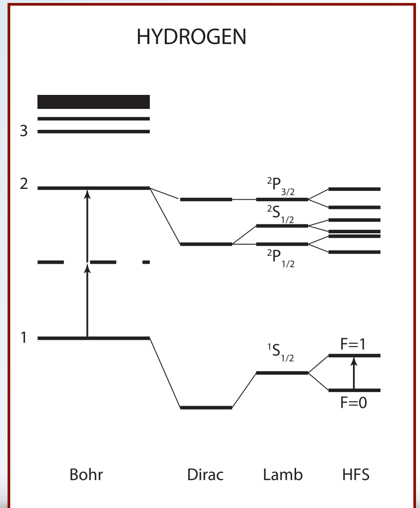


MEASUREMENT OF THE **HYDROGEN** HYPERFINE SPLITTING : TOWARDS **ANTIHYDROGEN** SPECTROSCOPY

Chloé Malbrunot [1,2]

[1] CERN, Geneva, SWITZERLAND

[2] Stefan Meyer Institute for Subatomic Physics, Vienna, AUSTRIA

MOTIVATIONS

10 000 000 001

MATTER

10 000 000 000

ANTIMATTER

MOTIVATIONS

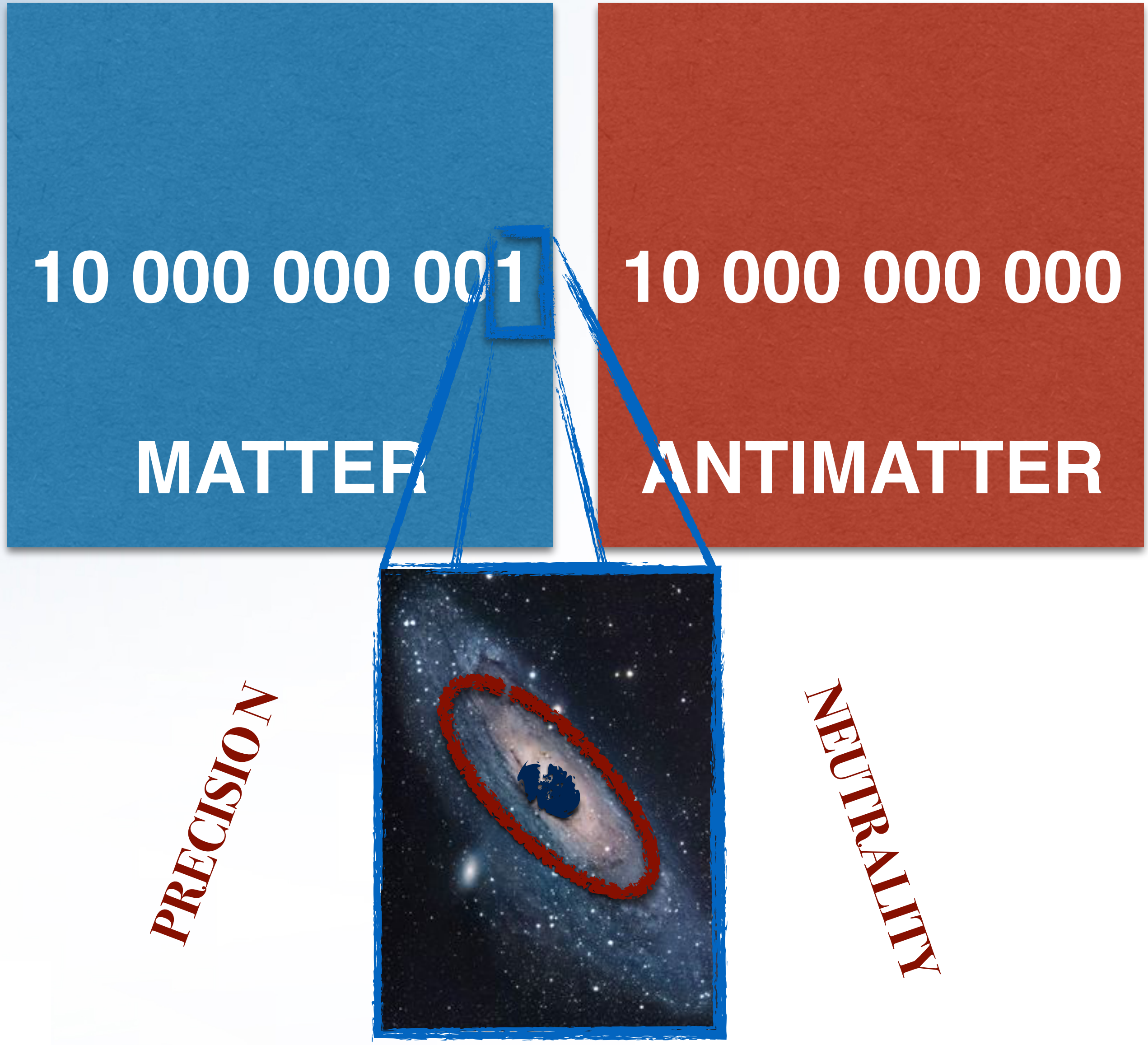
10 000 000 001

MATTER

10 000 000 000

ANTIMATTER

MOTIVATIONS



MOTIVATIONS

CPT Theorem

Quantum Field Theory

Lorentz invariance

Locality

Unitarity

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Implies : properties of matter & antimatter particles have to be exactly equal (mass) or opposite (charge, magnetic moment

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Implies : properties of matter & antimatter particles have to be exactly equal (mass) or opposite (charge, magnetic moment

Atomic structures identical

MOTIVATIONS

<u>**CPT Theorem**</u>

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Lorentz invariance

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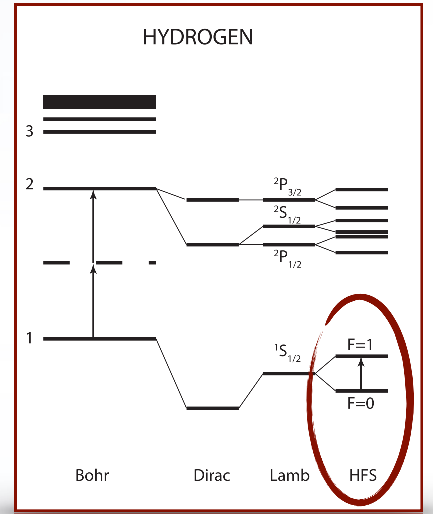
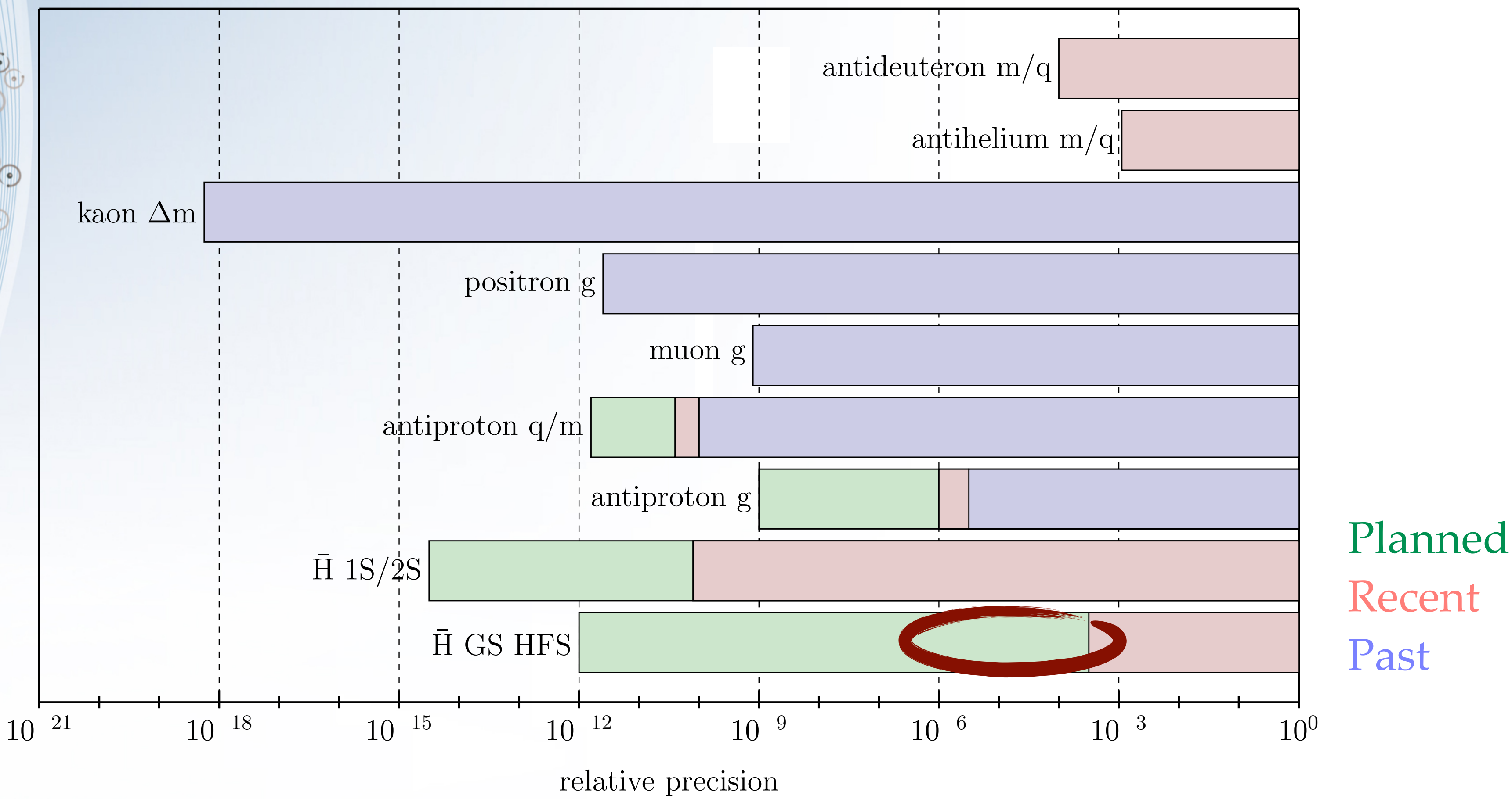


MOTIVATIONS

Tests in different systems:



MOTIVATIONS

$$\nu = 1.420405751768(1)\ \mathrm{GHz}$$

S. G. Karshenboim, Precision Physics of Simple Atomic Systems, pages 142–162, Springer, Berlin, Heidelberg, 2003, hep-ph/0305205.

Leading term: **Fermi contact term**

has been measured to better than 1 ppm

Nagahama H et al. Nat Commun. (2017) doi: 10.1038/ncomms14084.

