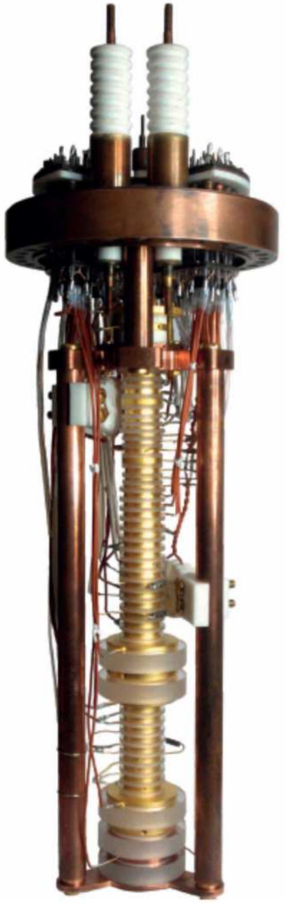
FFK Conference 2019, Tihany, Hungary

Precision measurements of the (anti)proton mass and magnetic moment



Wolfgang Quint
GSI Darmstadt and University of Heidelberg
on behalf of the BASE collaboration
spokesperson: Stefan Ulmer
2019 / 06 / 12

BASE – Collaboration

- **Mainz:** Measurement of the magnetic moment of the proton, implementation of new technologies.
- **CERN Antiproton Decelerator:** Measurement of the magnetic moment of the antiproton and proton/antiproton q/m ratio
- **Hannover/PTB:** Laser cooling project, new technologies


The European Physical Journal volume 224 · number 1 · February 2015

EPJ ST

Recognized by European Physical Society

Special Topics

THE BASE EXPERIMENT

BASE

edp sciences Springer


CERN Courier March 2018

BASE

Experiment of the moment

The BASE collaboration at CERN has measured the antiproton magnetic moment with extraordinary precision, offering more than 100-fold improved limits on certain tests of charge–parity–time symmetry.

The enigma of why the universe contains more matter than antimatter has been with us for more than half a century. While charge–parity (CP) violation can, in principle, account for the existence of such an imbalance, the observed matter excess is about nine orders of magnitude larger than what is expected from known CP-violating sources within the Standard Model (SM). This striking discrepancy inspires searches for additional mechanisms for the universe's baryon asymmetry, among which are experiments that test fundamental charge–parity–time (CPT) invariance by comparing matter and antimatter with great precision. Any measured difference between the two would constitute a dramatic sign of new physics. Moreover, experiments with antimatter systems provide unique tests of hypothetical processes beyond the SM that cannot be uncovered with ordinary matter systems.

The Baryon Antibaryon Symmetry Experiment (BASE) at CERN, in addition to several other collaborations at the Antiproton Decelerator (AD), probes the universe through exclusive antimatter "microscopes" with ever higher resolution. In 2017, following many years of effort at CERN and the University of Mainz in Germany, the BASE team measured the magnetic moment of the antiproton with a precision 350 times better than by any other experiment before, reaching a relative precision of 1.5 parts per billion (figure 1). The result followed the development of a multi-Penning-trap system and a novel two-particle measurement method and, for a short period, represented the first time that antimatter had been measured more precisely than matter.

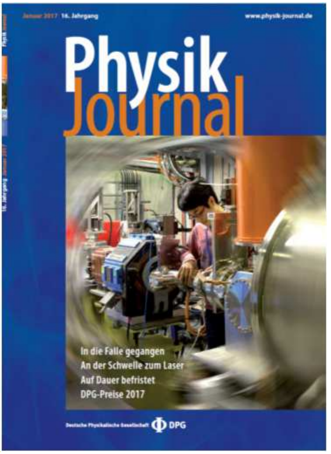
The BASE setup at CERN's Antiproton Decelerator.

Non-destructive physics

The BASE result relies on a quantum measurement scheme to observe spin transitions of a single antiproton in a non-destructive manner. In experimental physics, non-destructive observations of quantum effects are usually accompanied by a tremendous increase in measurement precision. For example, the non-destructive observation of electronic transitions in atoms or ions led to the development of optical frequency standards that achieve fractional precisions on the 10^{-18} level. Another example, allowing one of the most precise tests of CPT invariance to date, is the comparison of the electron and positron g-factors. Based on quantum non-demolition detection of the spin state, such studies during the 1980s reached a fractional accuracy on the parts-per-trillion level.

The latest BASE measurement follows the same scheme but targets the magnetic moment of protons and antiprotons instead of electrons and positrons. This opens tests of CPT in a totally different particle system, which could behave entirely differently. In practice, however, the transfer of quantum measurement methods from the electron/positron to the proton/antiproton system constitutes a considerable challenge owing to the

The multi-Penning-trap system used by BASE to detect the spin-flips of single trapped protons and antiprotons.


Januar 2017 16. Jahrgang www.physik-journal.de

Physik Journal

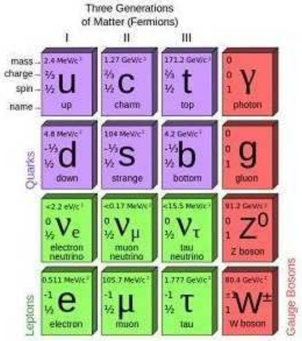
In die Falle gegangen
An der Schwelle zum Laser
Auf Dauer befristet
DPG-Preise 2017

Deutsche Physikalische Gesellschaft DPG

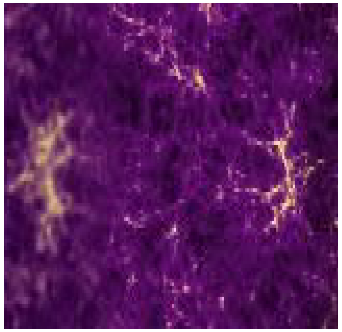
Institutes: RIKEN, MPI-K, CERN, University of Mainz, Tokyo University, GSI Darmstadt, University of Hannover, PTB Braunschweig

C. Smorra et al., EPJ-Special Topics, The BASE Experiment, (2015)

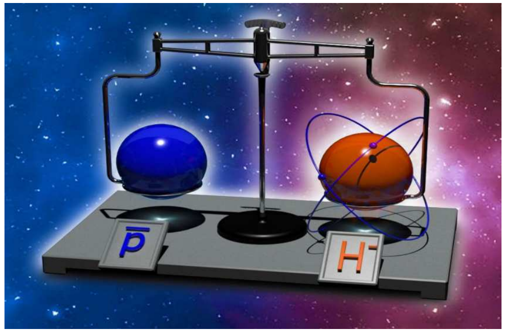
WE HAVE A PROBLEM



mechanism which created the obvious baryon/antibaryon asymmetry in the Universe is not understood

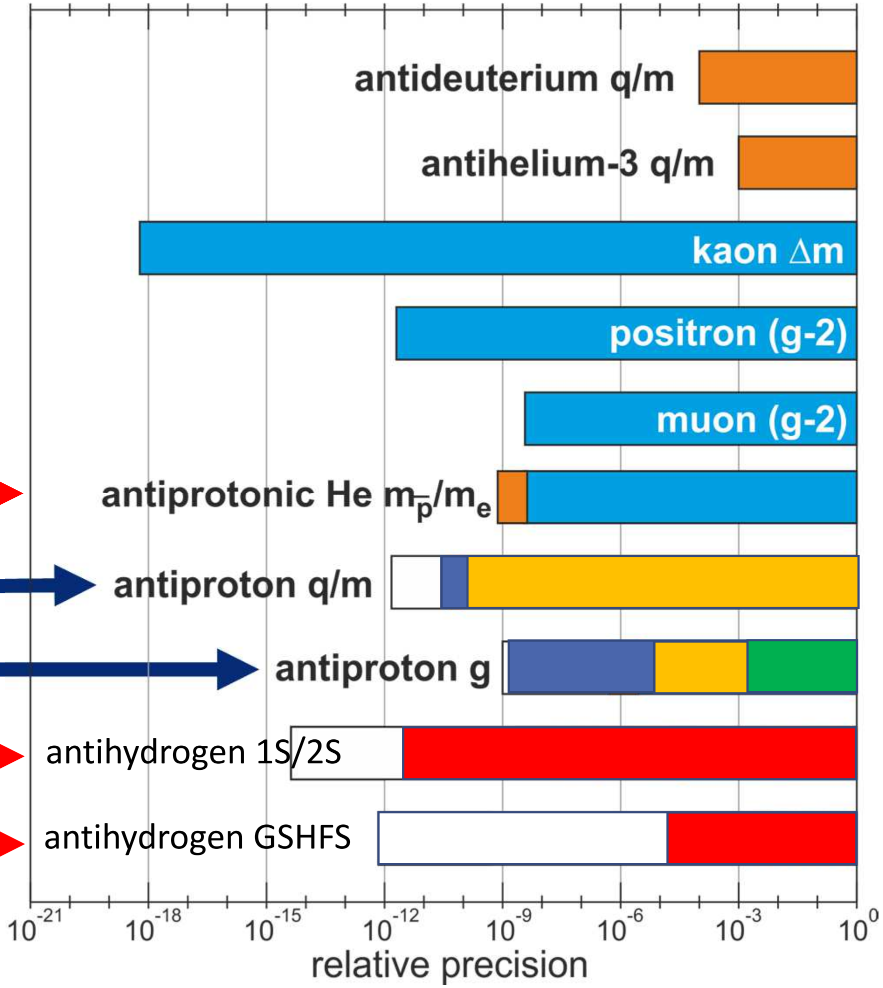


One strategy: Compare the fundamental properties of matter / antimatter conjugates with ultra-high precision



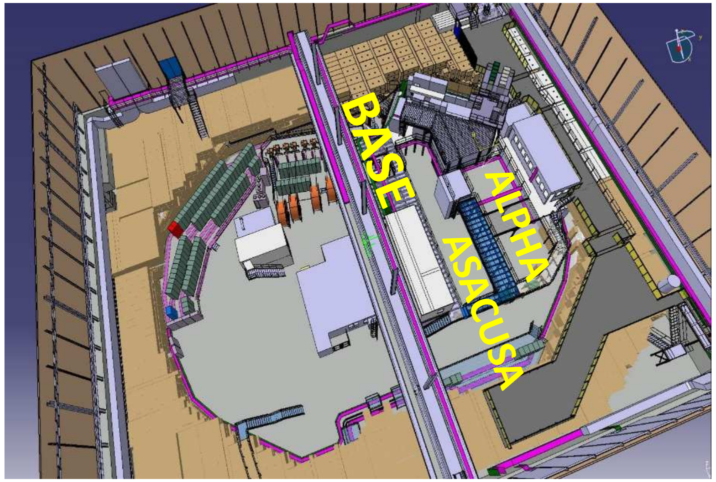
CPT tests based on particle/antiparticle comparisons

Recent
Past
Planned



CERN
ALICE

R.S. Van Dyck et al., Phys. Rev. Lett. **59**, 26 (1987).
B. Schwingenheuer, et al., Phys. Rev. Lett. 74, 4376 (1995).
H. Dehmelt et al., Phys. Rev. Lett. **83**, 4694 (1999).
G. W. Bennett et al., Phys. Rev. D **73**, 072003 (2006).
M. Hori et al., Nature **475**, 485 (2011).
G. Gabriesle et al., PRL **82**, 3199(1999).
J. DiSciacca et al., PRL **110**, 130801 (2013).
S. Ulmer et al., Nature **524**, 196-200 (2015).
ALICE Collaboration, Nature Physics **11**, 811–814 (2015).
M. Hori et al., Science **354**, 610 (2016).
H. Nagahama et al., Nat. Comm. **8**, 14084 (2017).
M. Ahmadi et al., Nature **541**, 506 (2017).
M. Ahmadi et al., Nature **586**, doi:10.1038/s41586-018-0017 (2018).



