In-beam hyperfine spectroscopy of antihydrogen, hydrogen, and deuterium for tests of CPT and Lorentz invariance

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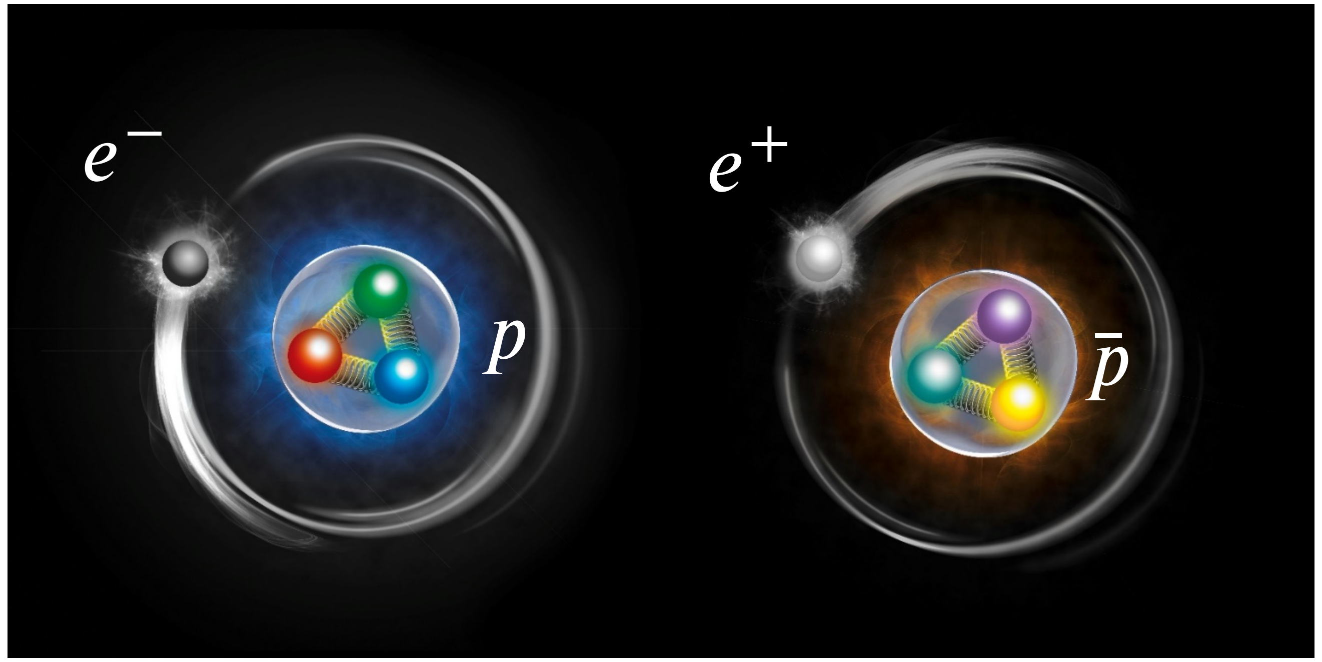
KAMPAI Workshop ECT*

Trento, 1 Oct 2024

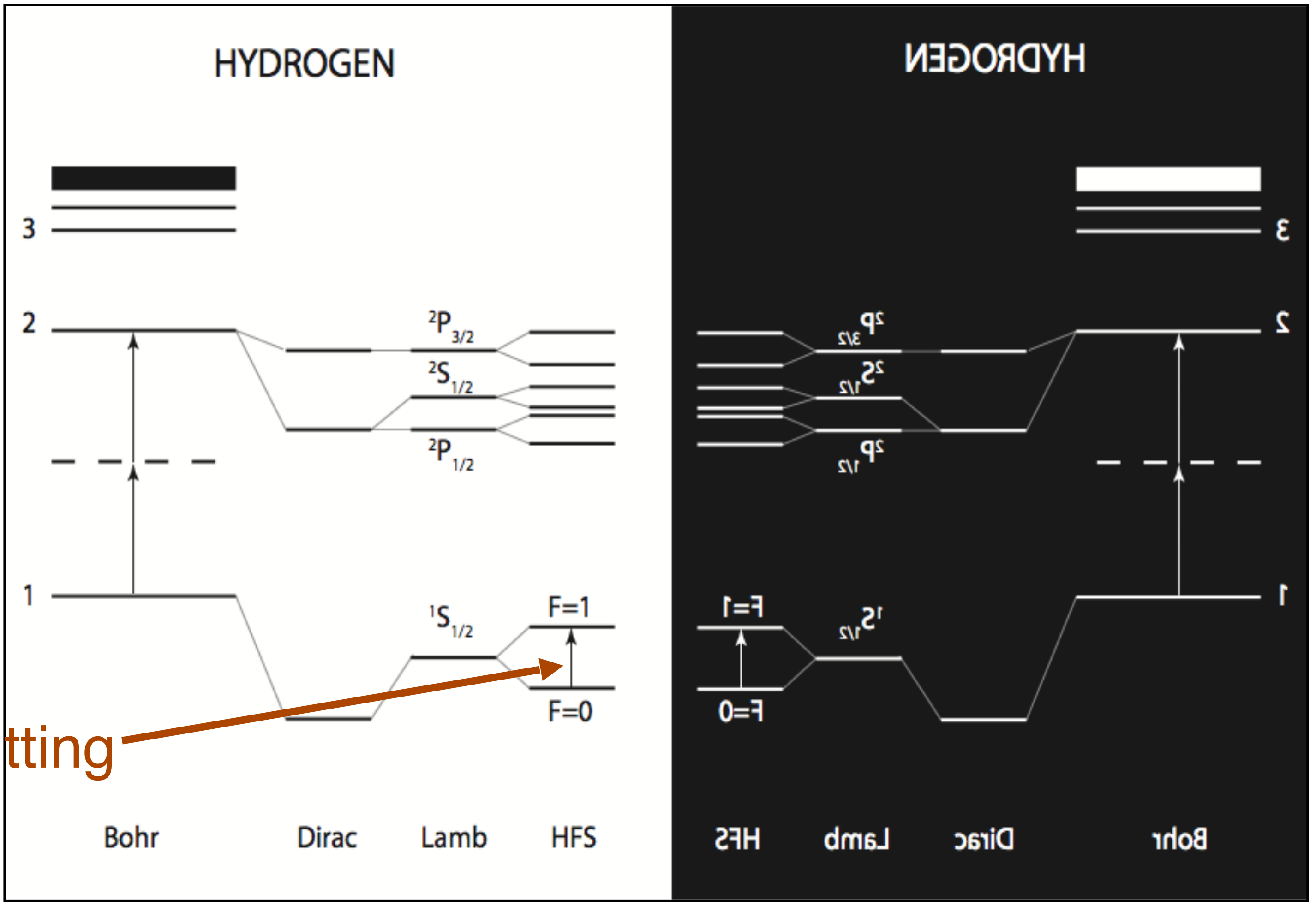
Antihydrogen experiments motivation

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



1s-2s
2 photon
λ=243 nm
$\Delta f/f=10^{-14}$

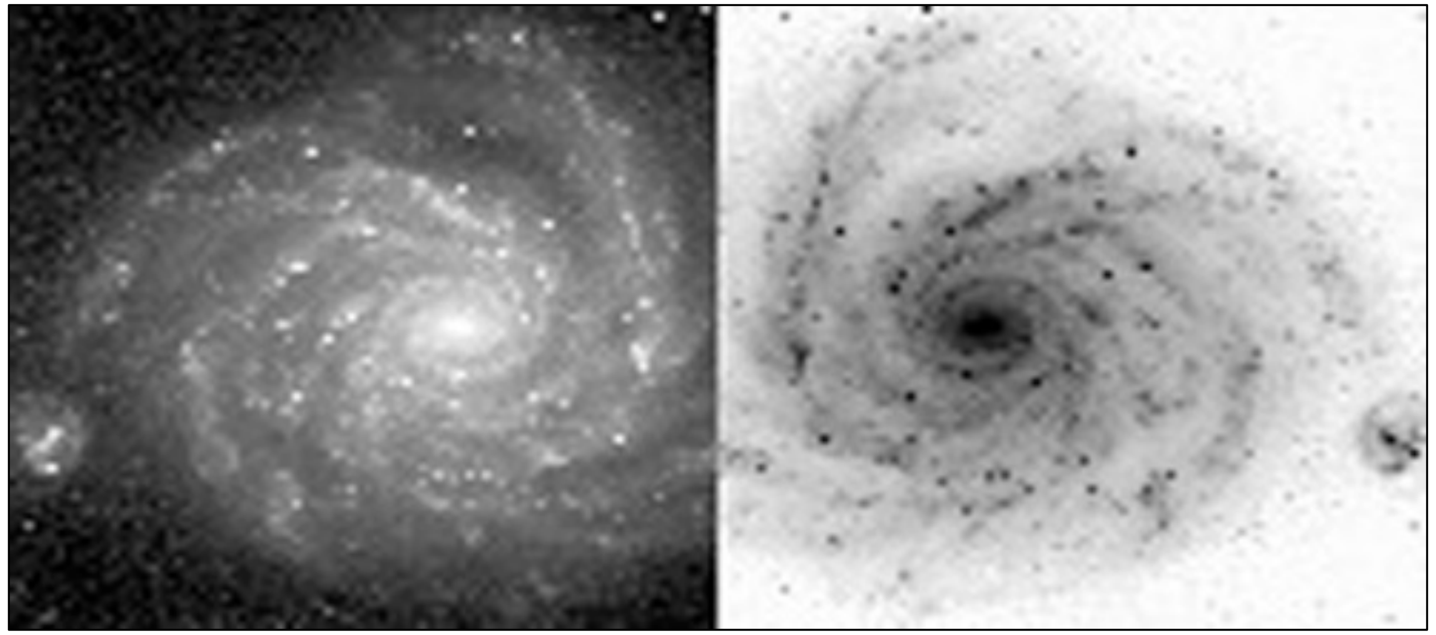
Ground state
hyperfine splitting
f = 1.4 GHz
$\Delta f/f=10^{-12}$



CPT symmetry & cosmology

- Mathematical theorem
  - not valid e.g. in string theory, quantum gravity
- Problem: antimatter absence in the universe
- Big Bang -> if CPT holds: equal amounts of matter / antimatter
  - Standard scenario for Baryogenesis (Sakharov 1967)
    - *Baryon-number non-conservation*
    - *C and CP violation*
    - *Deviation from thermal equilibrium*
  - Generate Baryon asymmetry during evolution
- Currently known CPV not large enough
  - Other source of baryon asymmetry?

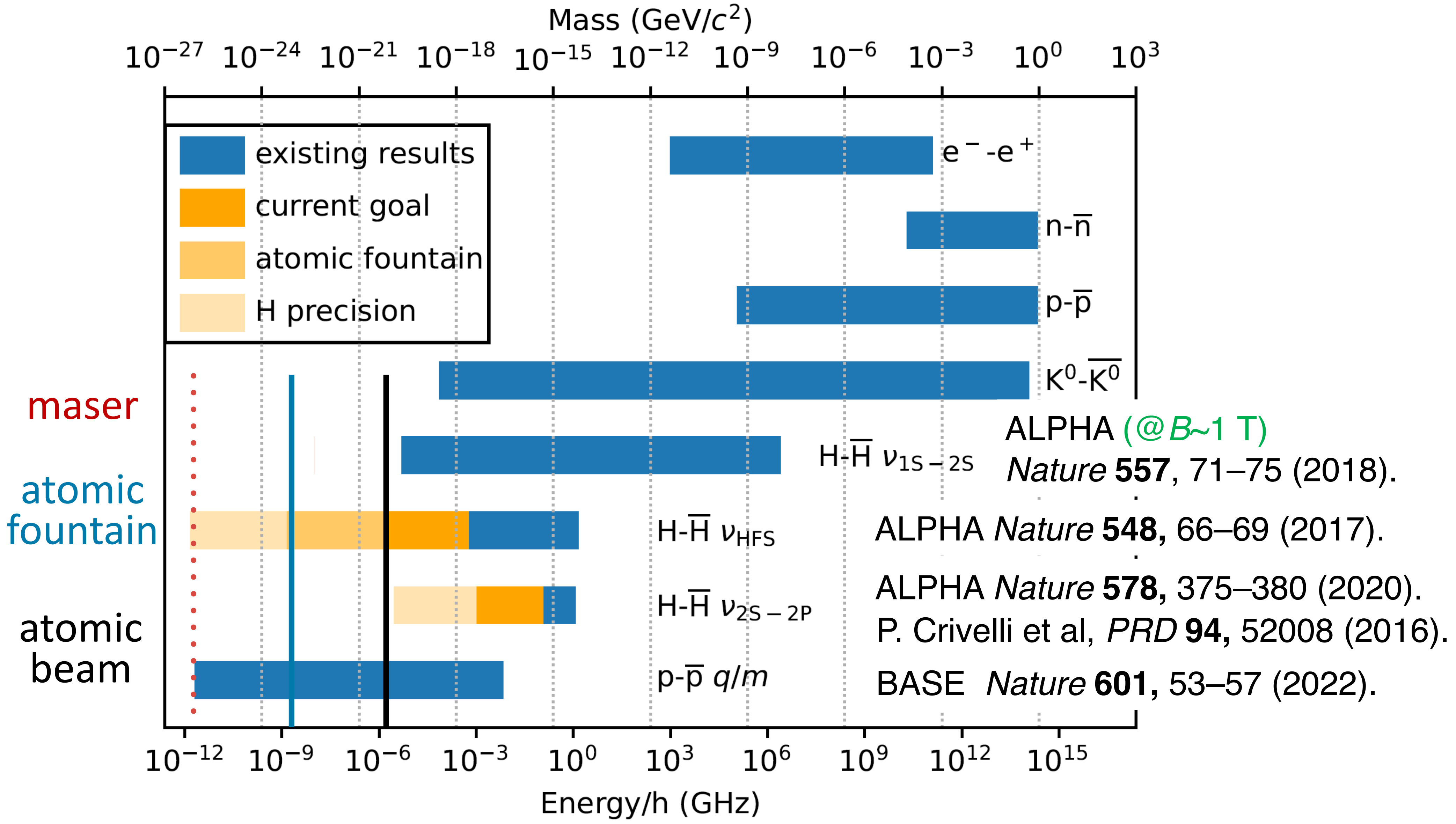
$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 6.1\ x\ 10^{-10}$$ WMAP



Bertolami, O., Colladay, D., Kostelecký, V. A. & Potting, R.
CPT violation and baryogenesis. *Physics Letters B* **395**, 178–183 (1997).

