PSI2019 – Villigen/Switzerland – 2019 / 10 / 21

Antimatter Under the Microscope

High-Precision Comparisons of the Fundamental Properties of Antiprotons and Protons

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RIKEN,

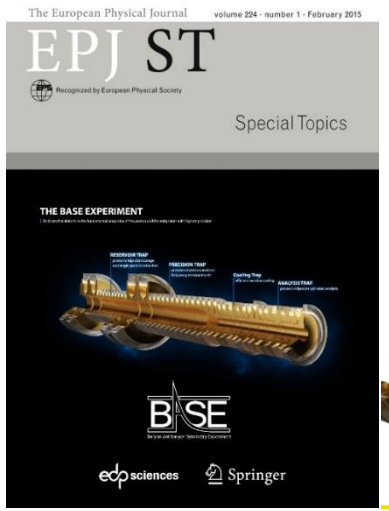
Ulmer Fundamental Symmetries Laboratory

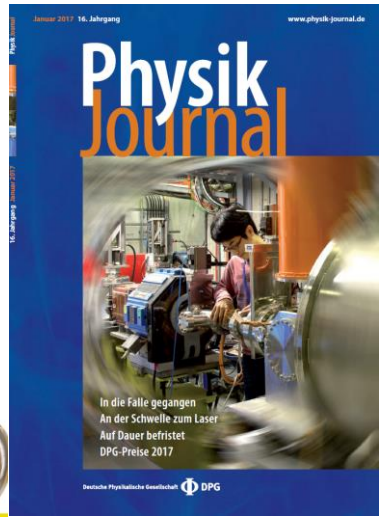
Spokesperson BASE collaboration, CERN

2019 / 10 / 21

BASE – Collaboration

- **Mainz:** Measurement of the magnetic moment of the proton, implementation of new technologies. (see poster Matt Bohman)
- **CERN-AD:** Measurement of the magnetic moment of the antiproton and proton/antiproton q/m ratio (see poster Elise Wursten)
- **Hannover/PTB:** QLEDS-laser cooling project, new technologies





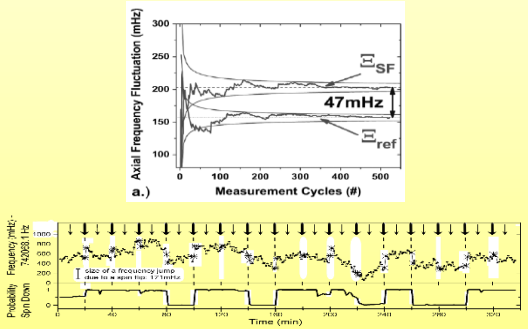
Institutes: RIKEN, MPIK, CERN, University of Mainz, Tokyo University, GSI Darmstadt, University of Hannover, PTB Braunschweig

RIKEN · MPIK · 東京大学 THE UNIVERSITY OF TOKYO · JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ · Leibniz Universität Hannover · GSI

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

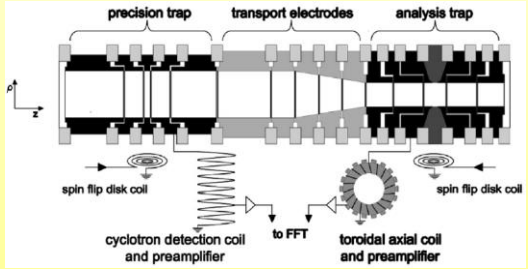
BASE achievements since 2011

Observation of spin flips with a single trapped proton



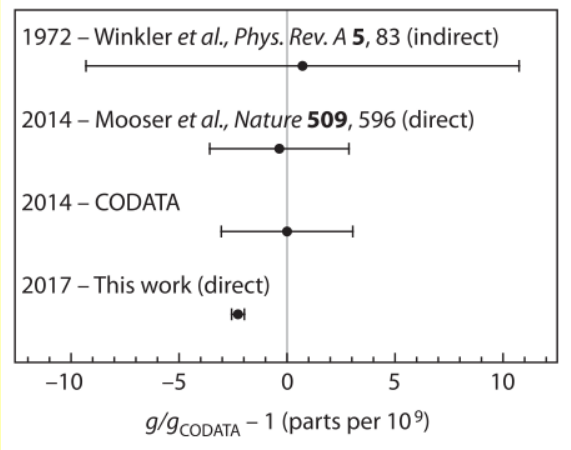
S. Ulmer, et al., **PRL 106, 253001 (2011)**
A. Mooser, et al., **PRL 110, (2013)**

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).

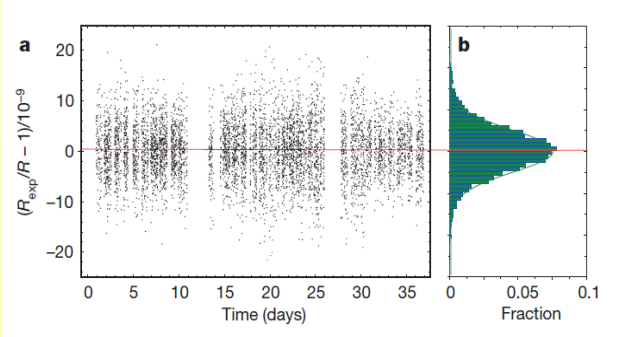
First direct high precision measurement of the proton magnetic moment.

g/2 = 2.792 847 344 62 (82)

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

Precise CPT test with baryons

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

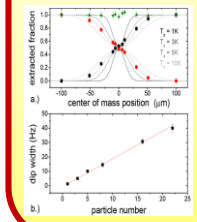


$$1 + \frac{(q/m)_{\bar{p}}}{(q/m)_{p}} = 1(69) \times 10^{-12}$$

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

To be improved by another factor of 10 to 100

Reservoir trap for antiprotons

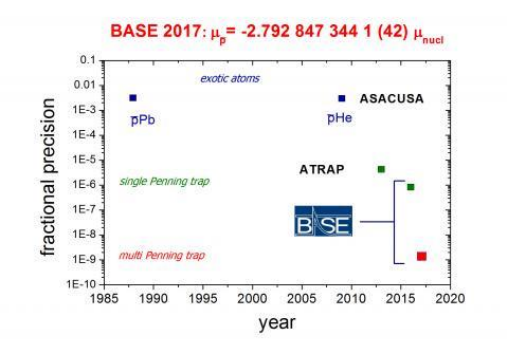


C. Smorra, et al., **Int. Journ. Mass Spec. 389, 10 (2015).**

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

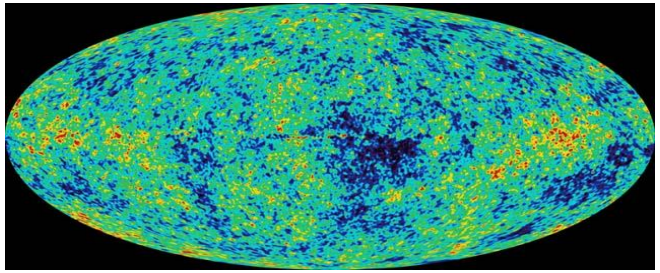
Partly comparable work by J. DiSciacca, G. Gabrielse et al.. (ATRAP/TRAP collaboration)

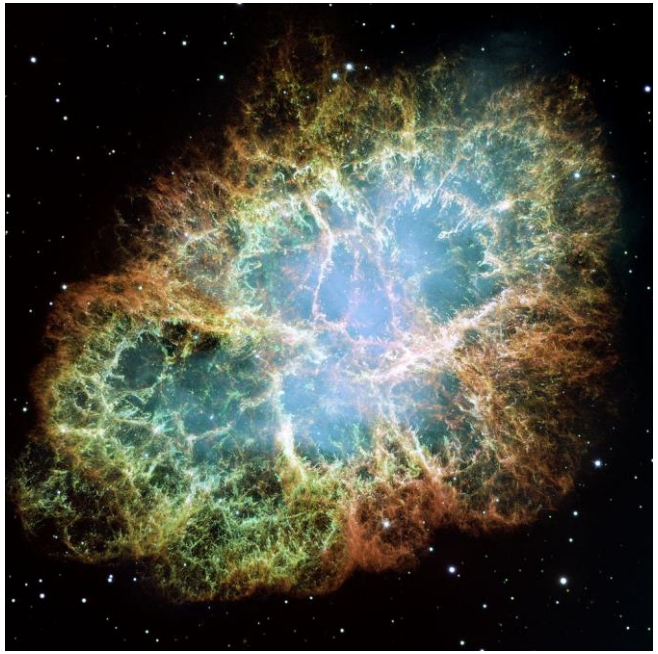
Problem: Big Bang Scenario and Consequences

1. A cosmic microwave background should exist as a fire-ball remnant of the Big Bang
   1. 1965 Penzias and Wilson **observed CMWB with a black body spectrum of 2.73(1)K, by far too intense to be of stellar origin**.

2. Understandable Big Bang nucleosynthesis scenario **describes exactly the observed light element abundances as found in «cold» stellar nebulae**.

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



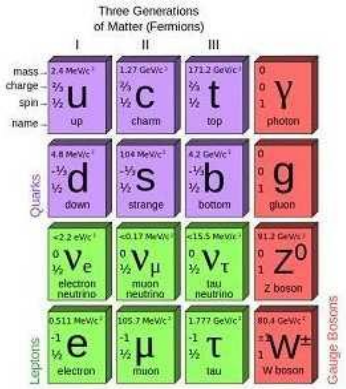


Prediction	
Baryon/Photon Ratio	10^{-18}
Baryon/Antibaryon Ratio	1

Observation	
Baryon/Photon Ratio	10^{-9}
Baryon/Antibaryon Ratio	0.0001

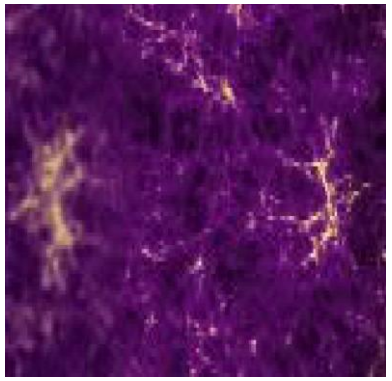
Following the current Standard Model of the Universe our predictions of baryon to photon ratio are **wrong by about 9 orders of magnitude**

Summary

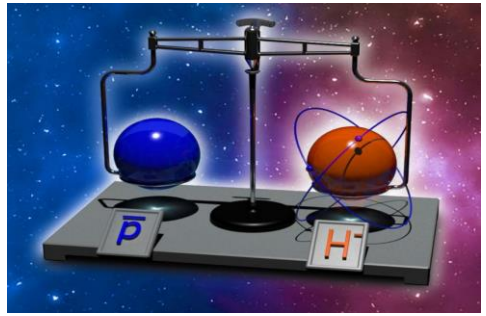


WE HAVE A PROBLEM

mechanisms which created the obvious baryon/antibaryon asymmetry in the universe have yet to be understood

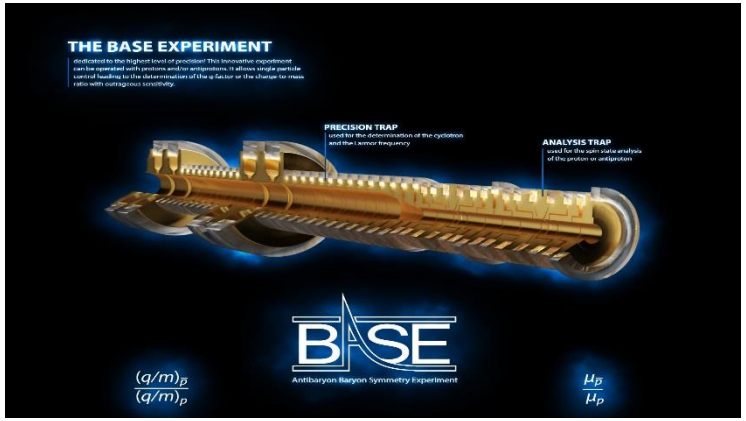


One strategy: Compare the fundamental properties of matter / antimatter conjugates with ultra high precision

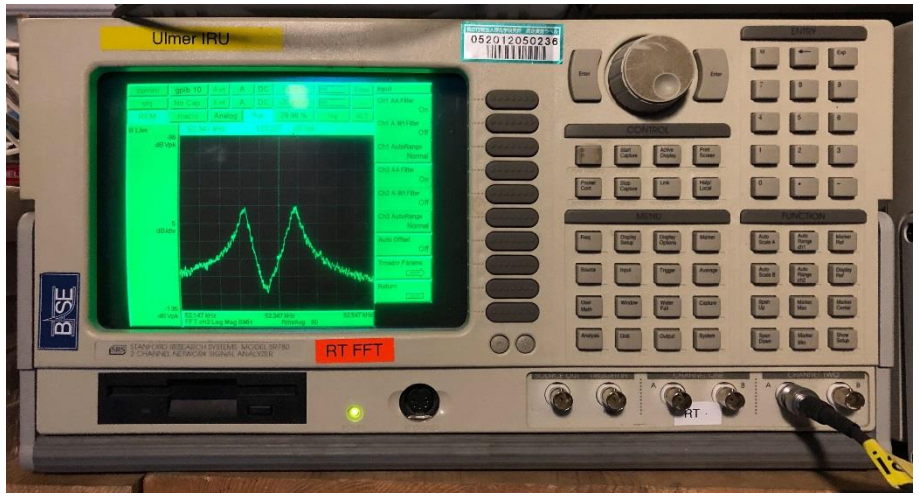


A special place (in the universe?) – the BASE trap

- We have
  - A vacuum of 5e-19 mbars
    - comparable to pressures in the interstellar medium
  - Antiproton storage times of several 10 years.
  - Not more than 3000 atoms in a vacuum volume of 0.5l
  - Order 100 to 1000 trapped antiprotons
  - A local inversion of the baryon asymmetry

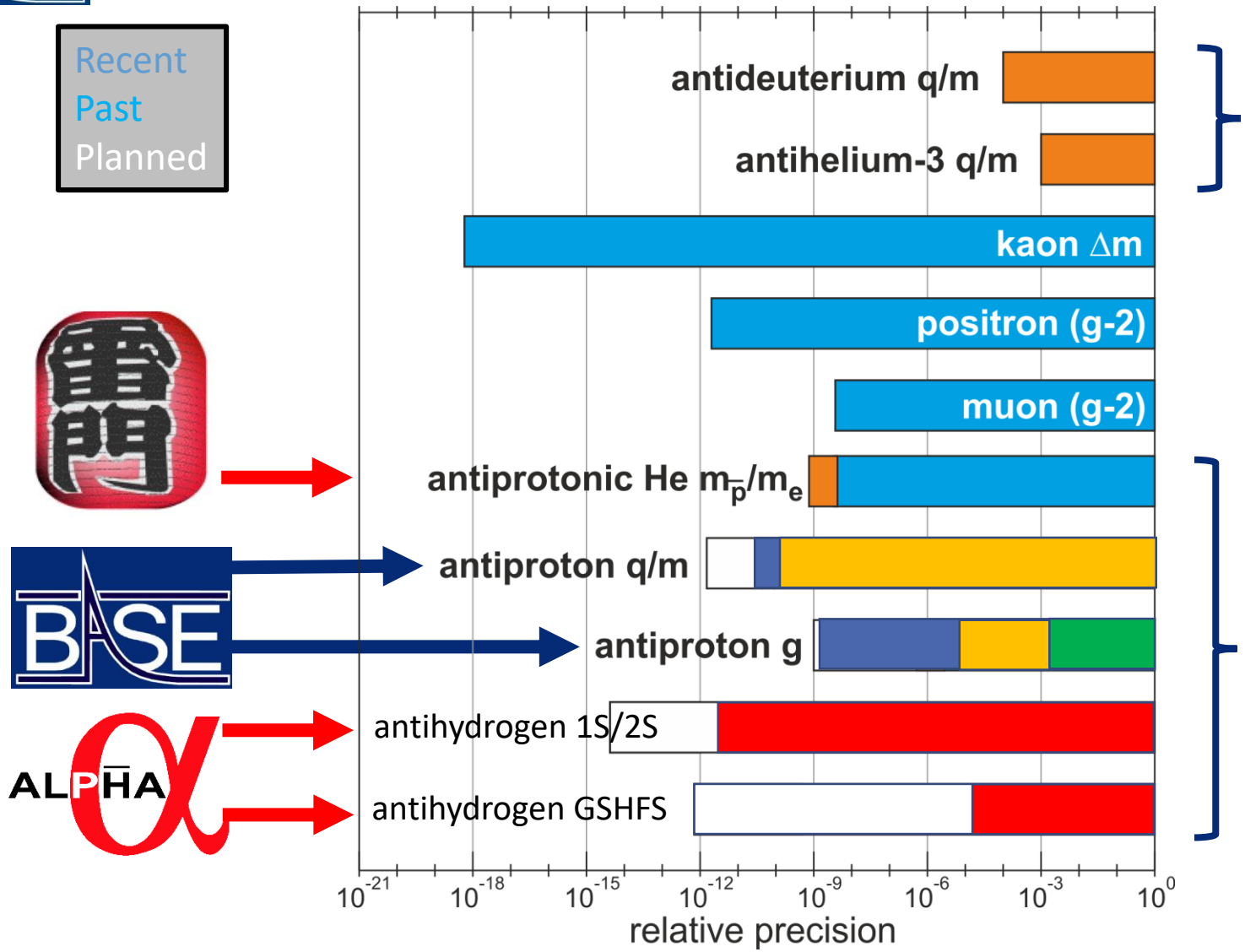


BASE ANTIMATTER INVERSION	
local volume	0.0001^3 m^3
Baryons in local trap volume	$1.65*10^{-7}$
Antibaryon in local trap volume	100
Antibaryon/Baryon Ratio	**$5.9*10^8$**
Ratio Inversion	**$3.8*10^{12}$**



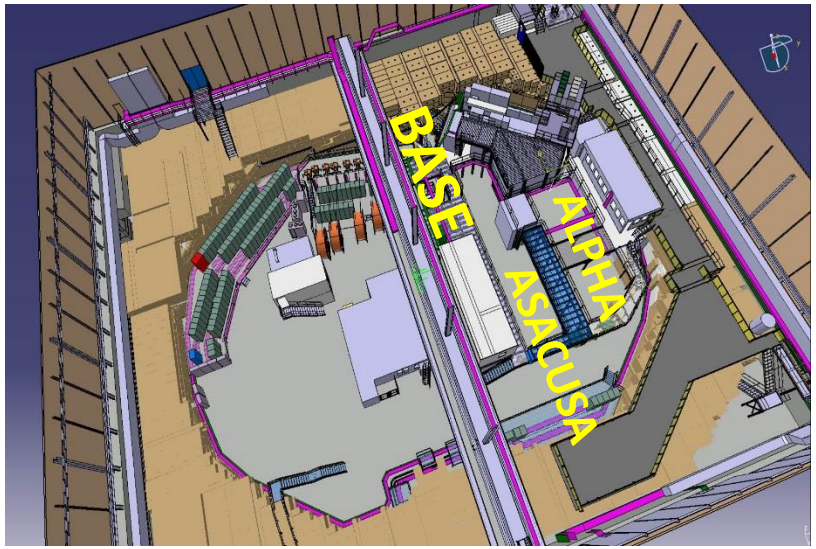
With this instrument: Investigate properties of antimatter very precisely

CPT tests based on particle/antiparticle comparisons



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 – ONE example

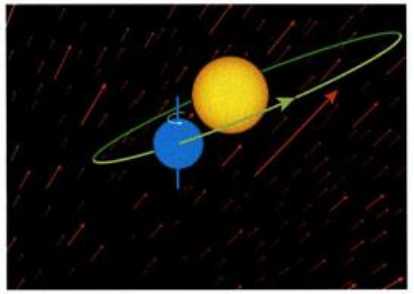
- Test the Standard Model (CPT invariance) by comparing the fundamental properties of protons and antiprotons with high precision

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

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

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

Dirac equation CPT-odd modifications

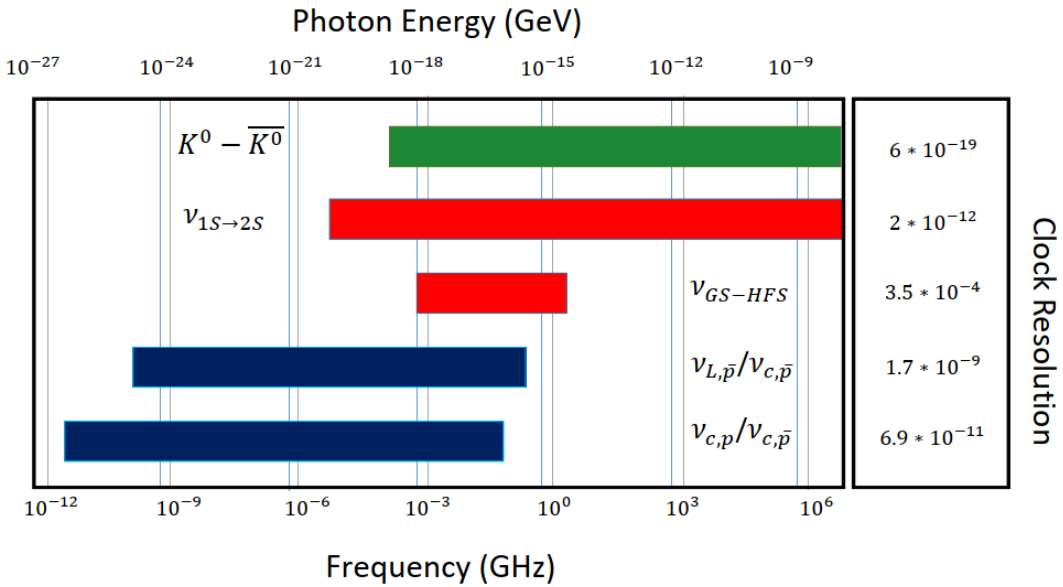


$$b_\mu\gamma_5\gamma^\mu \rightarrow b_x\begin{pmatrix}-\sigma_x & 0\\ 0 & \sigma_x\end{pmatrix} + b_y\begin{pmatrix}-\sigma_y & 0\\ 0 & \sigma_y\end{pmatrix} + b_z\begin{pmatrix}-\sigma_z & 0\\ 0 & \sigma_z\end{pmatrix}$$

