Low Energy Antiproton Annihilations on Nuclei

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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

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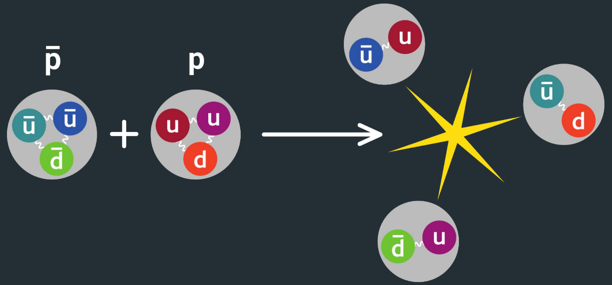
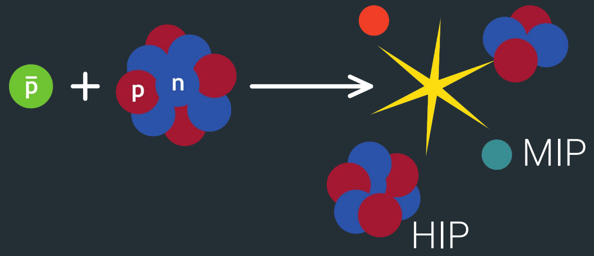
Antiproton-Nucleus ($\bar{p}A$) Annihilation

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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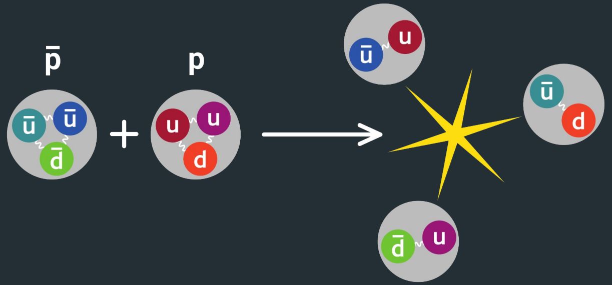

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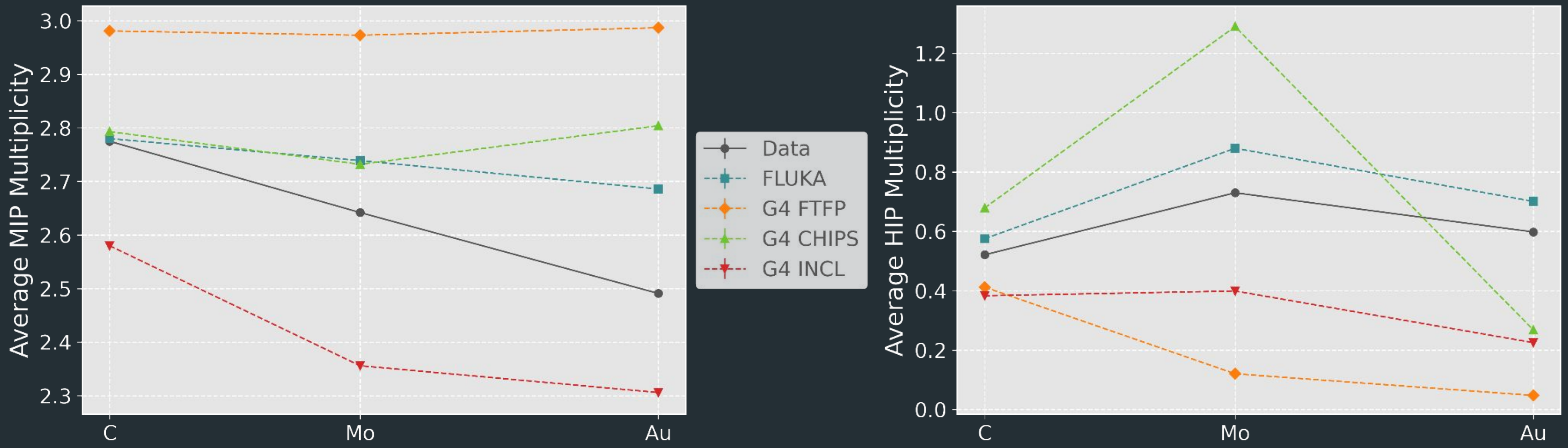
Prong Multiplicities

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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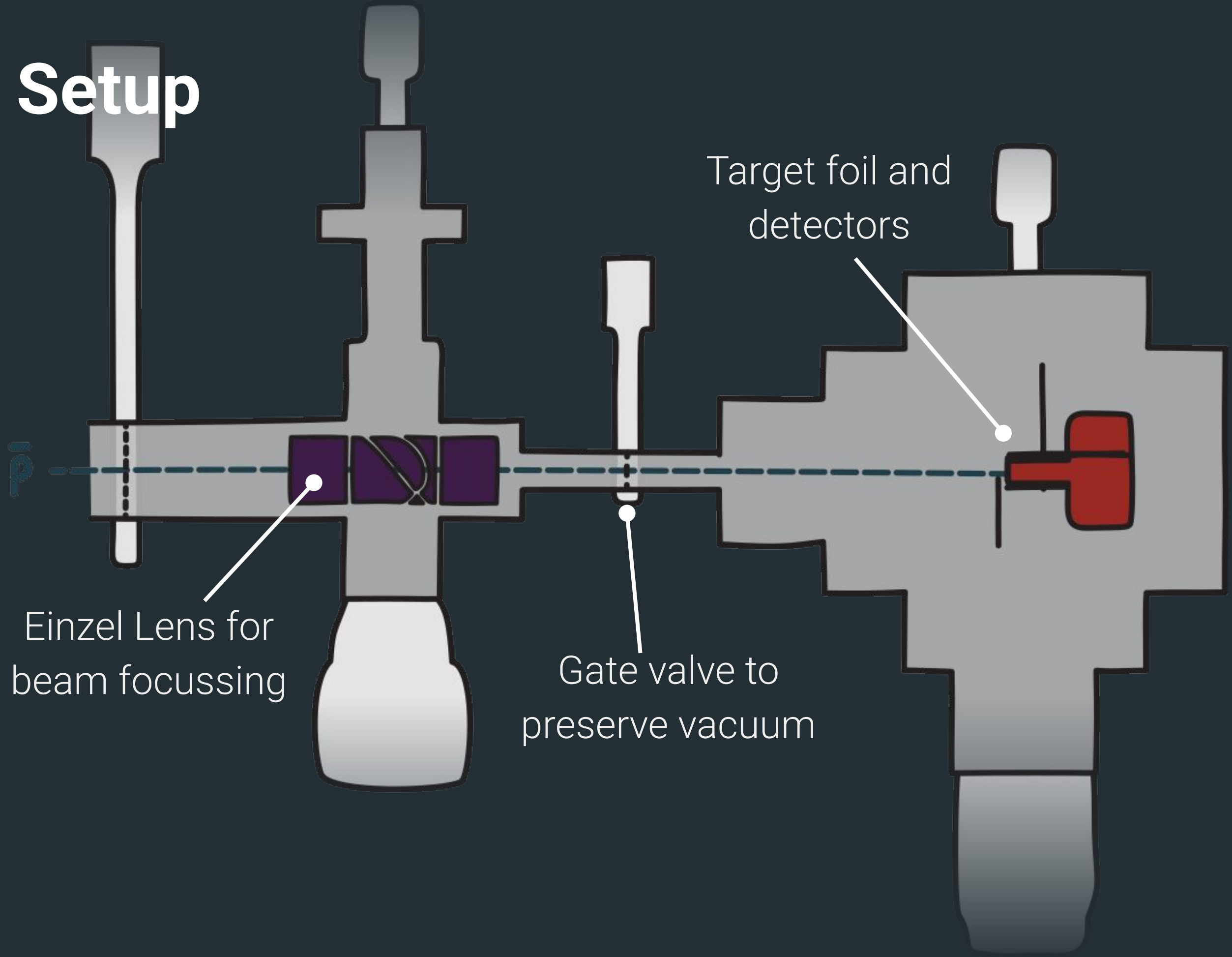
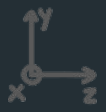
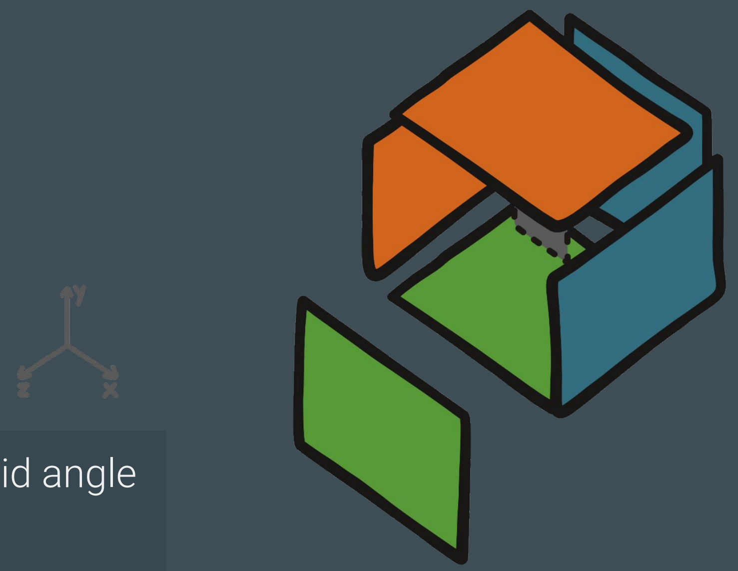
Experimental Setup