Comparison of CPT tests

- Mass & frequency



- Synopsis: CPT violating interaction appears at the level of Lagrangian
  - Relevant scale: absolute energy
- 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]

Comparison of CPT tests particle-antiparticle: SME

- Standard Model Extension SME

CPT & LORENTZ VIOLATION

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

LORENTZ VIOLATION

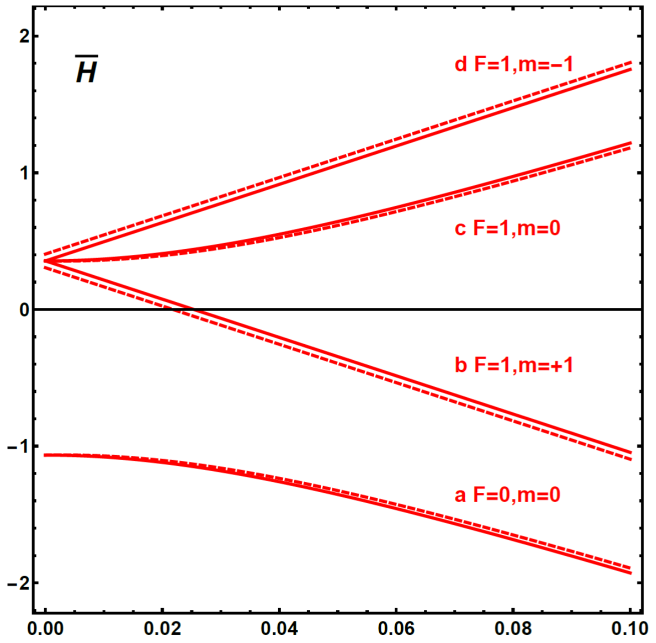
D. Colladay and V.A. Kostelecky, PRD 55, 6760 (1997)

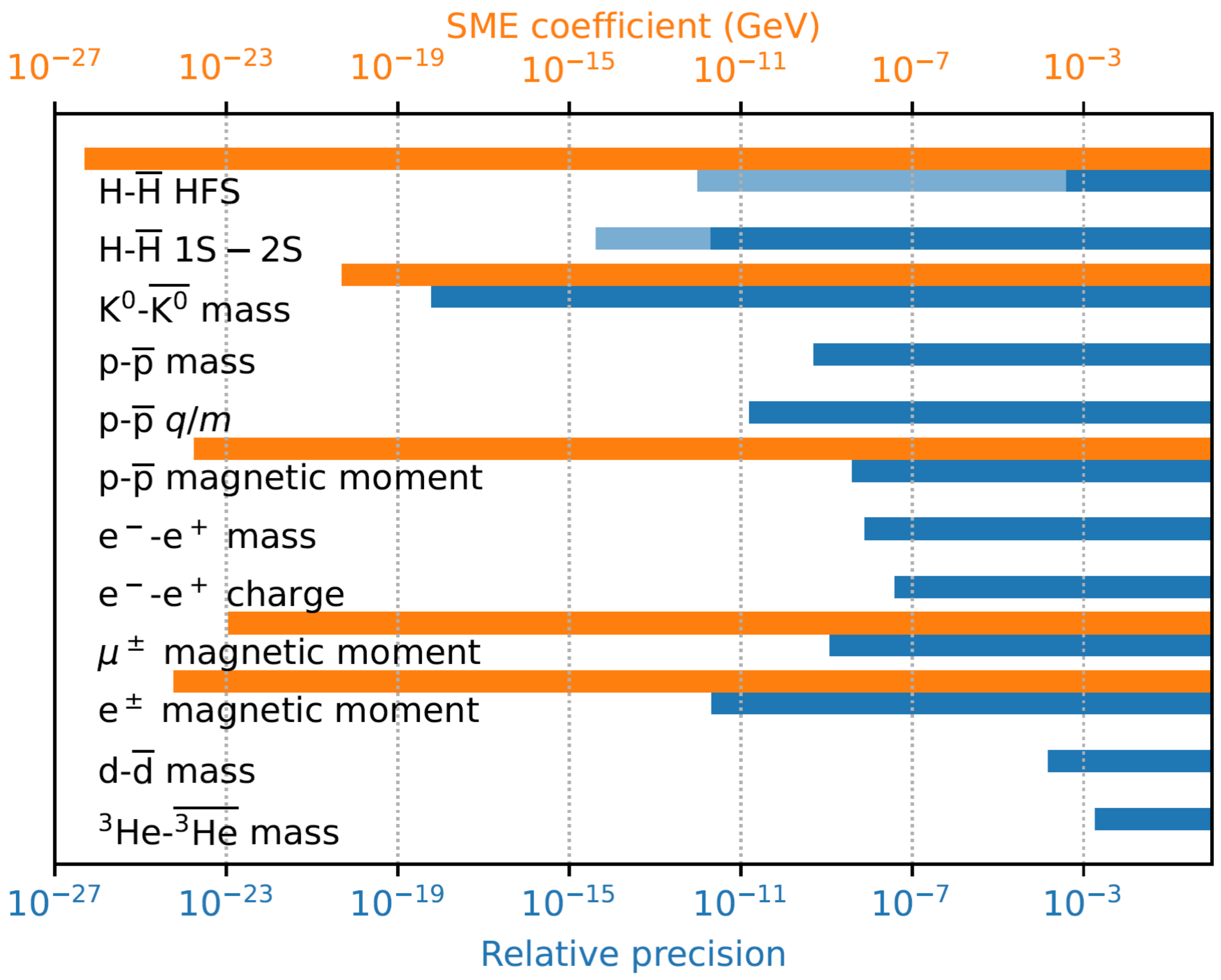
- Minimal SME: only HFS

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]

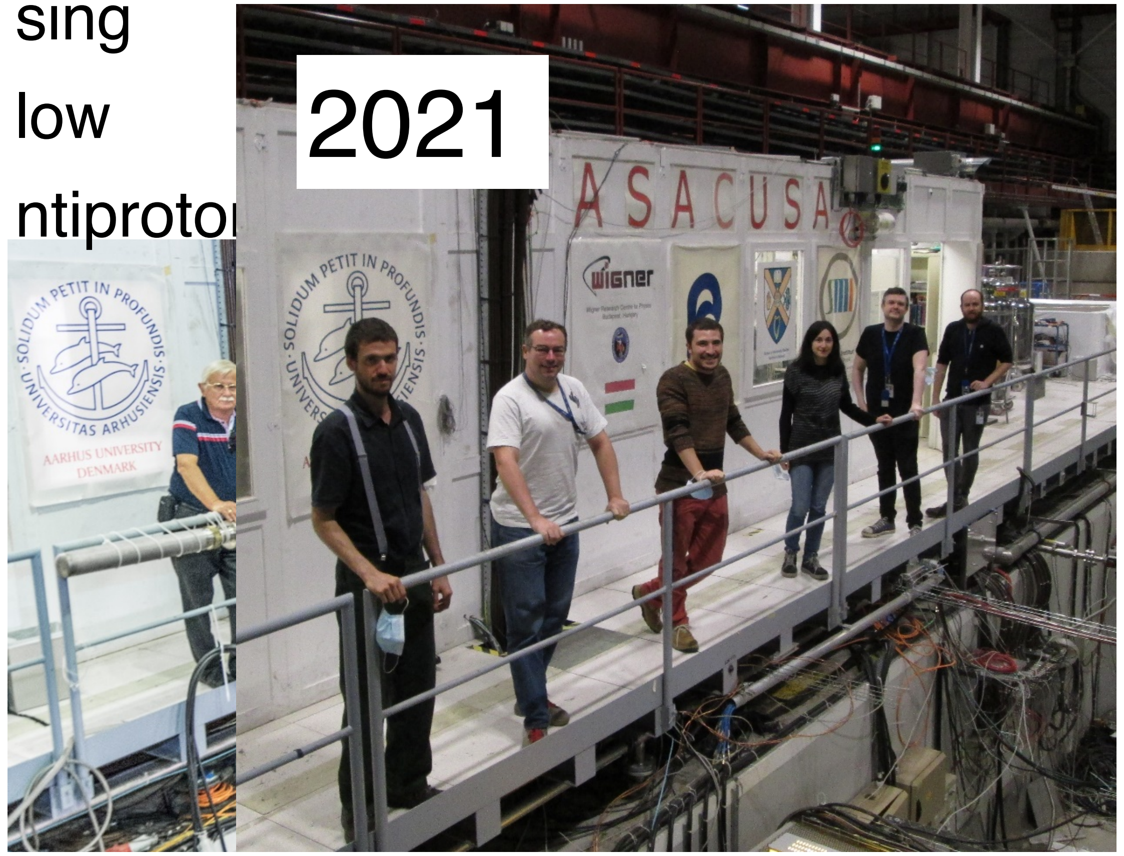
ASACUSA collaboration

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

Co-spokespersons

M. Hori MPQ

E.W.



ASACUSA Scientific projects

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

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

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

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

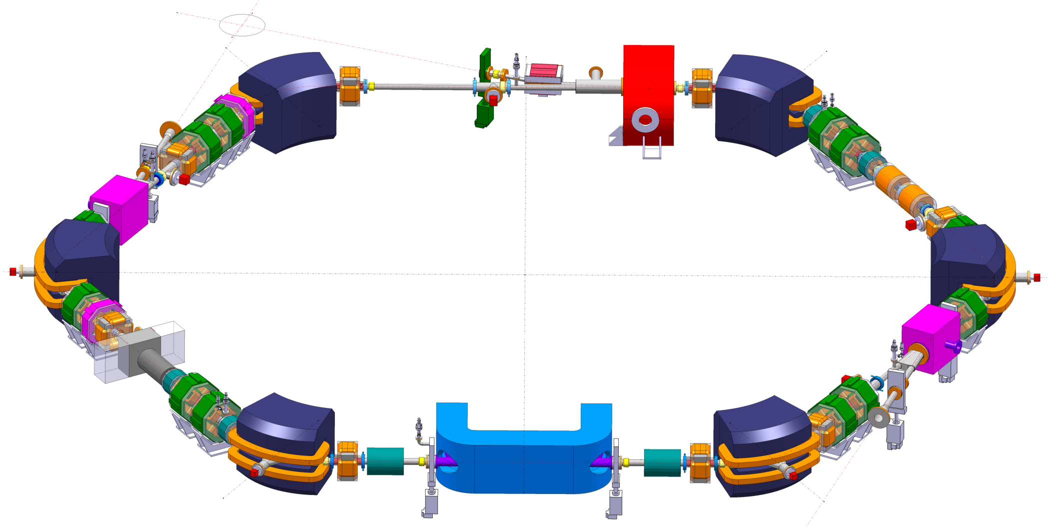
RIKEN: H. Breuker, Y. Kanai, M. Tajima, S. Ulmer, Y. Yamazaki

