Studies of antiproton annihilation at rest with nuclei using Timepix3

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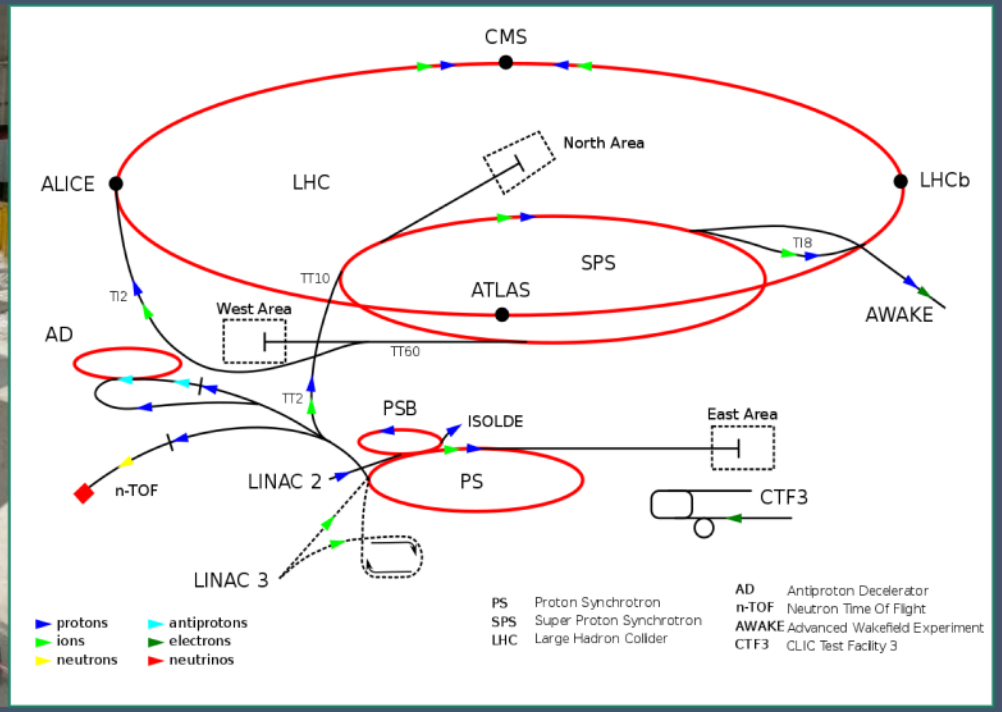
Outline:

- Antiproton Decelerator and ASACUSA experiment
- Measurements of antiproton-nucleus annihilation
- GEANT4 simulations
- Allpix^2 digitization and comparisons
- Conclusions and further work

Antiproton Decelrator (AD)



- Only facility in the world to produce a low energy beam of $\bar{p}$
- Slow $\bar{p}$ are used for antihydrogen production and ultra precise antimatter studies
- The facility hosts 5 different experiments (ASACUSA, AEgIS, ALPHA, BASE, GBAR)
- Main goals of the experiments are CPT violation studies and antimatter gravity acceleration measurements

ASACUSA Experiment

The collaboration:

- 38 reaserchers, 14 institutions, 4 countries
- First experiment to produce an $\bar{H}$ beam

Main foci of the experiment:

- Hyperfine structure of antihydrogen
  - Study of low antiproton annihilations
- Spectroscopy of Antiprotonic Helium

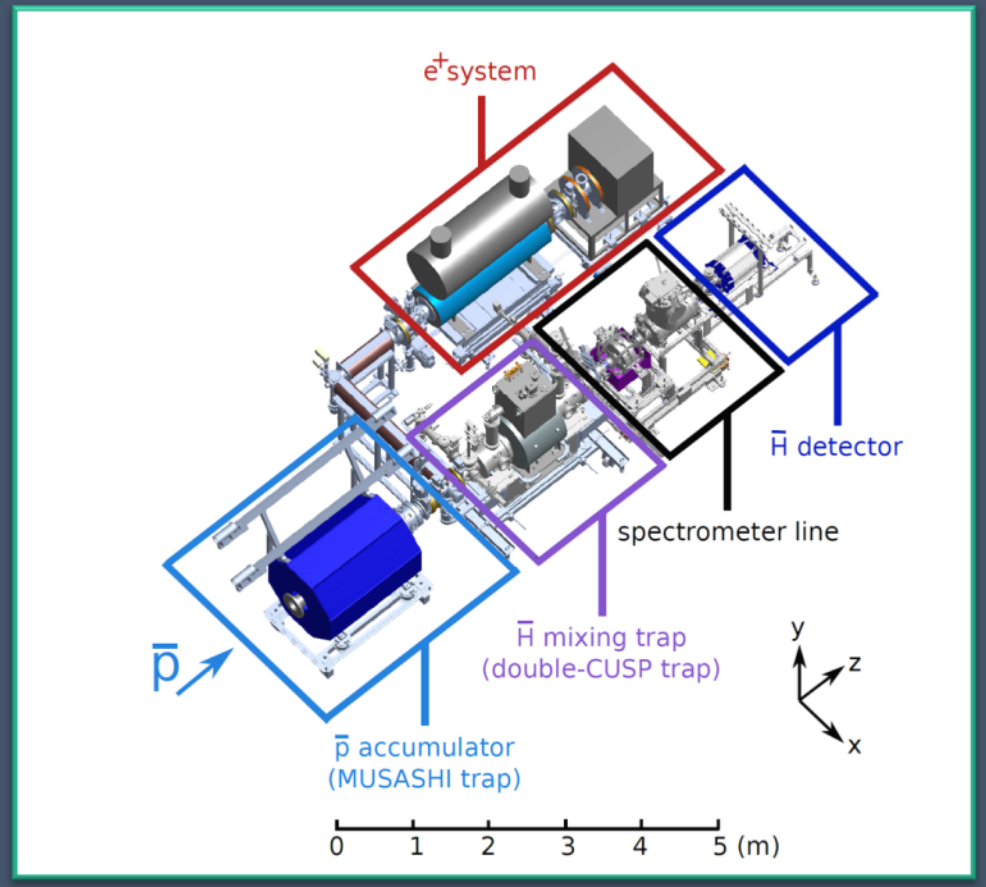
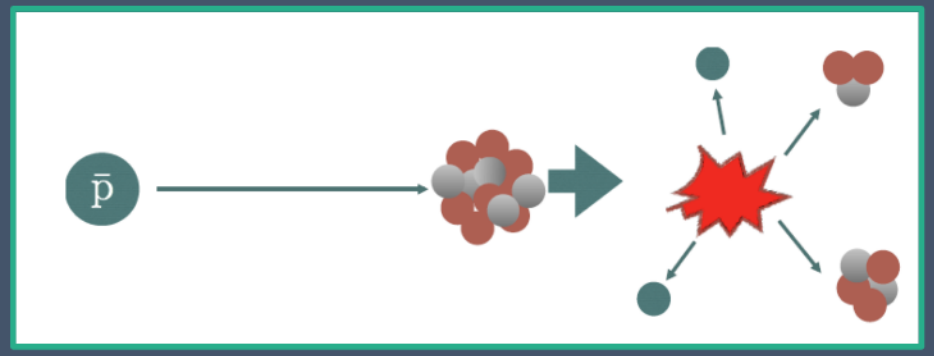


