ÖAW AUSTRIAN ACADEMY OF SCIENCES

SMI – STEFAN MEYER INSTITUTE

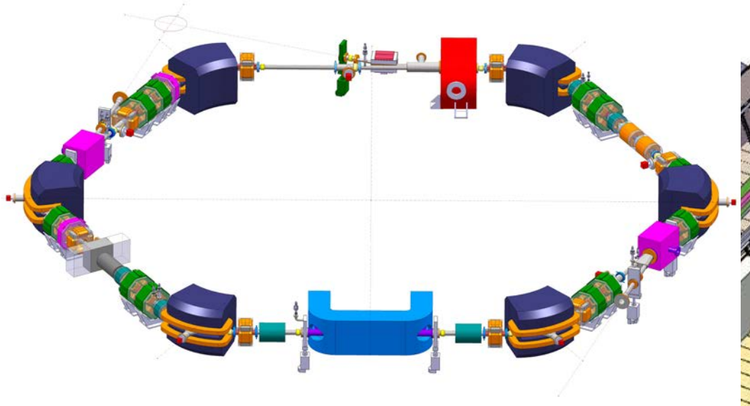
In-beam hyperfine spectroscopy of (anti)hydrogen

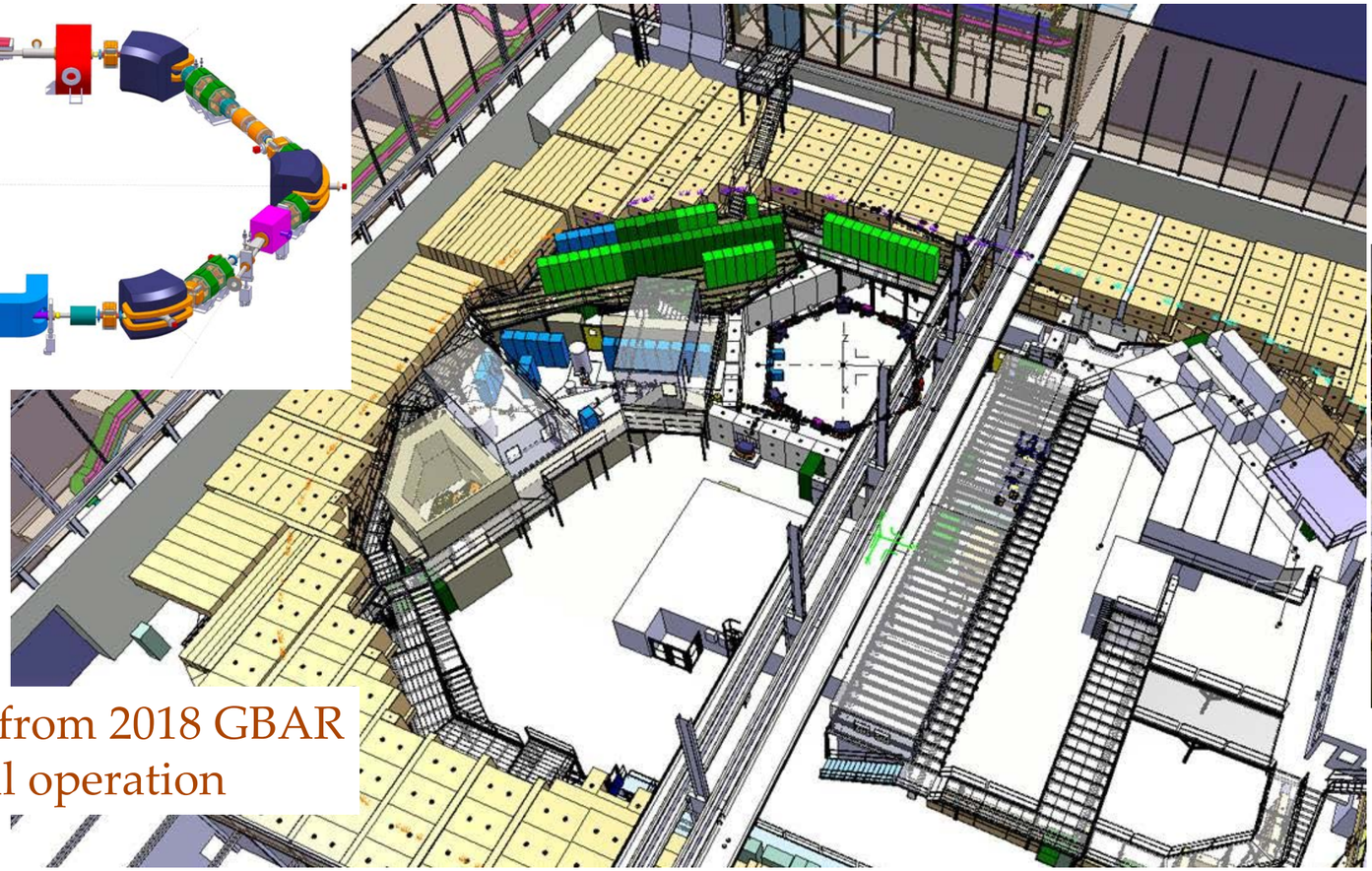
E. Widmann

Stefan Meyer Institute, Vienna

SSP2018 Aachen 11 Jun 2018

Antiproton Decelerator & ELENA @ CERN



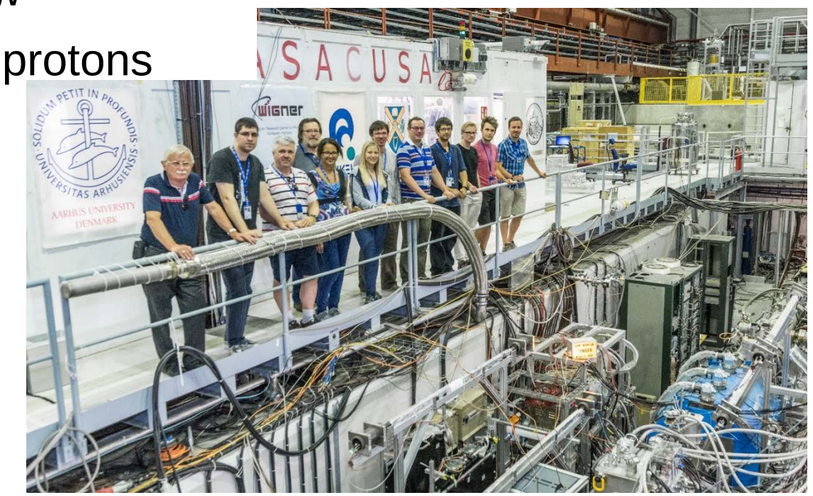


AD: 5 MeV
ELENA: 5 MeV → 100 keV
Pulsed beam, 3×10^7 $\bar{p}$ every ~ 100 s

ELENA operation from 2018 GBAR
2021 (after LS2) full operation

ASACUSA collaboration

A tomic
S pectroscopy
A nd
C ollisions
U sing
S low
A ntiprotons



ASACUSA Scientific projects

(1) Spectroscopy of $\bar{p}He$

(2) $\bar{p}$ annihilation cross-section

(3) $\bar{H}$ production and spectroscopy

The Antihydrogen team

University of Tokyo, Komaba: N. Kuroda, T. Matsudate, M. Tajima, Y. Matsuda

RIKEN: P. Dupré, Y. Kanai, Y. Nagata, B. Radics, S. Ulmer, Y. Yamazaki

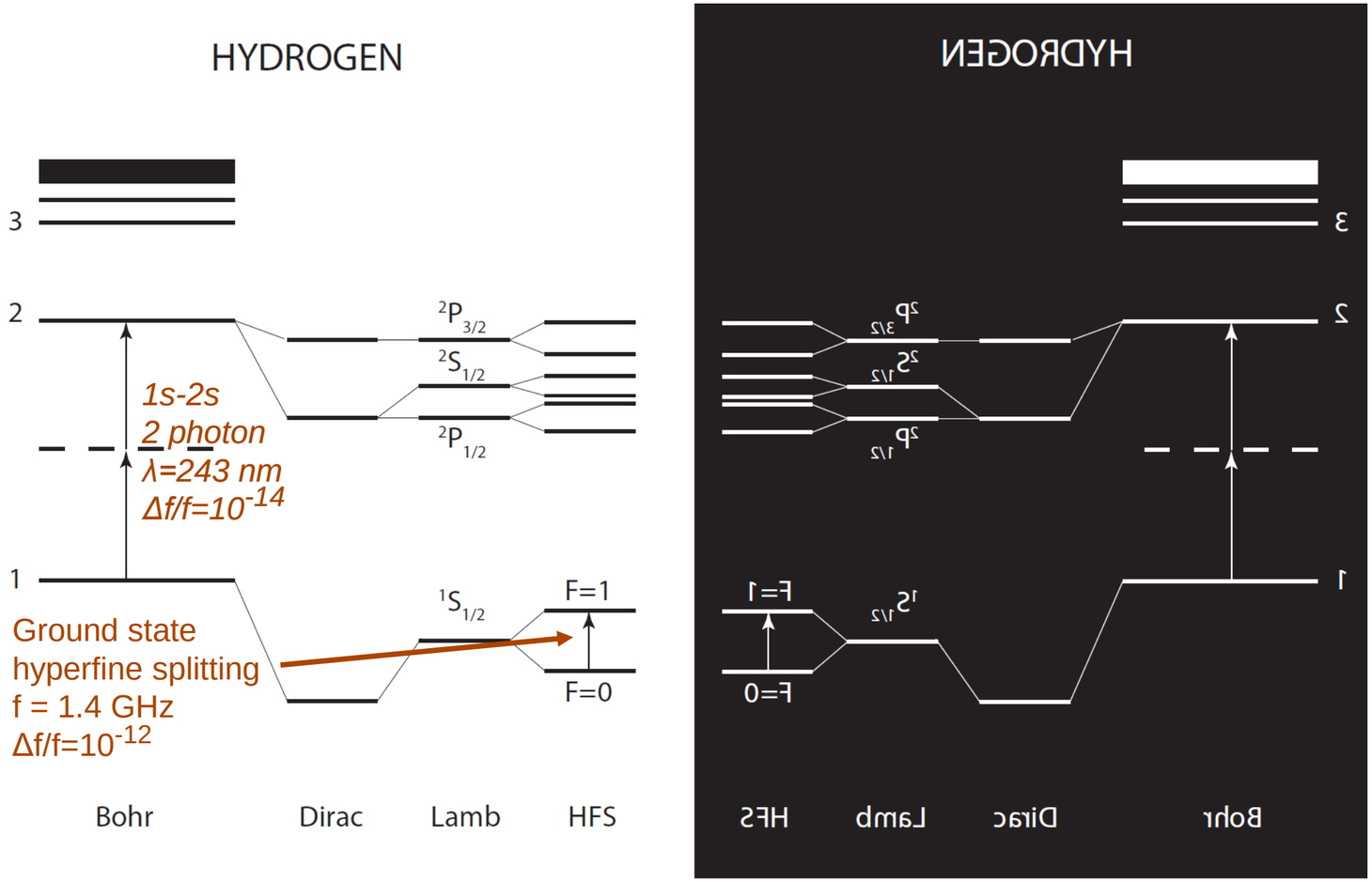
Hiroshima University: C. Kaga, H. Higaki

