ASACUSA: Measuring the Antiproton Mass and Magnetic Moment

Dezső Horváth

on behalf of the ASACUSA Collaboration

horvath.dezso@wigner.mta.hu

Wigner Research Centre for Physics,

Institute for Particle and Nuclear Physics, Budapest, Hungary

&

ATOMKI, Debrecen, Hungary

CPT Invariance

Charge conjugation: $C|\mathsf{p}(r,t)> = |\overline{\mathrm{p}}(r,t)>$

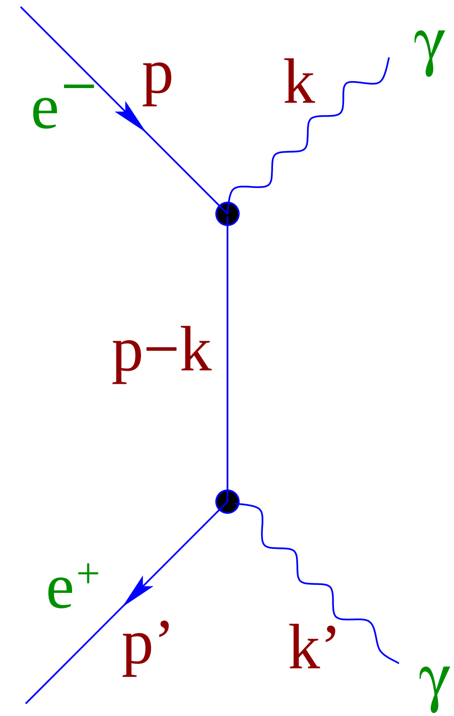
Space reflection: $P|\mathsf{p}(r,t)> = |\mathsf{p}(-r,t)>$

Time reversal: $T|\mathsf{p}(r,t)> = |\mathsf{p}(r,-t)>$

Basic assumption of field theory:

$CPT|\mathsf{p}(r,t)> = |\overline{\mathrm{p}}(-r,-t)> \sim |\mathsf{p}(r,t)>$

meaning free antiparticle $\sim$ particle going backwards in space and time.



Giving up CPT one has to give up:

- locality of interactions $\Rightarrow$ causality, or
- unitarity $\Rightarrow$ conservation of matter, information, ... or
- Lorentz invariance

The Antiproton Decelerator at CERN

has been built to test *CPT* invariance

Particle = – antiparticle ?

Three experiments test CPT:

ATRAP: $q(\overline{\mathrm{p}})/m(\overline{\mathrm{p}}) \leftrightarrow q(\mathsf{p})/m(\mathsf{p})$

$\overline{\mathrm{H}}(2S-1S) \leftrightarrow \mathrm{H}(2S-1S)$

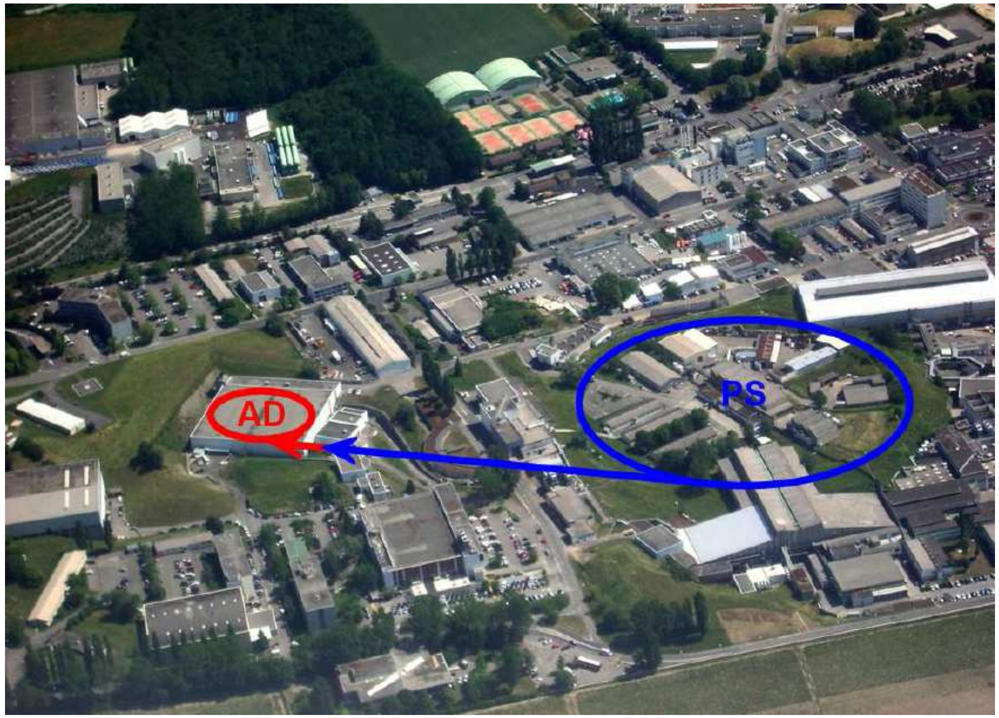
ALPHA: $\overline{\mathrm{H}}(2S-1S) \leftrightarrow \mathrm{H}(2S-1S)$

ASACUSA: $q(\overline{\mathrm{p}})^2 m(\overline{\mathrm{p}}) \leftrightarrow q(\mathsf{p})^2 m(\mathsf{p})$

$\mu_\ell(\overline{\mathrm{p}}) \leftrightarrow \mu_\ell(\mathsf{p})$

$\overline{\mathrm{H}} \leftrightarrow \mathrm{H}$ HF structure

RED: done, GREEN: planned



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Mass and Charge of Antiproton

Proton's well (?) known:

$m(\mathrm{p})/m(\mathrm{e}) = 1836.15267245(75)$

$q(\mathrm{e}) = 1.602176565(35) \times 10^{-19}$ C

Precision: $4 \cdot 10^{-10}$ and $2 \cdot 10^{-8}$

Relative measurements: proton vs. antiproton

Cyclotron frequency in trap $\rightarrow q/m$

TRAP $\Rightarrow$ ATRAP collaboration

Harvard, Bonn, München, Seoul

$\overline{\mathrm{p}}$ and H^{-} together $\Rightarrow 10^{-10}$ precision

Atomic transitions:

$E_n \approx -m_{\mathrm{red}} c^2 (Z\alpha)^2/(2n) \rightarrow m \cdot q^2$

PS-205 $\Rightarrow$ ASACUSA collaboration

Tokyo, Brescia, Budapest, Debrecen, Munich, Vienna

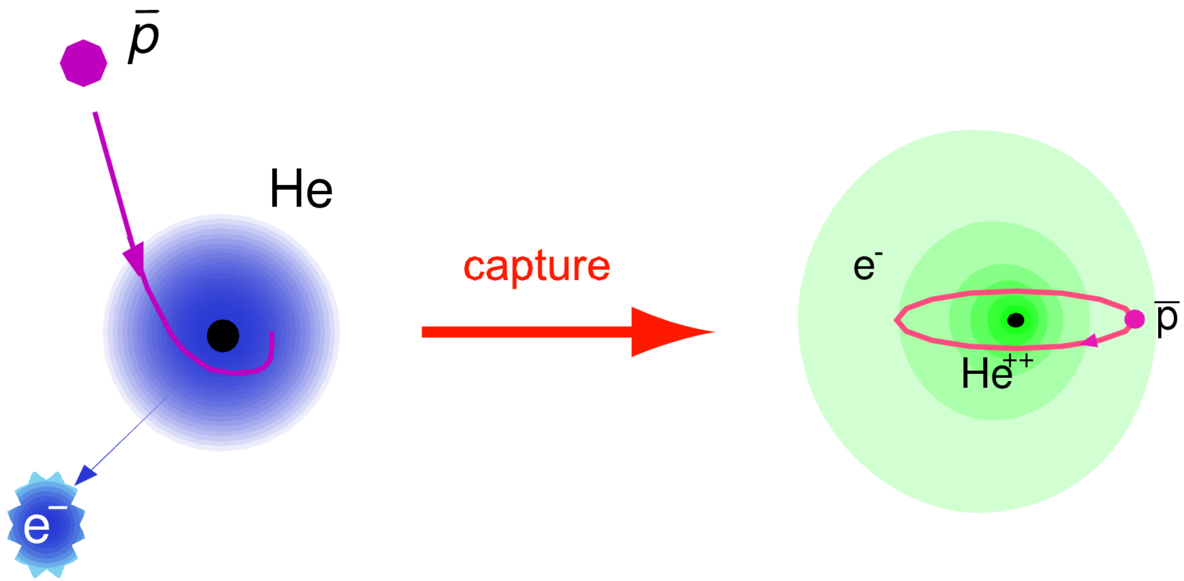
Atomic
Spectroscopy
And
Collisions
Using
Slow
Antiprotons

Asakusa, Tokyo

Metastable hadronic atoms

In matter (gas, liquid, solid) τ(hadron) $\tau \sim 1$ ps

except $\sim 3\%$ of X^-He: K^-, π^-: decay lifetime; $\bar{\mathrm{p}}$: 3–4 μs



Metastable 3-body system

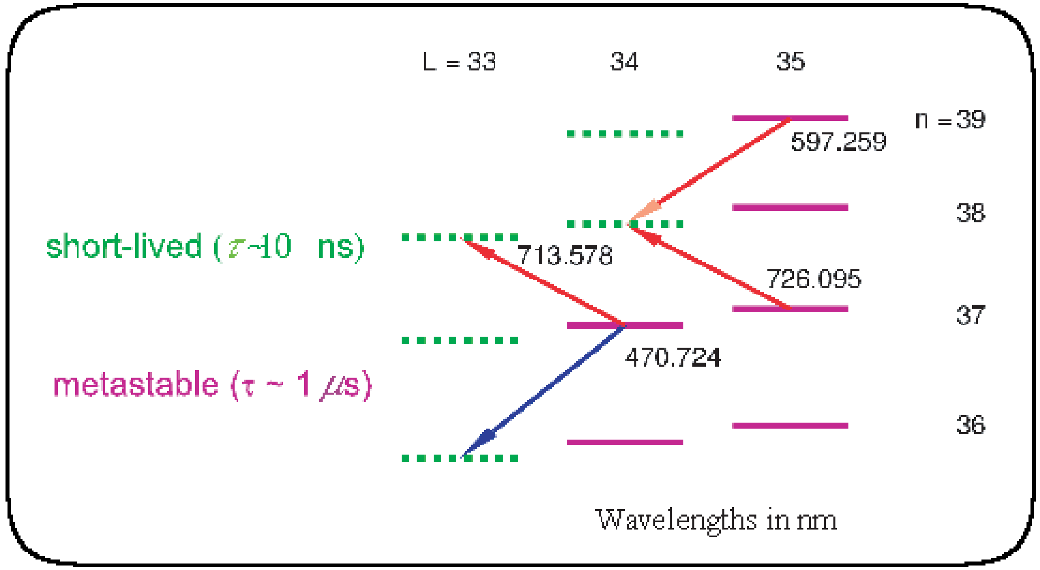
Auger suppressed, slow radiative transitions only

