



GBAR experiment

Gravitational Behaviour of Antihydrogen at Rest

- Goal
- Experiment description
- Measurement of cross-section of $\bar{p} + \text{Ps} \rightarrow \bar{\text{H}} + e^-$
- Measurement of cross-section of $\text{H} + \text{Ps} \rightarrow \text{H}^- + e^+$
- Personal outlook towards anti-ion



Patrice Pérez
Université Paris-Saclay

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Models

- **Cosmology** models → same quantity of matter and antimatter, but Antimatter not seen!
- Energy content: matter (4%), dark matter(22%), dark energy (74%) of **unknown nature**
 - modified gravity? Or even antigravity? gravitational repulsion?
 - negative gravitational masses (*Chardin*) gravitational dipoles (*Blanchet, Hajdukovic*)
 - Bi-metric theories → no change in this Universe (*Damour, Hossenfelder, Petit*)
- **Quantum theories** (superstrings, SUSY, ...) contain tensor + scalar and vector
 - components of repulsive gravity (*Scherk*)
- **SM Extension** (*Kostelecky & Tasson*) → gravity may depend on flavour content

Antimatter experiments

Arrival time of 1 (? : 90 % CL) neutrino and 18 antineutrinos from SN1987a

S. Paksava et al. Phys Rev D 39 (1989) 1761

Observation of the effect of gravity on the motion of antimatter (ALPHA experiment)

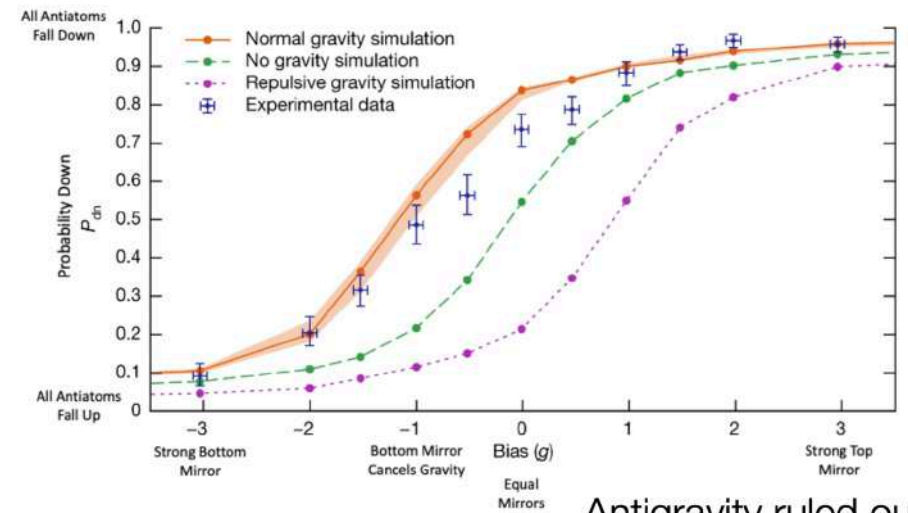
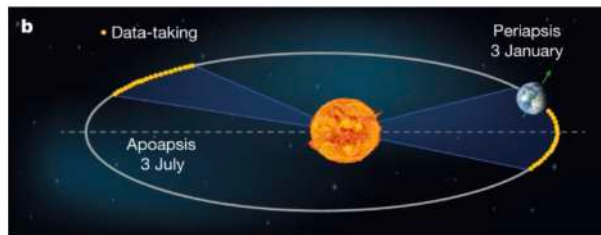
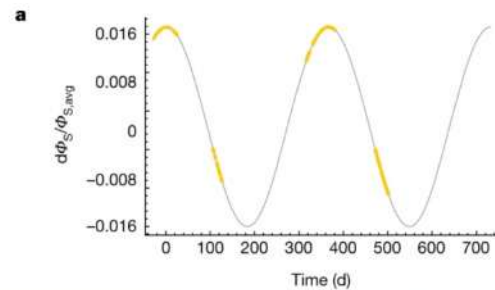
E.K. Anderson et al., Nature 621, 716–722 (2023)

$$\bar{g} = [0.75 \pm 0.13 \text{ (stat. + syst.)} \pm 0.16 \text{ (simu.)}] \times g$$

Antiproton vs H⁻ cyclotron frequency in Penning trap (BASE experiment)

M.J. Borchert et al., Nature 601, 53-57 (2022)

$$|\alpha_{g,D} - 1| < 0.03 \text{ (CL 0.68)}$$



Antigravity ruled out!

GBAR Principle

- free-fall measurement key:

initial velocity \rightarrow cold \bar{H}

- Doppler limit for neutrals ~ 1 mK

but can go lower with charged, i.e. $\bar{H}^+ = \bar{p} e^+ e^+$

- sympathetic cooling with already cooled matter ions

ex: $Be^+ \rightarrow 10 \mu K$

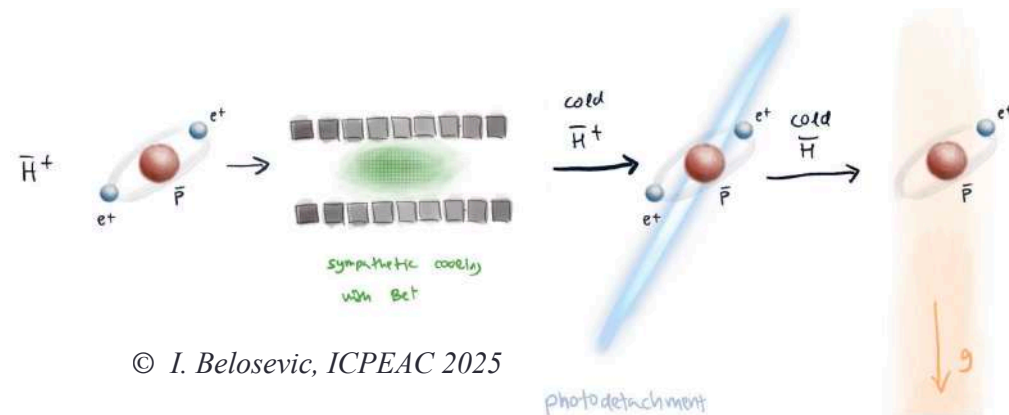
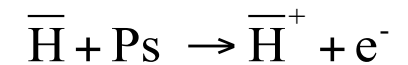
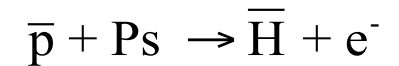
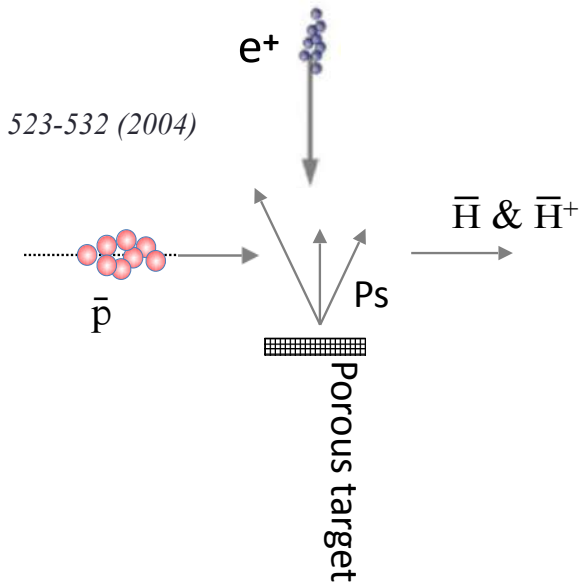
- Photo-detachment of one e^+

