(Anti-)hydrogen spectroscopy for tests of CPT and Lorentz invariance

E. Widmann

ASACUSA collaboration

Stefan Meyer Institute for subatomic Physics, Vienna

DISCRETE 2022

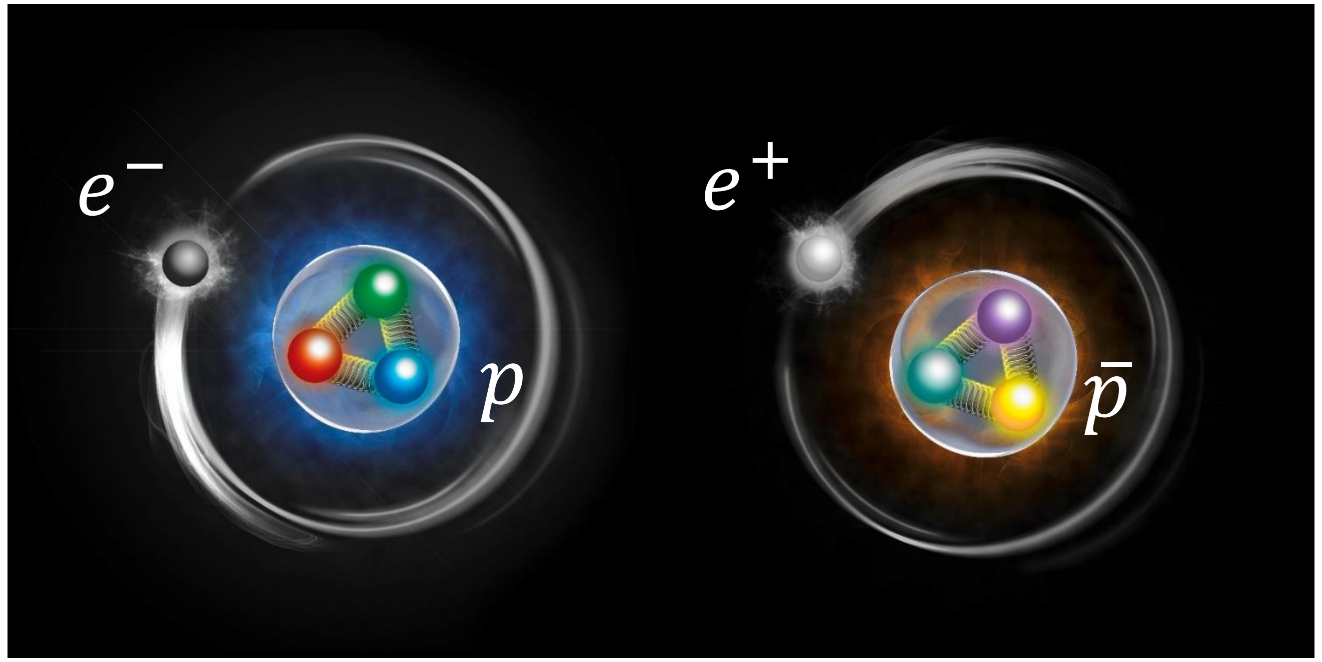
Baden-Baden, 11 November 2022

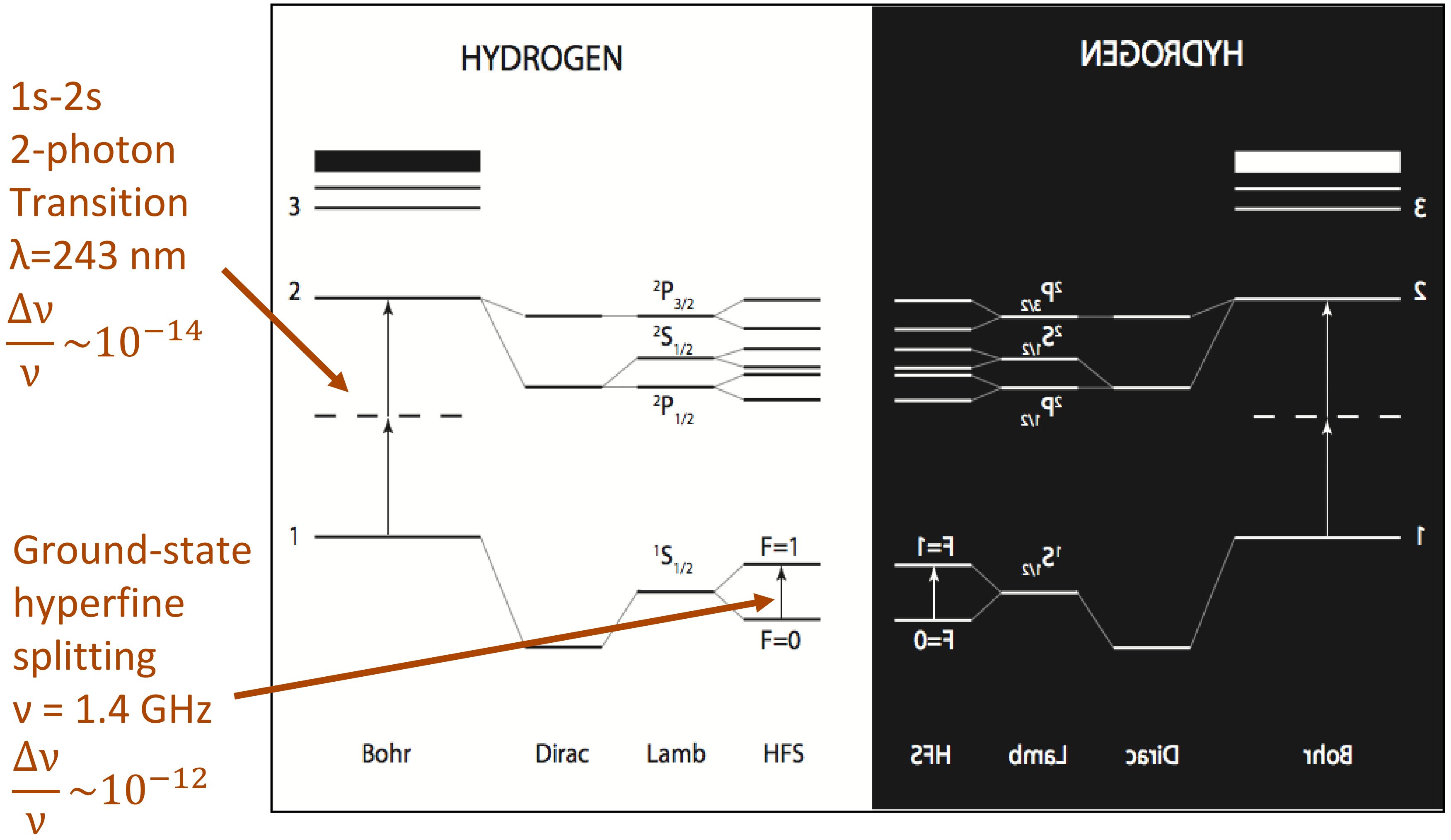
Content

- (Anti)hydrogen spectroscopy and CPT / Lorentz invariance
- Status of antihydrogen hyperfine measurement in a beam: CPT
- Hydrogen and deuterium in-beam hyperfine measurements: SME coefficients

Antihydrogen experiments

- Matter-Antimatter Symmetry
  - Charge conjugation-Parity-Time reversal: CPT
  - CPTV points to BSM physics





1s-2s
2-photon
Transition
λ=243 nm
$\frac{\Delta\nu}{\nu} \sim 10^{-14}$

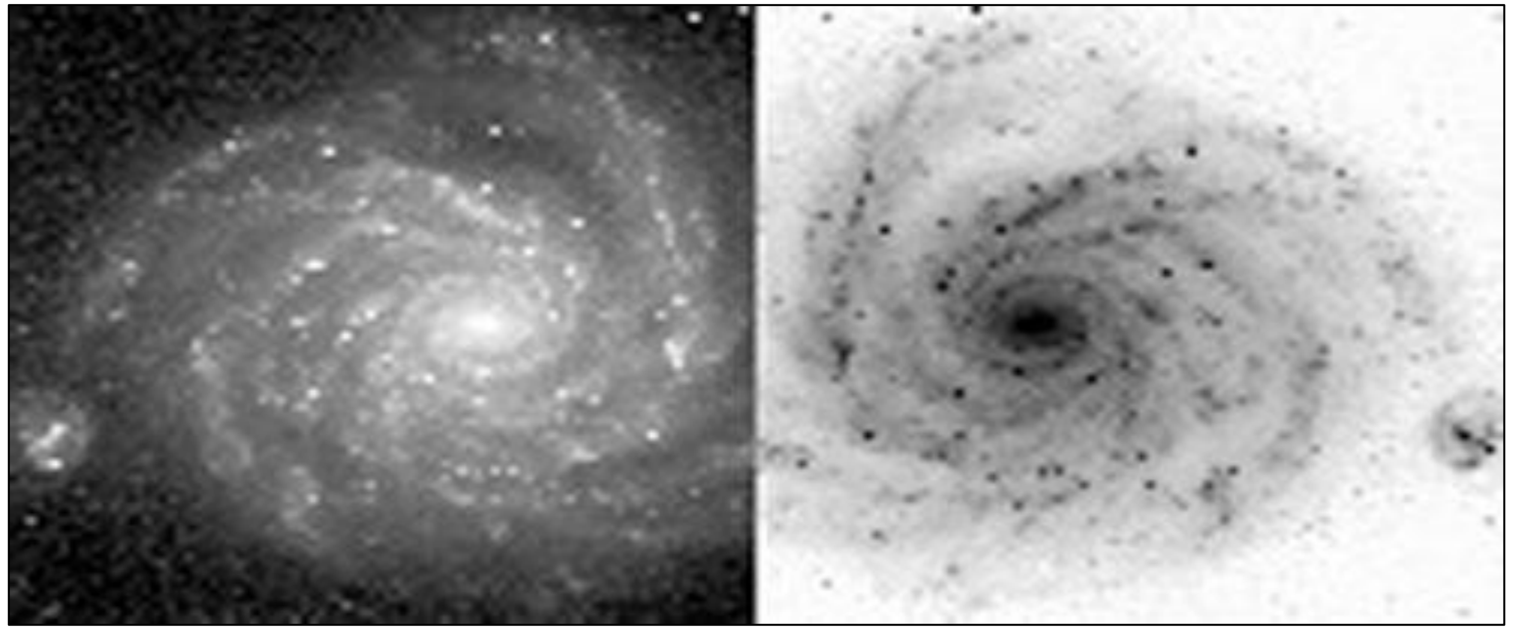
Ground-state
hyperfine
splitting
ν = 1.4 GHz
$\frac{\Delta\nu}{\nu} \sim 10^{-12}$

Matter/antimatter symmetry

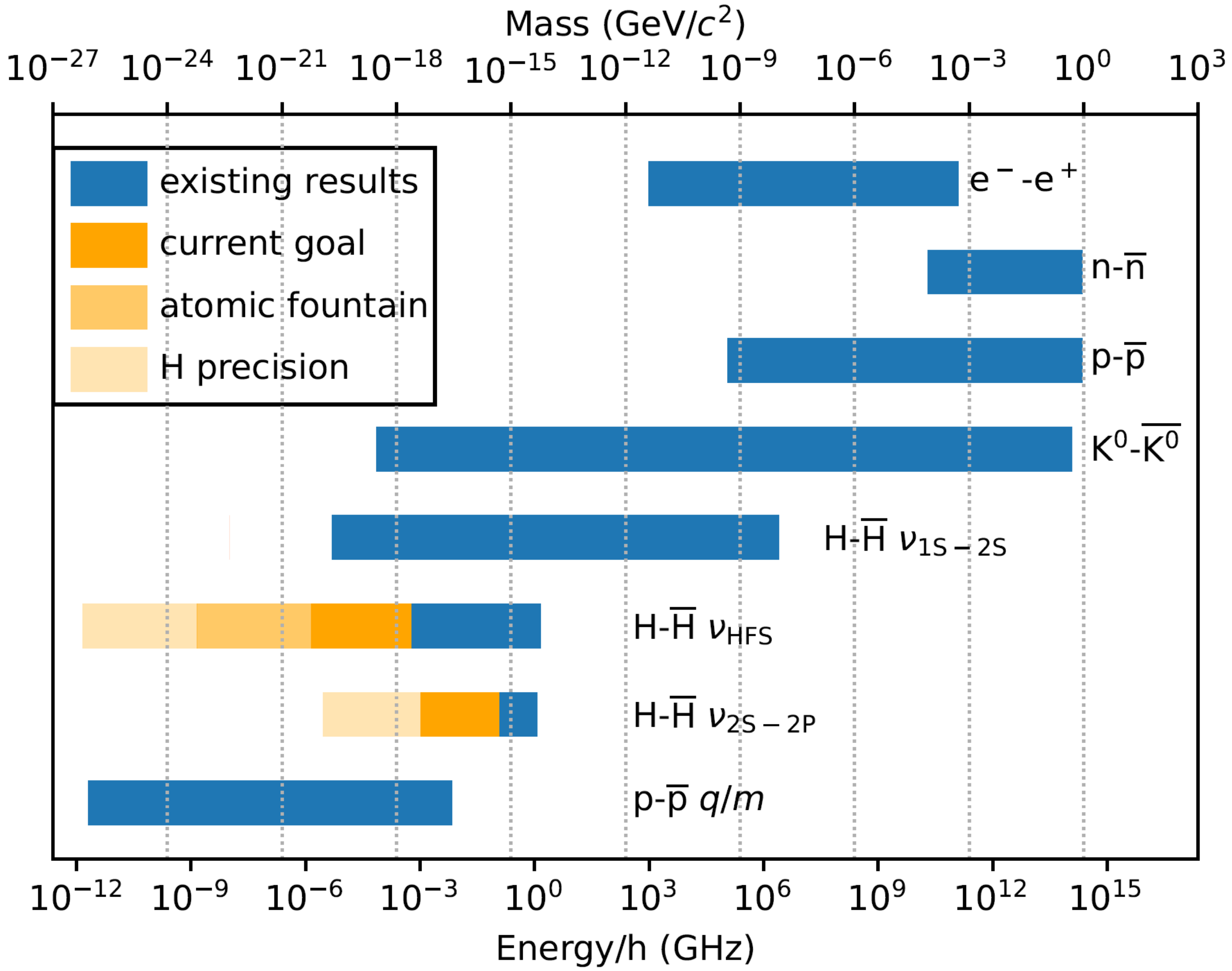
- Macroscopic: antimatter in the universe

$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 6.1\ x\ 10^{-10}$$

WMAP



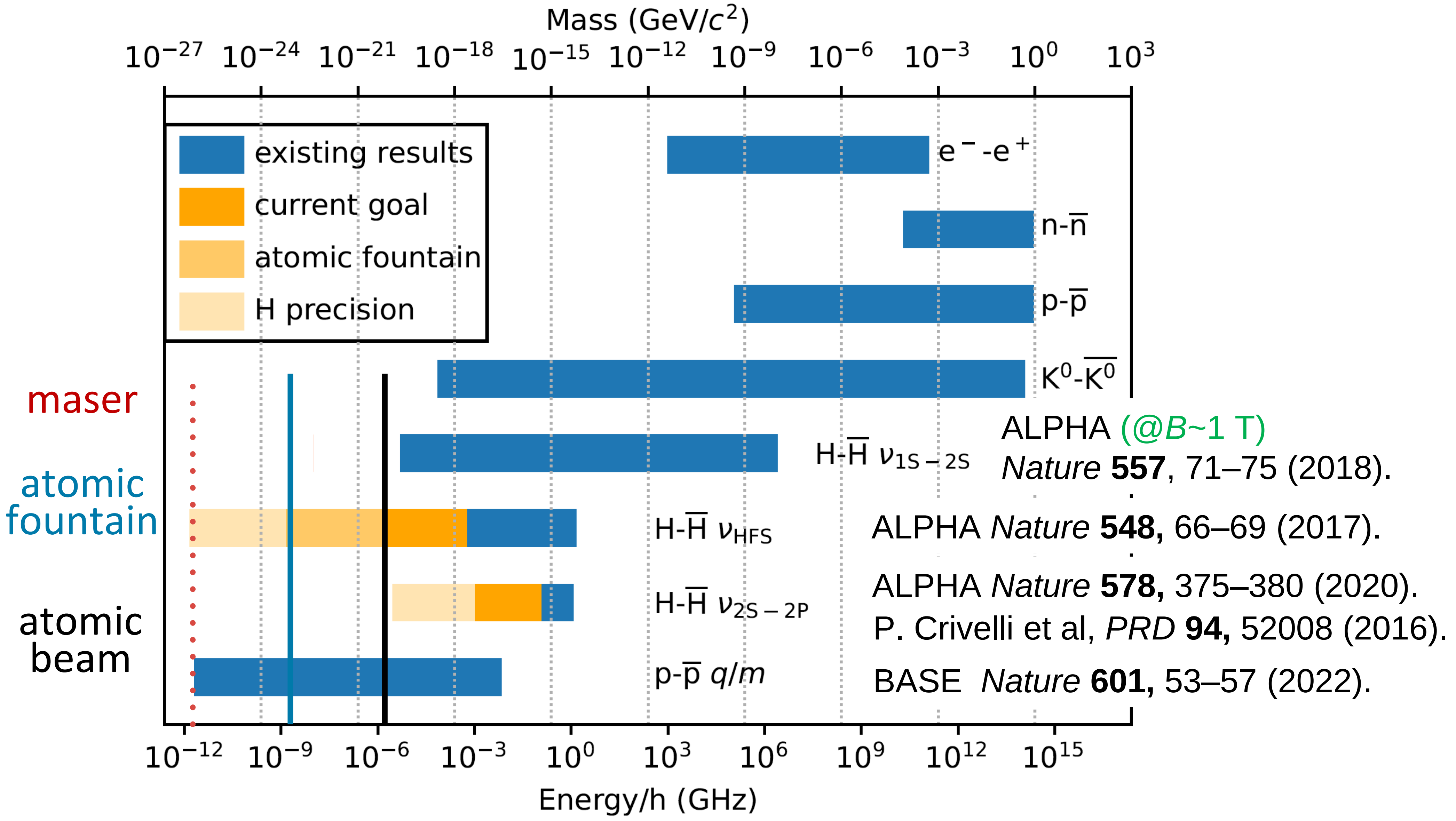
- Microscopic: particle – antiparticle



EW, Phys. Part. Nuclei **53**, 790–794 (2022).
arXiv:2111.04056 [hep-ex]

Comparison of CPT tests

- Mass & frequency



ALPHA (@*B*~1 T)
Nature **557**, 71–75 (2018).

ALPHA *Nature* **548,** 66–69 (2017).

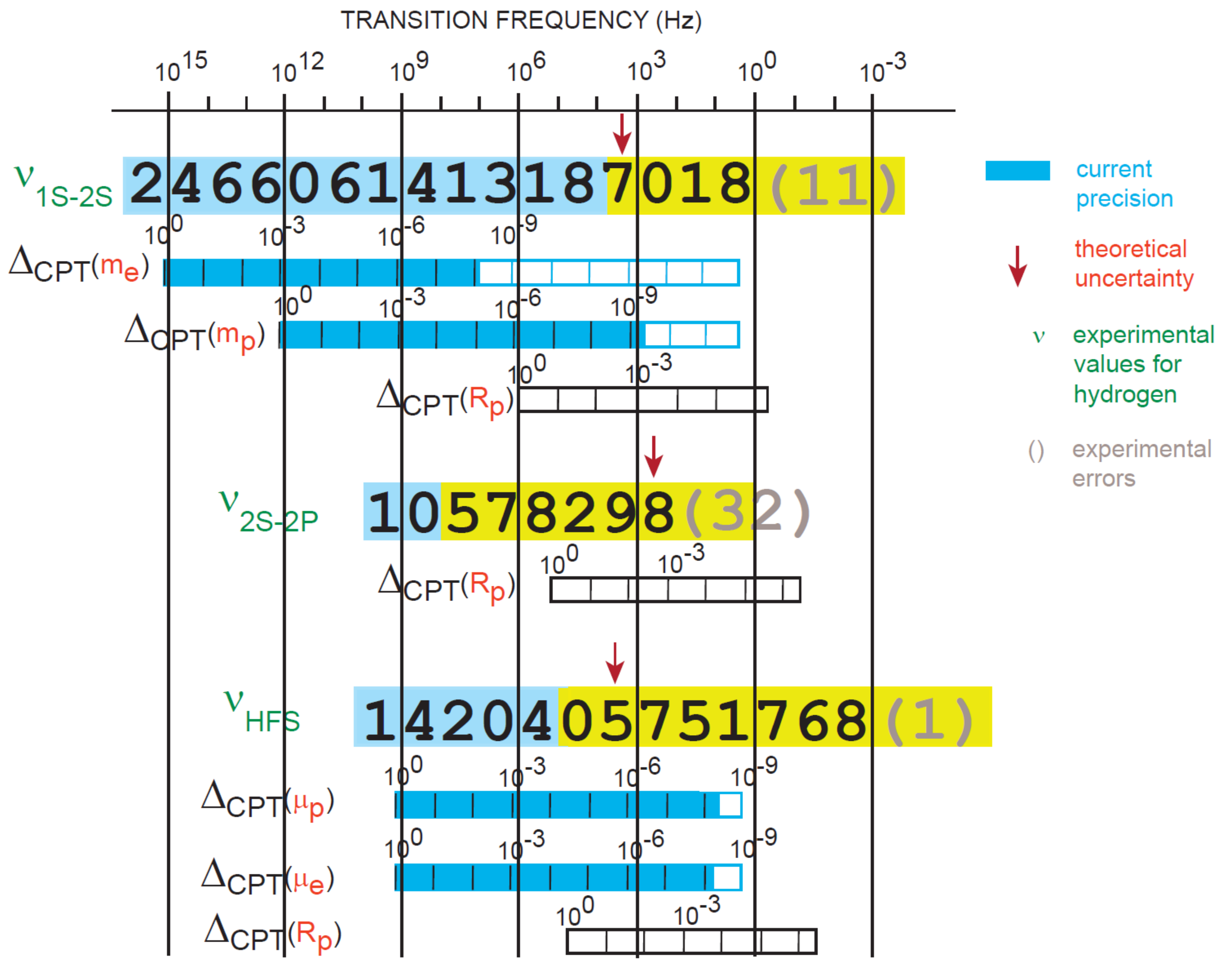
ALPHA *Nature* **578,** 375–380 (2020).
P. Crivelli et al, *PRD* **94,** 52008 (2016).

BASE *Nature* **601,** 53–57 (2022).

