Institute for Particle Physics
and Astrophysics

Production of a 6keV antihydrogen beam in the GBAR experiment

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Group of Prof. Dr. Paolo Crivelli, ETHZ

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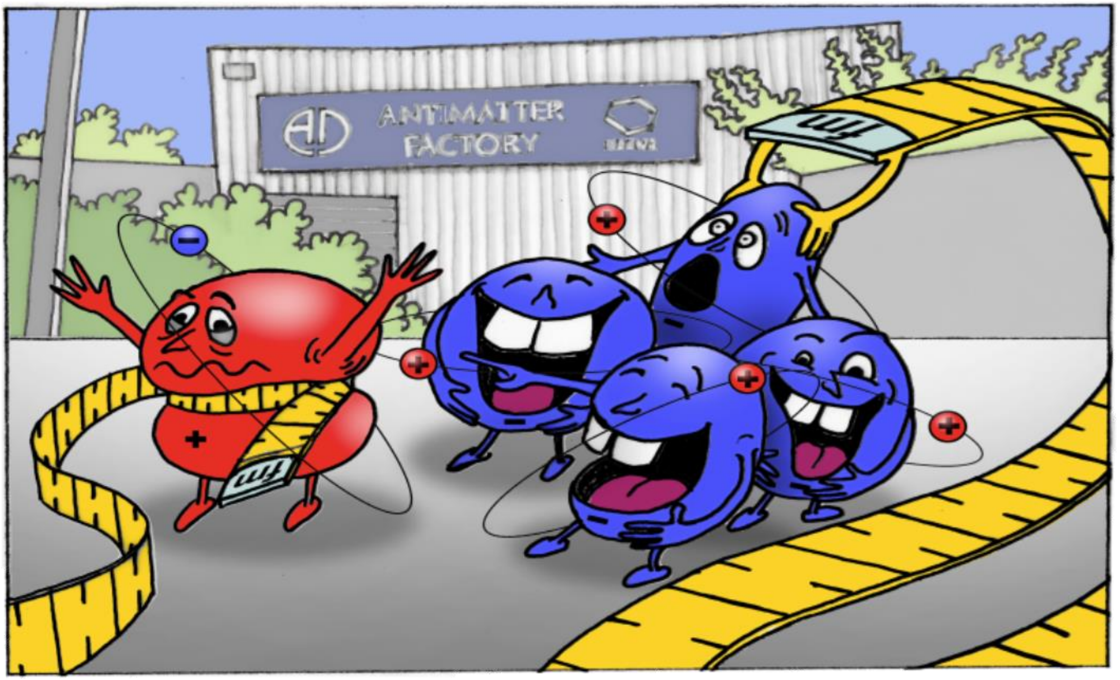
Antihydrogen – a blossoming field of research

- SM doesn't explain baryon asymmetry in the Universe
- New frameworks: 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
  - ALPHA-g: $(0.75 \pm 0.13(stat.+syst.) \pm 0.16(sim.))g$ [*]
  - BASE collaboration extracted $\bar{g}$ from gravitational redshift to $\frac{\Delta\bar{g}}{\bar{g}} = 3\%$ [**]

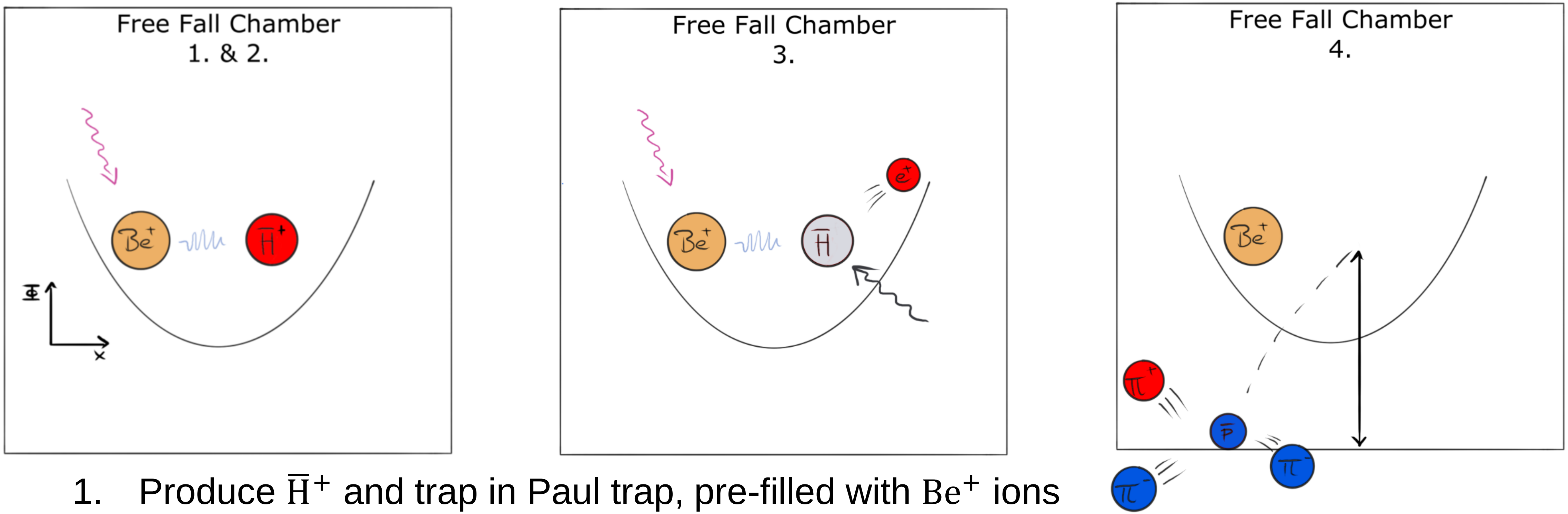


ALPHA, Nature 592, 35-42 (2021)
ALPHA, Nature 578, 375-380 (2020)
ALPHA, Nature 561, 211-215 (2018)
ALPHA, Nature 557, 71-75 (2018)
AEgIS, Commun Physics 4, 19 (2021)
ATRAP, Phys. Rev. Lett. 110, 130801 (2013)
ASACUSA, Nature 475, 484-488 (2011)

[*] ALPHA, Nature 621, 716-722 (2023)

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

GBAR main goal and principle



1. Produce $\overline{\mathrm{H}}^{+}$ 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 $\overline{\mathrm{H}}$ with trackers