- Time of flight

J. Walz & T. Hänsch, General Relativity and Gravitation, 36 (2004) 561.

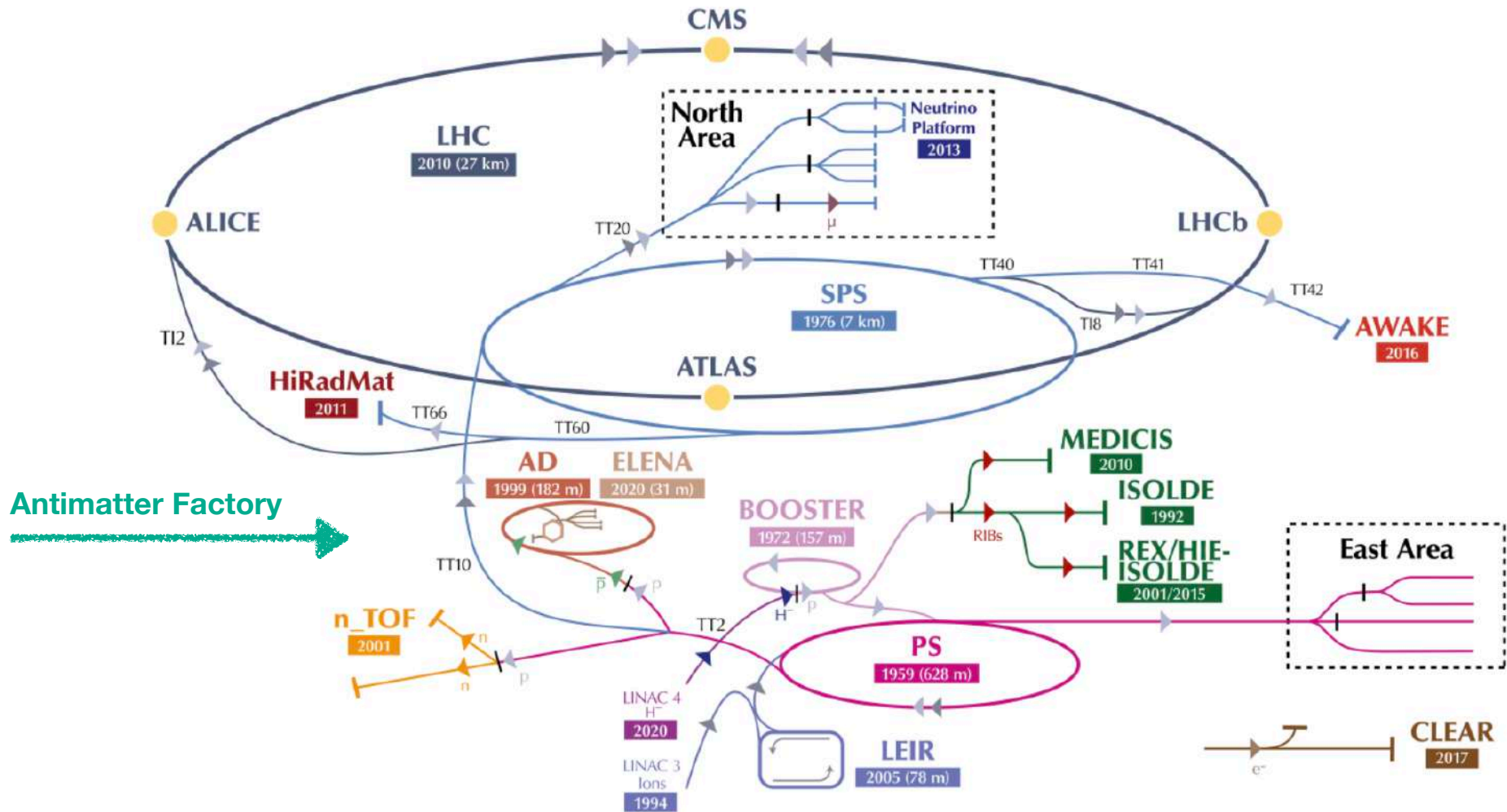
50 antihydrogen atoms at μK temperature \rightarrow gravitational acceleration measurement with 10^{-5} precision [*J. Guyomard et al., arXiv:2505.04771*]