Univerita di Brescia & INFN Brescia: M. Leali, E. Lodi-Rizzini, V. Mascagna, L. Venturelli

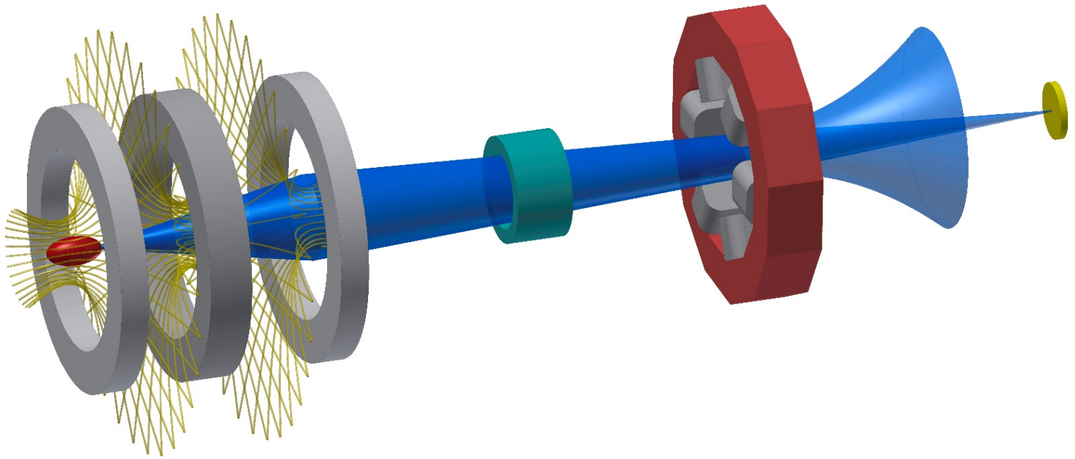
Stefan Meyer Institut für Subatomare Physik: C. Amsler, S. Cuendis, M. Fleck, A. Gligorova, B. Kolbinger, V. Mäckel, A. Nanda, M.C. Simon, H. Spitzer, M. Strube, D. Than, E. Widmann, M. Wiesinger, J. Zmeskal

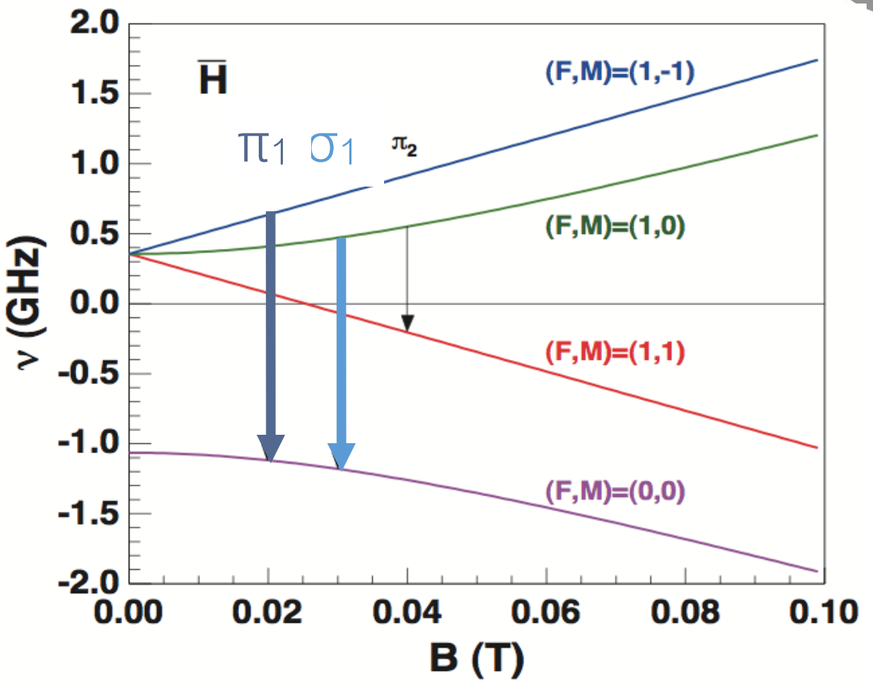
CERN: H. Breuker, C. Malbrunot

Antihydrogen spectroscopy



In-beam HFS spectroscopy





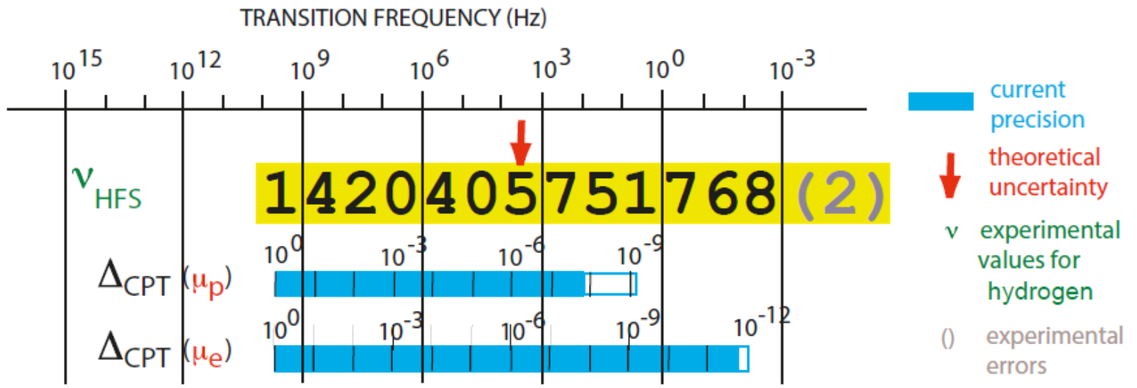
- Goals
  - In-beam measurement of ground-state hyperfine structure of antihydrogen to ppm-level and below
  - Produce polarized slow (<100 K) Hbar beam

- Resolution: line width $\Delta\nu \sim 1/T$
  - 1000 m/s, 10 cm:
  - 7×10^{-6} for T = 50 K *cf part IV*
  - > 100 $\bar{H}$/s in 1S state into 4π needed
  - event rate 1 / minute: background from cosmics, annihilations upstreams

Ground-State Hyperfine Splitting of H/$\overline{\text{H}}$

- spin-spin interaction positron - antiproton
- Leading: Fermi contact term

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



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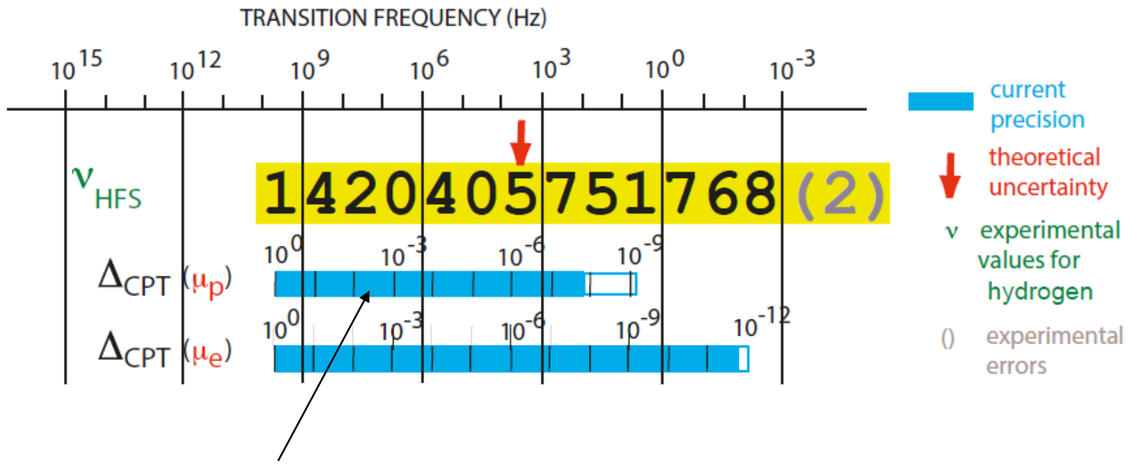
Hydrogen HFS and QED: finite size effects

H: deviation from Fermi contact term:	–32.77(1) ppm
finite electric & magnetic radius (Zemach corrections):	–41.43(44) ppm
polarizability of p/p̄	+1.88(64) ppm
remaining deviation theory-experiment:	+0.86(78) ppm

