Perspectives for a Ground State Hyperfine Spectroscopy of ANTIHYDROGEN

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ASACUSA Collaboration

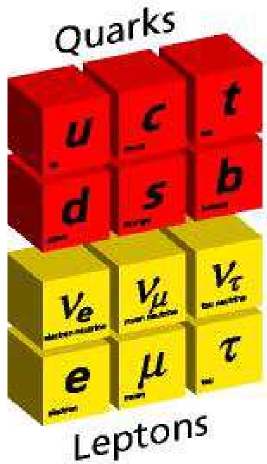
What Next – Fisica Fondamentale
GGI Arcetri-Firenze 4-6 May 2015

Antihydrogen

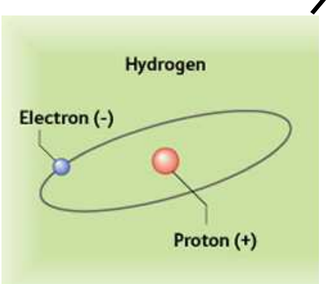
Antihydrogen is the bound state of an antiproton and a positron

Matter

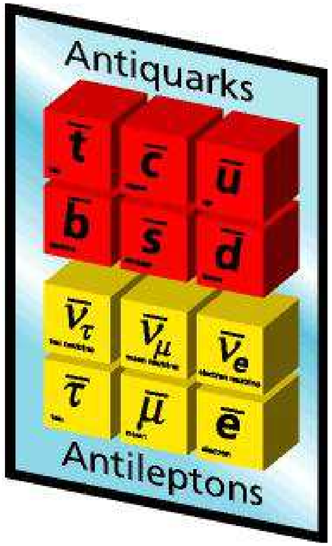
particles



elements

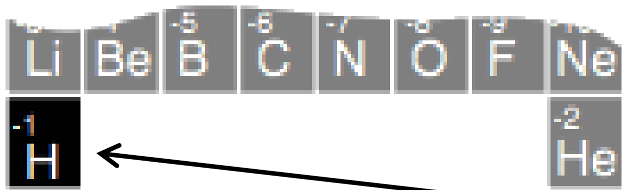


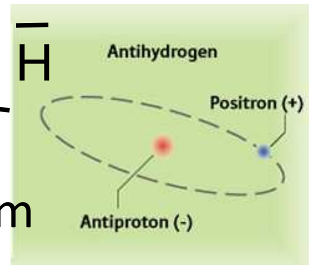
Anti-matter



antiparticles

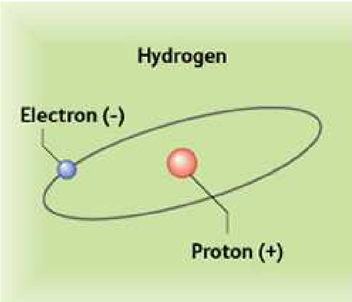
anti-elements





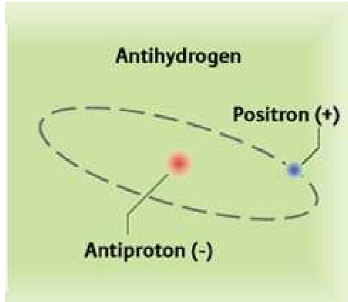
Antihydrogen is the simplest atom consisting entirely of antimatter

Antihydrogen: what is it known?



Hydrogen

Antihydrogen



$\overline{\mathrm{H}}$

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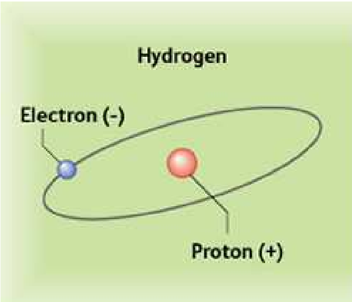
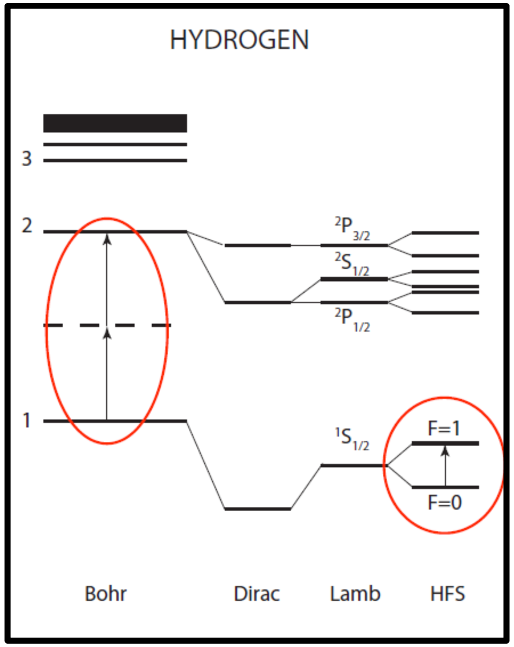


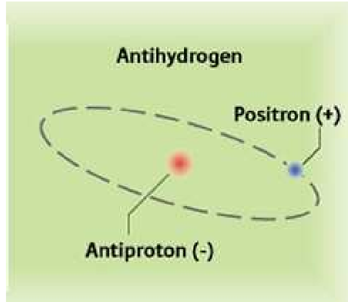
Hydrogen

one of the best understood and most precisely measured system



quantity	exp. value [Hz]	δ_{exp}/ν	δ_{th}/ν
$\nu_{1s\text{-}2s}$	$2\,466\,061\,413\,187\,035(10)$	4.2×10^{-15}	1×10^{-11}
$\nu_{2s\text{-}2p}$	$1\,057\,8450(29)\times10^{3}$	2.7×10^{-6}	3.8×10^{-11}
ν_{HFS}	$1\,420\,405\,751.7667(9)$	6.3×10^{-13}	$(3.5\pm0.9)\times10^{-6}$

