ASACUSA status report 2017 and plans for 2018

128th Meeting of the SPSC

23 January 2018

E. Widmann, Stefan Meyer Institute, Vienna

Co-spokesperson, ASACUSA

ASACUSA collaboration

C. Amsler[a], S. Arguedas Cuendis[a], D. Barna[b], A. Bianconi [c], H. Breuker[d], M. Corradini[c], P. Dupré[d], C. Evans[c], M. Fleck[a], A. Gligorova[a], R. Hayano[e], H. Higaki[f], **M. Hori**[g*], D. Horváth[b], Y. Kanai[h], B. Kolbinger[a], N. Kuroda[i], M. Leali[c], E. Lodi-Rizzini[c], V. Mäckel[a], C. Malbrunot[j,a], V. Mascagna[c], O. Massiczek[a], Y. Matsuda[i], D. Murtagh[a],Y. Nagata[k], A. Nanda[a], N. Ogawa[e], D. Phan[a], B. Radics[d1], M.C. Simon[a], A. Sótér[g], H. Spitzer[a], M. Strube[a], M. Tajima[d,i], Y. Tanaka[l], S. Ulmer[d], L. Venturelli[c], **E. Widmann**[a*], M. Wiesinger[a], Y. Yamazaki[d], J. Zmeskal[a]

[a]Stefan Meyer Institute, [b]Wigner Research Centre for Physics, [c]Dipartimento di Ingegneria dell'Informazione, Università degli Studi di Brescia, and INFN, [d]Ulmer Fundamental Symmetries Laboratory, RIKEN, [e]Department of Physics, The University of Tokyo, [f]Graduate School of Advanced Sciences of Matter, Hiroshima University, [g]Max-Planck-Institut für Quantenoptik, [h]Nishina Center for Accelerator-Based Science, RIKEN, [i]Institute of Physics, the University of Tokyo, [j]CERN, [k]Department of Physics, Tokyo University of Science, [l] GSI Helmholtzzentrum für Schwerionenforschung

[1]present address: ETH Zürich

***co-spokesperson**

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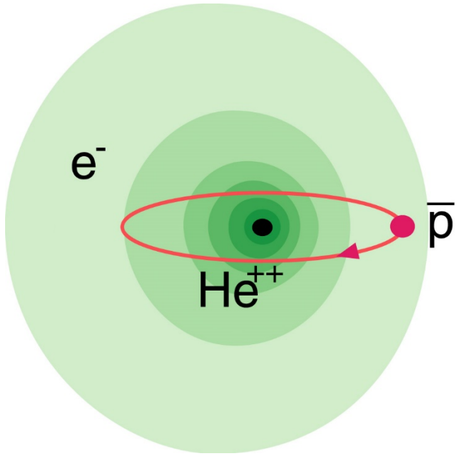
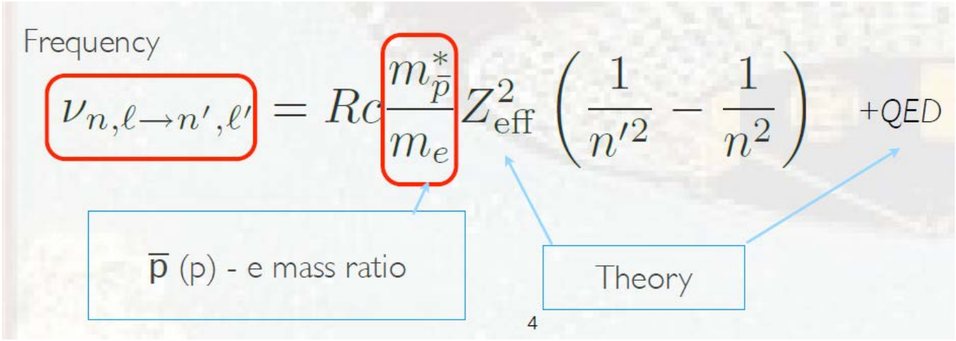
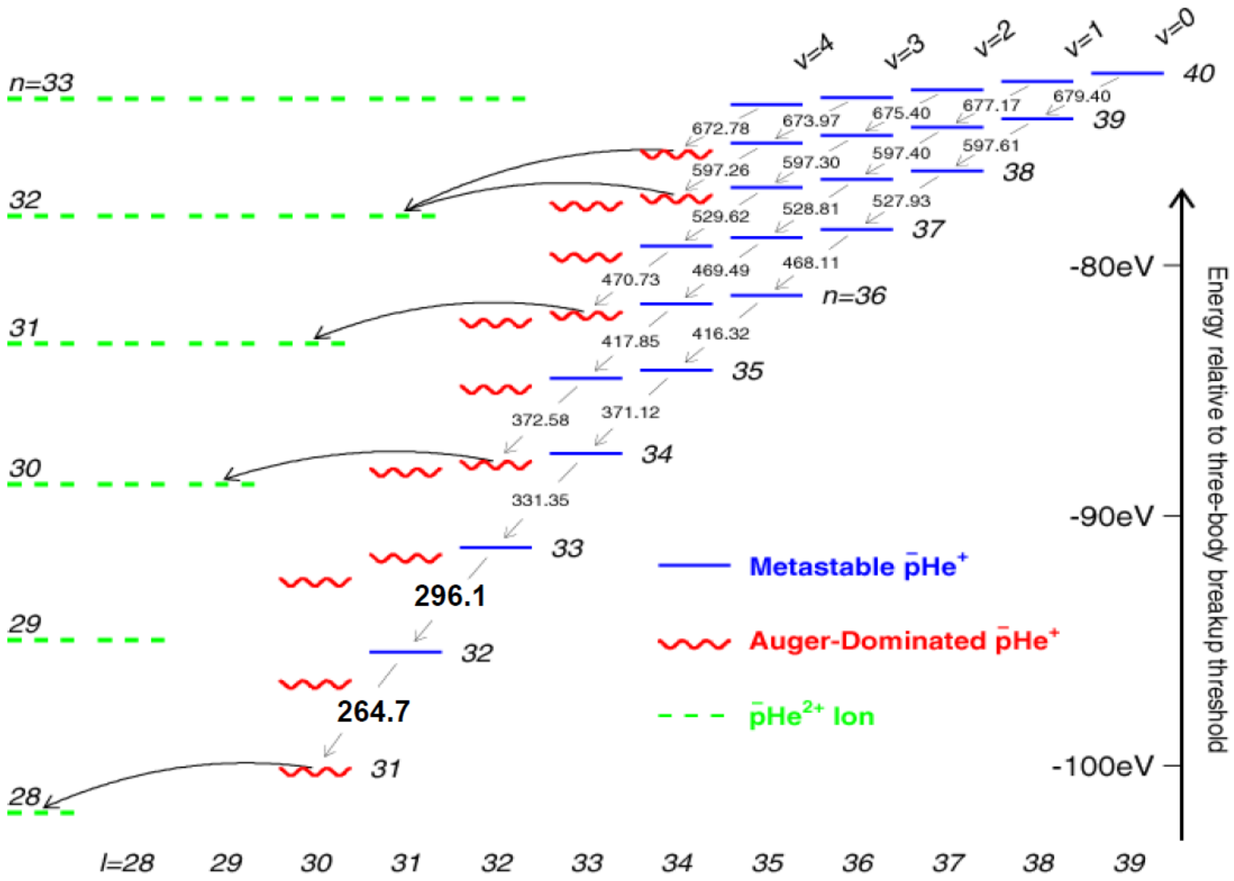
I Antiprotonic helium

Antiproton-to-electron mass ratio



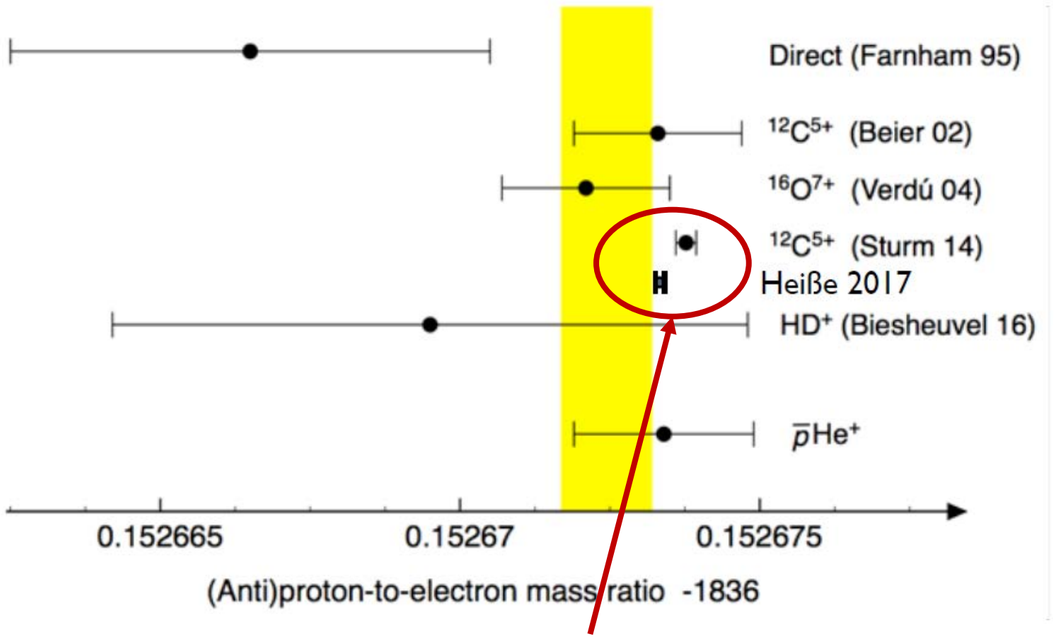


Needs 3-body theory



Previous results and methods

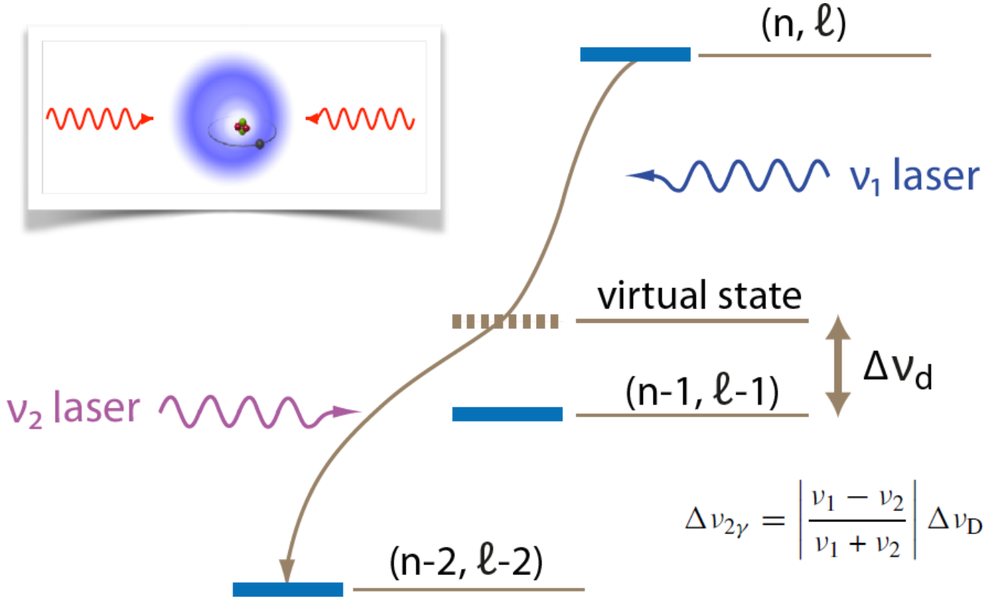
- $m_{\bar{p}}/m_e$ 2016



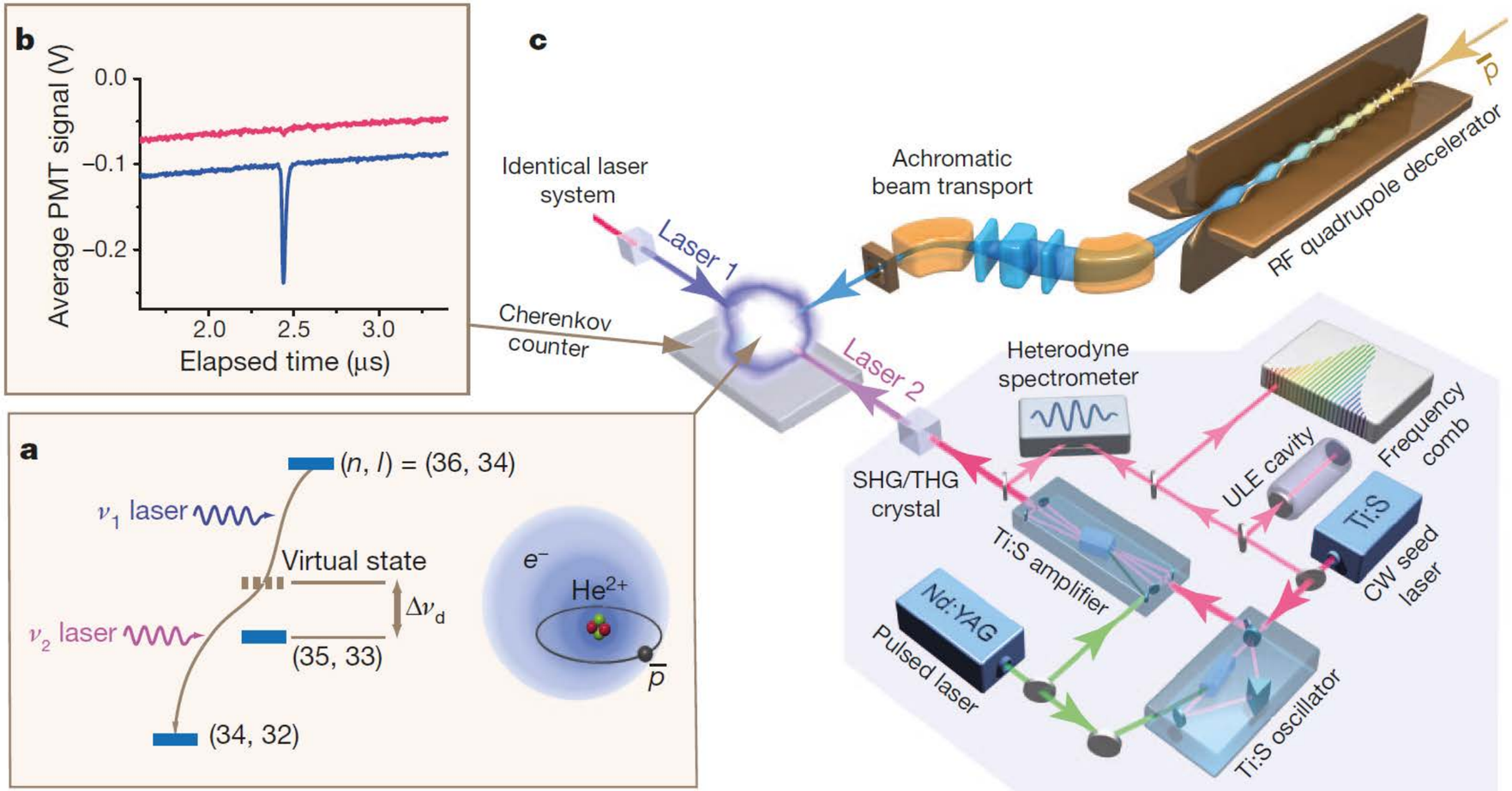
2-3 σ away from CODATA 2010

Antiproton-to-electron mass ratio 1836.1526734 (15)

