Probing Fundamental Physics with Antimatter

Stefan Ulmer (BASE)

for the

AD-Collaborations

Representing the AD Community

THE ALPHA COLLABORATION

- Aarhus University, Denmark
- University of British Columbia, Canada
- University of California Berkeley, USA
- University of Calgary, Canada
- Imperial College London
- University of Liverpool, UK
- University of Manchester, UK
- NRCN - Nuclear Res. Center Negev, Israel
- Purdue University, West Lafayette, USA
- Federal University of Rio de Janeiro, Brazil
- Stockholm University, Sweden
- Simon Fraser University, Canada
- TRIUMF, Canada
- University of Wales Swansea, UK
- Cockcroft Institute, UK
- York University, Canada

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AEgIS collaboration

- IPNL, Lyon
- Stefan Meyer Institut, Austria
- University Bern, Switzerland
- CERN, Switzerland
- INFN Genova, Italy
- MPI-K, Heidelberg, Germany
- U of Heidelberg, Germany
- INFN Milano, Italy
- Politecnico di Milano, Italy
- INR, Moscow, Russia
- U of Bergen, Norway
- University College London, UK
- Laboratoire Aimé Cotton, Orsay, France
- U of Oslo, Norway
- INFN Pavia/Brescia, Italy
- Czech Technical U, Prague, Czech Republic
- INFN Padova/Trento, Italy
- ETH Zurich, Switzerland

BASE: K. Blaum, Y. Matsuda, C. Ospelkaus, W. Quint, J. Walz, Y. Yamazaki

ALPHA · ATRAP · GBAR · BASE · AEgIS

60 Research Institutes/Universities – 339 Researchers – 6 Collaborations

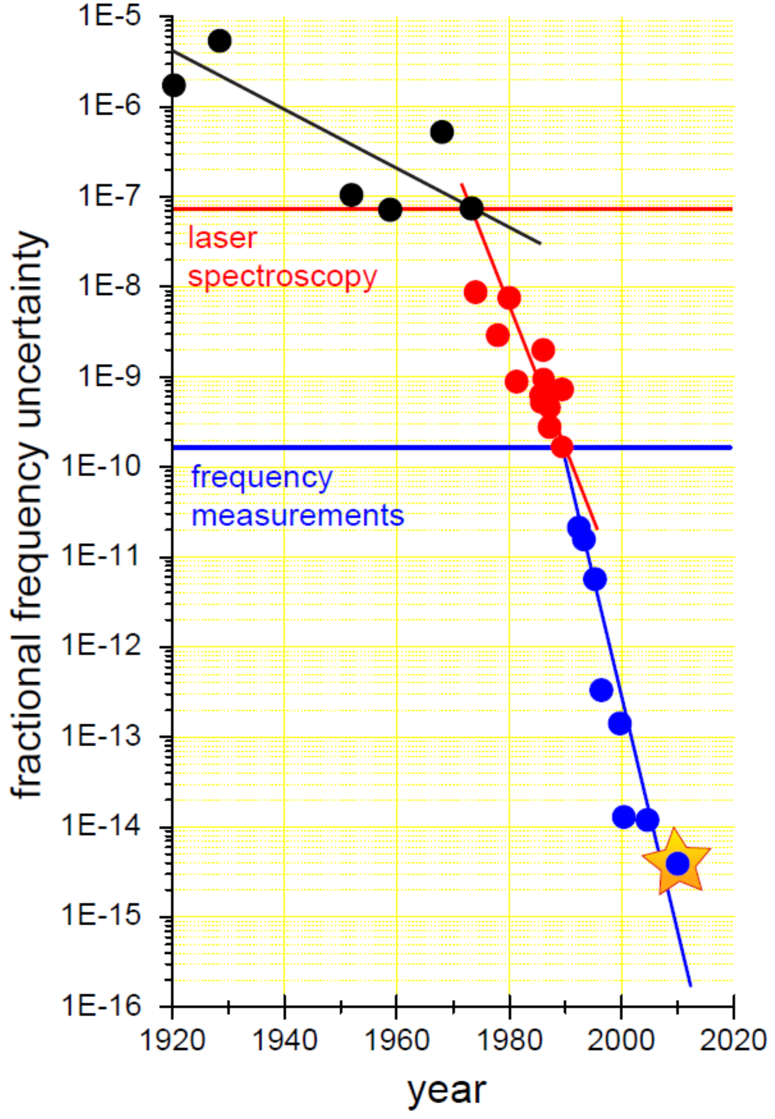
Outline

Introduction: physics motivation and goals

Methods: techniques applied by the AD collaborations

Results: major results of the last decade

Outlook: physics perspective in the ELENA epoche



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Strategy and Physics Motivation

- Precise comparisons of the fundamental properties of **simple baryonic matter/antimatter** conjugates at **low energy** and with **high precision**.
- Such comparisons provide stringent tests of CPT invariance.
- Simple systems can be understood, and understanding provides sensitivity with respect to deviations.

matter sector

proton lifetime (direct)	>1.67 e34 y
proton m	90 p.p.t.
proton magn. moment	3.3 p.p.b.
hydrogen 1S/2S	0.004 p.p.t.
hydrogen GSHFS	0.7 p.p.t.

antimatter sector

antiproton lifetime	>1.2 y
antiproton m	90 p.p.t.
antiproton m. moment	4.4 p.p.m.
antihydrogen 1S/2S	?
antihydrogen GSHFS	?

