High-precision measurements of the fundamental properties of the antiproton

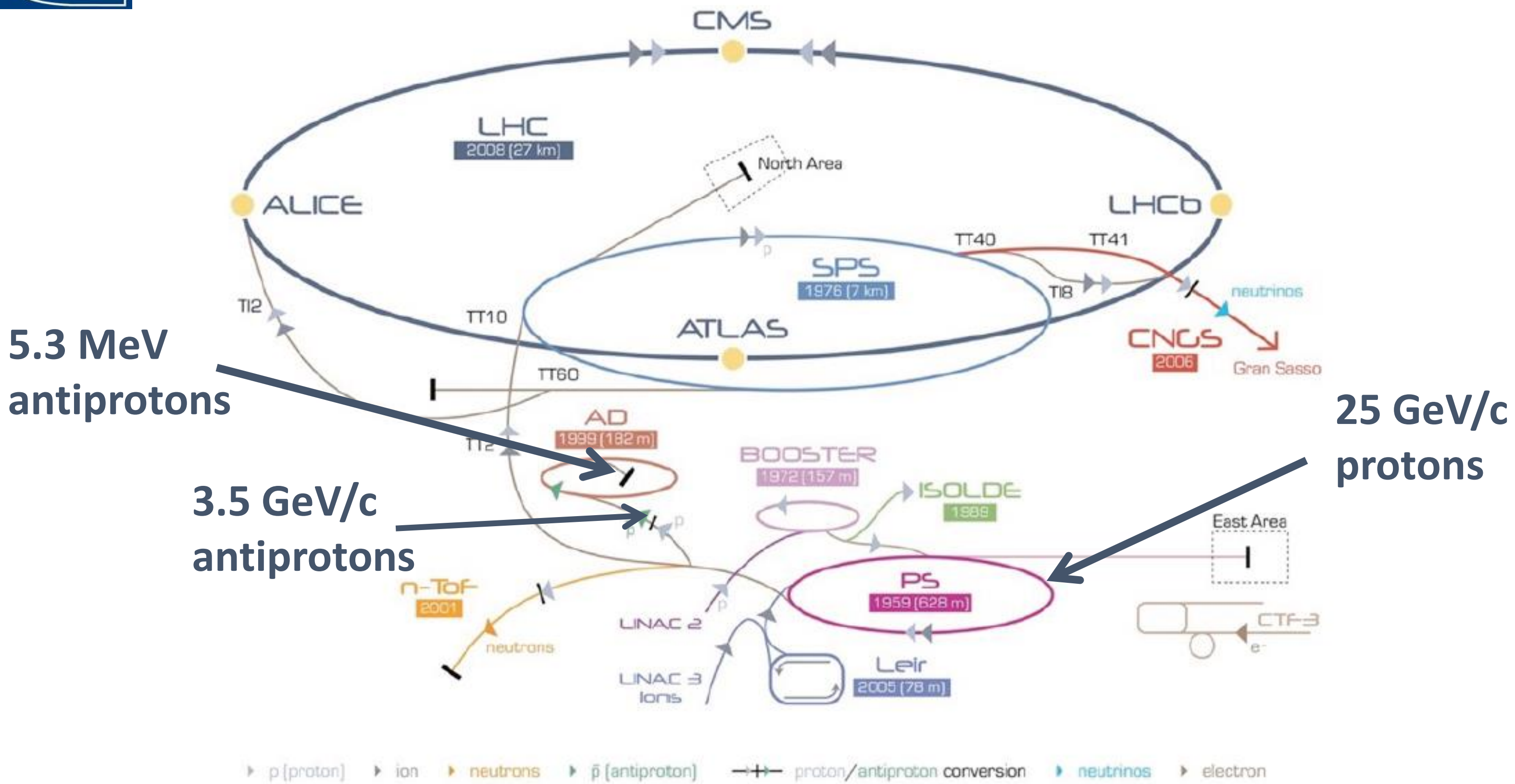
Hiroki Nagahama
on behalf of the BASE collaboration

PSAS' 2016, Jerusalem 26/May

Table of contents

- Goal of BASE
- Principle of CPT invariance
- Result from 2014 beamtime (High-precision comparison of the antiproton-to-proton charge-to-mass ratio)
- Update on 2015 beamtime (Statistical spinflips of a single trapped antiproton) <- Main topic of this talk

Our goal

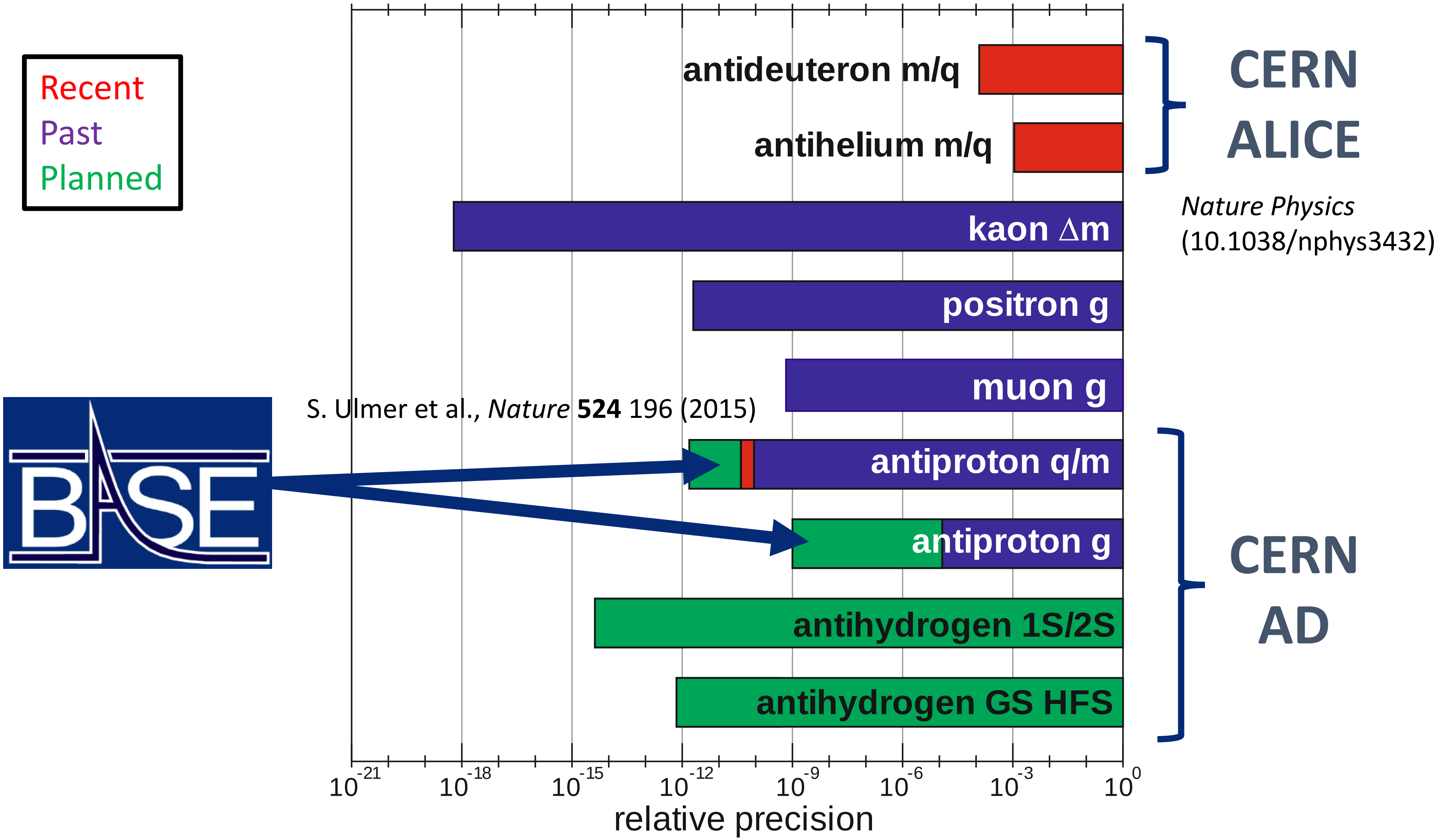


BASE aims at stringent tests of CPT invariance in the AD

Theory: fundamental properties of matter/antimatter identical.