C. E. Carlson et al., *PRA 78, 022517 (2008)*

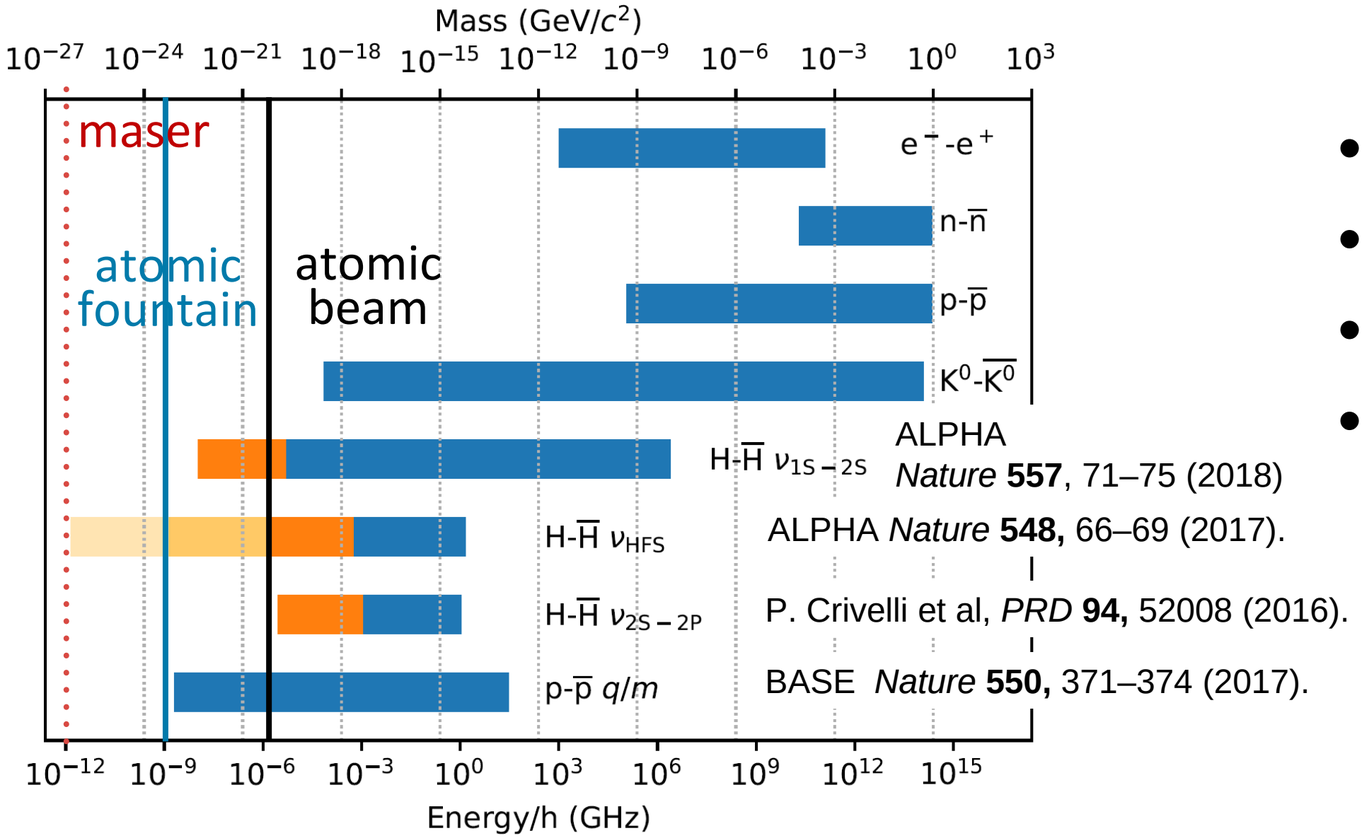


BASE C. Smorra et al.,. *Nature*, *550*(7676), 371–374.

Finite size effect of proton/antiproton important below ~ 10 ppm

Comparison of CPT tests I

- Mass & frequency



ALPHA *Nature* **557**, 71–75 (2018)

ALPHA *Nature* **548,** 66–69 (2017).

P. Crivelli et al, *PRD* **94,** 52008 (2016).

BASE *Nature* **550,** 371–374 (2017).

- Right edge: value
- Bar length: relative precision
- Left edge: absolute sensitivity
- Source: PDG

Comparison of CPT tests II

- Standard Model Extension SME

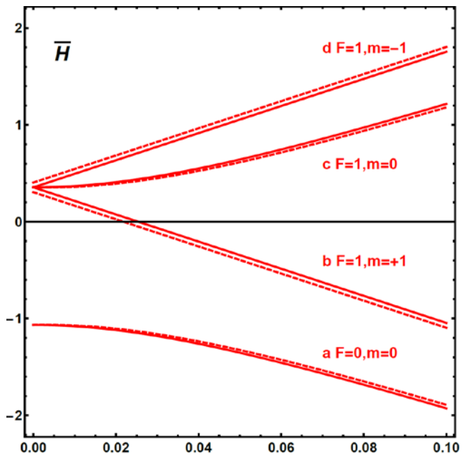
CPT & LORENTZ VIOLATION

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

LORENTZ VIOLATION

D. Colladay and V.A. Kostelecky, PRD 55, 6760 (1997)

- Minimal SME: only HFS
- Non-minimal SME: also 1S-2S shows CPTV



Bluhm, R., Kostelecky, V., & Russell, N., PRL *82*, 2254–2257 (1999).

Comparison of CPT tests II

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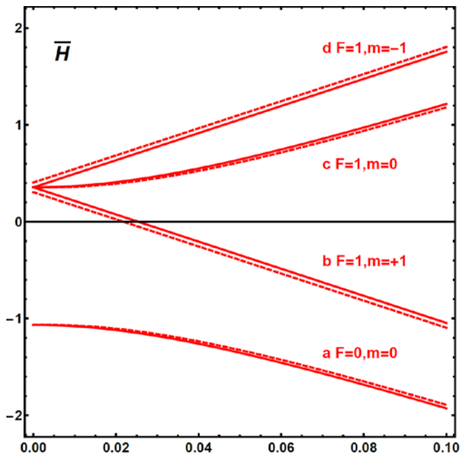
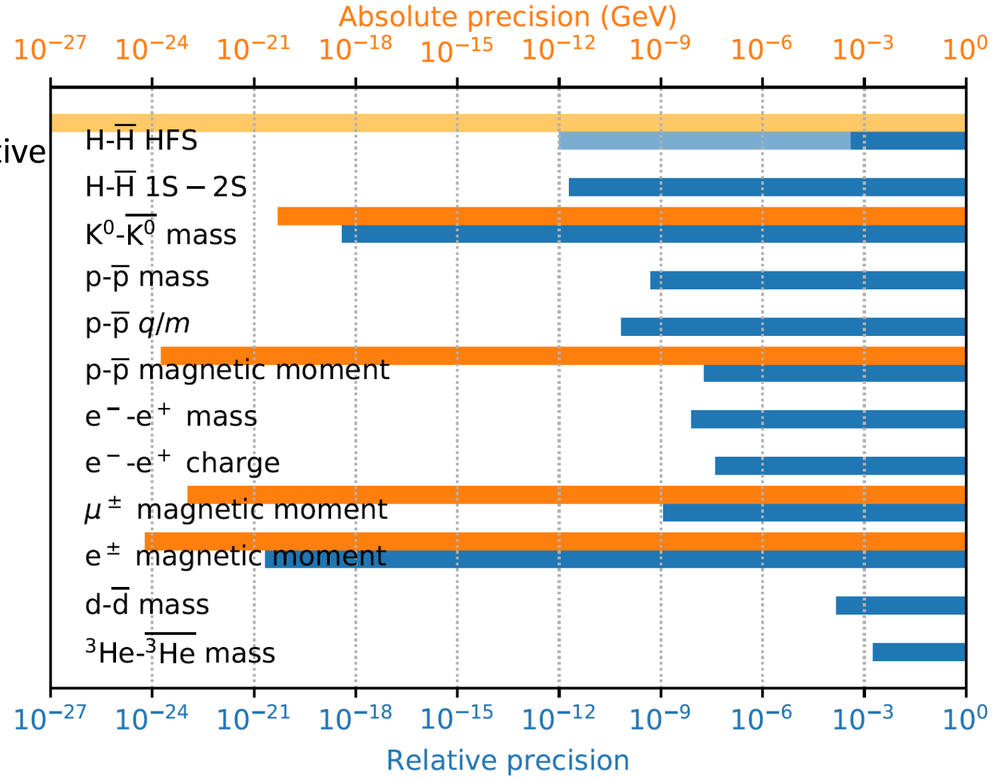


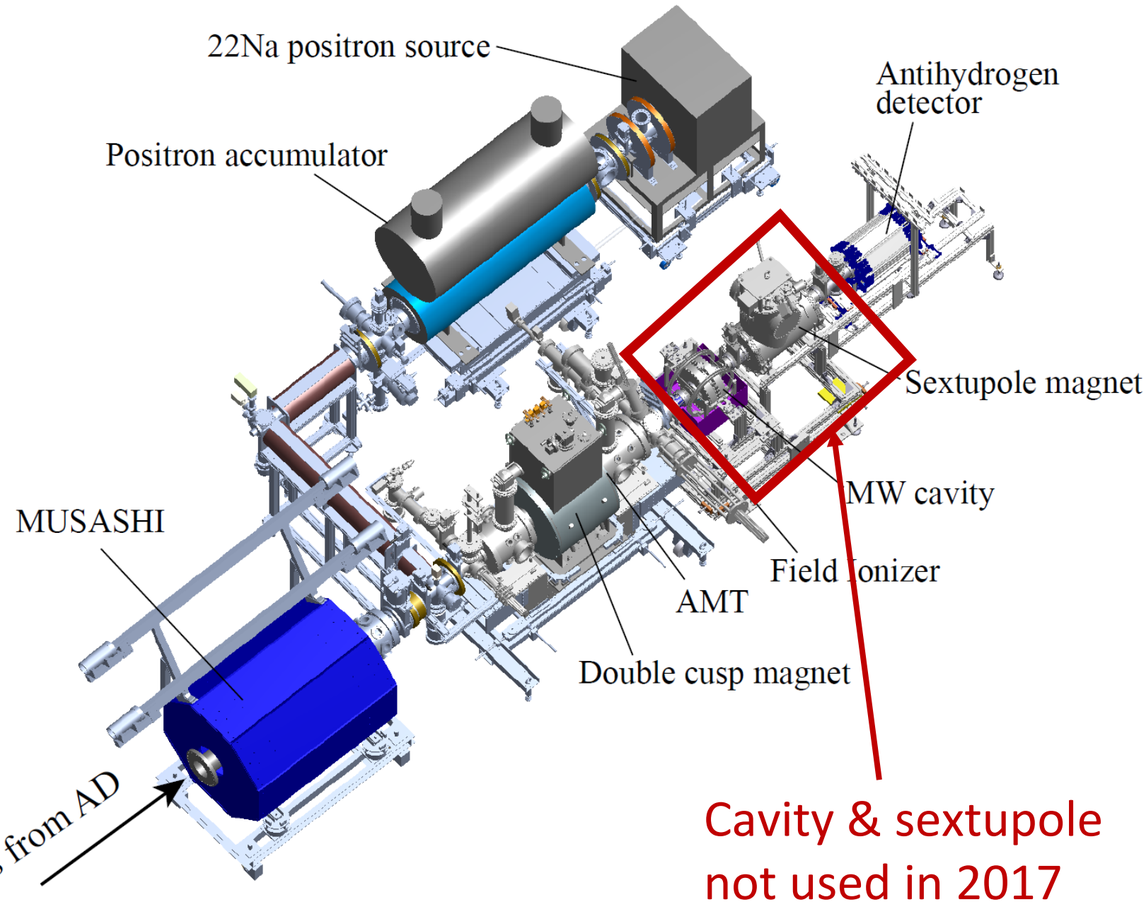
Bluhm, R., Kostelecky, V., & Russell, N., PRL *82*, 2254–2257 (1999).

