ÖAW AUSTRIAN ACADEMY OF SCIENCES

SMI - STEFAN MEYER INSTITUTE

Annihilation studies with slow extracted antiprotons

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FAKT Workshop

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CERN

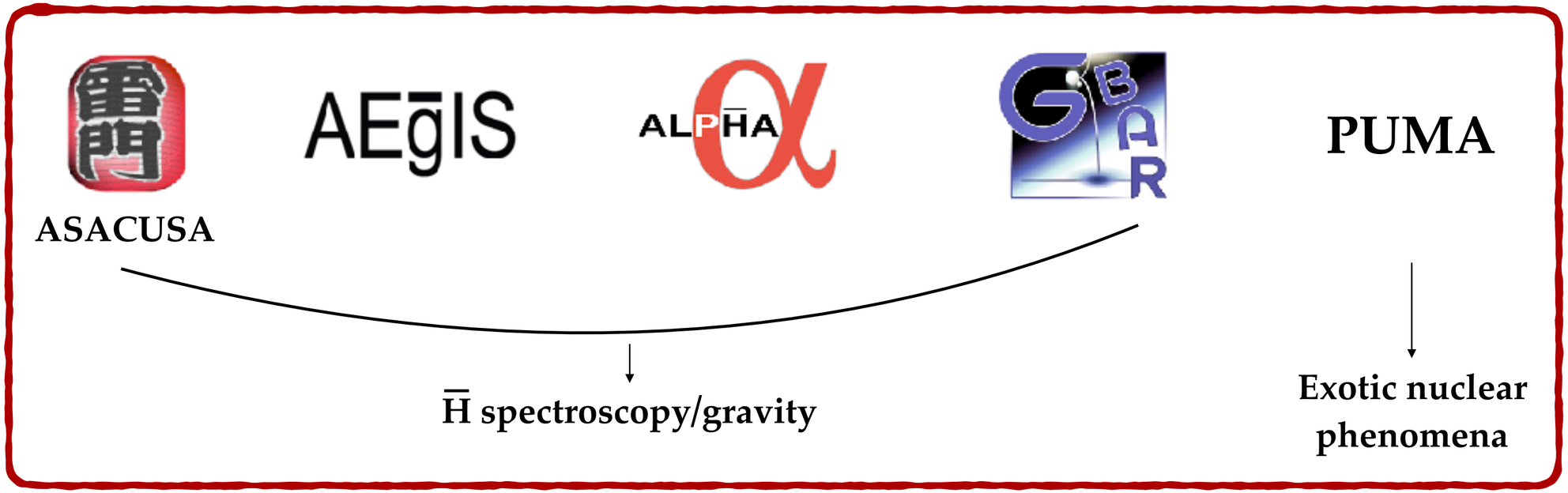
FWF Der Wissenschaftsfonds.

Overview

- **Motivation**
- **Antiproton-nucles annihilation**
  - **Fragmentation models (Geant4) validation**
  - **Measurements in ASACUSA**
- **Study of annihilations with slow extracted antiprotons**
  - **Objectives**
  - **Methods**
- **Conclusions**

Antimatter experiments at CERN

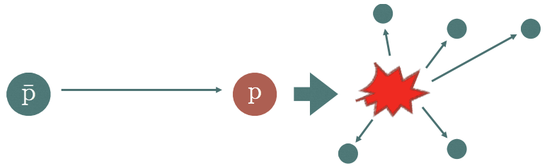
- **Experiments at the Antiproton Decelerator (AD) at CERN**



H̄/p̄ detection through annihilation

Antiproton annihilation

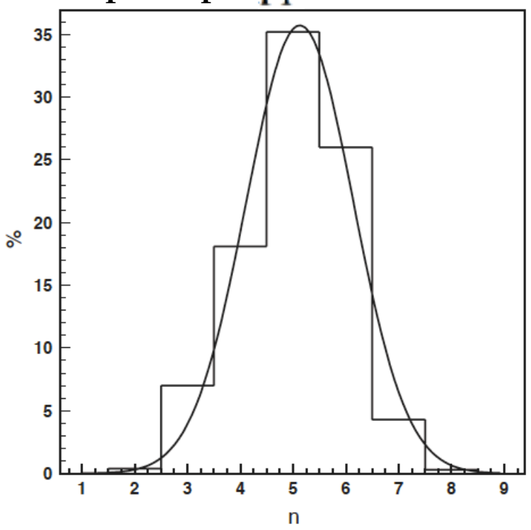
- **Antiproton-nucleon annihilation**



π, K (charged and neutral)

 # 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

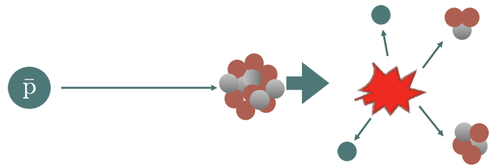


~1880 MeV energy ⇒
5 x 140 MeV/c² (rest mass)+
~230 MeV/pion

	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%

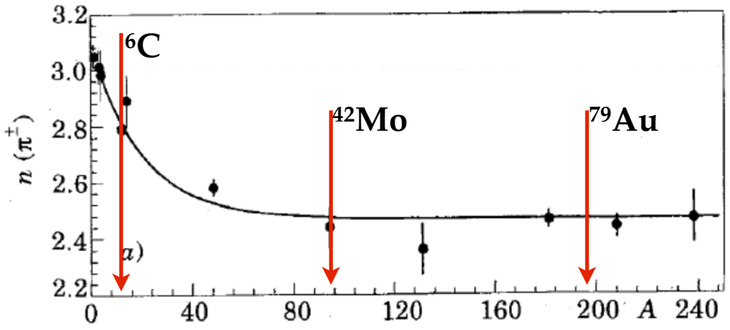
Eberhard Klempt, Chris Batty, and Jean-Marc Richard. The antinucleon-nucleon interaction at low energy; annihilation dynamics. Physics Reports, 413(4–5):197–317, 2005.