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

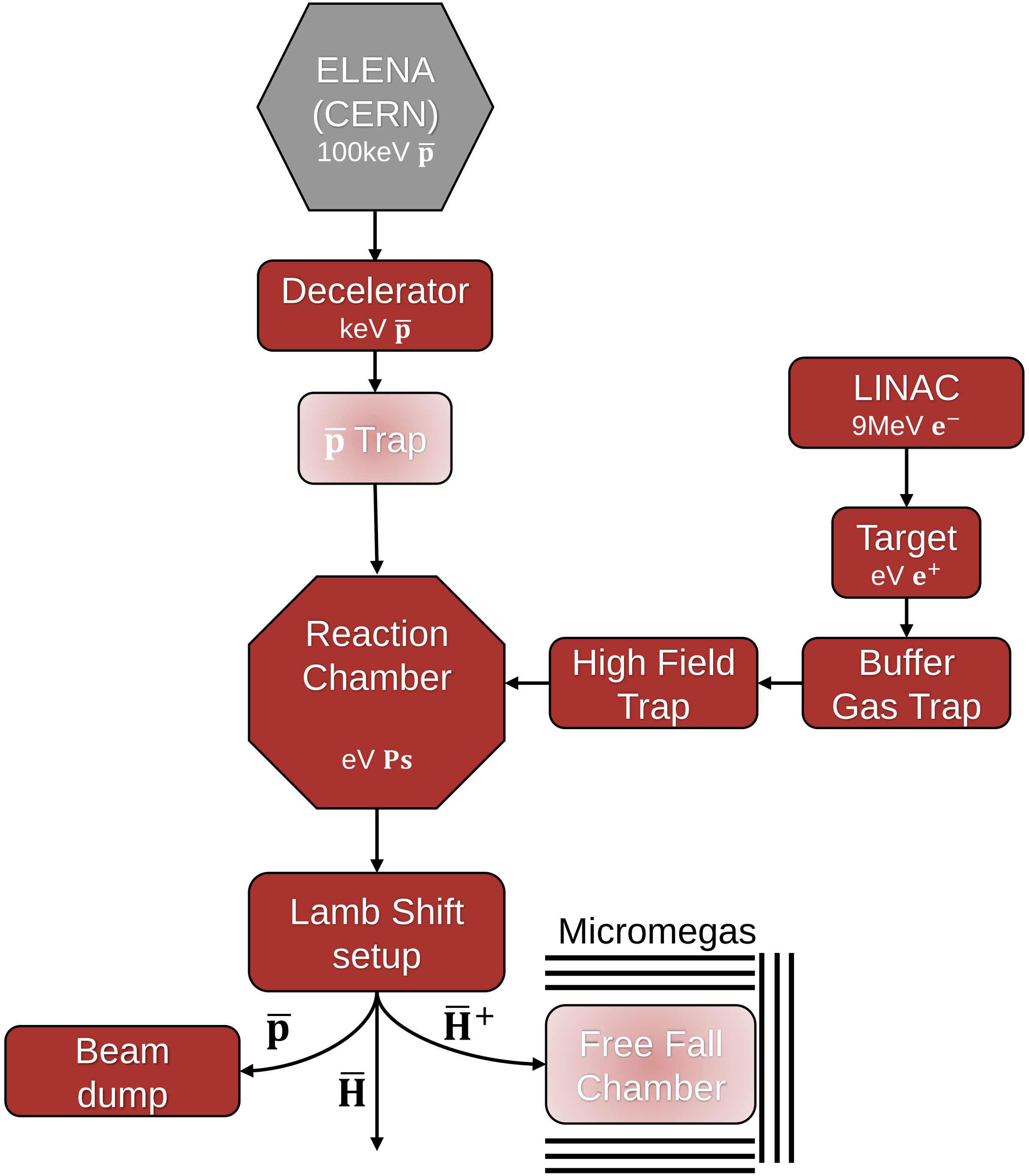
GBAR principle and schematic

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

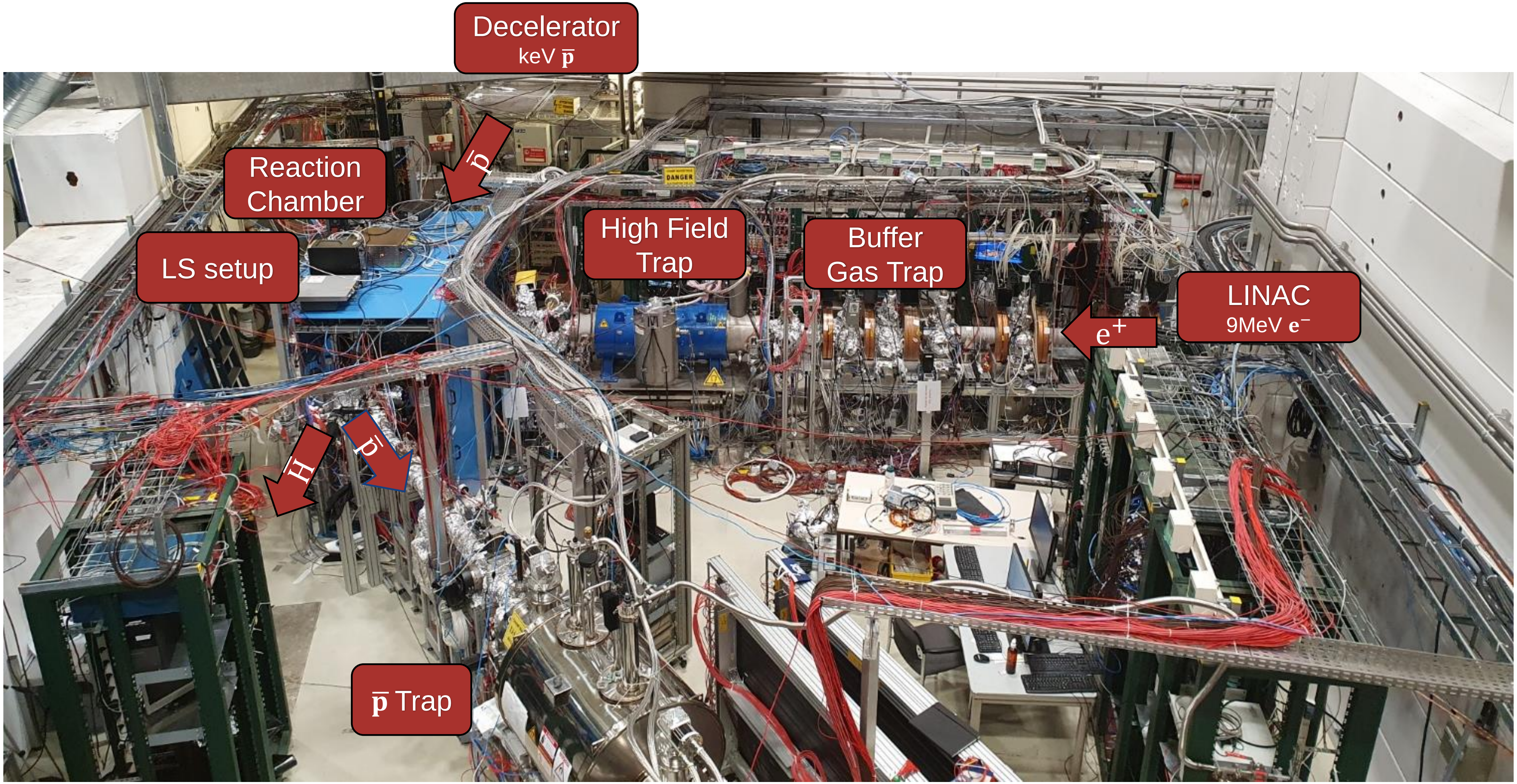
- $\bar{\mathrm{p}}$: antiprotons from the ELENA ring at $100\ \mathrm{keV}$ energy $110\ s$
- Ps: bound state of electron and positron