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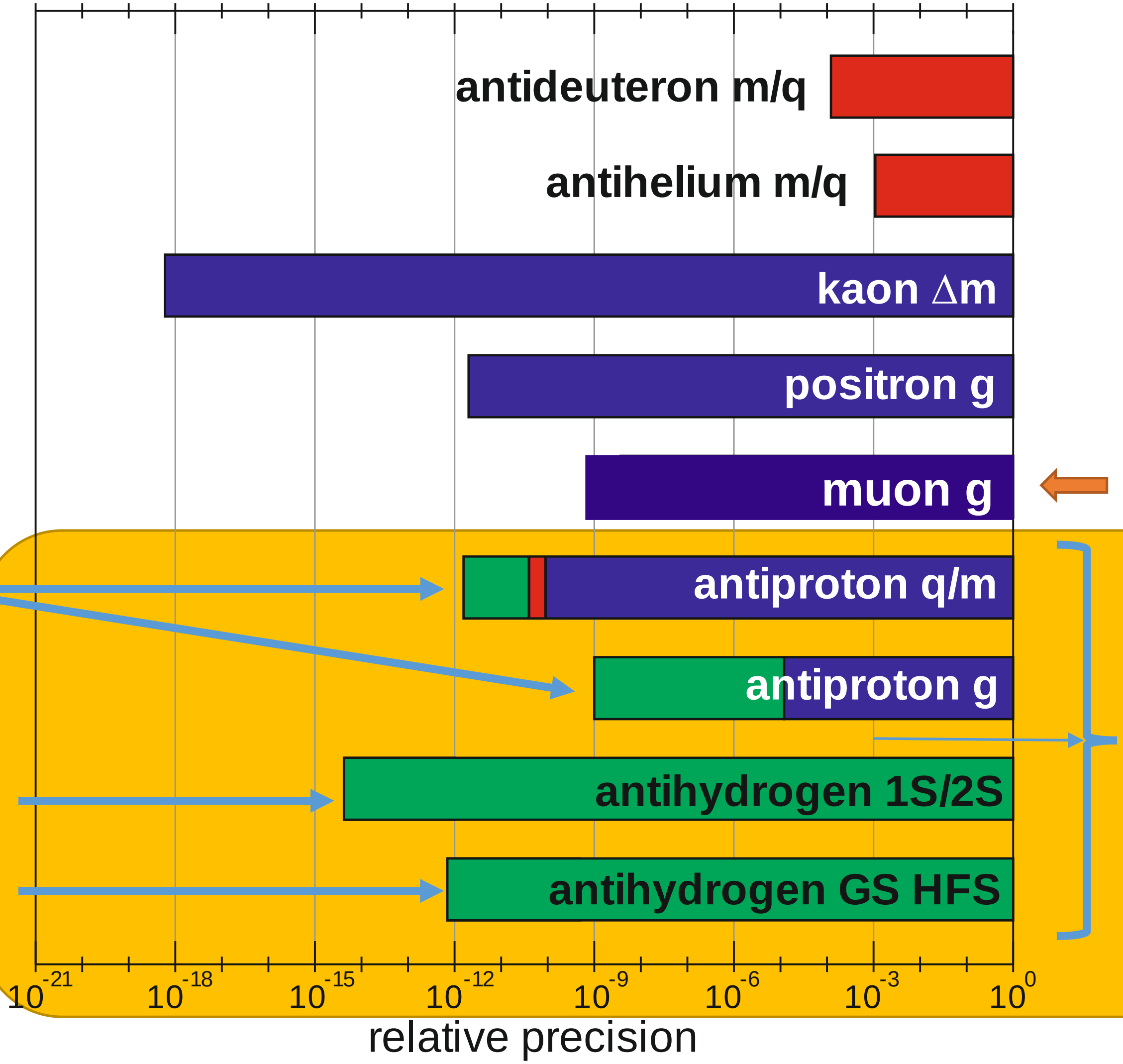
Tests of CPT Invariance

Red: Recent tests
Purple: Past tests
Green: Planned



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CPT test with fractional precision of 10^{-18} available… why continue measuring?