- **Antiproton-nucleus annihilation**



π, p, t, n, α, ^{3}He, ^{4}He, ^{6}He, ^{8}He...

- **Primarily produced pions can interact with the rest of the nucleus - Final States Interactions (FSI).**



G. Bendiscioli, D. Kharzeev Rivista del Nuovo Cimento vol. 17 N. 6

- **Intranuclear cascade ⇒ nucleus heated up to several 100s MeV.**
- **Residual nucleus decay mechanism:**
  - **≤2MeV/nucleon ⇒ successive evaporation/fission;**
  - **≥5 MeV/nucleon ⇒ phase transition into liquid-gas type ⇒ explosive decay (multifragmentation).**

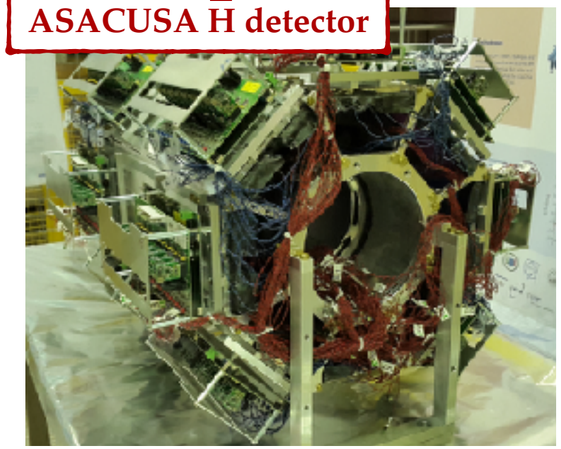
Motivation

- **Efficient detection, correct tagging and reconstruction of annihilation events**

  - **Detectors based on scintillating materials (scintillating fibres and bars)**

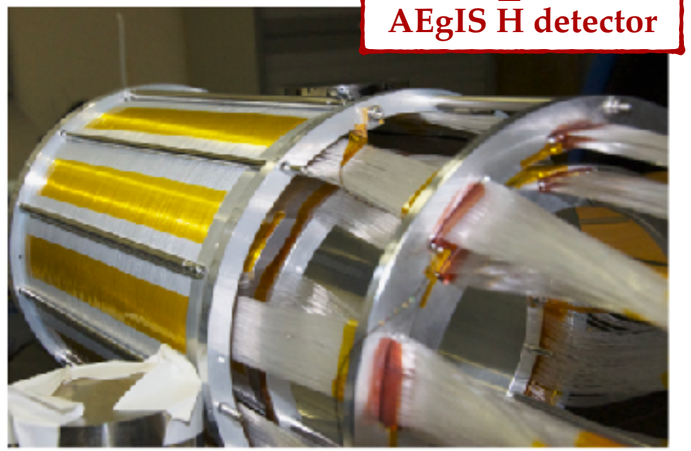
  - **Silicon-based and TPC detectors (Si strip/pixel, MWPC).**

ASACUSA $\bar{H}$ detector



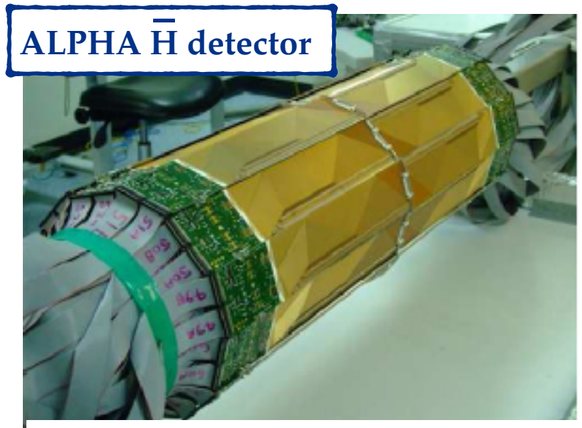
Nucl. Instrum. Methods Phys. Res., A 845 (2017) 579-582

AEgIS $\bar{H}$ detector



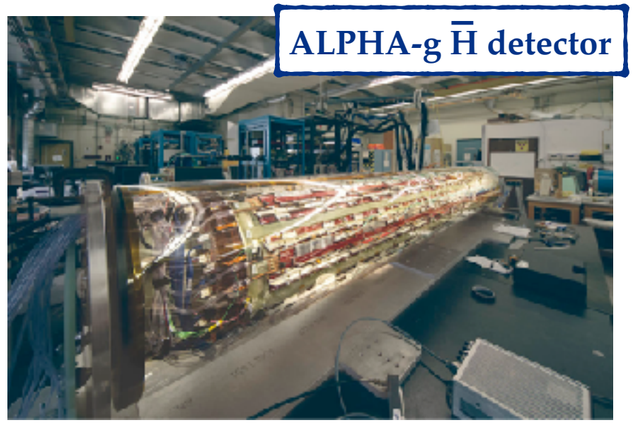
Nucl. Instrum. Methods Phys. Res., A 732 (2013) 437-441

ALPHA $\bar{H}$ detector



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

ALPHA-g $\bar{H}$ detector



JPS Conf. Proc. 18, 011015 (2017)

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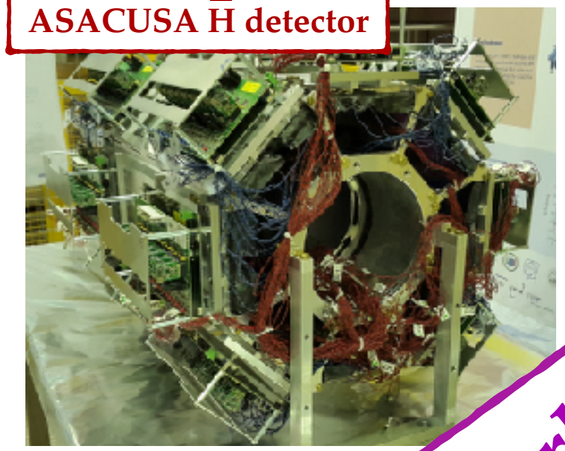