AEgIS

Antiprotons are slow extracted from the AEgIS trap





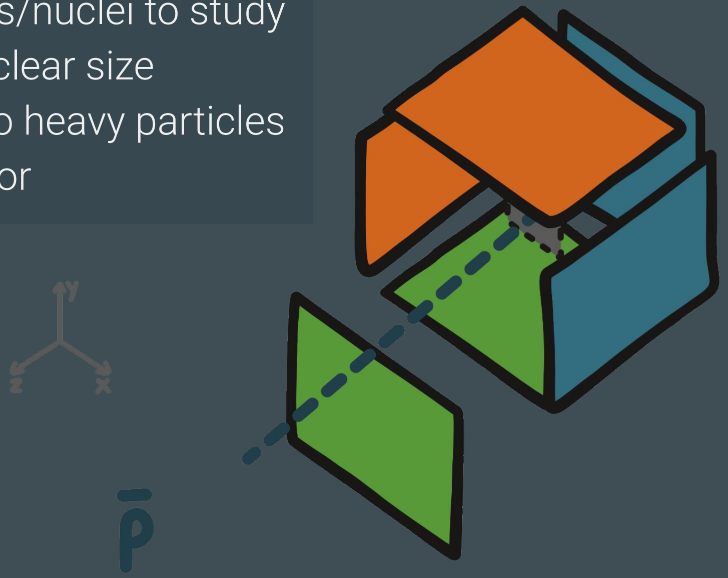


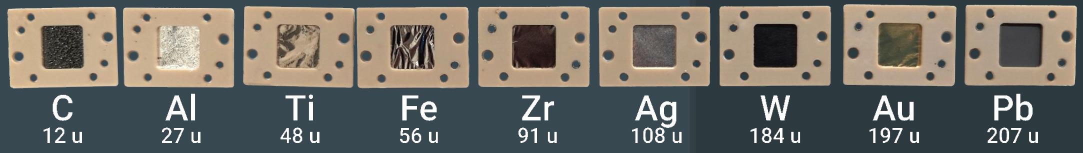
Detector covering large solid angle

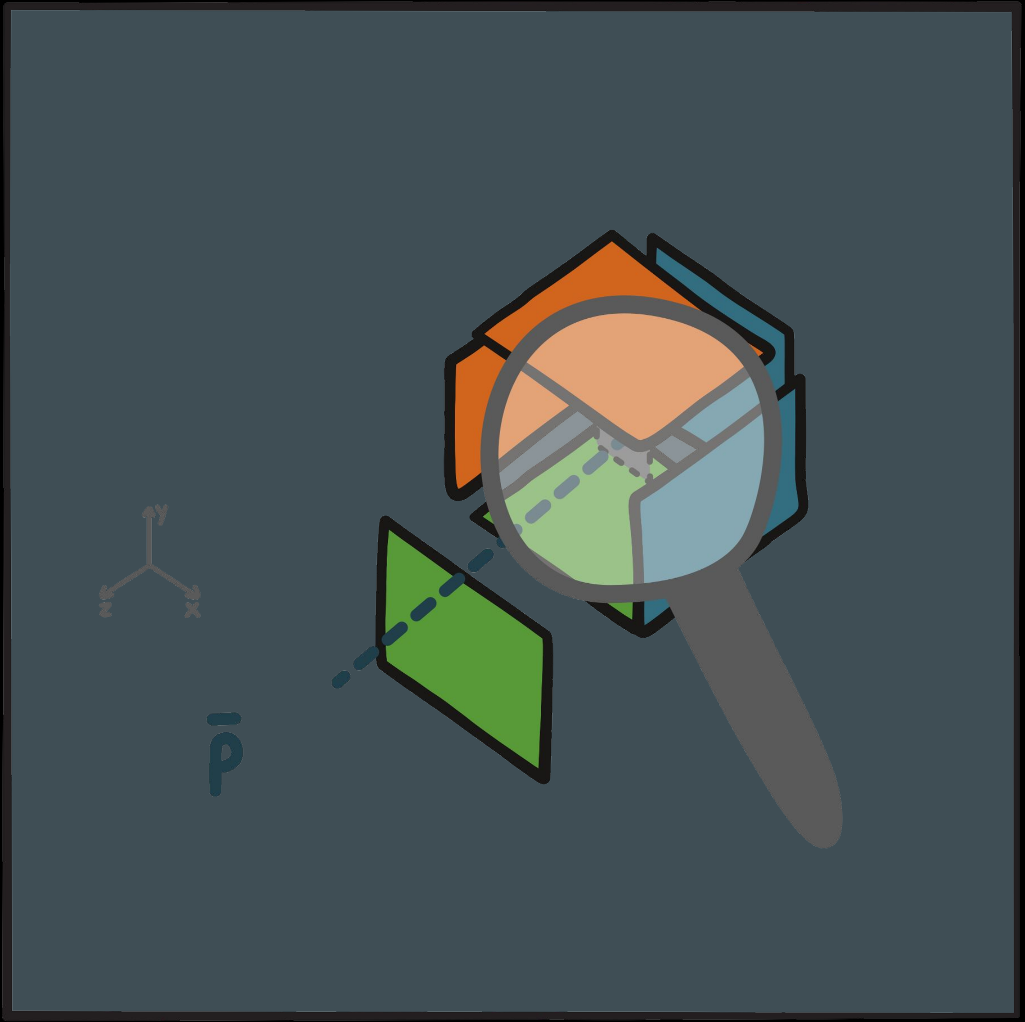
- Particle identification
- Multiplicities
- Energy deposit
- Angular distribution

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

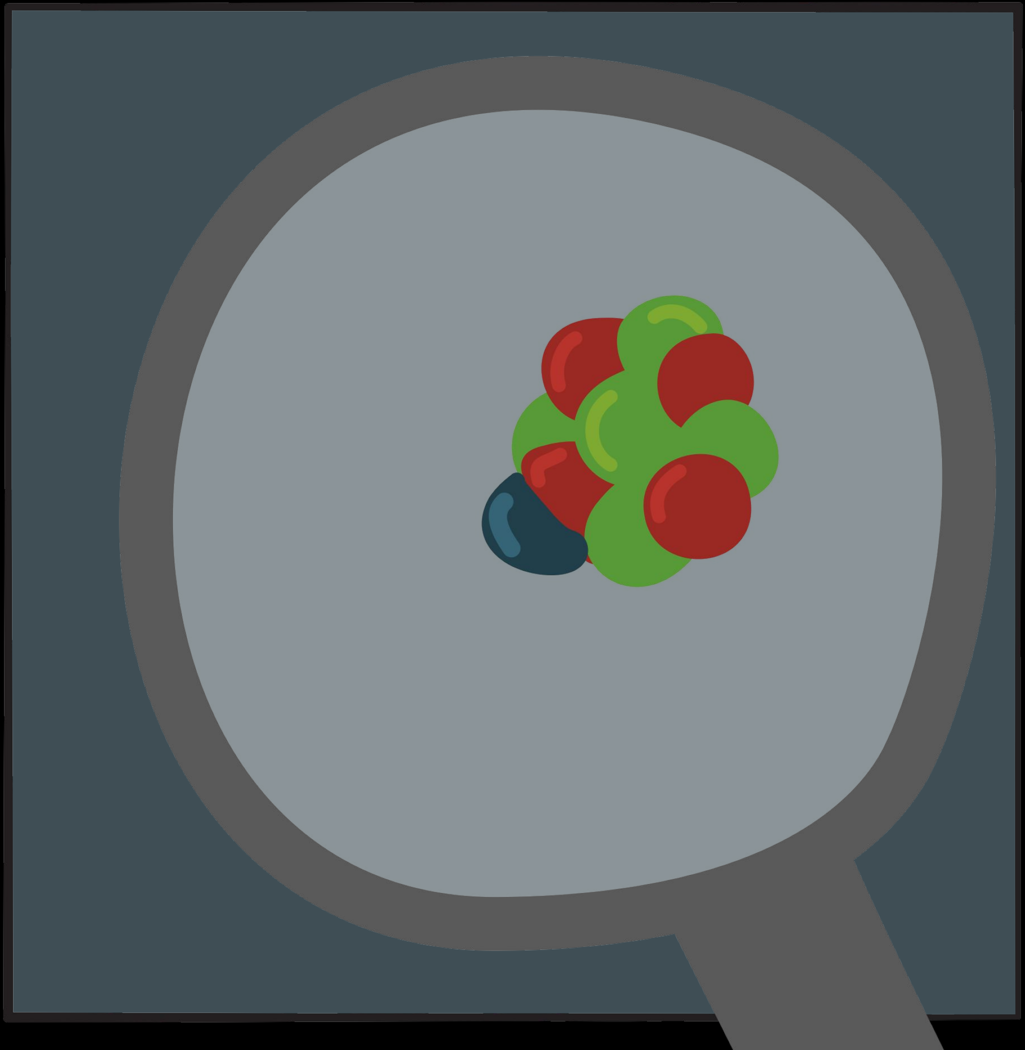
- Different target foils/nuclei to study dependence on nuclear size
- Thin foil allows also heavy particles to reach the detector