Limits on Exotic Physics

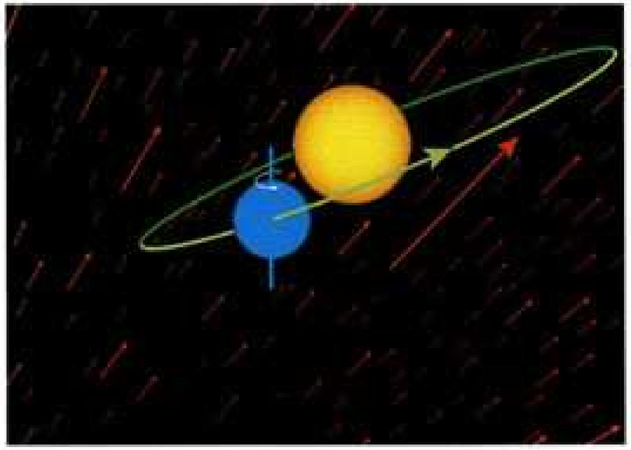
- Experiments test the Standard Model for exotic interactions

$$\left(\boxed{i\gamma^{\mu}D_{\mu} - m} - \boxed{a_{\mu}\gamma^{\mu} - b_{\mu}\gamma_5\gamma^{\mu}}\right)\psi = 0$$

Dirac equation CPT-odd modifications

$$\boldsymbol{H\,\psi = (H_0 + V_{exotic})\,\psi}$$

$$\boldsymbol{\Delta E_{exotic} = \langle\psi|V_{exotic}|\psi\rangle}$$



$$b_{\mu}\gamma_5\gamma^{\mu} \rightarrow b_x\begin{pmatrix}-\boldsymbol{\sigma_x} & \boldsymbol{0}\\ \boldsymbol{0} & \boldsymbol{\sigma_x}\end{pmatrix} + b_y\begin{pmatrix}-\boldsymbol{\sigma_y} & \boldsymbol{0}\\ \boldsymbol{0} & \boldsymbol{\sigma_y}\end{pmatrix} + b_z\begin{pmatrix}-\boldsymbol{\sigma_z} & \boldsymbol{0}\\ \boldsymbol{0} & \boldsymbol{\sigma_z}\end{pmatrix}$$

V. A. Kostelecky, N. Russell, 0801.0287v10 (2017).

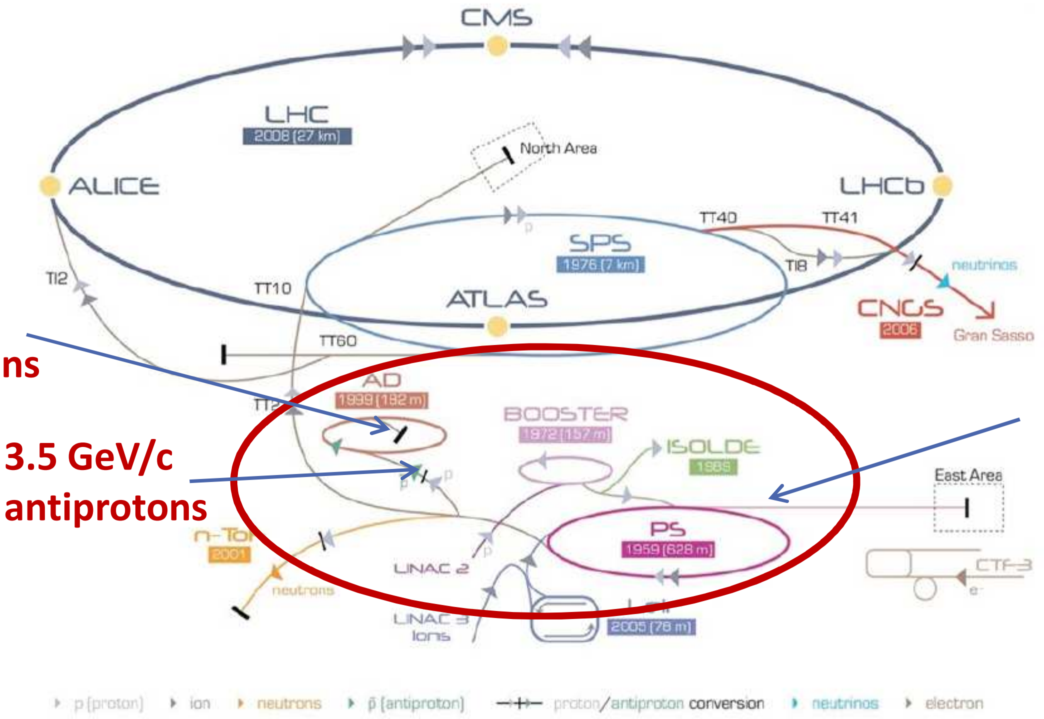
- Boson field exclusively coupling to antimatter

$$\Delta V_{int} = \widetilde{b_{z,D}}\begin{pmatrix}\boldsymbol{0} & \boldsymbol{0}\\ \boldsymbol{0} & \pm\boldsymbol{\sigma_z}\end{pmatrix}$$

Single particles in Penning traps test the SM
at an energy resolution of 10^{-24} to 10^{-26} GeV

sensitive: comparisons of particle/antiparticle magnetic moments in traps

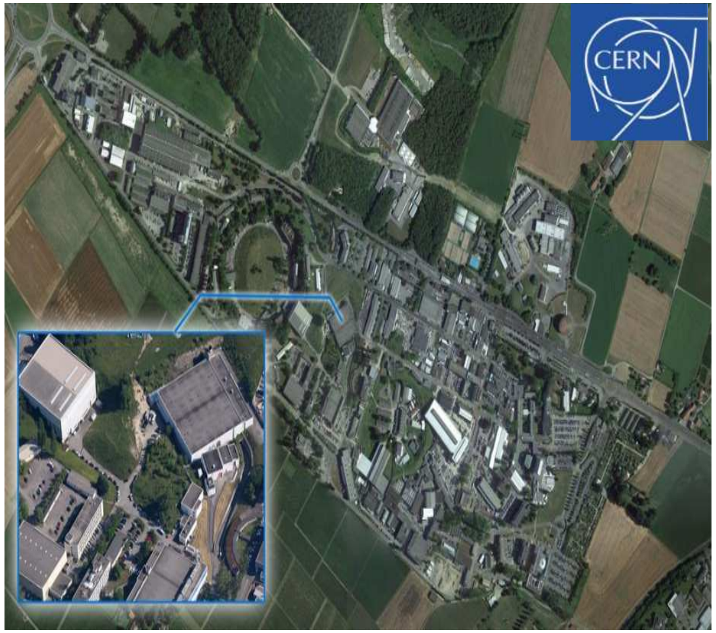
Antiprotons – CERN



5.3 MeV antiprotons

3.5 GeV/c antiprotons

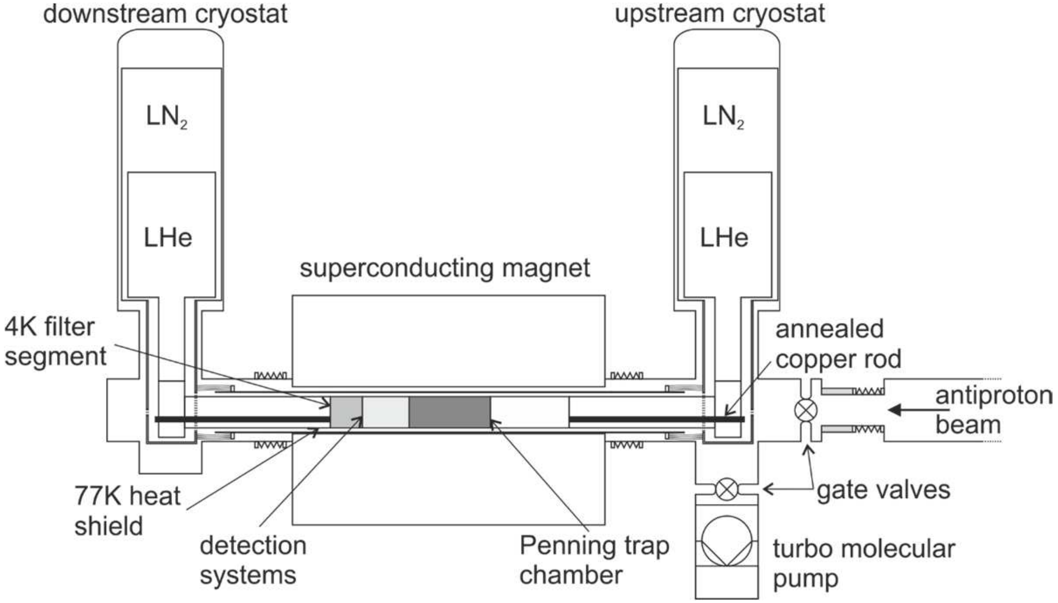
25 GeV/c protons

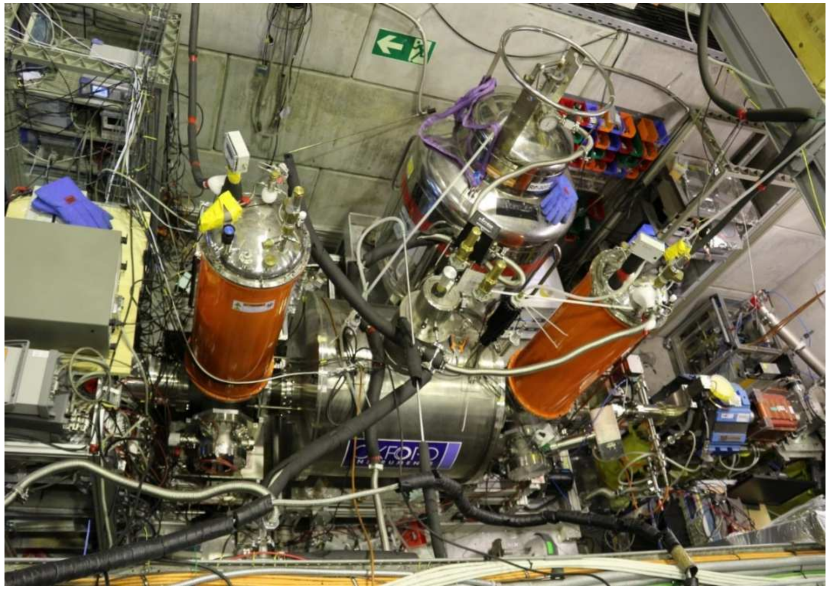


-> Degrader -> 1keV
-> Electron cooling -> 0.1 eV
-> Resistive cooling -> 0.000 3 eV
-> Feedback cooling -> 0.000 09 eV