Nucl. Instrum. Methods Phys. Res., A 845 (2

AEgIS $\bar{H}$ detector

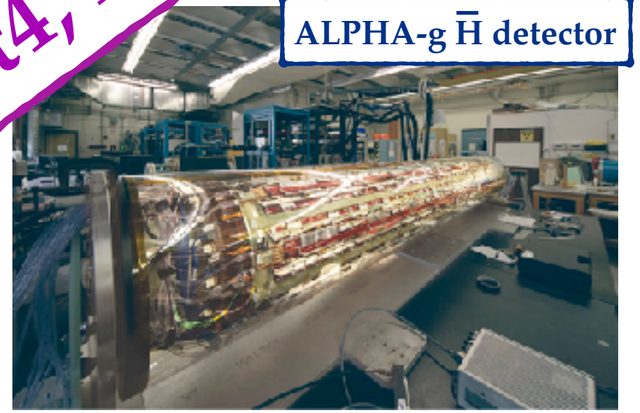
m. Methods Phys. Res., A 732 (2013) 437-441

Monte Carlo simulations (Geant4, FLUKA)

ALPHA $\bar{H}$ detect

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

ALPHA-g $\bar{H}$ detector



JPS Conf. Proc. 18, 011015 (2017)

Motivation

- **Models developed for HEP, extrapolated to low energies:**
  - CHIPS (CHiral Invariant Phase Space)
  - FTFP (FriTjoF Precompound)
  - FLUKA (FLUktuierende KAskade)

  } Geant4

- **The only available data is from LEAR (Low Energy Antiproton Ring) at CERN ('80s and early 90s):**
  - **~20 MeV antiprotons stopped in thick targets.**
- **Absence of model that describes well the annihilation at low energies/at rest, even for the existing data.**

- **Antiproton-nucleus annihilation is not well understood.**
  - **Complexity due to FSI**
- **The total multiplicity of prongs and their spectra is still unknown.**

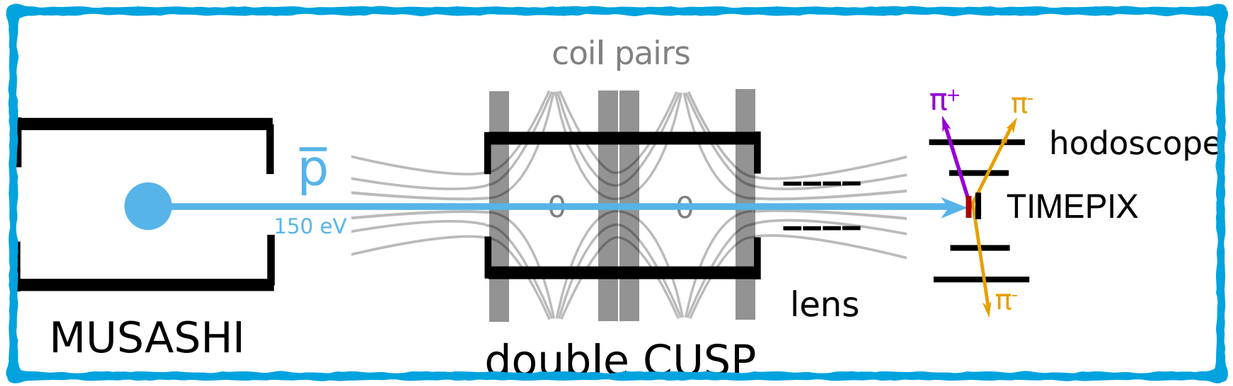
	Fragments	p (6-18 MeV)	d (8-24 MeV)	t (11-29 MeV)	^{3}He (36-70 MeV)	α (36-70 MeV)
^{12}C	LEAR data	23.3 ± 2	9.3 ± 0.8	4.5 ± 0.4	1.72 ± 0.17	1.14 ± 0.12
	Geant4 (FTFP)	3.0	0.0	0.0	0.4	12.0
	FLUKA	18.3	13.1	5.0	2.0	2.5
^{40}Ca	LEAR data	74.2 ± 4.1	18.1 ± 1.1	5.7 ± 0.4	2.22 ± 0.17	2.18 ± 0.16
	Geant4 (FTFP)	6.7	0.0	0.0	0.1	4.0
	FLUKA	30.2	19.1	8.1	0.2	1.6