P. Pérez & A. Rosowsky, NIM A 532, 523-532 (2004)

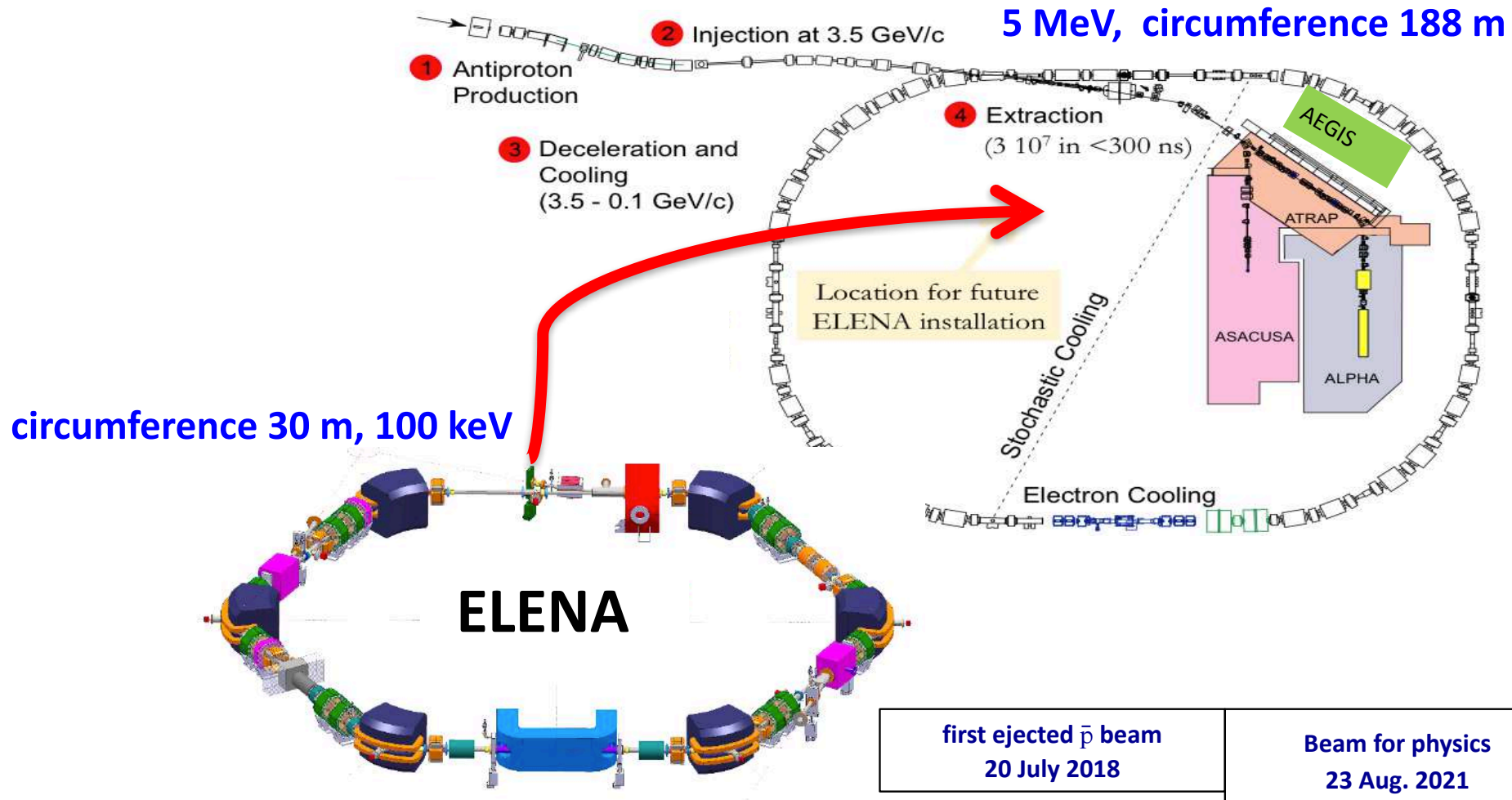


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CERN accelerator complex

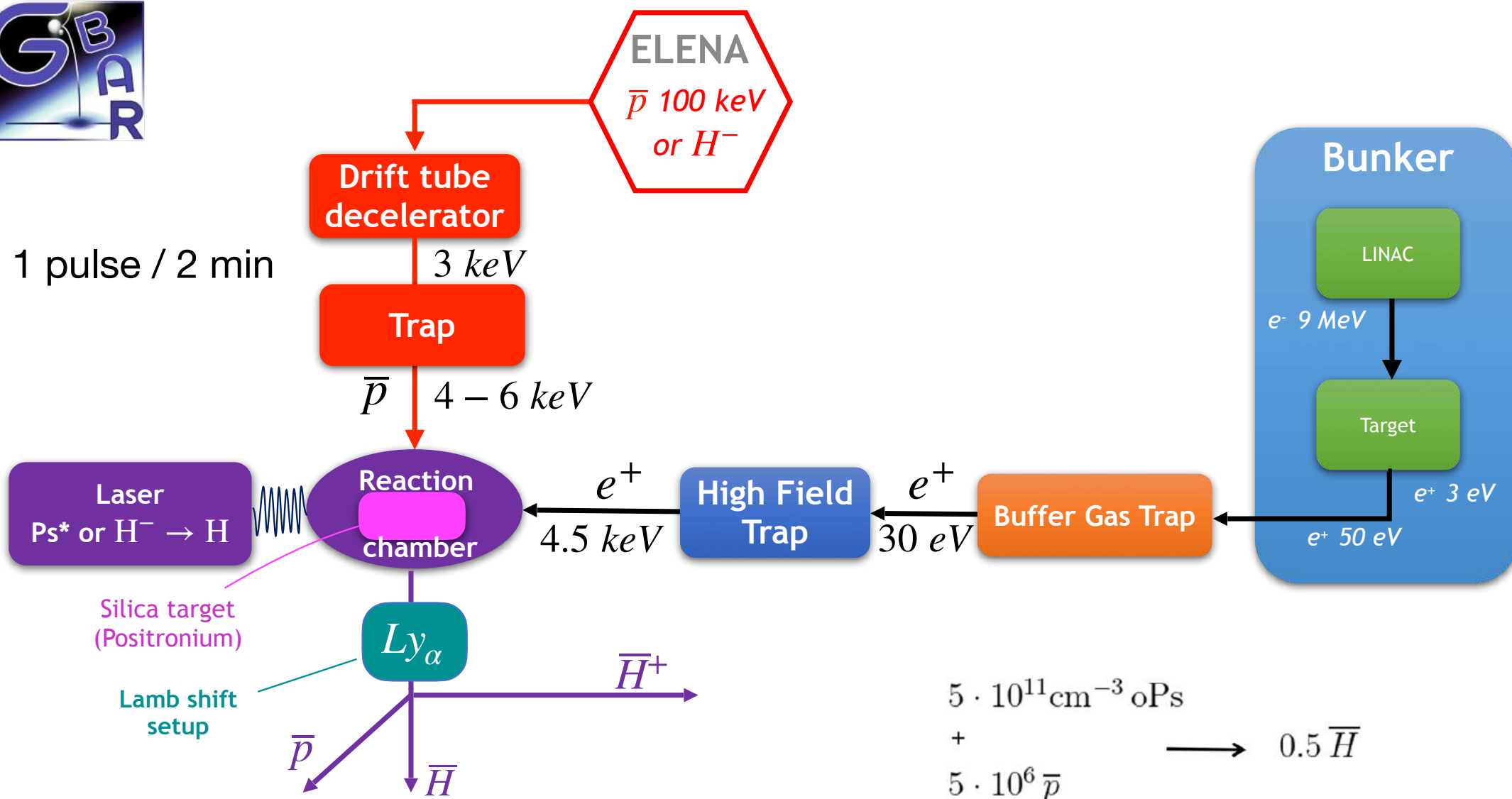


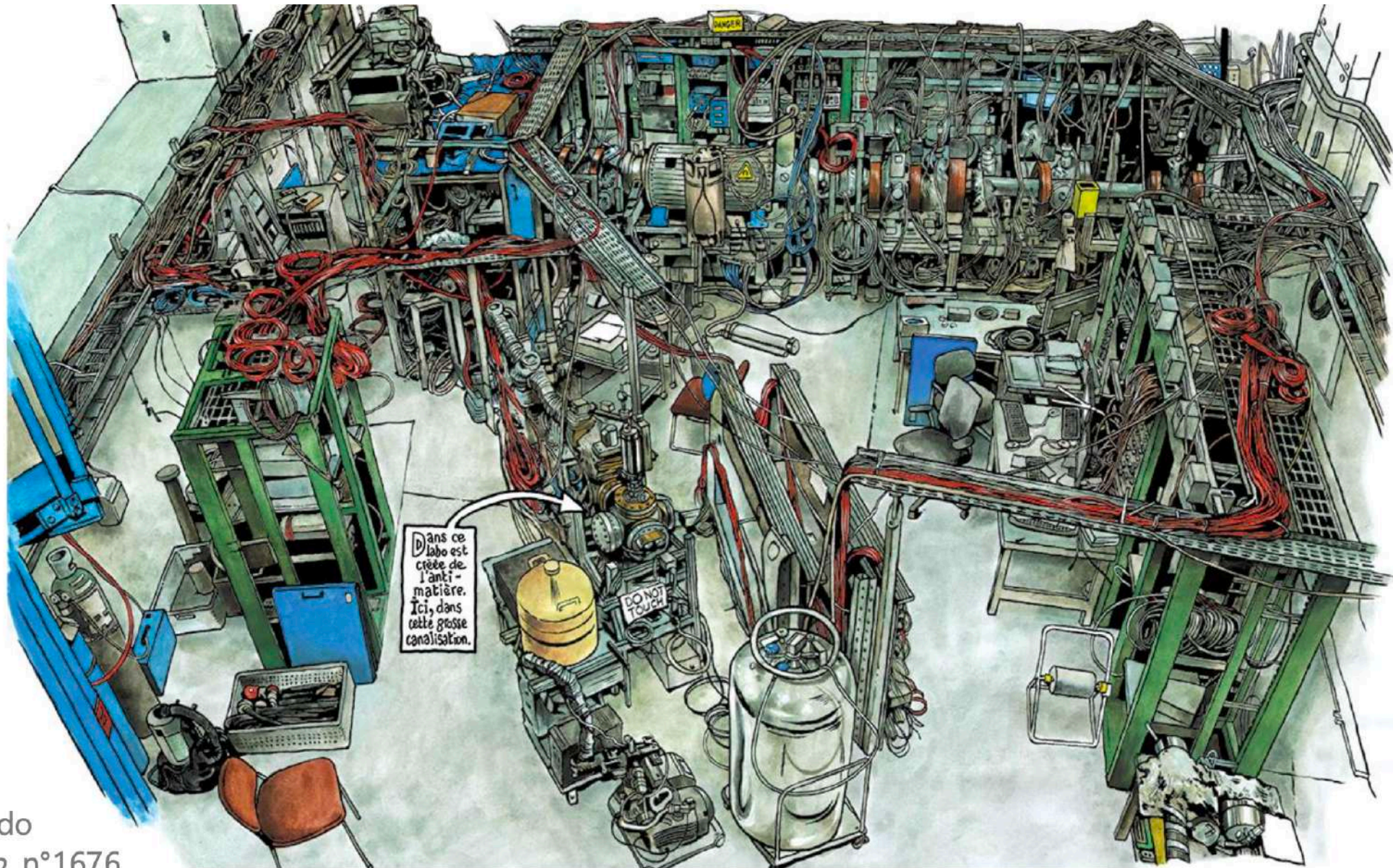