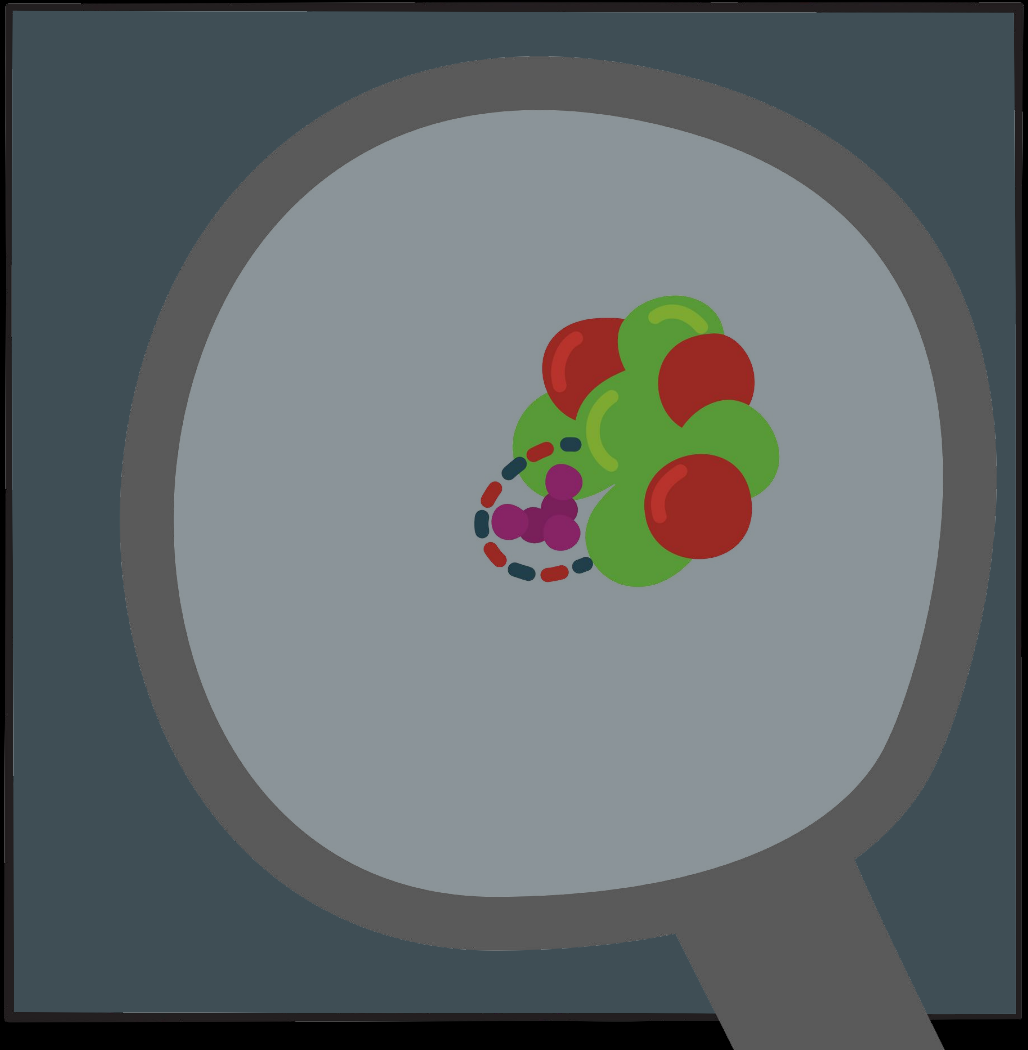


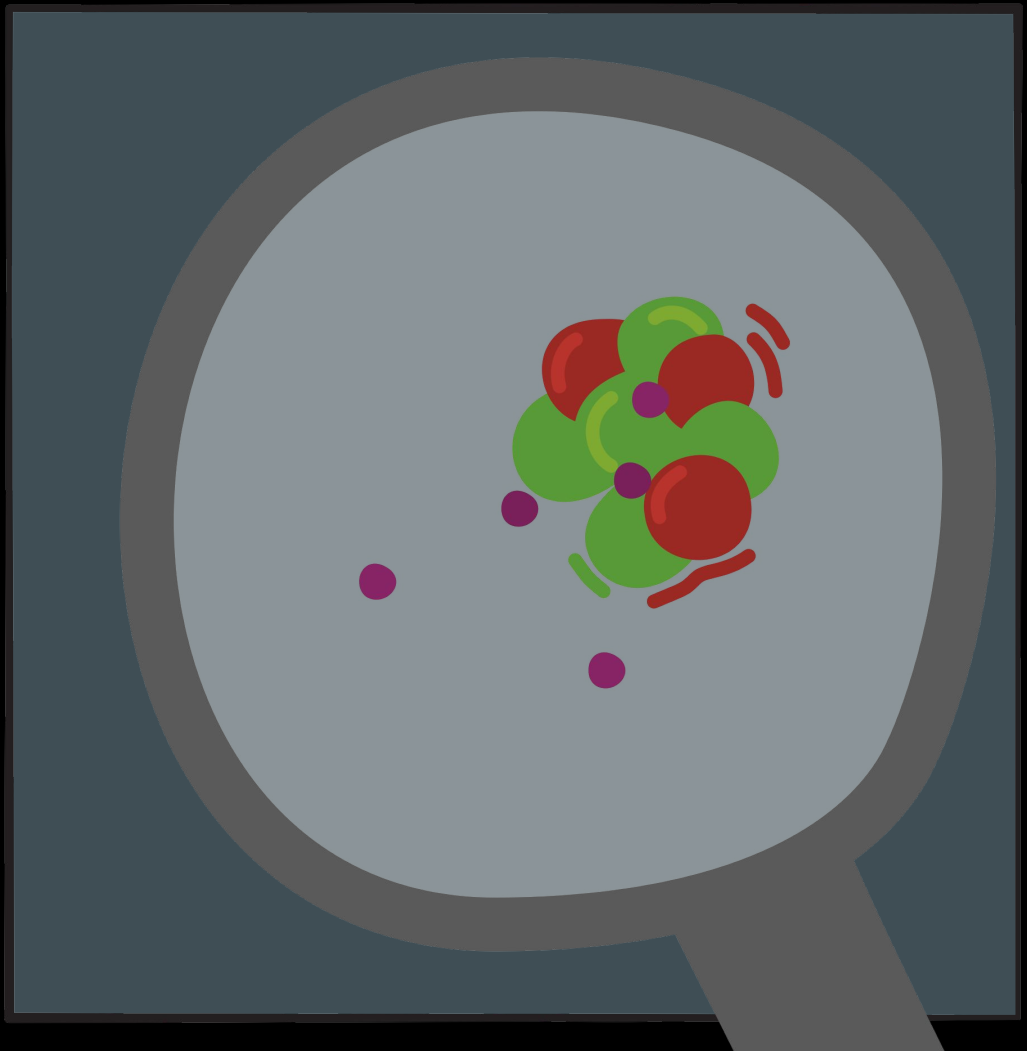



y
z
x
p̄

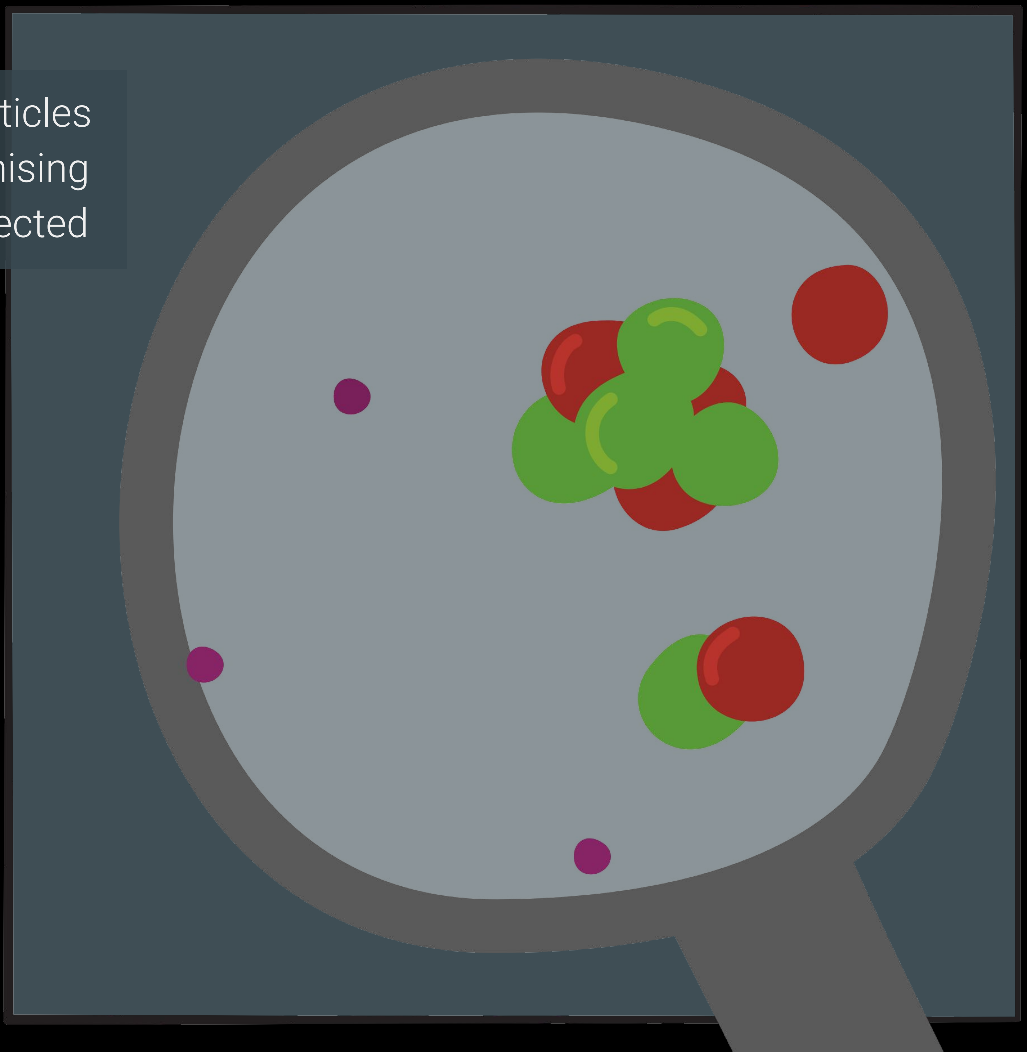

A
$\bar{p}$



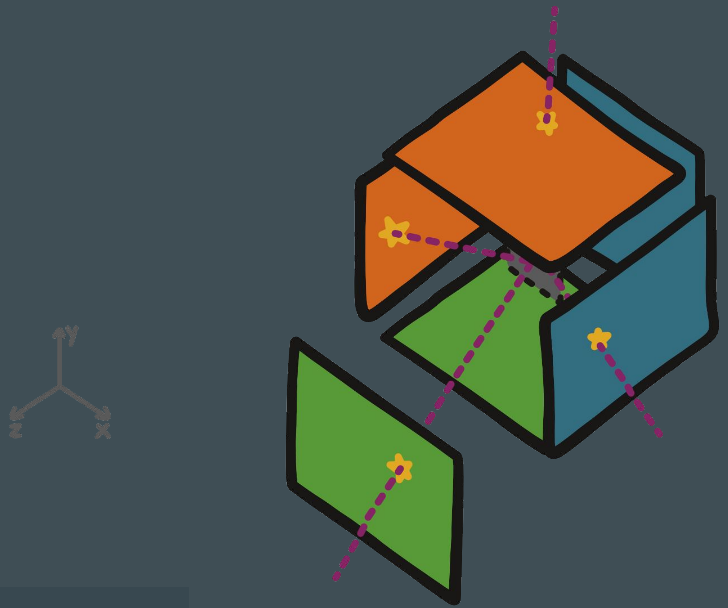




Minimum Ionising Particles (MIPs) and Heavily Ionising Particles (HIPs) are ejected