Energy Resolution

$$< \psi^* | \Delta V | \psi >= \Delta E$$

$$\mathcal{L}_p = \frac{\lambda}{M} \langle T \rangle \bar{\psi} \Gamma (i\partial)^k \psi$$

Kostelecky et al.

- Absolute energy resolution (normalized to m-scale) might be a more appropriate measure to characterize the sensitivity of an experiment with respect to CPT violation.
- Single particle measurements in Penning traps give high energy resolution.

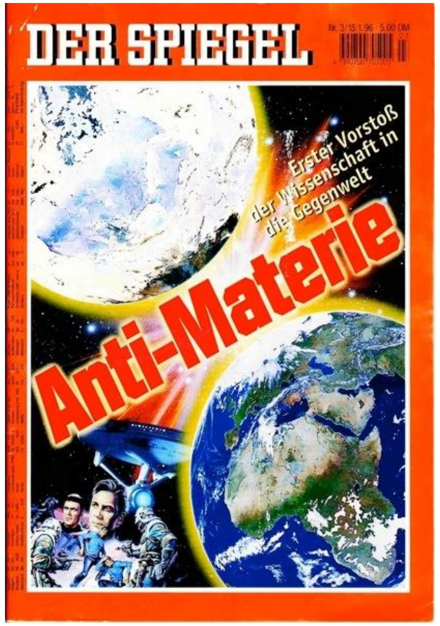
	Relative precision	Energy resolutio n	SME Figure of merit
Kaon Δm	$\sim 10^{-18}$	$\sim 10^{-9}$ eV	~ 10^{-18}
p-p̄ q/m	$\sim 10^{-11}$	$\sim 10^{-18}$ eV	~ 10^{-26}
p-p̄ g-factor	$\sim 10^{-6}$	$\sim 10^{-12}$ eV	~ 10^{-21}

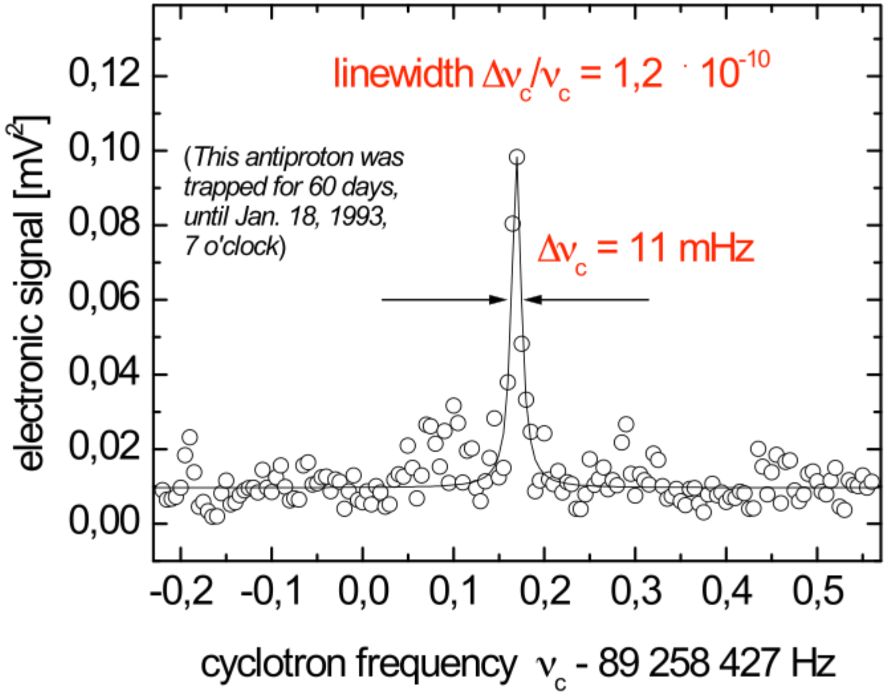
SME has no predictive power / missing link from EFT to particle physics

Pioneering Highlights

Production of 11(2) relativistic antihydrogen atoms at LEAR (PS210) in 1995.

G. Baur et al., Phys. Lett. B 368 (1996) 251





Comparison of the proton to antiproton charge to mass ratio at fractional precision of 90 p.p.t.