Experiment: **We should test that!**

Different CPT tests



Already up to a relative precision of 10^{-18} CPT test was succeeded… why do we still want to measure?

=> Necessary to think about a concept of CPT violation

Concept of CPT violation

Add CPT violating term to a Hamiltonian based on Standard Model

➡ Absolute energy change ΔE will be derived

$$H' = H_{SM} + \Delta V \quad \Longrightarrow \quad < \psi^* | \Delta V | \psi >= \Delta E$$

System based on SM → H_{SM}

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

different C's

Kostelecky et al.

Absolute energy resolution (normalized to m-scale) is the relevant measure to characterize sensitivity of an experiment to CPT violation.

Single-particle measurements in Penning traps give high energy resolution.

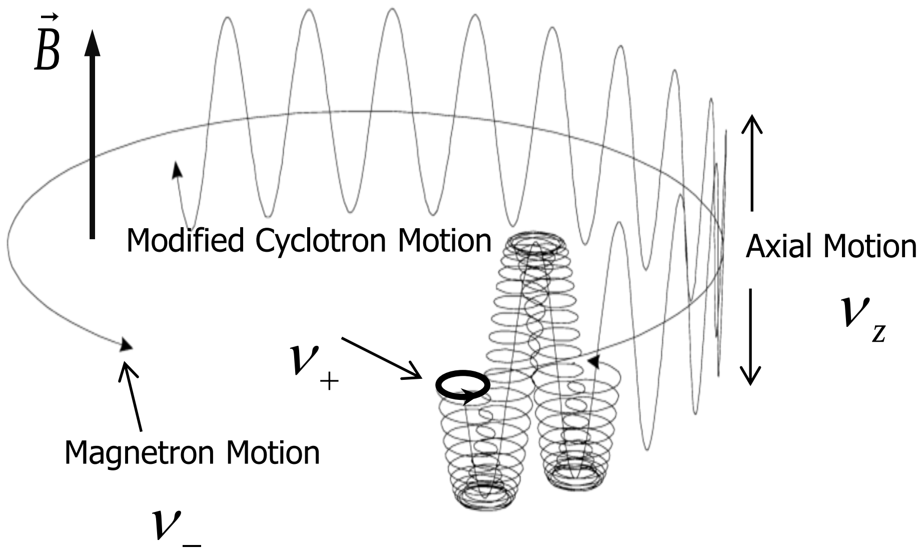
	Relative precision	Energy resolution
Kaon Δm	$\sim 10^{-18}$	$\sim 10^{-9}$ eV
p-$\bar{\text{p}}$ q/m	$\sim 10^{-11}$	$\sim 10^{-18}$ eV
p-$\bar{\text{p}}$ g-factor	$\sim 10^{-6}$	$\sim 10^{-12}$ eV

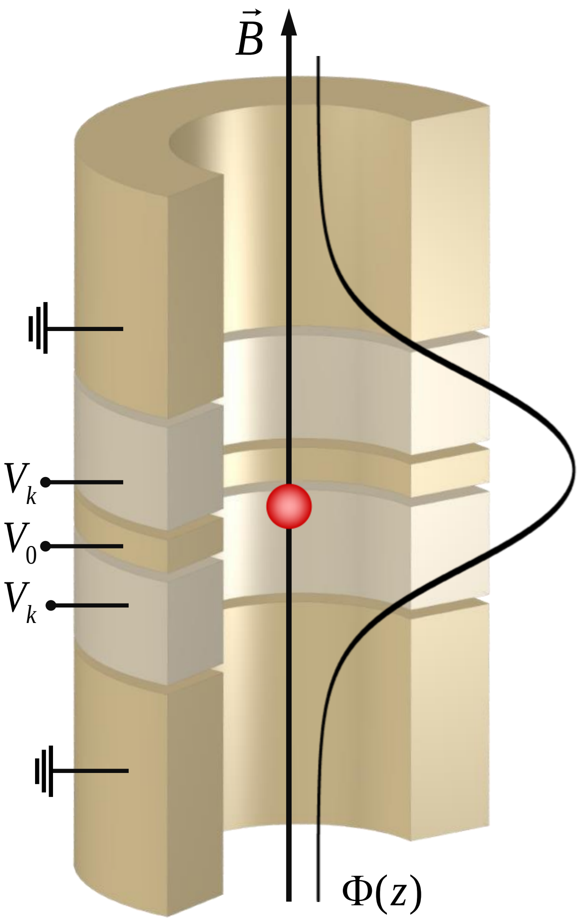
← BASE aims to improve with 10^{-9} relative precision

Main Tool: Penning Trap

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

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





Axial	$\nu_z = 680\,\mathrm{kHz}$
Magnetron	$\nu_- = 8\,\mathrm{kHz}$
Modified Cyclotron	$\nu_+ = 28{,}9\,\mathrm{MHz}$

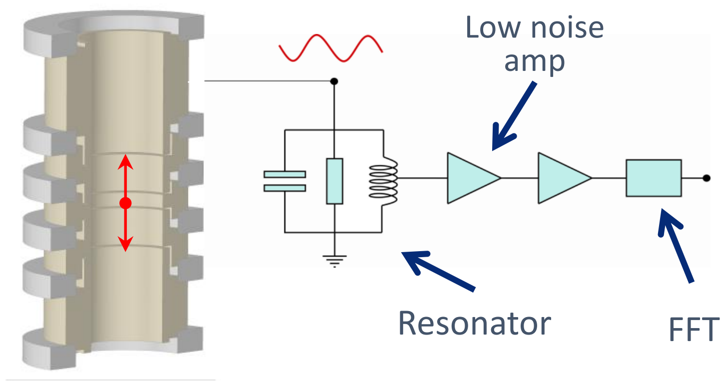
Invariance-Relation

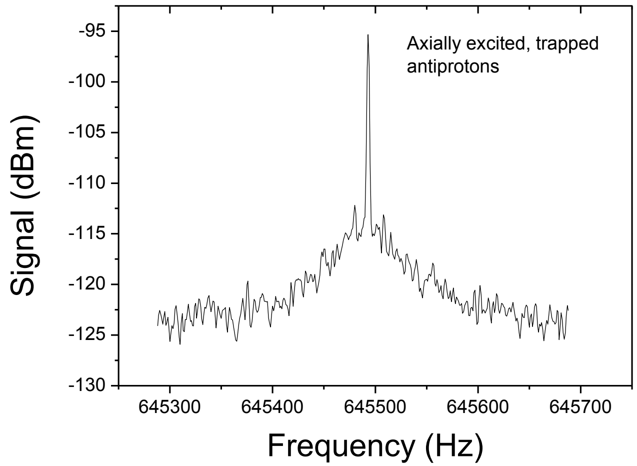
$$\nu_c = \sqrt{\nu_+^2 + \nu_-^2 + \nu_z^2}$$