- Synopsis: CPT violating interaction appears at the level of Lagrangian
  - Relevant scale: absolute energy
- Plot
  - Right edge: value
  - Bar length: relative precision
  - Left edge: absolute sensitivity
  - Source: PDG

EW, Phys. Part. Nuclei **53**, 790–794 (2022).
arXiv:2111.04056 [hep-ex]

Hydrogen spectroscopy



$$\Delta_{CPT}(X) = \frac{X(\text{antiparticle}) - X(\text{particle})}{X(\text{particle})}$$

Antihydrogen results

- $\nu^{\bar{H}}_{1S-2S}(B = 1.033\ \mathrm{T})=$ **2,466,061,103,079.4(5.4)kHz** [1]
  - B-field induced shift **310 MHz**
  - $\Delta\nu^{\bar{H}-H^{\mathrm{th,shifted}}}_{1S-2S} / \nu^{\bar{H}}_{1S-2S} = 2 \text{ x } 10^{-12}$
- $\nu^{\bar{H}}_{2S-2P}(B \to 0)$ = **0.99(11) GHz** [2]
  - $\Delta\nu^{\bar{H}-H}_{2S-2P} / \nu^{\bar{H}}_{2S-2P} = 11\%$
- $\nu^{\bar{H}}_{\mathrm{HFS}}(B = 0) =$ **1,420.4(5) MHz** [3]
  - $\Delta\nu^{\bar{H}-H}_{\mathrm{HFS}} / \nu^{\bar{H}}_{\mathrm{HFS}} = 4 \text{ x } 10^{-4}$

[1] Ahmadi, M. et al., *Nature* 557 (2018): 71–75.
[2] Ahmadi, M., B et al. *Nature* 578, (2020): 375–80.
from $\nu^{\bar{H}}_{1S-2S}$ and $\nu^{\bar{H}}_{1S-2P}$, extrapolated to B=0
[3] Ahmadi, M et al. *Nature* 548 (2017): 66–69.

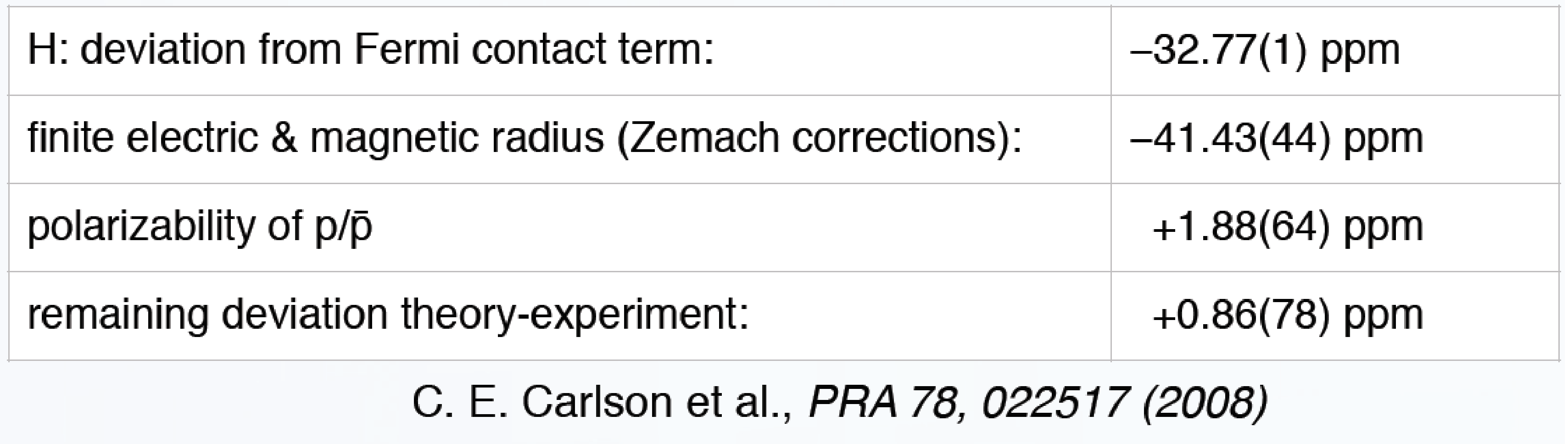
]

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

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

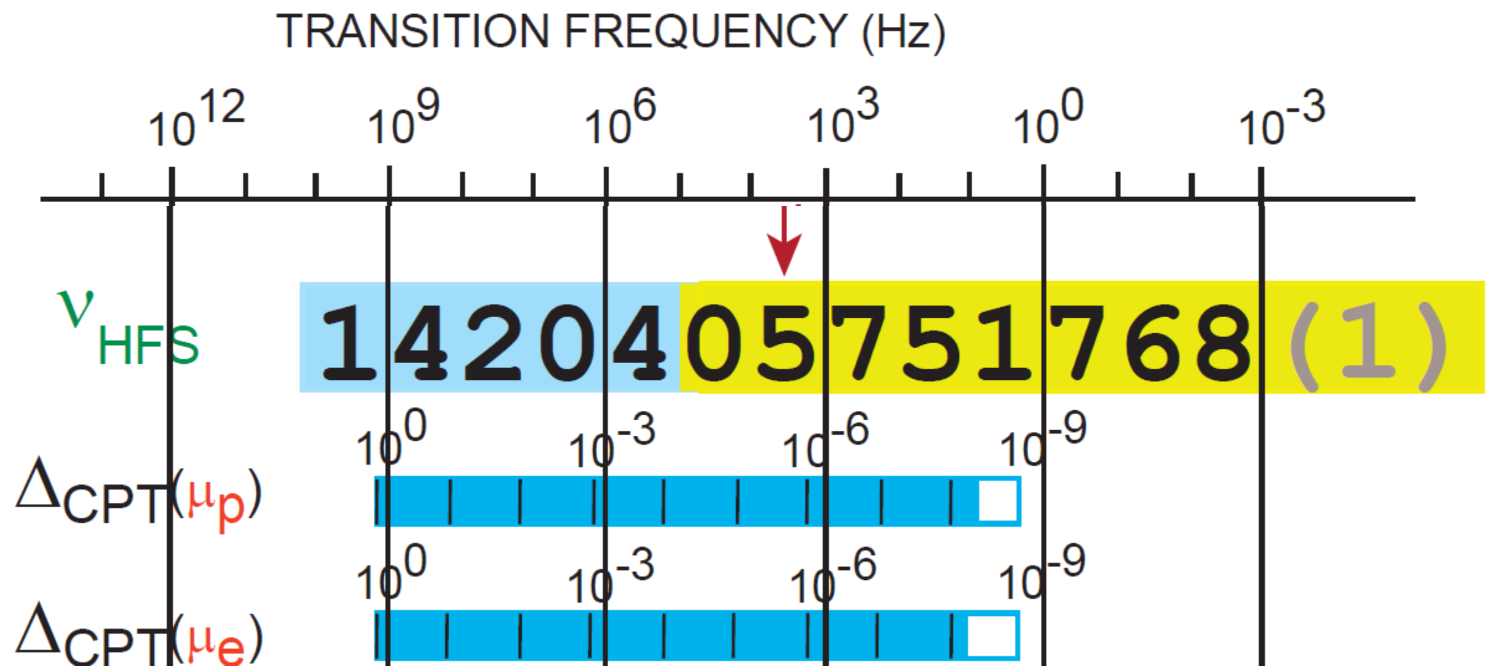
$$\nu_F = \frac{16}{3}\left(\frac{M_p}{M_p+m_e}\right)^3 \frac{m_e}{M_p}\frac{\mu_p}{\mu_N}\,\alpha^2 c\, Ry$$

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)*



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

Comparison of CPT tests: SME

- Standard Model Extension SME

CPT & LORENTZ VIOLATION

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

LORENTZ VIOLATION

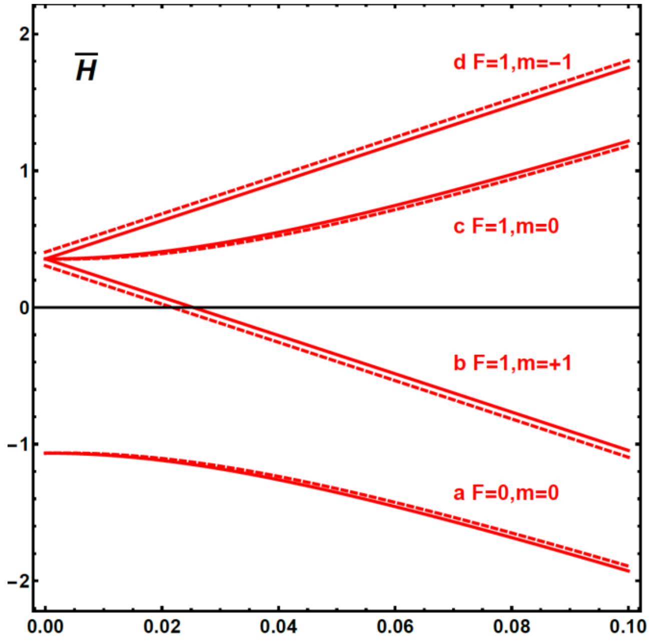
D. Colladay and V.A. Kostelecky, PRD 55, 6760 (1997)

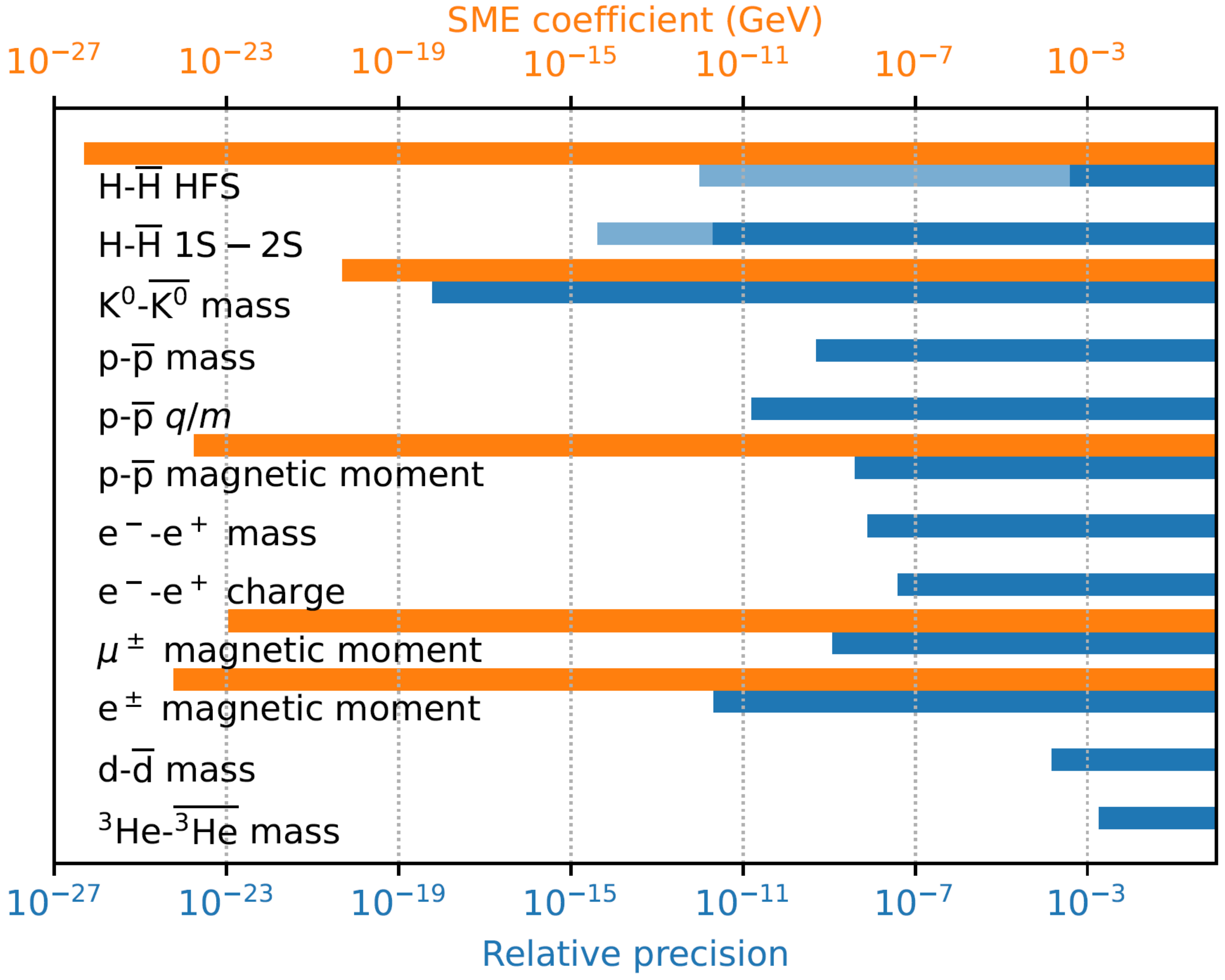
- Minimal SME: only HFS

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

- Non-minimal SME: 1S-2S shows higher-order CPTV

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





Source: PDG, Kostelecky & Bluhm arXiv:0801.0287 (updated annually)
EW, Phys. Part. Nuclei **53**, 790–794 (2022).
arXiv:2111.04056 [hep-ex]

ASACUSA collaboration

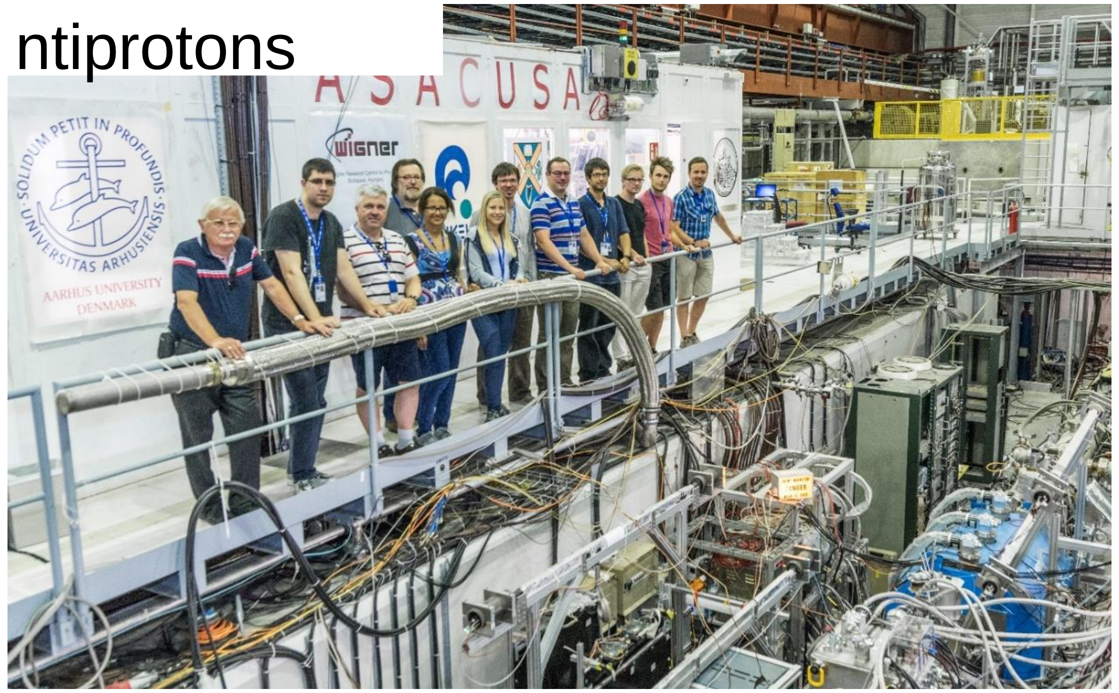
ASACUSA Scientific projects

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

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

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

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



Co-spokespersons

M. Hori MPQ

E.W.

The Antihydrogen team

Stefan Meyer Institute for Subatomic Physics: C. Amsler, S. Chesnevskaya, A. Gligorova, E. Hunter, C. Killian, V. Kletzl, V. Kraxberger, A. Lanz, V. Mäckel, D. Murtagh, A. Nanda, M.C. Simon, A. Weiser, E. Widmann, J. Zmeskal

Univesrita di Brescia & INFN Brescia: G. Constantini, G. Gosta, M. Leali, V. Mascagna, S. Migliorati, L. Venturelli

Politecnico di Milano: R. Ferragut, V. Toso; **Università degli Studi di Milano:** M. Romé, G. Maero; **Infn Milano:** M. Giammarchi

CERN: L. Nowak, C. Malbrunot, T. Wolz

University of Tokyo, Komaba: N. Kuroda, Y. Matsuda

RIKEN: H. Breuker, Y. Kanai, M. Tajima, S. Ulmer, Y. Yamazaki

Hiroshima University: H. Higaki

Tokyo University of Science: Y. Nagata

Aarhus University: U. Uggerhøj

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A tomic
S pectroscopy
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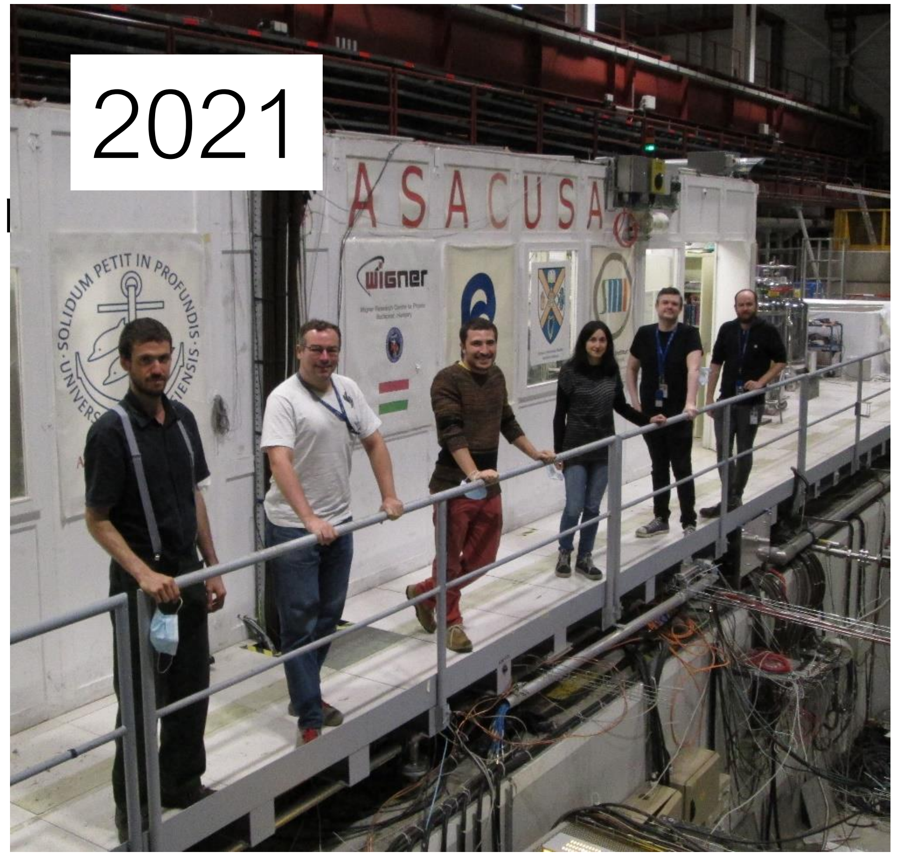

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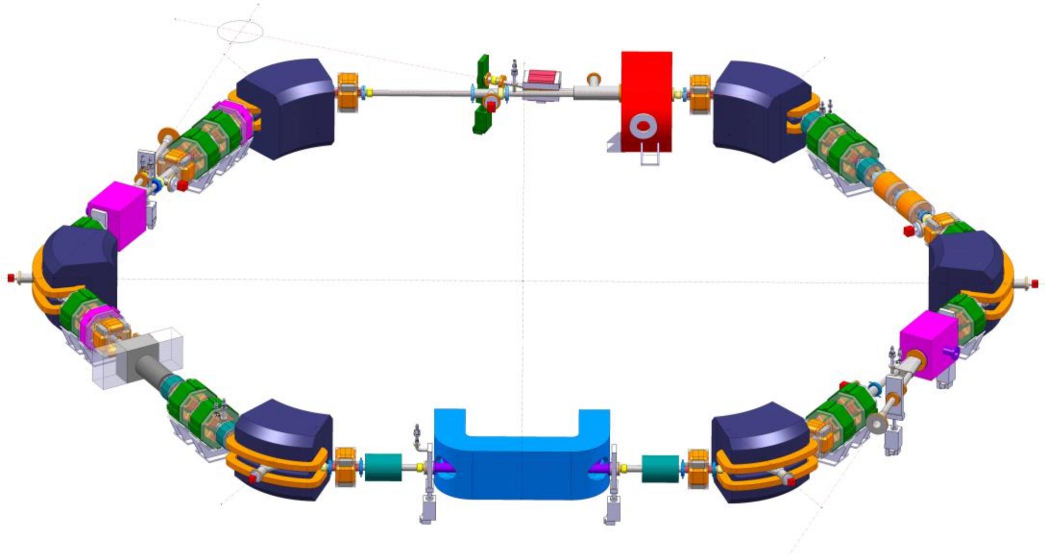
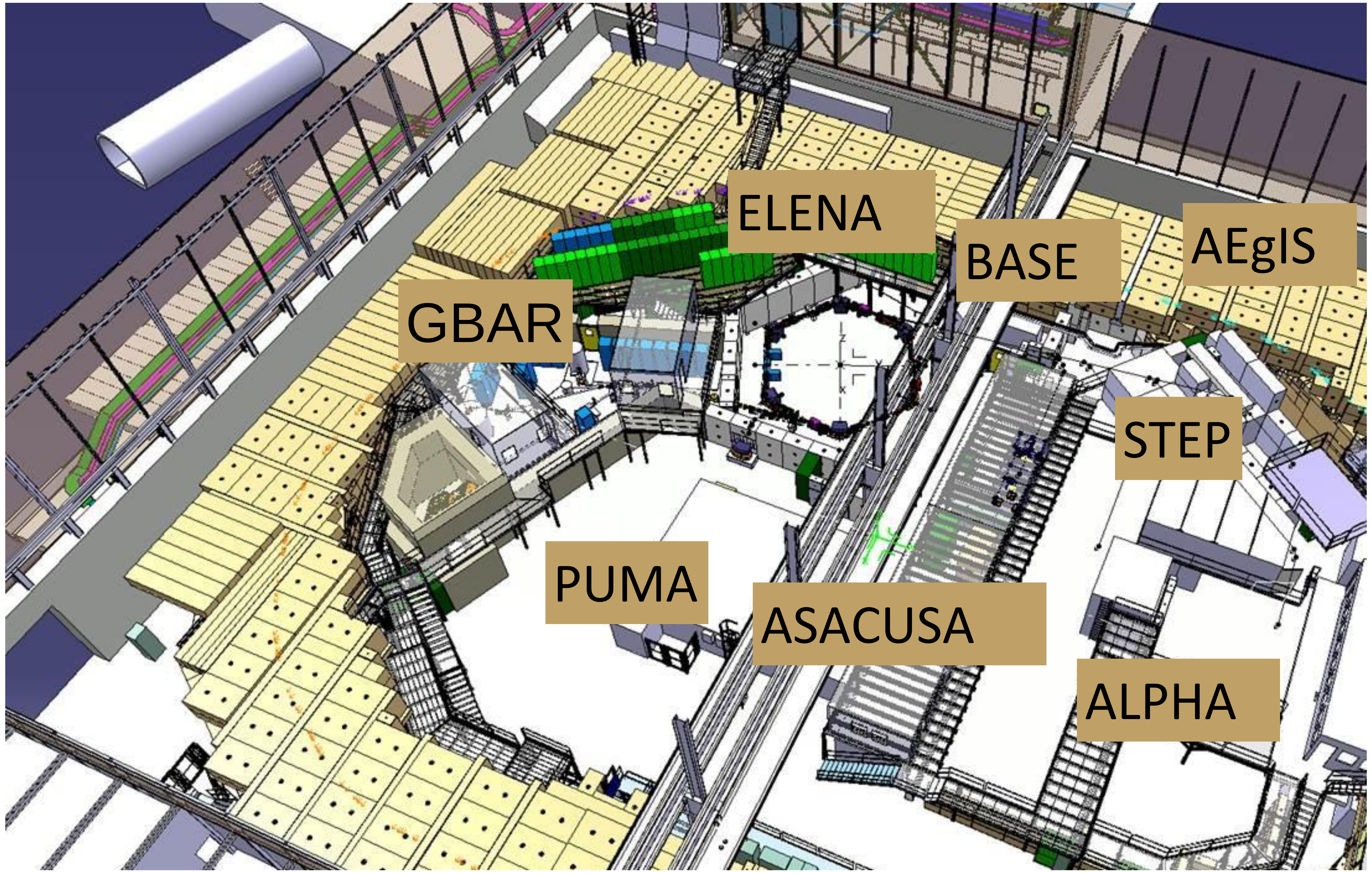
ELENA @ CERN