Image: B. Kolbinger «Machine Learning for Antihydrogen detection in ASACUSA»

Low energy antiproton annihilation

How it works:



- $\bar{p}$ annihilates on one nucleon and ~2 GeV energy is released, producing on average five pions
- Some of these pions penetrate inside the nucleus, (depending on the size of the nucleus ⇒ different probabilities)
- Residual nucleus ⇒ decay mechanism according to the excitation energy (Intranuclear Cascade Model)
- $\bar{p}$-nucleus annihilation at rest can produce: **p, π, d, t, n, α,** ^{3}He, ^{4}He, ^{6}He, ^{8}He, Li…

Why we study it:

- All antihydrogen experiments detect the $\bar{H}$ through annihilation ⇒ $\bar{p}$-nucleus annihilation is a key process!
- Annihilation/fragmentation models validation
  - CHIPS (CHiral Invariant Phase Space)
  - FTFP (FriTjoF Precompound)
  - FLUKA (FLUktuierende KAskade)
- All models developed for High Energy Physics and none of them uses annihilation data at rest

What we measure:

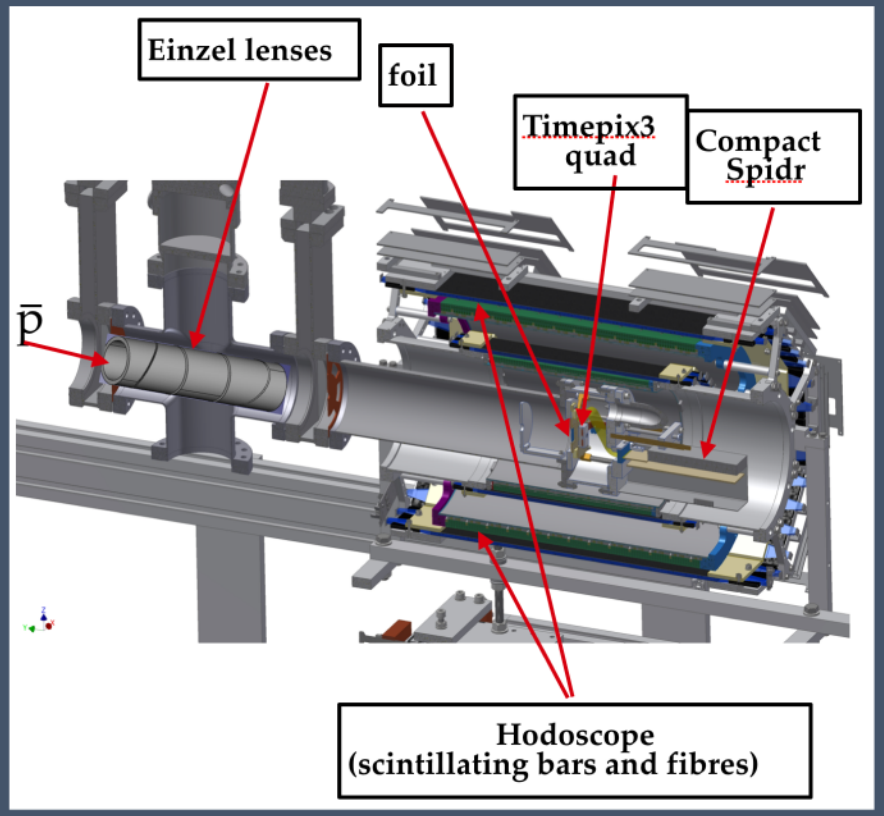
- Average multiplicity
- Deposited energy distribution of the annihilation fragments – heavy fragments stop inside the sensor

