Monte Carlo Simulations for a Low Energy Antiproton-Nucleus Annihilation Study

Viktoria Kraxberger[+o], Angela Gligorova[+]

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+ Stefan Meyer Institute for Subatomic Physics, Austrian Academy of Sciences, Vienna
○ University of Vienna, Vienna Doctoral School in Physics

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1. Antiproton-Nucleus Annihilation
2. Annihilation Studies Project
3. Detection System
4. Simulations

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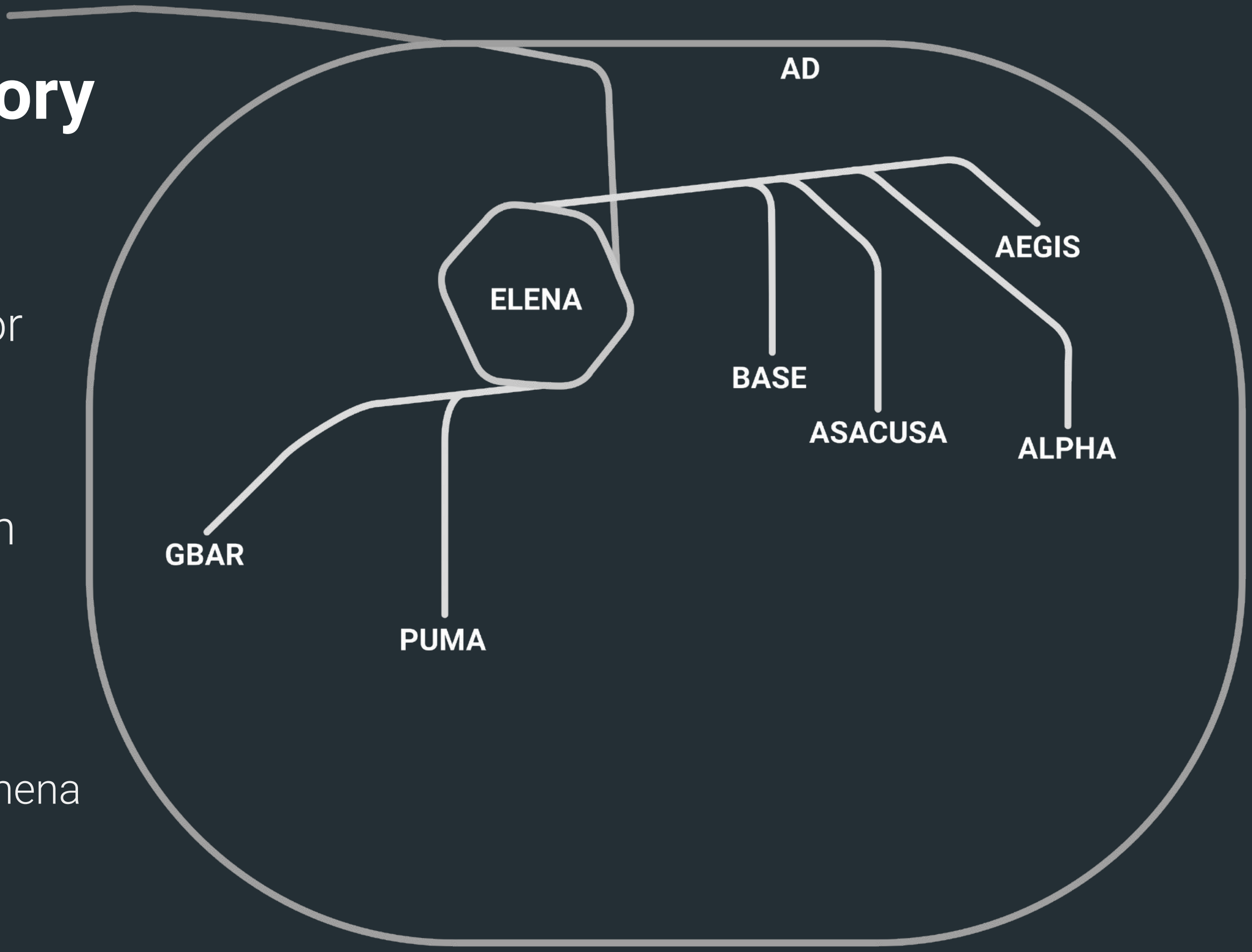
Antimatter Factory