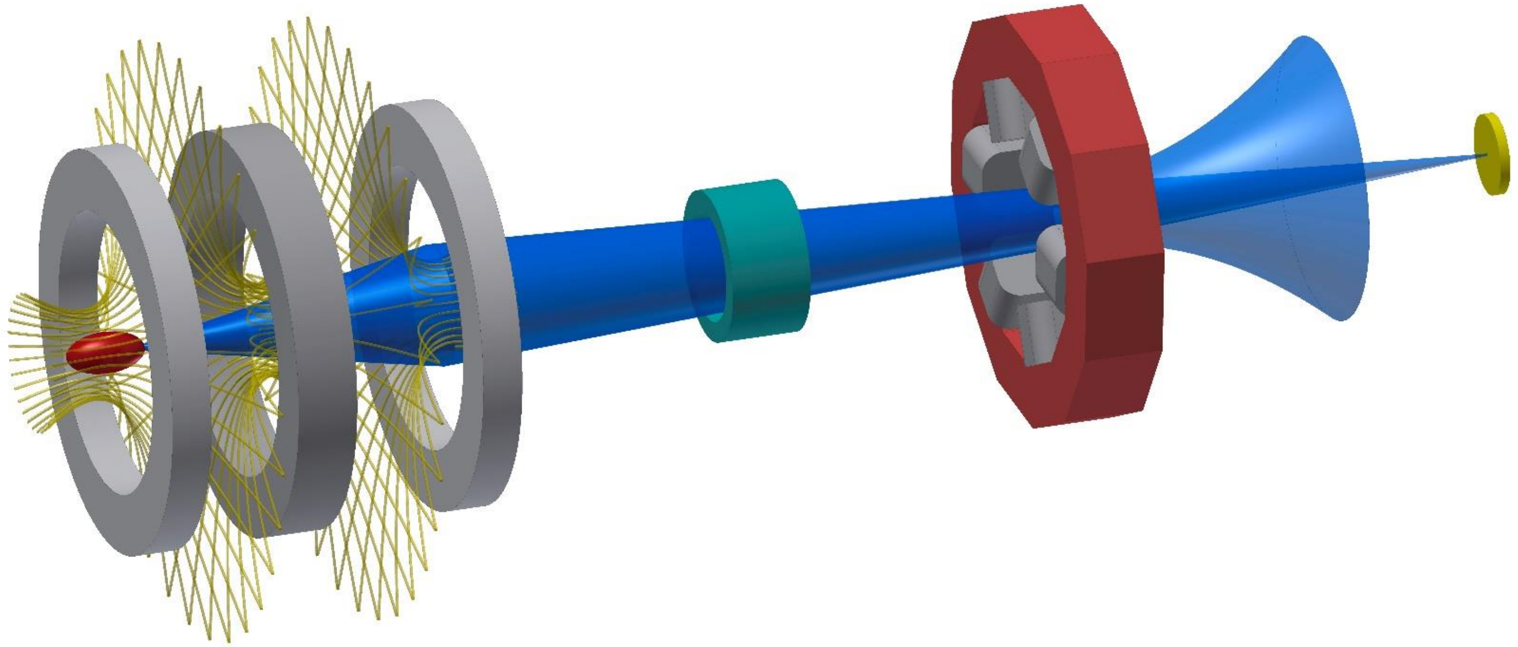


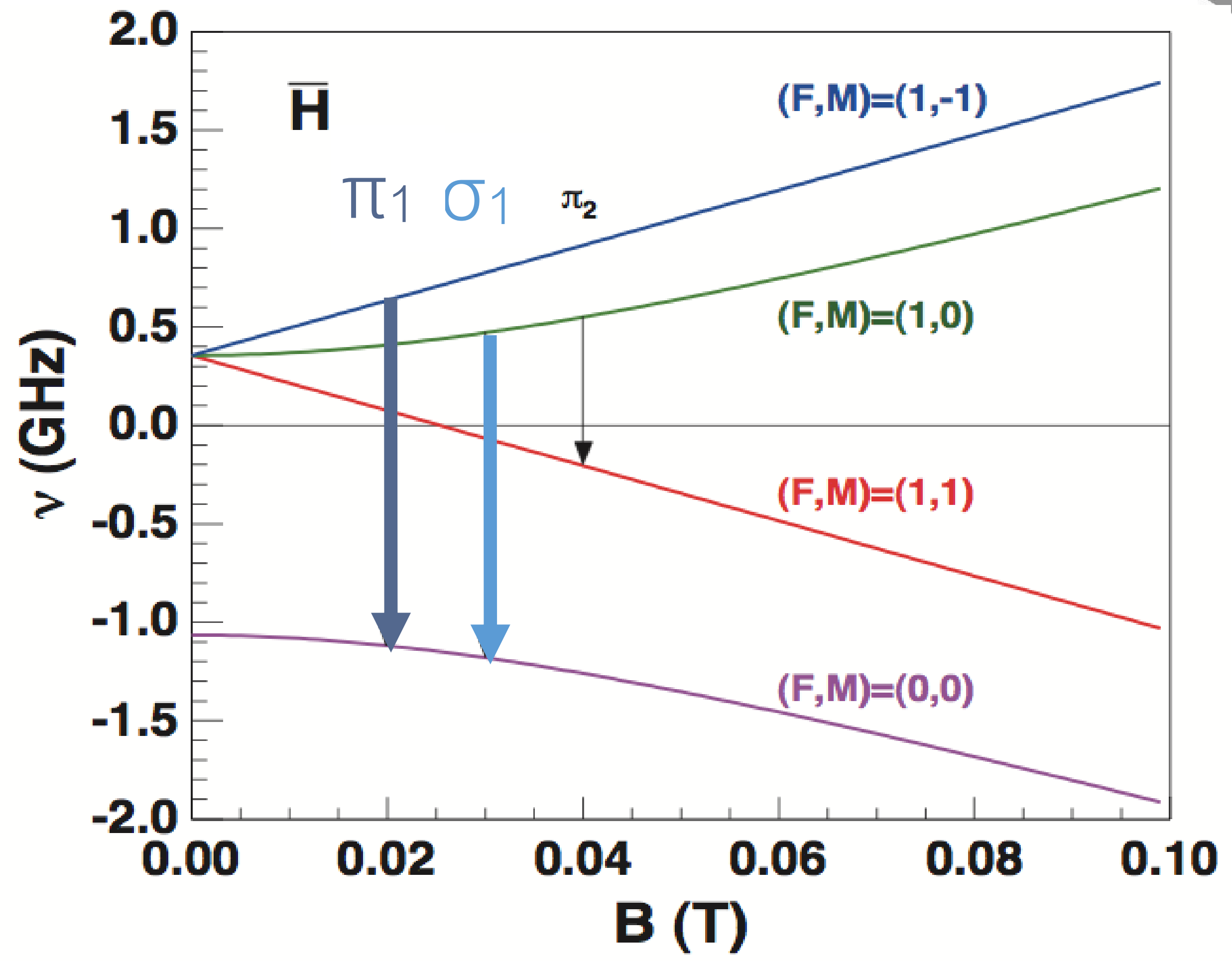
Energy range, MeV	5.3 - 0.1
Intensity of ejected beam	1.8×10^7
$\varepsilon_{x,y}$ of extracted beam, π·mm·mrad, [95%], standard	4 / 4
$\Delta p/p$ of extracted beam, [95%], standard	$8 \cdot 10^{-3}$



ELENA operation started Aug. 2021

In-beam HFS spectroscopy

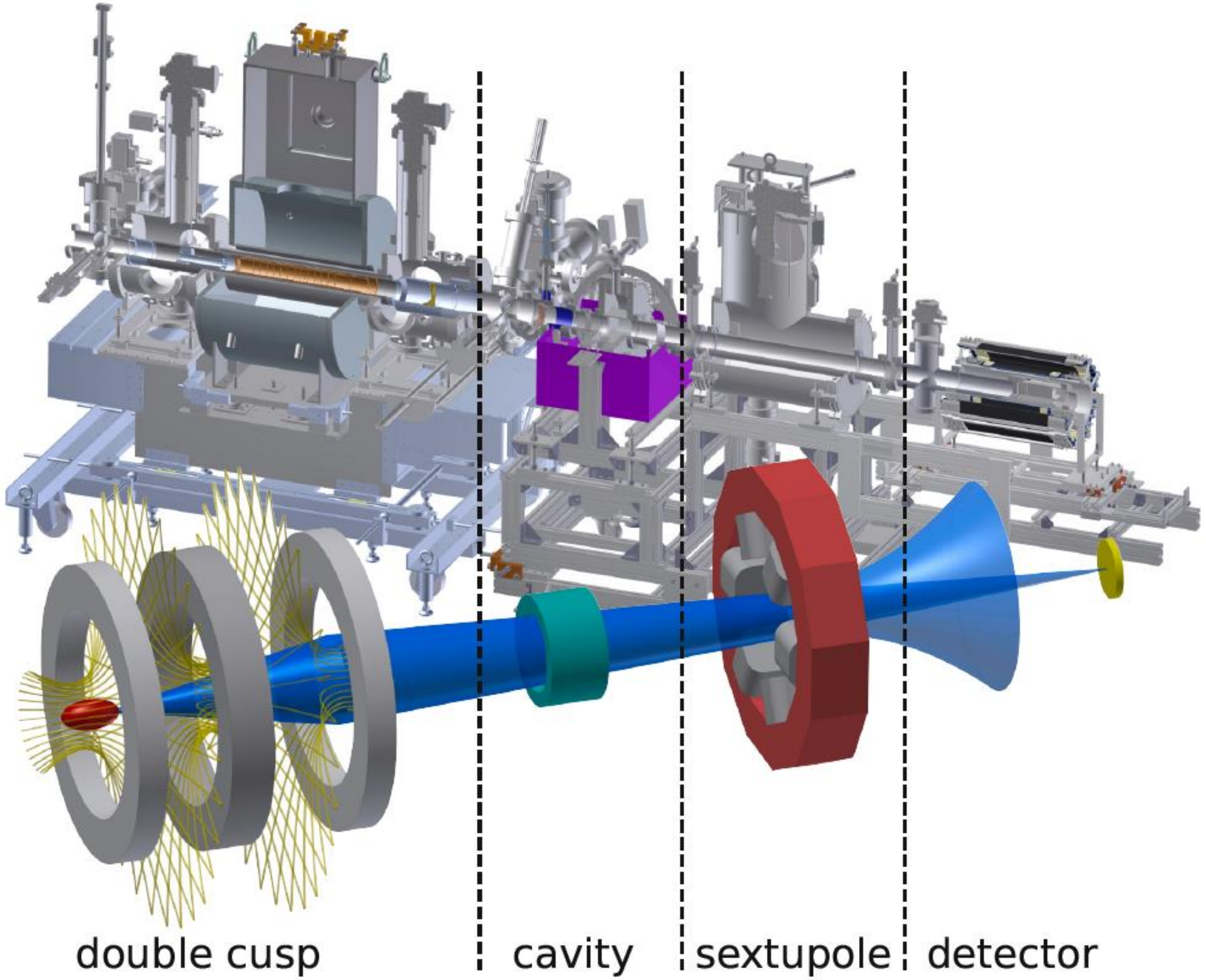




- Goals
  - In-beam measurement of ground-state hyperfine structure of antihydrogen to ppm-level and below
  - Produce polarized slow (<100 K) H̄ beam

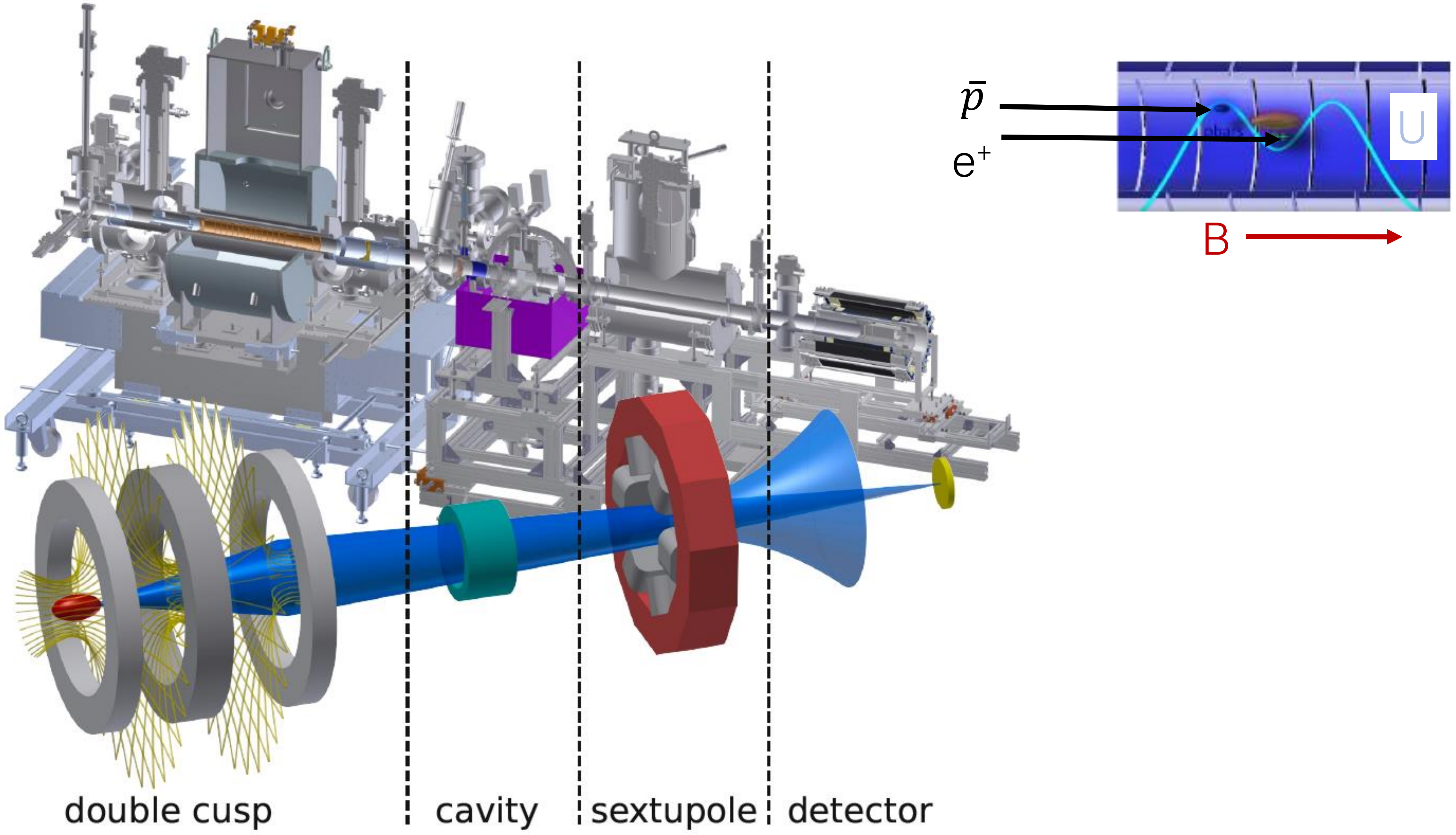
- Resolution: line width $\Delta\nu \sim 1/T_{\mathrm{TOF}}$
  - 1000 m/s, 10 cm:
  - **$\Delta\nu$ =7x10^{-6}** for T = 50 K
  - > 100 H̄/s in 1S state into 4π needed
  - event rate 1 / minute: background from cosmics, annihilations upstreams

ASACUSA Antihydrogen beam for HFS



ASACUSA Antihydrogen beam for HFS

- $\bar{\mathrm{H}}$ production 1st time in **2010** in nested Penning trap
  - Three body recombination (→Rydberg states)



ASACUSA Antihydrogen beam for HFS

- $\overline{\mathrm{H}}$ production 1st time in **2010** in nested Penning trap
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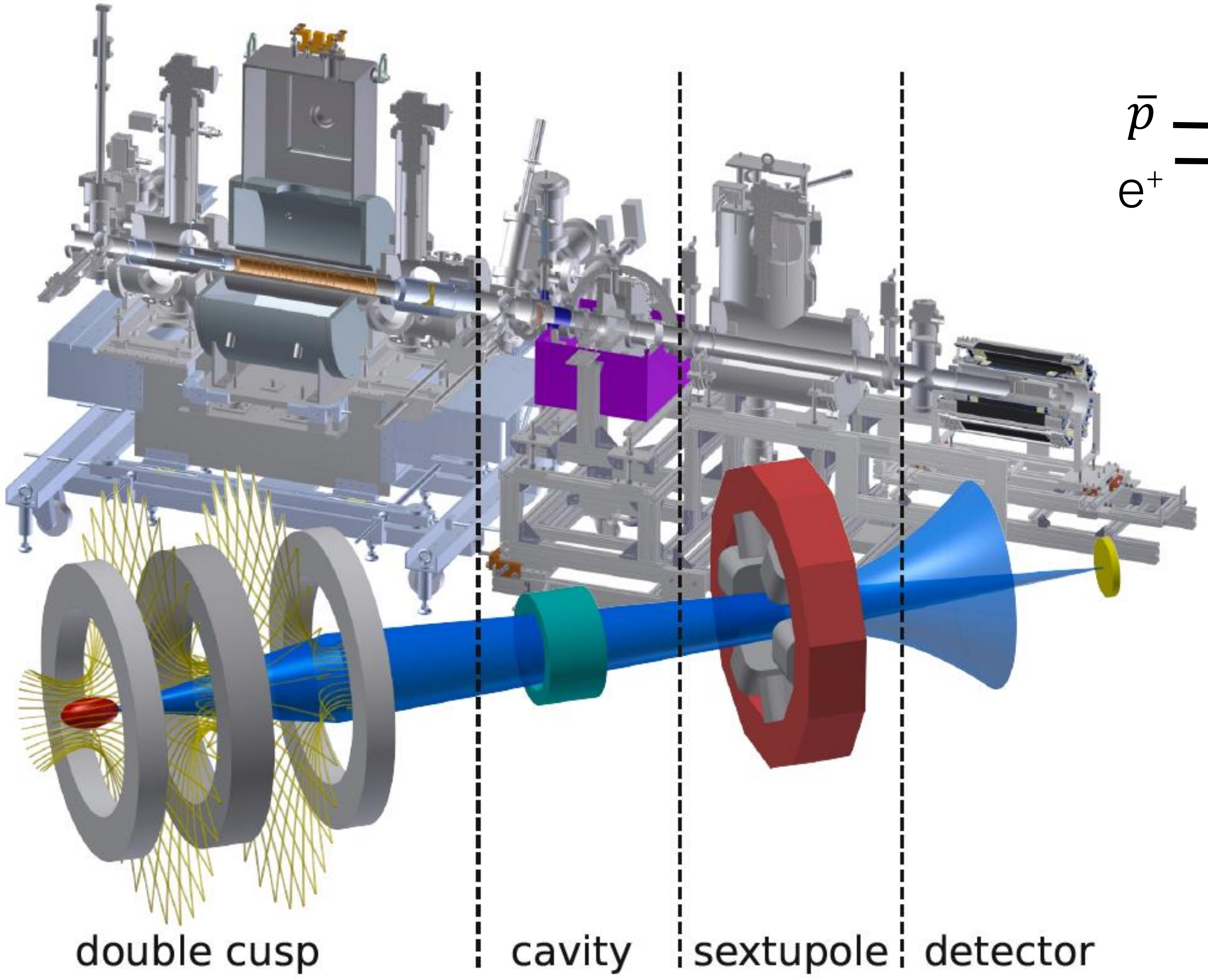
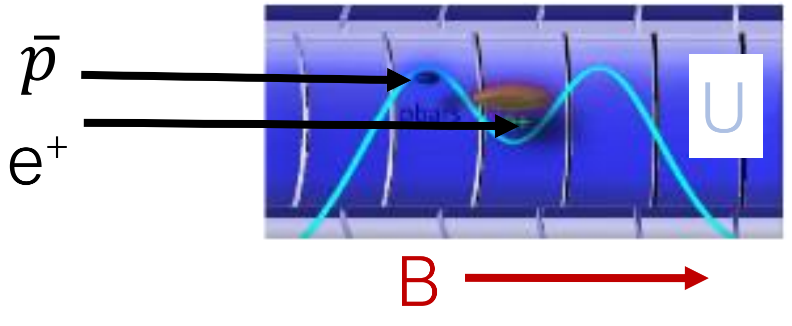
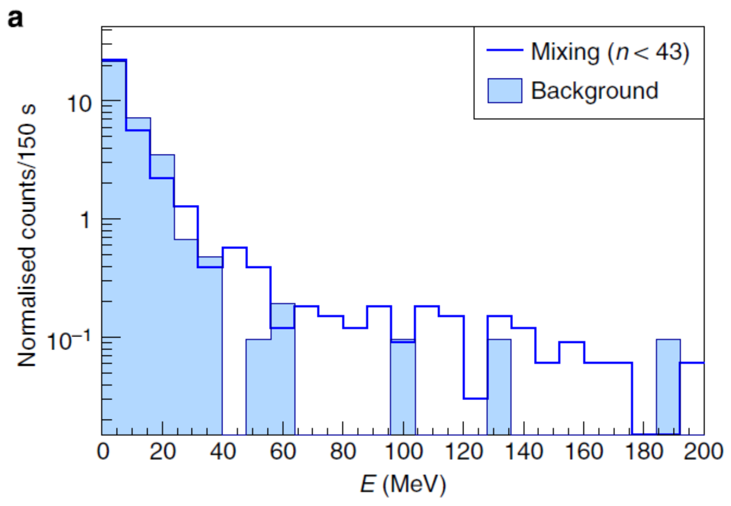
- 1st observation of beam in field free region **2014**
  - n≤43: 6 $\overline{H}$/15 min
  - n≤29: 4 $\overline{H}$/15 min