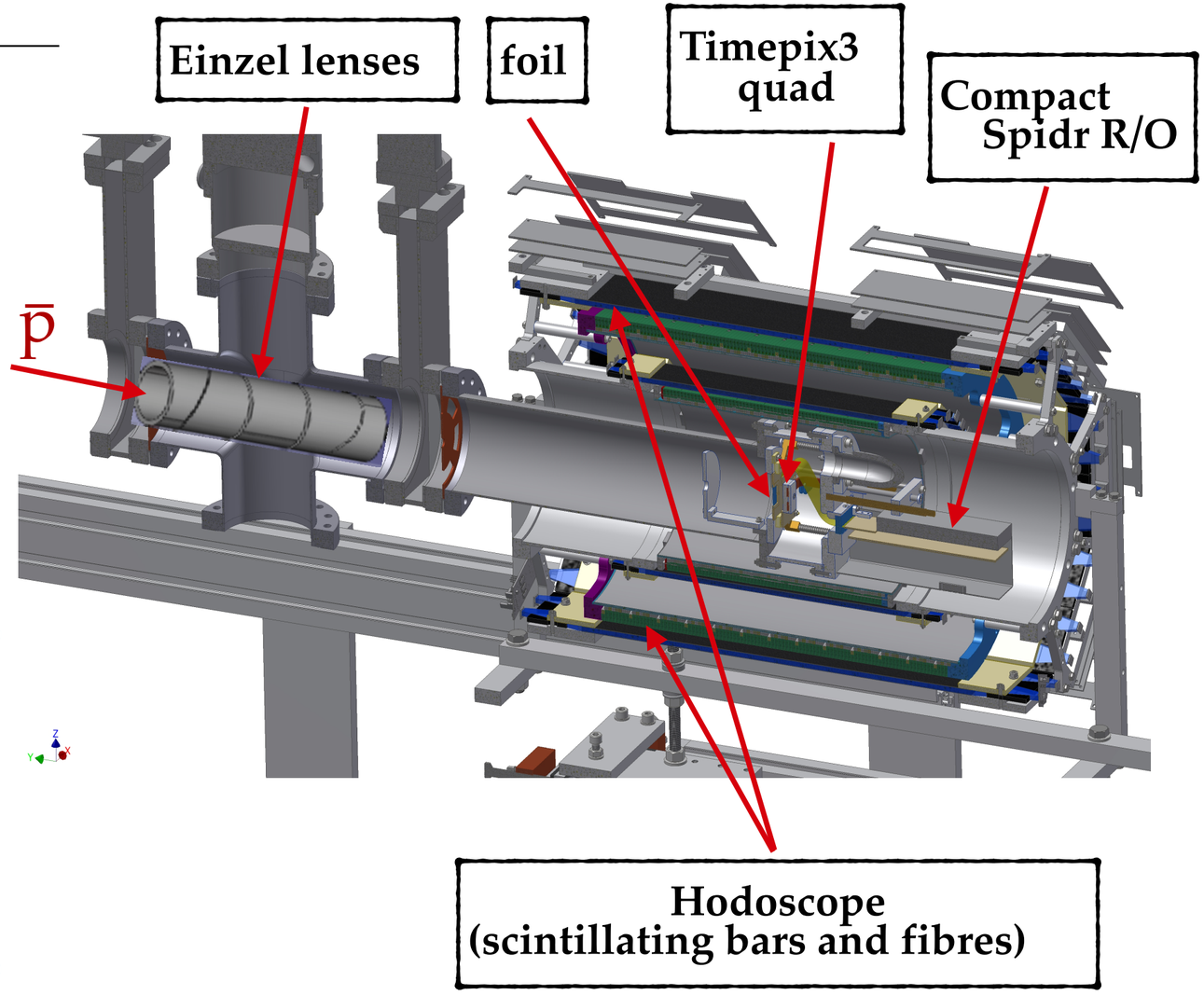
Total yields for p, d, t, ^{3}He and alpha per 100 pbar annihilations

Nuclear Physics A **485** 445 – 460 (1988)

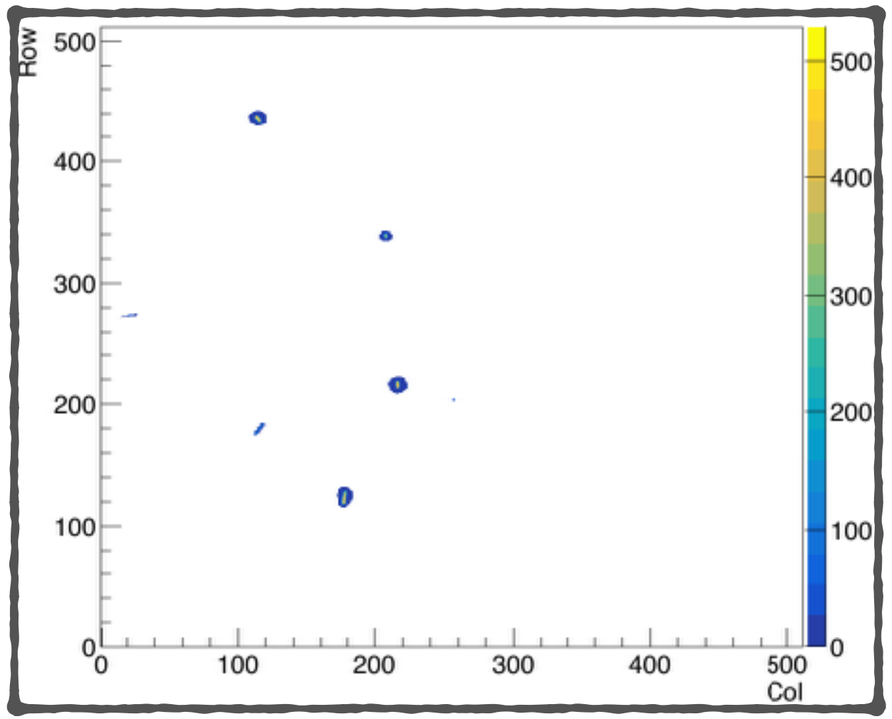
Measurements in ASACUSA

- Slow extracted antiprotons, 150 eV.
- Annihilation in C, Mo and Au.
- Two detectors:
  - Timepix3 (~23% solid angle, pixel):
  - Hodoscope (>80% solid angle, scintillating bars and fibres)

