ETH zürich

Institute for Particle Physics
and Astrophysics

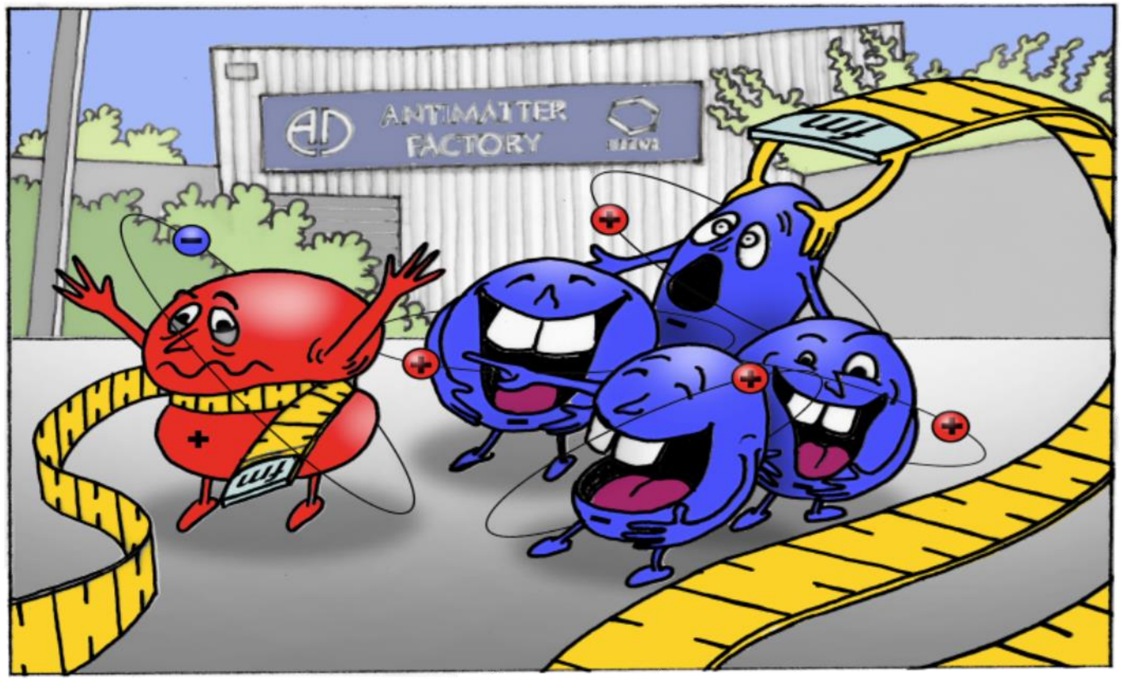
Gravitational Behaviour of Antihydrogen at Rest: First results on antihydrogen production

Philipp Blumer on behalf of the GBAR collaboration
Group of Prof. Dr. Paolo Crivelli, ETHZ

06. September 2023

Antihydrogen – a blossoming field of research

- SM doesn't explain baryon asymmetry in the Universe
- New models: e.g. Standard Model Extension (SME)
  - Built from SM, General Relativity and includes Lorentz- and CPT violating operators
  - Coefficients to be determined experimentally
  - Probe CPT by measuring the Lamb Shift of antihydrogen ($\overline{\mathrm{H}}$)
- Direct test of Weak Equivalence Principle with antimatter → Free fall experiment
  - Best and only result from free fall: $-65g < \bar{g} < 110g$ from ALPHA [*]
  - BASE collaboration extracted $\bar{g}$ from gravitational redshift to $\frac{\Delta\bar{g}}{\bar{g}} = 3\%$ [**]

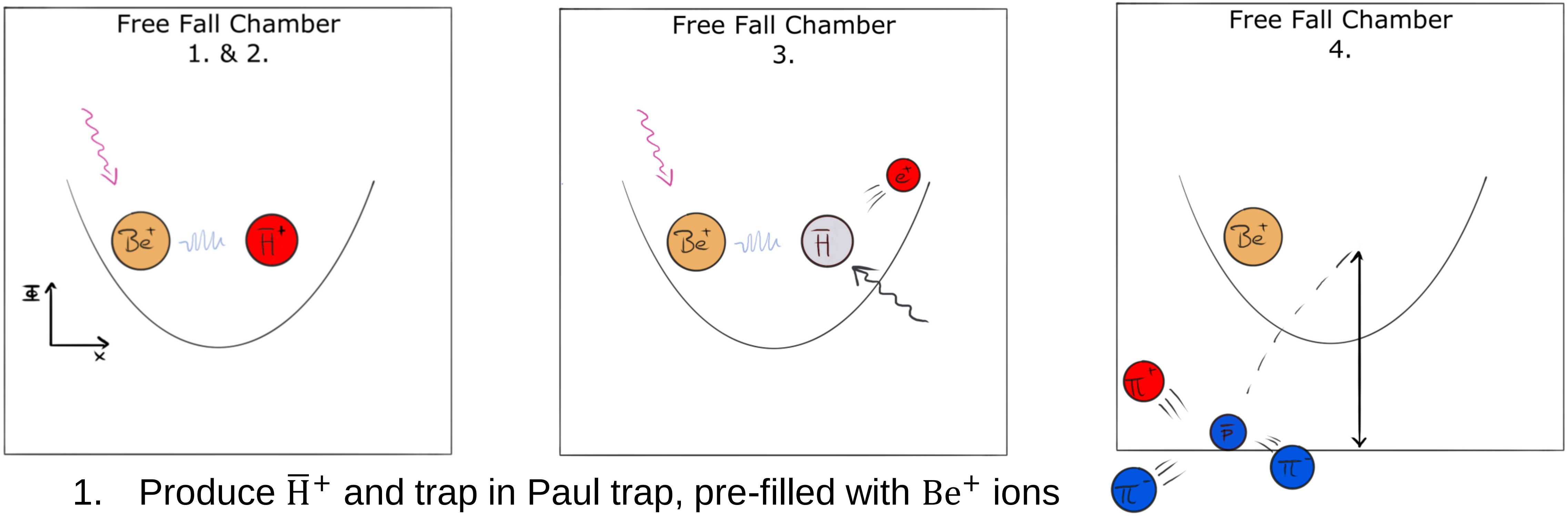


ALPHA, Nature 592, 35-42 (2021)
ALPHA, Nature 578, 375-380 (2020)
ALPHA, Nature 561, 211-215 (2018)
ALPHA, Nature 557, 71-75 (2018)
AEgIS, Commun Physics 4, 19 (2021)
ATRAP, Phys. Rev. Lett. 110, 130801 (2013)
ASACUSA, Nature 475, 484-488 (2011)

[*] ALPHA, Nat Commun 4, 1785 (2013)

[**] BASE, Nature 601, 53-57 (2022)

GBAR main goal and principle



1. Produce $\bar{\mathrm{H}}^+$ and trap in Paul trap, pre-filled with Be^+ ions
2. Sympathetically cool anti-ions to $10\ \mu\mathrm{K}$, cool Be^+ with $313\ \mathrm{nm}$ laser
3. Photo-detach excess positron with $1640\ \mathrm{nm}$ laser
4. Measure time of flight and annihilation position of $\bar{\mathrm{H}}$ with trackers

GOAL: first step $\frac{\Delta\bar{g}}{\bar{g}} \leq 1\%$, later to 10^{-5} with "quantum free fall"