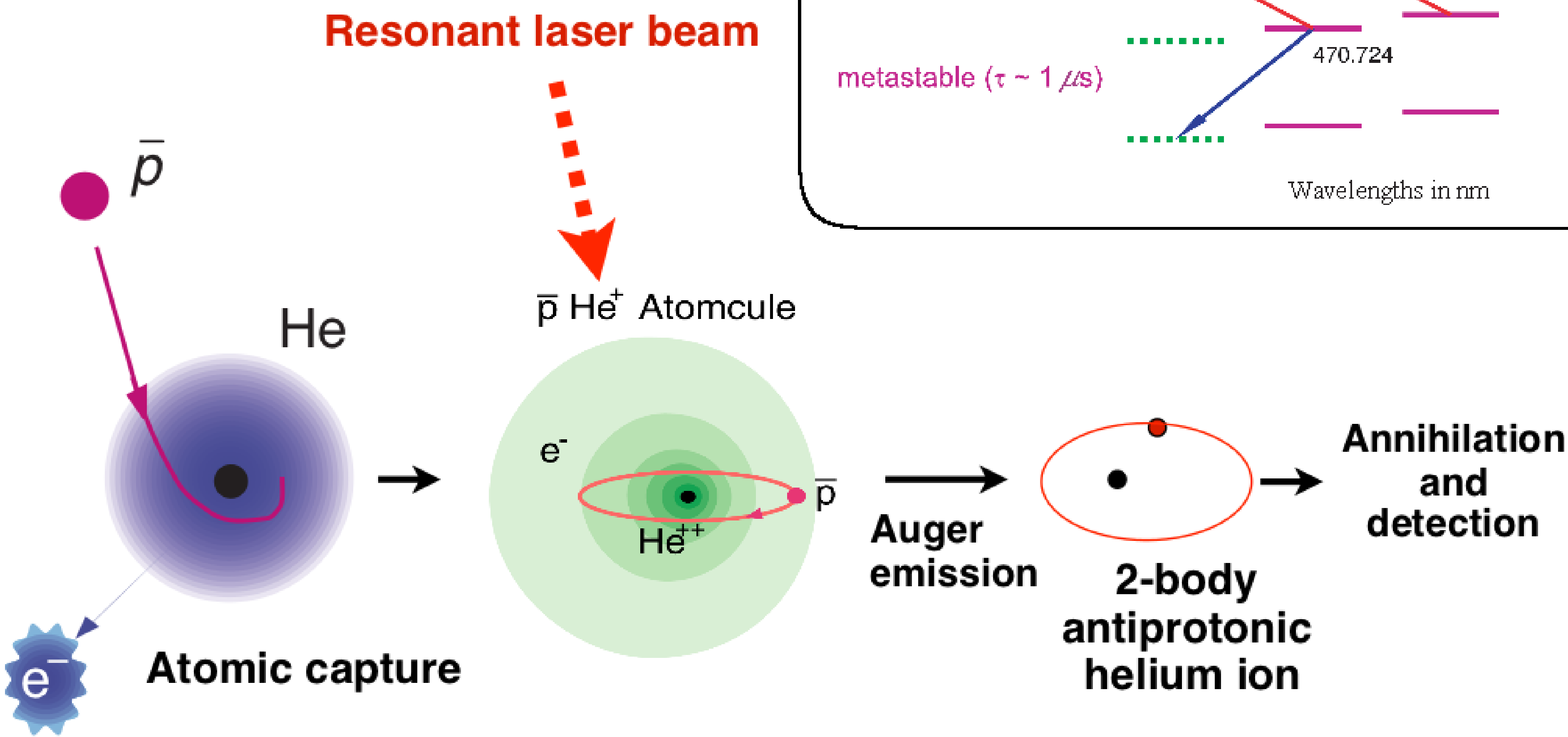
Electron *cloud* protects $\bar{\mathrm{p}}$ against collisions

Electron tightly bound: $1S$;

