ÖAW AUSTRIAN ACADEMY OF SCIENCES

SMI – STEFAN MEYER INSTITUTE FOR SUBATOMIC PHYSICS

Solid State Detectors for Antimatter Experiments

A. Gligorova
Stefan Meyer Institute for Subatomic Physics, ÖAW

AVA TopicalWorkshop
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MARIE CURIE ACTIONS
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Horizon 2020
European Union funding
for Research & Innovation

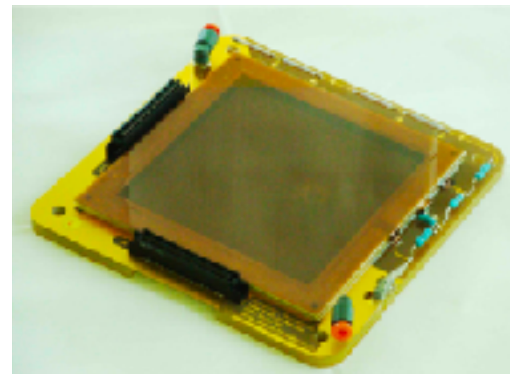
CERN

Outline

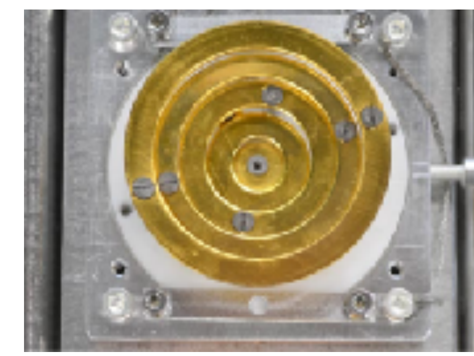
- Detection of antimatter in lab: how do we usually do it?
- Solid state detectors
  - How do they work?
  - Silicon detector technologies:
    - Strip detectors
    - Pixel detectors
- Antiproton annihilation in nuclei (physics)
- Antimatter detection with silicon detectors:
  - Indirect detection (hodoscope-like detector)
  - Direct detection (beam monitors, detection of individual annihilations)
- Conclusions

Detection of antimatter in the lab

- **Antiprotons**
  - Beam diagnostics (e.g. Gas Electron Multiplier (GEM), Monolithic active pixel sensor (MAPS)).
  - Antiproton plasma (e.g. Microchannel plate (MCP) +phosphor screen, Faraday cup).
  - Individual antiprotons (e.g. Si pixel/strip detectors, BGO crystal).

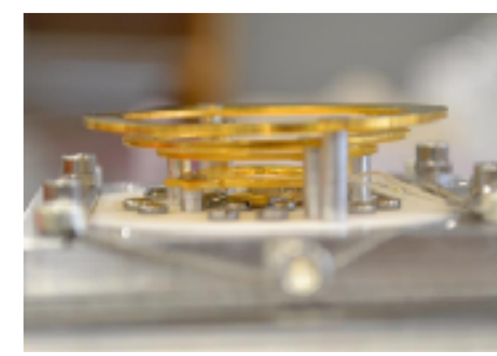


http://iopscience.iop.org/article/10.1088/1748-0221/7/03/C03001

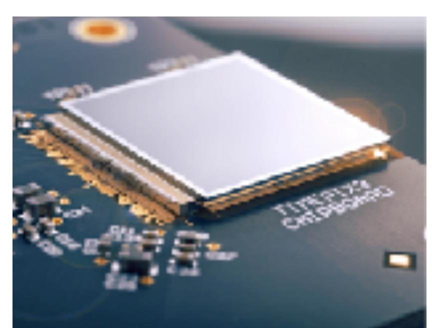


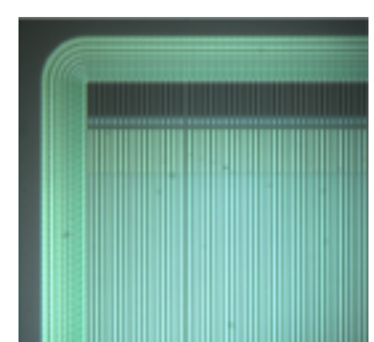
http://www.photonis.com

http://beamimaging.com/product/phosphor-screens/



https://aegis.web.cern.ch/aegis/multimedia.html





https://medipix.web.cern.ch/about-medipix-collaborations

Detection of antimatter in the lab

- **Positrons/Ps**
  - Positron pulses (e.g. MCP; NaI/CsI, $PbWO_4$, PbF_2, LYSO crystals coupled to MPPCs or PMTs).
  - Positron plasma (e.g. MCP, plastic scintillators).
  - Individual positrons (e.g. MCP, channeltron, scintillating crystals).

http://www.epic-scintillator.com/NaI(Tl)-detector-END04041601

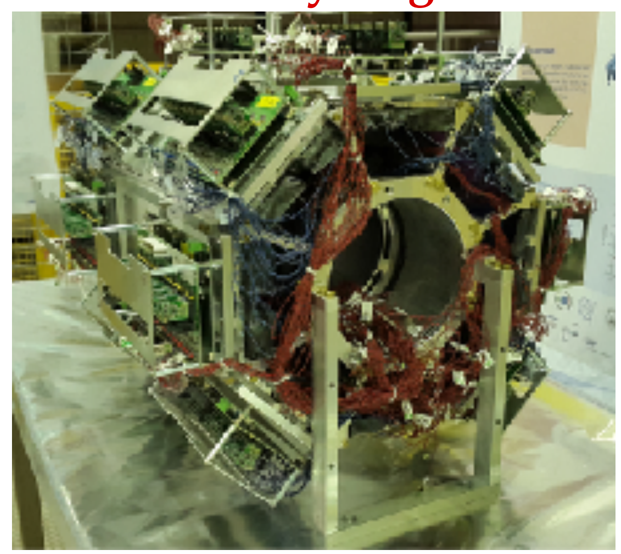
http://www.photonis.com

http://beamimaging.com/product/phosphor-screens/

Detection of anti hydrogen at the AD experiments

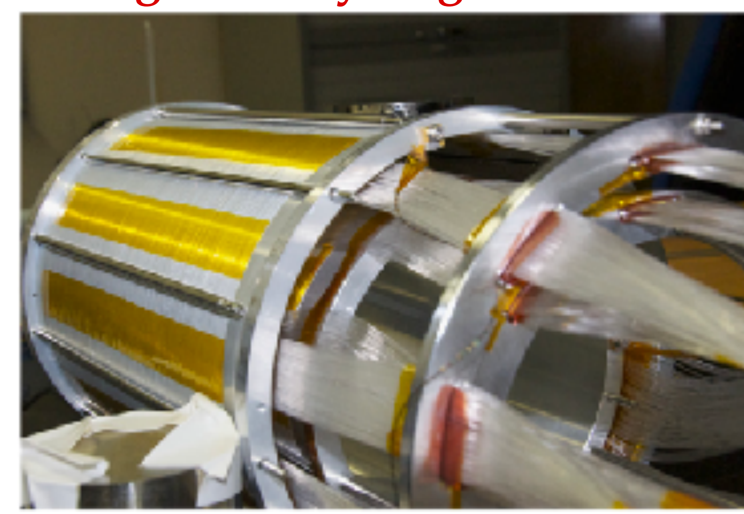
- **Antihydrogen (Hodoscope-like detectors)**
  - **Detectors based on scintillating materials** (e.g. Scintillating fibres and bars).
  - **Silicon-based detectors** (e.g. Si strip/pixel).

ASACUSA antihydrogen detector



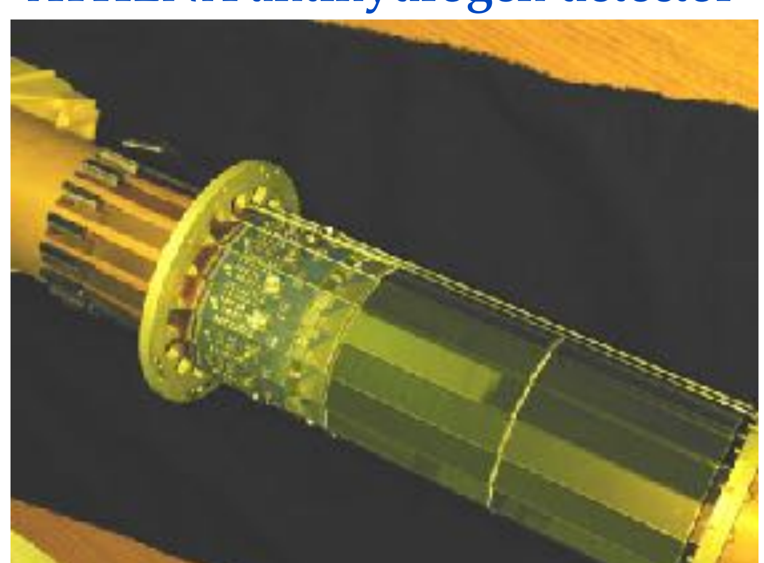
Nucl. Instrum. Methods Phys. Res., A 845 (2017) 579-582

AEgIS antihydrogen detector



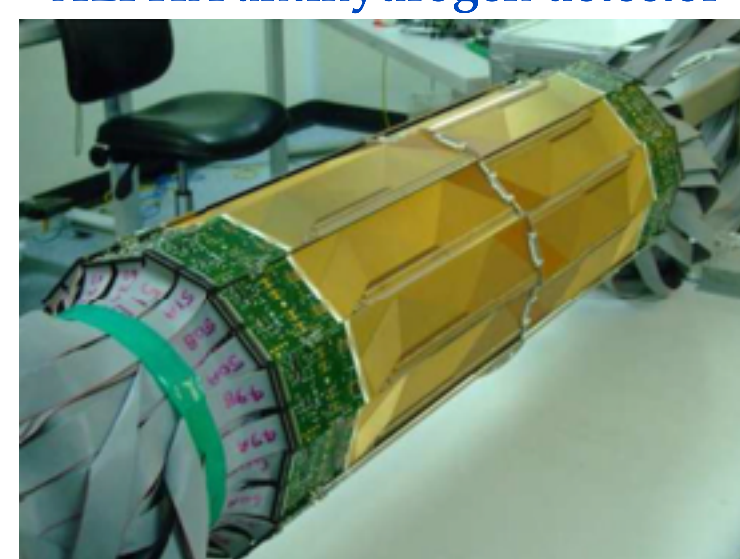
Nucl. Instrum. Methods Phys. Res., A 732 (2013) 437-441

ATHENA antihydrogen detector



Nucl. Instrum. Methods Phys. Res., A 518 (2004) 679-711

ALPHA antihydrogen detector



Nucl. Instrum. Methods Phys. Res., A 684 (2012) 73–81

Solid state detectors

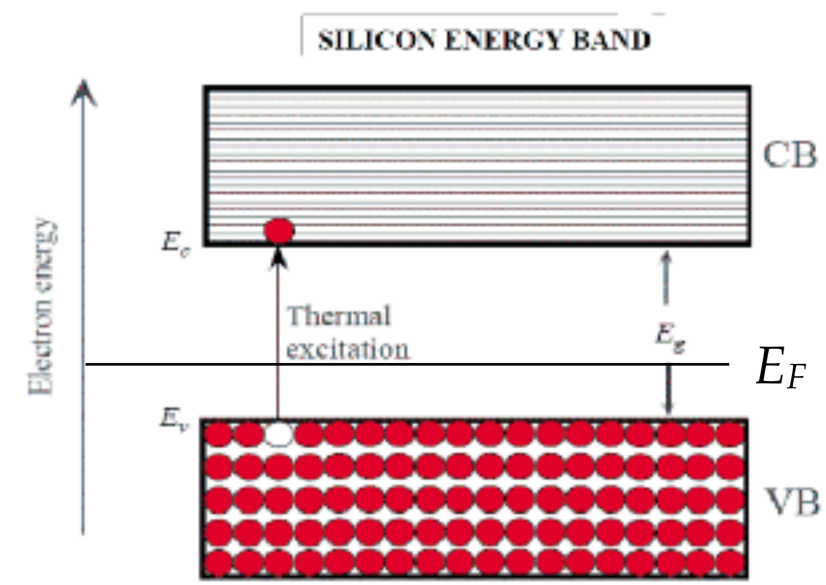
- Used for particle detectors since the 1970s (ionization-drift principle adopted from gaseous detectors), expansion of their use in the 90s (integrated electronics).
- **Detection of charged particles by exciting the electrons of the atoms and generating free carriers in the volume of a semiconductor material.**
- **Advantages:**
  - High material density ⇒ large number of charge carriers.
  - Fine segmentation possible ⇒ good position resolution.
  - Fast readout electronics.
  - Great robustness, simple handling and easy-manageable infrastructure.
- **Most commonly used material is Silicon.**
  - Alternative semiconductors: Ge, GaAs, diamond, SiN…

Silicon - how to obtain the signal?

