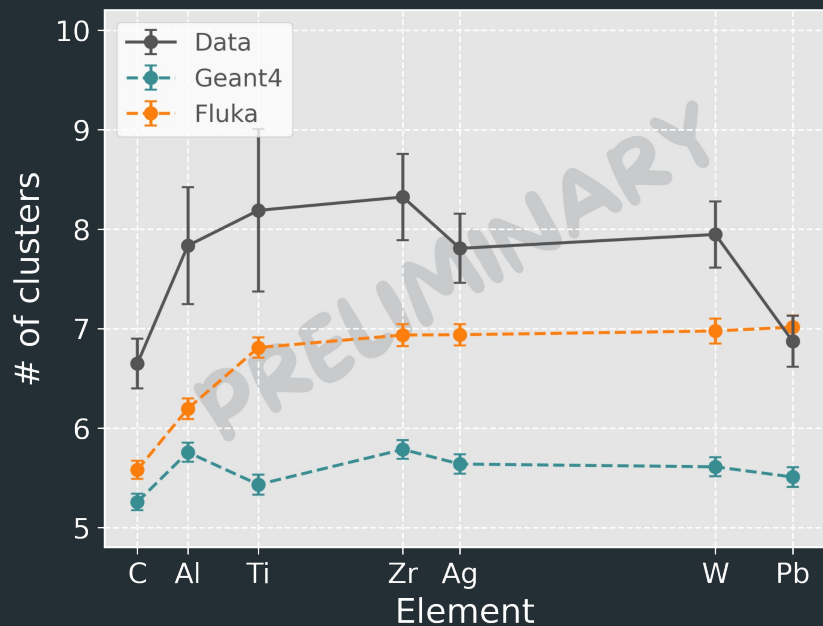
Data from only 3 runs per foil
Events where V_{rec} in $((-5, 5), (-5, 5), (-2, 2))$



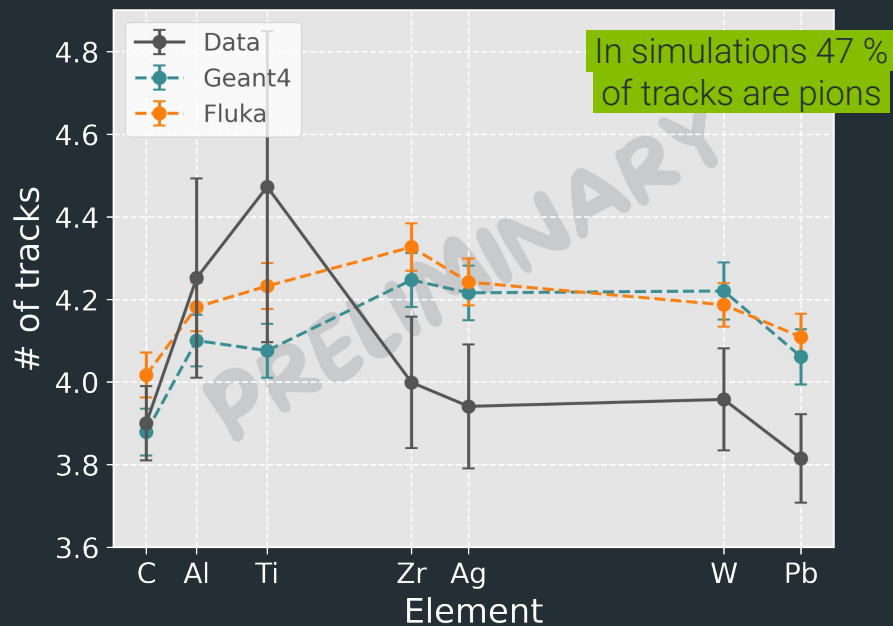
Cluster Multiplicities

Data from only 3 runs per foil
Events where V_{rec} in $((-5, 5), (-5, 5), (-2, 2))$