@ CERN

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

Study antimatter through

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



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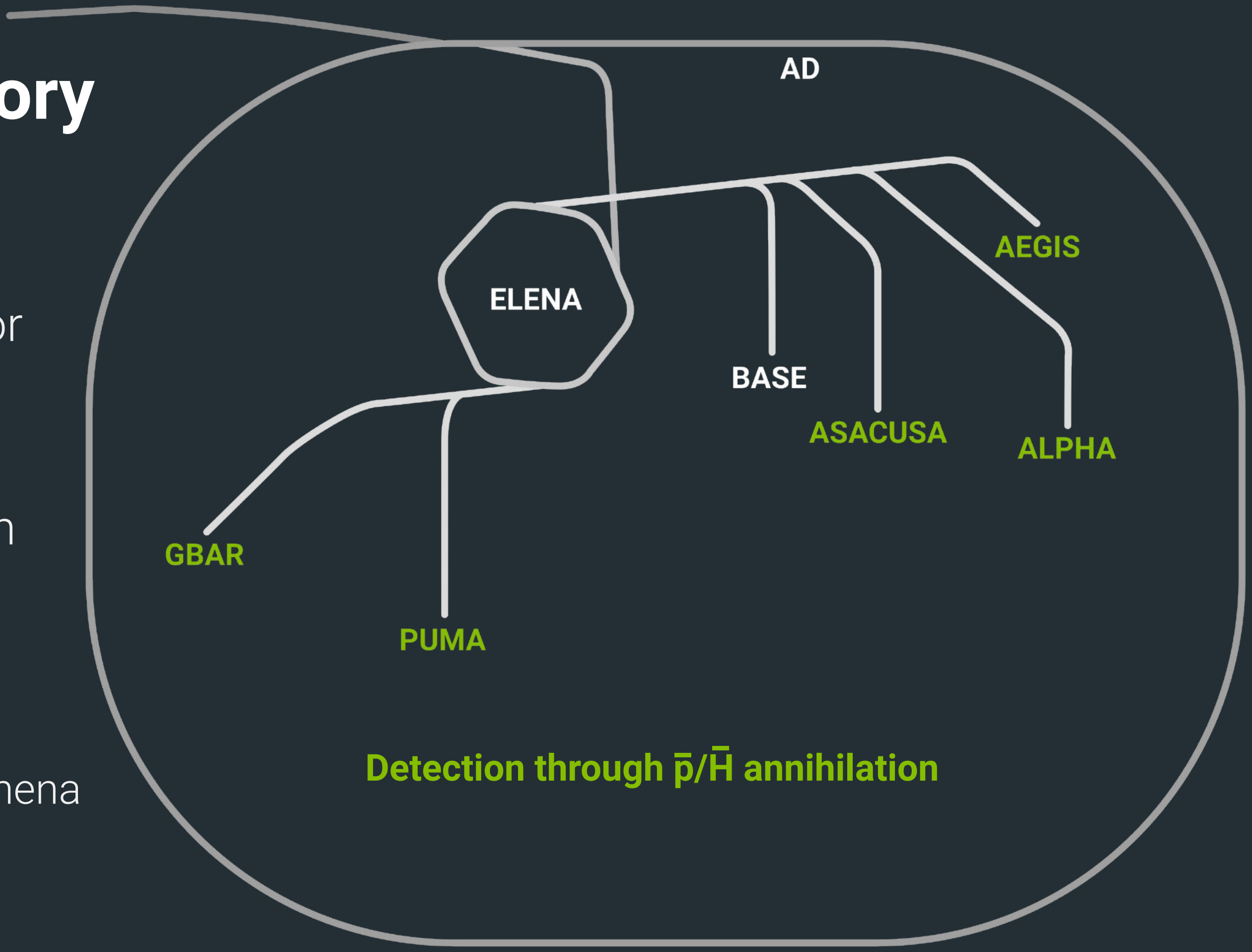
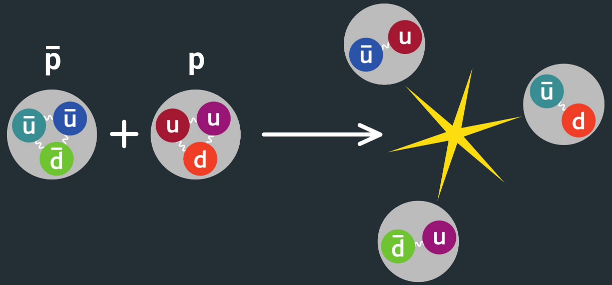
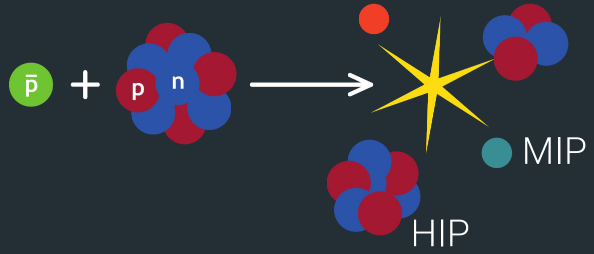