DiSciacca et al, Phys. Rev. Lett. 110, 13 (2013)

$$\nu_F = \frac{16}{3}\left(\frac{M_p}{M_p + m_e}\right)^3 \frac{m_e}{M_p} \frac{\overline{\mu_p}}{\mu_N} \alpha^2 c R_y$$

Finite electric and magnetic radius (**Zemach corrections**): ~-41ppm

access to the electric and magnetic form factors of the antiproton

$$\Delta\nu(\mathrm{Zemach}) = \nu_{\mathrm{F}} \frac{2Z\alpha m_e}{\pi^2} \int \frac{d^3p}{p^4} \left[\frac{G_E(p^2)G_M(p^2)}{1+\kappa} - 1\right]$$

e.g Friar et al. Phys.Lett. B579 (2004)

Polarizability of p(bar) =1.88±0.64 ppm

Carlson, Nazaryan, and Griffioen PRA 78, 022517 (2008)

Remaining deviation theory-experiment: **0.86±0.78 ppm**

MOTIVATIONS

Standard model extension (SME)

CPT Violation and the Standard Model, D. Colladay and A. Kostelecky, Phys. Rev. D 55, 6760 (1997)

Lorentz and CPT Tests in Hydrogen, Antihydrogen, and Related Systems, A. Kostelecky and A. Vargas, Phys. Rev. D 92, 056002 (2015)

Dirac equation in mSME :

$$(i\gamma^\mu D_\mu - m_e - a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu - \frac{1}{2} H^e_{\mu\nu} \sigma^{\mu\nu} + i c^e_{\mu\nu} \gamma^\mu D^\nu + i d^e_{\mu\nu} \gamma_5 \gamma^\mu D^\nu)\psi = 0$$

Different measurements (even of the same quantity) are sensitive (or not) to different SME coefficients

MOTIVATIONS

$$\nu_0 = \frac{g_+\sqrt{g_+^2\nu_\sigma^2 - 4g_-^2\nu_\pi^2 + 4g_-^2\nu_\pi\nu_\sigma} + g_-^2(2\nu_\pi - \nu_\sigma)}{g_+^2 + g_-^2}$$

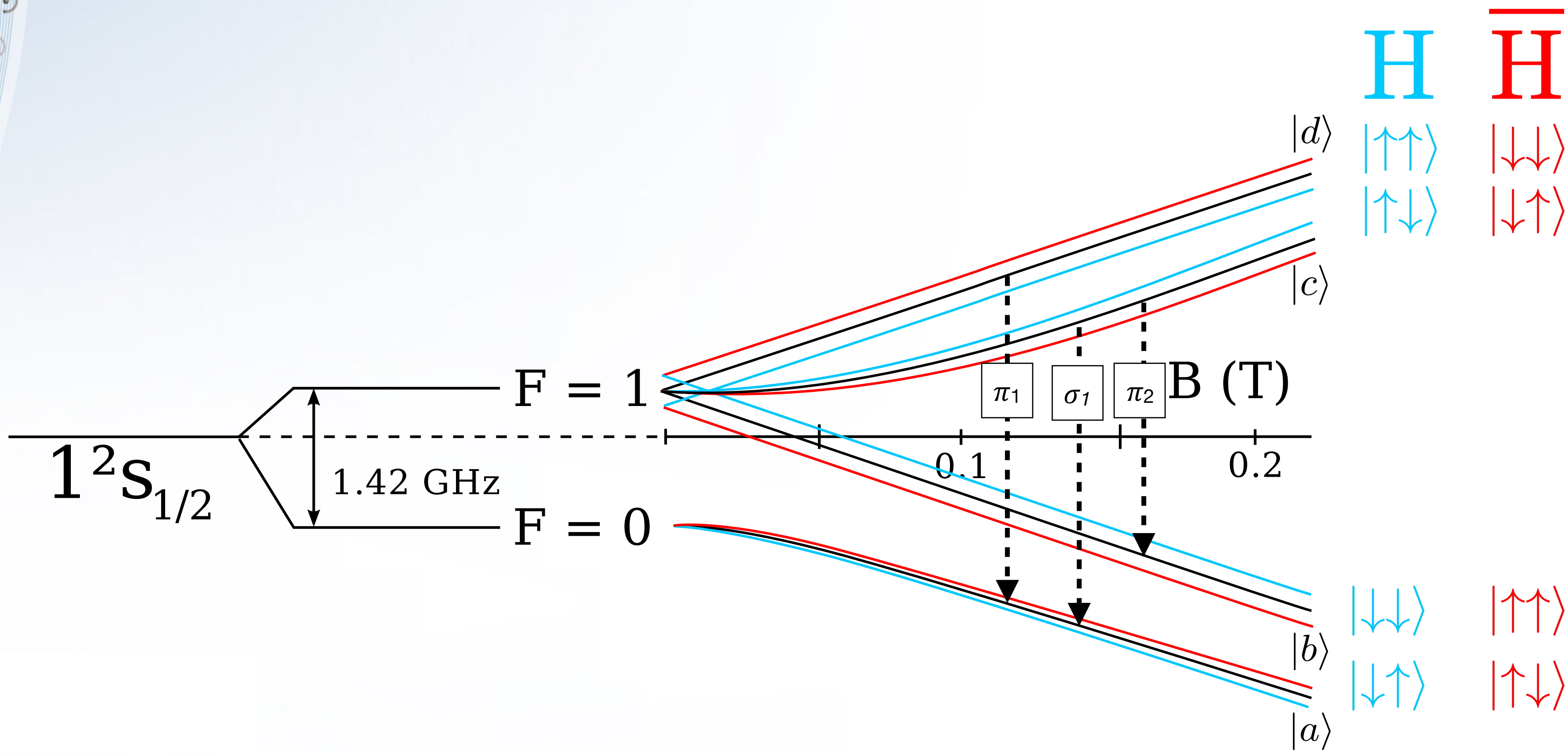
where $g_\pm = g_I \pm g_J$.

Measure ν_{HF} in antihydrogen :

π_1 - π_2

π_1 & σ_1

at a given field



MOTIVATIONS

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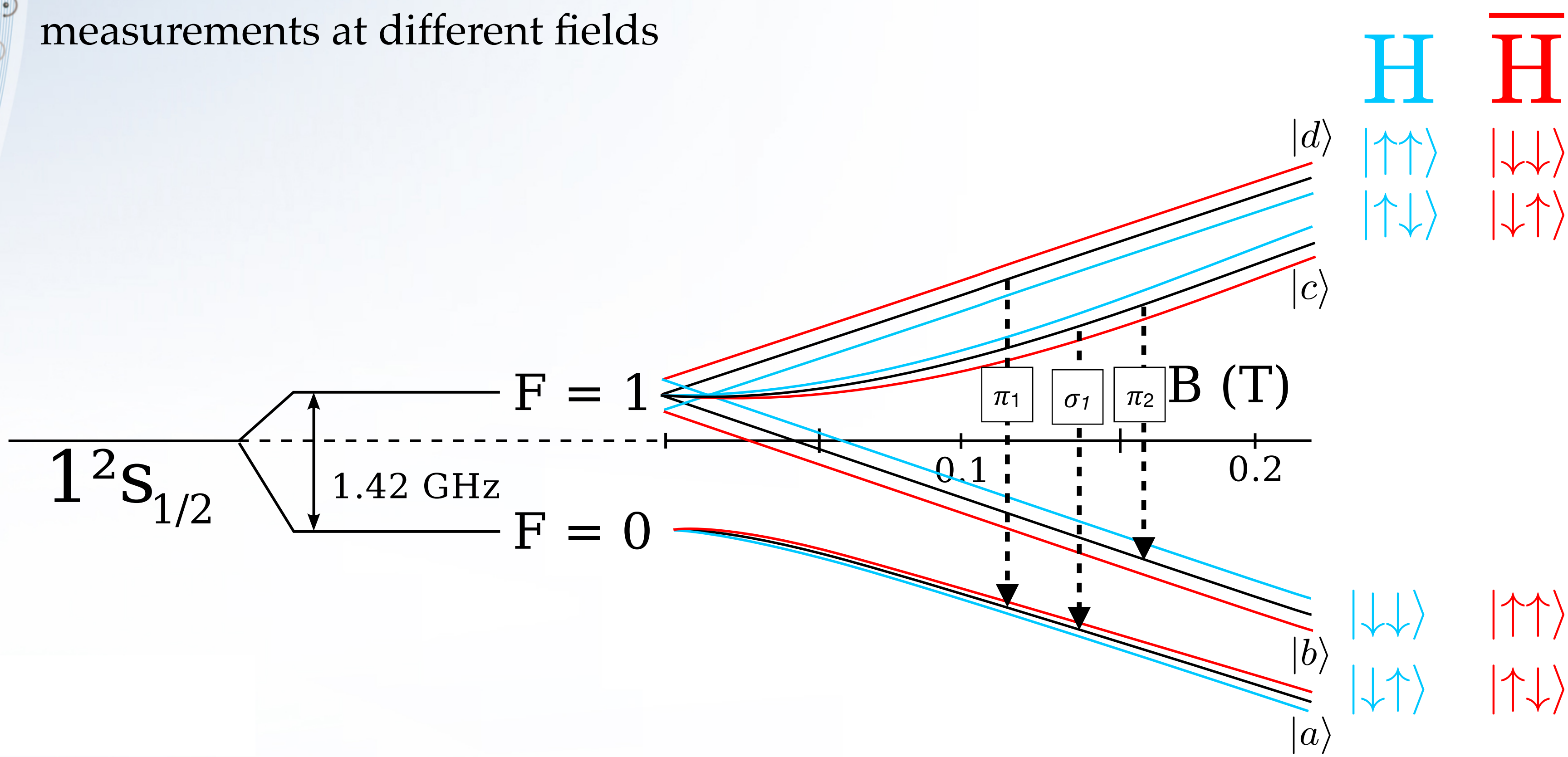
Extrapolate either transition from several measurements at different fields



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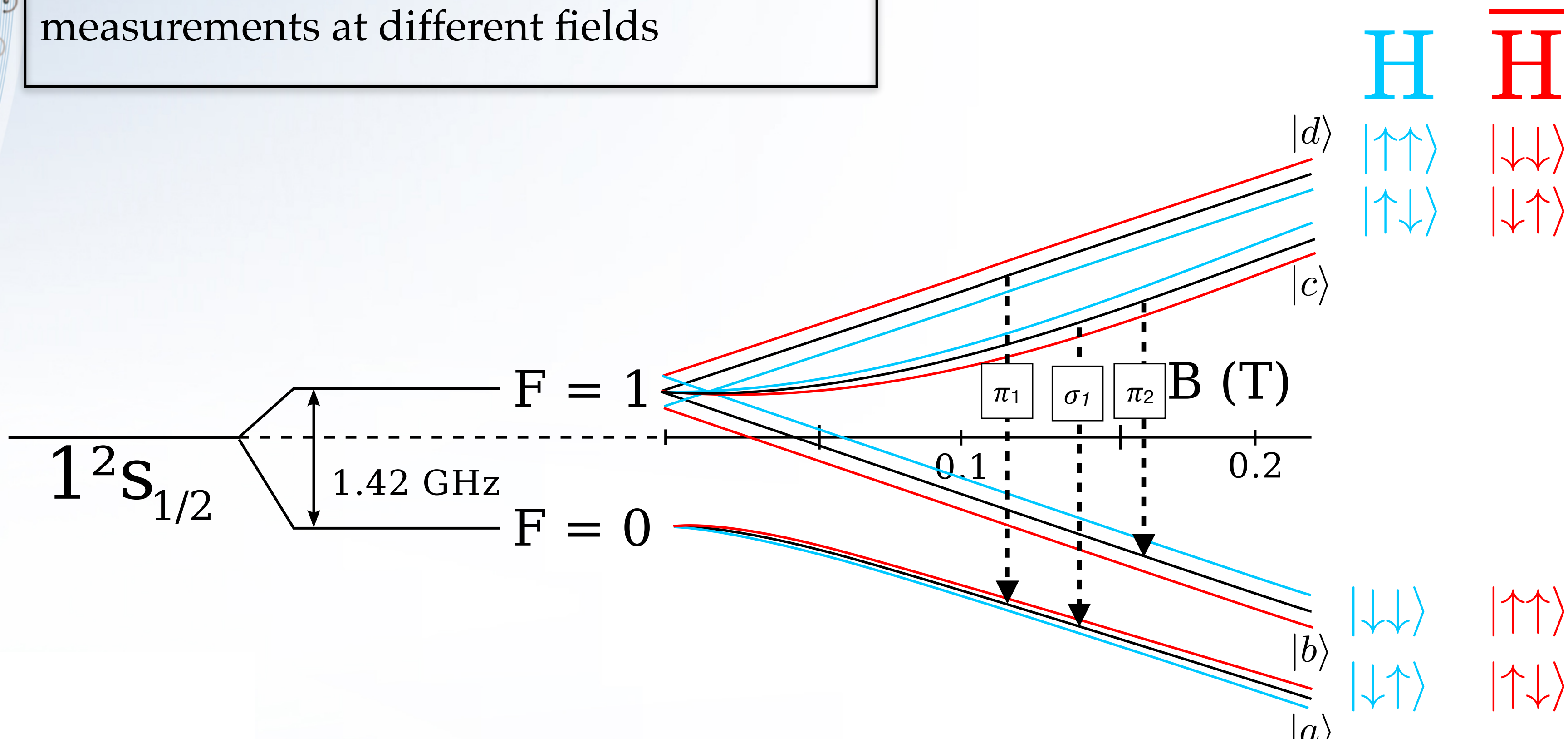
All are CPT tests