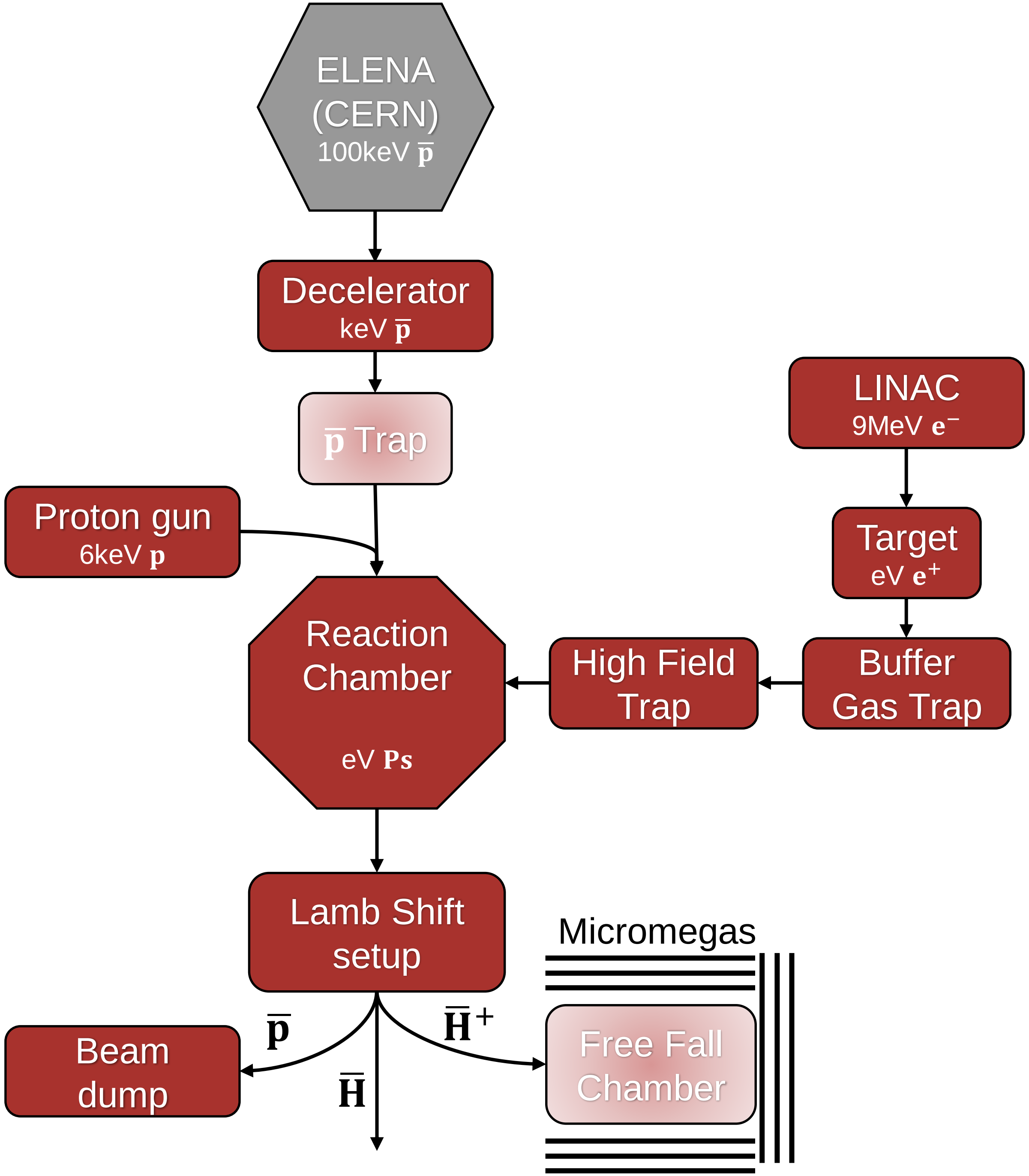
GBAR principle and schematic

(1) $$\bar{\mathrm{p}} + \mathrm{Ps} \rightarrow \bar{\mathrm{H}} + \mathrm{e}^{-}$$

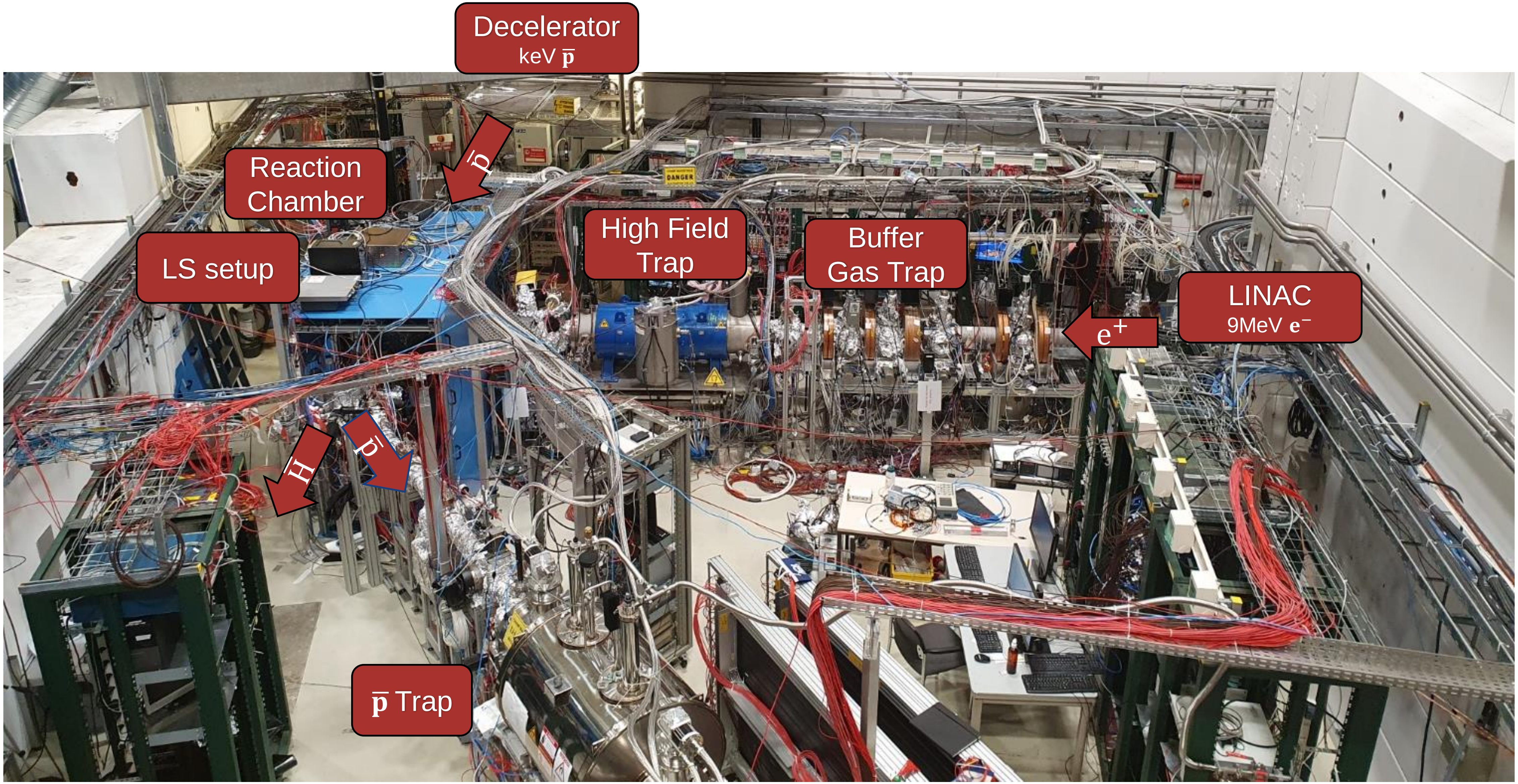
- $\bar{\mathrm{p}}$: antiprotons from the ELENA ring at $100\ \mathrm{keV}$ energy $110\ s$
- Ps: bound state of electron and positron

(2) $$\bar{\mathrm{H}} + \mathrm{Ps} \rightarrow \bar{\mathrm{H}}^{+} + \mathrm{e}^{-}$$