ALPHA: Not sensitive to SME

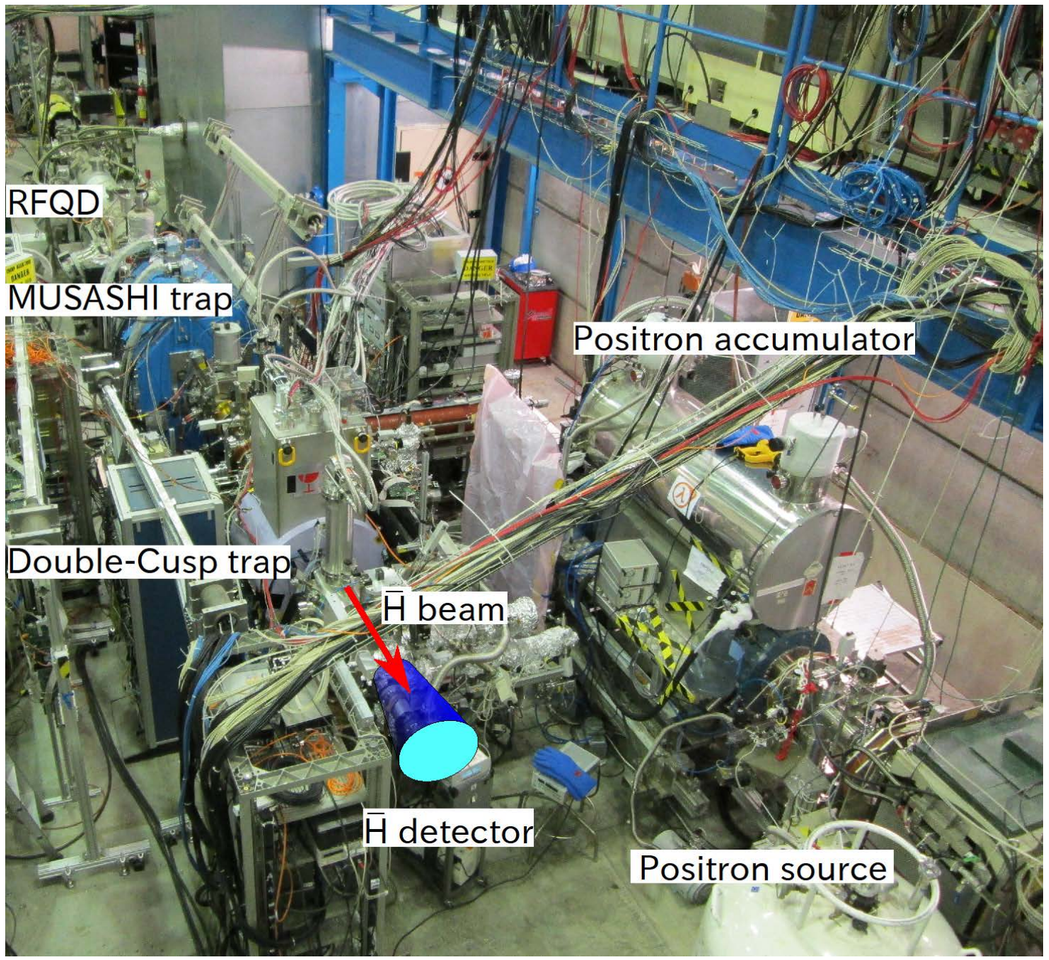


PDG, Kostelecky & Bluhm arXiv:0801.0287

Setup

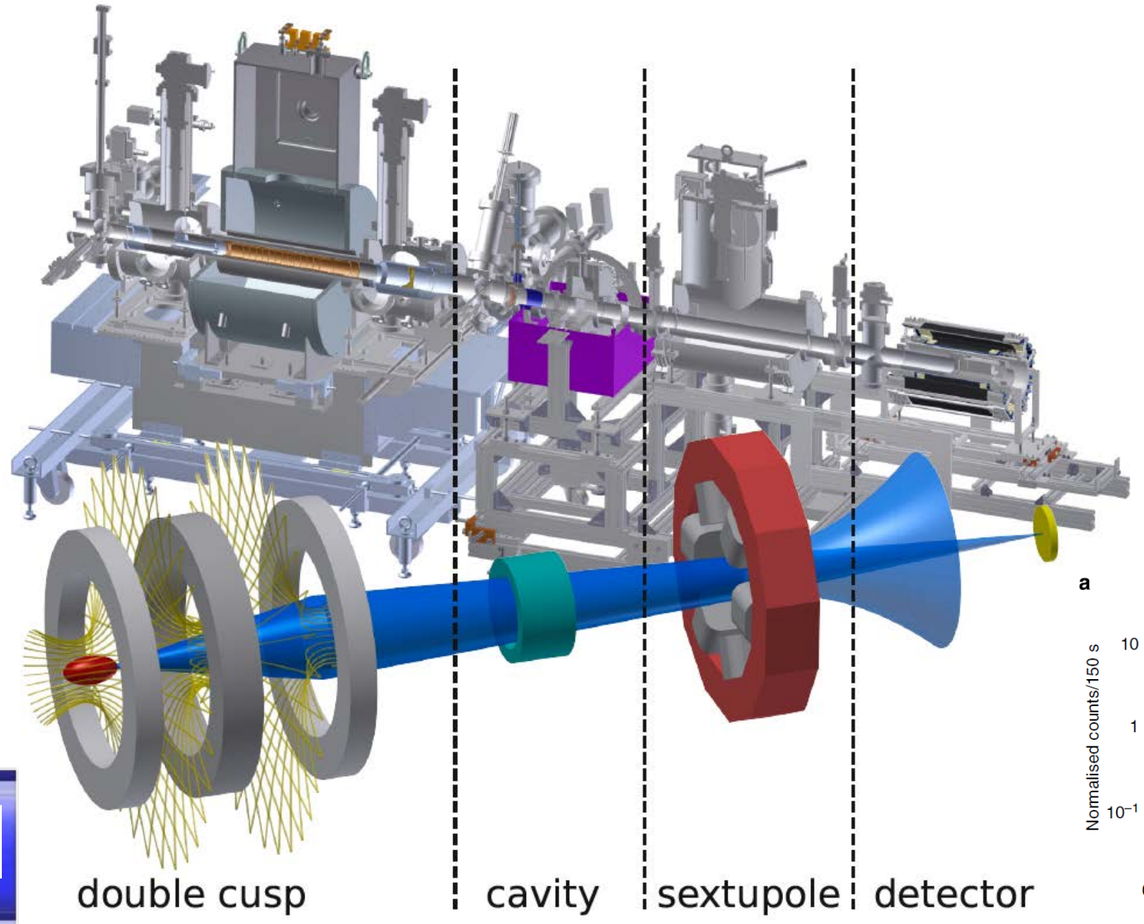


Cavity & sextupole not used in 2017

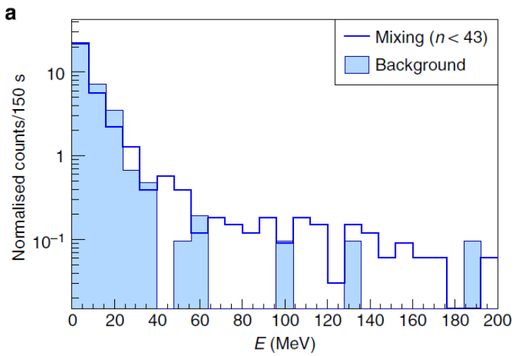


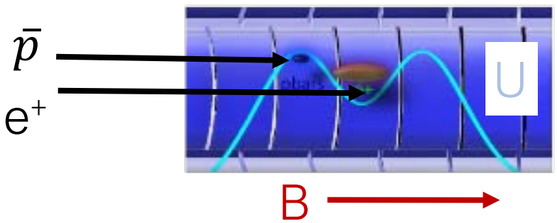
Antihydrogen beam status

- $\bar{H}$ production 1st time in 2010 in nested Penning trap
- Three body recombination expected to produce Rydberg states
- 1st observation of beam in field free region 2014
  - $n \leq 43$: 6 $\bar{H}$/15 min
  - $n \leq 29$: 4 $\bar{H}$/15 min



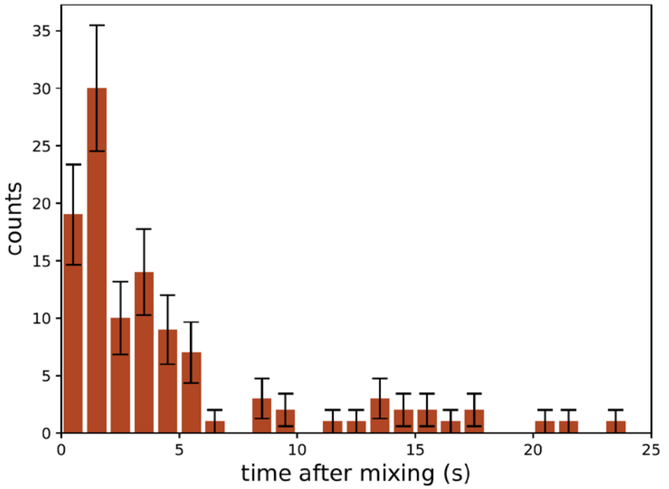
N. Kuroda et al, *Nat. Commun.* **5,** 3089 (2014).