But not all constrain SME parameters



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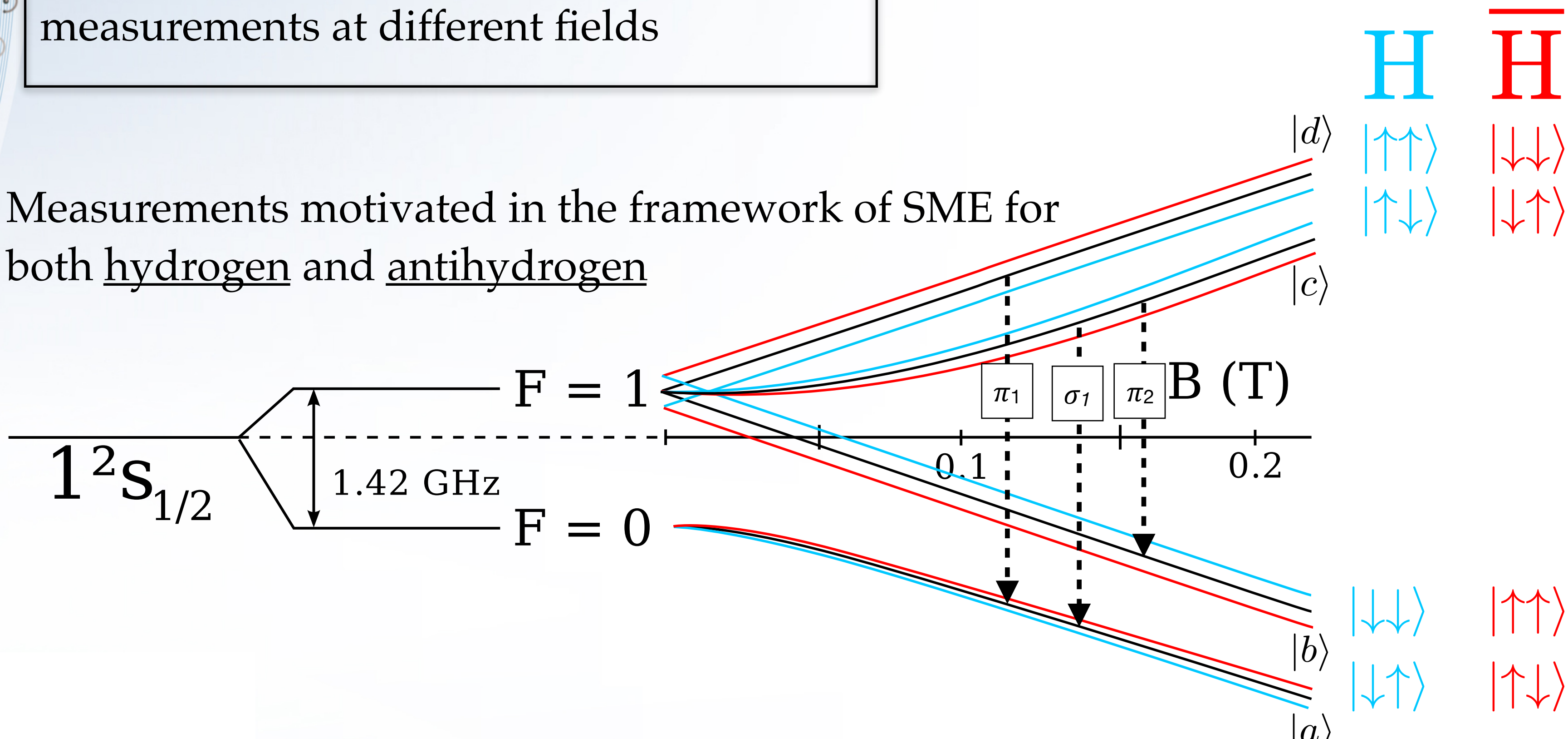
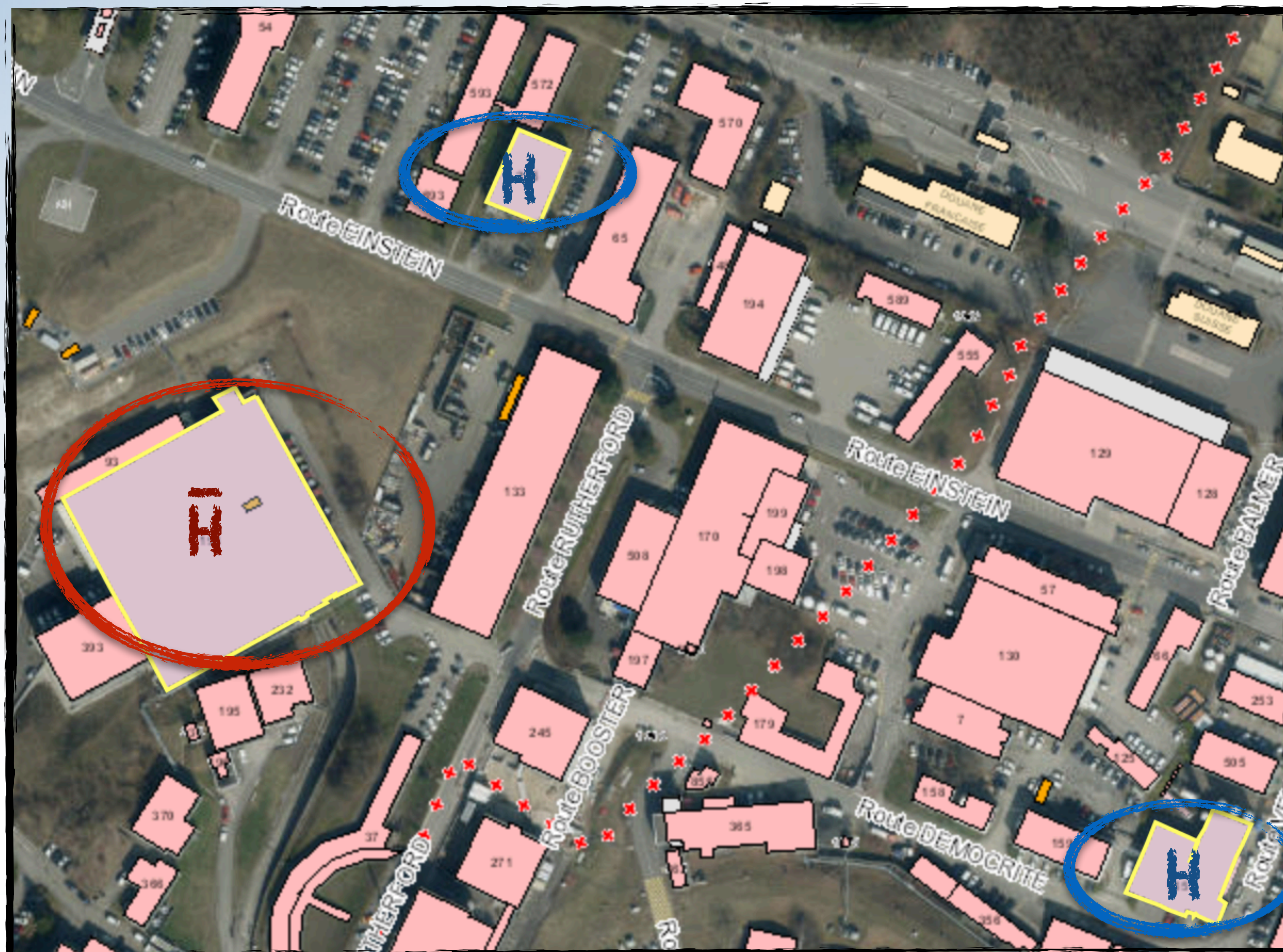
All are CPT tests

But not all constrain SME parameters

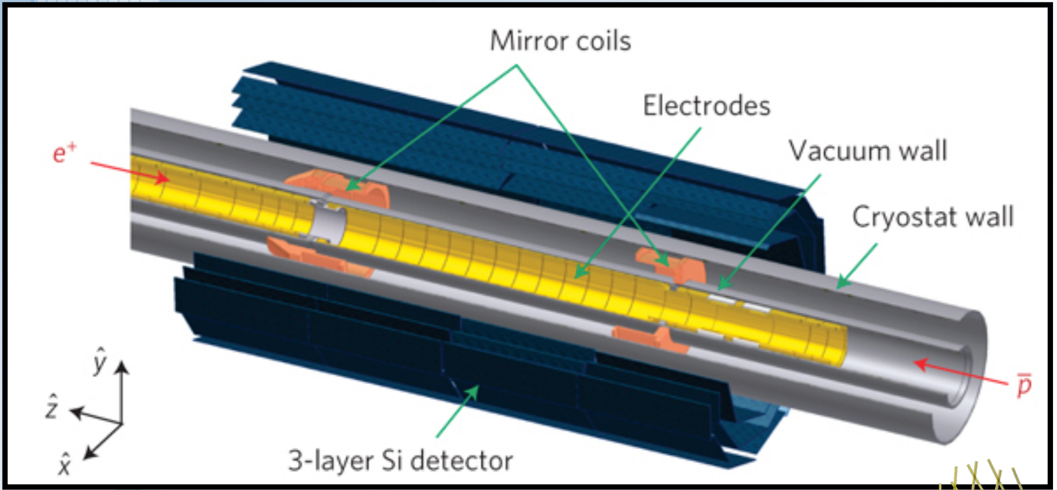
Measurements motivated in the framework of SME for both hydrogen and antihydrogen