- Unique approach of GBAR
- Threshold for reaction: 6keV

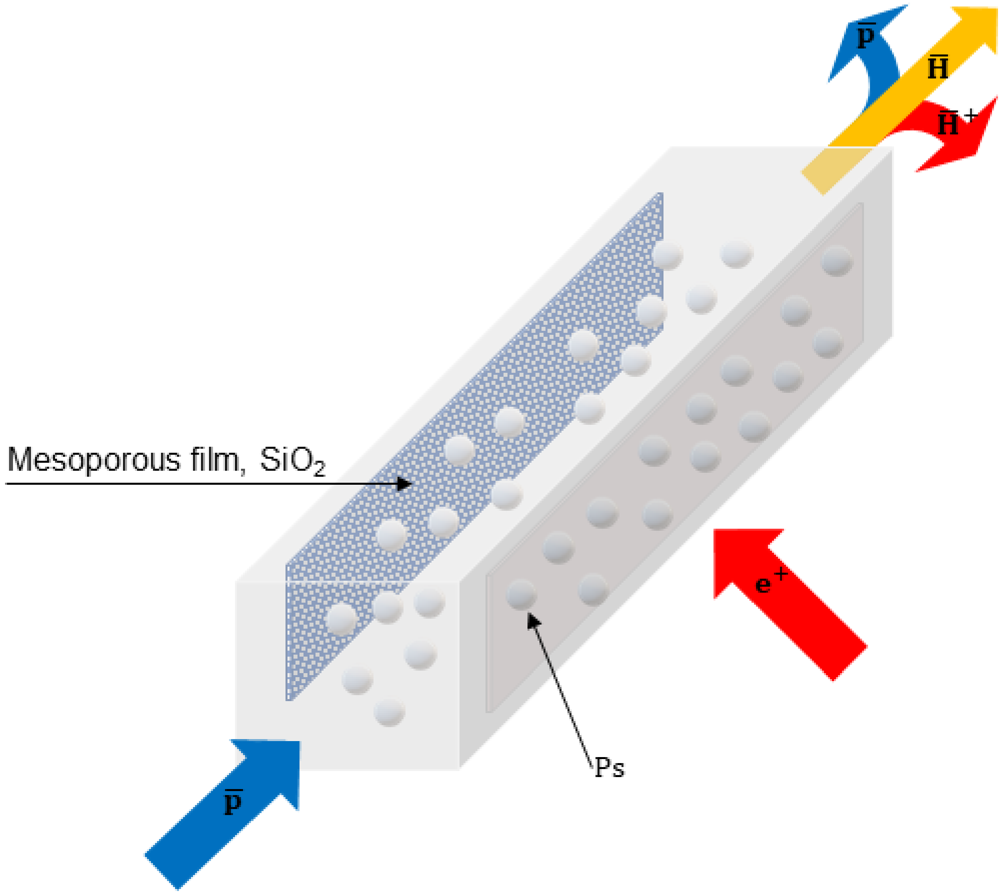


Status by the end of 2022



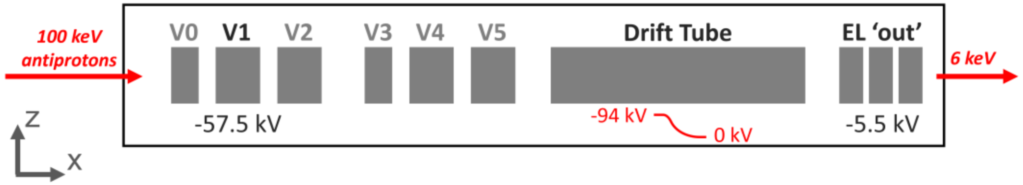
Positron and Positronium formation

- LINAC e^-:
  - Impinges on a tungsten target, which leads to high energy γ's → e^+ formation via pair production
  - During 2022 running at $200\ \mathrm{Hz}$ → $2.9 \times 10^7\ \mathrm{e}^+/\ \mathrm{s}$
- e^+:
  - Routinely trapping and accumulating $1.5 \times 10^8 \mathrm{e}^+$ per AD cycle
  - Maximum achieved: $1.4(2) \times 10^9\ \mathrm{e}^+/1100\ \mathrm{s}$
- Ps: bound state of electron and positron
  - Short lifetimes of $125\ \mathrm{ps}$ (p-Ps) and $142\ \mathrm{ns}$ (o-Ps)
  - During 2022 → no cavity but simpler flat target

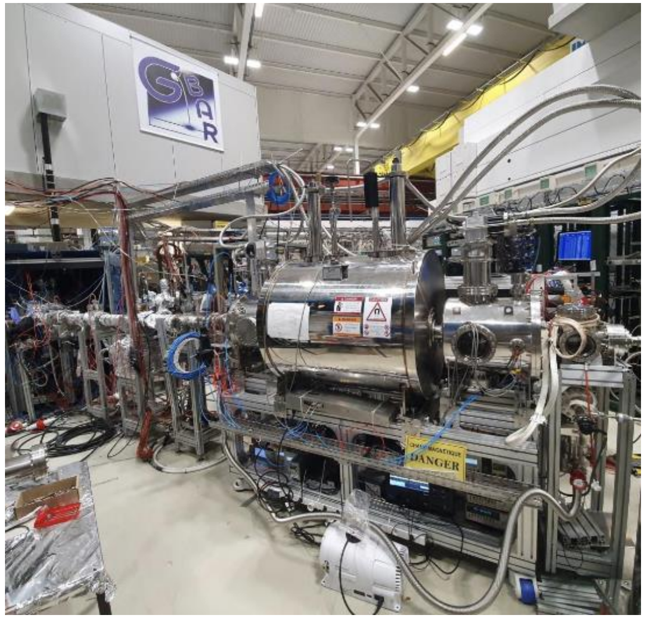


M. Charlton et al., NIMA, 985, 164657 (2021)
P. Blumer et al., NIMA, 1040, 167263 (2022)

Antiproton beam line and deceleration

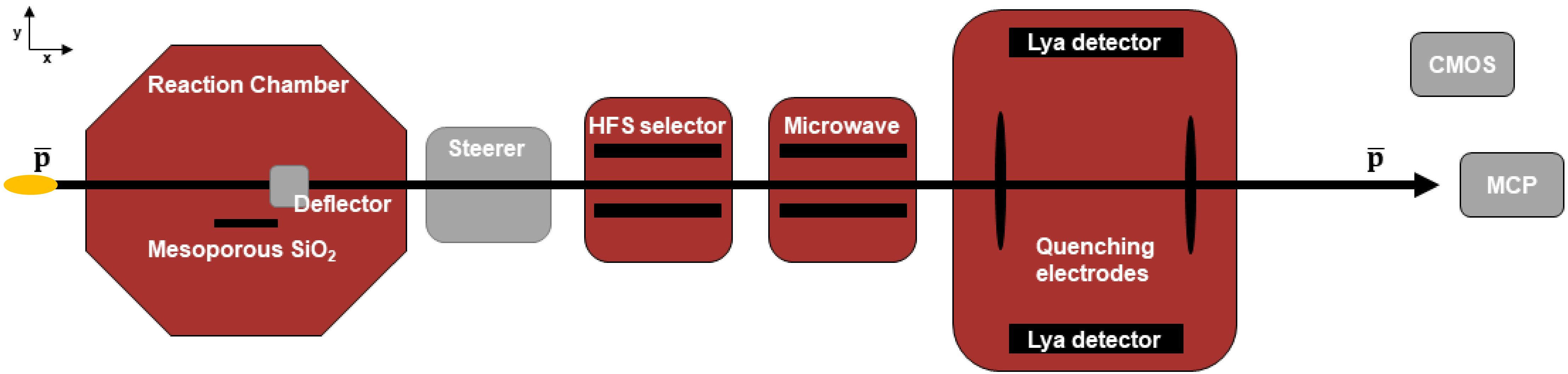


A. Husson et al., NIMA, 1002, 165245 (2021)

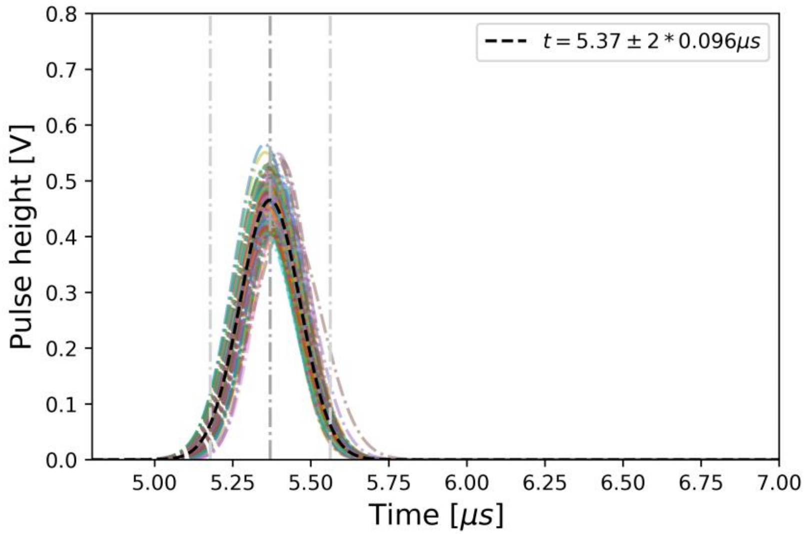


- Extra Low ENergy Antiproton (ELENA) ring:
  - $7 \times 10^6 \bar{\mathrm{p}}$ per AD cycle at $100\ \mathrm{keV}$ kinetic energy
- Drift tube: $100\ \mathrm{keV}$ to $1 - 10\ \mathrm{keV}$
  - Deceleration to $6.1 \pm 0.05\ \mathrm{keV}$ during 2022
- Antiproton flux interacting in the $\bar{\mathrm{H}}$ production
  - Determination with a CMOS sensor
  - Count number of traversing pions from antiproton annihilations
  - $(3.1 \pm 0.6) \times 10^6 \bar{\mathrm{p}}$ per AD cycle
- Antiproton trap:
  - Currently being installed
  - Cold $\bar{\mathrm{p}}$ can be focused through a denser Ps cloud yielding a higher charge exchange rate

Expected time of flight of Antihydrogen in 2022



- MCP measures electric signal with precise timing information and visualizes with a fast phosphor screen
- $\bar{p}$ pass in front of e^+ target and pass through a collimator/deflector (Ø 5mm)
- Measured time distribution of undeflected $\bar{p}$ defining signal window of neutral $\bar{H}$: $t = 5.37 \pm 2 \times 0.096$ µs



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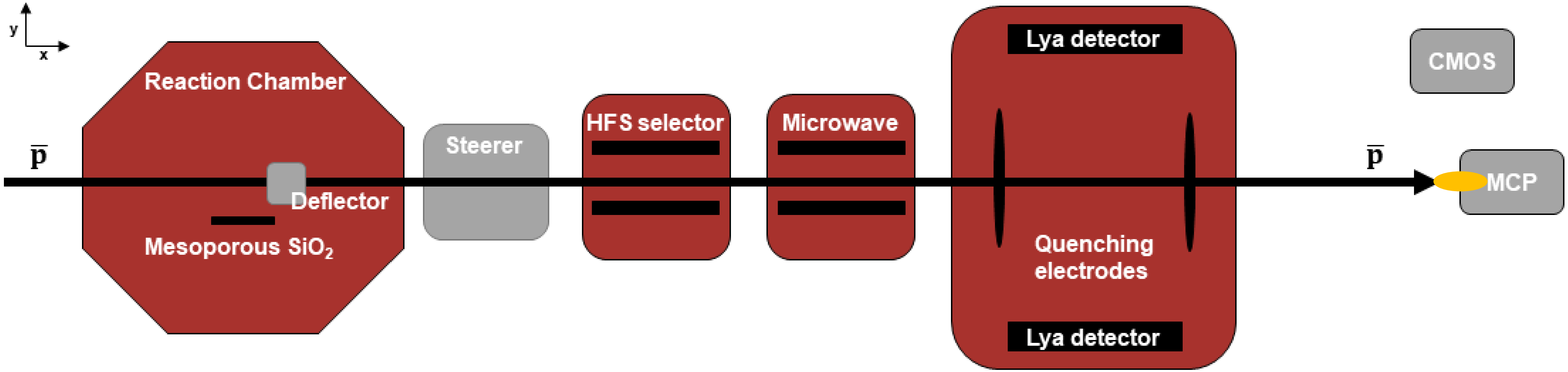