MIPs leave straight tracks
in the detectors



Vertex reconstruction important
to tag individual events

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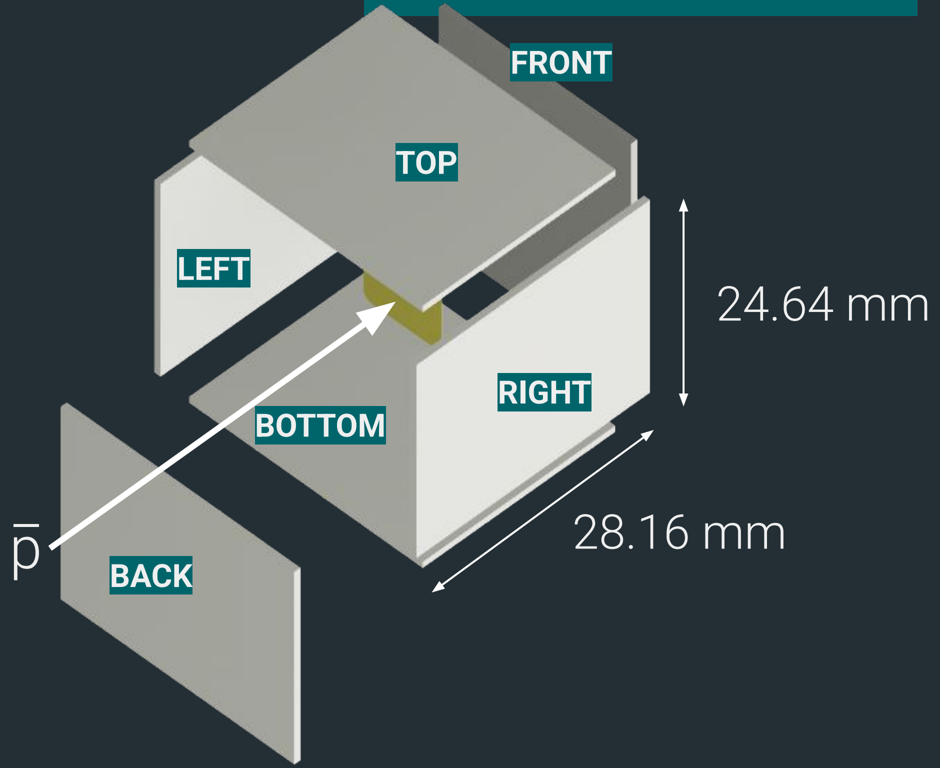
Detector Geometry

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

Target foil surrounded by detectors

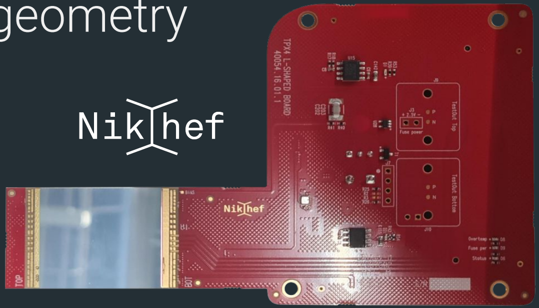
6 x 500 µm Si sensors coupled to Timepix4 ASICs:

- 1 sensor in the back with offset to allow beam to enter
- 5 sensors cover the other planes of the cube-like geometry