HYDROGEN & ANTIHYDROGEN EXPERIMENTS @ CERN

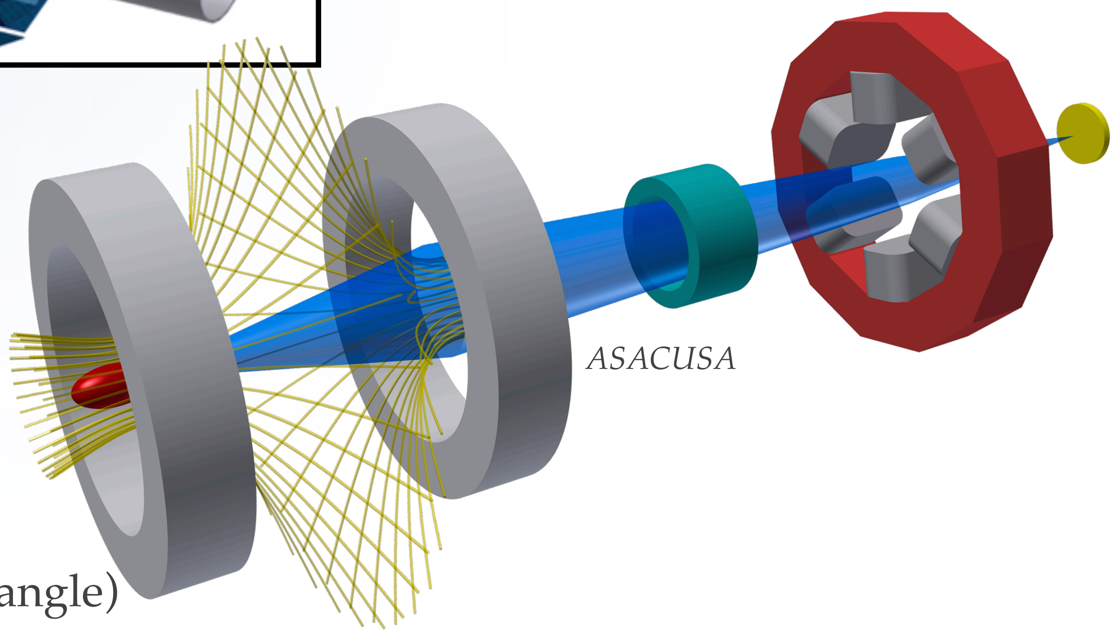


BEAM VS. TRAP



ALPHA

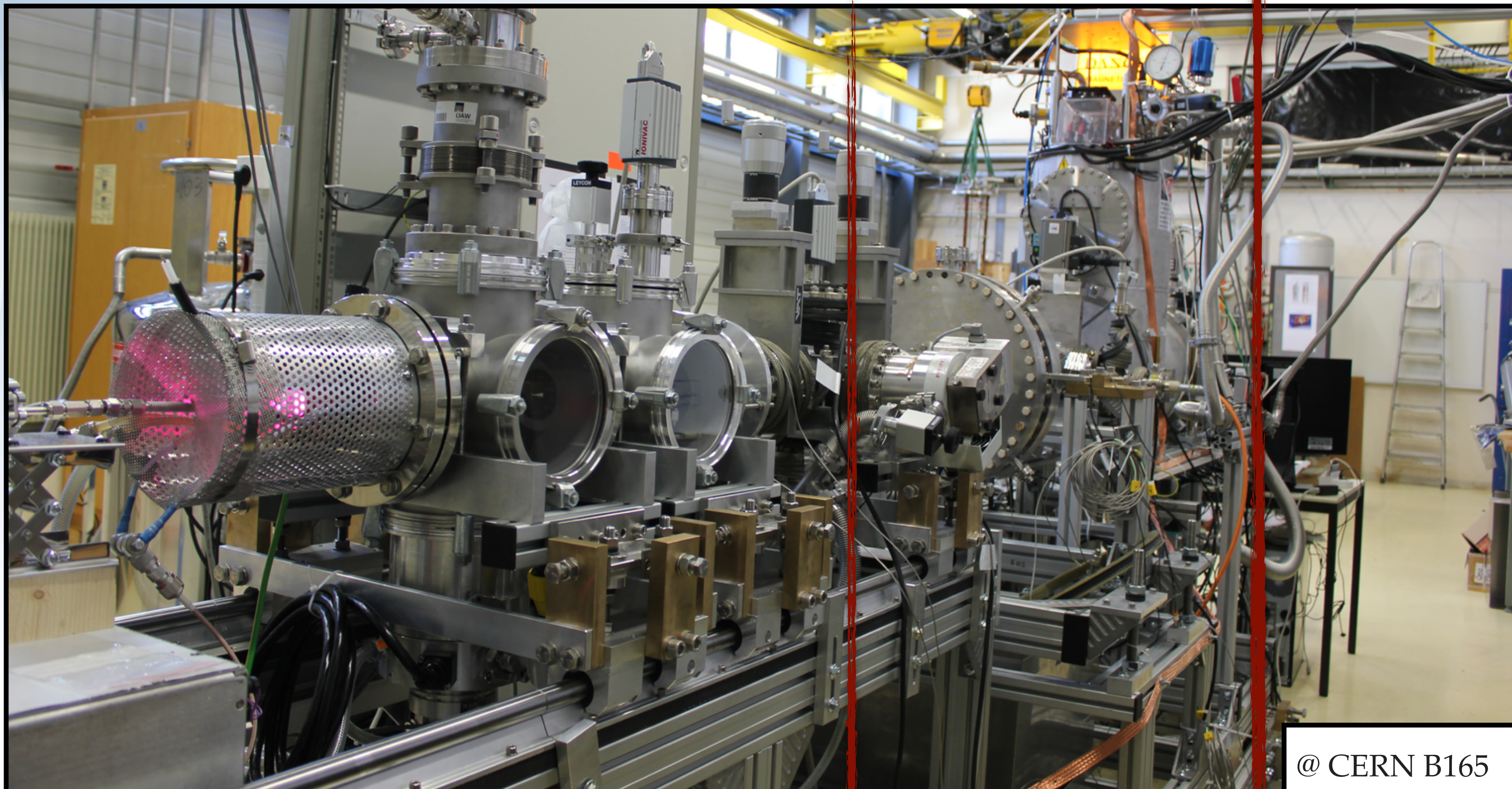
Advantage of beam:
Absence of strong field gradient
Lower requirement on the temperature of antihydrogen atoms



ASACUSA

Inconvenient of beam:
Need "focussing" (loss of solid angle)
Cannot easily control the quantum state at the detector
More difficult to control the polarization