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

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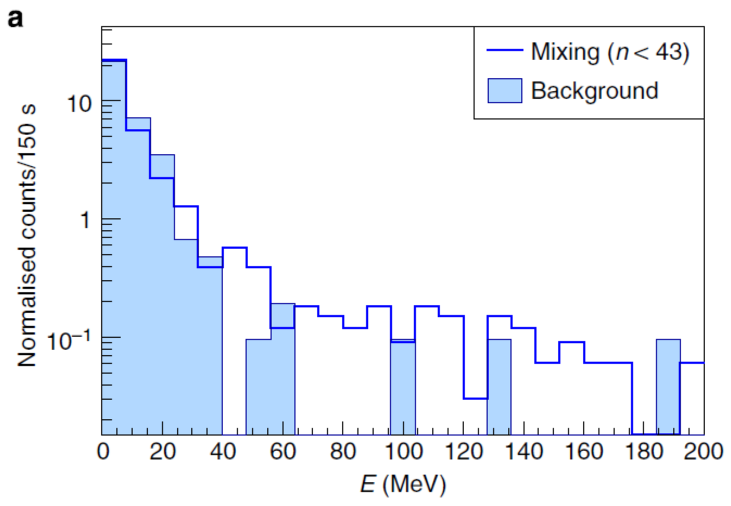

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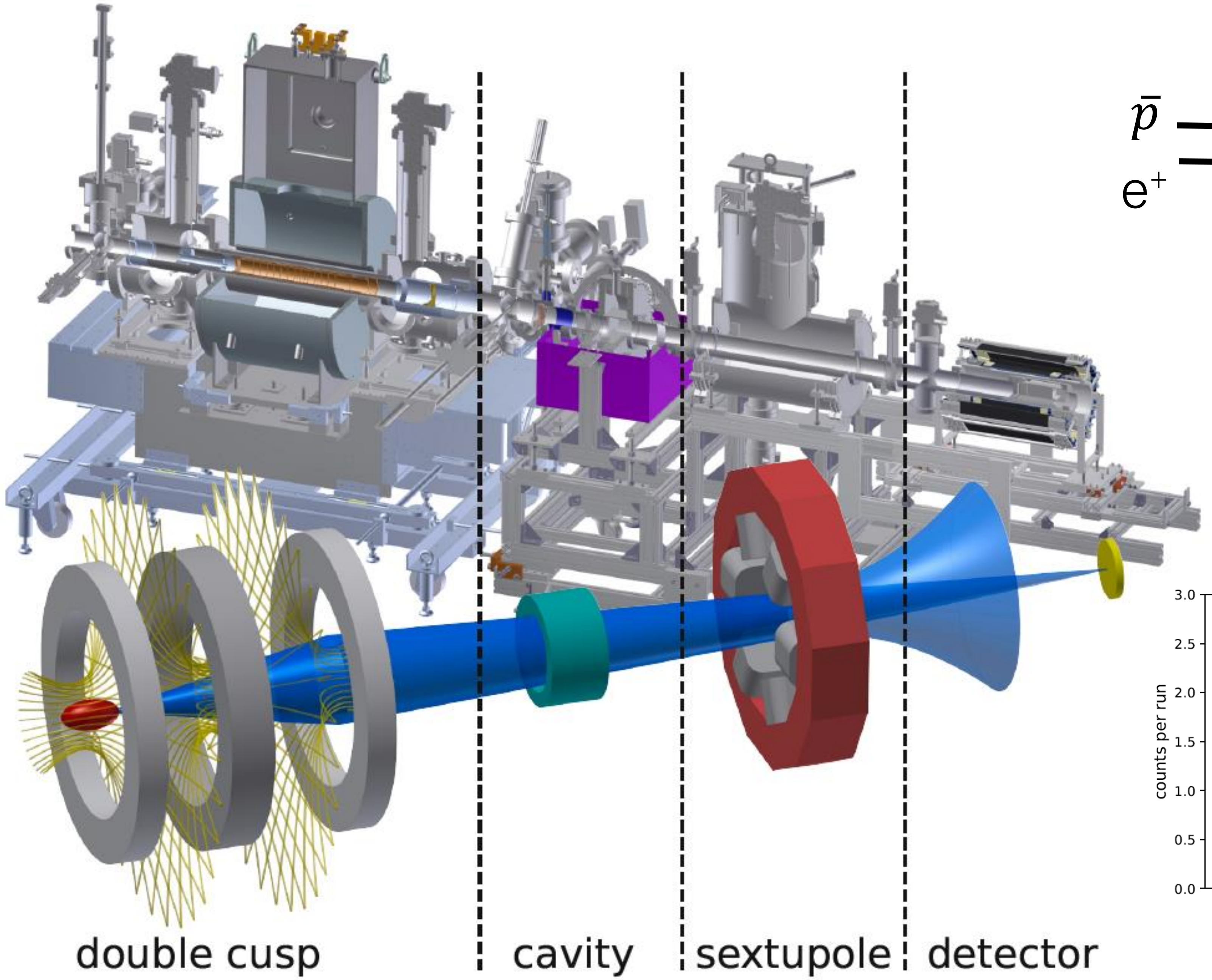
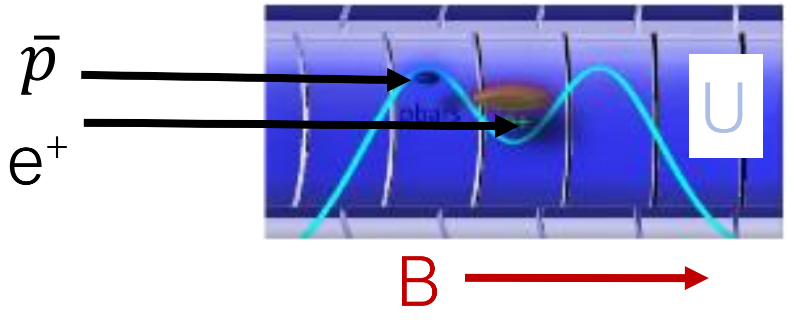
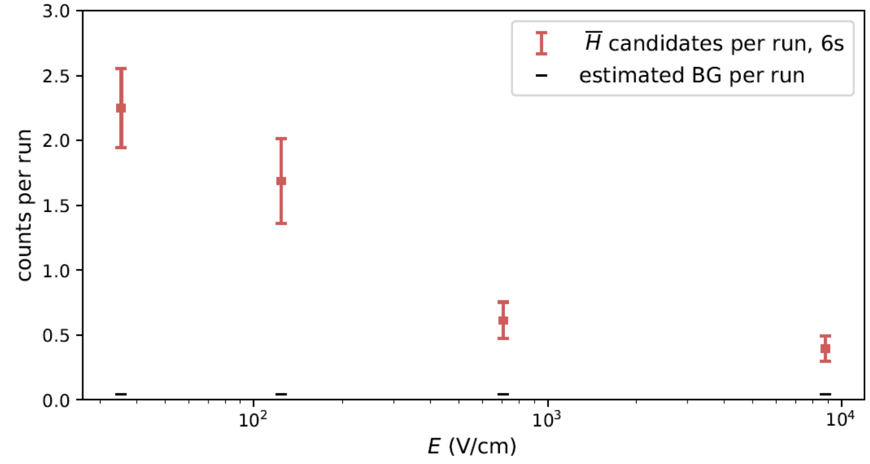




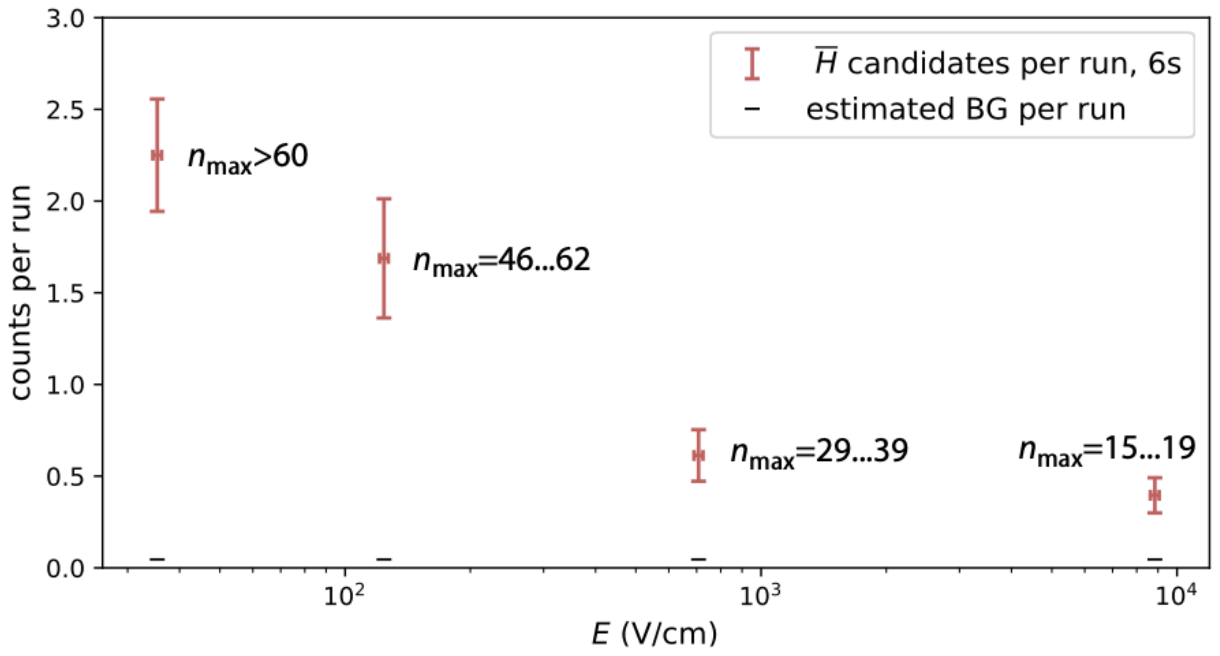
- Measurement of *n* distribution **2021**



B. Kolbinger et al. *EPJ D* 75, (2021) 91.

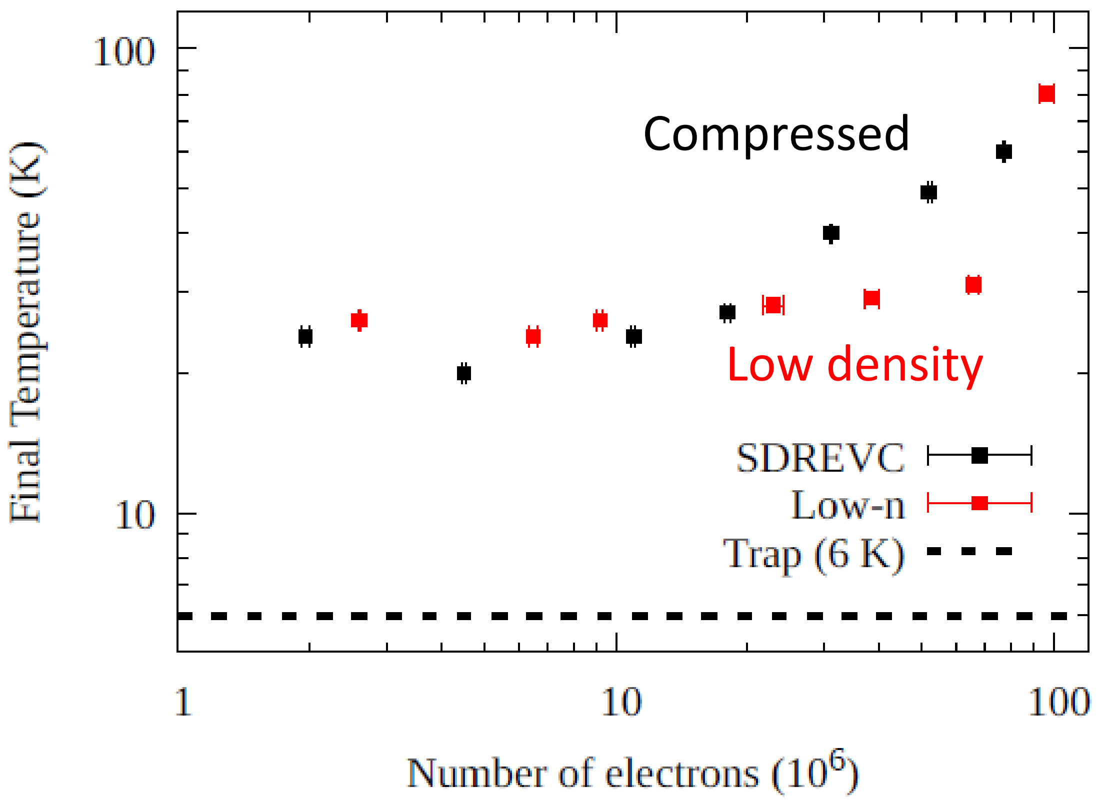
Recent milestones

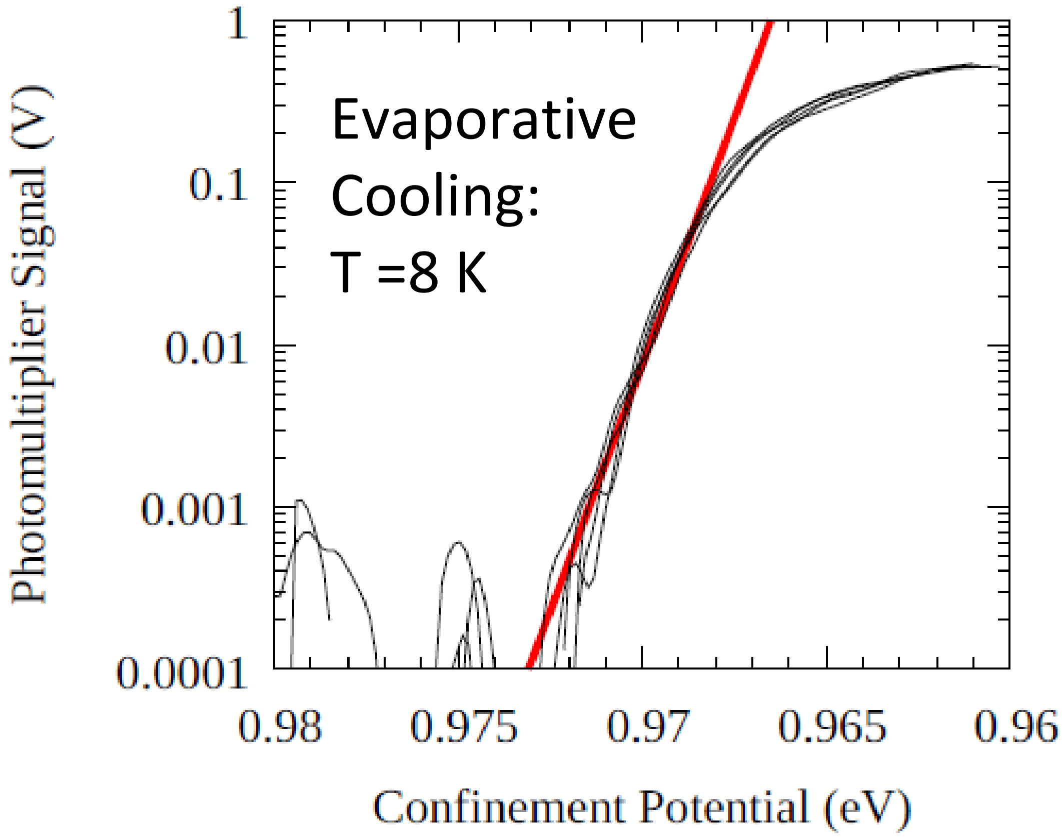
- Quantum number distribution of $\bar{\mathrm{H}}$ beam in field-free region



B. Kolbinger et al. "*Measurement of the principal quantum number distribution in a beam of antihydrogen atoms*"
Eur. Phys. J. D **75**, 91 (2021)

- 100 K colder electron plasmas compared to before
  - Meshes to block RF interference, better cooling



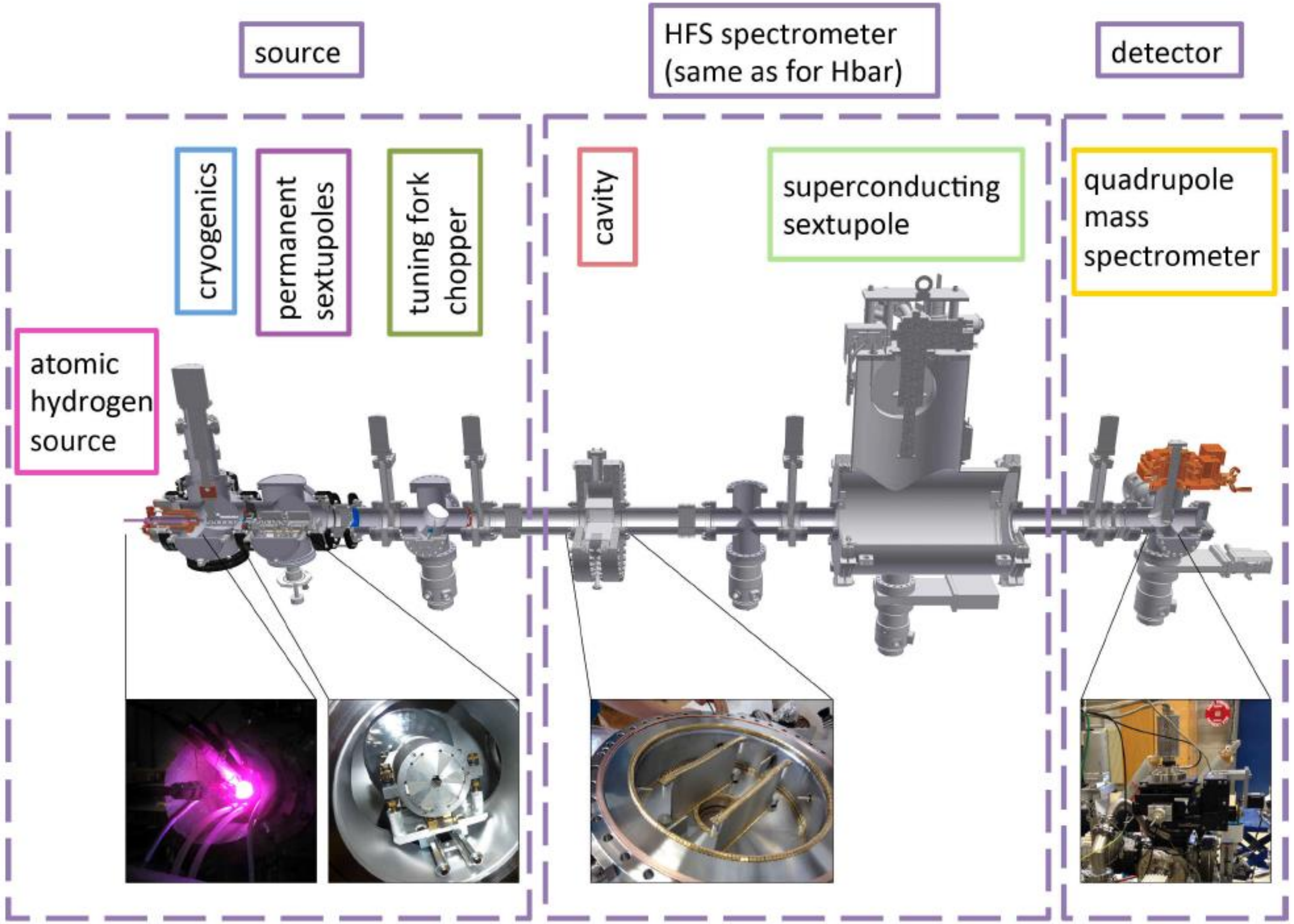


E. Hunter et al. EPJ Web Conf. 262 01007 (2022).
C. Amsler et al. *Physics of Plasmas* **29**, 083303 (2022).
arXiv:2203.14890 [physics.plasm-ph]