Total number of clusters per event



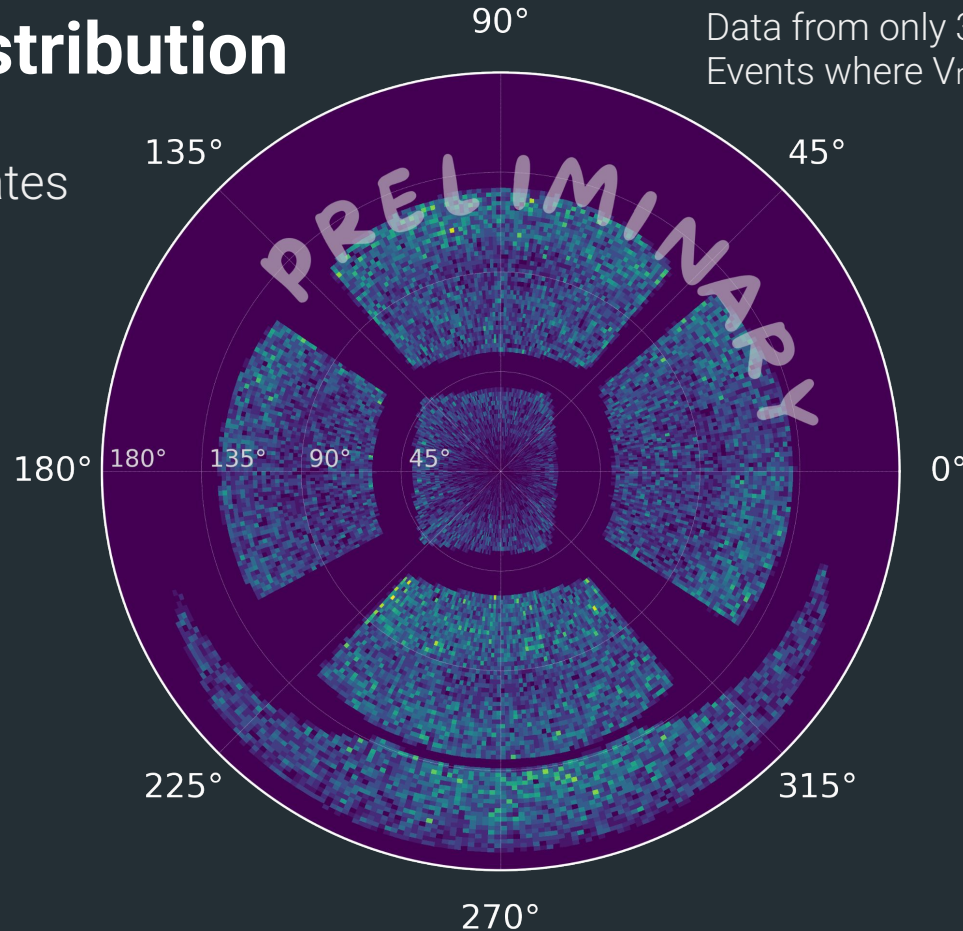
Number of clusters classified as track



Angular Distribution

Average coordinates
of each cluster in
polar distribution

Data from only 3 runs per foil
Events where V_{rec} in $((-5, 5), (-5, 5), (-2, 2))$

