ETH zürich

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Measurement of the Lamb shift of Antihydrogen atoms in GBAR

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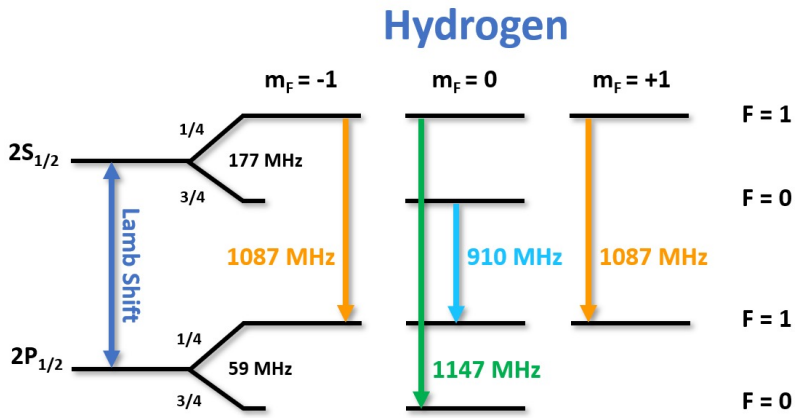
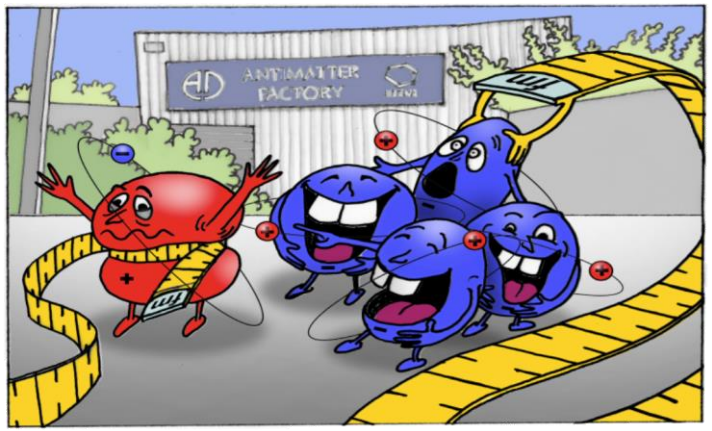
Swiss National
Science Foundation

Antihydrogen – A blossoming field of research

- Baryon – anti-baryon asymmetry in the Universe
- New theories: e.g. Standard Model Extension (SME)
  - Built from SM, General Relativity and includes Lorentz- and CPT violating operators
  - Coefficients to be determined experimentally
- Stringent test of CPT by measuring the Lamb shift of antihydrogen ($\overline{\mathrm{H}}$)!
  - At level of 100 ppm we can determine the antiproton charge radius at 10% level

