Test of the CPT Invariance with Antiprotonic Atoms

The ASACUSA experiment

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Outline

- CPT Invariance and its Tests
- The Antiproton Decelerator at CERN
- $\overline{\mathrm{p}}$-He Spectroscopy
- The Charge and Mass of the Antiproton
- The Magnetic Moment of the Antiproton
- Antihydrogen: Why, What and How?
- The Hyperfine Structure of Antihydrogen
- Outlook

R.S. Hayano, M. Hori, D. Horváth, E. Widmann:
Antiprotonic helium and CPT invariance,
Reports on Progress in Physics, in press

CPT Invariance

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

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

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

Basic assumption of field theory:

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

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

CPT Invariance: violation?

Theoreticians in general: CPT **cannot** be violated

CPT-violating theories:
(Alan Kostelecký, F.R. Klinkhamer, N.E. Mavromatos et al)

- Standard Model valid up to Planck scale ($\sim 10^{19}$ GeV). Above Planck scale new physics $\Rightarrow$ Lorentz violation possible
- Quantum gravity: fluctuations $\Rightarrow$ Lorentz violation loss of information in black holes $\Rightarrow$ unitarity violation

Motivation for testing CPT at low energy

- Quantitative expression of Lorentz and CPT invariance needs violating theory
- low-energy tests can limit possible high energy violation

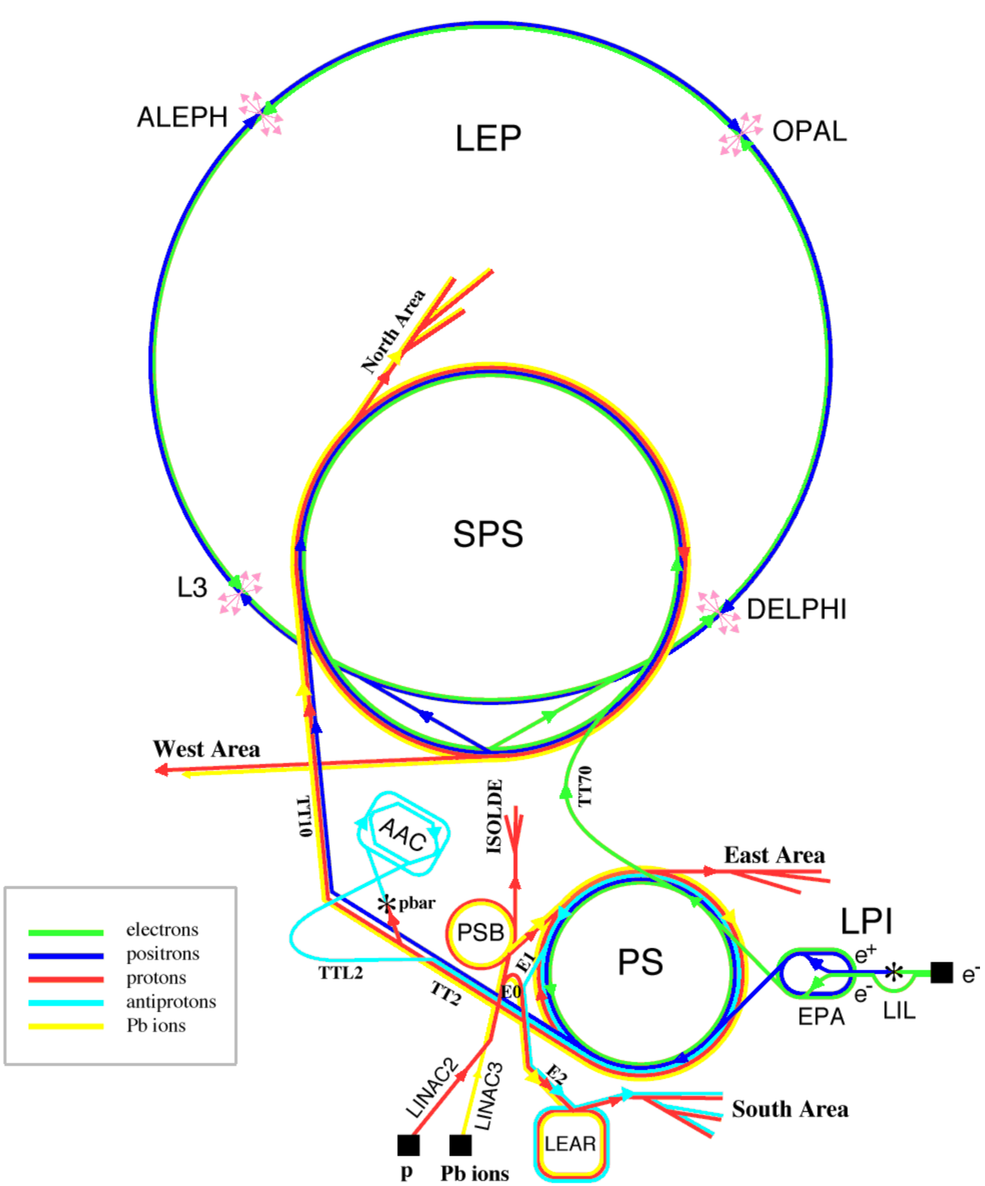
How to test CPT?

Particle = – antiparticle ?

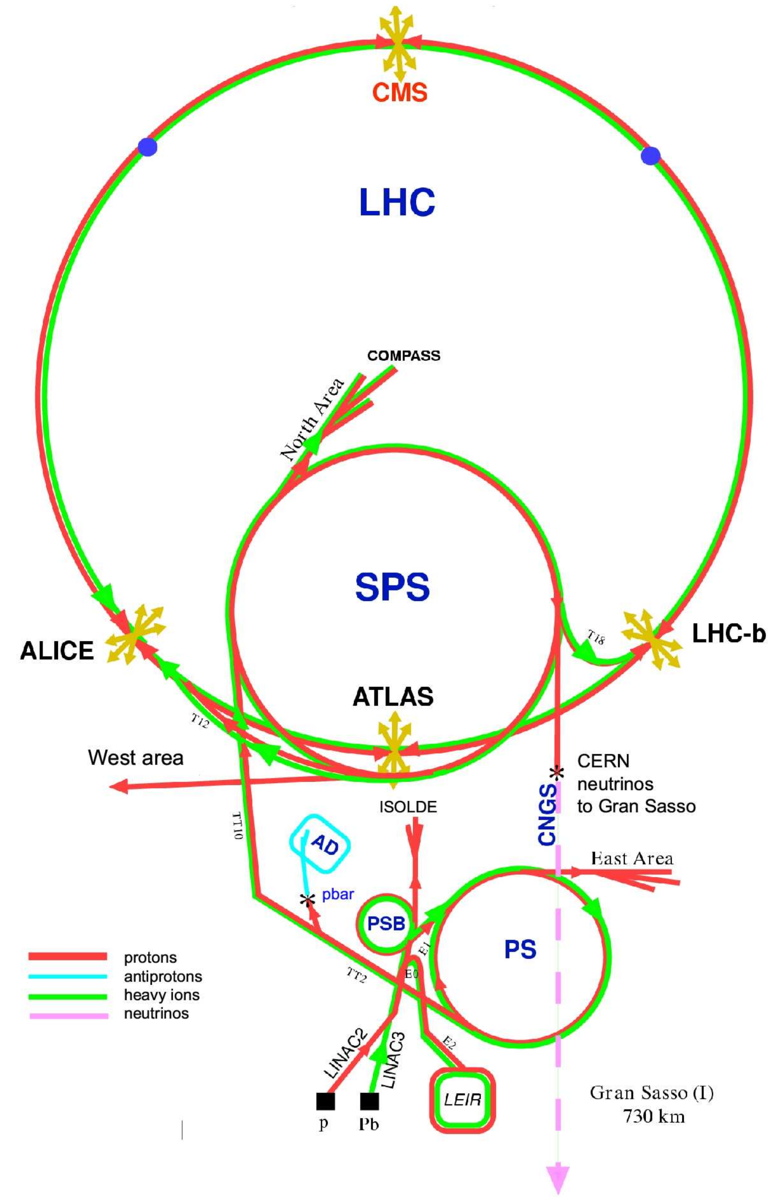
- $[m(\mathrm{K}^0) - m(\overline{\mathrm{K}}^0)]/m(\text{average}) < 10^{-18}$
- proton $\sim$ antiproton? (compare m, q, $\vec{\mu}$)
- hydrogen $\sim$ antihydrogen? ($2S - 1S$, HFS)

Accelerators at CERN

Until 1996



From 2007?