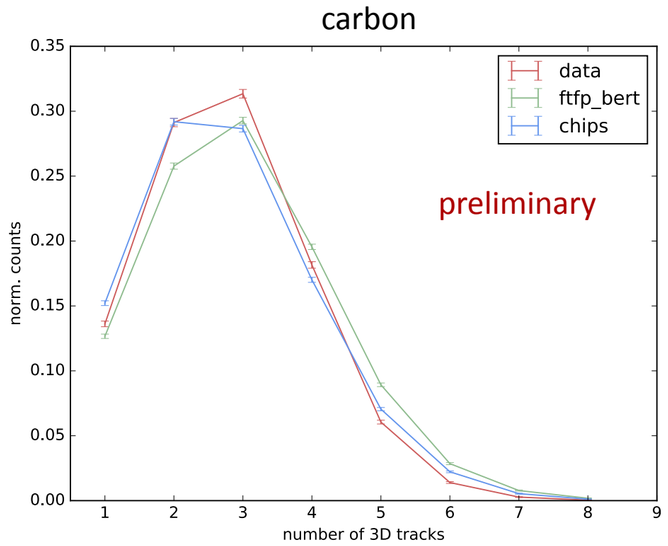


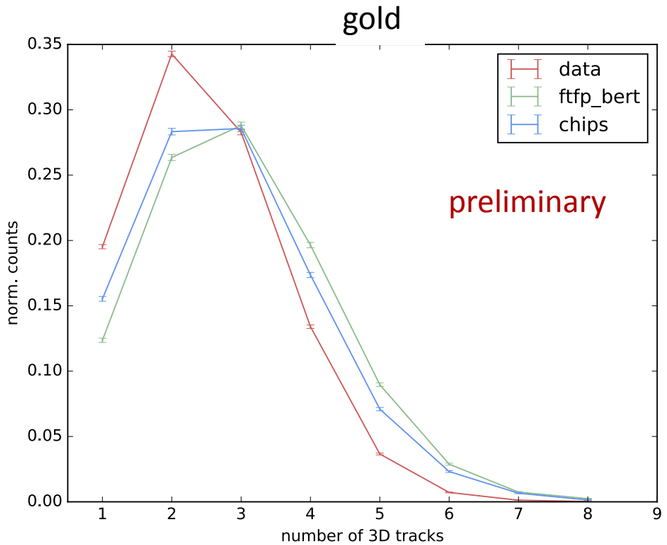


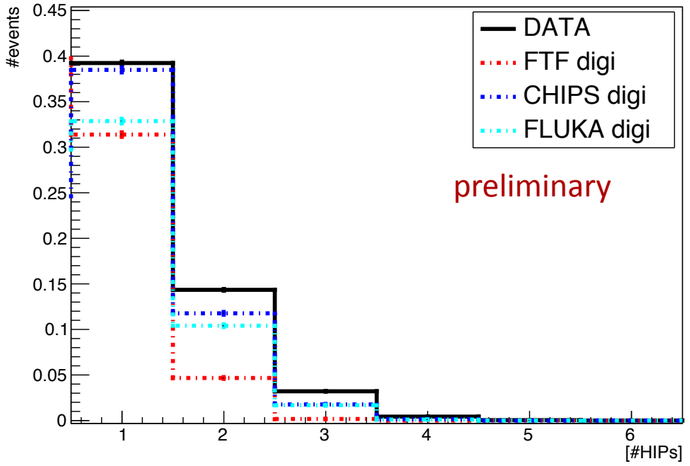
Multiplicity: pions and heavy fragments

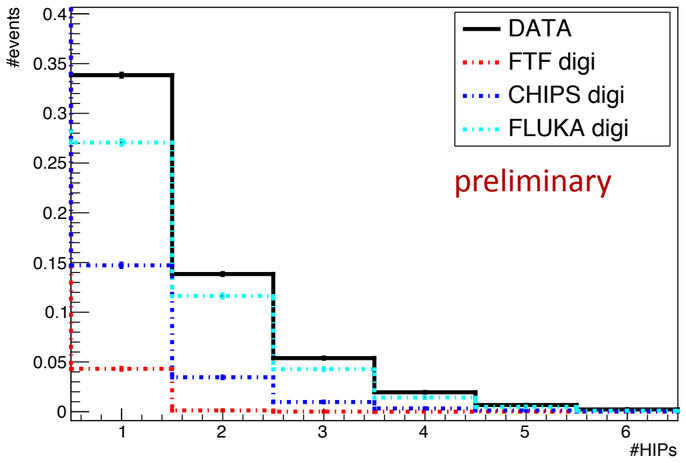


Sample hitmap for one event recorded with Timepix3









FWF Stand Alone Project

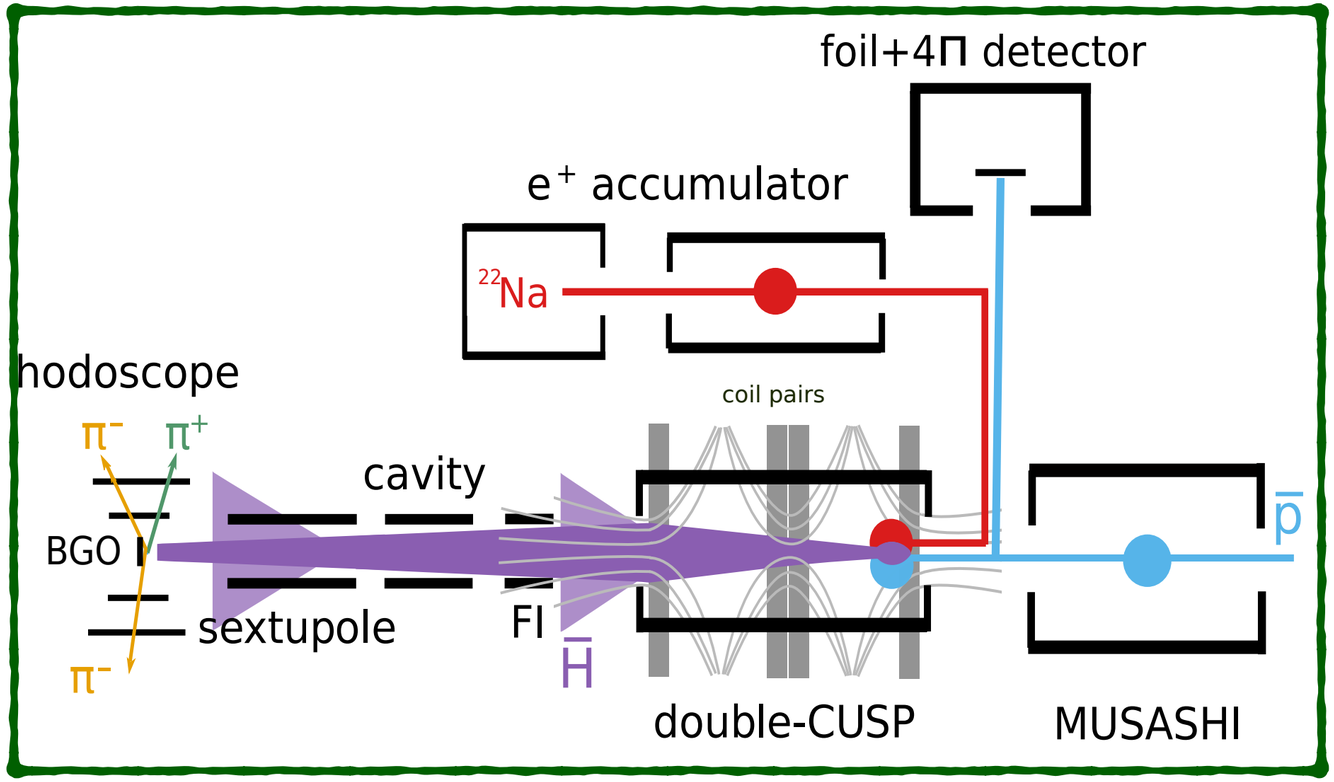
Study of annihilations with slow extracted antiprotons