$\bar{\mathrm{p}}$: $n \sim 40$, $l \sim n-1$, Rydberg state

Laser spectroscopy of antiprotonic helium



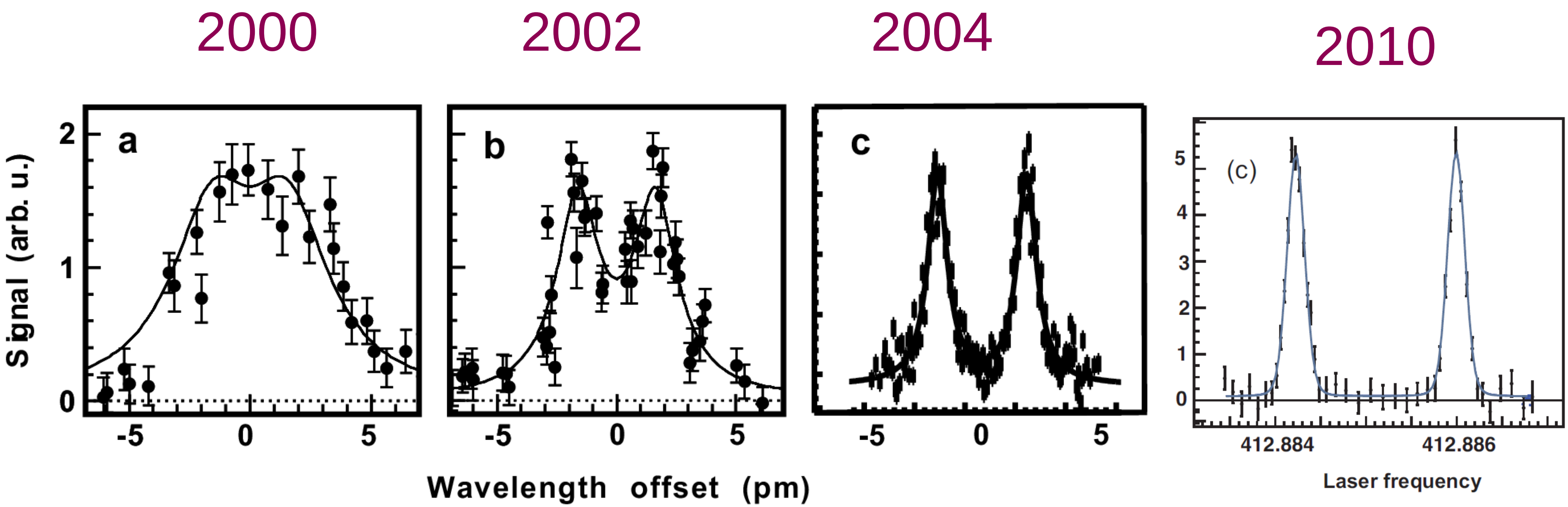


Induce transition between long-lived and short-lived states

⇓

Force prompt annihilation

Resolution and stability

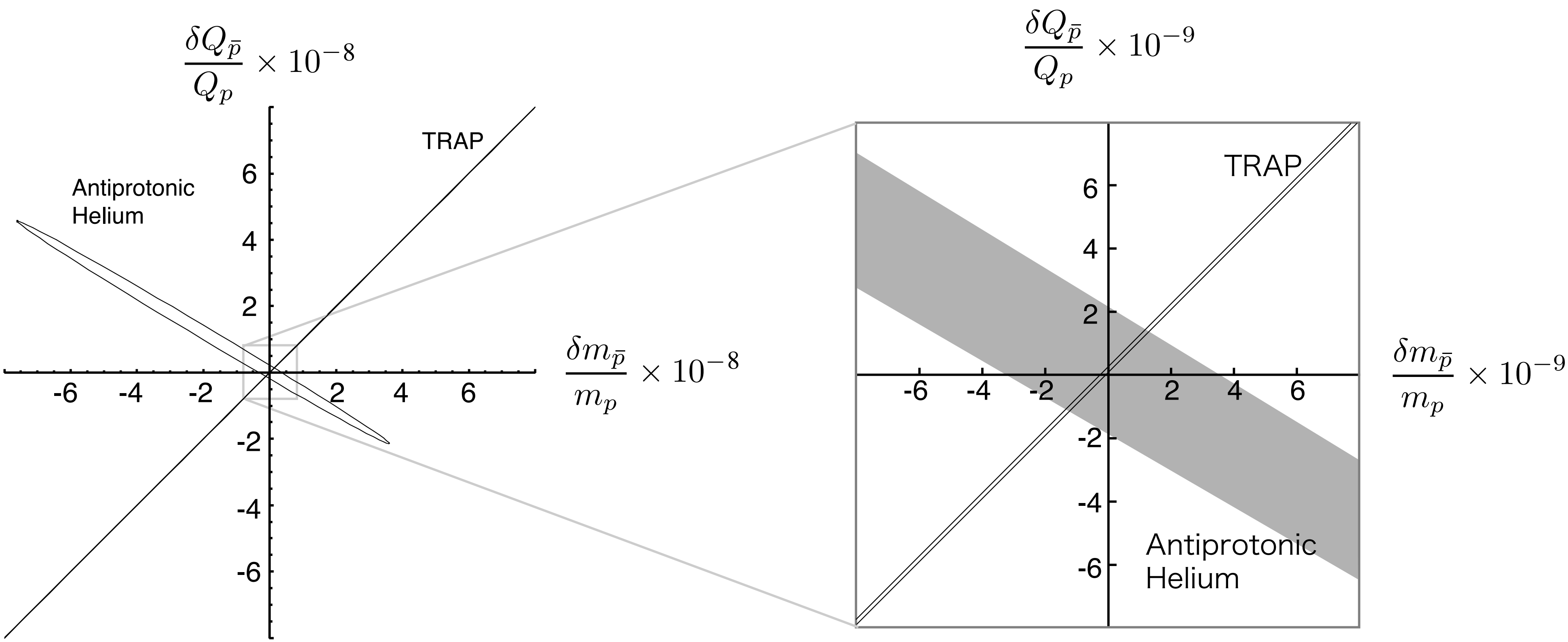


Dramatic improvement of resolution and stability

Resonance profile of the
$(n, \ell) = (37, 35) \rightarrow (38, 34)$ transition at $\lambda = 726.1$ nm

2010: He at $T = 1.5K$, Ti:Sapphire pulsed laser

Determination of $m(\bar{\mathrm{p}}), q(\bar{\mathrm{p}})$



Determination of antiproton mass and charge:
possible deviation from those of the proton

TRAP: m/Q;   ASACUSA: $m \cdot Q^2$

Two-photon spectroscopy

In low density gas main precision limitation:
thermal Doppler broadening even at $T < 10$ K

Excite $\Delta\ell = 2$ transition with 2 photons

Two counterpropagating photons with $\nu_1 \sim \nu_2$
eliminate 1st order Doppler effect

Laser linewidth should not overlap with resonance

M. Hori, A. Sótér, D. Barna, A. Dax, R.S. Hayano, S. Friedreich, B. Juhász, T. Pask, E. Widmann, D. Horváth, L. Venturelli, N. Zurlo: *Two-photon laser spectroscopy of pbar-He$^+$ and the antiproton-to-electron mass ratio*,
Nature 475 (2011) 484-488,
Few Body Syst. *54* (2013) 917-922.

Two-photon spectroscopy: results

$$M_{\overline{p}}/m_{\rm e} = 1836.1526736(23)$$

Uncertainties:

$$1.8 \times 10^{-6}({\rm stat}),\ 1.2 \times 10^{-6}({\rm syst}),\ 1.0 \times 10^{-6}({\rm theor})$$

Good agreement with proton results, similar (slightly higher) uncertainty.

Assuming CPT invariance our result can be included in the determination of $M_{\rm p}$ and $m_{\rm e}$.

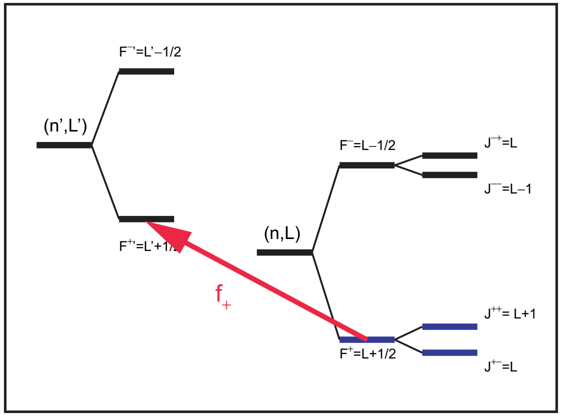
Upper limit for the charge and mass difference (i.e. possible CPT violation) at

$$\boxed{7 \times 10^{-10}}$$

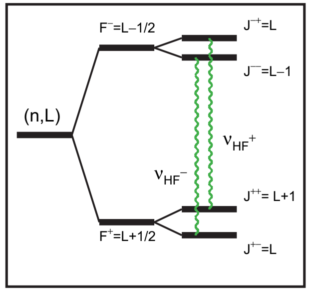
on a 90% confidence level.