Tuning of Monte Carlo simulations (GEANT4) to better match the measurements

Measurements of $\bar{p}$-nucleus annihilation

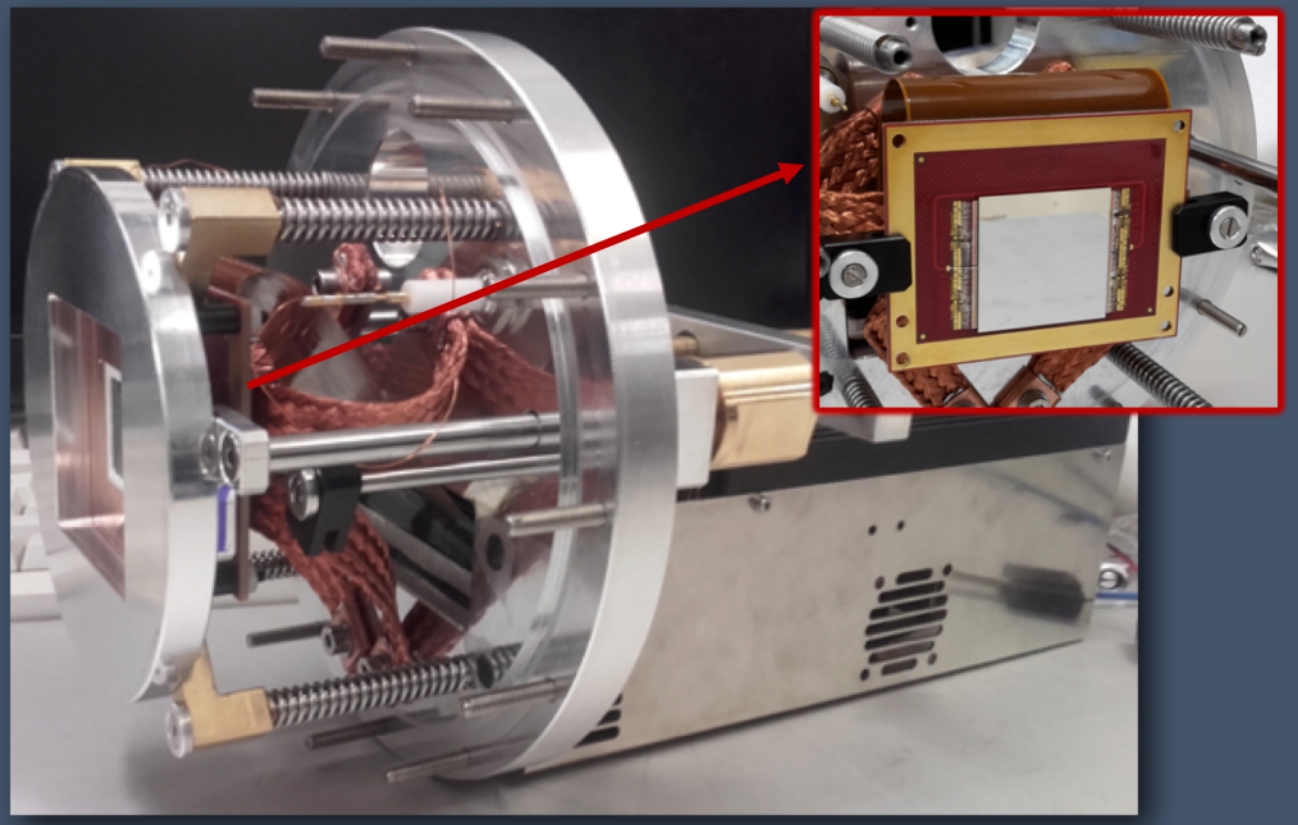
Measurements:

- Slow extraction of 150 eV $\bar{p}$ from a trap
- Beam focusing with Einzel lens
- $\bar{p}$ annihilating on ^{12}C, ^{42}Mo and ^{79}Au
  - 20 x 20 mm^2 foil, 2 µm thick



Timepix3 quad in ASACUSA:

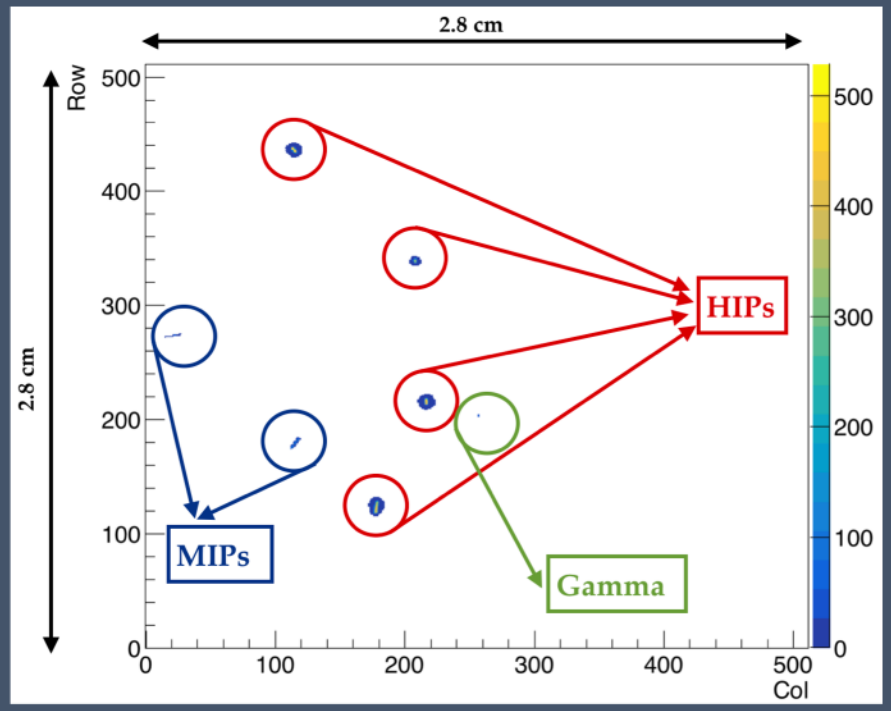
- 512 x 512 pixels (~ 28 x 28 mm^2 active area)
- 500 µm thick Si sensor
- 150 V bias voltage
- Compact Spidr readout system developed by NIKHEF