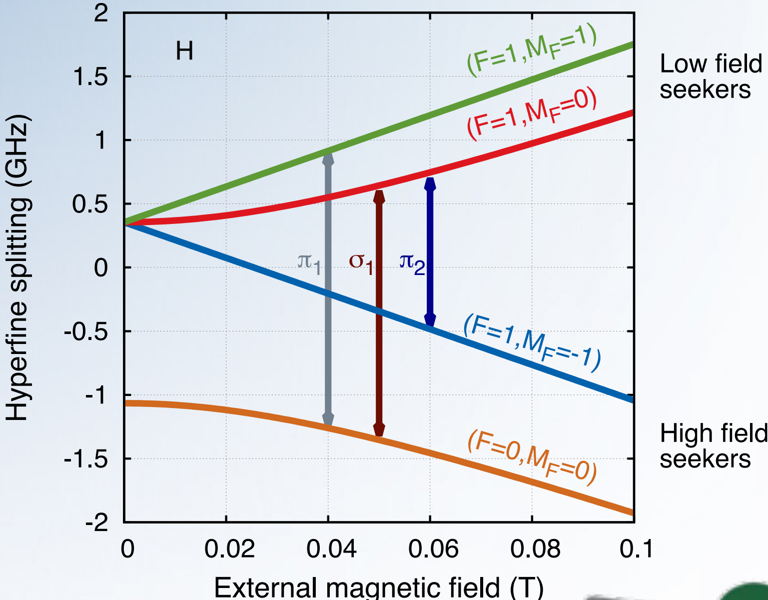
1ST HYDROGEN SETUP

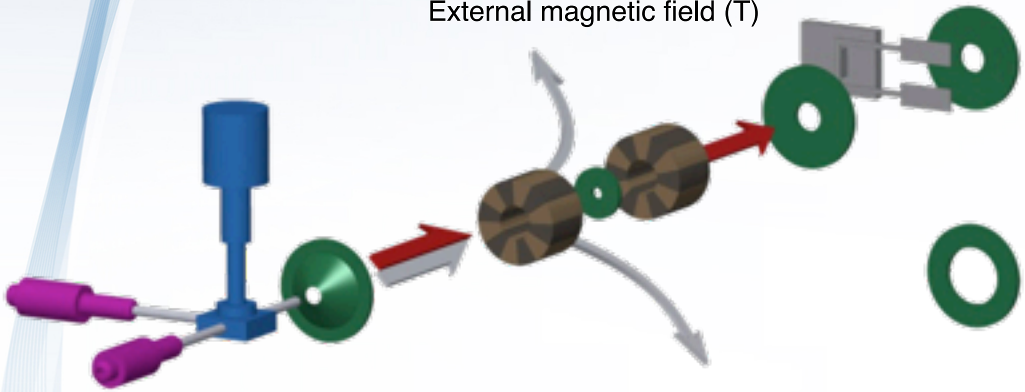


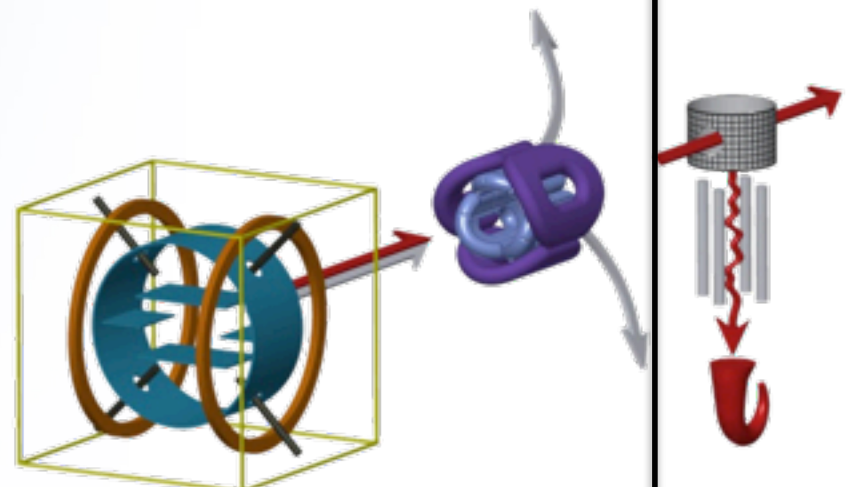
@ CERN B165

Antihydrogen
spectroscopy
apparatus

1ST HYDROGEN SETUP



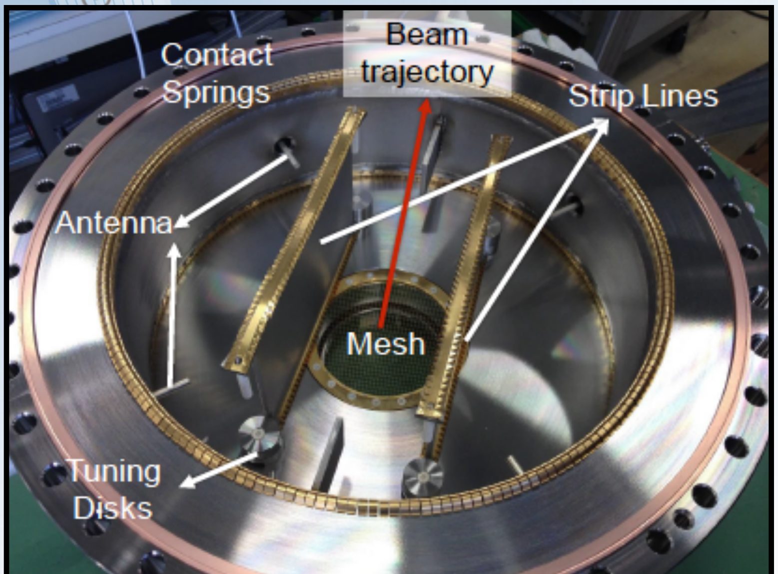


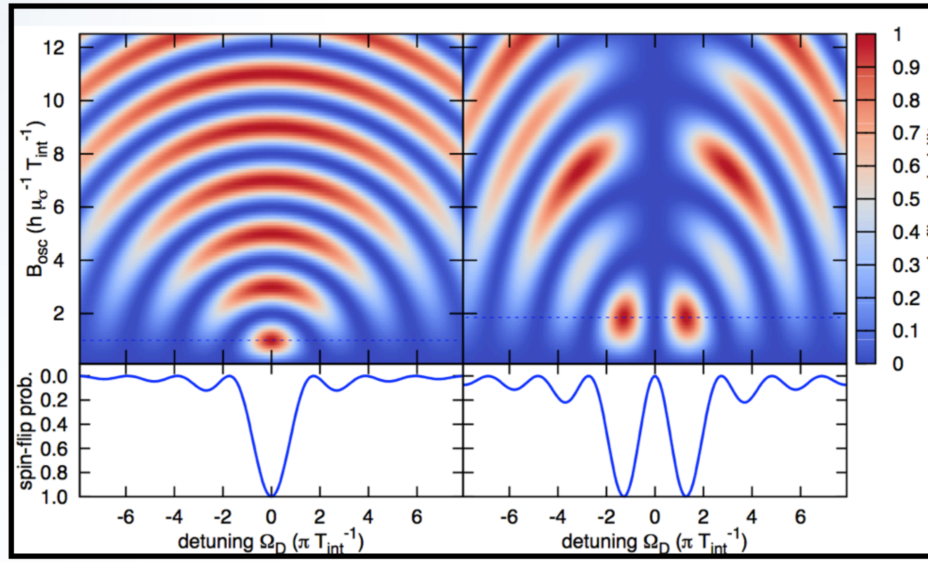


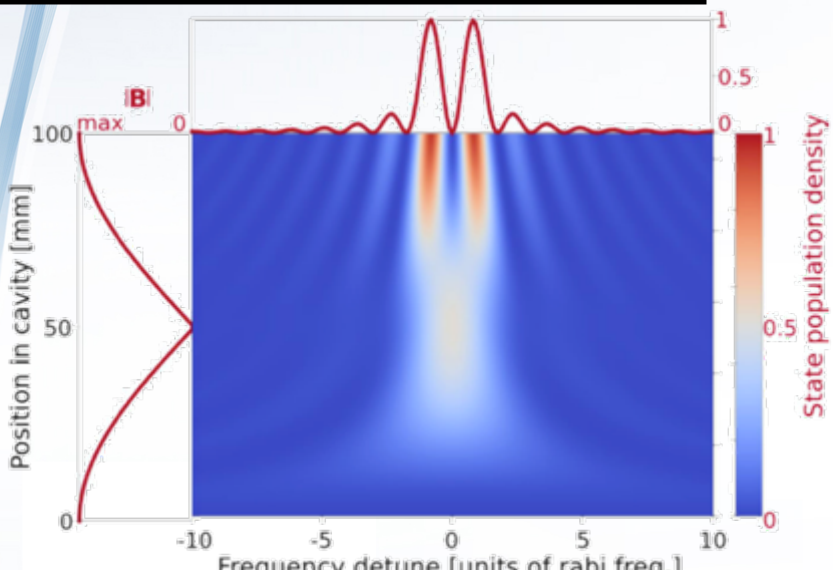
Antihydrogen spectroscopy apparatus

1ST HYDROGEN SETUP

"strip-line" cavity design







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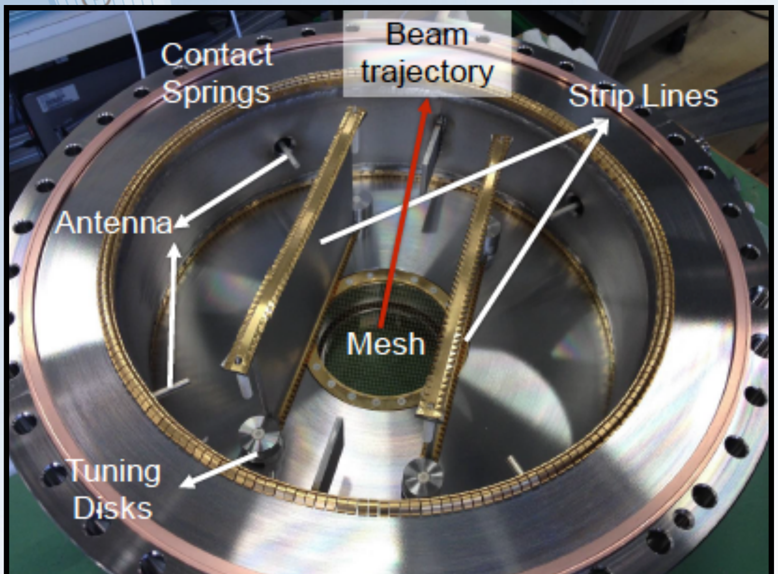
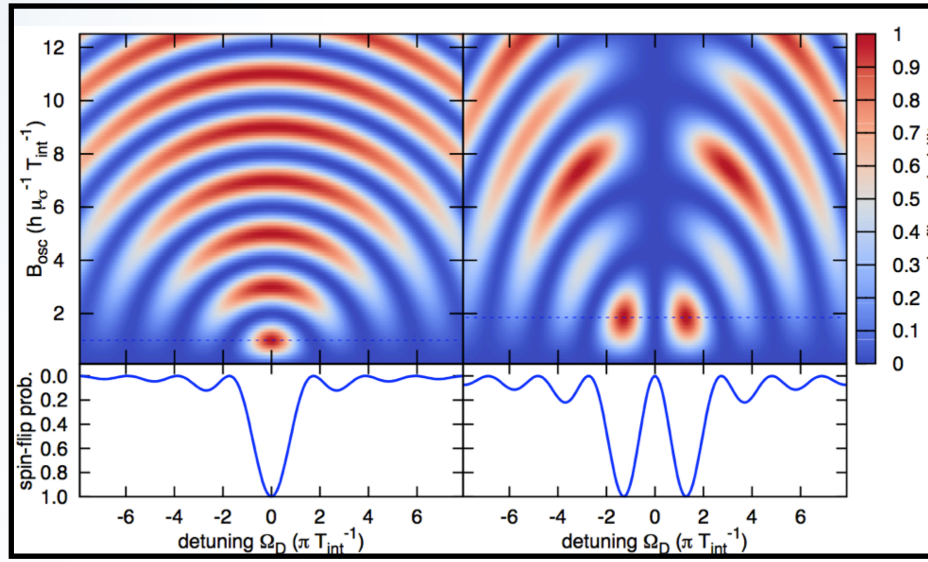
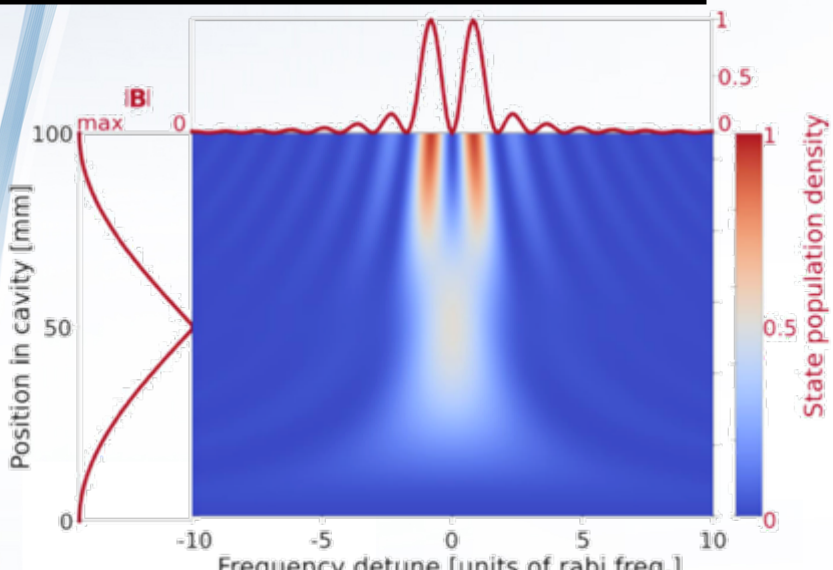
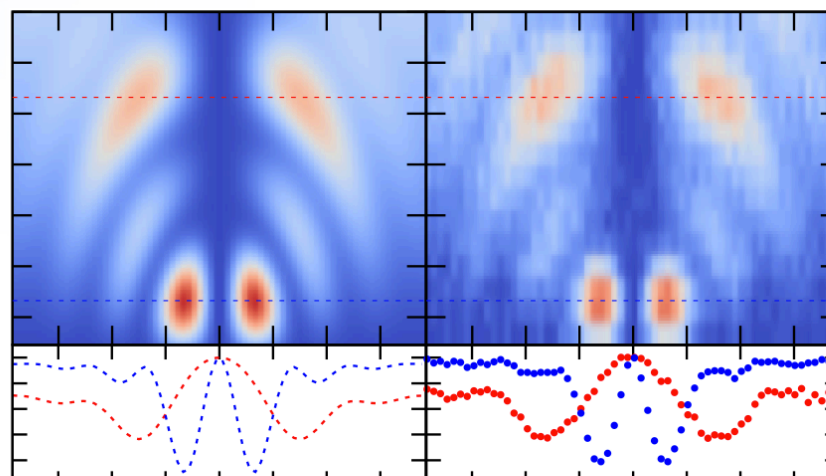
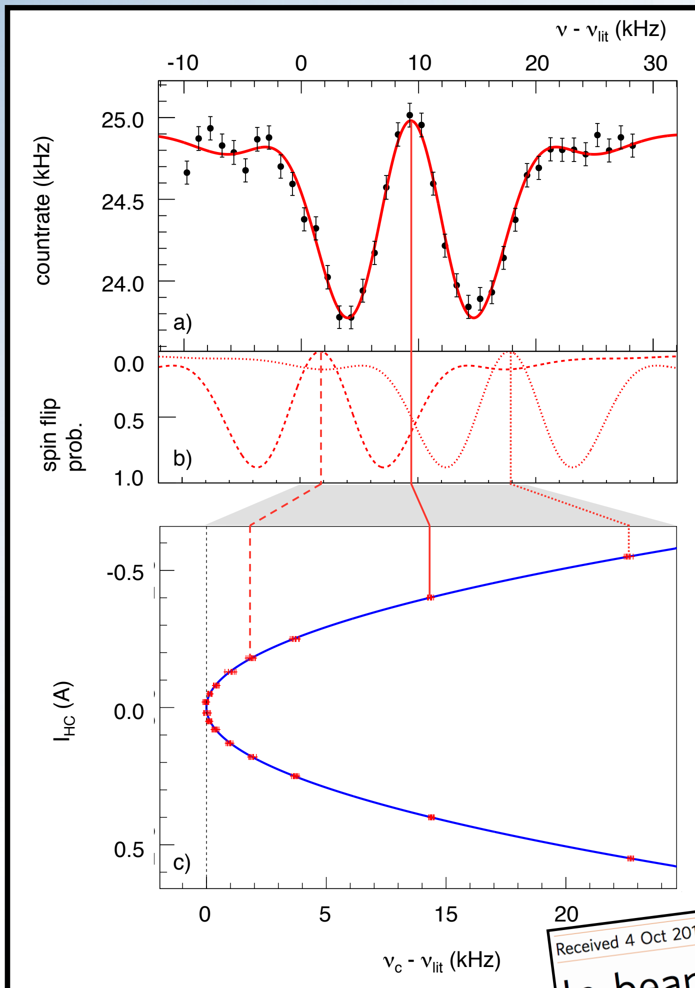