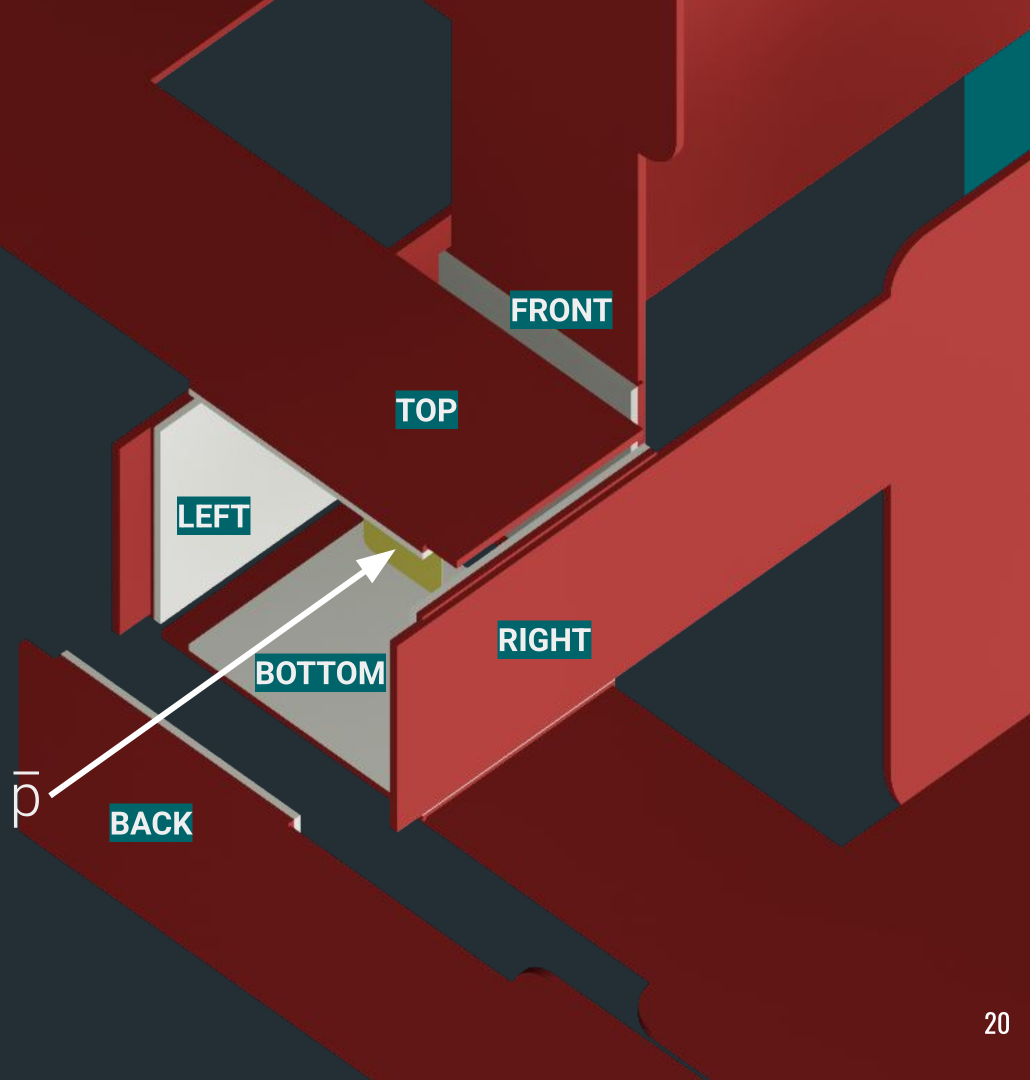


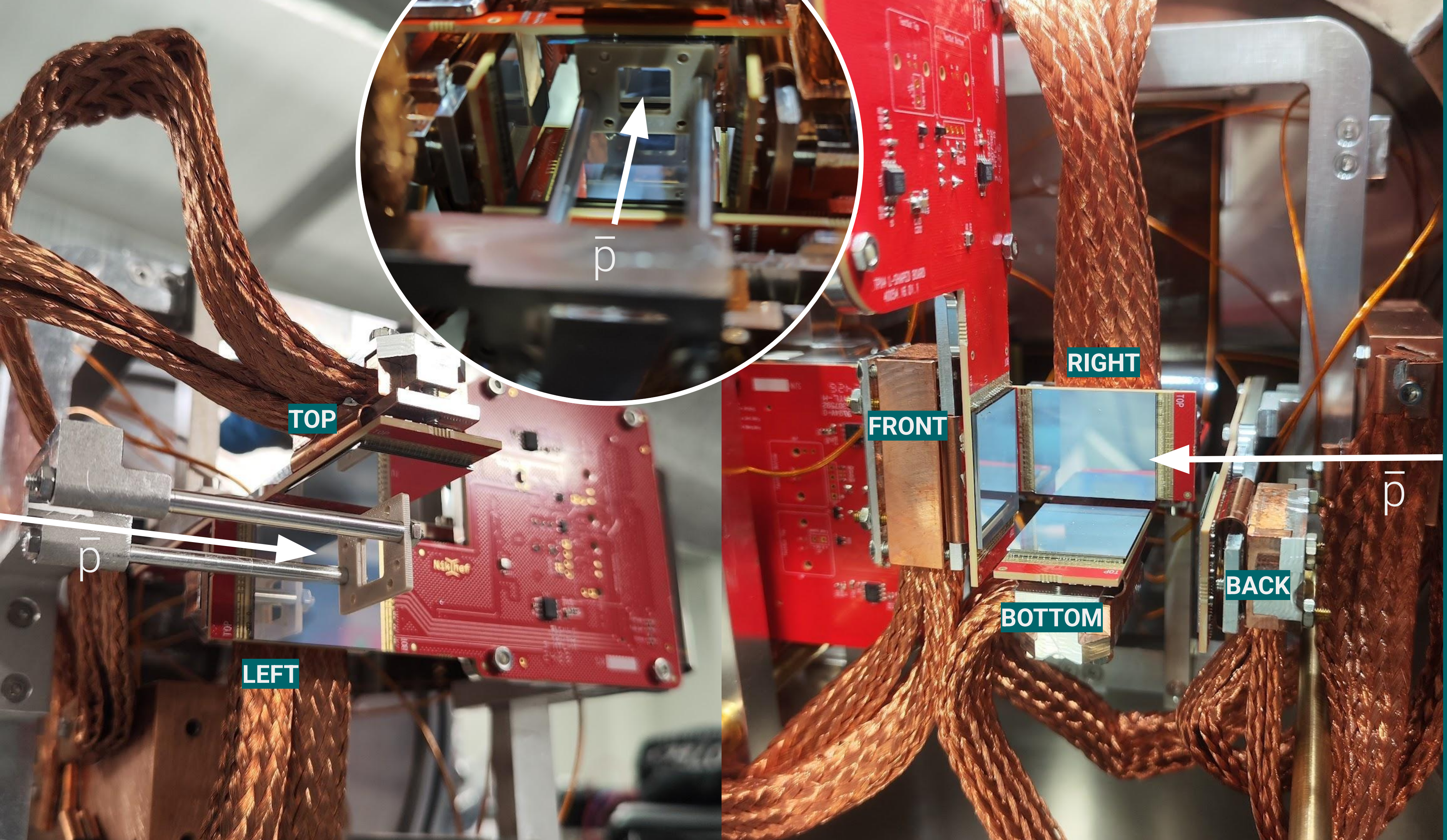
Annihilation Chamber

PCB boards specifically designed for our geometry



Cooling the detectors with water through copper pipes/blocks




TOP
LEFT
FRONT
RIGHT
BOTTOM
BACK
p̄
p̄
p̄

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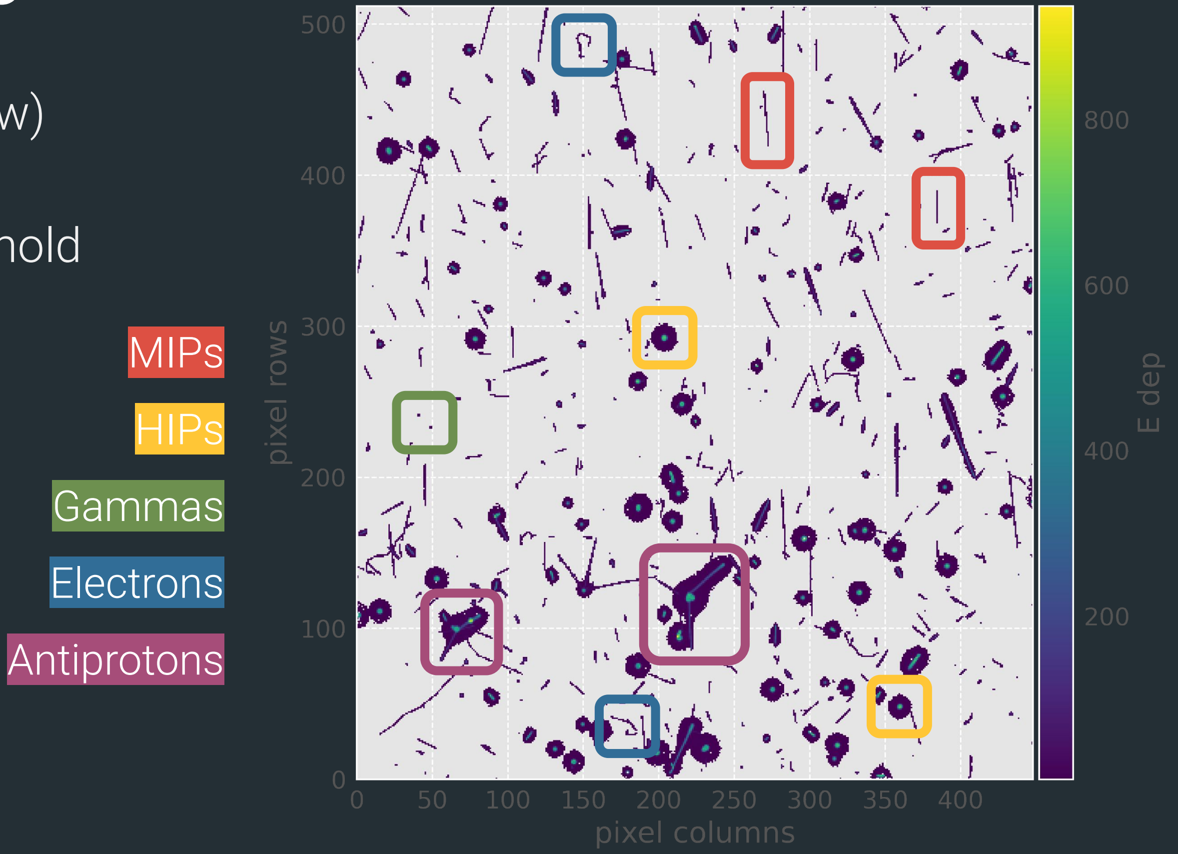
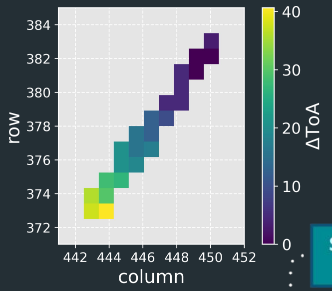
Data Structure

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



Algorithm



Seperate files for each detector are merged

Simulation → **Digitisation** → **Clustering I Signals**

Raw Data → **Clustering I Signals**

Clustering I Signals — one cluster/particle signal

→ **Signal Depth Reconstruction** — global x, y, z coordinates

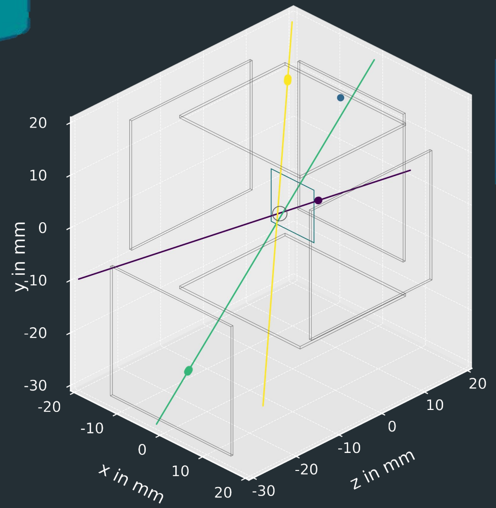
→ **Clustering II Time** — time bins for each event

→ **Is it a track?** — eccentricity > 0.8, cluster size > 3 px

→ **3D Parametrisation** — tracks are fitted to lines

→ **Points of Closest Approach** — for track pairs in time bin

→ **Vertex Reconstruction** — cluster PoCAs and take average of largest cluster



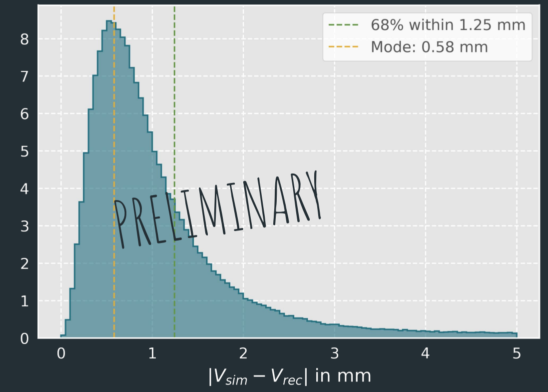
Kraxberger et al. (2025)

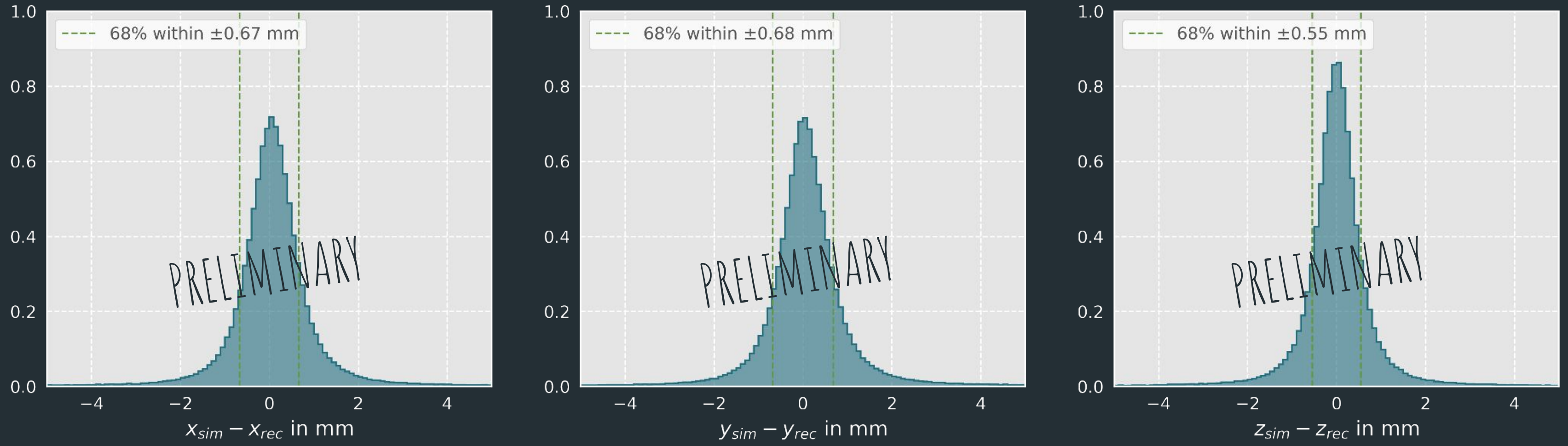
Vertex Reconstruction Resolution

Comparison of simulated annihilation position to reconstructed vertex

Statistical Uncertainty: 68 % radius

Systematic Uncertainty widens it by ~ 20 %





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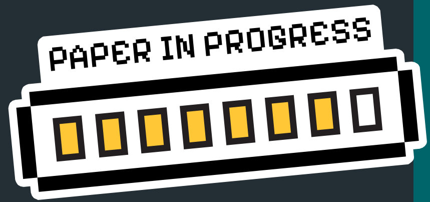
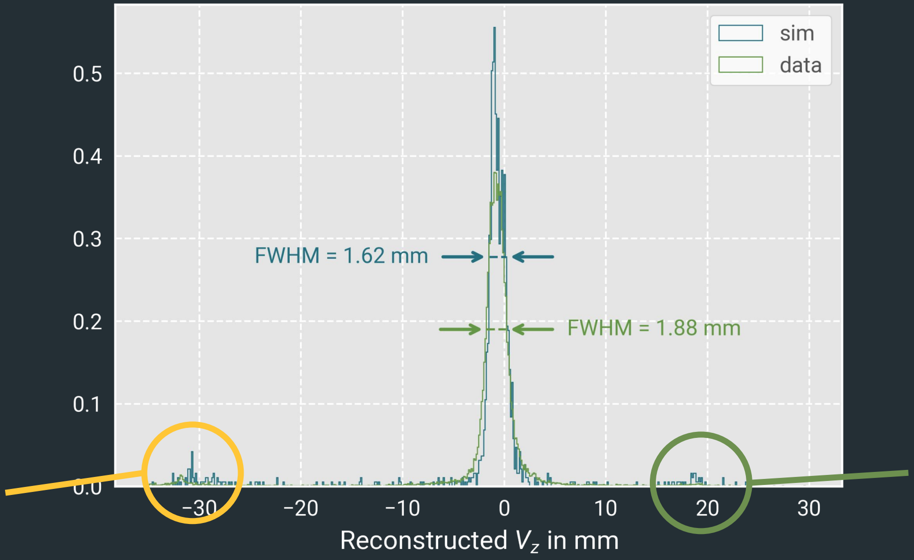
Evaluation of Vertex Reconstruction