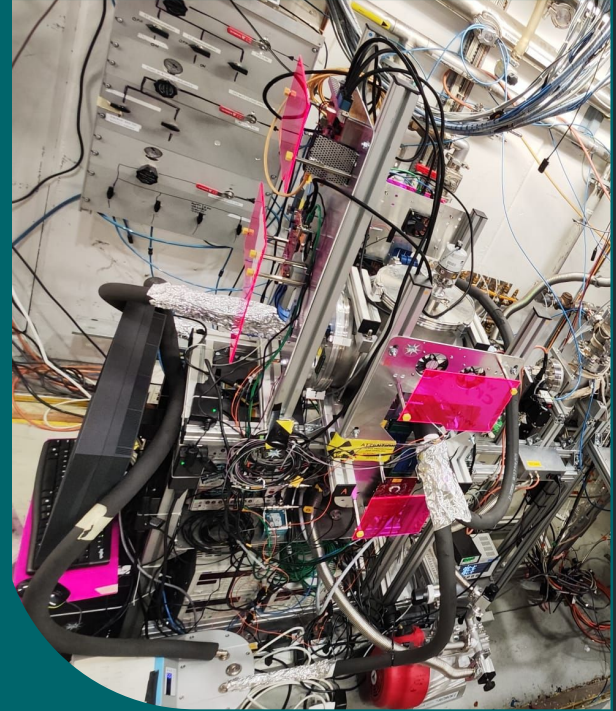
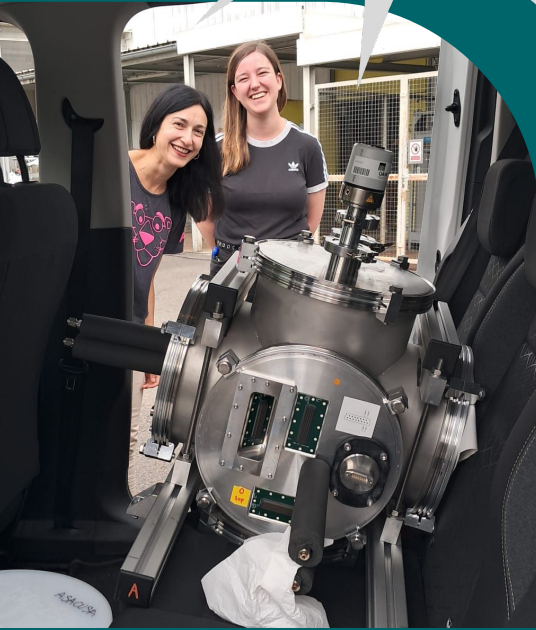


Summary

- 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!



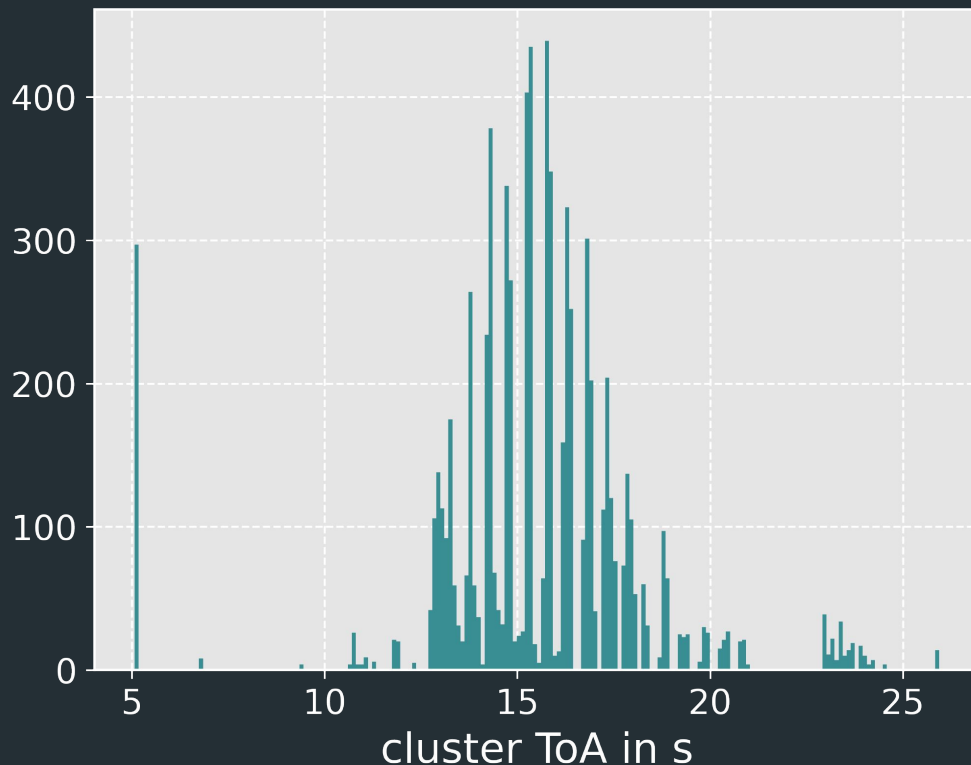
This research was funded in whole or in part by the Austrian Science Fund (FWF) [10.55776/P34438](https://www.fwf.ac.at/en/funding-number/10.55776/P34438).