Hiroshima University: H. Higaki

Tokyo University of Science: Y. Nagata

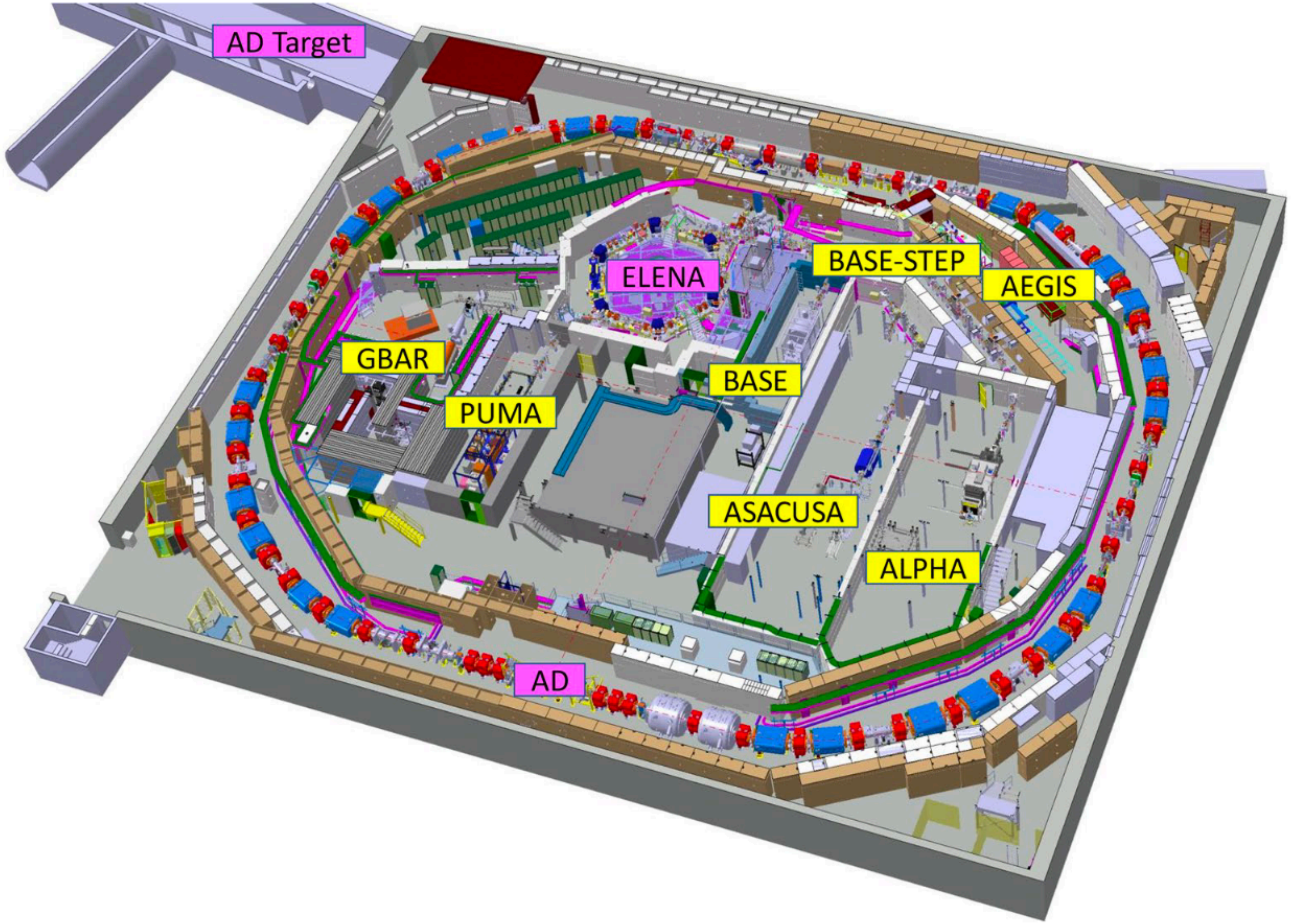
Aarhus University: U. Uggerhøj

AD/ELENA @ CERN

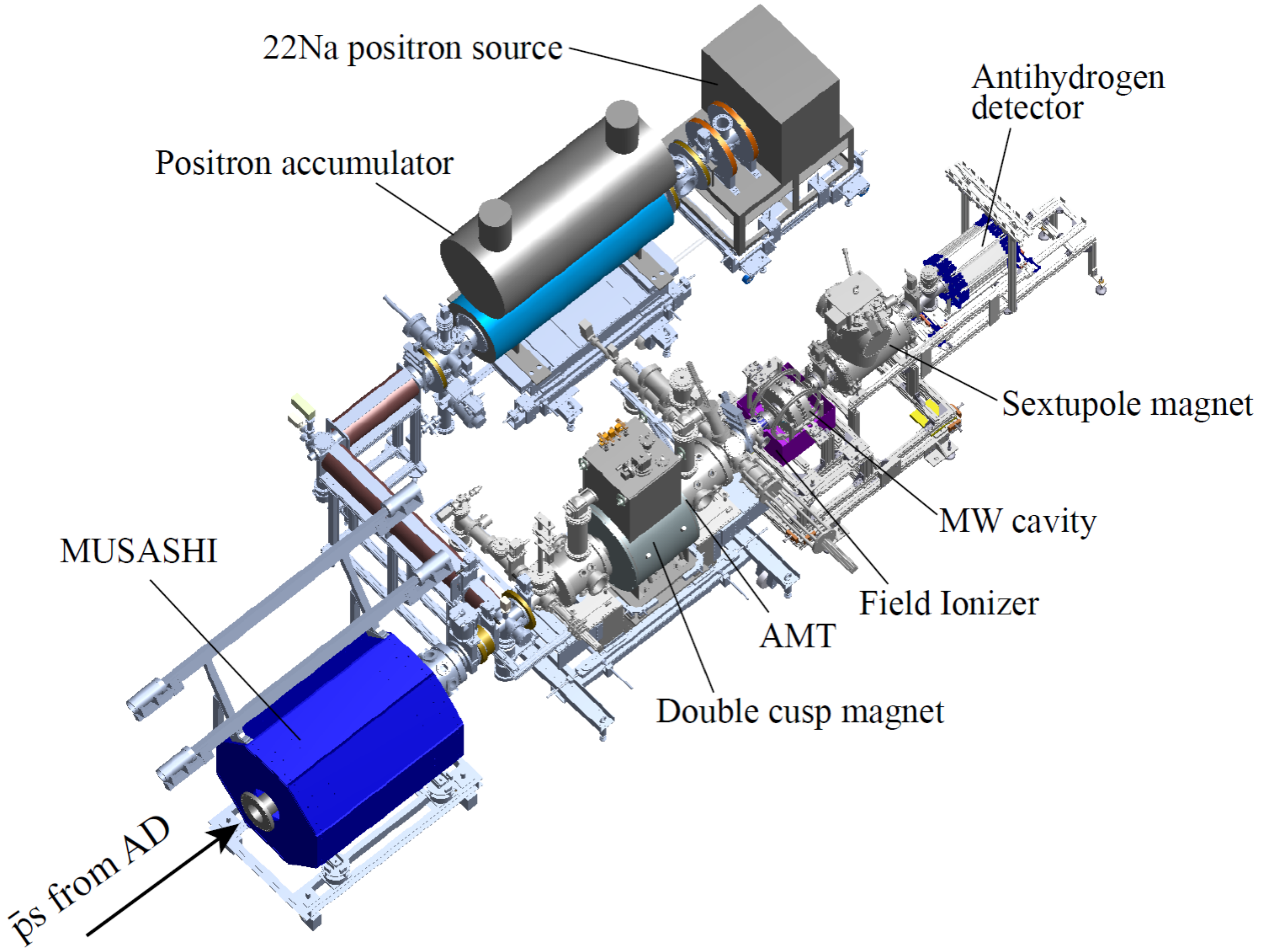


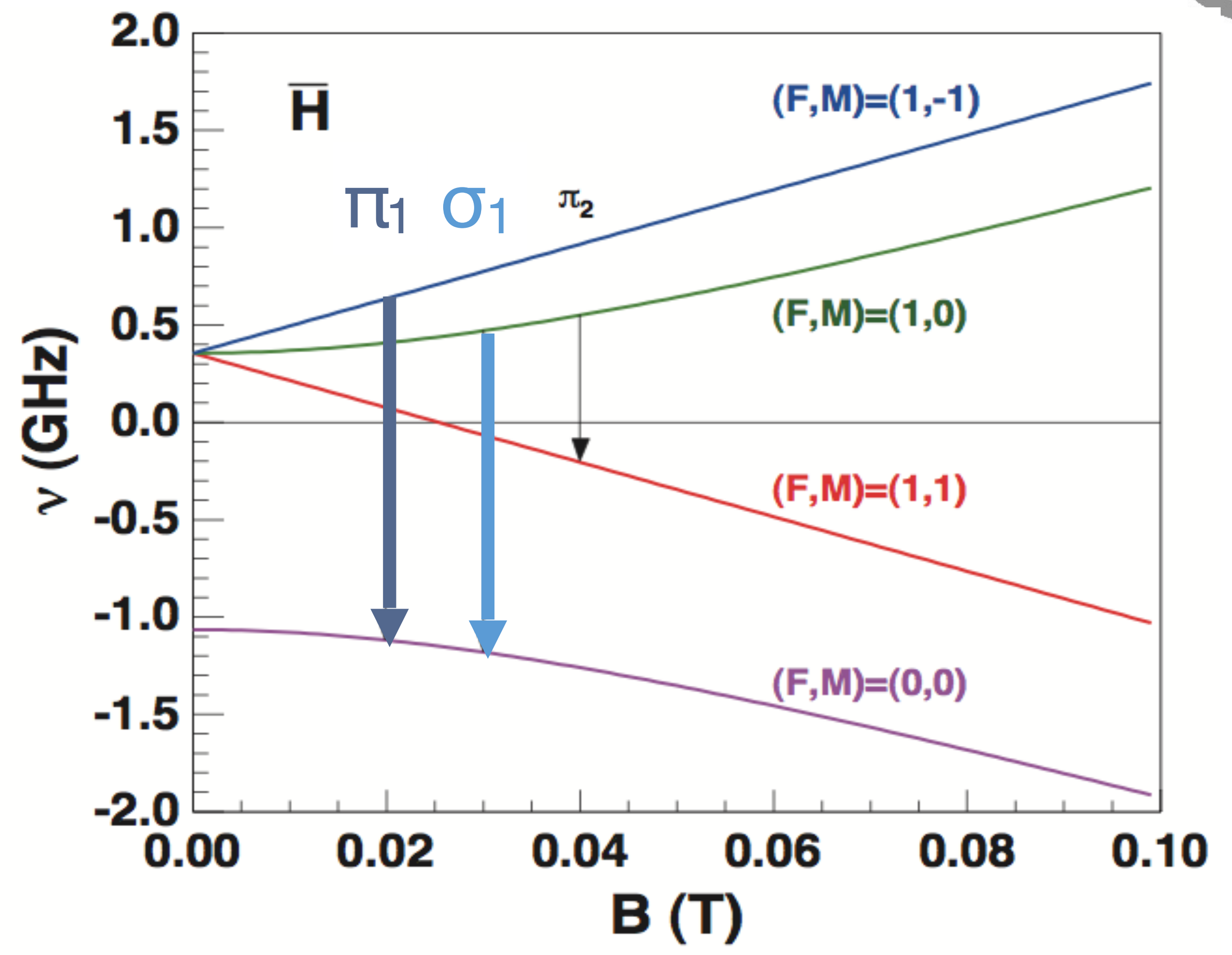
Energy range, MeV	5.3 - 0.1
Intensity of ejected beam	1.8×10^7
$\varepsilon_{x,y}$ of extracted beam, $\pi \cdot$mm$\cdot$mrad, [95%], standard	4 / 4
$\Delta p/p$ of extracted beam, [95%], standard	$8 \cdot 10^{-3}$

ELENA operation started Aug. 2021



In-beam HFS spectroscopy

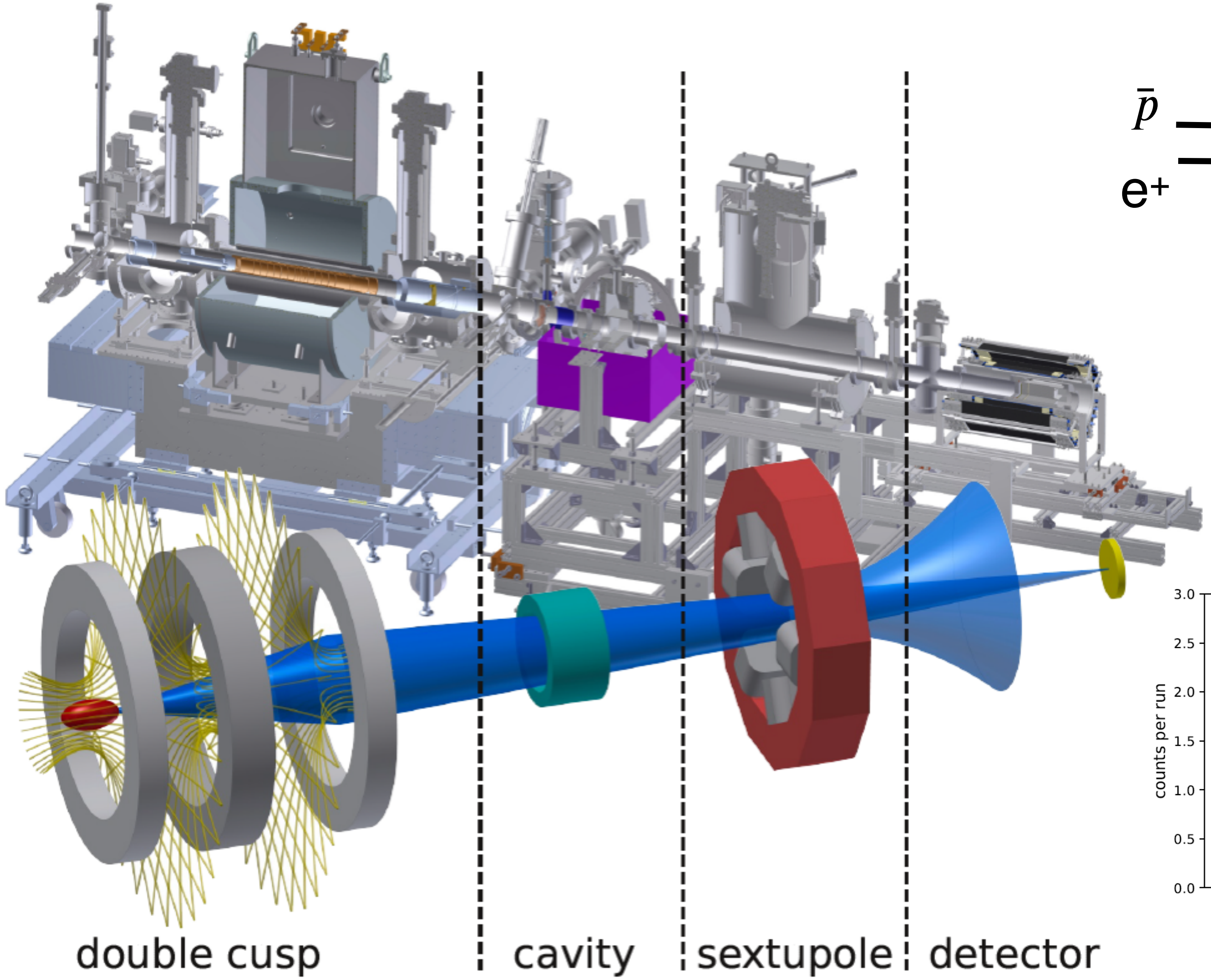


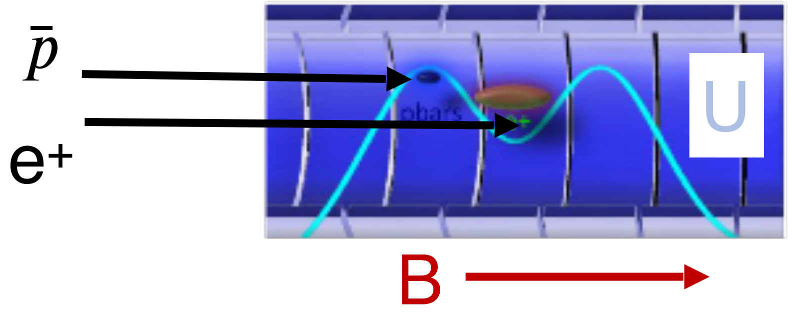


- Resolution: line width $\Delta\nu \sim 1/T$
  - 1000 m/s, 10 cm:
  - 7×10^{-6} for T = 50 K
  - > 100 $\bar{H}$/s in 1S state into 4π needed
  - event rate 1 / minute: background from cosmics, annihilations upstreams

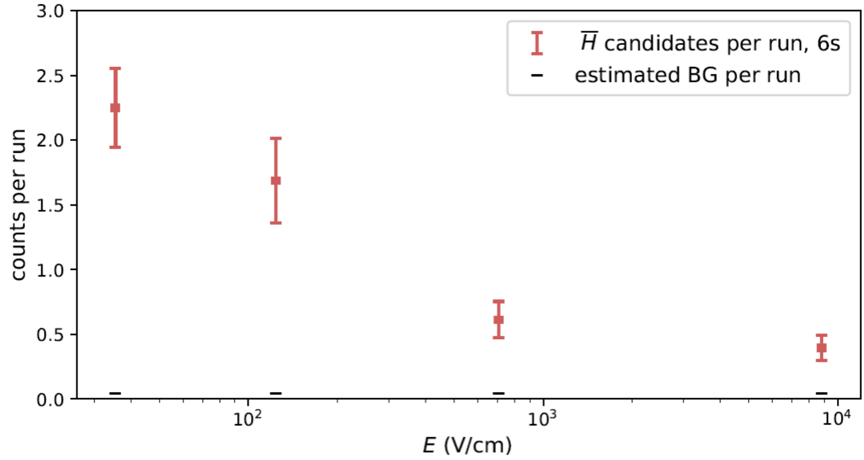
ASACUSA Antihydrogen beam for HFS

- $\bar{\mathrm{H}}$ production 1st time in **2010** in nested Penning trap
    - Three body recombination (→Rydberg states)
- 1st observation of beam in field free region **2014**
    - n≤43: 6 $\bar{H}$ / 15 min
    - n≤29: 4 $\bar{H}$ / 15 min

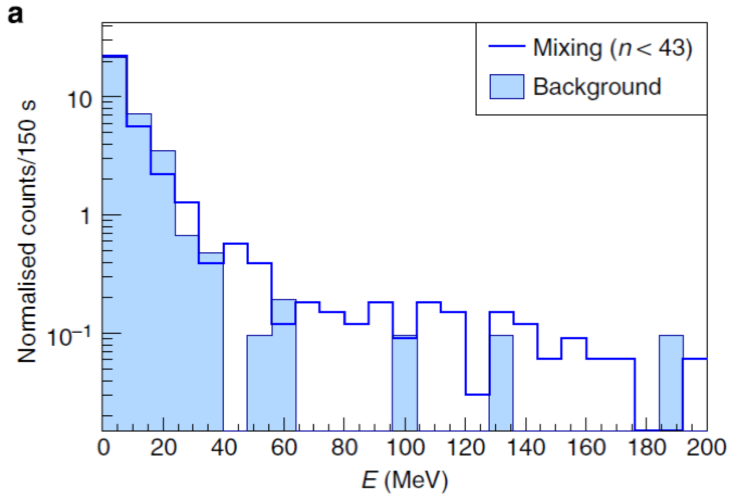




- Measurement of *n* distribution **2021**



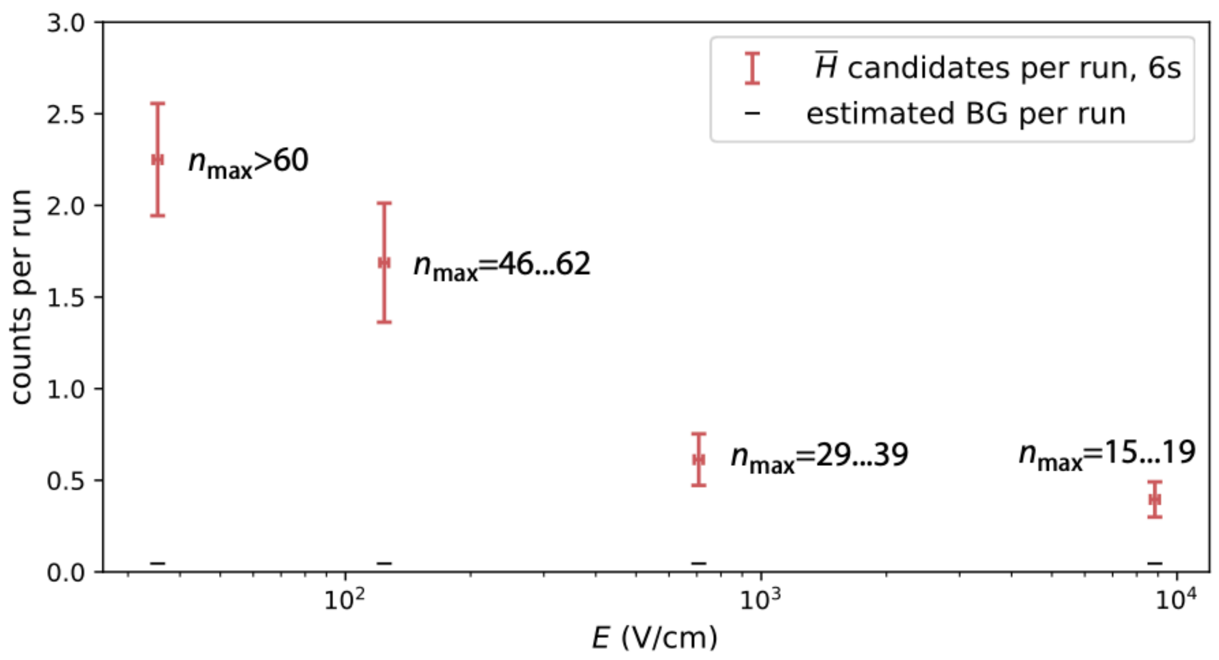
B. Kolbinger et al.
EPJ D 75, (2021) 91.