Annihilation event in data and in simulations

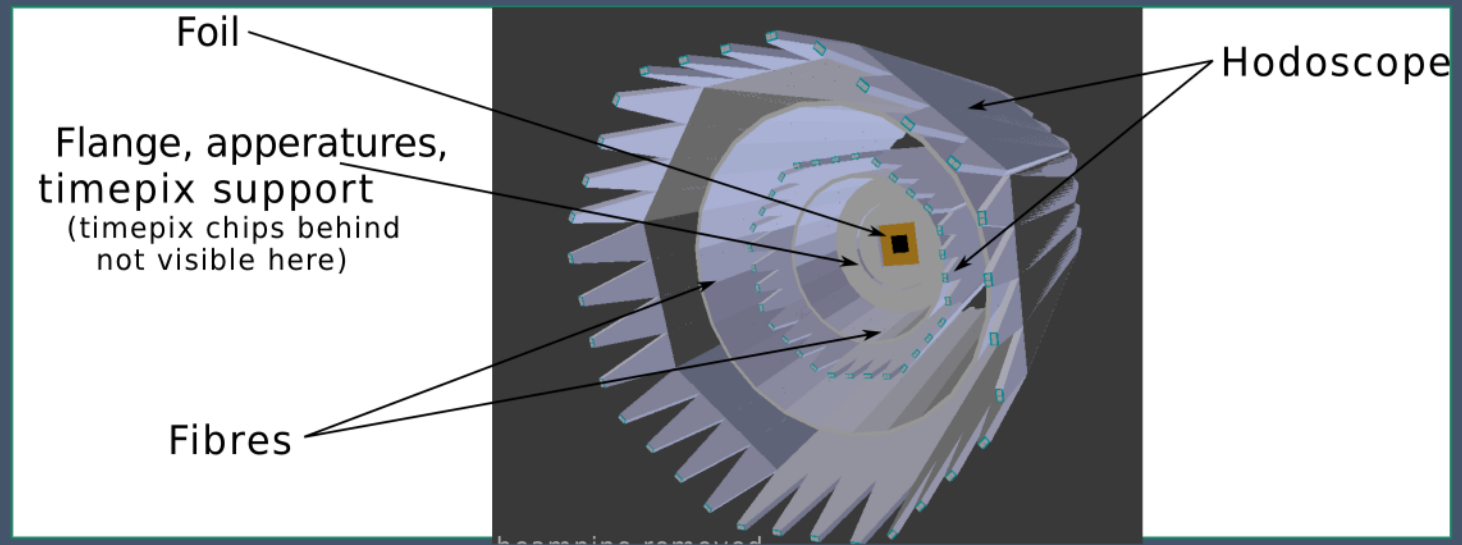
How we measure antipton-nucleus annihilation:

- Trigger from the hodoscope -> time stamped event in Timepix3
- Charged products of the annihilation
  - Minimum ionizing particle (MIP)
  - Highly ionizing particle (HIP)



How we simulate annihilation:

- GEANT4 (CHIPS and FTF models) and FLUKA:
  - 50,000 annihilation events per element
  - Full geometry of the set-up and the detectors
    - Timepix3 is a piece of silicon (no clusters)
- For direct comparison with data-> digitization is needed!



Timepix3 response to large energy depositions

Halo and volcano effect:

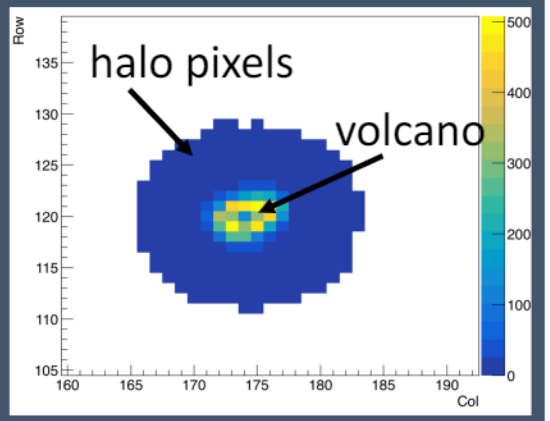
- Induced current in neighbouring pixels -> typically below 4-5 keV (removed in the data)