Lamb shift in hydrogen atom – birth of QED

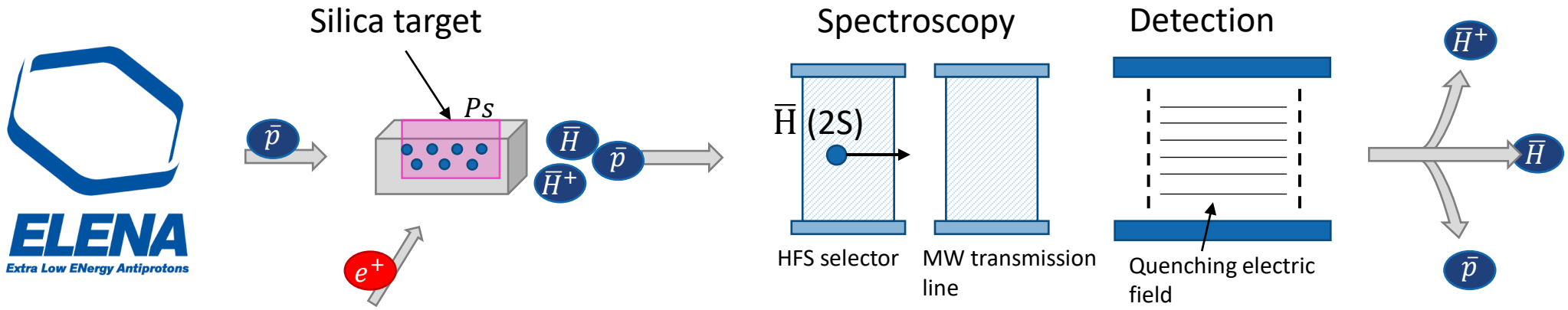




- Solution of Dirac equation degenerate for $2S_{1/2}$ and $2P_{1/2}$ states
- 1947: W. Lamb & R. Retherford
  - $\Delta E(2P_{1/2} - 2S_{1/2}) \neq 0$
  - Self-energy contribution (leading effect)
- Determine RMS charge radius of proton/antiproton [*]
  - Finite size effects (affects primarily S state)
  - $\Delta E_{\mathrm{nucl}} = \frac{2}{3}\frac{(Z\alpha)^4}{n^3} m_{\mathrm{R}}^3 R_{\mathrm{p}}^2$

[*] P. Crivelli, D. Cooke, M. W. Heiss,
"Antiproton charge radius", Phys. Rev. D 94, 052008 (2016)

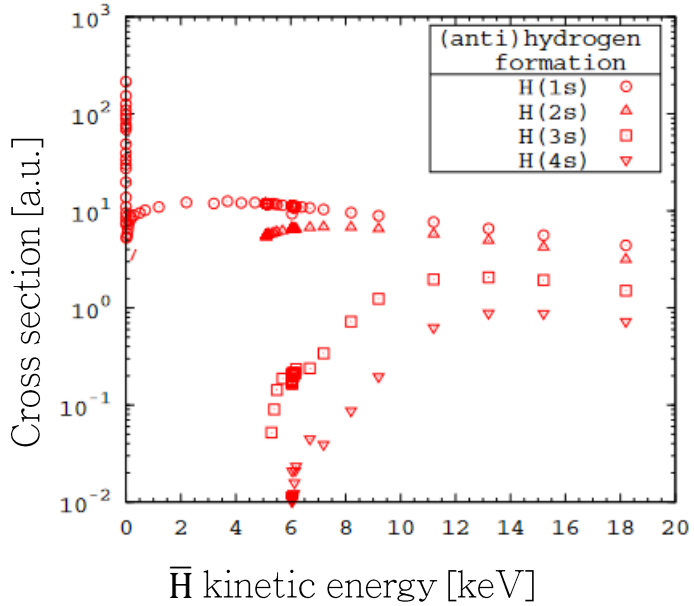
Lamb shift of $\overline{\mathrm{H}}$ in GBAR



Charge exchange reaction [*]:

- Lamb shift: $\bar{\mathrm{p}} + \mathrm{Ps} \rightarrow \overline{\mathrm{H}} + \mathrm{e}^-$
- Free Fall: $\overline{\mathrm{H}} + \mathrm{Ps} \rightarrow \overline{\mathrm{H}}^+ + \mathrm{e}^-$

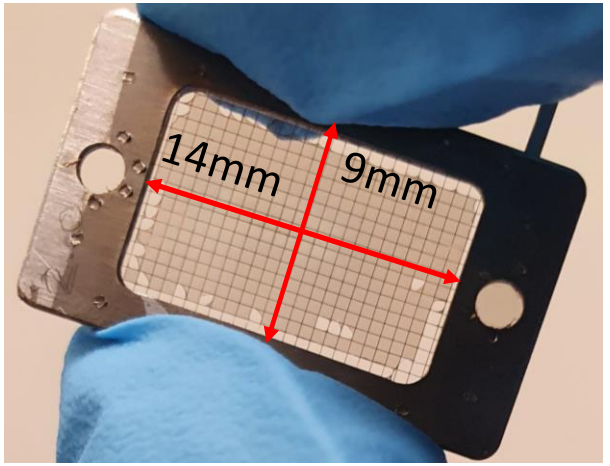
- 2S state: ~10%
- Metastable due to selection rule
- $\tau\left(2S_{1/2}\right) \sim 100\ \mathrm{ms}$