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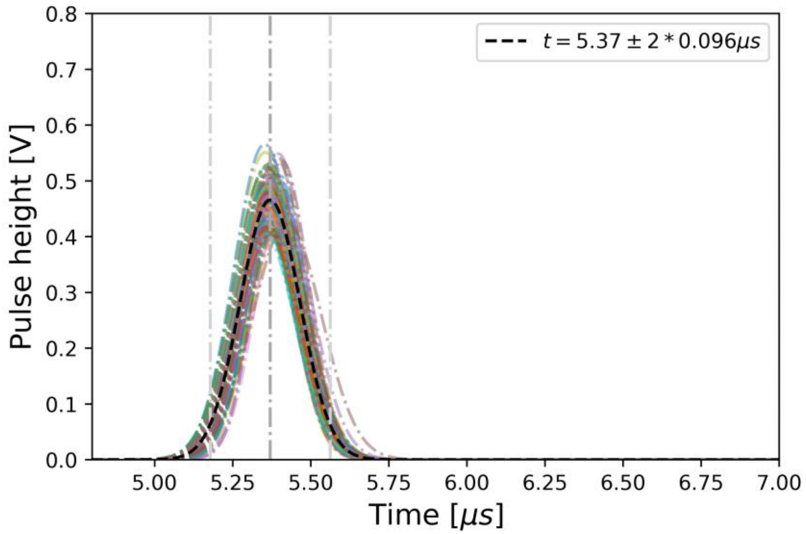
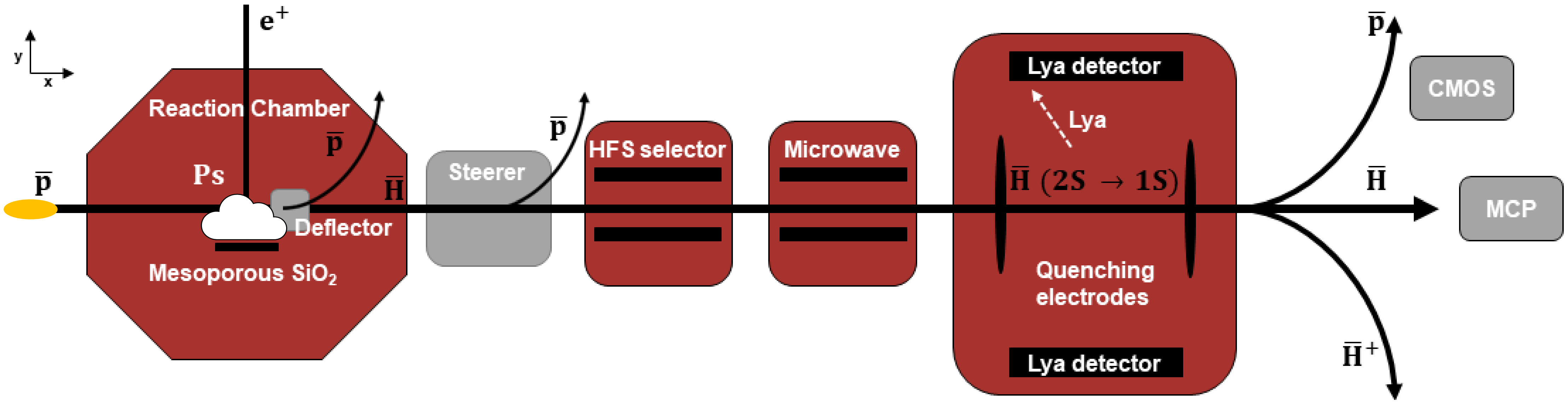
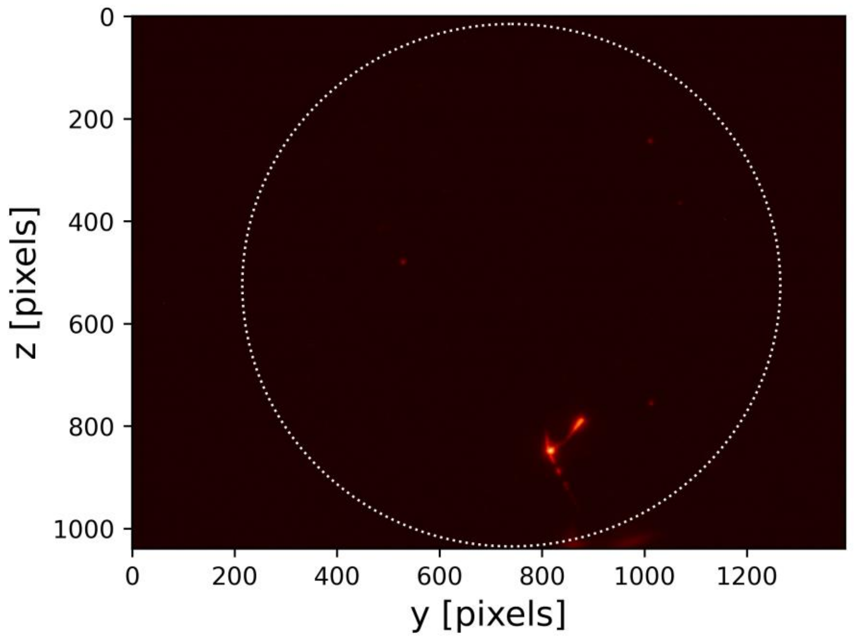


Antihydrogen production scheme in 2022



- Positronium cloud produced at flat nanoporous SiO_2 target (19mm)
- static electric fields used to deflect charged particles
- Neutral particle on straight trajectory
- Background ($\pi^{\pm}$ & γ) earlier in time



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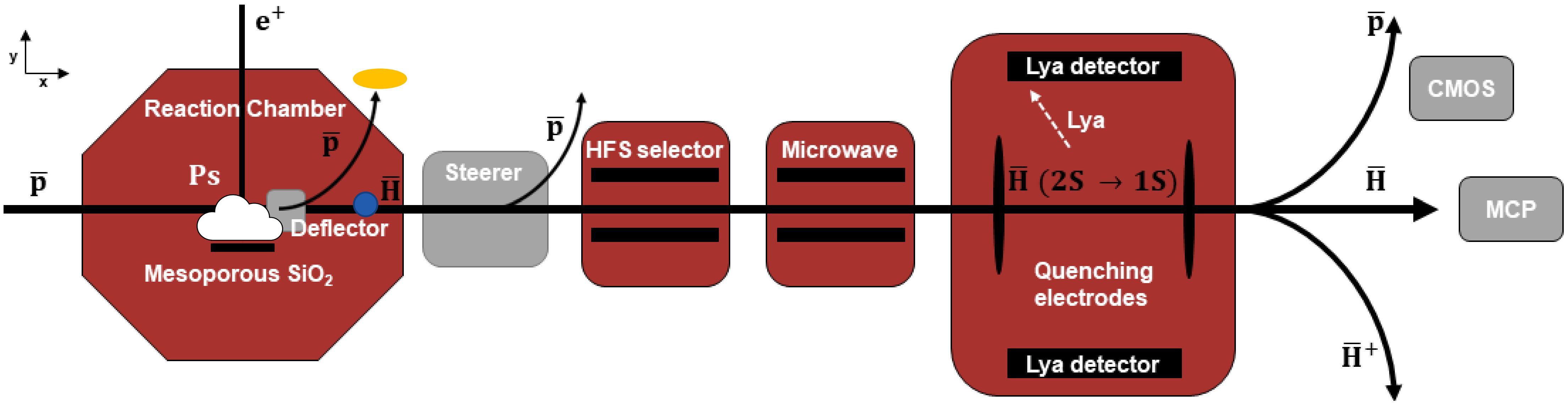

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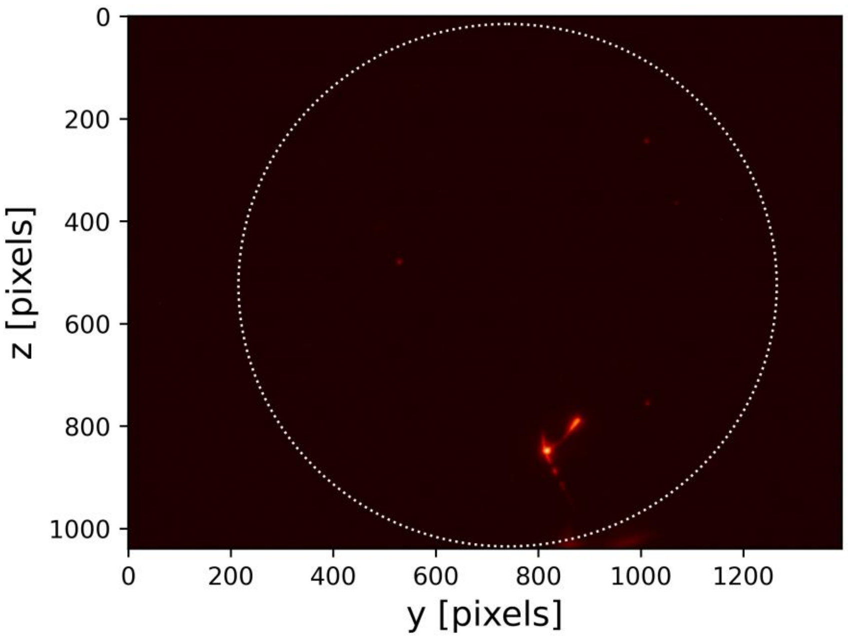

