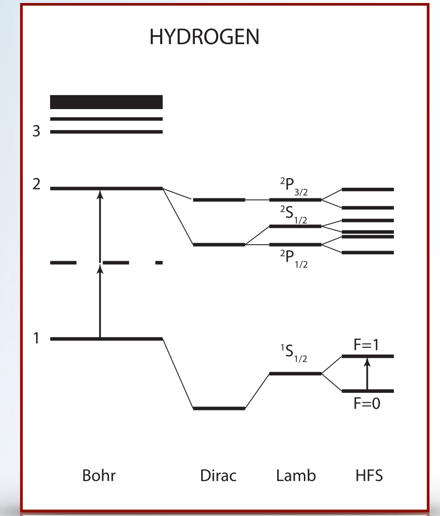

MEASUREMENT OF THE HYDROGEN HYPERFINE SPLITTING : RESULTS & PROSPECTS

Chloé Malbrunot [1,2]

[1] CERN, Geneva, SWITZERLAND

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

MOTIVATIONS

10 000 000 001	10 000 000 000
MATTER	ANTIMATTER

MOTIVATIONS

10 000 000 001

MATTER

10 000 000 000

ANTIMATTER

MOTIVATIONS

10 000 000 001

MATTER

10 000 000 000

ANTIMATTER

PRECISION

NEUTRALITY

MOTIVATIONS

CPT Theorem

Quantum Field Theory

Lorentz invariance

Locality

Unitarity

MOTIVATIONS

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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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Atomic structures identical

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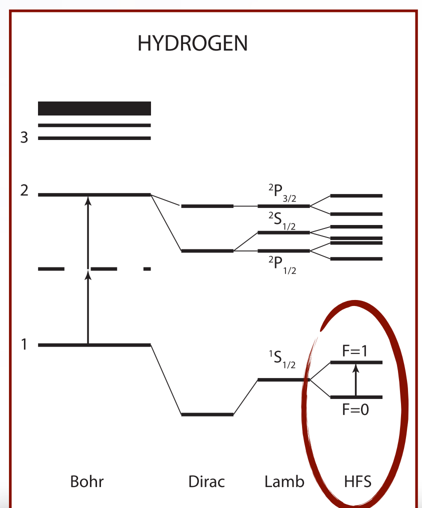
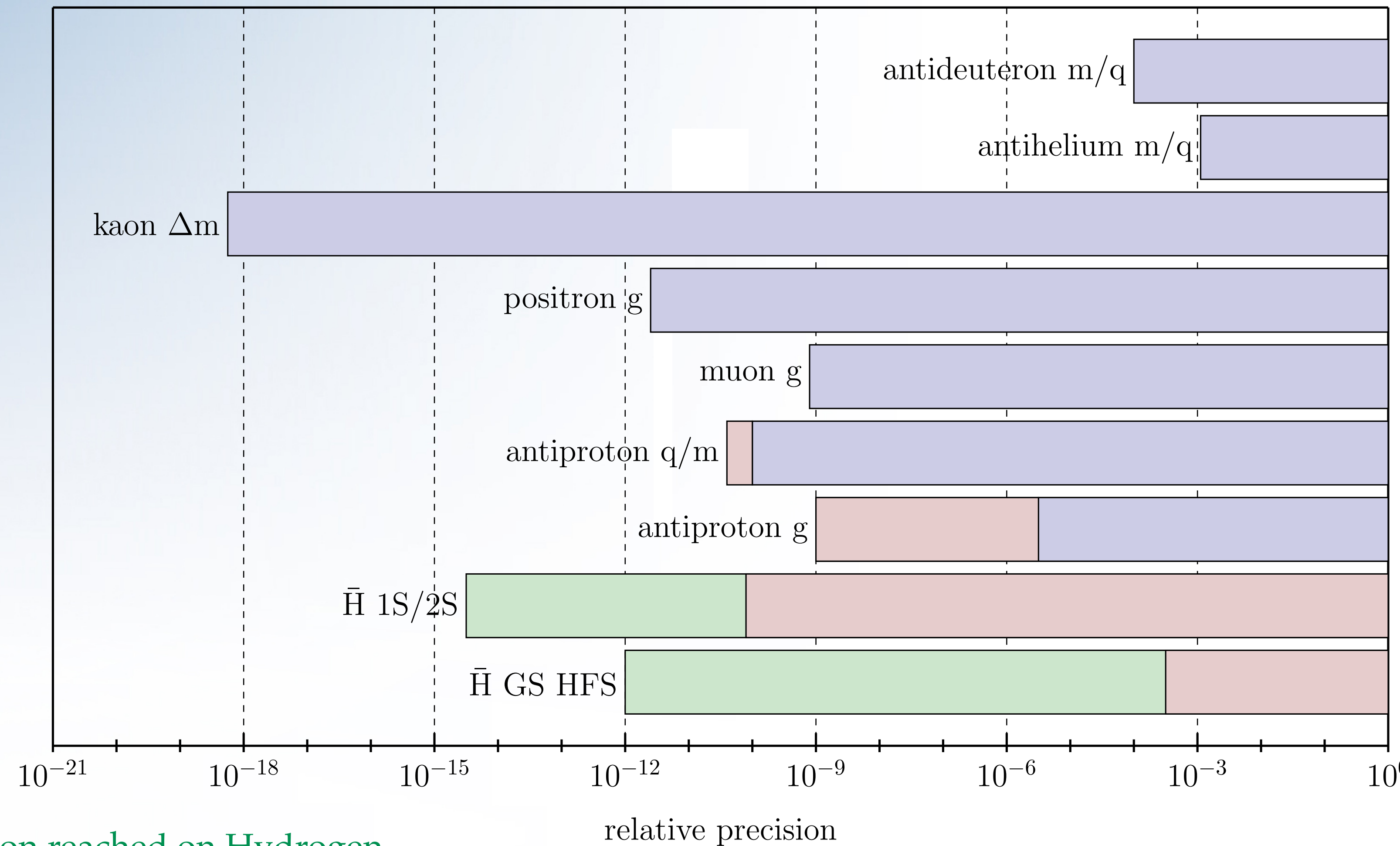


MOTIVATIONS

Tests in different systems:



Precision reached on Hydrogen
Recent publications (2017)
Past measurements

MOTIVATIONS

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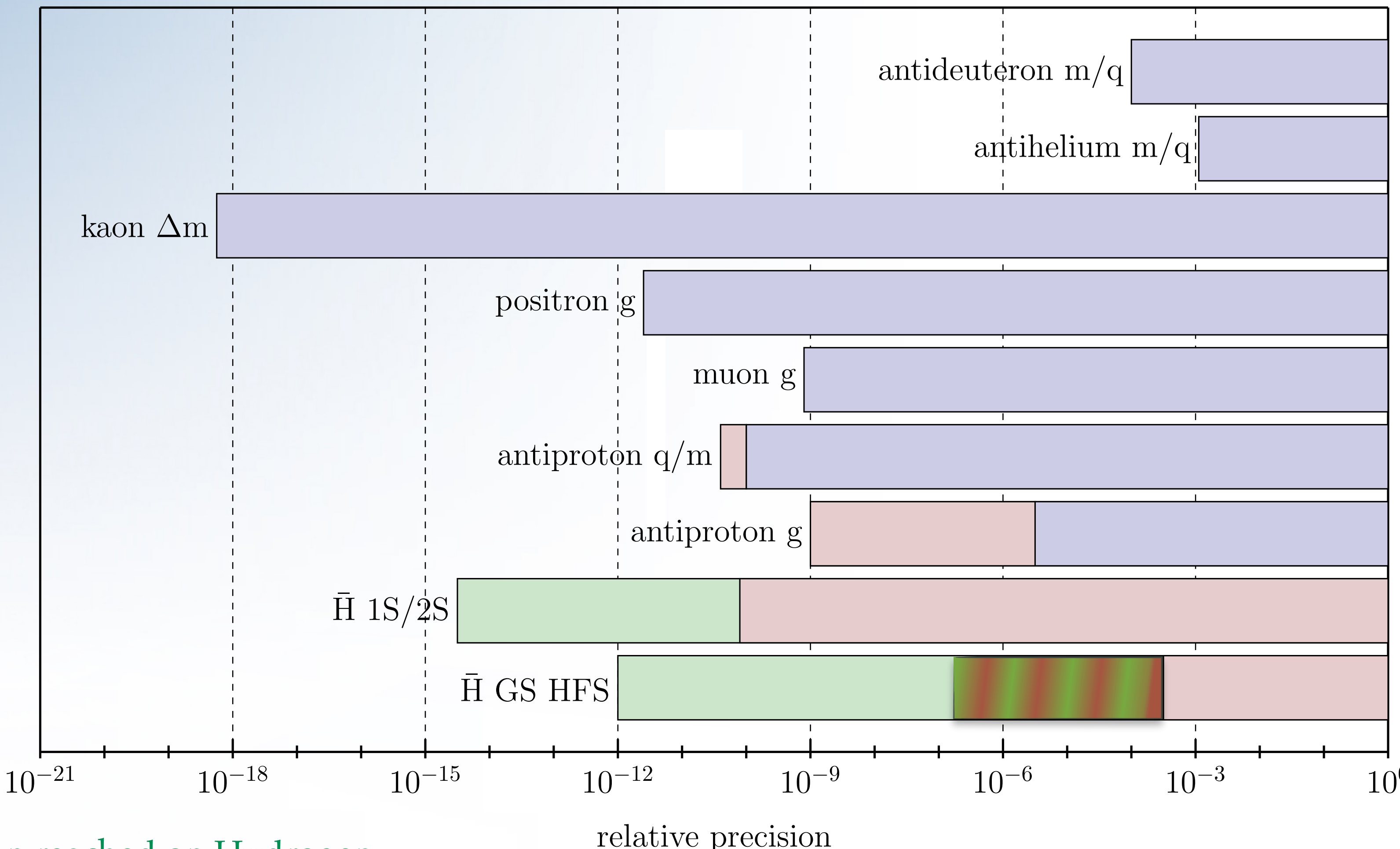


Precision reached on Hydrogen

Recent publications (2017)

Past measurements

MOTIVATIONS

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

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 1.5 ppb

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

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

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

access to the electric and magnetic form factors of the antiproton

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

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)

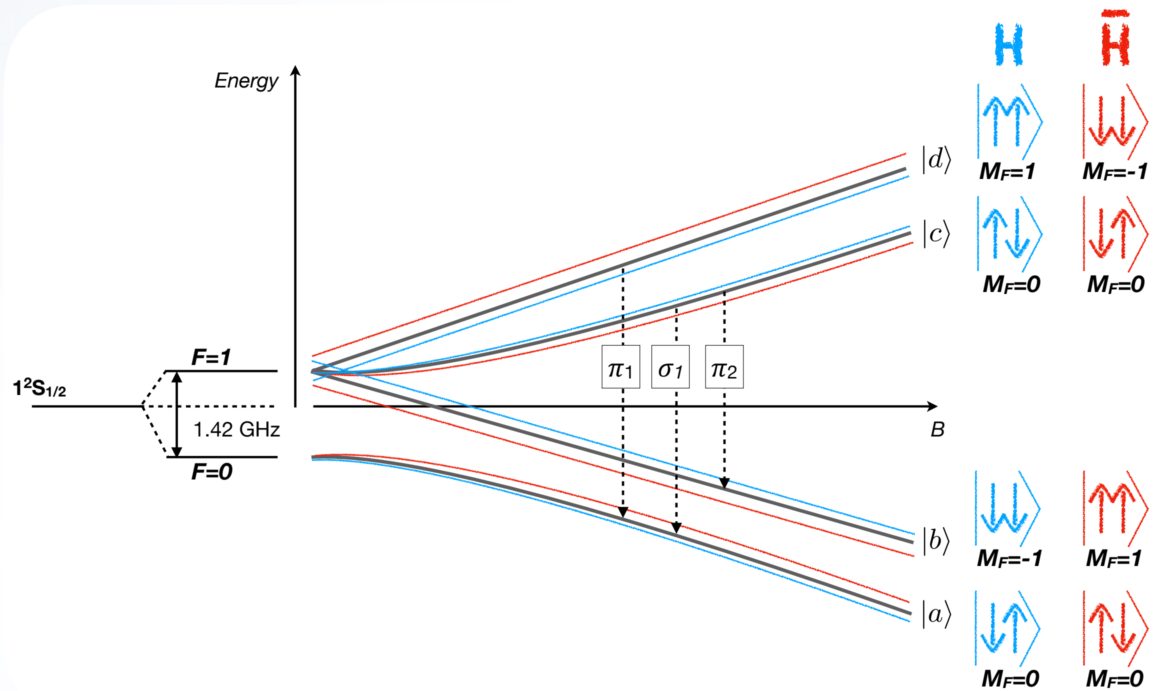
Dirac equation in mSME : $$(i\gamma^\mu D_\mu - m_e - a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu - \frac{1}{2} H^e_{\mu\nu} \sigma^{\mu\nu} + i c^e_{\mu\nu} \gamma^\mu D^\nu + i d^e_{\mu\nu} \gamma_5 \gamma^\mu D^\nu)\psi = 0$$

Effective field theory developed as a theoretical background for Lorentz violation search.