Pseudo-magnetic field, with different coupling to matter and antimatter, respectively

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

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

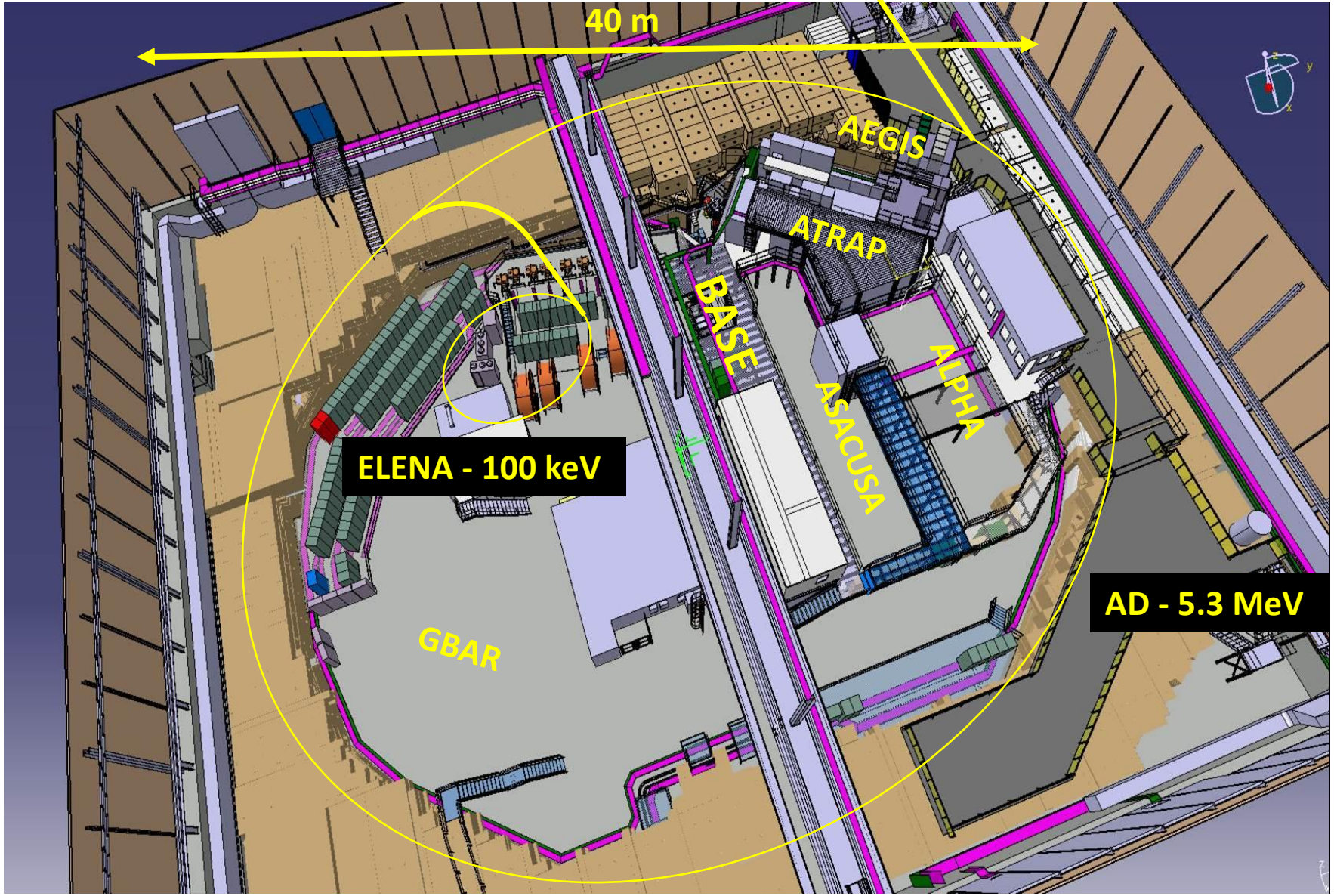


Would correspond to the discovery of a boson field which exclusively couples to antimatter.

sensitive: comparisons of particle/antiparticle magnetic moments in traps

The AD/ELENA-facility

Six collaborations, pioneering work by Gabrielse, Oelert, Hayano, Hangst, Charlton et al.



BASE, ATRAP,
Fundamental properties of the antiproton

ALPHA, ATRAP,
Spectroscopy of 1S-2S in antihydrogen

ASACUSA, ALPHA
Spectroscopy of GS-HFS in antihydrogen

ASACUSA
Antiprotonic helium spectroscopy

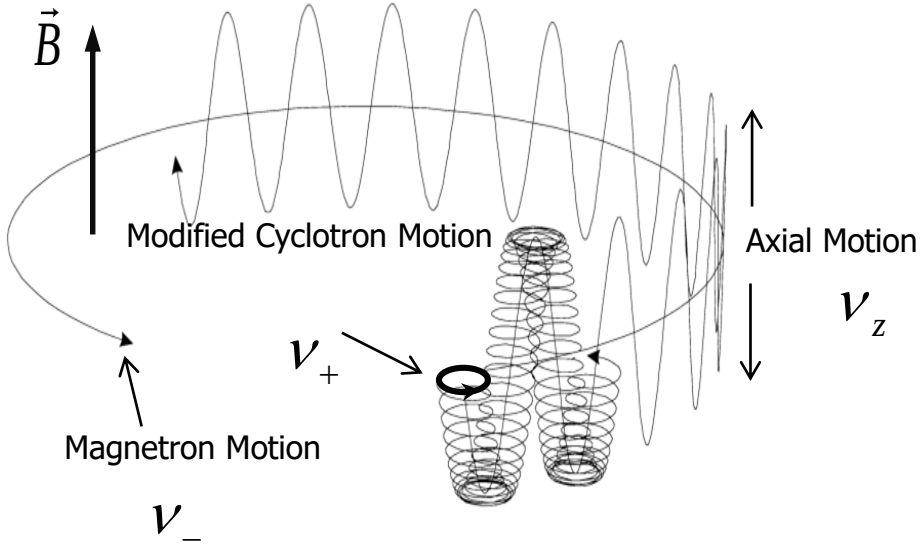
ALPHA, AEgIS, GBAR
Test free fall/equivalence principle with antihydrogen

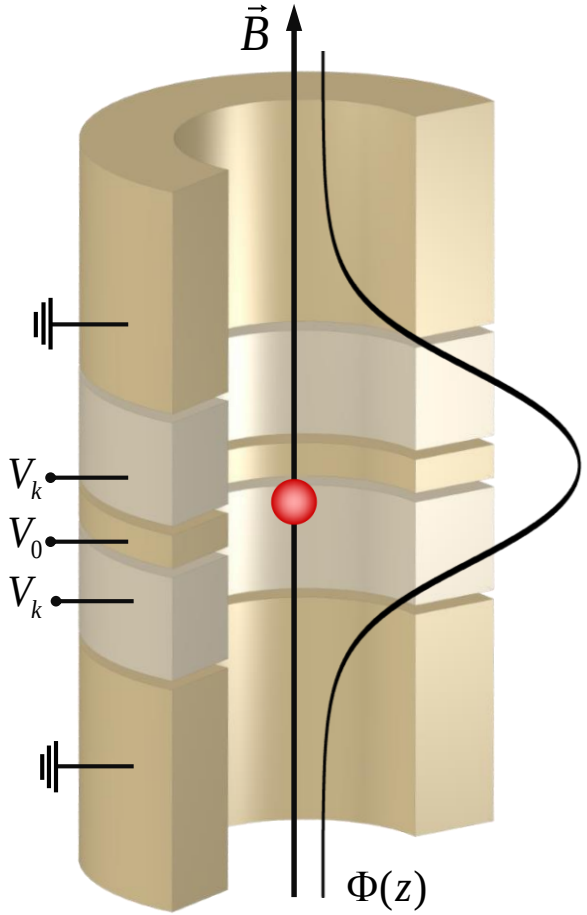
M. Hori, J. Walz, Prog. Part. Nucl. Phys. 72, 206-253 (2013).

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

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

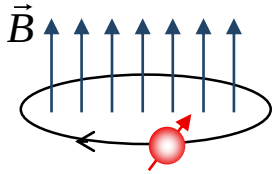
Cyclotron Frequency

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

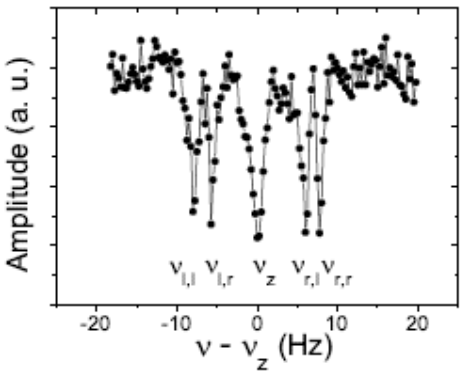
Cyclotron frequency connects measurable quantity to fundamental properties of trapped charged particle

Measurements in Penning traps

Cyclotron Motion



simple



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

g: mag. Moment in units of nuclear magneton

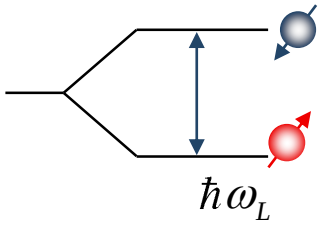
$$\omega_c = \frac{e}{m_p} B$$

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

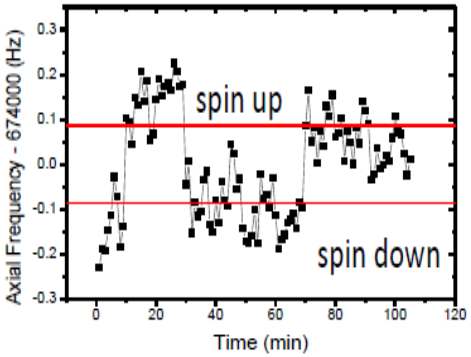
$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p}$$

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

Larmor Precession

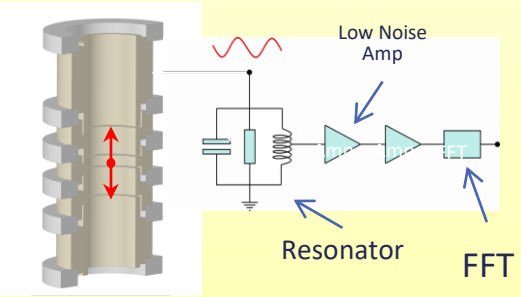


difficult



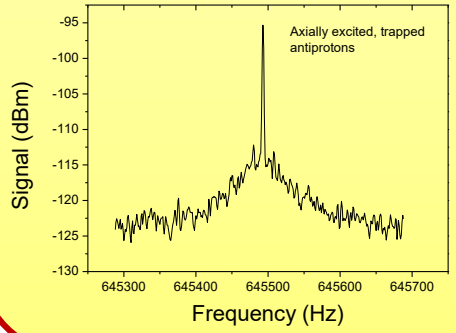
S. Ulmer, A. Mooser *et al.* PRL 106, 253001 (2011)

Image Current Detection



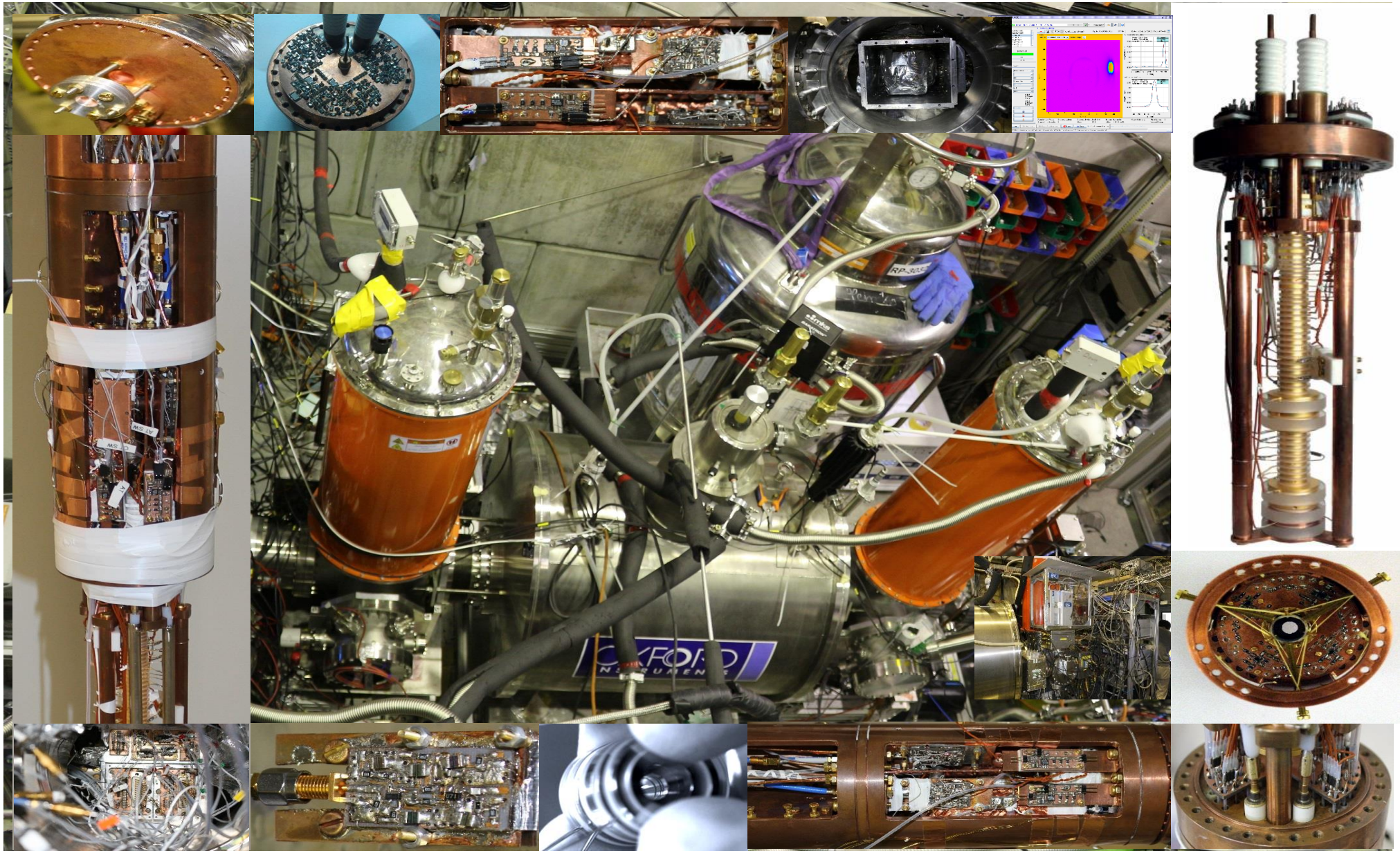
currents: 1 fA

Single Antiproton Signal



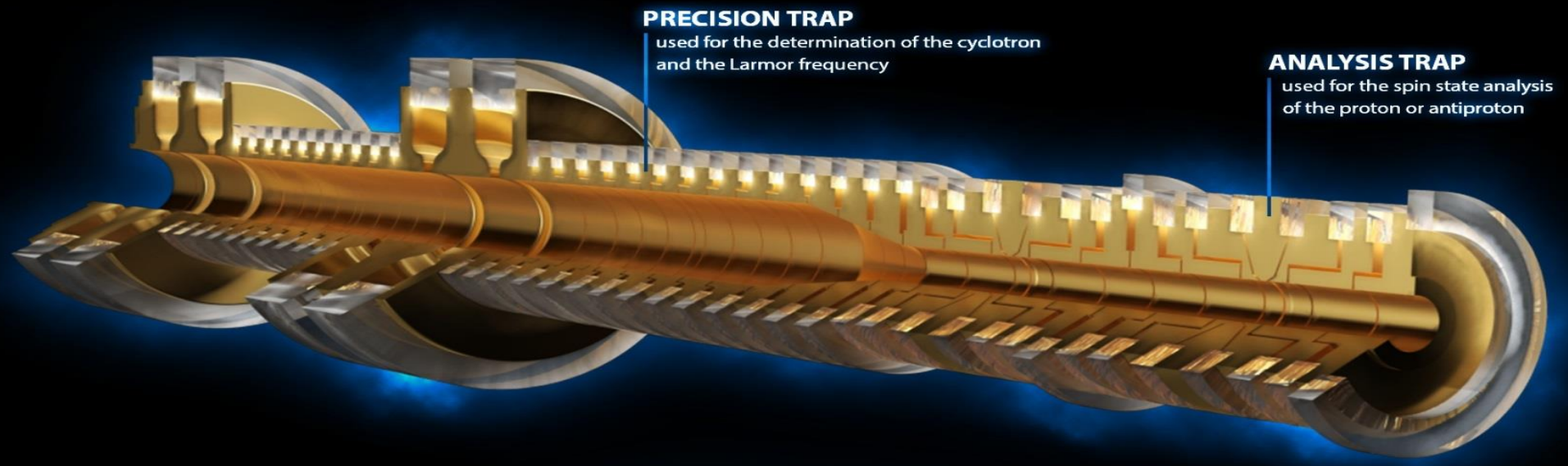
Determinations of the q/m ratio and g-factor reduce to measurements of frequency ratios -> in principle **very simple** experiments –> **full control, (almost) no theoretical corrections required.**

Experiment



THE BASE EXPERIMENT

dedicated to the highest level of precision! This innovative experiment can be operated with protons and/or antiprotons. It allows single particle control leading to the determination of the g-factor or the charge-to-mass ratio with outrageous sensitivity.