1st $\bar{\mathrm{H}}$ interaction with microwaves expected 2023

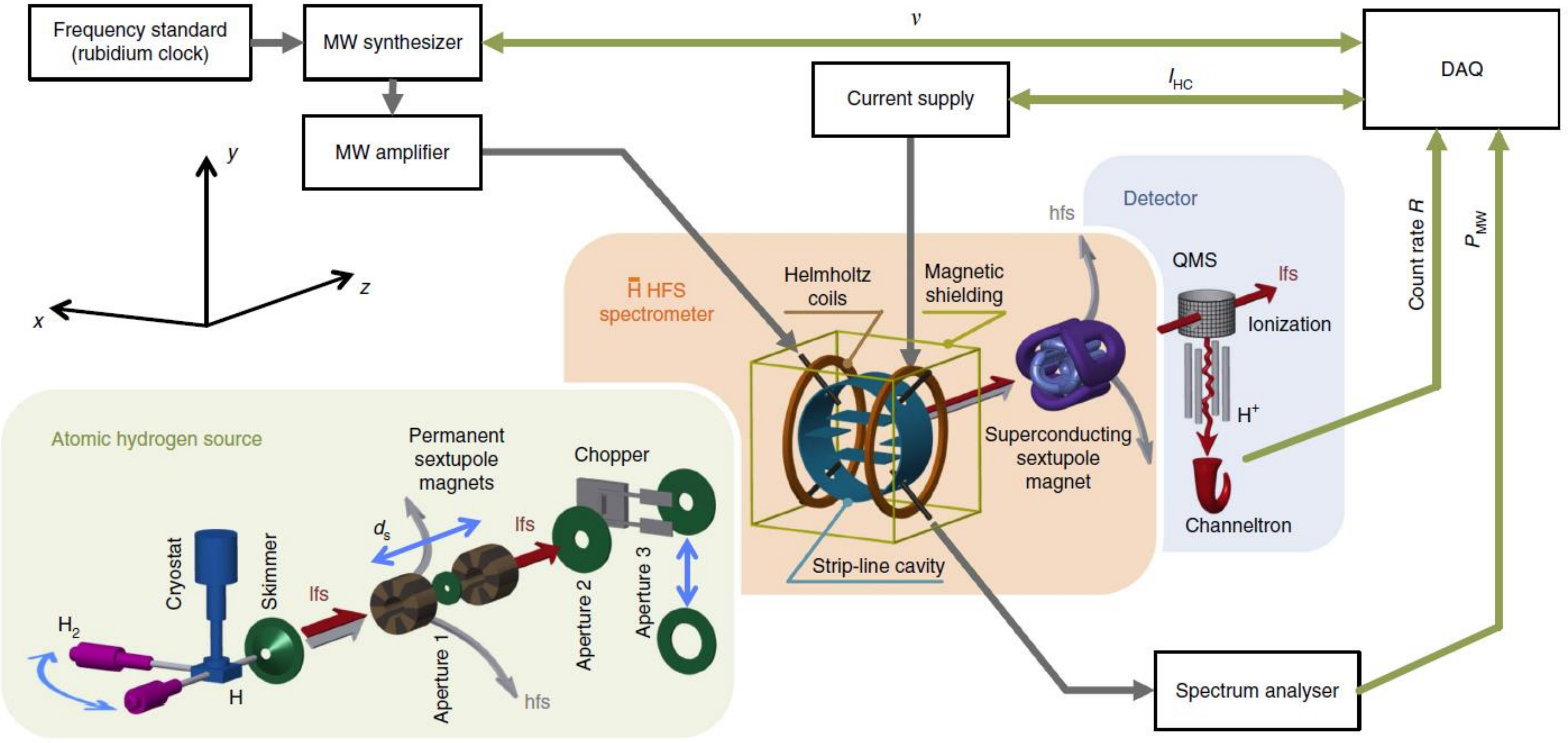
Hydrogen beam measurements

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

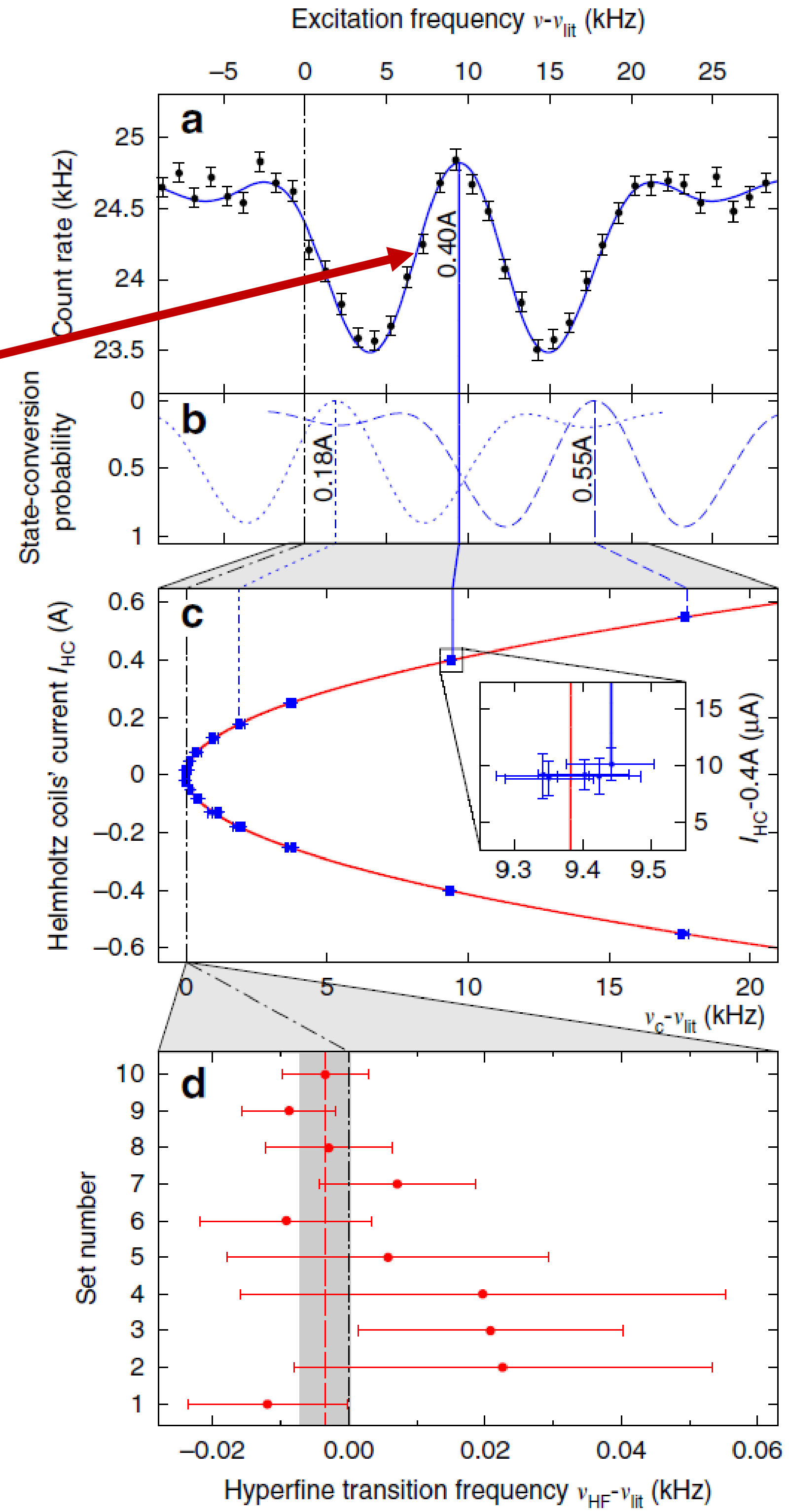


Malbrunot, C., et al., NIMA *935*, 110–120 (2019)

σ-transition in H using $\overline{\mathrm{H}}$ setup



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



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

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]

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 $\overline{\mathrm{H}}$: **8000** atoms needed to achieve **1 ppm**

Non-minimal SME & HFS

$$\mathcal{H}_{w\mathrm{r}} = -\sum_{kjm} |\boldsymbol{p}|^k \, {}_0Y_{jm}(\hat{\boldsymbol{p}}) \, \mathcal{T}_{w\,jkm}^{\mathrm{NR}(0\mathrm{B})},$$

$$\mathcal{H}_{w\pm} = -\sum_{kjm} |\boldsymbol{p}|^k \, {}_{\pm1}Y_{jm}(\hat{\boldsymbol{p}}) \, (i\mathcal{T}_{w\,jkm}^{\mathrm{NR}(1\mathrm{E})} \pm \mathcal{T}_{w\,jkm}^{\mathrm{NR}(1\mathrm{B})}),$$

- Extension to coefficients of arbitrary mass order

$\boldsymbol{p}$: momentum, k=2q, Y: spin-weighted spherical harmonics, w=e,p

- Hydrogen HFS

CPT odd CPT even

$$2\pi\delta\nu_\pi = -\frac{1}{2\sqrt{3\pi}} \sum_{q=0}^{2} (\alpha m_\mathrm{r})^{2q} (1+4\delta_{q2}) \sum_w \left[\boxed{g_{w(2q)10}^{\mathrm{NR}(0B)}} - \boxed{H_{w(2q)10}^{\mathrm{NR}(0B)}} + 2\boxed{g_{w(2q)10}^{\mathrm{NR}(1B)}} - 2\boxed{H_{w(2q)10}^{\mathrm{NR}(1B)}} \right],$$

w=e,p, m_r: reduced mass

- Transformation to sun-centered frame

Siderial variations: constrained by maser to mHz

Humphrey, M. A. *et al.*
PRA **68**, 063807 (2003).

$$\mathcal{K}_{wk10}^{\mathrm{NR,lab}} = \boxed{\mathcal{K}_{wk10}^{\mathrm{NR,Sun}} \cos\vartheta} - \boxed{\sqrt{2}\,\mathrm{Re}\,\mathcal{K}_{wk11}^{\mathrm{NR,Sun}} \sin\vartheta \cos\omega_\oplus T_\oplus + \sqrt{2}\,\mathrm{Im}\,\mathcal{K}_{wk11}^{\mathrm{NR,Sun}} \sin\vartheta \sin\omega_\oplus T_\oplus.}$$

Orientation dependence: unconstrained

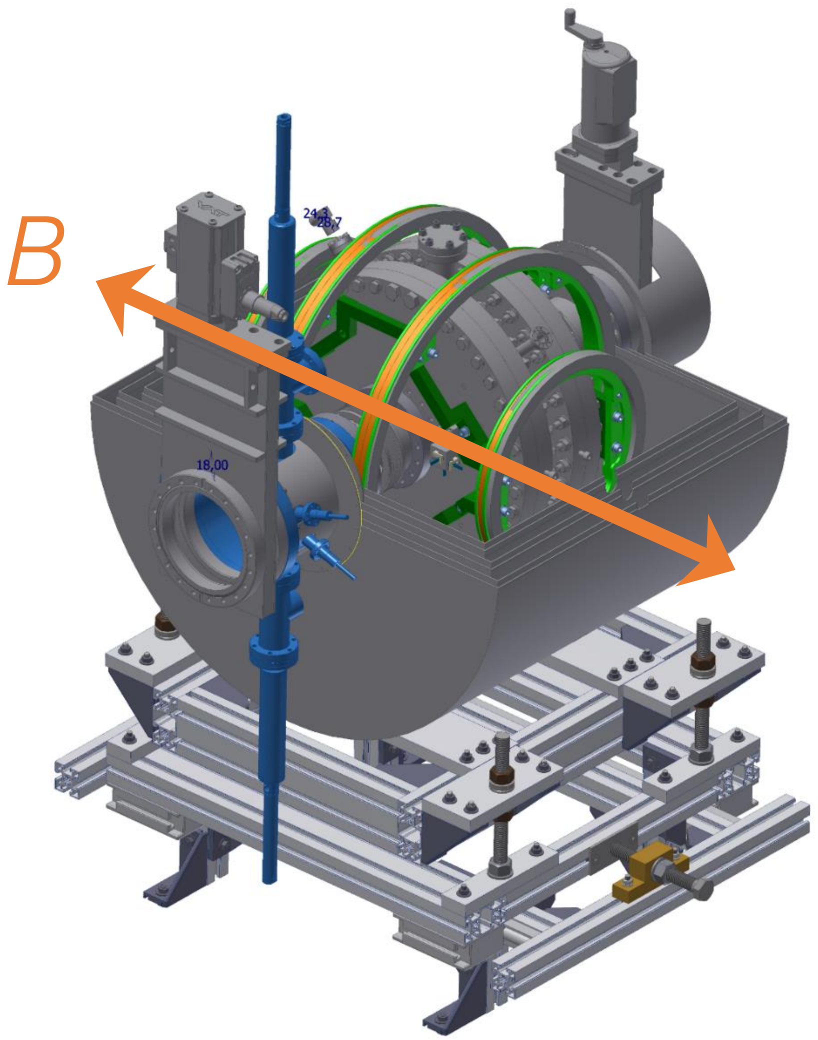
- e.g. inversion of direction of B field

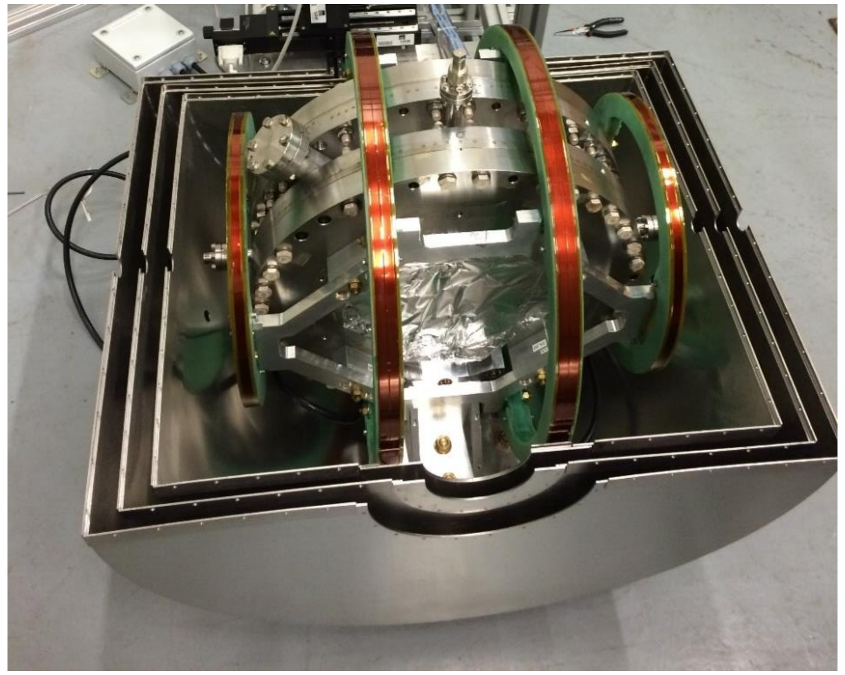
$$\begin{aligned}\Delta(2\pi\nu_\pi) &\equiv 2\pi\nu_\pi(\boldsymbol{B}) - 2\pi\nu_\pi(-\boldsymbol{B}) \\ &= -\frac{\cos\vartheta}{\sqrt{3\pi}} \sum_{q=0}^{2} (\alpha m_\mathrm{r})^{2q} (1+4\delta_{q2}) \sum_w \left[g_{w(2q)10}^{\mathrm{NR,Sun}(0B)} - H_{w(2q)10}^{\mathrm{NR,Sun}(0B)} + 2g_{w(2q)10}^{\mathrm{NR,Sun}(1B)}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

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

H-beam and non-minimal SME

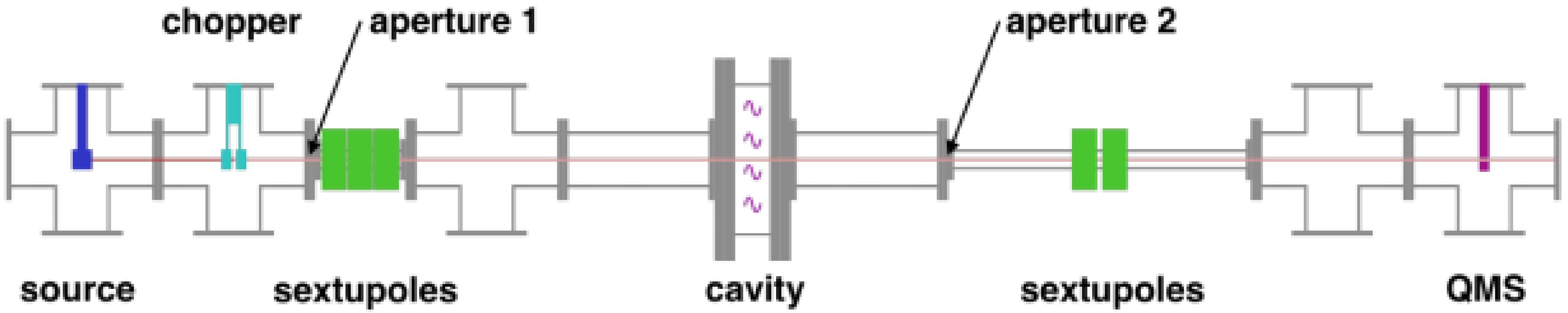
- π_1 transition
  - Better field homogeneity needed
    - Inproved coils, shielding
  - SME: effect only in π_1
  - Non-minimal SME: direction dependent coefficients accessible by beam experiments
- Conditions
  - Invert direction of B-field – data taken
  - Rotate B-field – not yet
  - Measure σ_1 (no CPTV) as reference



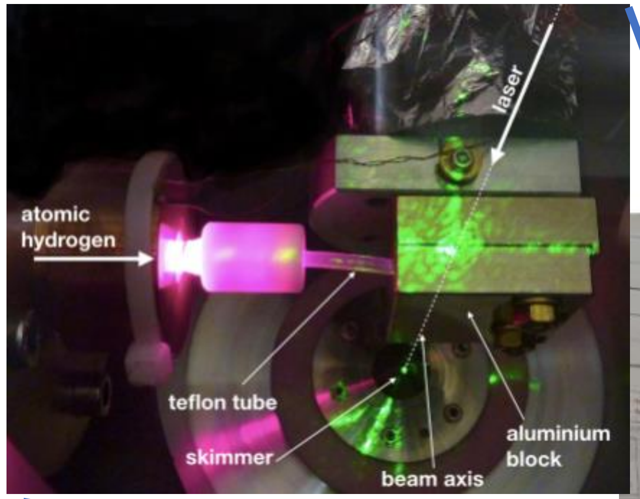


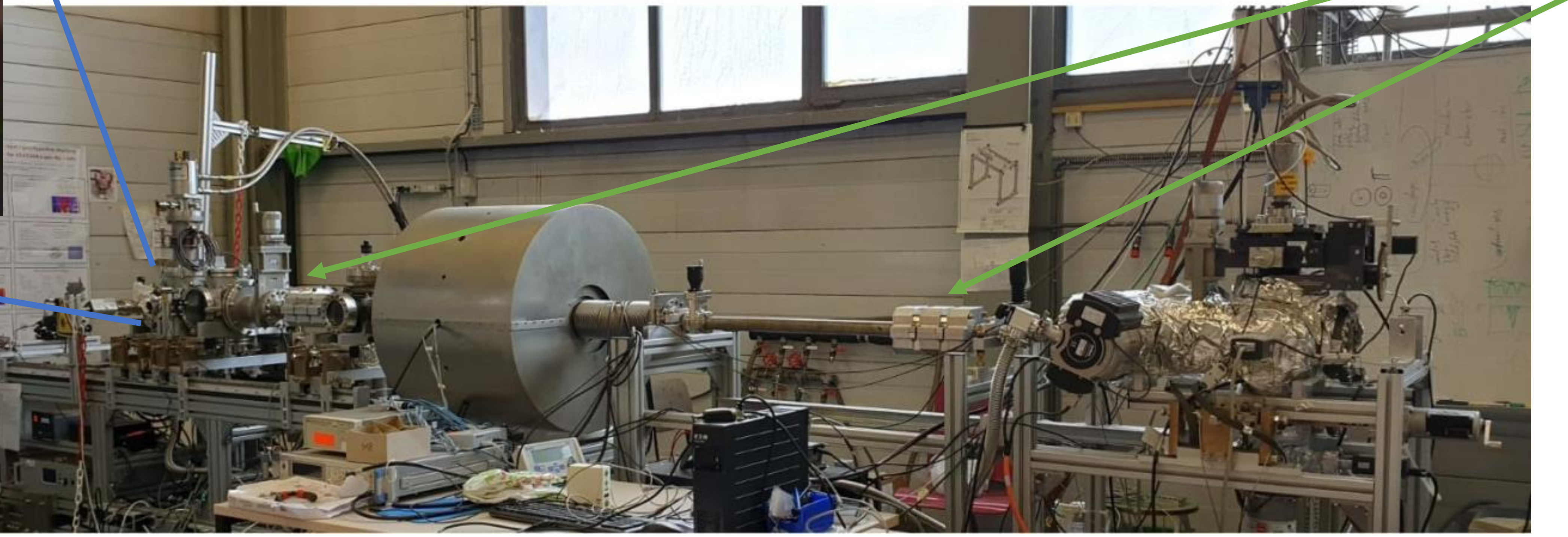
ASACUSA hydrogen beam line @ CERN

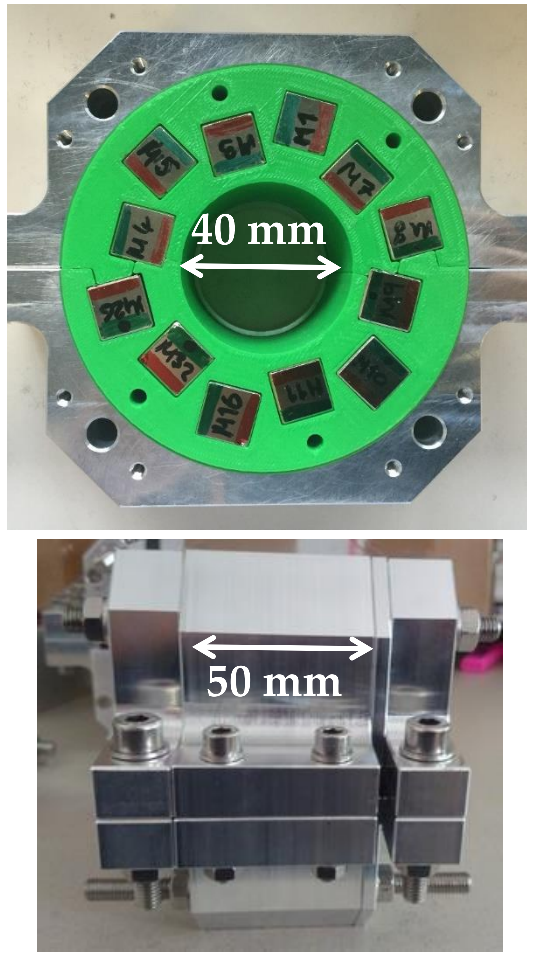
Schematic sketch of the hydrogen beamline:



20K hydrogen beam







Permanent sextupoles for focusing
$B(r\text{=}18\text{mm}) = 0.27$ T
$\int g_s(z)\mathrm{d}z = 85$ T/m