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

MOTIVATIONS

Measure ν_{HF} : several options



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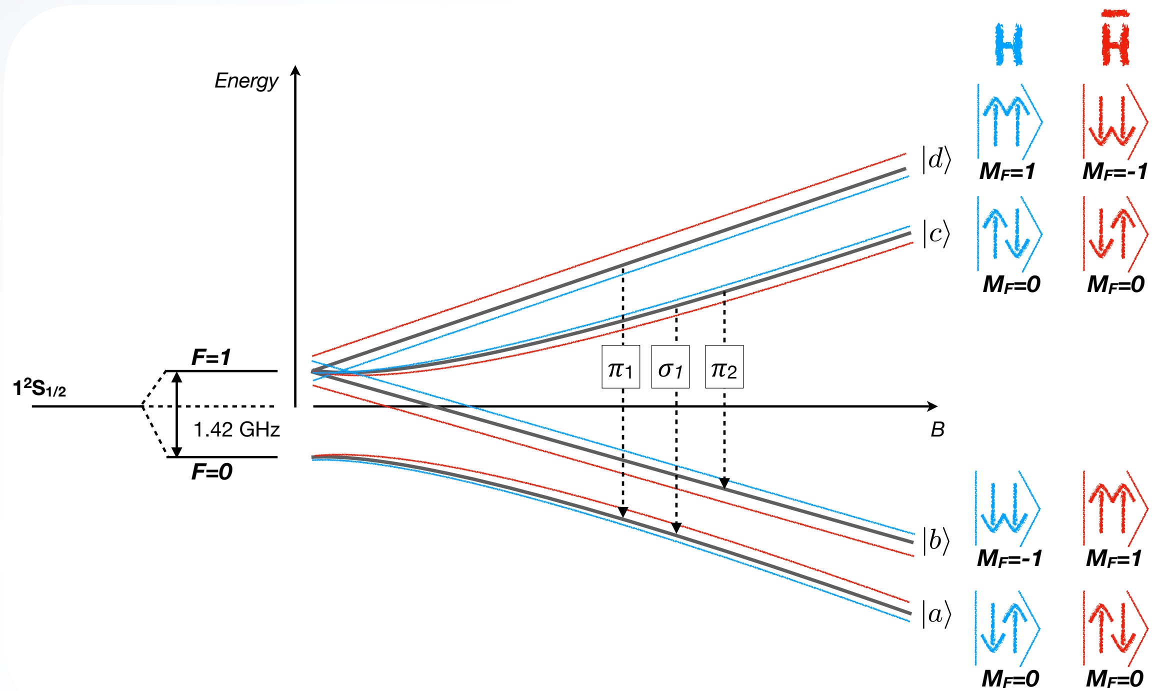
➡ π_1 - π_2 at a given B field

➡ π_1 and σ_1 at a given B field

➡ Extrapolate either transition from several measurements at different fields



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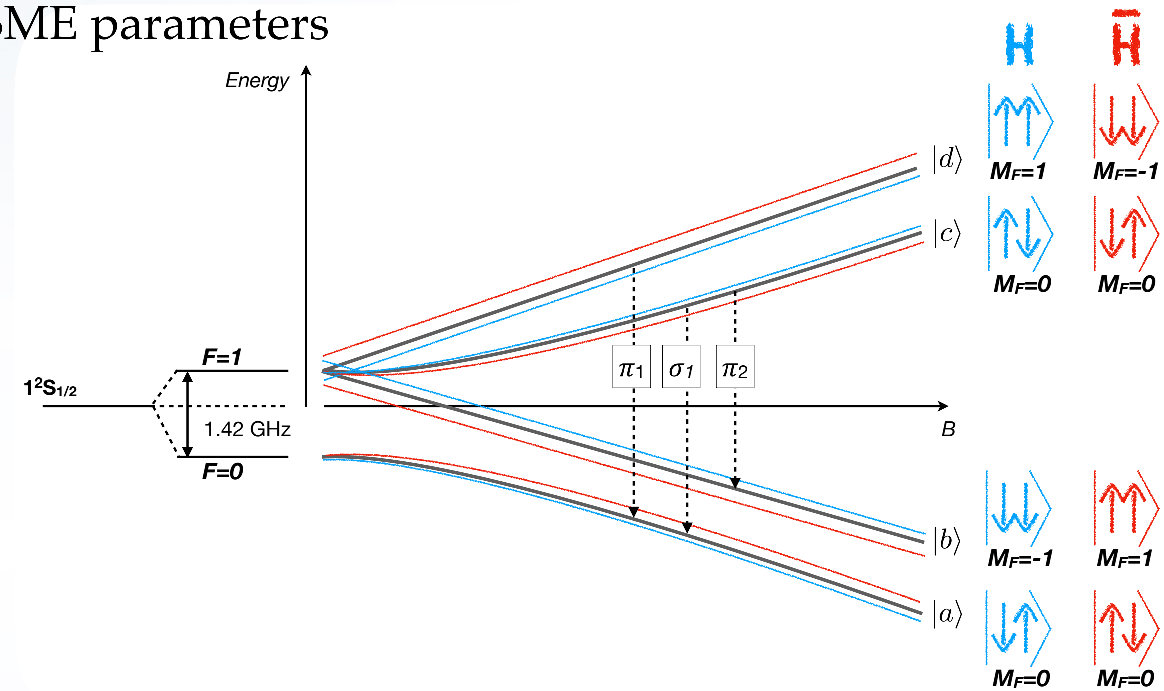
But NOT all constrain SME parameters



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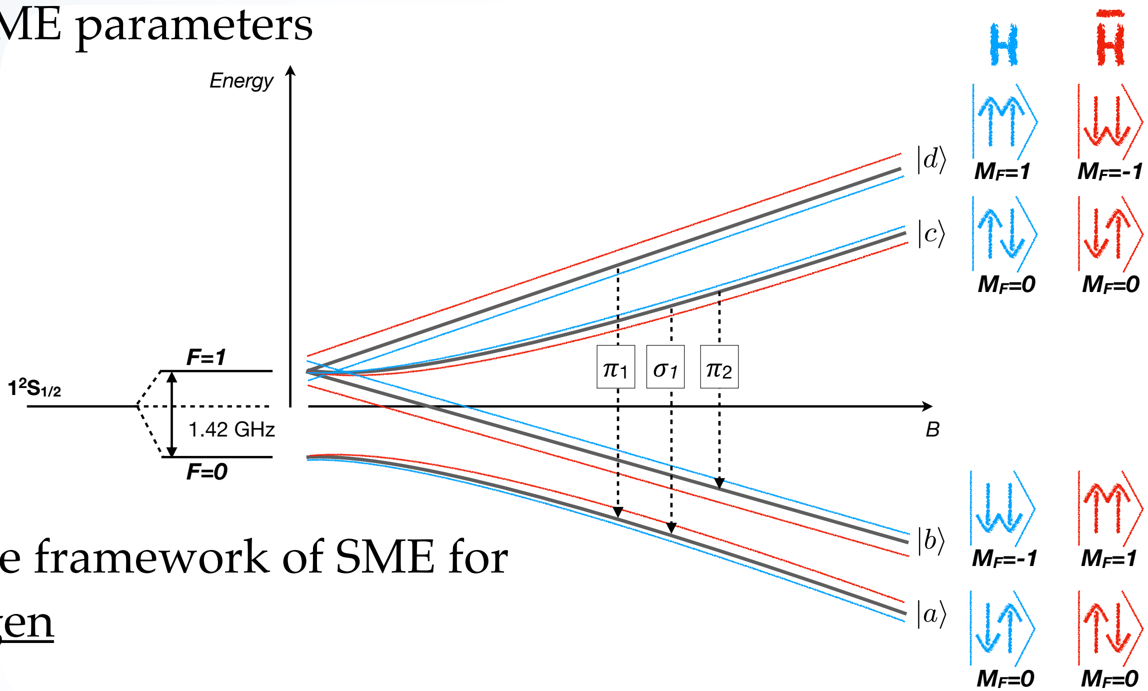
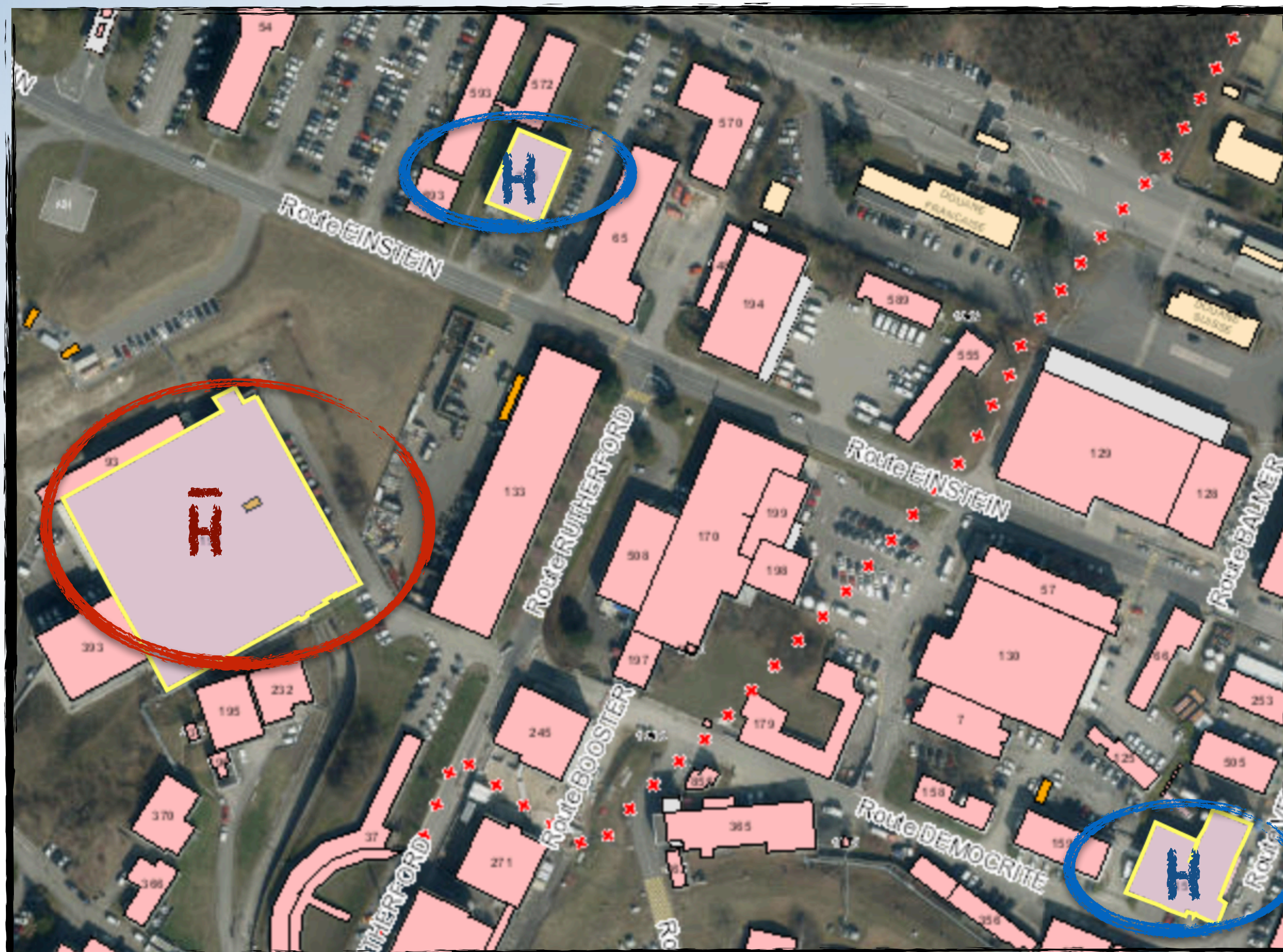
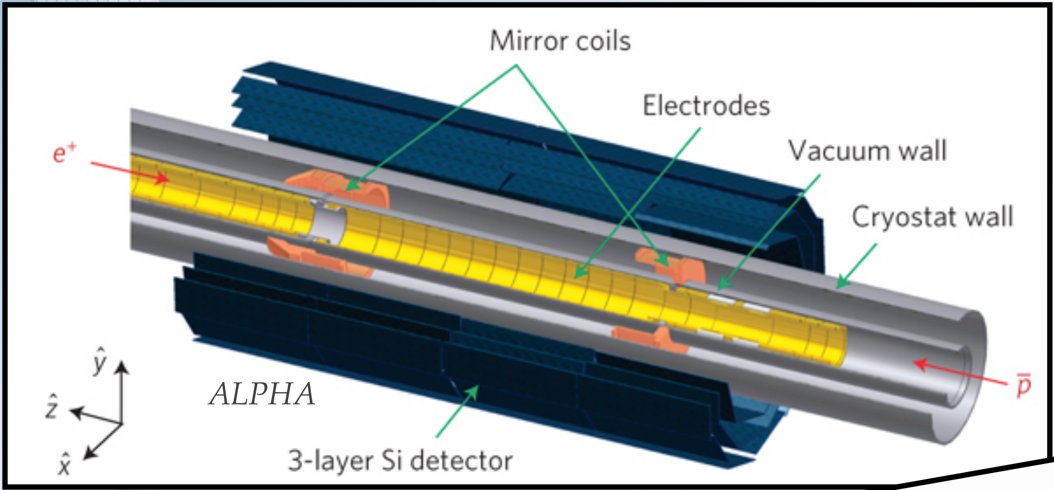