The Antiproton Decelerator at CERN

has been built to test *CPT* invariance

Three experiments test CPT:

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

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

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

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

$\mu_\ell(\bar{\mathrm{p}}) \leftrightarrow \mu_\ell(\mathrm{p})$

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

RED: done, GREEN: planned

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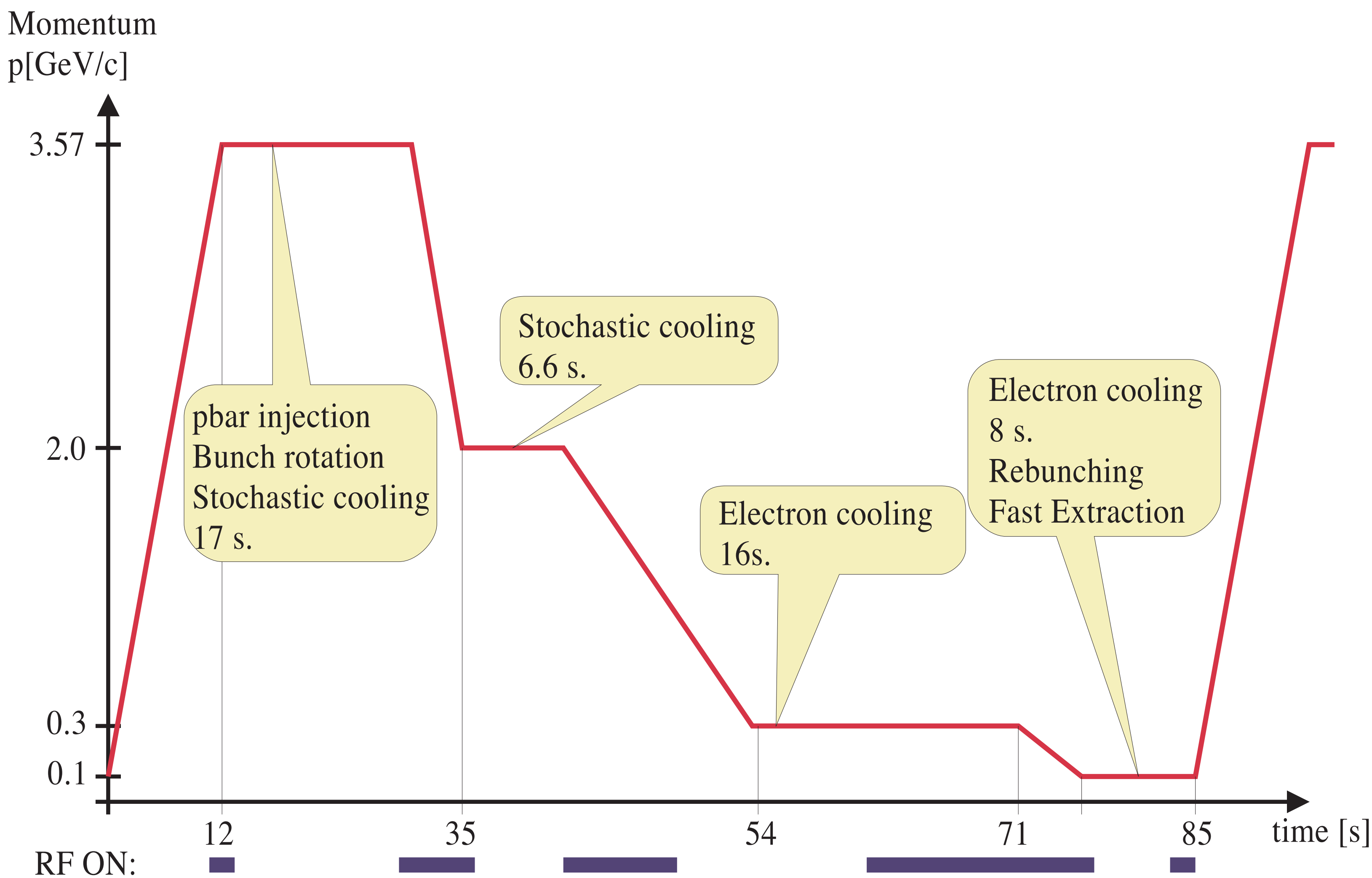
The Antiproton Decelerator: cooling



Mass and Charge of Antiproton

Proton's well (?) known:

$m(\text{p})/m(\text{e}) = 1836.15267261(85)$

$q(\text{e}) = 1.602176462(63)$ C

Precision: $5 \cdot 10^{-10}$ and $4 \cdot 10^{-8}$

Relative measurements: proton vs. antiproton

Cyclotron frequency in trap $\rightarrow q/m$

TRAP $\Rightarrow$ ATRAP collaboration

Harvard, Bonn, München, Seoul

$\bar{\text{p}}$ and H^- together $\Rightarrow 10^{-10}$ precision

Atomic transitions:

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

PS-205 $\Rightarrow$ ASACUSA collaboration

Tokyo, Budapest, Debrecen, Vienna

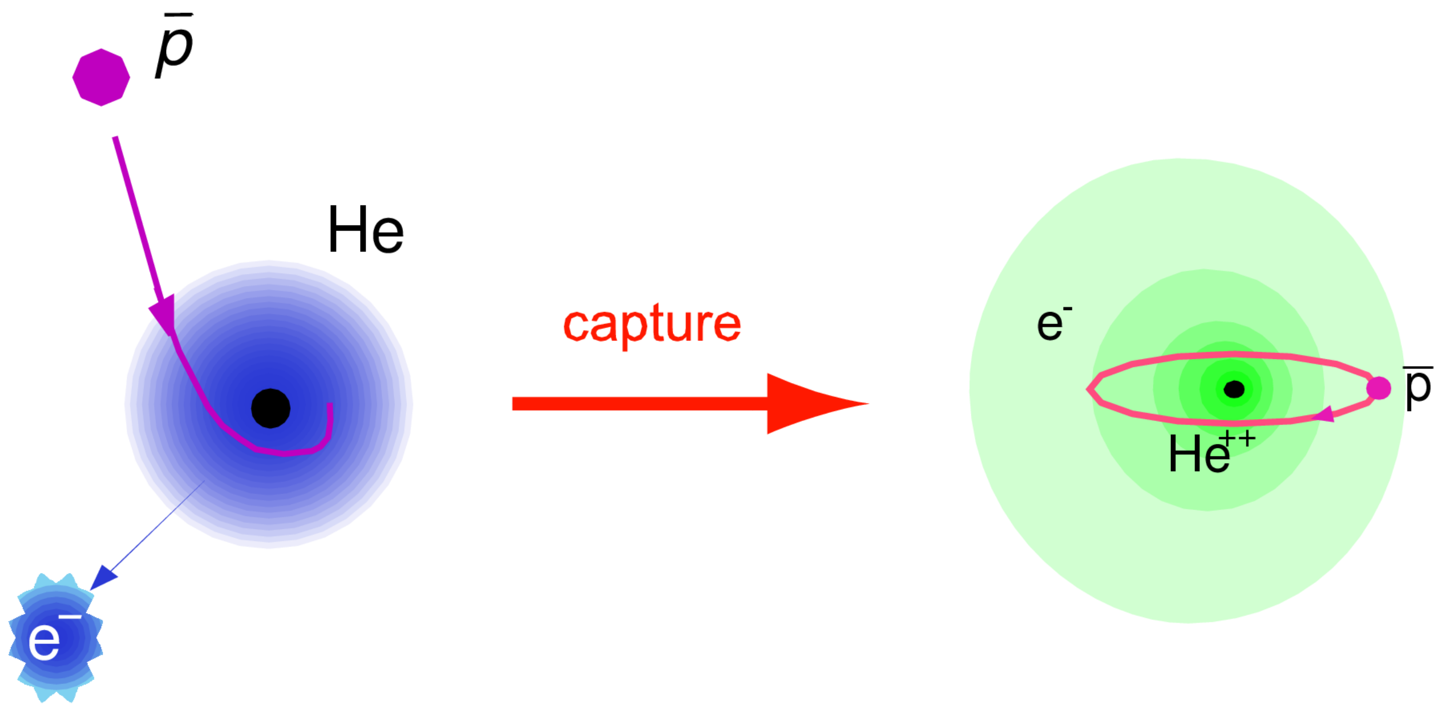
Atomic
Spectroscopy
And
Collisions
Using
Slow
Antiprotons