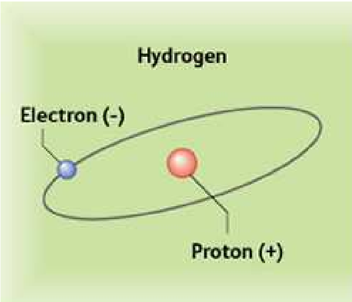
Antihydrogen

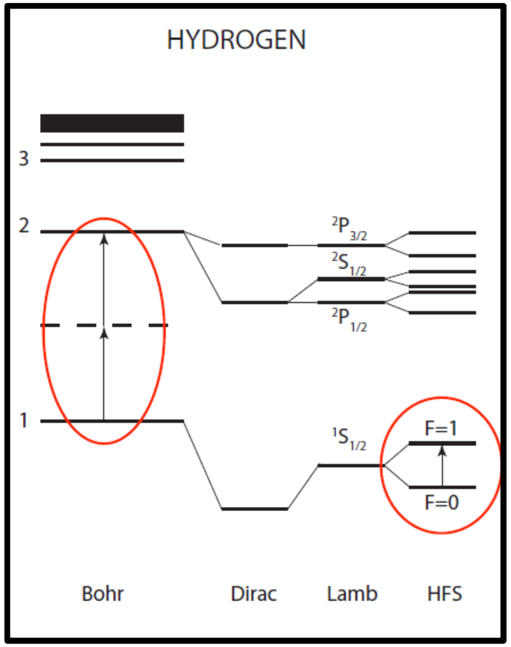


$\bar{H}$

Antihydrogen: what is it known?

Hydrogen





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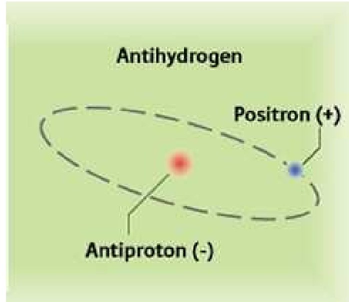
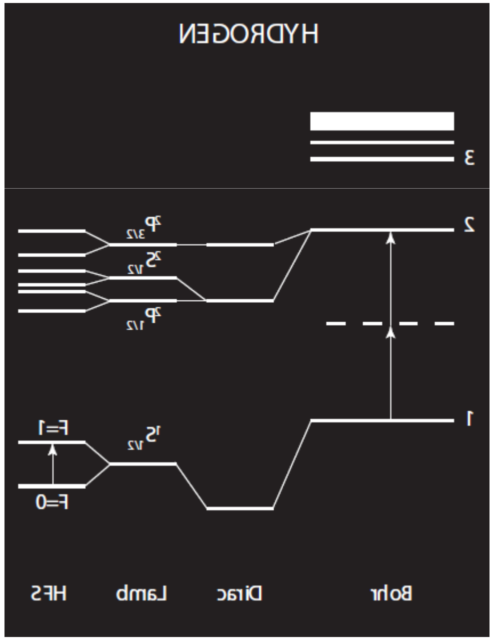


$\overline{\mathrm{H}}$



← Expected from CPT

significant milestones achieved (see Testera's talk)

but

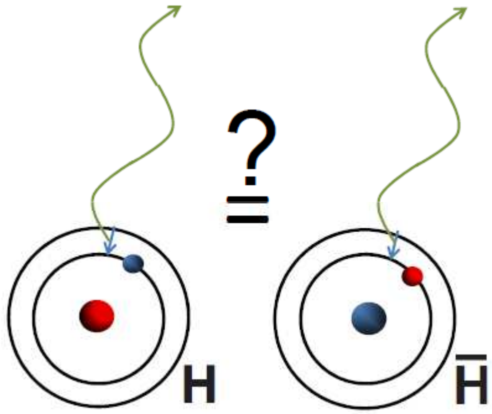
no precise measurement so far

Why?

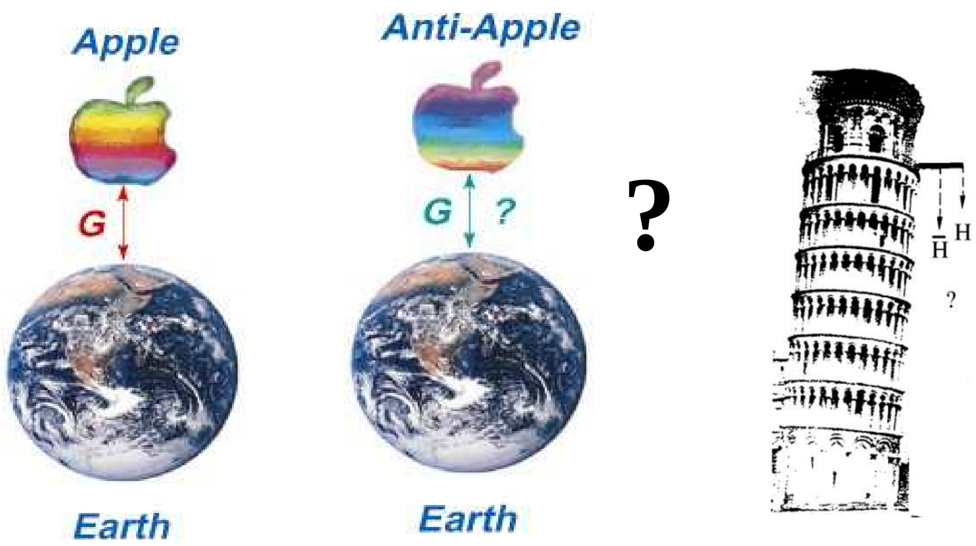
- Annihilations
- Antihydrogen study is young

Why study antihydrogen

1) Precise matter/antimatter comparison→ test of CPT symmetry



2) Measurement of the gravitational behaviour of antimatter→ test of WEP



Impossible with charged antiparticle

only with neutral system → $\bar{H}$

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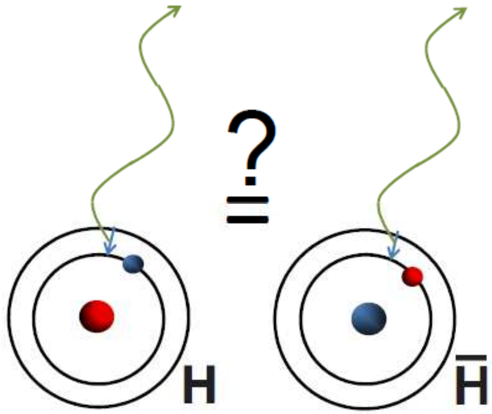