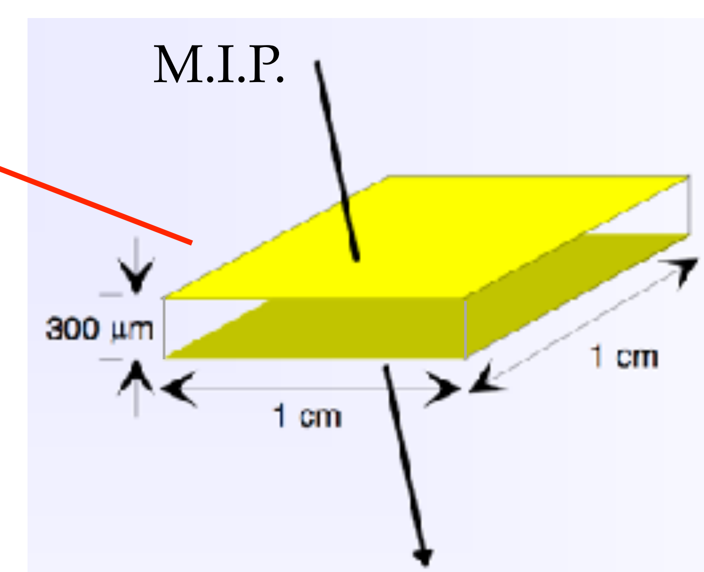
- Small band gap: E_g=1.12 eV ⇒ ***E*(e-h pair) = 3.6 eV** (30 eV for gas detectors).
- **Intrinsic (un-doped) semiconductor**

  ⇒ $p = n = n_i$

$$n_i = C \cdot T^{3/2} e^{\frac{-E_g}{2kT}} \qquad f(E) = \frac{1}{1+e^{\frac{E-E_F}{kT}}}$$

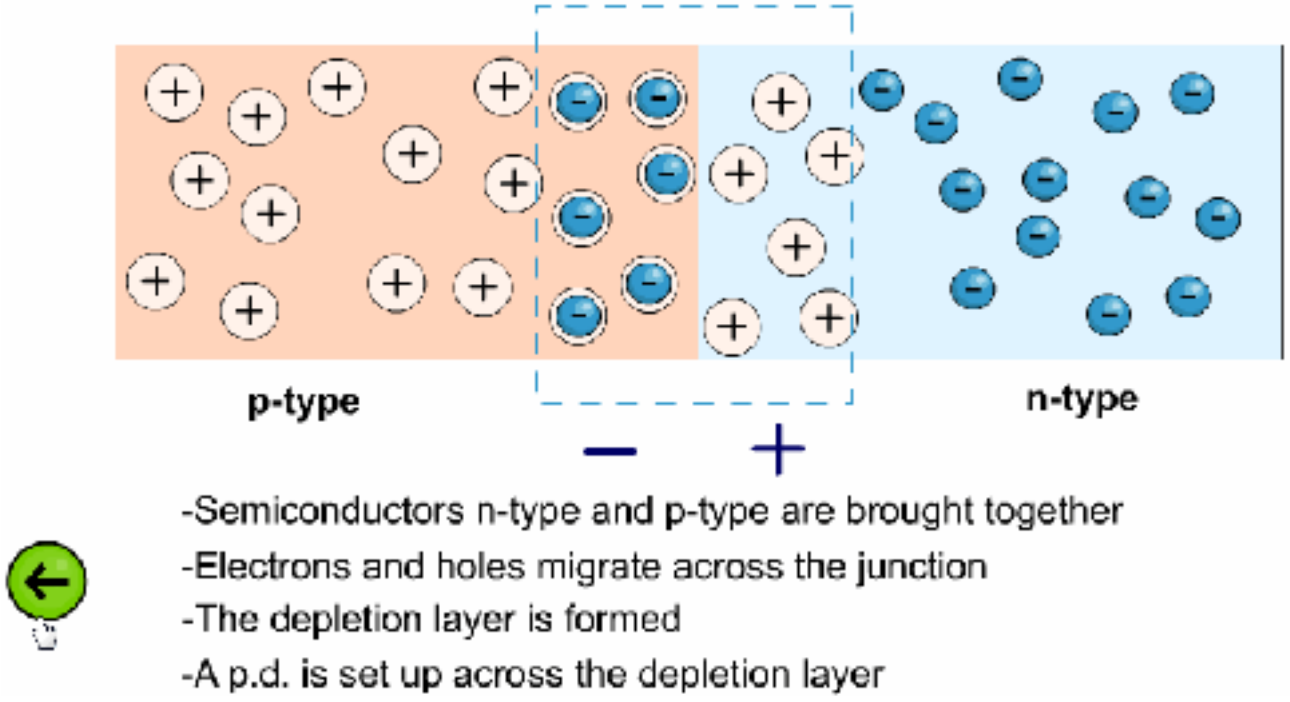


- **For Si: $n_i \approx 1.45\cdot10^{10}$ cm^{-3} (created by thermal excitations at room temperature).**
- **$4.5\cdot10^{8}$ free charge carriers in this volume**
- **dE/dx (M.I.P.) ≈ 0.3 keV/µm ≈ 80 e-h/µm** (average)
- **$2.4\cdot10^{4}$ e-h pairs produced by a M.I.P. (minimum ionizing particle) ⇒ Need to remove the thermally produced carriers, i.e. deplete the detector!**
- **Solution: Make use of reverse biased p-n junction.**



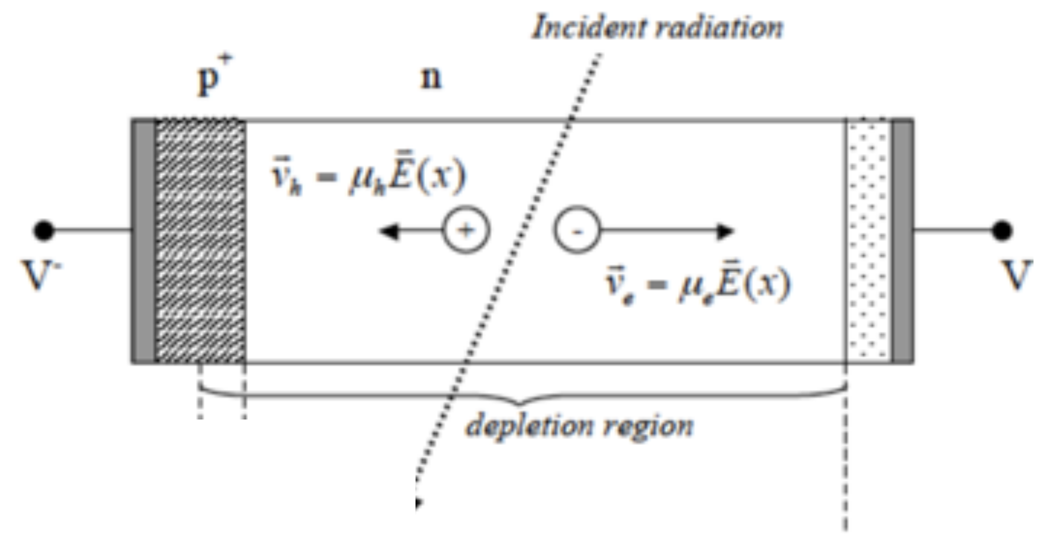
Solid state detectors - p-type and n-type semiconductors

- **Operation principle of a semiconductor detector is based of the <u>p-n junction</u>.**
  - **Doping: p-type Silicon** - add elements from III group ⇒ **acceptors** (B,..)
  - holes are majority carriers
  - **Doping: n-type Silicon** - add elements from V group ⇒ **donors** (P, As,..)
  - electrons are majority carriers



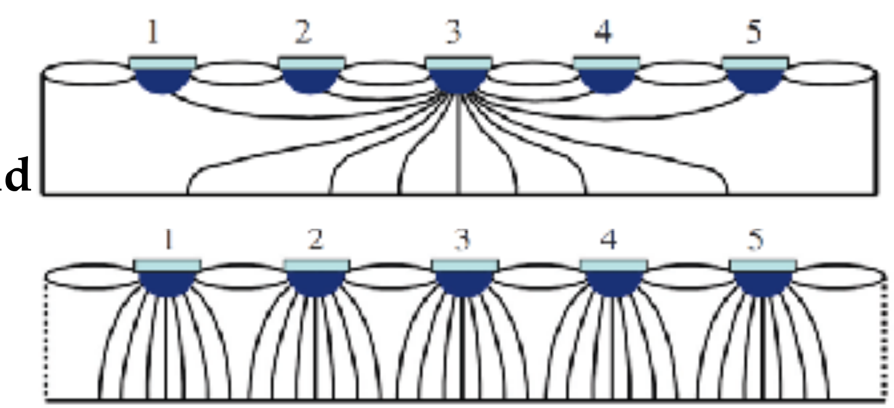
http://electricalacademia.com/electronics/pn-junction-formation-structure/attachment/forming-a-p-n-junction-diode/

Silicon detectors - how the signal is created



- **Carriers move through the detector ⇒ they induce a time-varying charge on the electrodes, creating a current (charge is not "collected" when the carriers reach the electrodes).**
- **Ramo's theorem:** $i(t) = -q\mathbf{v}(\mathbf{t}) \cdot \mathbf{E_W}$
  - **q - moving charge with velocity v(t)**
  - **E_W - weighting field**

Weighting field



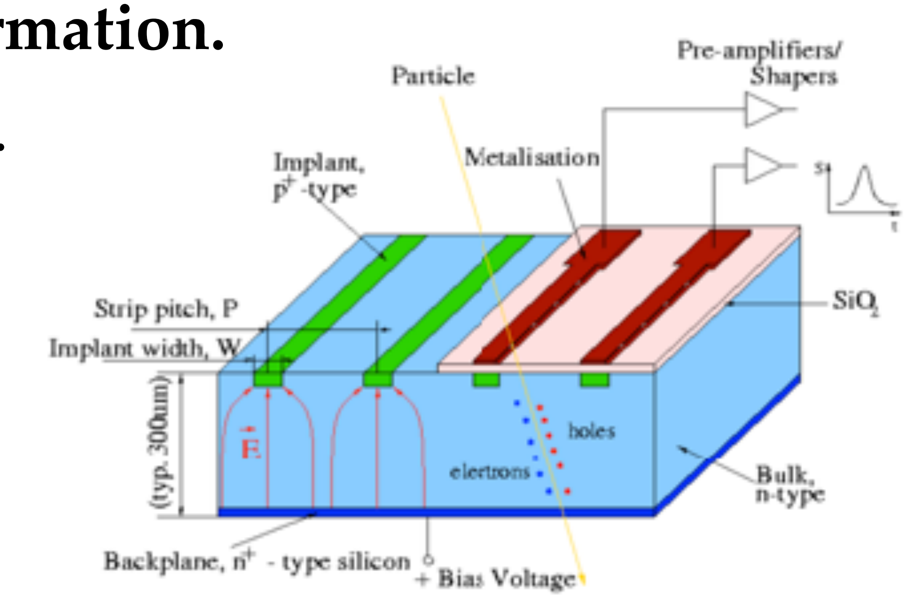
- High carrier mobility μ_e=1450 cm²/Vs, μ_h= 450 cm²/Vs ⇒ **fast charge collection**
  - **Charge collection time (~10 ns).**

$$T = \frac{d}{\mu E} = \frac{d^2}{\mu U}$$

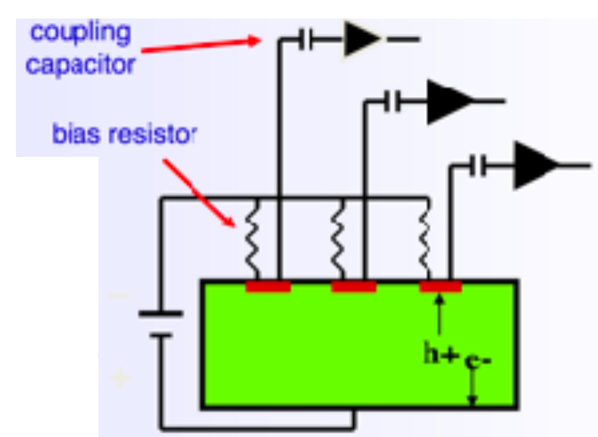
- Most commonly used segmentation of the readout electrodes: **strip** and **pixel.**

Silicon detectors technologies: strip detectors

- **Strip detectors: Segmentation of the p^+ layer (or both sides) into strips connected to individual read-out channels ⇒ spatial information.**
- Typical thickness: 300 µm (150µm - 500µm used).
- Depletion voltage ~ 150 V.



- **Bias resistor:** To isolate strips from each other to collect/measure charge on each strip ⇒ high impedance bias connection (≈1 MΩ resistor).
- **Coupling capacitor:** input amplifier(AC coupling) to avoid large DC input from leakage current.

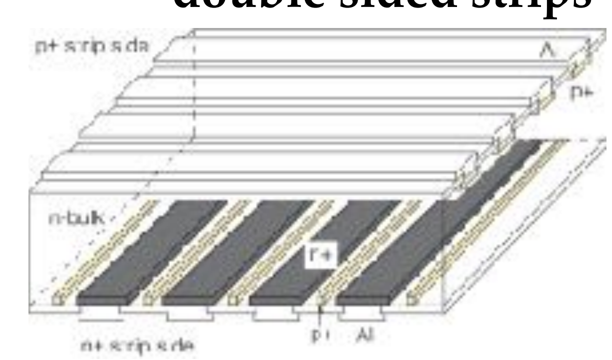


- **Resolution σ depends on the pitch p**

$$\sigma = \frac{p}{\sqrt{12}}$$

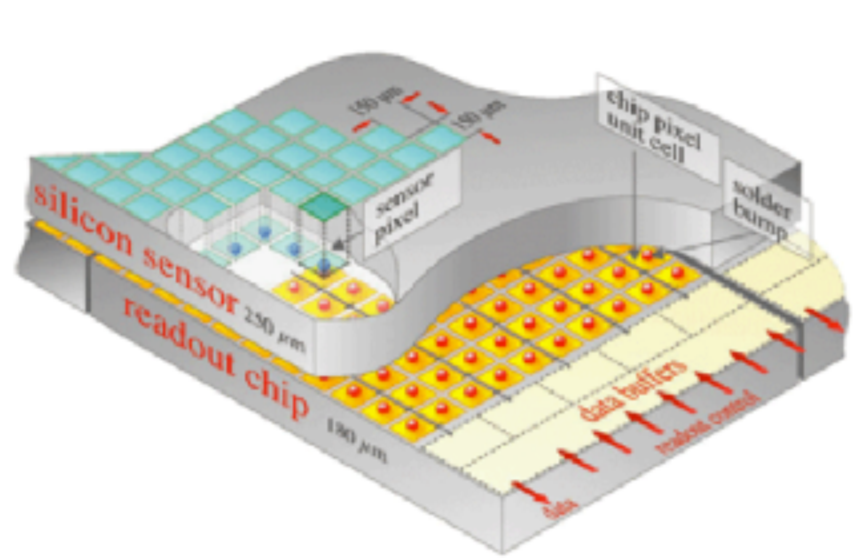
⇒ typical pitch values are 20 µm - 150 µm ⇒
50 µm pitch results in 14.4 µm resolution.