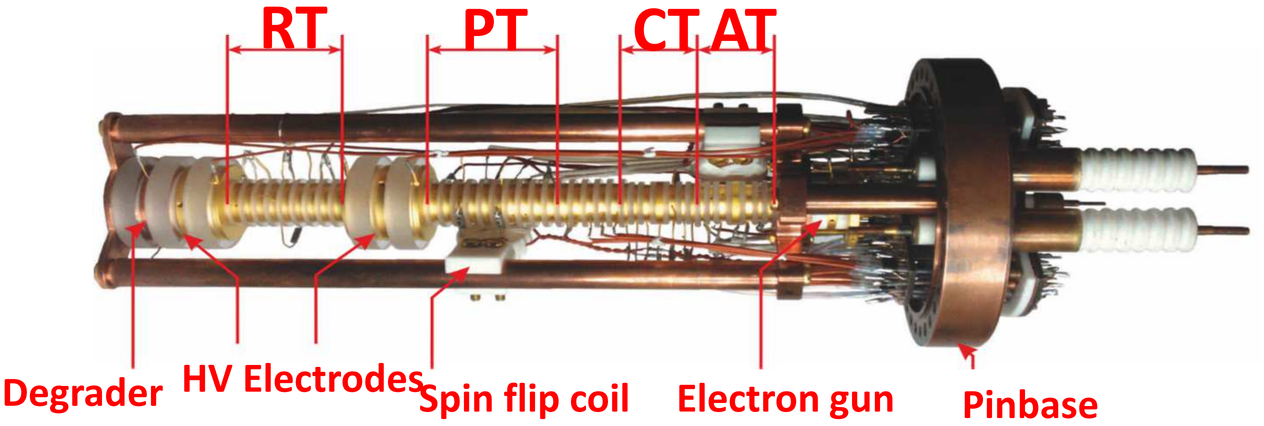
Within a production/deceleration cycle of 120s + 300s of preparation time we bridge 14 orders of magnitude

The BASE Apparatus at CERN





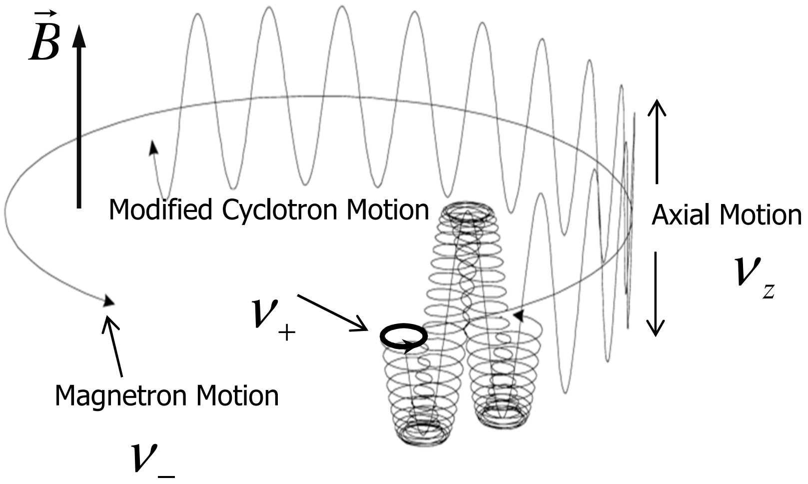
RT: Reservoir trap
PT: Precision trap
CT: Cooling trap
AT: Analysis trap

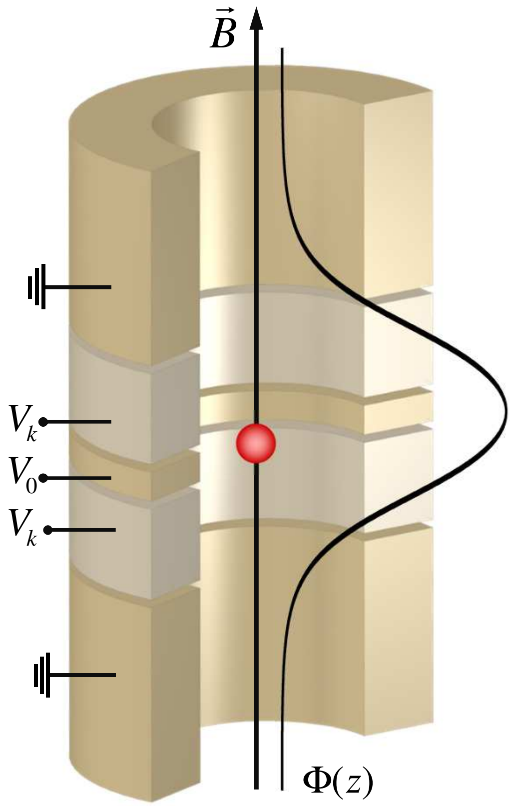


Main Tool: Penning Trap

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

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





Invariance-Relation

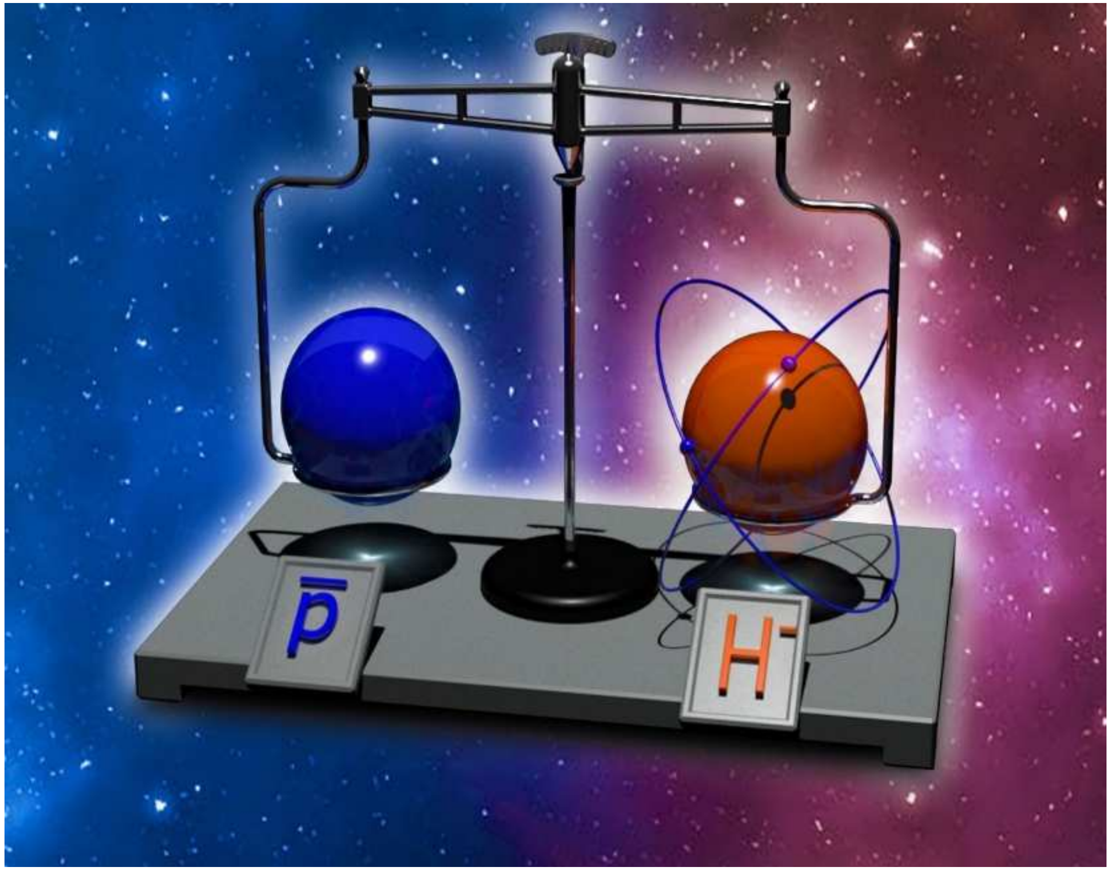
$$\nu_c = \sqrt{\nu_+^2 + \nu_-^2 + \nu_z^2}$$

Cyclotron Frequency

$$\boxed{\nu_c = \frac{1}{2\pi} \frac{q_{ion}}{m_{ion}} B}$$

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

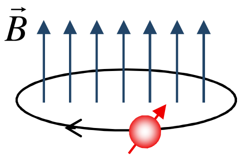
Proton/Antiproton Charge-to-Mass Comparison



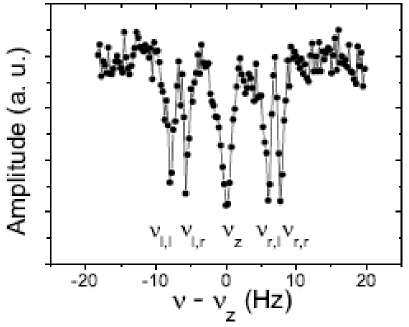
S. Ulmer et al., Nature **524**, 196 (2015)

Measurements in Penning traps

Cyclotron Motion



simple



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

g: magnetic moment in units of nuclear magneton

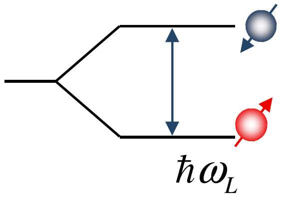
$$\omega_c = \frac{e}{m_p} B$$

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

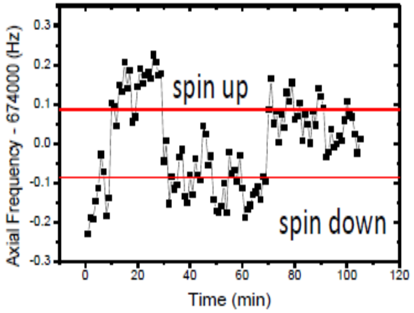
$$\frac{\mu_{\bar{p}}}{\mu_N} = \frac{g}{2} \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p} = \frac{\nu_L}{\nu_c}$$

$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p}$$

Larmor Precession



difficult

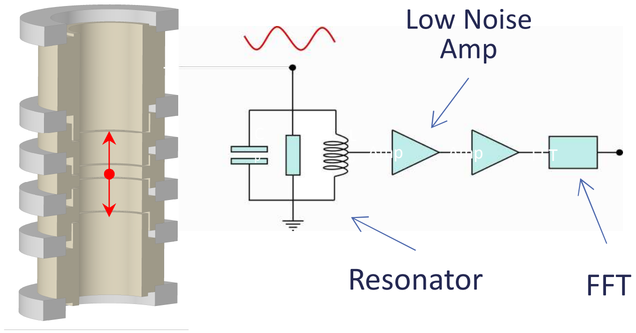


S. Ulmer, A. Mooser *et al.* PRL 106, 253001 (2011)

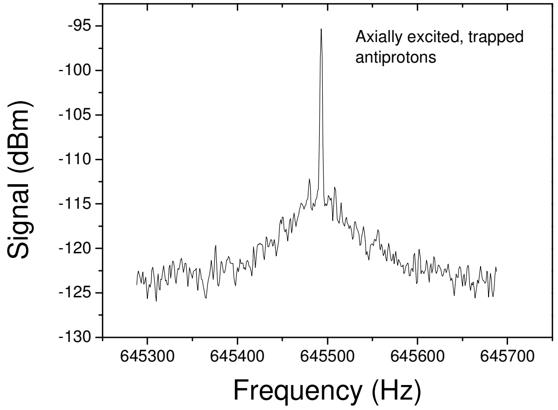
Determinations of the q/m ratio and g-factor reduce to measurements of frequency ratios -> in principle **very simple** experiments –> **full control, (almost) no theoretical corrections required.**