Measurements motivated in the framework of SME for both <u>hydrogen</u> and <u>antihydrogen</u>

ASACUSA HYDROGEN & ANTIHYDROGEN EXPERIMENTS



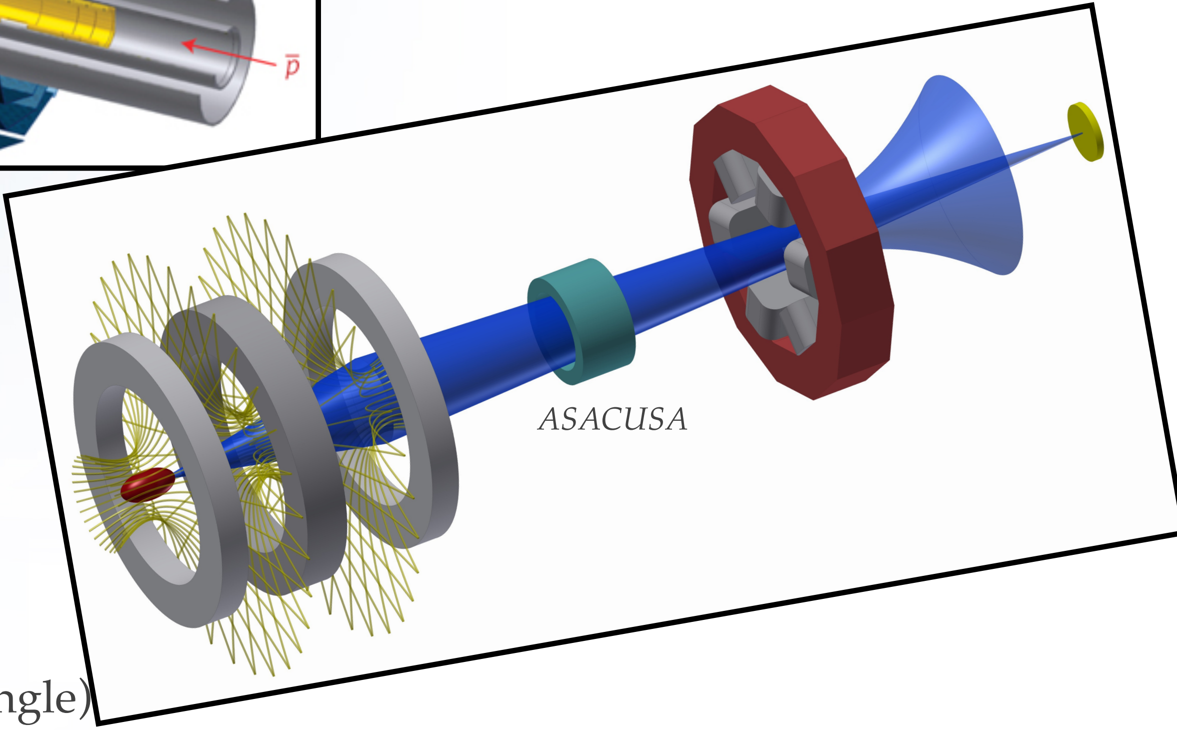
BEAM VS. TRAP



Advantage of beam:

Absence of strong field gradient

Lower requirement on the temperature of antihydrogen atoms



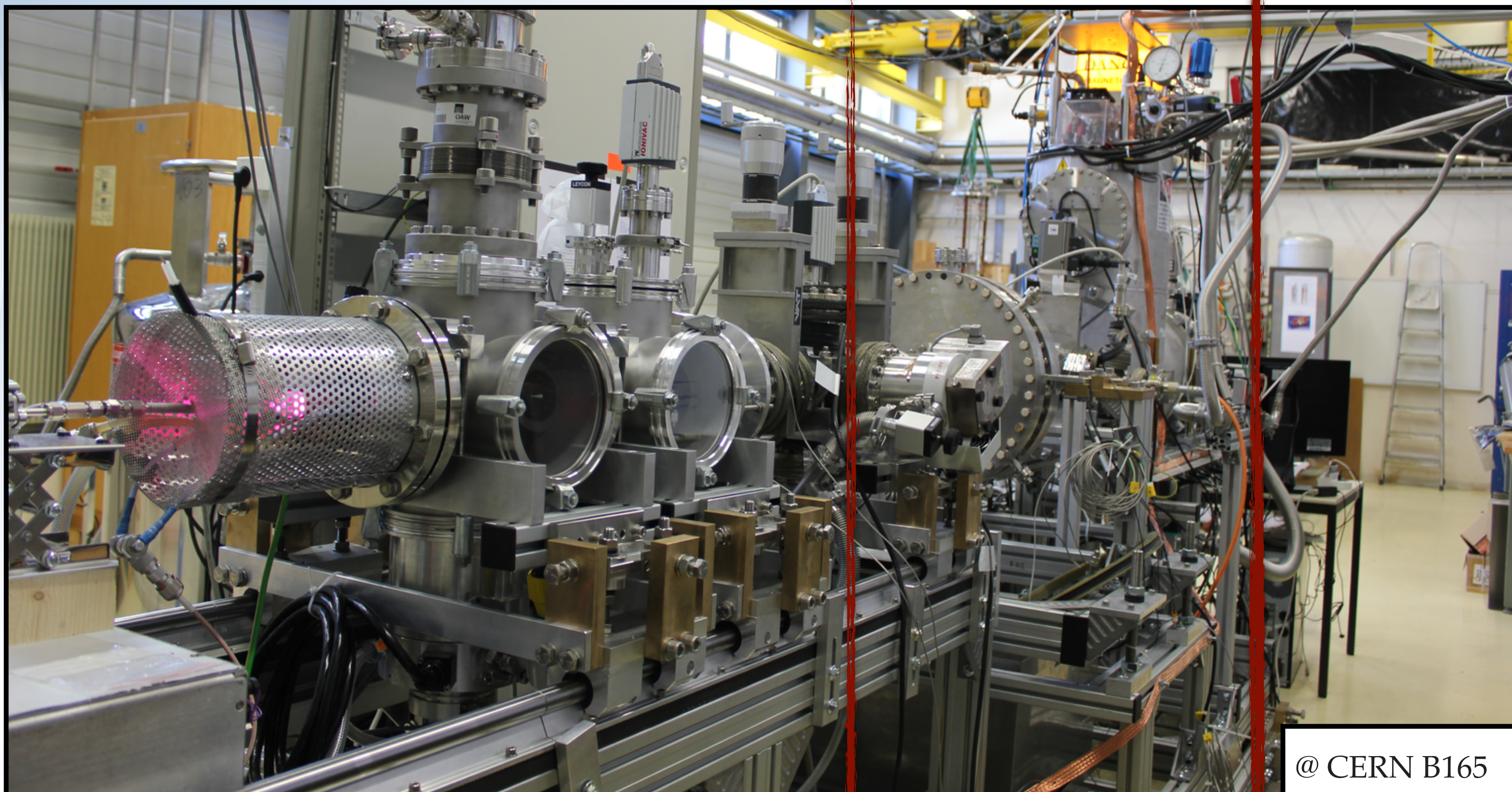
Inconvenient of beam:

Need "focussing" (loss of solid angle)