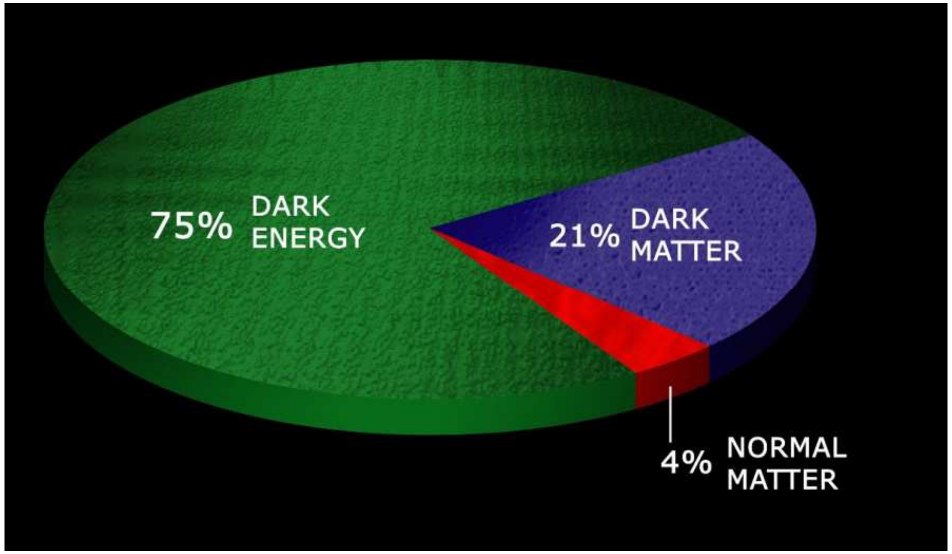
2) Measurement of the gravitational behaviour of antimatter→ test of WEP

antiparticle

utral system → $\bar{H}$

Not discussed here

Matter/antimatter asymmetry in the Universe

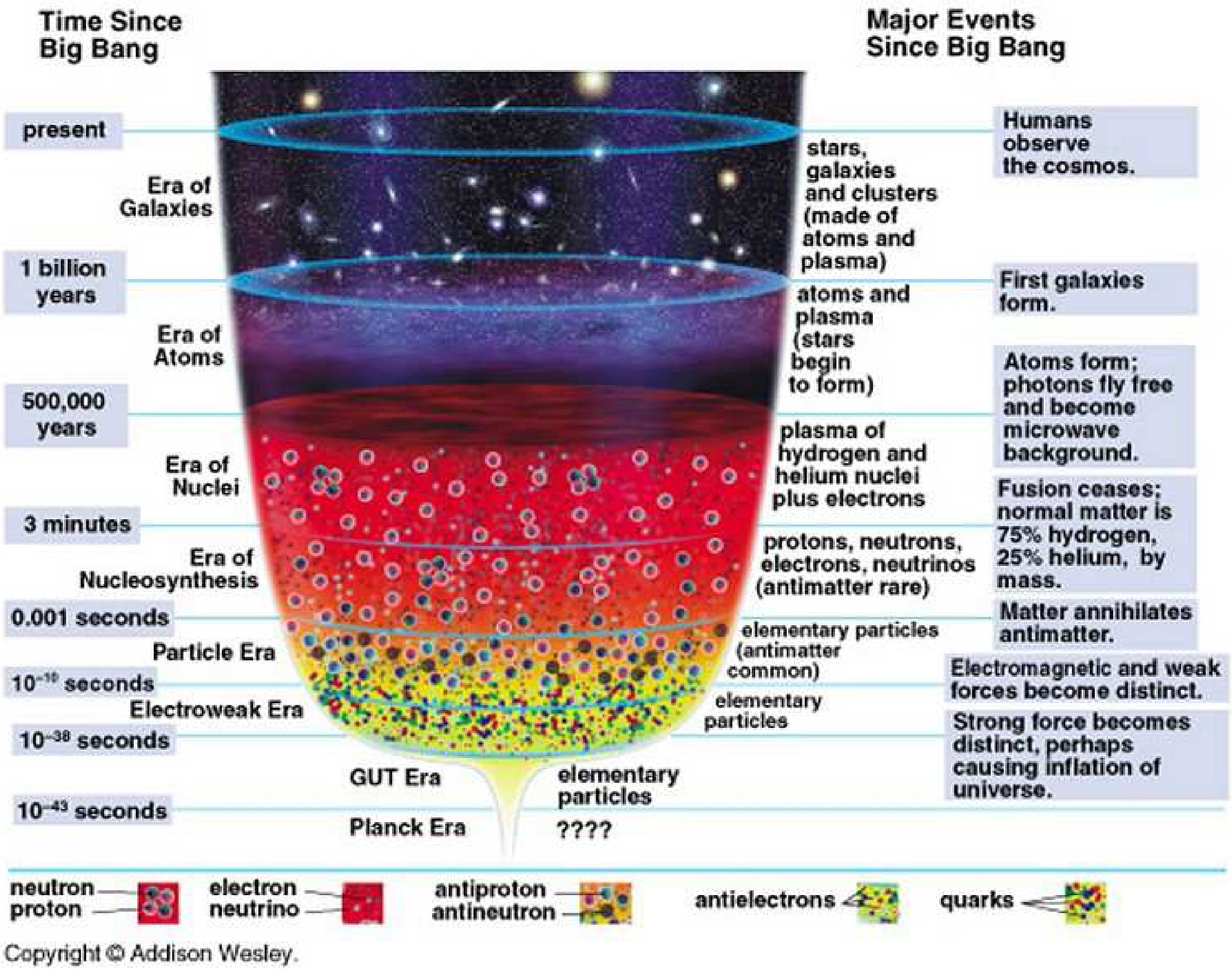


Positrons and antiprotons in the cosmics rays are compatible with secondary production (made in the matter collision with the interstellar medium)

Earth, Moon and planets made of matter

The visible Universe is made of matter

No primordial antimatter detected



$t \approx 0$ equal quantity of matter and antimatter ← expected from symmetry!?