Asakusa, Tokyo

Metastable hadronic atoms

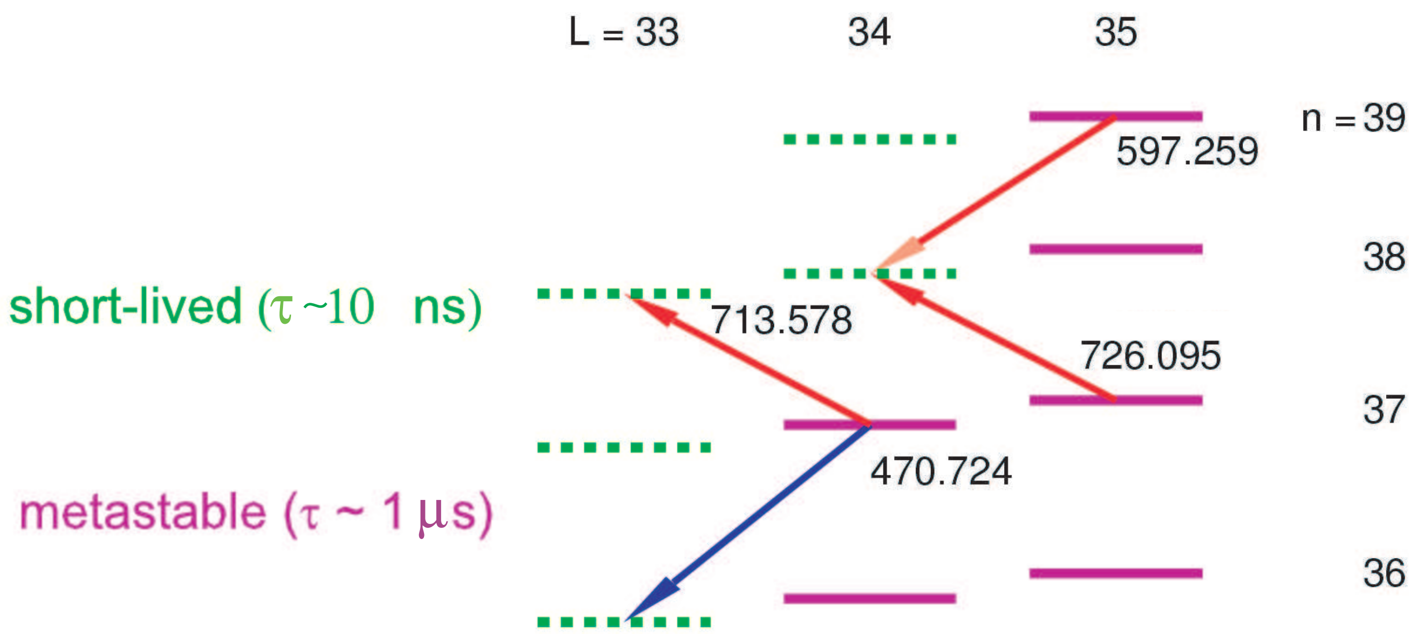
In matter (gas, liquid, solid) τ(hadron) $\sim$ 1 ps