Cannot easily control the quantum state at the detector

More difficult to control the polarization

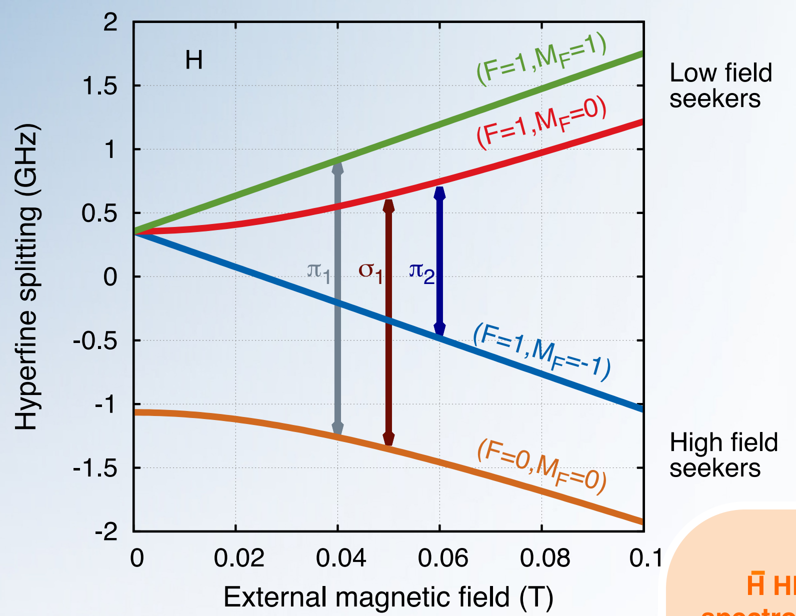
1ST HYDROGEN SETUP

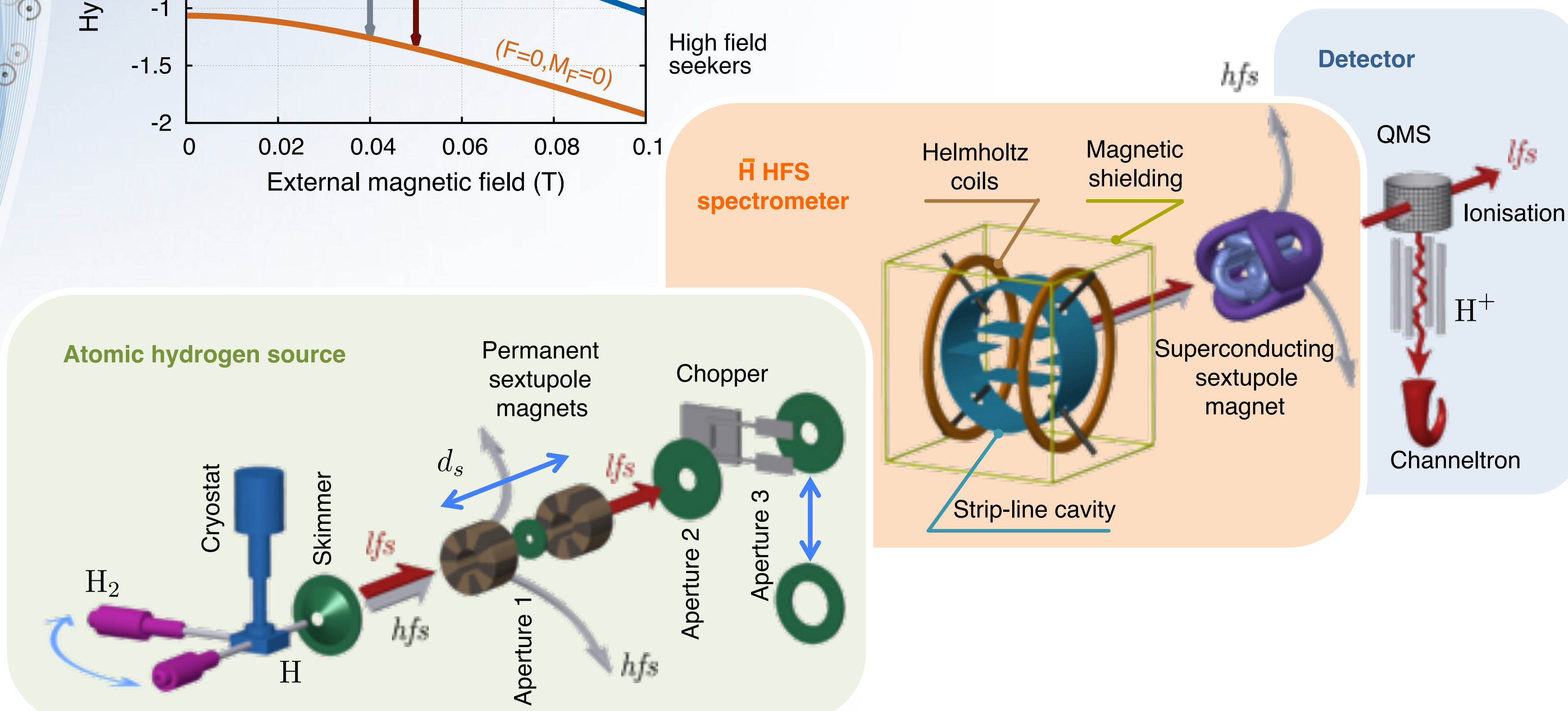


@ CERN B165

Antihydrogen spectroscopy apparatus

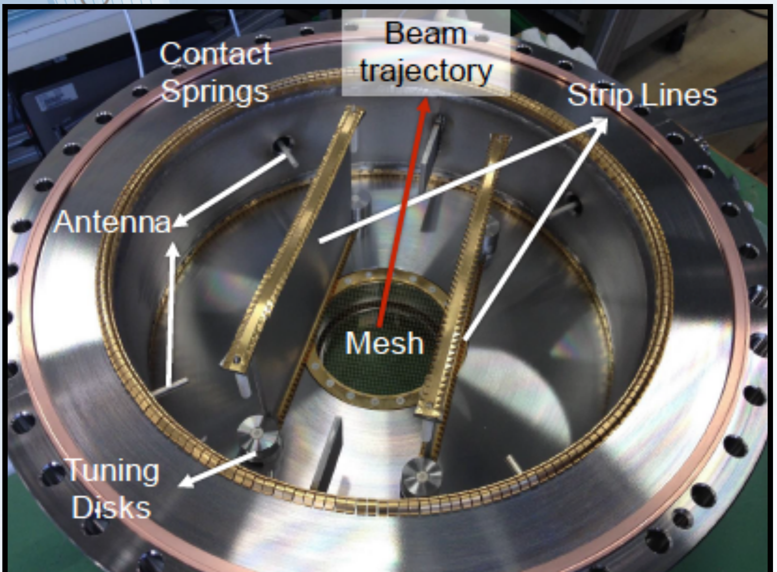
1ST HYDROGEN SETUP

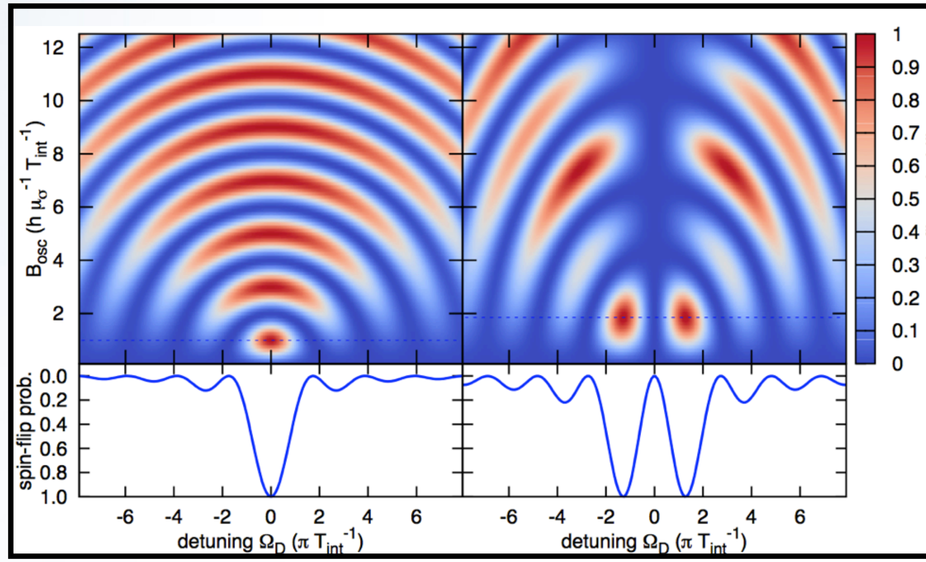


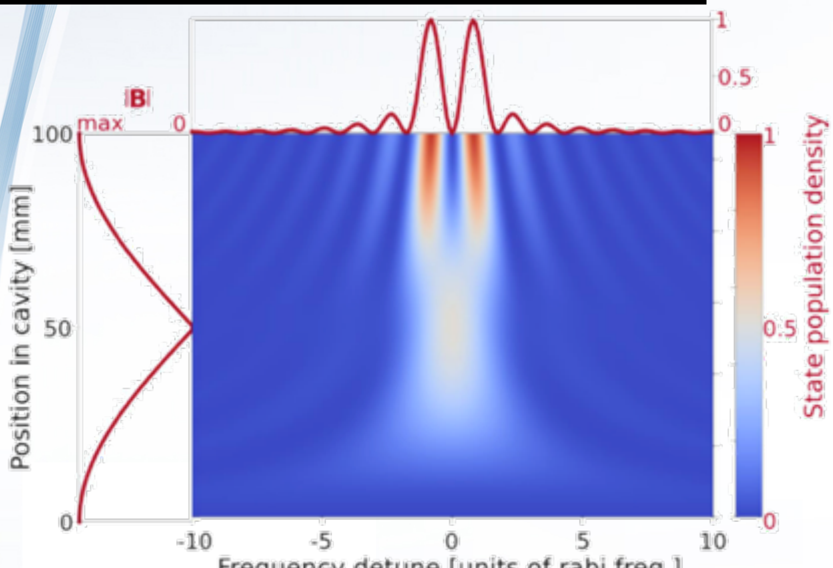


1ST HYDROGEN SETUP

"strip-line" cavity design







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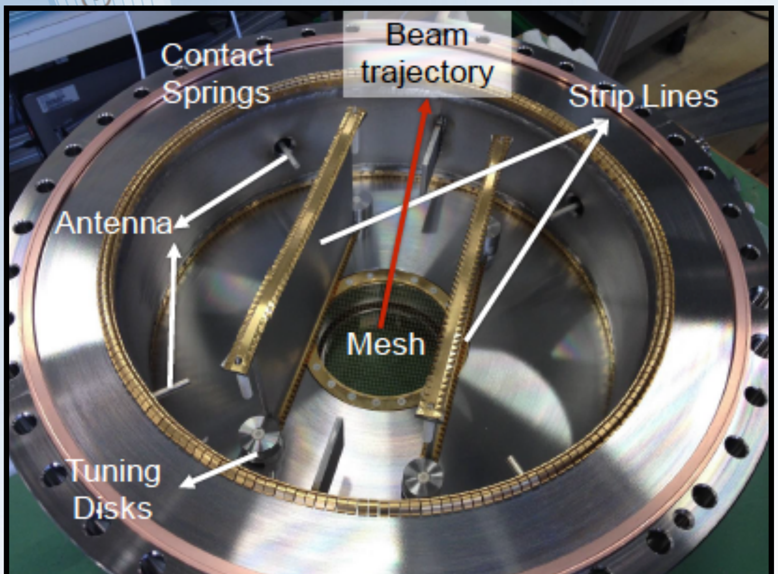
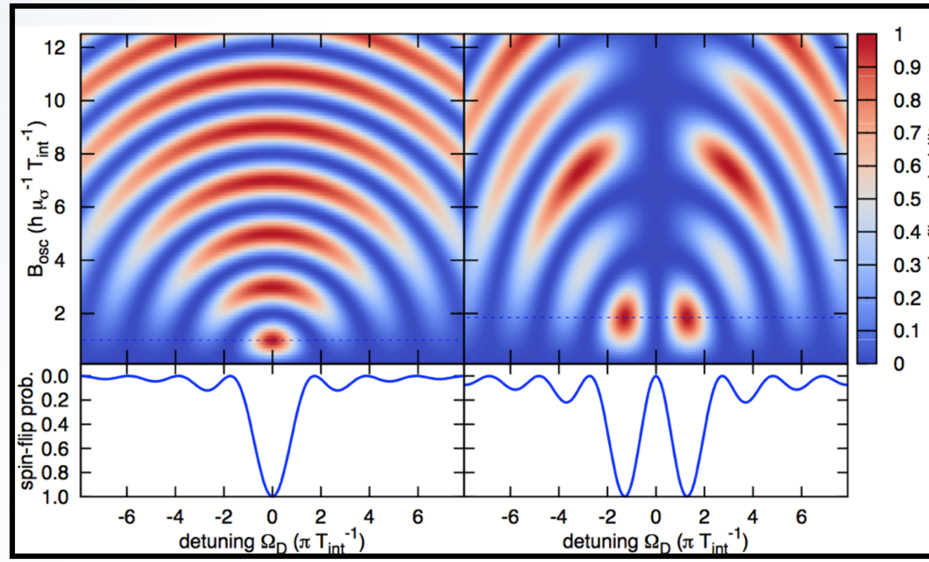
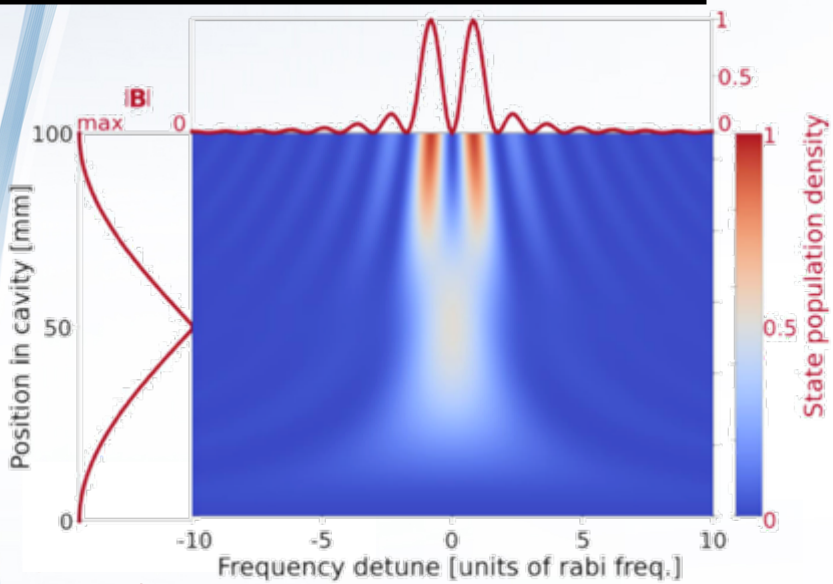
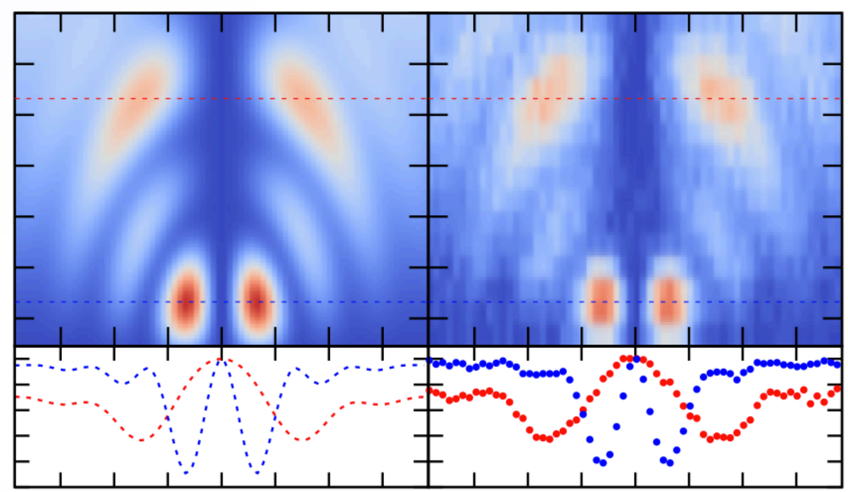
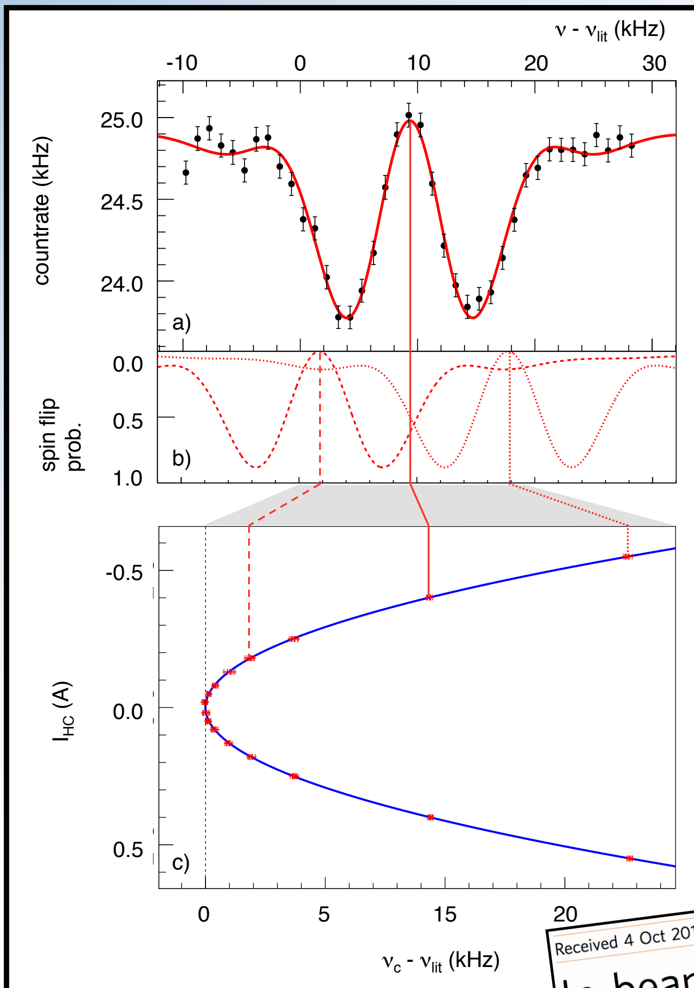








σ MEASUREMENT



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

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

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 and ready for $\bar{H}$ spectroscopy

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 antihydrogen should be in reach if enough statistics can be gathered