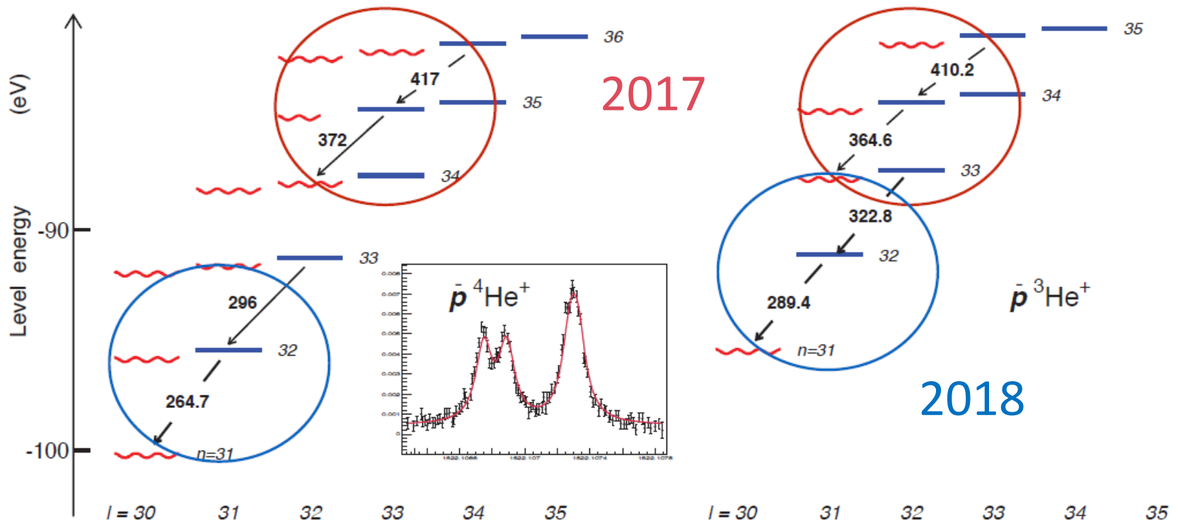
- Sub-Doppler two-photon laser spectroscopy

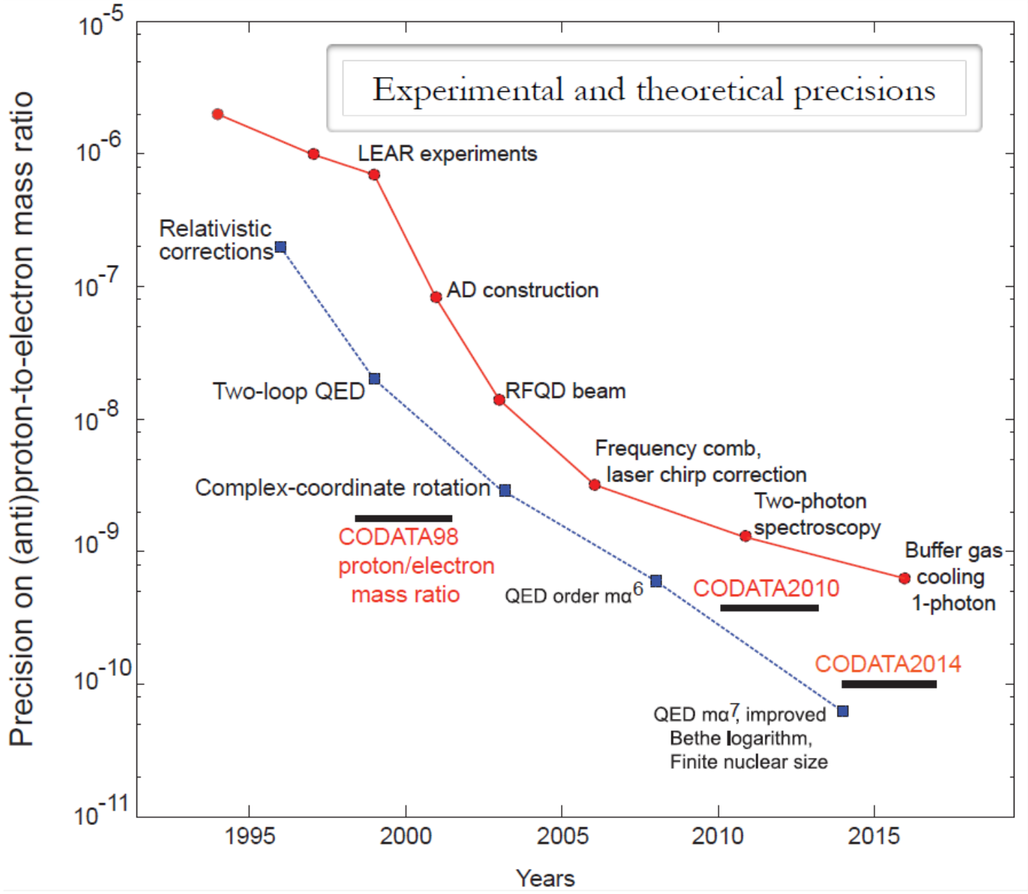


Setup for 2-photon spectroscopy



2017 results (under analysis)





- Goal: $m_{\bar{p}}/m_e < 0.5$ ppb

Beam usage 2017 and plans for 2018

- 2017: RFQD troubles
  - Lost 7 weeks

May, June, early July (7 weeks): RFQD problems, almost total loss of beam except for tuning. Realignment of upstream magnetic elements.

RFQD recovers and data-taking starts July 18th.

Weeks 29, 30, 31, 34	(4 weeks):	pbar-^{4}He$^+$	(36,34)→(34,32)
Week 35	(1 week):	pbar-^{3}He$^+$	(35,33)→(33,31)

Accumulated **29 days** of publishable data
(half of expected data)

- Plans for 2018

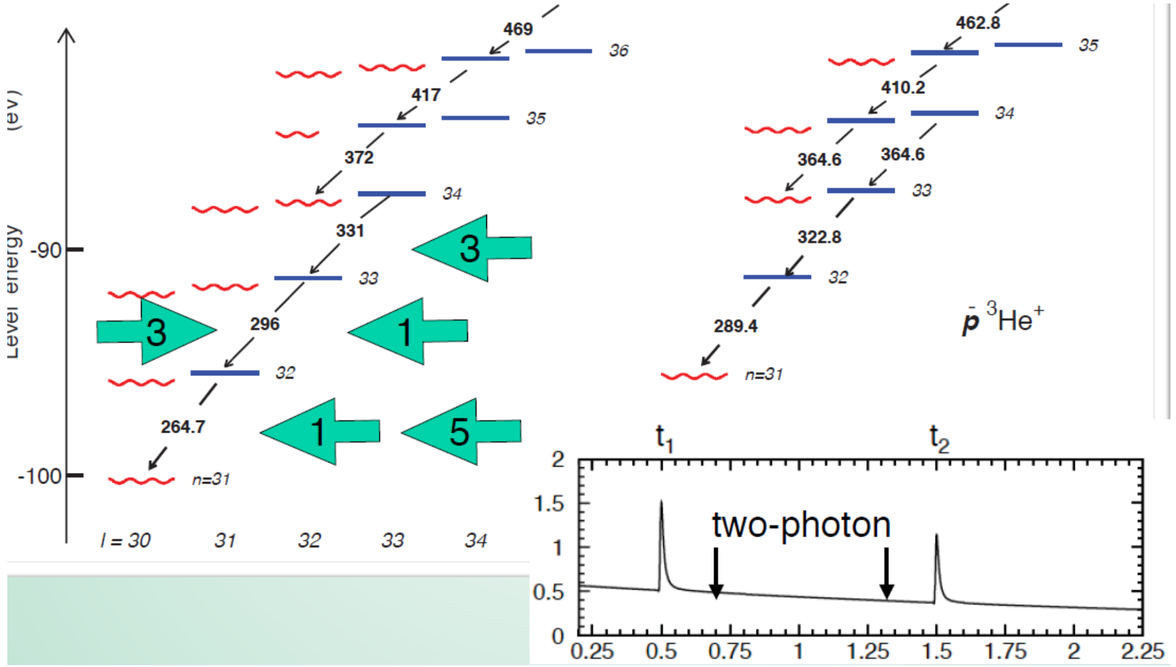
Continuation of pbar-4He two-photon

pbar-4He	(n,l)=(36,34)->(34,32)	Finished!
	(31,30)->(30,29)	
pbar-3He	**(35,33)->(33,31)**	**Now measuring**
	(30,29)->(29,28)	

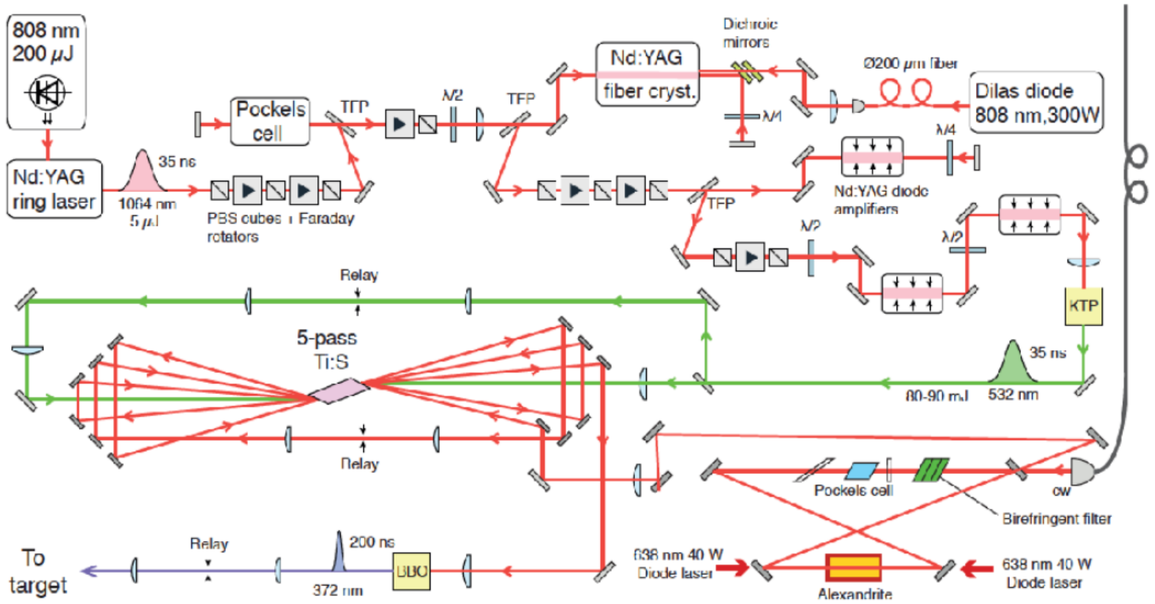
Goal: antiproton-to-electron mass ratio <5x10–10

Inprovements towards ELENA: lasers

- Metastable-to-metastable state transitions



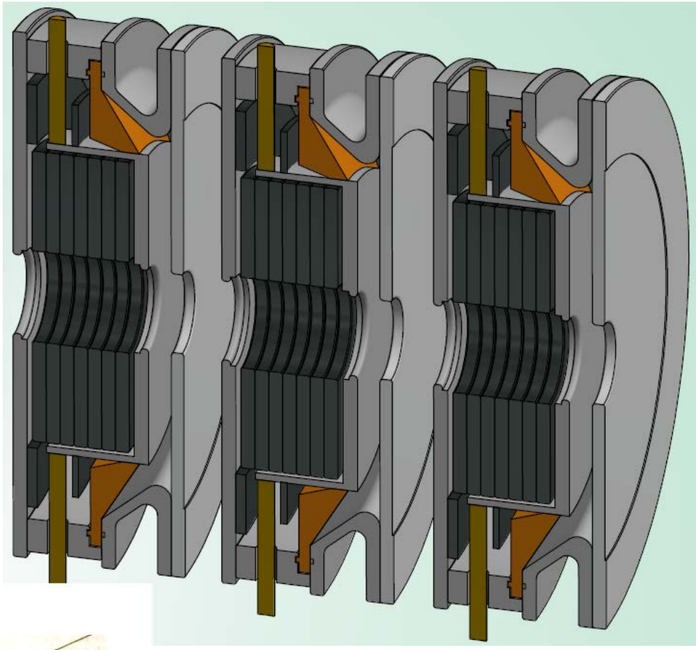
Fully DPSS Nd:YAG laser pumped Ti:Sapphire laser with long-pulse alexandrite oscillator

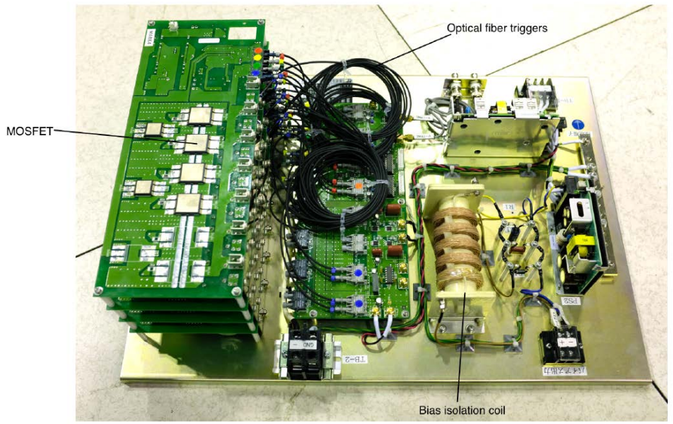


Potential improvement: factor 100

Induction deceleration cavity for $\bar{p}$

- Goal: minimize stopping volume of $\bar{p}$ in low-density gas for efficient laser spectroscopy
- Transformer with ferromagnetic cores
  - Primary winding = pulsed excitation
  - Secondary winding = beam
- Deceleration 100 keV to <50 keV
- R&D ongoing, operation after LS2
- Collaboration with KEK/J-PARC and CLIC