Antiprotons: CERN AD/ELENA





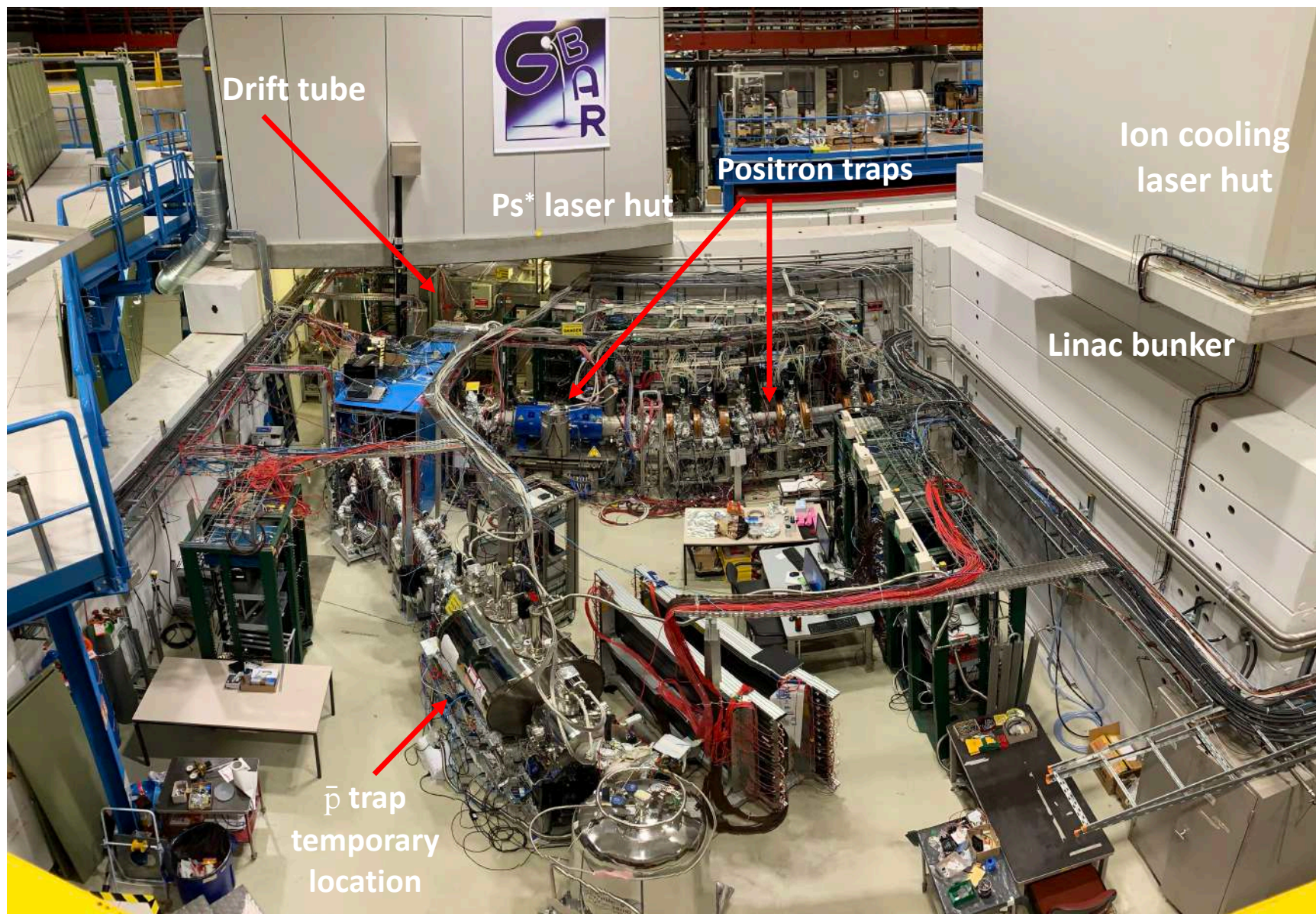
1 pulse / 2 min





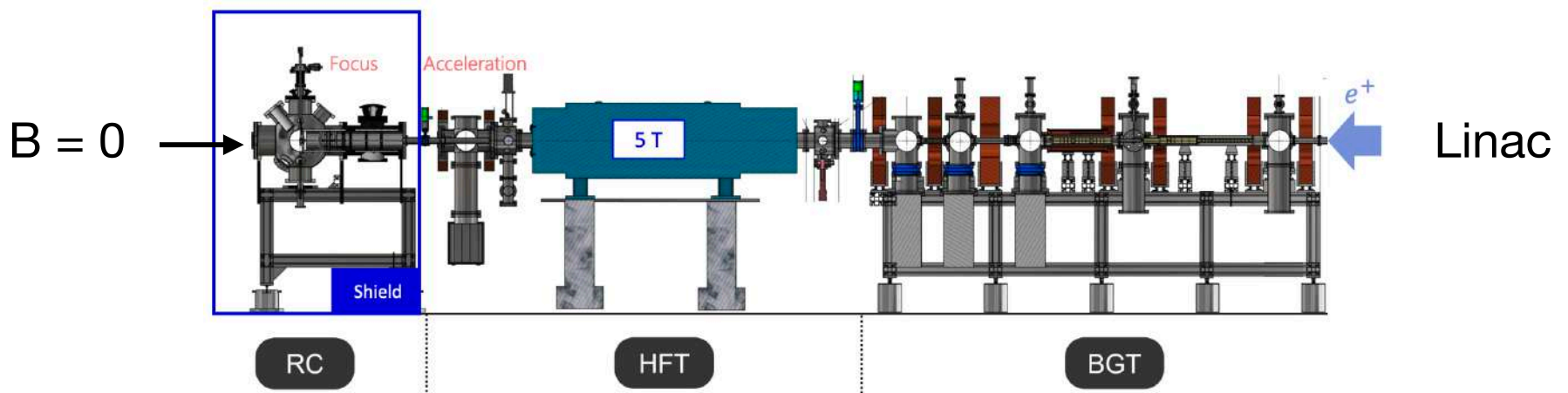
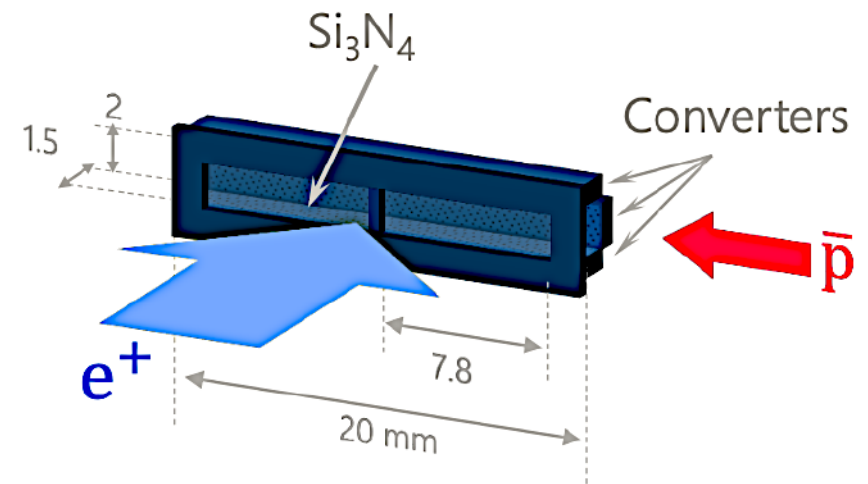
Dans ce labo est créée de l'anti-matière. Ici, dans cette grosse canalisation.