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

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

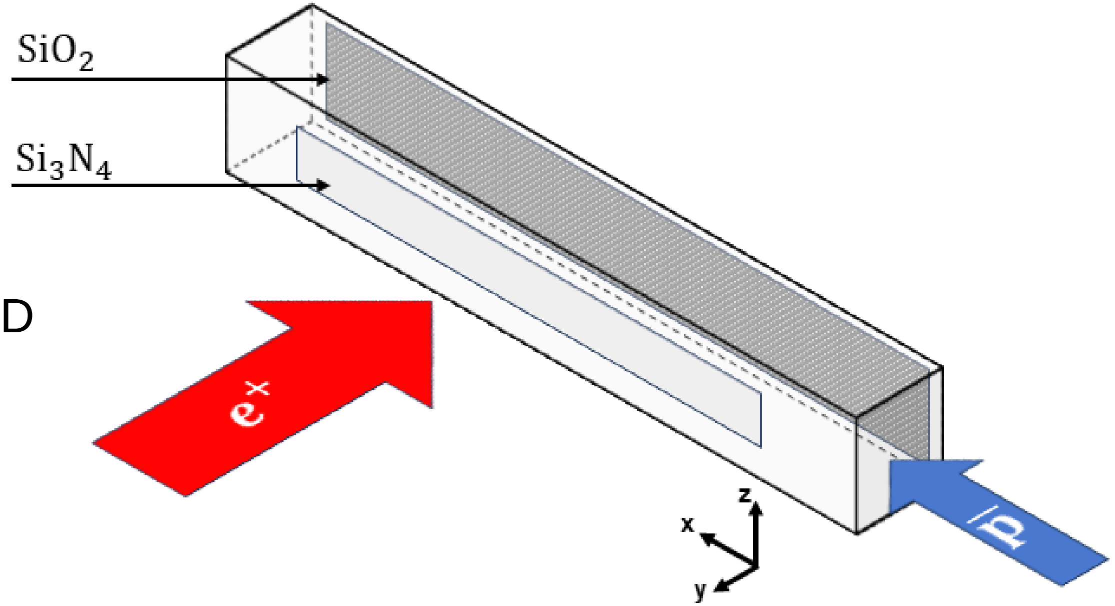


Status by the end of 2022



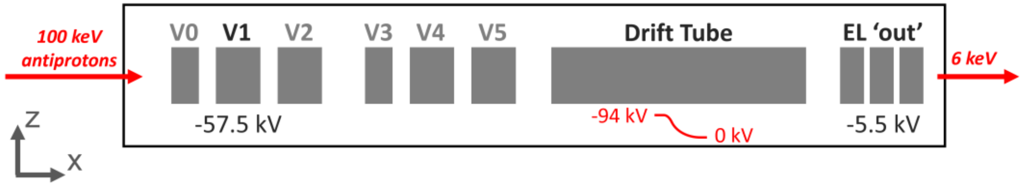
Positron and Positronium formation

- LINAC e^-:
  - Impinges on a tungsten target, which leads to high energy γ's → e^+ formation via pair production
  - During 2022 running at $200\ \mathrm{Hz}$ → $2.9 \times 10^7\ e^+/s$
- e^+:
  - Routinely trapping and accumulating $1.5 \times 10^8 e^+$ per AD cycle
  - Maximum achieved: $1.4(2) \times 10^9\ e^+/1100\ s$
- 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