Antiproton-Nucleus ($\bar{p}$A) Annihilation

Most 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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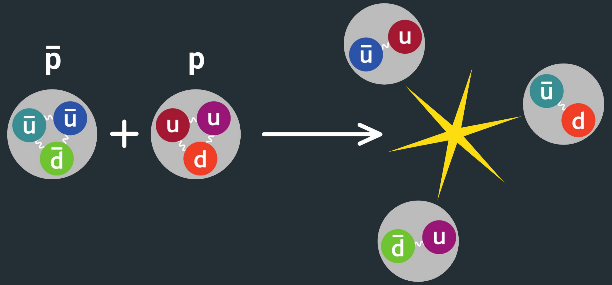

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$\bar{p}$A Annihilation Studies

250 eV antiprotons annihilating on thin target foils of 1-2 μm

- ~ 15 different nuclei to study dependencies on nuclear size
- Thin foil allows also heavy particles to reach the detector

Detector covering large solid angle

- Particle identification
- Total multiplicities
- Kinetic energies
- Angular distribution

Vertex reconstruction important to tag individual events

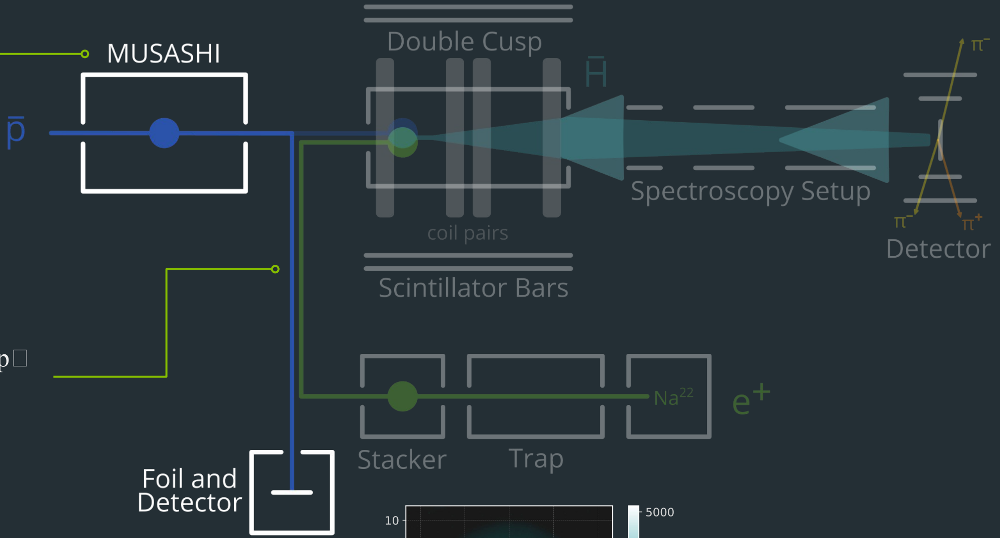
Experimental Setup

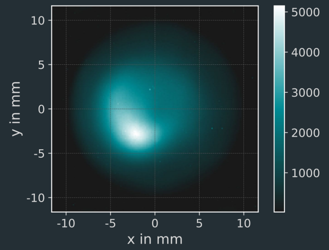
Secondary experiment at ASACUSA-CUSP

A trap based ultra-slow antiproton source can deliver a 150 or 250 eV monoenergetic DC-like beam after trapping, cooling and compression of the $\bar{p}$.

Electrostatic transport of $\bar{p}$ to
the 1-2 μm thick target foil.

Detection system that covers almost the full solid angle, able to identify annihilation products and measure the prong multiplicity for single events.





~ 25,000 antiprotons were counted on an MCP (microchannel plate detector) within a beam spot of under 10 mm.