M. Hori et al., **Nature** 475 (2011) 484-488

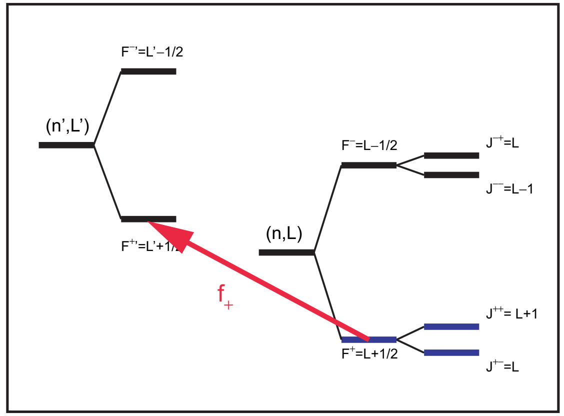
Level splitting in $\overline{\mathrm{p}}\mathrm{He}^+$ atoms



Step 1: depopulation of F$^+$ doublet with f_+ laser pulse



Step 2: equalization of populations of F$^+$ and F$^-$ by microwave



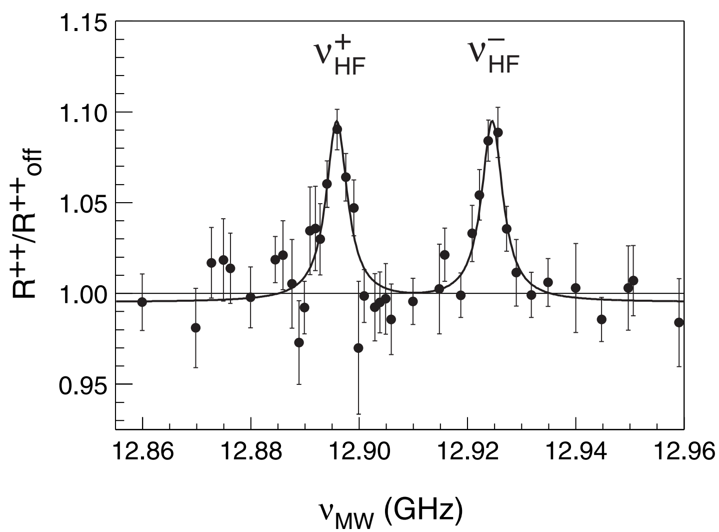
Step 3: probing of population of F$^+$ doublet with 2nd f_+ laser pulse

Magnetic moments

$\mu(\mathrm{p}) \sim \mu(\overline{\mathrm{p}}) \quad \Rightarrow$ *CPT* invariance OK

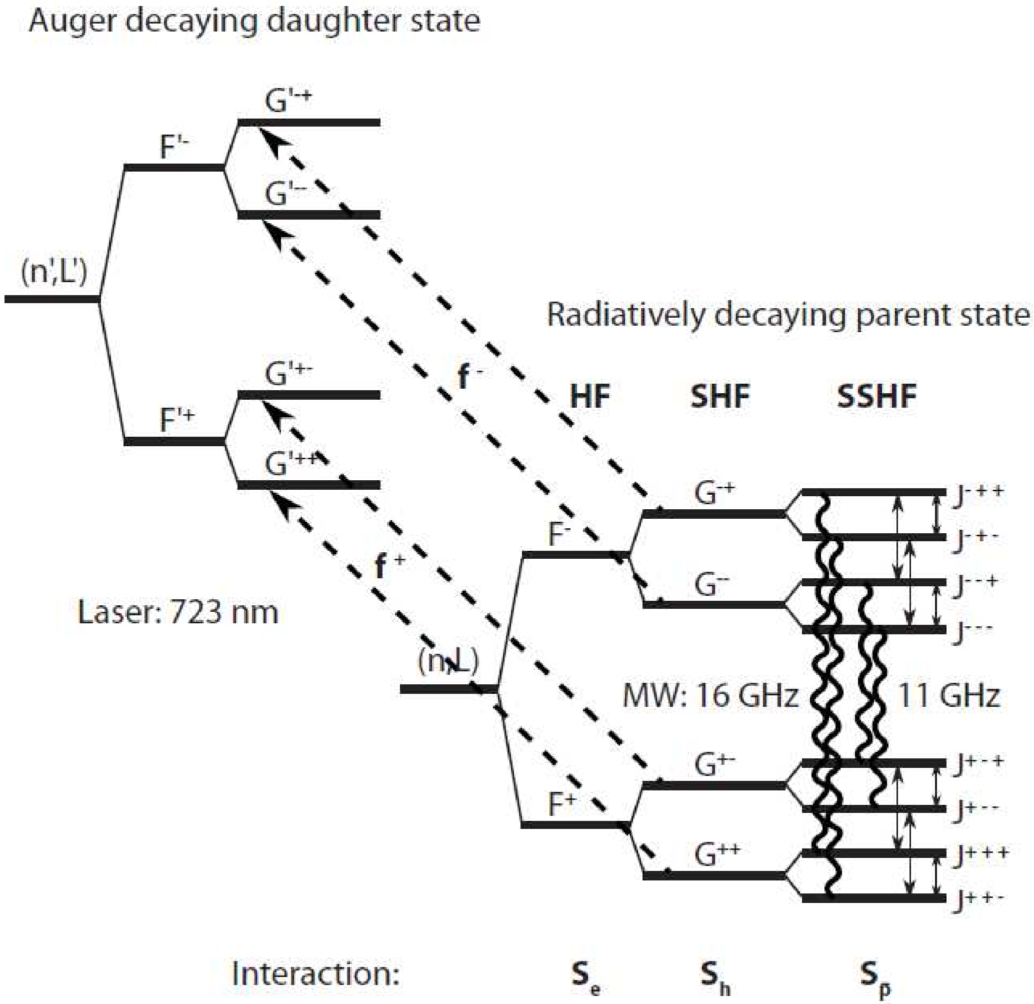
S. Friedreich, D. Barna, F. Caspers, A. Dax, R. S. Hayano, M. Hori, D. Horváth, B. Juhász, T. Kobayashi, O. Massiczek, A. Sótér, K. Todoroki, E. Widmann, J. Zmeskal:

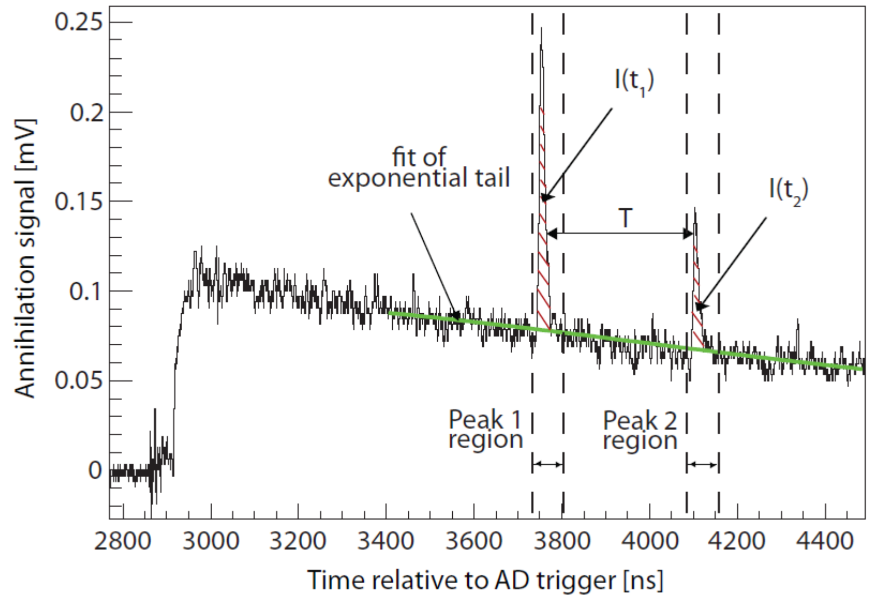
Physics Letters B *700* (2011) 1-6.