Objectives

- **Measure prongs in ~4π solid angle for individual annihilation events:**
  - **Multiplicity**
  - **Angular distribution**
  - **Energy**
- **Probabilities for final states:**
  - **#pions and heavy charged prongs, set the basis for precise branching ratios of different annihilation channels.**
- **Identification of the effects of FSI:**
  - **Annihilation on nuclei with fewer nucleons (Be or C).**
- **FSI mass and nuclear-size dependence: with Ca and Sn isotopes.**
- **Validate new calculations for INCL (Intranuclear Cascade de Liège) code to simulate pbar-nucleus annihilation at rest (J-C. David, CEA, Paris)**

Methods

- **Slow extraction of 250 eV pbras:**
  - **Parasitic use of the e^+ beam line at the current ASACUSA apparatus.**
- **Thin targets (1-2 μm).**
- **Novel detection system, ~4π sr:**
  - **Timepix3/Timepix4 ASICs.**
  - **Single plane pixel detectors.**



A scheme showing the particle trajectories of the two experiments operating at ASACUSA-CUSP.

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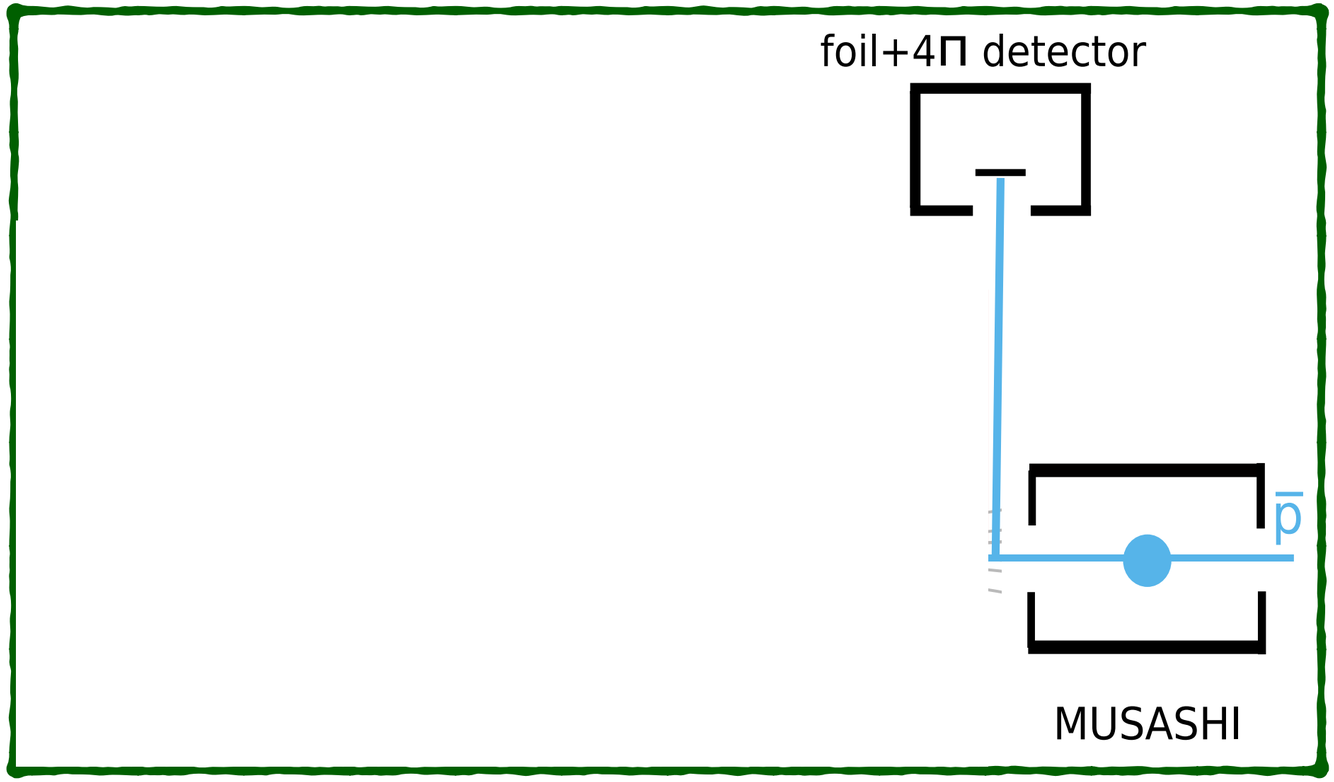