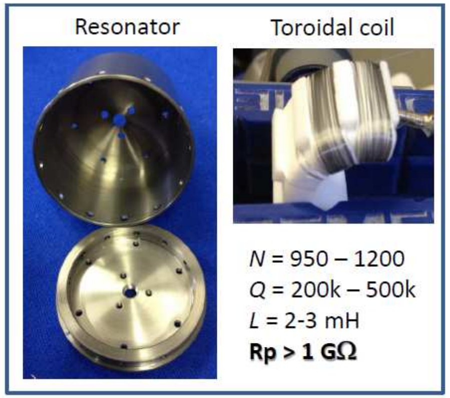
Frequency Measurements

- Measurement of tiny image currents induced in trap electrodes



currents: 1 fA

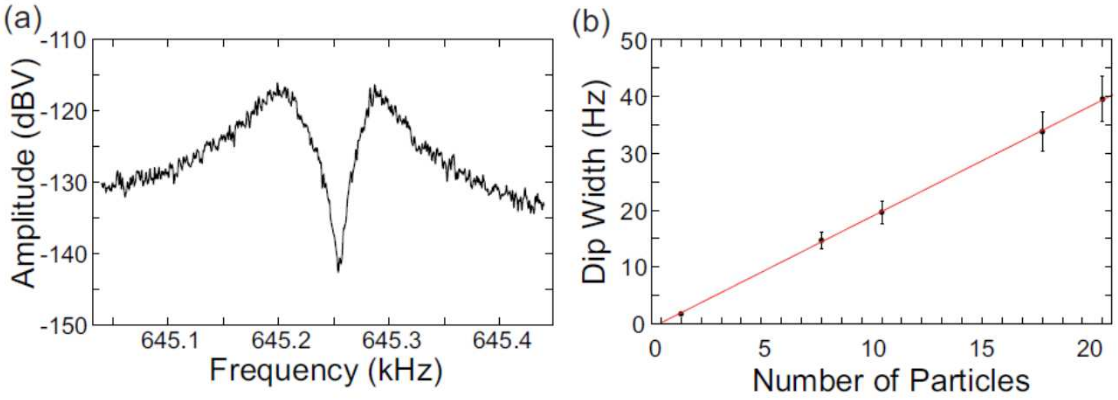




$N = 950 - 1200$
$Q = 200\text{k} - 500\text{k}$
$L = 2\text{-}3$ mH
Rp > 1 GΩ

- In thermal equilibrium:
  - Particles short noise in parallel
  - Appear as a dip in detector spectrum
  - Width of the dip -> number of particles

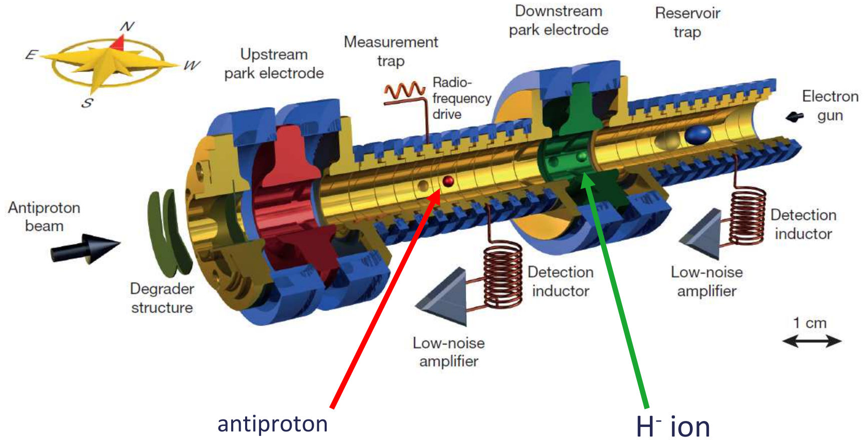
$$\Delta\nu = \frac{1}{2\pi}\frac{R}{m}\left(\frac{q}{D}\right)^2 \cdot N$$



H. Nagahama et al., Rev. Sci. Instrum. **87,** 113305 (2016)

Measurement configuration

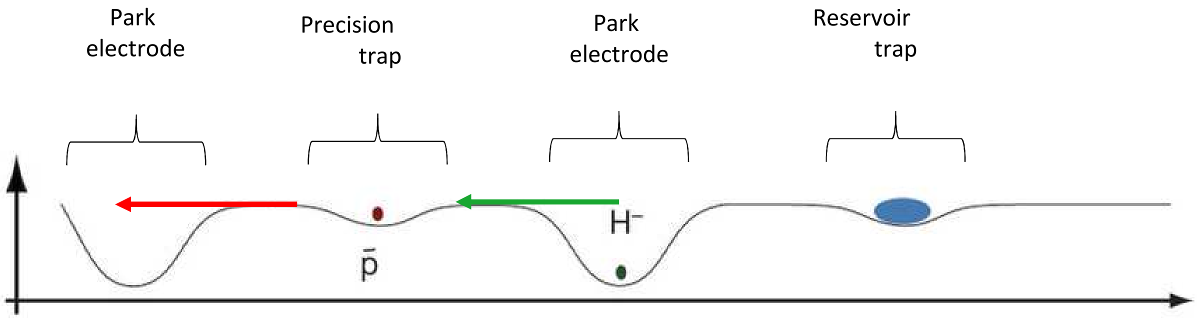
Extract antiprotons and H⁻ ions, compare cyclotron frequencies



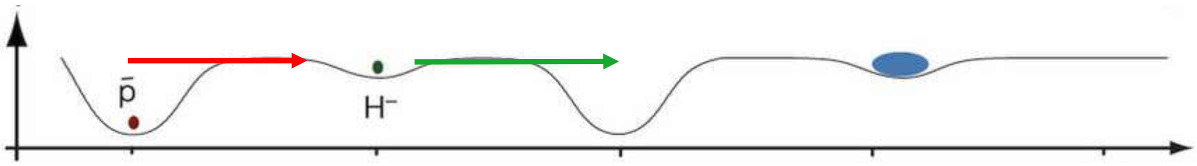
$$R = \frac{\nu_{c,\bar{p}}}{\nu_{c,H^-}} = \frac{(q/m)_{\bar{p}}}{(q/m)_{H^-}} \mathrm{x} \frac{B/2\pi}{B/2\pi} = \frac{(q/m)_{\bar{p}}}{(q/m)_{H^-}}$$

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

R_{theo} = 1.001 089 218 754 2(2)



Measure ν_z & $\nu_+ \Rightarrow \nu_c$



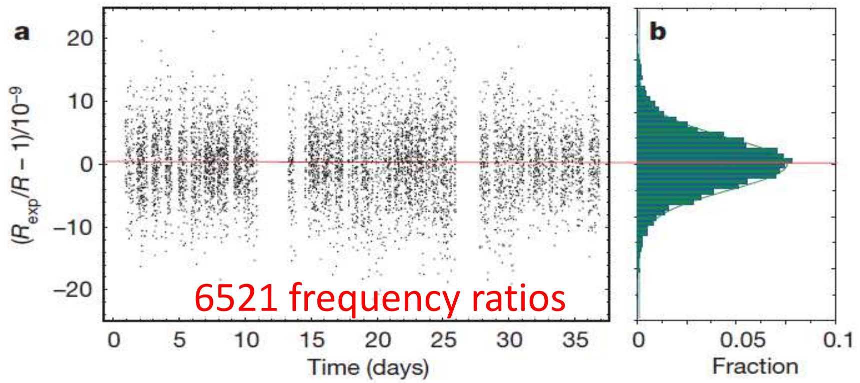
Measure ν_z& $\nu_+ \Rightarrow \nu_c$

Comparison of H-/antiproton cyclotron frequencies:

One frequency ratio per 4 minutes with ~ 6 ppb uncertainty

G. Gabriesle et al., PRL **82**, 3199 (1999).

Proton to Antiproton Q/M: Physics



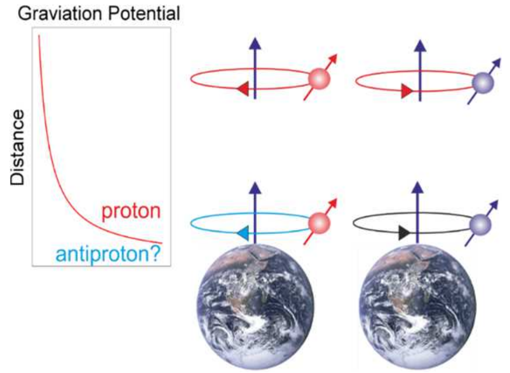
6521 frequency ratios

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

- 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)

- Constrain of the gravitational anomaly for antiprotons:



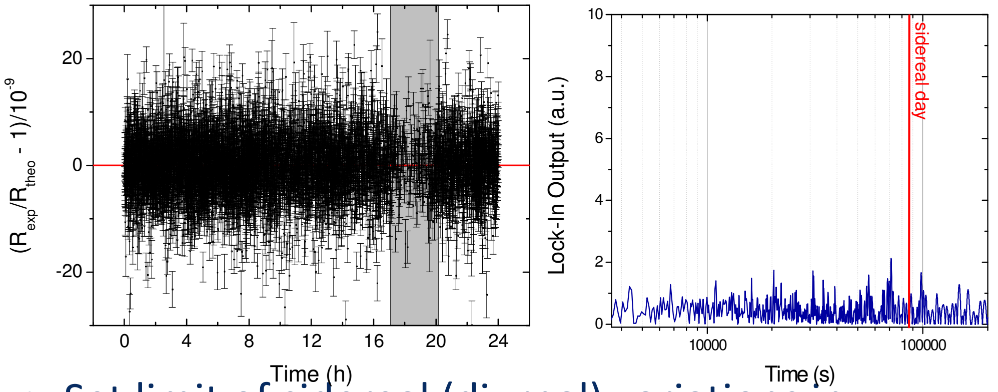
$$\frac{\omega_{c,p} - \omega_{c,\bar{p}}}{\omega_{c,p}} = -3(\alpha_g - 1)\ U/c^2$$

Our 69 ppt result sets a new upper limit of

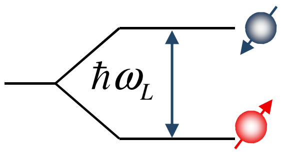
$$|\alpha_g - 1| < 8.7\times 10^{-7}$$

- Conclusion:

Matter and Antimatter clocks run at the same frequency

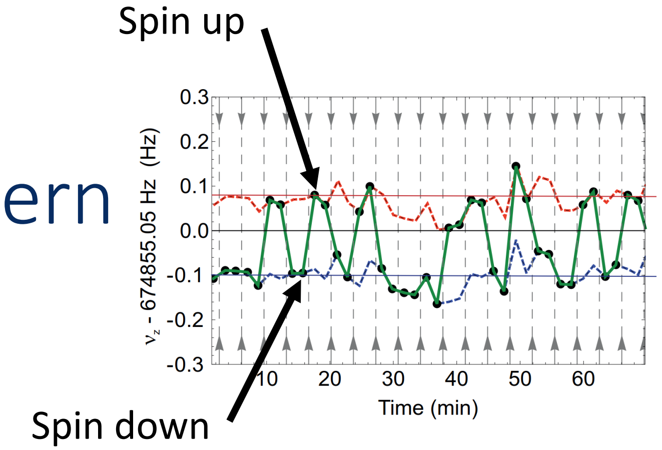


- Set limit of sidereal (diurnal) variations in proton/antiproton charge-to-mass ratios to **< 0.72 ppb/day**



Very very hard work

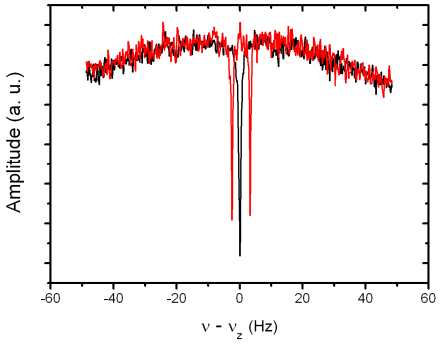
Continuous Stern Gerlach Effect

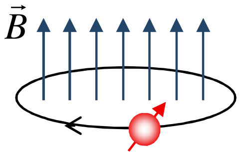


$$\frac{\mu_{\bar{p}}}{\mu_N} = \frac{g_{\bar{p}}}{2}\,\frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p} = \frac{\nu_L}{\nu_c}$$

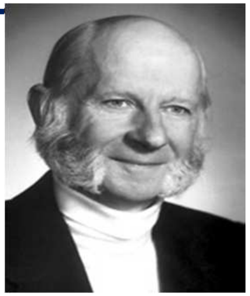
Straight-foward

Image Current Measurements

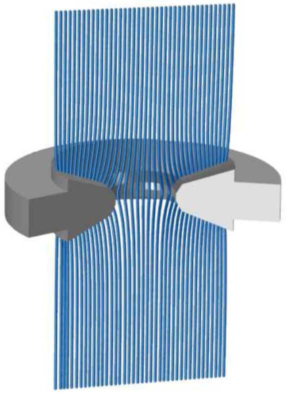




Larmor Frequency – extremely hard



Measurement based on continuous Stern-Gerlach effect.



Energy of magnetic dipole in magnetic field

$$\Phi_M = -(\overrightarrow{\mu_p} \cdot \vec{B})$$

Leading order magnetic field correction

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

This term adds a spin dependent quadratic axial potential
-> Axial frequency becomes a function of the spin state

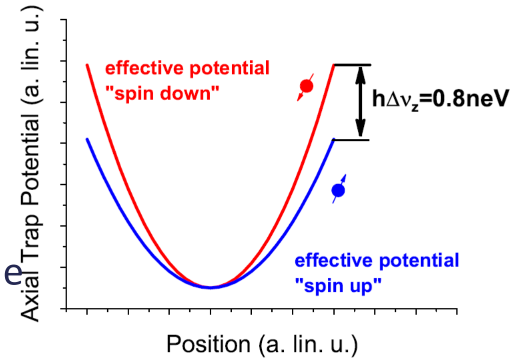
$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := \alpha_p \frac{B_2}{\nu_z}$$

- Very difficult for the proton/antiproton system.

$$B_2 \sim 0.3\; T/mm^2$$

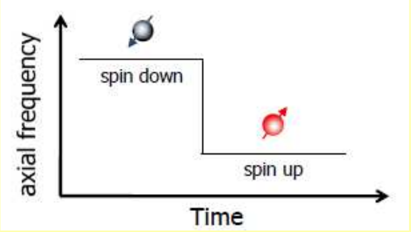
- Most extreme magnetic conditions ever applied to single particle.

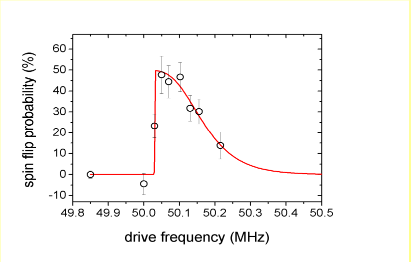
$$\Delta\nu_z \sim 170\; mHz$$



Frequency Measurement

Spin is detected and analyzed via an axial frequency measurement

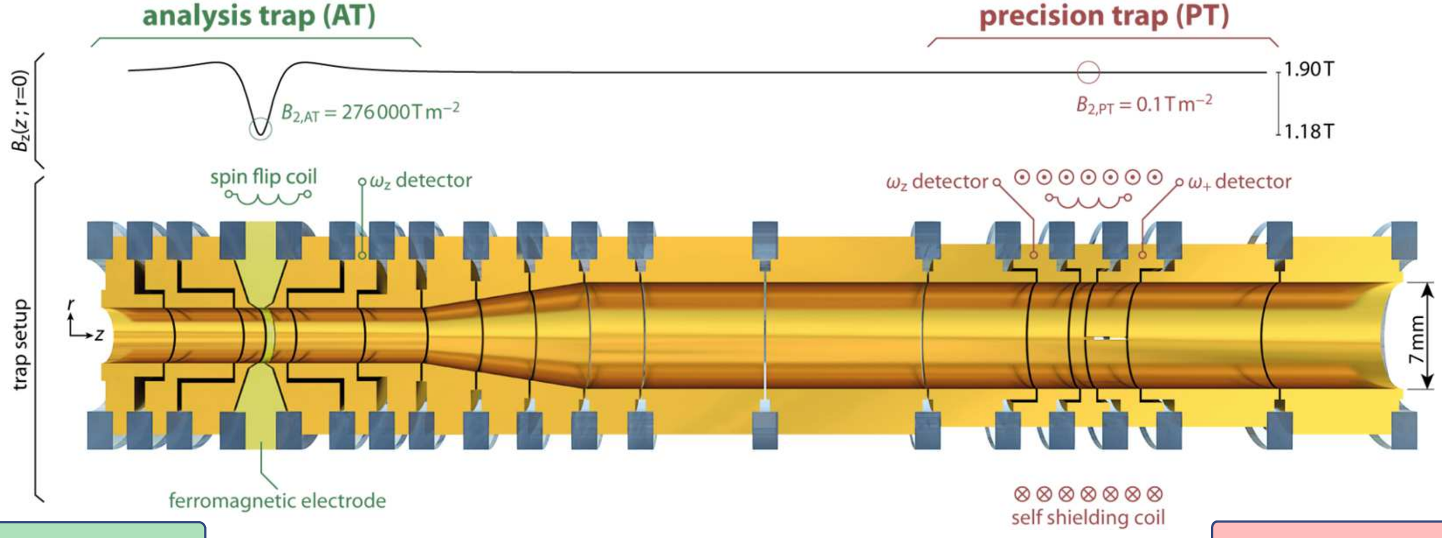


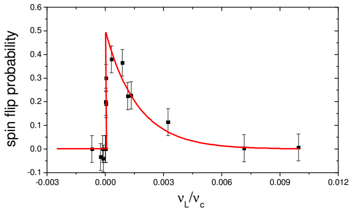


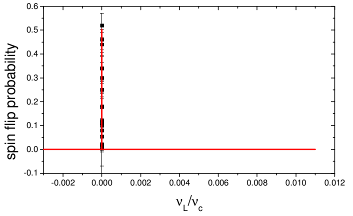
S. Ulmer, *et al.* PRL 106, 253001 (2011)