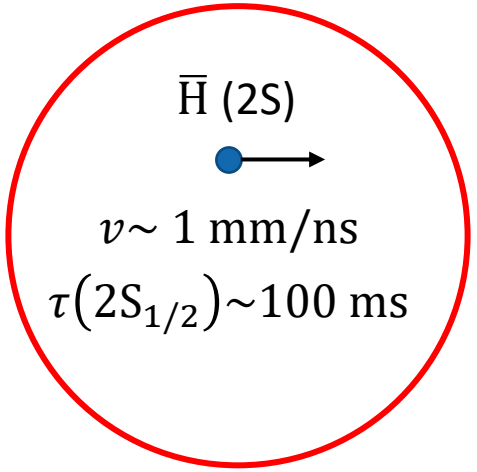


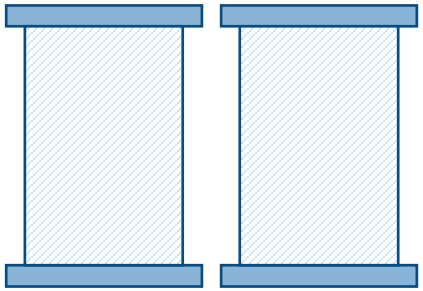
[*] C. M. Rawlins, A. S. Kadyrov, A. T. Stelbovics, I. Bray, M. Charlton,
Phys. Rev. A 93, 012709 (2016)

Lamb shift of $\overline{\mathrm{H}}$ - Hydrogen production

- Hydrogen: protons hitting C-foil target
- Carbon foil on copper grid
  - Cu mesh: 45 LPI → 88% transmission
  - C foil: ~ 2.0 µg/cm^2
  - 80% neutrals of which 5-10% are in the 2S state







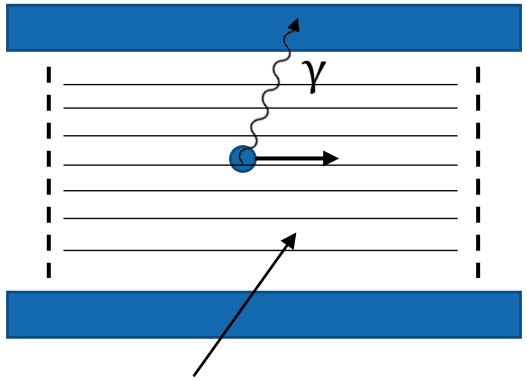
HFS selector

MW transmission line

$\overline{\mathrm{H}}$ (2S) → $\overline{\mathrm{H}}$ (2P)

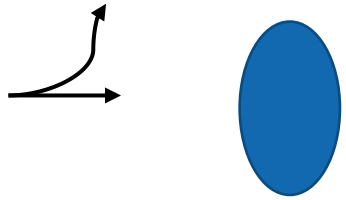
$\tau(2P_{1/2})\sim 1\ \mathrm{ns}$

CsI coated MCP



Quenching electric field

Deflection of charged particles

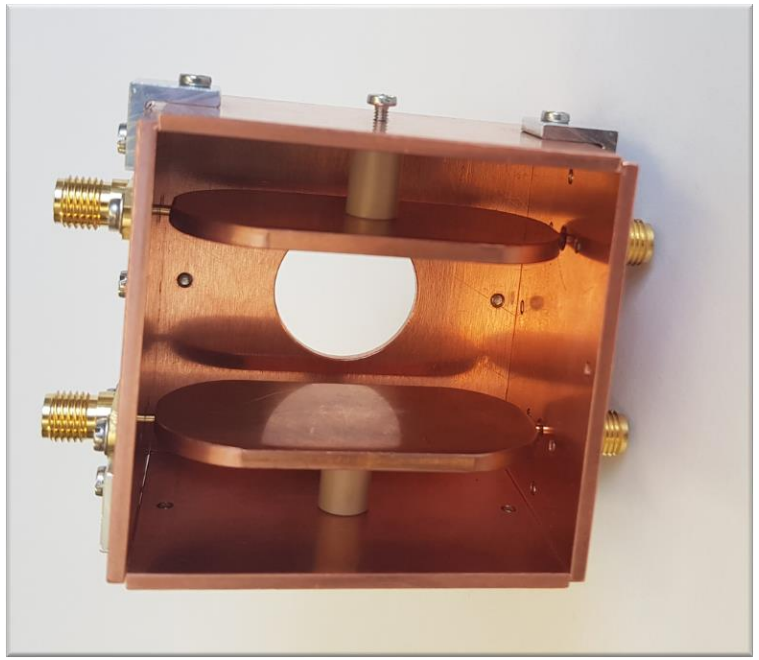


MCP with phosphor screen

$\overline{\mathrm{H}}$ (2S) → $\overline{\mathrm{H}}$ (2P) → $\overline{\mathrm{H}}$ (1S) + γ (121.5 nm)