©Riss
©Charlie Hebdo
Charlie Hebdo, n°1676

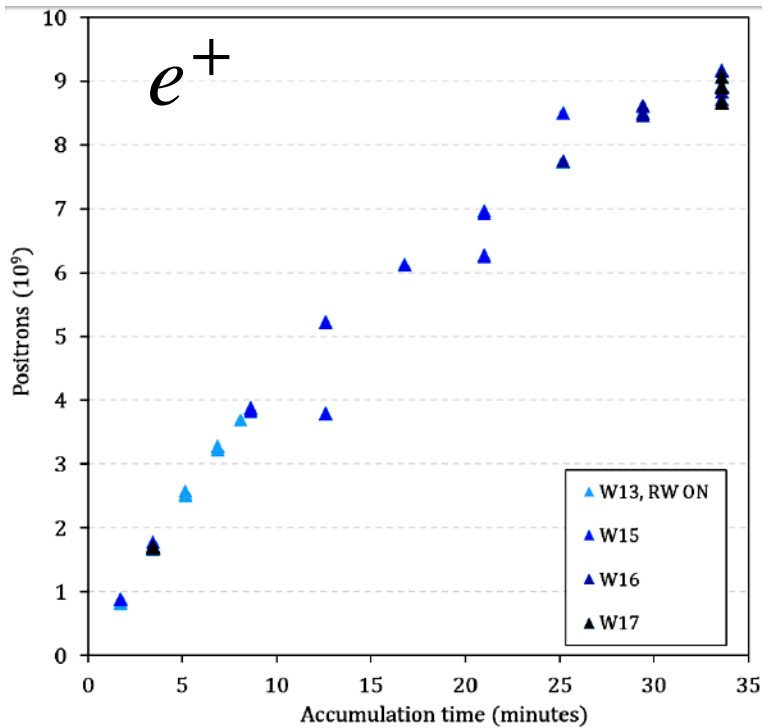


Reaction in $B = 0$ region

- Reaction volume made of
 - 3 plates coated with $e^+ \rightarrow P_S$ converter
 - 1 entrance window 30 nm Si_3N_4
- Challenge with present configuration
 - create intense e^+ and \bar{p} beams
 - focus those beams and inject into the reaction cavity



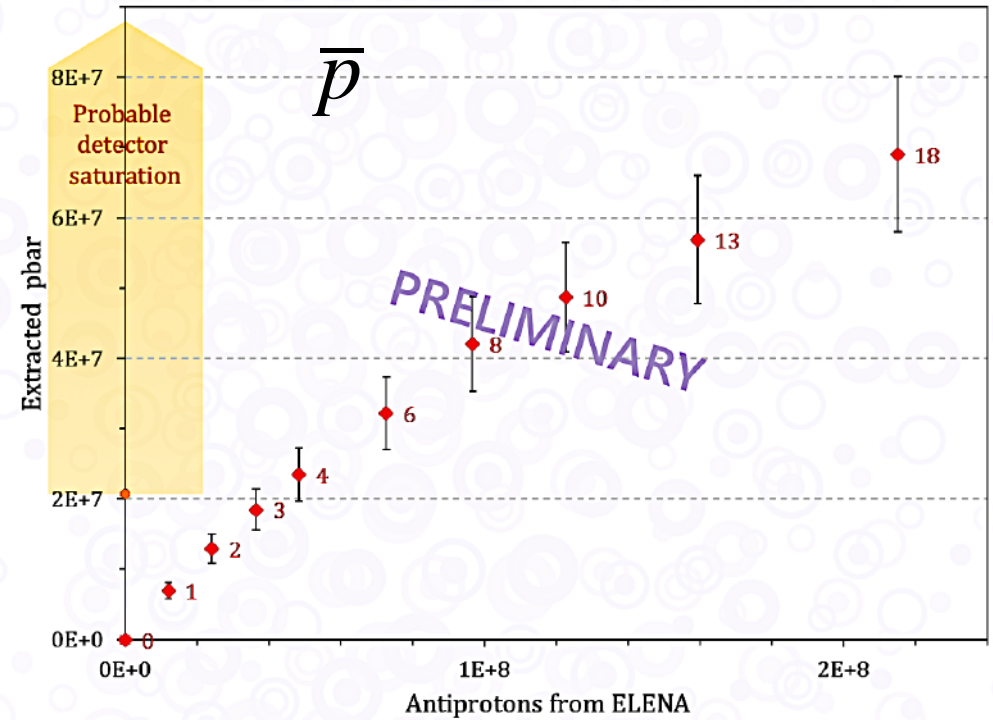
Trapped antiparticles



$6 \times 10^8 e^+$ per AD cycle (110 s)

$9 \times 10^9 e^+$ in 35 min.

L. Liskay, ICPA 20



$6 \times 10^6 \bar{p}$ per AD cycle (110 s)

$7 \times 10^7 \bar{p}$ in 35 min.

Transported antiparticles

$3 \times 10^8 e^+ \rightarrow 9 \times 10^7 e^+$ in target plane

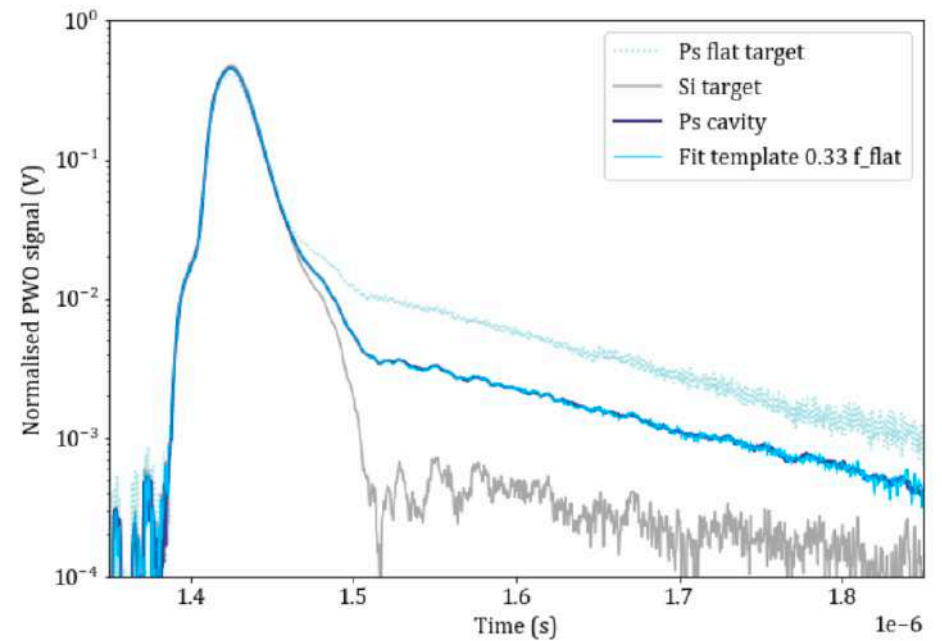
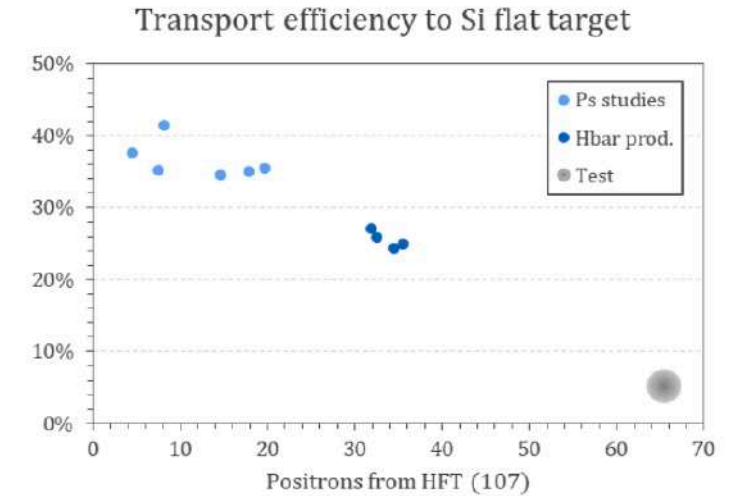
$\rightarrow 3 \times 10^7 e^+$ in target cavity