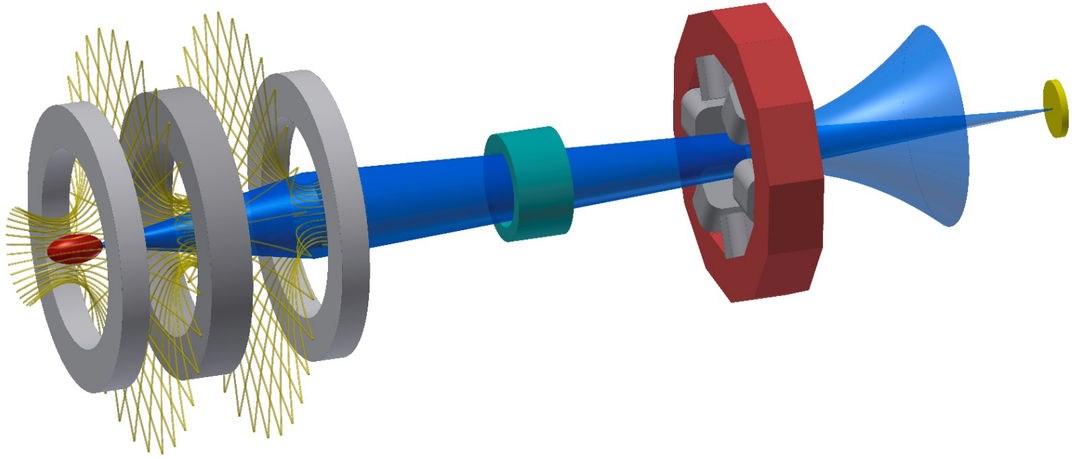


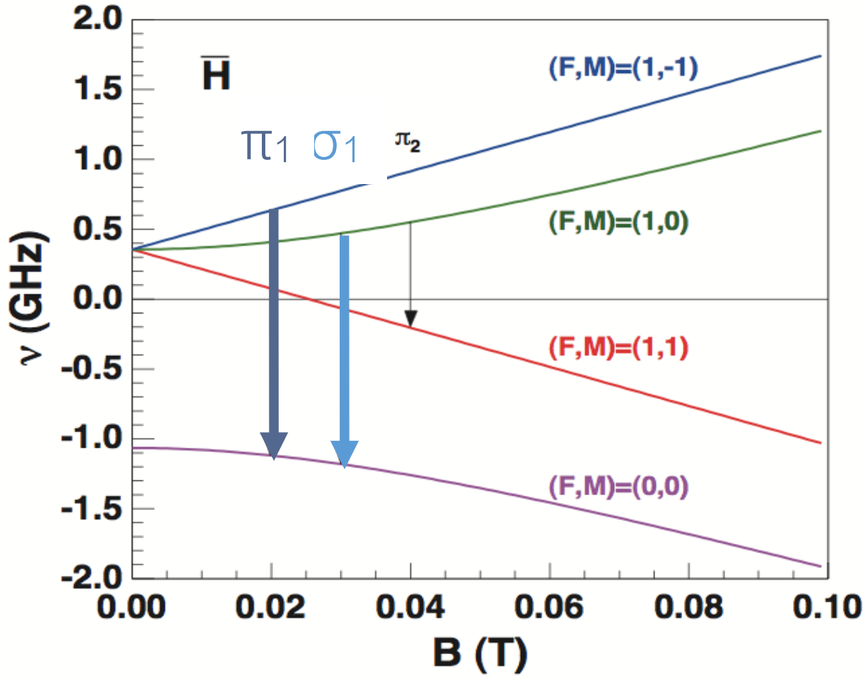


Test power supply

II. CUSP experiment for $\bar{\mathrm{H}}$ spectroscopy

In-beam HFS spectroscopy





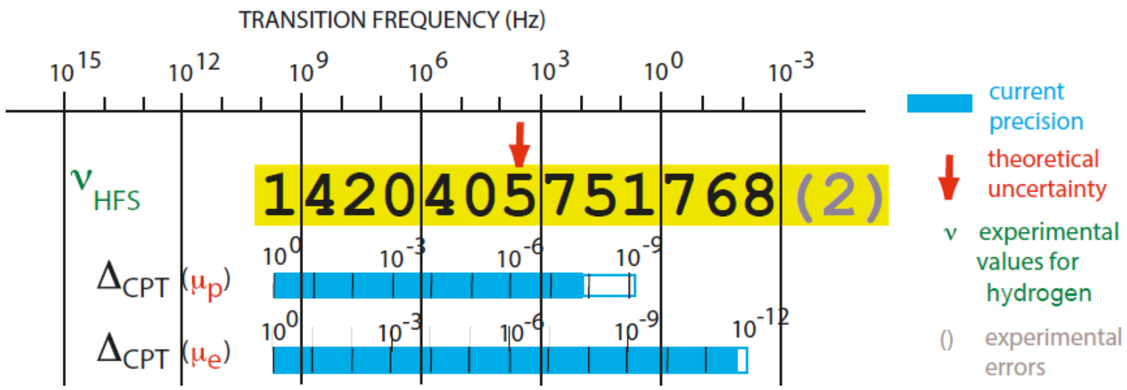
- Goals
  - In-beam measurement of ground-state hyperfine structure of antihydrogen to ppm-level and below
  - Produce polarized slow (<100 K) Hbar beam

- 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/$\overline{\mathrm{H}}$

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

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



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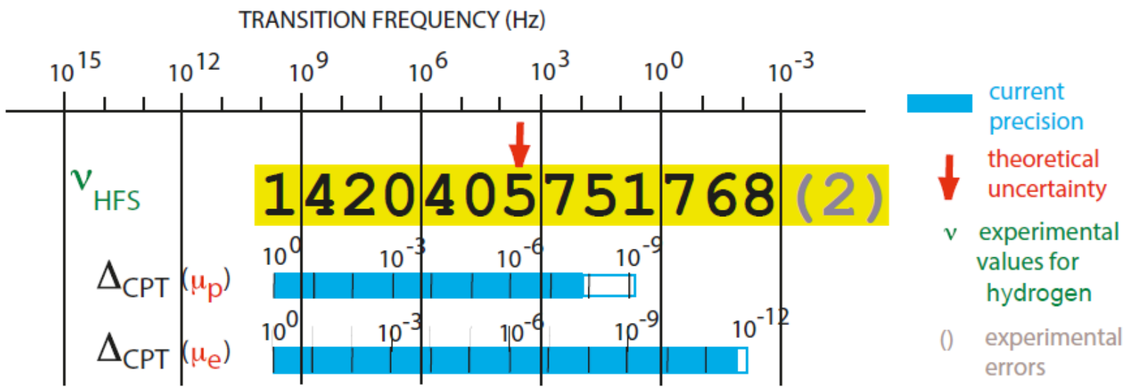


Hydrogen HFS and QED: finite size effects

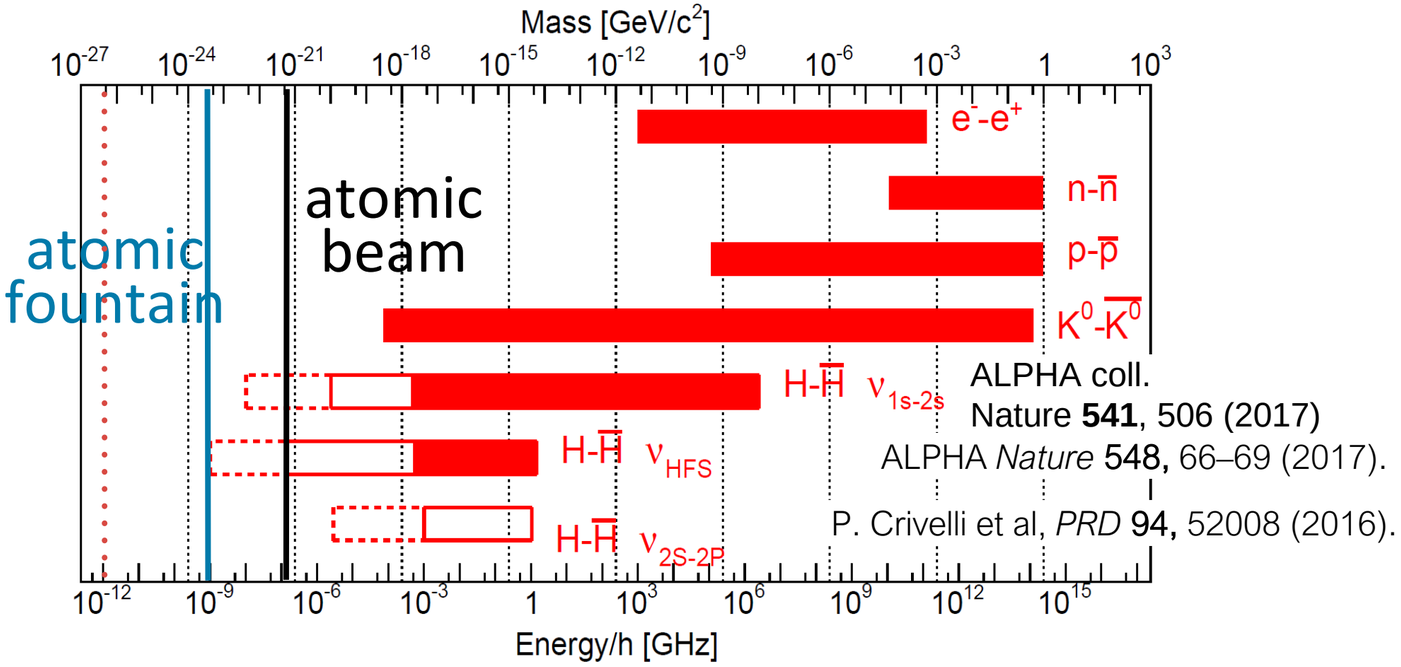
H: deviation from Fermi contact term:	–32.77(1) ppm
finite electric & magnetic radius (Zemach corrections):	–41.43(44) ppm
polarizability of p/p̄	+1.88(64) ppm
remaining deviation theory-experiment:	+0.86(78) ppm

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

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

Comparison of CPT tests

- Mass & frequency



ALPHA coll.
Nature **541**, 506 (2017)
ALPHA *Nature* **548**, 66–69 (2017).

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

Comparison of CPT tests

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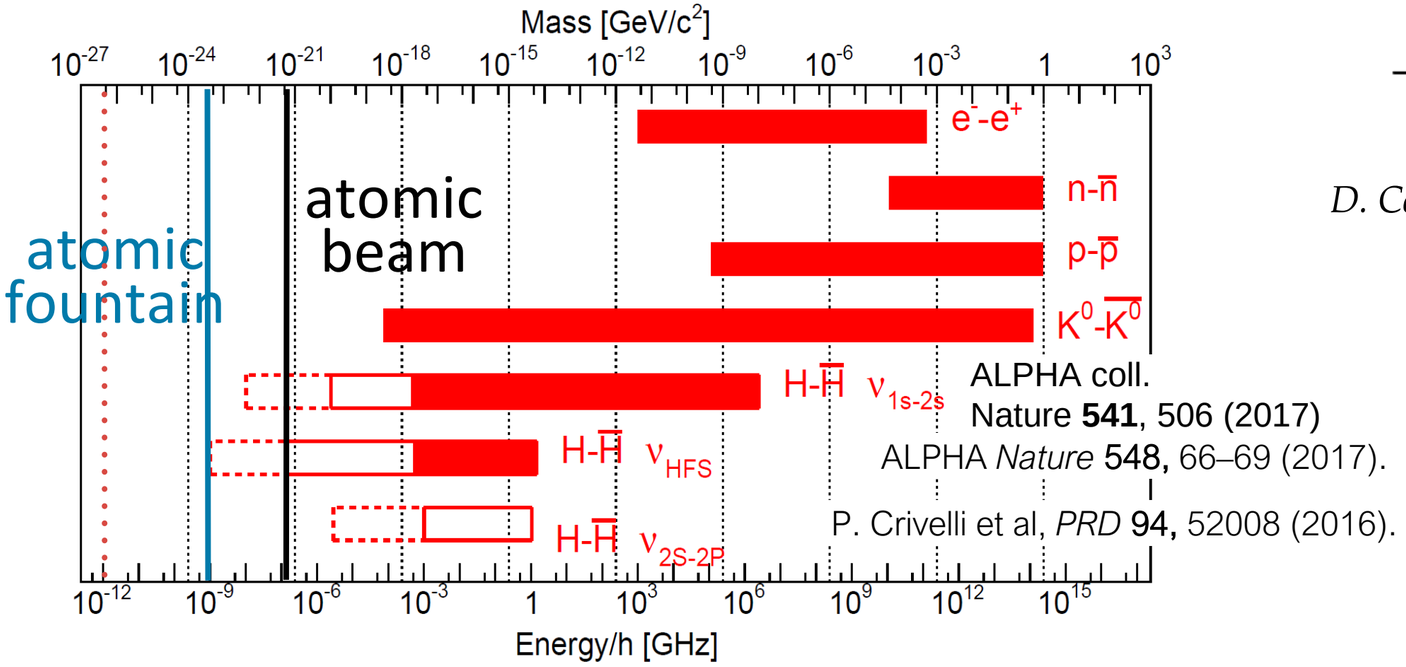

ALPHA coll. Nature **541**, 506 (2017)

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- Standard Model Extension SME