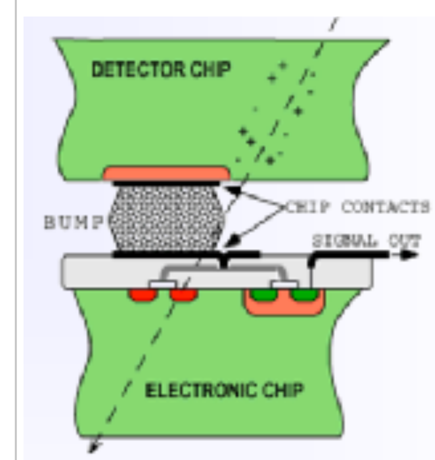
double sided strips



Silicon detectors technologies: pixel detectors

- **Thickness: 300 µm (150 - 500 µm used).**
- **Depletion voltage ~ 150 V.**
- Typical pixel pitch ~ 50-150 µm.
- Time resolution down to 1.56 ns.

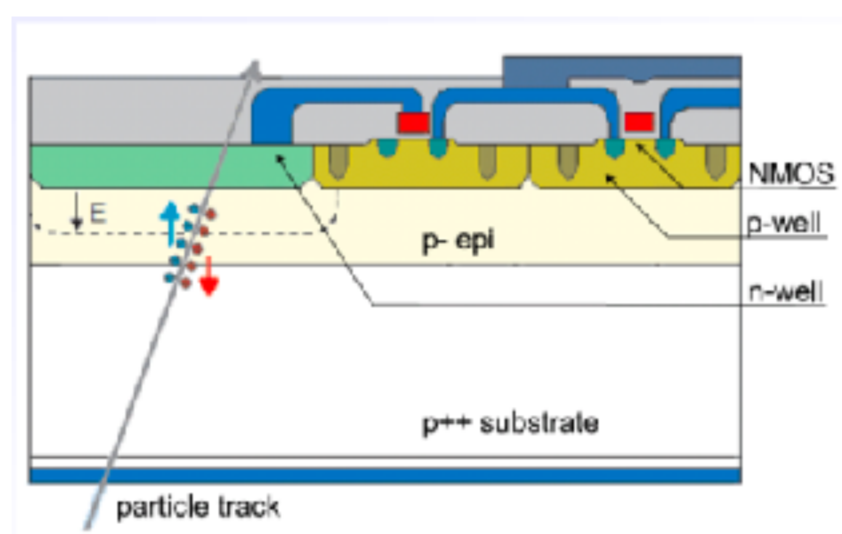




- **Pixel detectors**

→ **Hybrid**

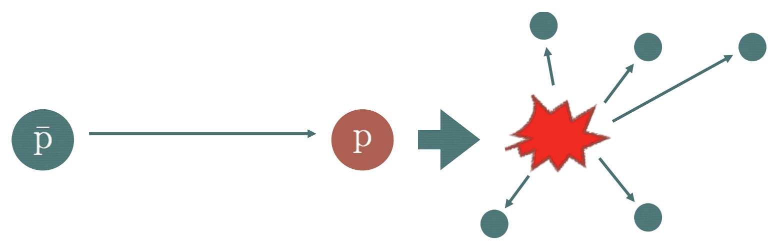
→ **Monolithic Active Pixel Sensor (MAPS)**



- Sensor and readout electronics in one chip.
- **Thickness: 15-20 µm**.
- **No bias applied**.
- Charge collected by diffusion (slow, ~100 ns).
- Can cope with large charge deposits.

Antiproton annihilation in materials

- **Antiproton-nucleon annihilation**



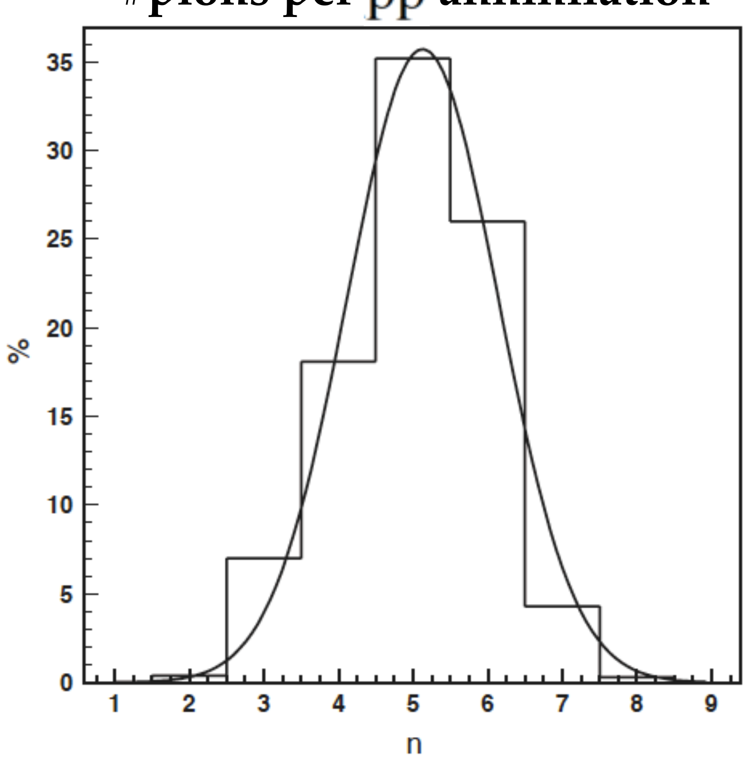
π, K (charged and neutral)

- **Nucleons (N) are not elementary particles ⇒ annihilation takes place at the quark level.**
- **$N\bar{N}$ annihilation ⇒ all the quark-antiquark pairs do not necessarily annihilate.**

~1880 MeV energy ⇒
5 x 140 MeV/c² (rest mass)+
~230 MeV/pion (kinetic energy)

 # π/annihilation:
3.05 ± 0.04 π^+, π^-
1.93 ±0.12 π^0
4.98 ± 0.35 total

#pions per $p\bar{p}$ annihilation



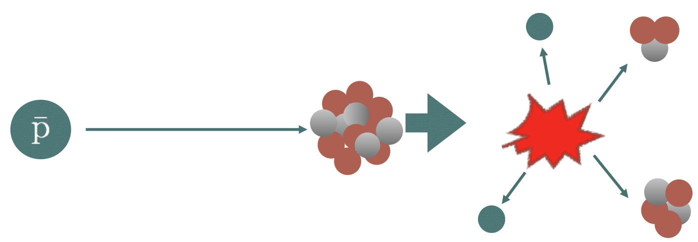
	BNL, CERN and Crystal Barrel
2 pions	0.38 ± 0.03%
3 pions	7.4 ± 0.3%
4 pions	18.1 ± 1.8%
5 pions	35.2 ± 3.7%
6 pions	23.3 ± 2.8%
7 pions	3.3 ± 0.3%

- $p\bar{p}/n\bar{p}$ annihilations still being actively studied ⇒ **not even the rates of the different decay channels are completely known.**

Eberhard Klempt, Chris Batty, and Jean-Marc Richard. The antinucleon-nucleon interaction at low energy; annihilation dynamics. Physics Reports, 413(4–5):197–317, 2005.

Antiproton annihilation in materials

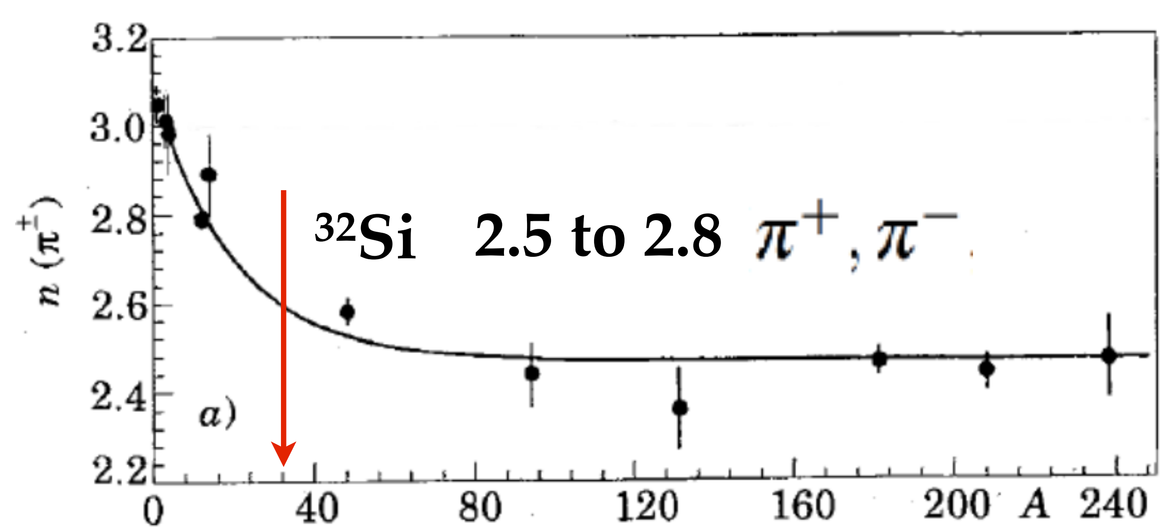
- **Antiproton-nucleus annihilation**



π and p, t, n, α, ^{3}He, ^{4}He, ^{6}He, ^{8}He, Li…

- Size of the nucleus ⇒ #**primarily produced pions that will penetrate inside the nucleus.**
- **Intranuclear cascade ⇒ nucleus up to several 100s MeV** ⇒ additional pions + fragmentation of the nucleus with emission of protons, neutrons (n), deuterons (d), tritions (t) or alpha particles.

- **Residual nucleus ⇒ decay mechanism** according to the excitation energy:
- ≤ **2 MeV/nucleon** ⇒ successive **nucleon evaporation and fission** ⇒ (depending on the mass number, A) **wide spectrum of residual nuclei.**
- ≥ **5 MeV/nucleon** , a **phase transition into liquid-gas type** ⇒ **explosive decay** of the residual nucleus - **multifragmentation.**

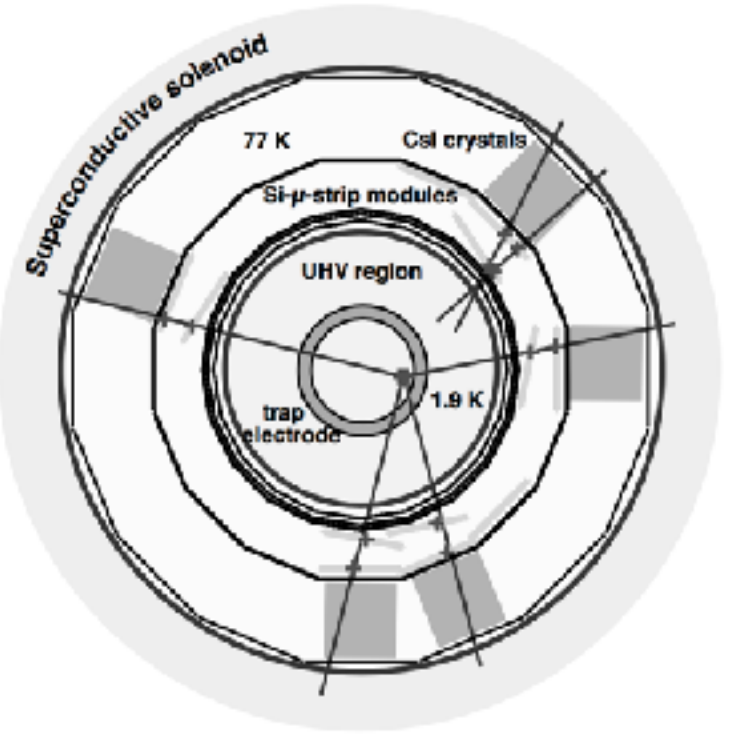


G. Bendiscioli and D. Kharzeev. Antinucleon-nucleon and antinucleon-nucleus interaction. a review of experimental data. La Rivista Del Nuovo Cimento Series 3, 17(6):1–142, 1994

Carlo Guaraldo. Low energy antiproton-nucleus annihilation. Nuclear Physics B - Proceedings Supplements, 8(0):243 – 254, 1989

Indirect detection of antiprotons/antihydrogen

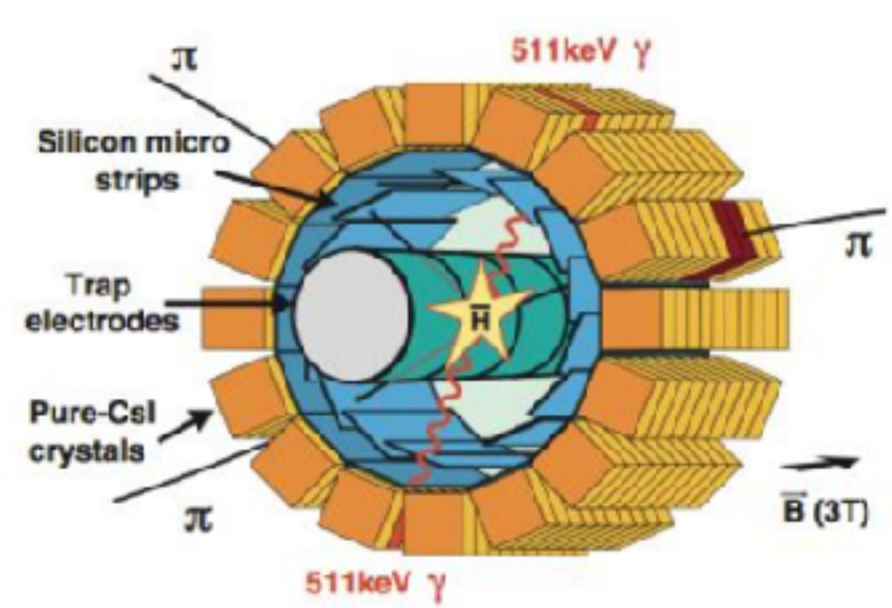
- **Antiproton/antihydrogen annihilate elsewhere, e.g. on the trap walls (indirect detection):**
  - Detection of charged pions.
  - Reconstruction of their trajectories.
  - Extrapolation of the trajectories.
  - Vertex fitting.
  - Typical 3D position resolution is few mm.