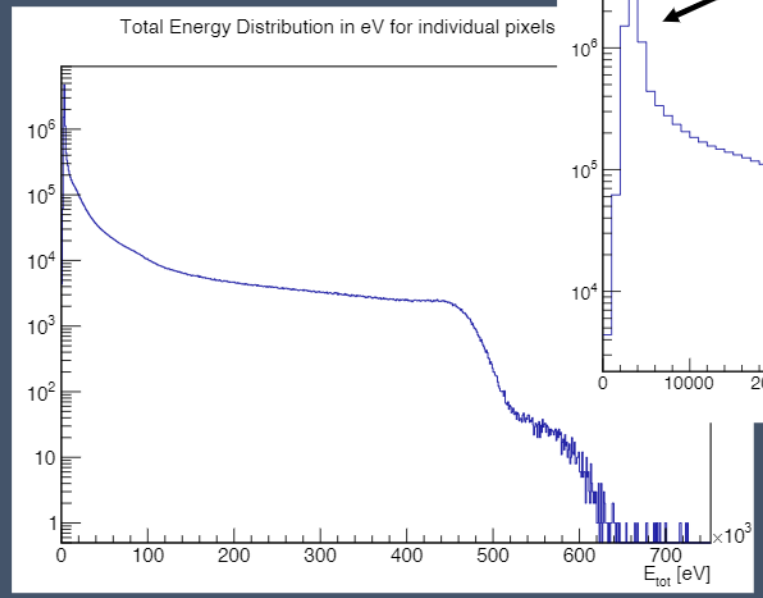
S. Aghion et al 2018 JINST 13 P06004

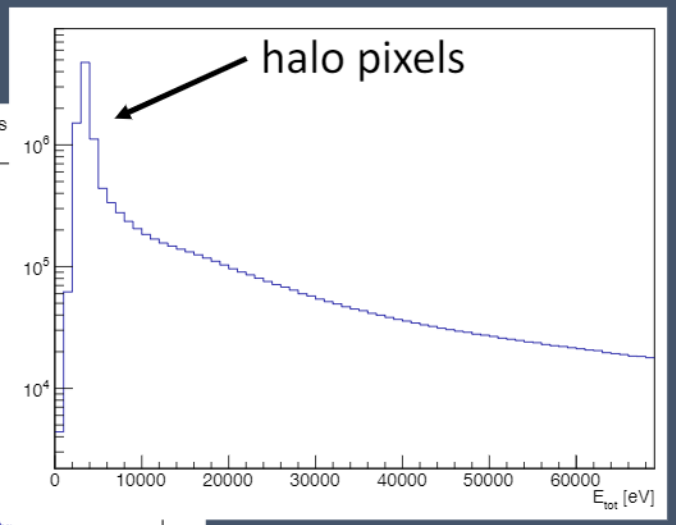
- Pixel taking random value when the energy deposit is $\gtrsim$ 500 keV (saturation effect) -> implemented in the current version of the digitization with Allpix²

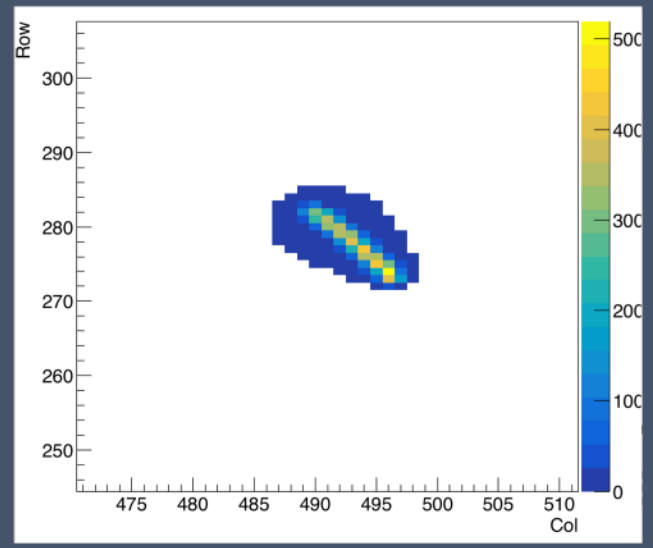
Plasma effect:

- Heavy charged particles (including alpha particles) exhibit substantially wider tracks (plasma effect screens the drift field) -> not yet included in Allpix²









Allpix^2

Modules for reading:

- Deposition reader → Read root files produced by FLUKA and GEANT4 simulationsboth

Modules for propagation:

- Electric field reader
- Project Propagation
- Simple transfer

→ Simple production and propagation of hole-charge pairs model using linear Electric field model

Module for digitization:

- Default digitizer → Tuned digitizer module with saturation option enabled for taking into consideration the volcano effect

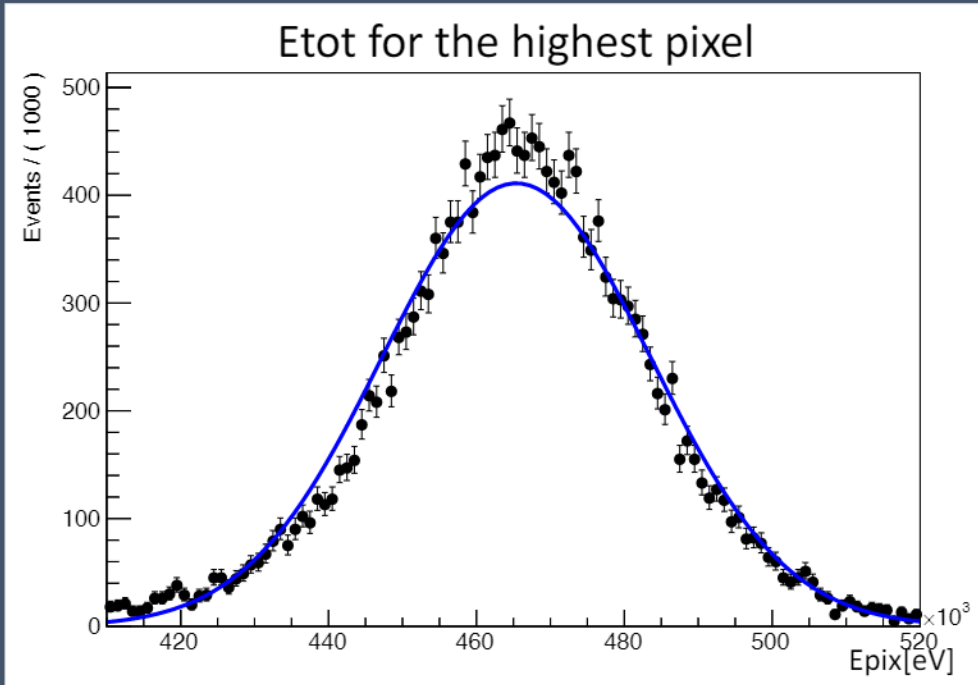
Module for output:

- ADTreeWriter → Ad-hoc module for production of root files needed for further cluster analysis (same for data and simulations!)