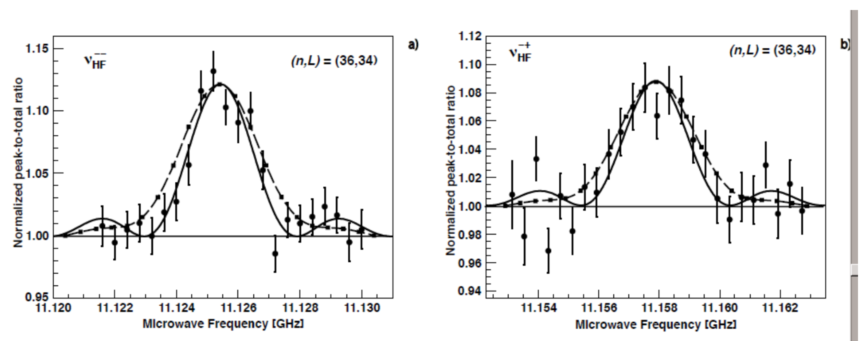


Microwave frequency scan

$\overline{\mathrm{p}}^3$He HF structure: laser & MW scan





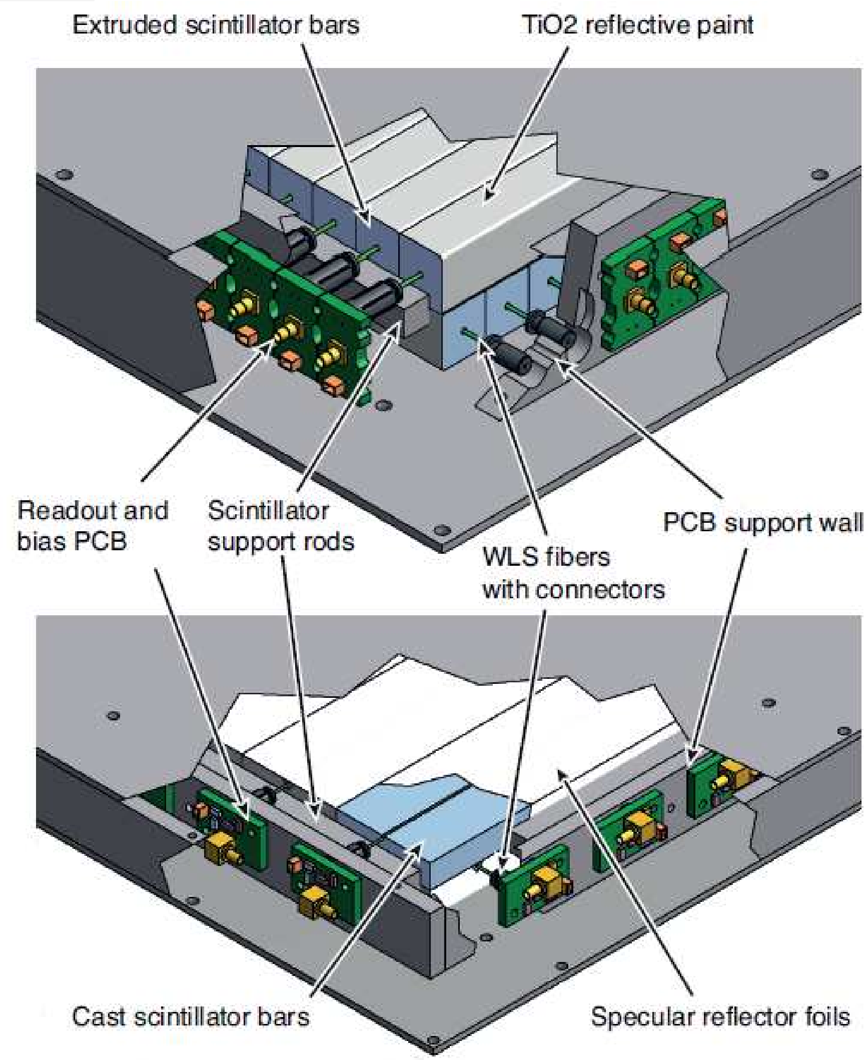


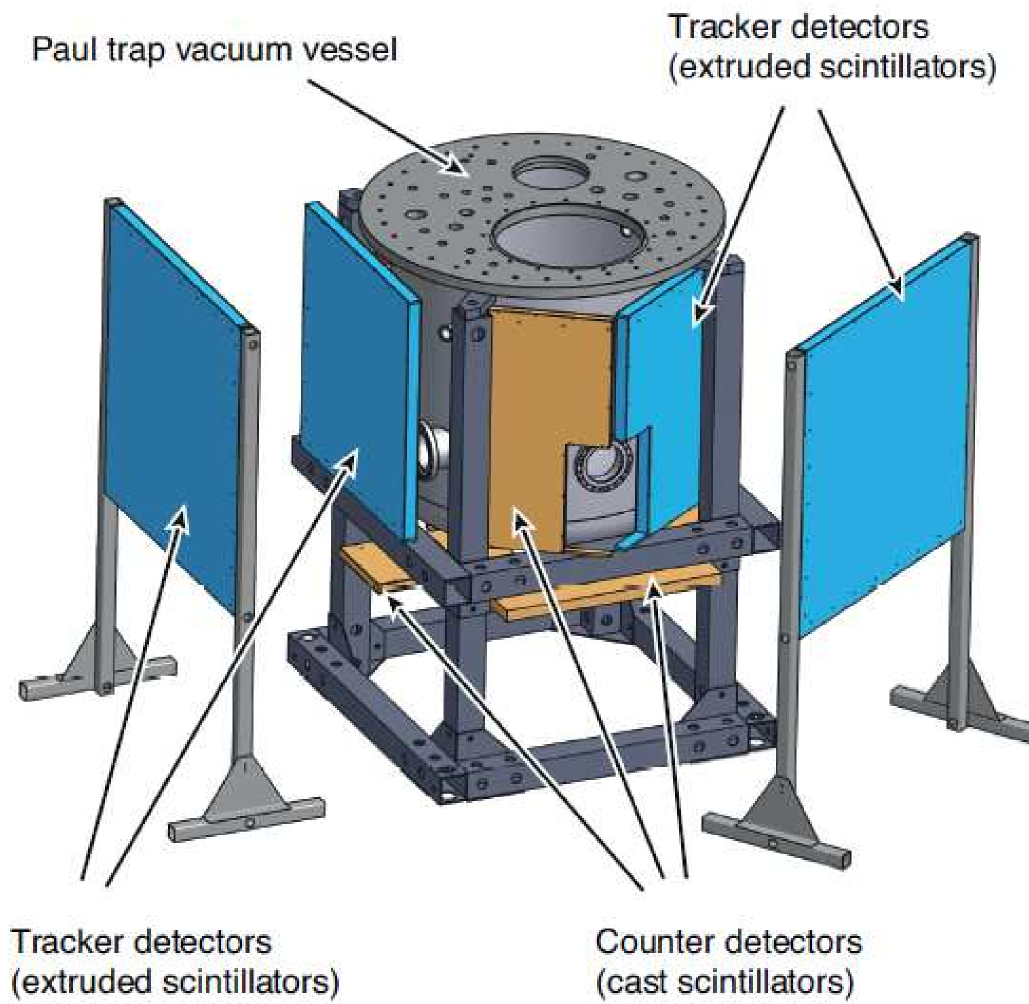
S. Friedreich et al.,

Physics Letters B 700 (2011) 1.

arXive:1303.2831, 2013.

Segmented detectors for Paul trap





A. Sótér, K. Todoroki, T. Kobayashi, D. Barna, D. Horváth, M. Hori:

Submitted to Nucl. Instr. Meth

Trap design: D. Barna, M. Hori

Stand: Wigner RCP

Extra Low ENergy Antiprotons

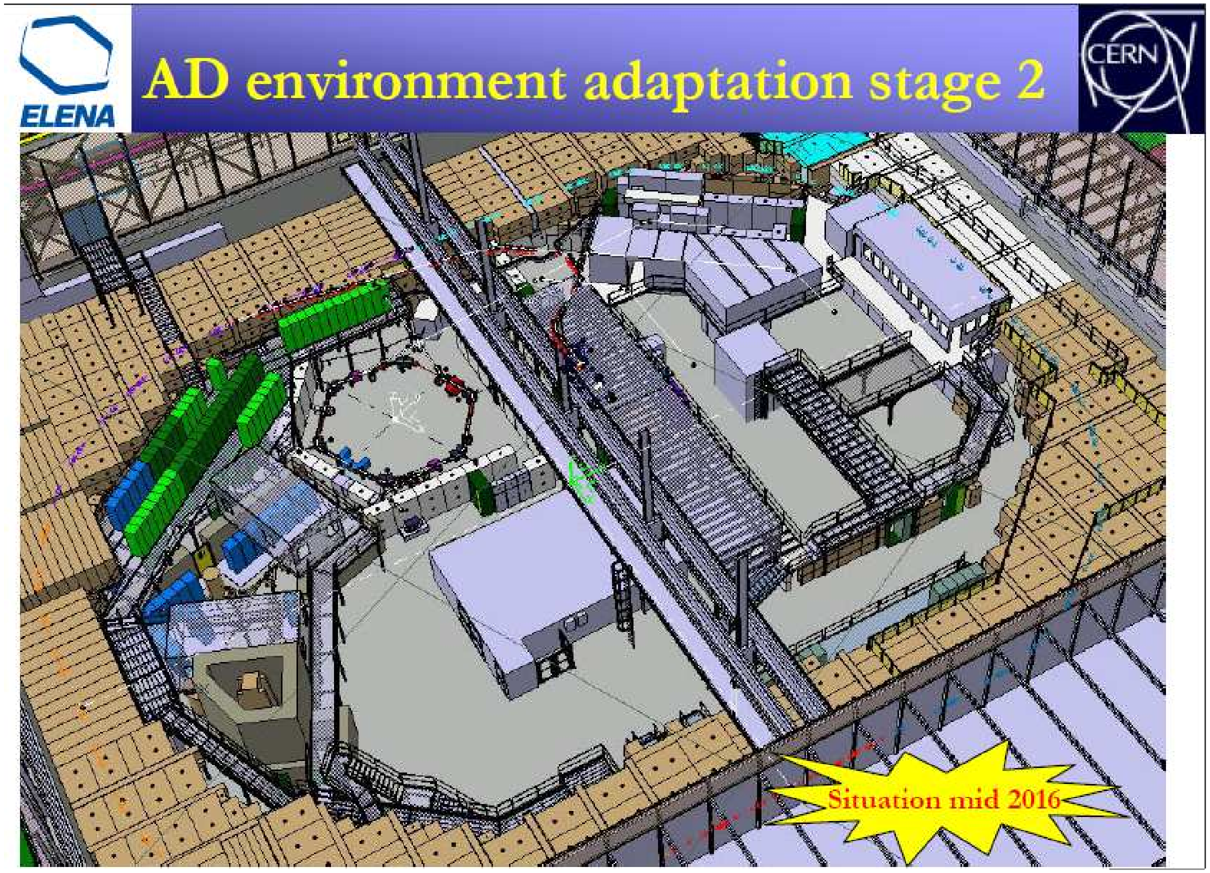
ELENA
Extra Low ENergy Antiprotons

Success of RFQ post-decelerator of ASACUSA $\Rightarrow$
CERN decided to build storage ring ELENA.