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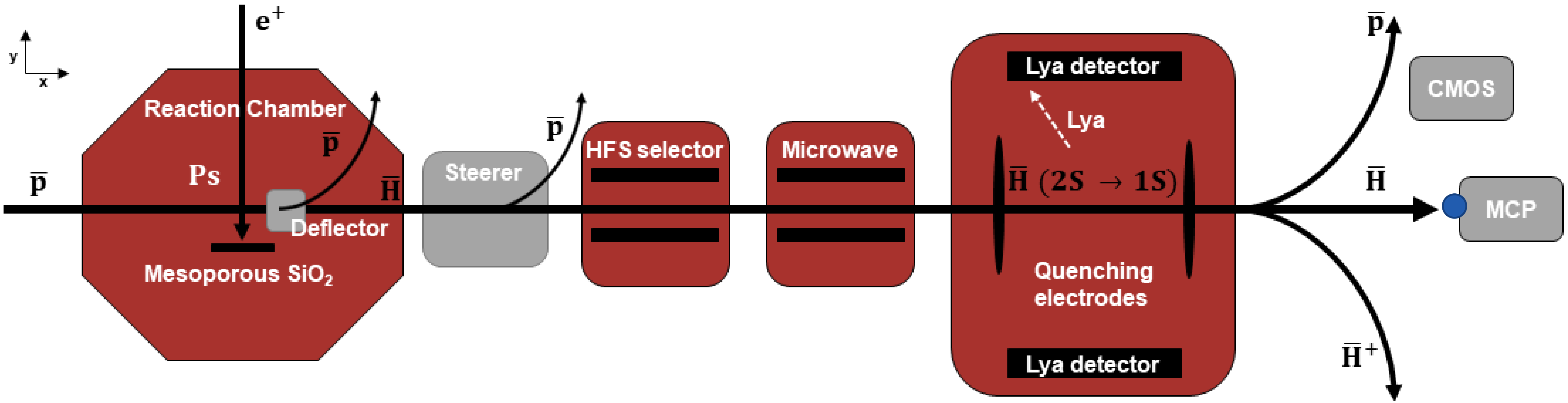

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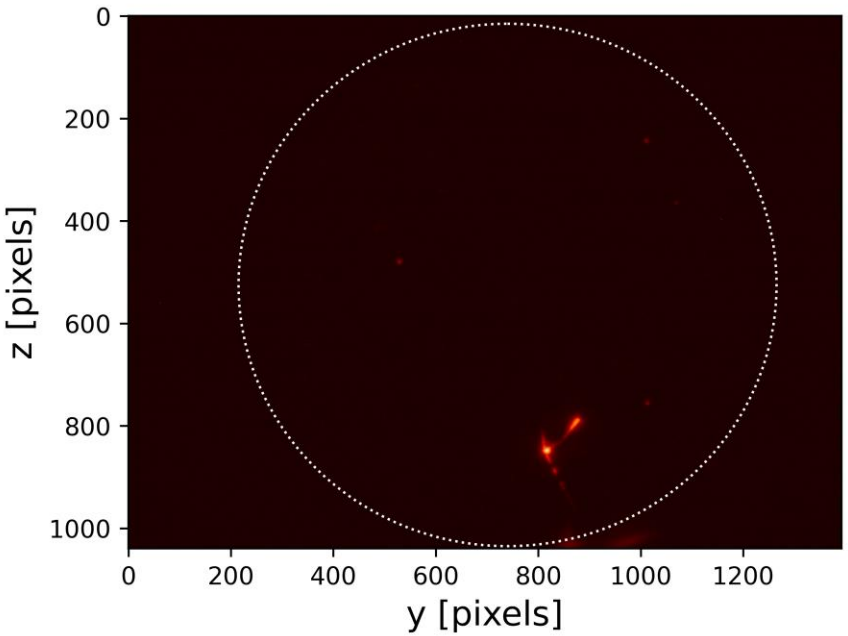
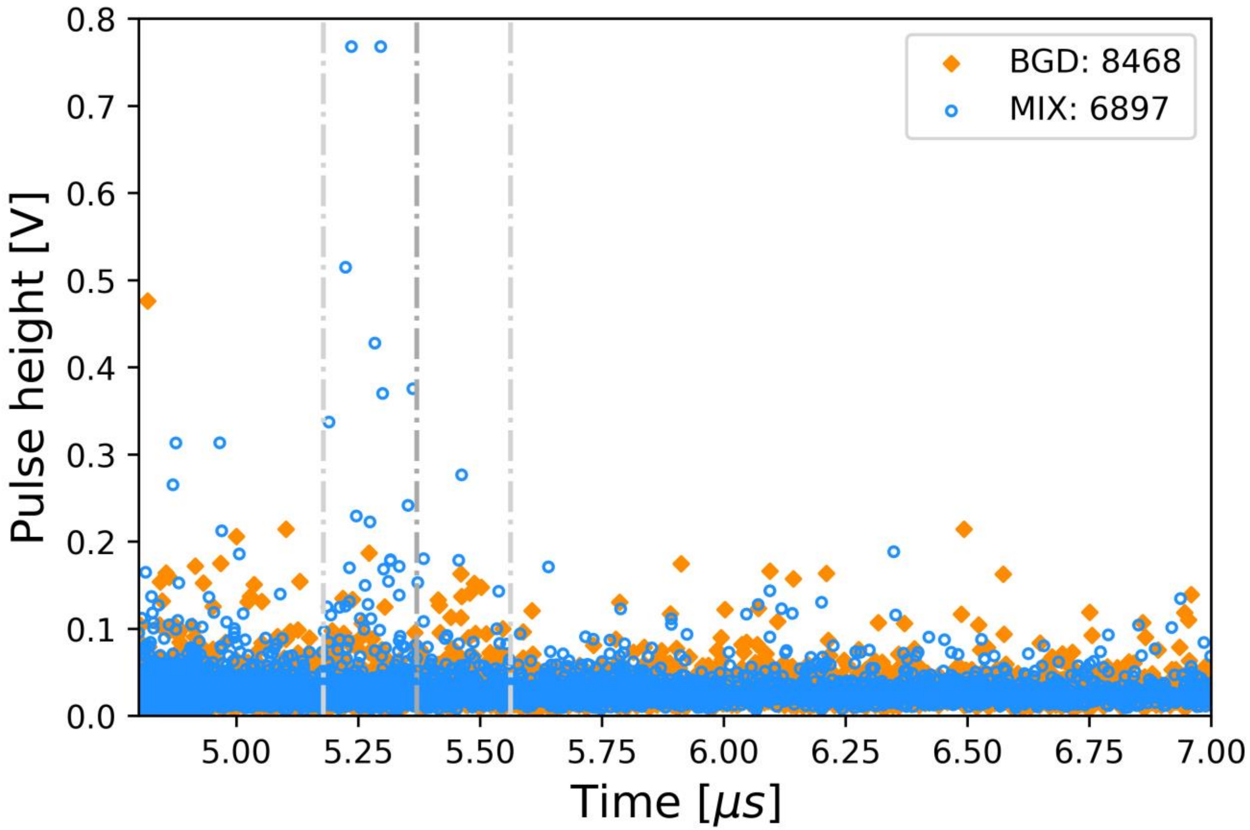


Antihydrogen production campaign – Analysis on electrical signal

- $\bar{\mathrm{p}}$ only: 8468 spills
  - main background due to charged pions from $\bar{\mathrm{p}}$ annihilations upstream
- Mixing: 6897 spills
- $\mathrm{P}s$ background negligible

- Expected production rate at 6keV

  $1.1 \pm 0.3\ \bar{\mathrm{H}}$ per 100 spills
  - $\mathrm{N_{Ps}} = (6.8 \pm 1.5) \times 10^6 \mathrm{P}s$
  - $\mathrm{N_{\bar{p}}} = (3.1 \pm 0.75) \times 10^6 \bar{\mathrm{p}}$