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

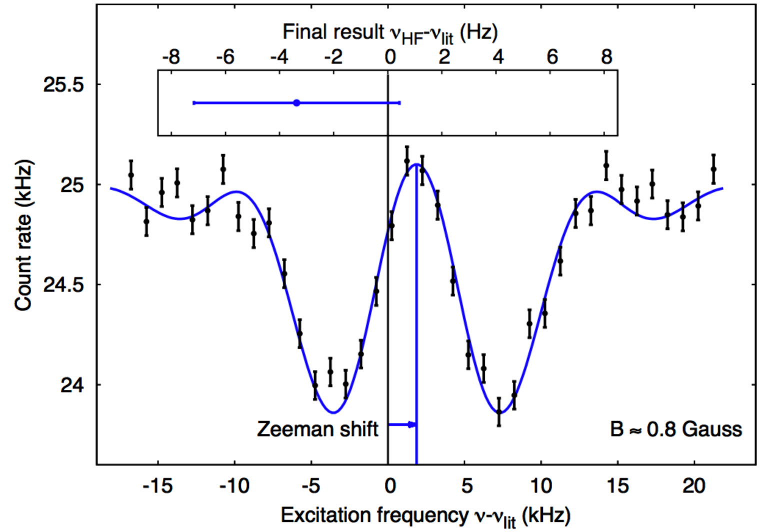
line-shape dependent factor

error bar of a data point

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 ppm measurement using 4 resonances we estimate ~ 8000 atoms should be recorded at the antihydrogen detector

➠ need to increase the $\bar{H}$ rate at the detector by > 1 order of magnitude

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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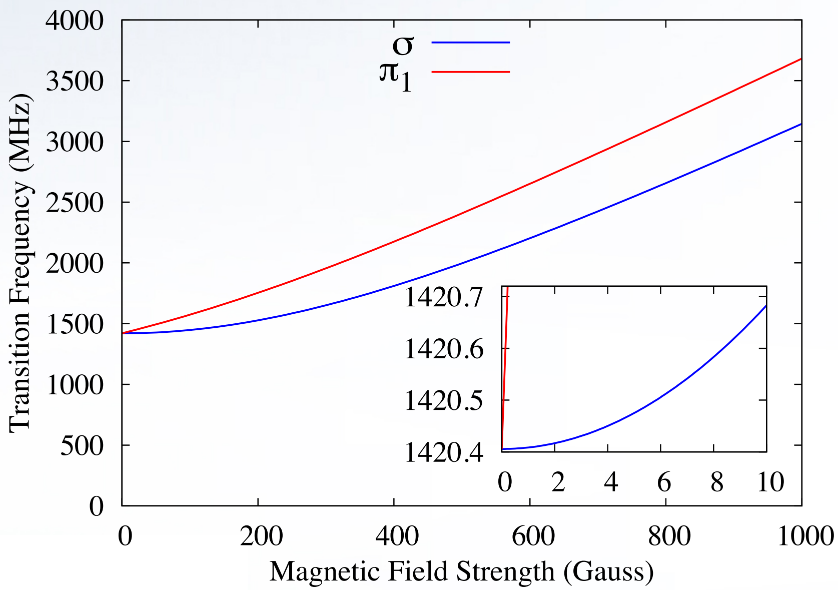

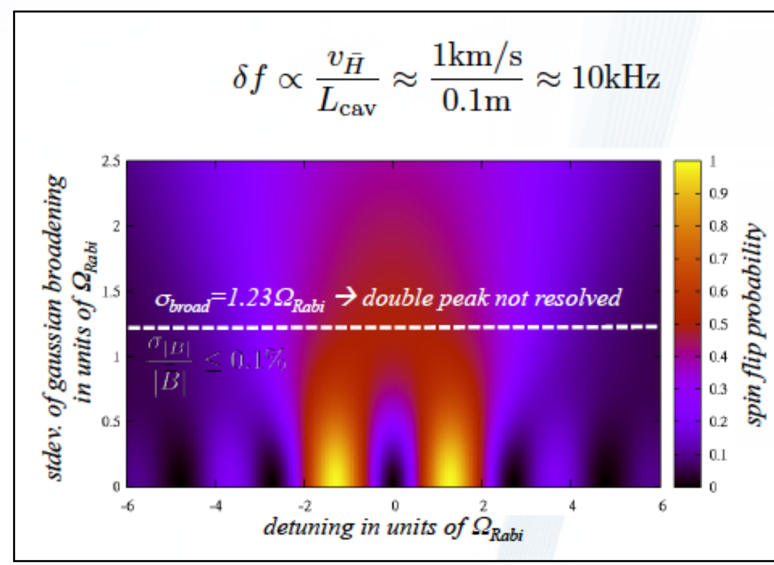

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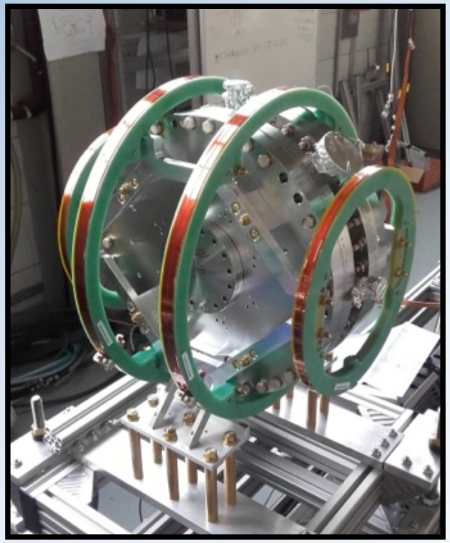
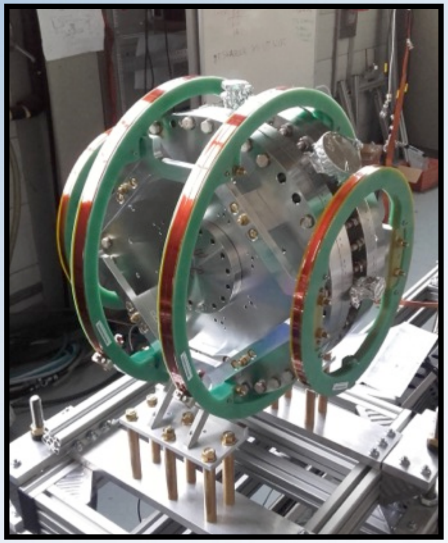


Helmohlz coils with corrections coils

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

π MEASUREMENT



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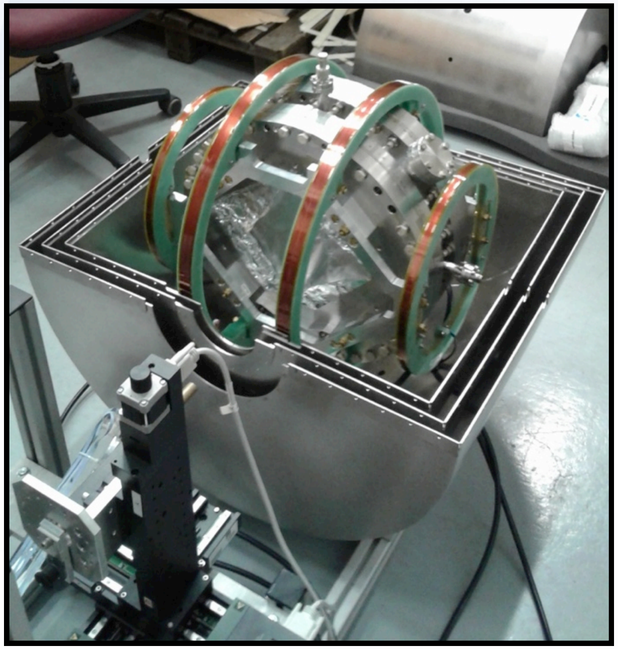
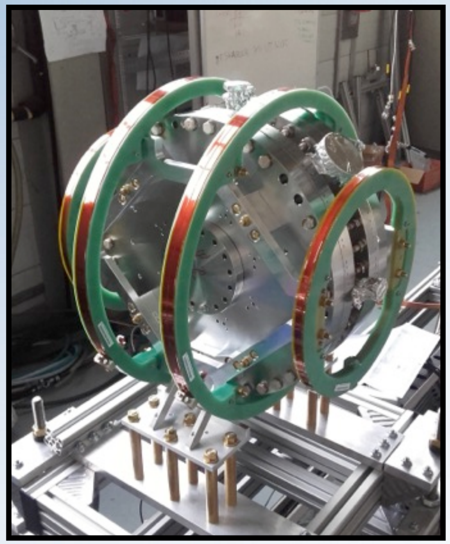