Backup

Beam Energies

Trapping potential in AEGLS 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



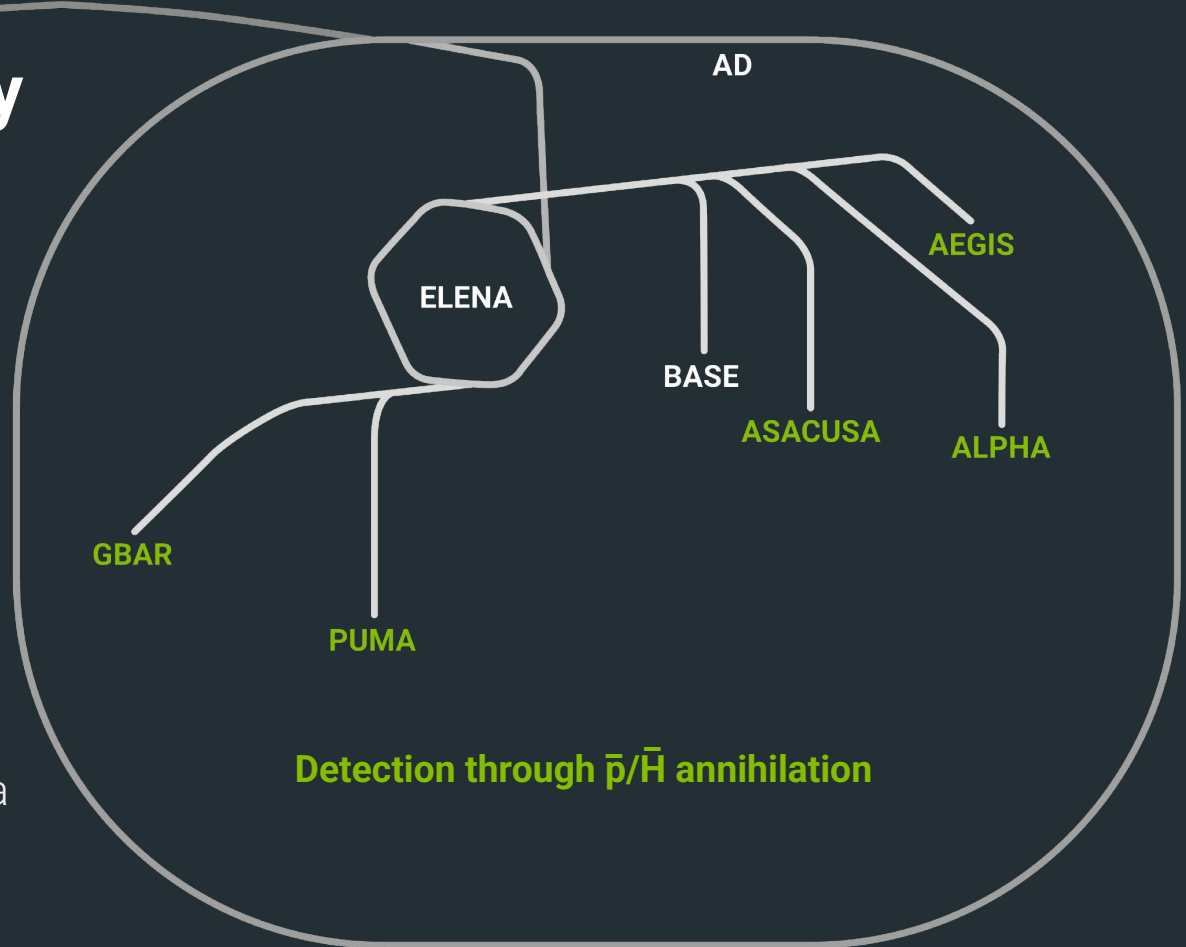
Antimatter Factory

@ CERN

Antiproton Decelerator
ELENA
100 keV \bar{p}

Study antimatter through

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



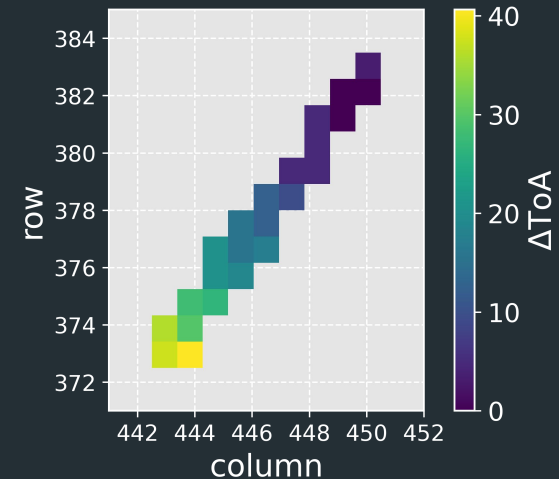
Signal Depth Reconstruction from ToA

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

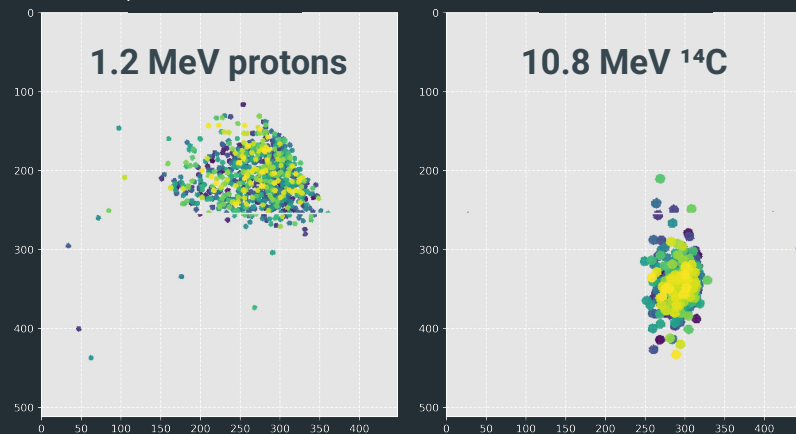
- Gather data sets for typical annihilation products
- Machine learning can be used to refine classical PID methods

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

Refined identification of particle types

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

Example of different cluster sizes from test beam at VERA



Track Fitting

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

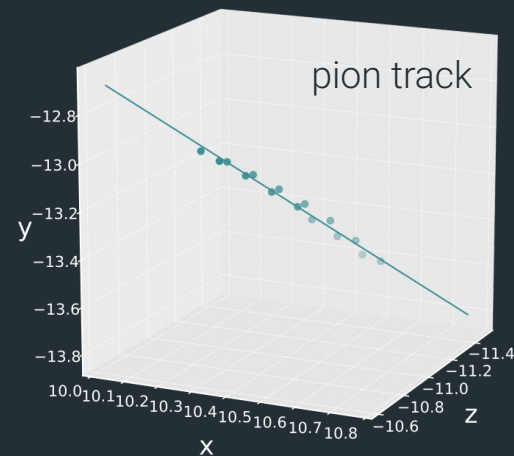
Tracks are defined as clusters with eccentricity > 0.9

Finding the direction vector \vec{v} is done using SVD (singular value decomposition)

$$\vec{p}_0 = (\overline{x_i} \quad \overline{y_i} \quad \overline{z_i})$$

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

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 $\sim 50\%$ 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