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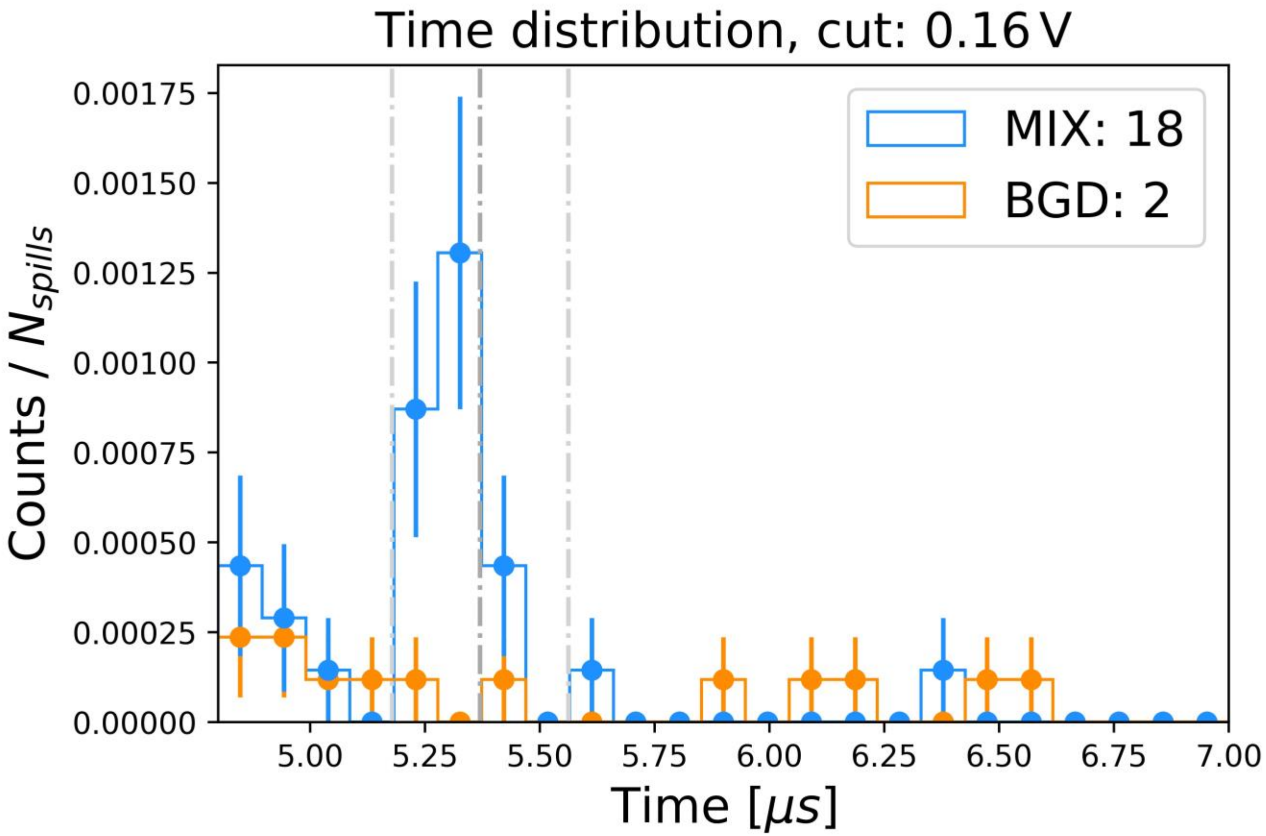
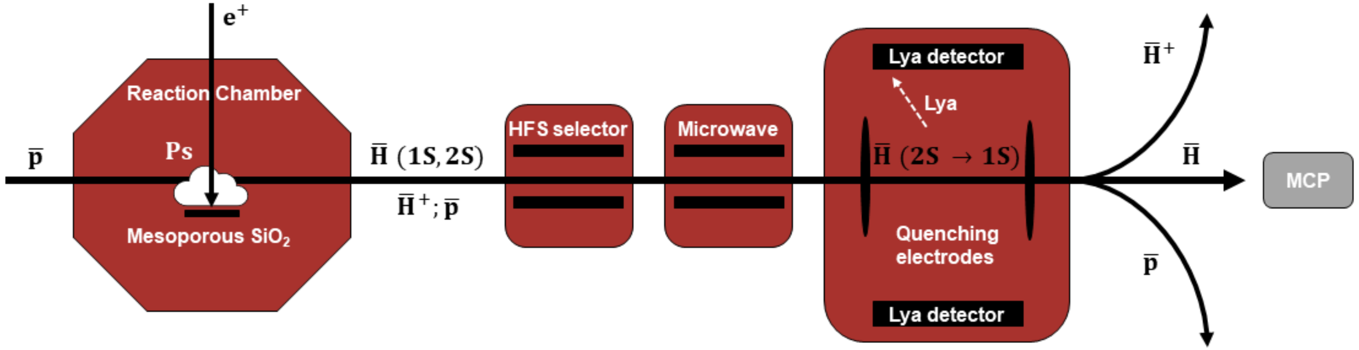


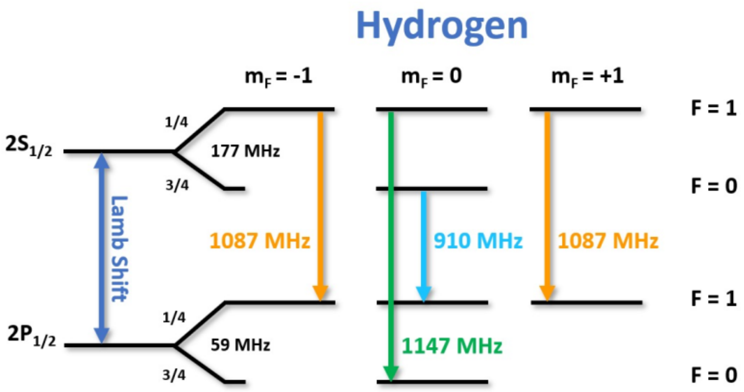
Short term outlook

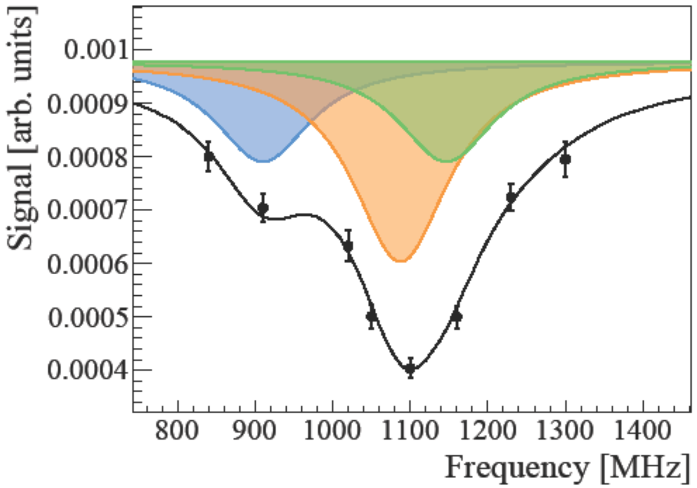
- Increase antihydrogen production rate
  - New positron trapping scheme with SiC remoderator and improvements on the e^+ transfer efficiency
  - Antiproton trap will confine $\bar{p}$ better and allow to intersect with a denser Ps cloud
  - Antihydrogen ion production

- First attempt of $\bar{H}$ Lamb shift measurement
  - GBAR uniquely producing $\bar{H}(2S)$, at 6keV 10%



Lamb shift setup commissioned in 2021 with hydrogen.