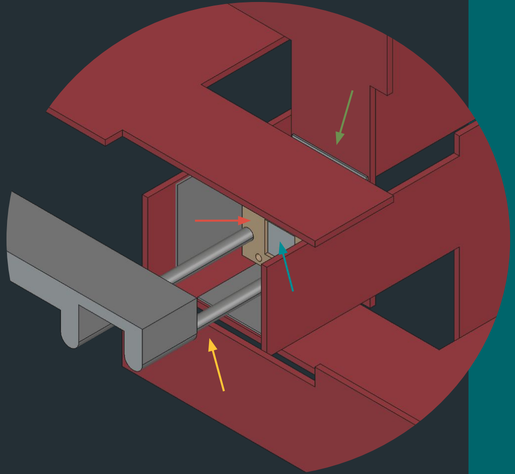


Algorithm verified and adjusted to real data

- Reconstructed z of vertex

  In reality annihilations happen either at z= -1 mm(target holder) or z=0 mm (target)





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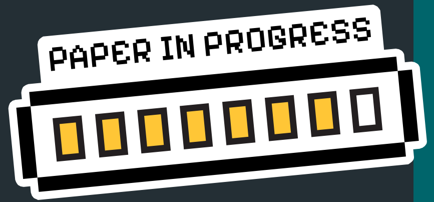
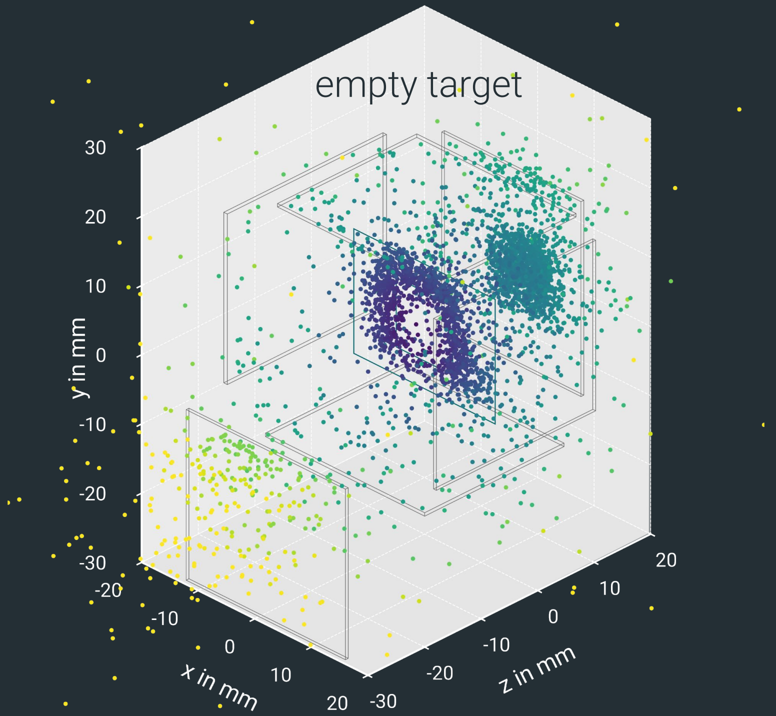
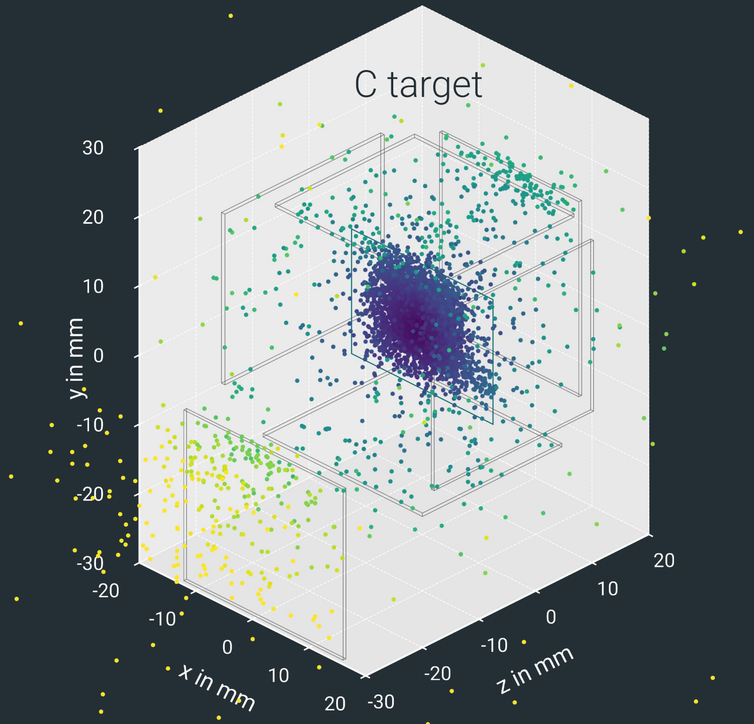


- Comparison of runs with empty target holder to runs with target





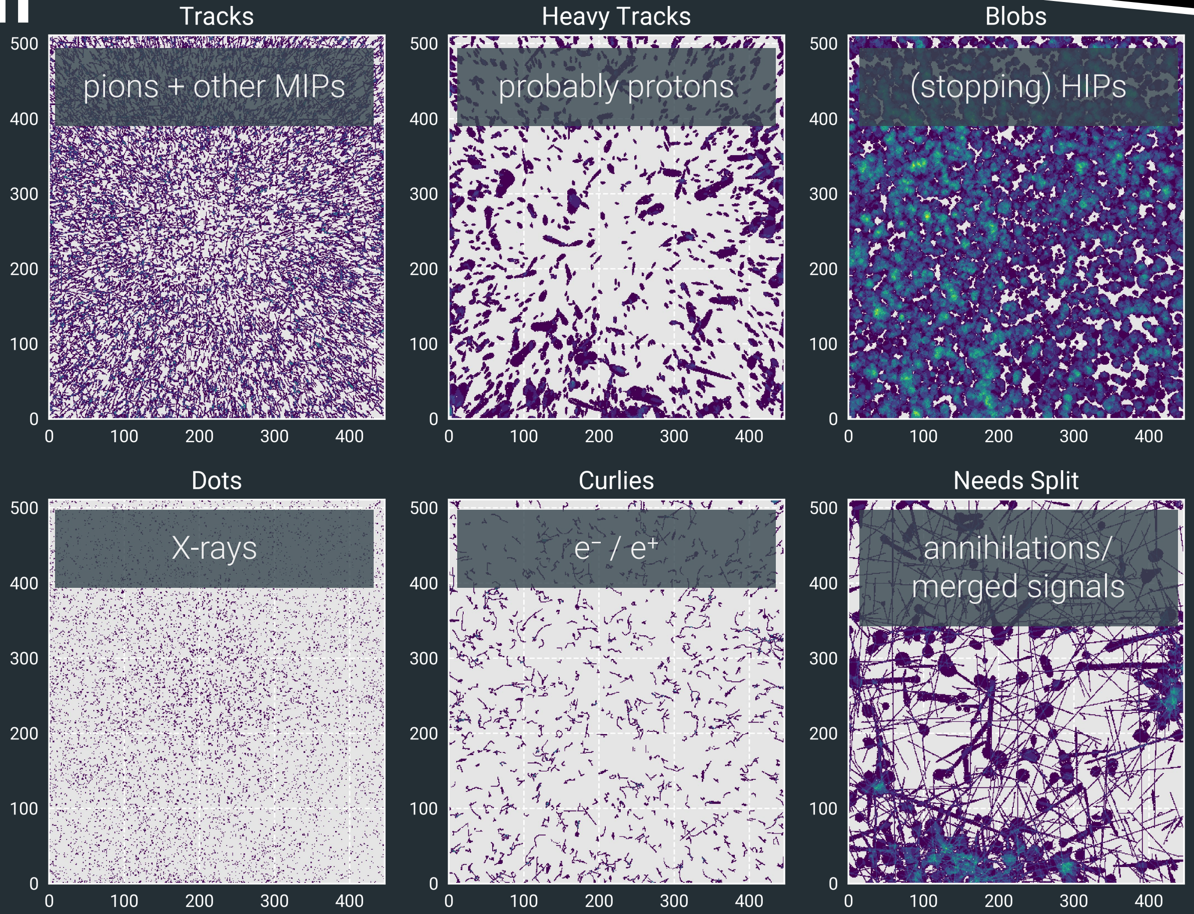
Data Classification

First coarse classification by cluster morphology:

- Cluster area
- Cluster length/width
- Cluster eccentricity
- Cluster solidity

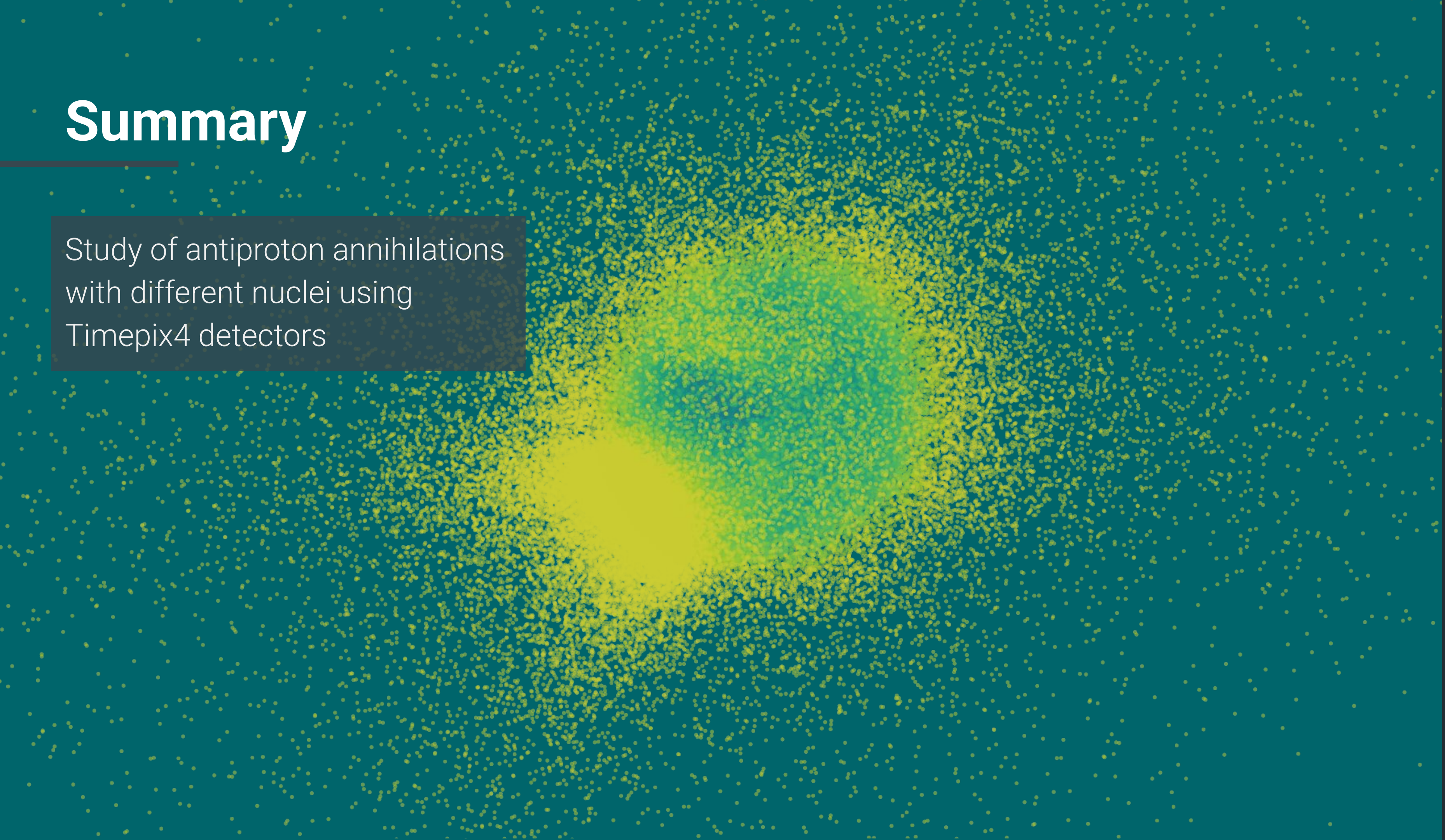
Further classification is worked on using:

- Energy deposit
- Stopping power
  (for tracks/heavy tracks)



Summary

Study of antiproton annihilations with different nuclei using Timepix4 detectors



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Study of antiproton annihilations with different nuclei using Timepix4 detectors

> 3 millions vertices reconstructed

Paper being finished on instrumentation and reconstruction with data

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Investigation of final state interactions by measuring:

- Multiplicities of MIPs and HIPs
- Deposited energy
- Angular distribution

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> 3 millions vertices reconstructed

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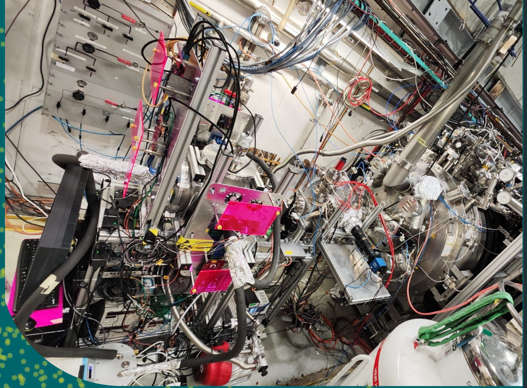
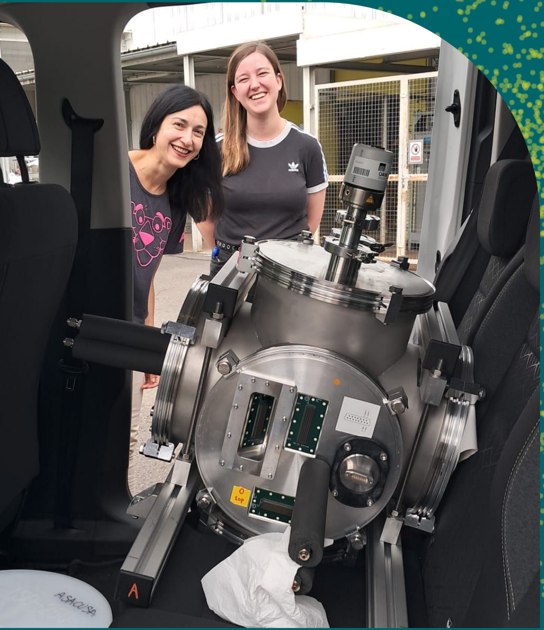
Investigation of final state interactions by measuring:

- Multiplicities of MIPs and HIPs
- Deposited energy
- Angular distribution

Results will be used for assessment of models and their potential tuning



Thank you!