$\rightarrow 6 \times 10^6 oPs$ in cavity / AD shot

peak instantaneous density $\sim 6.5 \times 10^7 \text{cm}^{-3}$

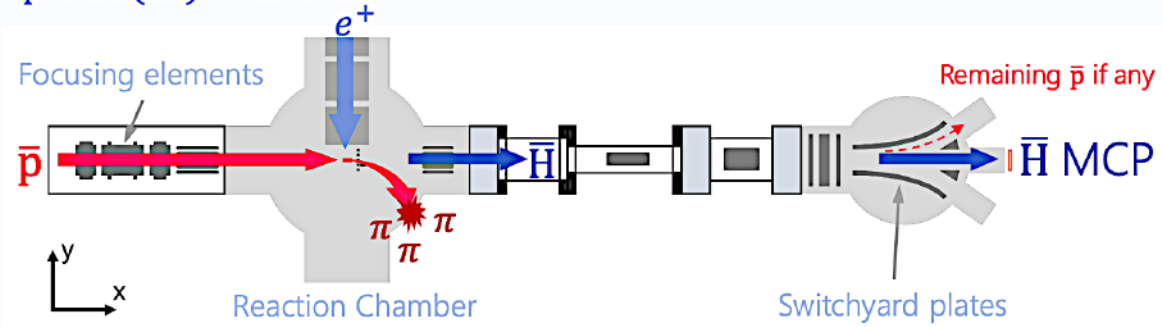
$8.5 \times 10^5 \bar{p}$ through target cavity at 6 keV

$4.5 \times 10^5 \bar{p}$ 4 keV

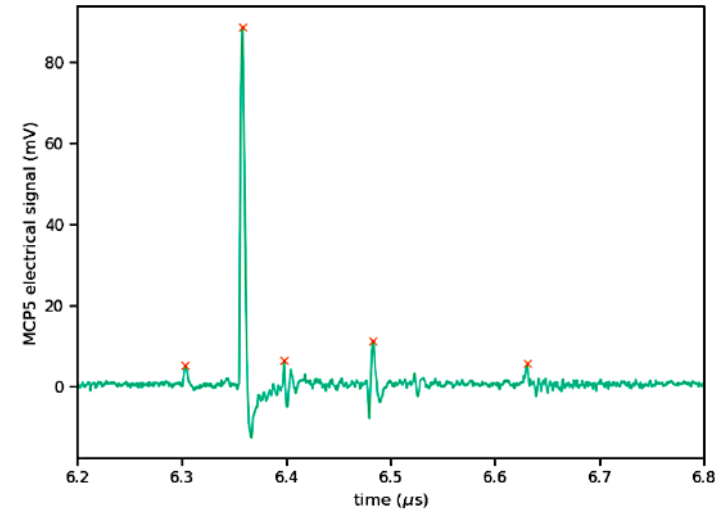
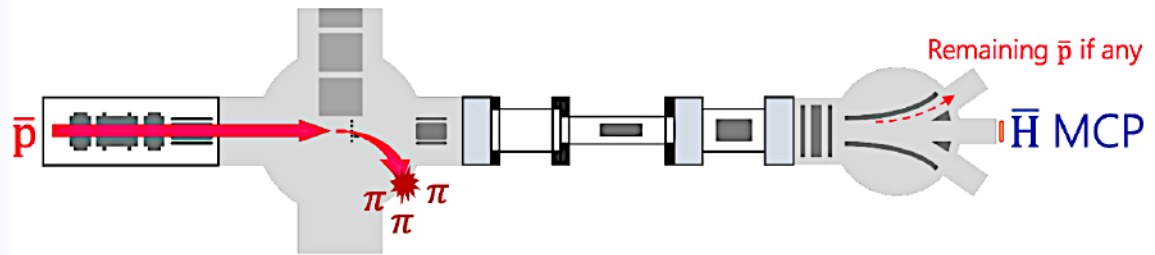


Antihydrogen formation cross-section measurement

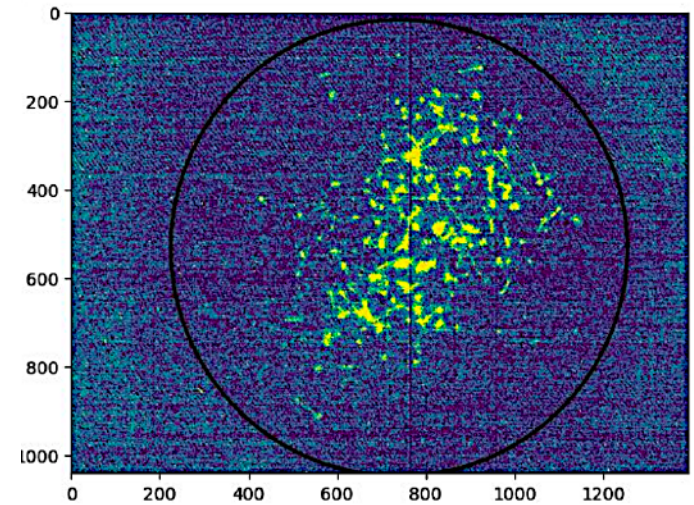
« Mixing » runs: $\bar{p} + \text{Ps}(1S) \rightarrow \bar{H} + e^-$