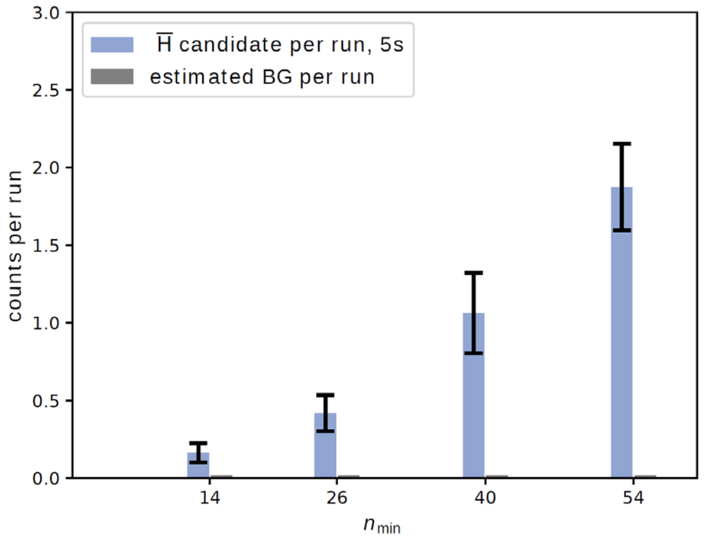




Results 2016

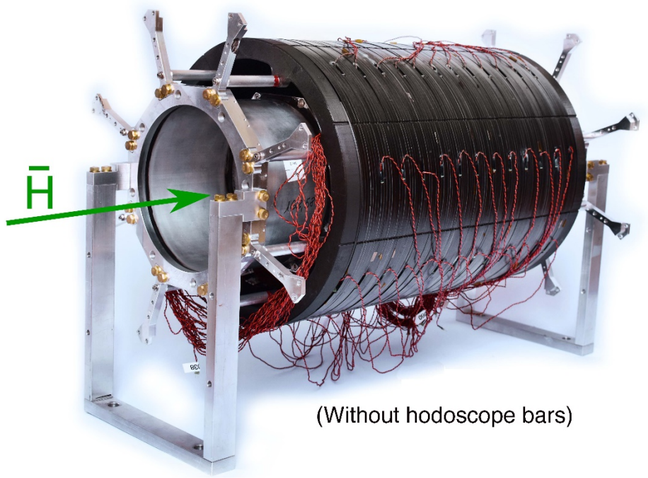
- Time distribution of $\bar{H}$ within mixing cycle
  - At cavity position
- Principal quantum number by field ionization
  - 0.5 m upstream of cavity
  - n<14 significance 4.5σ
    - Using machine learning techniques
  - τ(n=14) ~ 50 μs

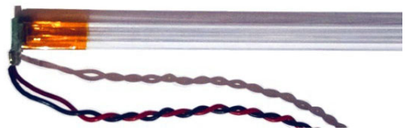


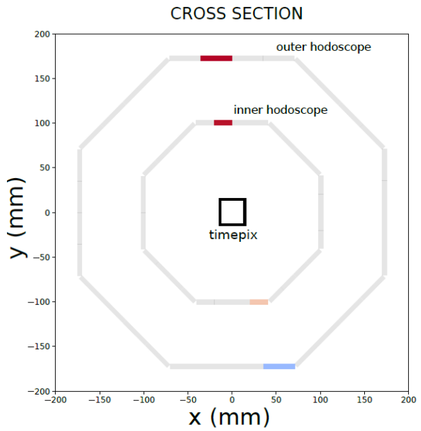


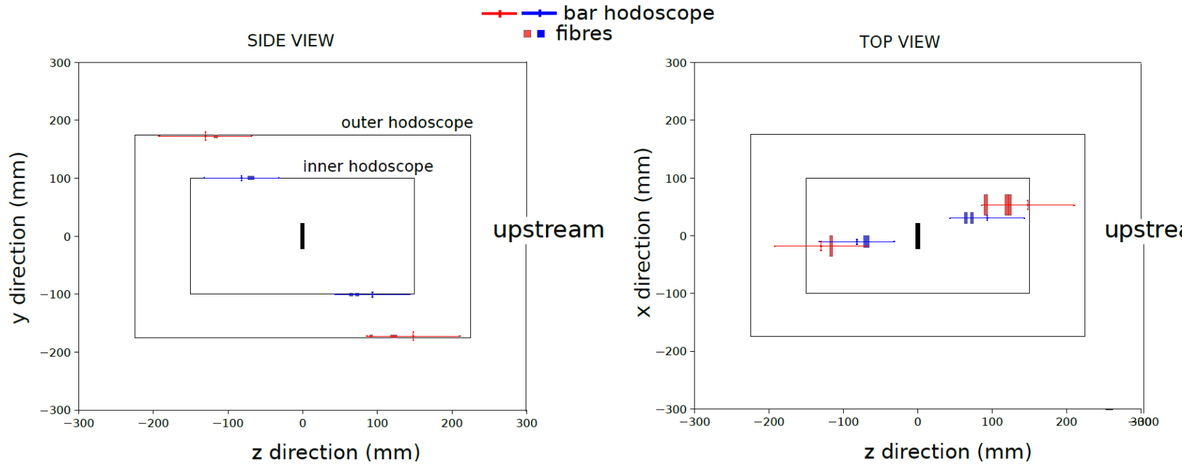
C. Malbrunot et al., Phil. Trans. R. Soc. A 376: 20170273 (2018)

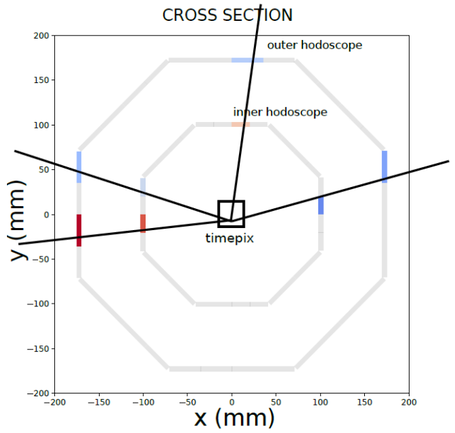
Antihydrogen detector fibre upgrade

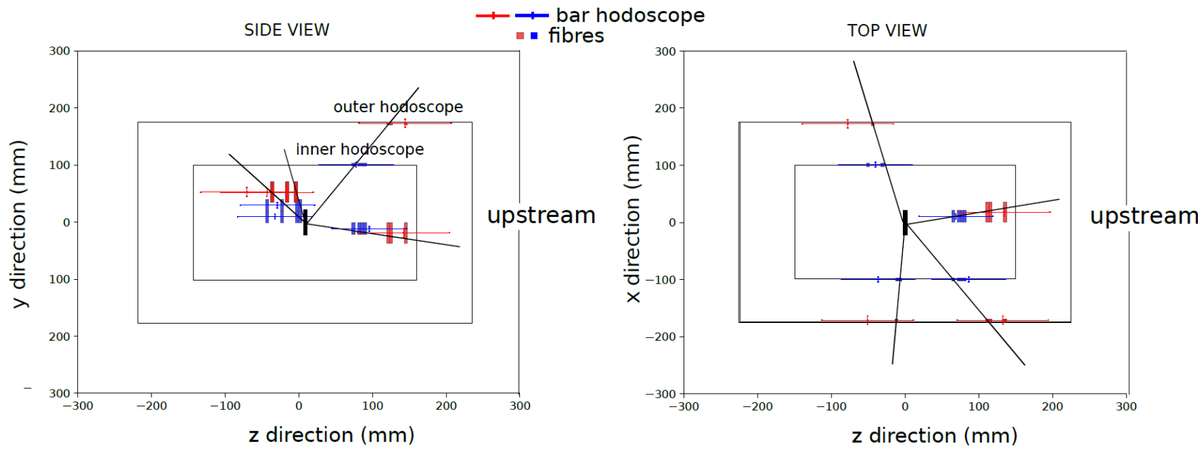






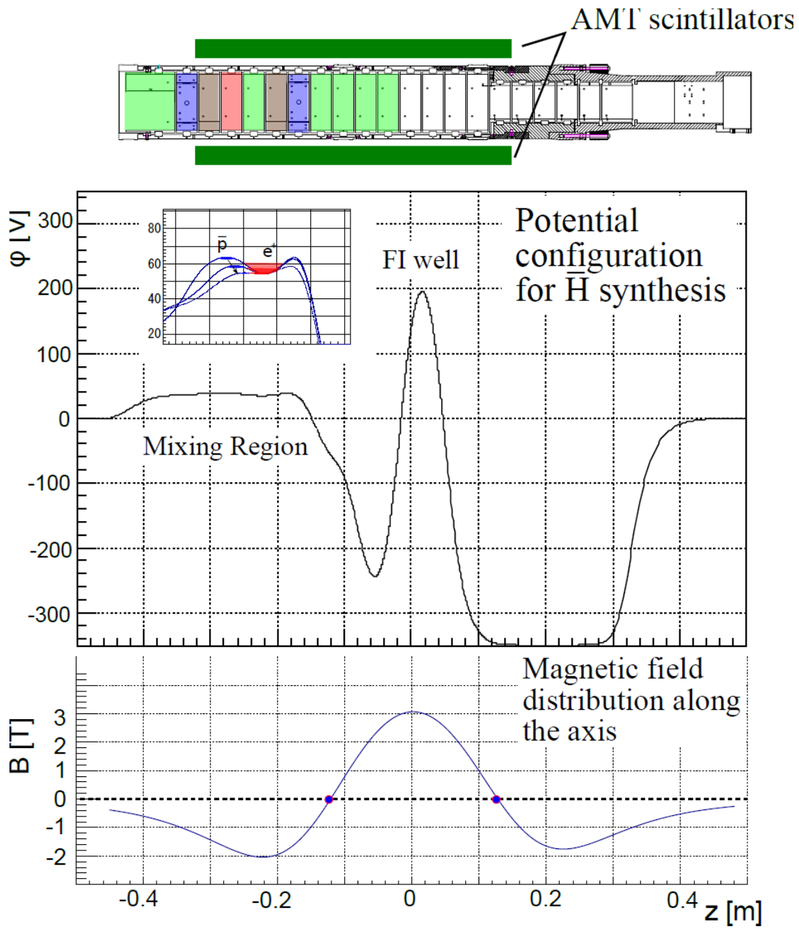




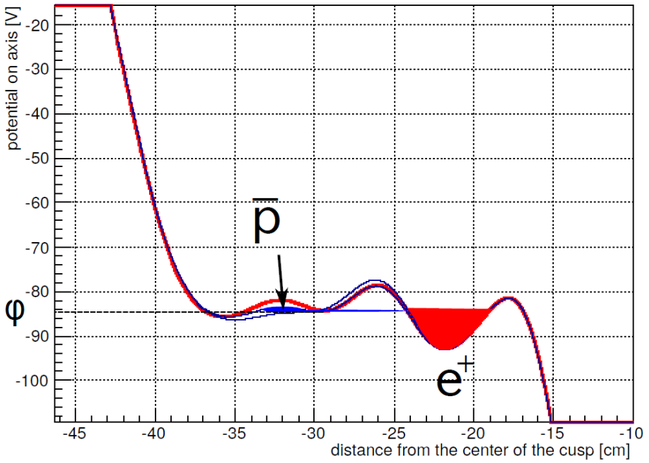


Fibre bundle 2x2 of 1x1 mm2 fibres
2 layers
7.7 mm geometrical resolution in *z* at *r*=0