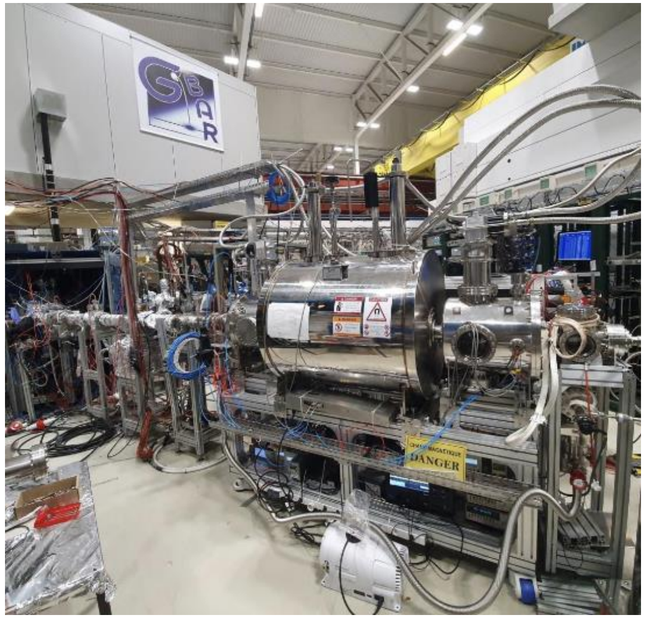


M. Charlton et al., NIMA, 985, 164657 (2021)
P. Blumer et al., NIMA, 1040, 167263 (2022)

Antiproton beam line and deceleration

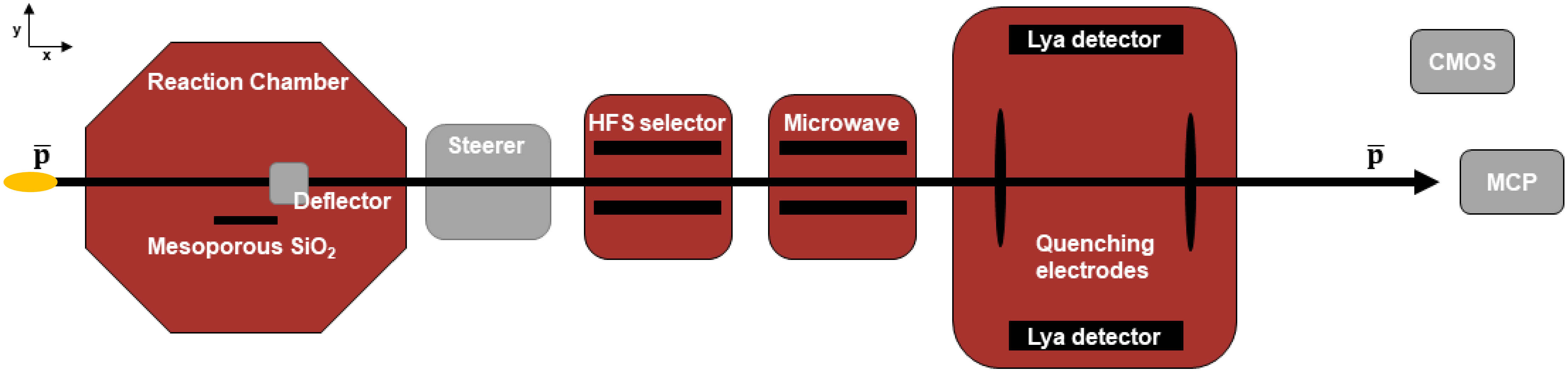


A. Husson et al., NIMA, 1002, 165245 (2021)

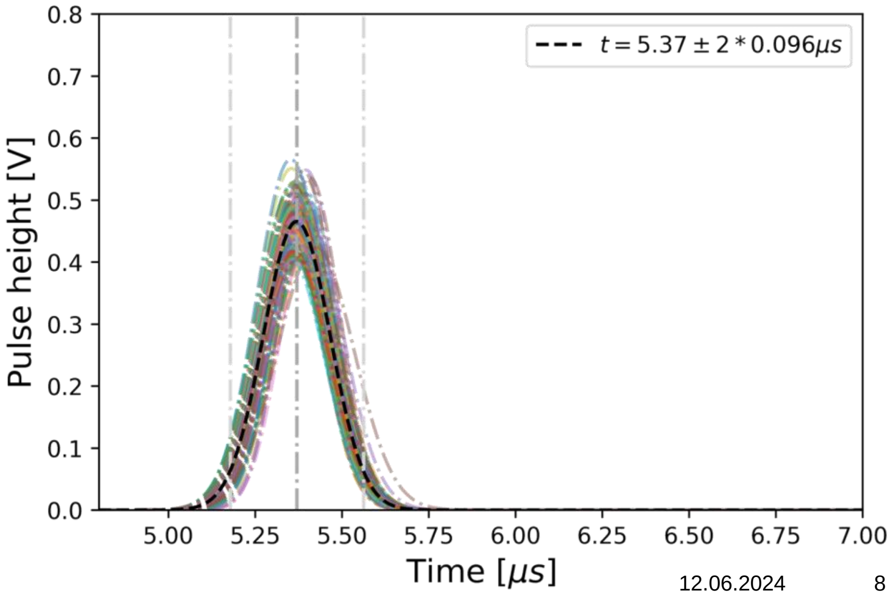


- Extra Low ENergy Antiproton (ELENA) ring:
  - $7 \times 10^6 \bar{\mathrm{p}}$ per AD cycle at $100\ \mathrm{keV}$ kinetic energy
- Drift tube: $100\ \mathrm{keV}$ to $1 - 10\ \mathrm{keV}$
  - Deceleration to $6.1 \pm 0.05\ \mathrm{keV}$
- Antiproton flux interacting in the $\bar{\mathrm{H}}$ production
  - 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 commissioned
  - Cold $\bar{\mathrm{p}}$ can be focused through a denser Ps cloud yielding a higher charge exchange rate

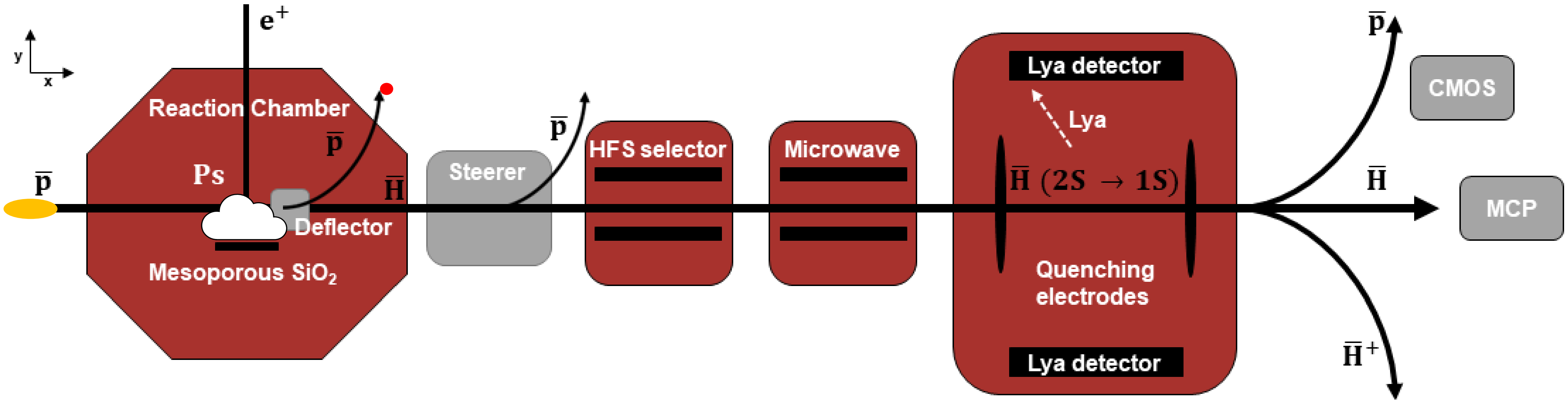
Expected time of flight of Antihydrogen



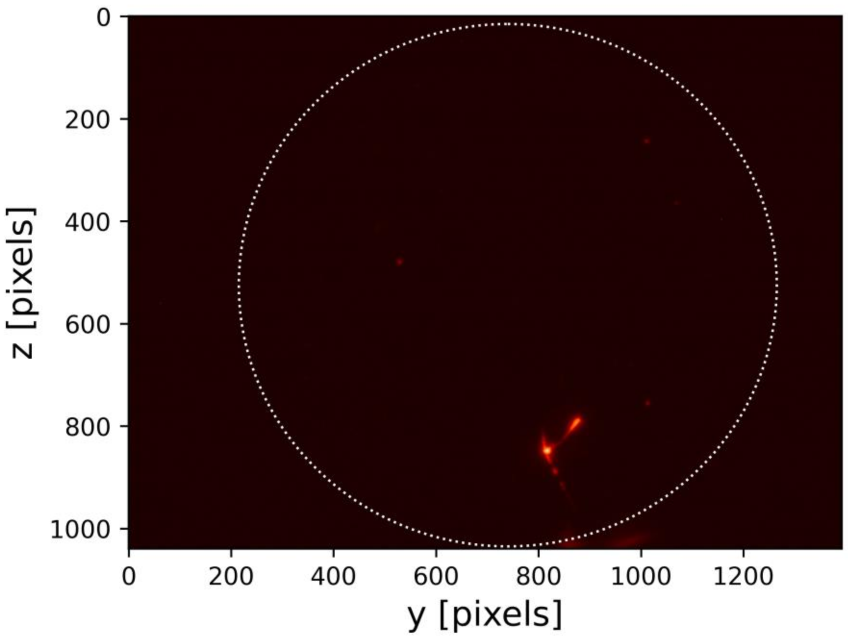
- MCP measures electric signal with precise timing information and visualizes with a fast phosphor screen
- $\bar{\mathrm{p}}$ pass in front of e^+ target and pass through a collimator/deflector (Ø 5mm)
- Measured time distribution of undeflected $\bar{\mathrm{p}}$ defining signal window of neutral $\bar{\mathrm{H}}$: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