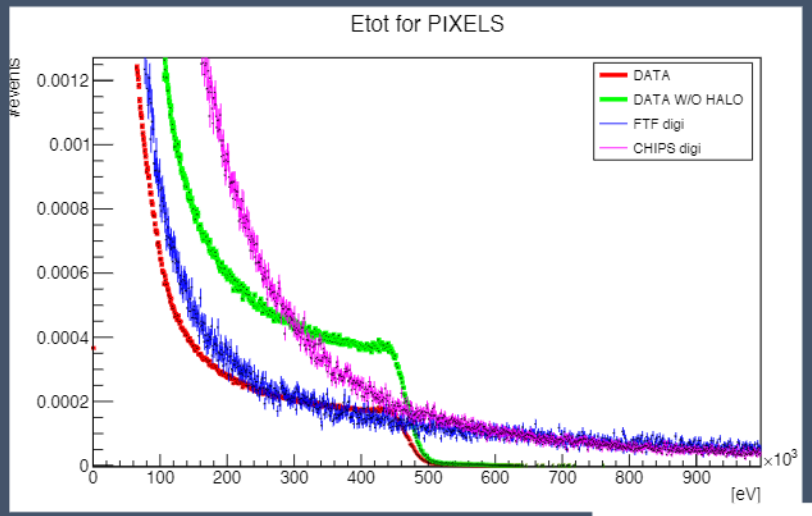
Volcano effect in Allpix²

Threshold obtained from data of direct $\bar{p}$ annihilations in Timepix3

- Gaussian fit of the most energetic pixel in a cluster:
  - μ: 130 ke- (~470 keV)
  - σ : 6 ke- (~20 keV)

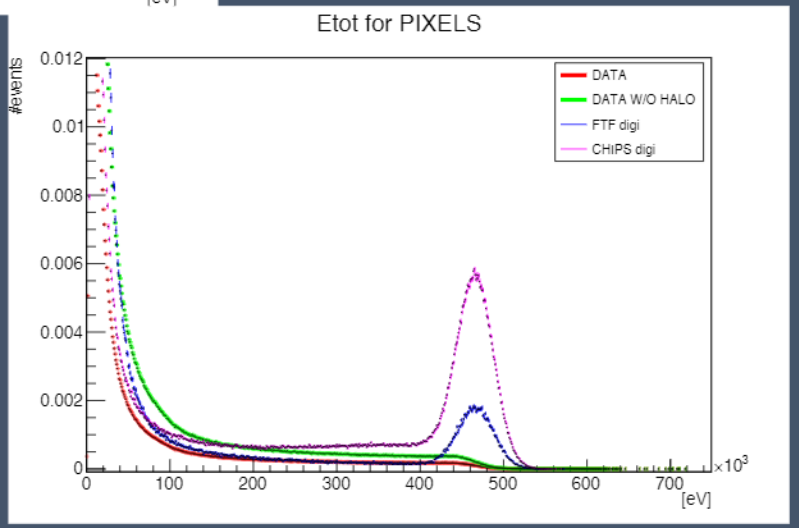


In Allpix² for $\bar{p}$ -nucleus simulations: set all pixels with an energy deposition above 500 keV to a random value following the Gaussian distribution



No threshold in Allpix²

With threshold in Allpix²



Energy deposits before and after Allpix²

GEANT4 simulations for carbon foil, FTF model:

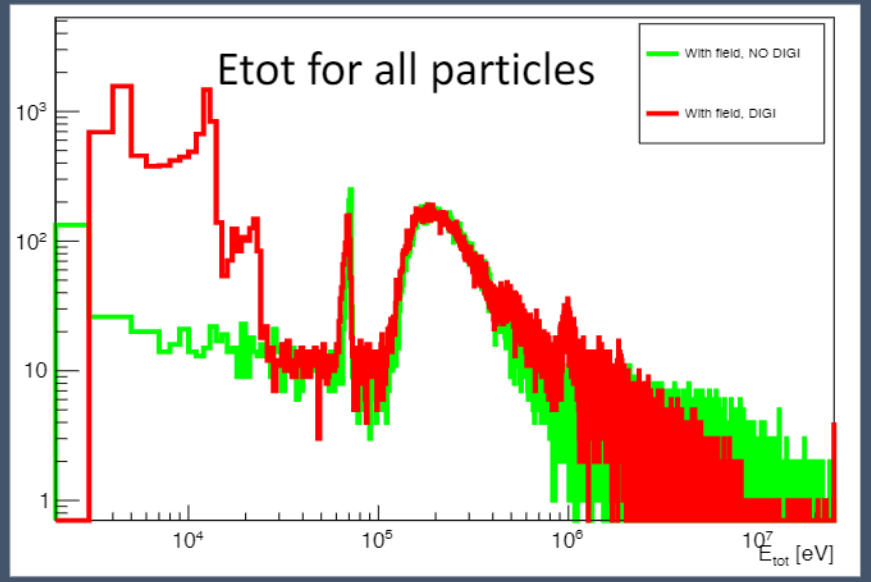
- Raw Geant4 simulations
- Allpix² simulations with saturation effect