L. S. Brown and G. Gabrielse, Phys. Rev. A **25**, 2423 (1982).

Frequency Measurements

Measurement of tiny image currents induced in trap electrodes

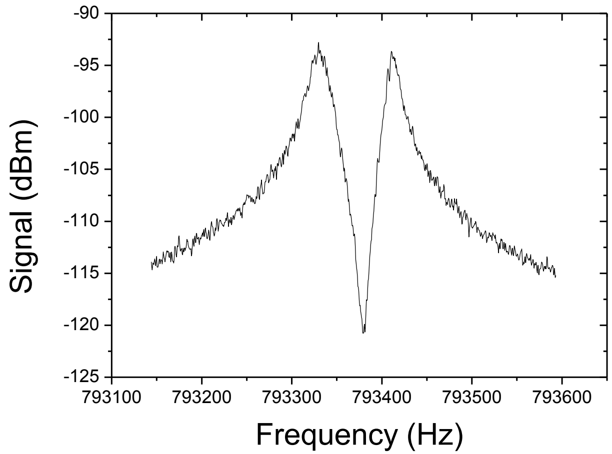




In thermal equilibrium:

- Particles short noise in parallel
- Appear as a dip in detector spectrum
- Width of the dip → number of particles

$$\Delta\nu = \frac{1}{2\pi}\frac{R}{m}\left(\frac{q}{D}\right)^2 \cdot N$$



Measurements in thermal equilibrium → tiny volumina / homogeneous condititions

Enables cyclotron frequency measurement at ~1 ppb

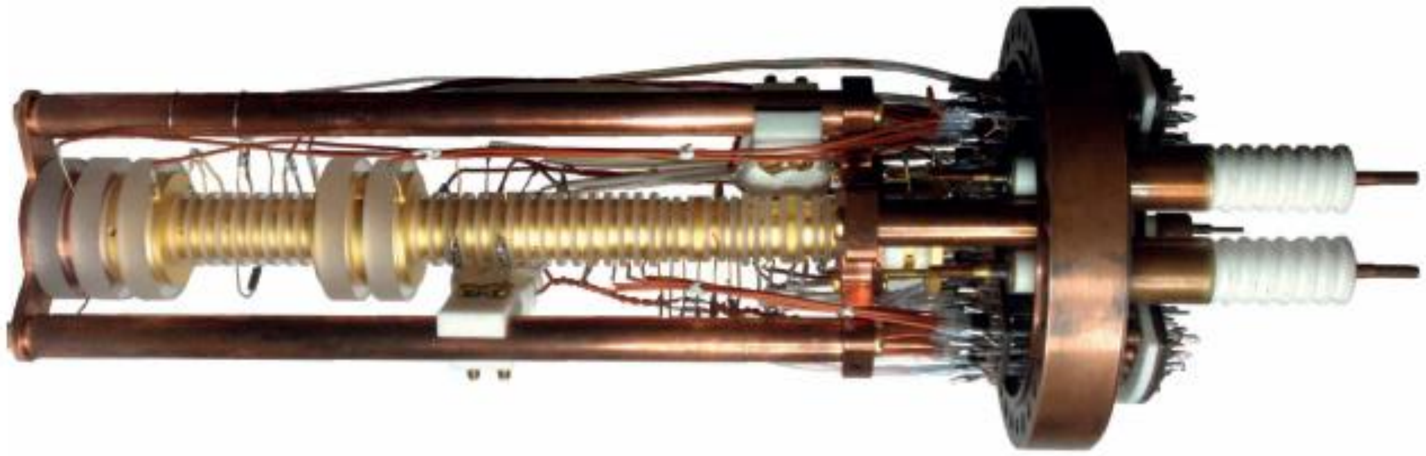
The BASE Trap

Access to beamline

Particles not continuously available

Reservoir Trap: Stores a cloud of antiprotons, suspends single antiprotons for measurements. Trap is "power failure save".

Cooling Trap: Fast cooling of the cyclotron motion, $1/\gamma < 4$ s **(10 x improved)**



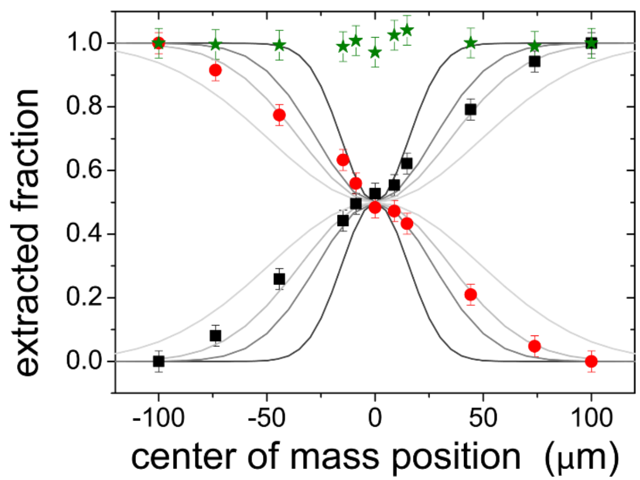
Precision Trap: Homogeneous field for frequency measurements, $B_2 < 0.5\ \mu T / mm^2$

Analysis Trap: Inhomogeneous field for the detection of antiproton spin flips, $B_2 = 300\ mT / mm^2$

Double Trap

Single particle extraction from the reservoir

- Superimpose a constant electric field over the Penning trap potential

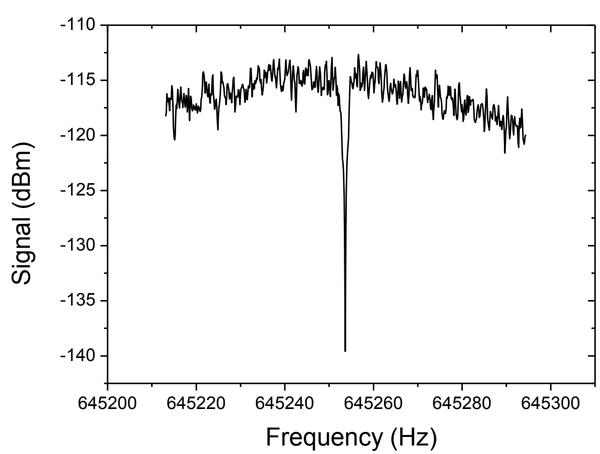


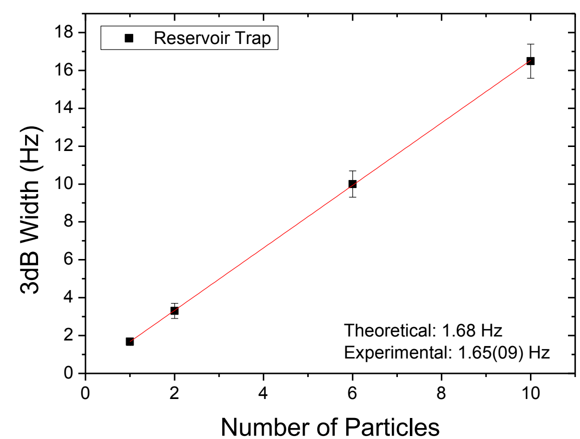
Measurement with an antiproton cloud

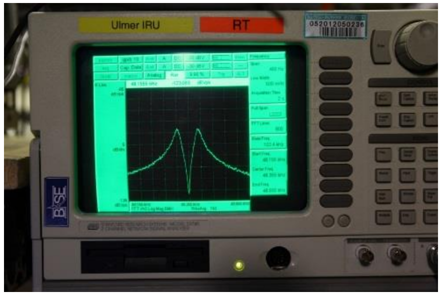
200 particle/50 cycles
No particle loss

C. Smorra, et al., Int. J. Mass Spectrom. (2015), http://dx.doi.org/10.1016/j.ijms.2015.08.007

- Count particles by measuring line-width of the particle dip.