Lamb shift of $\overline{\mathrm{H}}$ - MW system

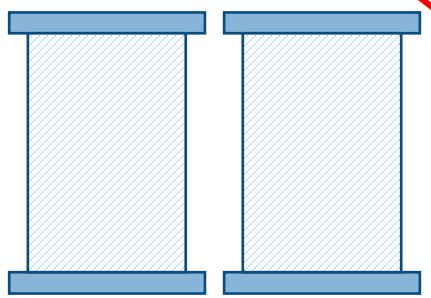
- MW transmission line induces 2S → 2P at resonance frequency



$\overline{\mathrm{H}}$ (2S)

$v \sim 1\ \mathrm{mm/ns}$

$\tau(2S_{1/2}) \sim 100\ \mathrm{ms}$



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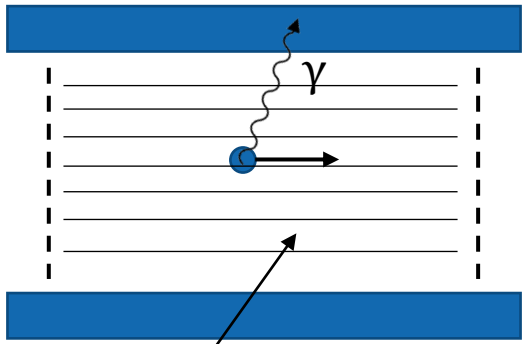

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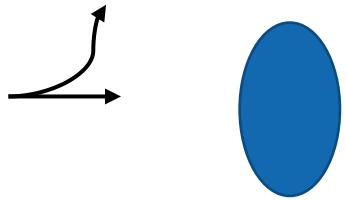

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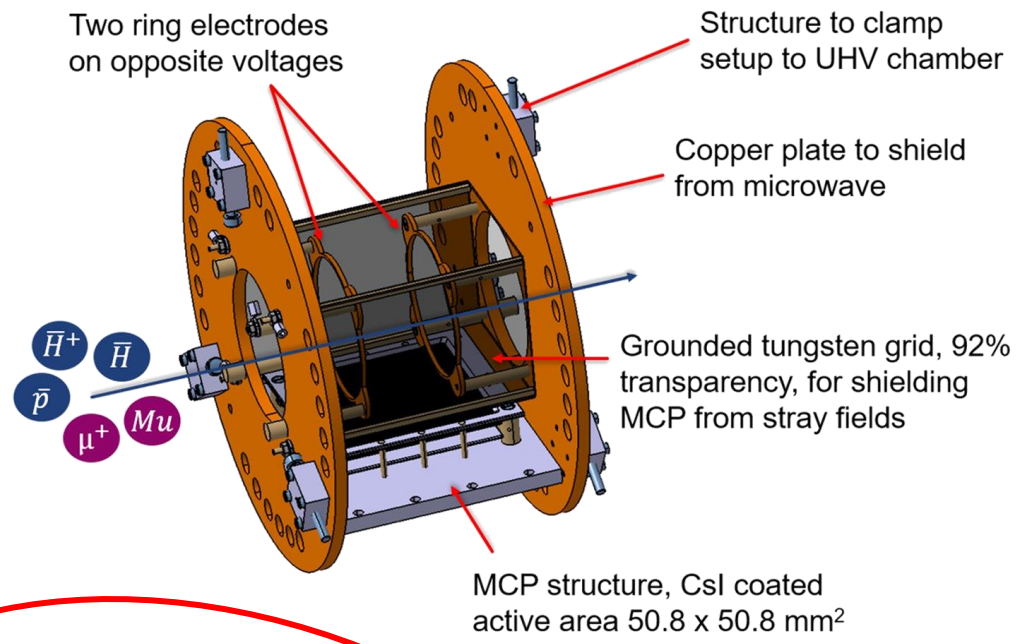
Lamb shift of $\overline{\mathrm{H}}$ - Detection setup

- E-field quenches remaining 2S → 2P states
- 4 CsI coated Microchanel plates (MCP) detect LyA photons
  - Estimated detection efficiency: ~40%
- Measure survival probability



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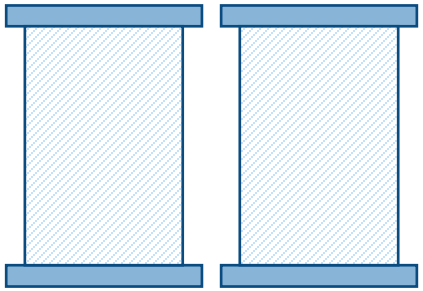