3-layers cylindrical shielding

π MEASUREMENT



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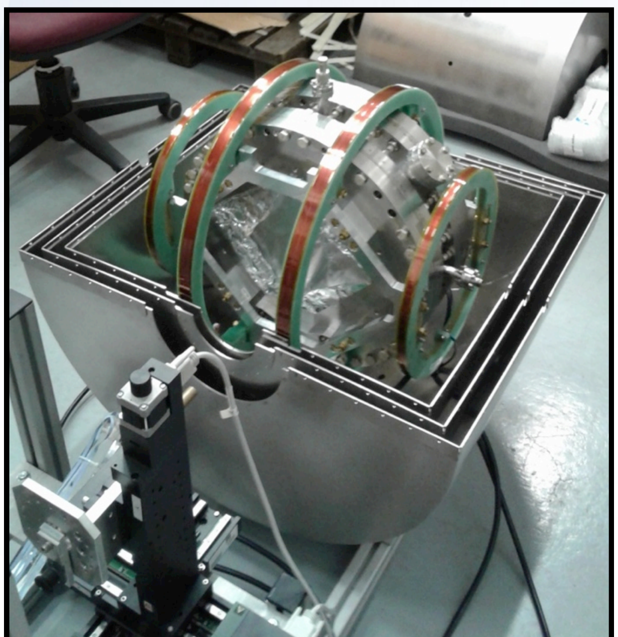

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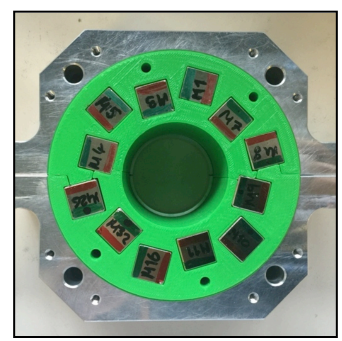

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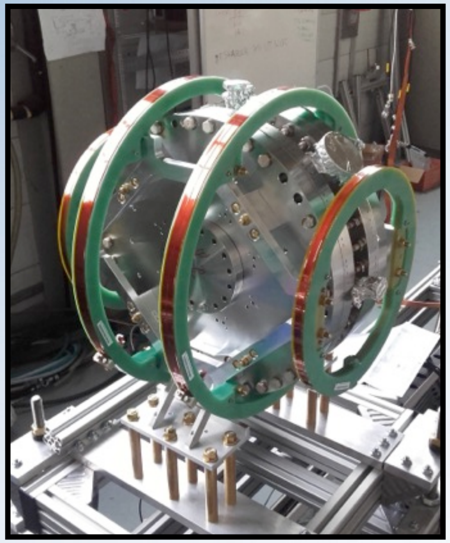

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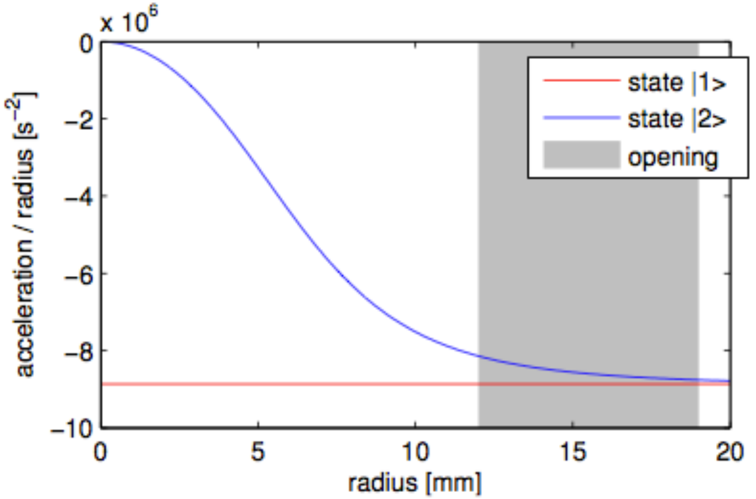

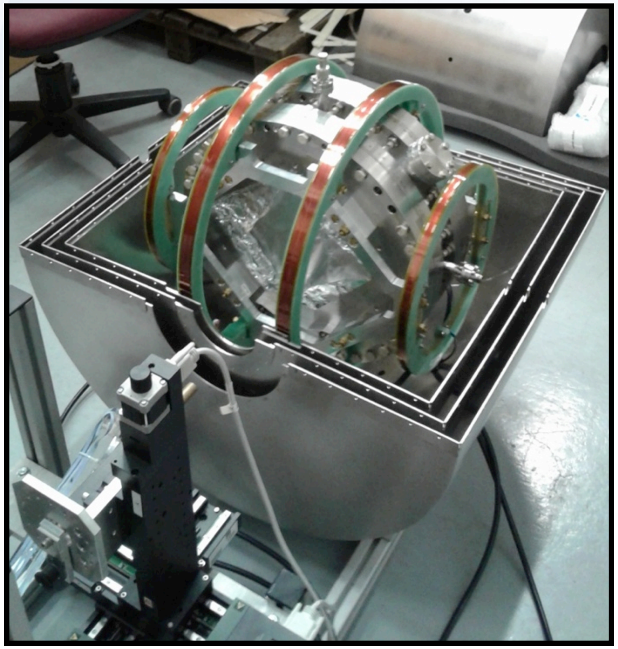

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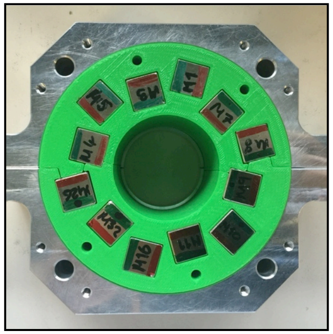
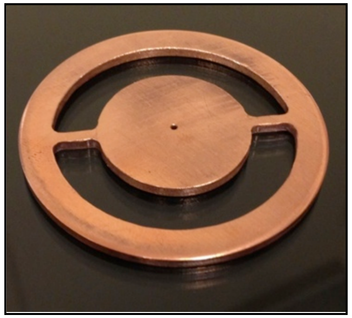
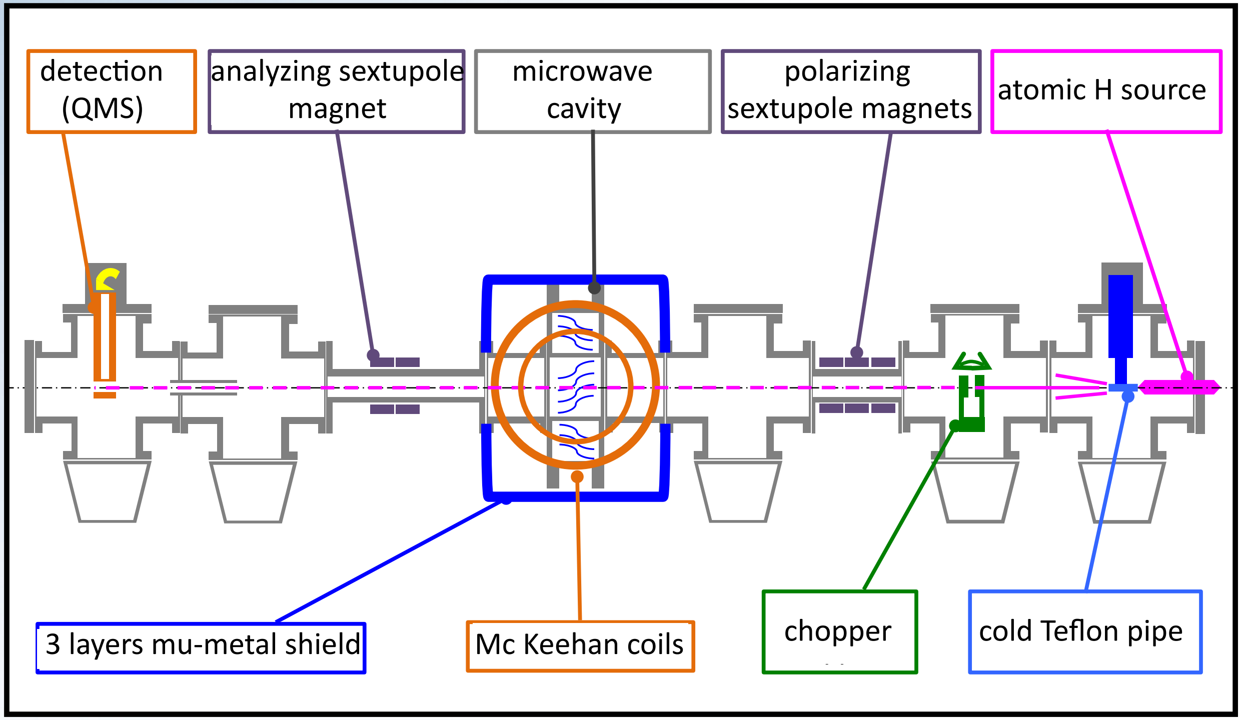
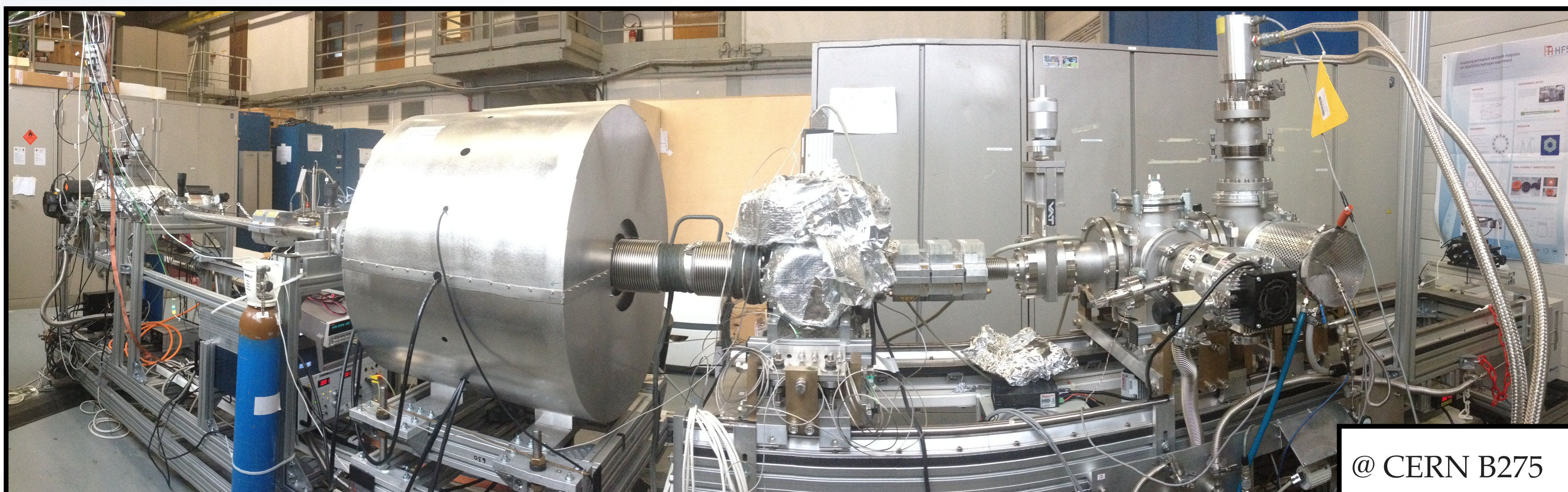