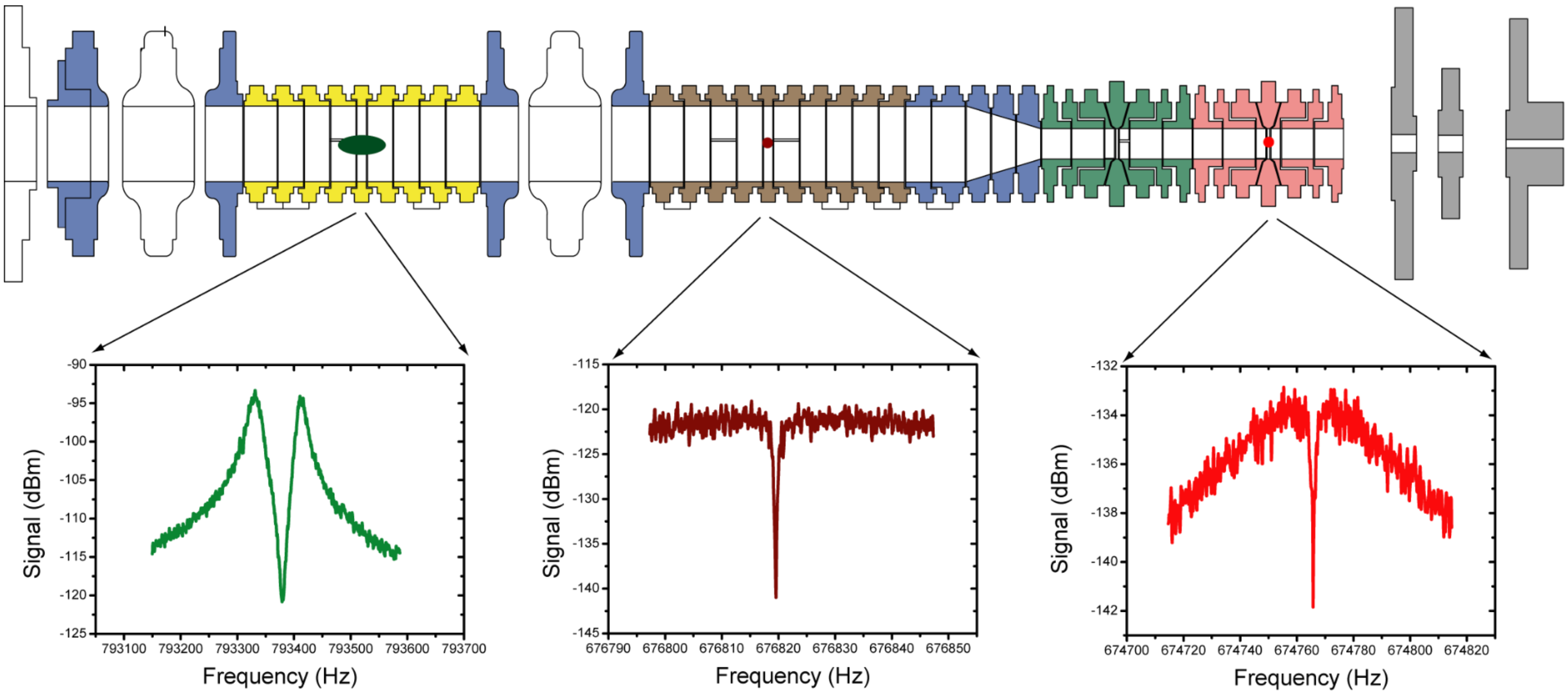




Antiprotons in the BASE trap stack

Beamtime 2015: Shuttling along entire trap stack (20cm/5s) established.

Current situation



5 antiprotons in reservoir trap

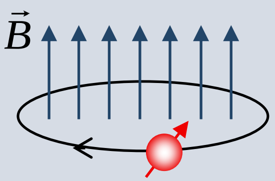
Single antiproton in precision trap

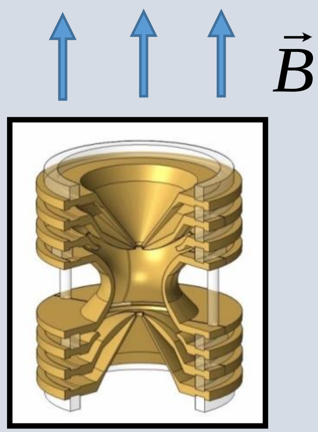
Single antiproton in analysis trap

The experiment using antiprotons is still ongoing in the AD!!!!

Measurement 1 (q/m)

BASE is an experiment using an advanced Penning trap.
Single particle sensitivity, confines particle within $\sim\mu m^3$





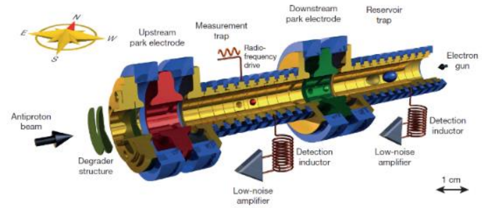
$$\nu_c = \frac{1}{2\pi}\frac{q}{m}\cdot B$$

Ratio of cyclotron frequencies leads to CPT test of charge-to-mass ratio comparison

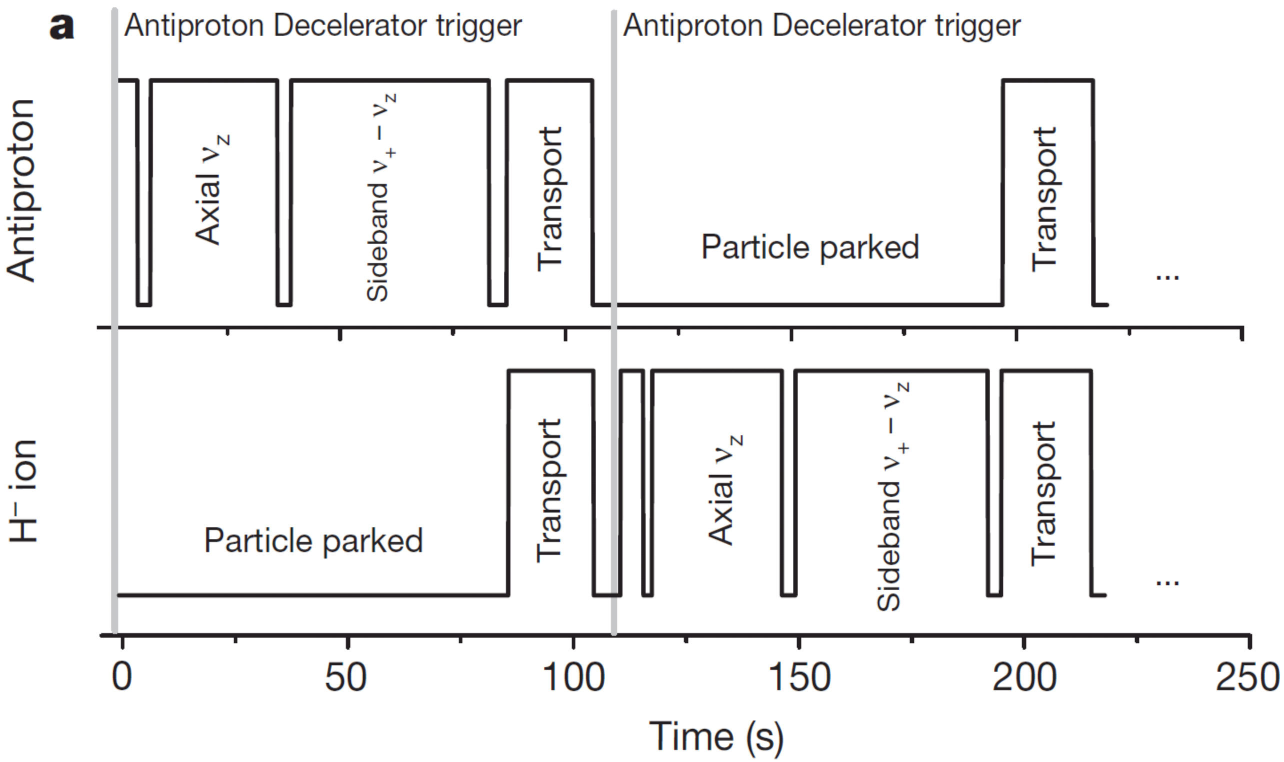
$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{q_{\bar{p}}/m_{\bar{p}}}{q_p/m_p}$$