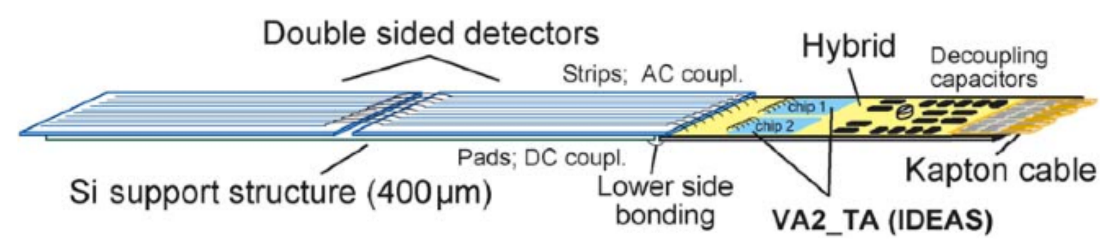


Nucl. Instrum. Methods Phys. Res., A 501 (2003) 65-71

ATHENA antihydrogen detector

- **Detection of charged pions+gamma rays:**
  - ~ 80% of the solid angle.
  - Coincidences between hadron tracks (Si strip) and 511 keV from e^+e^- (CsI crystals).
  - 2 layers of 384 double sided Si strip modules:
    - **46.5 µm pitch, 380 µm thickness.**
  - VLSI (Very-Large-ScaleIntegration) VA2 TA ASIC for R/O (IDE AS, Norway).
  - **Operation at ~140 K and in vacuum (10^{-7} mbar).**
  - Hit position resolution (2D): **28 µm .**
  - 3D reconstruction of the vertex:
    - **~4 mm position resolution** (curvature in 3T field not known, tracks extrapolated as straight lines).

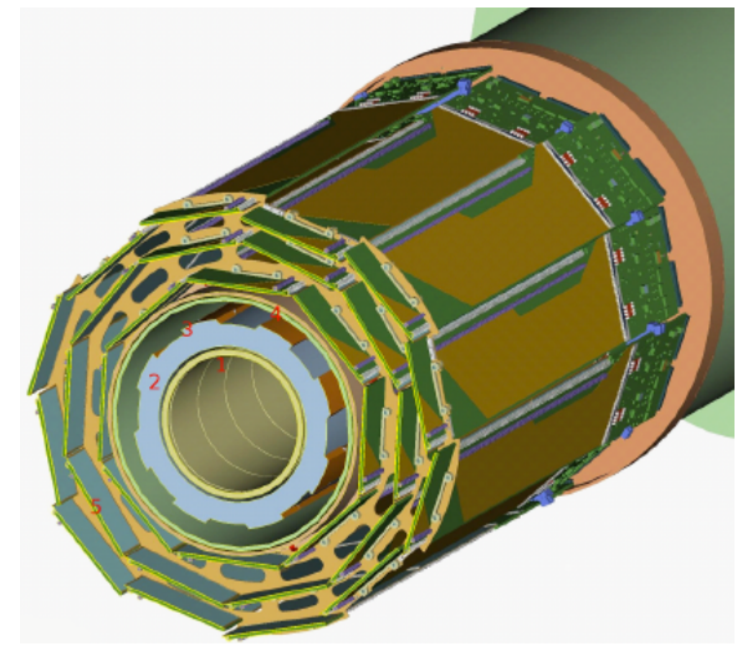




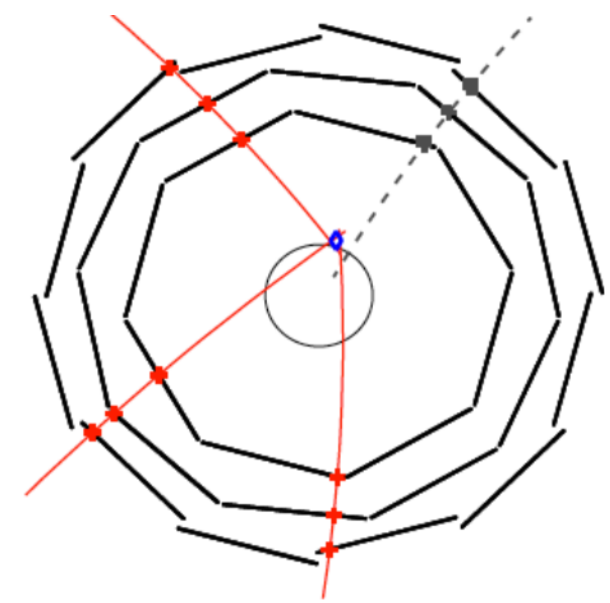
Nucl. Instrum. and Meth. in Phys. Res. A 518 (2004) 679–711

ALPHA antihydrogen detector

- **Detection of charged pions:**
  - ~ 90% of the solid angle.
  - 3 layers of 60 double sided Si strip modules:
    - **227 μm pitch in R - φ, 875 μm pitch in z direction.**
    - **300 μm thickness.**
  - R/O with VA1TA 128 channel ASICs (IDE AS), 30 720 readout channels.
  - **Dynamic range: ±10MIPs.**
  - **Operation at atmospheric pressure and room *T*.**
  - Hit position resolution (2D):
    - **65 μm in R - φ, 253 μm in z - direction.**
  - 3D reconstruction of the vertex (resolutions):
    - **7-8 mm, depending on the projection.**



G. B. Andresen et al. The ALPHA – detector: Module production and assembly. Journal of Instrumentation, 7(01):C01051, 2012.



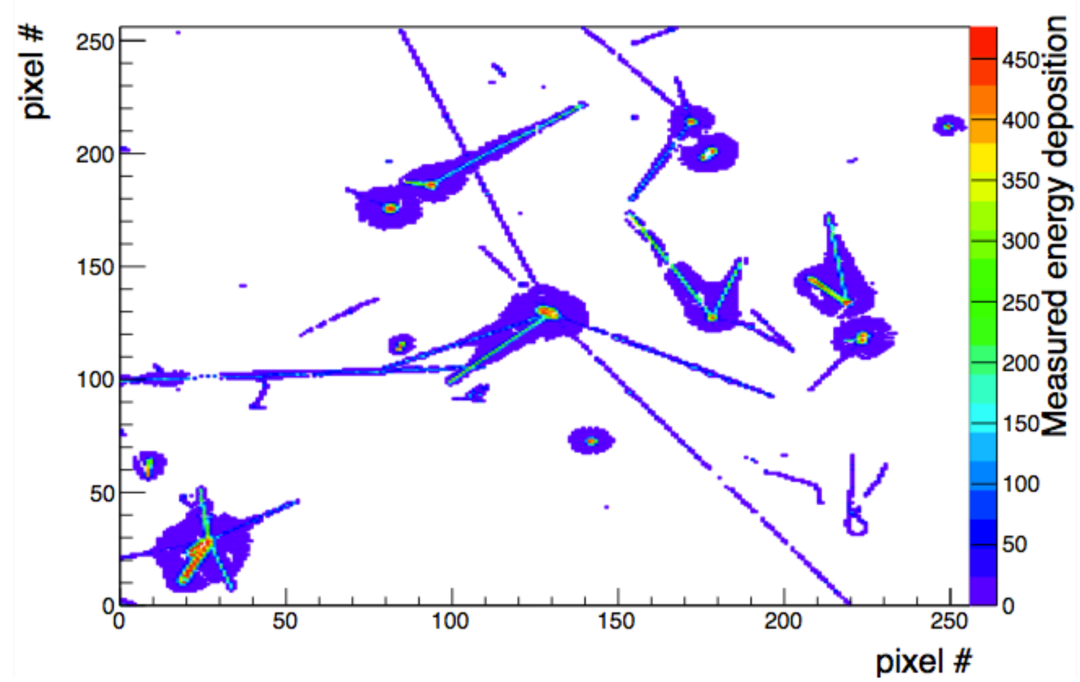
G.B. Andresen et al. Antihydrogen annihilation reconstruction with the ALPHA silicon detector. NIM A 684(0):73– 81, 2012.

Direct detection of antiprotons/antihydrogen

- **Beam of antiprotons passes through/is annihilated in the detector:**
  - Beam monitoring.

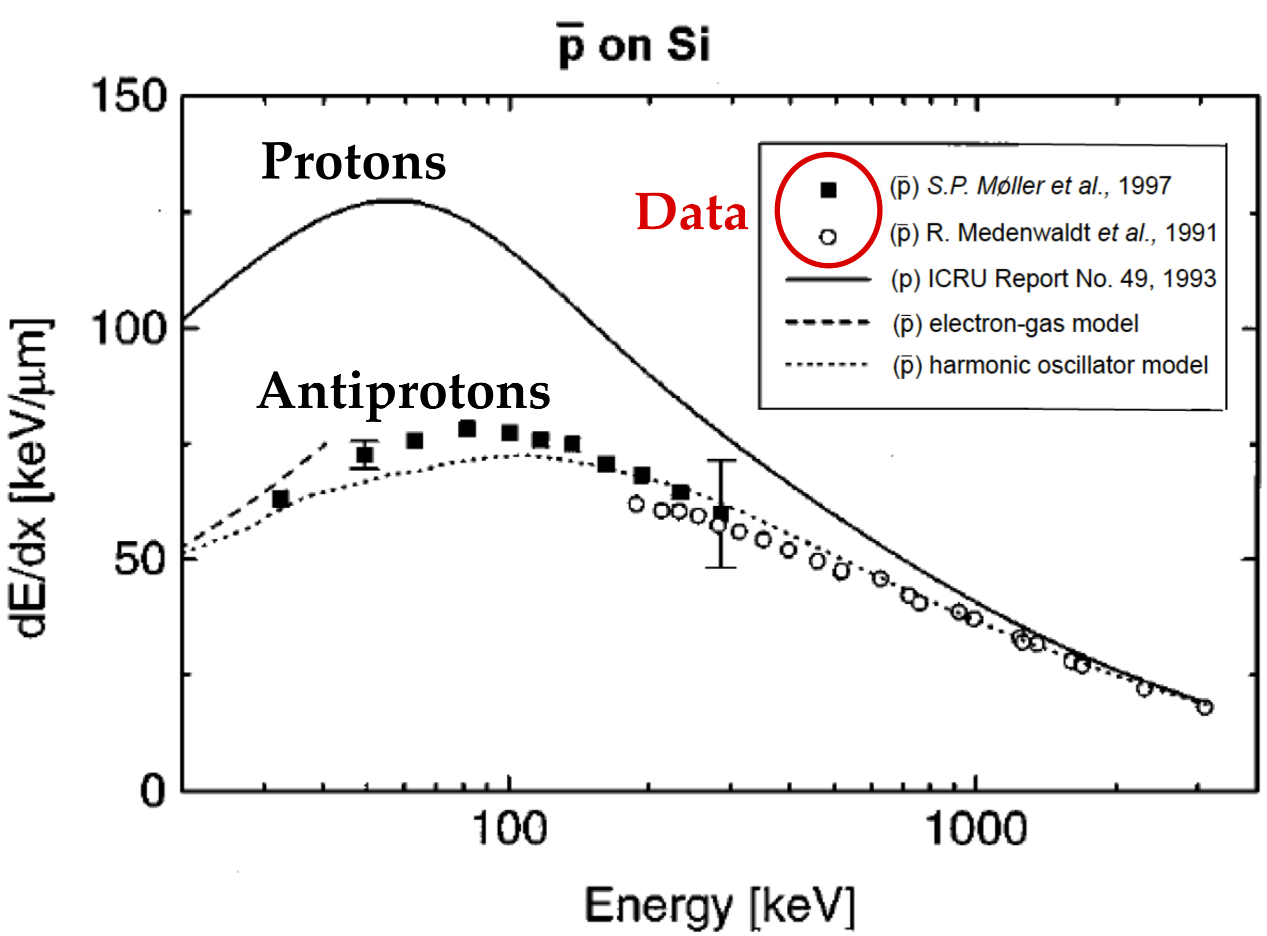
- **Individual antiprotons/antihydrogens annihilate in the detector:**
  - Detection of charged pions and heavier fragments.
  - Reconstruction of their trajectories.
  - Extrapolation of the trajectories.
  - Vertex fitting in 2D.
  - Typical 2D position resolution is ~10 μm.