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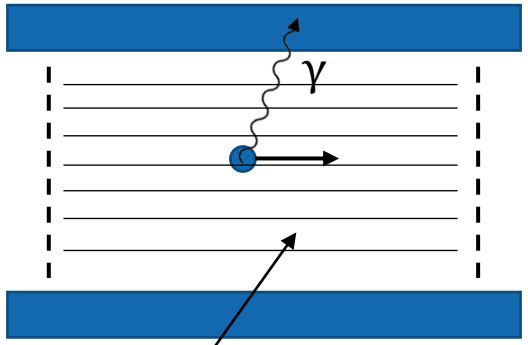

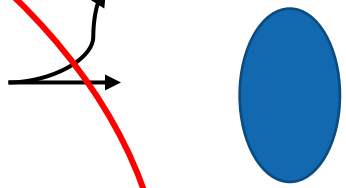

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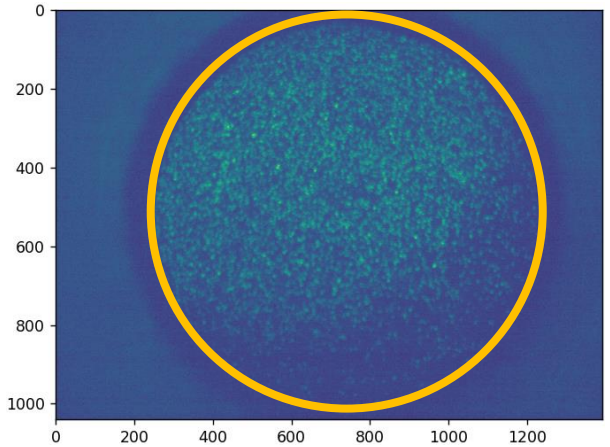
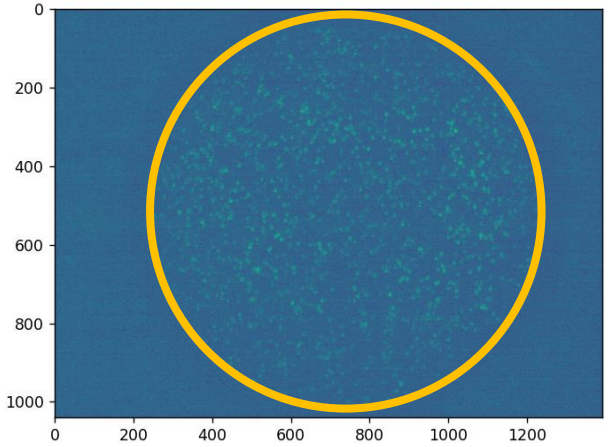


Charged particles detected on the MCP after the LyA setup

Deflection



Neutrals detected on the MCP after the LyA setup

$\overline{\mathrm{H}}$ (2S)

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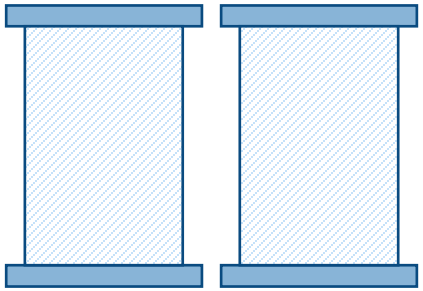
$\tau(2S_{1/2}) \sim 100\ \mathrm{ms}$



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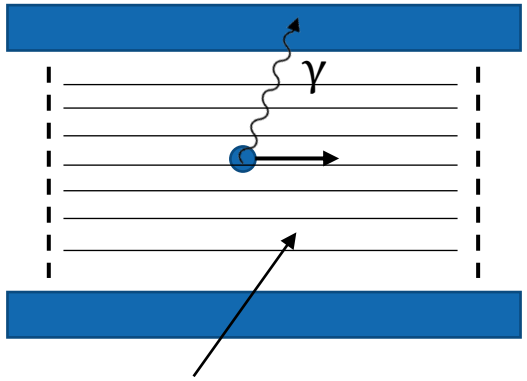