σ MEASUREMENT



$$\nu_{HF} = 1\ 420\ 405\ 748.4(3.4)(1.6)\ \text{Hz}$$

$$\Delta\nu/\nu = 2.7\ \text{ppb}$$

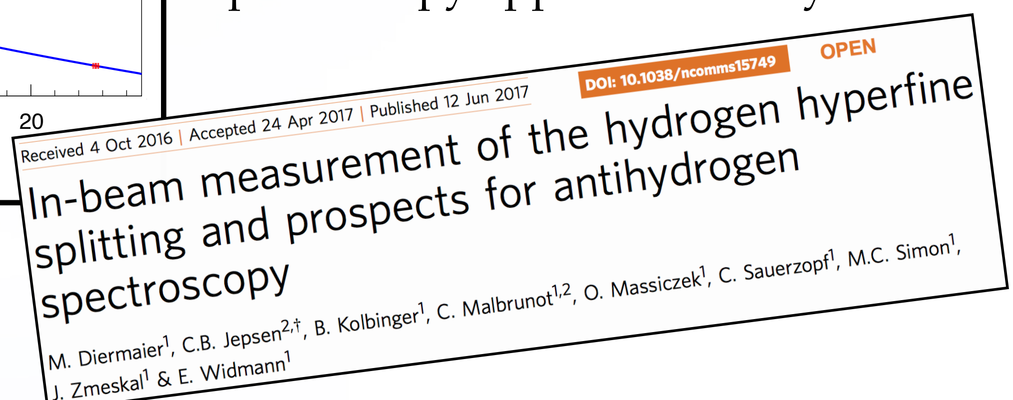
Table 2 | Error budget.

Contribution	1σ s.d. (Hz)
Systematic error	
Frequency standard	1.62
Common fit parameters	
$\bar{V}_H$	0.05
σ_V	0.03
B_{osc}	0.02
Systematic error total (σ_{sys})	1.62
Statistical error (σ_{stat})	3.43
Total error (σ_{tot})	3.79

Robust lineshape fit

Extraction of amplitude of oscillatory field, velocity and velocity spread

Spectroscopy apparatus if fully commissioned


Received 4 Oct 2016 | Accepted 24 Apr 2017 | Published 12 Jun 2017 DOI: 10.1038/ncomms15749 OPEN

In-beam measurement of the hydrogen hyperfine splitting and prospects for antihydrogen spectroscopy

M. Diermaier[1], C.B. Jepsen[2,†], B. Kolbinger[1], C. Malbrunot[1,2], O. Massiczek[1], C. Sauerzopf[1], M.C. Simon[1], J. Zmeskal[1] & E. Widmann[1]

σ MEASUREMENT

ppm result with <u>antihydrogen</u> should be in reach if <u>enough statistics</u> can be gathered

line-shape dependent factor

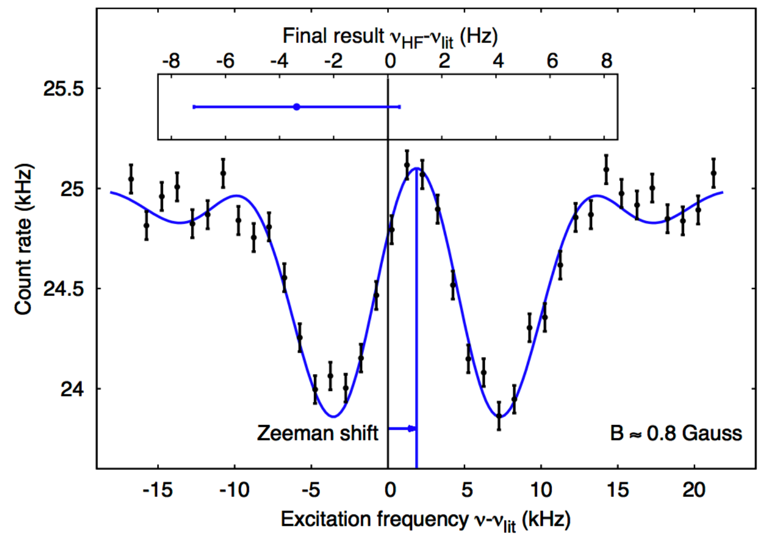
error bar of a data point

$$\delta\nu_c = \frac{C}{\varepsilon\, T_{int} \sqrt{N}} \frac{\sigma_R}{\Delta R}$$

Interaction time

Number of data points

Count rate drop



Assuming background :
- 50% atoms are in excited states
- 50% of remaining are in wrong lfs state
- polarisation P=1/3

Assuming MB distribution @ 50K

$$\mathcal{P} = \frac{f_{LFS} - f_{HFS}}{f_{LFS} + f_{HFS}}$$

For <u>ppm</u> measurement using <u>4</u> resonances we estimate ~ 8000 atoms should be recorded at the antihydrogen detector

π MEASUREMENT

Other possibility :

Measure π_1 & σ_1 at the same field (2 resonances needed, not sensitive to stray field (from the earth or from CUSP in the antihydrogen experiment)

Advantage : π_1 is sensitive to SME coefficients

BUT π_1 more sensitive to magnetic field inhomogeneities

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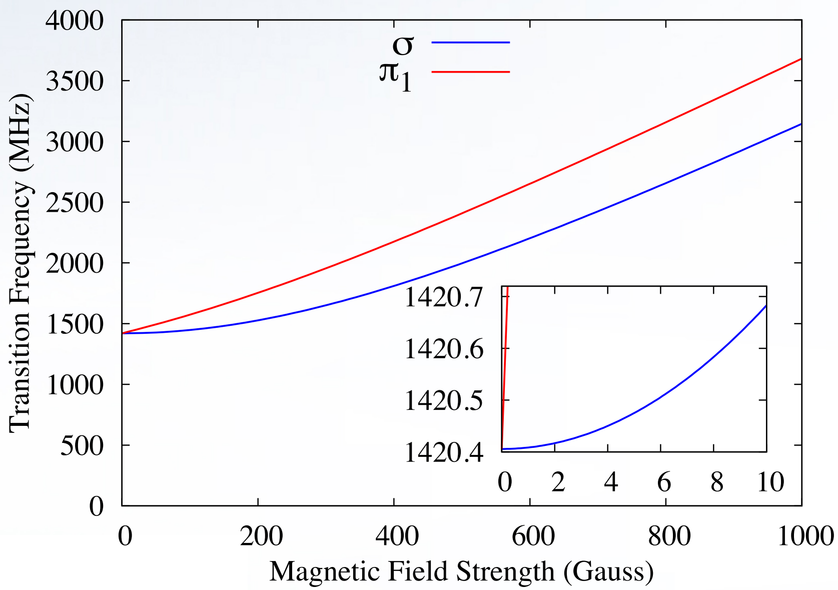
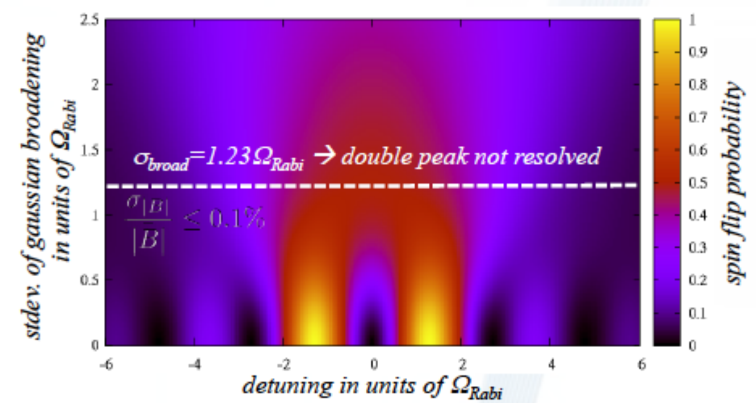


$$\delta f \propto \frac{v_{\bar{H}}}{L_{\text{cav}}} \approx \frac{1\text{km/s}}{0.1\text{m}} \approx 10\text{kHz}$$



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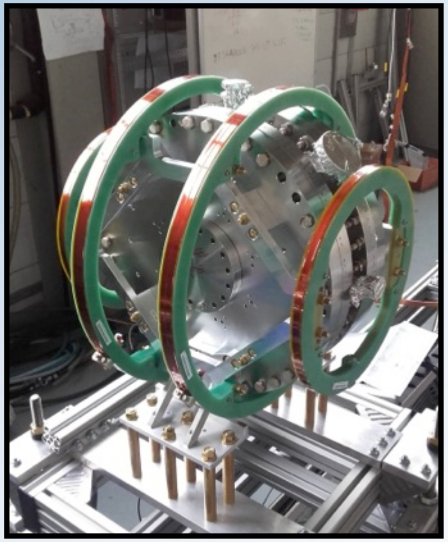
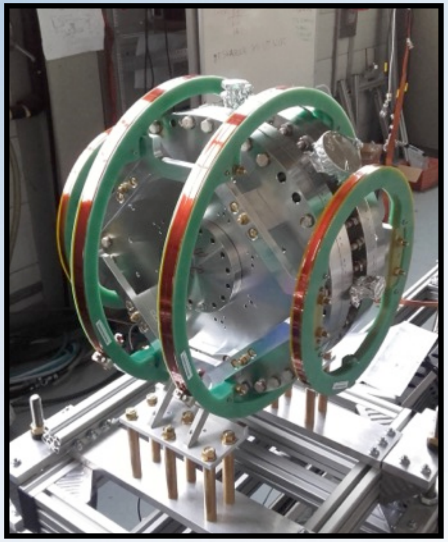