BASE

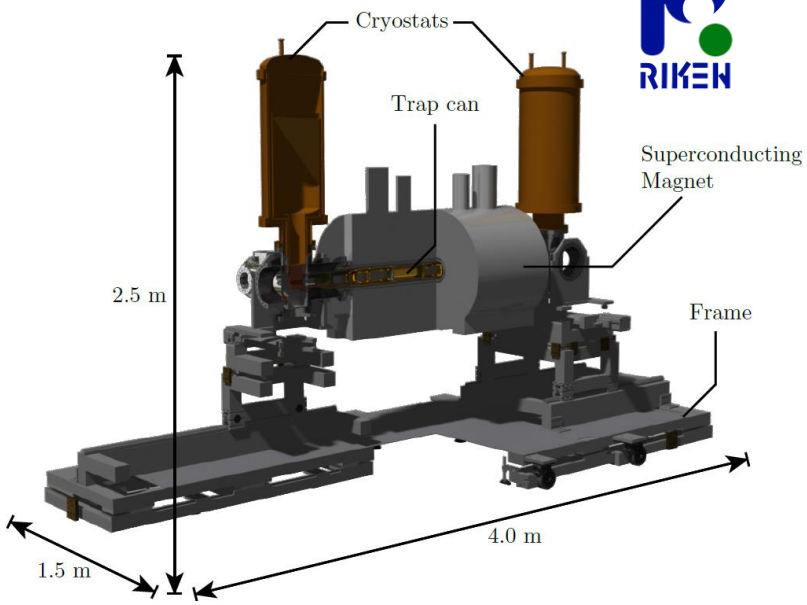
Antibaryon Baryon Symmetry Experiment

$$\frac{(q/m)_{\bar{p}}}{(q/m)_p}$$

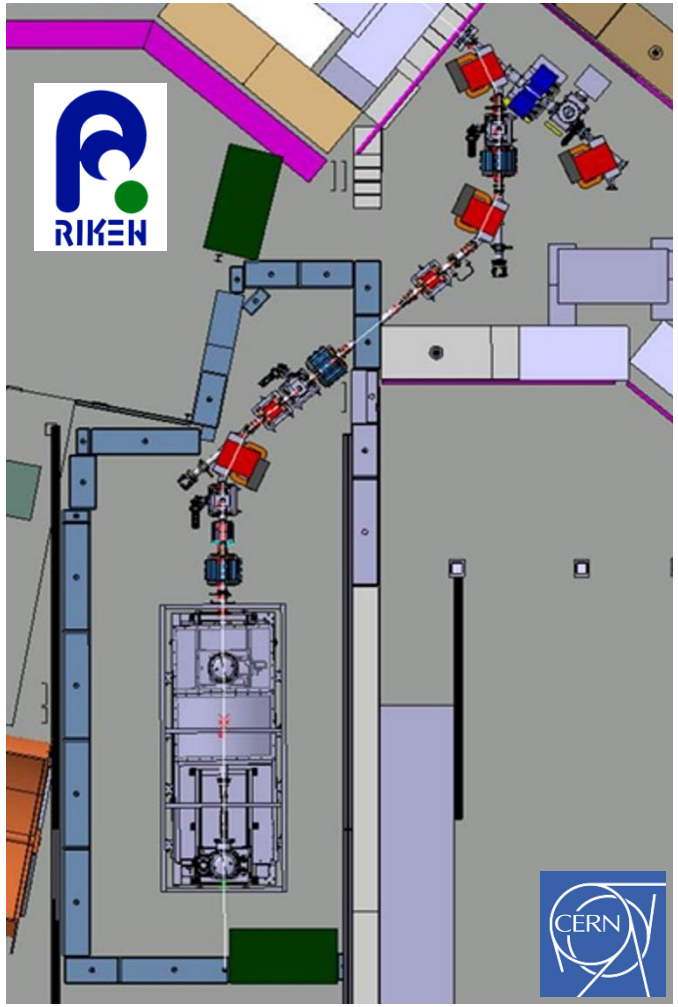
$$\frac{\mu_{\bar{p}}}{\mu_p}$$

BASE-CERN Apparatus (approved 2013)

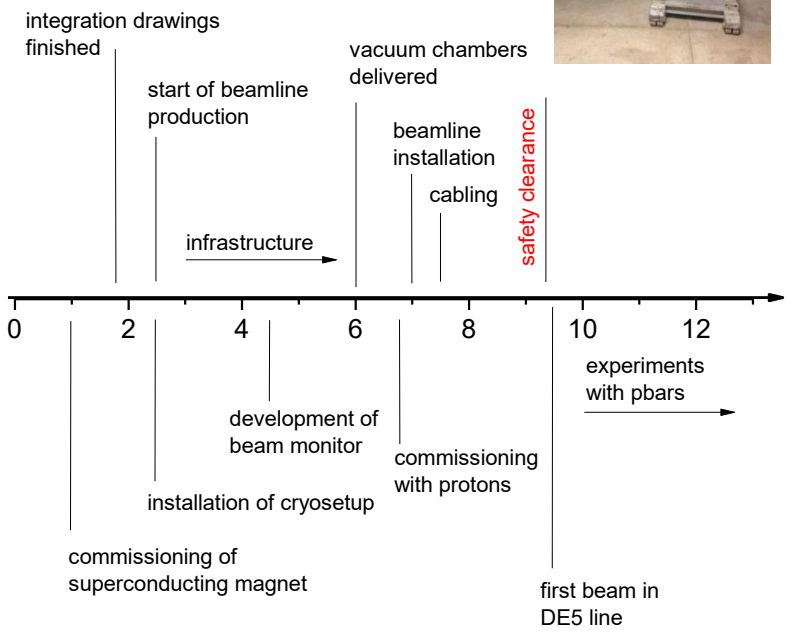
Constructed new apparatus



Integrated in a new experiment zone



Timeline:



Constructed antiproton transfer line

Thanks to L. Bojtar,
F. Butin and team
T Erkisson and team
R. Kersevan and team

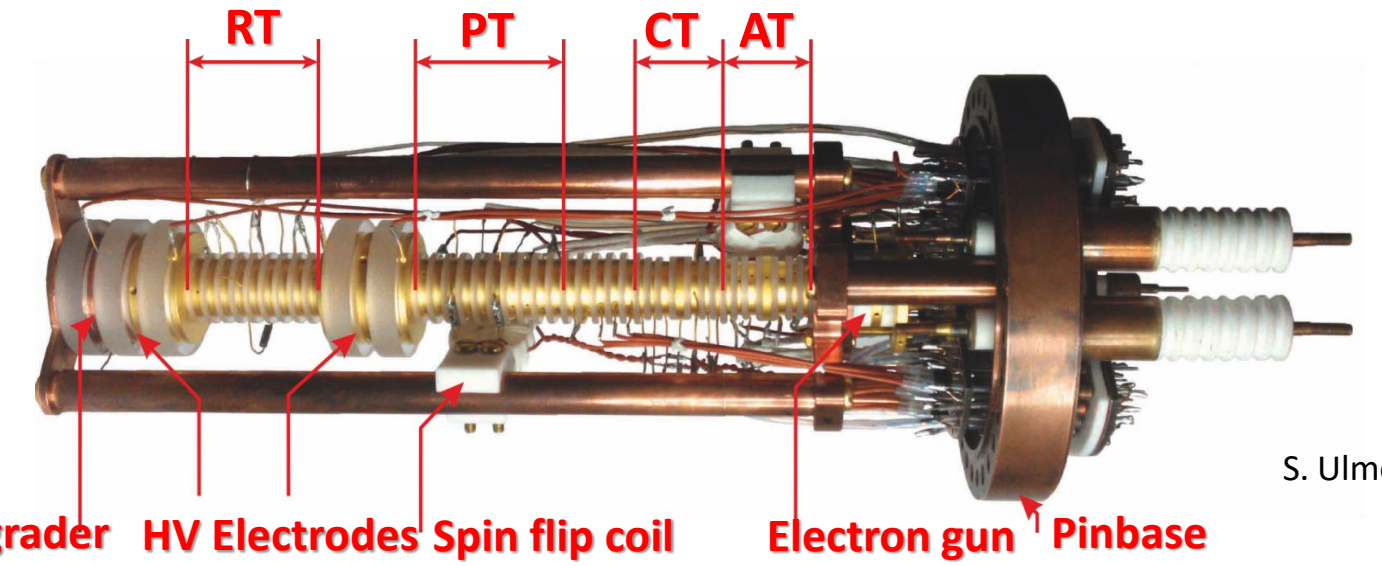
Implemented into the AD facility within 12 months – thanks to strong support by CERN

The BASE Trap System

Access to beamline

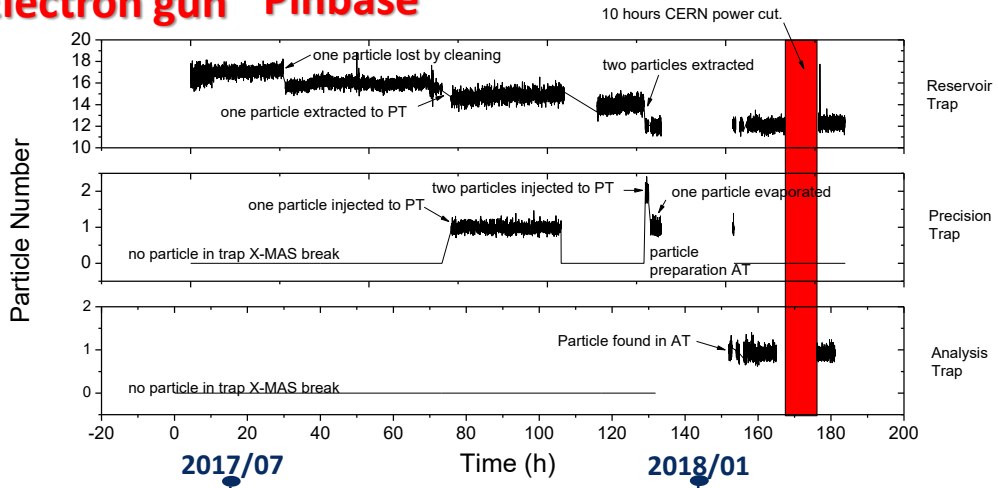
Particles not continuously available

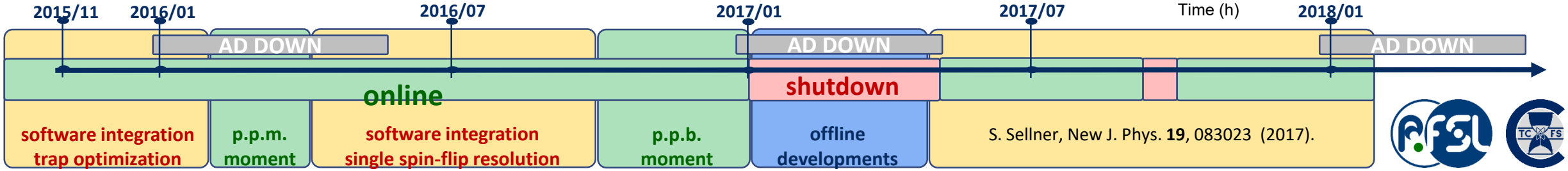
Trap for efficient cyclotron cooling



S. Ulmer et al., BASE TDR, CDS (2013).

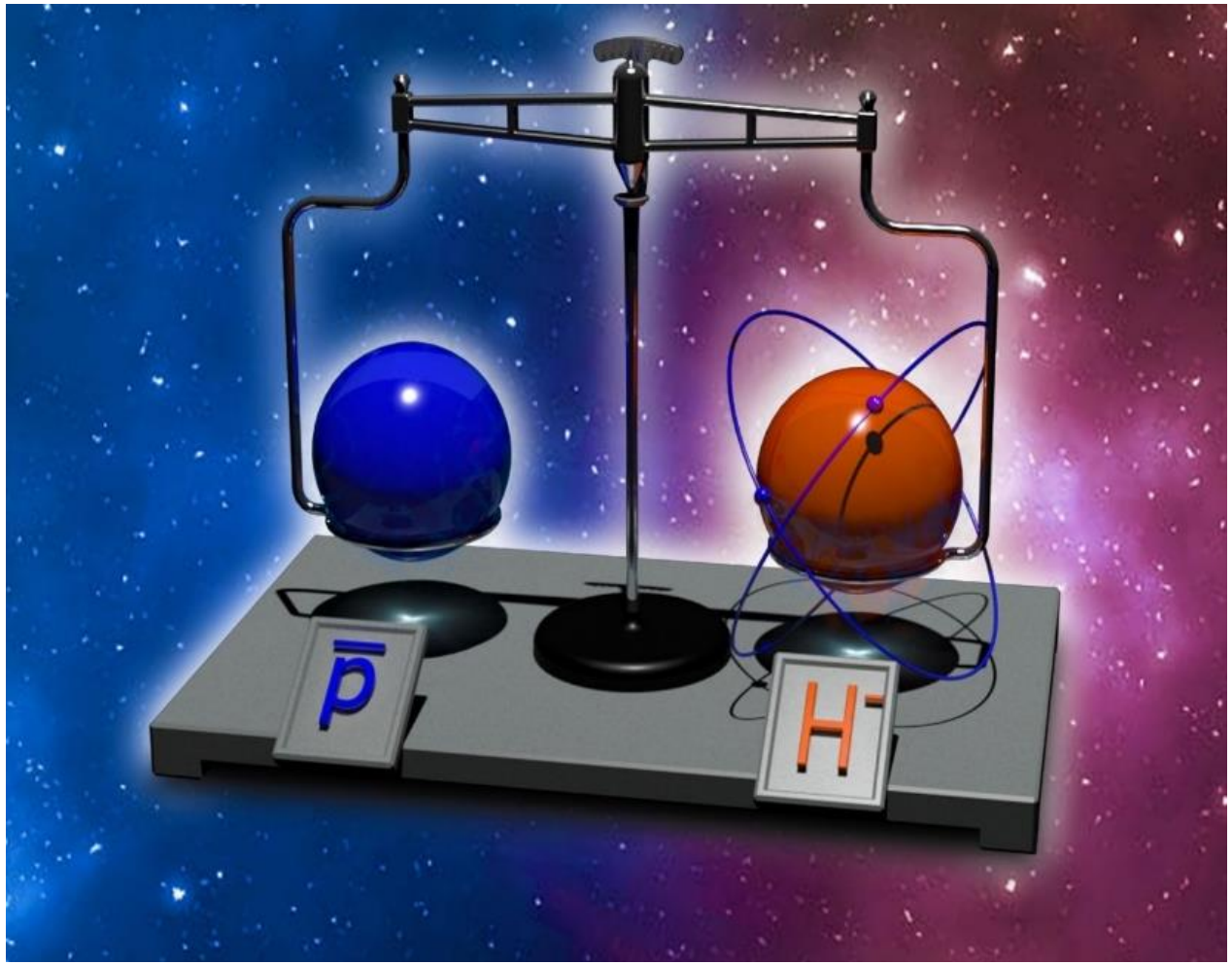
Reservoir Trap: Stores a cloud of antiprotons, suspends single antiprotons for measurements. Trap is "power failure save".
Precision Trap: Homogeneous field for frequency measurements, $B_2 < 0.5\ \mu T / mm^2$ **(10 x improved)**
Cooling Trap: Fast cooling of the cyclotron motion, $1/\gamma < 4$ s **(10 x improved)**
Analysis Trap: Inhomogeneous field for the detection of antiproton spin flips, $B_2 = 300\ mT / mm^2$





S. Sellner, New J. Phys. **19**, 083023 (2017).

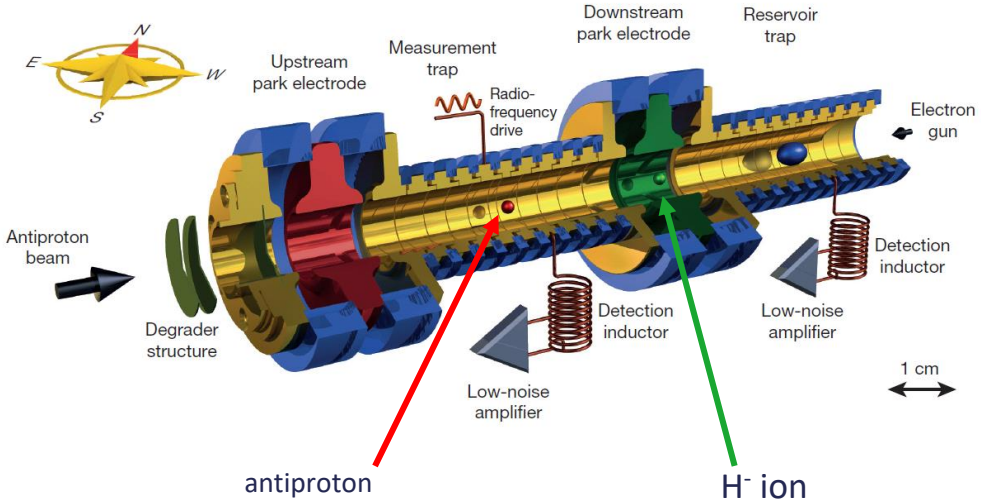
Proton/Antiproton Charge-to-Mass Comparison



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

Measurement configuration

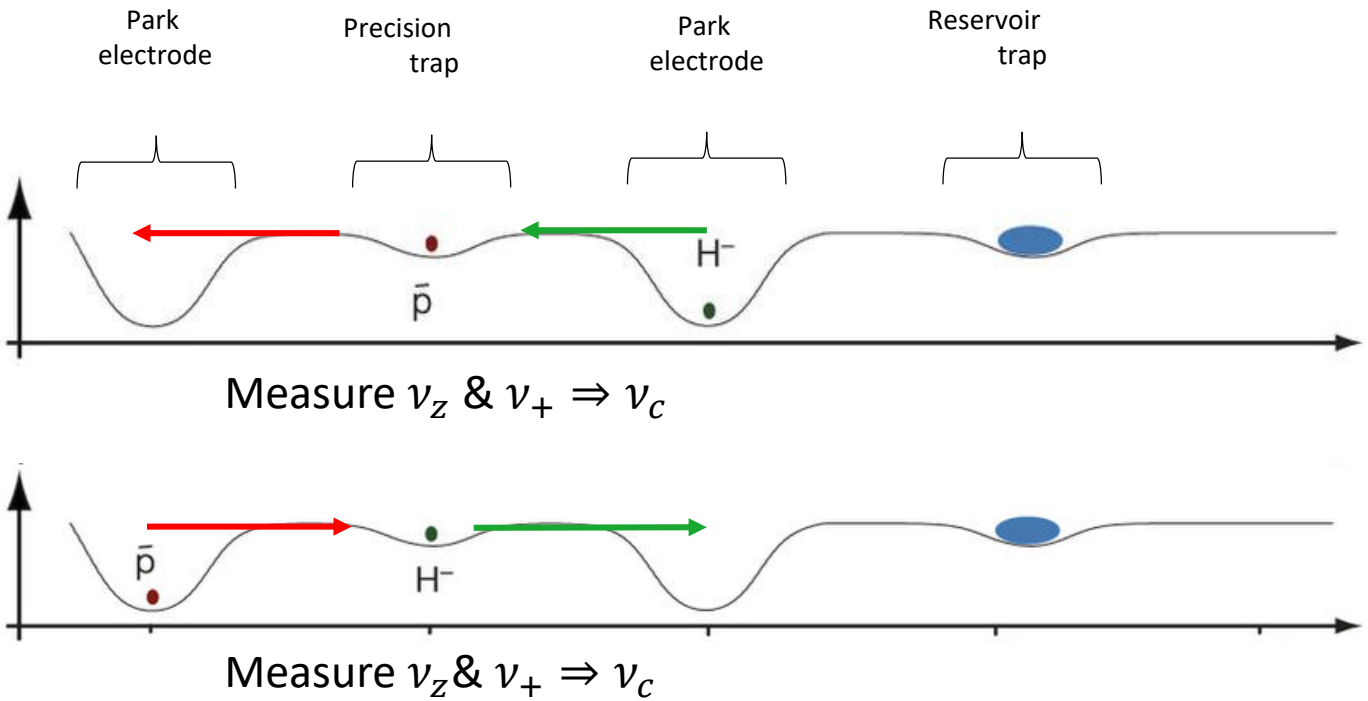
Extract antiprotons and H⁻ ions, compare cyclotron frequencies



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

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

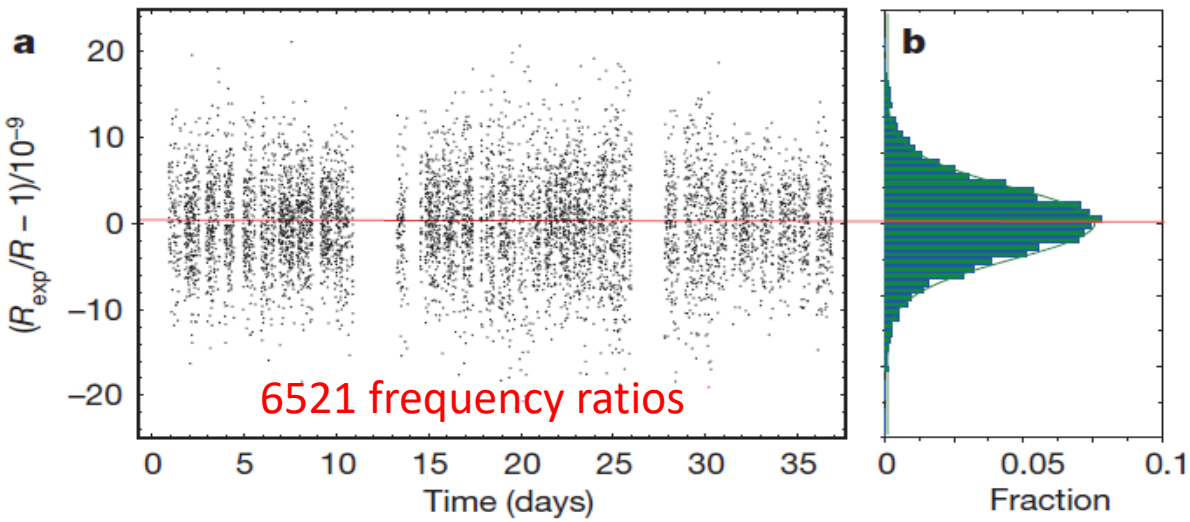
R_{theo} = 1.001 089 218 754 2(2)



Comparison of H-/antiproton cyclotron frequencies:
One frequency ratio per 4 minutes with ~ 6 ppb uncertainty

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

Proton to Antiproton Q/M: Physics

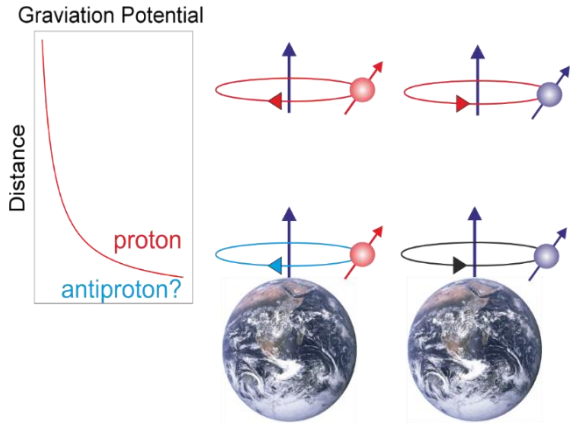


$$\frac{(q/m)_{\bar{p}}}{(q/m)_{p}} + 1 = 1(69) \times 10^{-12}$$

- 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)

- Constrain of the gravitational anomaly for antiprotons:



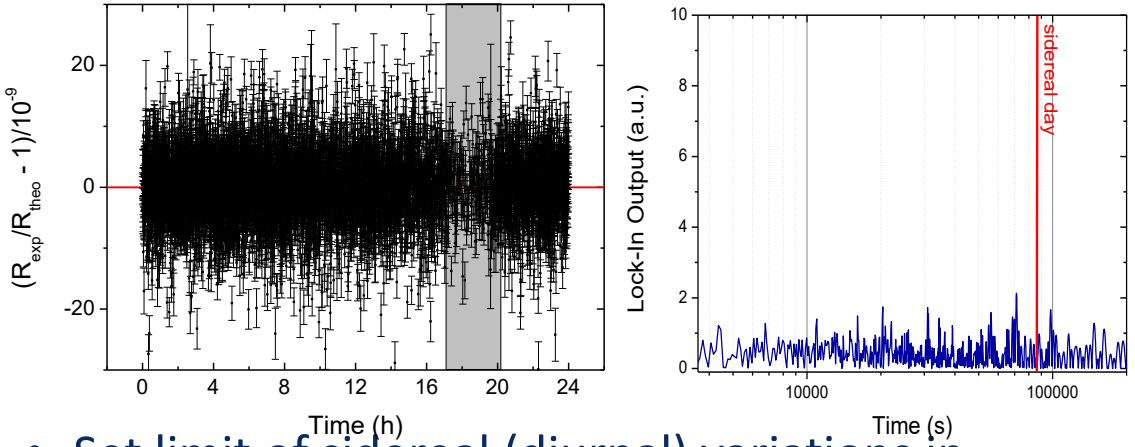
$$\frac{\omega_{c,p} - \omega_{c,\bar{p}}}{\omega_{c,p}} = -3(\alpha_g - 1)\, U/c^2$$

Our 69ppt result sets a new upper limit of

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

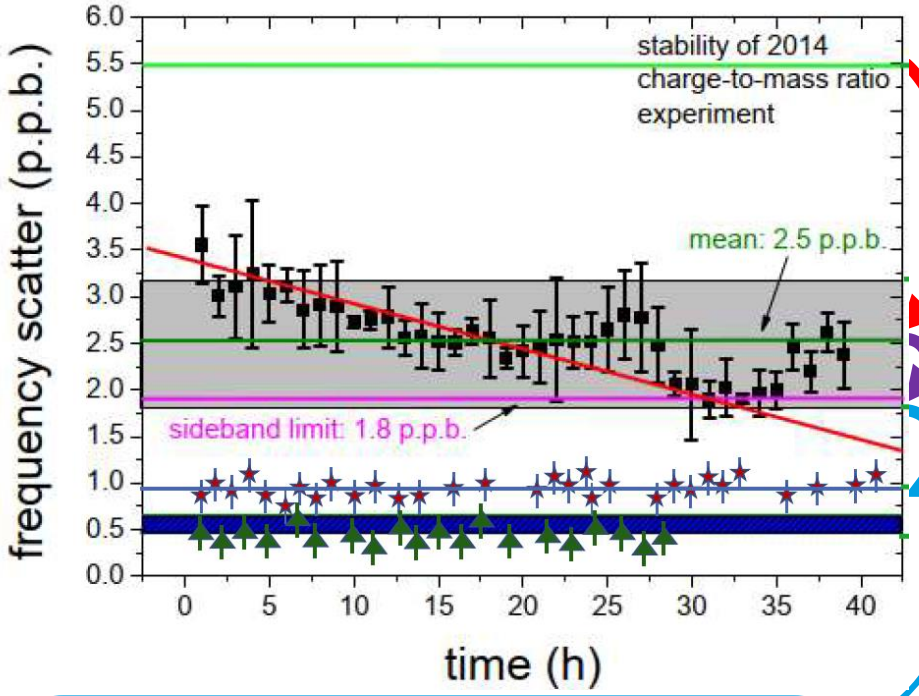
- Conclusion:

Matter and Antimatter clocks run at the same frequency



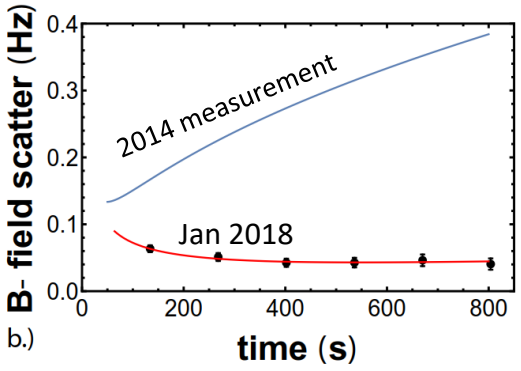
- Set limit of sidereal (diurnal) variations in proton/antiproton charge-to-mass ratios to **< 0.72 ppb/day**

Progress towards a better q/m measurement

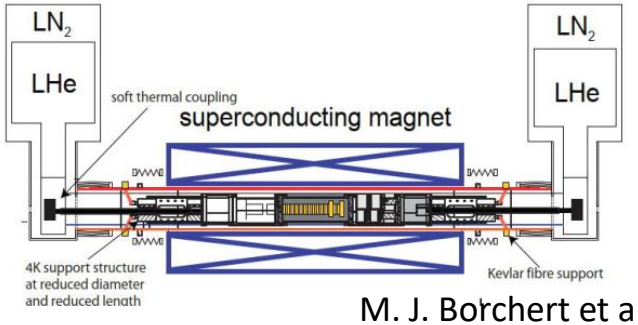


Better stabilisation of cryoliquid pressure, temperature improves magnetic stability

J. A. B.-Harrington et al.

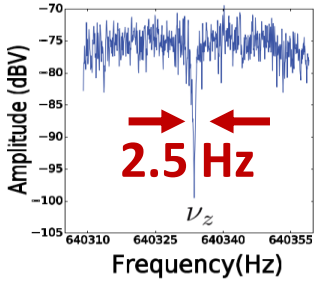


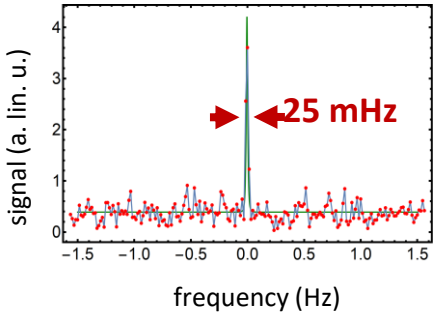
Mechanical upgrade more stable and lower heat load means fewer vibrations



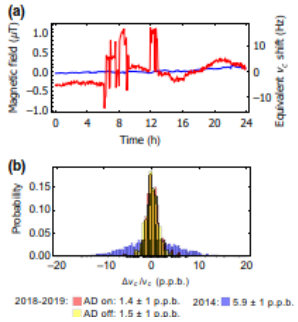
M. J. Borchert et al.

peak measurement technique

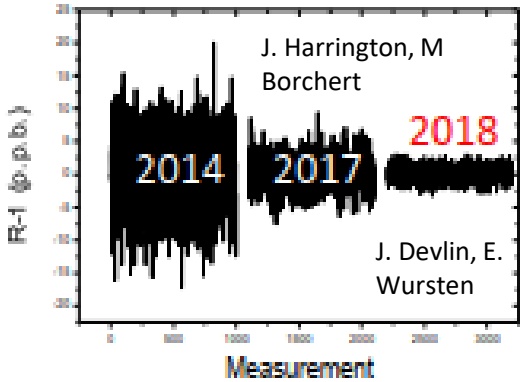




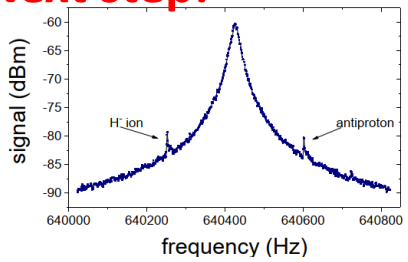
New magnetic shielding system



See poster by Elise Wursten

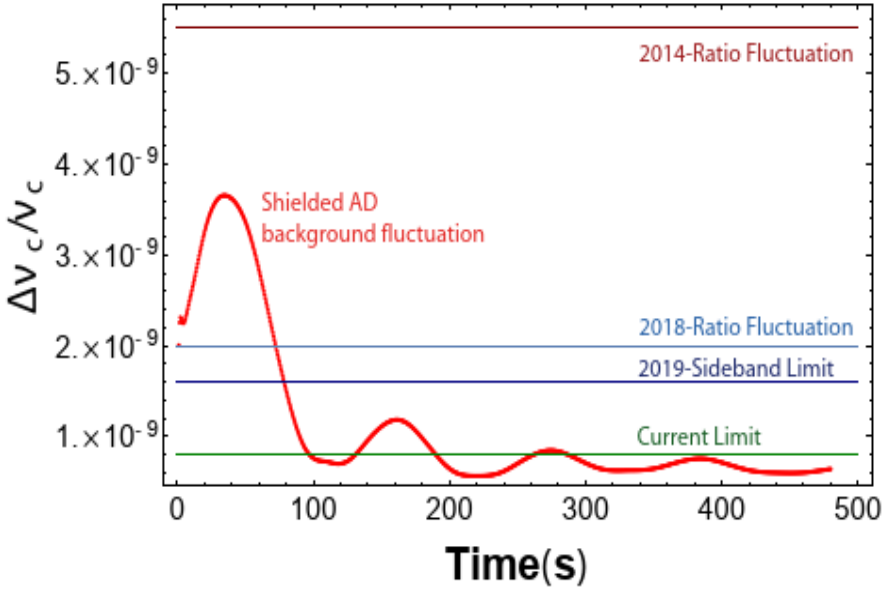


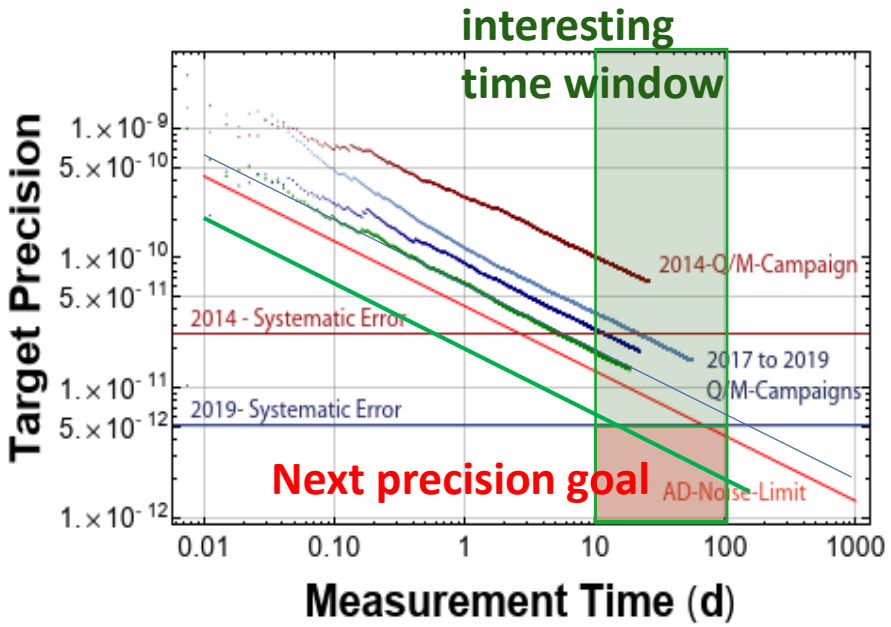
Next step:



Future Perspective

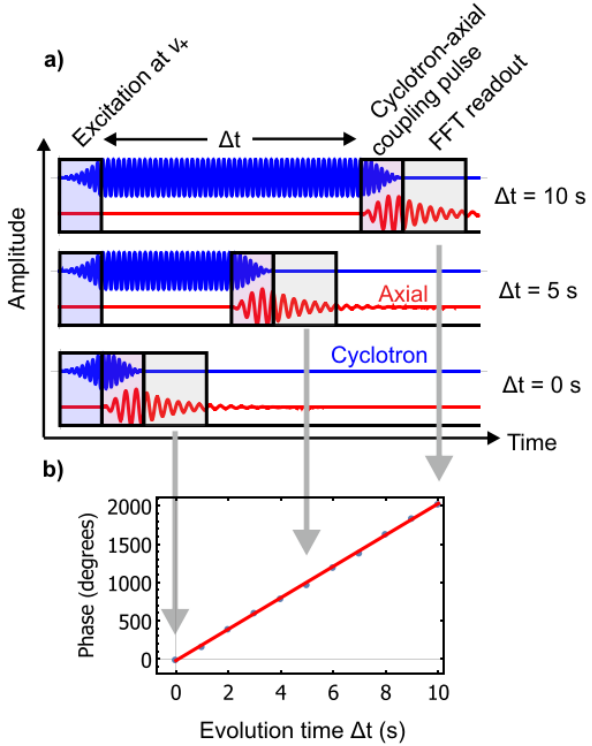
- Reached a ratio uncertainty of order 10 p.p.t. to 20 p.p.t.
- What would be the next step?





Phase measurements indicate

300 p.p.t. scatter (120s cycle)



- In the AD hall with accelerator active we would not be able to significantly improve the ratio
- Started poject to transport antiprotons out of the AD hall (ERC-grant Christian Smorra / BASE-STEP)

The Antiproton Magnetic Moment

A milestone measurement in antimatter physics

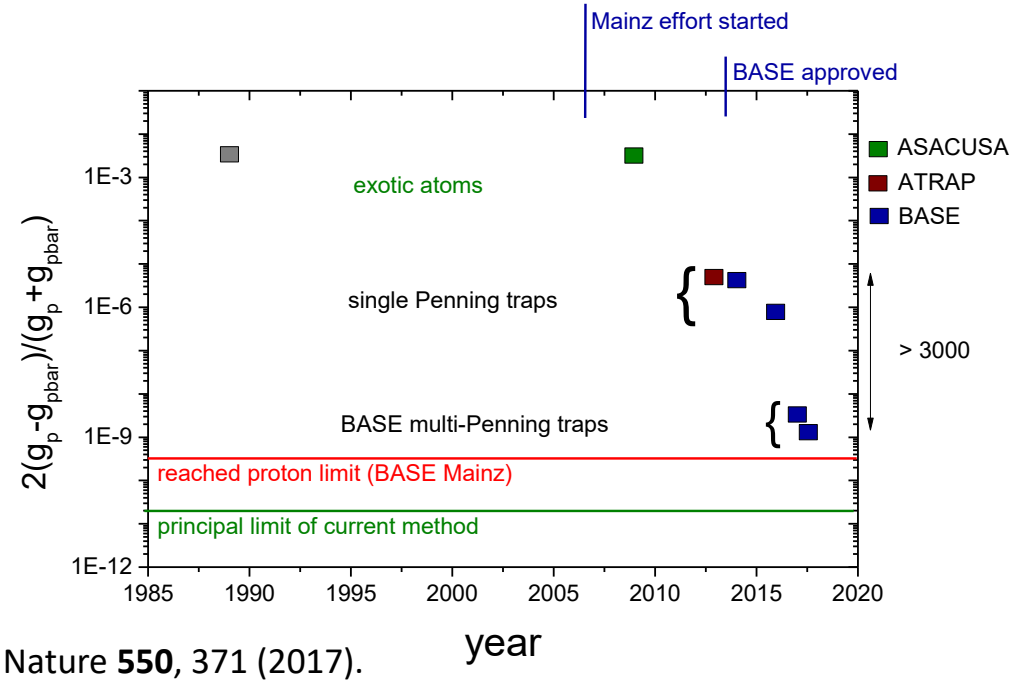
LETTER

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.

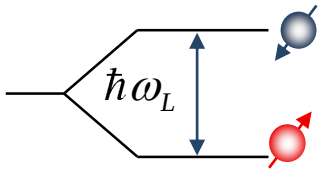
Non-destructive physics

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.

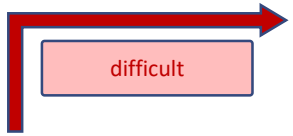
The latest BASE measurement follows the same scheme but targets the magnetic moment of protons and antiprotons instead of electrons and positrons. This opens tests of CPT in a totally different particle system, which could behave entirely differently. In practice, however, the transfer of quantum measurement 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.

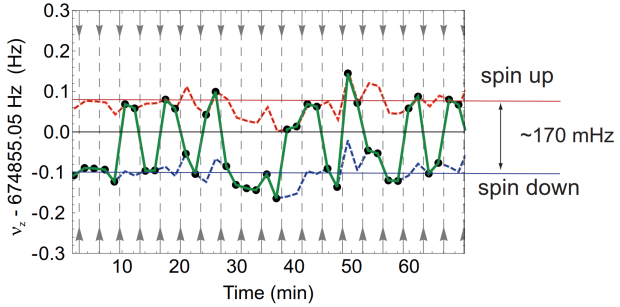
CERN COURIER, 3 / 2018.



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

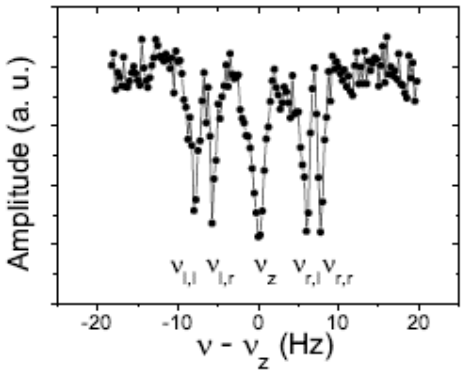


Continuous Stern Gerlach Effect

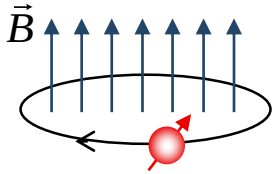


$$\frac{\mu_{\bar{p}}}{\mu_N} = \frac{g_{\bar{p}}}{2}\frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p} = \frac{\nu_L}{\nu_c}$$

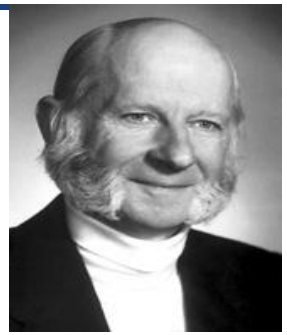
Image Current Measurements



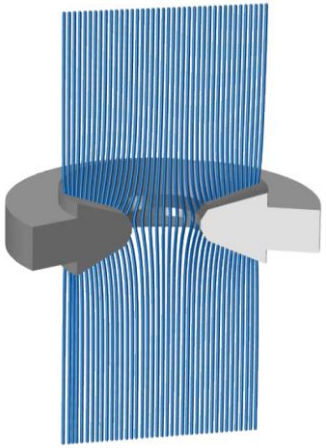
S. Ulmer *et al.*, PRL 107, 103002 (2011)



Larmor Frequency – extremely hard



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

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

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

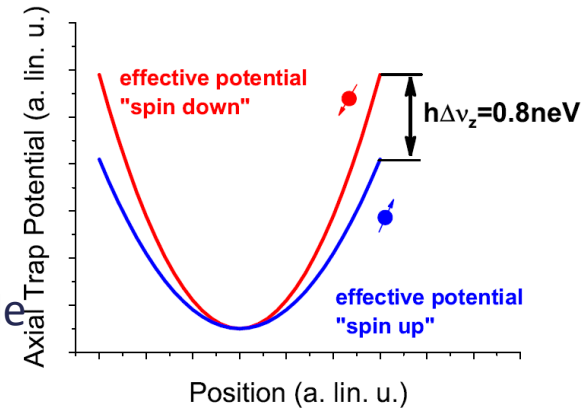
$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := \alpha_p \frac{B_2}{\nu_z}$$

- Very difficult for the proton/antiproton system.

$$B_2 \sim 300000\ T/m^2$$

- Most extreme magnetic conditions ever applied to single particle.