$t < 0.001$ s All antimatter disappeared and only (part of) matter (and we) survive

Possible explanations rely on the fundamental symmetries violations

The CPT theorem

50’s – Pauli, Schwinger , Lüders, Jost

The **CPT** theorem (1954): **“Any Lorentz-invariant local quantum field theory is invariant under the successive application of C, P and T”**

Assumptions:

- flat space-time, Lorentz-invariance, local interactions, unitarity, point-like particles

Consequences:

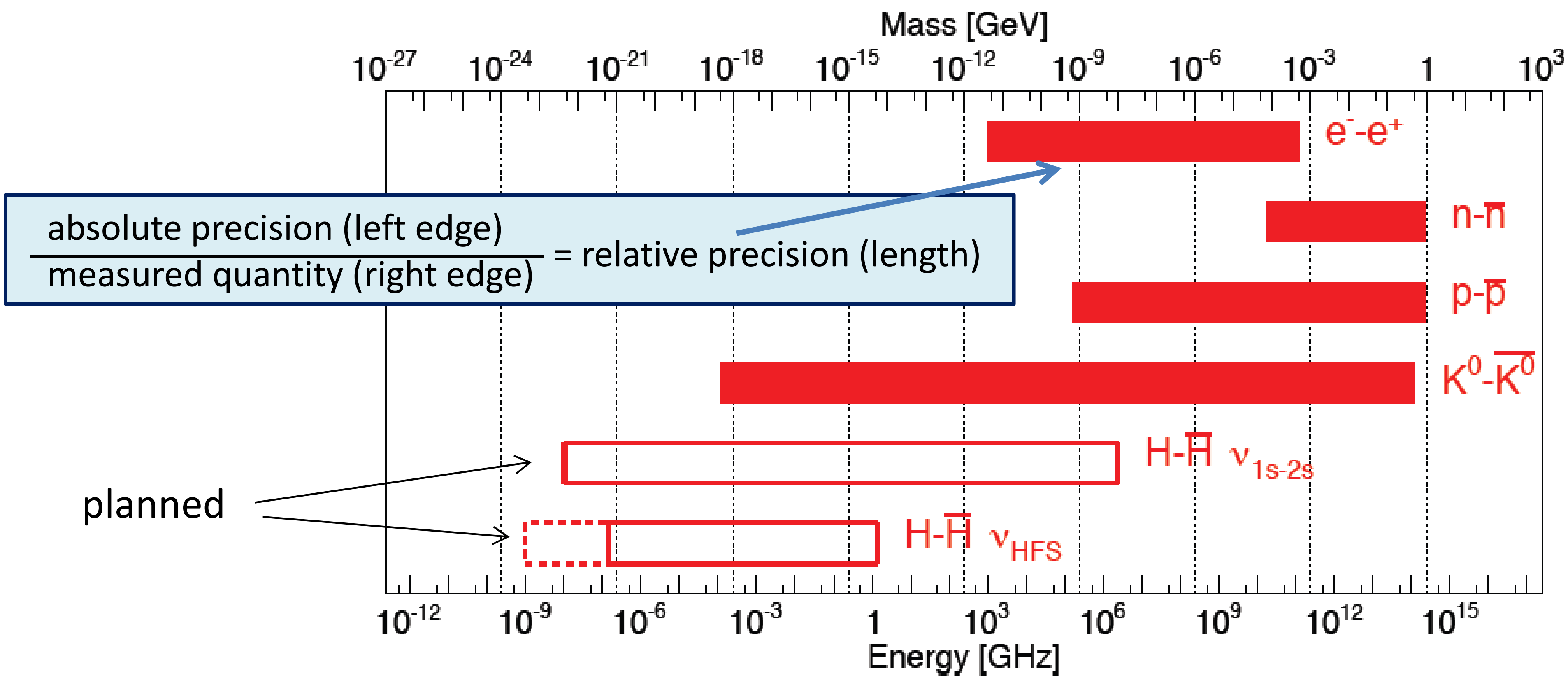
- particle/antiparticle: equal mass, lifetime; equal and opposite charge and magnetic moment
- **atom/antiatom: identical energy levels**

CPT invariance is inside the Standard Model

In string theory (and quantum gravity): assumptions non valid
→ CPT violations as a signature of string theory?

No measurement of CPT violation exists

CPT tests: relative & absolute precisions



Considered “best CPT test”: $K^0 - \overline{K}^0$ $\Delta m/m \sim 10^{-18} \Leftrightarrow 10^5$ Hz

but absolute precision could be relevant …→ $H - \overline{H}$ highly competitive

Where CPT violation might appear is unknown

CPT violation in Standard Model Extension

Indiana group, Kostelecky et al. (since 1997)

Standard Model can be extended with CPT violation

Standard Model Extension (SME) is an effective field theory which contains:
- General Relativity
- Standard Model
- Possibility of Lorentz Invariance Violation
- CPT violation comes with Lorentz violation

Modified Dirac equation

CPT Violating terms

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

Lorentz Invariance Violating terms

R.Bluhm, A.Kostelecky, N.Russell,
Phys. Rev. Lett. 82, 2254 (1999)

- a & b have energy dimensions (→ absolute comparisons are important)