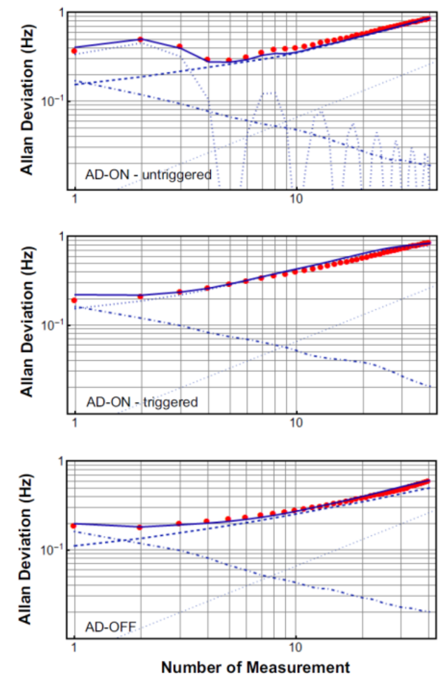
S. Ulmer et al., *Nature* **524** 196 (2015)
G. Gabrielse et al., *Phys. Rev. Lett.* **82** 3198 (1999)

Measurement



AD cycle





$$\nu_c^2 = \nu_+^2 + \nu_-^2 + \nu_z^2$$

Measurement cycle is triggered by the antiproton injection into the AD

One BASE charge-to-mass ratio measurement is by 50 times faster than achieved in previous proton/antiproton measurements.

First high-precision mass spectrometer which applies this fast shuttling technique

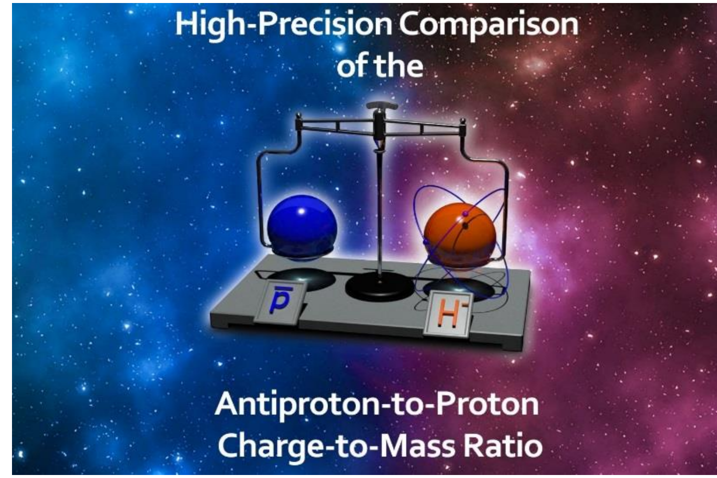
Most precise q/m comparison for proton and antiproton

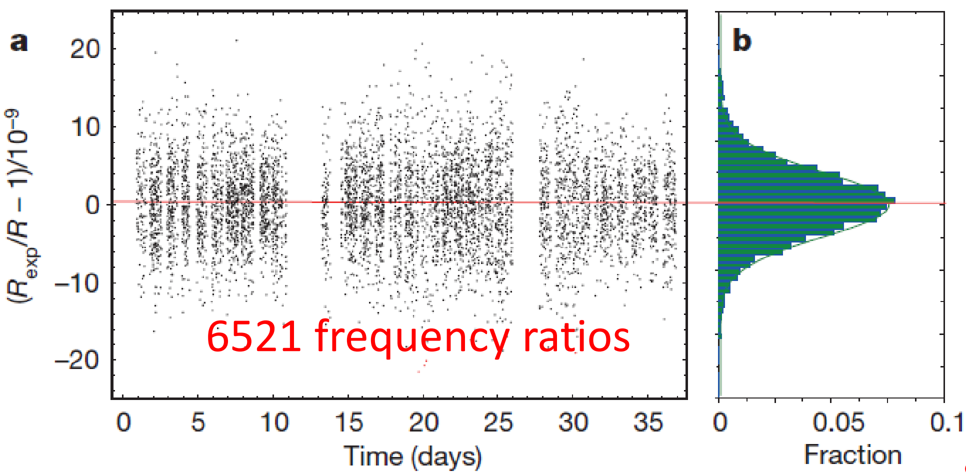
LETTER

OPEN
doi:10.1038/nature14861

High-precision comparison of the antiproton-to-proton charge-to-mass ratio

S. Ulmer[1], C. Smorra[1,2], A. Mooser[1], K. Franke[1,3], H. Nagahama[1,4], G. Schneider[1,5], T. Higuchi[1,4], S. Van Gorp[6], K. Blaum[3], Y. Matsuda[4], W. Quint[7], J. Walz[5,8] & Y. Yamazaki[6]





Final result

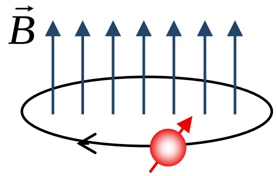
$$\frac{(q/m)_{\bar{p}}}{(q/m)_{p}} - 1 = 1(69) \times 10^{-12}$$

- In agreement with CPT conservation
- Exceeds the energy resolution of previous result by a factor of 4*.

*S. Ulmer et al., *Nature* **524** 196 (2015)
G. Gabrielse et al., *Phys. Rev. Lett*. **82** 3198 (1999)

Measurement 2 (*g*-factor)

Cyclotron Motion

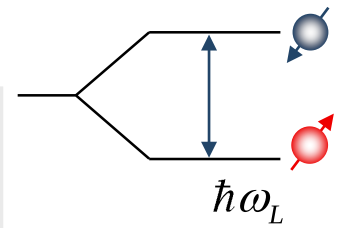


g: magnetic Moment in units of nuclear magneton

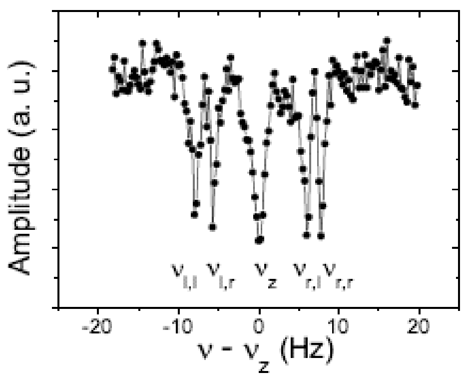
$$\omega_c = \frac{e}{m_p} B$$

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

Larmor Precession



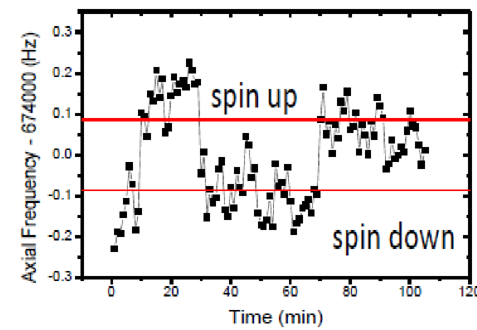
simple



S. Ulmer, A. Mooser *et al.* PRL 107, 103002 (2011)

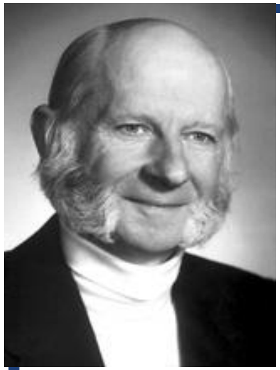
$$\frac{\mu_{\bar{p}}}{\mu_N} = \frac{g}{2} \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p} = \frac{\nu_L}{\nu_c}$$