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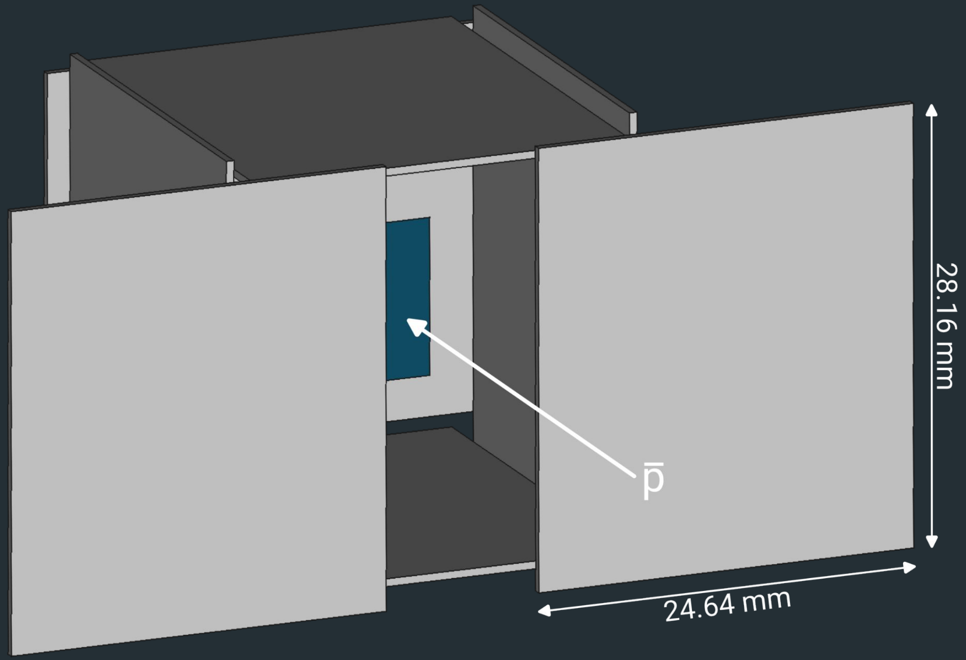
Detector Geometry

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

Target foil surrounded by detectors

7 x 500 µm Si sensors coupled to Timepix4 ASICs:

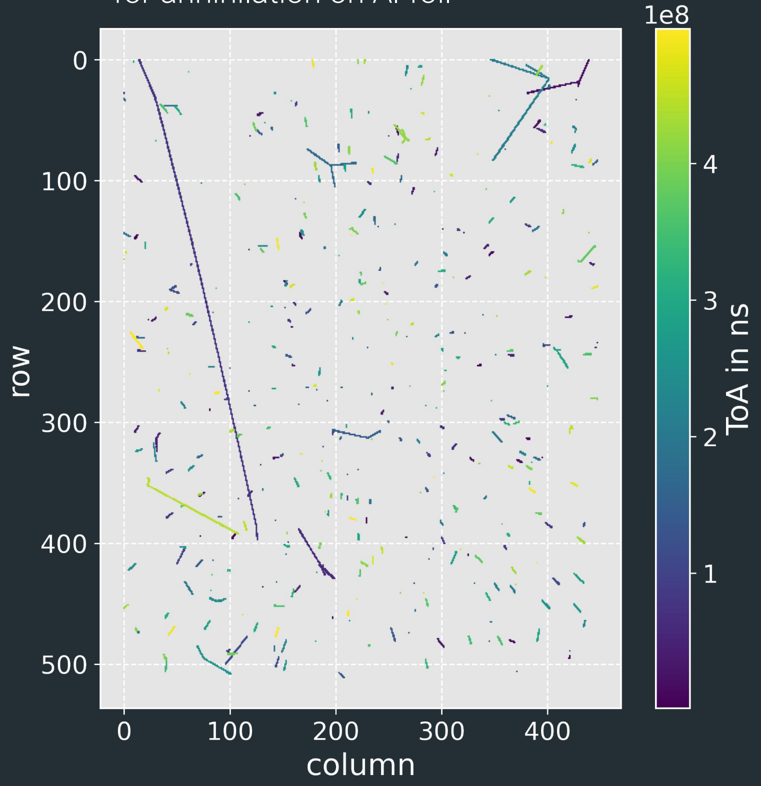
- 2 sensors placed such that a beam of ~ 10 mm diameter can enter
- 5 sensors cover the other planes of the cube-like geometry



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
- Signals from different particles are differentiated by clustering of [column, row, ToA]

Digitised simulation on one sensor for annihilation on Al-foil



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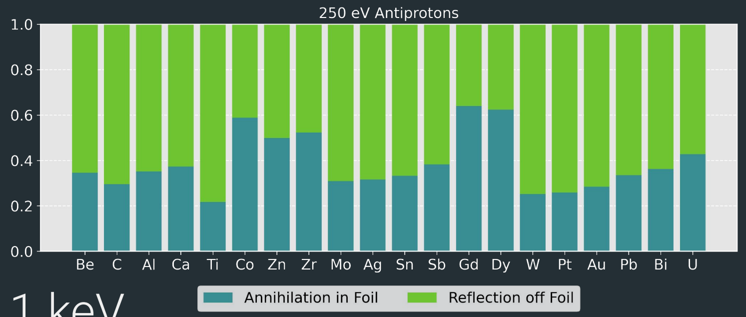
Simulation Models