New Helmohlz coils with corrections coils

Cavity tilted at 45° to allow both transitions at the same time

Rotation and up/down movements possible for systematic studies

π MEASUREMENT



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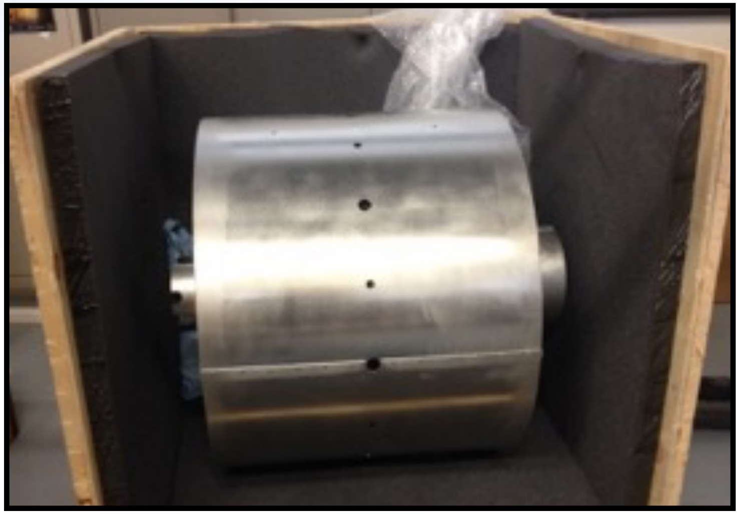
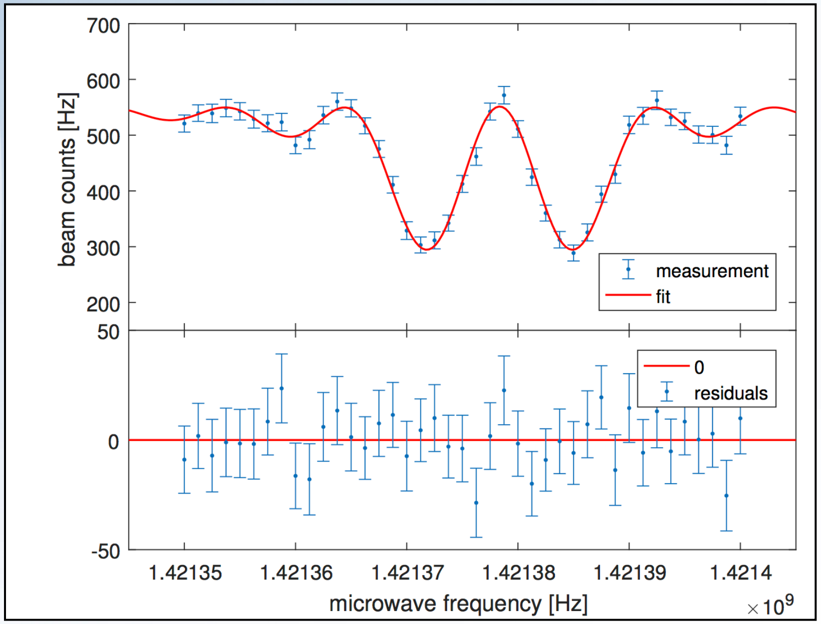
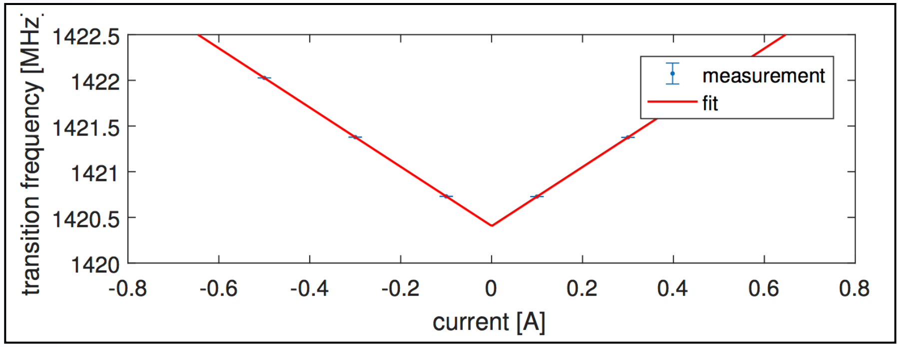


New 3-layers cylindrical shielding

π MEASUREMENT

First π_1 resonance observed





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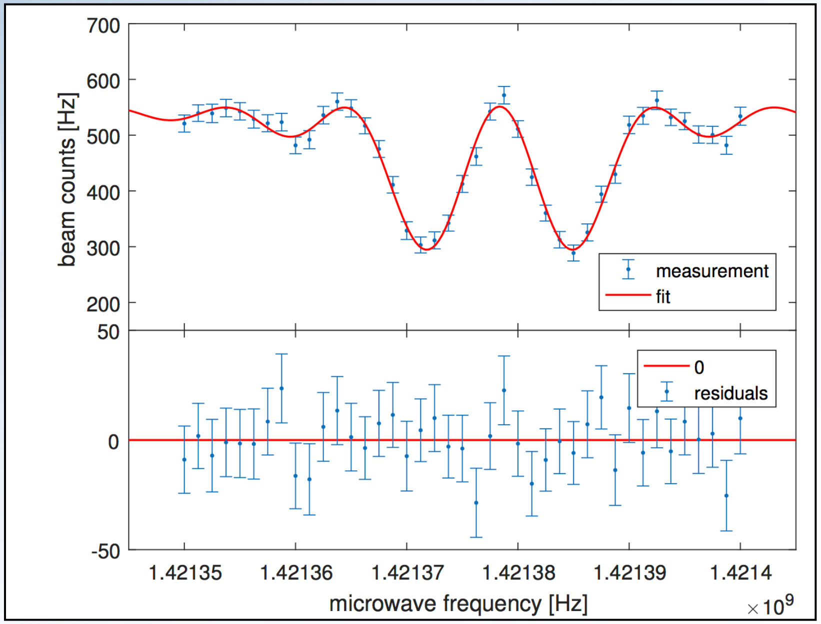
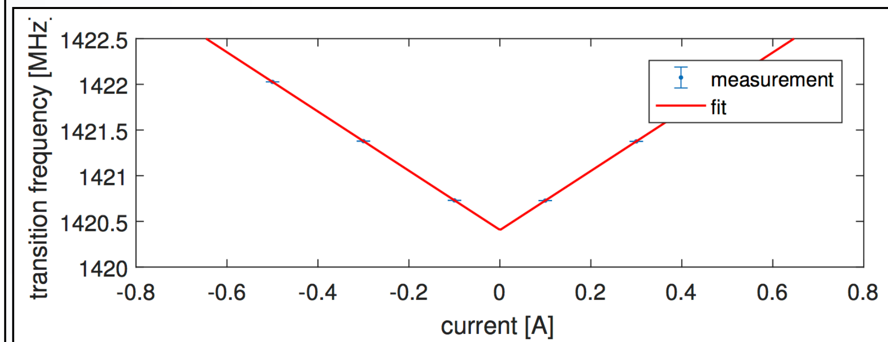




π_1 & σ_1 measured at the same time and same field

ppb measurement in reach

Systematic studies for antihydrogen experiment

2ND HYDROGEN SETUP

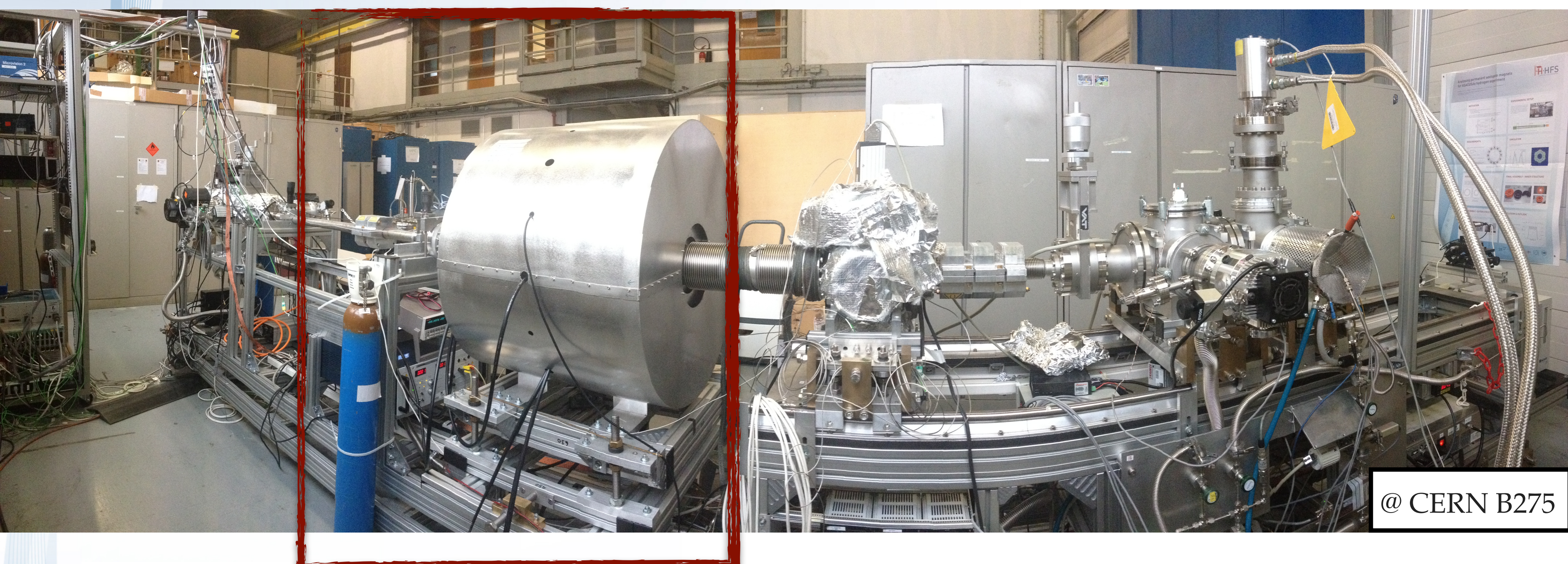
Siderial variations constrained by Harvard-Smithsonian maser at mHz level

PHYSICAL REVIEW A **68**, 063807 (2003)

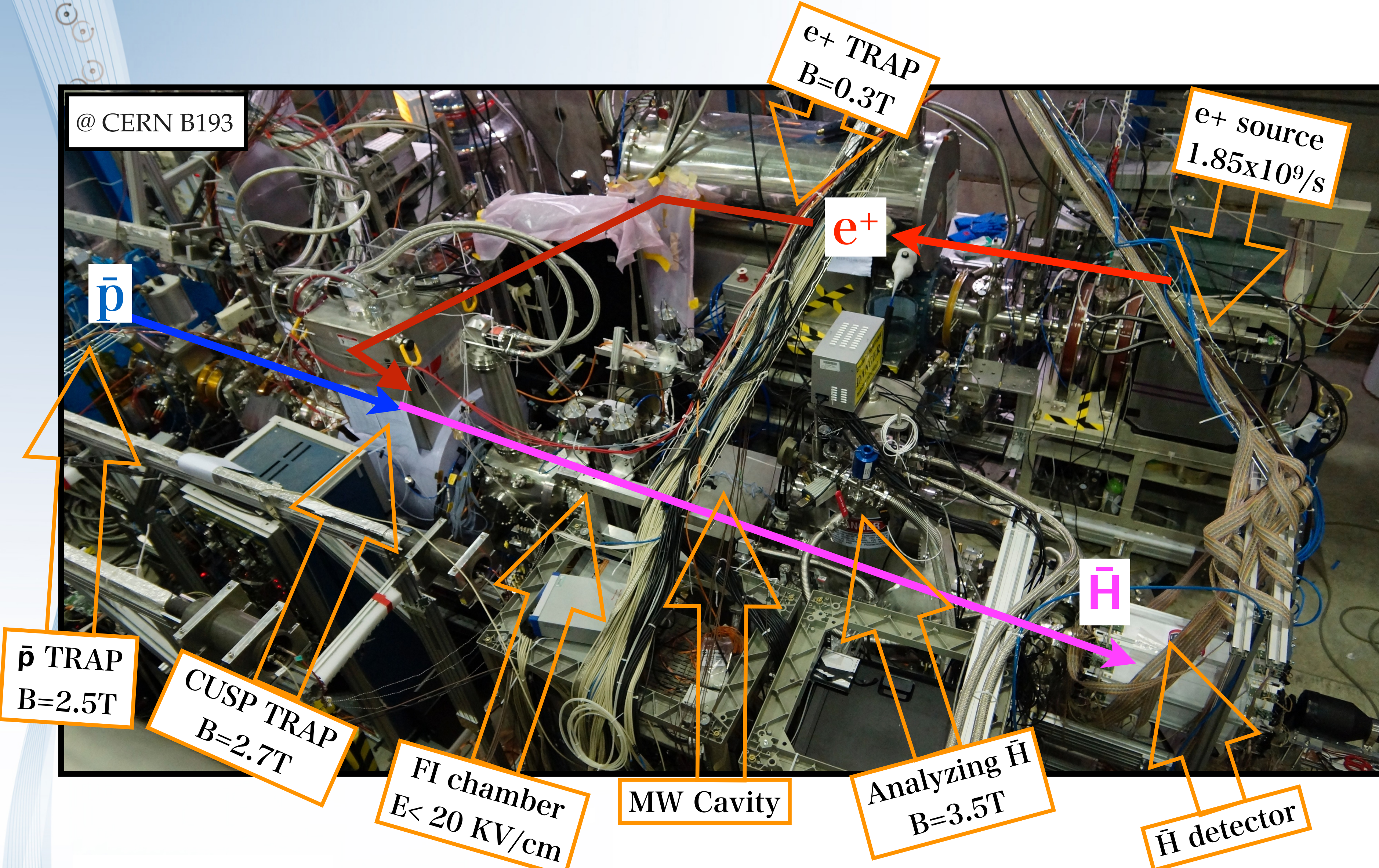
Testing *CPT* and Lorentz symmetry with hydrogen masers