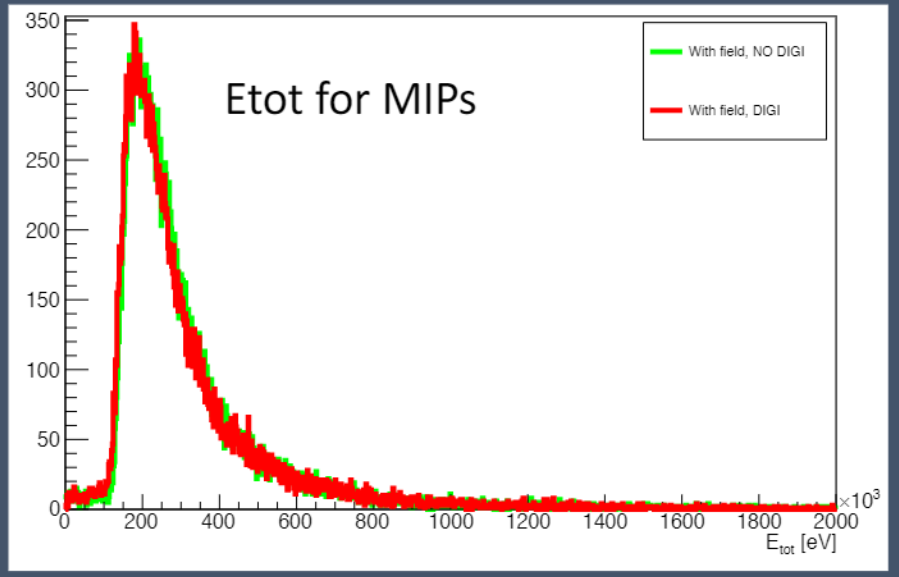
MIPs:

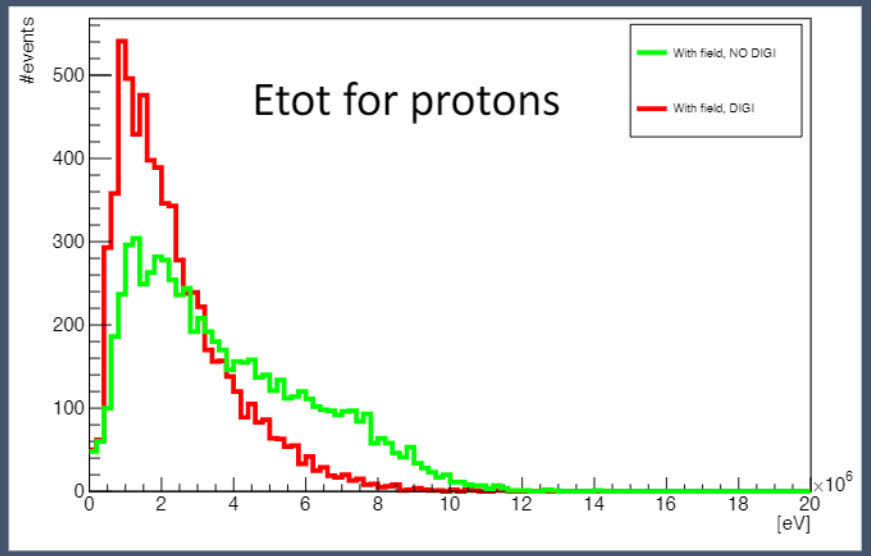
- Same energy deposit between particles in Geant4 and clusters in Allpix²

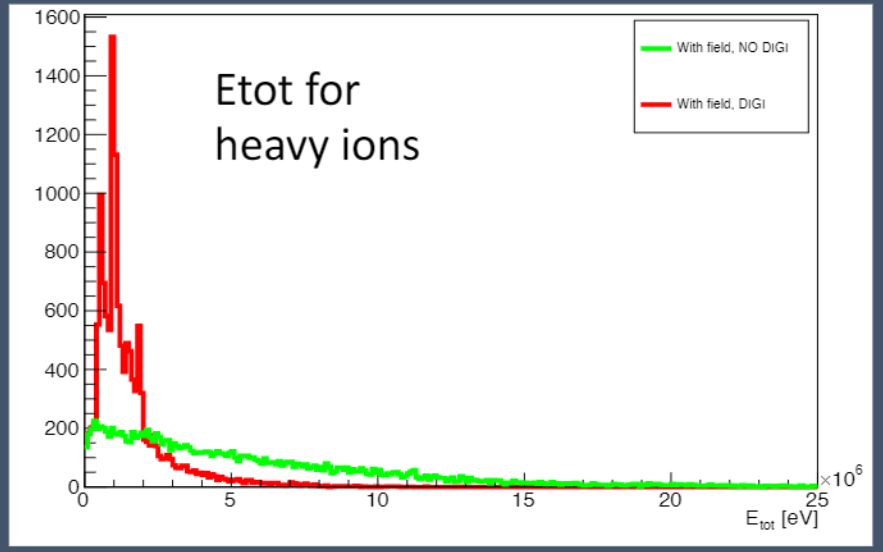
HIPs:

- Smaller energy deposit in the clusters



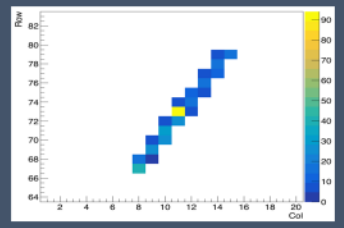




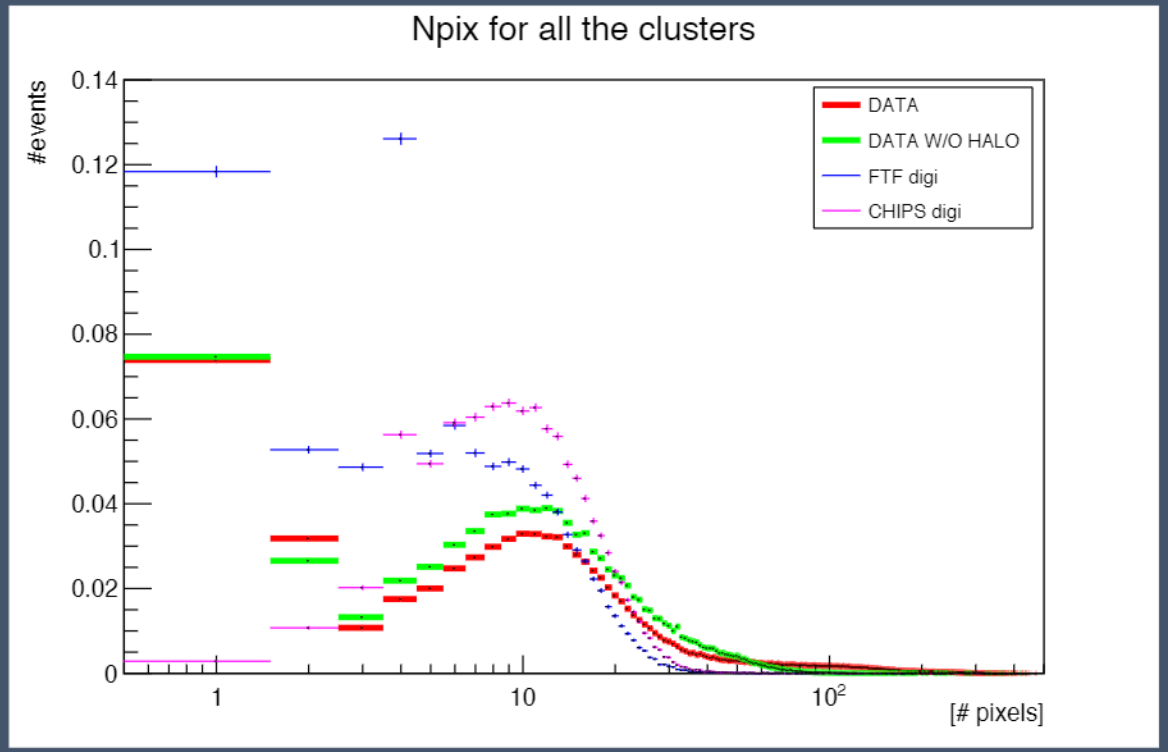


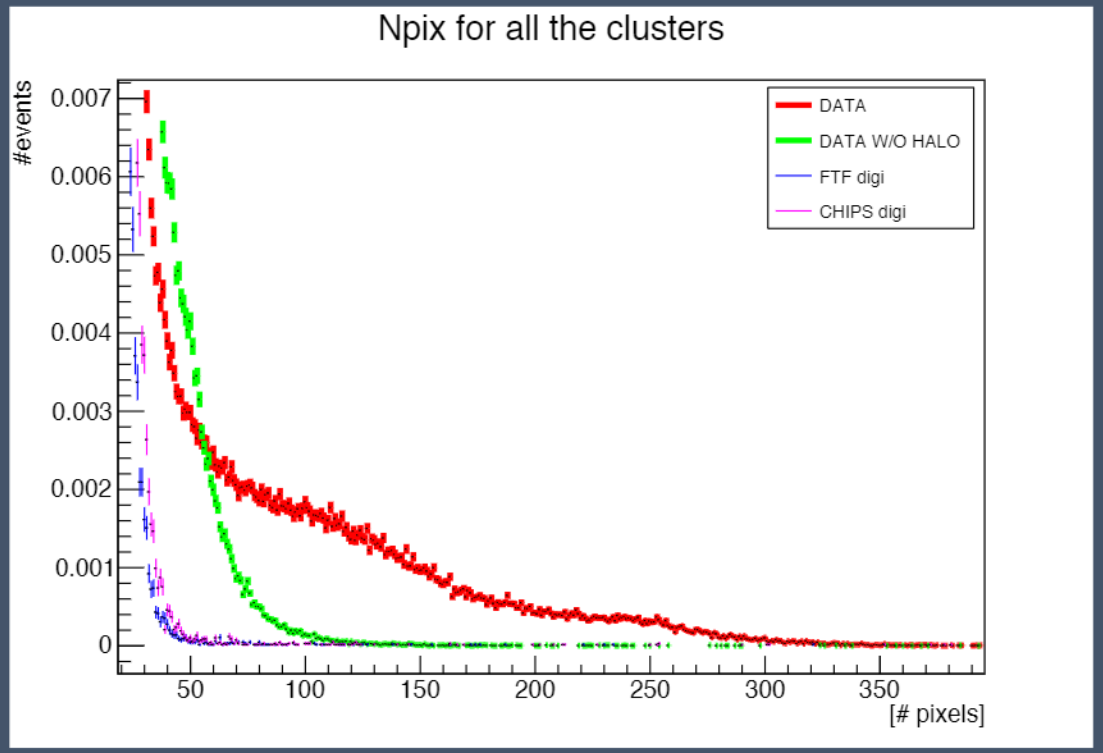
Cluster size in data and simulations

- **MIPs:**
  - same in data and Allpix²: small/straight line clusters, ~ 5-20 pixels
- **HIPs:**
  - In data: blobs > 20 pixels, even with halo removed
  - In Allpix²: small clusters, typically < 10 pixels



Maybe plasma effect needs to be introduced?





Conclusions and further work:

- Allpix^2 is being successfully used for studying low energy antiproton-nuclei annihilation via comparison with different Monte Carlo models (Geant4, FLUKA is still work in progress)

- Thanks to the involvement of the Allpix^2 developers (Simon, Paul) it has been customized by adding physical effects intrinsically present in the DAQ, which are essential in our case

  - Energy deposits/cluster topology from MIPs show great agreement with data
  - Energy deposits/cluster topology from HIPs show somewhat good agreement with data but more work is needed
    - Further simulations of α particles impinging on the detector will be compared with data from ^{241}Am to further verify the digitization with Allpix^2 for heavily ionizing particles

- We are setting up a new, large scale physics study of $\bar{p}$-nucleus annihilation:
  - ~20 different targets
  - Cube-like, 4π detector based on Timepix3/Timepix4 ASICs
  - Allpix^2 for the detector response model in simulations

Thank you for your attention ☺