- 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

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

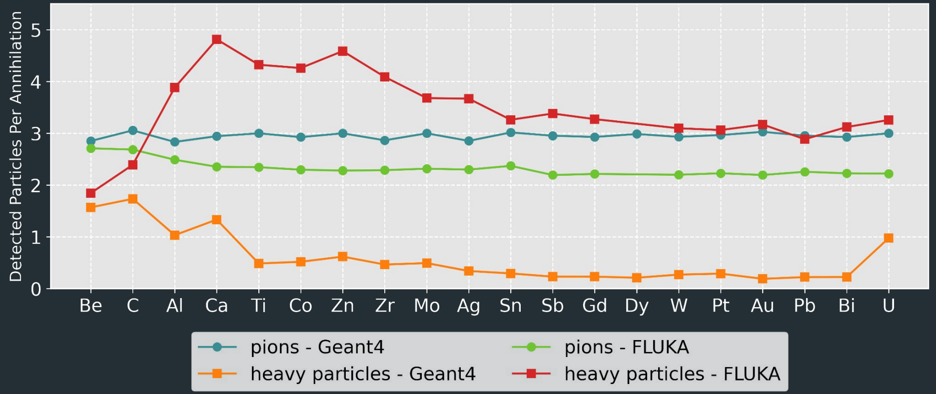


- Fluka does not calculate stopping powers < 1 keV

- 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

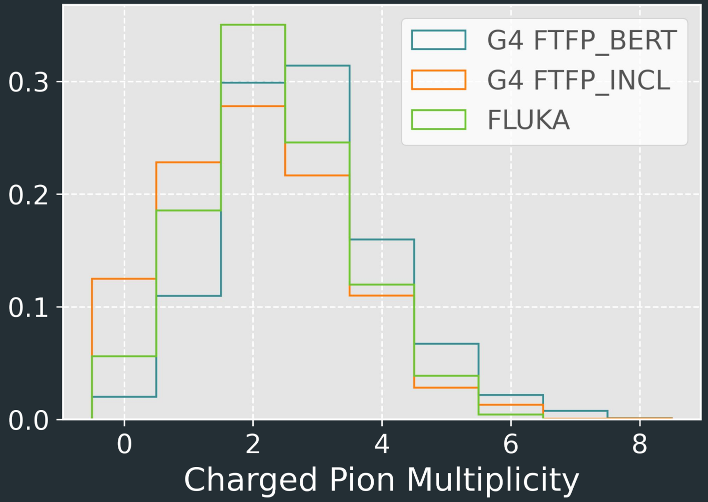
Annihilation Products

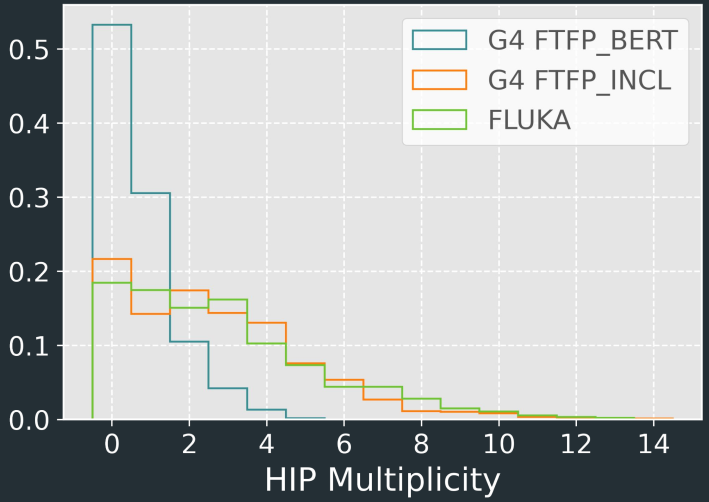
Models predict different MIP/HIP multiplicities