Antihydrogen production scheme



- 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

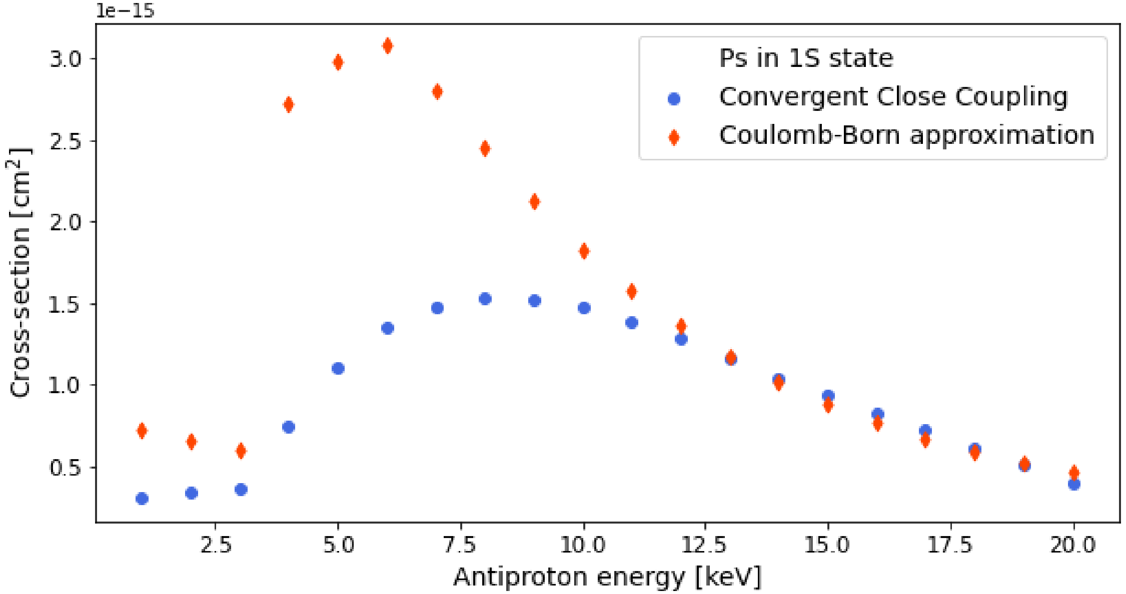


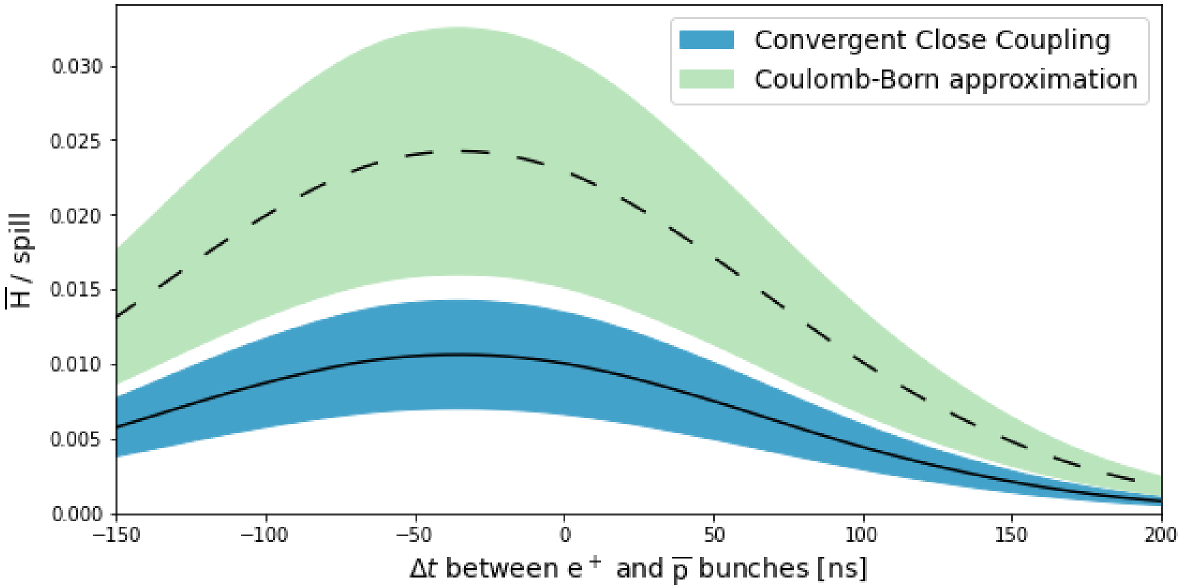
Estimation of antihydrogen production – Monte Carlo simulation

- Charge exchange reaction: $\bar{\mathrm{p}} + \mathrm{Ps} \rightarrow \bar{\mathrm{H}} + \mathrm{e}^-$

- With a realistic MC simulation considering:
  - e^+ and $\bar{\mathrm{p}}$ bunch distribution
  - Ps decay and diffusion from SiO_2
  - Overlap between Ps and $\bar{\mathrm{p}}$
  - $\mathrm{N_{Ps}} = (6.8 \pm 1.5) \times 10^6 \mathrm{Ps}$
  - $\mathrm{N}_{\bar{\mathrm{p}}} = (3.1 \pm 0.75) \times 10^6 \bar{\mathrm{p}}$
  - $\sigma_{\bar{\mathrm{H}}} = 13.4 \times 10^{-16} \mathrm{cm}^2$