difficult



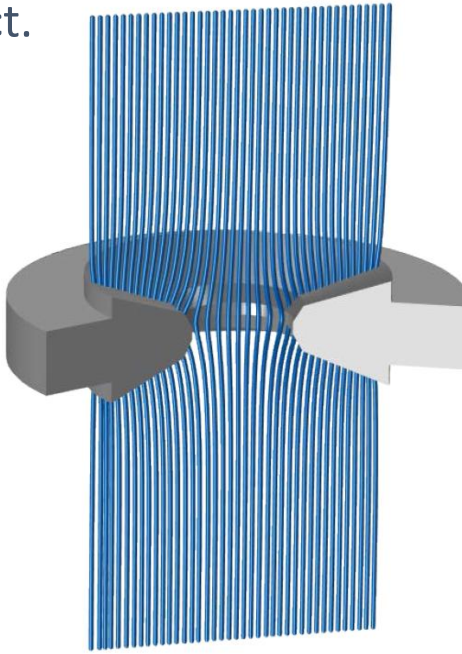
S. Ulmer, A. Mooser *et al.* PRL 106, 253001 (2011)

g-factor measurement reduces to measurement of a frequency ratio



Larmor Frequency

Measurement based on continuous Stern Gerlach effect.



Energy of magnetic dipole in magnetic field $\Phi_M = -(\vec{\mu_p} \cdot \vec{B})$

Leading order
magnetic field correction

$$B_z = B_0 + B_2 \left(z^2 - \frac{\rho^2}{2}\right)$$

Spin dependent quadratic axial potential
→ Axial frequency becomes function of spin state

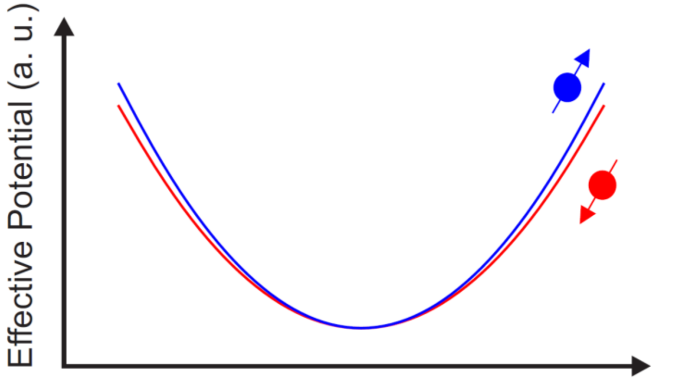
$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := \alpha_p \frac{B_2}{\nu_z}$$

Very difficult for the proton/antiproton system:

$$B_2 \sim 300000\ \mathrm{T/m^2}$$

Most extreme magnetic conditions ever applied to single particle.

$$\Delta\nu_z \sim 170\ \mathrm{mHz}$$



The Challenge

Typical axial frequency: 700 kHz

$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := 0.4 \cdot \mu Hz \cdot B_2$$

We use: $B_2 = 300000\, T/m^2$

→ 170 mHz out of 700 kHz

Magnetic bottle coupling: $\Delta\nu_z = \frac{1}{4\pi^2 m \nu_z} \frac{B_2}{B_0} (dE_+ + dE_-)$ -> 1 Hz/µeV

One cyclotron quantum jump (70 neV) shifts axial frequency by 70mHz

Tiny heating of the radial mode results in significant fluctuation of the axial oscillation frequency

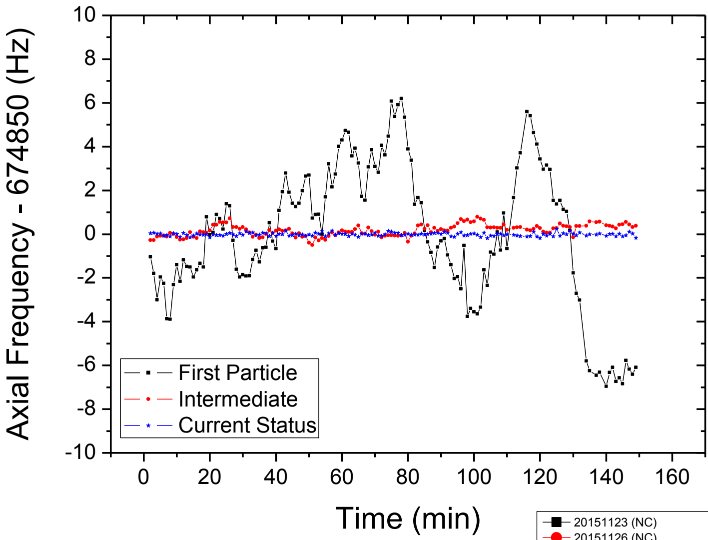
$$\frac{dn_+}{dt} \propto n_+ \Gamma^2_{i\rightarrow f}$$

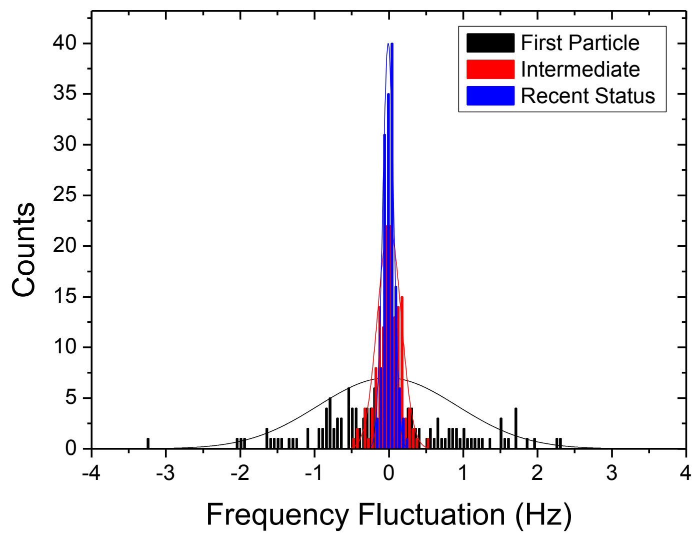
Heating rates scale with the cyclotron quantum number!

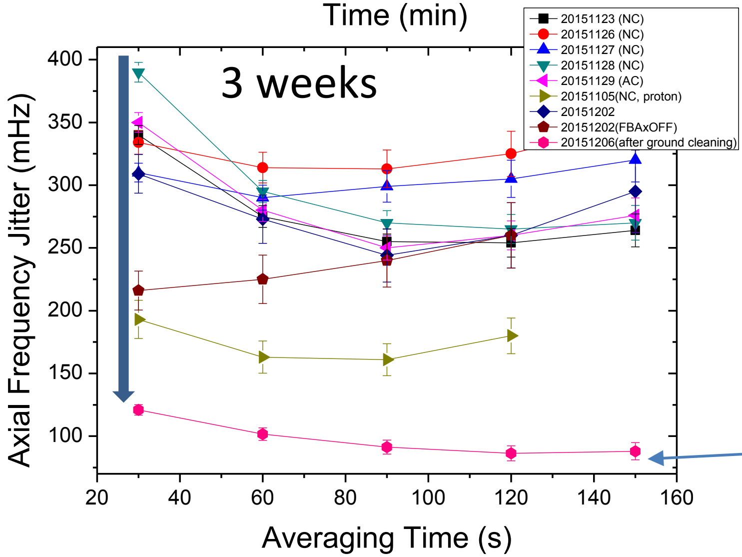
Our heating rates correspond to noise on electrodes of some pV/Hz$^{1/2}$.
For further details, see talk by A. Mooser tomorrow

Progress Analysis Trap 2015

In the magnetic bottle: need to resolve spin flip induced axial frequency jumps of 180 mHz:







- Trap cleaning
- Proper grounding
- Temperature of the cyclotron detector

Cyclotron heating rate:
< 1 quantum transition in 240s
In this case: Single spin flip resolution

Statistical Detection of Spin Flips

Measure axial frequency stability:

1) reference measurement with detuned drive on

2) measurement with resonant drive on.