FTFP_BERT

250 eV antiprotons on Au foil

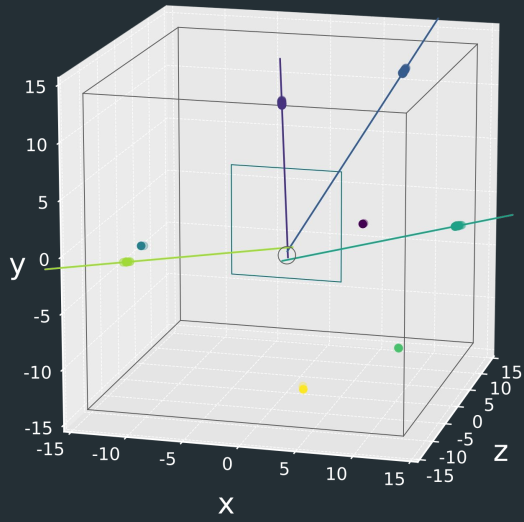


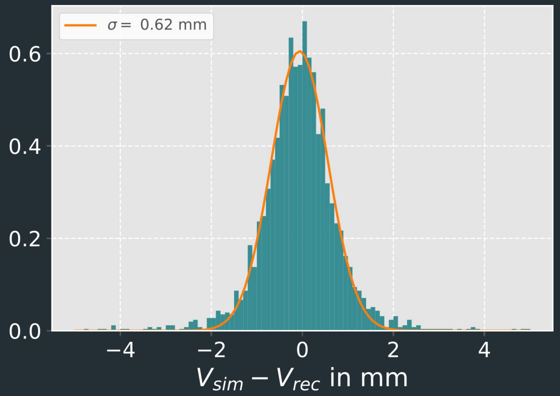


Vertex Reconstruction

With digitised data an algorithm was developed for reconstruction of annihilation vertex

- Signal depth reconstruction using ToA + drift time
- Each particle track fitted -> parametric equation
- Finding nearest points between all tracks in event
- Clustering nearest points and taking mean of biggest cluster as vertex
- Sub-mm resolution for reconstructed vertex





Summary

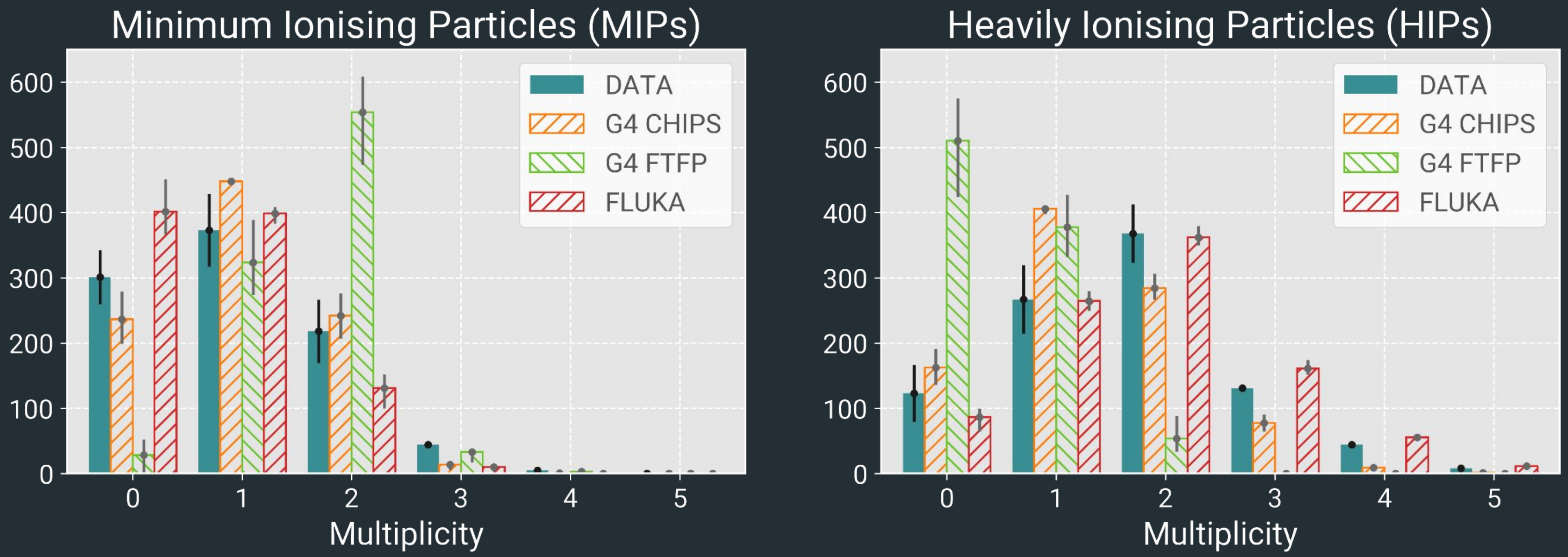
- Study of antiproton annihilations at rest with different nuclei using ~4π detector coverage with Timepix4 is in preparation
- Simulation models do not agree at low energies
  - Different multiplicities
  - No stopping power calculation in Fluka < 1 keV
    Variation in Geant4 annihilation/reflection ratio not explained
- Results of experiment will be used for assessment of models such as the Liège Intranuclear Cascade model, and their potential tuning

Thank you!