$$\mathrm{N}_{\bar{\mathrm{H}}} = 0.011 \pm 0.003$$



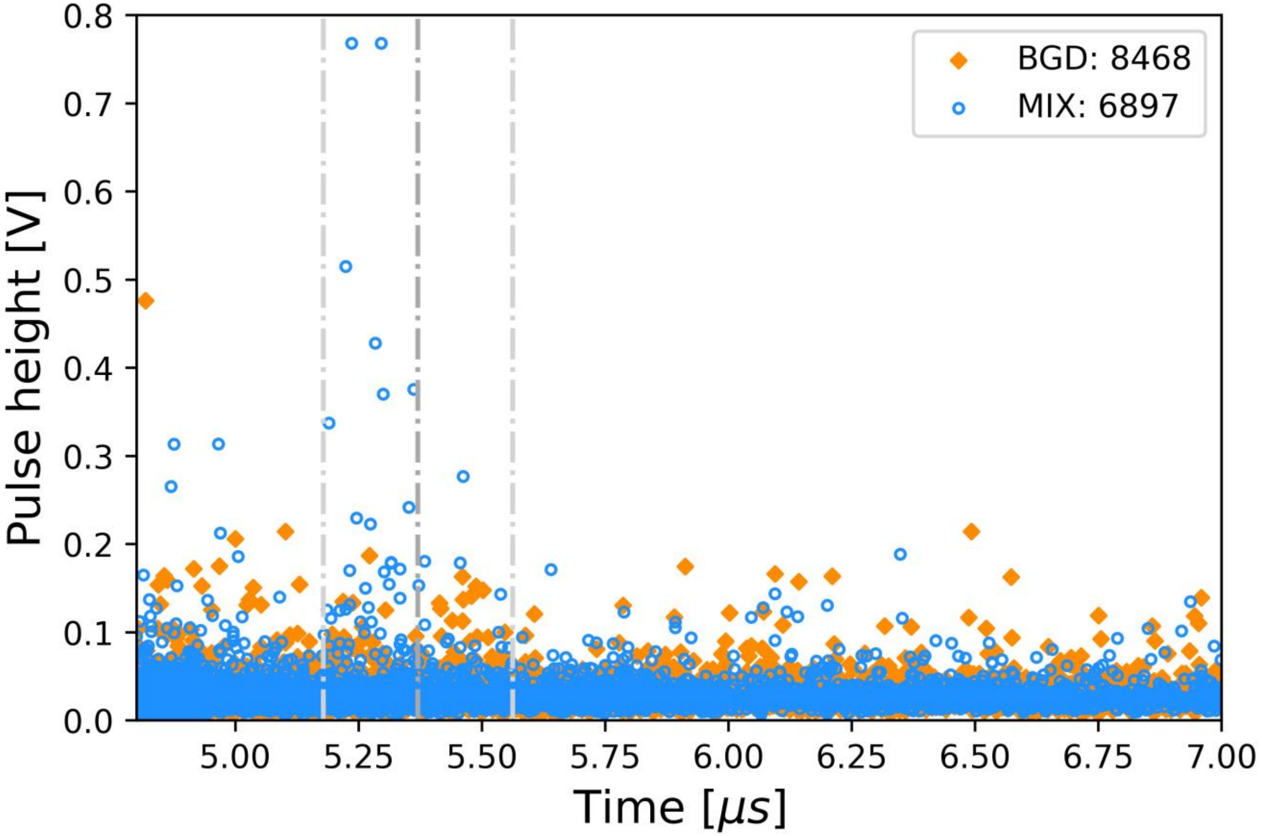


Antihydrogen production campaign – Analysis on electrical signal

- $\bar{\mathrm{p}}$ 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

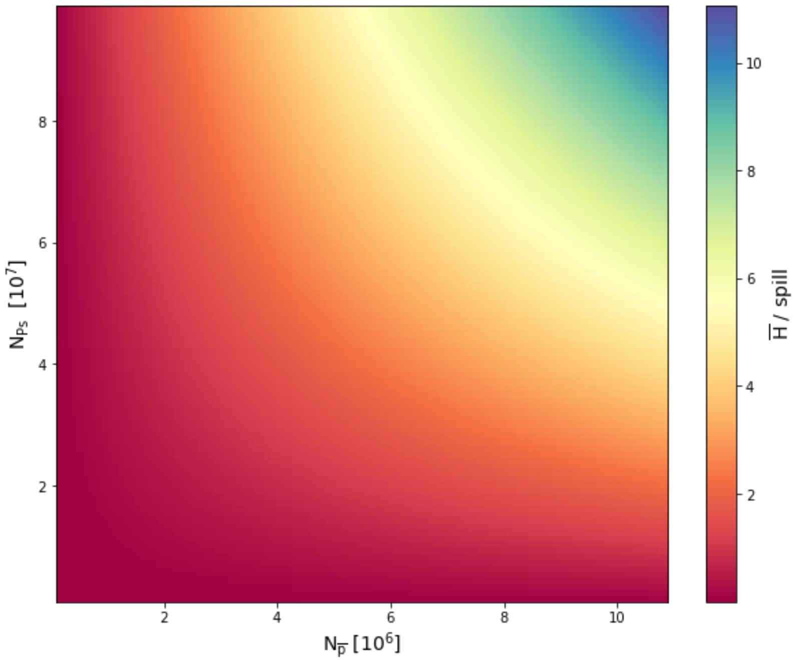
  $1.1 \pm 0.3\ \bar{\mathrm{H}}$ per 100 spills
  - $\mathrm{N_{Ps}} = (6.8 \pm 1.5) \times 10^6 \mathrm{P}s$
  - $\mathrm{N}_{\bar{\mathrm{p}}} = (3.1 \pm 0.75) \times 10^6 \bar{\mathrm{p}}$

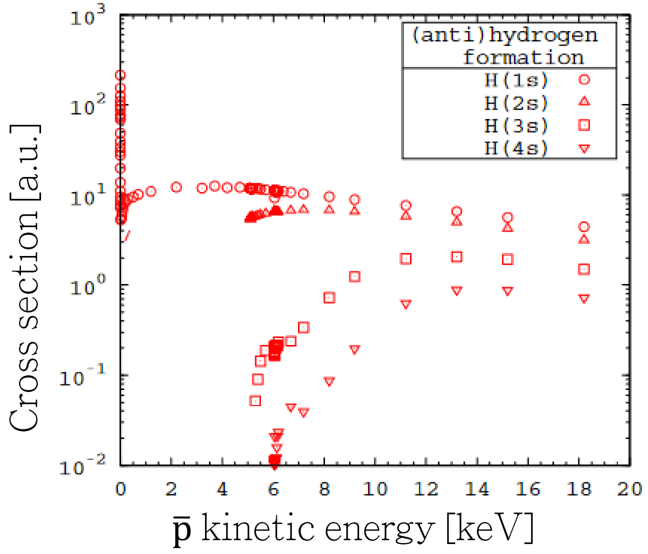


Short term outlook

- Increase antihydrogen production rate
  - New positron trapping scheme with SiC remoderator and improvements on the e^+ transfer efficiency
  - Antiproton trap will confine $\bar{\mathrm{p}}$ better and allow to intersect with a denser Ps cloud
  - Antihydrogen ion production
- First attempt of $\bar{\mathrm{H}}$ Lamb shift measurement
  - GBAR uniquely producing $\bar{\mathrm{H}}(2S)$; at 6keV 10%
  - Finite size effects (affects primarily S state)
  - $\Delta E_{\text{nucl}} = \frac{2}{3}\frac{(Z\alpha)^4}{n^3} m_{\mathrm{R}}^3 R_{\mathrm{p}}^2$
  - At level of 100 ppm determine the antiproton charge radius at 10% level