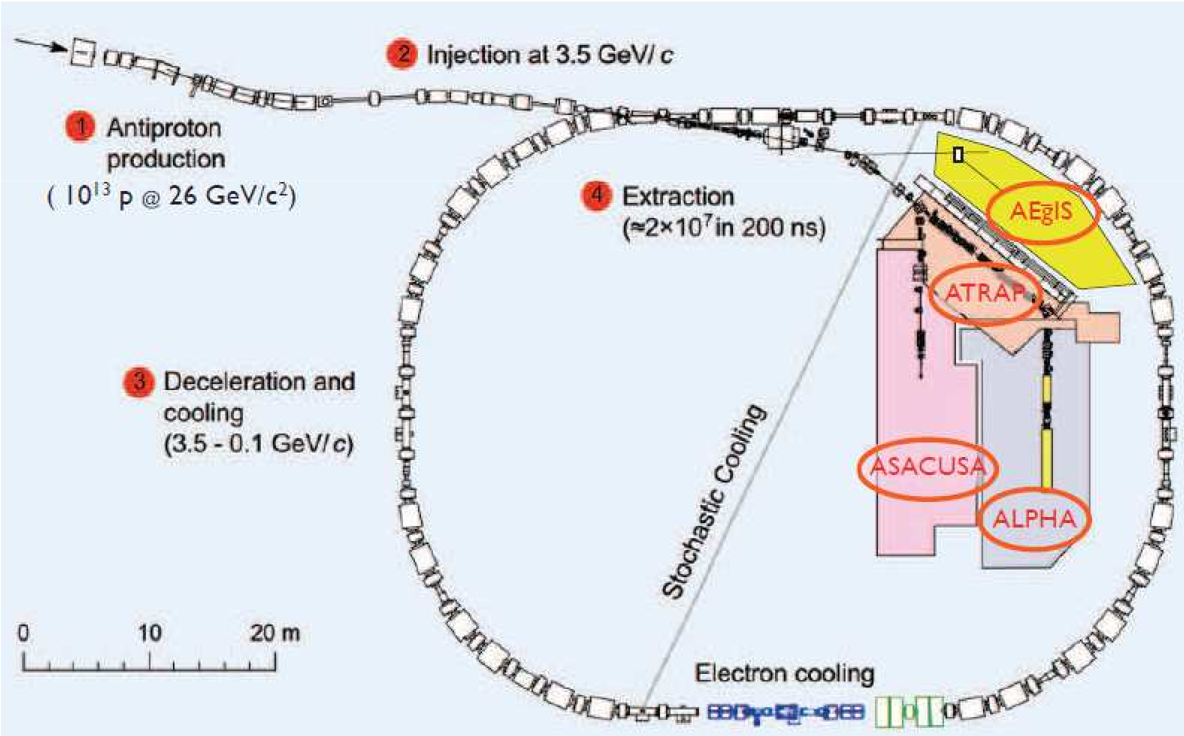
- No quantitative prediction

Antihydrogen formation

Antiproton Decelerator-AD @CERN

AD is the only source of low-energy antiprotons

All-in-one machine: antiproton capture , deceleration & cooling



AD delivers to the experiments :

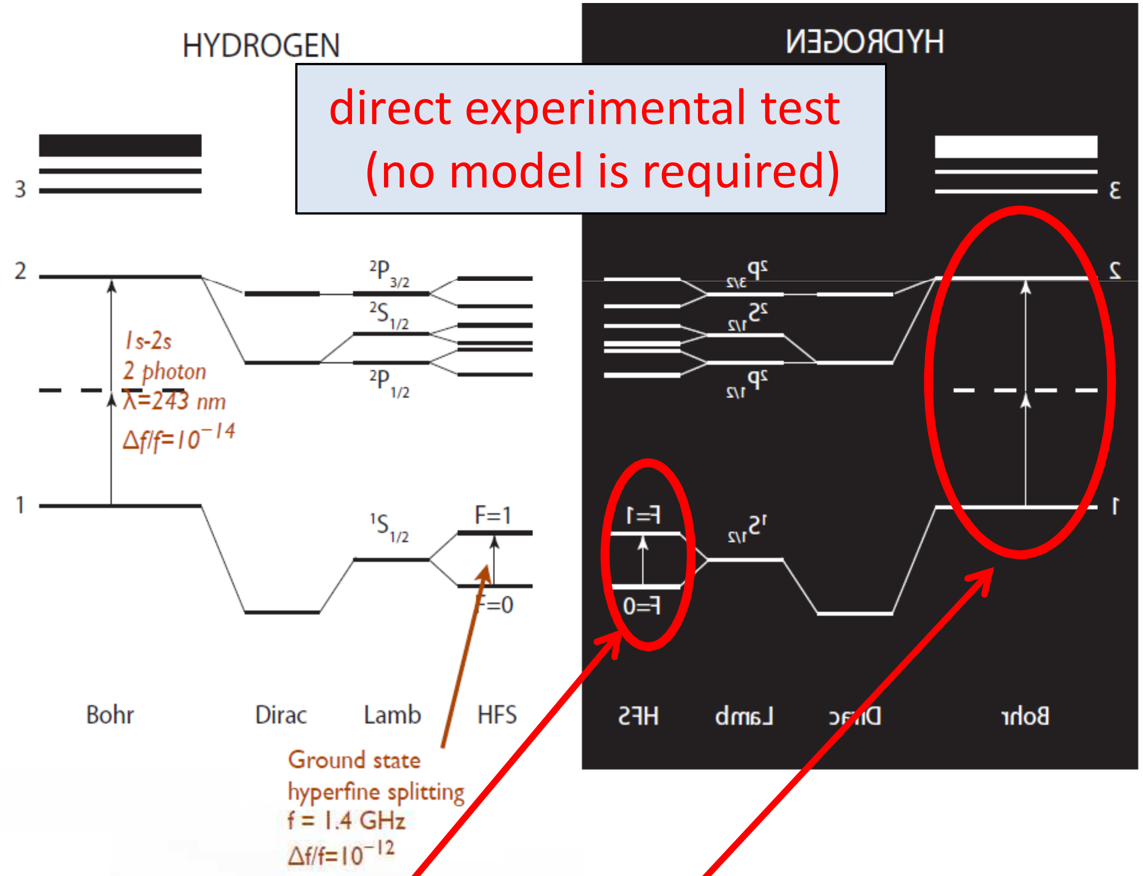
- 2-4 10^7 antiprotons per bunch
  (150-300 ns length)
- 1 bunch/ 100 s
- Energy = 5.3 MeV (100 MeV/c)