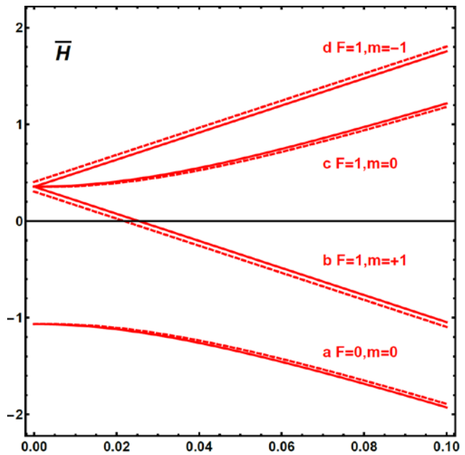
CPT & LORENTZ VIOLATION

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

LORENTZ VIOLATION

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

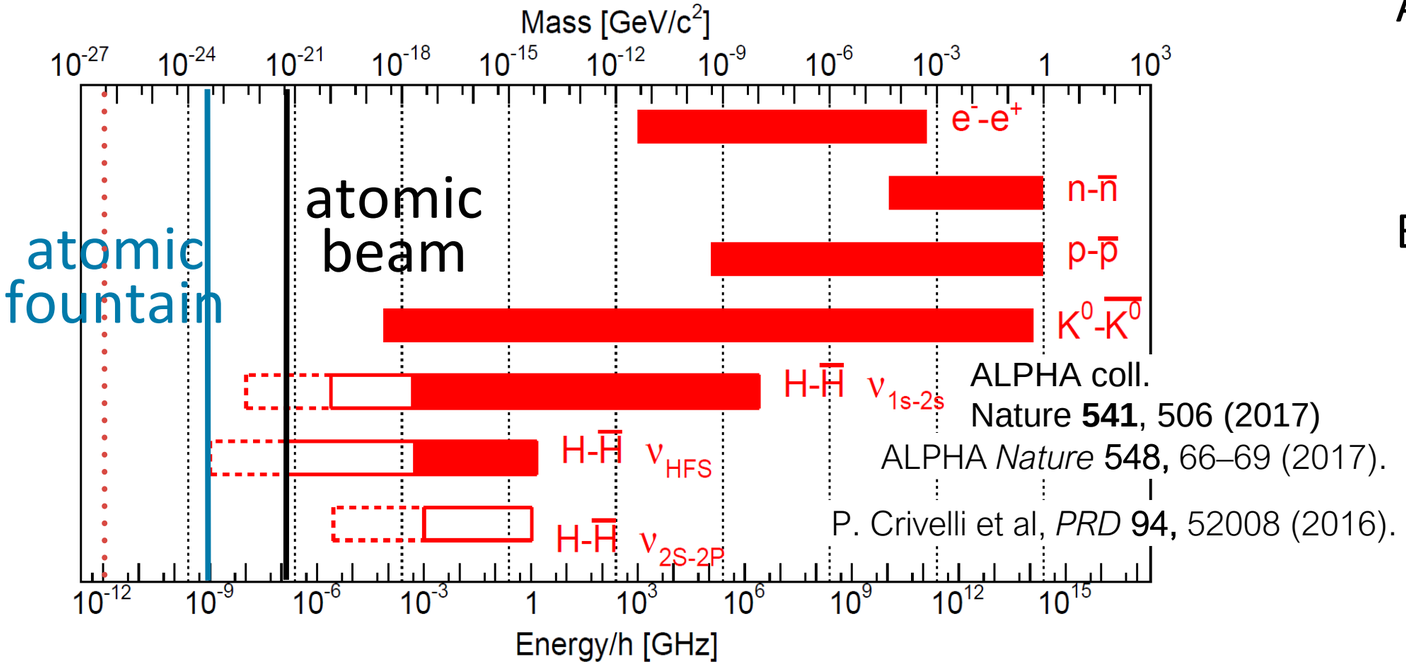
- Minimal SME: only HFS
- Non-minimal SME: also 1S-2S shows CPTV



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

Comparison of CPT tests

- Mass & frequency



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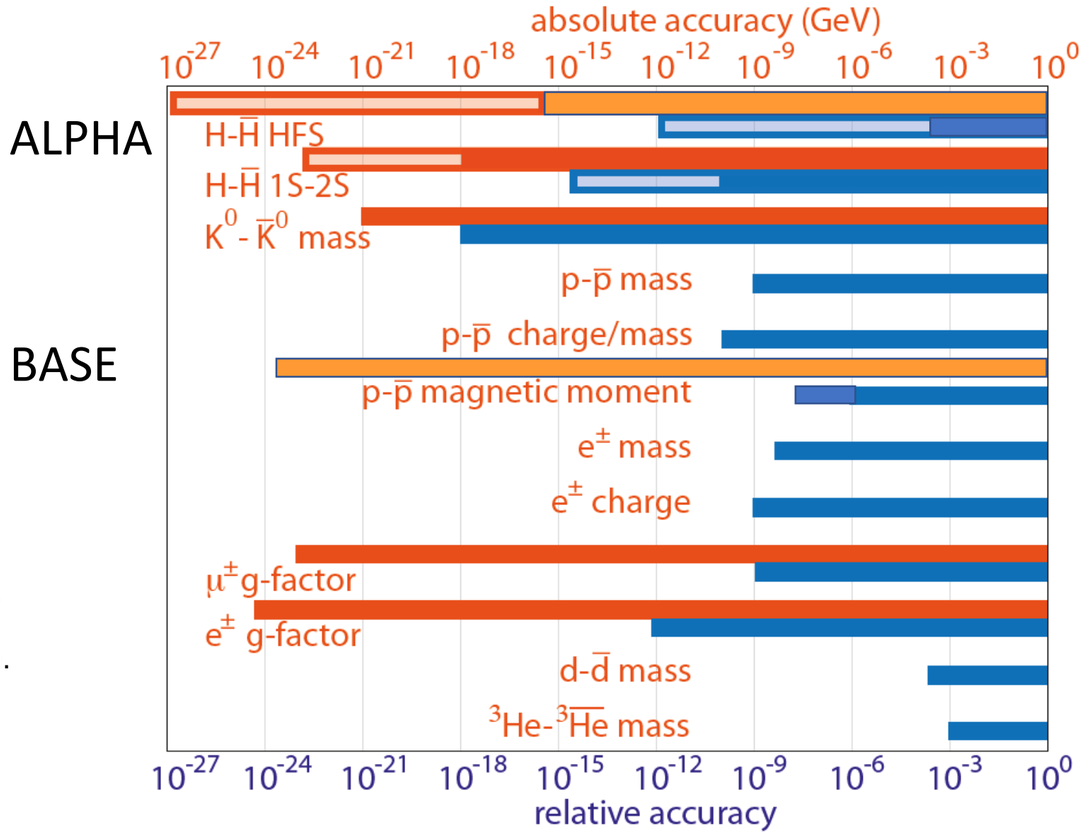
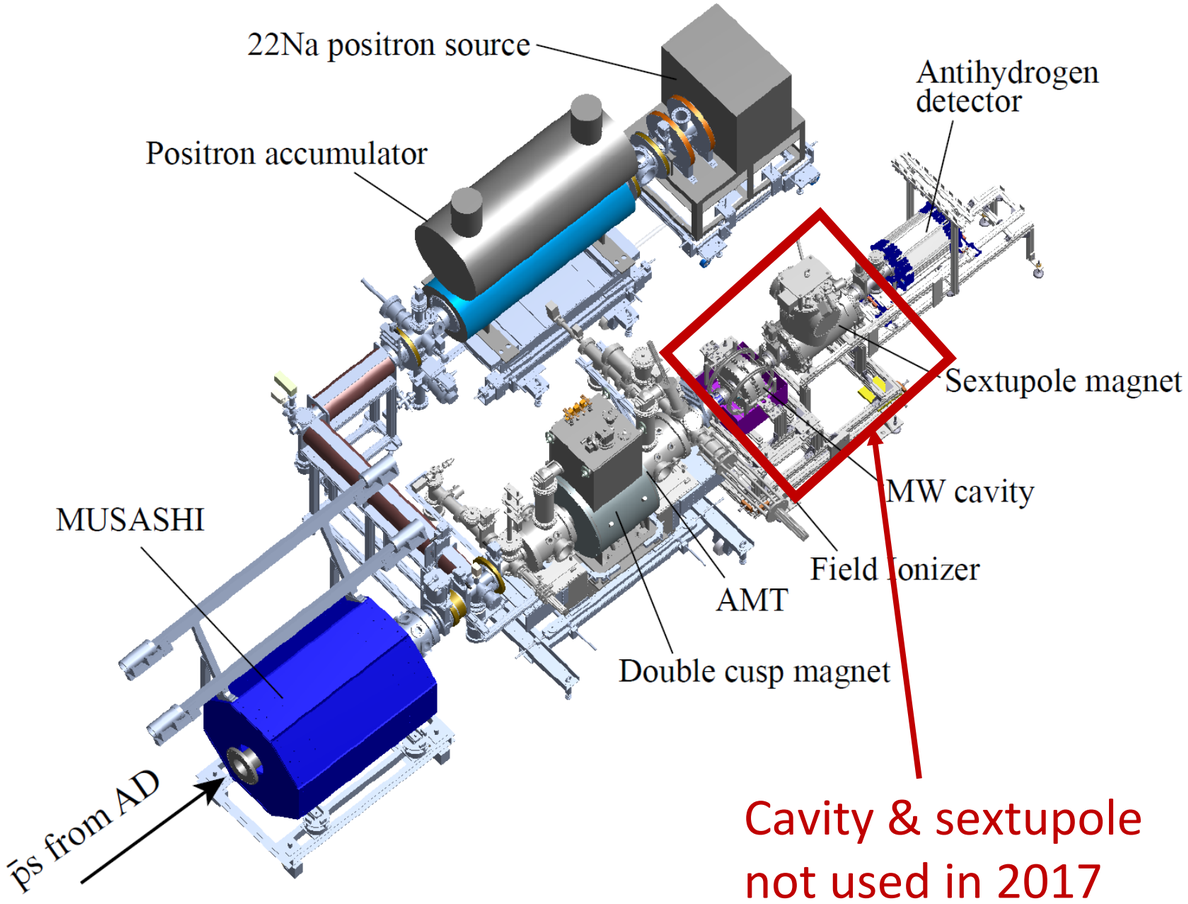
- Standard Model Extension SME

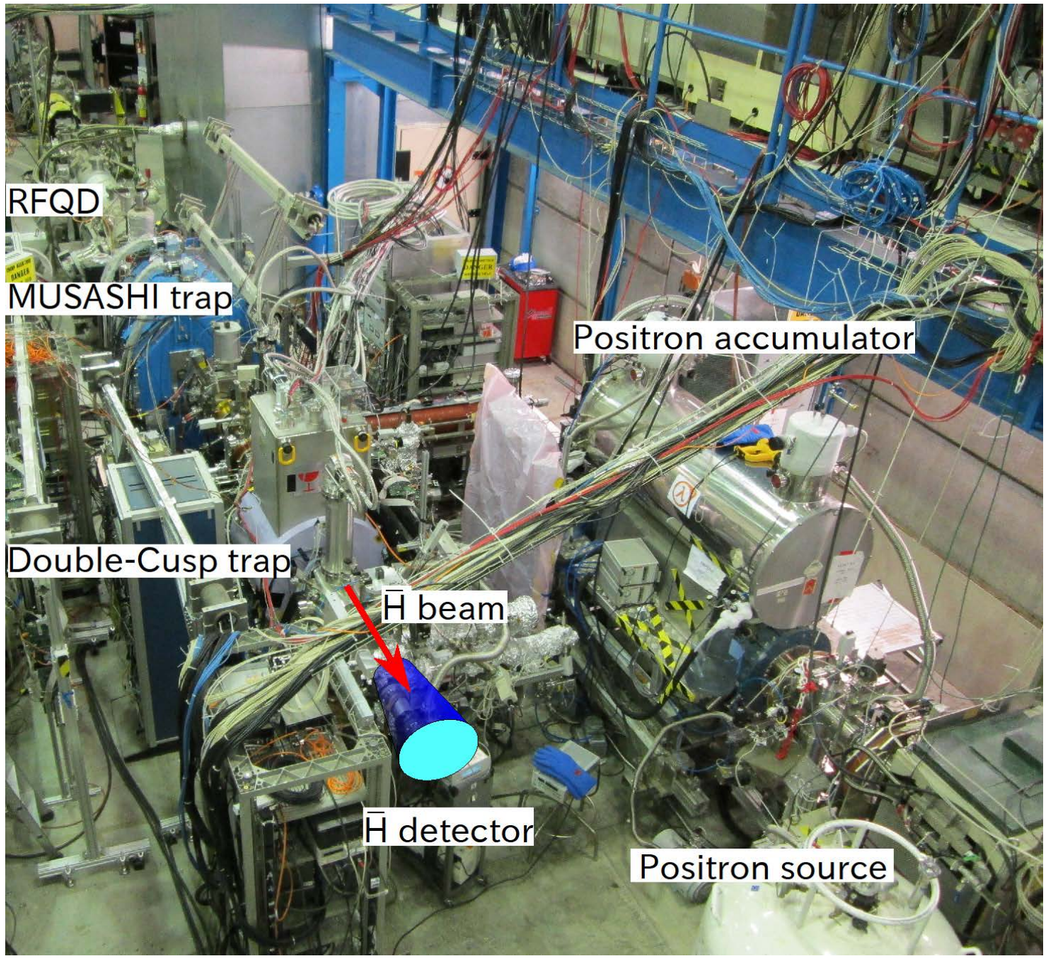


From: NuPECC Long Range Plan 2017 (M. Doser) + EW *Kostelecky & Bluhm arXiv:0801.0287*

Setup



Cavity & sextupole not used in 2017

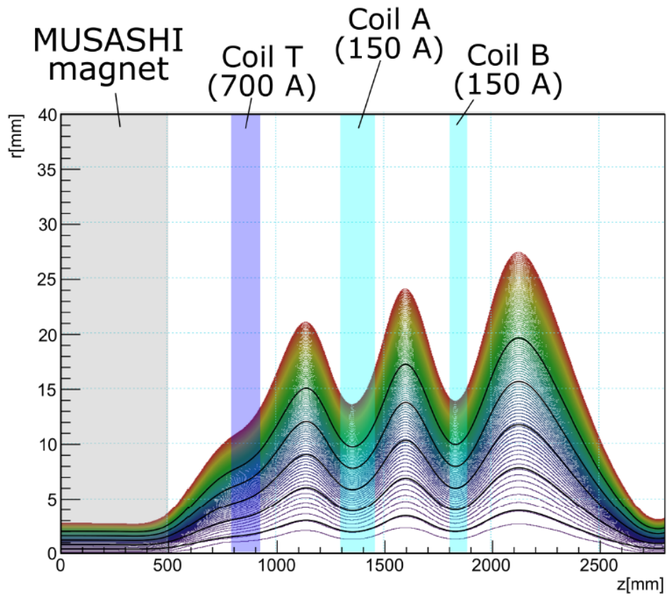


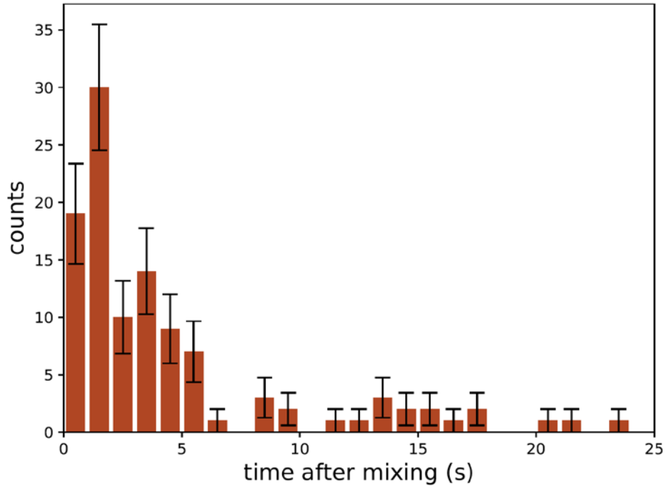
Status before 2017

- Mixing scheme: *direct injection* MUSASHI → CUSP
- $\bar{H}$ beam observed 2.7m downstream, low rate[1]
- $\bar{H}$ quantum state studied by external field ionizer FID & $\bar{H}$ detector
- Fast axial separation of $\bar{p}$ and e^+ observed: low $\bar{H}$ yield