Backup

Previous Annihilation Data

For ~ 100 keV antiprotons on silver nuclei:



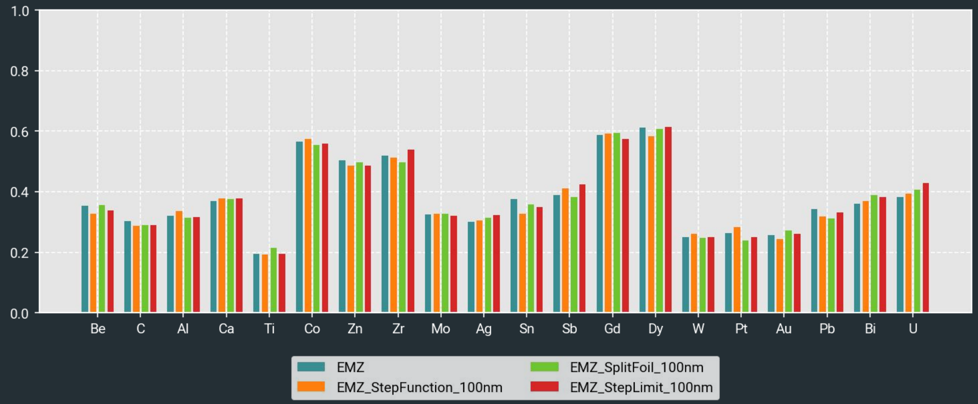
Aghion, S. et al., Journal of Instrumentation (2017)

Exploring Geant4 Models

Before CHIPS model described annihilation process most precisely.
Now only Fritiof model still available

Results varied a lot with different electromagnetic models
Geant4 group suggested EMZ for "low energies"

Trying different step size models to reach stability within EMZ:



Particle Identification (PID)

Differentiation by energy deposit, dE/dx and cluster morphology

Test beams with different particles and energies

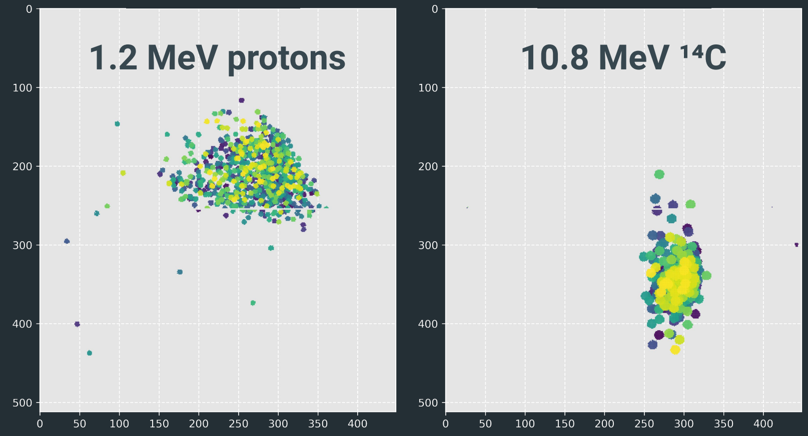
- Gather data sets for typical annihilation products
- Machine learning can be used to refine classical PID methods