Backup

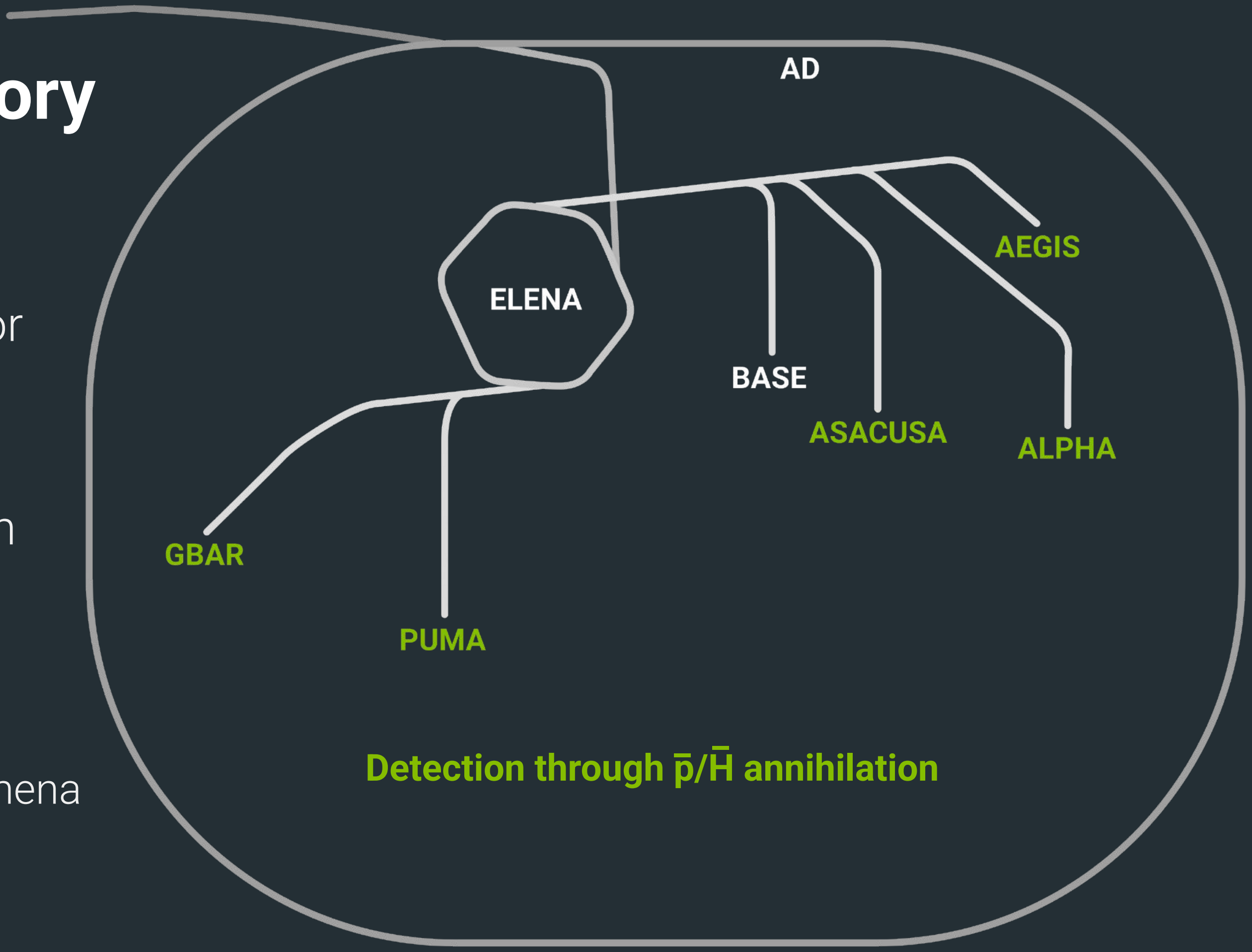
Antimatter Factory

@ CERN

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

Study antimatter through

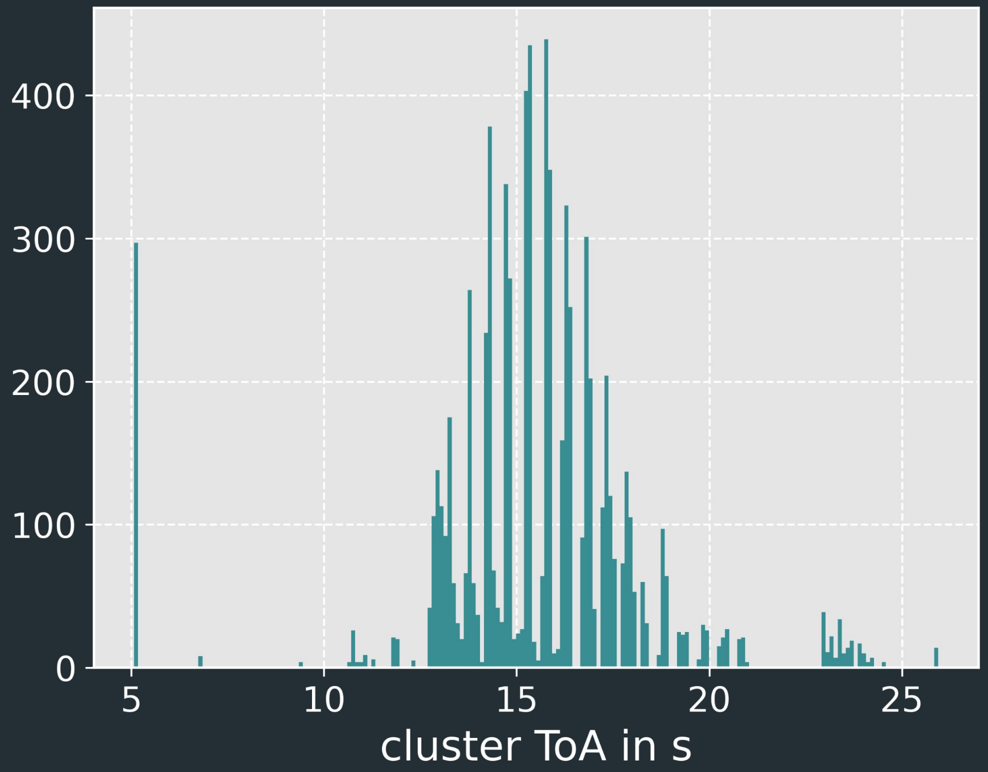
- Spectroscopy
- Gravitational behavior
- Magnetic moments
- Exotic nuclear phenomena



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



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

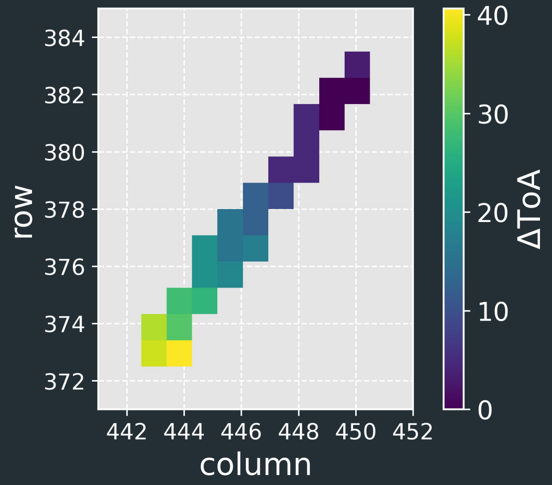
Signal Depth Reconstruction from ToA

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

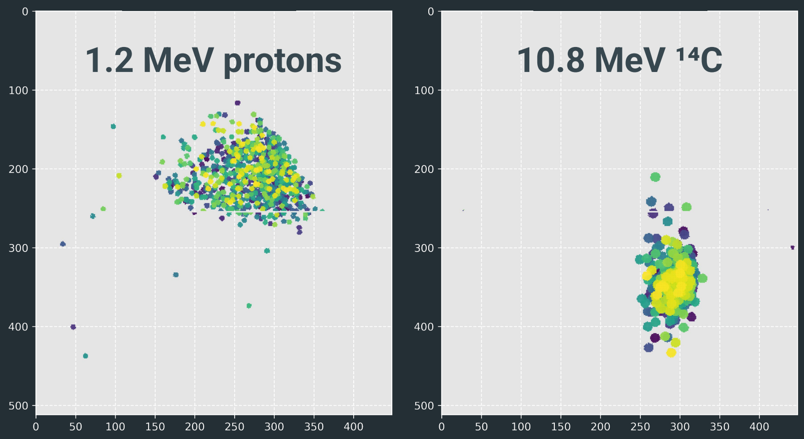
- Gather data sets for typical annihilation products
- Machine learning can be used to refine classical PID methods

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

Refined identification of particle types

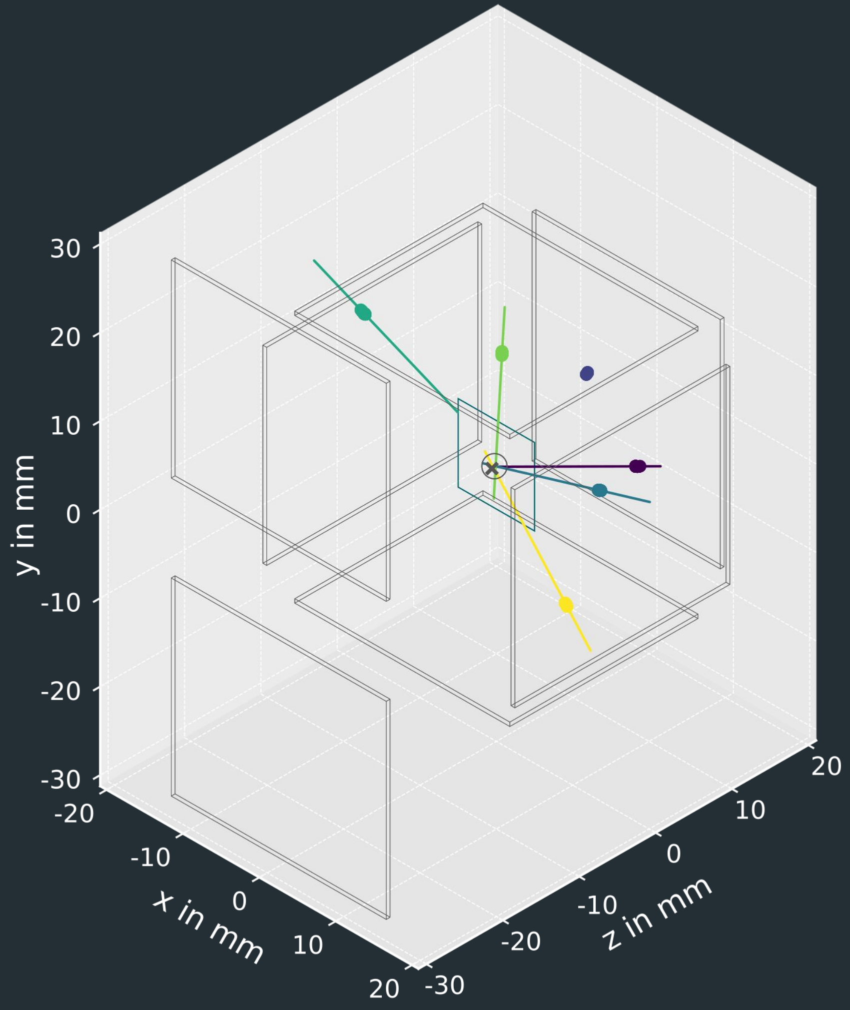
Previously only distinguished between minimum ionizing (MIPs) and heavily ionizing particles (HIPs)

Example of different cluster sizes from test beam at VERA



Vertex Reconstruction

- Clustering all events by ToA
- Each particle track fitted
  -> parametric equation in 3D
- Finding nearest points between all pairs of tracks in event
- Clustering nearest points and taking mean of biggest cluster as vertex



Track Fitting

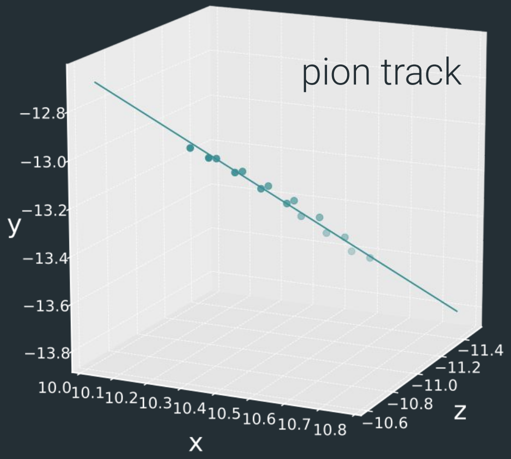
[row, col, z(ToA)] in each sensor $\longrightarrow$ [x, y, z] global coordinates

Tracks are defined as clusters with eccentricity > 0.9

Finding the direction vector *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 $\longrightarrow$ 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:

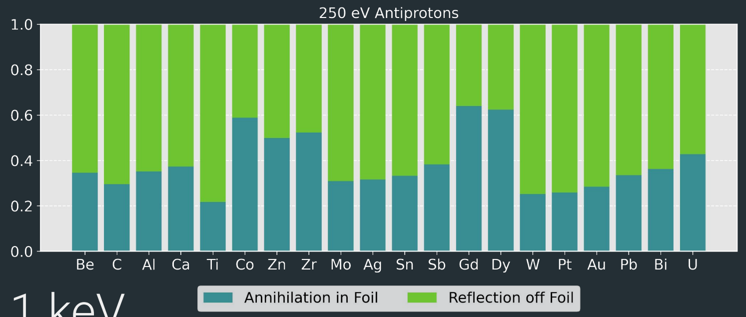
$$I = \vec{p_0} \pm \frac{||\vec{v} \times \overrightarrow{p_0 q_0}||}{||\vec{v} \times \vec{u}||}\vec{u}$$

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