except X^-He: K^-, π^-: τ_0; $\overline{p}$: 3–4 μs



Metastable 3-body system

Principle of laser spectroscopy



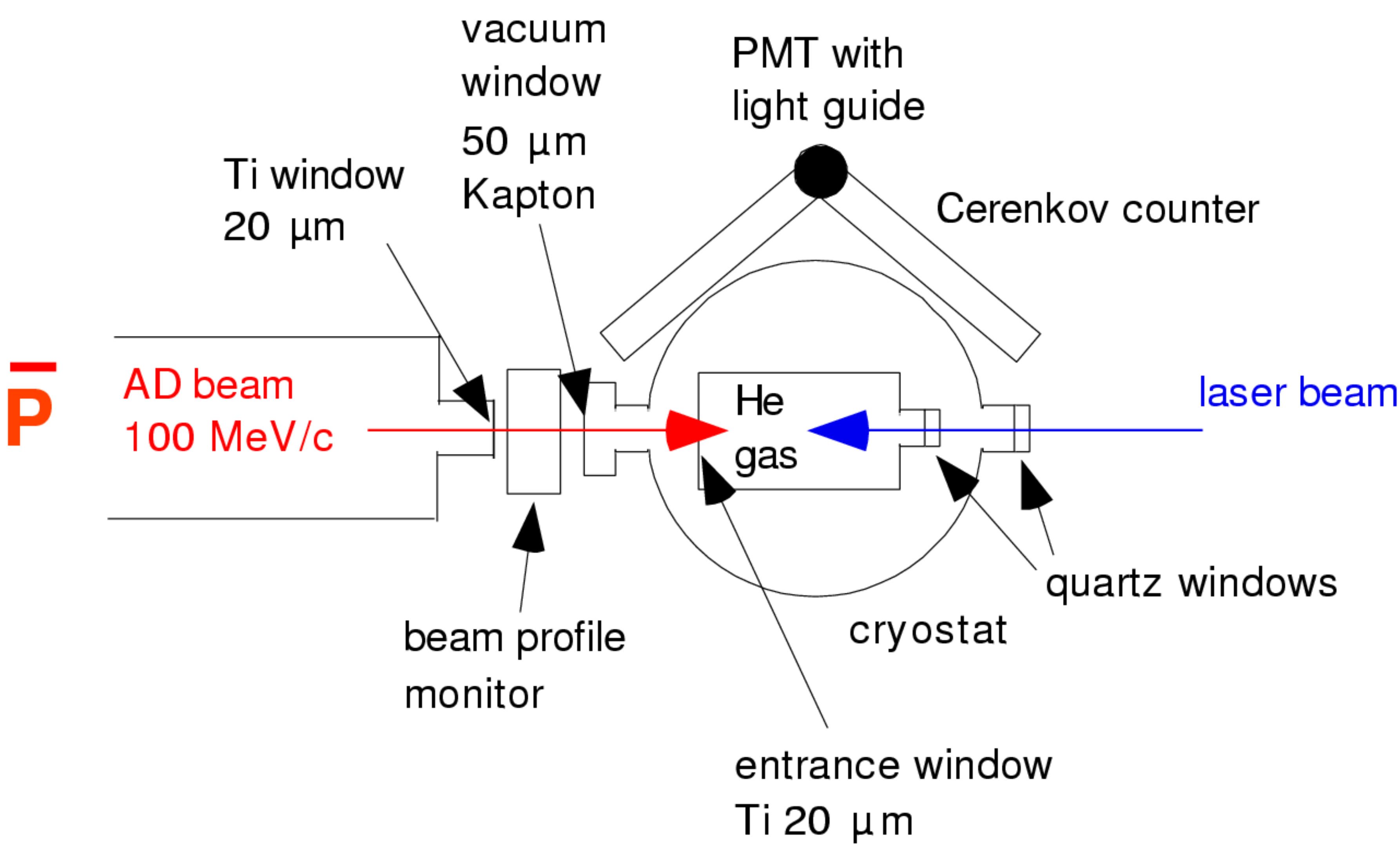
Wavelengths in nm

Induce transition between long-lived and short-lived state

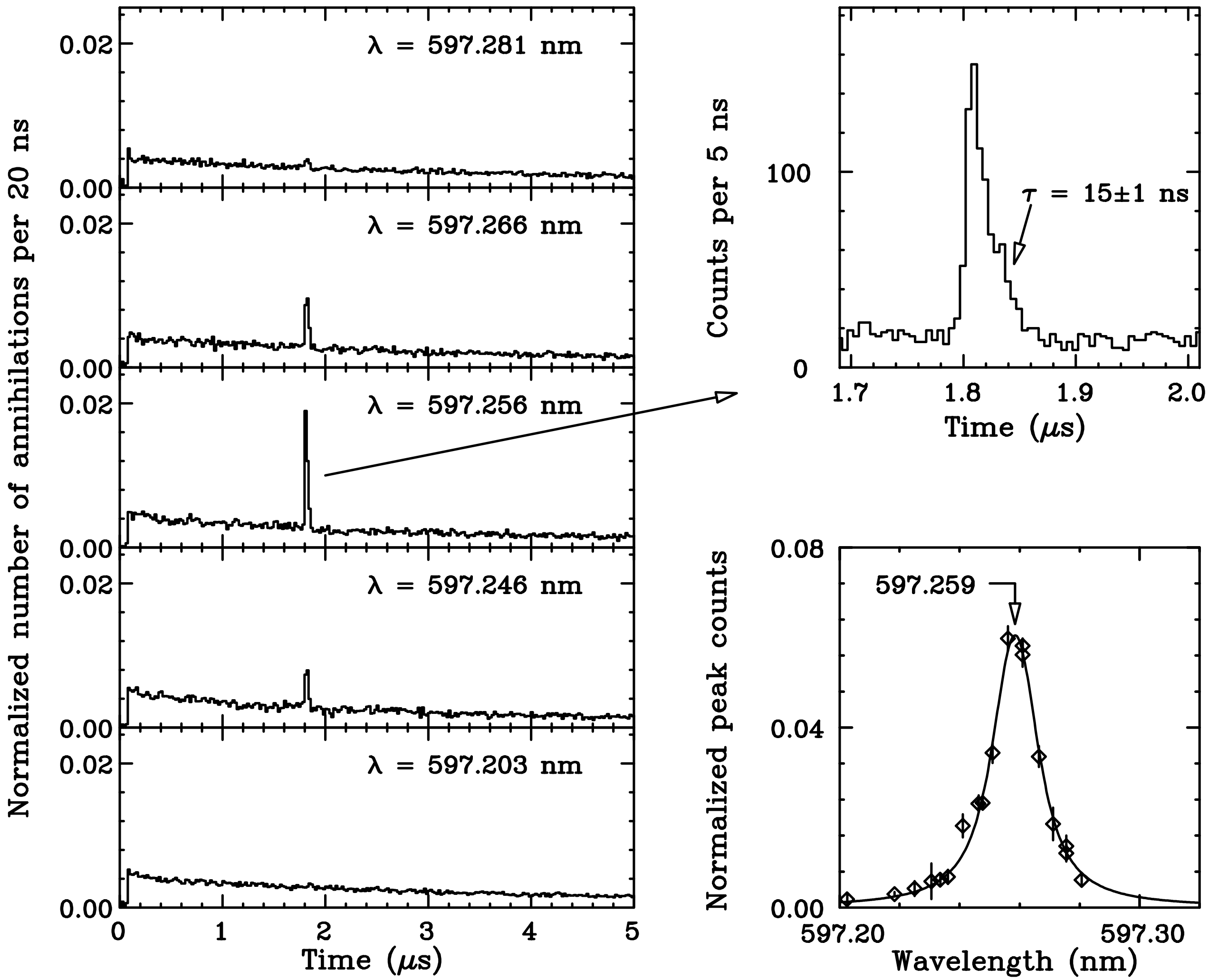
⇓

Force prompt annihilation

ASACUSA: Spectroscopy Setup

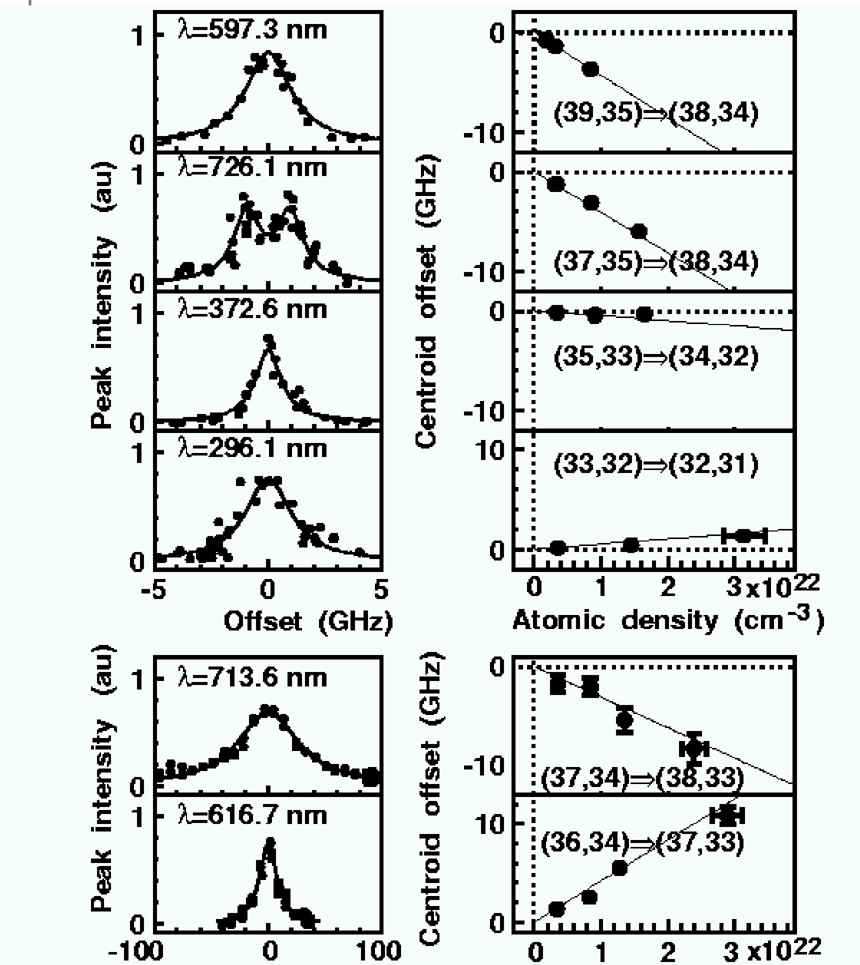


Laser spectroscopy of antiprotonic helium



N. Morita et al, **Phys. Rev. Lett.** *72* (1994) 1180–1183.

Transition frequencies in isolated $\overline{p}He^+$ atoms



M. Hori et al.,

Phys. Rev. Lett. *87* (2001) 093401.

Exp. precision limited by: collisions, Doppler broadening, laser bandwidth

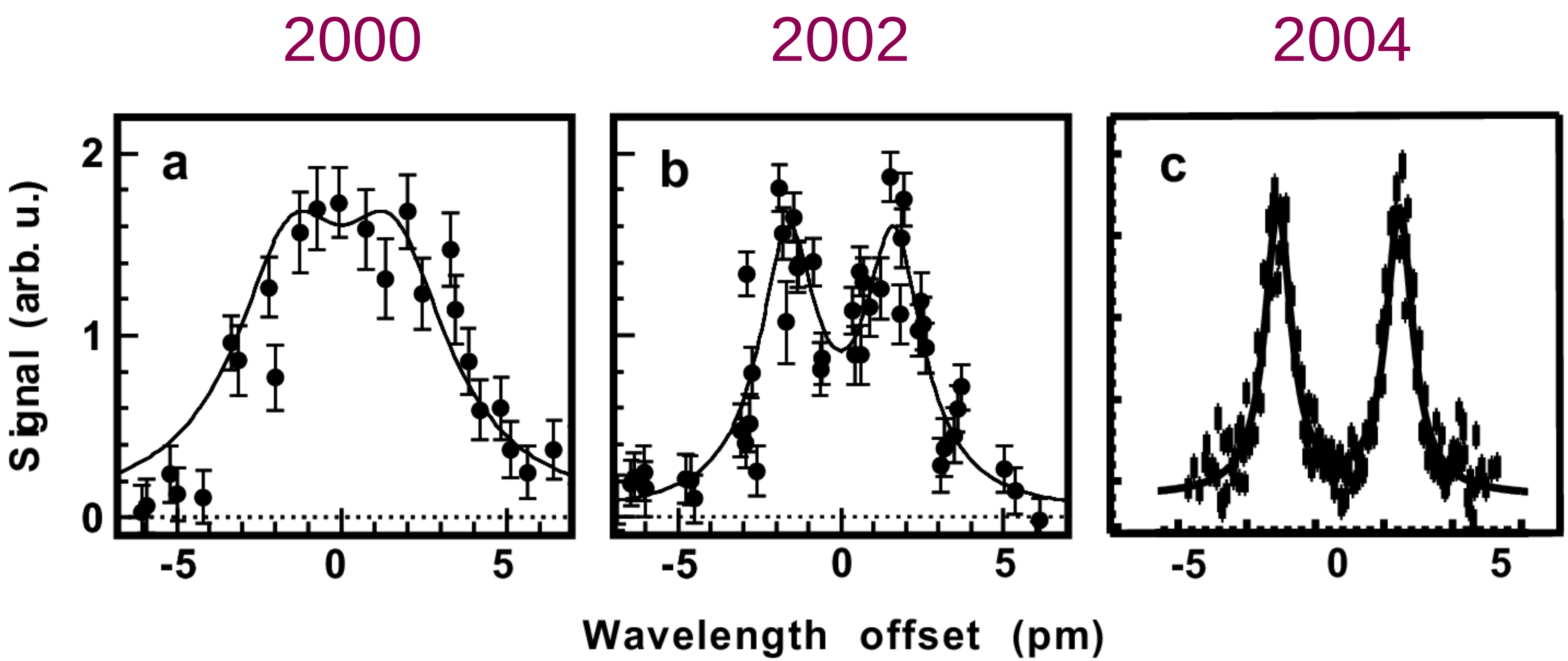
- 1996-2002: measured density dependence, extrapolated to zero
- 2003-2004: reduced collisional effects by stopping slow $\overline{p}$ from RFQ post-decelerator in low-pressure (< 1 mbar), cryogenic target
- 2005-2006: reduce laser bandwidth using frequency comb
- 2007: start 2-photon spectroscopy

Last published CPT-violation limit:

2 ppb (2×10^{-9})

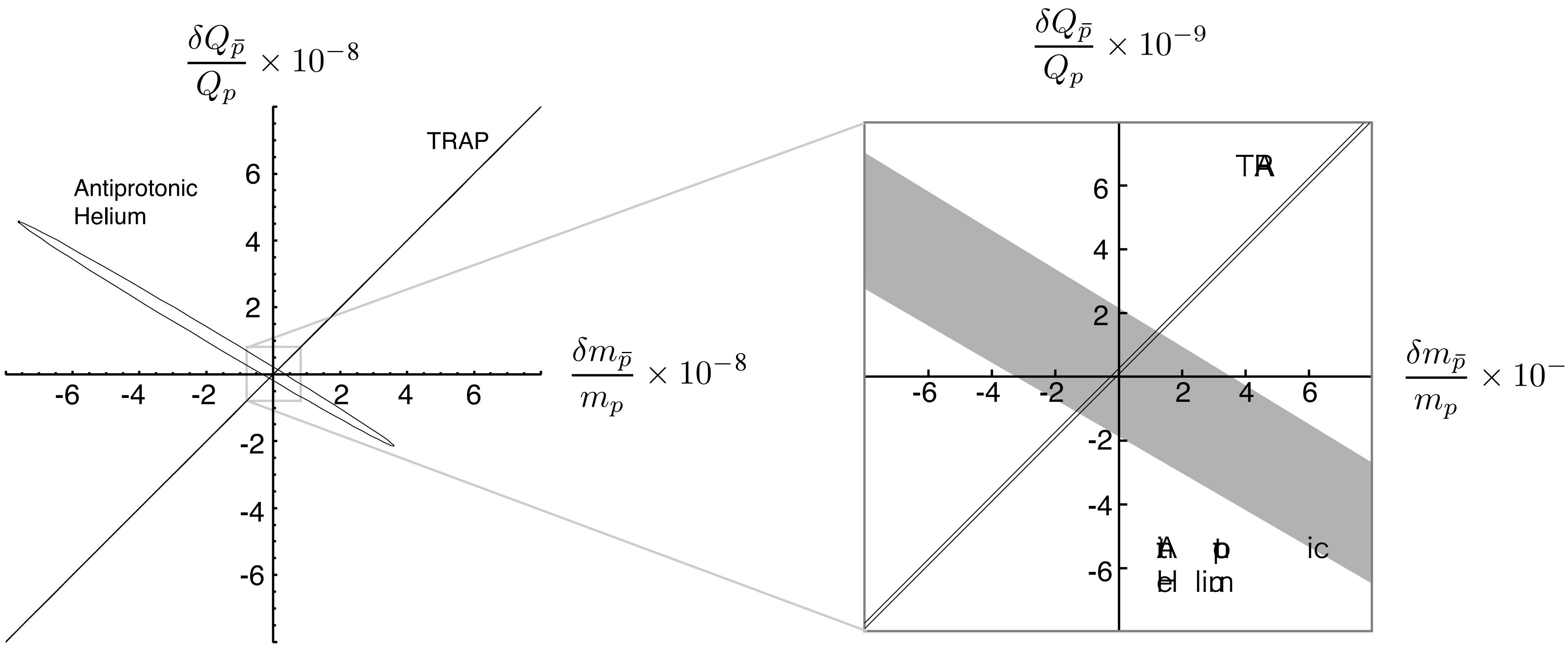
M. Hori et al., **Phys. Rev. Lett.** *96* (2006) 243401.