Individual annihilations recorded with Timepix3



Stopping power of antiprotons in silicon

- **Antiprotons can either annihilate or pass through the detector, depending on:**
  - **Energy of antiprotons** (A **pion is a MIP** at around **350 MeV in silicon**, while a **proton is a MIP** at around **2350 MeV**).
  - **Thickness of the detector.**

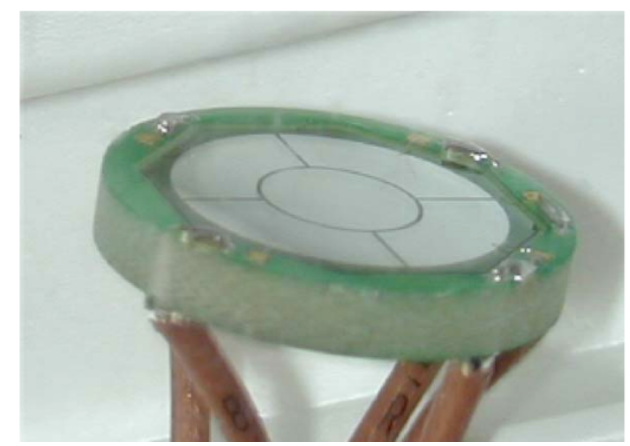


- Stopping power (dE/dx) for 188 keV antiprotons is 32% lower than for the protons with same velocity.
- **Barkas effect:** When the velocity of the particle is very low, atomic electrons have enough time to move. Positively charged particles pull the electrons towards their path, while the negative particles repel them ⇒ increased local electron density for the positive particles, and a decreased local electron density for the negative ones.

Beam monitoring with silicon detectors

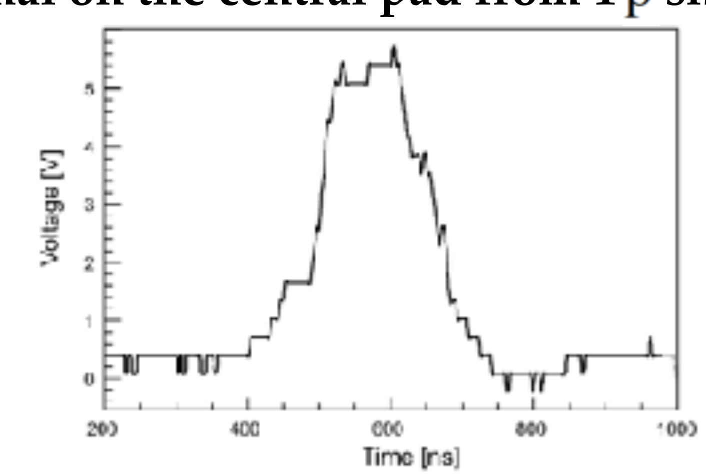
- **Measurement of the beam parameters: beam intensity, beam profile and beam position.**
  - Huge number of antimatter particles passes through the detector (non destructive) or is annihilated in it (destructive), depending on its thickness.

- **Si beam monitor in ATHENA** →



  - Segmented diode; Thickness: 67 μm; Diameter 15 mm.
  - Operation at 10 - 80 K, in vacuum 10^{-8} mbar and 3T magnetic field.
  - **5.3 MeV antiproton ⇒ 11.4 keV/μm (in Si) ⇒ 3200 e-h pairs/μm (only 80 e-h pairs from a MIP!) 10^{7} incoming antiprotons give $3.2 \cdot 10^{10}$ e-h pairs/μm.**
  - Direct R/O of the signal, no amplifier needed.
  - The total charge obtained by integration of the data from the oscilloscope

Signal on the central pad from 1 $\bar{p}$ shot)

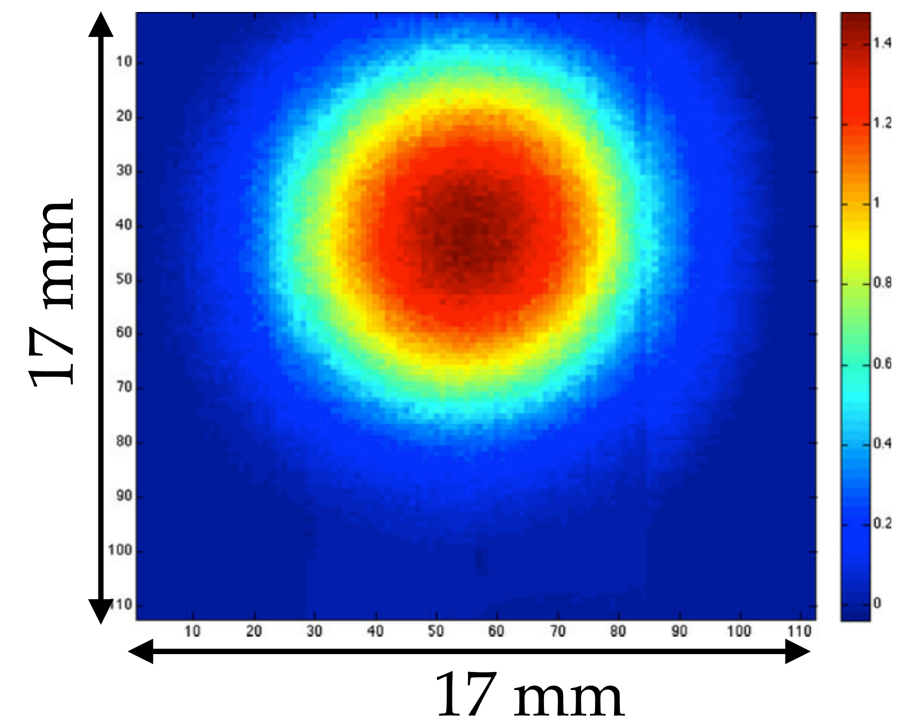


M. Amoretti et al. The ATHENA antihydrogen apparatus. NIM A: 518(3):679 – 711, 2004.

Beam monitoring with silicon detectors in ACE

- **ACE (Antiproton cell experiment): a study of the overall biological effect of antiprotons on biological targets.**
- **Si MAPS detector (MIMOTERA) in ACE**
  - **126 MeV** antiprotons in ~ 500 ns long pulses.
  - **Beam profile of a single shot containing $3 \cdot 10^7$ antiprotons.**
  - **112 x 112 pixels: 153 µm pitch; 14 µm thickness.**
  - Remarkable dynamic range (30 keV - 30 MeV per pixel).
  - R/O clock frequencies up to 40 MHz.

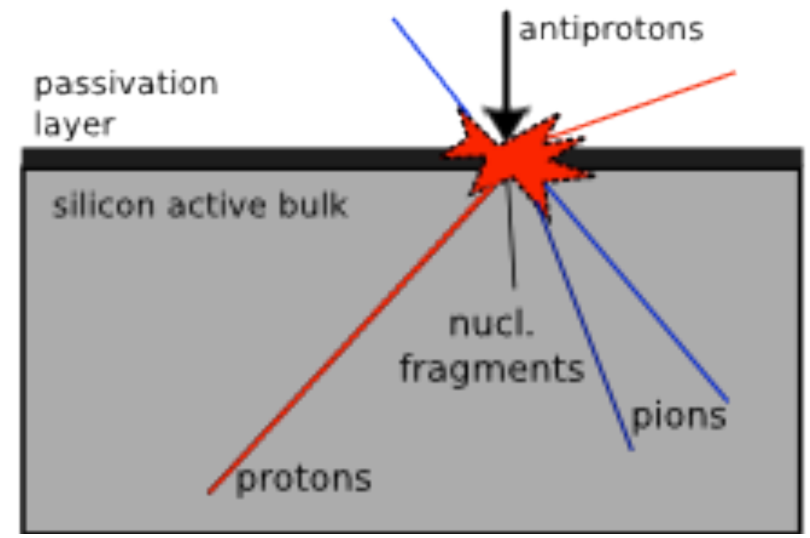
One shot of $3 \cdot 10^7$ $\bar{p}$ recorded with MIMOTERA



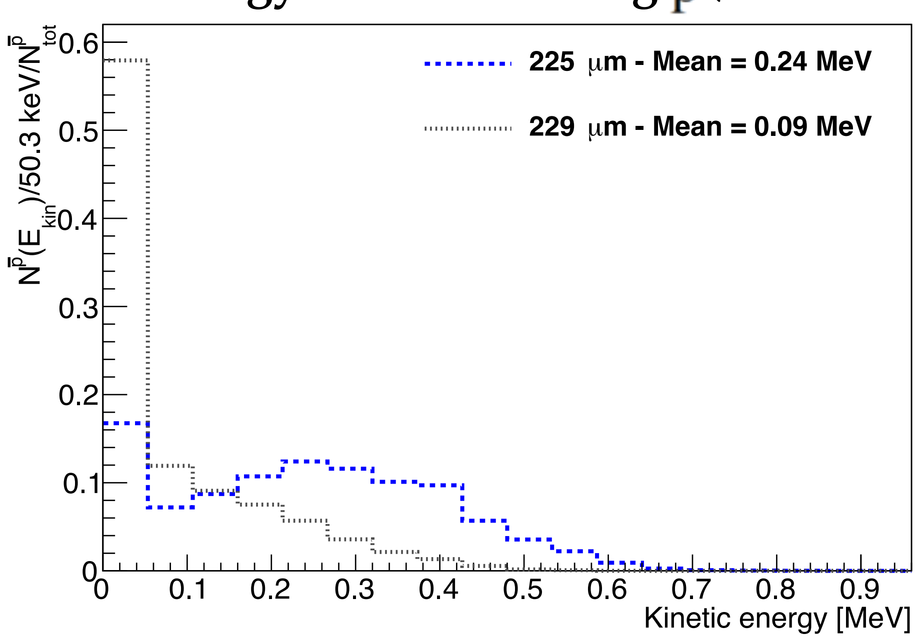
Stefan Sellner et al., Hyperfine Interactions, 213(1-3):159–174, 2012.

Low energy antiprotons in silicon detectors

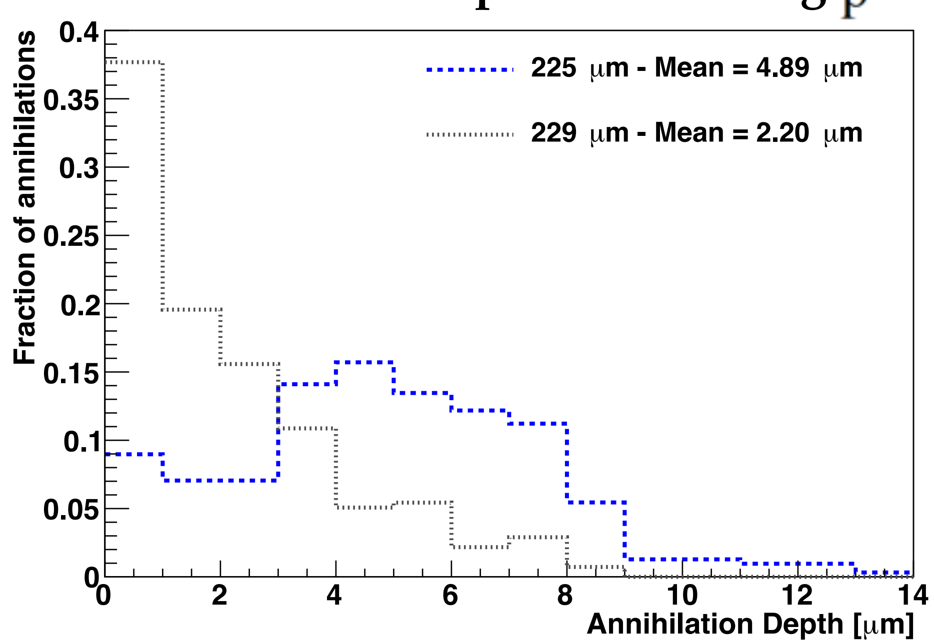
- **Antiprotons with energies between 0-100 keV.**
  - **Individual annihilations** takes place **in the first few microns of the silicon bulk** (GEANT4 simulations).
  - Annihilation prongs are emitted isotropically; pions and heavy fragments can be measured.



Kinetic energy of the incoming $\bar{p}$ (GEANT4)



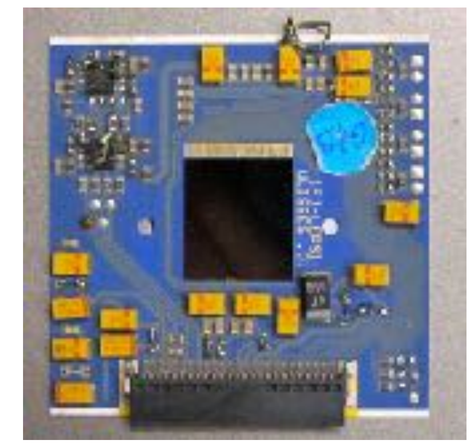
Annihilation depth of incoming $\bar{p}$



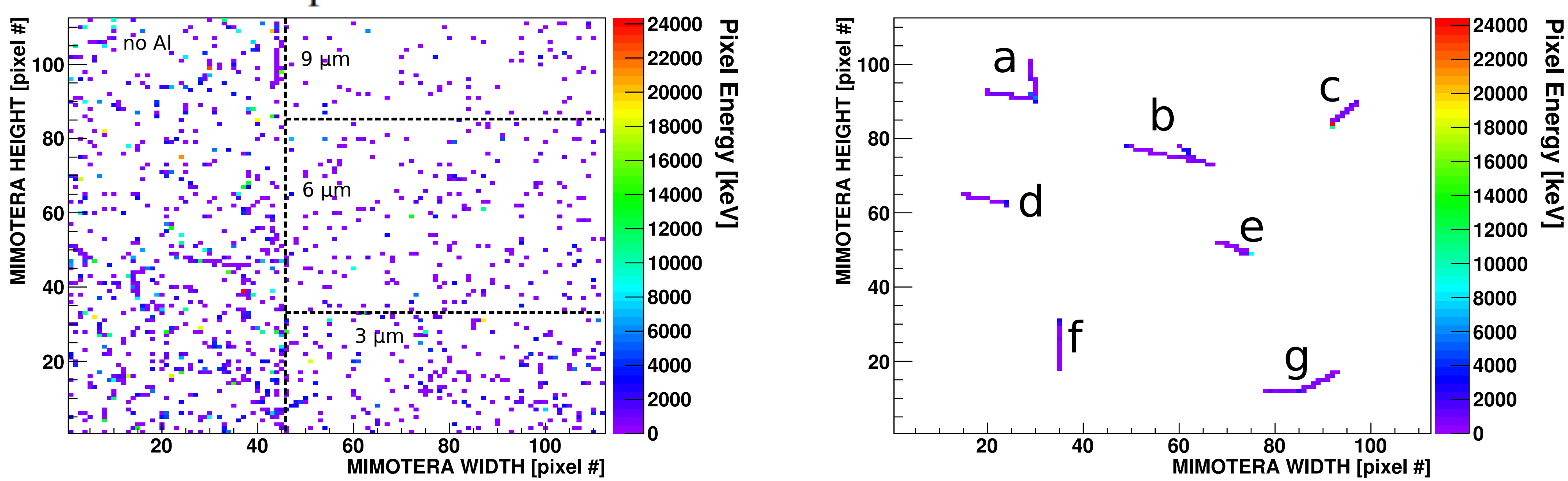
S Aghion et al 2014 JINST ***9*** *P06020*

Individual antiproton annihilations in MAPS

- MIMOTERA detector:
  - Active area: 17 x 17 mm^2; 112 x 112 pixels: 153 μm pitch.
- Thickness: Only 14 μm!
- **Measurements done in AEgIS (0-100 keV antiprotons).**



$\bar{p}$ annihilations recorded with MIMOTERA



- Large pixels compared to the thickness ⇒ mostly small clusters produced (1-2 pixels).
- Cluster energies up to 40 MeV.