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

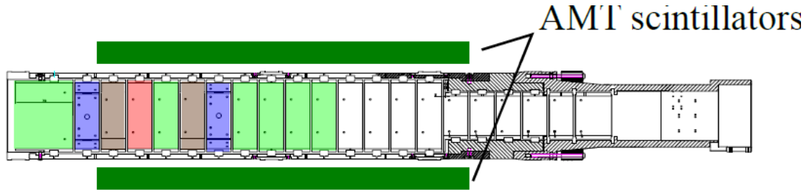
Beam trajectories for $\bar{p}$ transfer

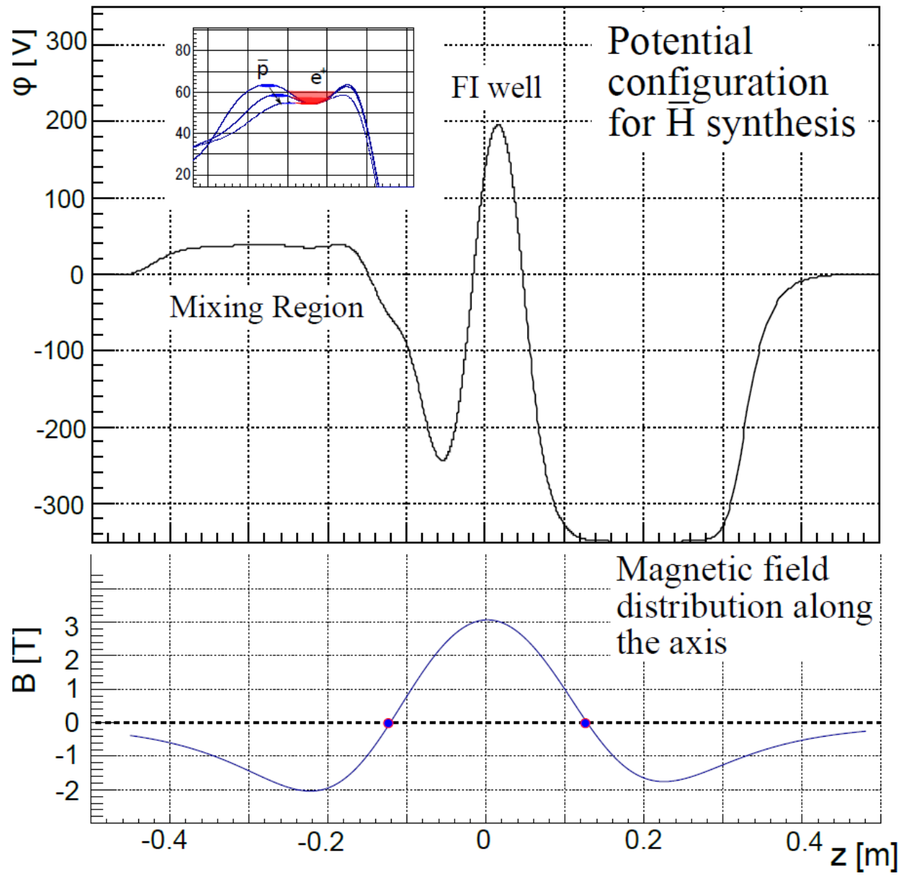




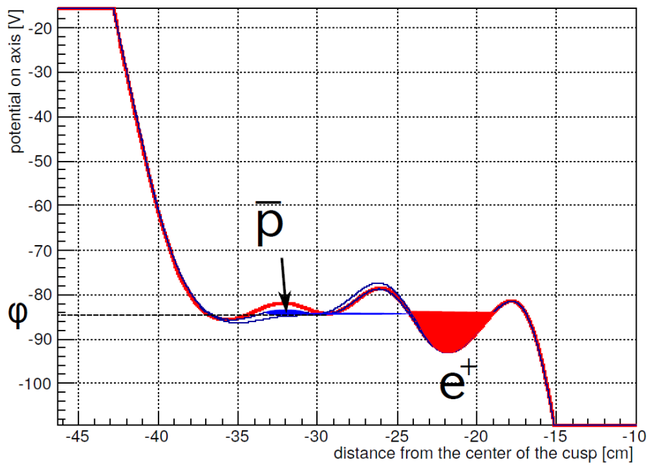
$\bar{H}$ counts (110) at the detector during 104 mixing cycles with FID in 2017

New mixing schemes 2017

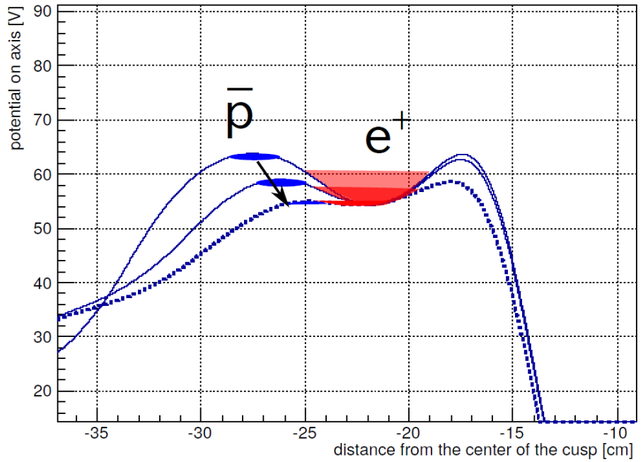




- Slow extraction scheme

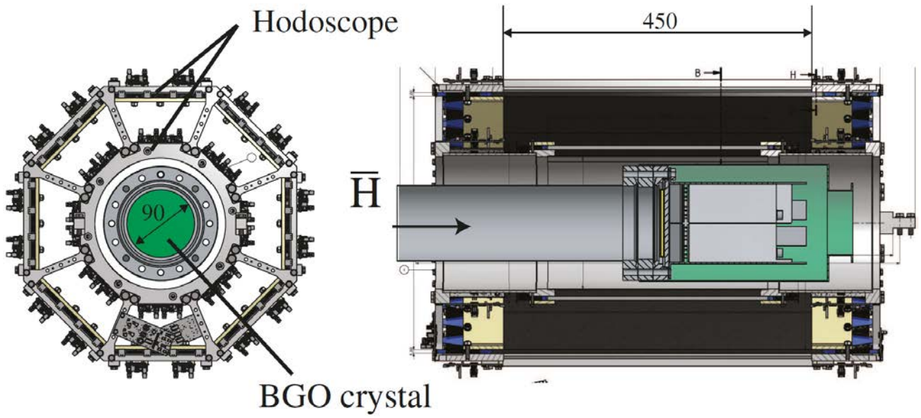


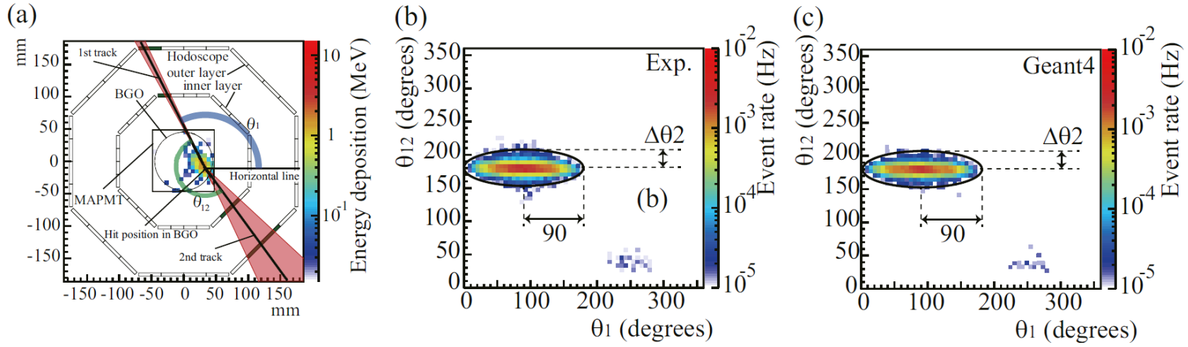
- Cross merging scheme



$\bar{H}$ detector analysis

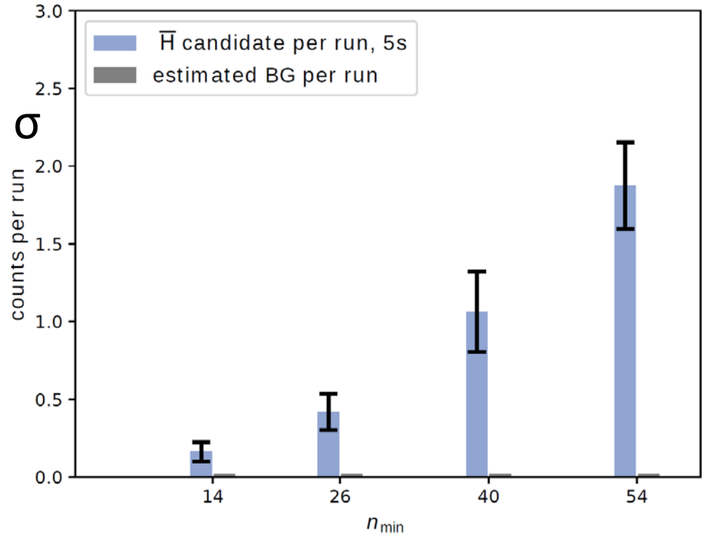
- 2D BGO & track fitting





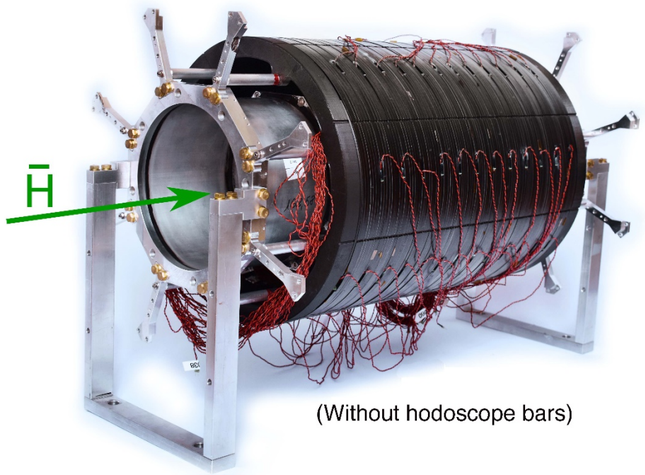
- Machine learning
  - Cosmics rejection 99,7%
  - False positive rate: 0.0039 s^{-1}
  - $\bar{p}$ efficiency ~ 80%

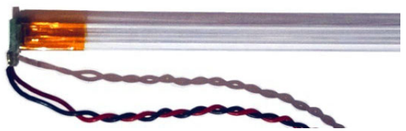
n=14 significance 4.5 σ
τ(n=14) ~ 50 μs

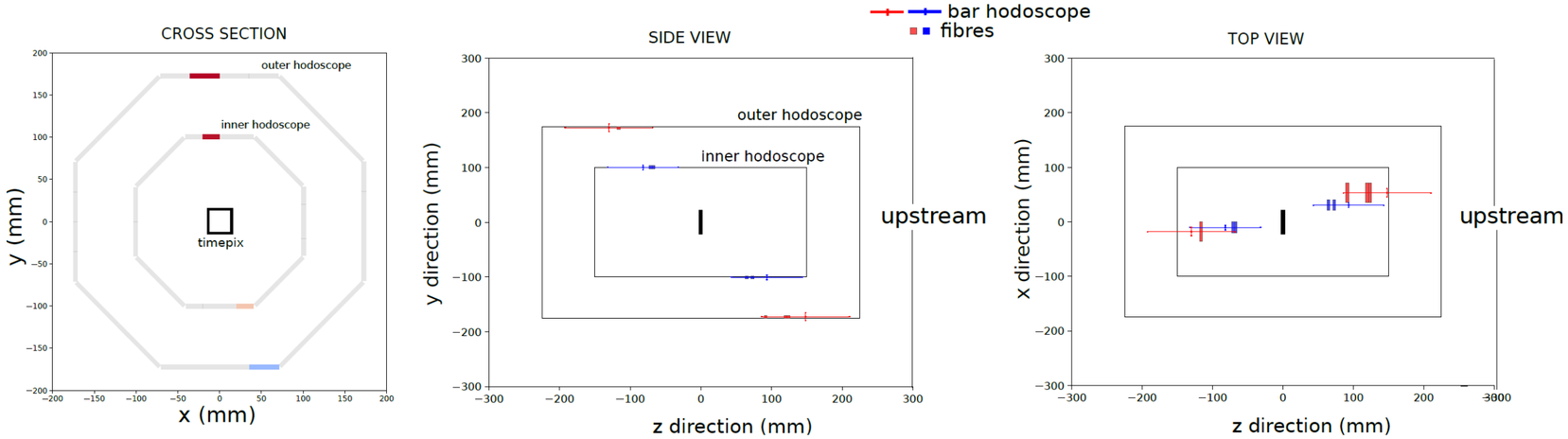


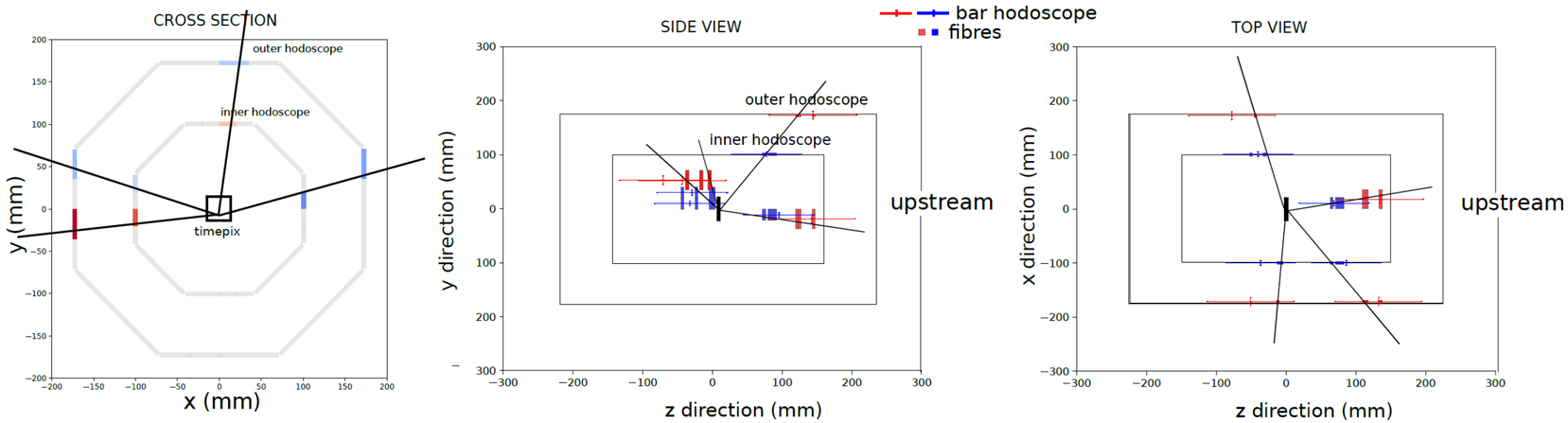
C. Malbrunot et al., Phil. Trans. A 2018, in print