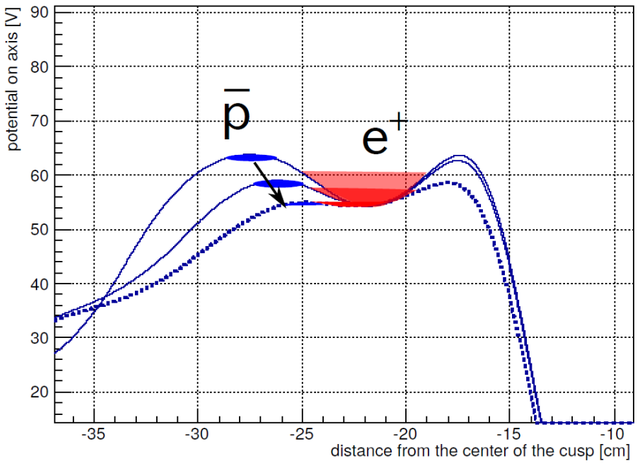
New mixing schemes 2017~



- Slow extraction scheme



- Cross merging scheme



Future directions

- Increase production rate
  - Positron temperature, density

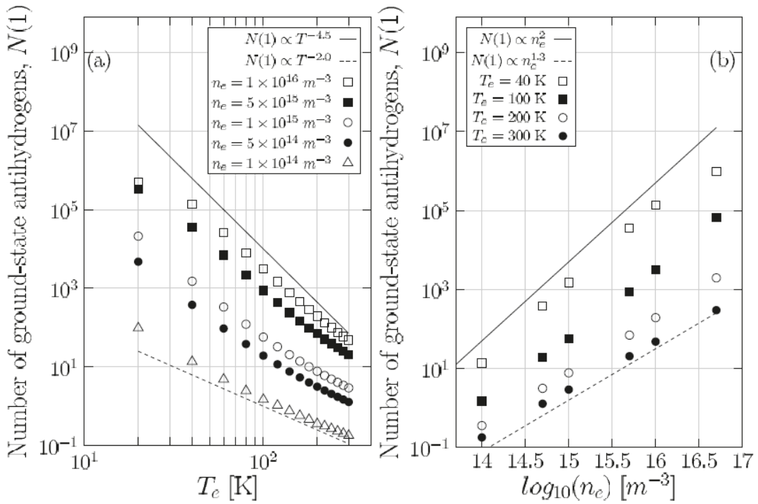


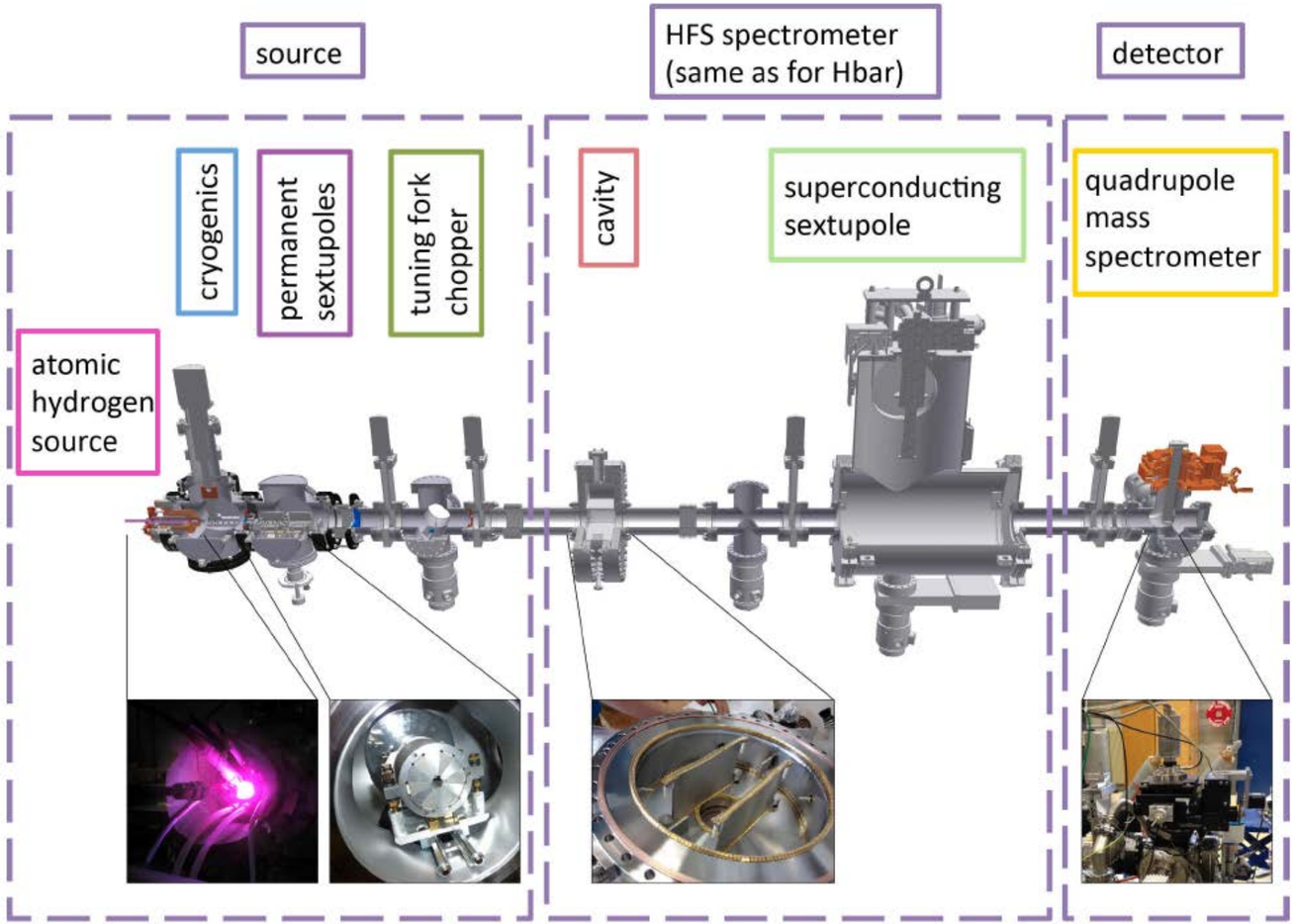
FIG. 6. Dependence of ground-state antihydrogen atoms on positron temperature (a) and density (b) for various positron density and temperature values (respectively) after 1 ms of flight. The $\propto n_e^2 T_e^{-4.5}$ (solid line) and $\propto n_e^{1.3} T^{-2.0}$ (dashed line) scaling behaviors are indicated for reference.

- Other improvements
  - Deexcite high-n Hbar
    - Starck mixing: simulations
    - THz radiation, MW: Chloé
- Other geometries
  - Inhomogeneous CUSP field -> mixing in MUSASHI?
    - CUSP magnet makes inhomoeneous field at cavtiy
  - New ideas?

Radics, B., Murtagh, D. J., Yamazaki, Y. & Robicheaux, *Phys. Rev. A* **90,** 1–6 (2014).

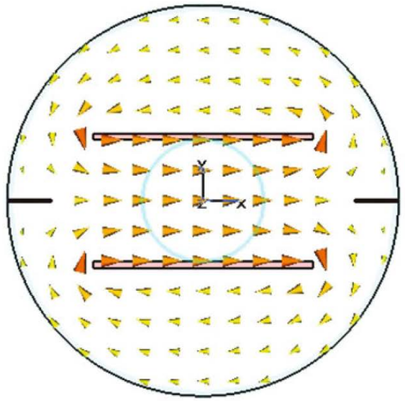
Hydrogen beam measurments

- Polarized source of cold hydrogen
- Primary goal: verify spectroscopy method:
  - reproduce expected antihydrogen beam parameters
  - Use same spectroscopy apparatus

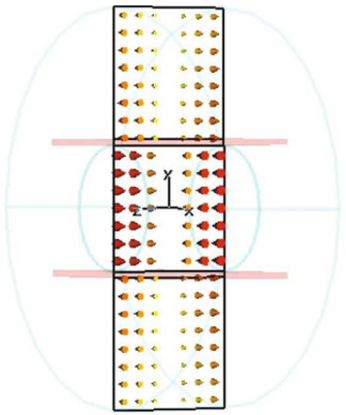


Spin-flip resonator

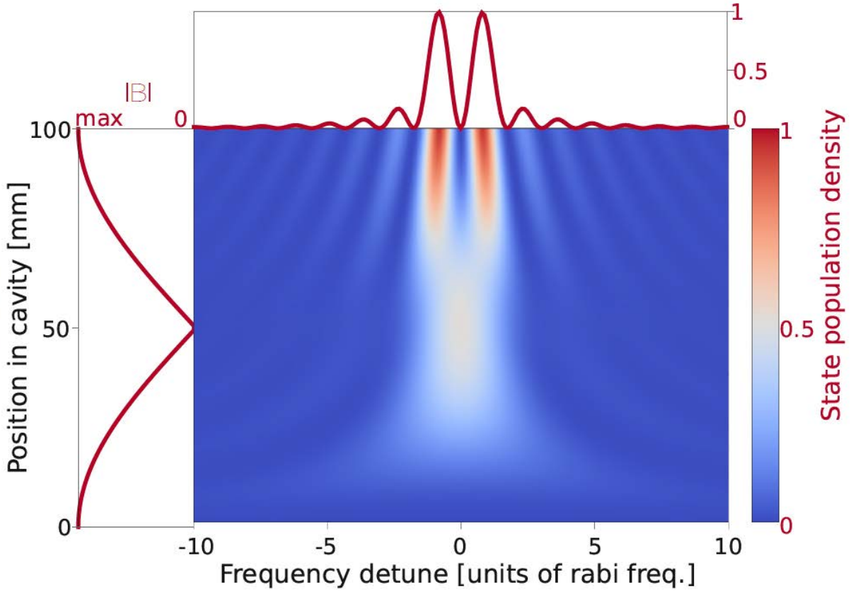
- f = challenge: homogeneity over $10x10x10cm^3$@ λ=21cm
- solution: strip line
- 1.420 GHz, Δf = few MHz,



transverse field: homogeneous



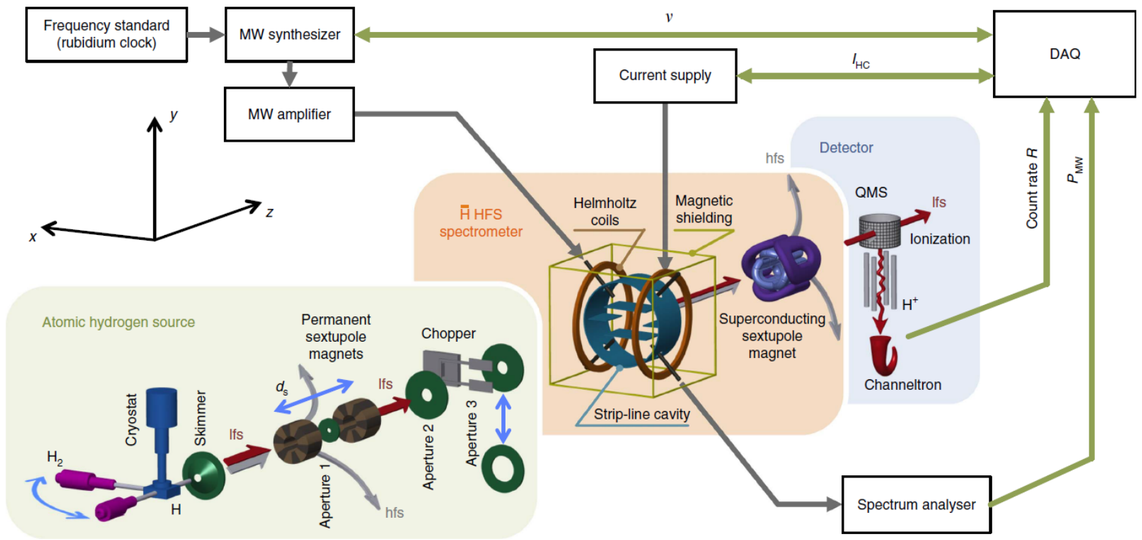
longitudinal field: cos(z)