Current status of *B*-direction dependence

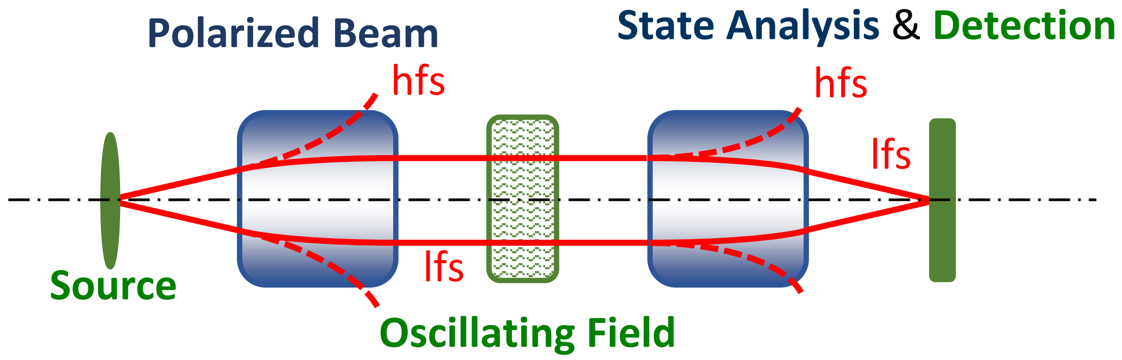
- Extensive series of measurements in Jan – Mar 2022
  - Sequence $\nu_\sigma\ (+\boldsymbol{B}), \nu_\pi\ (+\boldsymbol{B}),\ \nu_\sigma\ (-\boldsymbol{B}),\ \nu_\pi\ (-\boldsymbol{B})$
- Data still blinded
  - Systematics investigation ongoing
- Current status
  - First estimation
    Error $\Delta\nu_\pi\ (+B) - \Delta\nu_\pi\ (-B) \sim 210$ Hz (1σ)
  - Current status of analysis
    Error $\Delta\nu_\pi\ (+B) - \Delta\nu_\pi\ (-B) \sim$ **71 Hz** (1σ)
    close to final

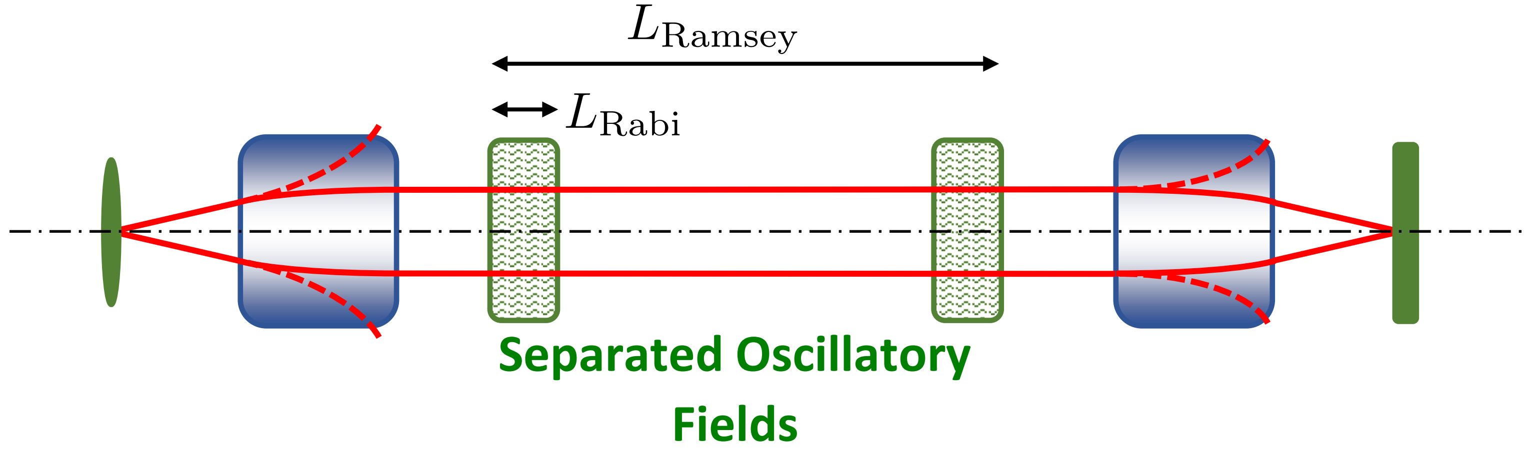
- SME coefficients

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

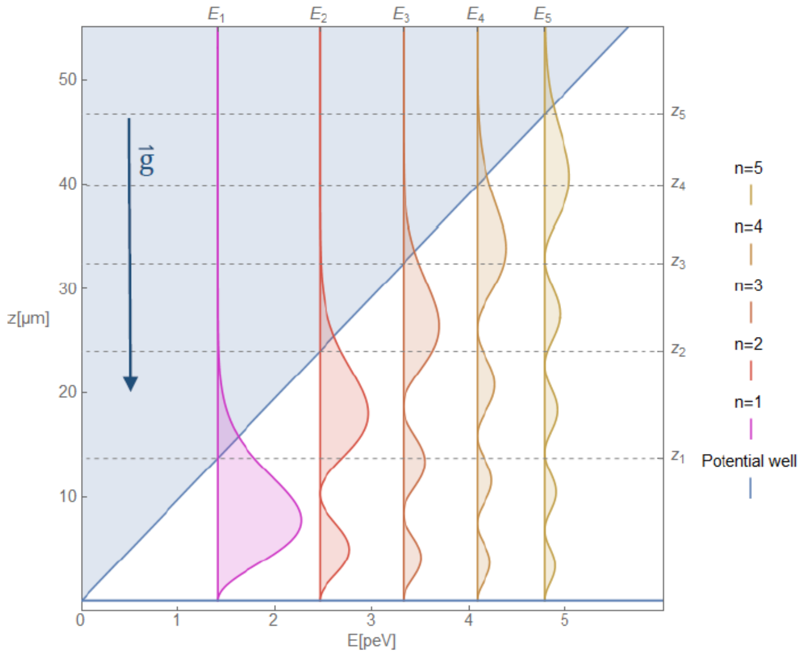
- $\cos\vartheta \sim -0.26$ (angle $\boldsymbol{B}$, earth axis)
- *q*=0, both p,e: $g_{010}^{\mathrm{NR,Sun(0B)}} < 6.4x10^{-20}$ GeV
  $< \mathbf{2.1x10^{-20}}$ **GeV**
  (preliminary)
- dto. $g_{010}^{\mathrm{NR,Sun(1B)}}, H_{010}^{\mathrm{NR,Sun(0B)}}, H_{010}^{\mathrm{NR,Sun(1B)}}$

Prospects





- Current limitation:
  - Low sensitivity of ν_σ at low B (few Gauss)
  - Improvement: magnetrometry
- Improvement of precision
  - Current H beam (50 K, 1 km/s): ~ Hz
  - Angle B, Earth axis: / 3
  - Colder beam (6 K, 250 m/s), L_{Rabi}=10→30 cm: / 10
  - Ramsey-method: / 10+
- Best: gravitational quantum states
  - Reflection by Casimir Polder potential
    - also applicable to $\bar{\text{H}}$
  - E~ peV

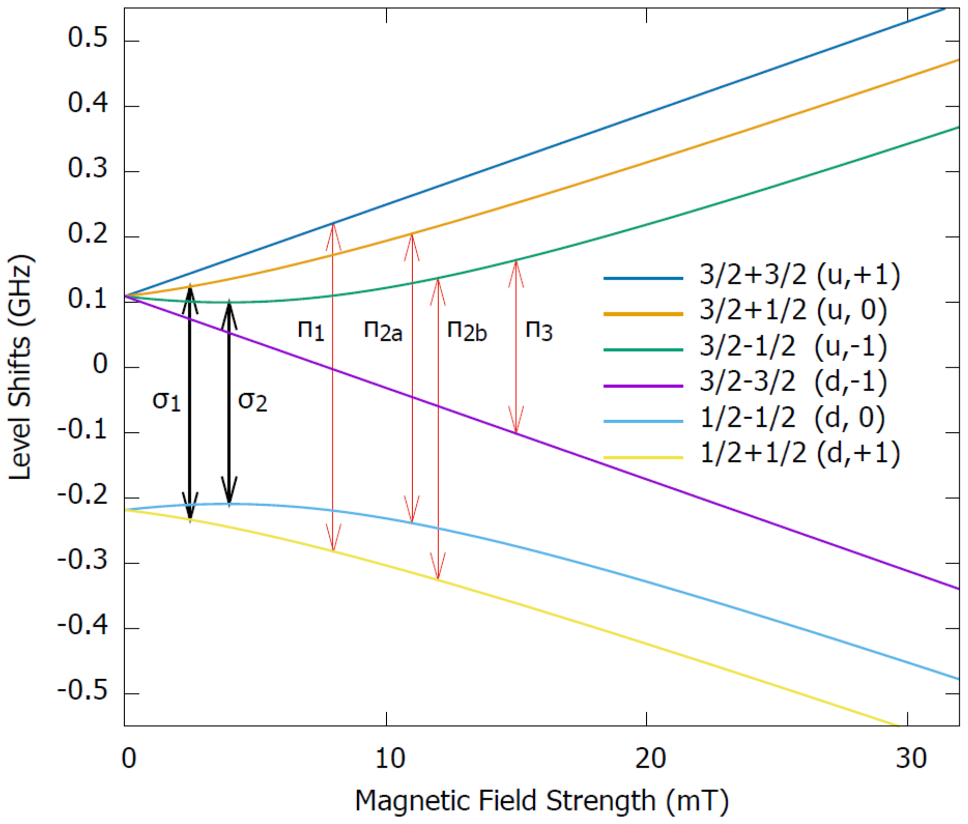


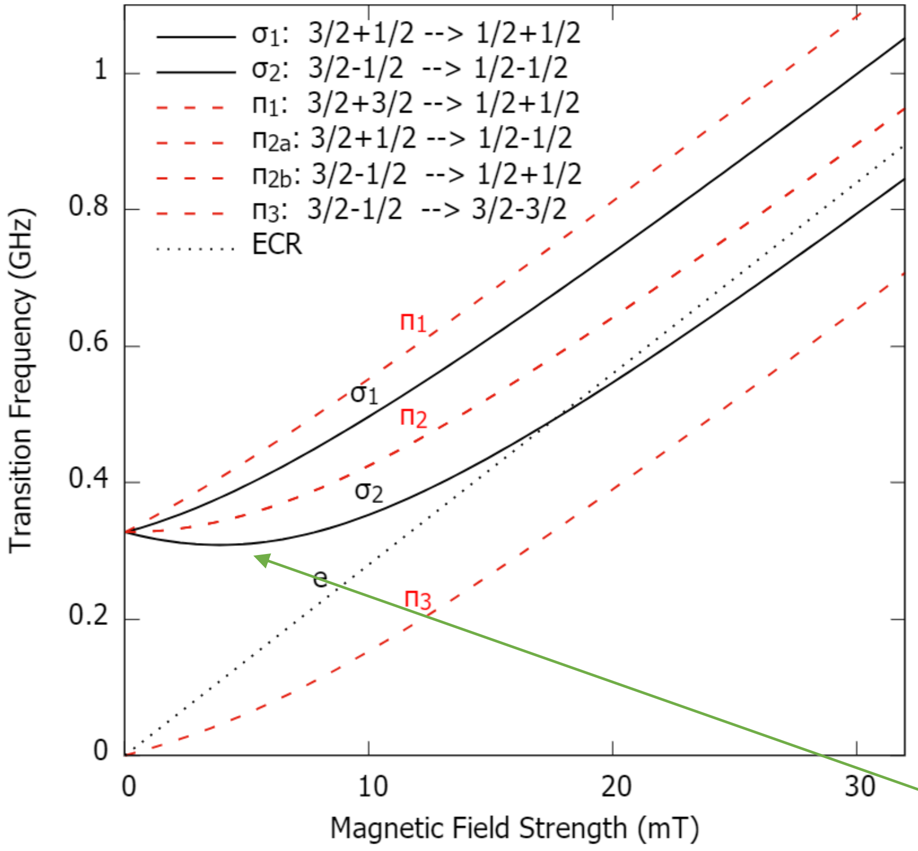
GRASIAN

Deuterium HFS and SME

Kostelecký V. A., Vargas A. J. Phys. Rev. D 92, 056002 (2015)

$$\begin{aligned}\delta\epsilon(F,m_F) &= \frac{1}{\sqrt{5\pi}}\frac{2F-1}{(8m_F^2-10)}\sum_{q=0}^{2}\langle p_{pd}^{2q}\rangle\sum_w \mathcal{V}_{w(2q)20}^{\mathrm{NR}} \\ &\quad -\frac{1}{3\sqrt{6\pi}}\frac{m_F}{2^{F-2}}\sum_{q=0}^{2}\langle p_{pd}^{2q}\rangle \\ &\quad \times\sum_w\left(\mathcal{T}_{w(2q)10}^{\mathrm{NR}(0B)}+2\mathcal{T}_{w(2q)10}^{\mathrm{NR}(1B)}\right) \\ &\quad -\frac{m_F}{3\sqrt{3\pi}}\sum_{q=0}^{2}\frac{(\alpha m_r)^{2q}}{2(F-1)}(1+4\delta_{q2}) \\ &\quad \times\left(\mathcal{T}_{e(2q)10}^{\mathrm{NR}(0B)}+2\mathcal{T}_{e(2q)10}^{\mathrm{NR}(1B)}\right), \qquad (123)\end{aligned}$$

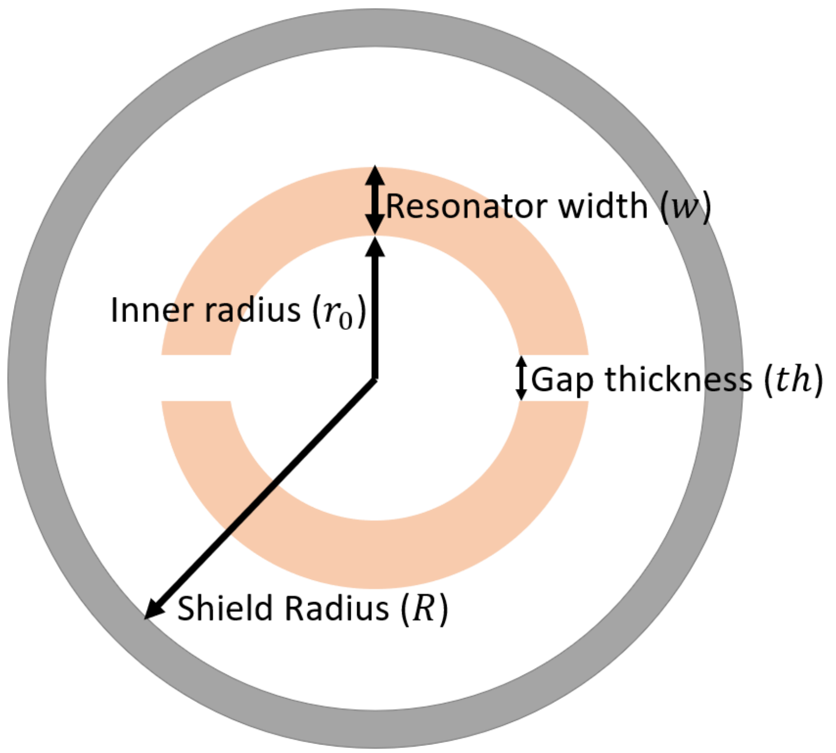


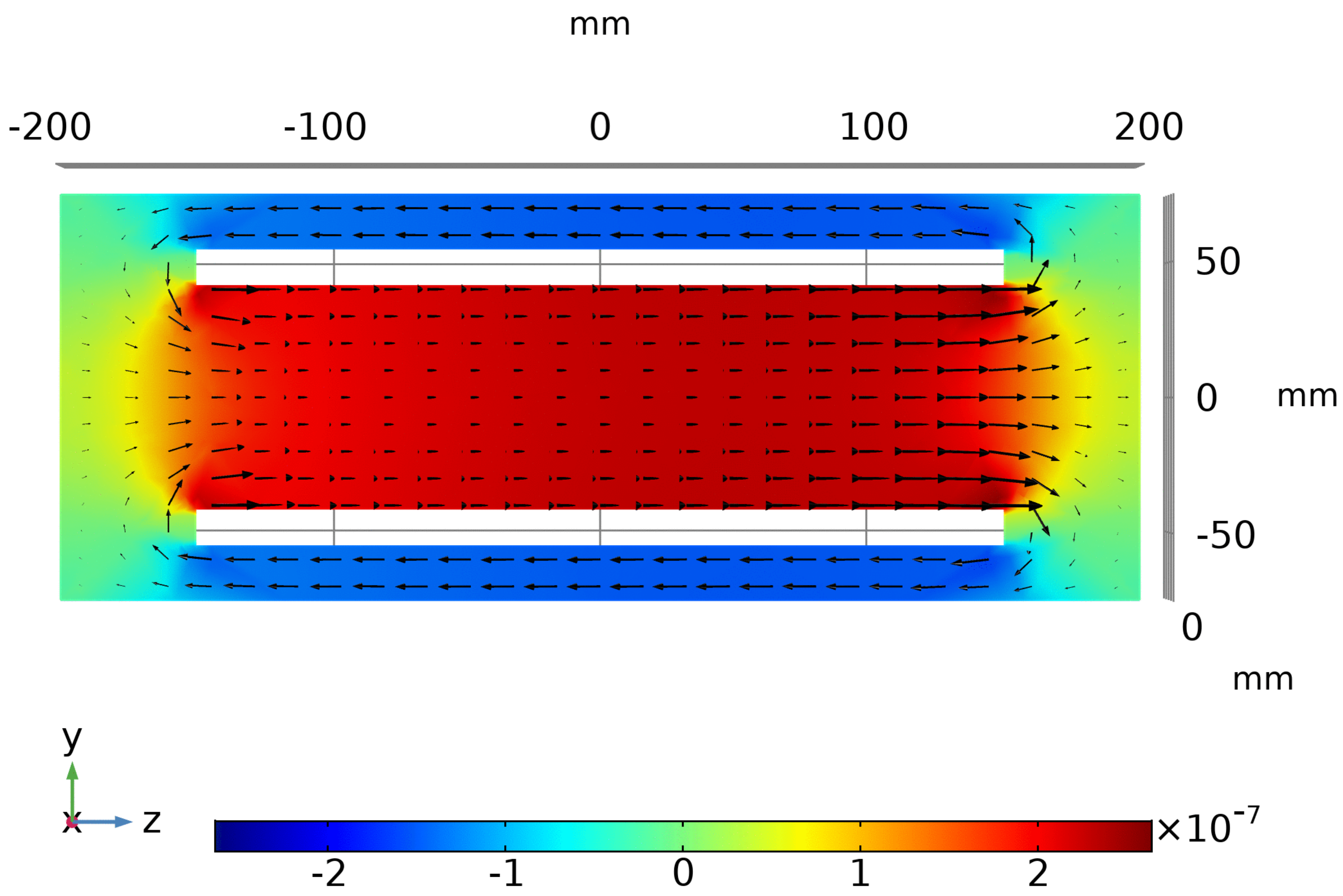


Nafe, J. E. & Nelson, E. B. The hyperfine structure of hydrogen and deuterium. *Physical Review* **73**, 718–728 (1948).

- σ_1 and σ_2 show sidereal variations
- Enhanced sensitivity of q = 1 (10^9) and 2 (10^{18}) : relative momentum p,d
- Also oscillations at twice the sidereal frequency occur
- *Plan: sit in minimum of σ_2 and look for siderial variations*

Double split ring resonator





Eigenmode B field

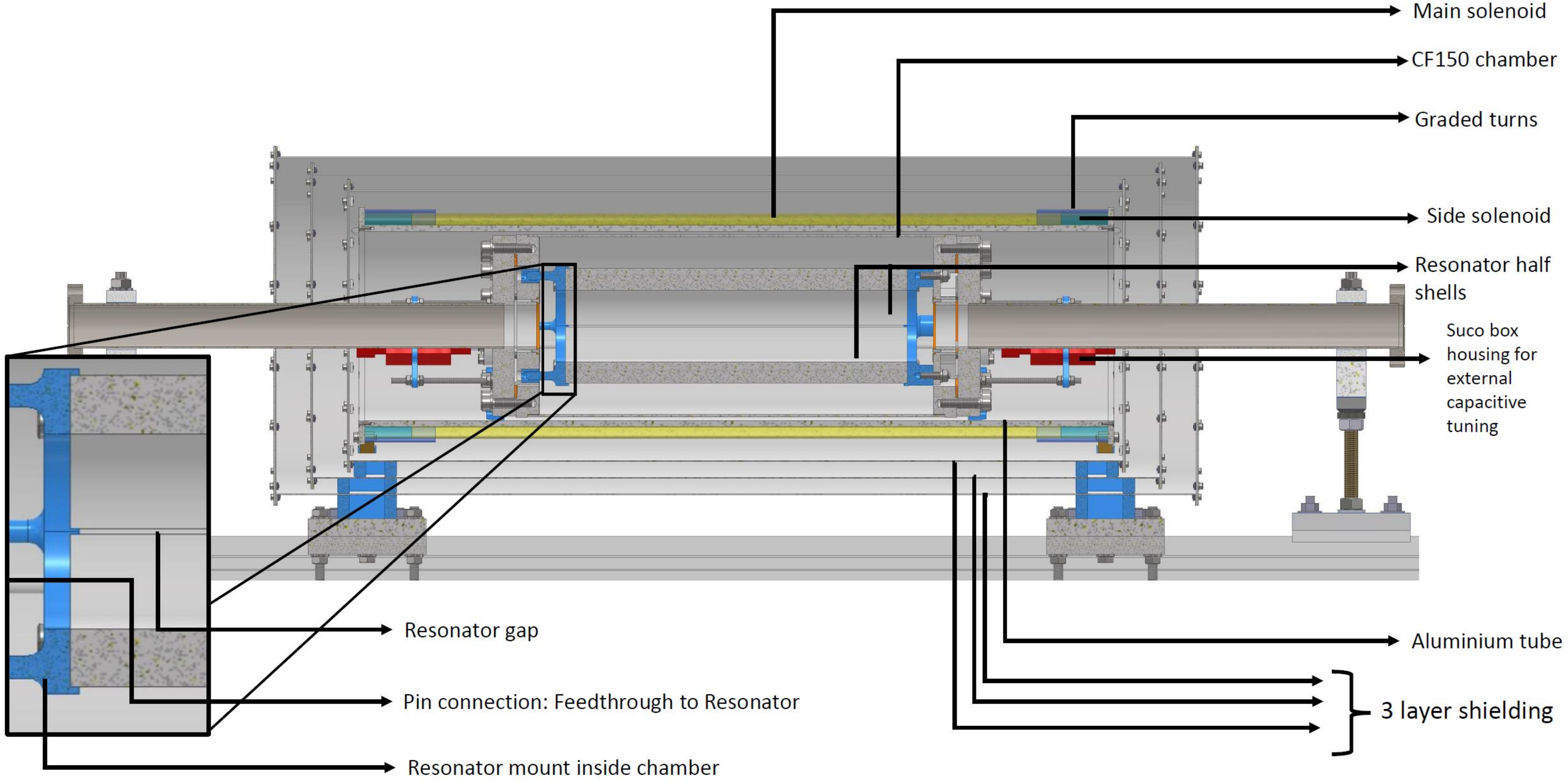
$$\omega_0 = 2\pi f_0 = \left(1 + \frac{A_1}{A_2}\right)^{1/2} \left(\frac{n \cdot th}{\pi w}\right)^{1/2} \frac{c}{r_0} \left(\frac{1 + \frac{\Delta Z}{Z}}{1 + \frac{\Delta w}{w}}\right)^{1/2}$$

$$A_1 = \pi r_0^2 \text{ and } A_2 = \pi[R^2 - (r_0 + w)^2]$$

M. Mehdizadeh, et. al., Loop-gap resonator: A lumped mode microwaveresonant structure. IEEE Transactions on Microwave Theory and Techniques, 31(12):1059–1064, Dec 1983.