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

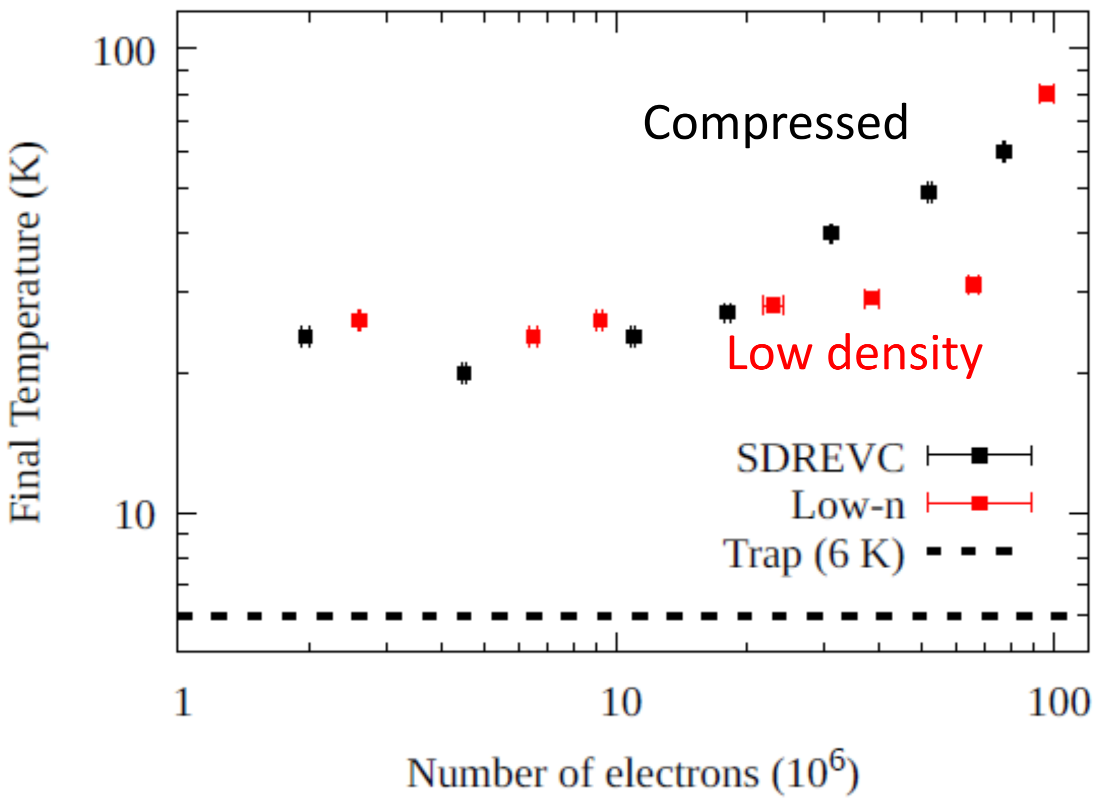
Recent milestones

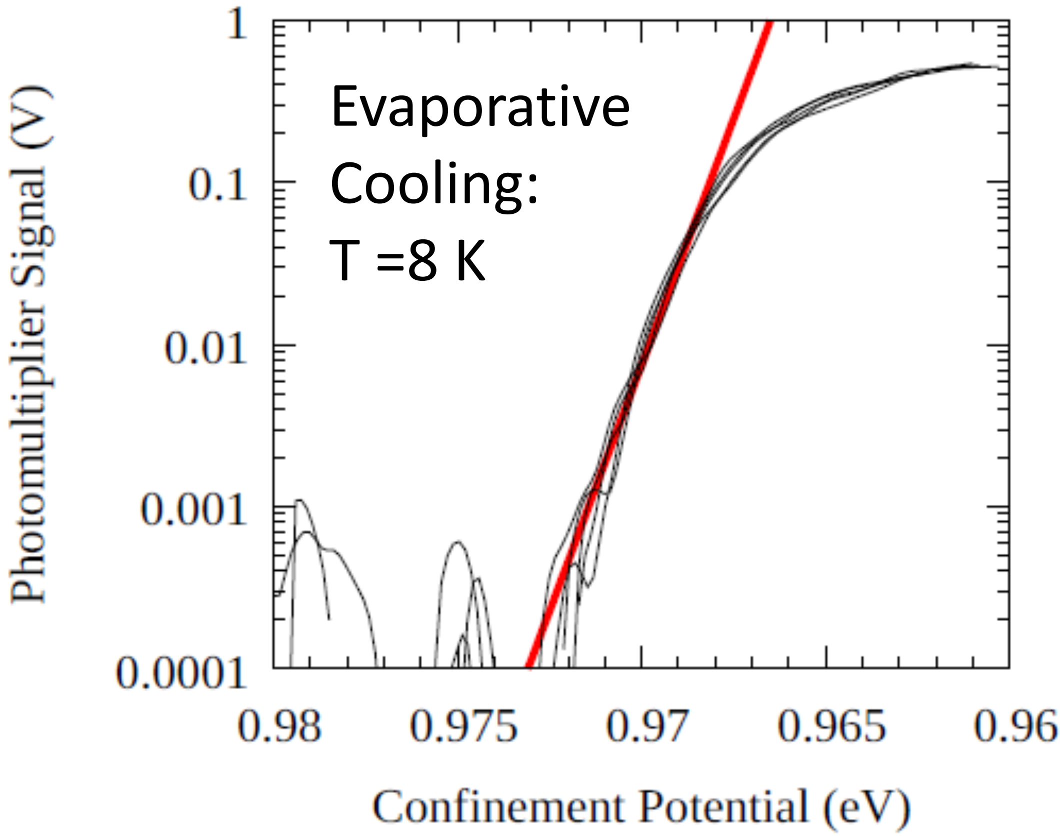
- Quantum number distribution of $\bar{\mathrm{H}}$ beam in field-free region



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

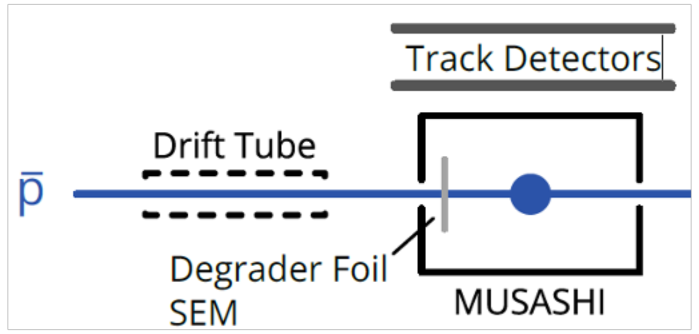


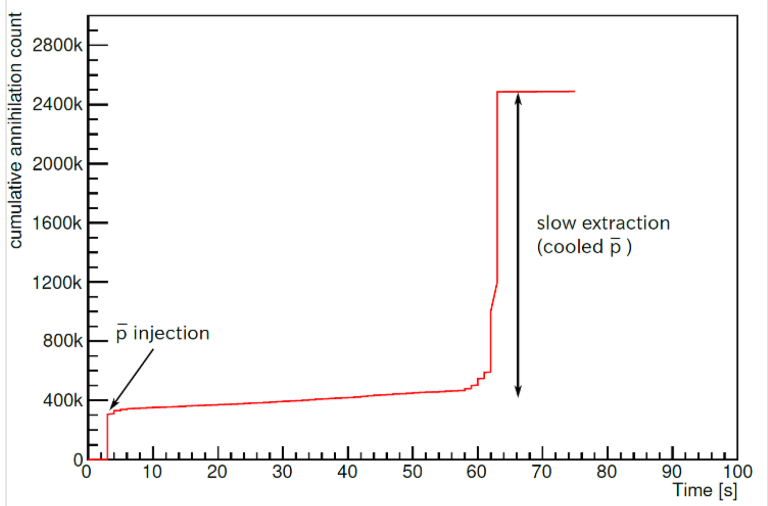


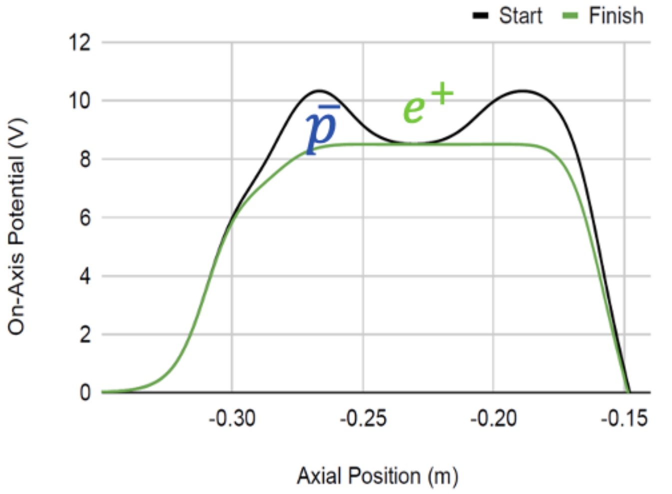
E. Hunter et al. EPJ Web Conf. 262 01007 (2022)
C. Amsler et al. arXiv:2203.14890 [physics.plasm-ph]

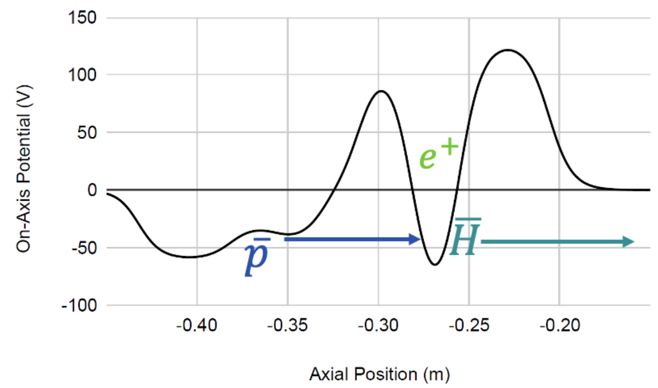
Antihydrogen experiment status

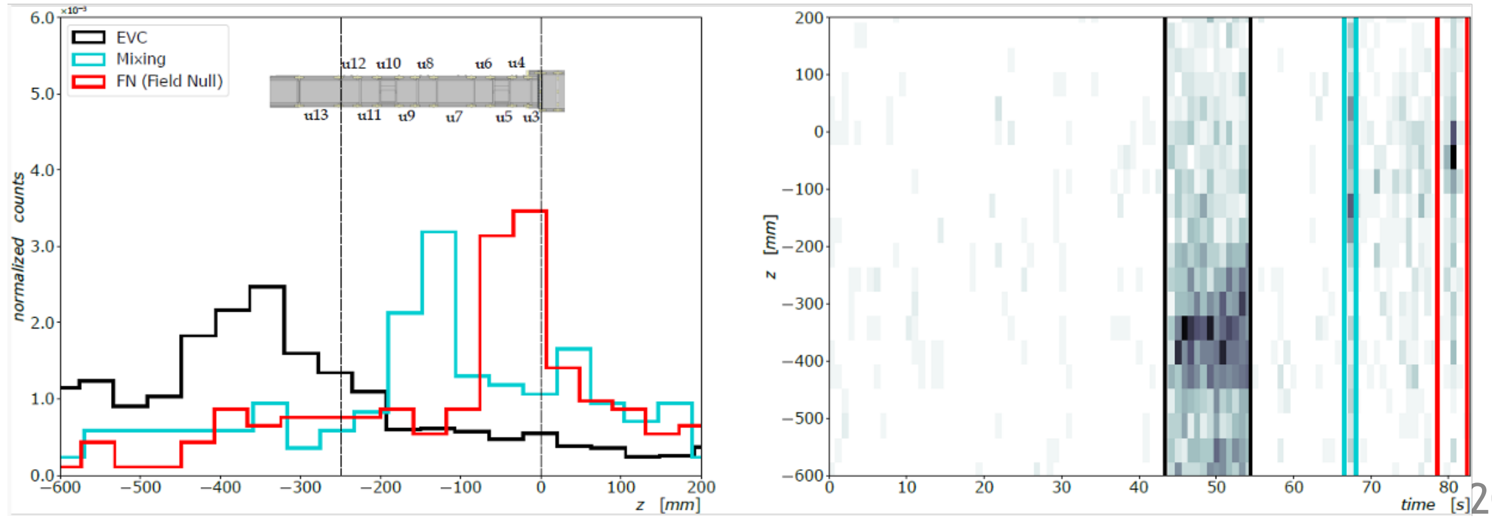
- > 2 M $\bar{p}$ trapped per AD shot
- > 50% transferred to Cusp trap
- ALPHA style mixing: 50-80% conversion to $\overline{\text{H}}$
    - **0.25-0.4 M** $\overline{\text{H}}$ per AD shot
- Tracking detector show formation in trap region
- No beam component observed
- Different mixing scheme being tried 2024
    - *Beam scheme*
    - Challenge: low temperature high density e^+ plasma needed
- New 50 mCi e^+ source procured in 2023