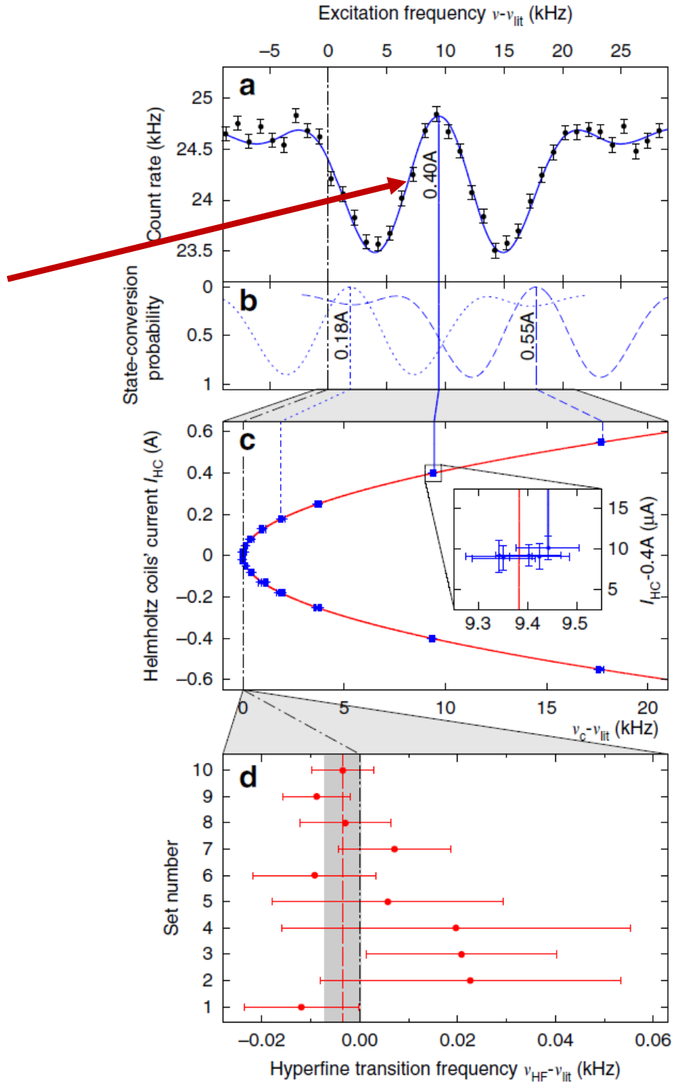
Line shape by optical Bloch equations for single velocity

- Full line shape: sum of simulated line shape for velocity distribution

σ-transition in H using $\bar{H}$ setup



Line width ~ 6 kHz:
4 ppm
(v~900 m/s)



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

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DOI: 10.1038/ncomms15749 OPEN

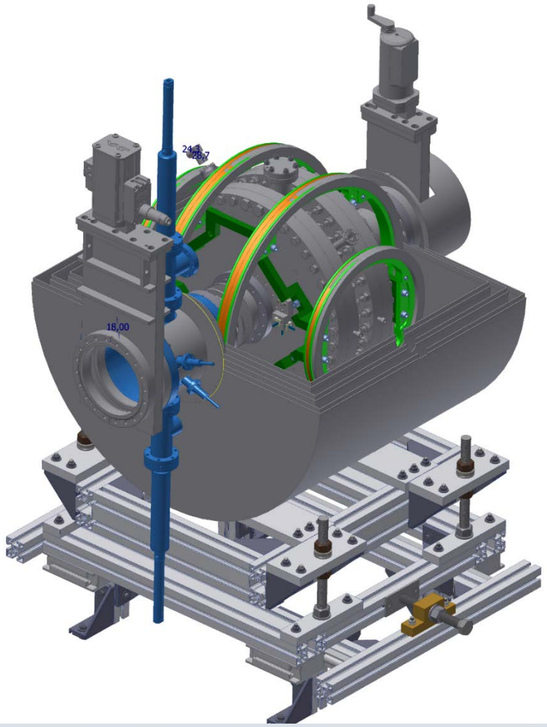
In-beam measurement of the hydrogen hyperfine splitting and prospects for antihydrogen spectroscopy

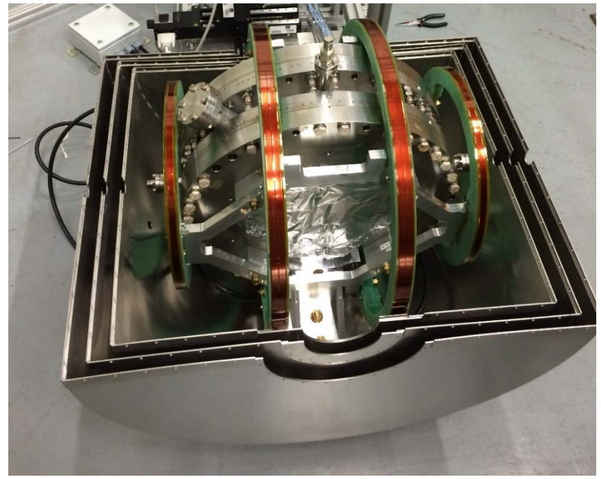
M. Diermaier[1], C.B. Jepsen[2,†], B. Kolbinger[1], C. Malbrunot[1,2], O. Massiczek[1], C. Sauerzopf[1], M.C. Simon[1], J. Zmeskal[1] & E. Widmann[1]

Error **2.7 ppb**: 18x improvement over *Kush, Phys. Rev. 100, 1188 (1955)*
Deviation from maser ($\Delta f/f \sim 10^{-12}$) :
3.4 Hz < 1σ error
Extrapolation to $\bar{H}$: **8000** atoms needed to achieve **1 ppm**

H-beam next steps and non-minimal SME

- π_1 transition
  - Better field homogeneity
    - Inproved coils, shielding
  - SME: effect only in π_1
  - Non-minimal SME: direction dependent coefficients accessible by beam
- Conditions
  - Invert direction of B-field
  - Rotate B-field
  - Measure also σ_1 (no CPTV) as reference



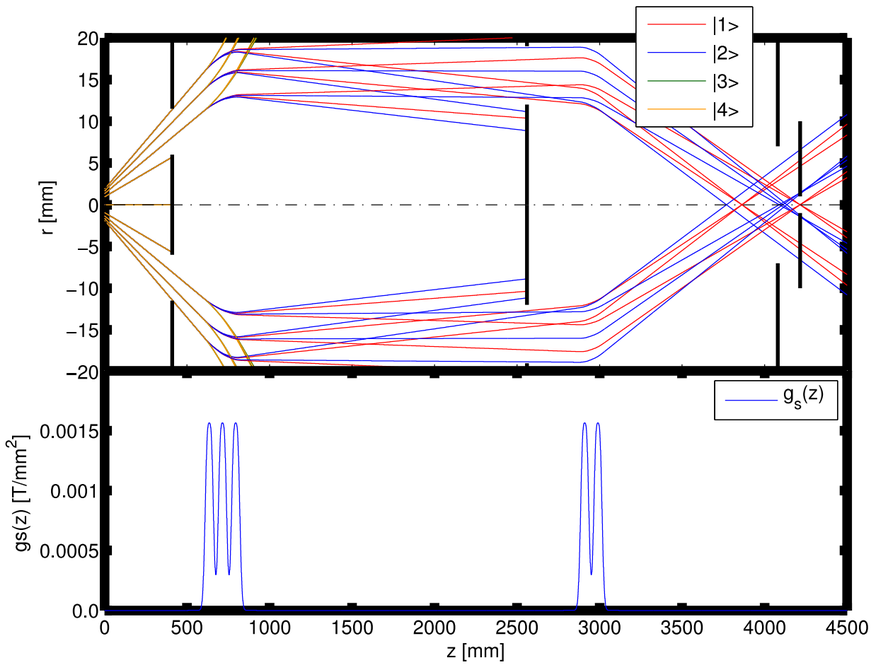


$$\begin{aligned}\Delta(2\pi\nu_\pi) &\equiv 2\pi\nu_\pi(\boldsymbol{B}) - 2\pi\nu_\pi(-\boldsymbol{B}) \\ &= -\frac{\cos\vartheta}{\sqrt{3\pi}}\sum_{q=0}^{2}(\alpha m_{\mathrm{r}})^{2q}(1+4\delta_{q2})\sum_{w}\left[g_{w\,(2q)10}^{\mathrm{NR,Sun}(0B)} - H_{w\,(2q)10}^{\mathrm{NR,Sun}(0B)} + 2g_{w\,(2q)10}^{\mathrm{NR,Sun}(1B)} - 2H_{w\,(2q)10}^{\mathrm{NR,Sun}(1B)}\right]\end{aligned}$$