$$\frac{Q_{\bar{p}}}{M_{\bar{p}}} \Big/ \frac{Q_p}{M_p} = -0.999'999'999'91(9)$$

G. Gabrielse et al., Phys. Rev. Lett. 82 (1999) 3198

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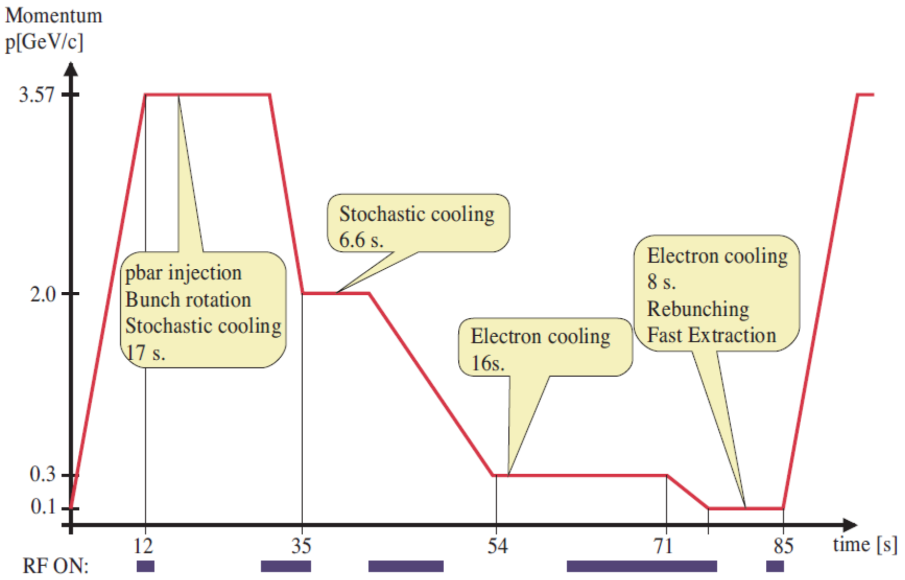
Convinced CERN to start the AD program.

Methods – the antiproton decelerator



AD provides: 30.000.000 antiprotons at 5.3 MeV each 120s

- Degrading / RFQ-D
- Catching
- Electron Cooling and kickout
- Compression

resistive cooling –> particles at 8ueV

bridge 6 orders of magnitude within a few 100s

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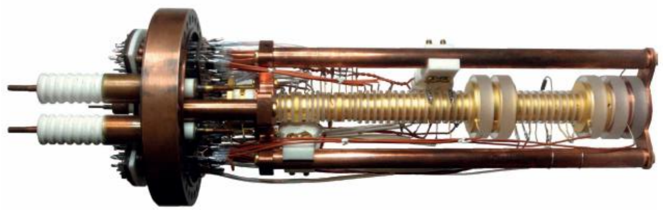
work pioneered by the TRAP collaboration

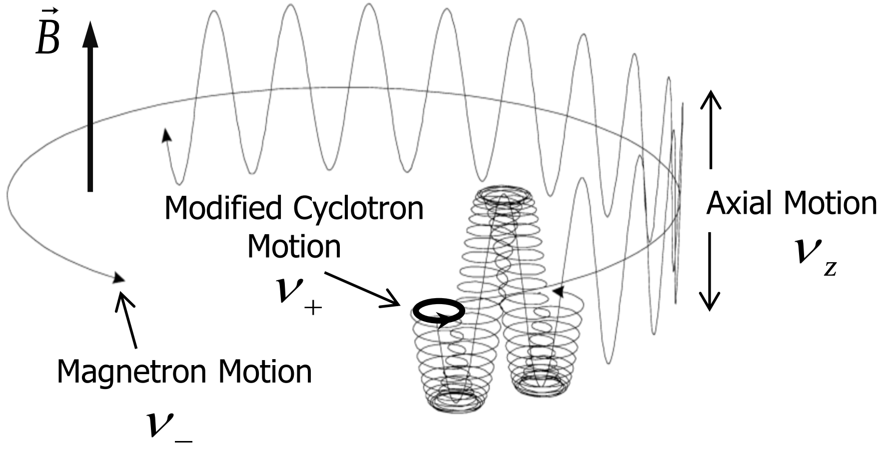
Catching: G. Gabrielse et al, PRL 57, 2504 (1986)
Cooling: G. Gabrielse et al, PRL 63, 1360 (1989)
Measurement: G. Gabrielse et al, PRL 65, 1317 (1990)

Methods: Workhorse Penning Trap

radial confinement: $\vec{B} = B_0 \hat{z}$

axial confinement: $\Phi(\rho, z) = V_0 c_2 \left(z^2 - \frac{\rho^2}{2} \right)$