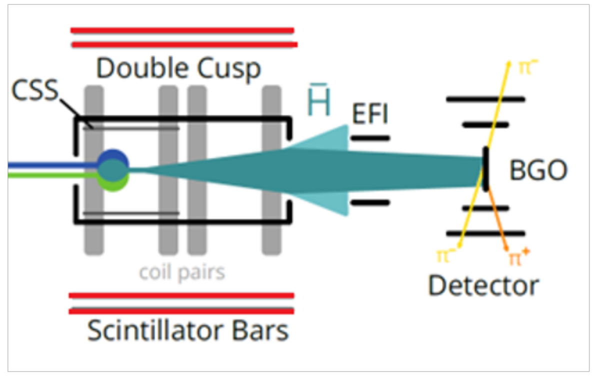






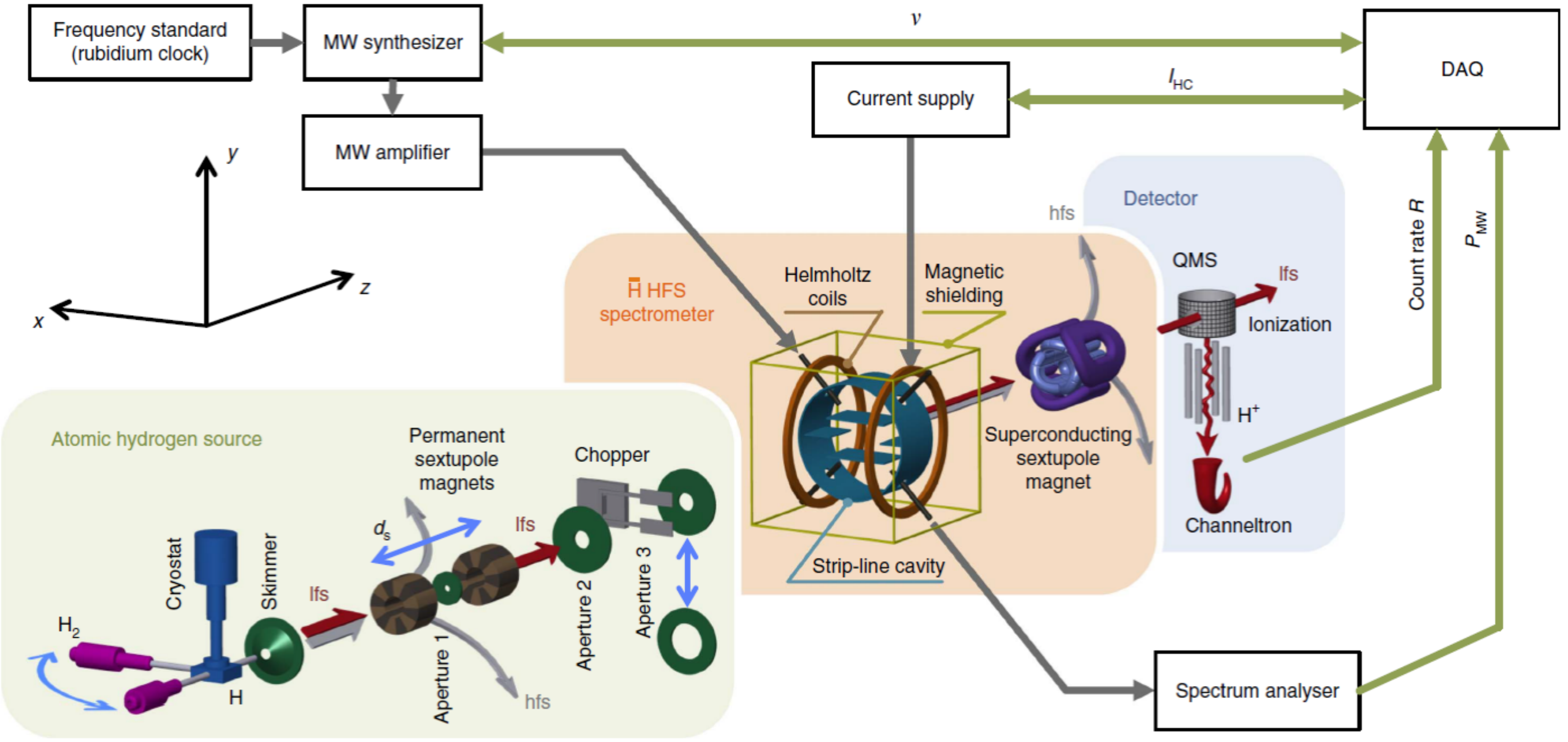






σ-transition $B \to 0$ in H using $\overline{\mathrm{H}}$ setup

Not sensitive to SME



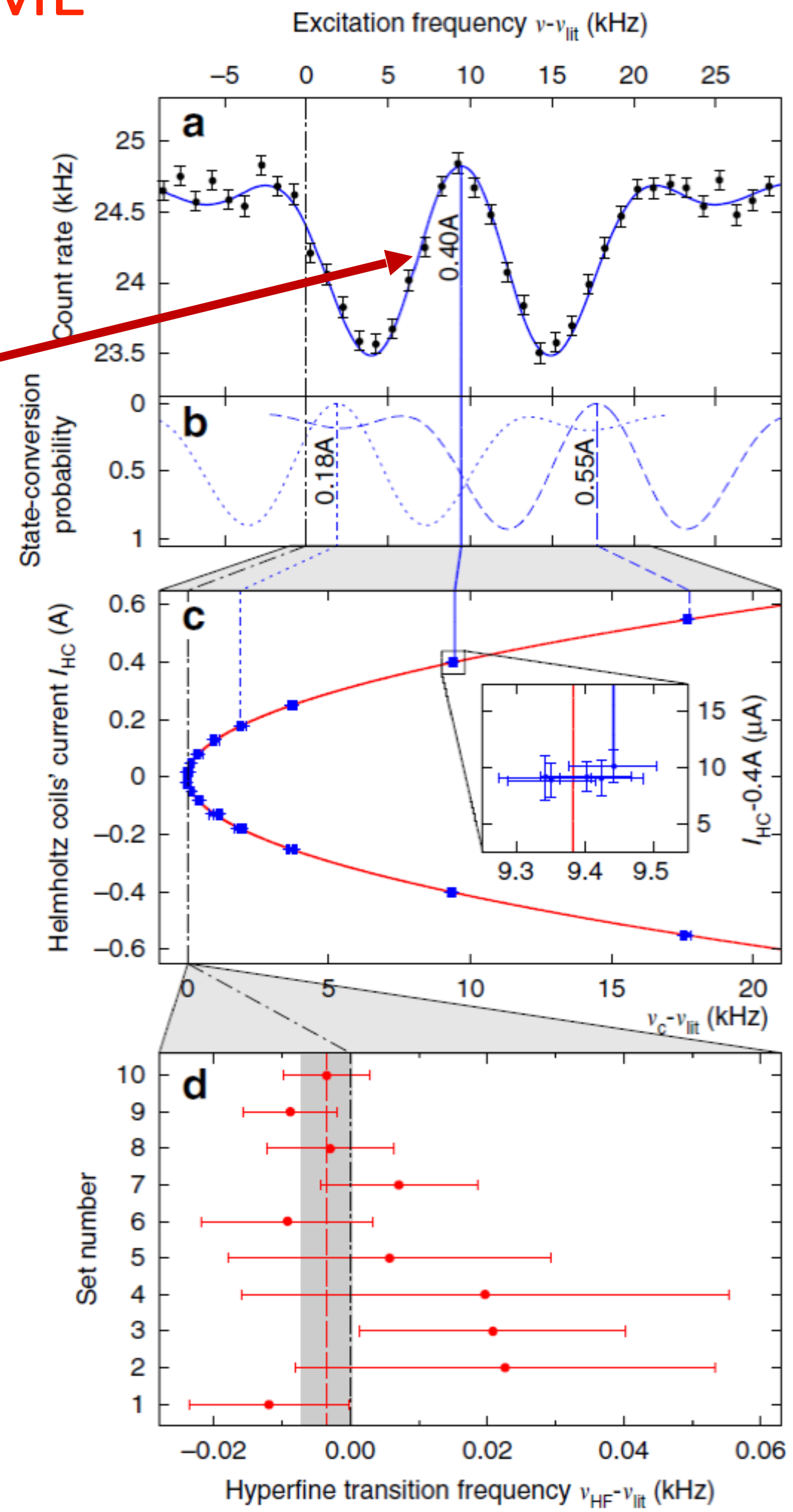
$$\boxed{\nu_{\mathrm{HF}} = 1\ 420\ 405\ 748.4(3.4)(1.6)\ \mathrm{Hz}}$$

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]

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



Error **2.7 ppb**: 18x improvement over *Kush, Phys. Rev. 100, 1188 (1955)*
Deviation from maser ($\Delta f/f$~10^{-12}) :
3.4 Hz < 1σ error

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

Spectroscopic signatures in SME

$$\mathcal{L} \supset \frac{1}{2}\overline{\Psi}_w(\gamma^\mu i\partial_\mu - m_w + \boxed{\hat{Q}_w})\Psi_w + \text{h.c.}$$

w=e,p,n

$\hat{Q}_w$: sum of all Lorentz invariance and CPT violating terms compatible with QFT: low-energy manifestation of unknown theory at M_{Pl}

V.A. Kostelecký and M. Mewes, PRD 88 096006 (2013)

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

p: particle momentum

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

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

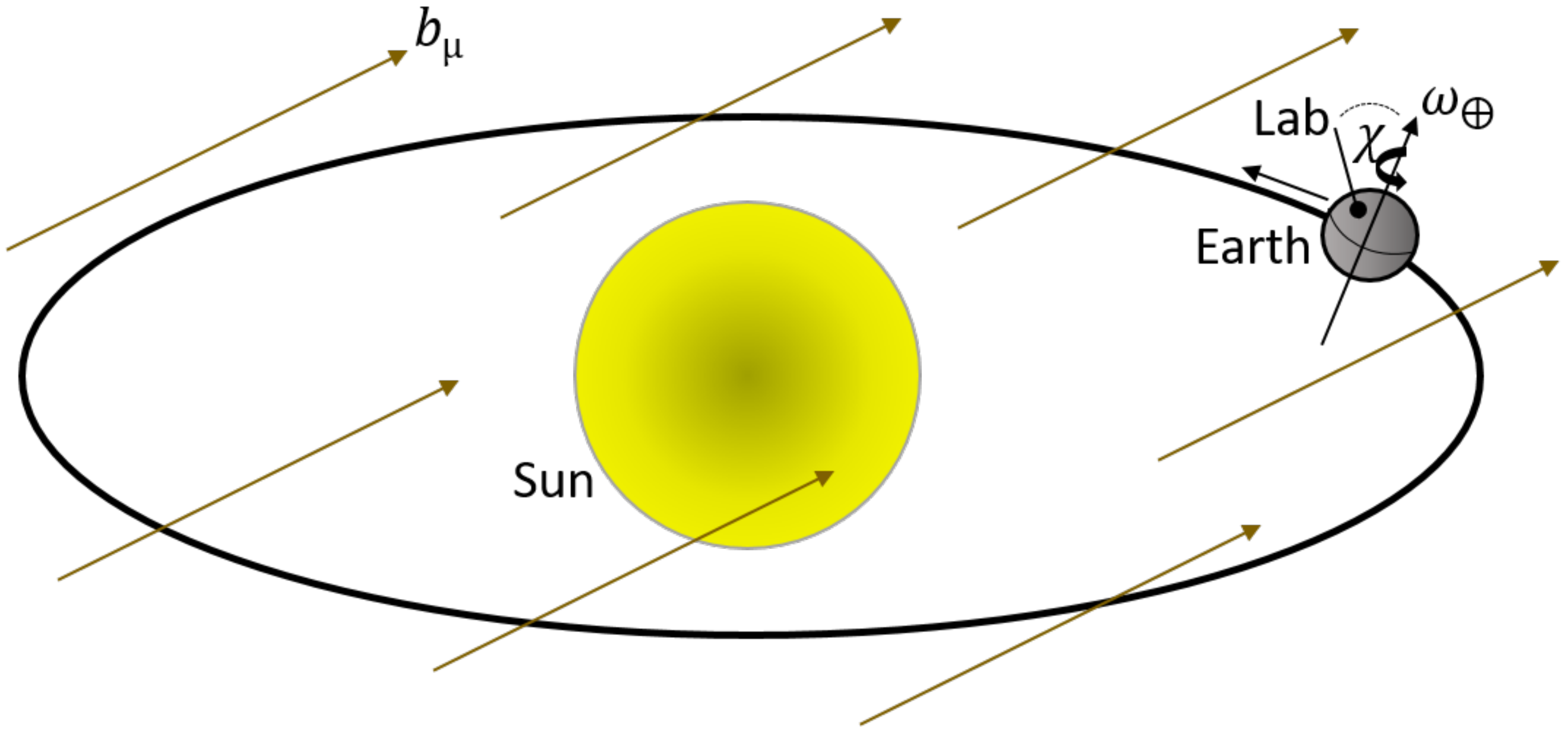
$$\mathcal{V}^{\text{NR}}_{wkjm} = c^{\text{NR}}_{wkjm} - a^{\text{NR}}_{wkjm},$$

Isotropic (spin-independent)

$$\mathcal{T}^{\text{NR(qP)}}_{wkjm} = g^{\text{NR(qP)}}_{wkjm} - H^{\text{NR(qP)}}_{wkjm},$$

Anisotropic (spin-dependent)

***a*, *g*: CPT odd**
***c*, *H*: CPT even**



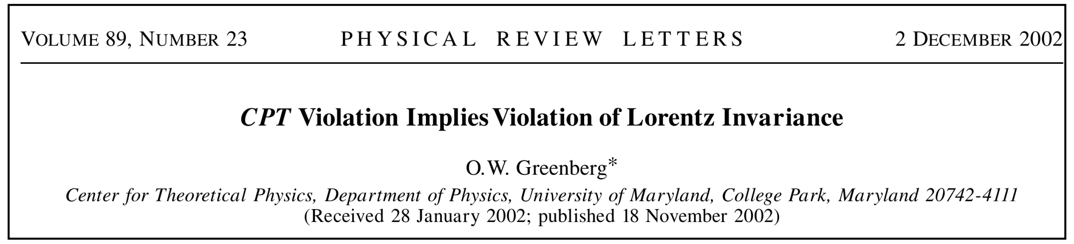
$$\mathcal{K}^{\text{NR,lab}}_{wk10} = \boxed{\mathcal{K}^{\text{NR,sun}}_{wk10}\cos\vartheta} \; \boxed{-\sqrt{2}\text{Re}\mathcal{K}^{\text{NR,sun}}_{wk11}\sin\vartheta\cos\omega_\oplus T_\oplus + \sqrt{2}\text{Im}\mathcal{K}^{\text{NR,sun}}_{wk11}\sin\vartheta\sin\omega_\oplus T_\oplus,}$$

Orientation dependence
ϑ: *B* field - Earth rotation axis

Sidereal variations

Simultaneous measurement of σ and π_1 transition in H

- **Anti-CPT theorem**



VOLUME 89, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 2002

CPT Violation Implies Violation of Lorentz Invariance

O.W. Greenberg*

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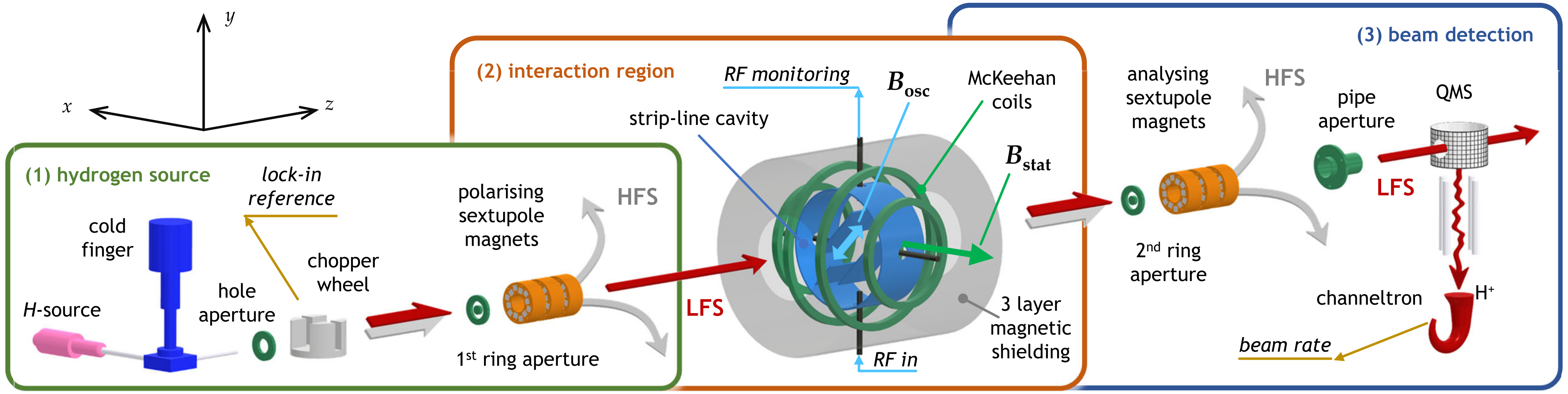
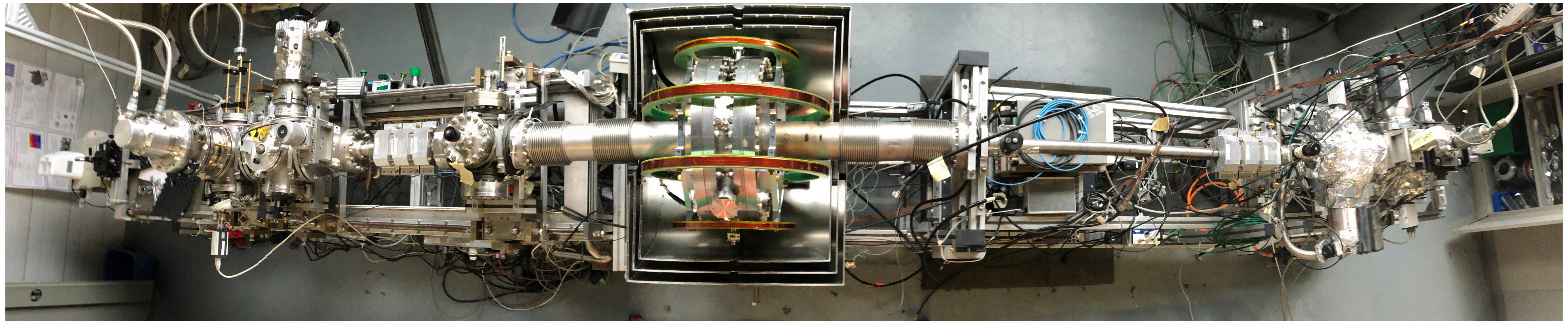
(Received 28 January 2002; published 18 November 2002)

- Atom optics to create same trajectories for HF states involved in σ and π_1 transitions
- New sextuples made of permantent magnets
- $T \sim 50$ K, $v \sim 900$ m/s
- Cavity $L = 10.5$ cm ($\lambda/2$)
- Line width
  - $\Delta\nu \sim 1/t_L \sim 8$ kHz