Resolution development



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

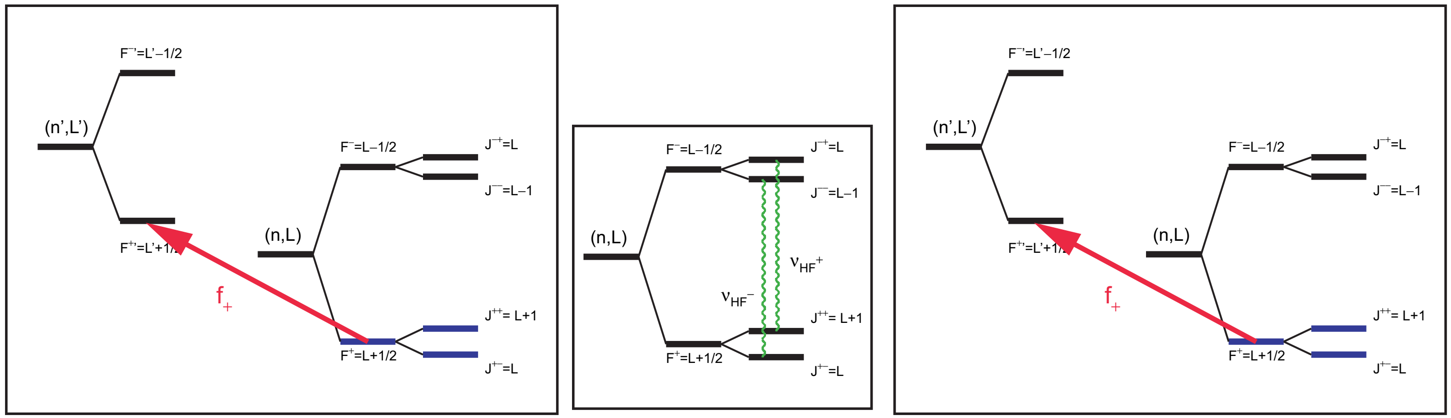
Determination of $m(\bar{\mathrm{p}}), q(\bar{\mathrm{p}})$



Determination of antiproton mass and charge:

possible deviation from those of the proton

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



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

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

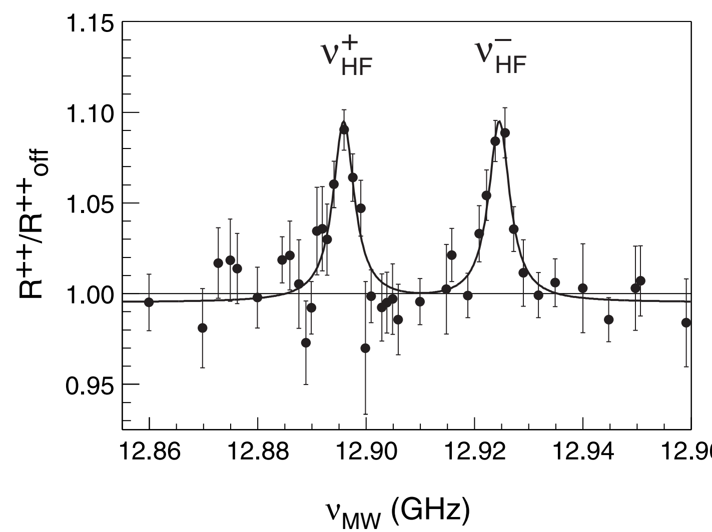
Step 3: probing of population of F^+ doublet with 2nd f_+ laser pulse

Magnetic moments

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

E. Widmann, R.S. Hayano, T. Ishikawa, J. Sakaguchi, H. Yamaguchi, J. Eades, M. Hori, H.A. Torii, B. Juhász, D. Horváth, T. Yamazaki:

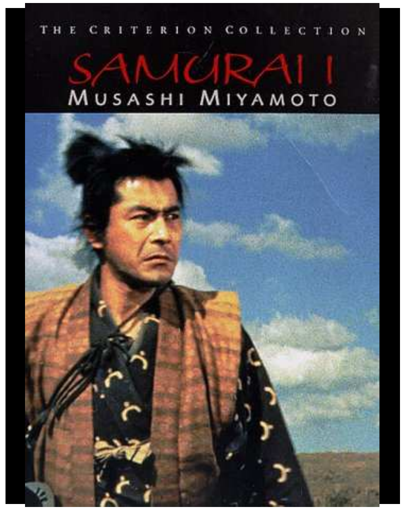
Phys. Rev. Lett. *89* (2002) 243402.



Microwave frequency scan

MUSASHI: slow antiproton beam

Monoenergetic
Ultra
Slow
Antiproton
Source for
High–precision
Investigations

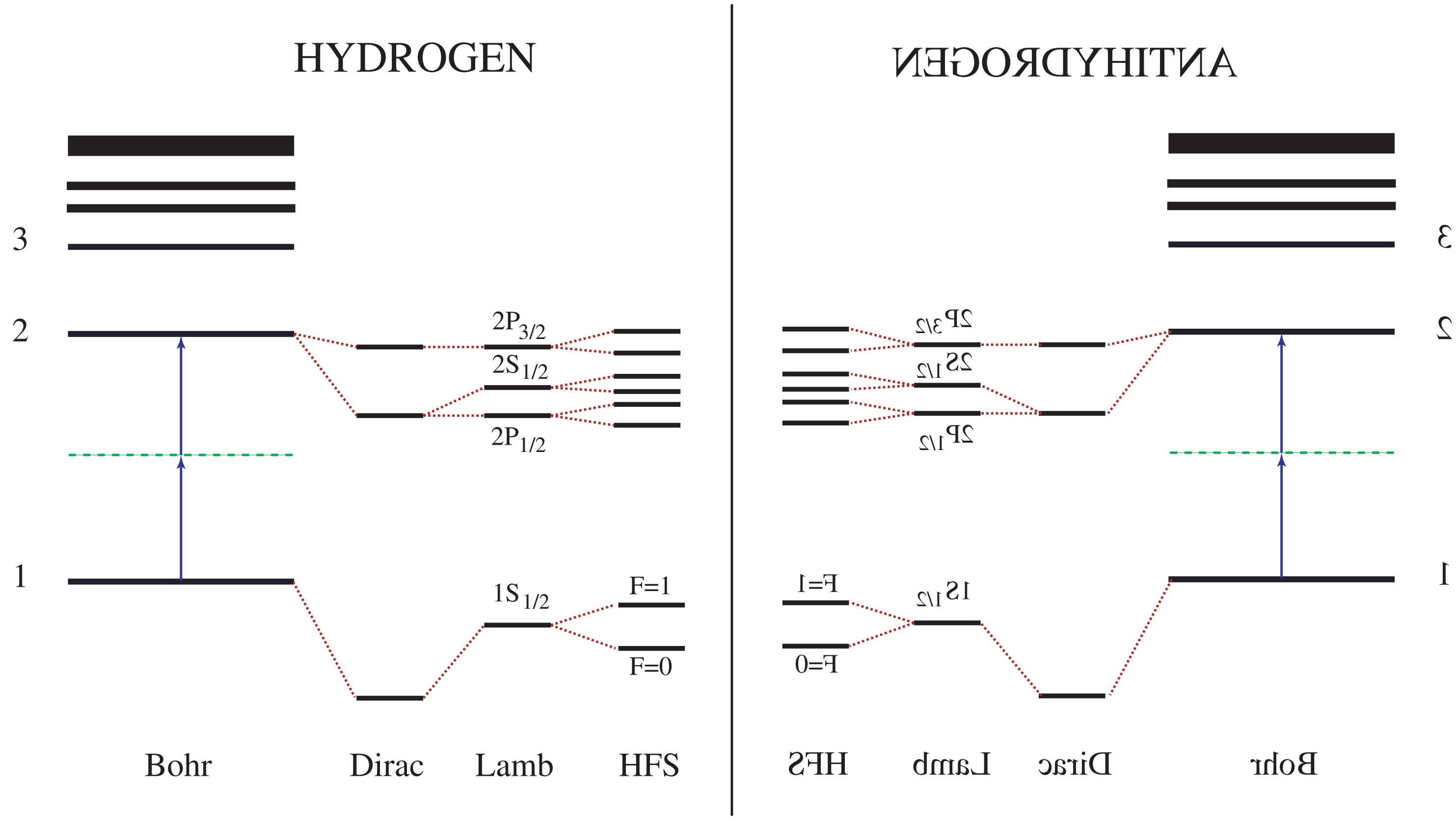


- 5.8 MeV $\bar{p}$ injected into RFQ
- 100 keV $\bar{p}$ injected into trap
- 10^6 $\bar{p}$ trapped and cooled (2002)
- Slow $\bar{p}$ extracted (2004)

Aim: atomic collisions, antihydrogen
nuclear studies

N. Kuroda,...B. Juhász, D. Horváth, Y. Yamazaki:
Phys. Rev. Lett. *94* (2005) 023401.

Antihydrogen: e^+–$\bar{p}$ atom



$2S - 1S$ transition with 2-photon (Doppler-free) spectroscopy at 10^{-18} precision

M. Charlton, J. Eades, D. Horváth, R. J. Hughes, C. Zimmermann:

Antihydrogen physics, **Physics Reports** *241* (1994) 65.