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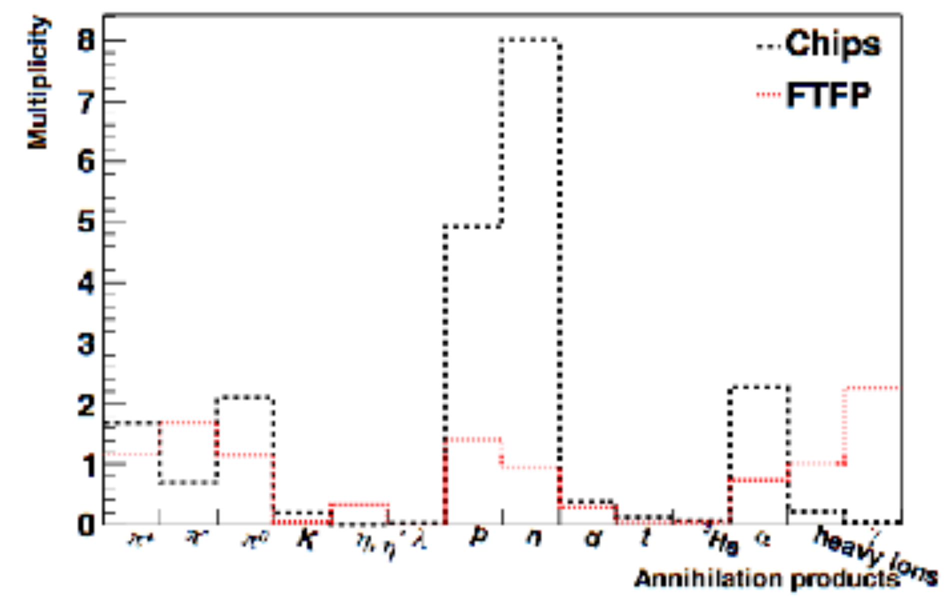
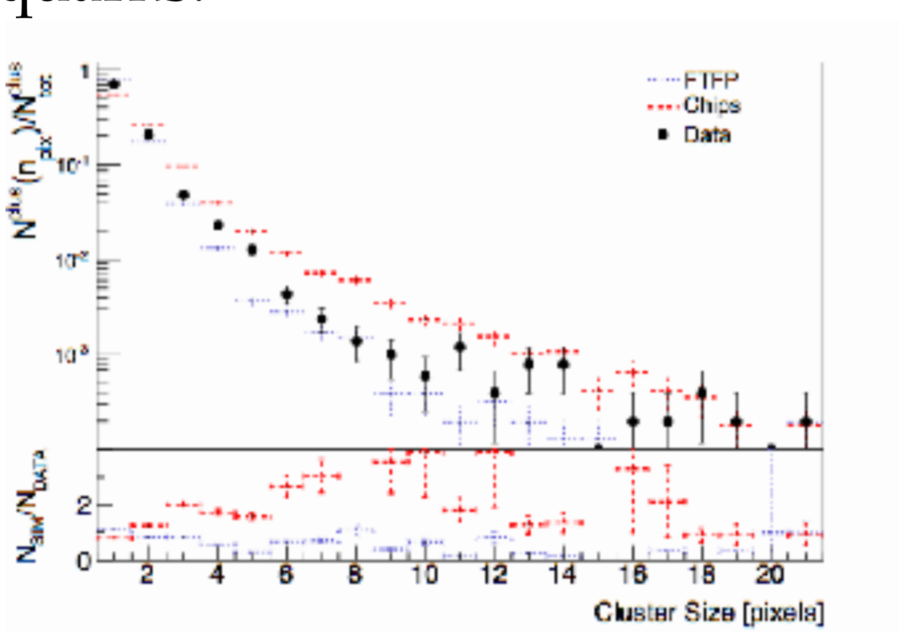
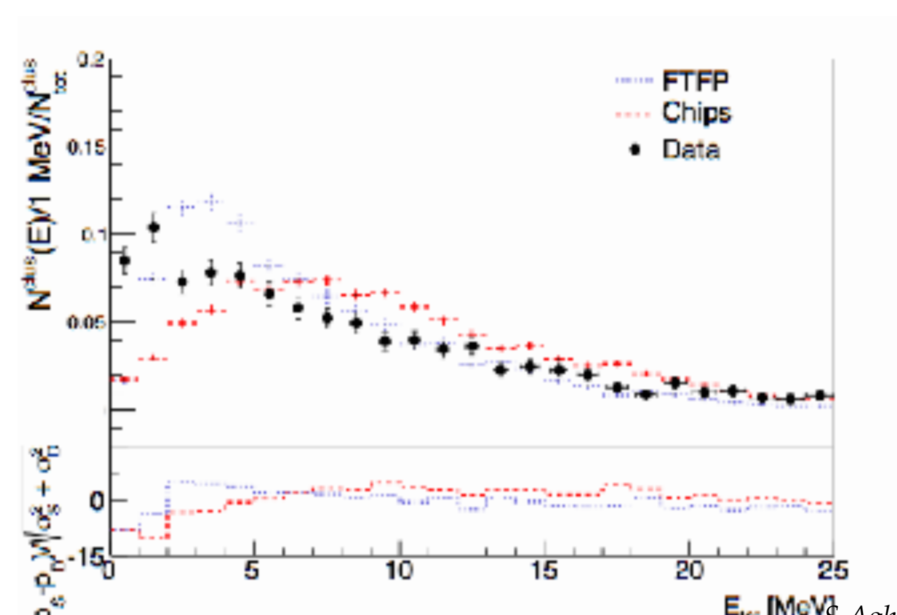
Monolithic active pixel sensor (MAPS) - MIMOTERA

- First comparison of simulations to data for low-energy antiprotons in silicon.
- CHIPS (CHiral Invariant Phase Space) model is a 3D quark-level event generator for the fragmentation of excited hadronic systems into individual hadrons.
- FTFP (FRITIOF Precompound) model relies on a string model to describe the interactions between quarks.

Multiplicity of prongs for $\bar{p}$ annihilation in silicon







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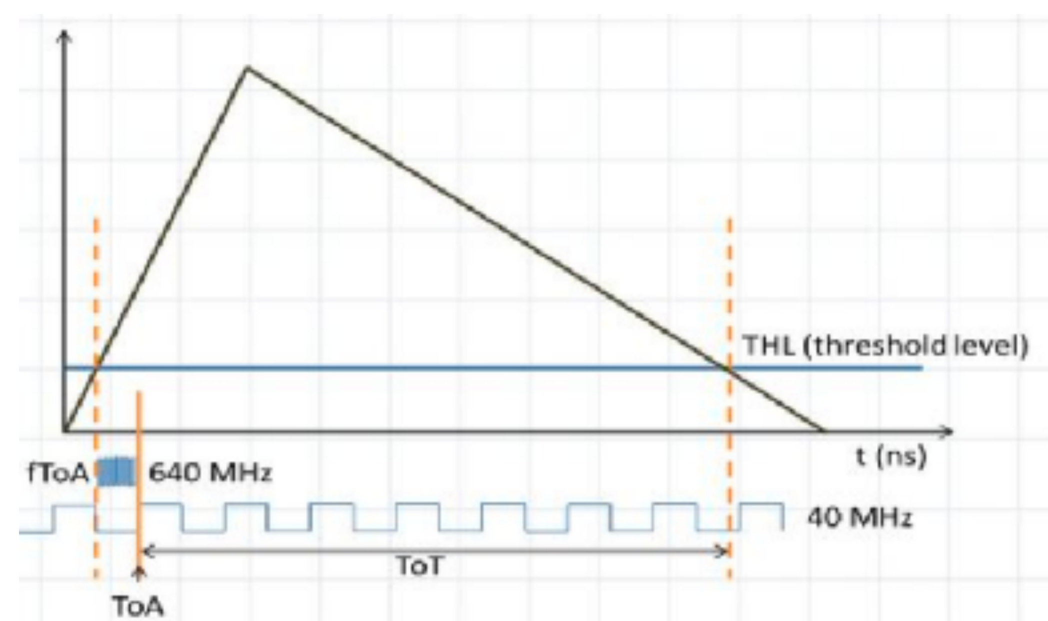
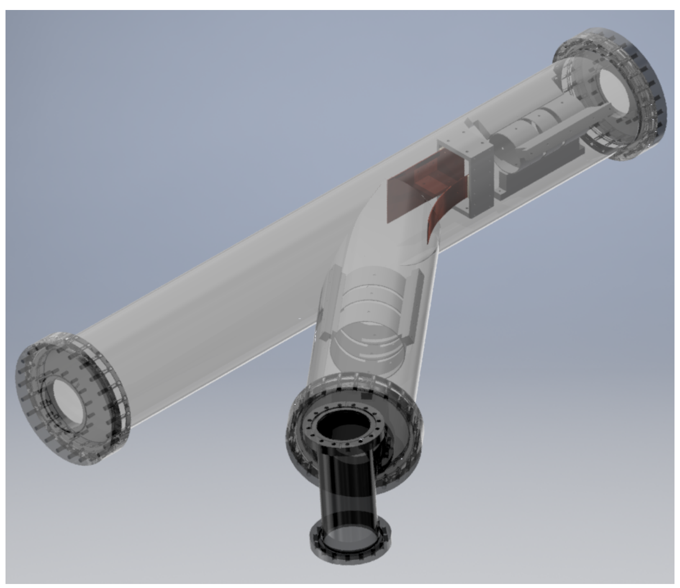
Timepix3 ASIC

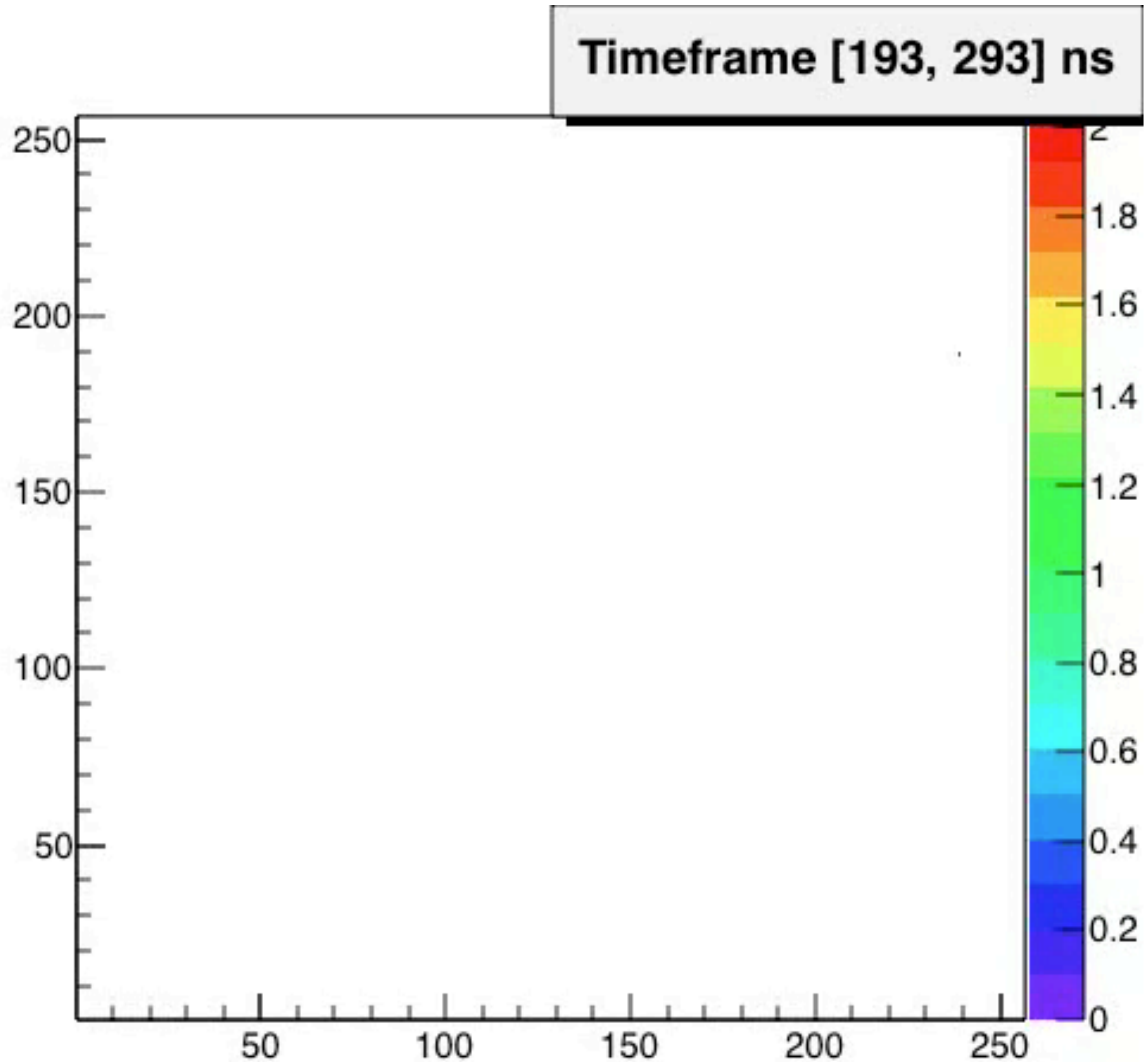
- **Timepix3:**
  - Developed by the Medipix3 collaboration (CERN)
  - 55 µm pixel pitch.
  - 256 x 256 pixels; active area: 17x17 mm^2.
  - **Simultaneous measurement of ToT and ToA**.
  - 40 MHz readout, 640 MHz fast clock for the ToA.
  - Time resolution of 1.6 ns.
  - Dynamic range: up to ~500 keV/pixel.
  - Operation down to ~200 K.
- **Hybrid pixel detector:**
  - Bump bonded to a 675 µm thick Si sensor.
  - Suitable for study of individual antiproton annihilations and vertex reconstruction.