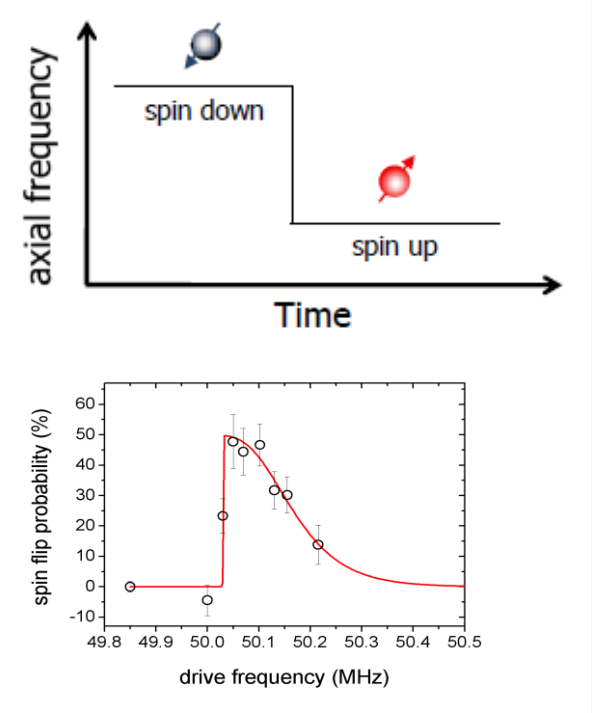
$$\Delta\nu_z \sim 170\ mHz$$



Single Penning trap method is limited to the p.p.m. level

Frequency Measurement

Spin is detected and analyzed via an axial frequency measurement



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

Antiproton g-factor results – single trap

Performed 6 Larmor resonance and 12 cyclotron resonance scans

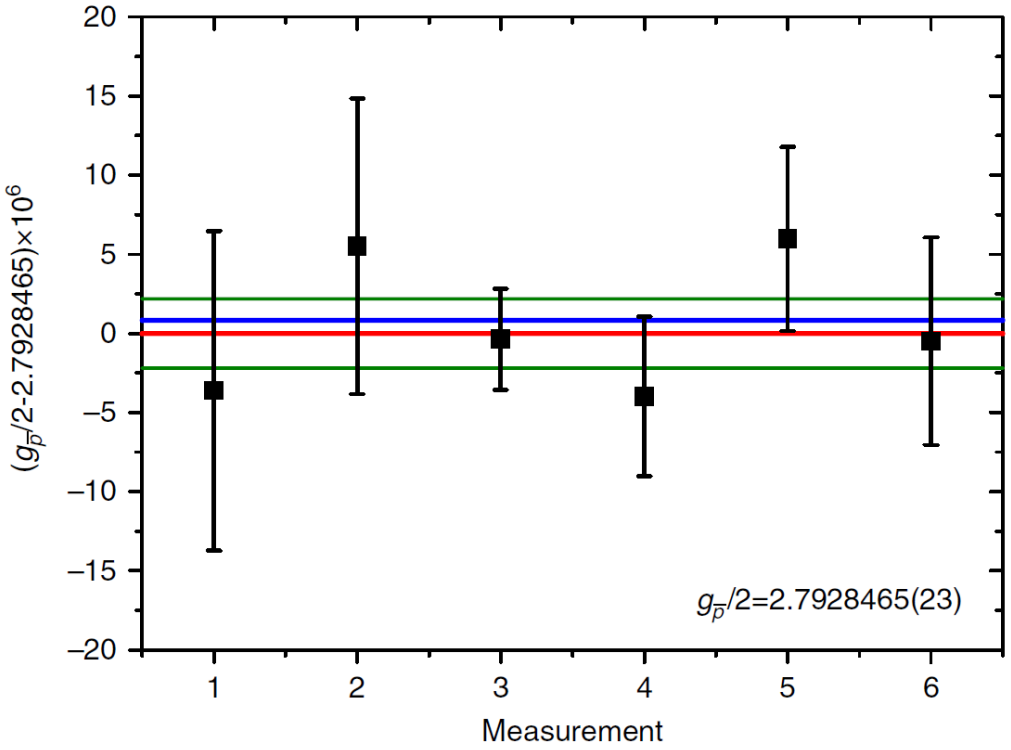


Table 1 | List of all SME-coefficients constrained by this measurement.

Coefficient	Constraint
$\lvert\tilde{b}^{Z}_{\mathrm{p}}\rvert$	$<2.1\times10^{-22}$ GeV
$\lvert\tilde{b}^{*Z}_{\mathrm{p}}\rvert$	$<2.6\times10^{-22}$ GeV
$\lvert\tilde{b}^{XX}_{\mathrm{F,p}}+\tilde{b}^{YY}_{\mathrm{F,p}}\rvert$	$<1.2\times10^{-6}$ GeV^{-1}
$\lvert\tilde{b}^{ZZ}_{\mathrm{F,p}}\rvert$	$<8.8\times10^{-7}$ GeV^{-1}
$\lvert\tilde{b}^{*XX}_{\mathrm{F,p}}+\tilde{b}^{*YY}_{\mathrm{F,p}}\rvert$	$<8.3\times10^{-7}$ GeV^{-1}
$\lvert\tilde{b}^{*ZZ}_{\mathrm{F,p}}\rvert$	$<3.0\times10^{-6}$ GeV^{-1}

Based on Ding, Y. & Kostelecký, V. A. *Lorentz-violating spinor electrodynamics and Penning traps*. *Phys. Rev. D* **94**, 056008 (2016).

$$g_{\bar{p}}/2 = 2.7928465(23)$$

Six fold improved uncertainty of the antiproton magnetic moment

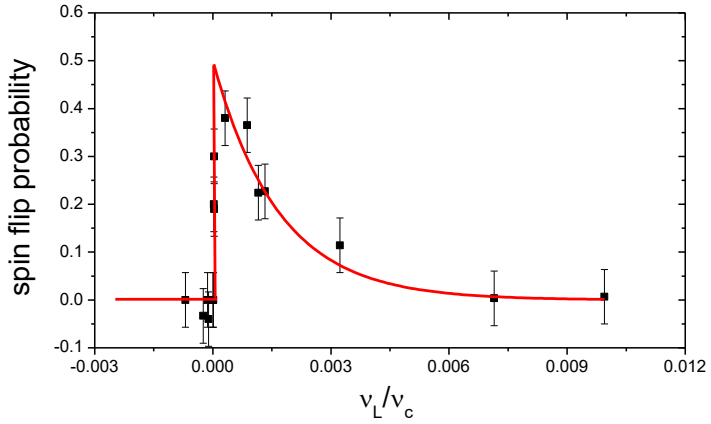
$$\frac{g_{\bar{\mathrm{p}}}}{g_{\mathrm{p}}} - 1 = -0.31(82)\times10^{-7}$$

Respective limits on SME coefficients for CPT violation improved up to a factor 20

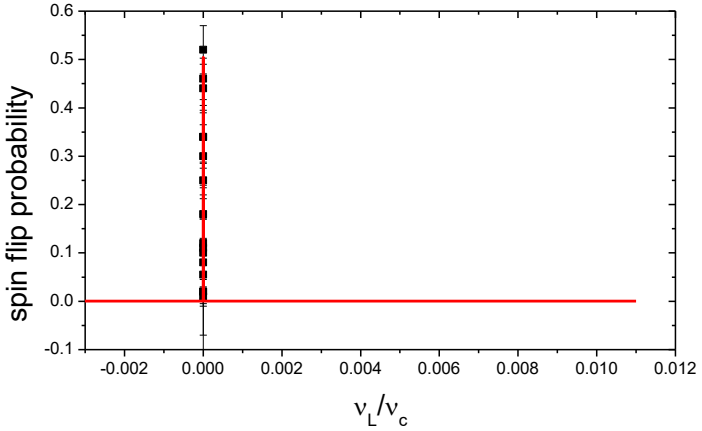
Earlier work: J. DiSciacca et al., PRL **110**, 130801 (2013).

H. Nagahama et al., Nat. Comm. 8, 14084 (2017).

??? How can we do better ???



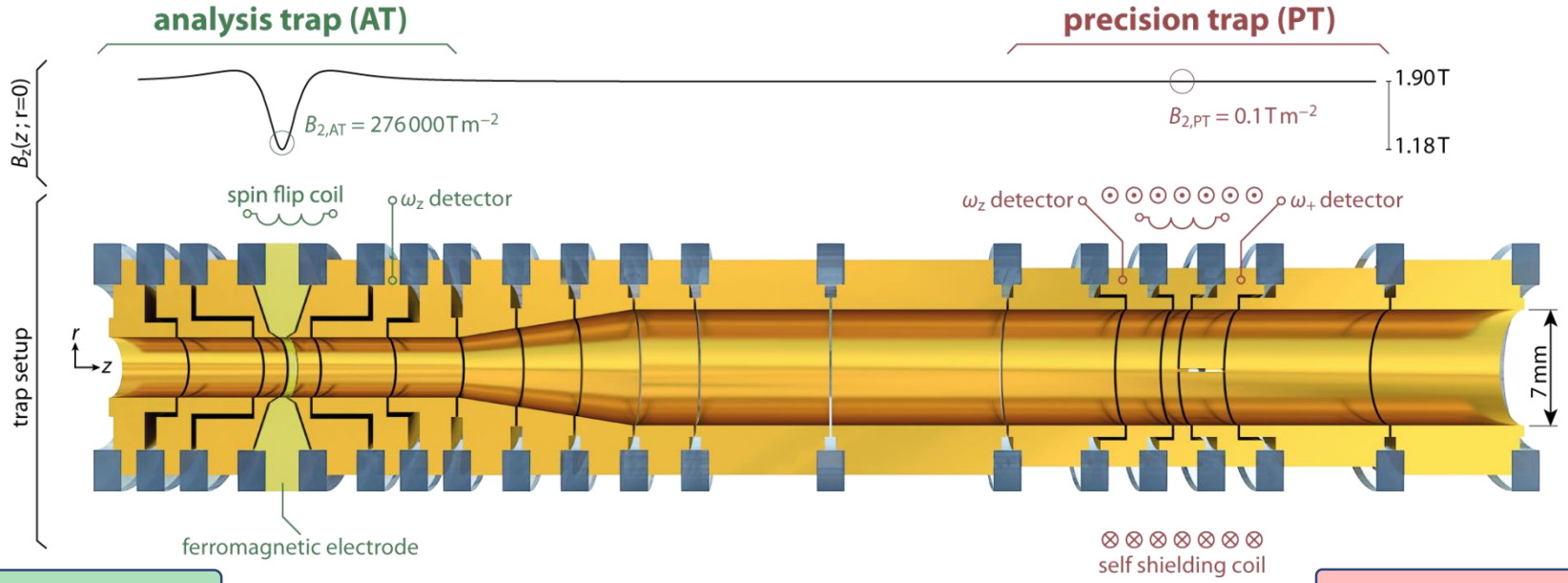
???

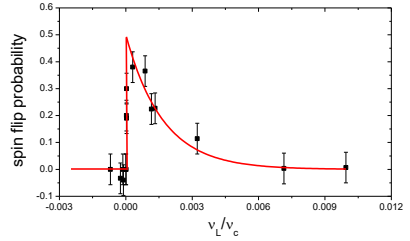


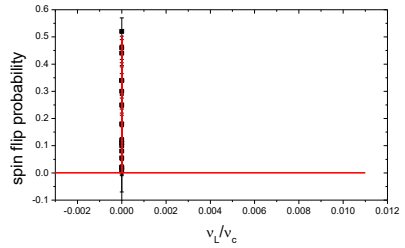
Next Step: The Double Penning-Trap Method

Invented at Univ. of Mainz by H. Haeffner, W. Quint, G. Werth and company

(2000 - 2008)







Initialize the spin state

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

particle transport

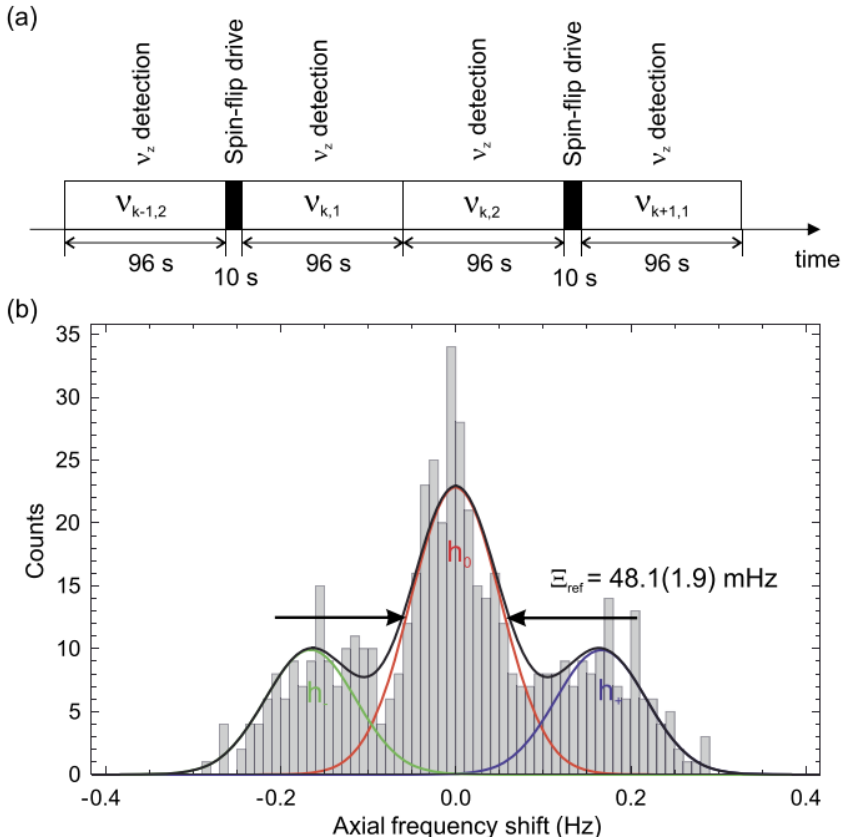
analyze the spin state

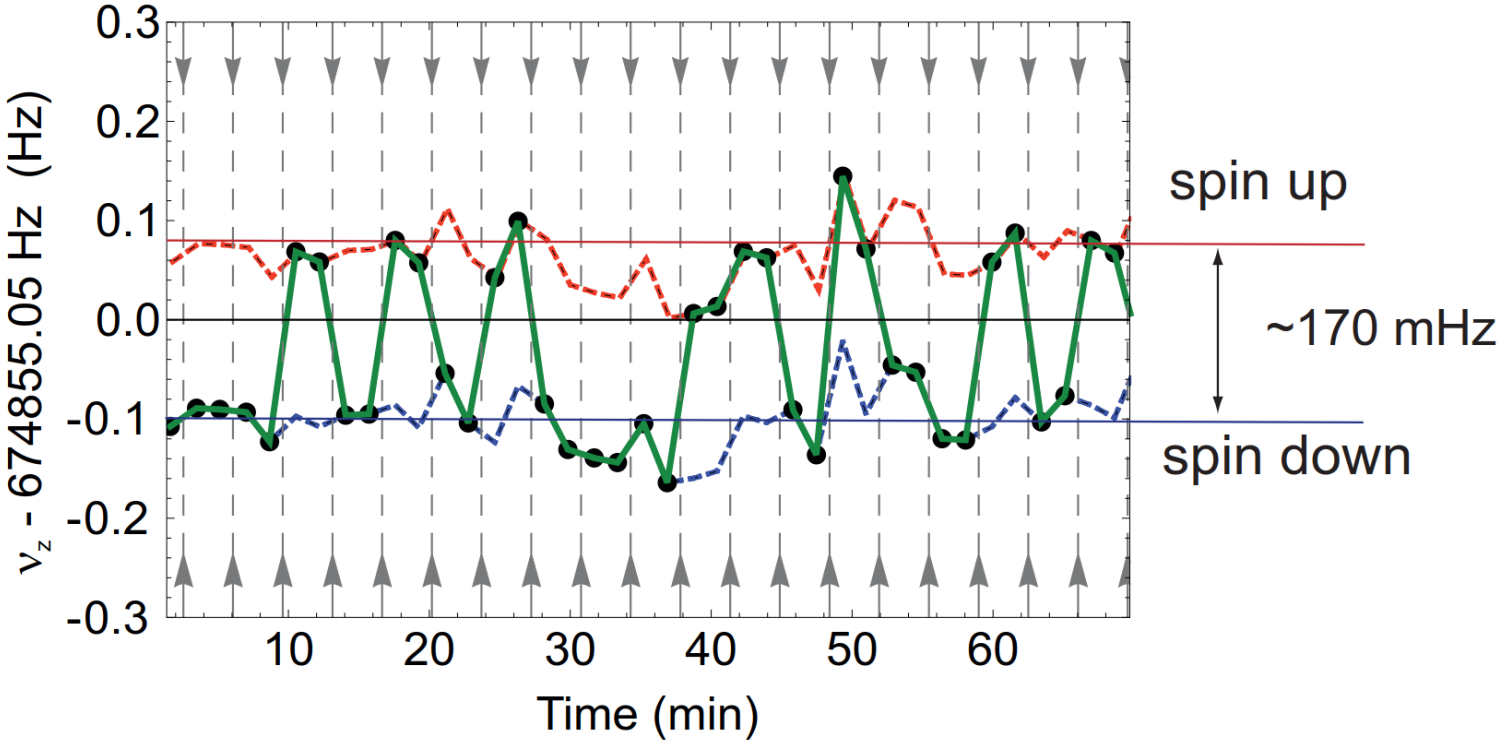
no spin-flip in PT

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





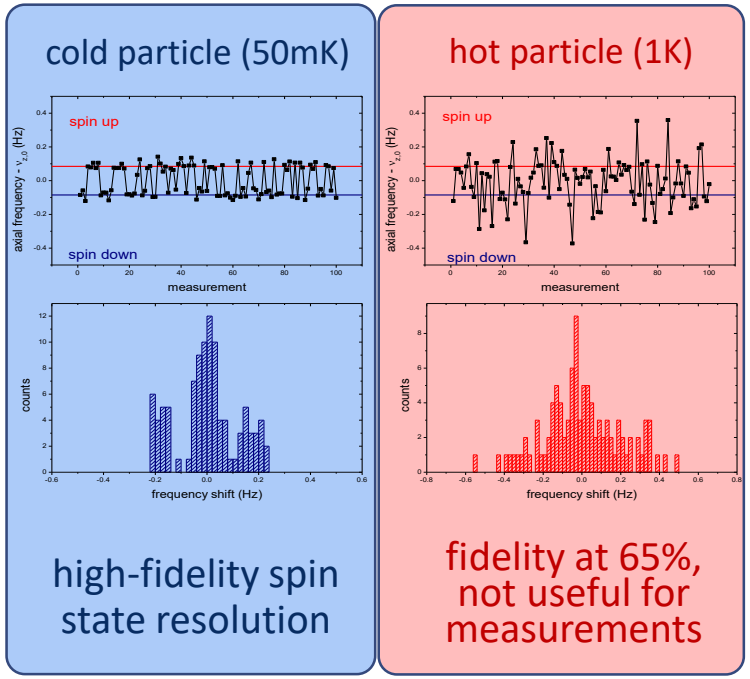
C. Smorra *et al.*, Phys. Lett. B 769, 1 (2017)

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

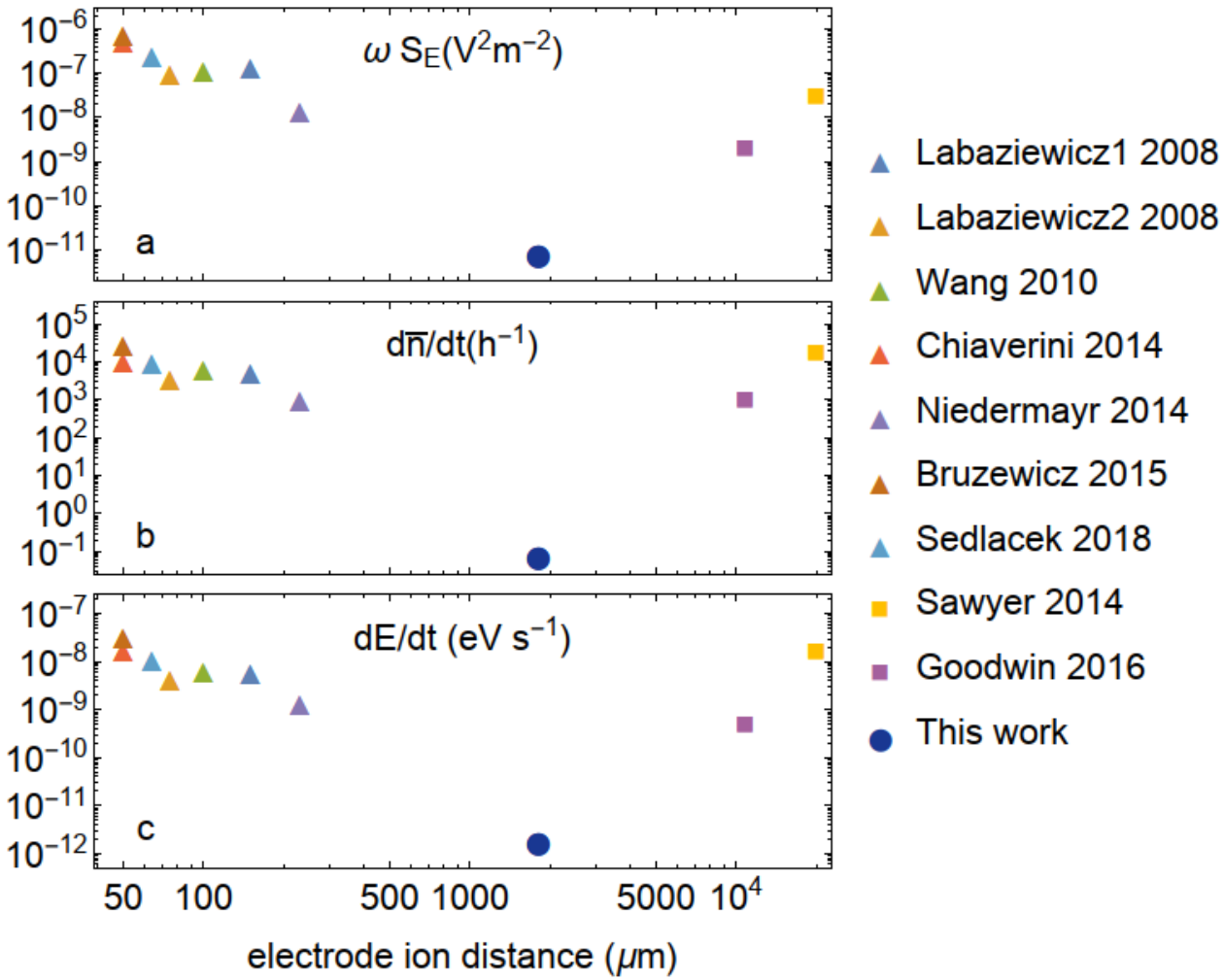
Heating Rates

- Achieve single spin flip resolution only with cold particles.
- Reason: Heating rates scale with particle energy

$$\frac{dn_{+,-}}{dt} \approx \frac{q^2}{2m_{\bar{p}}h\nu_{+,-}} n_{+,-} \Lambda^2 \langle e_n(t), e_n(t-\tau) \rangle$$