Background runs



single shot electrical signal



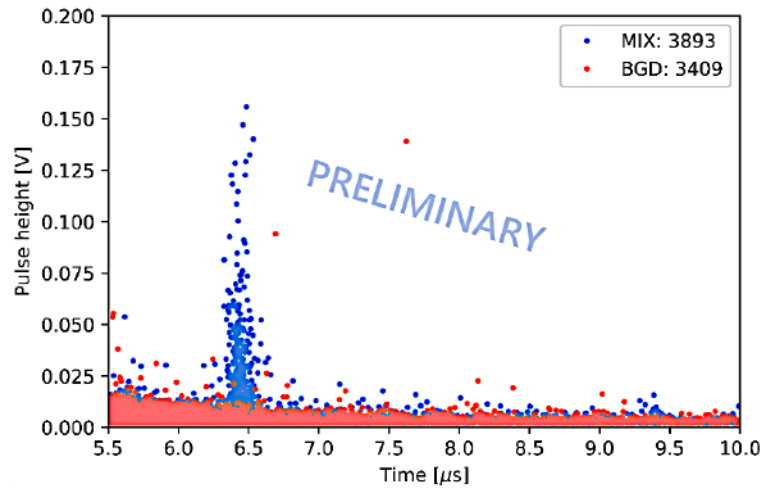
Antihydrogen « beamspot » at 6 keV

\bar{H} candidates

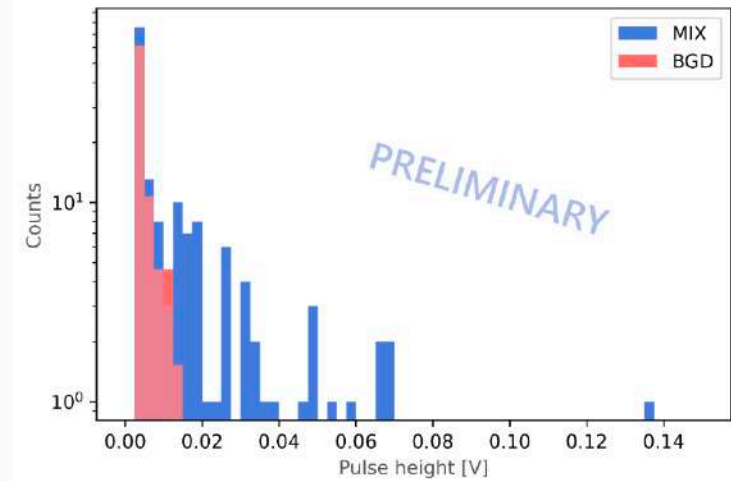
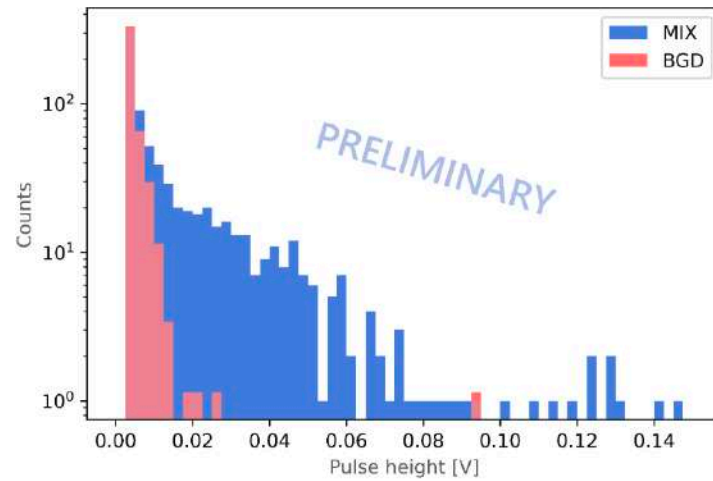
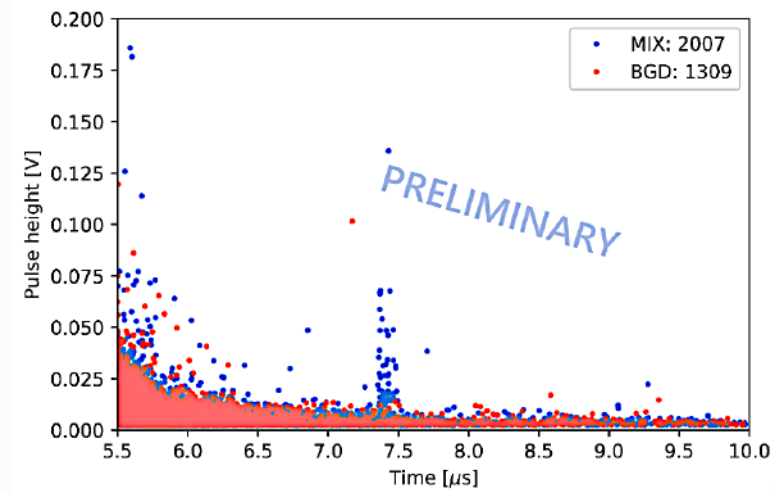
6 keV 3893 shots

4 keV 2007 shots

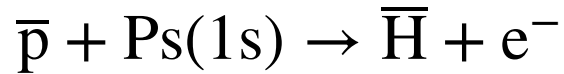
6 keV: $357.1 \pm 39.9(\text{stat}) \pm 31.9(\text{sys})$



4 keV: $76.8 \pm 18.5(\text{stat}) \pm 6.9(\text{sys})$



Preliminary cross section measurement



Theory:

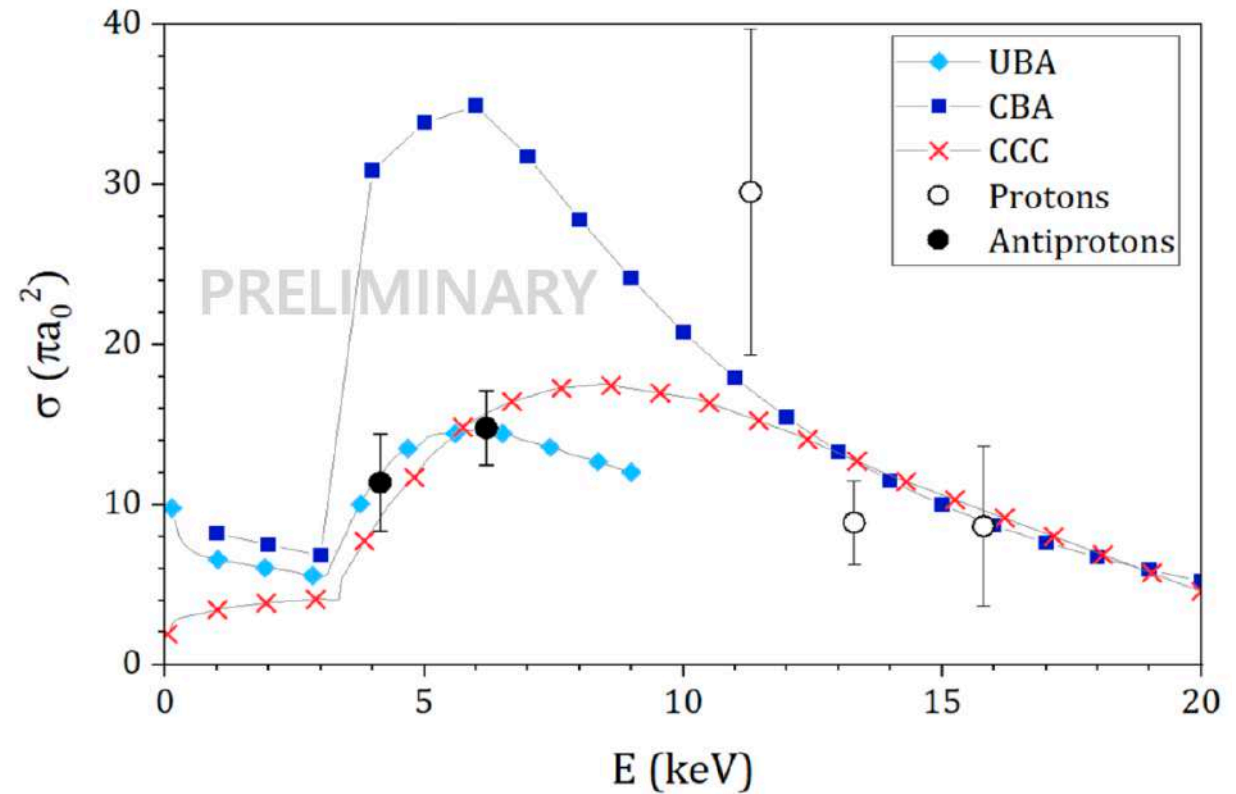
[UBA] J. Mitroy, Phys. Rev. A 52, 2859 (1995)

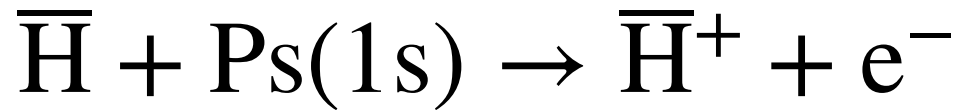
[CBA] K. Lévêque-Simon & P.A. Hervieux,
Phys. Rev. A 107, 052813 (2023)