Antihydrogen detector fibre upgrade









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

Beam usage 2017 and plans for 2018

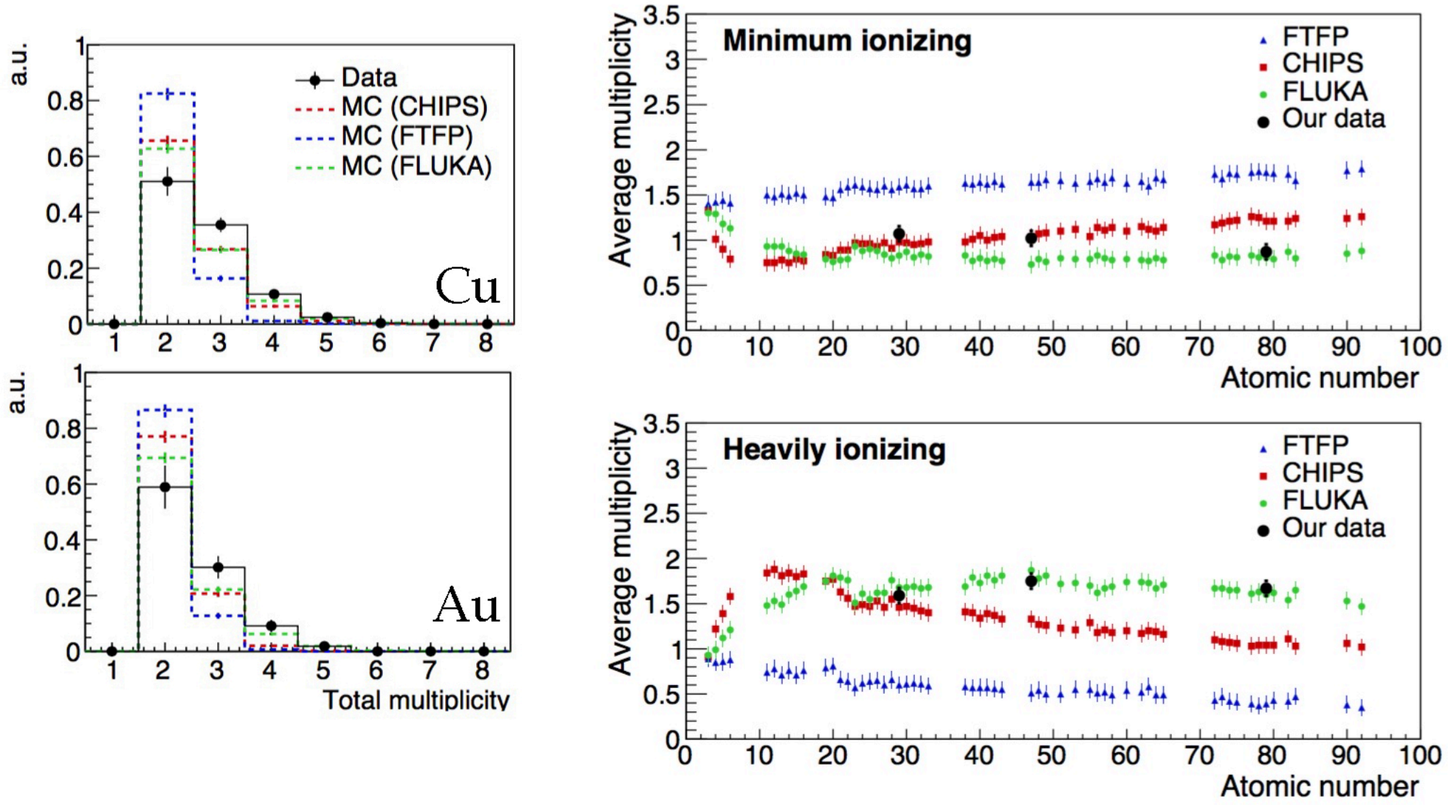
Weeks 38,39,40	$\bar{p}$ transfer MUSASHI -> CUSP
Weeks 42,43,44	Trials of new merging schemes
Weeks 46,47,48	Slow extraction scheme & Cross merging scheme
Week 50	Slow continuous extraction of $\bar{p}$ to Timepix3

- Continue optimizing new mixing schemes
- Control of positron plasma parameters (temperature, density)
- Implement 3D tracking for the antihydrogen detector
- Determine *n*-distribution for new mixing schemes and e^+ conditions
- $\bar{p}$ annihilation studies for different targets
  - 1-2 weeks at the end with 1-2 w break

III Fragmentation studies in antiproton-nucleus annihilations

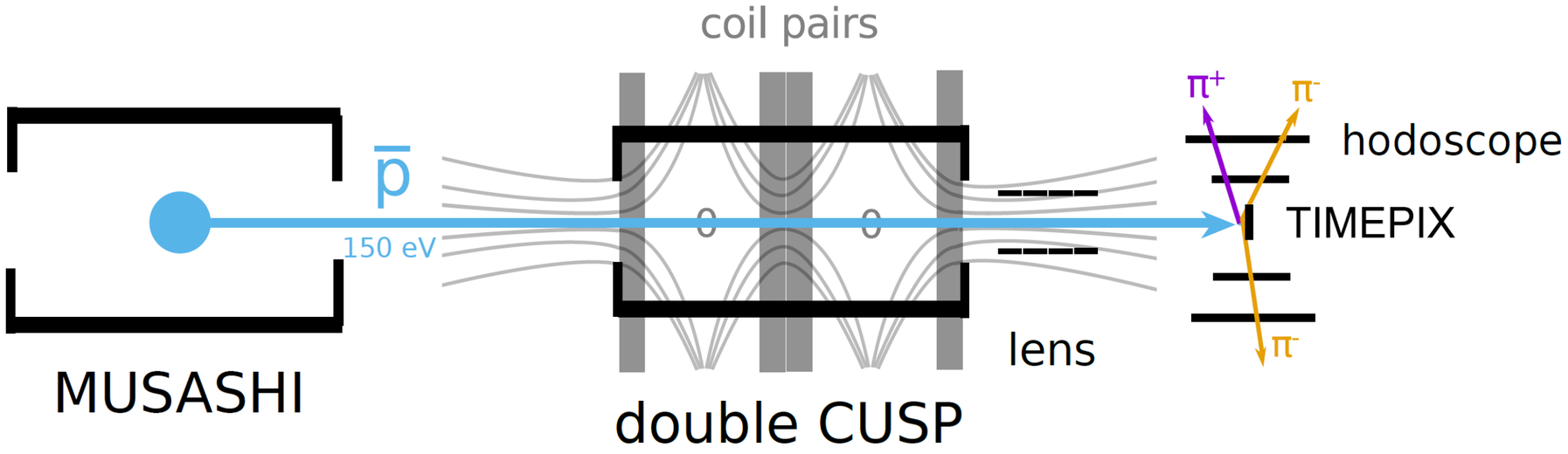
Existing studies

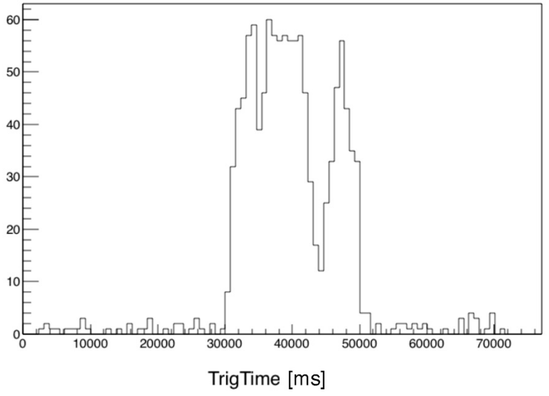
- Data from GRACE (AEgIS)
  - Emulsion
  - Low statistics
- No good agreement with Monte Carlo codes
  - GEANT4: Chips, Fritiof
  - FLUKA
- More data welcome

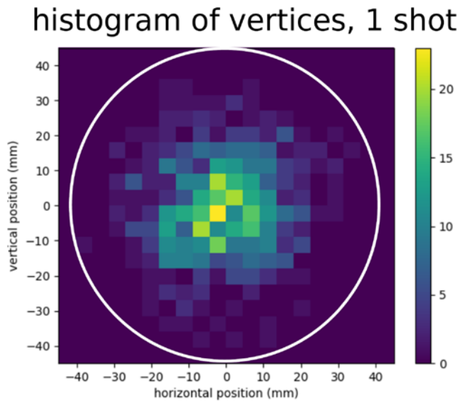


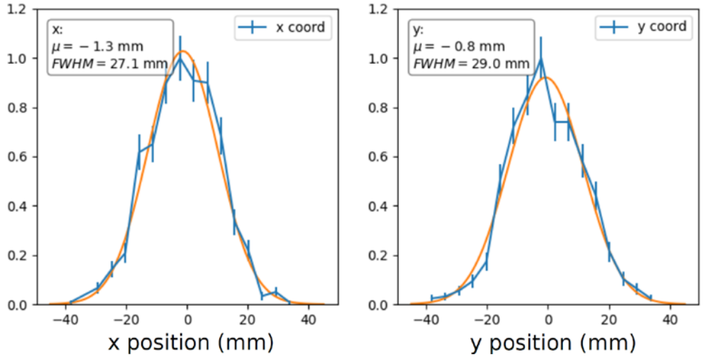
AEgIS collaboration, *Journal of Instrumentation* 12, P04021 (2017)

Slow extraction from MUSASHI



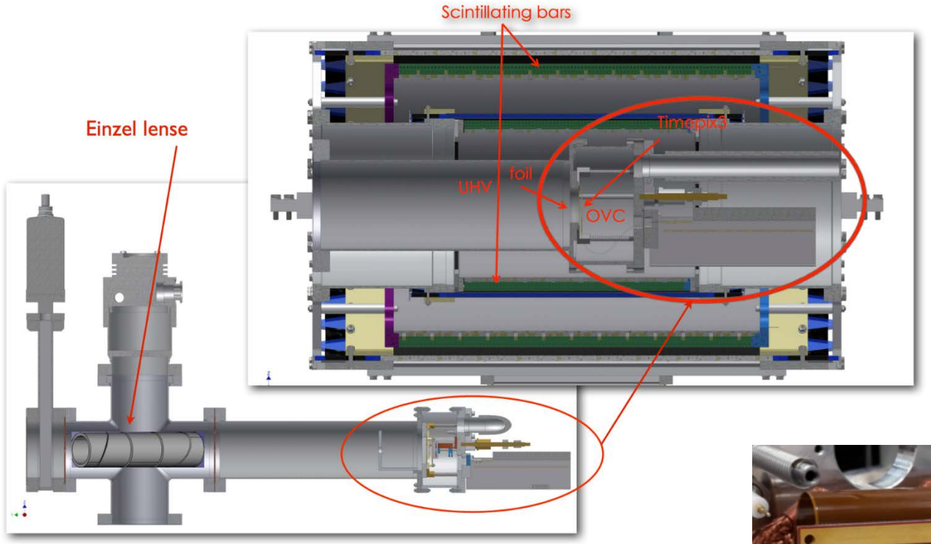


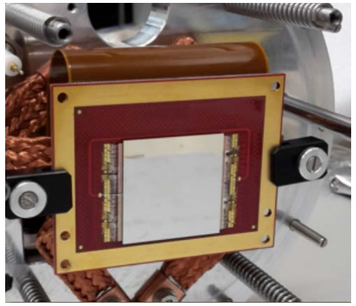




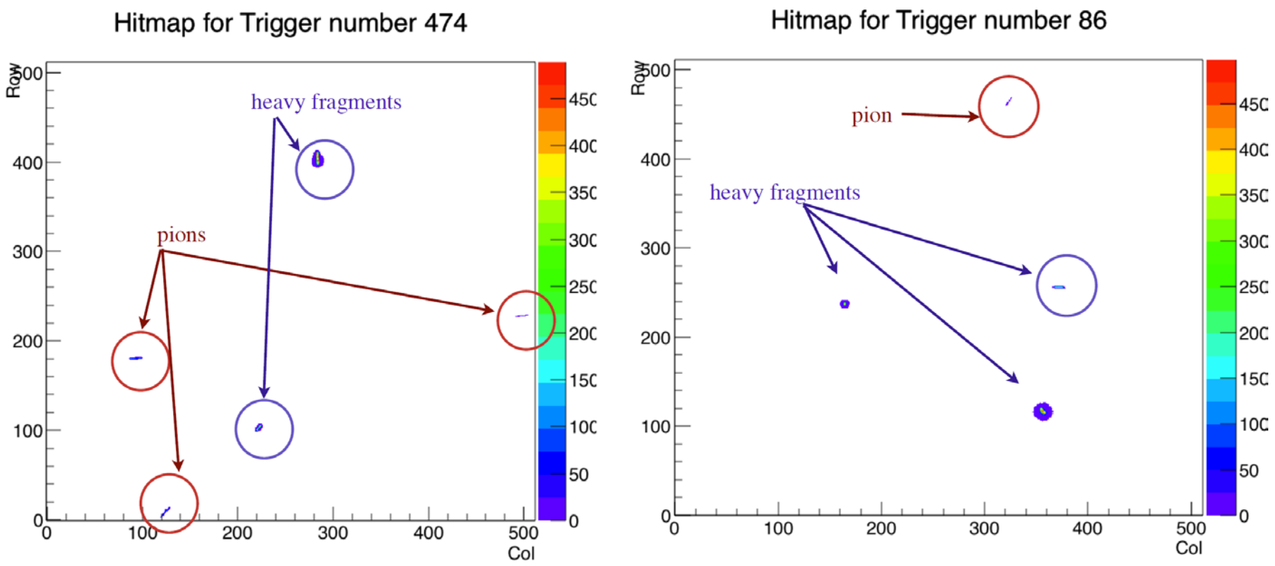
- Energy 150 eV
- 240 $\bar{p}$/4 cm^2 / 2 AD shots
- 100 extractions / shift
- Duration 20 s

First results





Timepix3 hits in coincidence with hodoscope tracks



- 90‘000 annihilation events in C taken during ~4 shifts, analysis ongoing
- Plans for 2018: measure several different target foils

IV Experiments with a polarized hydrogen beam

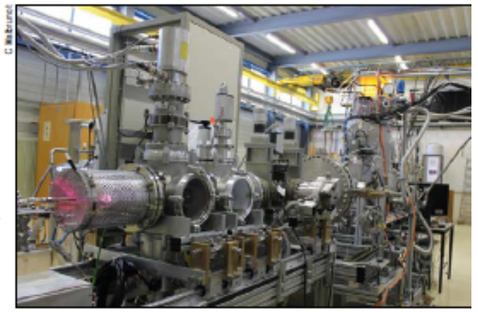
Goal

- Validate the spectroscopy technique for $\bar{H}$ using H-beam
  - Source of polarized 50 K H-beam
  - Parts of $\bar{H}$ apparatus used, setup located at CERN cryolab, now Bat. 275
- Perform measurements to determine SME coefficients
  - Permantent sextupoles
  - New optics for alternating measurements of σ and π transitions

CERN Courier December 2017

Hyperfine structure: from hydrogen to antihydrogen

Earlier this year, the ASACUSA experiment at CERN's Antiproton Decelerator published the most precise in-beam measurement of the hydrogen ground-state hyperfine splitting, and is now preparing for new measurements.