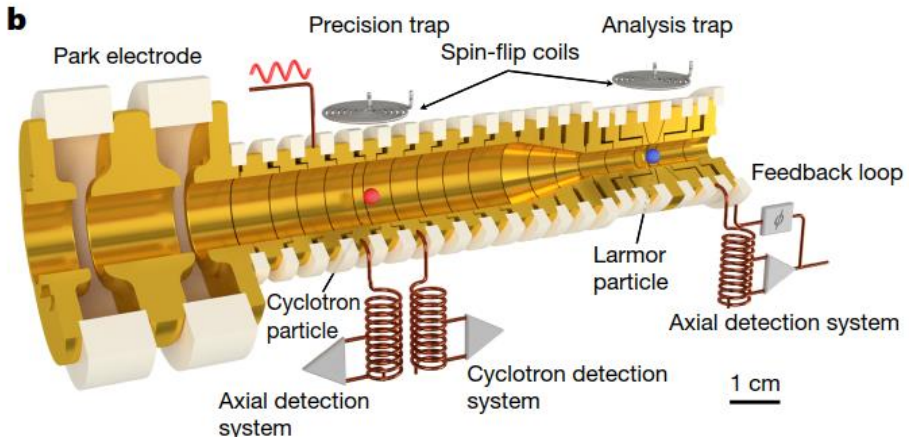
takes hours per preparation cycle

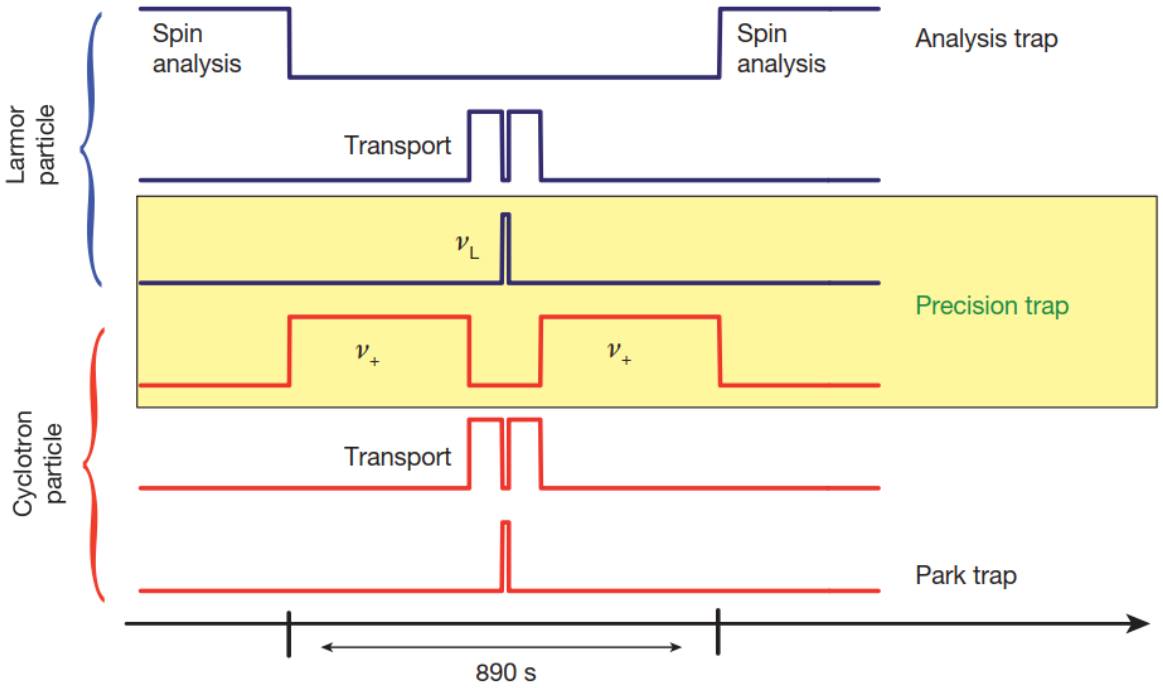


M. J. Borchert, Phys. Rev. Lett. **122**, 043001 (2019)

Invented: BASE Two-Particle Method

Idea: divide measurement to two particles





«hot» cyclotron particle which probes the magnetic field in the precision trap

«cold» cyclotron particle to flip and analyze the spin-eigenstate

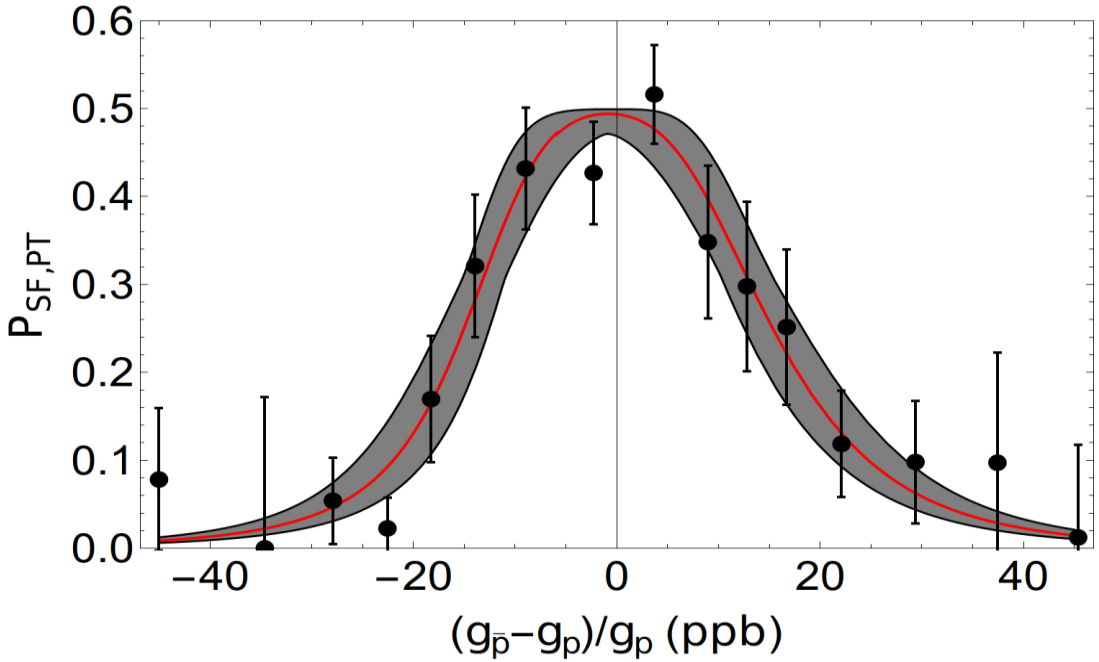
pay: measure with two particles at different mode energies

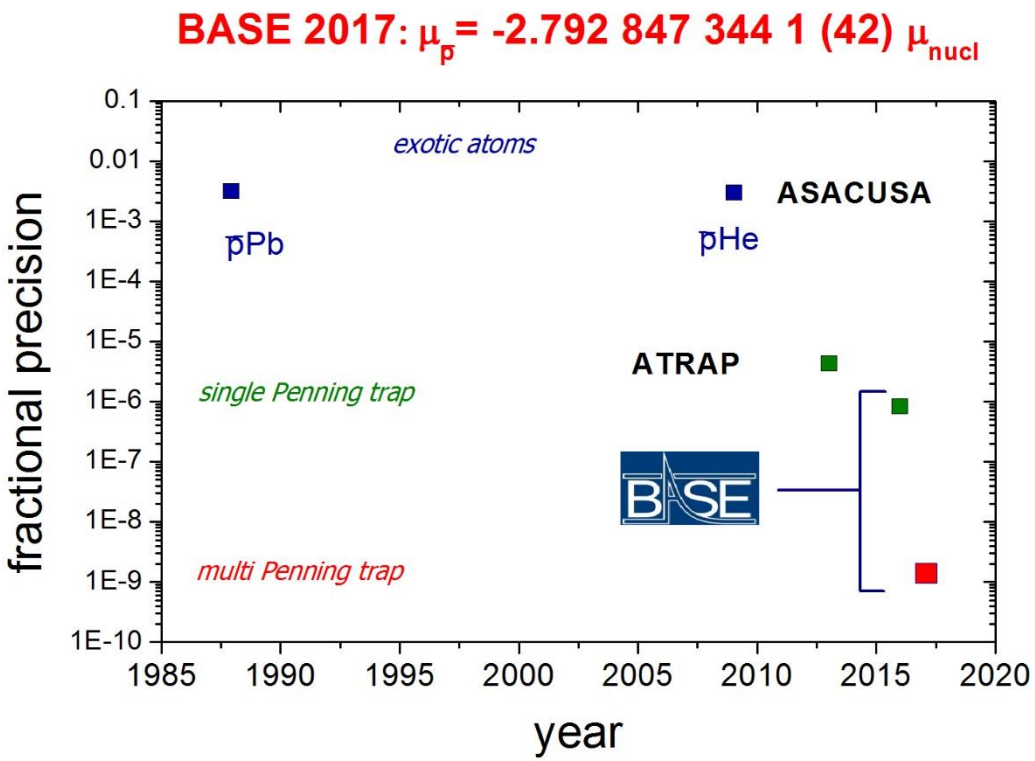
win: 60% of time usually used for sub-thermal cooling useable for measurements

challenges:

- transport without heating
- more challenging systematics

The Magnetic Moment of the Antiproton





time-base analysis of these data in progress (Smorra, Stadnik, Budker)

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

$$\frac{g_p}{2} = 2.792\,847\,350\,(9)$$

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

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

first measurement ever which was more precise for antimatter than for matter conjugate...

...so how about the proton magnetic moment?

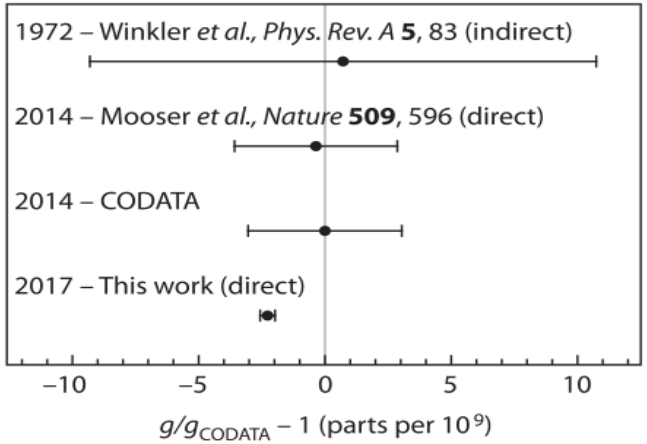
The Magnetic Moment of the Proton

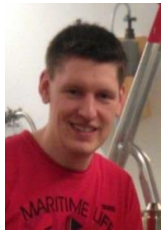
RESEARCH

NUCLEAR PHYSICS

Double-trap measurement of the proton magnetic moment at 0.3 parts per billion precision

Georg Schneider,[1,2]* Andreas Mooser,[2] Matthew Bohman,[2,3] Natalie Schön,[1] James Harrington,[3] Takashi Higuchi,[2,4] Hiroki Nagahama,[2] Stefan Sellner,[2] Christian Smorra,[2] Klaus Blaum,[3] Yasuyuki Matsuda,[4] Wolfgang Quint,[5] Jochen Walz,[1,6] Stefan Ulmer[2]





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

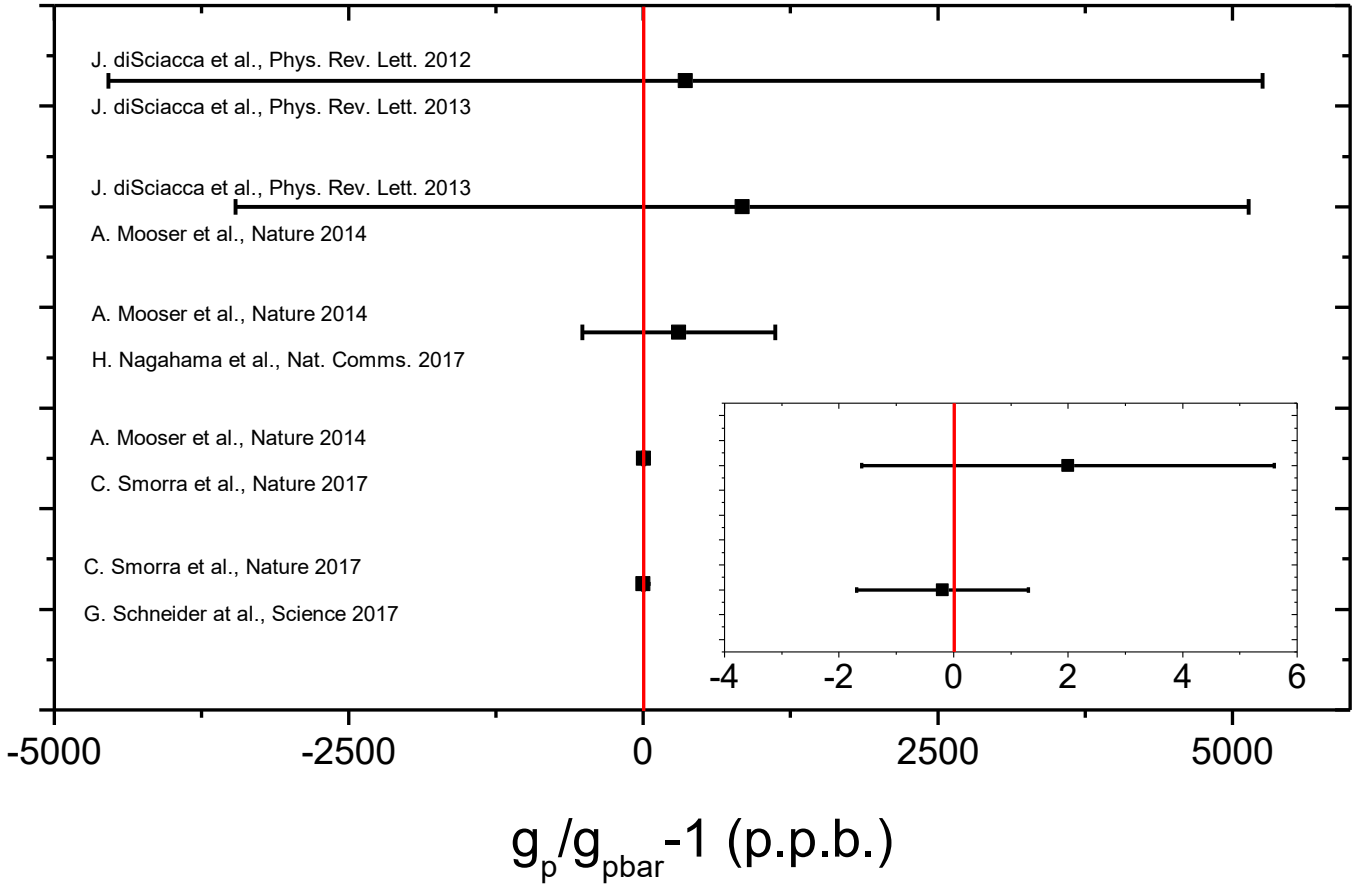
G. Schneider *et al.*, Science **358**, 1081 (2017)

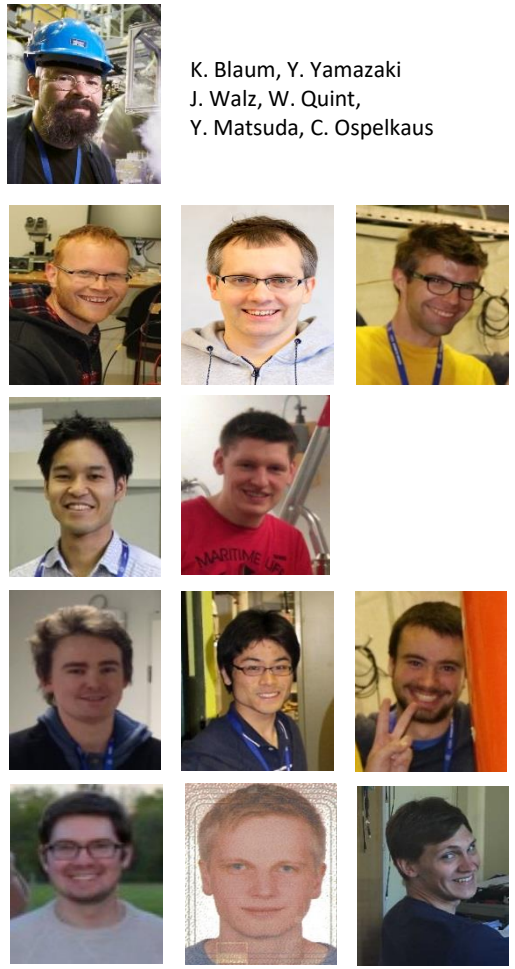
- Plugging all the methods together (in AD)
  - New magnetic shielding system
  - Phase methods
  - Local magnet shims
  - new type of trap (cooling trap)

Reach 0.8 ppb frequency scatter (AD limited)

BASE is prepared for antiproton/proton magnetic moment measurements at the level of 100 p.p.t. fractional uncertainty

Year	Proton $g_p/2$	Antiproton $g_{pbar}/2$	CPT $\lvert g_p/g_{\bar{p}} \rvert - 1$	Collaboration
2011	2.792 847 353 (28)	2.786 2 (83)	0.002 4 (29)	Pask (ASACUSA)
2013	2.792 846 (7)	2.792 845 (12)	0.000 000 4 (49)	diSciacca (ATRAP)
2014	**2.792 847 349 8 (93)**	2.792 845 (12)	0.000 000 8 (43)	Mooser(BASE)/diSciacca (ATRAP)
2016	**2.792 847 349 8 (93)**	**2.792 846 5 (23)**	**0.000 000 30 (82)**	**Mooser/Nagahama (BASE)**
2017/1	**2.792 847 349 8 (93)**	**2.792 847 344 1 (42)**	**0.000 000 002 0 (36)**	**Mooser/Smorra (BASE)**
2017/2	**2.792 847 344 62 (82)**	**2.792 847 344 1 (42)**	**-0.000 000 000 2 (15)**	**Schneider/Smorra (BASE)**



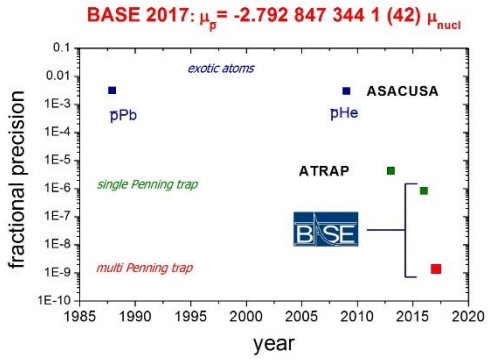


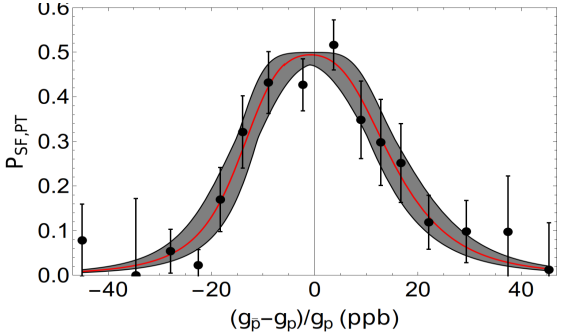
K. Blaum, Y. Yamazaki
J. Walz, W. Quint,
Y. Matsuda, C. Ospelkaus

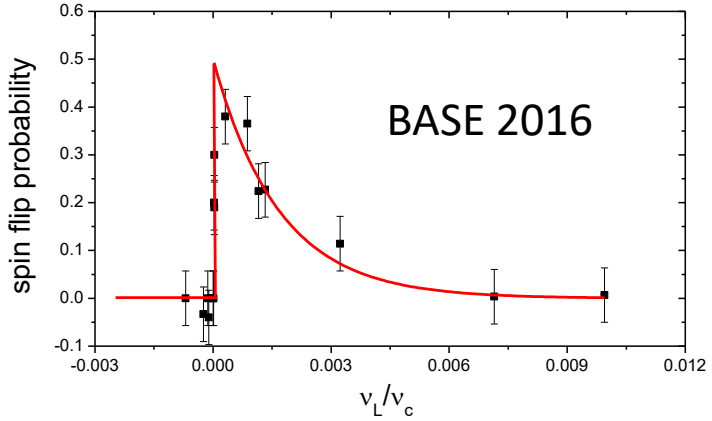
$$\frac{g_p}{g_{\bar{p}}} - 1 = -0.000\,000\,000\,2\,(15)$$