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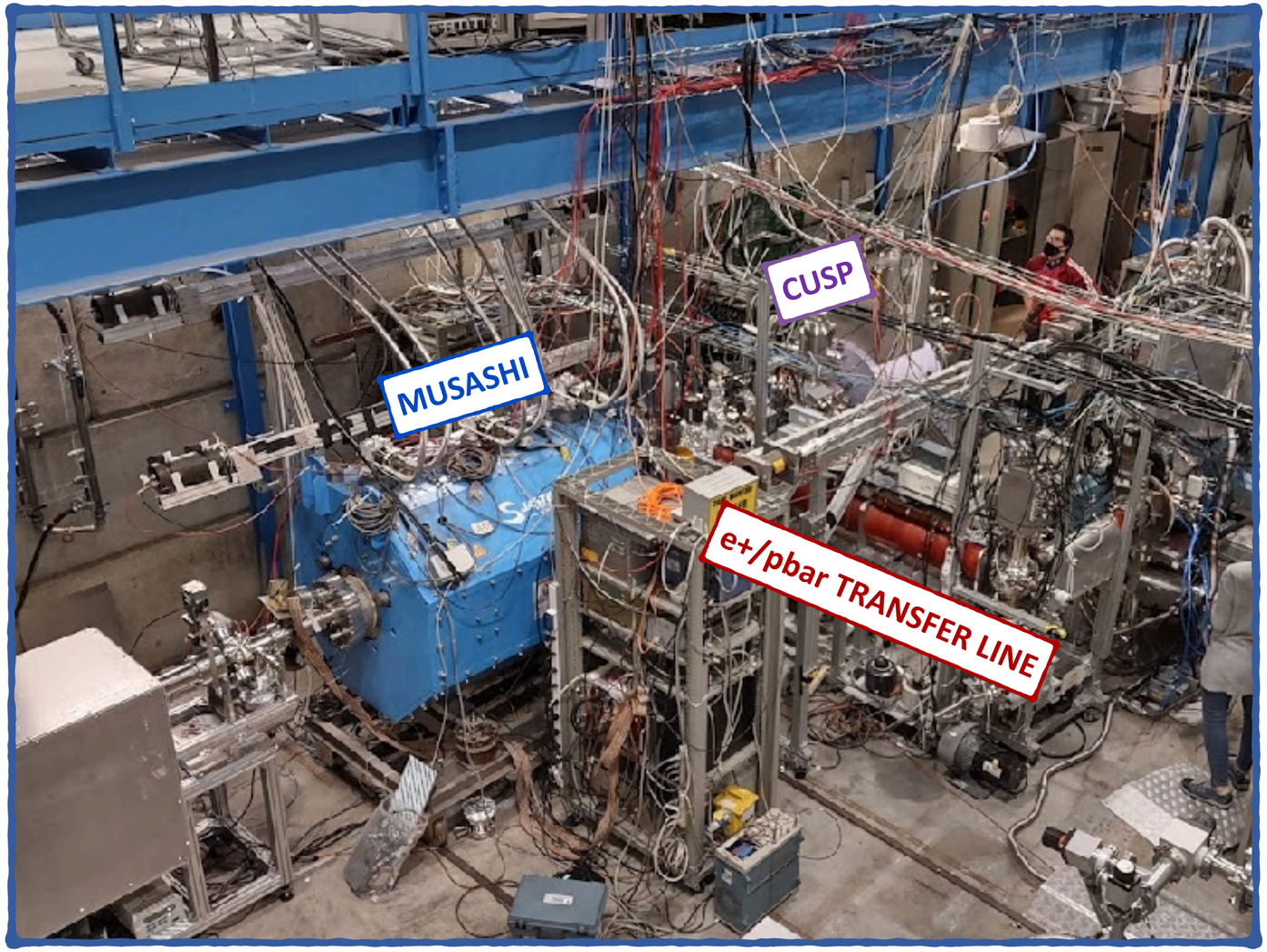
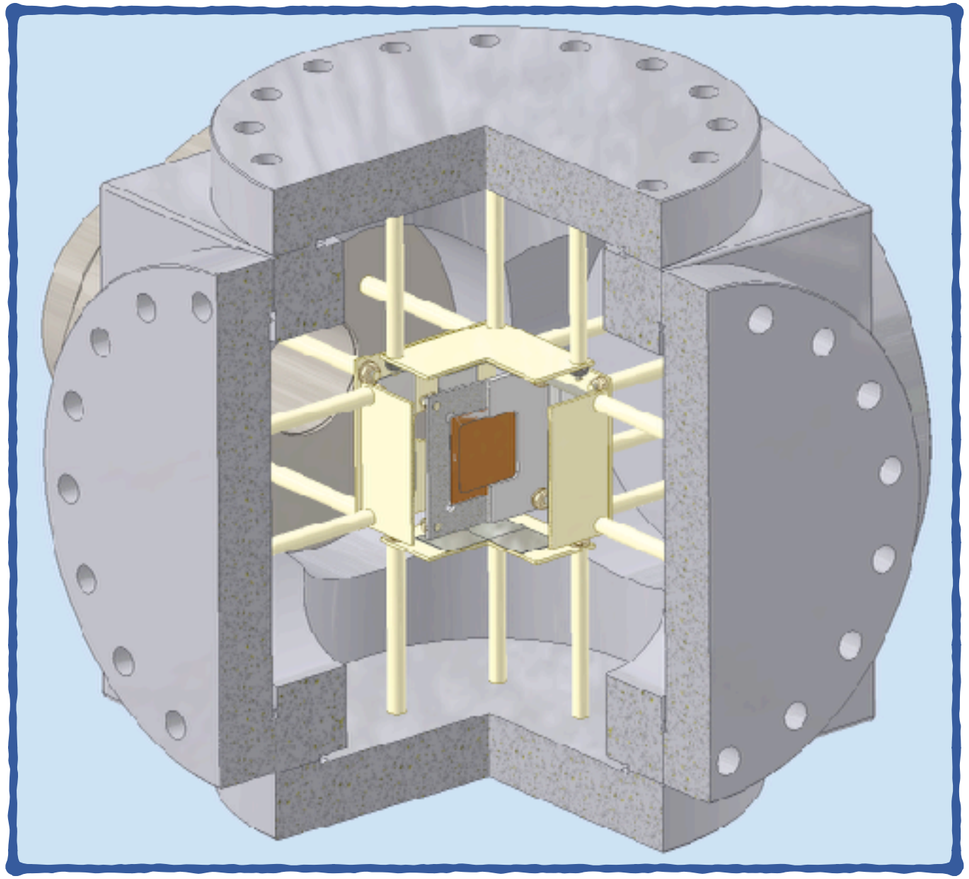