Spin flips add up

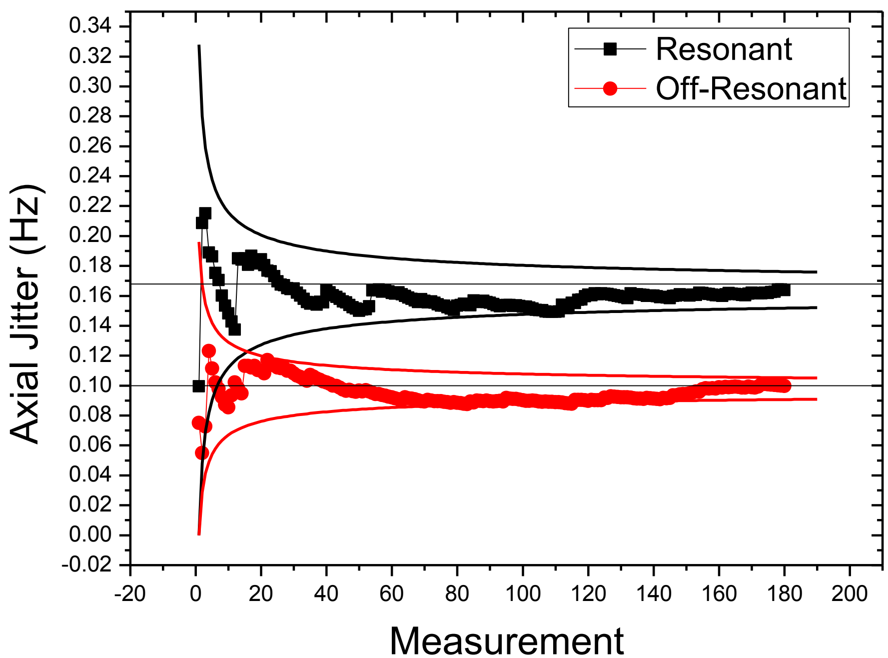
$$\Xi_{SF} = \sqrt{\Xi_{ref}^{\;2} + P_{SF}\Delta\nu_{z,SF}^2}$$

S. Ulmer, *et al.*, Phys. Rev. Lett **106**, 253001 (2011)

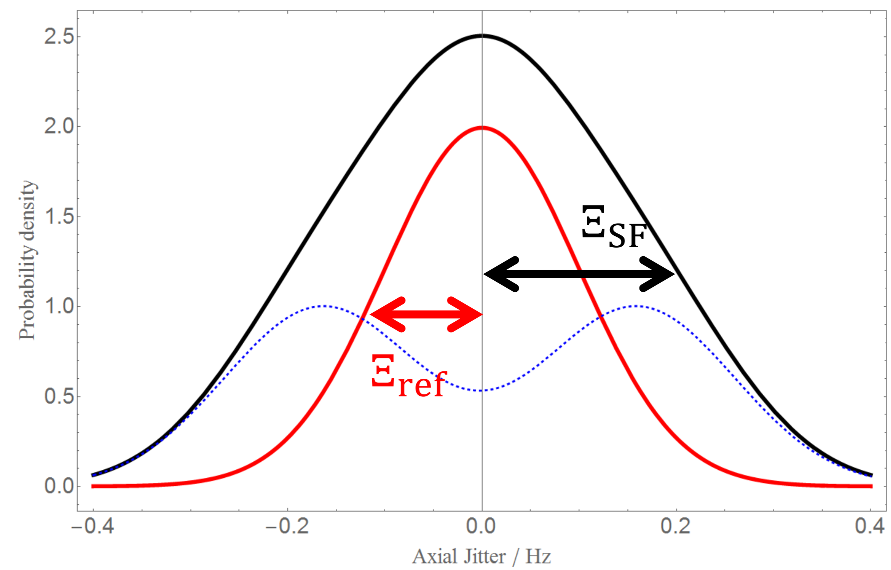
Cumulative measurement:

Black – frequency stability with superimposed spin flips.

Red – background stability

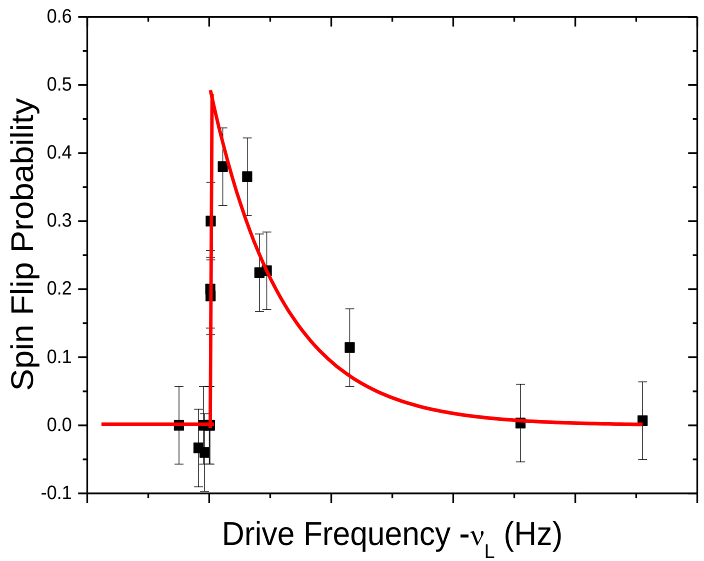


Blue dash line - Axial frequency change due to spinflips

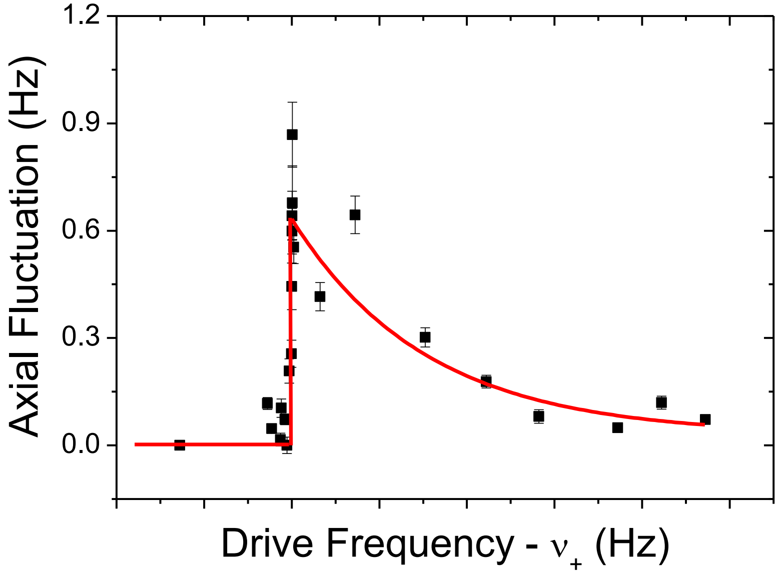


Resonances

Larmor



Cyclotron



Work in progress, experiment is still ongoing

Summary

- In 2014, we compared the charge-to-mass ratio of antiproton-to-proton with unprecedented precision of 69 ppt. It has a factor of 4 higher energy resolution than the previous result.
- In 2015, we succeeded to observe spinflips of a single antiproton in the analysis trap.
- We still have in total 7 antiprotons in our trap system.
- Measurement of $g_{\bar{p}}$ is ongoing.