Experiments: - (2015) ALPHA, ATRAP, ASACUSA, AEgIS, BASE

- ATHENA (ended), ACE (ended), GBAR (future)

Antihydrogen for CPT test

matter-antimatter precise comparison by means of spectroscopy



Plans for antihydrogen:

- measurements: - Hyperfine splitting of ground state
  - 1S-2S transition

- methods: - Antihydrogen trapping
  - Antihydrogen beam

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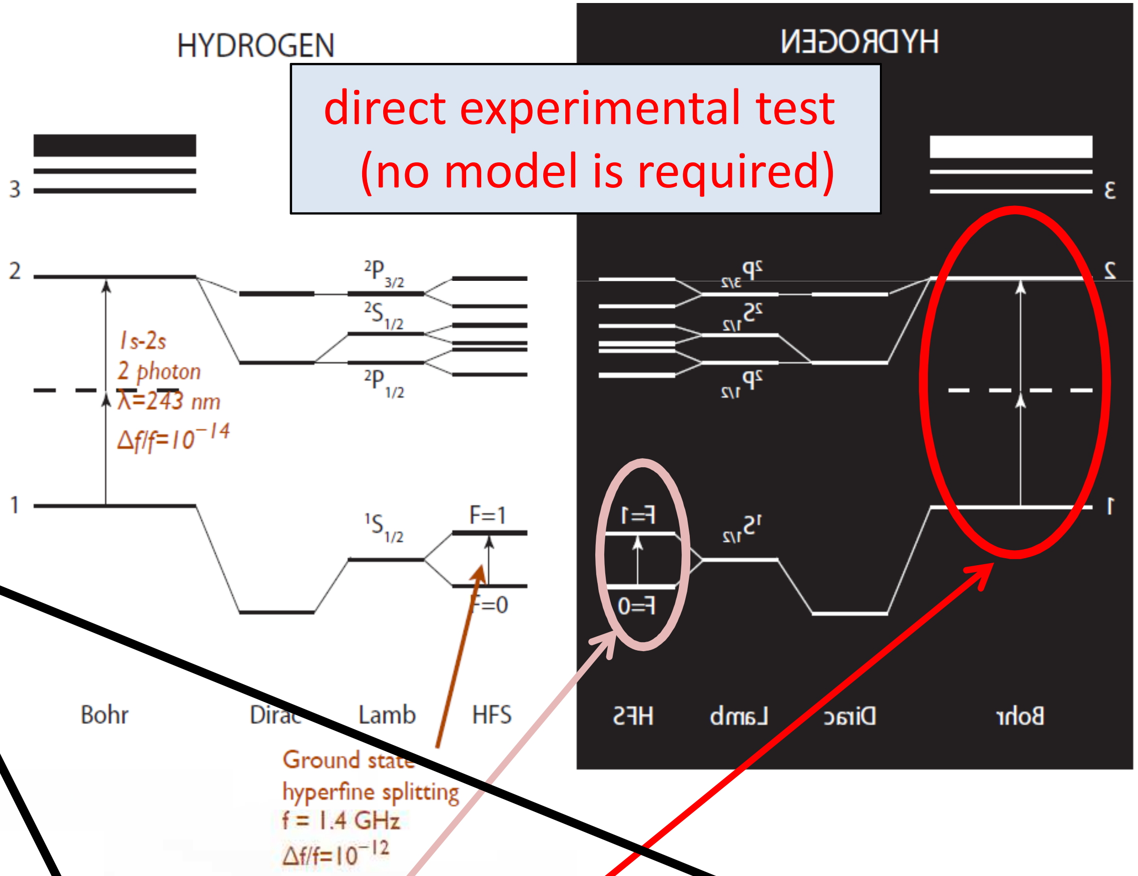

ALPHA
ATRAP

Plans for antihydrogen:

- measurements: - Hyperfine splitting of ground state
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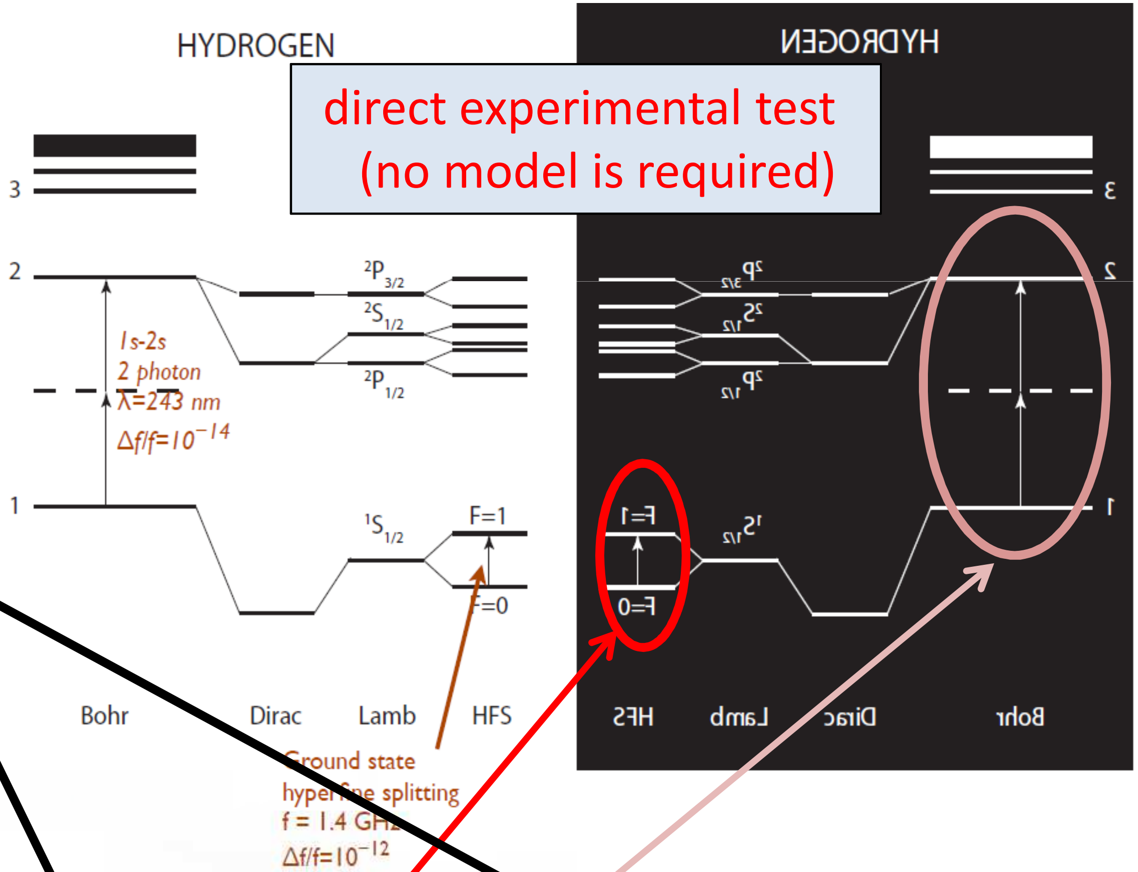