Detector and data taking

- **Cube-like configuration of Timepix3/Timepix4 ASICs bump bonded to 500/675 μm Si sensors.**
  - **Identification of pions and different heavy fragments.**
    - **Deposited energy and the angular distribution.**
    - **Direction and the specific ionization (dE/dx) -> 3D vertex.**
- **Measurements with Timepix4 @VERA in Vienna (7-9 March).**
- **Data taking:**
  - **15 target foils + 4 isotopes (^{40}Ca, ^{48}Ca, ^{112}Sn, ^{124}Sn).**
  - **Measurements scattered over 2023 and 2024.**

Be (4)	C (6)	Al (13)	Ti (22)	Co (27)	Zn (30)	Zr (40)	Mo (42)	Ag (47)
Sb (51)	Gd (64)	Dy (66)	W (74)	Pt (78)	Au (79)	Pb (82)	Bi (83)	U (92)
^{40}Ca (20)	^{48}Ca (20)	^{112}Sn (50)	^{124}Sn (50)					



3D drawing of the 4Pi detector and the target foil inside the chamber.

Conclusions

- **Antiproton-nucleus annihilation is still not well understood.**
  - **Scarce measurements, mostly from the LEAR era.**
  - **Lack of model that describes even the existing data.**
- **Measurements in ASACUSA with three nuclei: C, Mo and Au.**
  - **GEANT4 models are off w.r.t. data by ~ 15% for MIP multiplicity, and 8x for HIPs.**
- **Large scale study on ~15 nuclei is in preparation:**
  - **~4Pi detection of the outcoming prongs.**
  - **Explore the FSI: identification of the effects, nuclear size and mass dependence…**
  - **Validation of new calculations to establish a reliable model for the low energy antimatter experiments.**

Thank you for your attention

https://gatzefieling.de/otto-proton-otto-antiproton/

Feasibility study for measuring $\bar{p}^3He \rightarrow np$

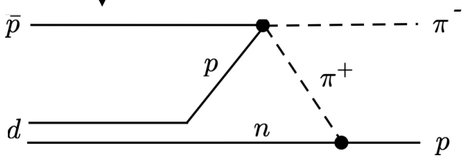
Pontecorvo annihilations

Unusual, involve > 1 nucleon

$\bar{p}d \rightarrow \pi^- p, \pi^0 n, \eta n, \Lambda K^0, \Sigma^0 K^0$ $\bar{p}$2N annihilation have been measured at LEAR

rates 10^{-6} to 10^{-5}

e.g.



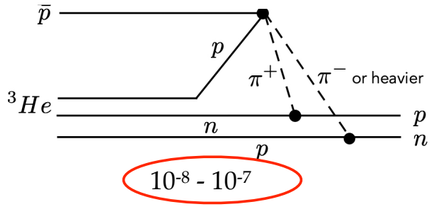
Rescattering

or

annihilation on one nucleon (quark "fireball") followed by quark rearrangement with second nucleon (Cugnon & Vandermeulen, 1989)

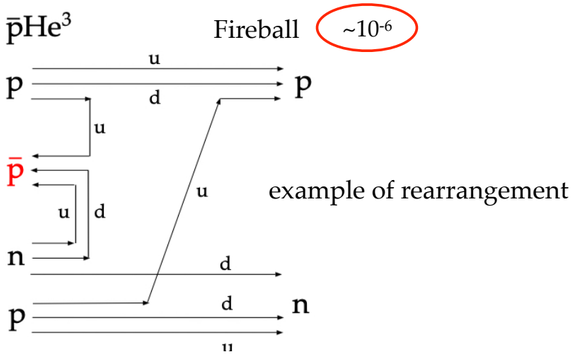
→ Good agreement with $\bar{p}$2N data

Check with $\bar{p}$3N annihilation: $\bar{p}^3He \rightarrow np$



10^{-8} - 10^{-7}

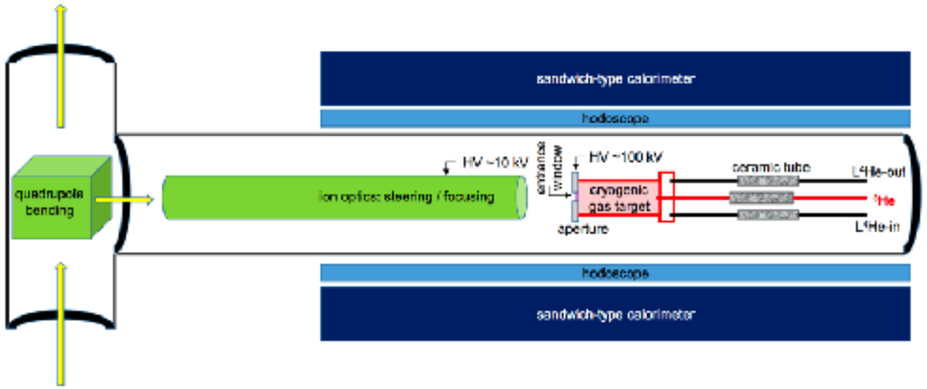
or



example of rearrangement

see arXiv:1908.08455

- **Feasibility study (simulations):**
  - **Acceleration to 100 keV.**
  - **LHe target + 2 μm window.**
  - **Geometry configuration of the set-up.**
  - **Detection efficiencies.**
  - **Rates predicted by different models.**



- **Outcome:**
  - **Required beam time and statistics.**
  - **Resources.**