[CCC] A. S. Kadyrov et al., Phys. Rev. Lett. 114, 183201
(2015)

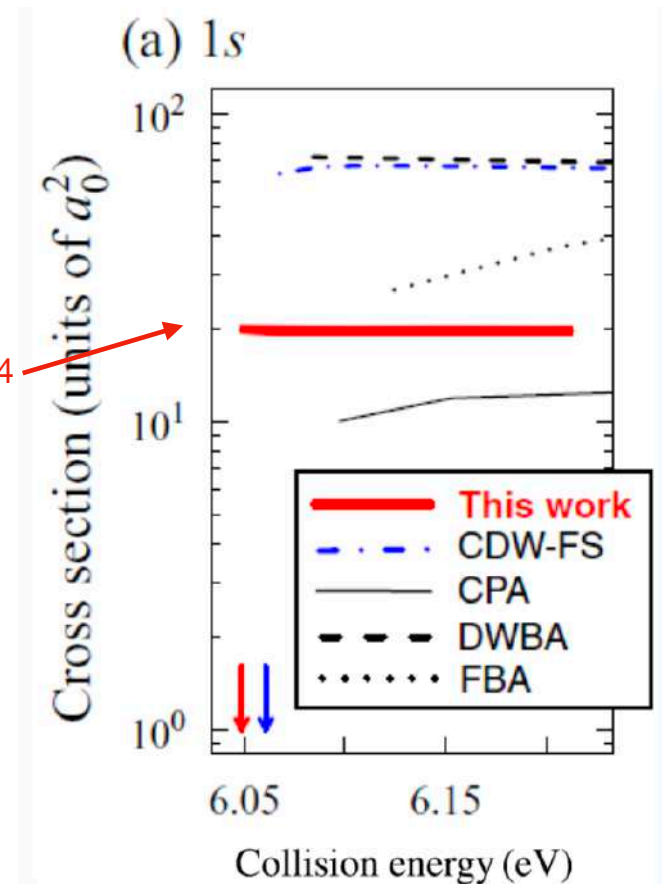
Proton experiment:

J. P. Merrison et al., Phys. Rev. Lett., 78, 2728 (1997)





- Models predict largely different x-sections
- $\bar{\text{H}}$ flux too low
- \rightarrow measure $\text{H} + \text{Ps} \rightarrow \text{H}^- + e^+$
 - use pulsed H^- beam from ELENA
 - obtain $\text{H}(1s)$ by photo detachment in flight
 - $\sim 2 \times 10^5$ H through the target cavity every 15 s
 - expect $\sim 0.001 - 0.02$ H^- per shot

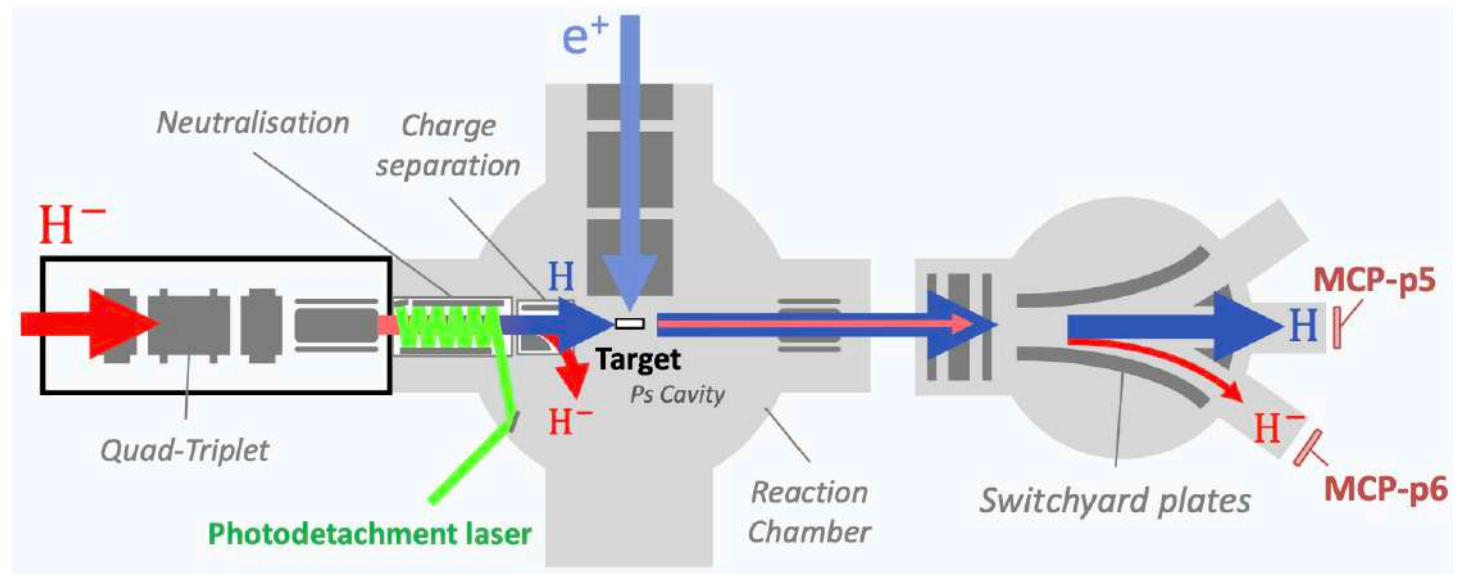


Adapted from:
Yamashita *et al.*,
Phys Rev A 105, 052812 (2022)

$H + Ps \rightarrow H^- + e^+$ measurement scheme

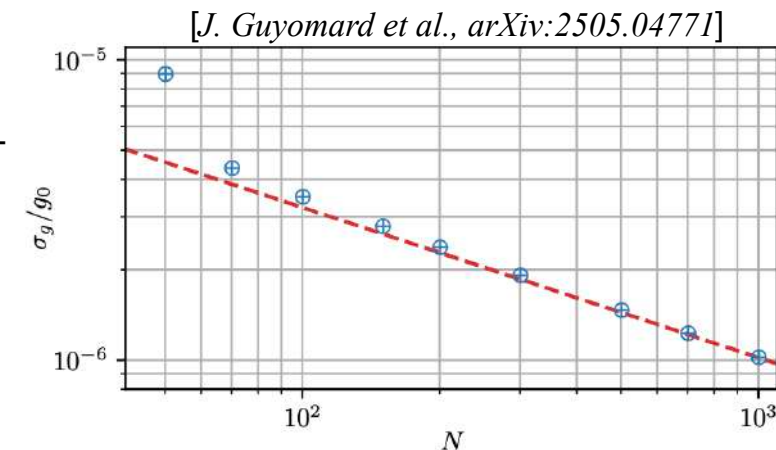
compare rates
with/without oPs

Currently taking data



Personal outlook toward producing anti-ions

- Accumulated numbers of antiparticles approach estimates in experiment's proposal
- But transport to target in $B = 0$ region has too small efficiency
 - > present configuration not adapted for anti-ion production
- Production inside trap would remove transport problem —> reconfigure layout
- Estimate with presently obtained trapped antiparticles in 3 AD cycles, i.e. 6 minutes
 - $3 \times 10^9 e^+ \rightarrow 7 \times 10^8 oPs$
 - $2 \times 10^7 \bar{p} \rightarrow 2 \times 10^{-3} - 4 \times 10^{-2} \bar{H}^+$
 - 0.02 - 0.4/h —> 4 weeks 10 - 250 \bar{H}^+ produced
 - 50% detected —> $\Delta g/g = 10^{-5}$





Many thanks to
SSP2025 organisers



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