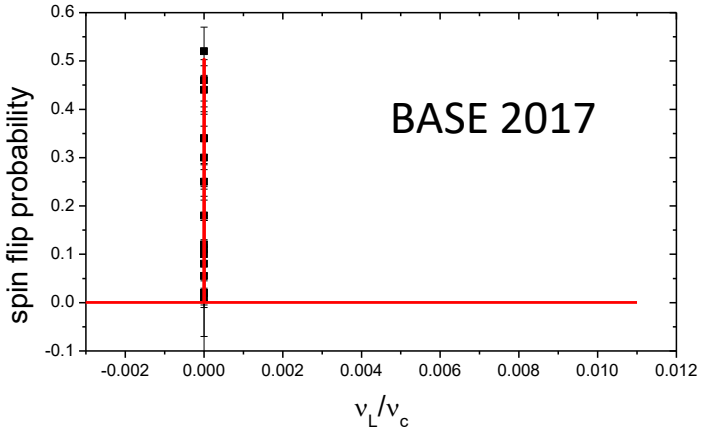
Summary and Outlook

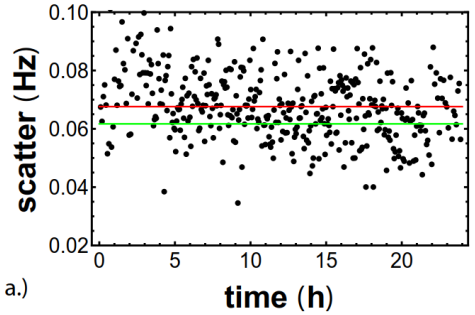
- Performed a 69 p.p.t. - test of CPT invariance with baryons by comparing proton/antiproton charge-to-mass ratios
- Performed the most precise measurement of the proton magnetic moment with a fractional precision of 0.3 p.p.b.
- Performed the most precise measurement of the antiproton magnetic moment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

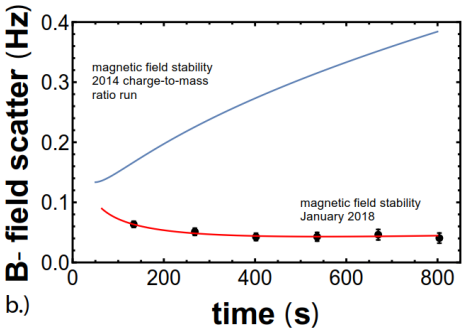






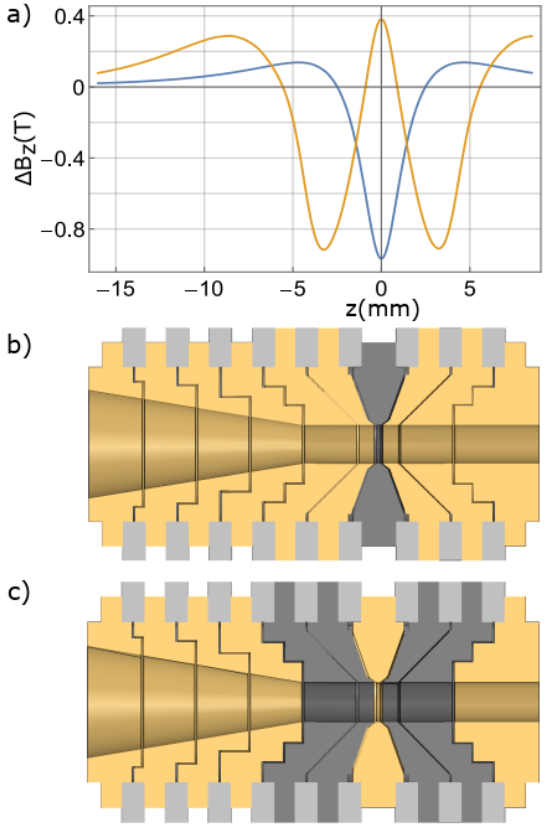






Several open positions available in BASE

- Post Doc and PhD positions to
  - Implement transportable antimatter traps
  - Implement sympathetic cooling of antiprotons
  - Develop advanced magnetic shielding systems
  - Implement new Penning trap architectures



…to investigate matter / antimatter asymmetry with highest precision…

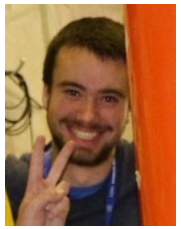
Thanks for your attention!

S. Ulmer
RIKEN

J. Devlin
RIKEN

E. Wursten
CERN / RIKEN

J. Harrington
MPIK/RIKEN



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M. Fleck
RIKEN/U. Tokyo

M. Sato
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C. Smorra
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M. Bohman
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M. Wiesinger
RIKEN/MPIK

P. Blessing
GSI & RIKEN

J. Schaper
Hannover /RIKEN

T. Kielinski
CERN

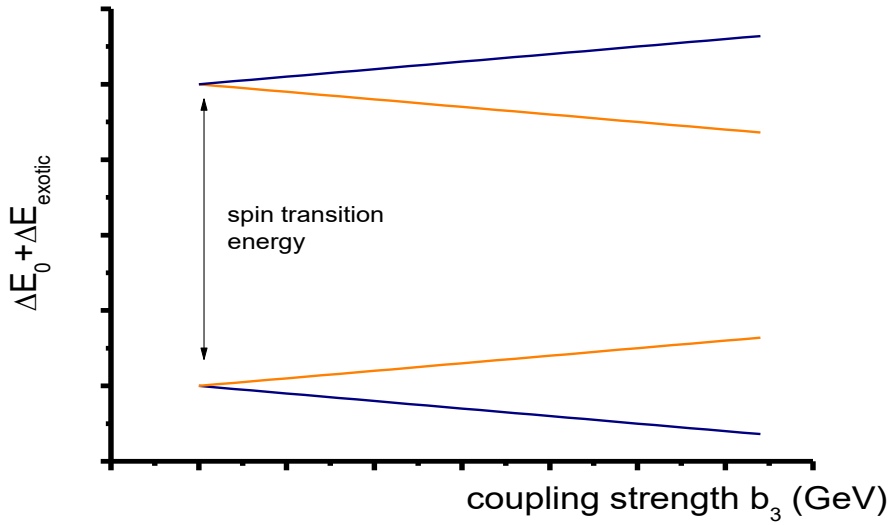
K. Blaum, Y. Matsuda,
C. Ospelkaus, W. Quint,
J. Walz, Y. Yamazaki

Moment CPT Tests

Year	Matter $g/2$	Antimatter $\overline{g}/2$	CPT $\lvert g/\overline{g}\rvert - 1$	System	SME $\lvert b_L\rvert$ (GeV)	$\lvert f_X^0\rvert$ (μ_B)
1987	1.001 159 652 188 9 (43)	1.001 159 652 187 9 (43)	0.000 000 000 000 5 (21)	electron/positron	$6 * 10^{-25}$	$2 * 10^{-12}$
2006	1.001 165 921 5 (11)	1.001 165 920 4 (12)	0.000 000 001 1 (12)	muon (μ^-, μ^+)	$1 * 10^{-23}$	$3 * 10^{-11}$
2017	**2.792 847 344 62 (82)**	**2.792 847 344 1 (42)**	**-0.000 000 000 2 (15)**	**proton/antiproton**	$\mathbf{2 * 10^{-24}}$	$\mathbf{6 * 10^{-12}}$

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

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



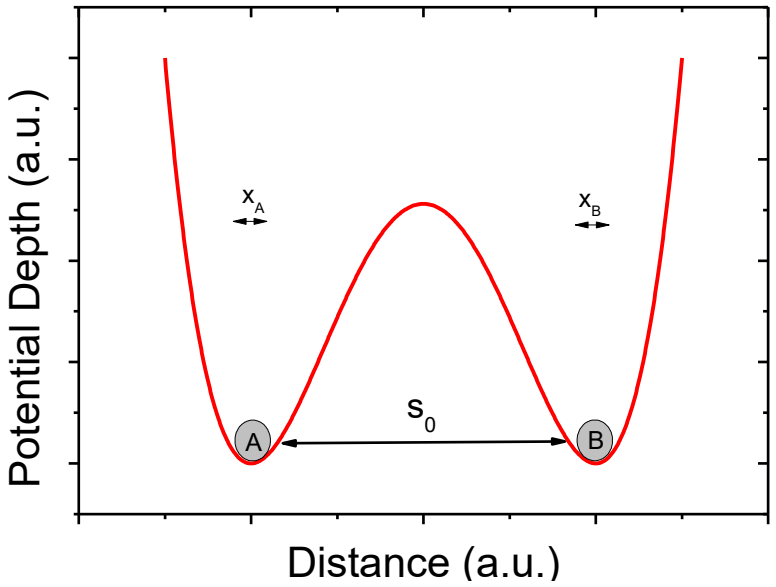
Theoretical framework provided by A. Kostelecky (SME) and Y. Stadnik, V. Flambaum et al.

Sympathetic Cooling of Antiprotons

Goal: Accelerate magnetic moment measurement cycles

Two charged particles trapped in direct vicinity coupled by coulomb interaction.

Of utmost importance for future BASE precision studies



$$U(x_a,x_b) = \frac{1}{4\pi\varepsilon_0}\frac{q_a q_b}{s_0 - x_a + x_b}$$

$$\approx \frac{1}{4\pi\varepsilon_0}\frac{q_a q_b}{s_0}\left(1 + \frac{x_a - x_b}{s_0} + \frac{x_a^2}{s_0^2} + \frac{x_b^2}{s_0^2} - \frac{2x_a x_b}{s_0^2}\right)$$

Static

Dynamic

$$\frac{-q_a q_b}{2\pi\varepsilon_0 s_0^3}(x'_a x'_b) = -\hbar\Omega_{ex}(a+a^\dagger)(b+b^\dagger) \approx -\hbar\Omega_{ex}(ab^\dagger + a^\dagger b) \longrightarrow \Omega_{ex} \equiv \frac{q_a q_b}{4\pi\varepsilon_0 s_0^3\sqrt{m_a m_b}\sqrt{\omega_{0a}\omega_{0b}}}$$

Resonant Coupling:

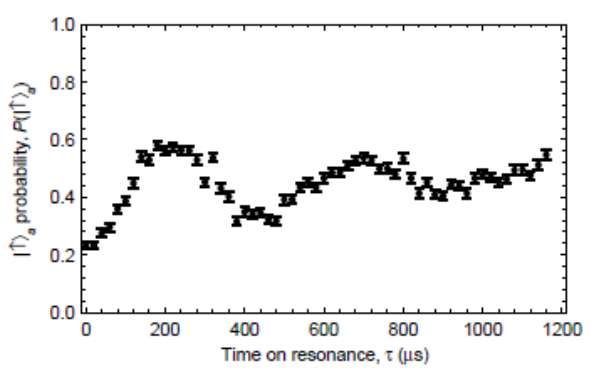
$$a^\dagger(t) = \exp(i\omega_0 t)(a^\dagger(0)\cos(\Omega_{ex}t) - ib^\dagger(0)\sin(\Omega_{ex}t))$$

$$b^\dagger(t) = \exp(i\omega_0 t)(b^\dagger(0)\cos(\Omega_{ex}t) - ia^\dagger(0)\sin(\Omega_{ex}t))$$

Effective Energy Exchange

Effective Energy Exchange

Successfully demonstrated in Paul trap with Be ions



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

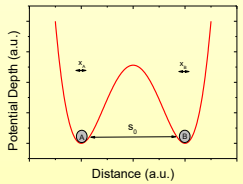
See also: M. Harlander, R. Lechner, M. Brownnutt, R. Blatt, W. Hänsel, Nature **471**, 200 (2011).

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

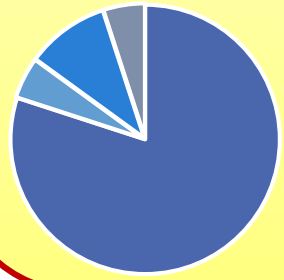
Couple protons/antiprotons sympathetically to laser cooled $^9Be^+$ ions and imprint Doppler temperatures to the antiproton



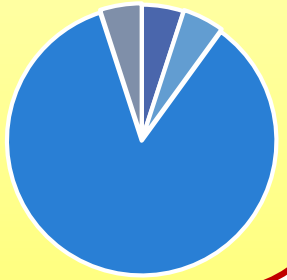
Publication: K. R. Brown, C. Ospelkaus, Y. Colombe, A. C. Wilson, D. Leibfried, D. J. Wineland, Nature **471**, 196 (2011).

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

Current Time Budget

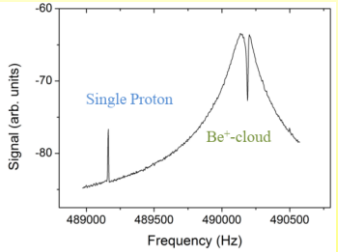


Laser Time Budget



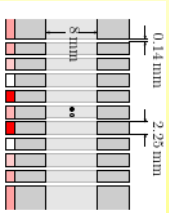
Effort at University of Mainz

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

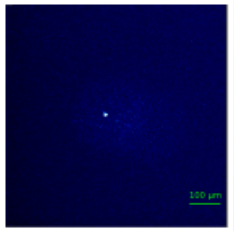


C. Smorra, A. Mooser, M. Bohman, M. Wiesinger et al.

Effort at University of Hannover and PTB

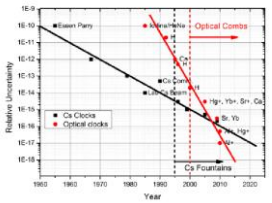


Recent dramatic progress:
Detection of a single laser cooled $^9Be^+$ ion, in a Penning trap system which is fully compatible with the BASE trap system at CERN



J. M. Cornejo, M. Niemann, T. Meiners, J. Mielke **C. Ospelkaus** et al.

The Vision

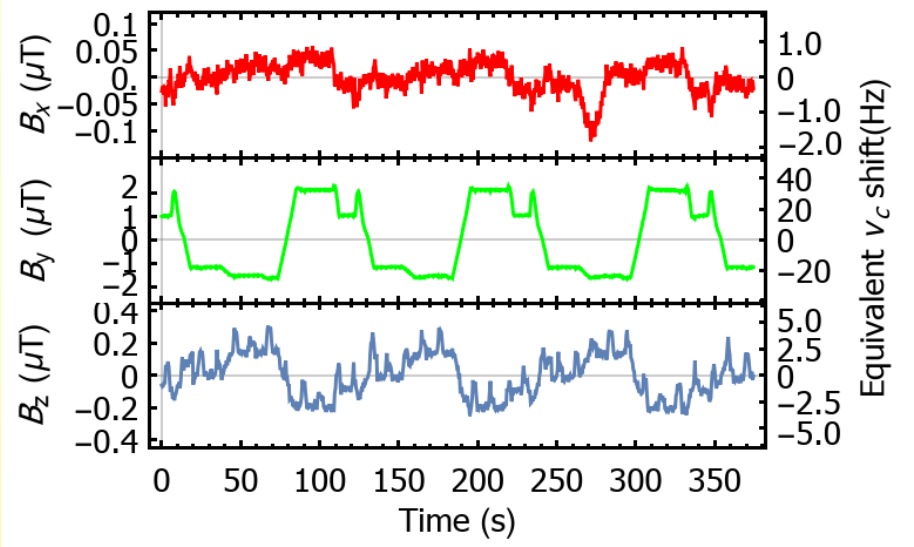


>100-fold improved antiproton cooling time seems to be in reach

Planned Developments – Transportable Antiproton Traps

Why would this make sense?

- BASE demonstrated measurements at a level of 20 parts in a trillion -> 500uHz
- On the other hand:



For measurements at sub-p.p.t. precision particles need to be moved to a dedicated high-precision laboratory.

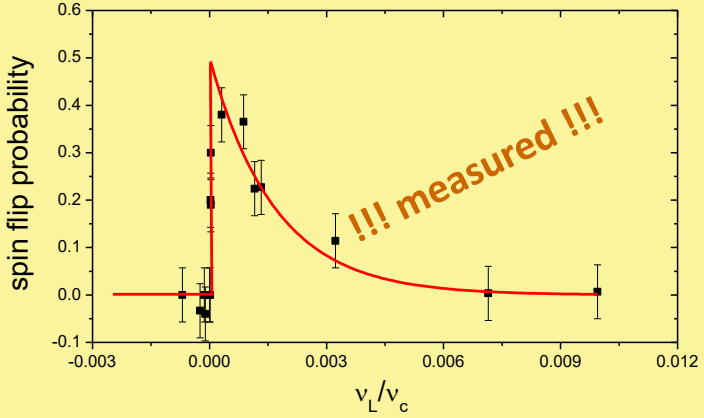
Feasibility:

- Need to be able to…:
  - …catch and cool antiprotons
  - …store antiprotons for quasi-infinite amount of time
  - …extract small amount of antiprotons from a large reservoir
  - …shuttle antiprotons between traps
- Yet to be developed: Transport trap and transfer to another trap experiment

Exciting potential to multiply the antiproton physics program

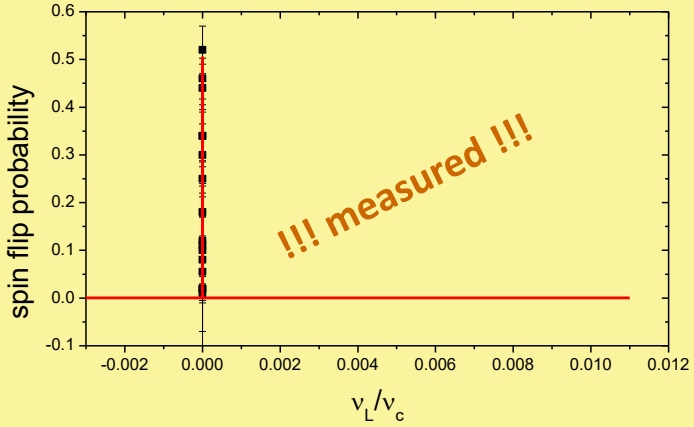
Single Trap – Double Trap – Triple Trap

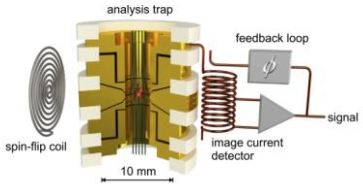
single-trap method

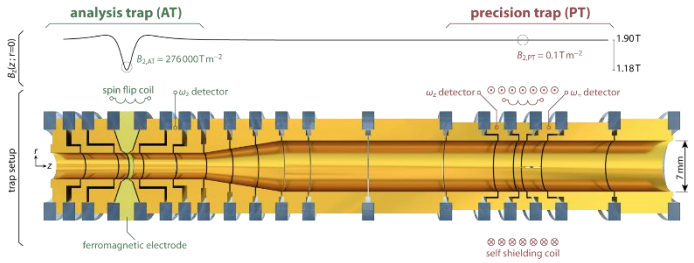


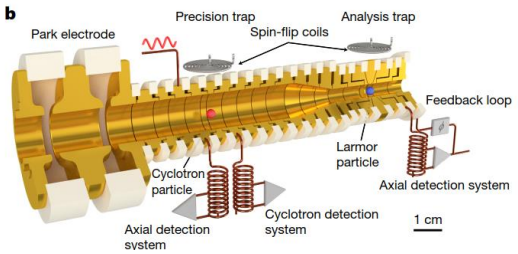
$$\frac{B_{2,AT}}{B_{2,PT}} > 10^6$$

multi-trap method

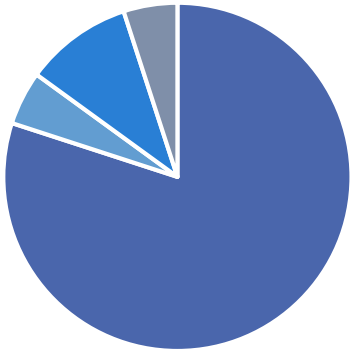




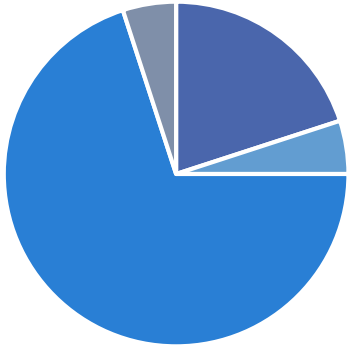




Time Budget Double Trap



Time Budget Two Particle



■ Cooling ■ Maintenance ■ Measurement ■ Shuttling ■ Cooling ■ Maintenance ■ Measurement ■ Shuttling

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.