A. Nanda (SMI)

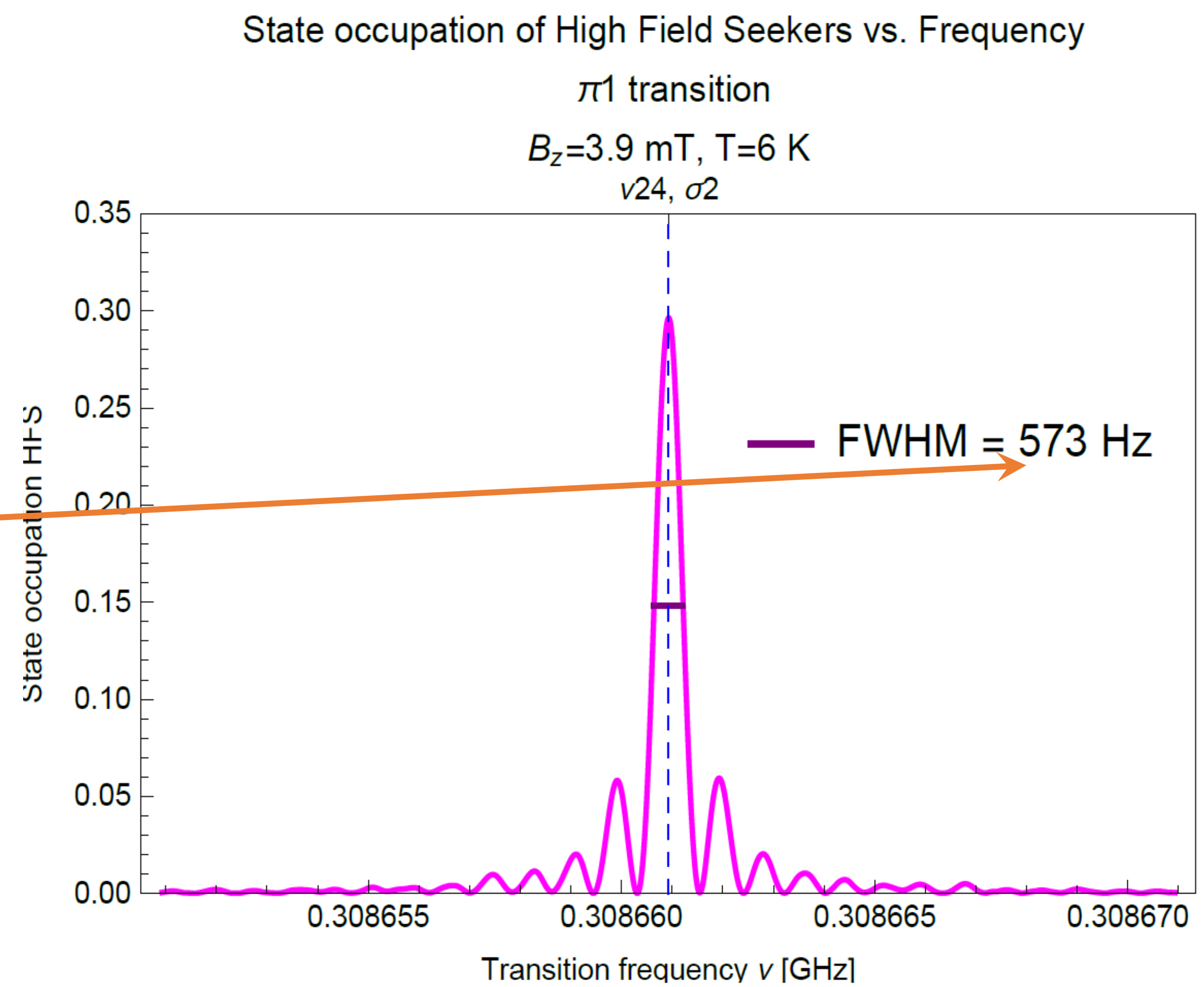
Resonator, static B-field, magnetic shielding



Expected resolution

- H beam
  - $T = 50$ K, $v \sim 1$ km/s, cavity length d=10 cm:
  - $\Delta\nu_{\mathrm{FWHM}} \sim 1/\mathrm{TOF} = 10$ kHz
- D
  - $m_{\mathrm{D}} = 2\, m_{\mathrm{H}}$: $v/\sqrt{2}$
  - $T = 6$ K* $v/\sqrt{50/6} \sim v/2.9$
  - $d = 30$ cm $v/3$
  - $\Delta\nu_{\mathrm{FWHM}} \sim 0.8$ kHz
- Start of experiment ~ fall 2022

- Lineshape simulation
  - optical Bloch equations


State occupation of High Field Seekers vs. Frequency

π1 transition

B_z=3.9 mT, T=6 K

v24, σ2

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* Cooper et al. *Review of Scientific Instruments* **91**, 013201 (2020).

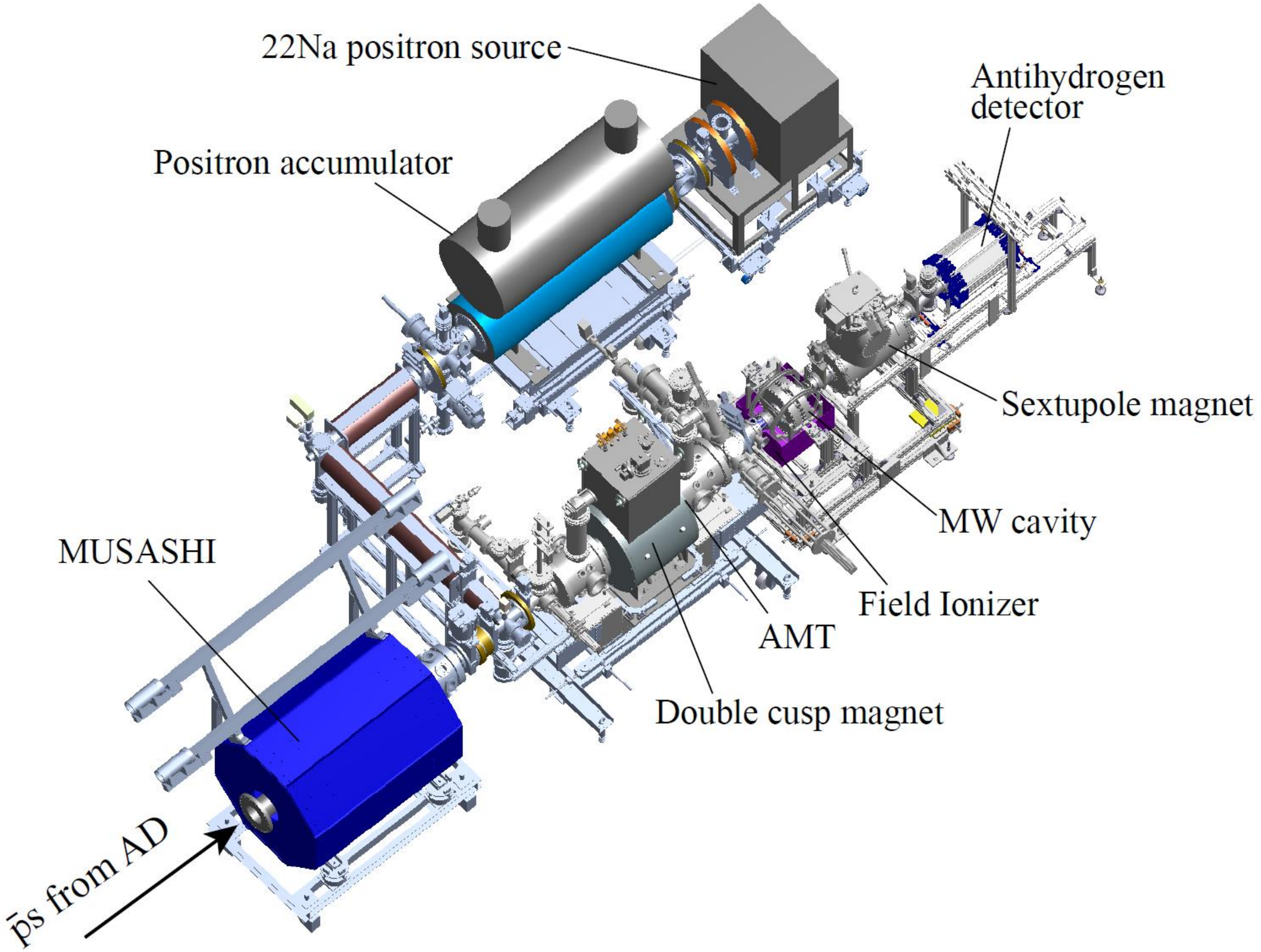
Summary and outlook

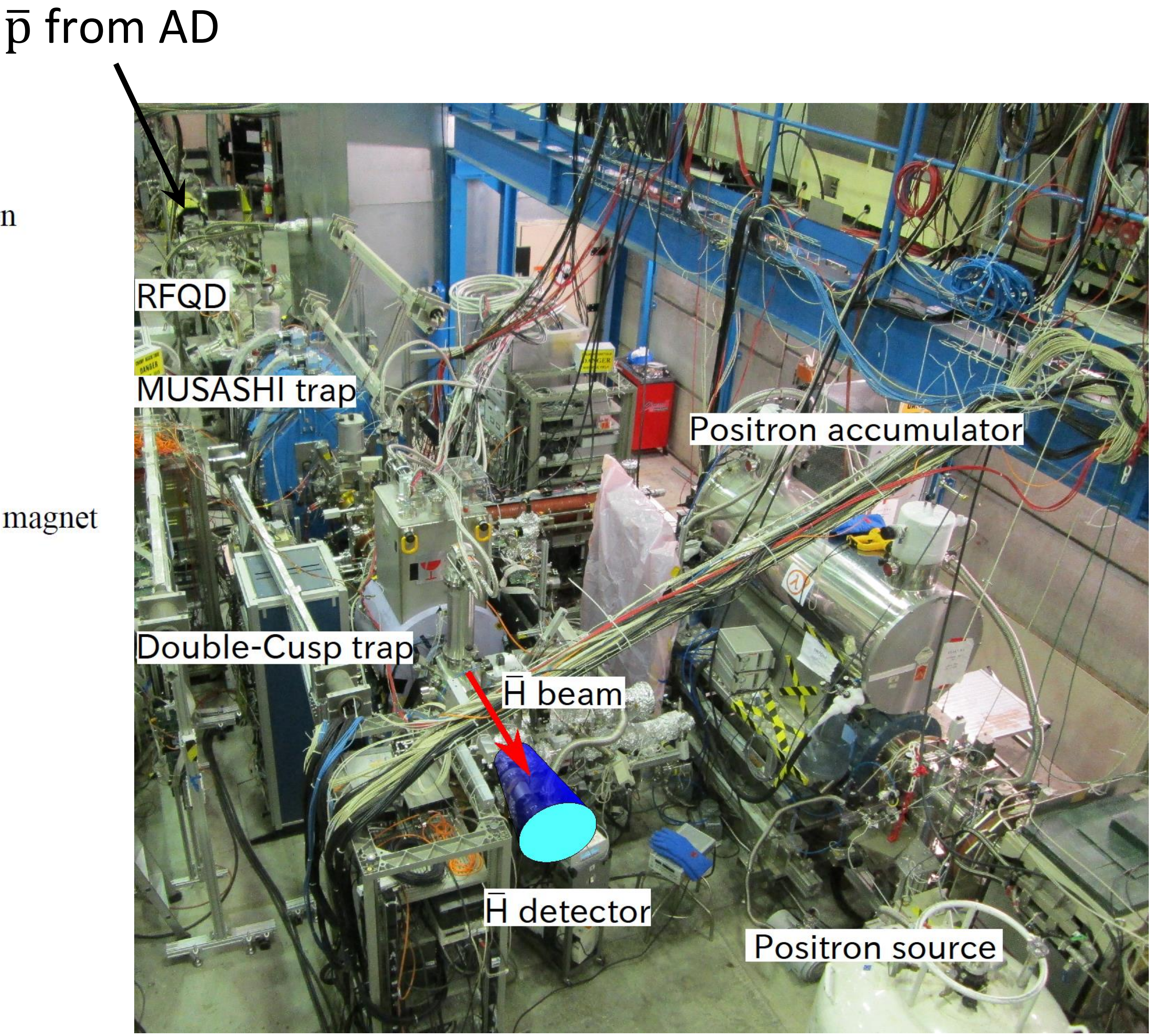
- ELENA@CERN-AD started operation
  - new results on spectroscopy and gravity expected
- In-beam HFS measurement of $\bar{\mathrm{H}}$
  - $\bar{\mathrm{H}}$ formation rate and temperature being improved
  - First microwave experiment expected in 2023
- H and D beams for testing SME
  - ν_{HFS}(H) for different B-field orientations: experiment finished, data analysis ongoing
  - ν_{HFS}(D) : experiment in preparation

FWF Der Wissenschaftsfonds.
INFN
erc
Japan Society for the Promotion of Science • Founded 1932 •

The end

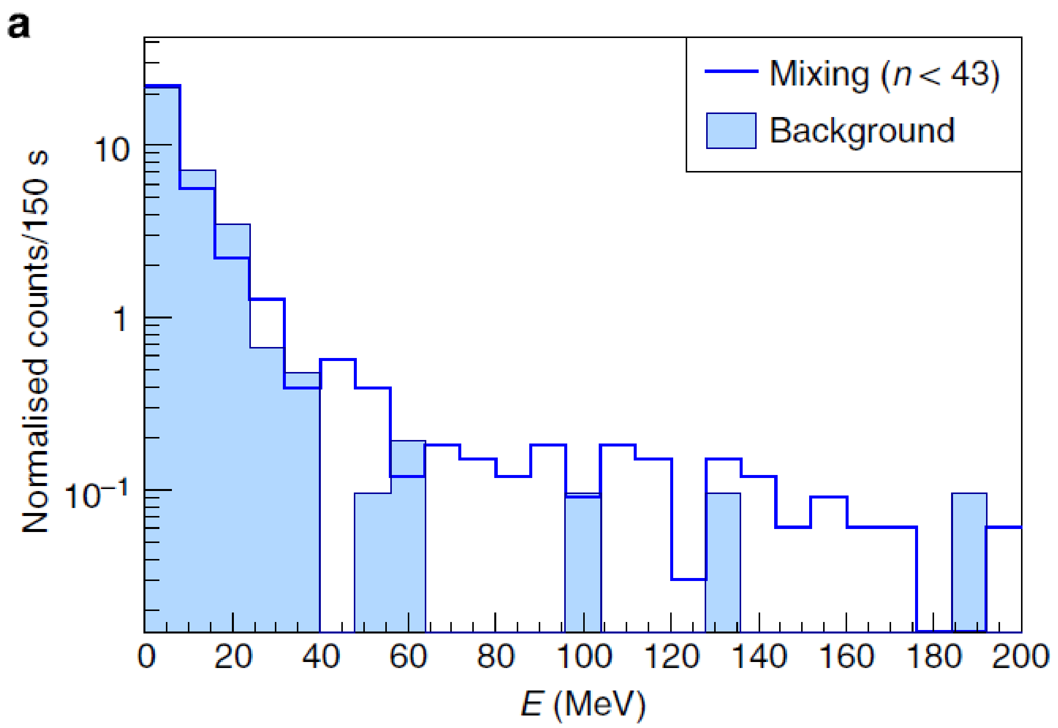
Setup ASACUSA





First observation of $\bar{\mathrm{H}}$ beam

- $\bar{\mathrm{H}}$ beam observed with 5 σ significance
  - $n \lesssim 43$ (field ionization)
  - 6 events / 15 min
- significant fraction in lower n
  - $n \lesssim 29$: 3 σ
  - 4 events / 15 min
  - τ ~ few ms



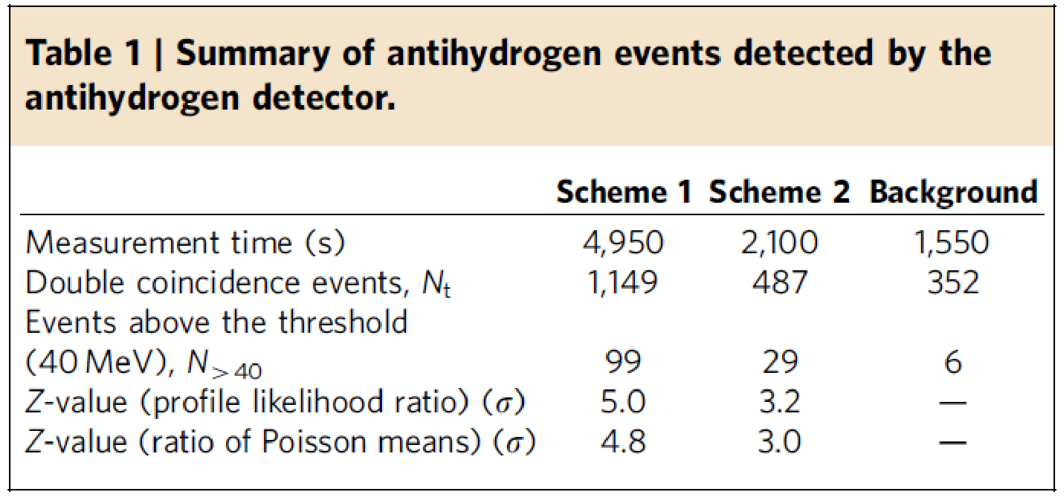


Table 1 | Summary of antihydrogen events detected by the antihydrogen detector.

	Scheme 1	Scheme 2	Background
Measurement time (s)	4,950	2,100	1,550
Double coincidence events, N_t	1,149	487	352
Events above the threshold (40 MeV), $N_{>40}$	99	29	6
Z-value (profile likelihood ratio) (σ)	5.0	3.2	—
Z-value (ratio of Poisson means) (σ)	4.8	3.0	—

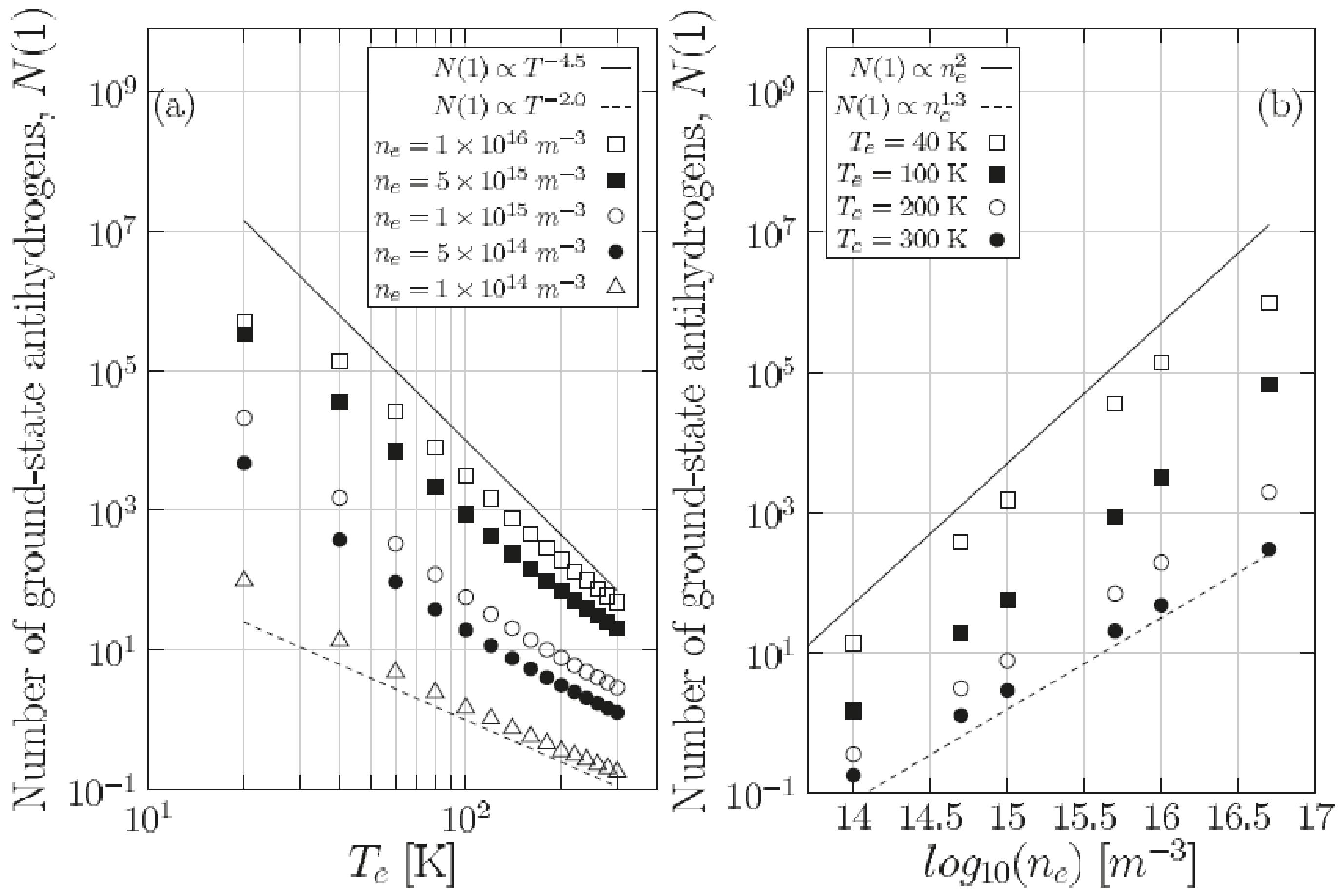
$n \le 43$ $n \le 29$

N. Kuroda[1], S. Ulmer[2], D.J. Murtagh[3], S. Van Gorp[3], Y. Nagata[3], M. Diermaier[4], S. Federmann[5], M. Leali[6,7], C. Malbrunot[4,†], V. Mascagna[6,7], O. Massiczek[4], K. Michishio[8], T. Mizutani[1], A. Mohri[3], H. Nagahama[1], M. Ohtsuka[1], B. Radics[3], S. Sakurai[9], C. Sauerzopf[4], K. Suzuki[4], M. Tajima[1], H.A. Torii[1], L. Venturelli[6,7], B. Wünschek[4], J. Zmeskal[4], N. Zurlo[6], H. Higaki[9], Y. Kanai[3], E. Lodi Rizzini[6,7], Y. Nagashima[8], Y. Matsuda[1], E. Widmann[4] & Y. Yamazaki[1,3]