ASACUSA

AEGIS

Plans for antihydrogen:

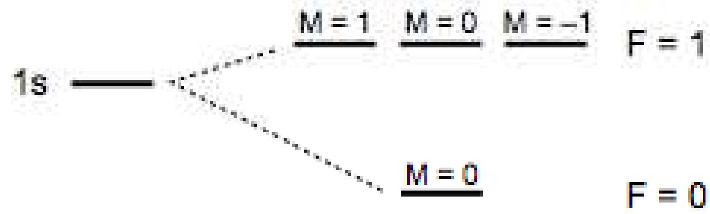
- measurements: **- Hyperfine splitting of ground state** - 1S-2S transition	- methods: - Antihydrogen trapping **- Antihydrogen beam**

Ground-state hyperfine splitting of antihydrogen

(Anti)hydrogen ground-state hyperfine splitting

- Interaction between (anti)proton and (anti)electron spin magnetic moments

- Between the triplet (F = 1) and singlet (F = 0) sublevels :



Leading term: $$\nu_{\mathrm{HF}} = \frac{16}{3}\left(\frac{m_p}{m_p+m_e}\right)^3 \frac{m_e}{m_p}\frac{\mu_p}{\mu_N}\alpha^2 c R_\infty (1+\delta) \simeq 1.42\ \mathrm{GHz}$$

- ν_{HF} is proportional to the (anti)proton magnetic moment $\mu_{\bar{p}}$ (5 ppm 2012 Gabrielse, previously 0.3%)

- δ: higher-order QED & strong interaction corrections: ~10^{-3}

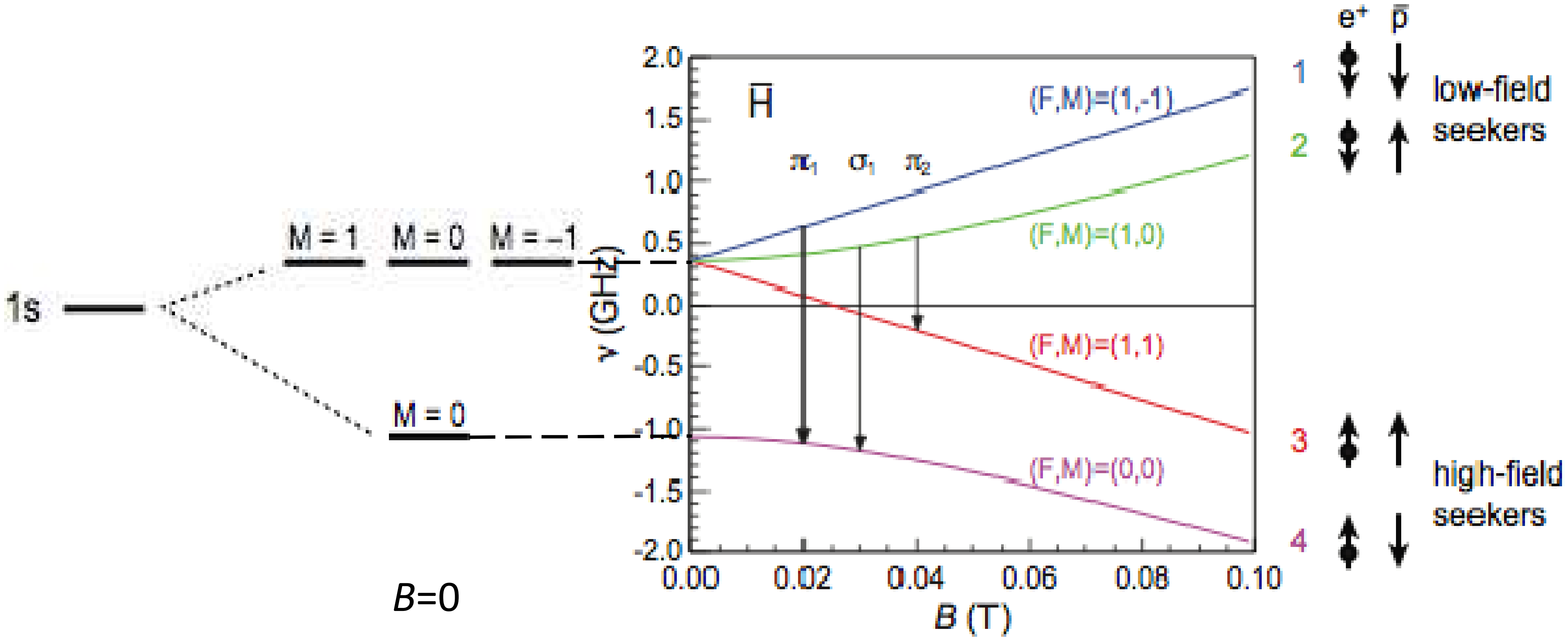
- Theoretical uncertainty on δ: ~10^{-6}