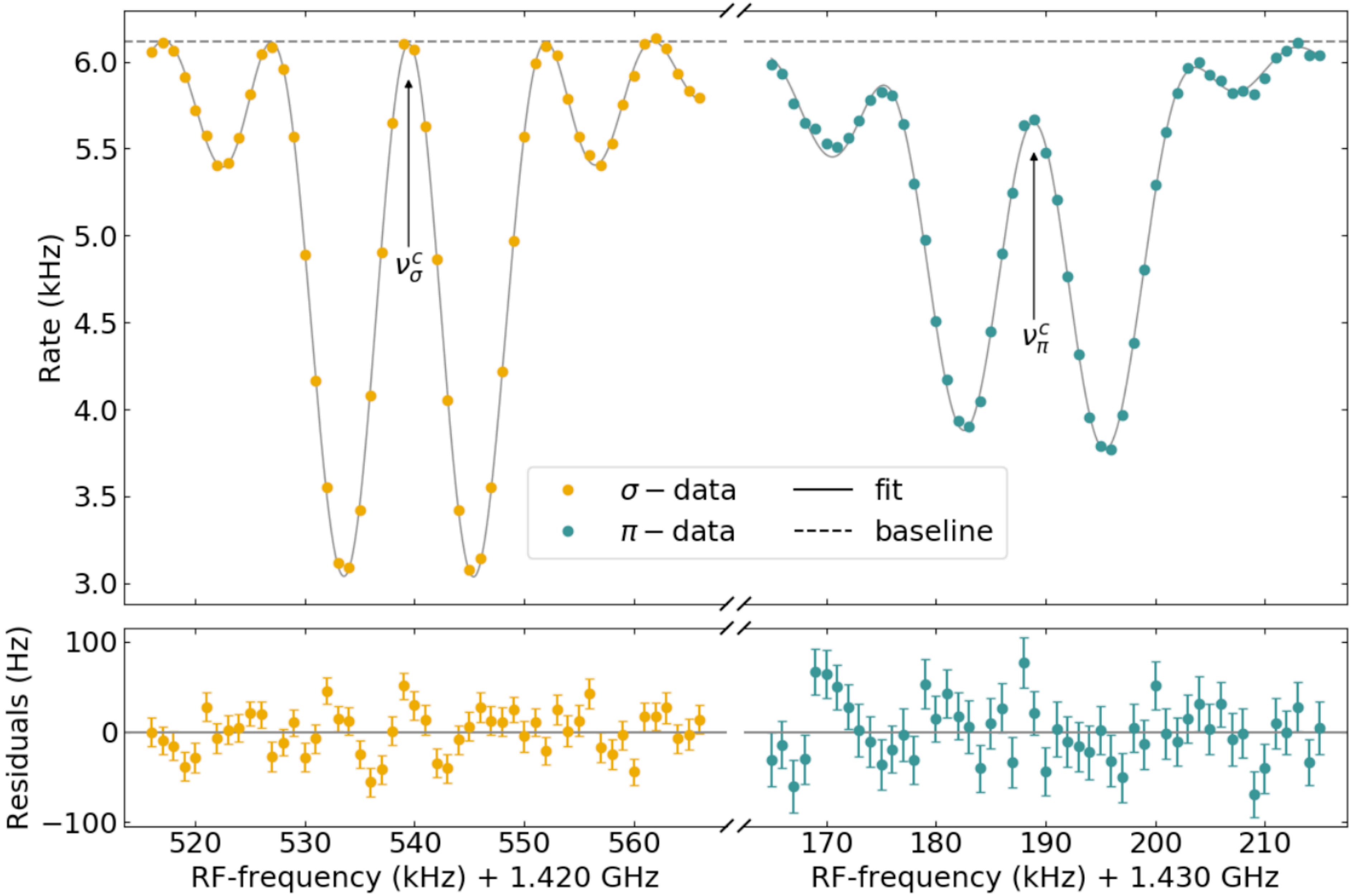




Hydrogen beam @Bat 275 CERN

Experimental challenge

- π transitions is very sensitive to magnetic field inhomogeneities
  - Needed very elaborate treatment to obtain satisfactory fit



Results of *B*-direction dependence

- Series of measurements in Jan – Mar 2022
  - Sequence $\nu_\sigma(+\boldsymbol{B}), \nu_\pi(+\boldsymbol{B}), \nu_\sigma(-\boldsymbol{B}), \nu_\pi(-\boldsymbol{B})$
- Result of blind analysis

$$\boxed{\Delta\nu_\pi^+ - \Delta\nu_\pi^- = (19 \pm 51)\,\mathrm{Hz}}$$

$$\boxed{|\,h(\Delta\nu_\pi^+ - \Delta\nu_\pi^-)\,|\,\frac{\sqrt{3\pi}}{\cos\theta} = (0.9 \pm 2.3)\times 10^{-21}\ \mathrm{GeV}}$$

Natural units

- @CERN: $\cos\theta = -0.26$ (angle $\boldsymbol{B}$, earth axis)

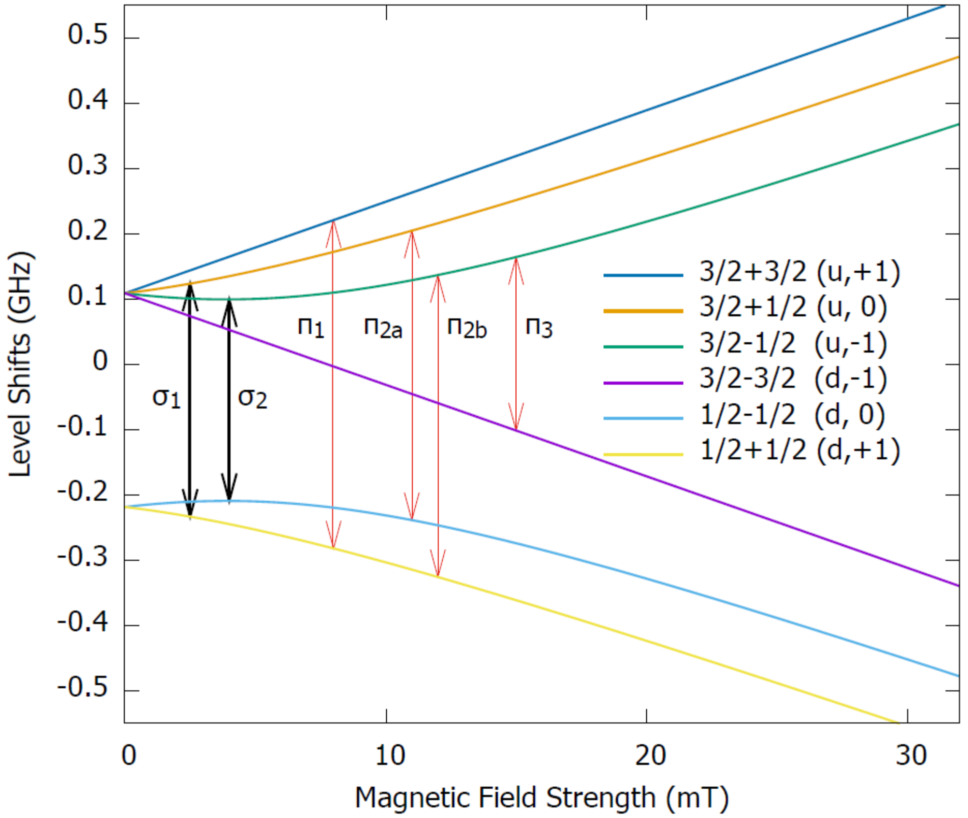
$$\begin{aligned}\Delta(2\pi\nu_\pi) &\equiv 2\pi\nu_\pi(\boldsymbol{B}) - 2\pi\nu_\pi(-\boldsymbol{B}) \\ &= -\frac{\cos\vartheta}{\sqrt{3\pi}}\sum_{q=0}^{2}(\alpha m_r)^{2q}(1+4\delta_{q2})\sum_w \Big[g_{w(2q)10}^{\mathrm{NR,Sun}(0B)} - H_{w(2q)10}^{\mathrm{NR,Sun}(0B)} \\ &\quad + 2g_{w(2q)10}^{\mathrm{NR,Sun}(1B)}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

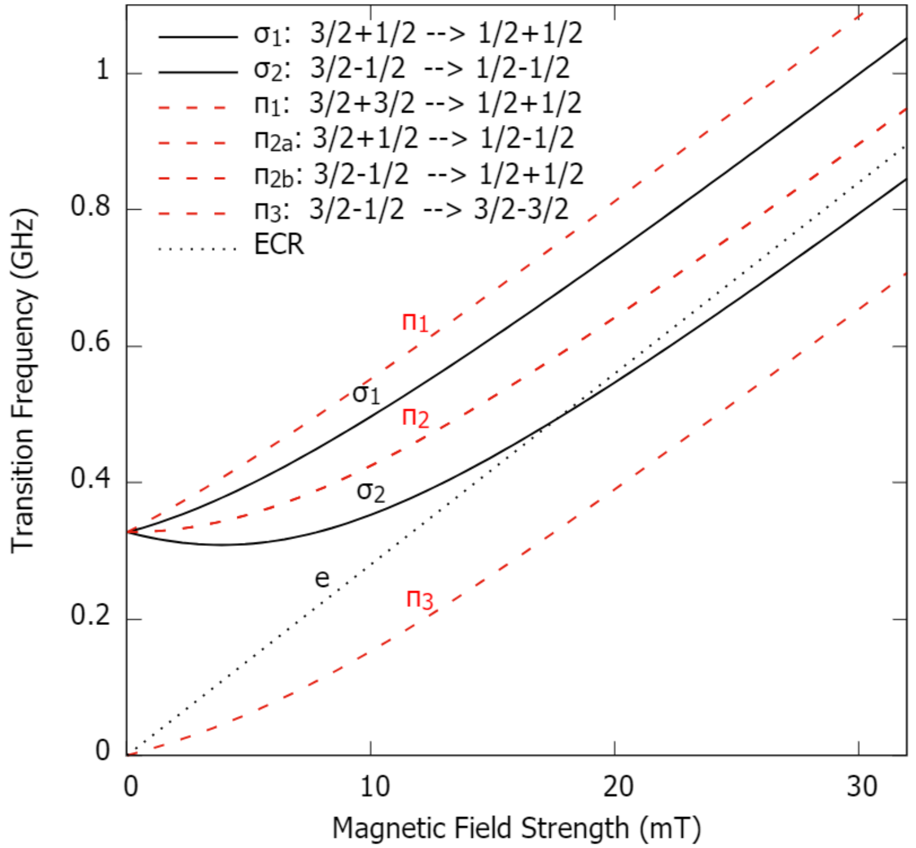
Kostelecký, V. A., & Vargas, A. J. *PRD*, *92*, 056002 (2015).

Coefficient $\mathcal{K}$	Constraint on $\lvert\mathcal{K}\rvert$
proton	
$H^{\mathrm{NR(0B),Sun}}_{p010}$, $g^{\mathrm{NR(0B),Sun}}_{p010}$	$< 1.2\times10^{-21}$ GeV
$H^{\mathrm{NR(1B),Sun}}_{p010}$, $g^{\mathrm{NR(1B),Sun}}_{p010}$	$< 5.8\times10^{-22}$ GeV
$H^{\mathrm{NR(0B),Sun}}_{p210}$, $g^{\mathrm{NR(0B),Sun}}_{p210}$	$< 8.4\times10^{-11}$ GeV^{-1}
$H^{\mathrm{NR(1B),Sun}}_{p210}$, $g^{\mathrm{NR(1B),Sun}}_{p210}$	$< 4.2\times10^{-11}$ GeV^{-1}
$H^{\mathrm{NR(0B),Sun}}_{p410}$, $g^{\mathrm{NR(0B),Sun}}_{p410}$	< 1.2 GeV^{-3}
$H^{\mathrm{NR(1B),Sun}}_{p410}$, $g^{\mathrm{NR(1B),Sun}}_{p410}$	< 0.6 GeV^{-3}
electron	
$H^{\mathrm{NR(0B),Sun}}_{e010}$, $g^{\mathrm{NR(0B),Sun}}_{e010}$	$< 7.7\times10^{-19}$ GeV
$H^{\mathrm{NR(1B),Sun}}_{e010}$, $g^{\mathrm{NR(1B),Sun}}_{e010}$	$< 3.8\times10^{-19}$ GeV
$H^{\mathrm{NR(0B),Sun}}_{e210}$, $g^{\mathrm{NR(0B),Sun}}_{e210}$	$< 5.5\times10^{-8}$ GeV^{-1}
$H^{\mathrm{NR(1B),Sun}}_{e210}$, $g^{\mathrm{NR(1B),Sun}}_{e210}$	$< 2.8\times10^{-8}$ GeV^{-1}
$H^{\mathrm{NR(0B),Sun}}_{e410}$, $g^{\mathrm{NR(0B),Sun}}_{e410}$	$< 8.0\times10^{2}$ GeV^{-3}
$H^{\mathrm{NR(1B),Sun}}_{e410}$, $g^{\mathrm{NR(1B),Sun}}_{e410}$	$< 4.0\times10^{2}$ GeV^{-3}

First limits on this type of coefficients
Nowak, L. et al. PLB 858 (2024) 139012.
arXiv.2403.17763

Deuterium HFS and SME





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

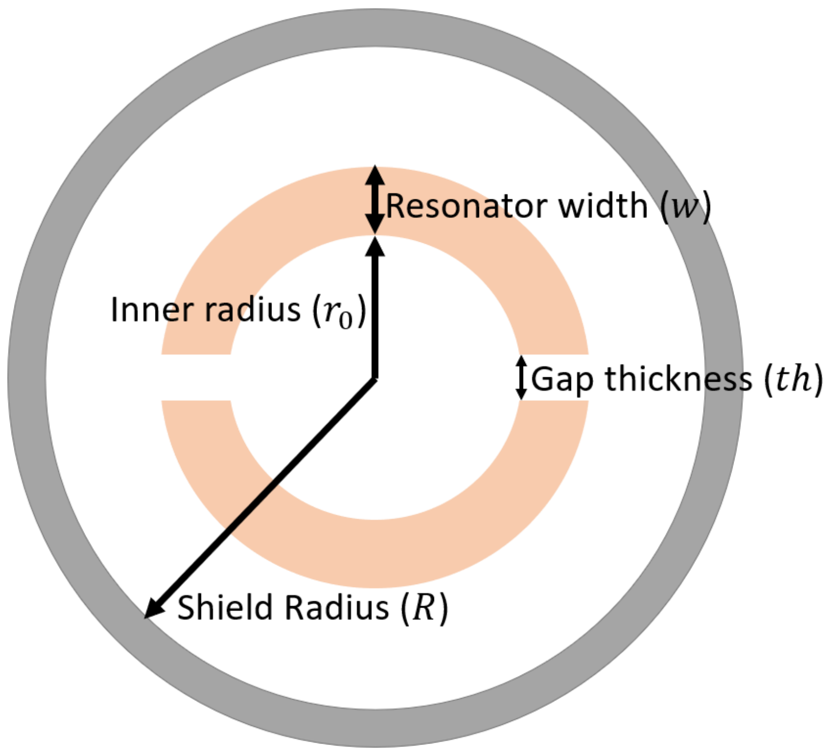
Kostelecký V. A., Vargas A. J. Phys. Rev. D 92, 056002 (2015)

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

- σ_1 and σ_2 show sidereal variations
- Enhanced sensitivity of q = 1 (10^9) and 2 (10^{18}) : relative momentum p,n
- Also oscillations at twice the sidereal frequency occur