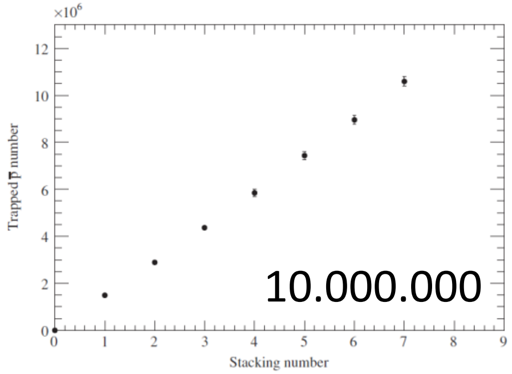


Measurements

$\omega_c = \frac{e}{m_p} B$ — charge-to-mass ratios

$\omega_L = g \frac{e}{2m_p} B$ — magnetic moments

- accumulation and compression of antiproton / positron plasmas

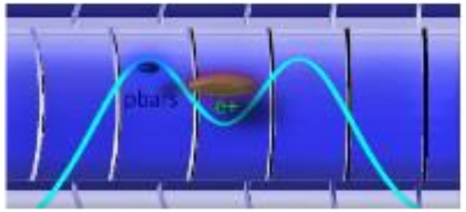


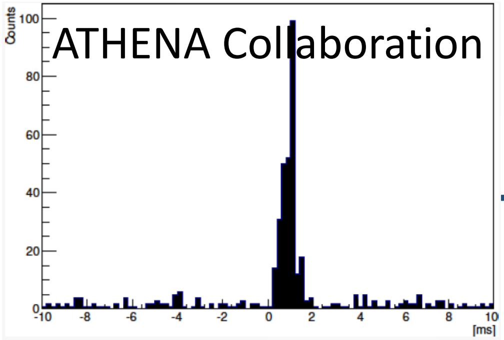
N. Kuroda, Phys. Rev. ST **15** (2012) 024702.

- antihydrogen formation using a nested trap scheme.

Proposed: G. Gabrielse, Phys. Lett. A **129** (1988) 38.

First Demonstration: M. Amoretti, Nature **419** (2002) 456.





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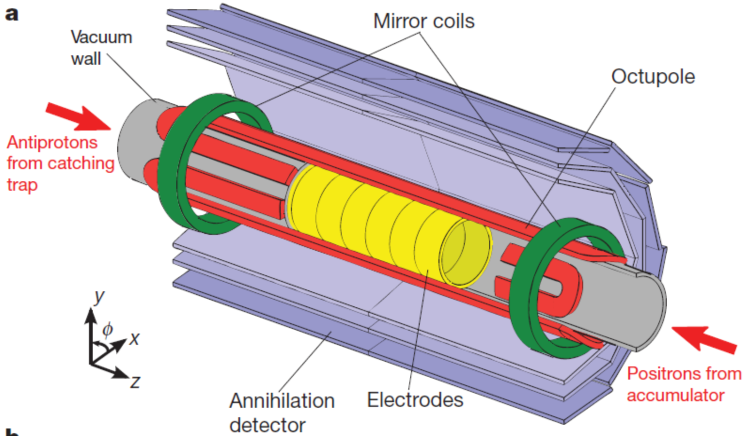
Physics Measurements



- Antihydrogen 1S/2S laser spectroscopy in magnetic trap.
- Hydrogen in trap: 5 p.p.t.
- Trapping via atomic magnetic moment, Challenge: shallow trap (0.5 K)

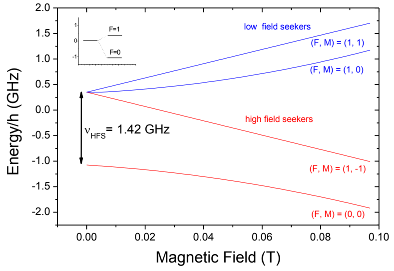
C. L. Cesar, Phys. Rev. Lett. **77** (1996) 255.

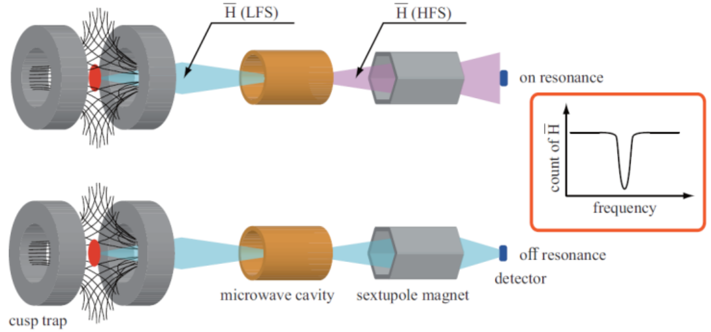
- Antihydrogen beam spectroscopy (ASACUSA Scheme)

1ppb

$$\nu_{HF} = \frac{16}{3}\cdot \mathrm{Ry}\cdot\alpha^2 c\cdot\left(\frac{1}{1+\frac{m_e}{m_p}}\right)^3\cdot\frac{m_e}{m_p}\cdot\frac{\mu_e}{\mu_B}\cdot\frac{\mu_p}{\mu_N}\cdot(1+\delta_{str}+\delta_{QED})$$

<1ppb





- extract antiproton magnetic moment
- probe antiproton substructure
- Test SME coefficients