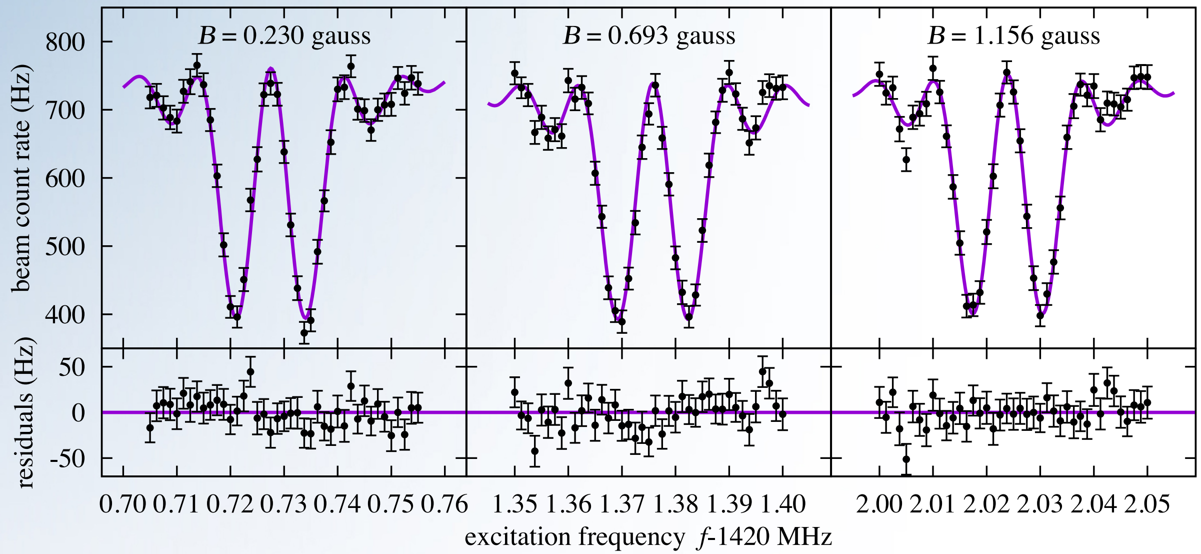


2ND HYDROGEN SETUP





π MEASUREMENT



"Simultaneous" measurement of π_1 and σ_1 ➠ **ppb** precision reached!

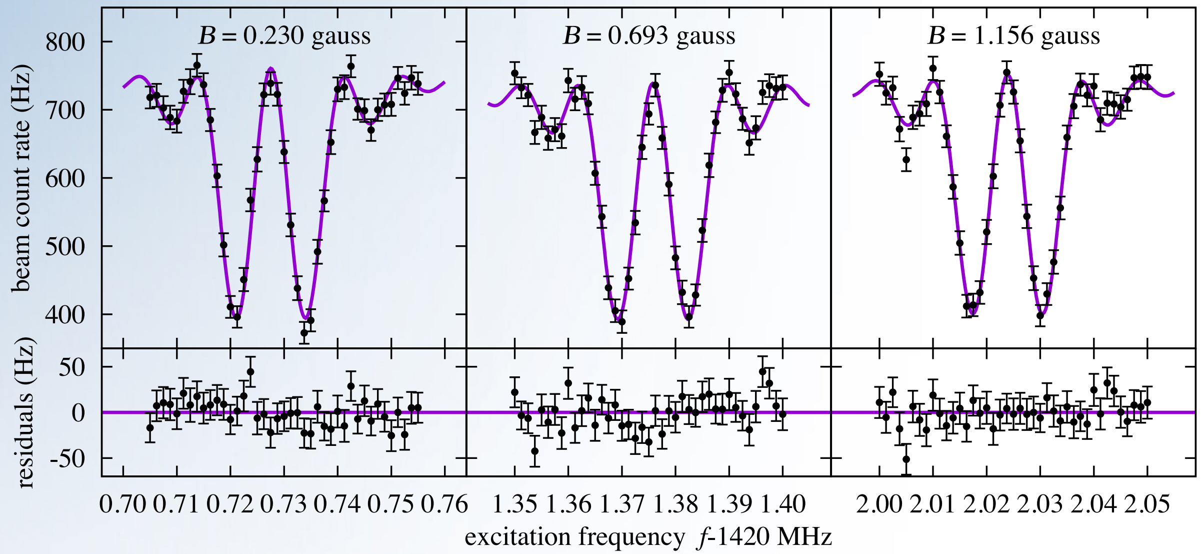
$$\nu_{\sigma_1} = \frac{E_2 - E_4}{h} = \frac{E_0}{h}\sqrt{1 + \frac{(g_J - g_I)^2 \mu_B^2 B^2}{E_0^2}}$$

$$\nu_{\pi_1} = \frac{E_1 - E_4}{h} = \left(\frac{E_0}{2} + \frac{1}{2}(g_J + g_I)\mu_B B + \frac{E_0}{2}\sqrt{1 + \frac{(g_J - g_I)^2 \mu_B^2 B^2}{E_0^2}}\right) \cdot \frac{1}{h}$$

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

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

π MEASUREMENT



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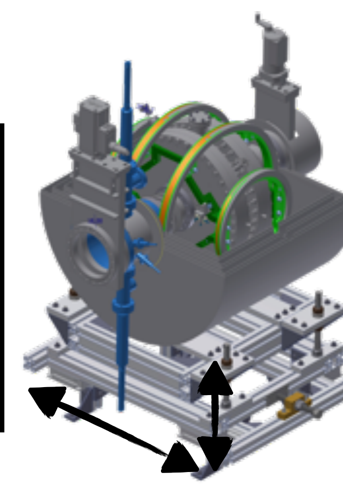


This new apparatus will be used for further systematic studies for $\bar{\mathrm{H}}$ experiment

SME MEASUREMENTS

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)

coefficients in the lab-frame are associated with three independent coefficients in the Sun-centred frame :

$$\mathcal{K}^{Lab}_{w_{k10}} = \mathcal{K}^{Sun}_{w_{k10}} \cos(\theta) - \sqrt{2}\,\Re e(\mathcal{K}^{Sun}_{w_{k11}}) \sin(\theta) \cos(\omega_\oplus T_\oplus) + \sqrt{2}\,\Im m(\mathcal{K}^{Sun}_{w_{k11}}) \sin(\theta) \sin(\omega_\oplus T_\oplus)$$

angle between B-field and Earth's rotational axis

Earth rotation frequency

sidereal time

72 SME coefficients involved. 48 constrained, 24 remaining and can be constrained by swapping the direction of the static B-field and measuring π_1 while using σ_1 as a proxy

$$2\pi\delta\nu(\Delta M_F) = \frac{\Delta M_F}{2\sqrt{3\pi}} \sum_{q=0}^{2} (\alpha m_r)^{2q}\,(1+4\delta_{q2}) \sum_{w} \left[-g^{0B}_{w(2q)10} + H^{0B}_{w(2q)10} - 2g^{1B}_{w(2q)10} + 2H^{1B}_{w(2q)10}\right]$$

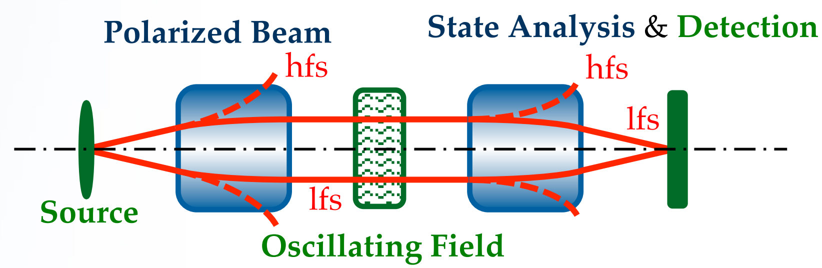
ppb foreseen (Hz level precision) in a first stage :

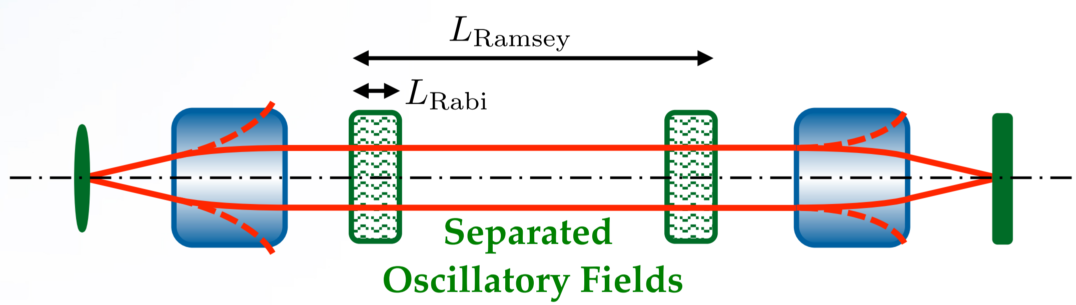
Improvement possible with slower beam, Ramsey method, higher count rate

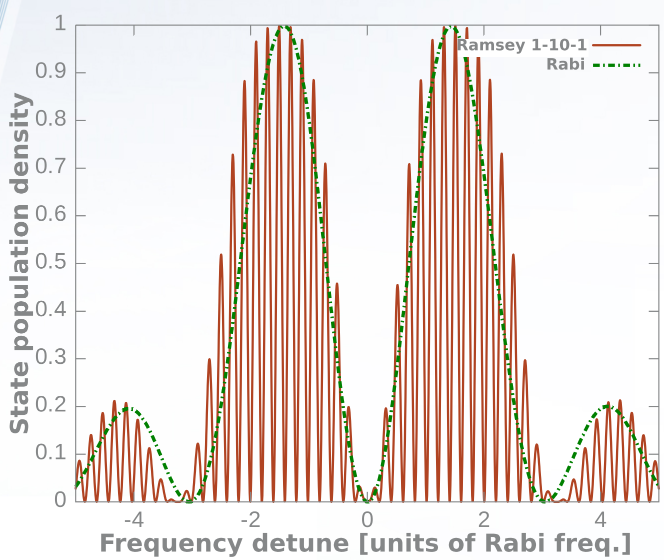
TOWARDS HIGHER PRECISION

- Ramsey's separated oscillatory field method

$$\delta\nu \propto \tau_{\text{int}}^{-1} = \frac{v_{\text{beam}}}{L_{\text{Osc.F.}}}$$