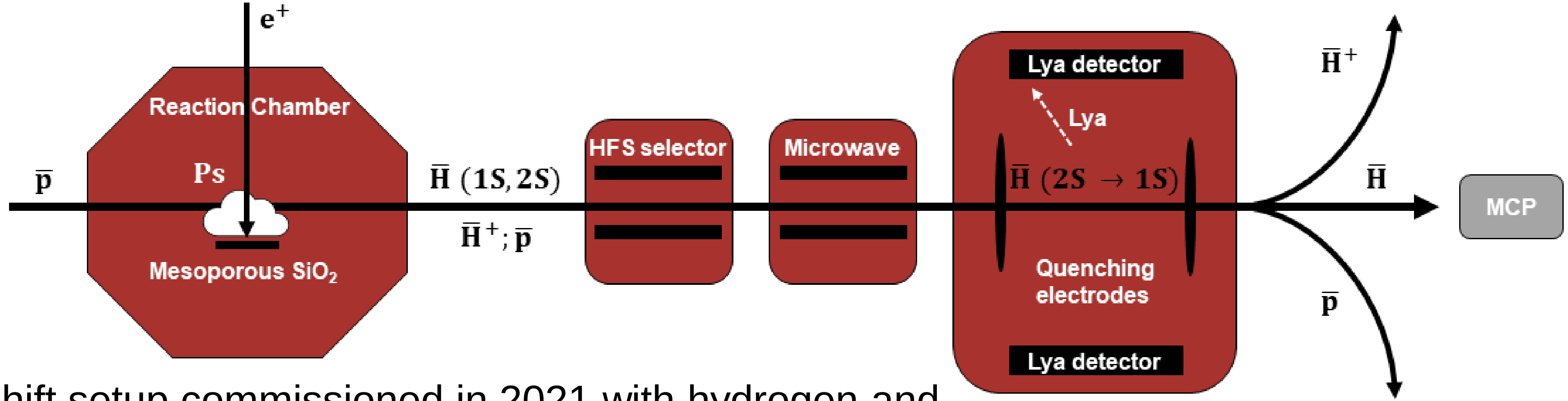
P. Crivelli, D. Cooke, M. W. Heiss, “Antiproton charge radius”, Phys. Rev. D 94, 052008 (2016)