Single Penning trap method is limited to the ppm level

Next Step: The Double Penning-Trap Method





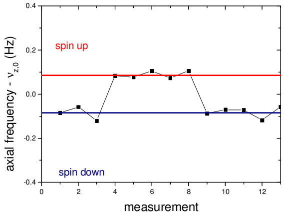


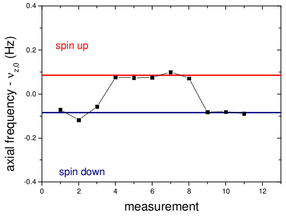
Initialize the spin state

1.) measure cyclotron ν_c
2.) drive spin transition at ν_{rf}

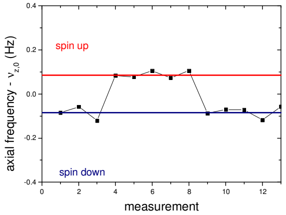
particle transport

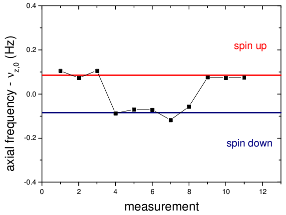
analyze the spin state





no spin-flip in PT

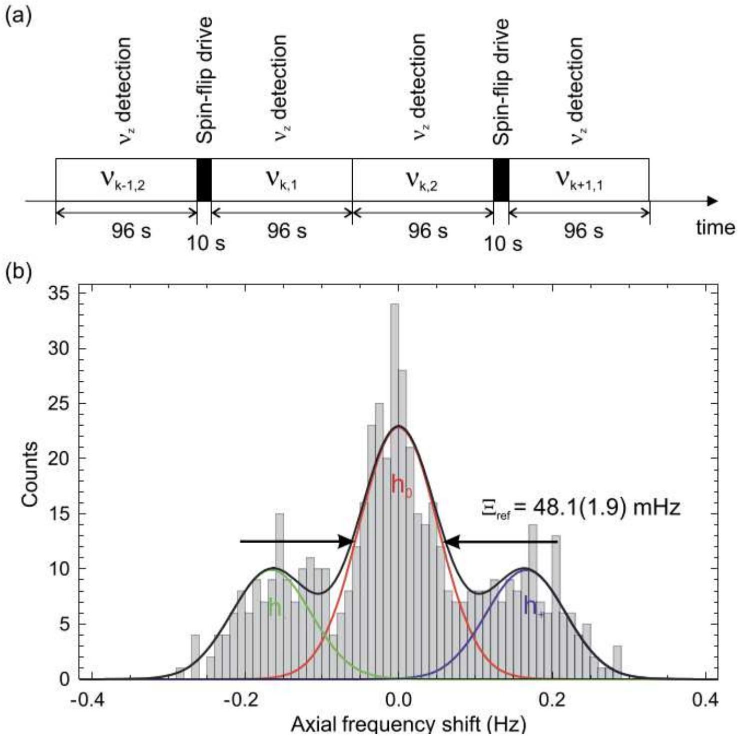


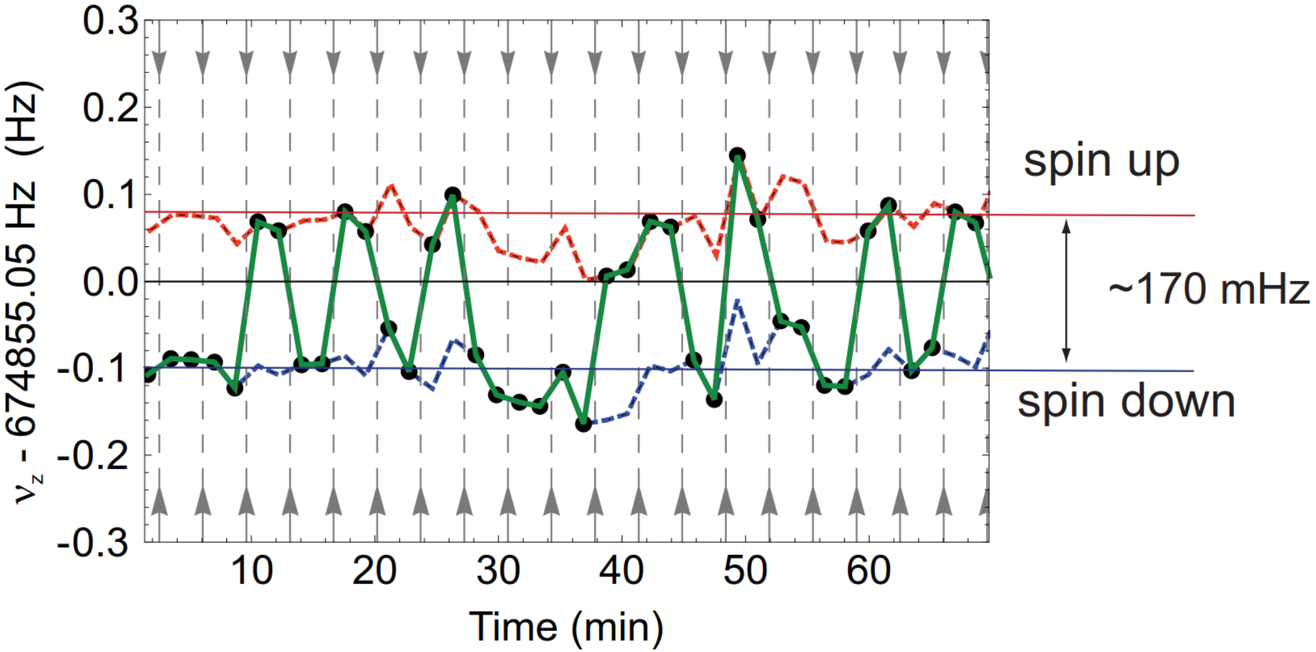


spin flipped in PT

measures spin flip probability as a function of the drive frequency in the homogeneous magnetic field of the precision trap

The holy-grail: single antiproton spin flips

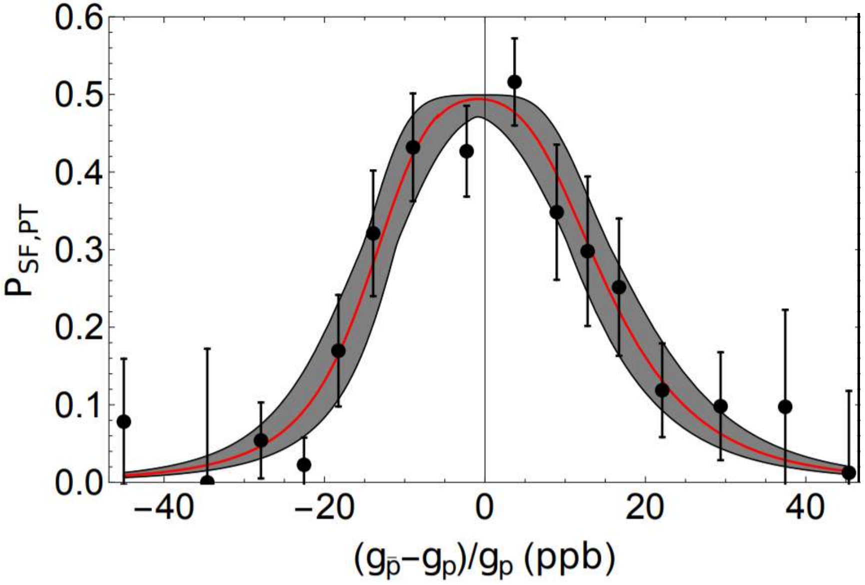


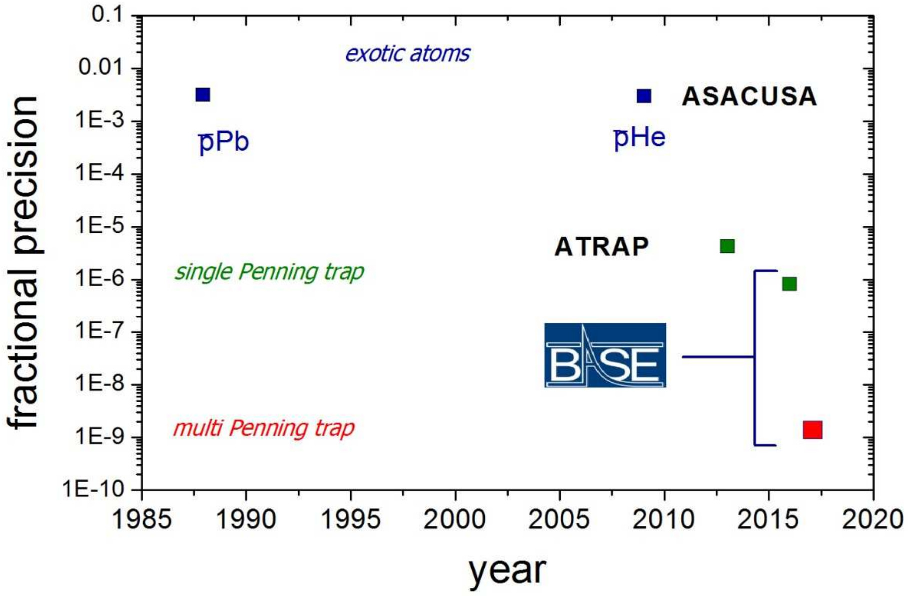


C. Smorra *et al.,* Phys. Lett. B 769, 1 (2017)

- **First non-destructive observation of single antiproton spin quantum transitions.**

The Magnetic Moment of the Antiproton





3000-fold improvement in g factor difference

$$f_p^0 = \left(\frac{g_{\bar{p}}}{2} - \frac{g_p}{2}\right)\frac{\mu_N}{2}$$

G. Schneider *et al.*, Science **358**, 1081 (2017)

$$\frac{g_p}{2} = 2.792\,847\,344\,62\,(82)$$

$$\frac{g_{\bar{p}}}{2} = 2.792\,847\,344\,1\,(42)$$

C. Smorra *et al.*, Nature **550**, 371 (2017)

The Antiproton Magnetic Moment

A milestone measurement in antimatter physics

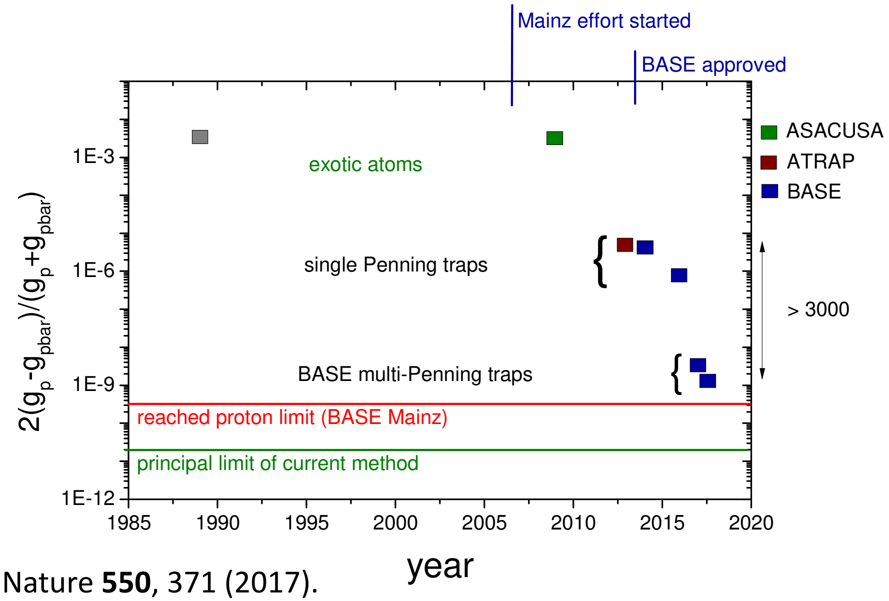
LETTER

OPEN

doi:10.1038/nature24048

A parts-per-billion measurement of the antiproton magnetic moment

C. Smorra[1,2], S. Sellner[1], M. J. Borchert[1,3], J. A. Harrington[4], T. Higuchi[1,5], H. Nagahama[1], T. Tanaka[1,5], A. Mooser[1], G. Schneider[1,6], M. Bohman[1,4], K. Blaum[4], Y. Matsuda[5], C. Ospelkaus[3,7], W. Quint[8], J. Walz[6,9], Y. Yamazaki[1] & S. Ulmer[1]



C. Smorra et al., Nature **550**, 371 (2017).


CERN Courier March 2018

BASE

Experiment of the moment

The BASE collaboration at CERN has measured the antiproton magnetic moment with extraordinary precision, offering more than 100-fold improved limits on certain tests of charge–parity–time symmetry.

The enigma of why the universe contains more matter than antimatter has been with us for more than half a century. While charge–parity (CP) violation can, in principle, account for the existence of such an imbalance, the observed matter excess is about nine orders of magnitude larger than what is expected from known CP-violating sources within the Standard Model (SM). This striking discrepancy inspires searches for additional mechanisms for the universe's baryon asymmetry, among which are experiments that test fundamental charge–parity–time (CPT) invariance by comparing matter and antimatter with great precision. Any measured difference between the two would constitute a dramatic sign of new physics. Moreover, experiments with antimatter systems provide unique tests of hypothetical processes beyond the SM that cannot be uncovered with ordinary matter systems.

The Baryon Antibaryon Symmetry Experiment (BASE) at CERN, in addition to several other collaborations at the Antiproton Decelerator (AD), probes the universe through exclusive antimatter "microscopes" with ever higher resolution. In 2017, following many years of effort at CERN and the University of Mainz in Germany, the BASE team measured the magnetic moment of the antiproton with a precision 350 times better than by any other experiment before, reaching a relative precision of 1.5 parts per billion (figure 1). The result followed the development of a multi-Penning-trap system and a novel two-particle measurement method and, for a short period, represented the first time that antimatter had been measured more precisely than matter.

The BASE setup at CERN's Antiproton Decelerator.

Non-destructive physics

The BASE result relies on a quantum measurement scheme to observe spin transitions of a single antiproton in a non-destructive manner. In experimental physics, non-destructive observations of quantum effects are usually accompanied by a tremendous increase in measurement precision. For example, the non-destructive observation of electronic transitions in atoms or ions led to the development of optical frequency standards that achieve fractional precisions on the 10^{-18} level. Another example, allowing one of the most precise tests of CPT invariance to date, is the comparison of the electron and positron g-factors. Based on quantum non-demolition detection of the spin state, such studies during the 1980s reached a fractional accuracy on the parts-per-trillion level.