Plan: launch it in 2016.

AD:
5.8 MeV $\overline{\mathrm{p}}$, 3×10^7/shot
ELENA:
100 keV $\overline{\mathrm{p}}$,
1.8×10^7/shot
4 bunches to 4 expts
every 120 sec

Dániel Barna:
Design of beam line



Financing

Supported by:

- Hungarian Scientific Research Fund (OTKA)
  - 2008-2012: T72172, HUF 8,854,000
  - 2012-2016: K103917, HUF 15,916,000
- Hungarian Academy of Sciences
- Generous collaborating institutes
  (U. Tokyo, MPQ Munich, SMI Vienna)

Thanks for your attention

Near-resonant two-photon spectroscopy

$$(n,\ell) = (36,34) \rightarrow (34,32)$$

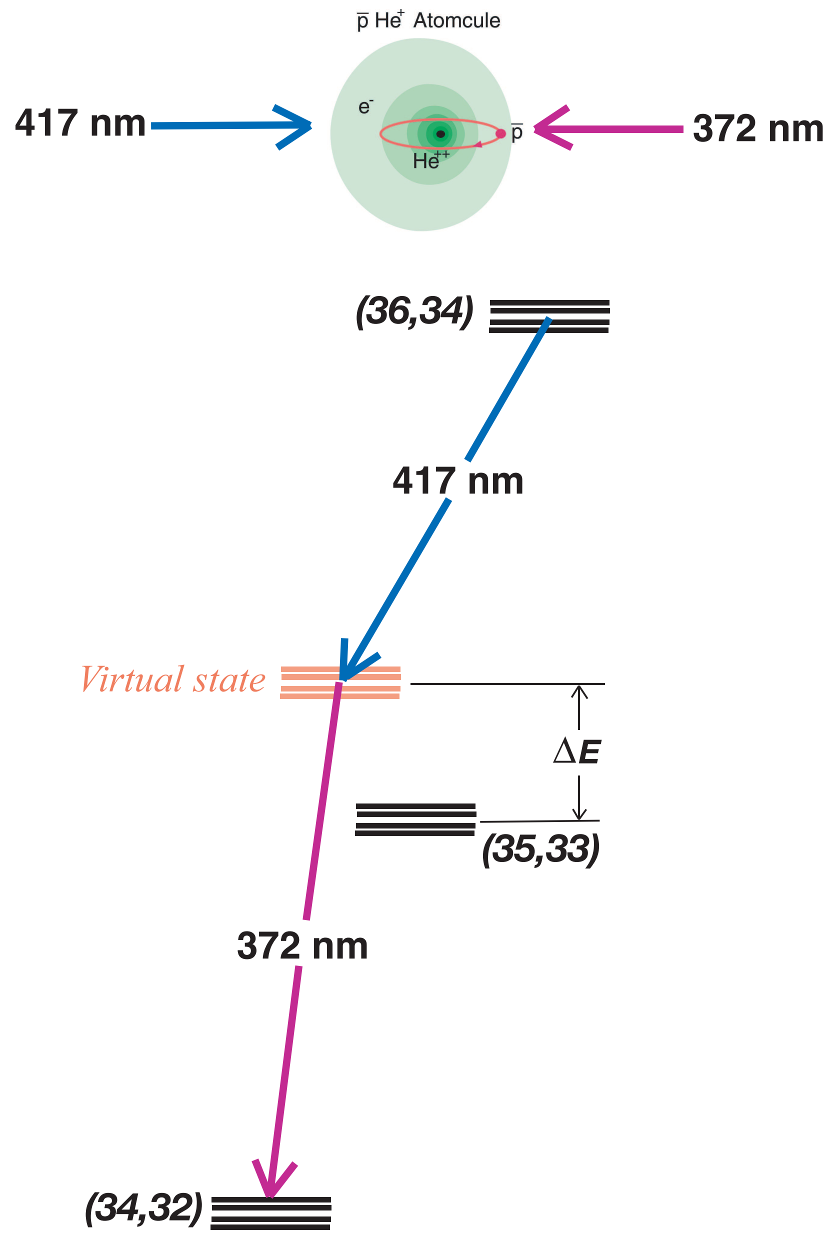
Doppler suppression:

$$\Delta\nu_{\gamma_1\gamma_2} = \left|\frac{\nu_1 - \nu_2}{\nu_1 + \nu_2}\right| \Delta\nu_{\text{Doppler}}$$

Gain: $\sim 20\times$

Limitation: residual Doppler, frequency chirp systematics

Expected $\Delta f \sim$ few MhZ



MUSASHI: slow antiproton beam

Musashi Miyamoto self-portrait ~ 1640

Monoenergetic
Ultra
Slow
Antiproton
Source for
High–precision
Investigations

5.8 MeV $\overline{\mathrm{p}}$ injected into RFQ

100 keV $\overline{\mathrm{p}}$ injected into trap

10^6 $\overline{\mathrm{p}}$ trapped and cooled (2002)

~ 350000 slow $\overline{\mathrm{p}}$ extracted (2004)

Cold $\overline{\mathrm{p}}$ compressed in trap (2008)

$(5 \times 10^5\ \overline{\mathrm{p}}, E = 0.3$ eV, $R = 0.25$ mm)

N. Kuroda,...D. Barna, D. Horváth, Y. Yamazaki: **Phys. Rev. Lett.** *100* (2008) 203402.

References

R.S. Hayano , M. Hori, D. Horváth, E. Widmann:
Antiprotonic helium and CPT invariance,
Reports on Progress in Physics, 70 (2007) 1995-2065.

M. Hori, A. Sótér, D. Barna, A. Dax, R.S. Hayano, S. Friedreich, B. Juhász, T. Pask, E. Widmann, D. Horváth, L. Venturelli, N. Zurlo: *Two-photon laser spectroscopy of pbar-He$^+$ and the antiproton-to-electron mass ratio*,
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H. Aghai-Khozani, D. Barna, ... A. Sótér, ... N. Zurlo:
„First experimental detection of antiproton in-flight annihilation on nuclei at $\sim$ 130 keV", Eur. Phys. J. Plus **127** (2012) 125.