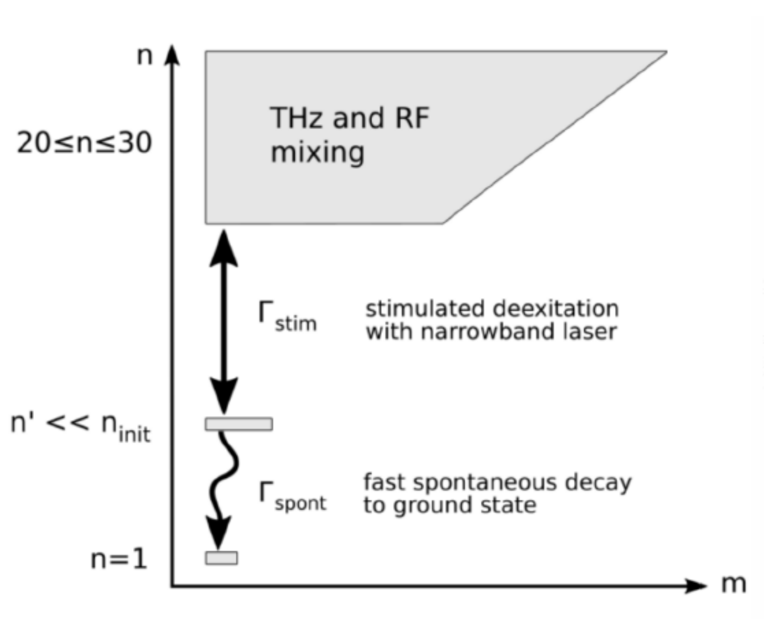
NATURE COMMUNICATIONS | 5:3089 | DOI: 10.1038/ncomms4089 | www.nature.com/naturecommunications

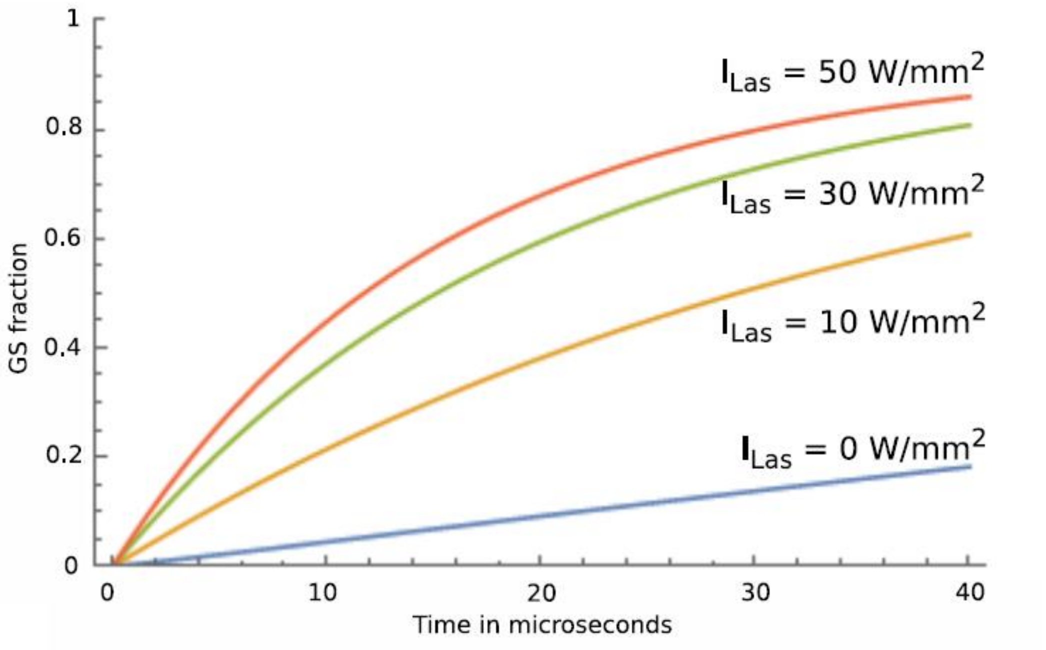
Improving the rate of ground-state $\bar{H}$

- Increase production rate
  - Positron temperature, density
- Stimulated deexcitation
  - Being studied using excited H* beam



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



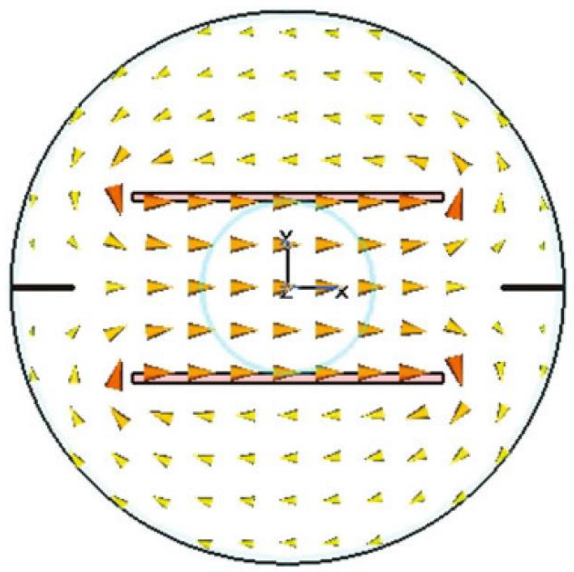


Wolz, T., Malbrunot, C., Vieille-Grosjean, M. & Comparat, D. Stimulated decay and formation of antihydrogen atoms. *Phys. Rev. A* **101**, 043412 (2020).

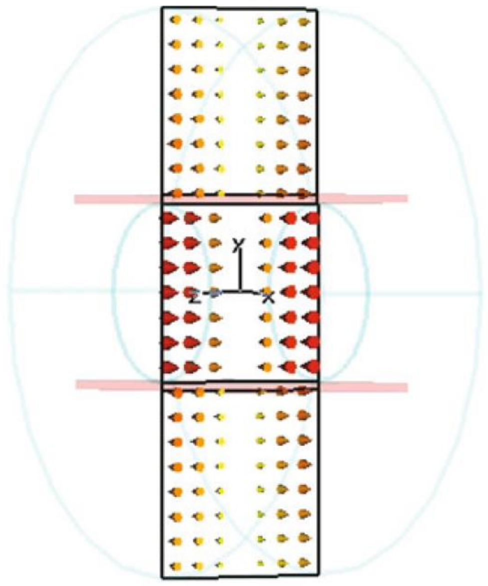
Experimental constraints

- Different B-field dependence σ_1, π_1
  - π_1 more sensitive to homogeneity
- Selection by orientation of $\vec{B}_{osc}, \vec{B}_{ext}$

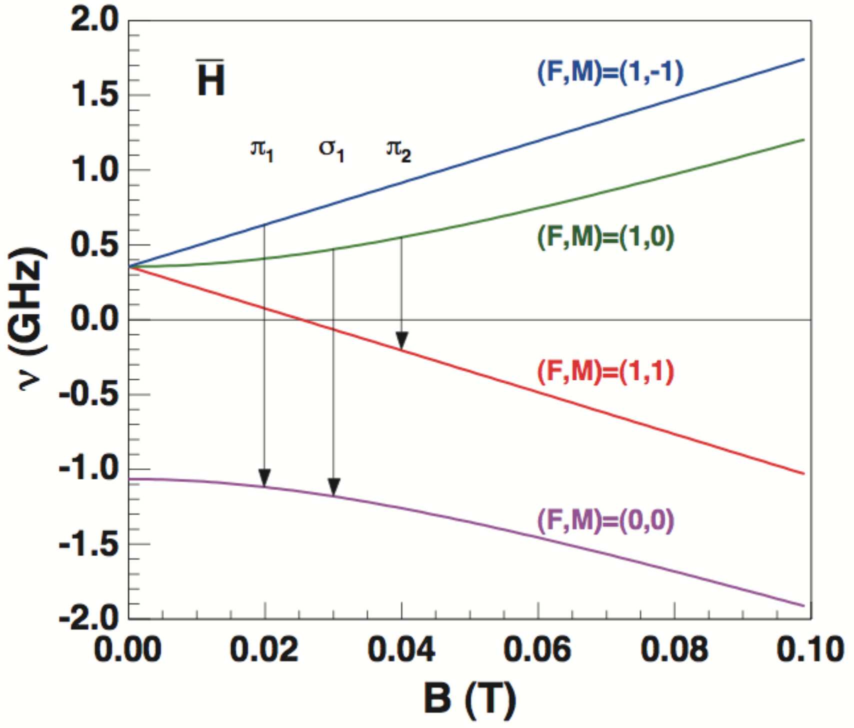
- Stripline cavity

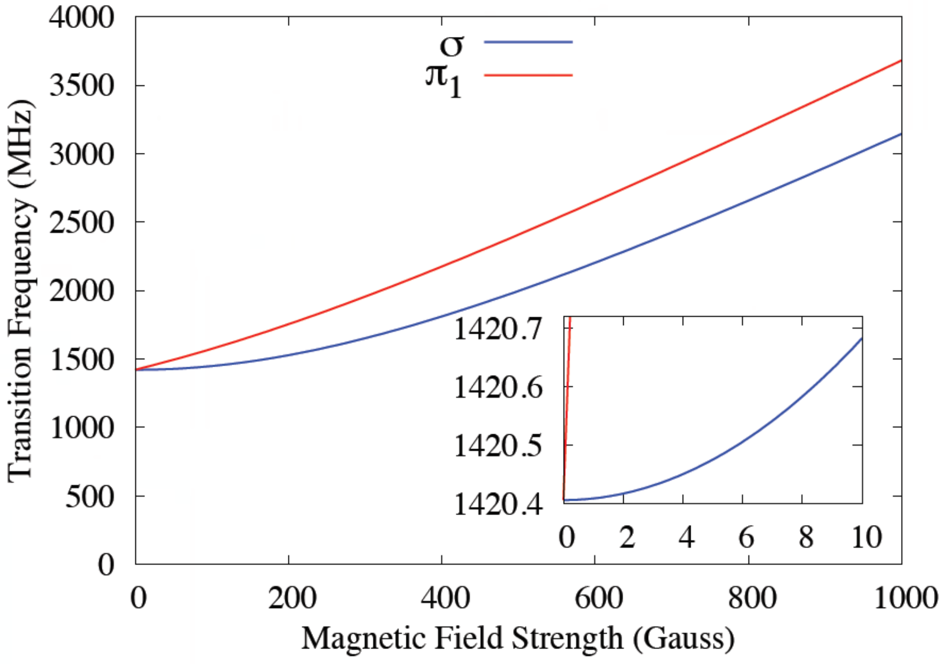


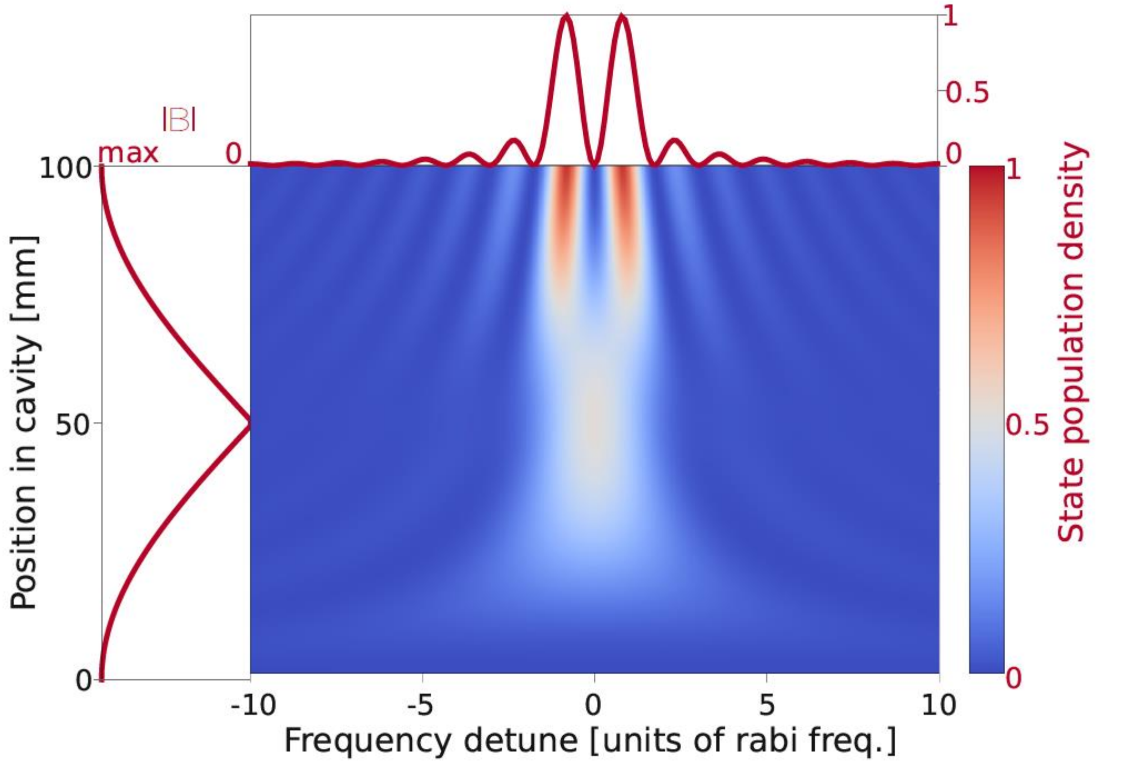
transverse field:
homogeneous



longitudinal field:
cos(z)







Line shape by
Solving optical
Bloch equations
for single velocity

π_1 measurements and zero-field frequency

- Two ways:
  - Extrapolate $\nu_{\sigma,\pi}(B_i)$ for various B_i
  - Measure $\nu_\sigma(B_1)$ and $\nu_\pi(B_1)$ at same B_1 and solve Breit-Rabi equation for ν_0 and B_1

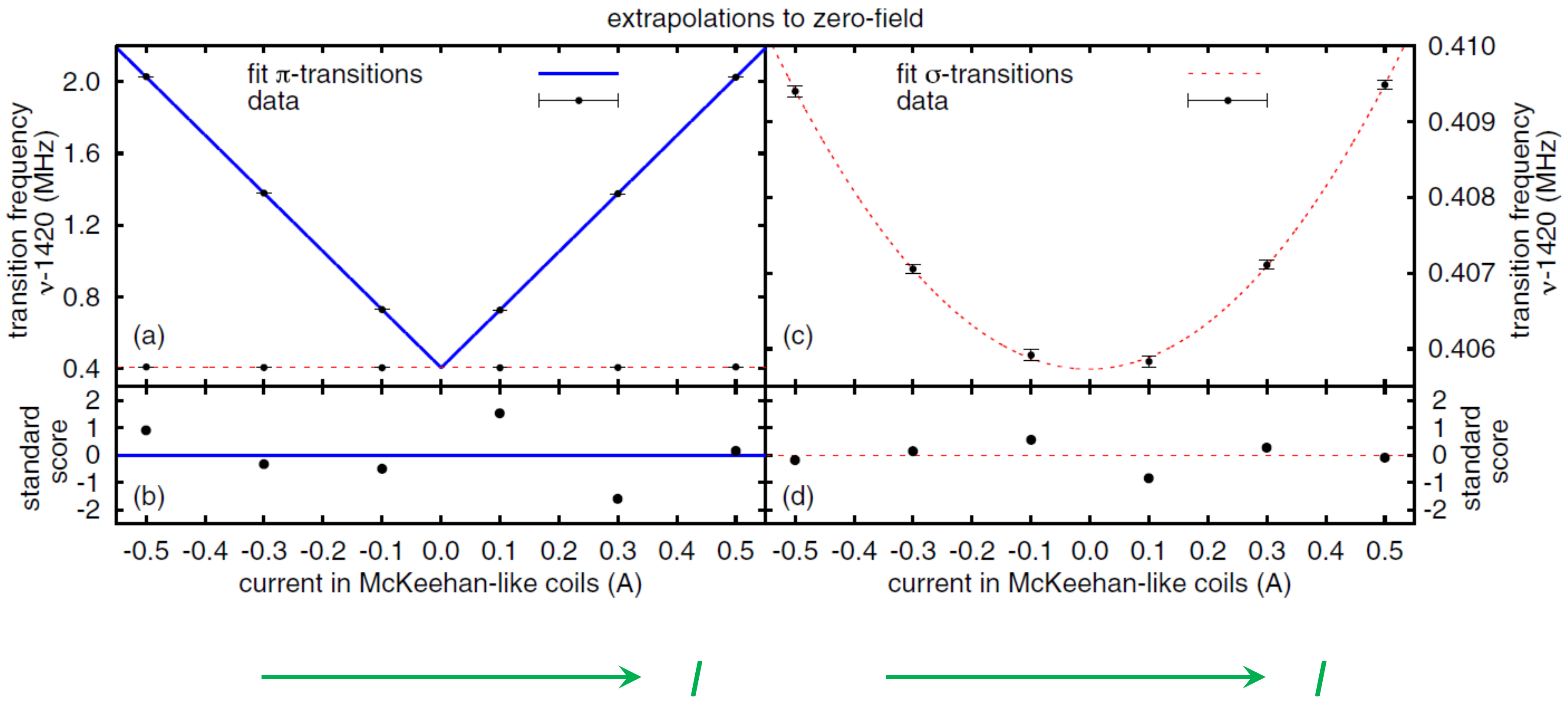
$$\nu_0 = \frac{g_+\sqrt{g_+^2\nu_\sigma^2 - 4g_-^2\nu_\pi^2 + 4g_-^2\nu_\pi\nu_\sigma} + g_-^2(2\nu_\pi - \nu_\sigma)}{g_+^2 + g_-^2}$$

$$g_\pm = g_I \pm g_J$$

	ν_0 [Hz]	Relative error	$\nu_0 - \nu_{\rm lit}$ [Hz]
σ_1 extrapolation	1 420 405 767(15)	1.04×10^{-8}	15
π_1 extrapolation	1 420 405 760(34)	2.38×10^{-8}	8
Mean value of the two extrapolations	1 420 405 766(14)	9.96×10^{-9}	14
ν_σ and ν_π determined at same static magnetic field	1 420 405 753(8)	5.60×10^{-9}	1

8 Hz

E. W. et al., Hyperfine Interact (2019) 240: 5



First results on B-field direction dependence

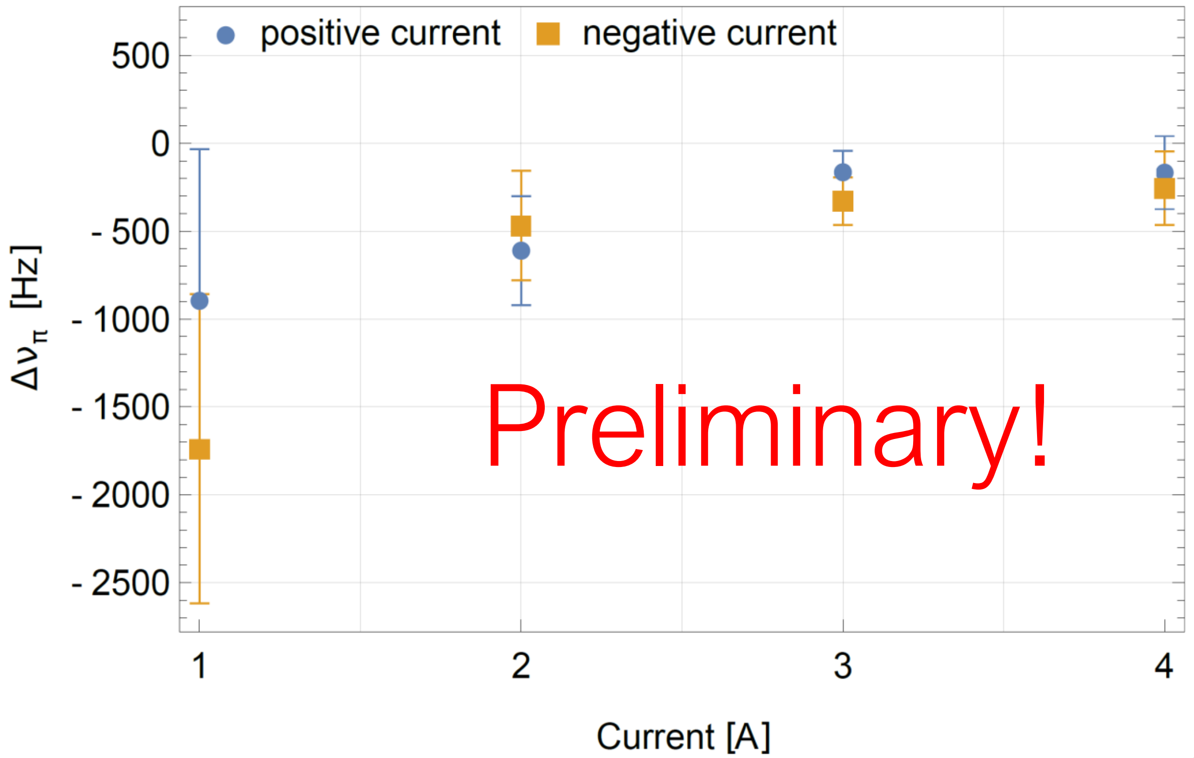
- $\nu_\pi(B) - \nu_\pi(-B)$ by inverting coil current
- Ensure same B-field: ν_σ
  - From Breit-Rabi formula

$$\nu_\sigma = \sqrt{{\nu_0}^2 + \left(\frac{\mu_- B}{h}\right)^2} \rightarrow B_\sigma = \sqrt{\nu_\sigma^2 - \nu_0^2} * \frac{h}{\mu_-}$$

$$\nu_\pi^{exp} = \frac{1}{2}\left(\nu_0 + \frac{\mu_+ B_\sigma}{h} + \sqrt{{\nu_0}^2 + \left(\frac{\mu_- B_\sigma}{h}\right)^2}\right)$$

$\mu_\pm = |g_e|\mu_B \pm g_p \mu_N$

- $\Delta\nu_\pi = \nu_\pi^{data} - \nu_\pi^{expected}$ for $B, -B$



- Test run, issues with frequency reference
  - Offset arbitrary
- High quality & statistics data under blind analysis

Test setup DSRR