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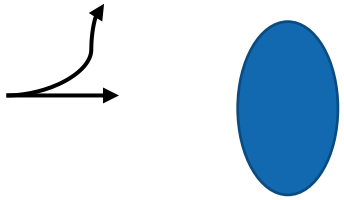
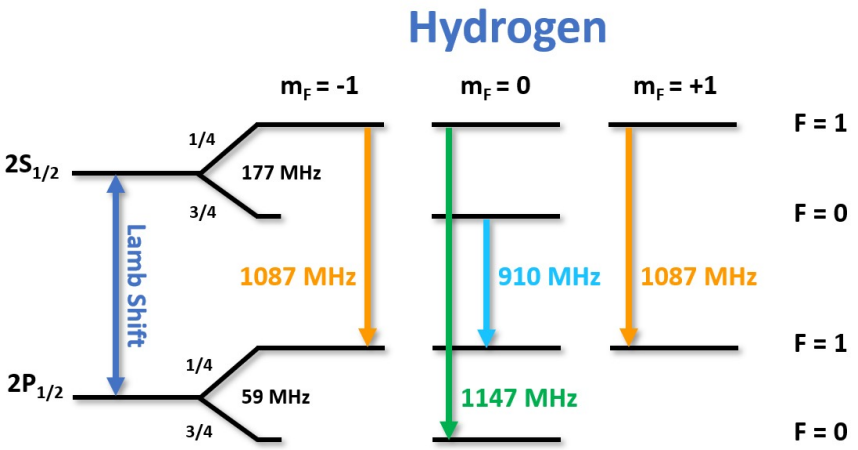


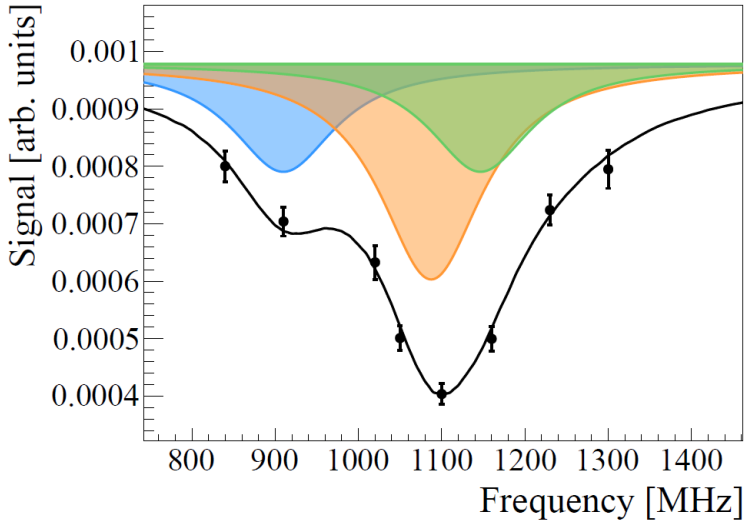
MCP with phosphor screen

Commissioning of Lamb shift setup with Hydrogen

- Measurement @ PSI
- Same MW transmission line
- Analogous LyA detection
- $\Delta E_{\mathrm{LS}} = 1057.5 \pm 4.7\ \mathrm{MHz}$

- $\Delta E_{\mathrm{theo}} = 1057.839 \pm 0.004\ \mathrm{MHz}$ [*]
- Most precise measurement at kHz range [**]





[*] K. Pachucki et al
J. Phys. B: At. Mol. Opt. Phys. 29 177

[**] N. Bezginov, T. Valdez, M. Horbatsch, A. Marsman, A. C. Vutha, E. A. Hessels
Science 365, 1007-1012 (2019)

Summary and outlook

- Measurement setup is installed in GBAR.
- First Lamb shift transitions were detected for Hydrogen atoms.
- Thanks to the ELENA ring and the GBAR experiment a Lamb shift of $\overline{\mathrm{H}}$ seems possible at a level of 100 ppm.
- Lorentz and CPT test and allows to determine the antiproton charge radius at 10% level.

- First antiproton beamtime after LS2 started 23.08.21
- System ready to hunt LyA photons of $\overline{\mathrm{H}}$ atoms.
- 2022: first line shape measurement with a precision of 10 MHz for 1000 events.

Backup

$\overline{H}$ production in the GBAR experiment

- Gravitational Behaviour of Antimatter at Rest
- Determine gravitational acceleration of $\overline{H}$ in Earth's gravity

- Unique characteristic: $\overline{H}^+$ via two charge exchange production

$$\bar{p} + Ps \rightarrow \overline{H} + e^-$$

$$\overline{H} + Ps \rightarrow \overline{H}^+ + e^-$$

- Lamb shift simultaneously measured: proposed and developed by ETHZ