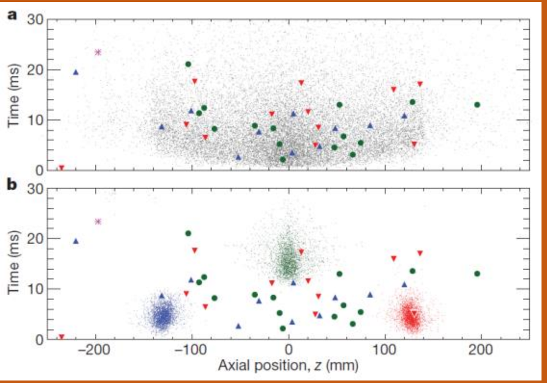
Achieved 3.3 p.p.b. using hydrogen beam (Widmann Group in ASACUSA)

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

ATRAP

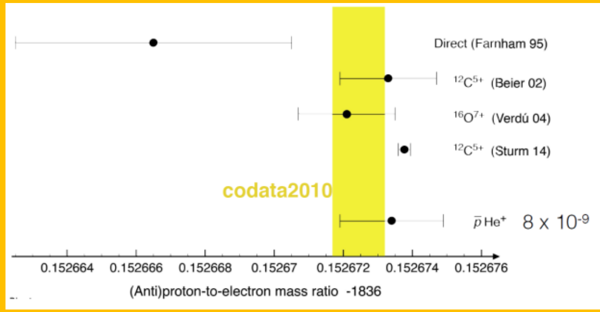
Highlights – CPT Sector

trapped antihydrogen



ALPHA, Nature 468, (2010) 674.
sim. res. ATRAP, PRL (2012)

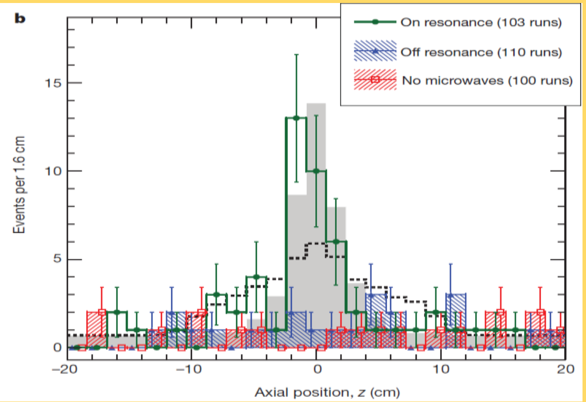
antiproton/electron mass ratio



2-photon spectroscopy of anti-protonic helium / 8 p.p.b.

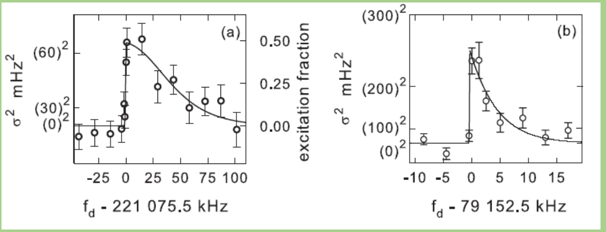
ASACUSA, Nature **484** (2011) 475.

«rf-spectroscopy»



ALPHA, Nature 483, (2012) 442.

antiproton mag. moment



4.4 p.p.m. measurement using single Penning trap technique

ATRAP, Phys. Rev. Lett **110** (2013) 130810

Antihydrogen Beam

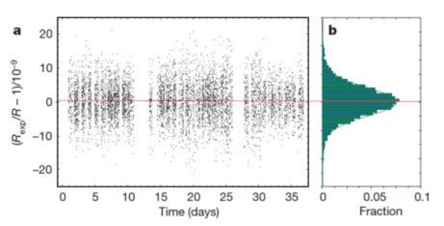
Table 1 | Summary of antihydrogen events detected by the antihydrogen detector.

	Scheme 1	Scheme 2	Background
Measurement time (s)	4,950	2,100	1,550
Double coincidence events, N_t	1,149	487	352
Events above the threshold (40 MeV), $N_{>40}$	99	29	6
Z-value (profile likelihood ratio) (σ)	5.0	3.2	—
Z-value (ratio of Poisson means) (σ)	4.8	3.0	—

Major step towards planned antihydrogen spectroscopy.

ASACUSA, Nature Comm. **3** (2014) 475.

antiproton/proton Q/M ratio



69 p.p.t. measurement using two particle Penning trap technique

BASE, Nature **493** (2014) 502.

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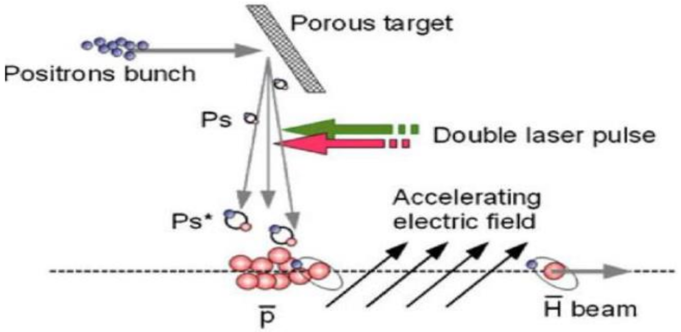
Tests of the weak equivalence principle

- AEgIS Scheme (Moire Defl.)