The ASACUSA experimental set-up, with the source of hydrogen visible by its characteristic pink glow.

Since the discovery of the positron in 1932 and the antiproton in 1955, physicists have striven to confront the properties of leptonic and baryonic matter and antimatter. A major advance in the story took place in 1995 when the first antihydrogen atoms were observed at CERN's LEAR facility. Then, in 2002, the ATHENA and ATRAP collaborations produced cold (trappable) antihydrogen at CERN's Antiproton Decelerator (AD), paving the way to the first measurement of antihydrogen's atomic transitions. An intense research programme at the AD has followed to compare the atomic states of antimatter with the most well-known atomic transitions in matter.

The physical properties of antimatter particles are tightly constrained within the Standard Model of particle physics (SM). For all local Lorentz-invariant quantum-field theories of point-like particles like the SM, the combination of the discrete symmetries charge-conjugation, parity and time-reversal (CPT) is conserved. An implication of the CPT theorem is that the properties of matter and antimatter are equal in absolute value. In this respect the lack of observation of primordial antimatter in the universe is tantalising, hinting that the universe has a preference for matter over antimatter despite their perfect symmetry on the microscopic scale as imposed by the SM. Although violations of CP symmetry, from which an imbalance in matter and antimatter can arise, have been observed in several systems, the effect is many orders of magnitude too small to account for the observed cosmological mismatch.

The hydrogen atom has been a source of profound theoretical developments.

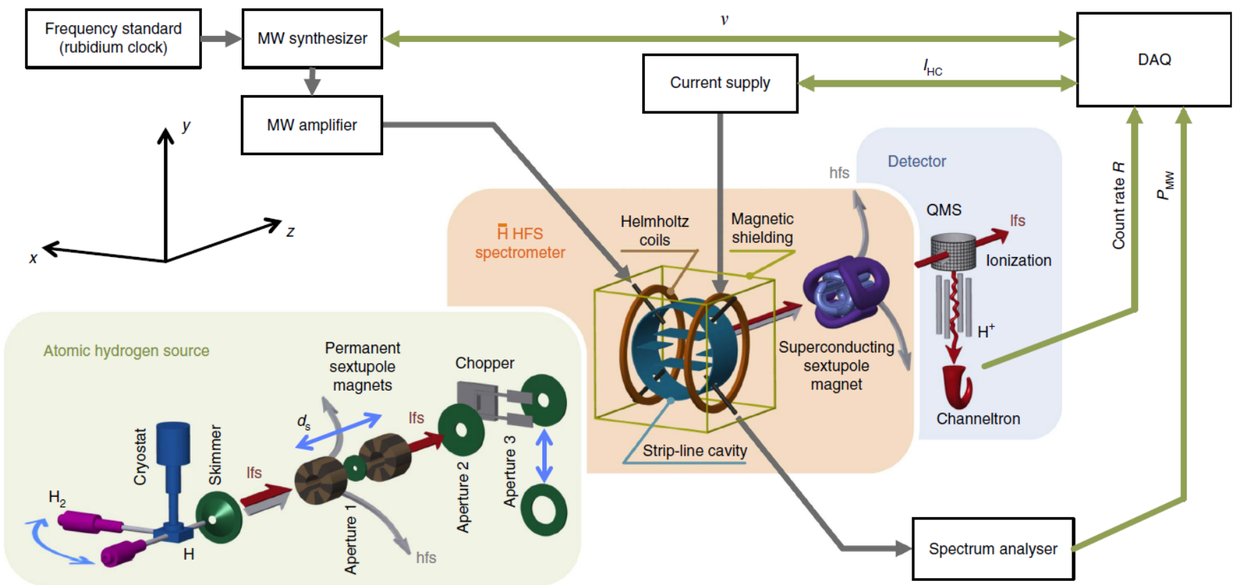
In the quest for a quantitative explanation to the baryon asymmetry in the universe, one could question the validity of our formulation of the laws of physics in terms of quantum-field theory. This is additionally motivated by the notable absence of the gravitational force in the SM and would suggest that CPT symmetry (or Lorentz invariance) need not be conserved. A framework called Standard Model Extension (SME), an effective field theory that contains the SM and general relativity but also possible CPT and Lorentz violating terms, allows researchers to interpret the results of experiments designed to search for such effects.

Any measurement with antihydrogen atoms constitutes a model-independent test of CPT invariance. Given the precision at which they have been measured in hydrogen, two atomic transitions in antihydrogen are of particular interest: the 1S–2S transition and the ground-state hyperfine splitting (which corresponds to the 21 cm microwave-emission line between parallel and antiparallel antiproton and positron spins). These were determined over the past few decades in hydrogen with an absolute (relative) precision of 10 Hz (4×10^{-15}) and 2 mHz (1.4×10^{-12}), respectively. Reaching similar precision in antihydrogen, hydrogen's CPT conjugate would provide one of the most sensitive CPT tests in what was until recently a yet unprobed atomic domain. But this is a daunting challenge.

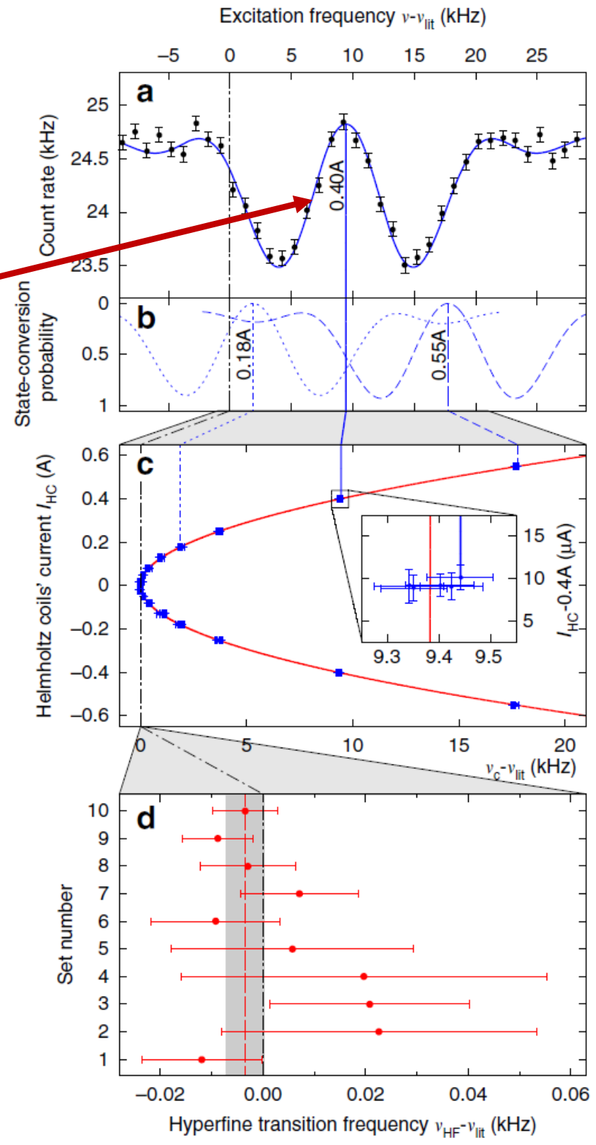
Status and prospects

Measurements of the hyperfine splitting of hydrogen reached their apogee in the 1970s. It is only recently that interest in such measurements has been revived, motivated by the possibility to further ▷

σ-transition in H using $\bar{\mathrm{H}}$ 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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In-beam measurement of the hydrogen hyperfine splitting and prospects for antihydrogen spectroscopy

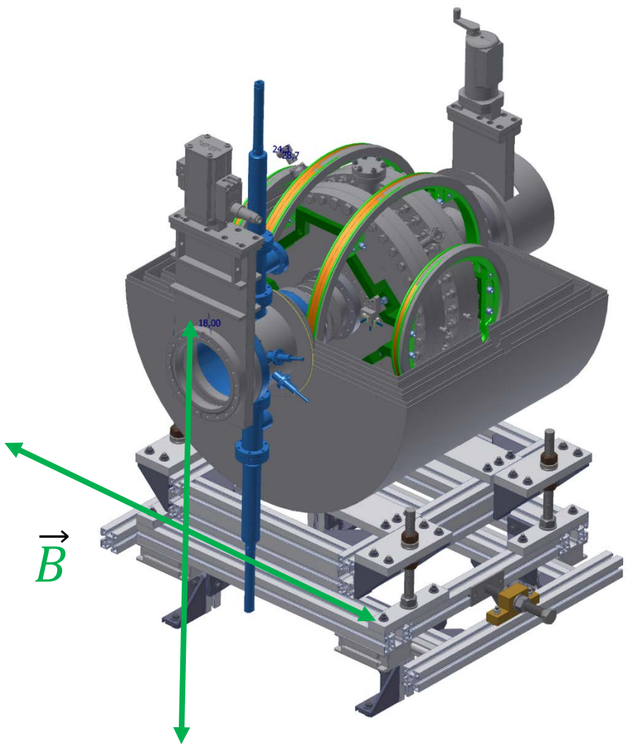
M. Diermaier[1], C.B. Jepsen[2,†], B. Kolbinger[1], C. Malbrunot[1,2], O. Massiczek[1], C. Sauerzopf[1], M.C. Simon[1], J. Zmeskal[1] & E. Widmann[1]

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

Non-minimal SME & H-beam

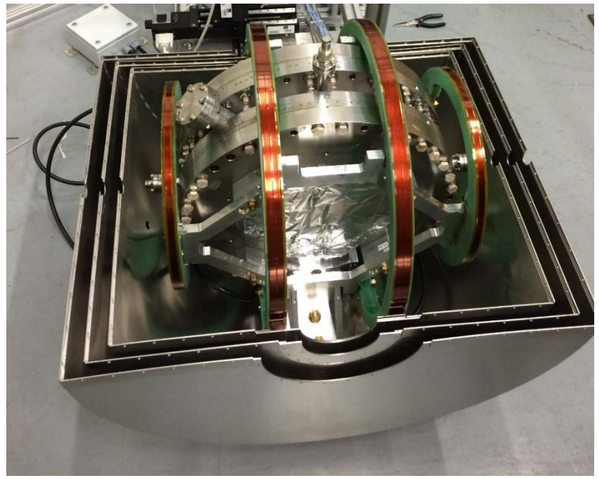
- Shift only for π-transition ($\Delta m_F \neq 0$)

$$2\pi\delta\nu = -\frac{\Delta m_F}{2\sqrt{3\pi}}\sum_{q=0}^{2}(\alpha m_{\mathrm{r}})^{2q}(1+4\delta_{q2}) \times \sum_{w}[g_{w(2q)10}^{\mathrm{NR}(0B)} - H_{w(2q)10}^{\mathrm{NR}(0B)} + 2g_{w(2q)10}^{\mathrm{NR}(1B)} - 2H_{w(2q)10}^{\mathrm{NR}(1B)}].$$



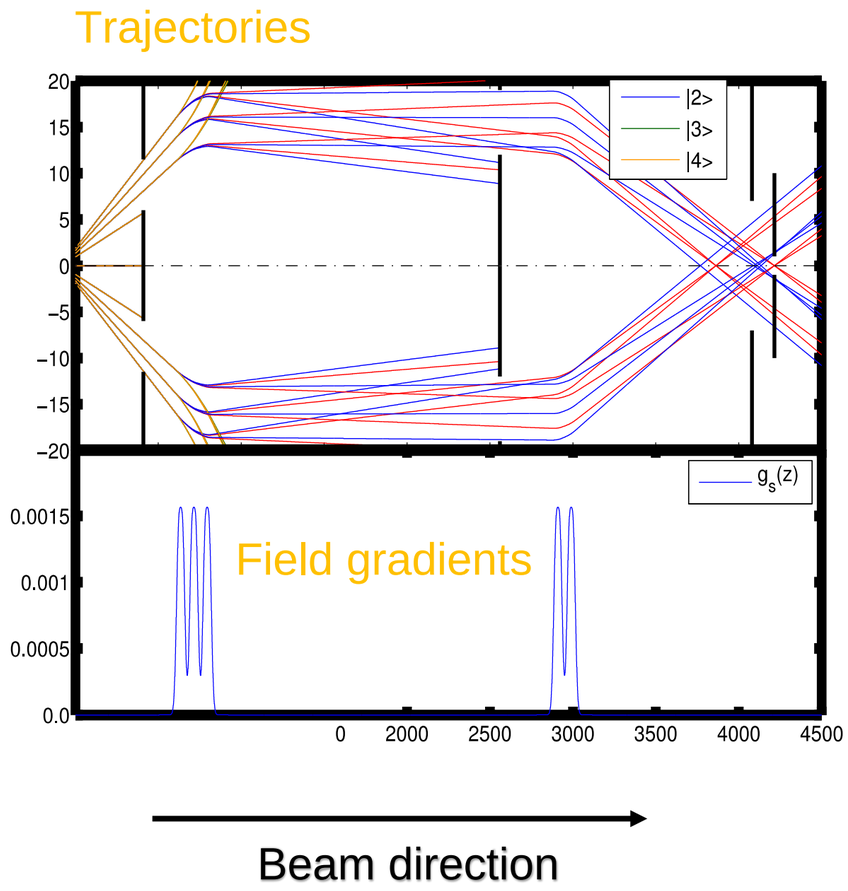
- B direction dependence

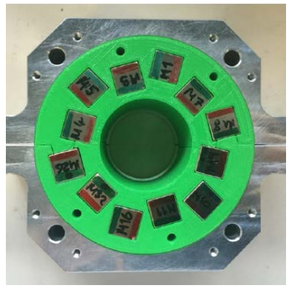
$$\Delta(2\pi\nu_\pi) \equiv 2\pi\nu_\pi(\boldsymbol{B}) - 2\pi\nu_\pi(-\boldsymbol{B}) = -\frac{\cos\vartheta}{\sqrt{3\pi}}\sum_{q=0}^{2}(\alpha m_{\mathrm{r}})^{2q}(1+4\delta_{q2})\sum_{w}[g_{w(2q)10}^{\mathrm{NR,Sun}(0B)} - H_{w(2q)10}^{\mathrm{NR,Sun}(0B)} + 2g_{w(2q)10}^{\mathrm{NR,Sun}(1B)} - 2H_{w(2q)10}^{\mathrm{NR,Sun}(1B)}]$$