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

classical trap shifts

shifts induced by 2 particle approach

The Magnetic Moment of the Proton

- Compared to the CERN experiment, the Mainz experiment has:
  - more homogeneous magnetic field
  - magnetic field has higher stability
  - shallower heating rate scaling
  - lower detector temperature

  accelerator hall
- double-trap measurement at (compare 2014)

  A. Mooser *et al.*, Nature **509**, 596 (2014)
  - improved magnetic field homogeneity
  - improved magnetic field stability (SSC)
  - improved cyclotron cooler
  - elimination of main systematic limitations

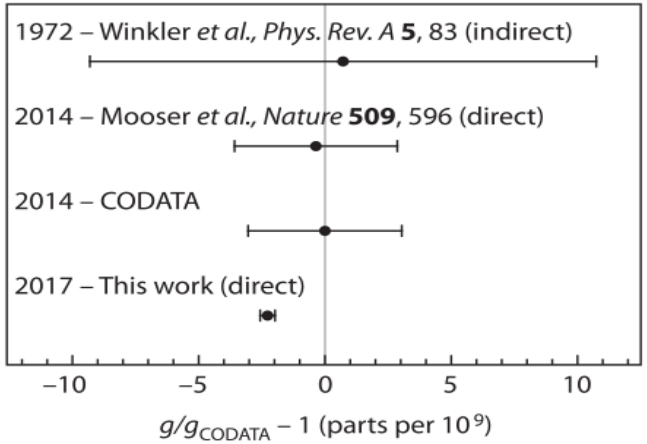
Note: At this level of precision a factor of 11 required 3 years

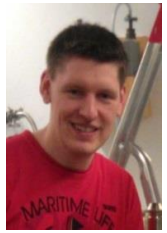
RESEARCH

NUCLEAR PHYSICS

Double-trap measurement of the proton magnetic moment at 0.3 parts per billion precision

Georg Schneider,[1,2*] Andreas Mooser,[2] Matthew Bohman,[2,3] Natalie Schön,[1] James Harrington,[3] Takashi Higuchi,[2,4] Hiroki Nagahama,[2] Stefan Sellner,[2] Christian Smorra,[2] Klaus Blaum,[3] Yasuyuki Matsuda,[4] Wolfgang Quint,[5] Jochen Walz,[1,6] Stefan Ulmer[2]



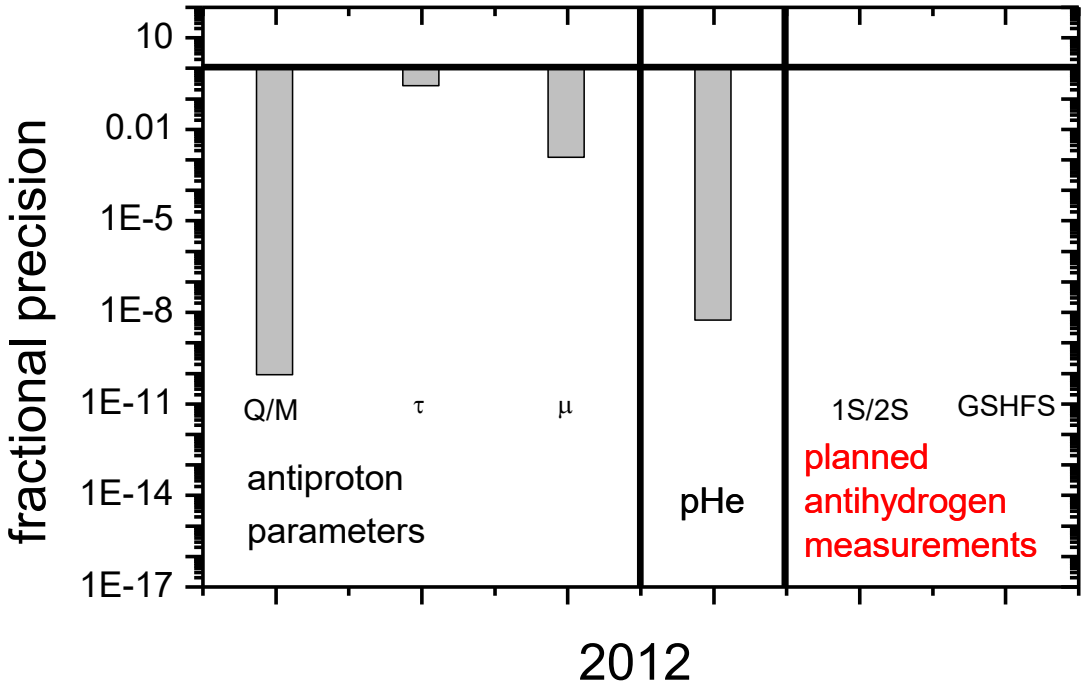


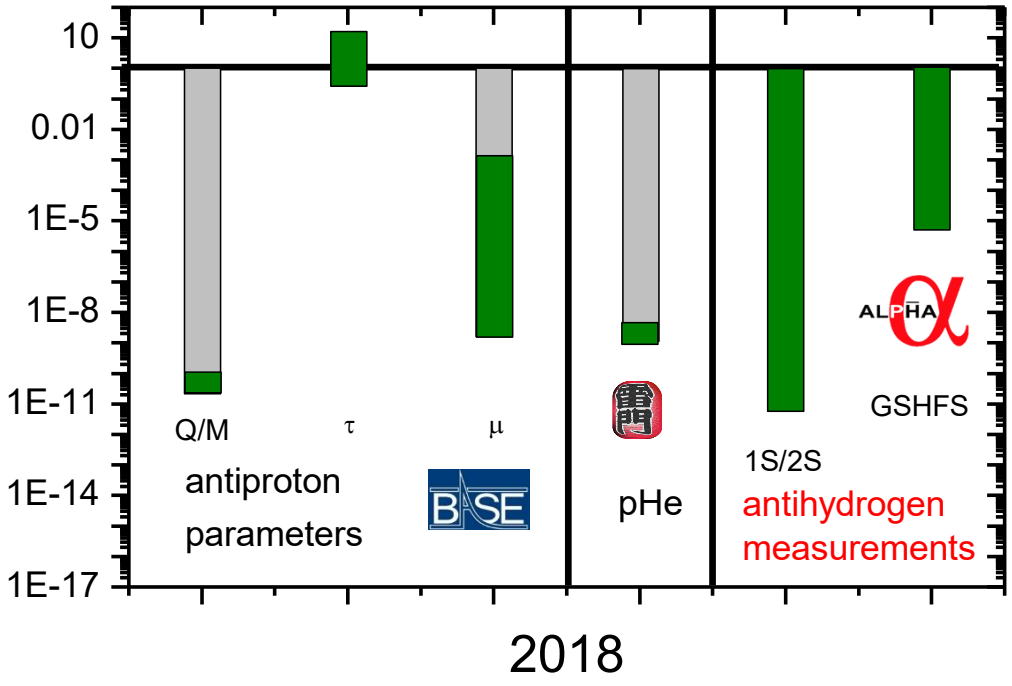
$$\frac{g_p}{2} = 2.792\,847\,344\,62\,(82)$$

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

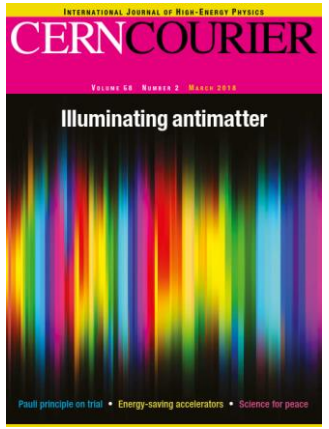
methods developed to improve antiproton moment by at least a factor of 5

Momentum in the AD community since 2013

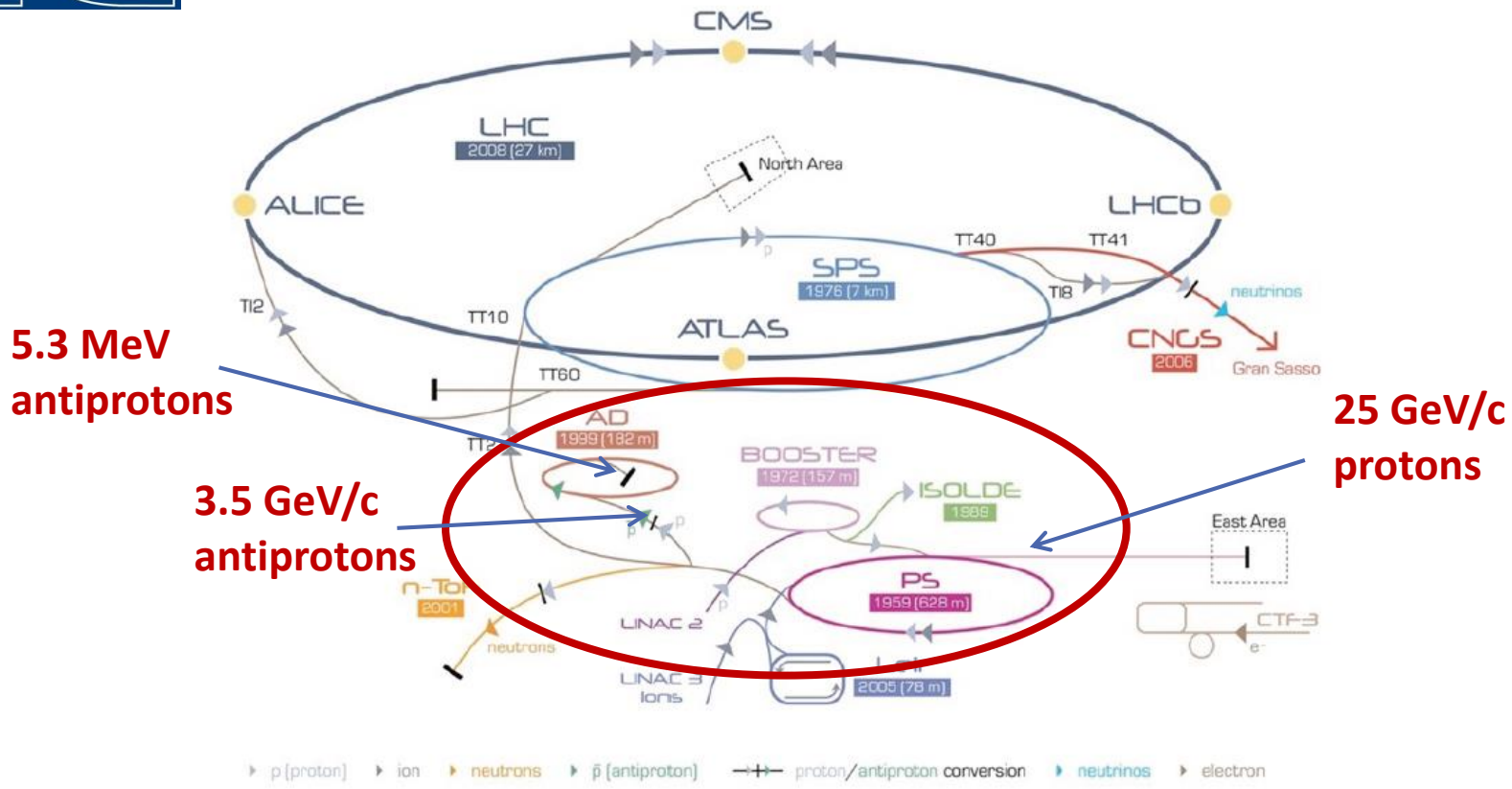




- Summarized in CERN courier, issue 2018/03
- J. Hangst – «Illuminating Antimatter»
- S. Ulmer – «Experiment of the Moment»



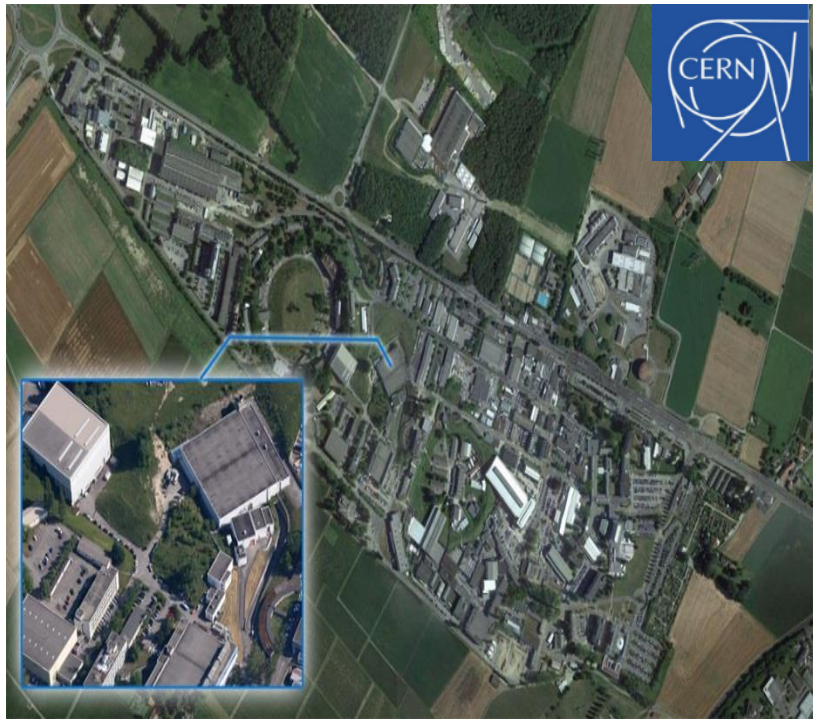
Antiprotons – CERN



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

Limits on Exotic Physics – ONE example

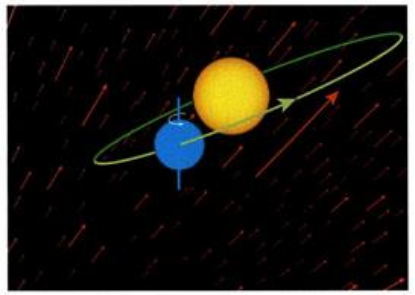
- Test the Standard Model (CPT invariance) by comparing the fundamental properties of protons and antiprotons with high precision

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

Dirac equation CPT-odd modifications

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

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

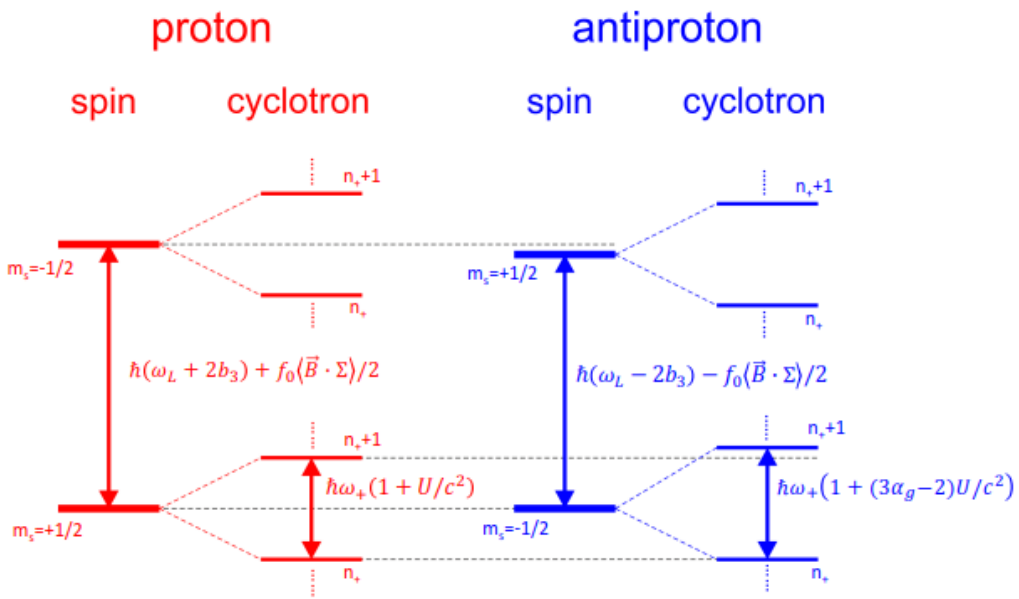


$$b_\mu\gamma_5\gamma^\mu \rightarrow b_x\begin{pmatrix}-\sigma_x & 0\\ 0 & \sigma_x\end{pmatrix} + b_y\begin{pmatrix}-\sigma_y & 0\\ 0 & \sigma_y\end{pmatrix} + b_z\begin{pmatrix}-\sigma_z & 0\\ 0 & \sigma_z\end{pmatrix}$$

Pseudo-magnetic field, with different coupling to matter and antimatter, respectively

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

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

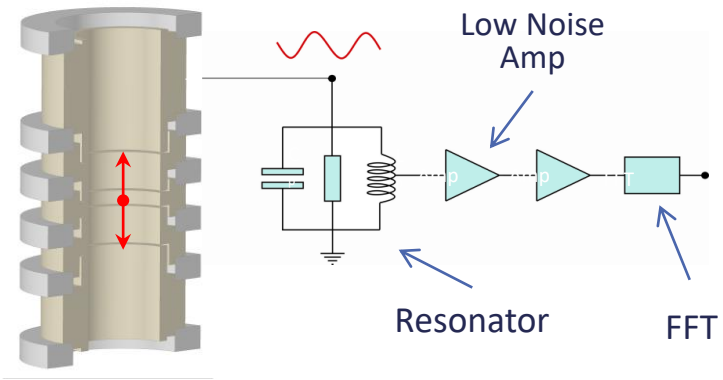


Would correspond to the discovery of a boson field which exclusively couples to antimatter.

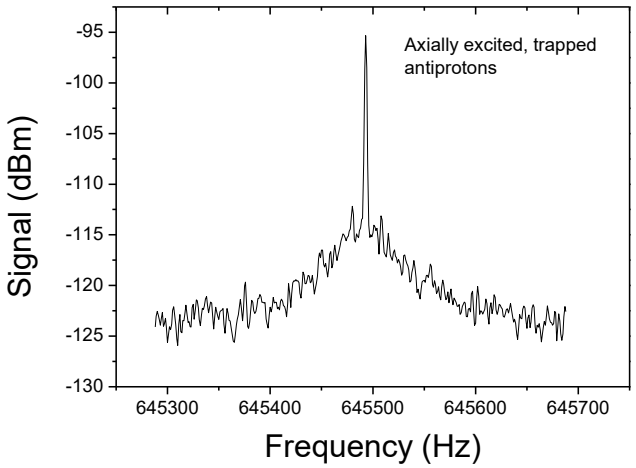
sensitive: comparisons of particle/antiparticle magnetic moments in traps

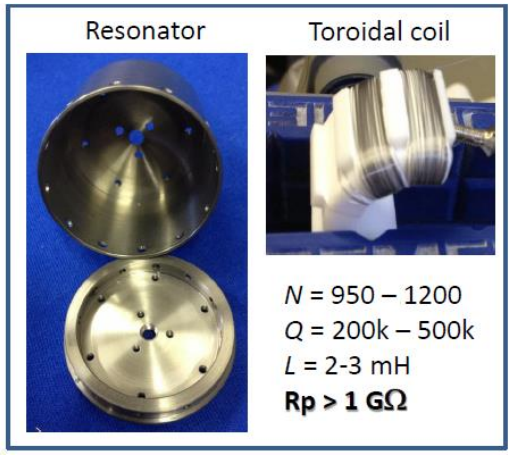
Frequency Measurements

- Measurement of tiny image currents induced in trap electrodes



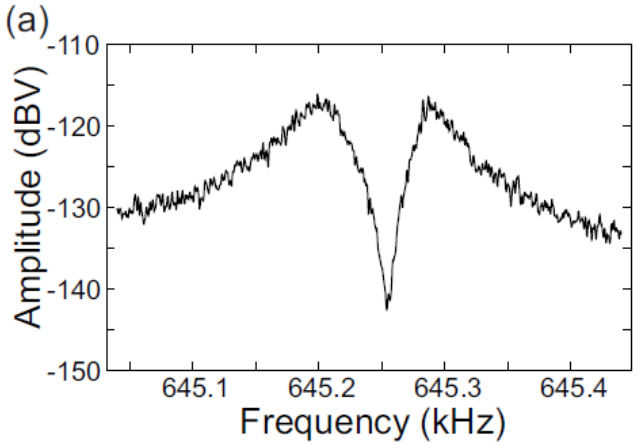
currents: 1 fA

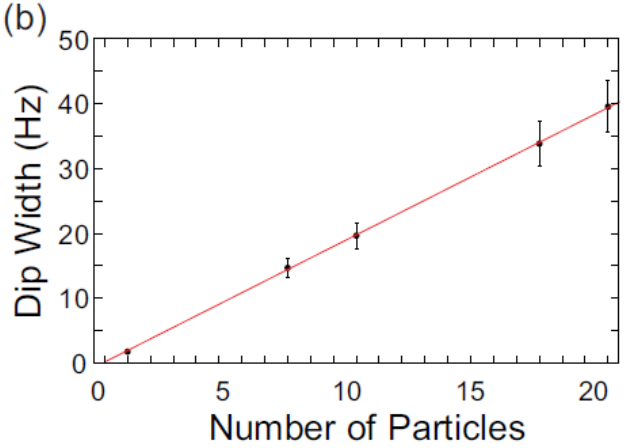




- In thermal equilibrium:
  - Particles short noise in parallel
  - Appear as a dip in detector spectrum
  - Width of the dip -> number of particles

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





- Measurements in thermal equilibrium -> tiny volumina / homogeneous condititions

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