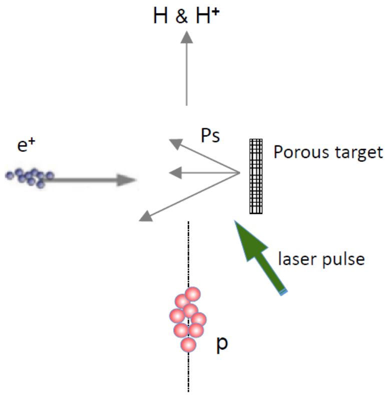
$$\bar{p} + Ps^* \rightarrow \bar{H}^* + e^-$$

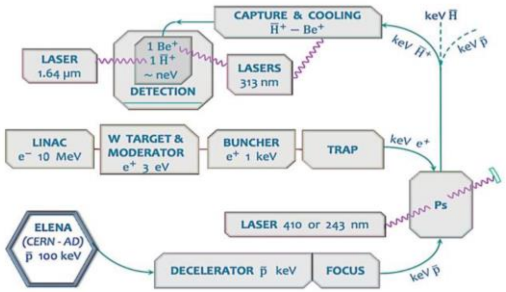
Demonstration: AEgIS, Nature. Comm. **5** (2014) 4538.

precision goal: order %

Goal: First gravity measurement before LS2

- GBAR Scheme





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

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

precision goal: order %

Status: Under construction / beam in 2017

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Production of the antihydrogen ion is highly promising

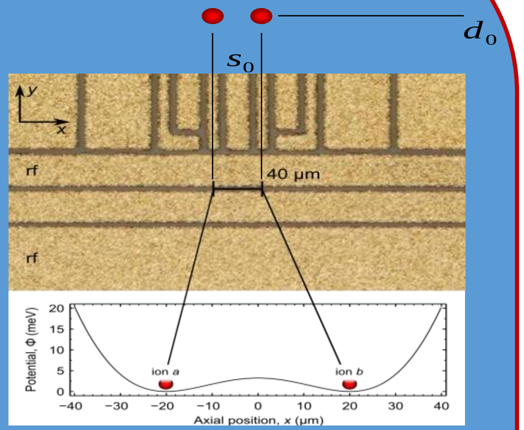
Potential of the antihydrogen ion

Charged particle

Sympathetic cooling has been demonstrated in Paul traps

Doppler temperatures can be reached easily

Stripping by «resonant» lasers is a routine.



Scheme has been demonstrated for two co-trapped laser-cooled Be-ions.

Is planned to be established and applied to antihydrogen ions by the gbar collaboration and to antiprotons by the BASE collaboration.

Publication: K. R. Brown, C. Ospelkaus, Y. Colombe, A. C. Wilson, D. Leibfried, D. J. Wineland, Nature **471**, 196 (2011).

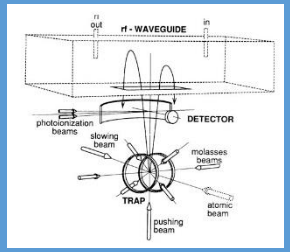
See also: M. Harlander, R. Lechner, M. Brownnutt, R. Blatt, W. Hänsel, Nature **471**, 200 (2011).

Production of a high-quality beam

Cool particles sympathetically.

Accelerate particles with electric field.

Strip one positron.

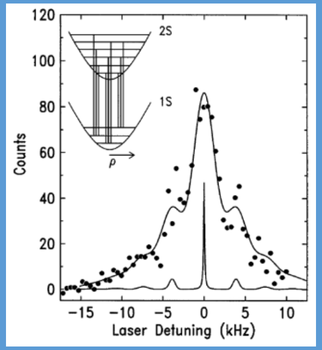


Apply to ASACUSA ideas (Rabi / Ramsey beam-scheme)

1S/2S spectroscopy at improved temperature distribution

Apply the «classical» ideas by ALPHA and ATRAP however with drastically improved initial temperature distribution

Smaller gradient traps, higher precision



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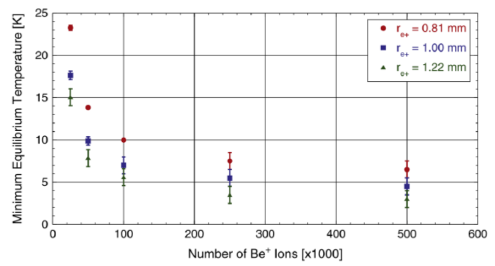
Future Projects