H beam apparatus at Lab. Aimé Cotton (Saclay) with D cavity

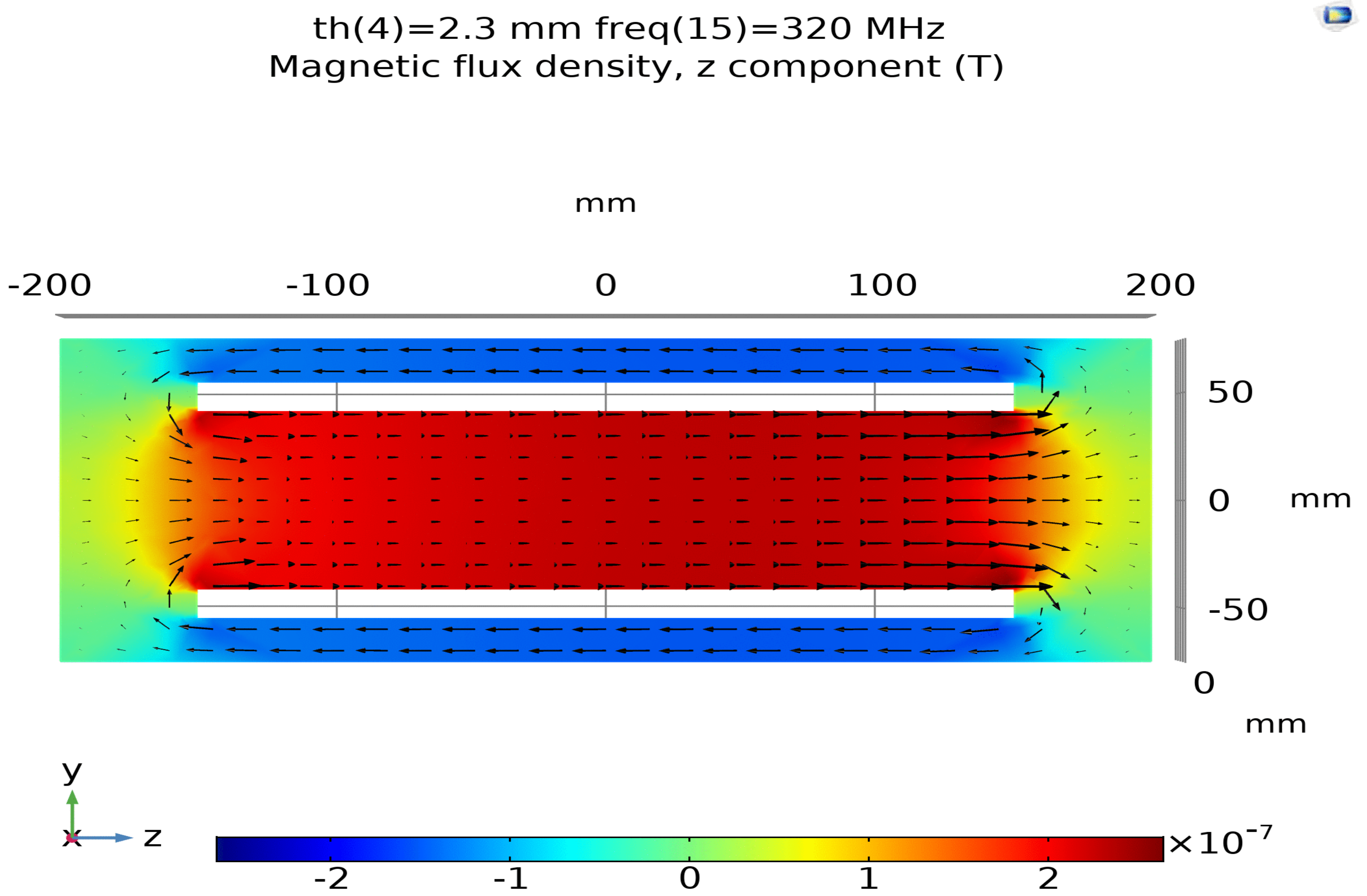
Double split ring resonator



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

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

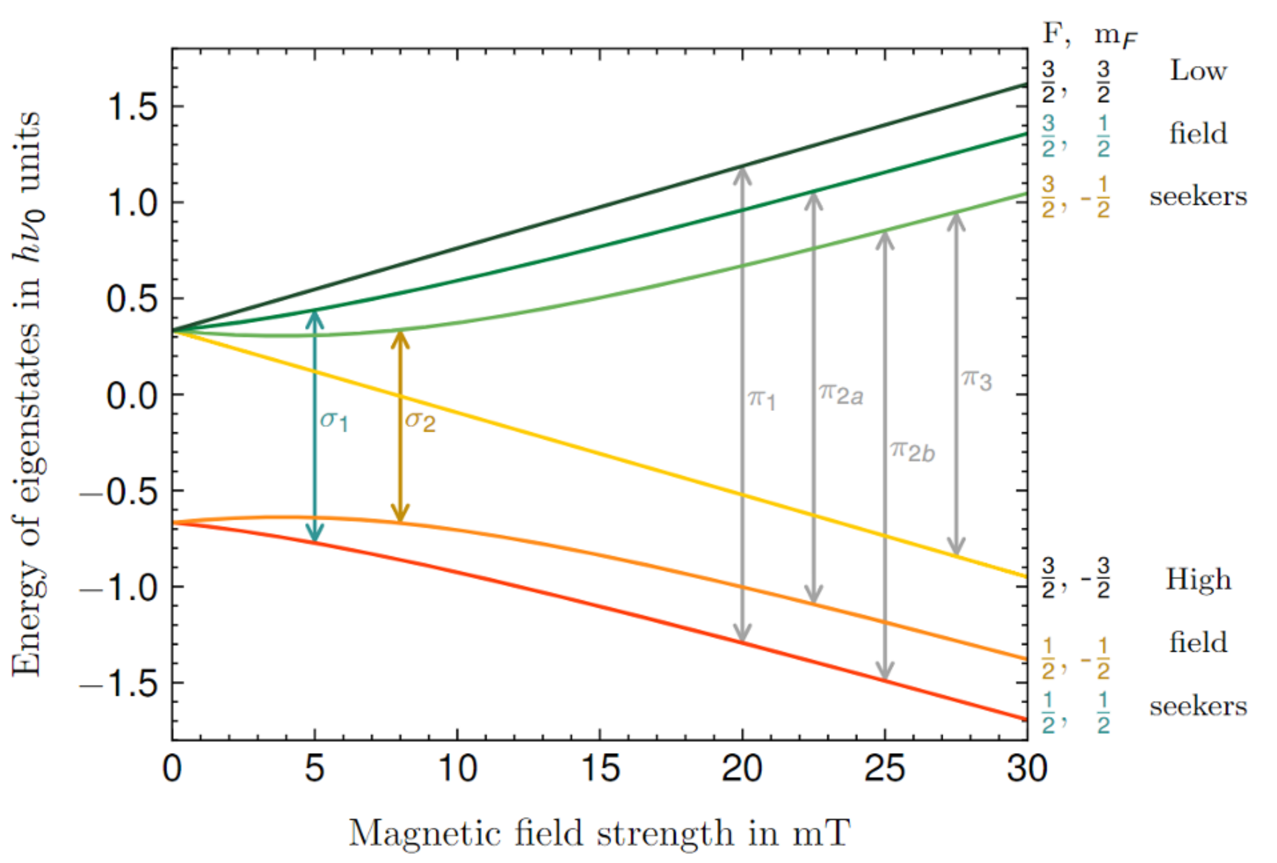
M. Mehdizadeh, et. al., Loop-gap resonator: A lumped mode microwaveresonant structure. IEEE Transactions on Microwave Theory and Techniques, 31(12):1059–1064, Dec 1983.

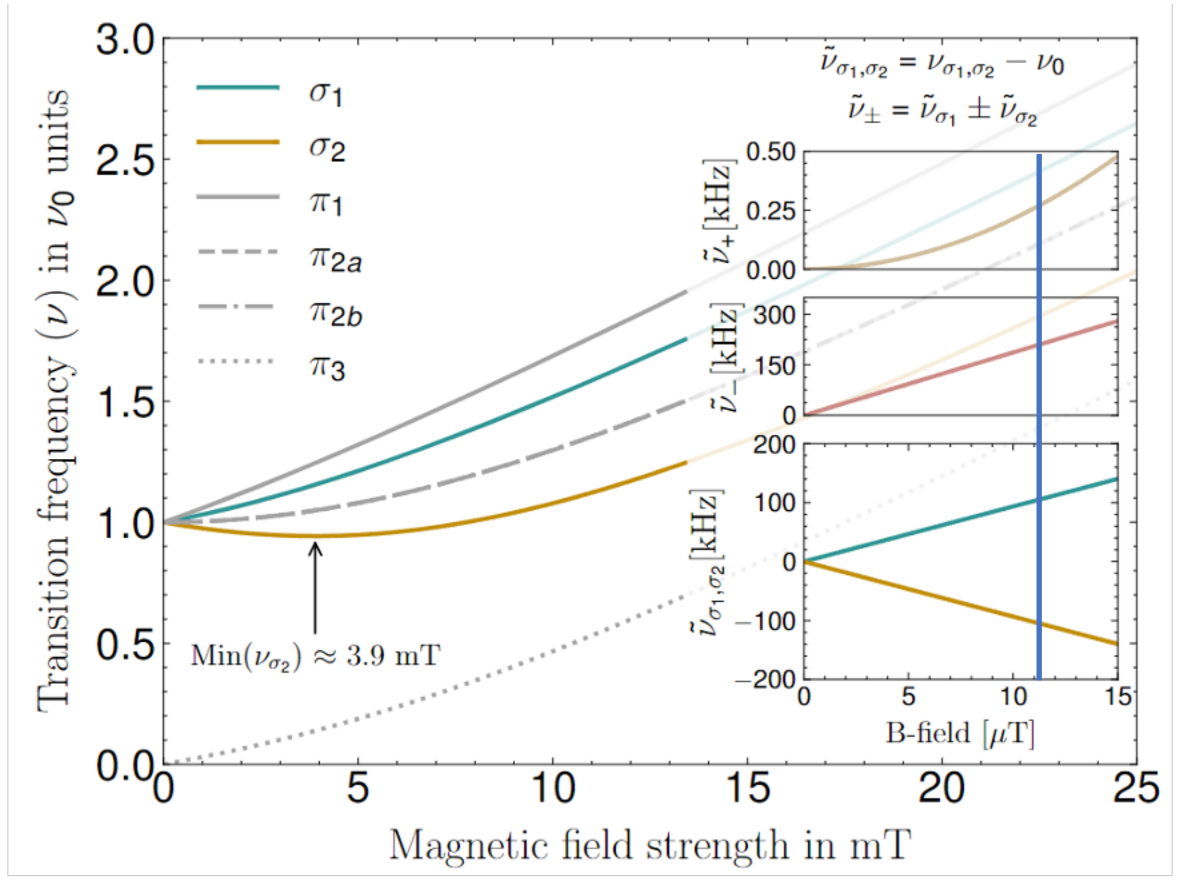


Eigenmode B field

A. Nanda (SMI)

Deuterium GS-HFS structure and transitions



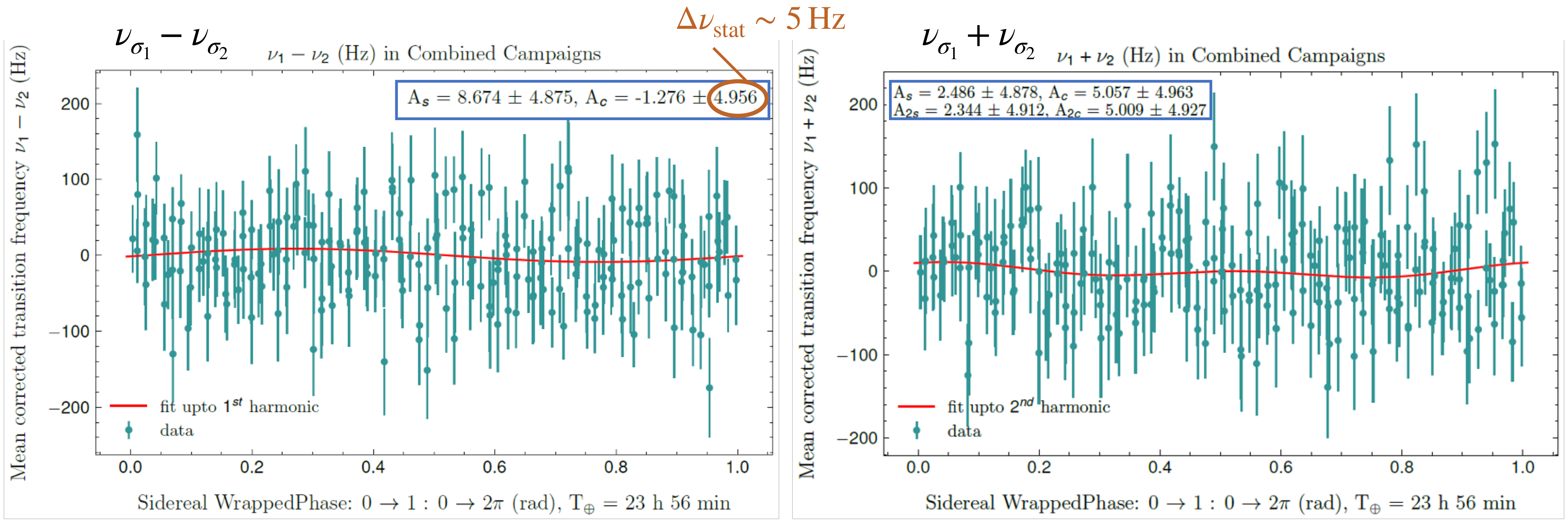


$\tilde{\nu}_+$ *B*-field insensitive

$B_{\text{ext}} \sim 11.2\ \mu\text{T}$

$\Delta\nu_{\text{HF}}^{\text{D}} = 327\ 384\ 352.5222(17)\,\text{Hz}$ Wineland, D. J. & Ramsey, N. F., Physical Review A 5, 821–837 (1972).

Results: data wrapped into one sidereal period



$A_0^0 = 0$: data normalised to mean since B_{ext} was
Different for two campaigns

$$2\pi\delta\nu^{(0)} = A_0^0 + A_c^{(0)}\cos(\omega_\oplus T_L) + A_s^{(0)}\sin(\omega_\oplus T_L) + A_{2c}^{(0)}\cos(2\omega_\oplus T_L) + A_{2s}^{(0)}\sin(2\omega_\oplus T_L)$$

Vargas, A. J. *Phys. Rev. D* **109**, 055001 (2024).

Results for SME coefficients

- Results for p coefficients
  - e, n: better limits exist from other experiments (*except in linear boost*)

Coefficient $\mathcal{K}^{\mathrm{Sun}}$	$\Re(\mathcal{K})$	$\Im(\mathcal{K})$	Units
$H_{p011}^{\mathrm{NR(0B)}}, g_{p011}^{\mathrm{NR(0B)}}$	0.5 ± 2.2	3.2 ± 2.2	10^{-22} GeV
$H_{p011}^{\mathrm{NR(1B)}}, g_{p011}^{\mathrm{NR(1B)}}$	0.2 ± 1.0	1.4 ± 1.0	10^{-22} GeV
$H_{p211}^{\mathrm{NR(0B)}}, g_{p211}^{\mathrm{NR(0B)}}$	0.3 ± 1.3	2.0 ± 1.3	$10^{-20}\,\mathrm{GeV}^{-1}$
$H_{p211}^{\mathrm{NR(1B)}}, g_{p211}^{\mathrm{NR(1B)}}$	0.7 ± 3.1	4.6 ± 3.1	$10^{-20}\,\mathrm{GeV}^{-1}$
$H_{p411}^{\mathrm{NR(0B)}}, g_{p411}^{\mathrm{NR(0B)}}$	0.8 ± 3.8	5.7 ± 3.8	$10^{-20}\,\mathrm{GeV}^{-3}$
$H_{p411}^{\mathrm{NR(1B)}}, g_{p411}^{\mathrm{NR(1B)}}$	-0.2 ± 1.0	-1.4 ± 1.0	$10^{-19}\,\mathrm{GeV}^{-3}$
$c_{p221}^{\mathrm{NR}}, a_{p221}^{\mathrm{NR}}$	1.8 ± 1.7	-0.6 ± 1.7	$10^{-20}\,\mathrm{GeV}^{-1}$
$c_{p222}^{\mathrm{NR}}, a_{p222}^{\mathrm{NR}}$	-3.0 ± 3.0	1.3 ± 3.0	$10^{-20}\,\mathrm{GeV}^{-1}$
$c_{p421}^{\mathrm{NR}}, a_{p421}^{\mathrm{NR}}$	-1.0 ± 1.0	0.3 ± 1.0	$10^{-19}\,\mathrm{GeV}^{-3}$
$c_{p422}^{\mathrm{NR}}, a_{p422}^{\mathrm{NR}}$	1.6 ± 1.6	-0.7 ± 1.6	$10^{-19}\,\mathrm{GeV}^{-3}$

Inferior to H maser results

By 4 O.M.