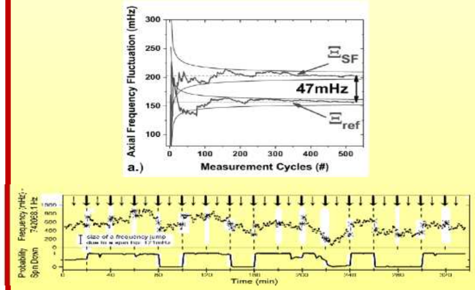
The latest BASE measurement follows the same scheme but targets the magnetic moment of protons and antiprotons instead of electrons and positrons. This opens tests of CPT in a totally different particle system, which could behave entirely differently. In practice, however, the transfer of quantum measurement methods from the electron/positron to the proton/antiproton system constitutes a considerable challenge owing to the

The multi-Penning-trap system used by BASE to detect the spin-flips of single trapped protons and antiprotons.

CERN COURIER, 3 / 2018.

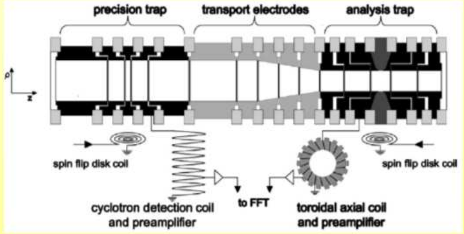
BASE achievements since 2011

Observation of spin flips with a single trapped proton



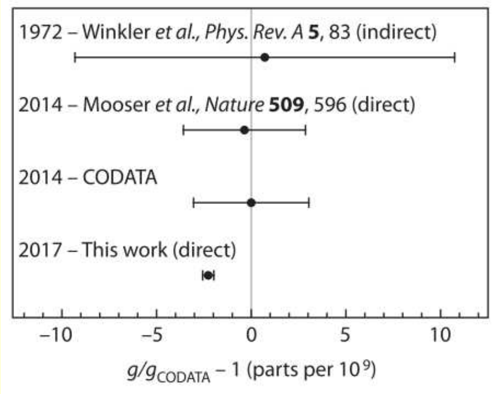
S. Ulmer, et al., **PRL 106, 253001 (2011)**
A. Mooser, et al., **PRL 110, (2013)**

Application of the double Penning-trap technique



A. Mooser, et al., **PLB 723, 78 (2013)**

Most precise proton g-factor measurment



g/2 = 2.792 847 350 (9)

A. Mooser *et al.*, Nature **509**, 596 (2014).

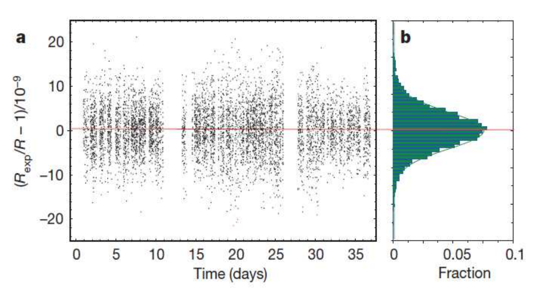
First direct high precision measurement of the proton magnetic moment.

g/2 = 2.792 847 344 62 (82)

G. Schneider et al., Science **358**, 1081 (2017).

Precise CPT test with baryons: comparison of cyclotron frequencies

S. Ulmer, et al., **Nature 524, 196 (2015)**

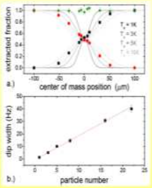


$$1+\frac{(q/m)_{\bar{\mathrm{p}}}}{(q/m)_{\mathrm{p}}} = 1(69)\times 10^{-12}$$

$R_{\text{exp,c}}$ = 1.001 089 218 755 (64) (26)

To be improved by another factor of 10 to 100

Reservoir trap for antiprotons



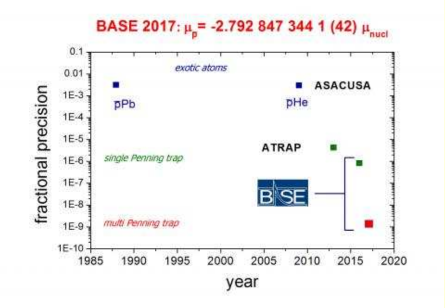
C. Smorra, et al., **Int. Journ. Mass Spec. 389, 10 (2015).**

Idea: Enable operation with antiprotons independent of accelerator run times.

Most precise antiproton g-factor measurment

H. Nagahama, et al., Nature Comms. **8, 14084 (2017)**

C. Smorra *et al.*, Nature **550**, 371 (2017)



g/2 = 2.792 846 5 (23)

Sixfold improvement compared to previous measurement

g/2 = 2.792 847 344 1 (42)

350-fold improvement compared to previous measurement

Partly comparable work by J. DiSciacca, G. Gabrielse et al.. (ATRAP/TRAP collaboration)

BASE

Thanks for your attention!


S. Ulmer
RIKEN


J. Devlin
RIKEN/CERN


E. Wursten
CERN / RIKEN


T. Higuchi
RIKEN / Tokyo


J. Harrington
MPIK/RIKEN


M. Borchert
Hannover/RIKEN


S. Erlewein
MPIK/RIKEN


P. Blessing
GSI & RIKEN


J. Schaper
RIKEN / Hanover


C. Smorra
RIKEN


M. Bohman
MPIK/RIKEN


M. Wiesinger
RIKEN/MPIK


A. Mooser
RIKEN/MPIK


G. Schneider
RIKEN/Mainz

RIKEN
Programs for Junior Scientists
MAX-PLANCK-GESELLSCHAFT
CERN
東京大学
THE UNIVERSITY OF TOKYO
JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ
GSI
PTB
Leibniz Universität Hannover

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

BASE
TC FS

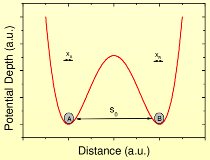
Funding: RIKEN / Max Planck Society / ERC Advanced / Helmholtz Gemeinschaft / DFG / C-TCFS

Planned Developments – Sympathetic Cooling of pbars

- Current antiproton magnetic moment measurements are limited by particle preparation time and particle mode temperature
- Expect: With traditional methods another 50-fold improvement is possible, **afterwards: limit of traditional methods will be reached!**

New Method

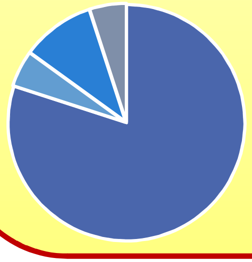
Couple protons/antiprotons sympathetically to laser cooled $^9Be^+$ ions and imprint Doppler temperatures to the antiproton



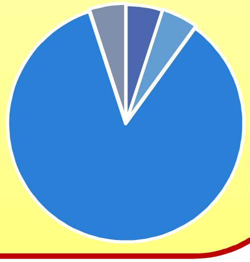
Publication: K. R. Brown, C. Ospelkaus, Y. Colombe, A. C. Wilson, D. Leibfried, D. J. Wineland, Nature **471**, 196 (2011).

Was demonstrated for $^9Be^+$ ions in Paul traps – implement same in Penning traps

Current Time Budget

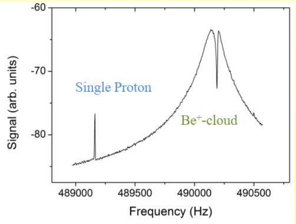


Laser Time Budget



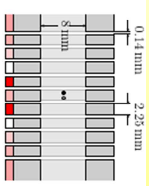
Effort at University of Mainz

5 trap design implemented and simultaneous detection of $^9Be^+$ ion and proton in common endcap trap was demonstrated.



C. Smorra, A. Mooser, M. Bohman, M. Wiesinger et al.

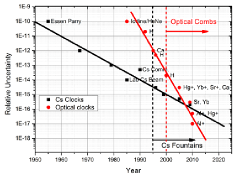
Effort at University of Hannover and PTB



Recent dramatic progress:
Detection of a single laser cooled $^9Be^+$ ion, in a Penning trap system which is fully compatible with the BASE trap system at CERN

M. Niemann, J. M. Cornejo, **C. Ospelkaus** et al.

The Vision

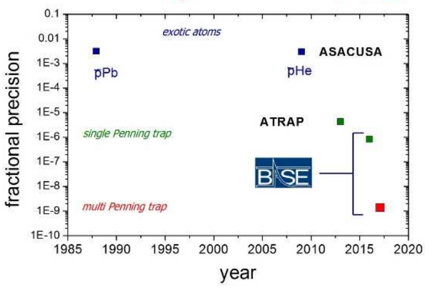


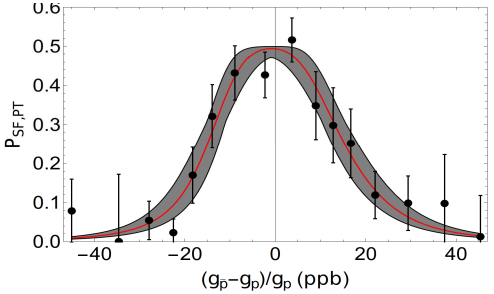
>100-fold improved antiproton cooling time seems to be in reach

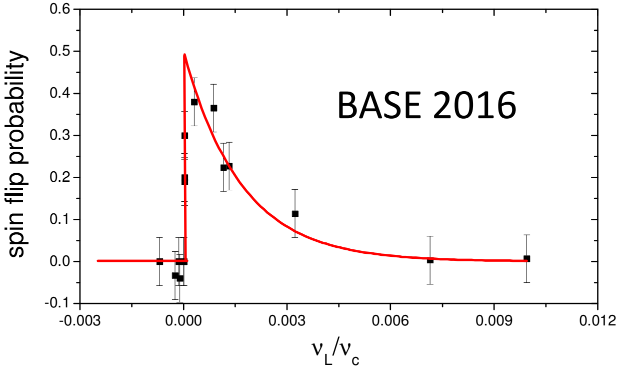
Summary and Outlook

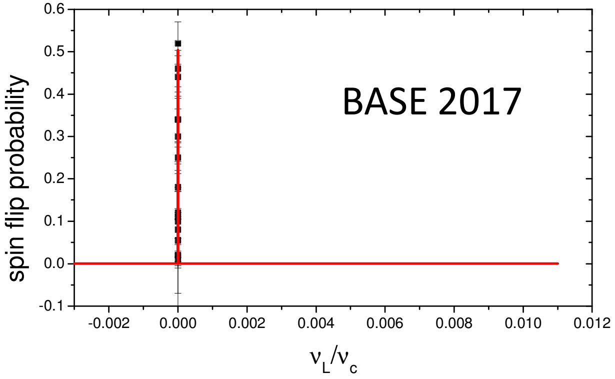
- Performed a 69 p.p.t. - test of CPT invariance with baryons by comparing proton/antiproton charge-to-mass ratios
- Performed the most precise measurement of the proton magnetic moment with a fractional precision of 0.3 p.p.b.
- Performed the most precise measurement of the antiproton magnetic moment with a fractional precision of 1.5 p.p.b.
- Feasibility to improve Q/M comparison by factor of 5 to 10 demonstrated.