Slow antiproton annihilations recorded with the Timepix3

- **Measurements done in AEgIS test beam-line (0-5 keV antiprotons).**

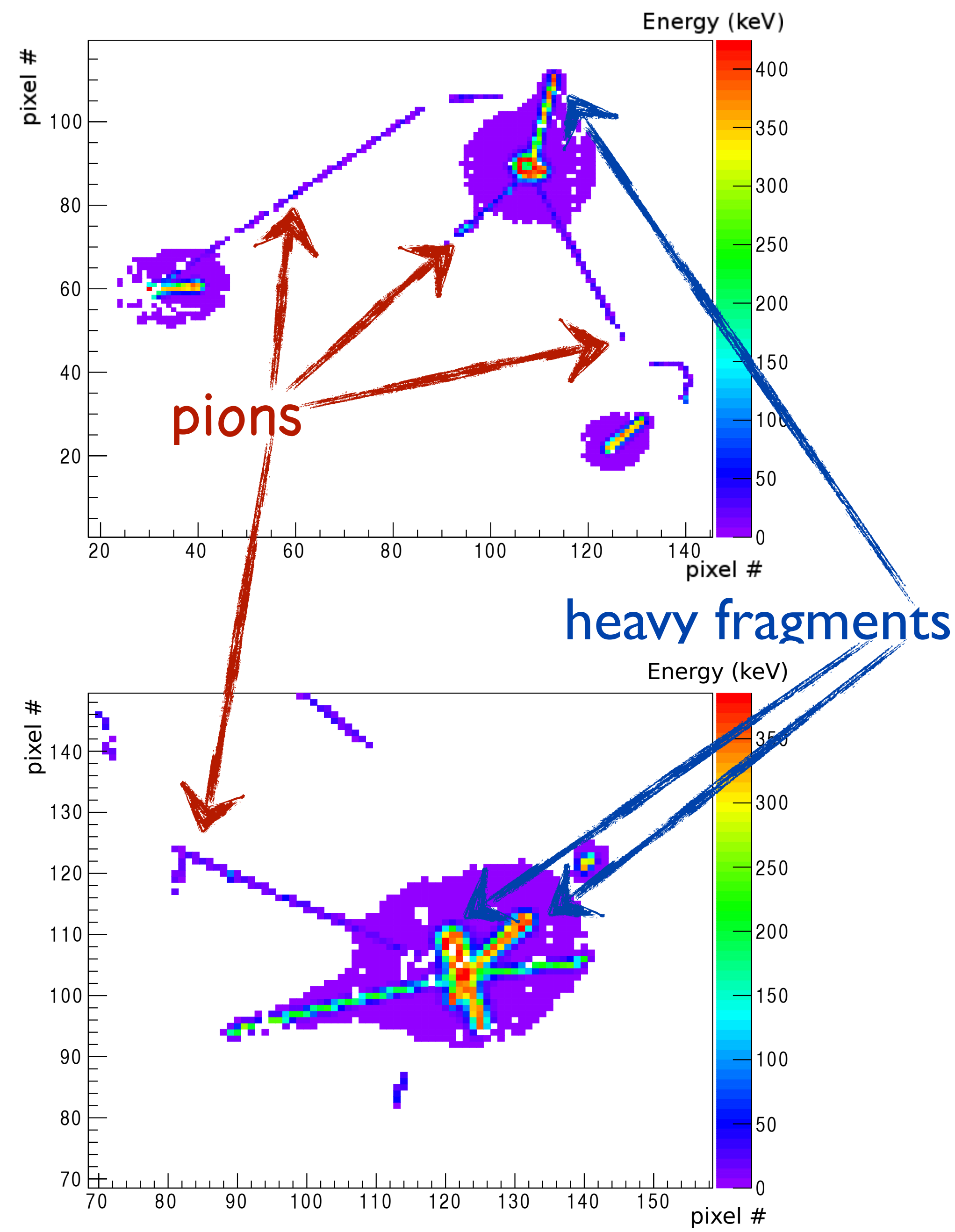




Antiproton annihilation signature and tagging

- **Tagging of antiproton annihilations: identification of tracks from pions and heavy fragments.**
- **Tagging efficiency of 54%.**
- Large energy deposition: up to **50 MeV/cluster:**
- Induced current in neighbouring pixels (**"halo"**).
- **Volcano effect above 500 keV/pixel.**
- **Heavy charged particles** (including alpha particles) exhibit **substantially wider tracks** (plasma effect screens the drift field).
- Dead time (ToT+475) ns, causing dead pixels in the clusters.

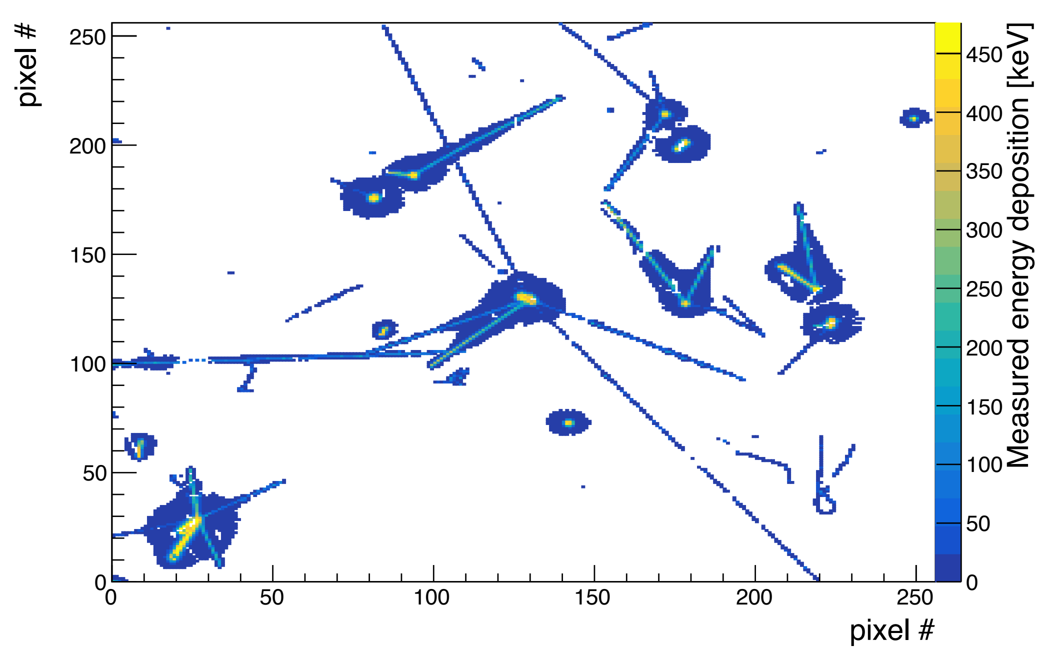
Individual annihilations recorded with Timepix3



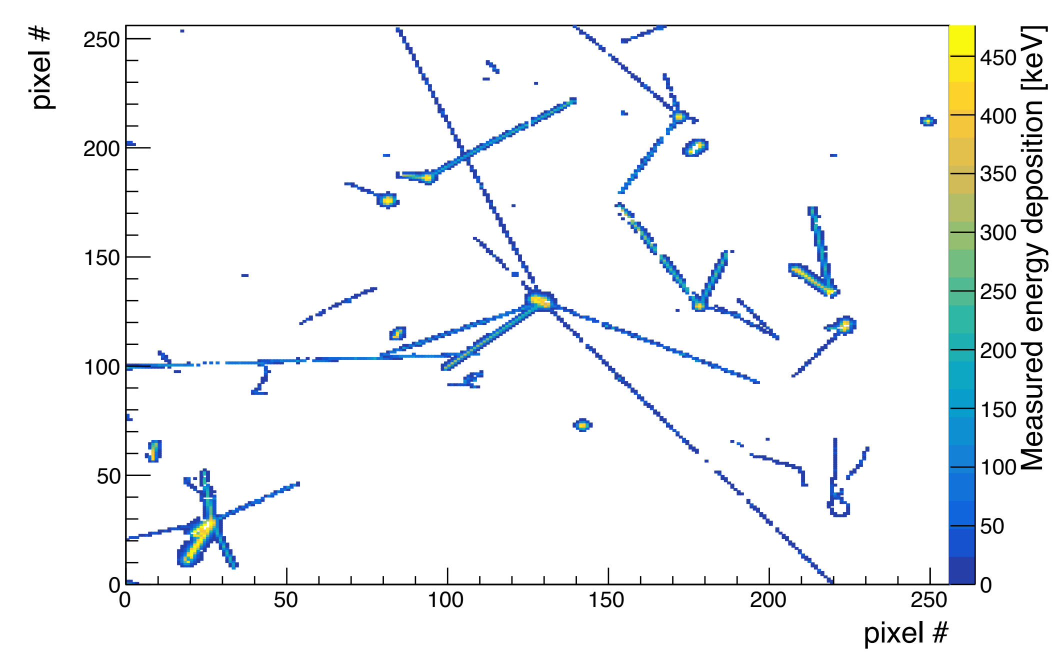
Reconstruction of the annihilation point

- Removing hits caused by induced current ("halo"), 5 keV cut applied.
- Identification of the center of the cluster.
- Hough transformations to identify the straight lines from the tracks of the annihilation prongs.
- Fitting of the lines with orthogonal least square method.
- The annihilation point is identified as the intersection between two of the lines (at least two prongs needed).