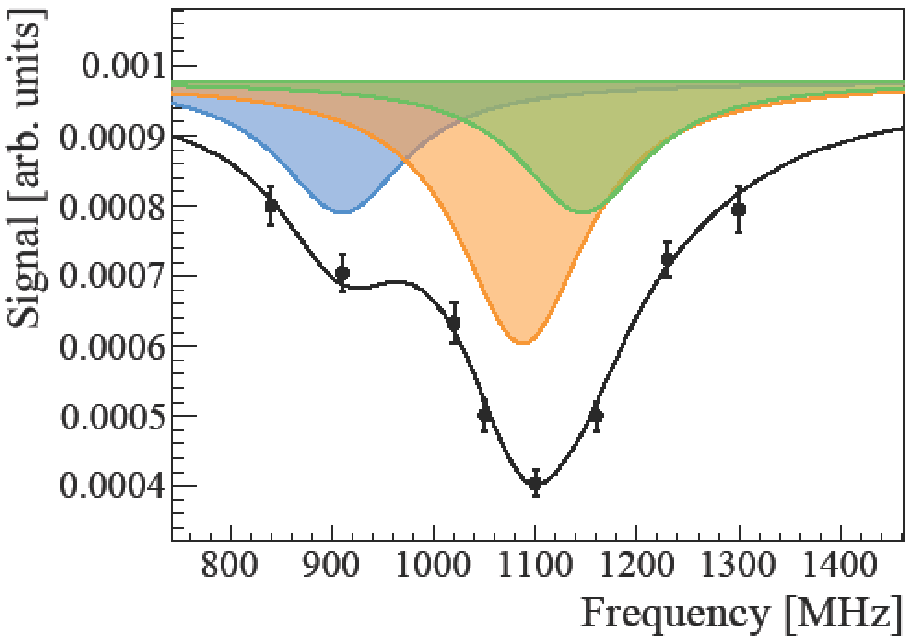


C. M. Rawlins, A. S. Kadyrov, A. T. Stelbovics, I. Bray, M. Charlton,
Phys. Rev. A 93, 012709 (2016)

Lamb shift measurement

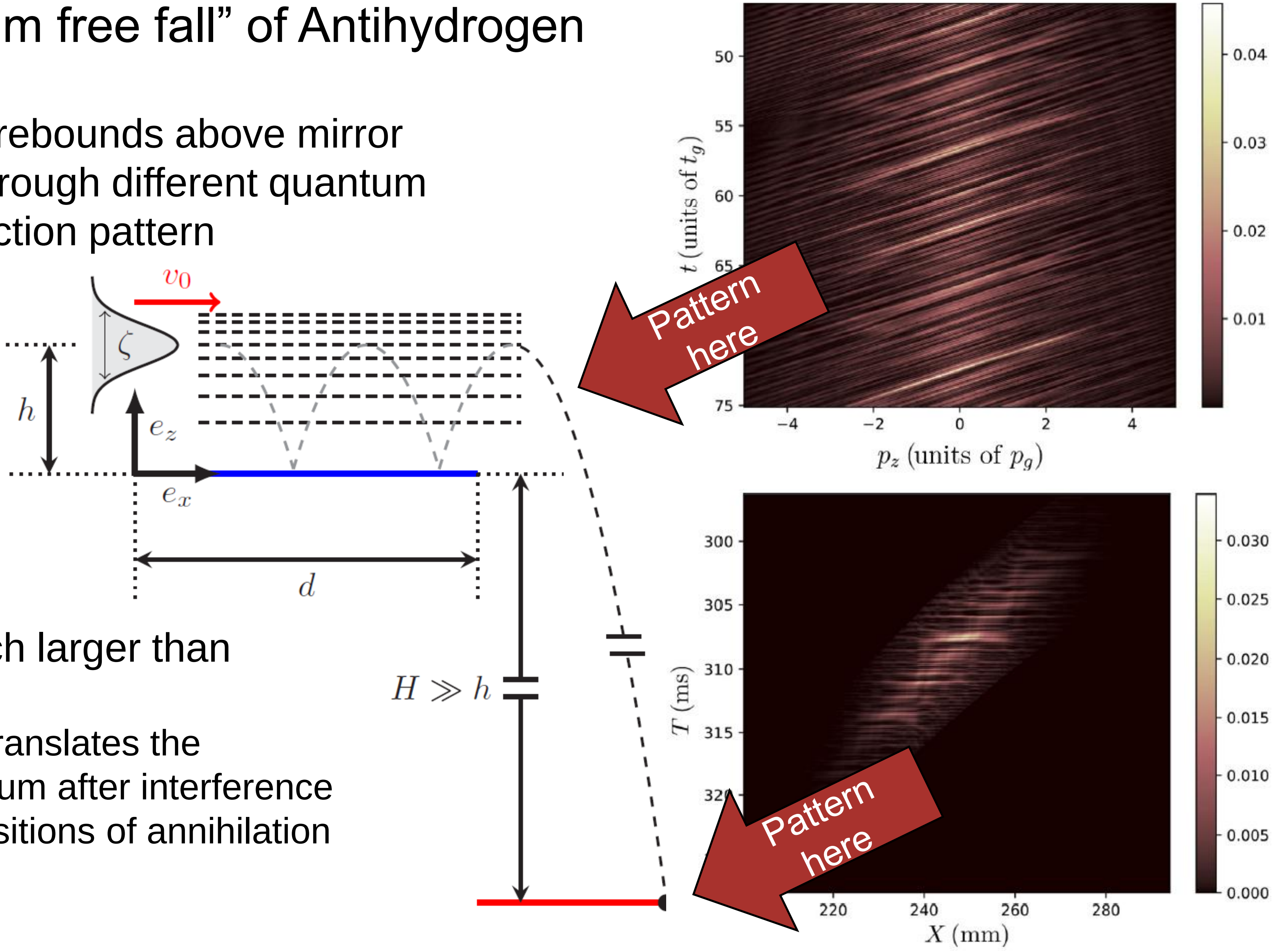


- Lamb shift setup commissioned in 2021 with hydrogen and currently running with ELENA H^- beam trough a C-foil
- Geant4 MC simulation, validated with H and M at PSI:
  - Estimated detection efficiency: $\varepsilon_{\text{LyA}} \times \varepsilon_{\text{Geo/Qnch}} = 16\%$
    - $\varepsilon_{\text{LyA}} = \varepsilon_{\text{MCP}} \times \varepsilon_{\text{QE}} = 40\%$ Measurement ETH
    - $\varepsilon_{\text{Geo/Qnch}} = 40\%$ SIMION simulation
- Assuming reaction tube, $3 \times 10^6 \bar{\mathrm{p}}$ and $10^8 \mathrm{Ps}$ per spill:
  - $\bar{\mathrm{H}}(2S)$: 0.3 per spill
  - Assume duty cycle of ELENA of 80%
  - Measure LS to 10MHz precision within 35 days



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

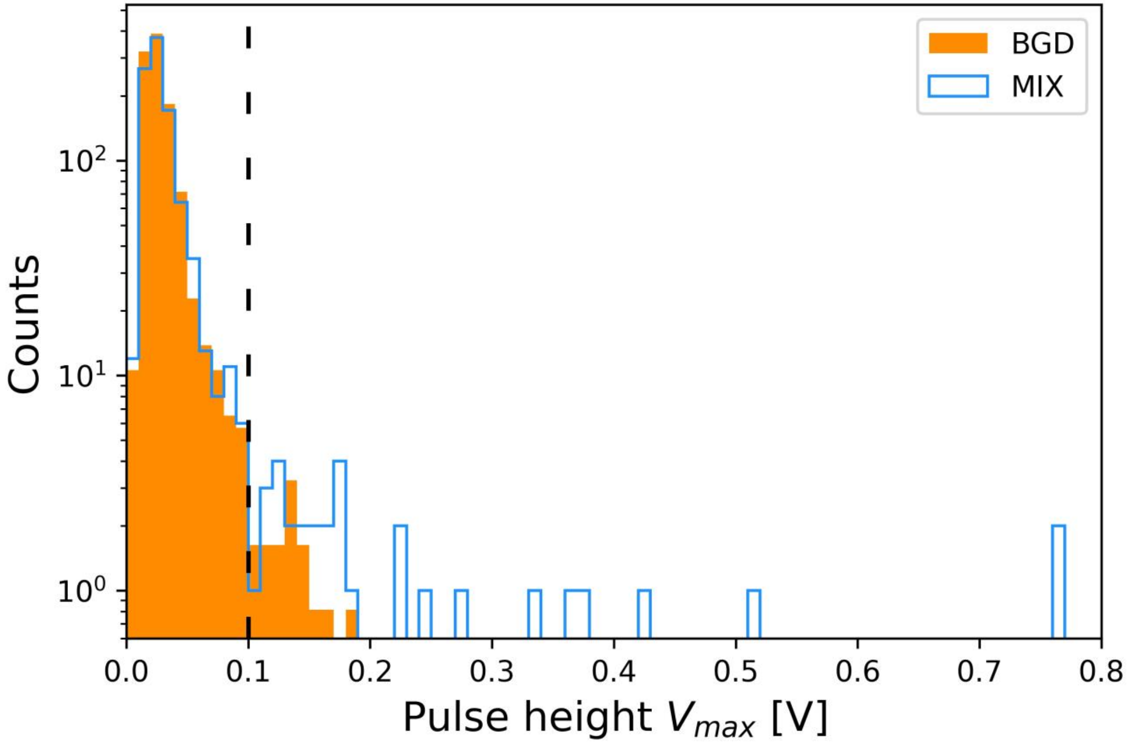


Crépin et al.,
Phys. Rev. A 99, 042119 (2019)

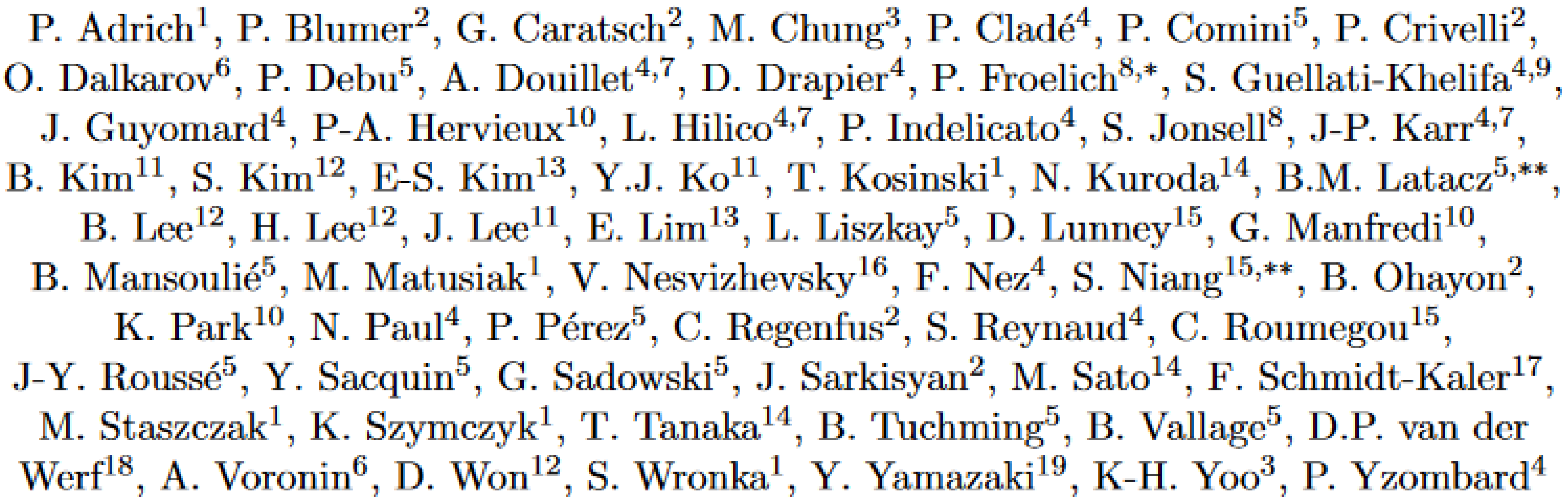
- Height of free fall must be much larger than dispersion of wave packet
  - Acts as diffraction process, translates the interaction time and momentum after interference zone into space and time positions of annihilation event
- Expected precision $\frac{\Delta\bar{g}}{\bar{g}} \sim 10^{-5}$

Summary

- During 2022 (2^{nd} 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
  - Installation and operation 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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