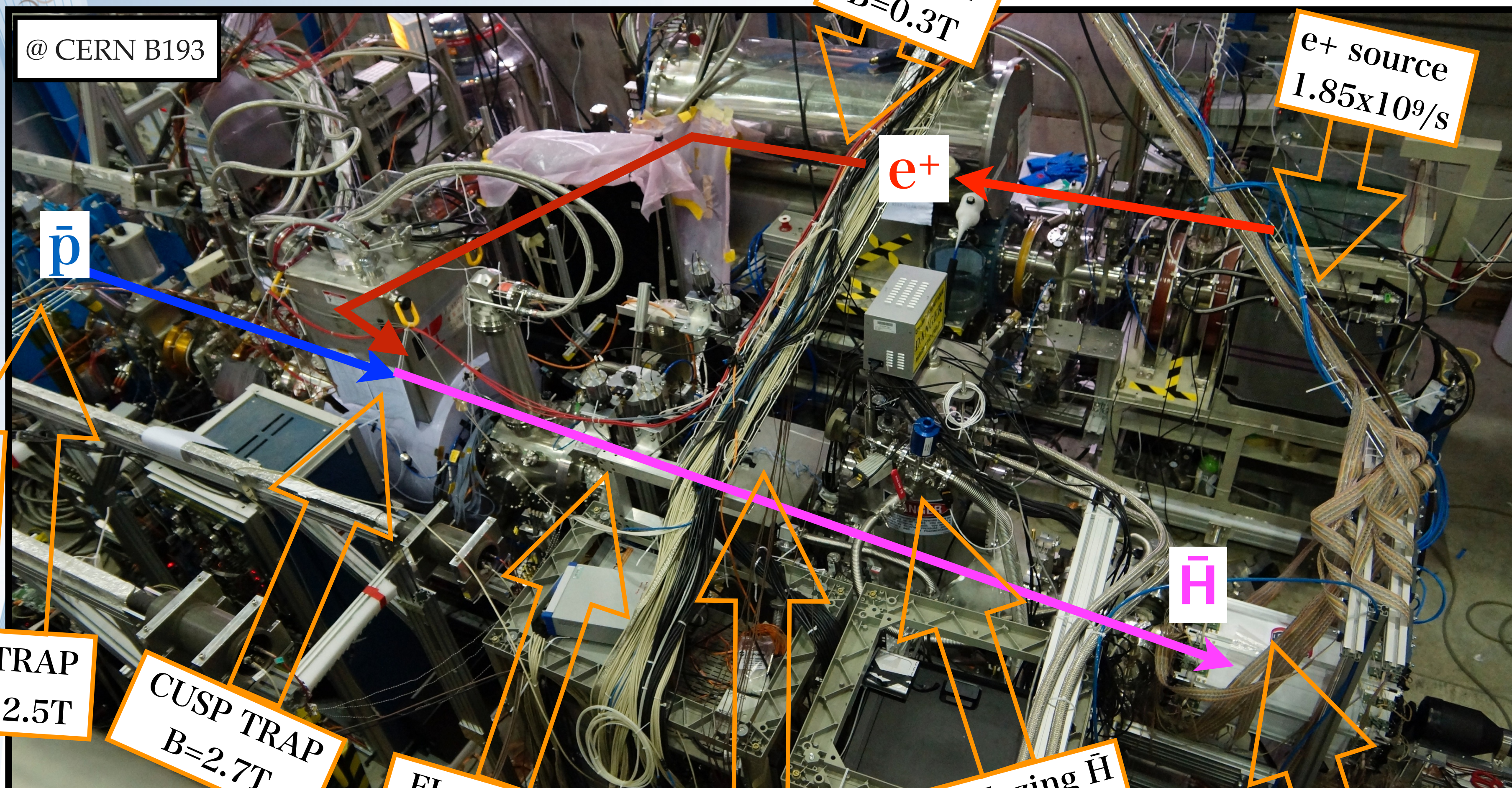




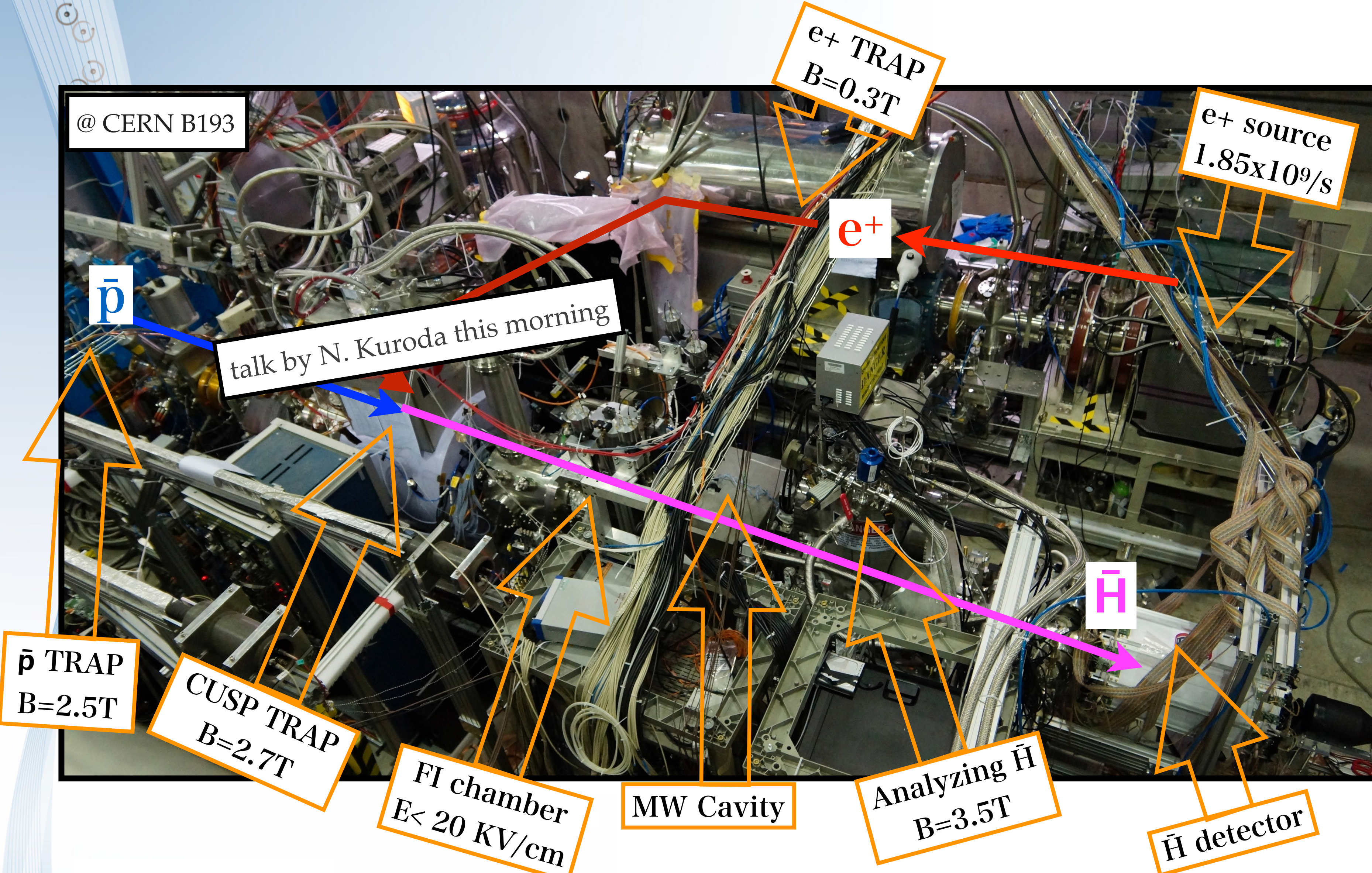


- New cavity design studies on-going

ANTIHYDROGEN SETUP



ANTIHYDROGEN SETUP



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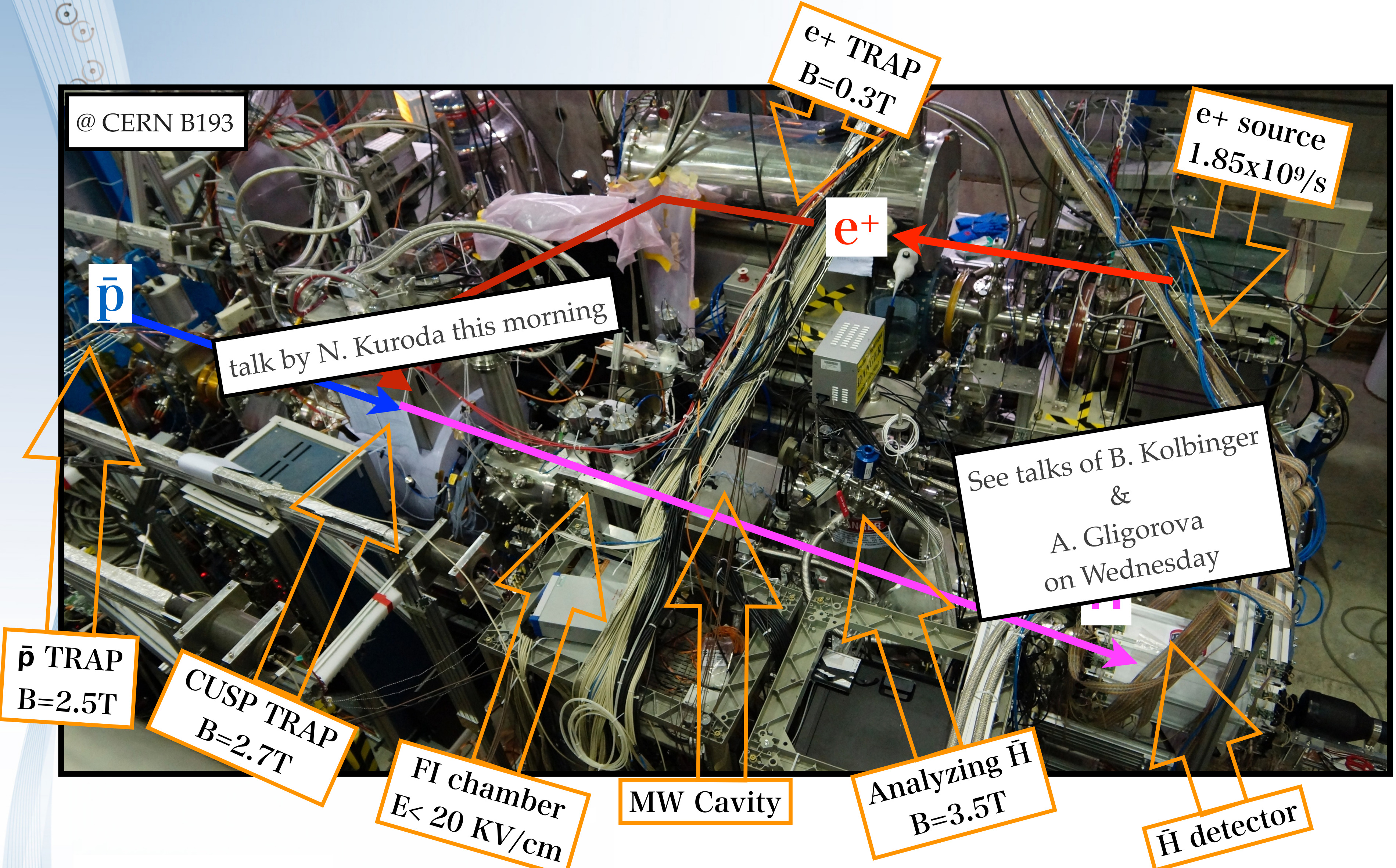
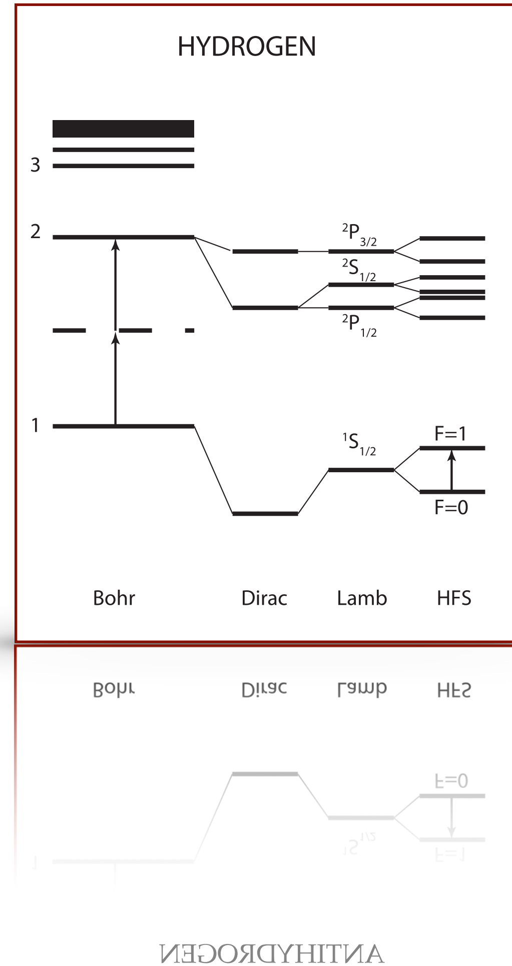


CONCLUSIONS

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

- Further assessment of potential systematics for $\bar{H}$ measurement

- Constraints on SME coefficients

ASACUSA-CUSP COLLABORATION & FUNDING