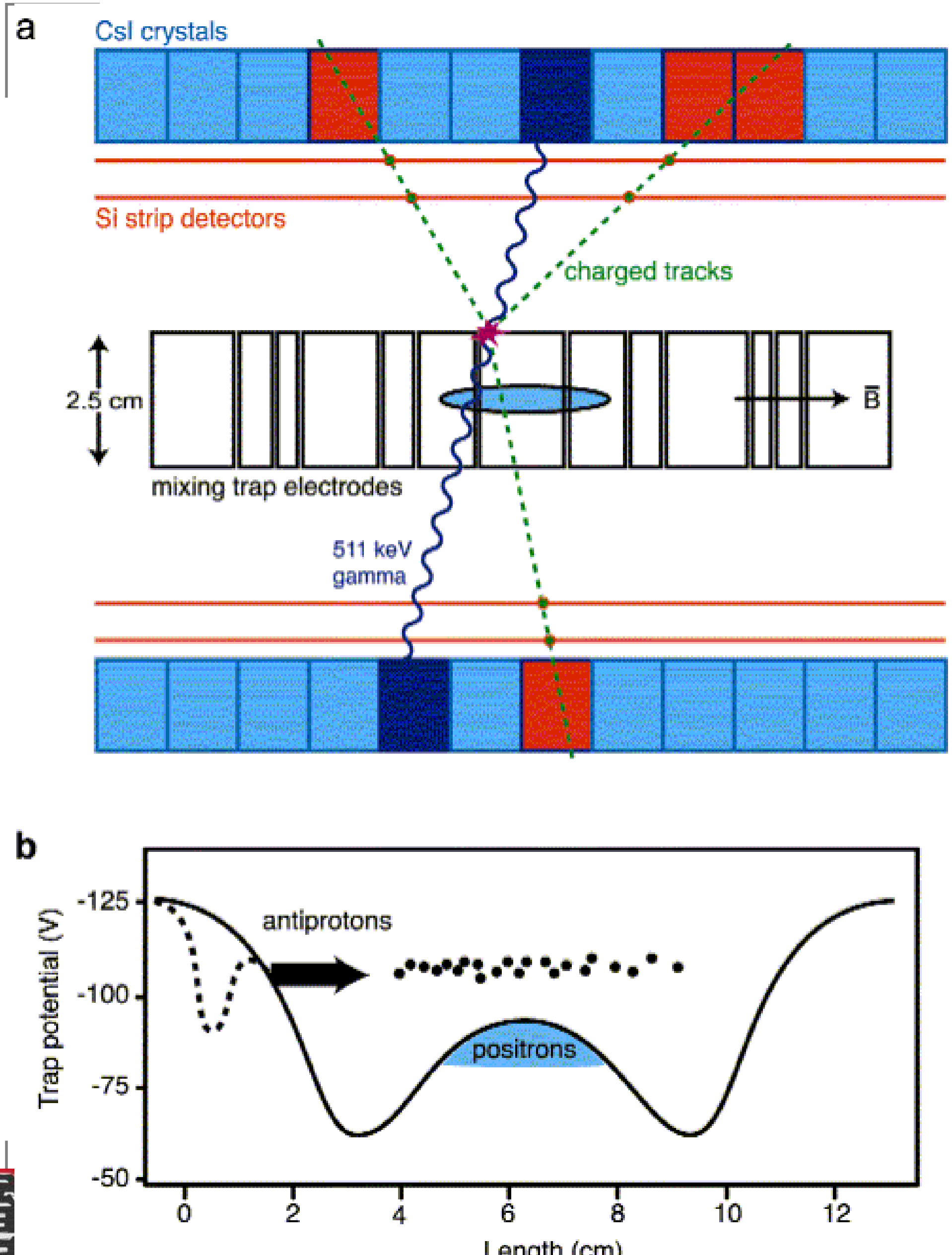
Cold Antihydrogen: How?

1. Trap $\overline{\mathrm{p}}$ and e^+ in nested Penning trap
2. Mix $\overline{\mathrm{p}}$ with e^+ at high particle densities
3. In $\overline{\mathrm{p}}$+ e^++e^+ collisions excited $\overline{\mathrm{H}}$ atoms form
4. Confine $\overline{\mathrm{H}}$ in quadrupole field (e^+ spin)
5. Stimulate deexcitation with laser
6. Make two-photon spectroscopy

1 — 3 are done by ATHENA and ATRAP, rest is planned

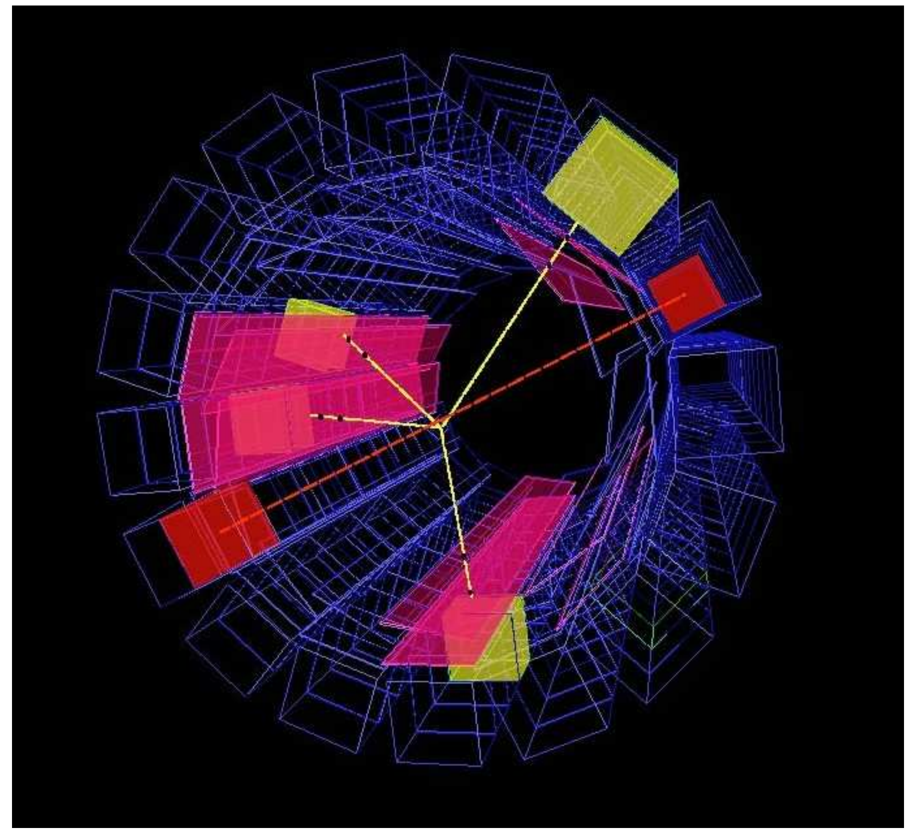
ATHENA: M. Amoretti et al., **Nature** *419* (2002) 456.
ATRAP: G. Gabrielse et al., **Phys. Rev. Lett.** *89* (2002) 213401.