Thank you for your attention!

RIKEN

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GSI

CERN

東京大学 THE UNIVERSITY OF TOKYO

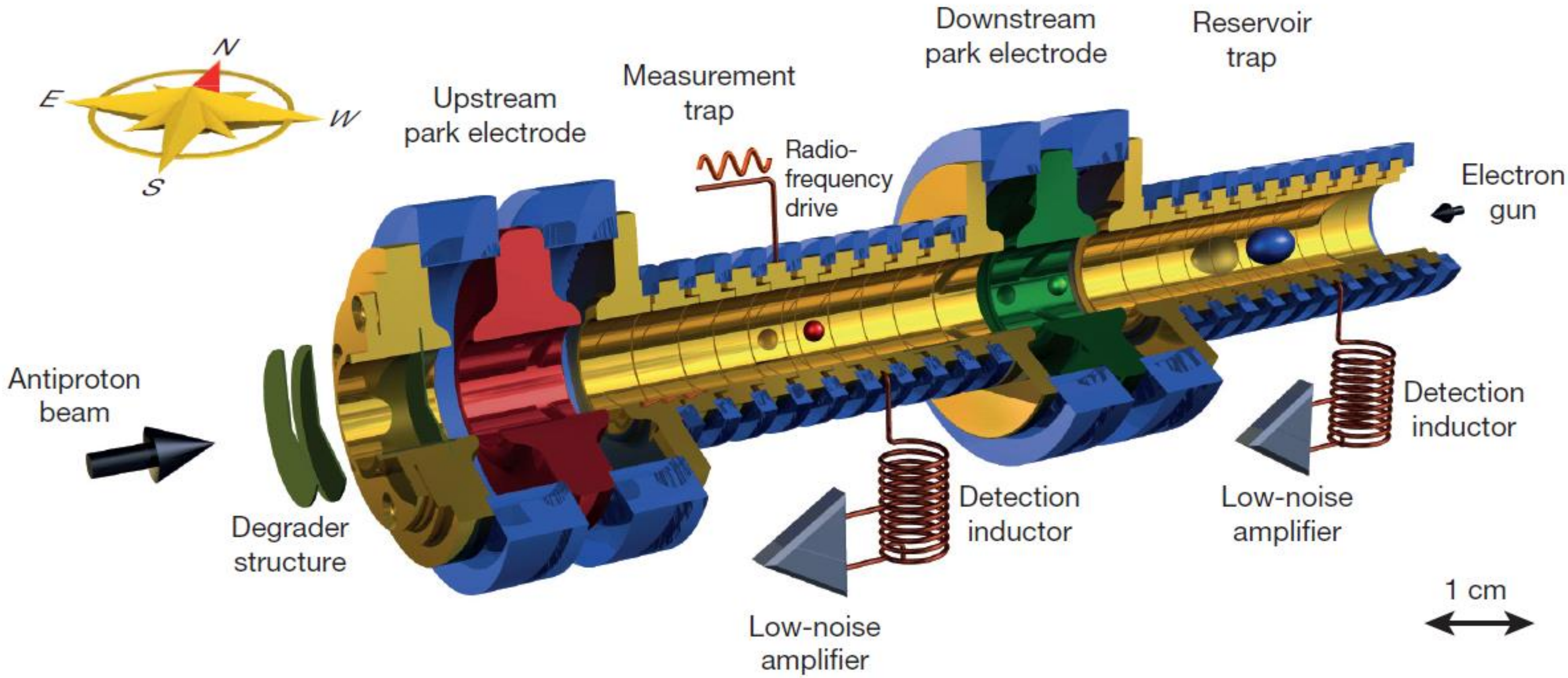
K. Blaum, Y. Matsuda, C. Ospelkaus, W. Quint, J. Walz, Y. Yamazaki

Leibniz Universität Hannover

PTB

Measurement scheme

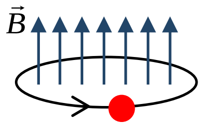
- After the antiproton injection by the AD, a cloud which consists of many antiprotons and H^{-} ions is prepared.
- Extracted a single antiproton and a single H^{-} ion from the cloud.
- Cyclotron frequency of a single particle is measured in Measurement trap, while the other one is parked in Upstream/Downstream park electrode.



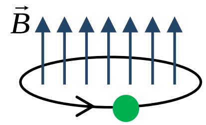
H^- ions: perfect proxies for protons

- Measure free cyclotron frequencies of antiproton and H^- ion.

*using proton=>opposite charge=>position in the trap changes



antiproton



H^- ion

- Take a ratio of measured cyclotron frequency of antiproton $\nu_{c\bar{p}}$ to H^- ion ν_{cH^-} => reduces to antiproton to proton charge-to-mass ratio

$$R = \frac{\nu_{c\bar{p}}}{\nu_{cH^-}} = \frac{(q/m)_{\bar{p}}}{(q/m)_{H^-}} \times \frac{B/2\pi}{B/2\pi} = \frac{(q/m)_{\bar{p}}}{(q/m)_{H^-}}$$

Magnetic field cancels out!

$$m_{H^-} = m_p\left(1 + 2\frac{m_e}{m_p} - \frac{E_b}{m_p} - \frac{E_a}{m_p} + \frac{\alpha_{pol,H^-} B_0^2}{m_p}\right)$$

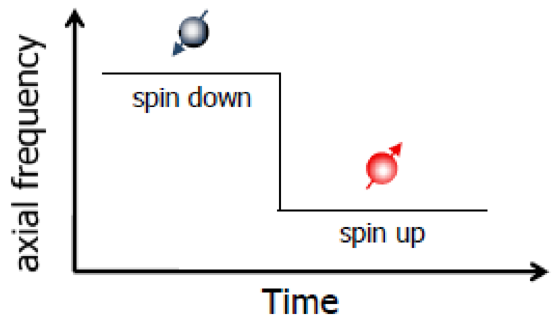
$$R_{theo} = 1.0010892187542(2)$$

Comparable measurements were carried out by the TRAP collaboration in 1990 to 1998

TRAP Collaboration, Phys. Rev. Lett. **82**, 3198 (1999).

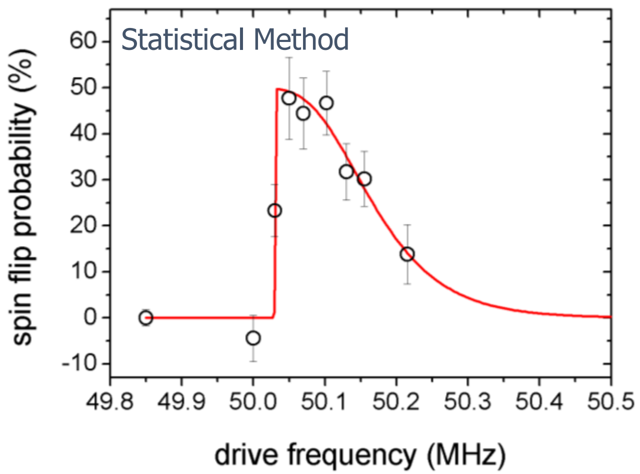
Larmor Frequency Measurement

Spin is detected and analyzed via an axial frequency measurement



Larmor Frequency is measured by repetition and evaluating the spin flip probability

Together with cyclotron frequency measurement:



g/2 = 2.792 848 (24) Rodegheri et al., NJP 14, 063011, (2012)

g/2 = 2.792 846 (7) di Sciacca et al., PRL 108, 153001 (2012)

Statistical Method:
Limited to the ppm level due to the strong magnetic bottle.

S. Ulmer et al., Phys. Rev. Lett 106, 253001 (2011)