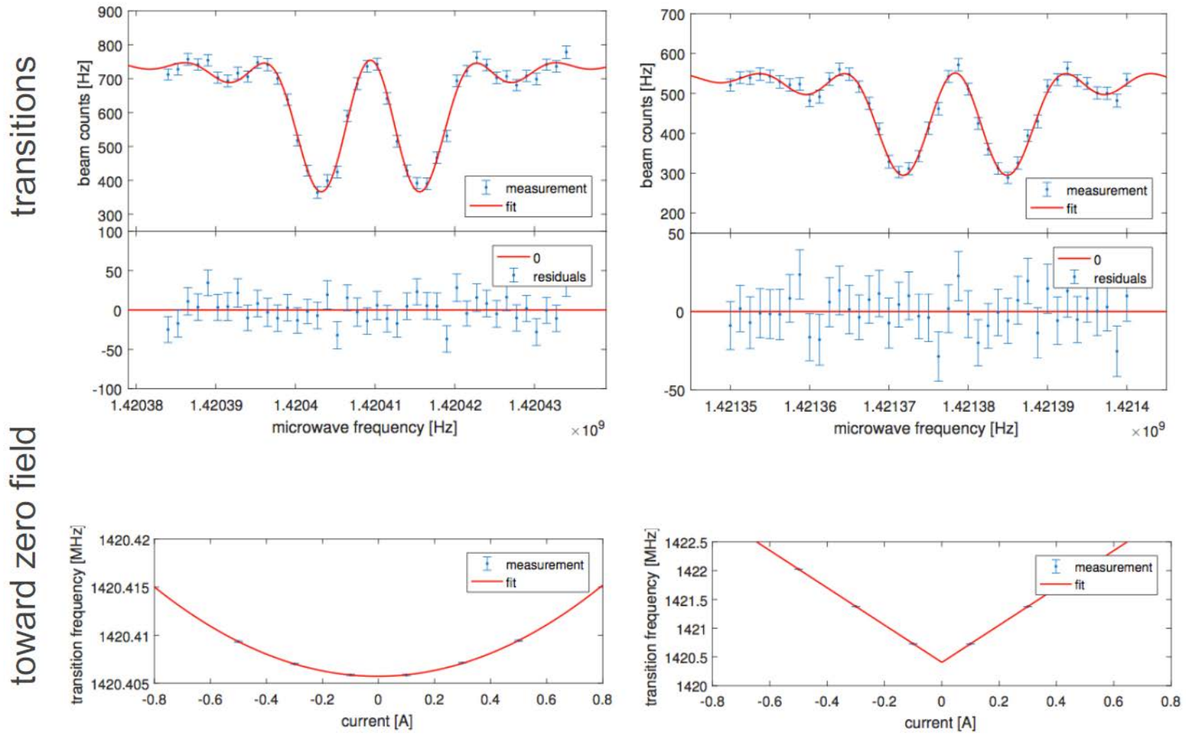


Kostelecký, V. A., & Vargas, A. J. *PRD*, *92*, 056002 (2015).

σ and π transitions in same setup condition



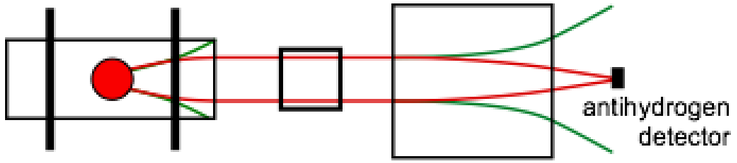


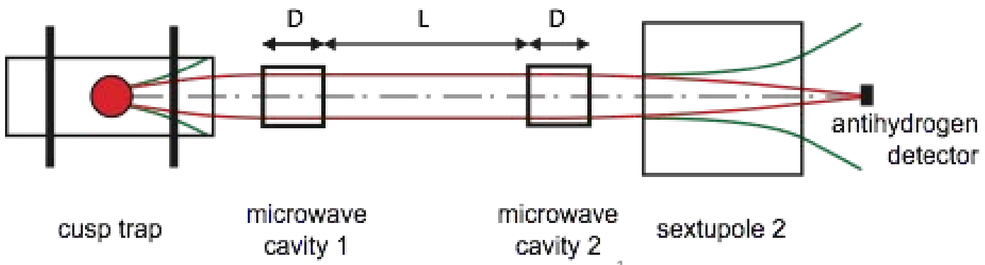


Method	$\nu_0 \pm \delta\nu$ (Hz)	$\delta\nu/\nu_{\rm lit}$ (pbb)	$\nu_0 - \nu_{\rm lit}$ (Hz)
σ-extrapolation, eq. (5)	1 420 405 767 ± 15	10	+15
π_1-extrapolation, eq. (6)	1 420 405 760 ± 34	24	+ 8
weighted mean of above	1 420 405 766 ± 14	10	+14
σ-π-pairs, eq. (7)	1 420 405 753 ± 8	6	+ 1

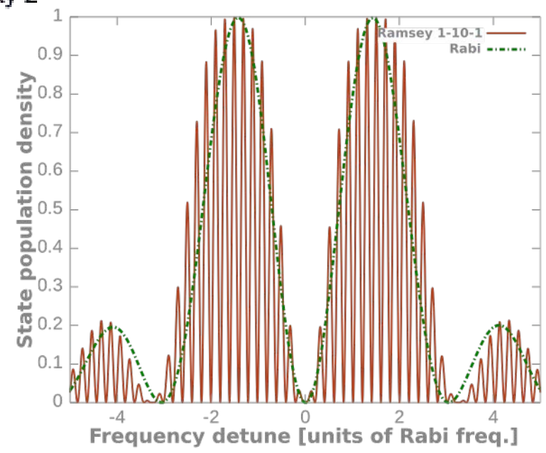
Ramsey method

- Reduce line width by D/L

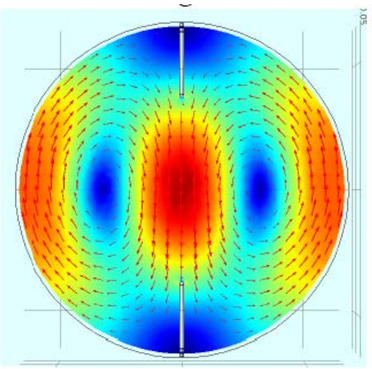




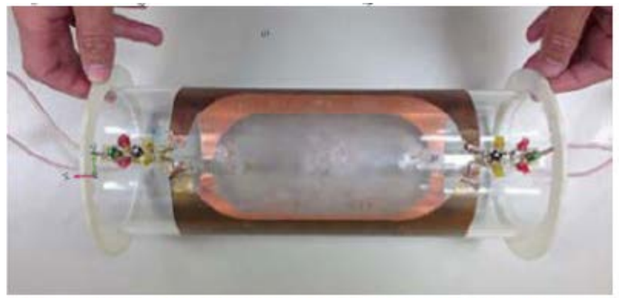
- Strip-line cavity line shape not ideal
  - D = 10 cm L = 1 m



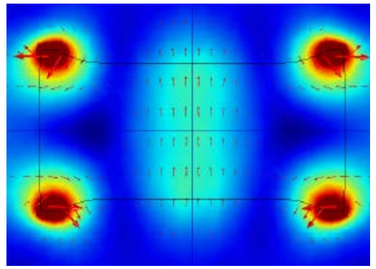
- Other microwave generation methods under study
  - TM_{110} cylindrical cavity
  - B_{osc} constant in z



  - Current-driven plates

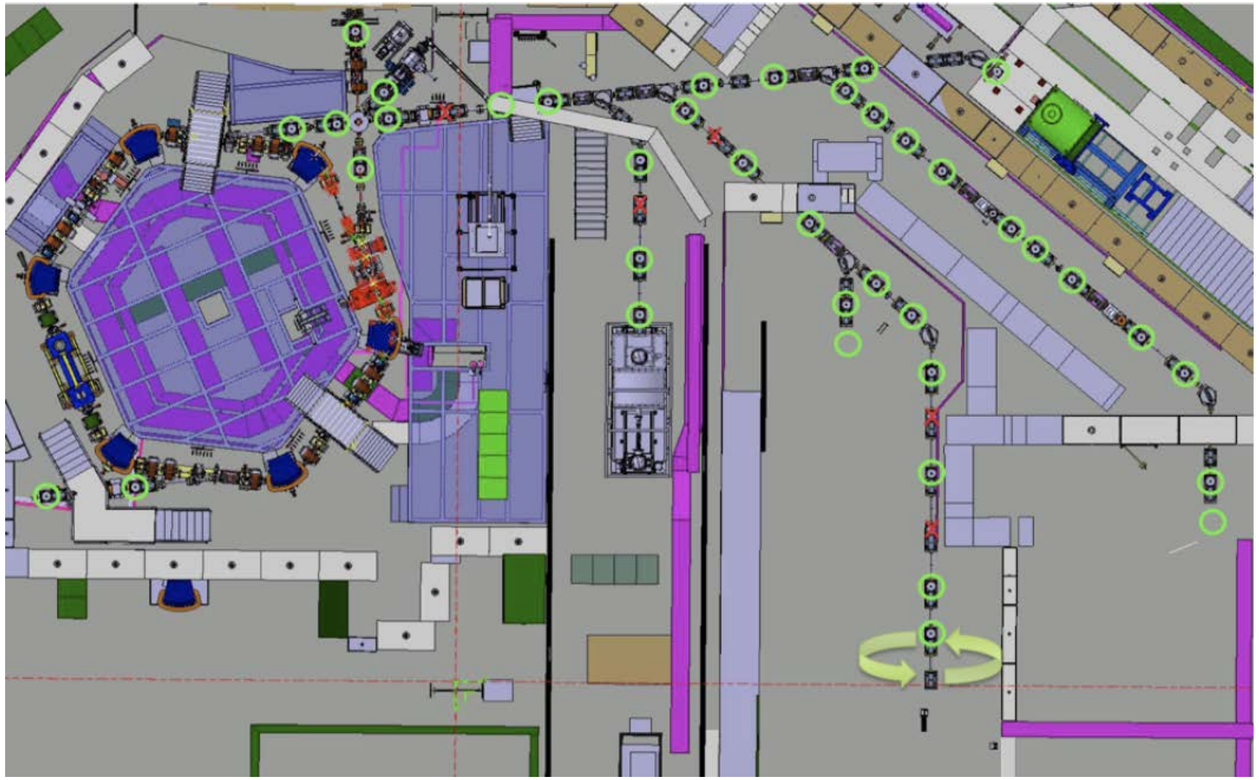


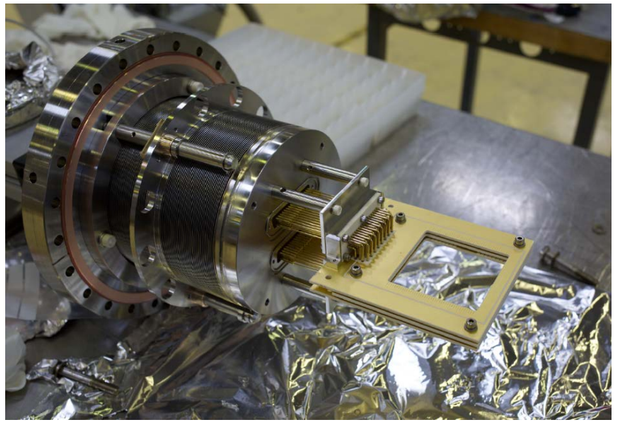
Magn Reson Med. 2015 November ; 74(5): 1482–1491

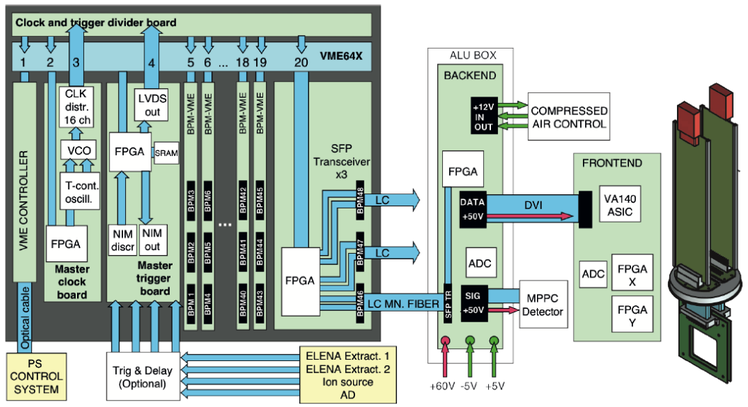


V. ASACUSA hardware contribution to ELENA

Beam profile monitors







- 42 beam profile monitors under construction
- 26 translater stages at CERN, 16 under repair
- 12 electrode sets at CERN, 30 more in production

- 3 operational and tested
- Readout systen being developed
- 15% of cost not covered

Acknowledgements

- AD team for providing antiproton beam
- BE-RF group for RFQD troubleshooting
- Funding sources

Spares

Calculated two-photon transition frequency
(n,l)=(36,34)→(34,32)

Non-relativistic energy	1 522 150 208.13 MHz
$m\alpha^4$ order corrections	-50320.64
$m\alpha^5$ order corrections	7070.28
$m\alpha^6$ order corrections	113.11
$m\alpha^7$ order corrections	-10.46(20)
$m\alpha^8$ order corrections	-0.12(12)
Transition frequency	1 522 107 060.3(2)
Uncertainty from alpha charge radius	+/-0.007
Uncertainty from antiproton charge radius	< 0.0007

Korobov, Hilico, Karr, *PRL* 112, 103003 (2014).
Korobov, Hilico, Karr, PRA 89, 032511 (2014).
Korobov, Hilico, Karr, *PRA* 87, 062506 (2013).