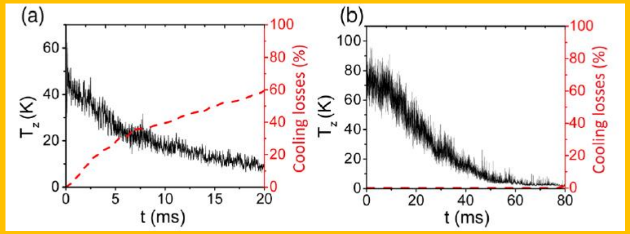
Sympathetic cooling of positrons (ALPHA)

$$\text{Rate} \propto n_{e^+}^2 / T_{e^+}^{9/2}$$



Drastically improved Hbar production rate

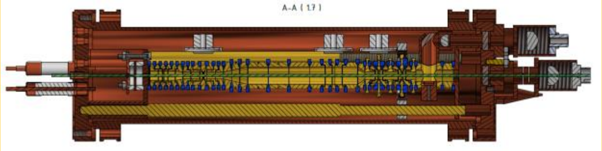
Sympathetic cooling of antiproton-plasmas (Borealis / AEgIS)



Use molecular anions C2-
Colder Hbar beams

P. Yzombard et al., Phys. Rev. Lett. ***114*** *213001 (2015)*

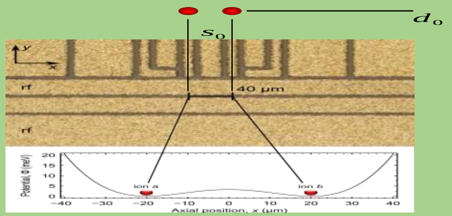
Sympathetic cooling of single antiprotons (BASE)

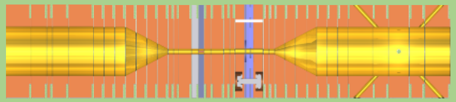


Cool single antiproton by laser cooled Be ions
Aim at sub-ppt measurements

A. Mooser, G. Schneider, J. Walz (BASE)

Quantum Logic Spectroscopy of antiprotons (Ospelkaus)





Quantum Logic inspired readout of the spin state.

Transportable Traps

Scheme to extract single antiprotons from a reservoir has been developed recently
Trapping of antiprotons for > 5 years has been demonstrated

First step towards transportable antiproton traps.

C. Smorra et al., Int. Journ. M.S. ***114*** *213001 (2014)*

Space for one more experiment

ALPHA

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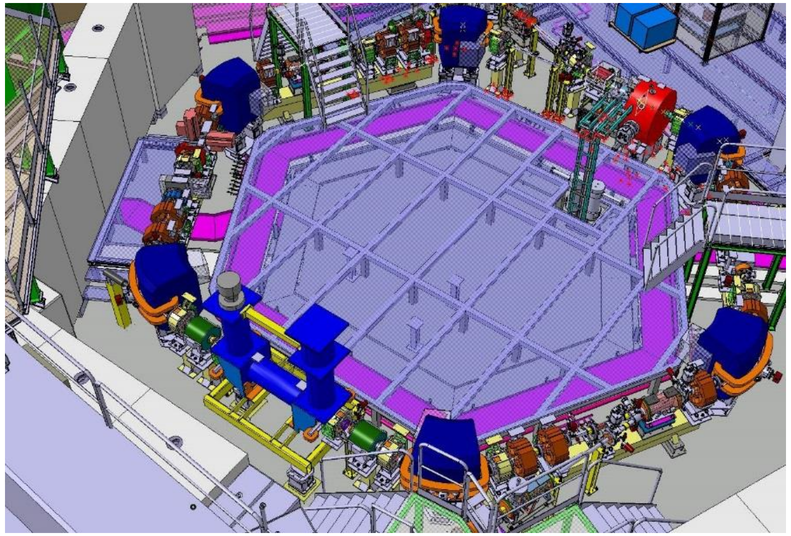
ELENA

- Antiprotons are caught in Penning traps using degraders – 99.9% of particles are lost.
- ELENA provides antiprotons decelerated to 100keV – compared to the AD – at improved beam emittance.
- Degrading at low particle energies is much more efficient

Experiment	ELENA Gain Factor
ALPHA	100
ATRAP	100
ASACUSA	10
AEgIS	100



- **ELENA will be able to deliver beams almost simultaneously to all experiments resulting in an essential gain in total beam time for each experiment. This also opens up the possibility to accommodate an extra experimental zone**

Provides bright future perspective for antiproton-physics at CERN

Thanks very much for your attention

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K. Blaum, Y. Matsuda,
C. Ospelkaus, W. Quint,
J. Walz, Y. Yamazaki

ATRAP

60 Research Institutes/Universities – 339 Researchers – 6 Collaborations

Possibilities

antiprotons

- free
  - charge-to-mass ratio
  - magnetic moment
- bound

fundamental properties

pbarHe | **antihydrogen** | **antihydrogen ions**

fundamental properties and e/m interactions

spectroscopy

gravity

ATRAP