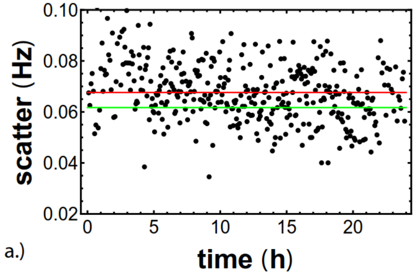
BASE 2017: $\mu_p = -2.792\,847\,344\,1\,(42)\ \mu_{nucl}$



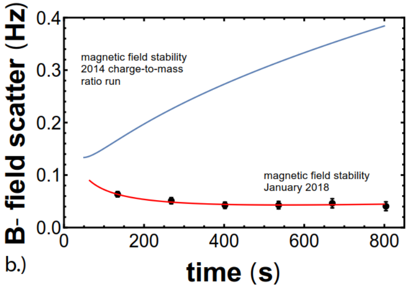






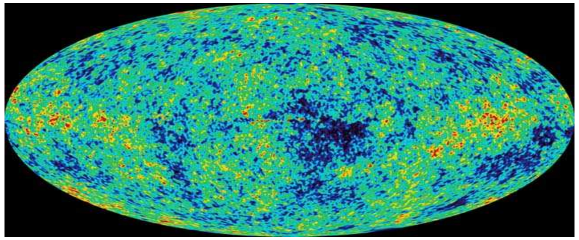


a.)



b.)

What inspires experiments with antimatter?

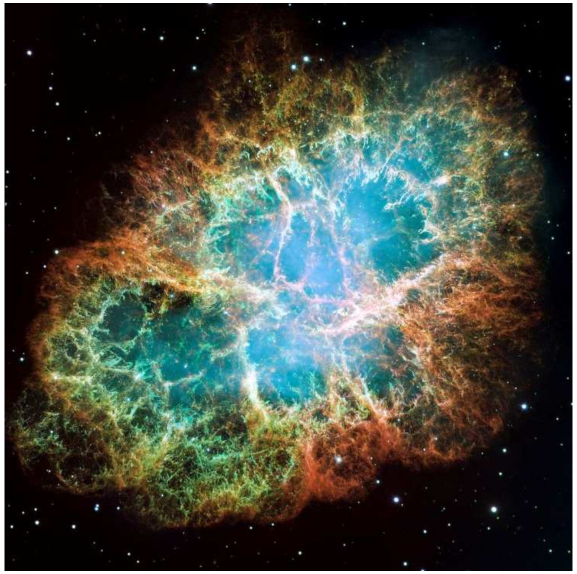


1. Big Bang scenario supported by
   1. Hubbles law
   2. Discovery of **CMWB with a black body spectrum of 2.73(1)K, by far too intense to be of stellar origin**.
   3. BBN scenario **describes exactly the observed light element abundances as found in «cold» stellar nebulae**.

2. Using the models which successfully describe 1., 2. and 3.:

Prediction	
Baryon/Photon Ratio	10^{-18}
Baryon/Antibaryon Ratio	1

Observation	
Baryon/Photon Ratio	10^{-9}
Baryon/Antibaryon Ratio	10000

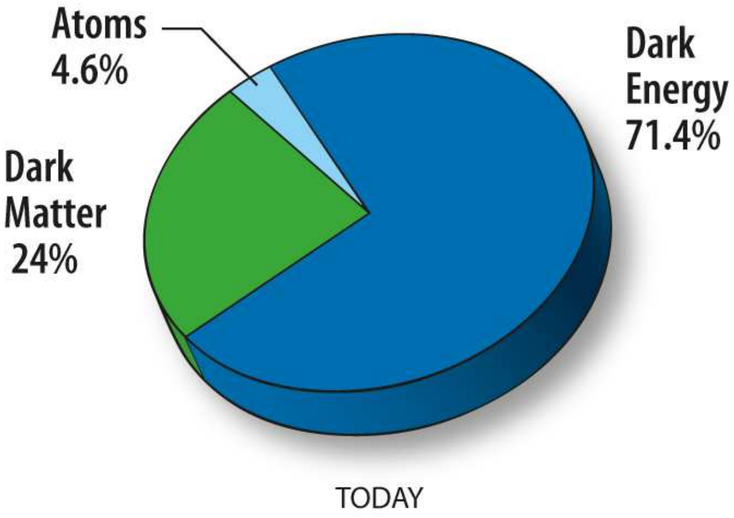


Following the current Standard Model of the Universe our predictions of baryon to photon ratio are **wrong by about 9 orders of magnitude** while our baryon/antibaryon ratio is **wrong by about four orders of magnitude**.

Antimatter and Dark Matter

- Given our current understanding of the Universe there are several problems
  - Energy content of the universe has **yet to be understood**.
  - We even **do not understand** why these 5% of baryonic matter exist.

Could these problems be related?

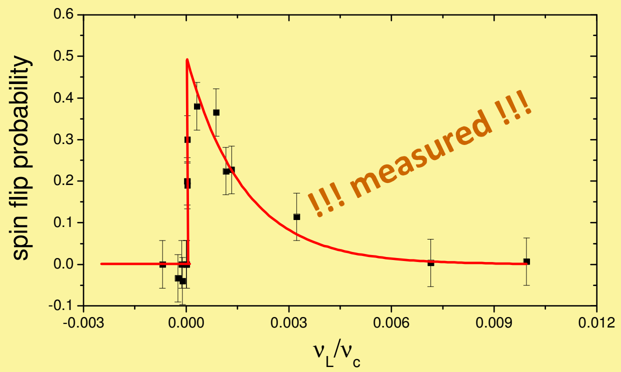


Search for time-base signatures in antimatter data, mediated by axion / antiproton coupling:

$$H_{\text{int}}(t) \approx \frac{C_{\bar{p}} a_0}{2 f_a} \sin(m_a t)\, \boldsymbol{\sigma}_{\bar{p}} \cdot \boldsymbol{p}_a$$

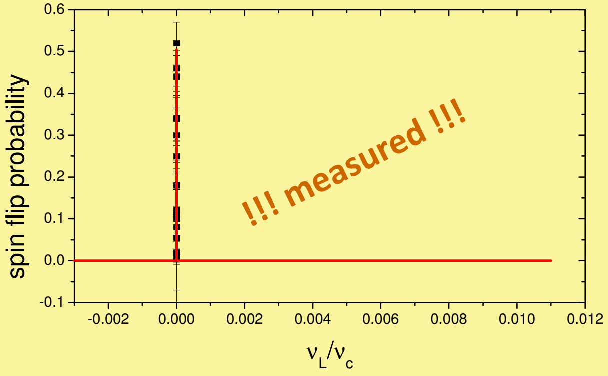
Single Trap – Double Trap – Triple Trap

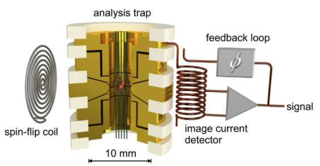
single-trap method

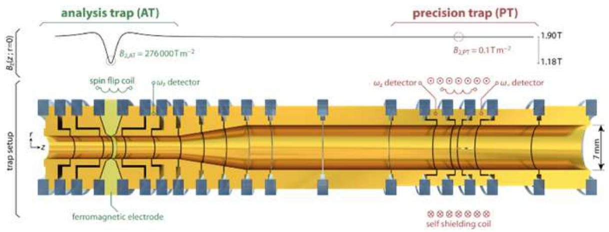


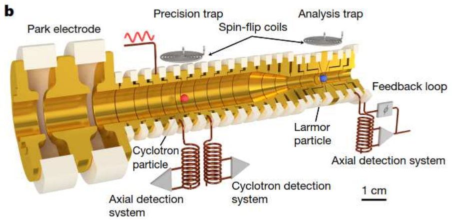
$$\frac{B_{2,AT}}{B_{2,PT}} > 10^6$$

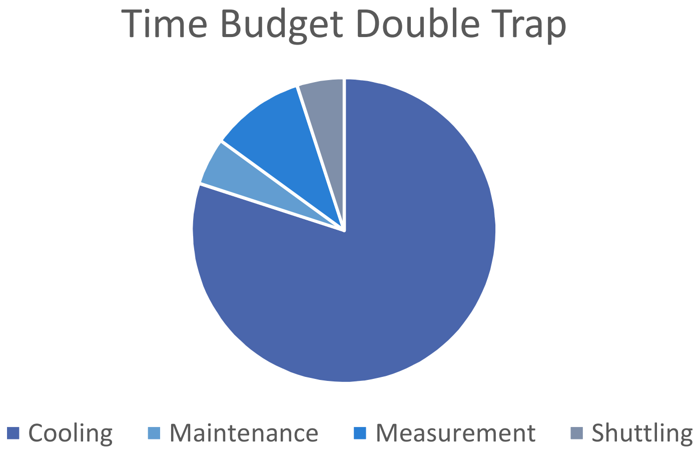
multi-trap method

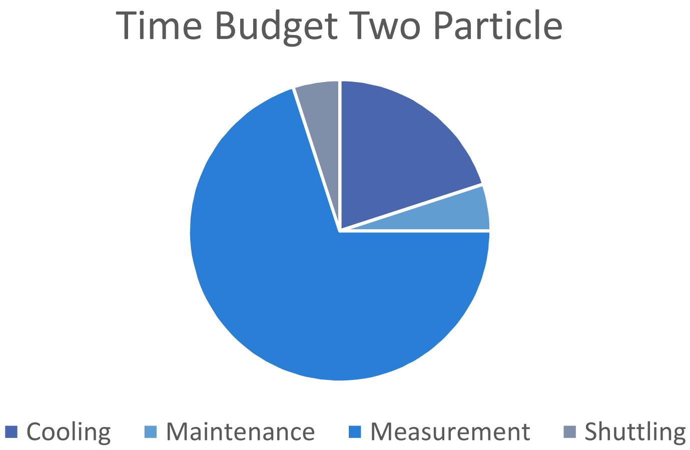












two years compared to two months…

Systematics

Table 1 | Error budget of the antiproton magnetic moment measurement

Effect	Correction (p.p.b.)	Uncertainty (p.p.b.)	
🟦 Image-charge shift	0.05	0.001	calculate
🟥 Relativistic shift	0.03	0.003	measure T / calculate
🟥 Magnetic gradient	0.22	0.020	measure / calculate
🟥 Magnetic bottle	0.12	0.009	measure / calculate
🟦 Trap potential	−0.01	0.001	measure / calculate
🟦 Voltage drift	0.04	0.020	measure / calculate
🟥 Contaminants	0.00	0.280	measure / constrain
🟥 Drive temperature	0.00	0.970	measure / constrain
🟦 Spin-state analysis	0.00	0.130	measure / simulate / constrain
Total systematic shift	0.44	1.020	

The table lists the relative systematic shifts (column 2) by which the measured magnetic-moment value was corrected; column 3 is the uncertainty of the correction. Details of these systematic effects and their quantification are given in Methods.

🟦 classical trap shifts

🟥 shifts induced by 2 particle approach

this dominant error is not present in double trap measurements.
Has been estimated with the conservative 95% C.L