M. A. Humphrey, D. F. Phillips, E. M. Mattison, R. F. C. Vessot, R. E. Stoner, and R. L. Walsworth
Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138, USA
(Received 4 August 2003; published 9 December 2003)

72 SME coefficients involved. 48 constrained, 24 remaining and can be constrained using different orientation of the static B-field



ANTIHYDROGEN SETUP



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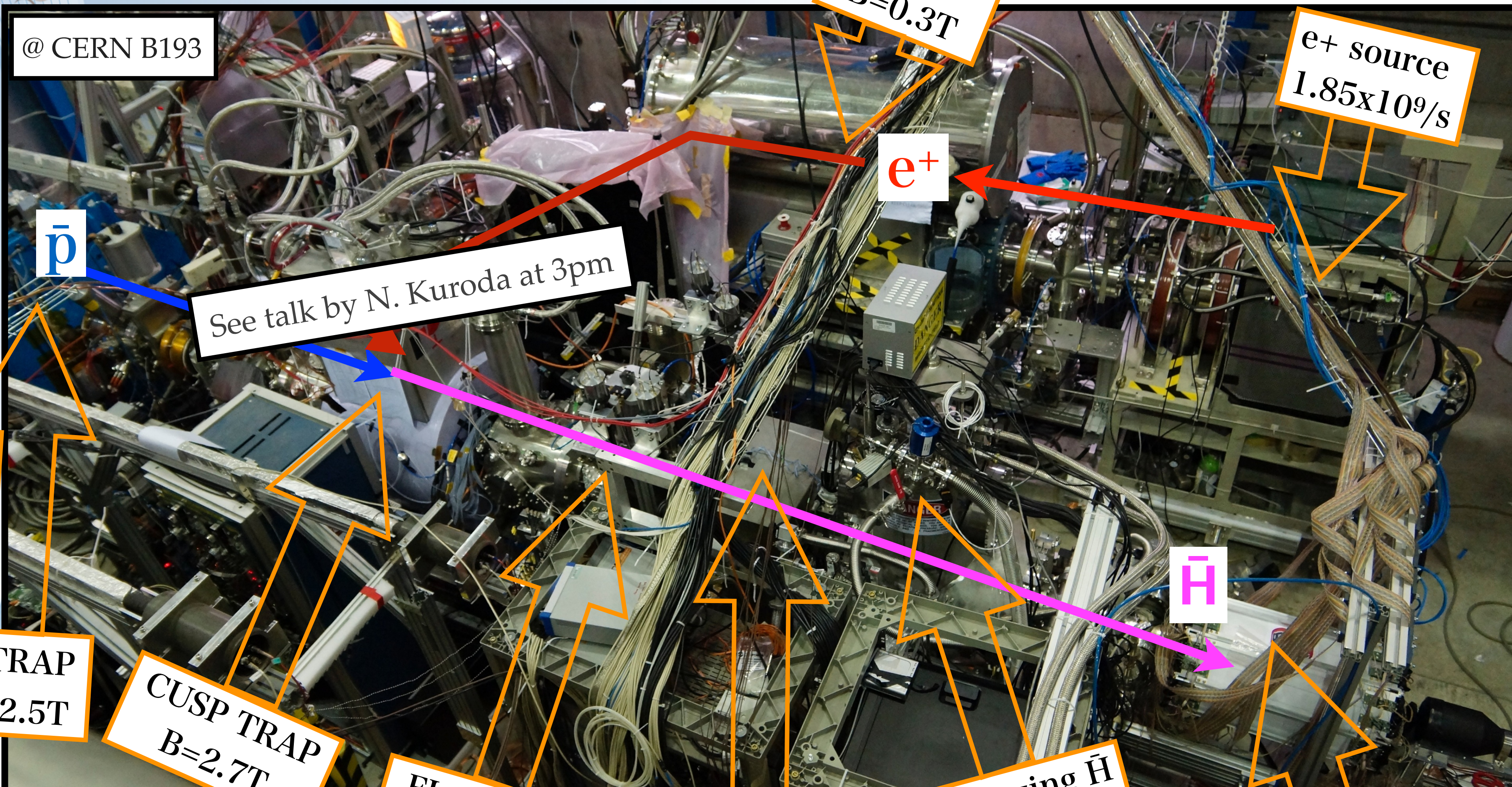

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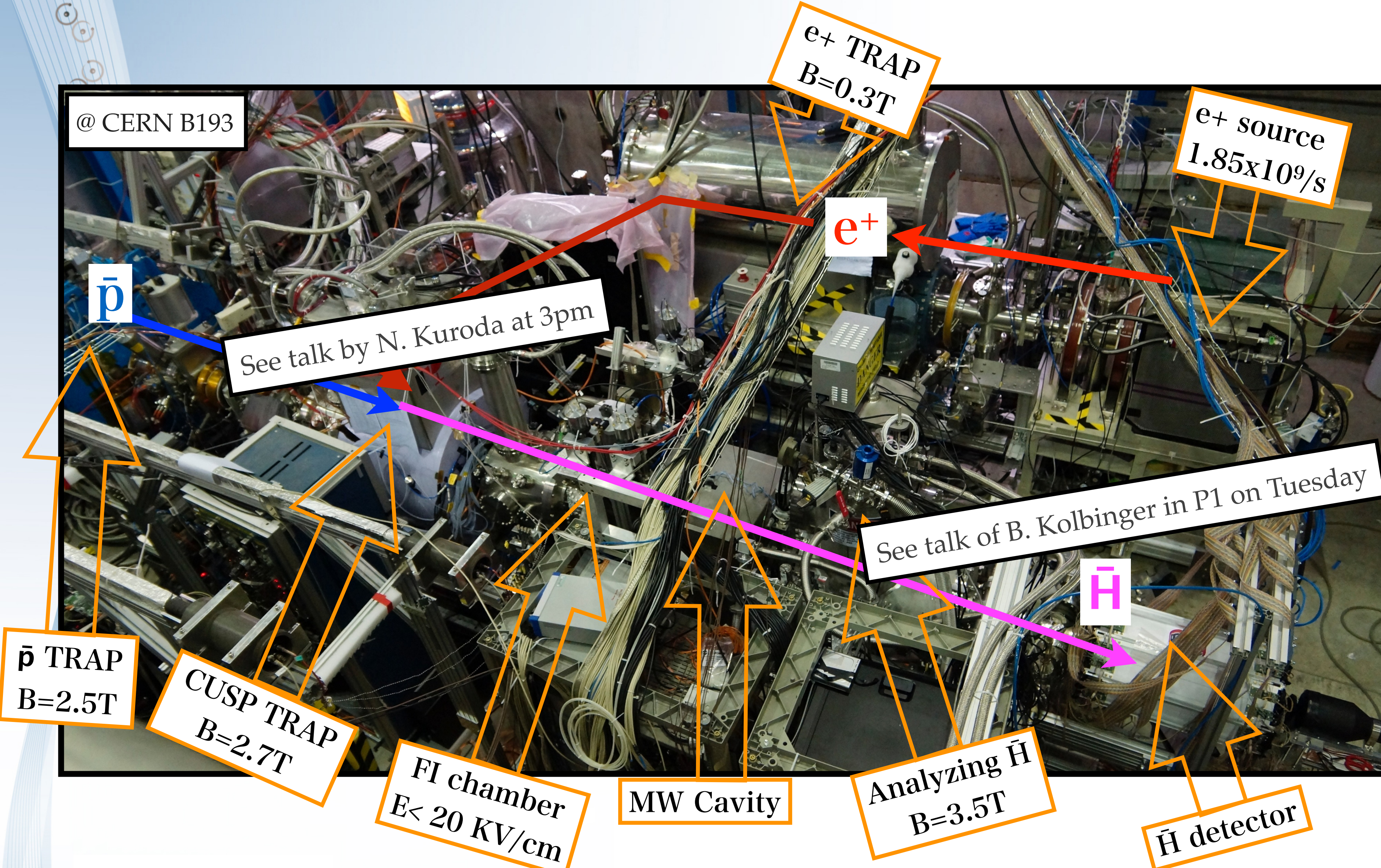
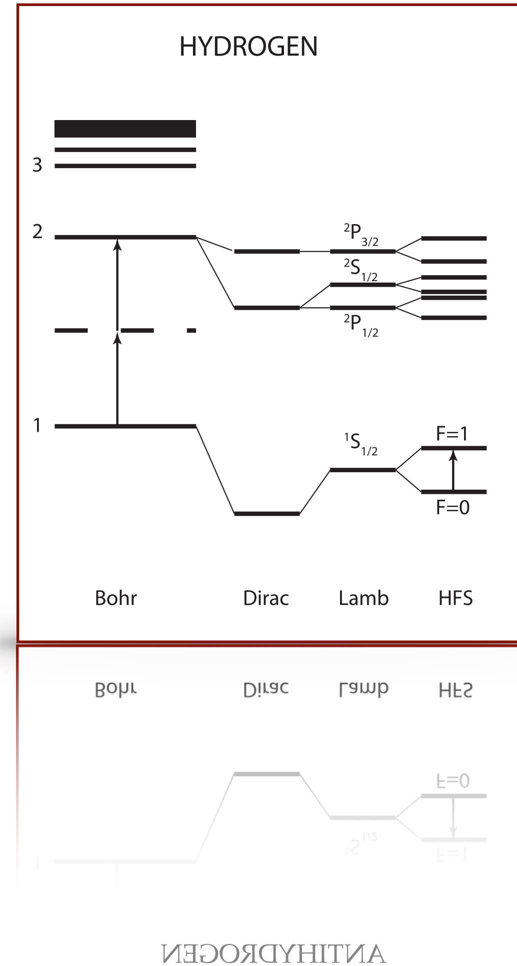


CONCLUSIONS

Two fronts:

- Hydrogen beam: ppb measurement achieved on σ transition.

- Characterization of $\bar{H}$ beam —> towards spectroscopy



New program with Hydrogen :

- Measurement of σ and π

- Constraints on SME coefficients