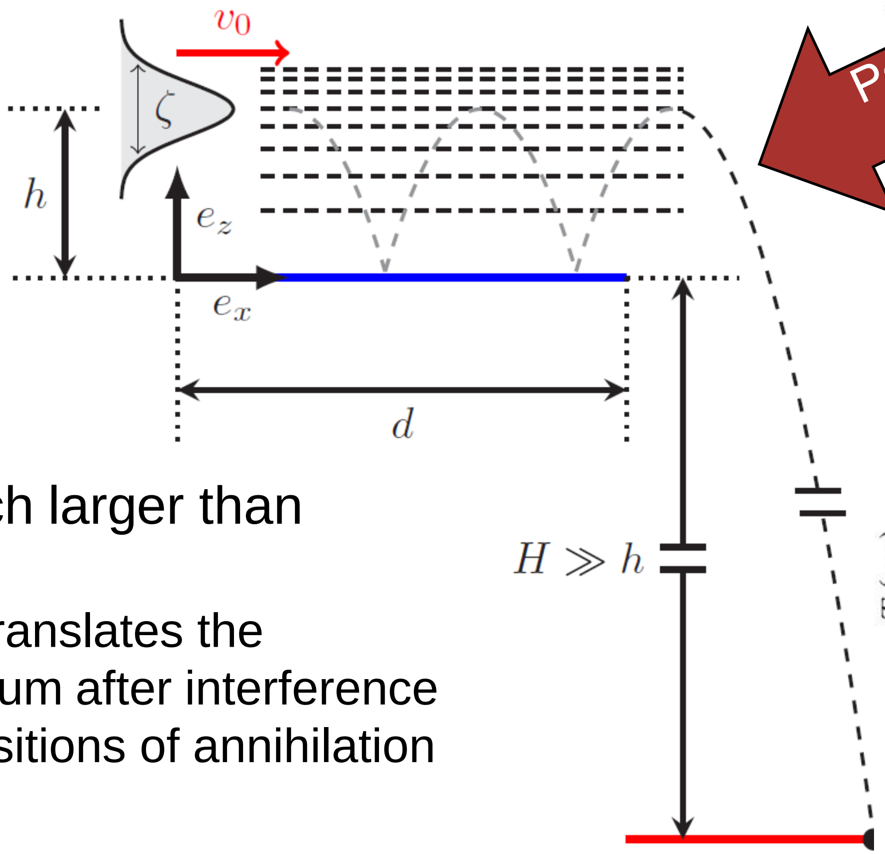


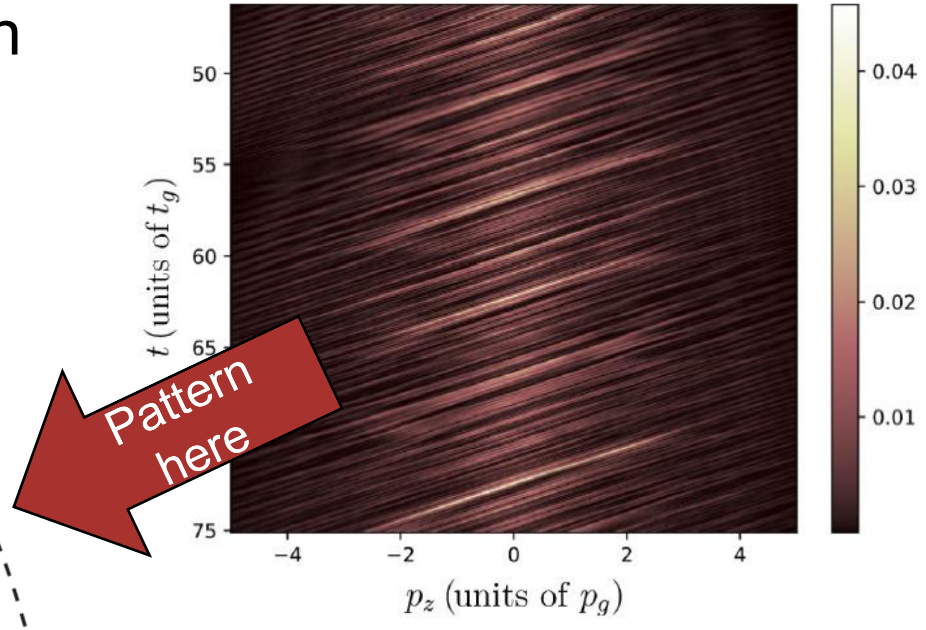
C. M. Rawlins, A. S. Kadyrov, A. T. Stelbovics, I. Bray, M. Charlton,
Phys. Rev. A 93, 012709 (2016)

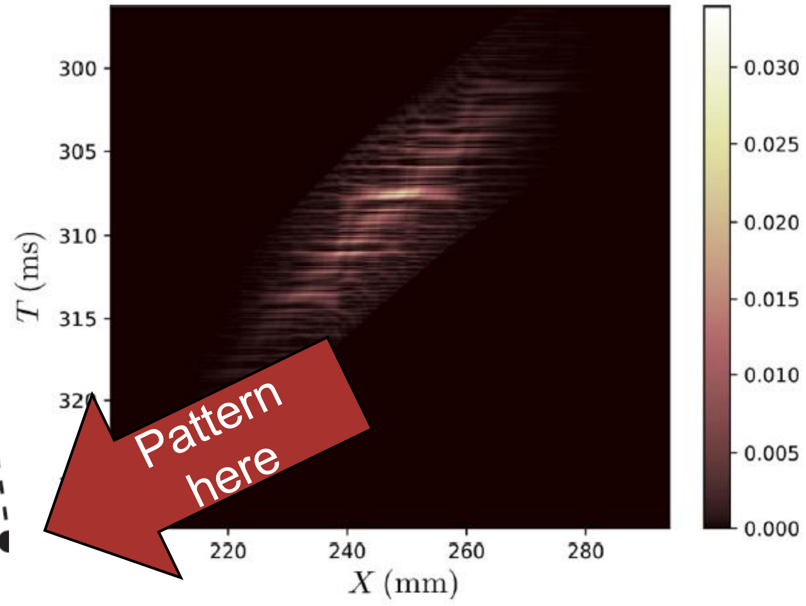
P. Crivelli, D. Cooke, M. W. Heiss,
Phys. Rev. D 94, 052008 (2016)
G. Janka, ETHZ PhD Thesis (2022)

Long term outlook - “Quantum free fall” of Antihydrogen

Parabolas: classical motion with rebounds above mirror
Dashed horizontal lines: paths through different quantum states which interfere in the detection pattern





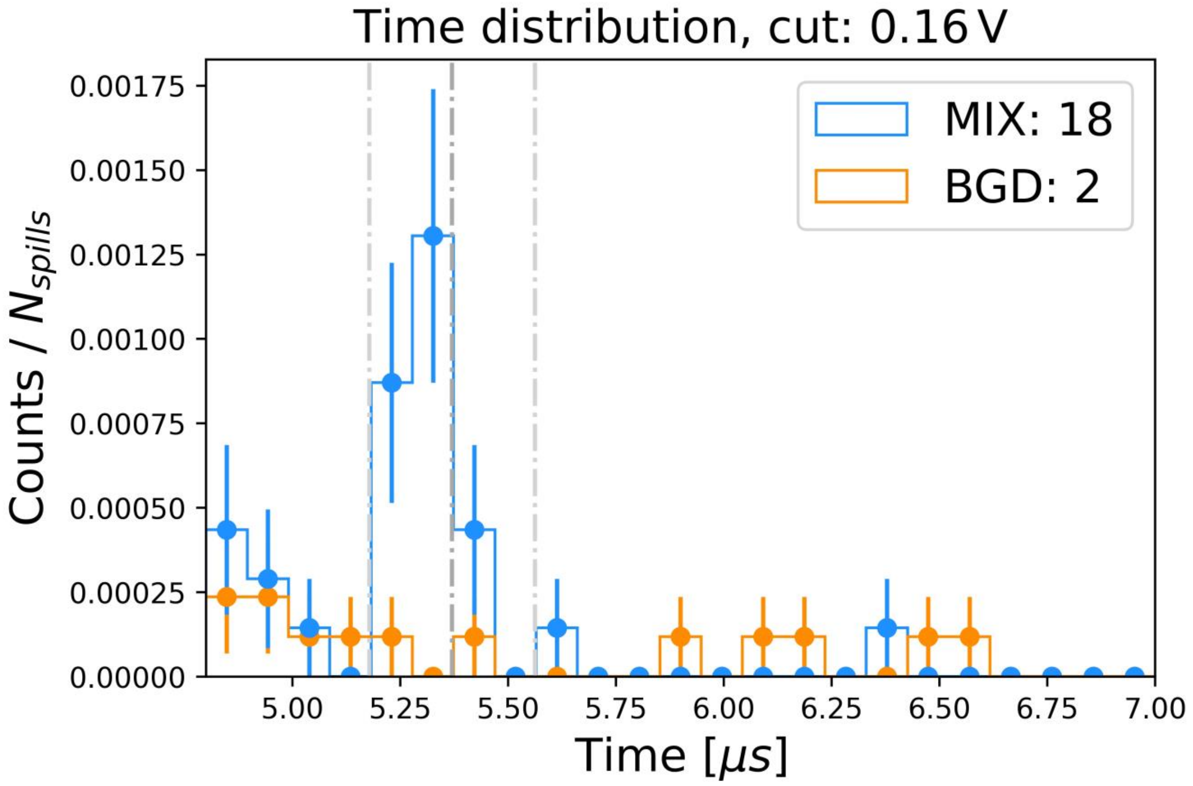


- Height of free fall must be much larger than dispersion of wave packet
  - Acts as diffraction process, translates the interaction time and momentum after interference zone into space and time positions of annihilation event
- Expected precision $\frac{\Delta\bar{g}}{\bar{g}} \sim 10^{-5}$

Crépin et al.,
Phys. Rev. A 99, 042119 (2019)

Summary

- During 2022 (2nd GBAR beamtime) first time coherent operation of GBAR experiment
  - First in-flight production of antihydrogen at 6keV
  - Results consistent with calculated expected rate
- Increase $\overline{\mathrm{H}}$ yield in 2023
  - Installation of antiproton trap
  - Increase positron number
- Measure $\overline{\mathrm{H}}$ Lamb Shift transition in 2024-2025
- After LS3 attempt synthesizing antihydrogen ion
  - Design study of "quantum free fall" in progress



Acknowledgments – GBAR collaboration

P. Adrich[1], P. Blumer[2], G. Caratsch[2], M. Chung[3], P. Cladé[4], P. Comini[5], P. Crivelli[2], O. Dalkarov[6], P. Debu[5], A. Douillet[4,7], D. Drapier[4], P. Froelich[8,*], S. Guellati-Khelifa[4,9], J. Guyomard[4], P-A. Hervieux[10], L. Hilico[4,7], P. Indelicato[4], S. Jonsell[8], J-P. Karr[4,7], B. Kim[11], S. Kim[12], E-S. Kim[13], Y.J. Ko[11], T. Kosinski[1], N. Kuroda[14], B.M. Latacz[5,**], B. Lee[12], H. Lee[12], J. Lee[11], E. Lim[13], L. Liszkay[5], D. Lunney[15], G. Manfredi[10], B. Mansoulié[5], M. Matusiak[1], V. Nesvizhevsky[16], F. Nez[4], S. Niang[15,**], B. Ohayon[2], K. Park[10], N. Paul[4], P. Pérez[5], C. Regenfus[2], S. Reynaud[4], C. Roumegou[15], J-Y. Roussé[5], Y. Sacquin[5], G. Sadowski[5], J. Sarkisyan[2], M. Sato[14], F. Schmidt-Kaler[17], M. Staszczak[1], K. Szymczyk[1], T. Tanaka[14], B. Tuchming[5], B. Vallage[5], D.P. van der Werf[18], A. Voronin[6], D. Won[12], S. Wronka[1], Y. Yamazaki[19], K-H. Yoo[3], P. Yzombard[4]