Production of Antihydrogen



ATHENA experiment

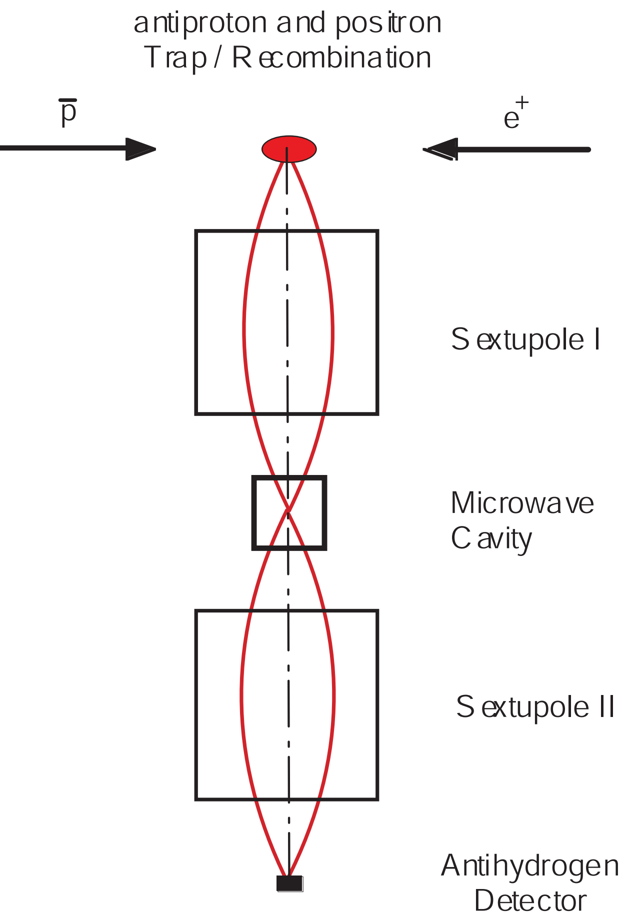
$\overline{\mathrm{H}}$ annihilation event, 2002

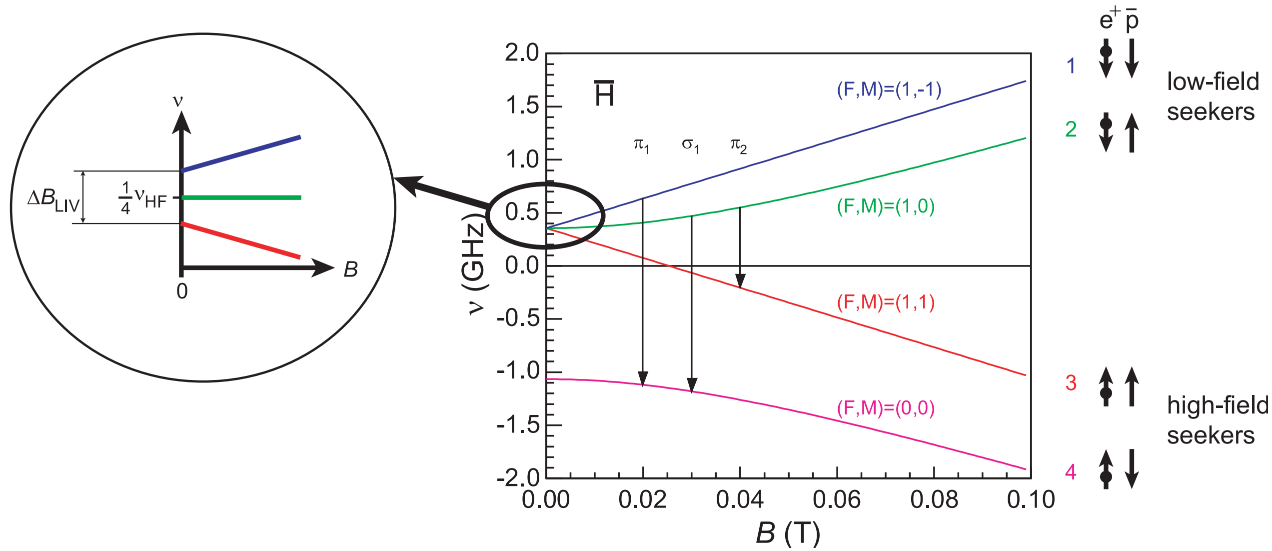


ATHENA, ATRAP, 2003

$> 10^5$ cold $\overline{\mathrm{H}}$ produced

Hyperfine structure of antihydrogen





Possible CPT-violation predicted by

R. Bluhm et al., Phys. Rev. Lett. 82 (1999) 2254.

$v(\bar{p}) \sim$ 350m/s, L(MW cavity) = 20 cm

$\Delta\nu_{HF} \sim$ 3kHz $\Rightarrow$ ppm precision

E. Widmann, R.S. Hayano, M. Hori, T. Yamazaki, **Nucl. Instr. Meth. B** *214* (2004) 31.

Summary

- Nobody expects CPT violation, but it must be tested
- CPT is tested at CERN's Antiproton Decelerator
- In 2008-2009 $\overline{\mathrm{H}}$ spectroscopy expected to start
- MUSASHI will soon work as a user facility
- A new antiproton machine is planned: FLAIR at GSI
  (Facility for Low-energy Antiproton and Ion Research)

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- Monbukagakusho (Grant No. 15002005),
- the Hungarian National Research Foundation (OTKA T046095)
- and EU FP6 Project MKTD-CT-2004-509252.

Spare slides

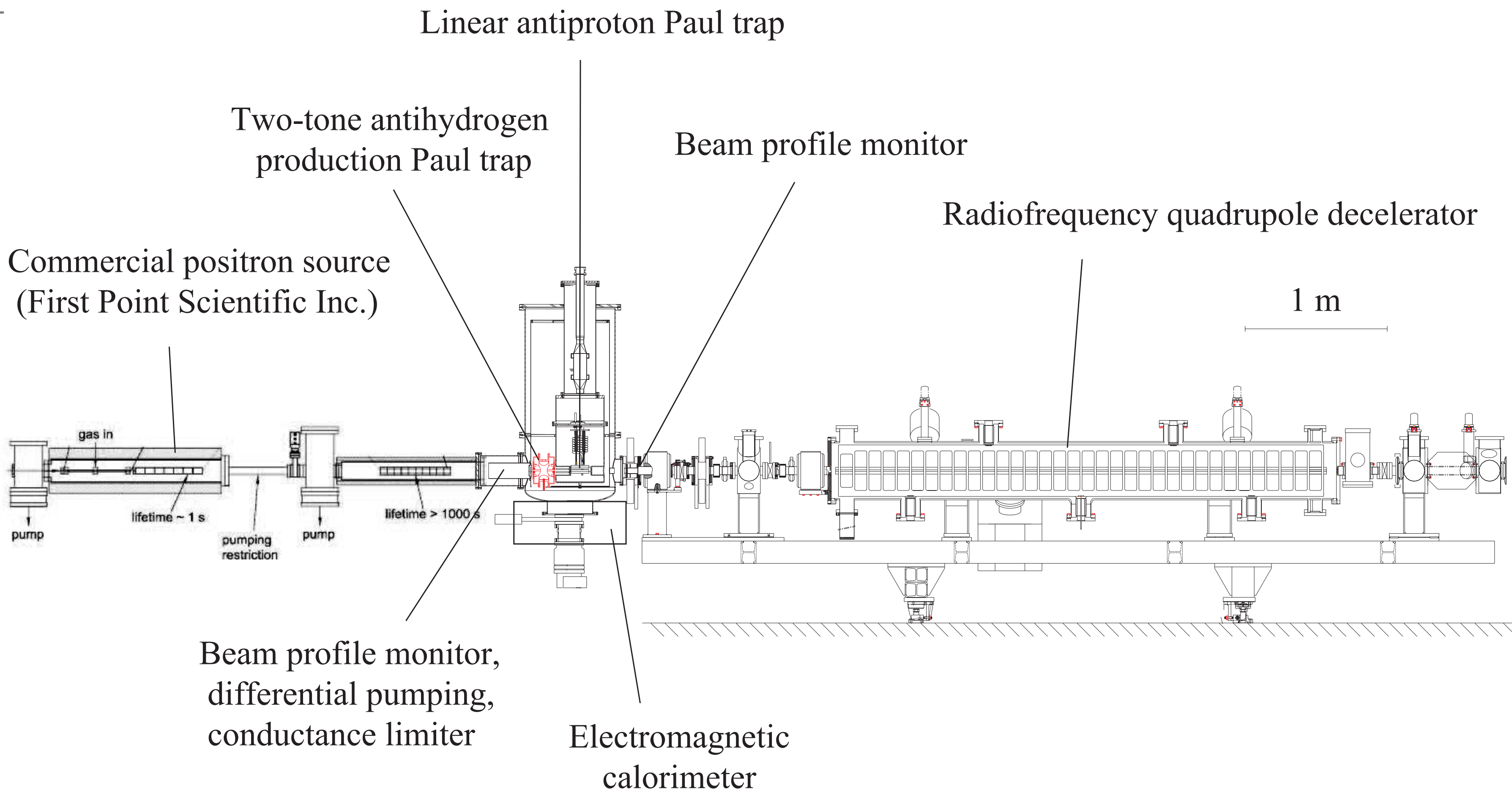
Is it really antihydrogen?

Antiprotons and positrons mix in nested trap

- In collisions neutral particles are produced which leave the trap and could be ionised to e^+ and $\overline{p}$.
- e^+ cools $\overline{p}$: if $\overline{p}$ is overcooled it sinks in its well and stops colliding $\Rightarrow$ no $\overline{H}$.
- The particles can be heated with RF and the $\overline{H}$ production rate driven.
- When $\overline{H}$ production is on, most annihilations happen at the walls, with no $\overline{H}$ the $\overline{p}$ annihilate on residual gas.