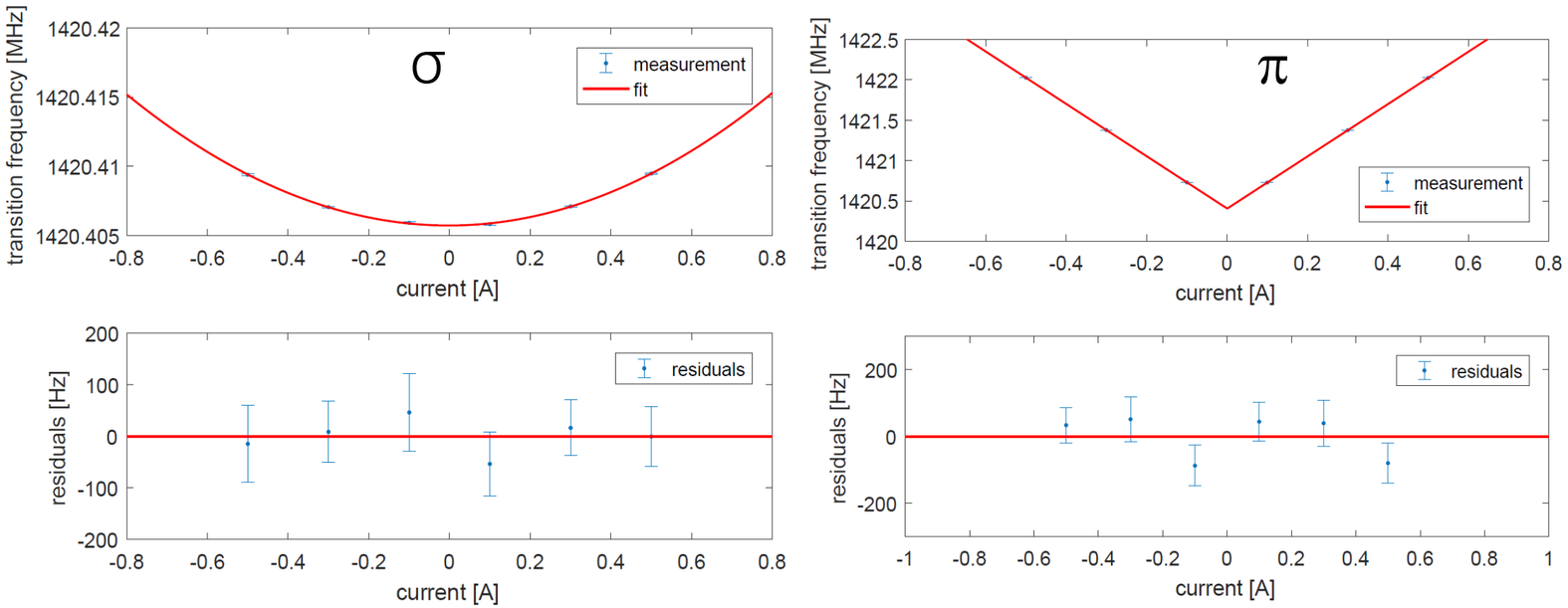
Kostelecký, V. A., & Vargas, A. J. *PRD*, *92*, 056002 (2015).

First π_1 measurements

- New optics



- 1st extrapolations



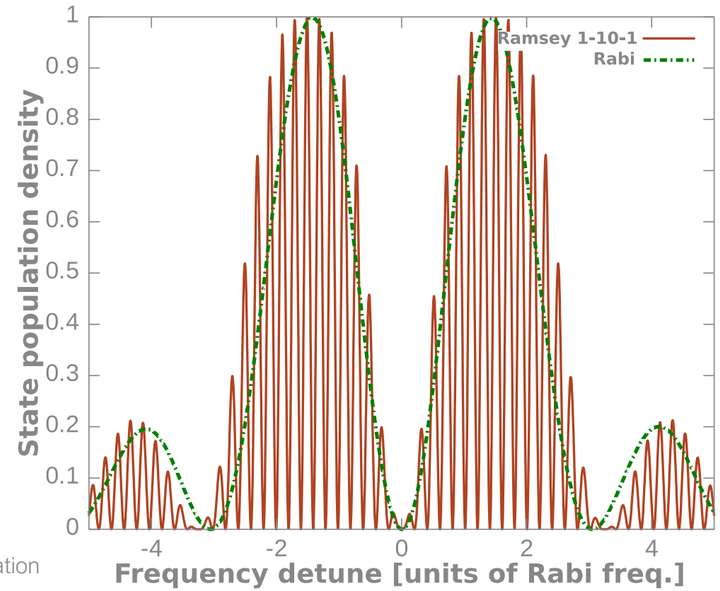
- Accuracy $\nu_{HF}(B = 0)$~ 10 Hz
  - ~ 100 hours of data taking
  - Measurement campaign to start

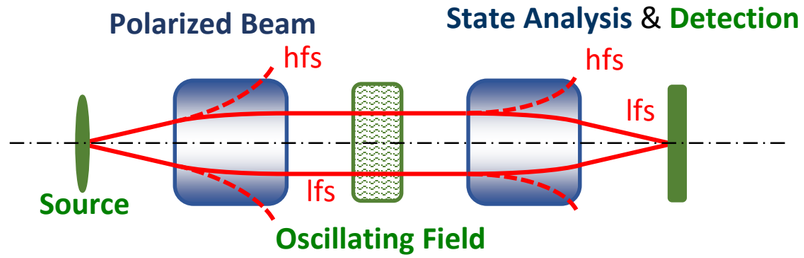
From Rabi to Ramsey

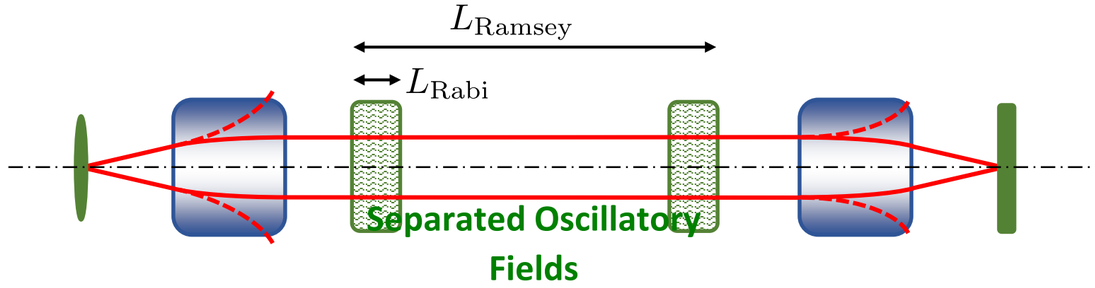
- Amit Nanda (AVA Fellow)
- Boost precision of HFS in-beam measurement by introducing Ramsey's method

Resolution:

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







→ strip-line cavity:
line-shape not ideal for Ramsey

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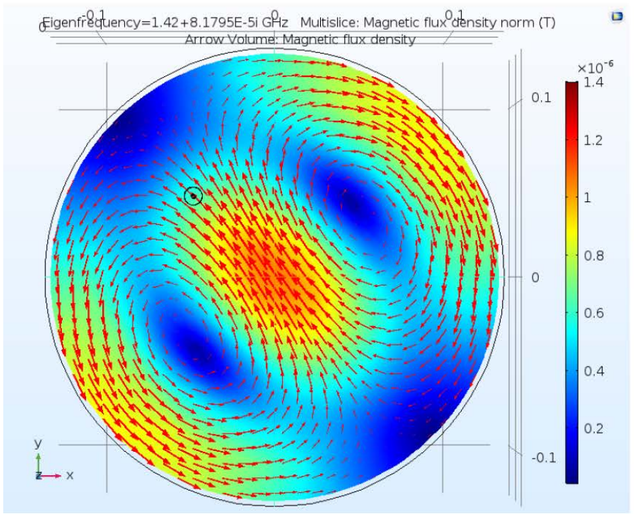
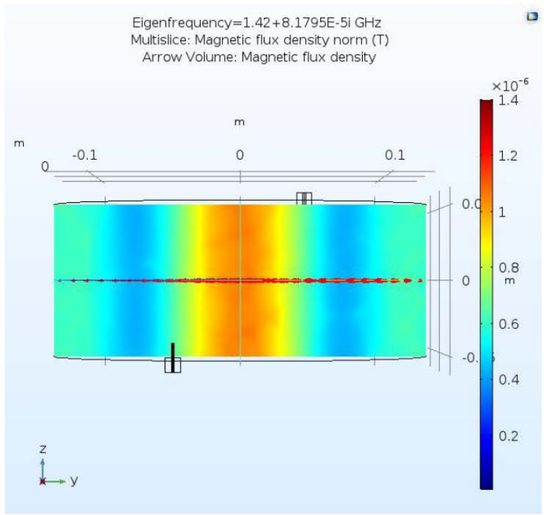
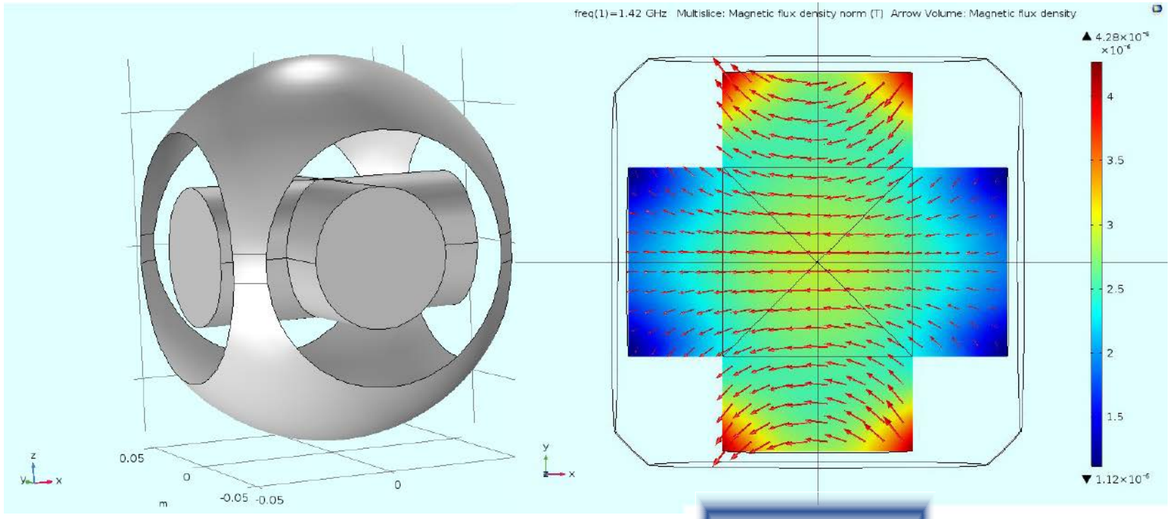
New RF structure: cavity vs. Surface coils







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Summary

- Precise measurement of the hyperfine structure of antihydrogen promises one of the most sensitive tests of CPT symmetry
  - First "beam" of $\bar{H}$ observed in field-free region
  - 1st quantum state distribution at zero B-field
  - Next steps: optimize rate, check polarization, velocity
- HFS measurement in H beam of 2.7 ppb achieved
  - Proof-of-principle for $\bar{H}$ measurement
  - Potential to measure non-minimal SME coefficients
  - Modifications to increase precision being studied
  - Other atoms: D looks feasible

erc
ERC Advanced Grant 291242
HbarHFS
www.antimatter.at
PI EW

bmwfw
Bundesministerium für Wissenschaft, Forschung und Wirtschaft

FWF
Der Wissenschaftsfonds.

DOKTORATSKOLLEG PI
∫dk Π
Particles and Interactions

Spares

ASACUSA collaboration

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