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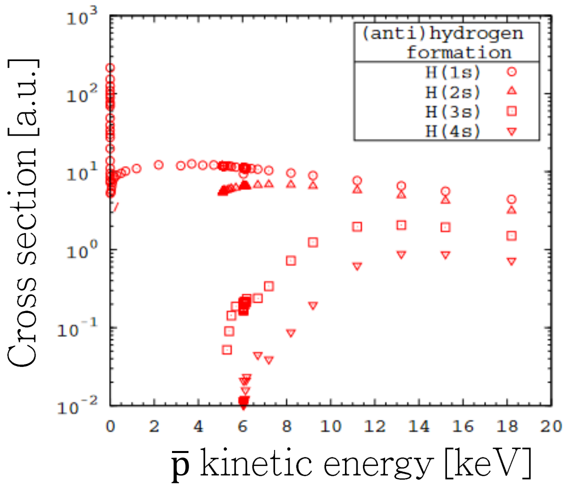
Swiss National Science Foundation

Backup

Estimation of antihydrogen production – Monte Carlo simulation

- Charge exchange reaction: $\bar{\mathrm{p}} + \mathrm{Ps} \rightarrow \bar{\mathrm{H}} + \mathrm{e}^-$
- Estimate: $N_{\bar{H}} = \sigma \times N_{\bar{p}} \times n_{Ps} \times \frac{1}{e} = 0.0417$
  - $N_{\bar{p}} = 3.1 \times 10^6 \bar{p}$
  - $n_{Ps} = 6.8 \times 10^6 Ps/0.25 cm^2$
  - $\sigma_{\bar{H}} = 13.4 \times 10^{-16} cm^2$
- With a precise MC simulation considering:
  - e^+ and $\bar{p}$ bunch distribution
  - Ps decay and diffusion from SiO_2
  - Overlap between Ps and $\bar{p}$

$$N_{\bar{H}} = 0.011 \pm 0.003$$



C. M. Rawlins, A. S. Kadyrov, A. T. Stelbovics, I. Bray, M. Charlton,
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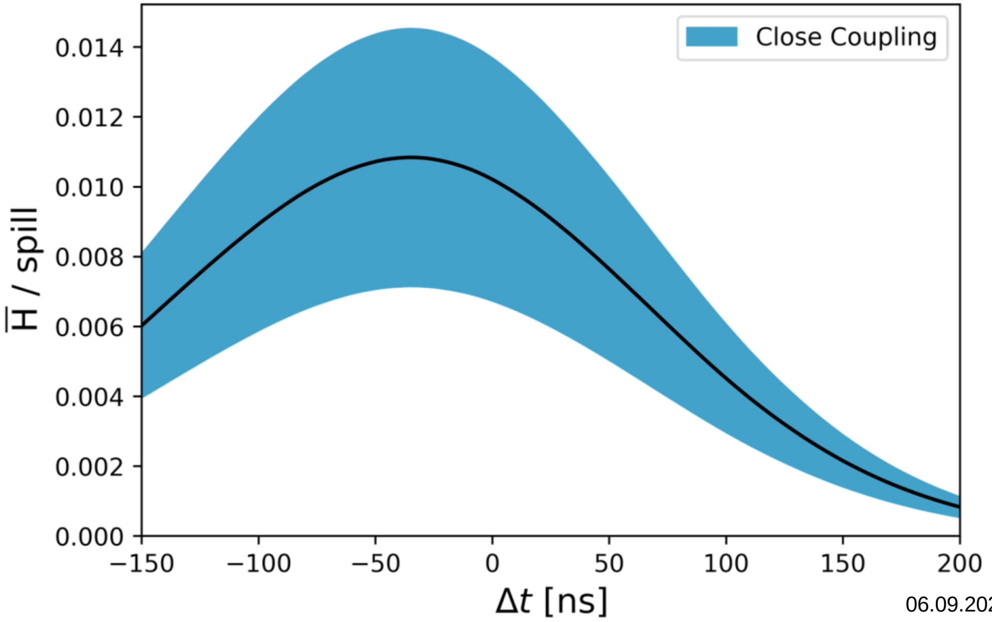
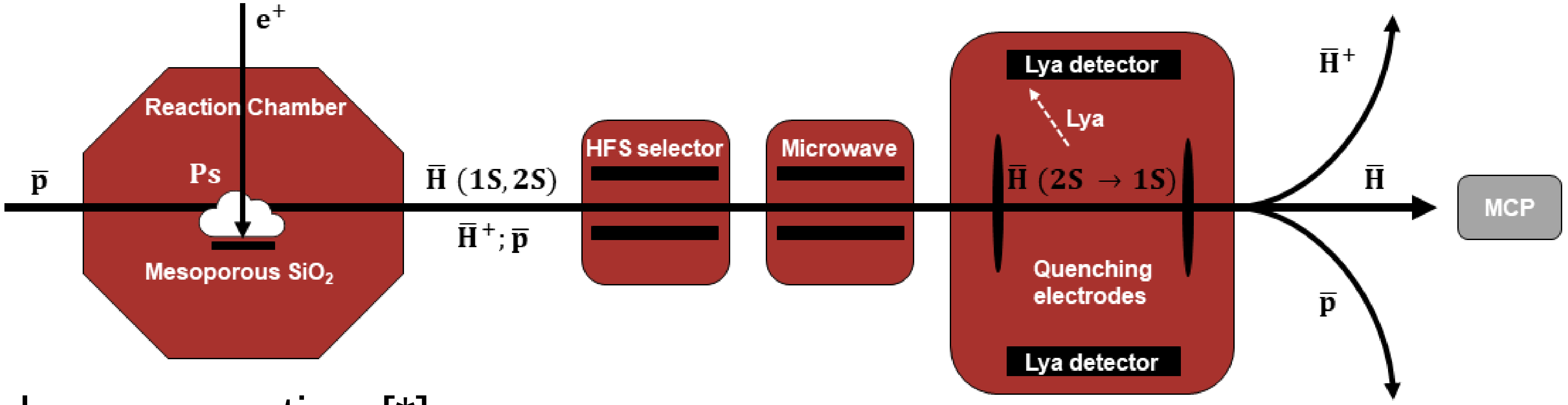


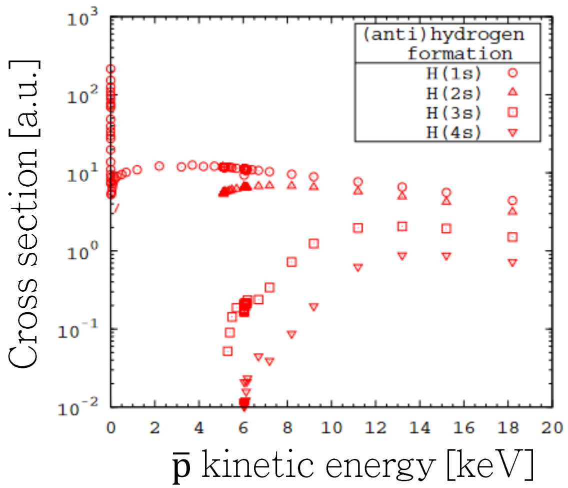
Antihydrogen Lamb Shift measurement as a byproduct of $\bar{\mathrm{H}}$ production



Charge exchange reaction [*]:

- Lamb shift: $\bar{\mathrm{p}} + \mathrm{Ps} \rightarrow \bar{\mathrm{H}} + \mathrm{e}^-$
- Assuming: $N_{\bar{H}} = \sigma \times N_{\bar{p}} \times n_{Ps} \times 1/e =$
  - $N_{\bar{p}} = 5 \times 10^6 \bar{p}$
  - $n_{Ps} = 10^8 Ps/0.04 cm^2$
  - $\sigma_{\bar{H}_{1S}} = 2.8 \times 10^{-16} cm^2$
  - $\sigma_{\bar{H}_{2S}} = 1.96 \times 10^{-16} cm^2$
  - $\sigma_{\bar{H}_{2P}} = 6.72 \times 10^{-16} cm^2$

$\bar{H}(1S+2P)$: 4.3 per spill
$\bar{H}(2S)$: 0.9 per spill



[*] C. M. Rawlins, A. S. Kadyrov, A. T. Stelbovics, I. Bray, M. Charlton,
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Geant4 Monte Carlo simulation of the classical free fall

- Trapping and sympathetically cooling $\overline{\mathrm{H}}^+$ to 10 μK
  - Corresponds to velocities of $\sim 1\,\mathrm{m/s}$
  - $h = v_z t + \frac{1}{2}\bar{g}t^2$, v_z unknown
  - $\frac{\Delta\bar{g}}{\bar{g}} \leq 1\%$
- Quantum reflection of neutral atoms on material surface due to Casimir-Polder potential