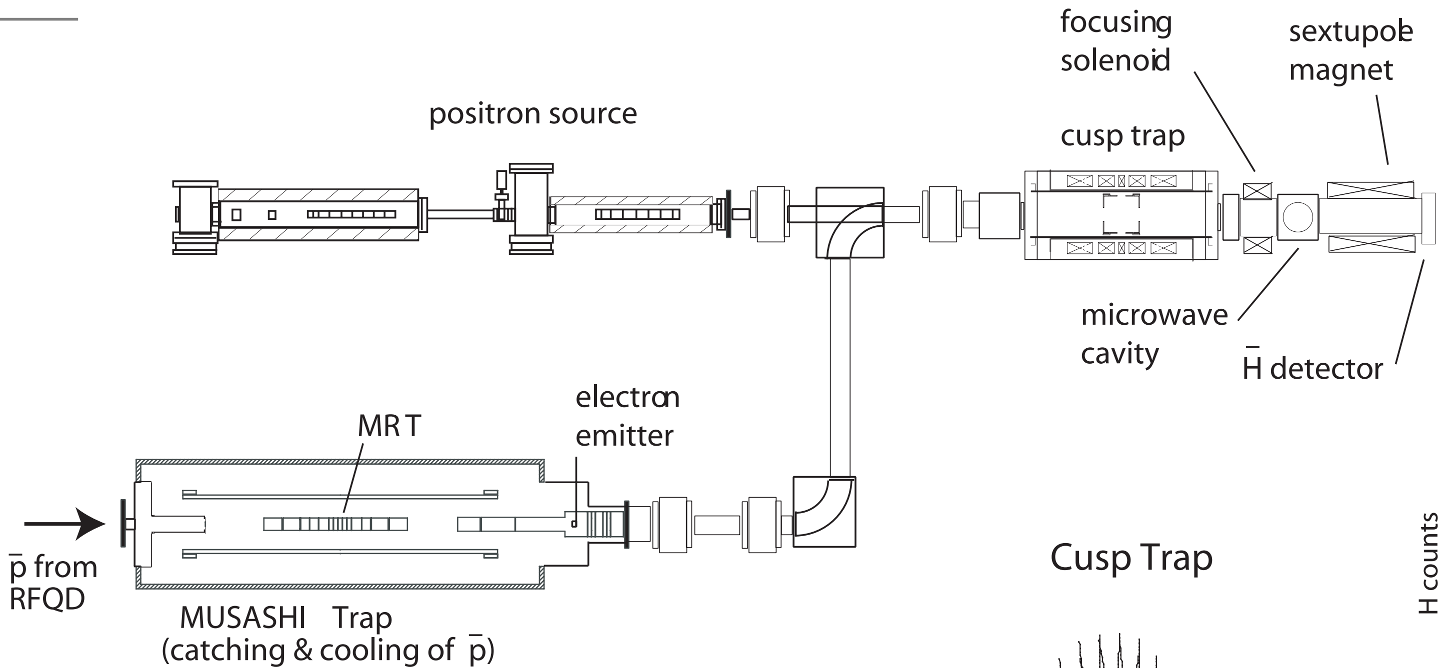
ATHENA: M. Amoretti et al., **Phys. Lett. B** *583* (2004) 59.
ATRAP: G. Gabrielse et al., **Phys. Rev. Lett.** *89* (2002) 233401.

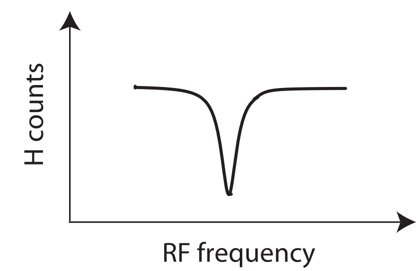
Making antihydrogen: Paul trap

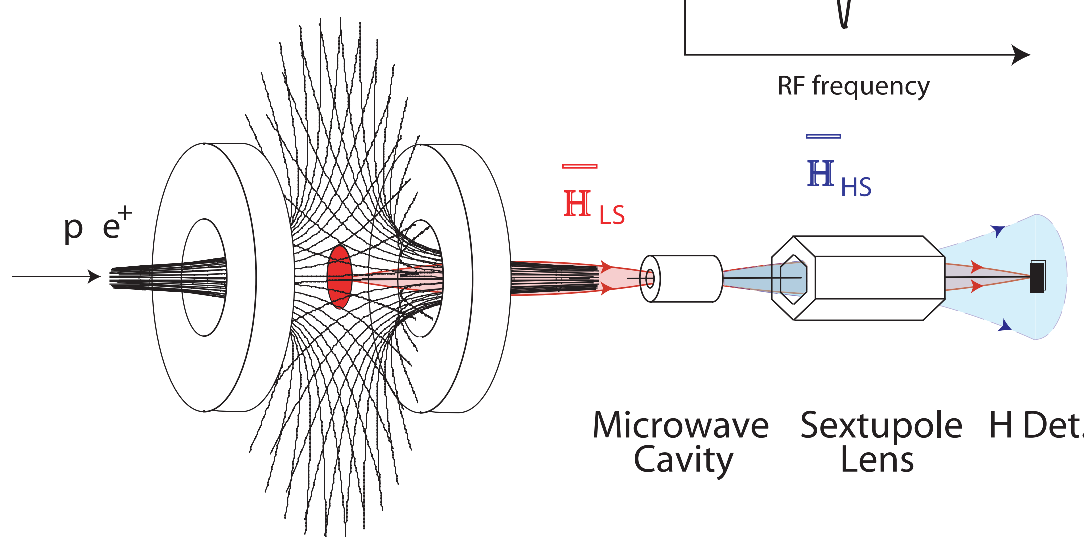


ASACUSA Collaboration, Addendum to Proposal, CERN-SPSC-2005-002

Making antihydrogen: cusp trap

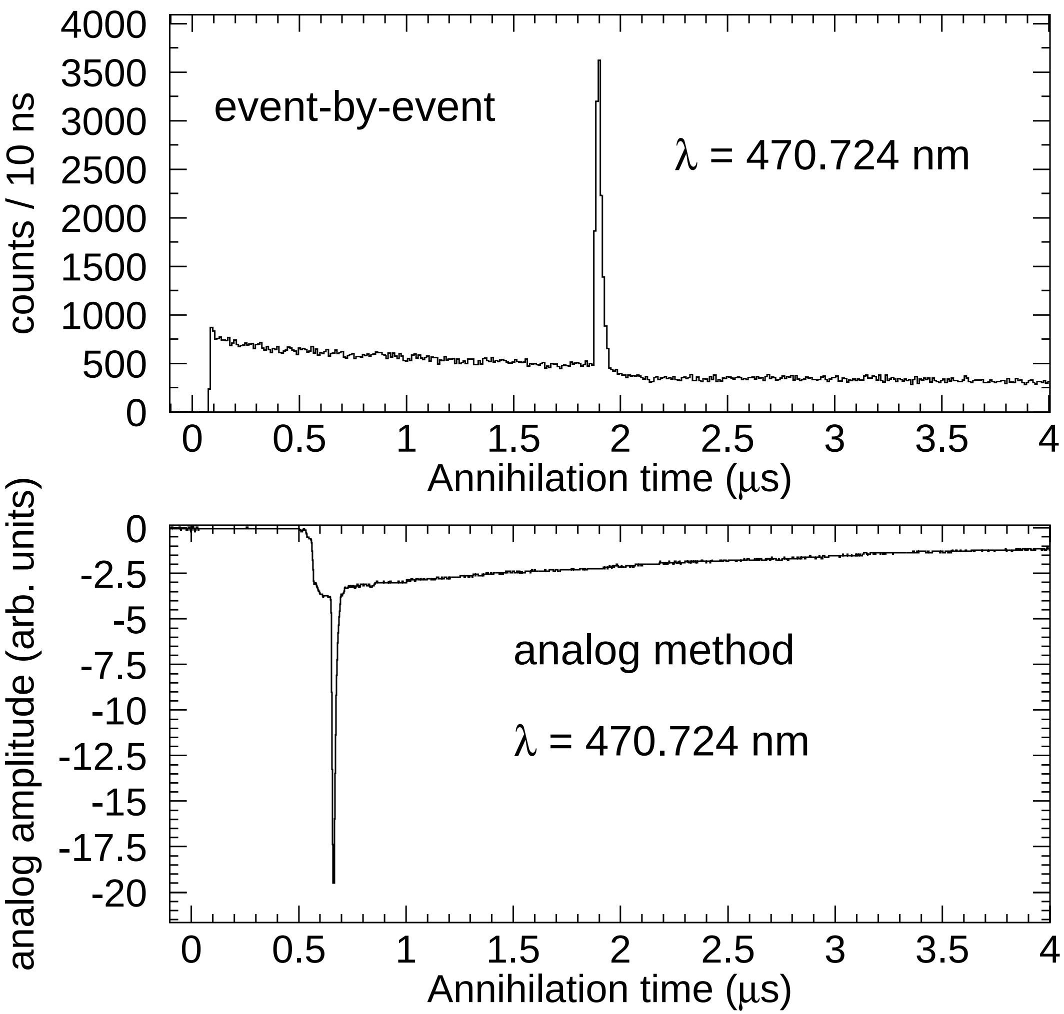






A. Mohri, Y. Yamazaki, Europhys. Lett. **63** (2003) 207.

Laser spectroscopy: LEAR vs AD



LEAR: slow extraction
10^6 laser shot, 50 min

AD: fast extraction
1 laser shot, 2 min

Gated phototube: prompt annihilation (97% $\bar{p}$) off
(Hamamatsu)