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

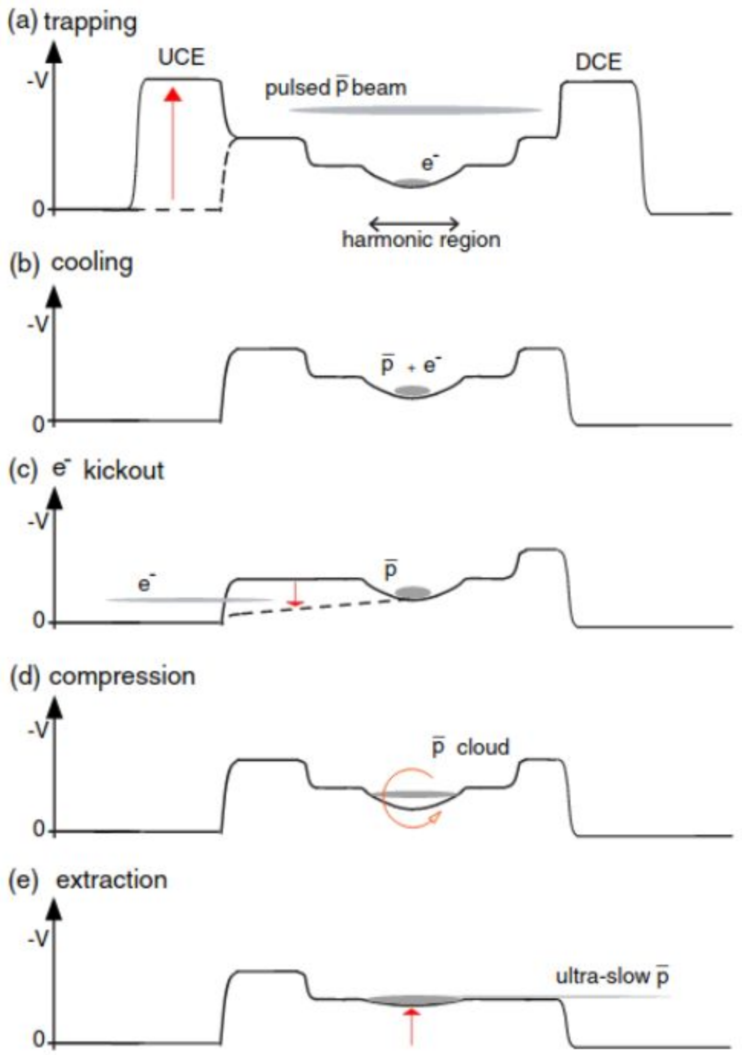


Slow Extraction

Kuroda et al., Physical Review Special Topics - Accelerators and Beams (2012)

Gradually decreasing the depth of the trapping potential allows for DC extraction

Potential difference between the barrier potential and the ground defines the kinetic energy



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

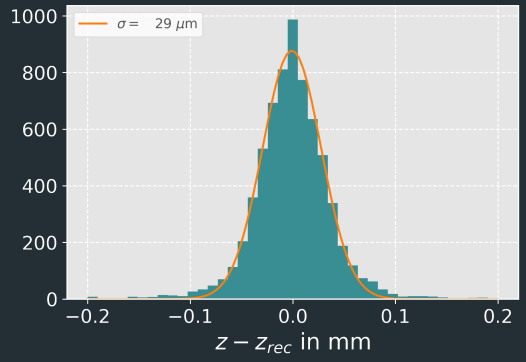
Signal Depth Reconstruction from ToA

Each sensor is similar to a time projection chamber :

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

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

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



Comparing the mean values from the raw Geant4 *z*-coordinates to the reconstructed one

Track Fitting

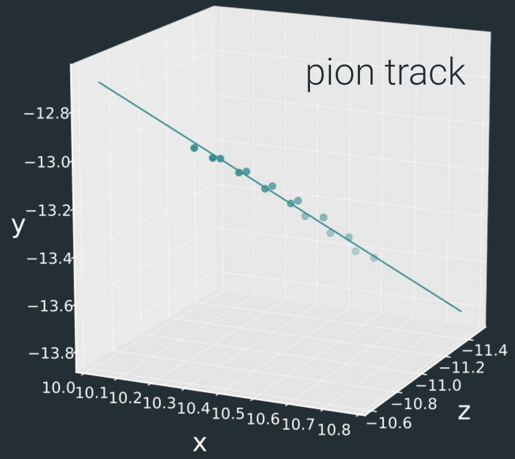
[row, col, z(ToA)] in each sensor → [x, y, z] global coordinates

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

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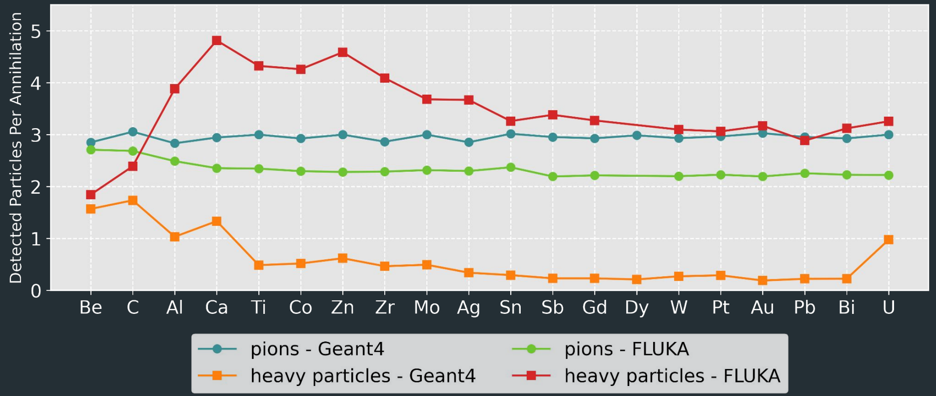

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