Before 5 keV cut



After 5 keV cut



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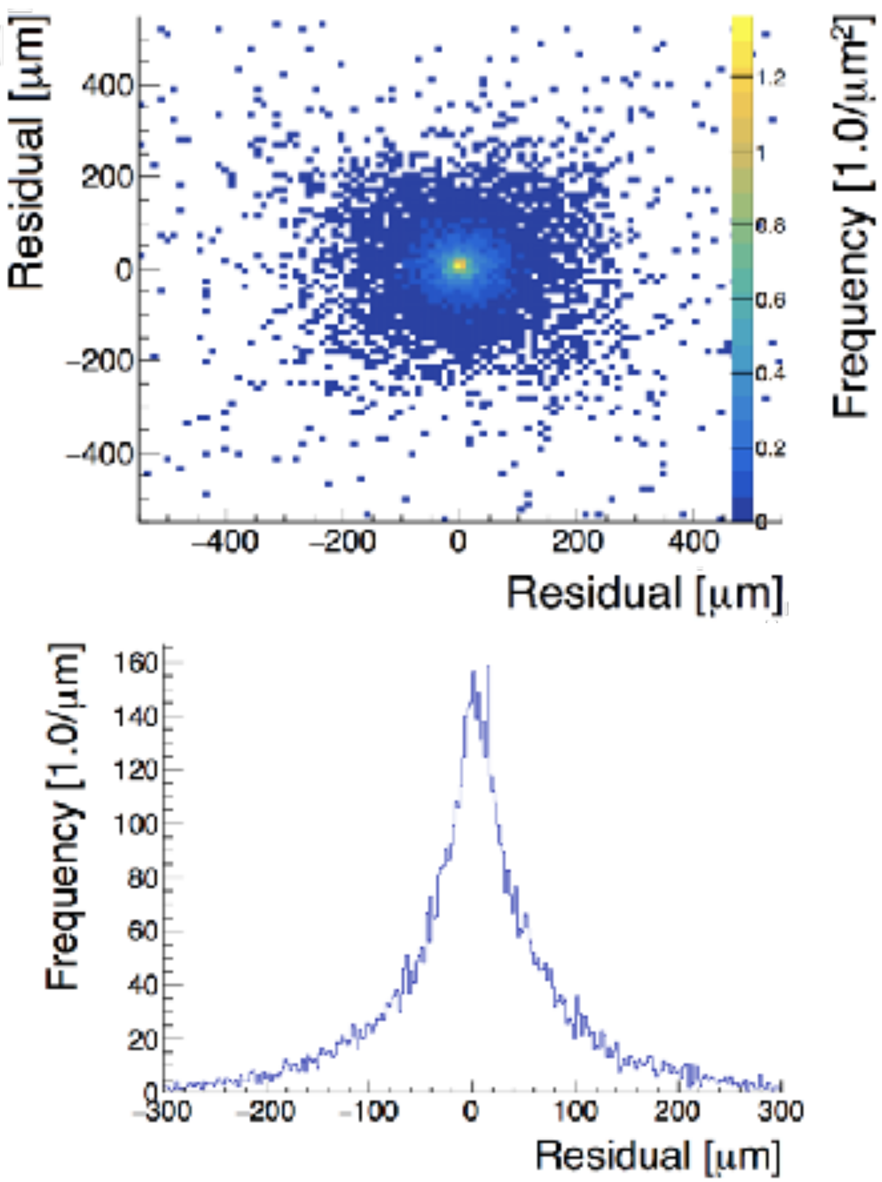
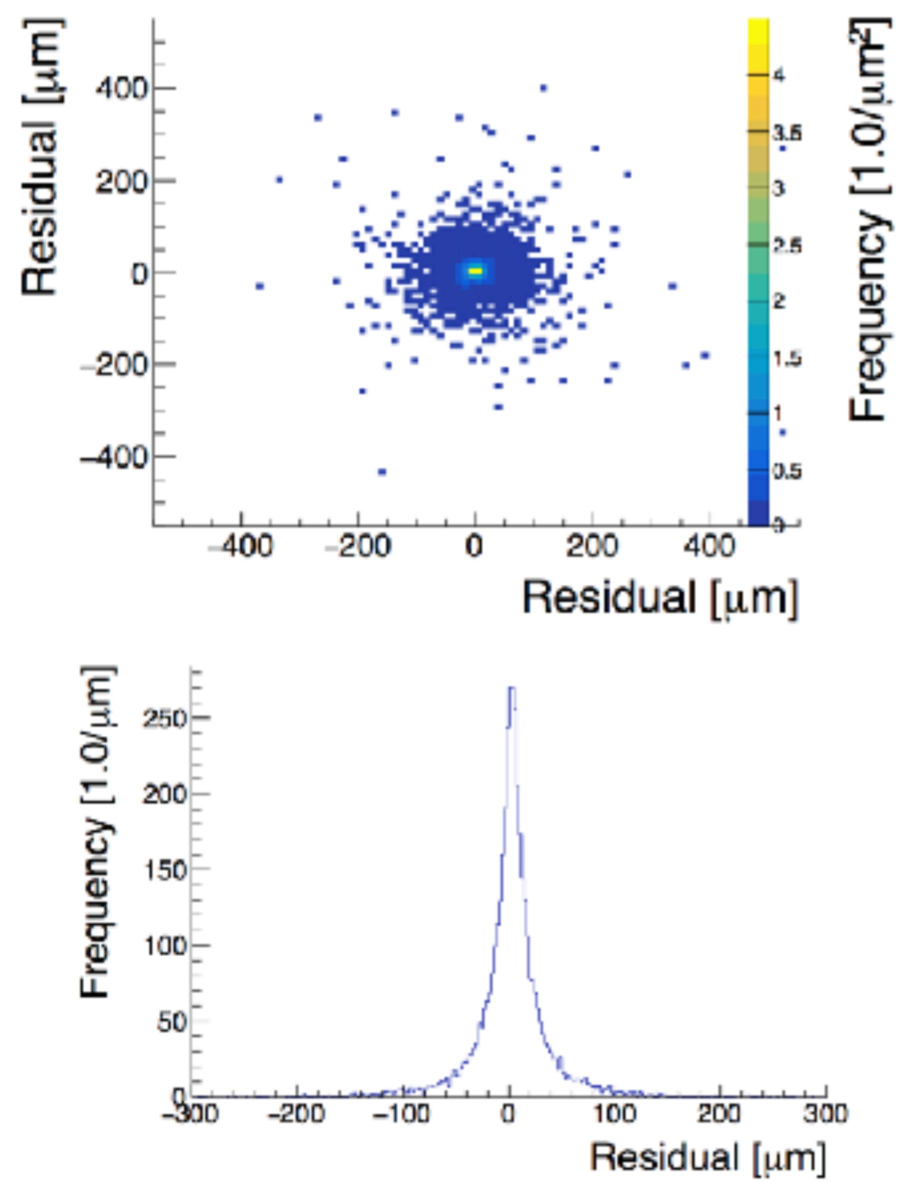
Vertical position resolution with Timepix3

- **Center of mass method, <u>σ=96.6 μm</u>**
- **Vertex fitting method, <u>σ=22.1 μm</u>**





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GEANT4 (FTFP) and FLUKA simulation models

- FLUKA (FLUktuierende KAskade) models the annihilation of an antiproton with a nucleus in two steps:
  1. First as an antiproton-nucleon annihilation that results in pions (branching ratios to different pionic multiplicities are tuned to experimental data).
  2. Interaction between the nucleus and the pions using PEANUT model (INC cascade, evaporation and fragmentation).
- FLUKA shows better agreement with data for antiproton-nuclei annihilation.
- None of the models predicts correctly the pion multiplicity in $p\bar{p}$ annihilation.

Pion multiplicity in $p\bar{p}$ annihilation

Number of pions	Combined percentage abundance from experiments [25]	Geant4	FLUKA
2	0.38±0.03 %	5.5 %	5.1%
3	7.4±0.03 %	12.6 %	8.9%
4	18.1±1.8 %	30.8 %	26.6%
5	35.2±3.7 %	34.1 %	20.0%
6	23.2±2.8 %	14.6 %	21.4%
7	3.3±0.03 %	1.2 %	16.2%
8	0 %	0 %	0.4%
9	0 %	0 %	0.9%

Prongs multiplicity in $\bar{p}$ - nucleus annihilation

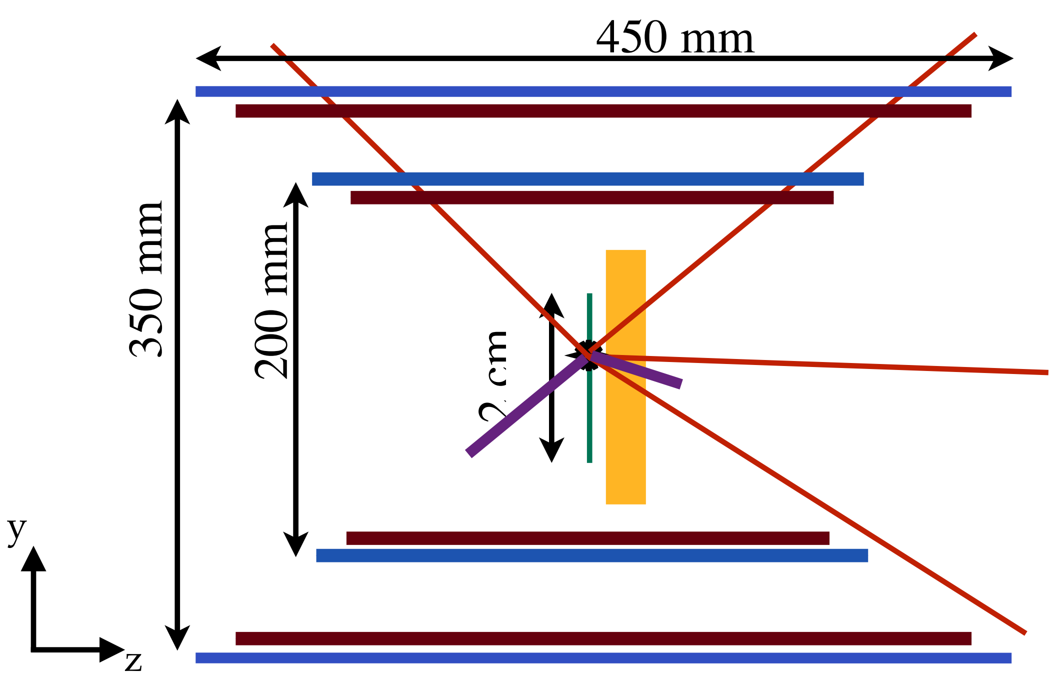
Fragments	p (6-18 MeV)	d (8-24 MeV)	t (11-29)	^{3}He (36-70)	α (36-70)
LEAR ^{12}C	23.3±2	9.3±0.8	2.8±0.1	1.7±0.17	1.14±0.12
Geant4 ^{12}C	3.0	0.0	0.0	0.4	12
FLUKA ^{12}C	18.3	13.1	5.0	2.0	2.5
LEAR ^{40}Ca	74.2±4.1	18.1±1.1	5.7±0.4	2.22±0.17	2.18±0.16
Geant4 ^{40}Ca	6.7	0	0	0.1	4.0
FLUKA ^{40}Ca	30.2	19.1	8.1	0.2	1.6

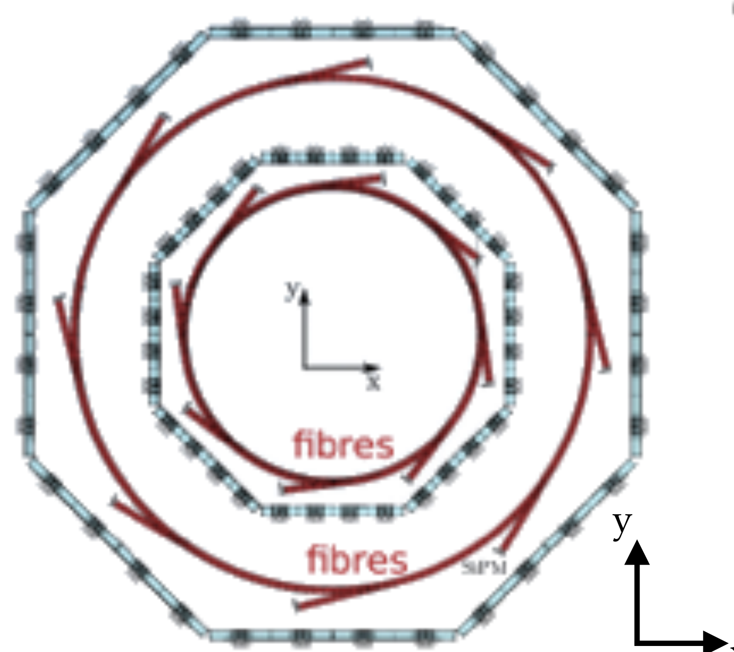
H. Holmestad, Data analysis, simulations, and reconstruction of antiproton annihilations in a silicon pixel detector, PhD thesis ISSN 1501-7710

Measurement of antiproton annihilation in different nuclei

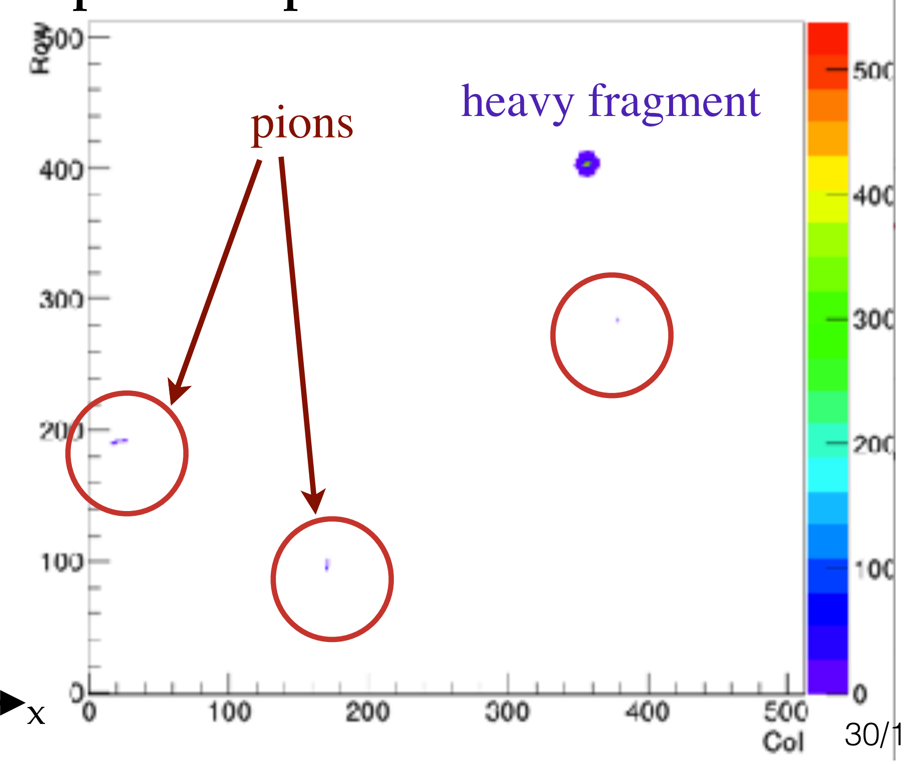
- Annihilation/fragmentation models validation:
  - CHIPS, FTFP and FLUKA
- Antiproton annihilation in different materials: a systematic study of the prongs average multiplicity and the energy distribution
- Analysis in progress

- Set-up in ASACUSA:
  - **Carbon foil** in front of **Timepix3 quad**.
  - Combined data from two detectors: **Timepix3+Hodoscope**
  - Slow extraction of **150 eV antiprotons**:
  - Background-free measurement





Hitmap of Timepix3 for 1 annihilation event



Conclusions

- **Silicon detectors**
  - **Operation principle - pn diode**
- **Choice of detector depends on:**
  - **Operating conditions**
  - **What kind of information do we need**
    - **Beam profile (MAPS, Segmented diodes)**
    - **Antihydrogen/antiprotons**
      - **Tagging efficiency [~80% strip, 50±10 % Timepix3 (much greater?)]**
      - **Energy deposit (MAPS for high energy deposits from fragments)**
      - **Position resolution [2D (22.1 μm with Timepix3) or 3D (~mm)]**
        - **Solid angle (microstrip modules)**
  - **Energy of the antiprotons.**
- **… no detector is perfect!**

ÖAW AUSTRIAN ACADEMY OF SCIENCES

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