Improvement over limits set by H-Maser results

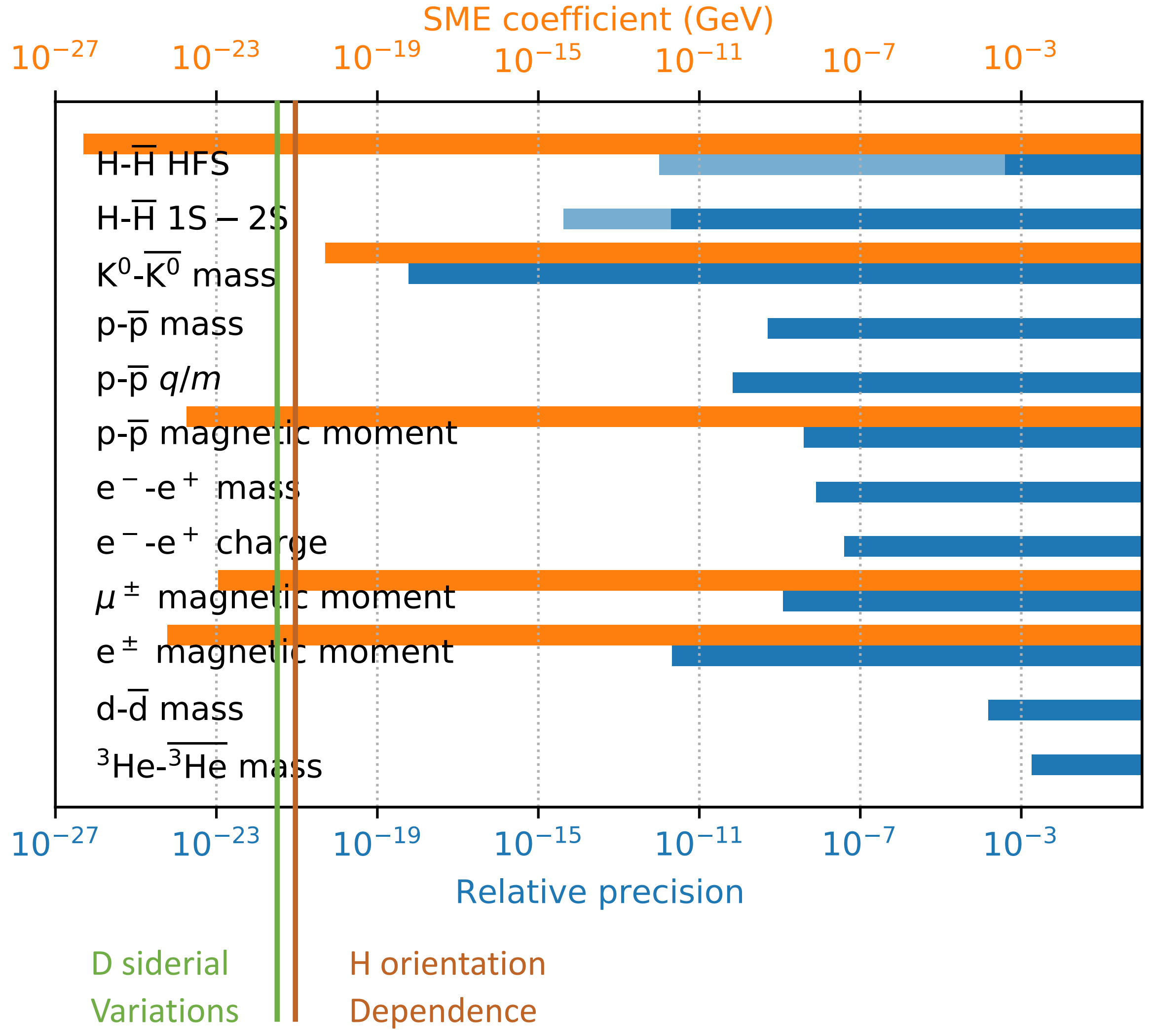
By 14 O.M.

New results for proton coefficients

Publication in preparation

Summary

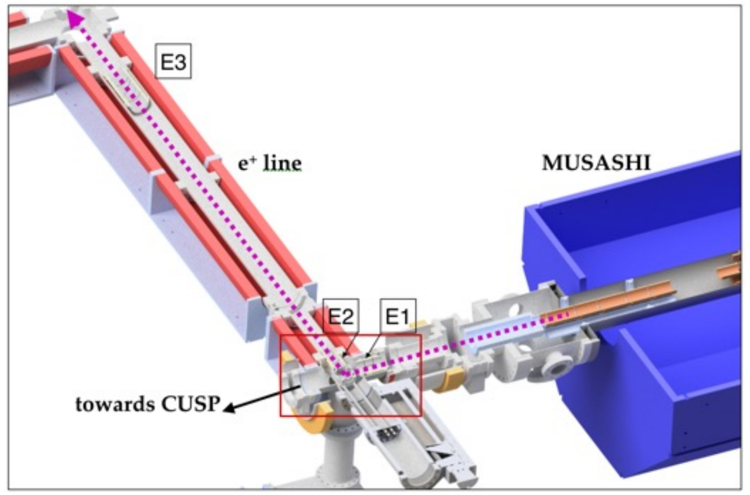
- H orientation dependence (*upublished*)
  - Exp error 50 Hz, improvement by magnetometry
    - Possible improvement x5 p, x10³ e coefficients
  - 1st limits on $\mathcal{T}^{\text{NR(sB),sun}}_{010} \sim 10^{-21}$ GeV p, 10^{-18} GeV e
  - Precision for zero.-field splitting
    $\nu_{\text{HF}}^{\text{exp}}/\nu_{\text{HF}}^{\text{maser}}(B=0) = 0.14 \pm 0.59(\text{stat}) \pm 0.23(\text{syst})\,\text{Hz}\,(4.4\times 10^{-10})$
- D sidereal variations (*in preparation fro submission*)
  - Exp. error 5 Hz (stat), 0.1 - 2 Hz (syst)
  - Limits on $\mathcal{T}^{\text{NR(sB),sun}}_{011} \sim 10^{-22}$ GeV (*p: new k=2, k=4*),
    $\mathcal{V}^{\text{NR(sB),sun}}_{221} 10^{-20}$ GeV^{-1} (*p: new*)
  - More constraints possible from linear boost measurements
    - 1st *step possible with existing data, more measurements needed for better accuracy)*

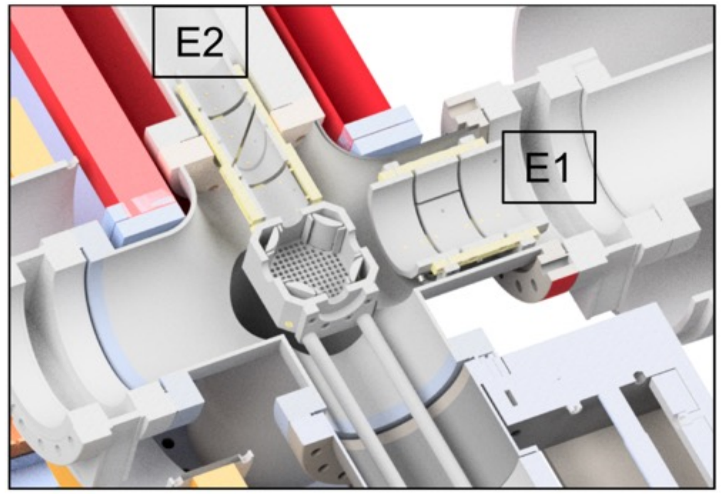


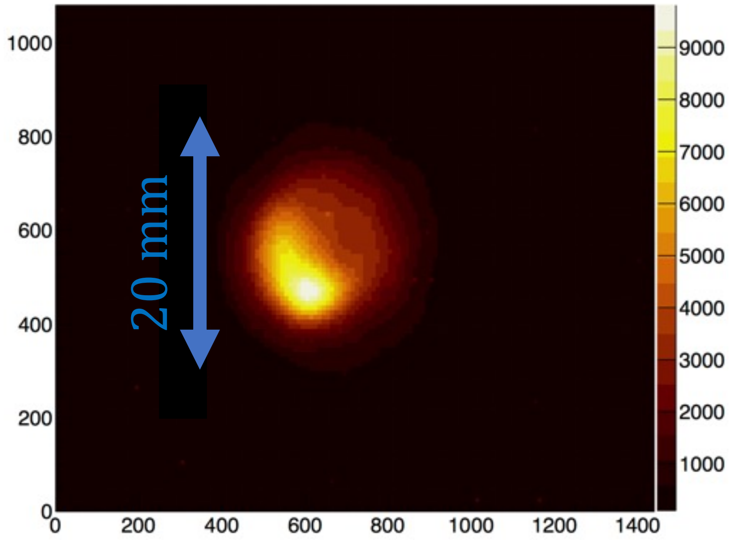
E. Widmann, Phys. Part. Nucl. 53, 790 (2022)
Source: PDG & arXiv:0801.0287v17

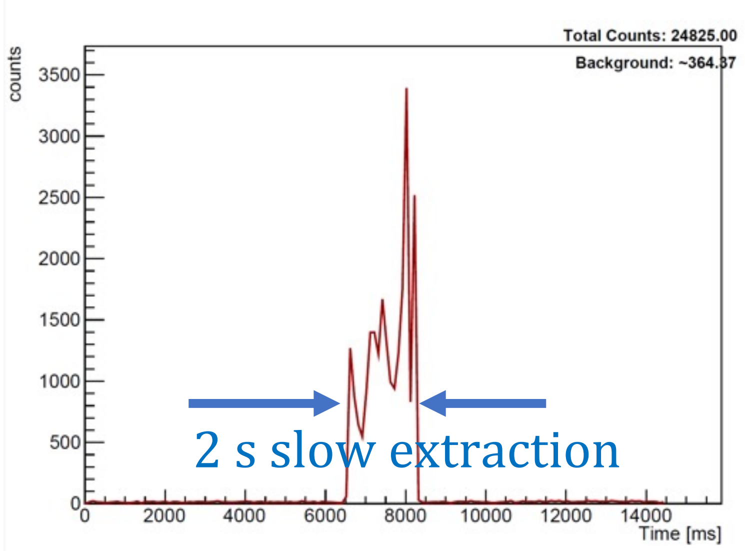
Slow extraction beam line

- Experiments to transport a slow extracted beam of $\bar{p}$ out of MUSASHI along the existing e^+ transfer line using electrostatic beam elements
- Approximately 25,000 $\bar{p}$ detected and imaged on an MCP detector
  - Transport efficiency $\sim$ 10%
  - Beamspot < 1cm



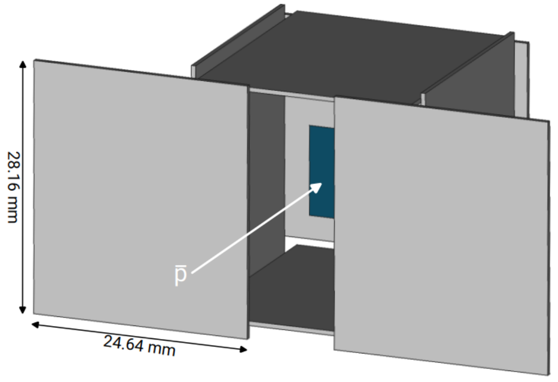


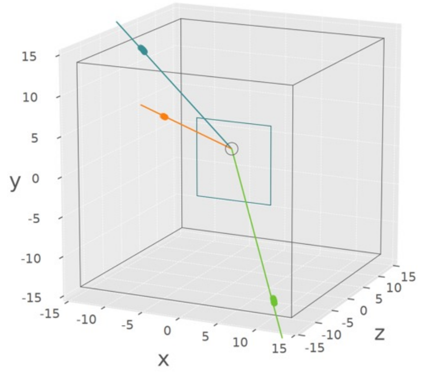


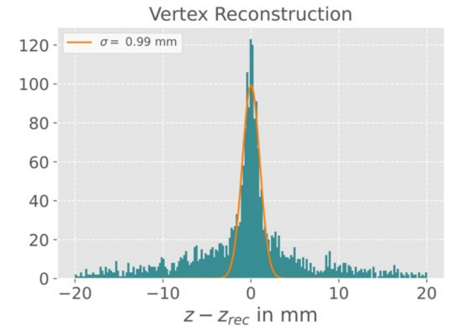


Annihilation measurements

- Systematic studies of antiproton – nucleus annihilation
  - Using thin targets (~ 15)
  - Detection of prongs with ~ 4π solid angle
    - Detector based on Timepix 4
    - 3D vertex reconstruction with single plane pixel detectors
  - Multiplicity, Kinetic Energy, and Angular Distributions







Possible topic: Pontecorvo reaction

- $\bar{p}^3He \rightarrow pn$
- High branching ratio 10^{-6}

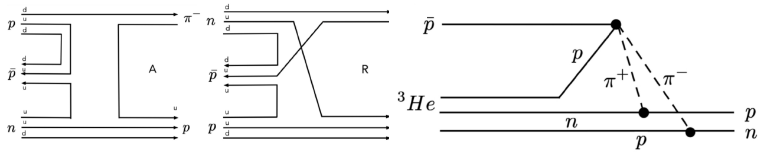
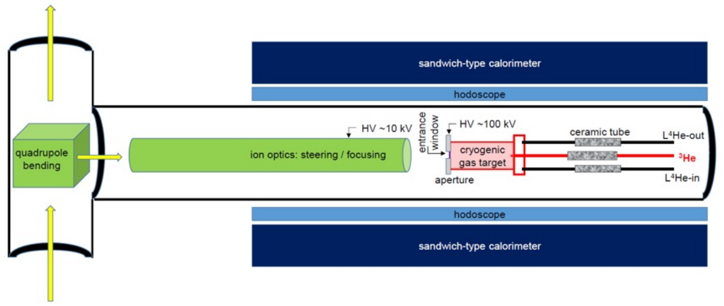


Figure 68 – Left: annihilation and rearrangement graphs in the fireball model. Right: rescattering diagram for $\bar{p}^3He \rightarrow np$.

C. Amsler, "Nucleon-antinucleon annihilation at LEAR," 2019. [Online]. Available: https://arxiv.org/abs/1908.08455



Antiprotons accelerated to 100 keV	$1.0 \cdot 10^3$ s^{-1}
Antiprotons stopped in the target cell: 90%	$0.9 \cdot 10^3$ s^{-1}
Neutron detection efficiency: solid angle 50%; intrinsic efficiency 60%	
Proton detection efficiency: solid angle 50%; intrinsic efficiency 100%	
Coincidence rate neutron-proton: 15%	$1.4 \cdot 10^2$ s^{-1}
Pontecorvo reaction branching ratio 10^{-6}	$1.4 \cdot 10^{-4}$ s^{-1}
Detected proton-neutron pairs per day	**~ 10**

- Other topics
  - Continuation of fragmentation studies
  - Antiprotonic atom spectroscopy for QED tests

Questions

- Efficient antihydrogen beam formation
- Making colder hydrogen and antihydrogen beams

- Usefulness of slow extracted beam for experiments