Antihydrogen GS-HFS in magnetic field

Hyperfine levels depend on magnetic field:

Energy increases for (F, M) = (1, −1) and (1, 0): low-field seekers ($\mu < 0$)

Energy decreases for (F, M) = (1, 1) and (0, 0): high-field seekers ($\mu > 0$)

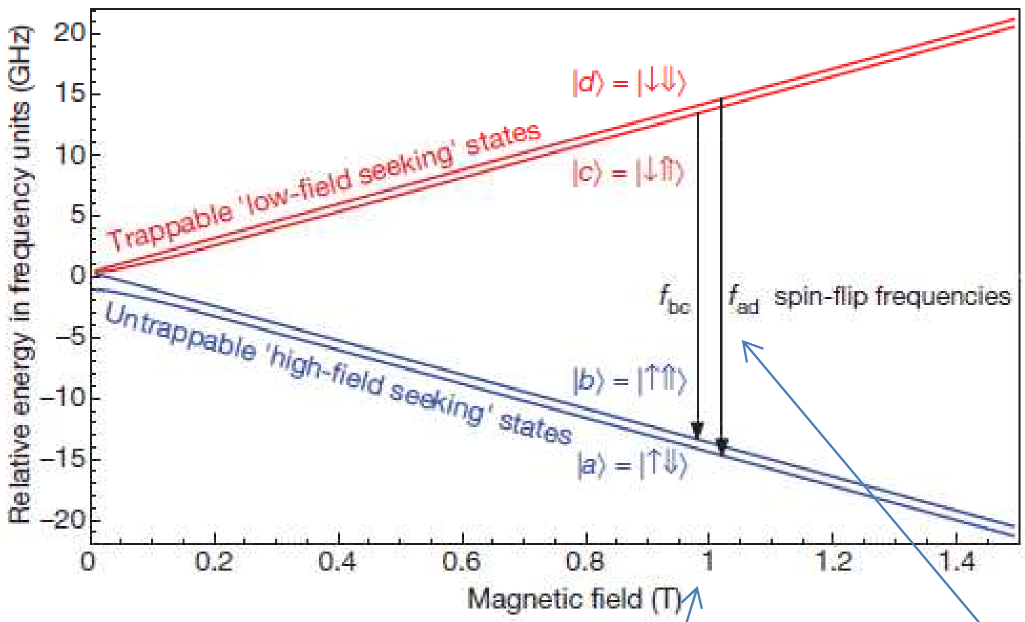


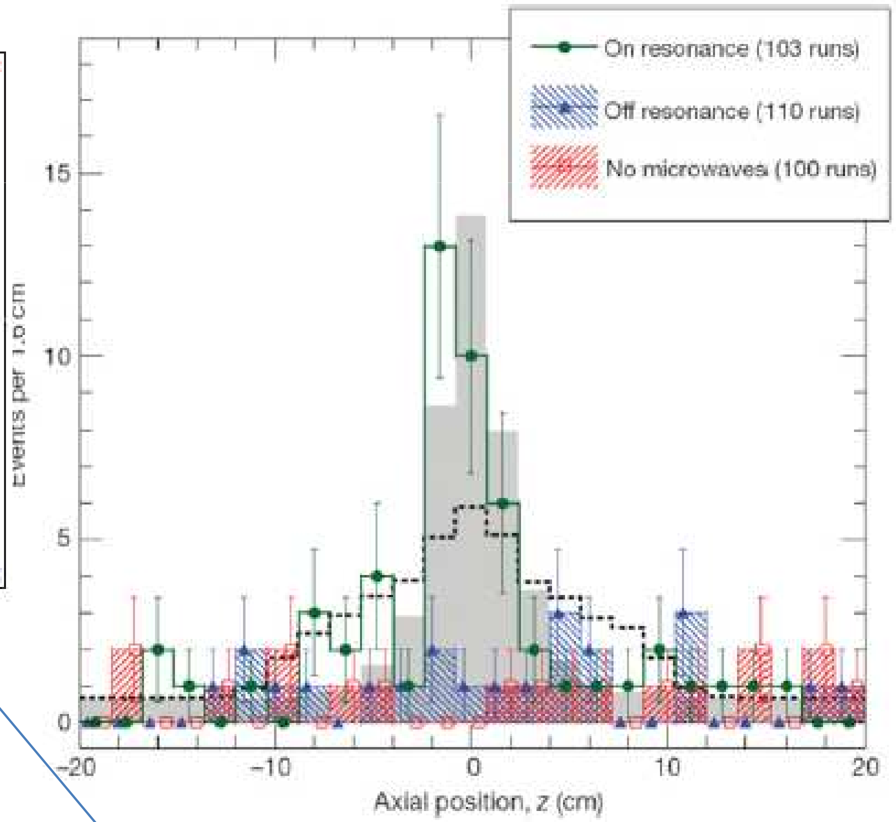
Antihydrogen GS-HFS measurement

- For hydrogen: 10^{-12} precision (hydrogen maser)
- But maser not possible for antihydrogen
- Spectroscopy of trapped antihydrogen → low precision due to strong confining field
- Spectroscopy of $\bar{H}$ beam
    - far from large **B**
    - atomic beam method can work up to 50-100 K (for trapped $\bar{H}$: << 1 K)
    - $\bar{H}$ can be guided with inhomogeneous magnetic field

ALPHA: Antihydrogen GS-HFS in a trap

C. Amole et al., Nature 483, 439 (2012)





High magnetic field

Only proof of principle ($\Delta f/f$=100 MHz/29 GHz = 4 10^{-3})

Start of Hbar spectroscopy

ASACUSA antihydrogen beam for GS-HFS measurement

Institute of Physics, Graduate School of Arts and Sciences, University of Tokyo, Tokyo 153-8902, Japan

Ulmer Initiative Research Unit, RIKEN, Saitama 351-0198, Japan

Atomic Physics Laboratory, RIKEN, Saitama 351-0198, Japan

Stefan-Meyer-Institut für Subatomare Physik, Österreichische Akademie der Wissenschaften, 1090 Wien, Austria

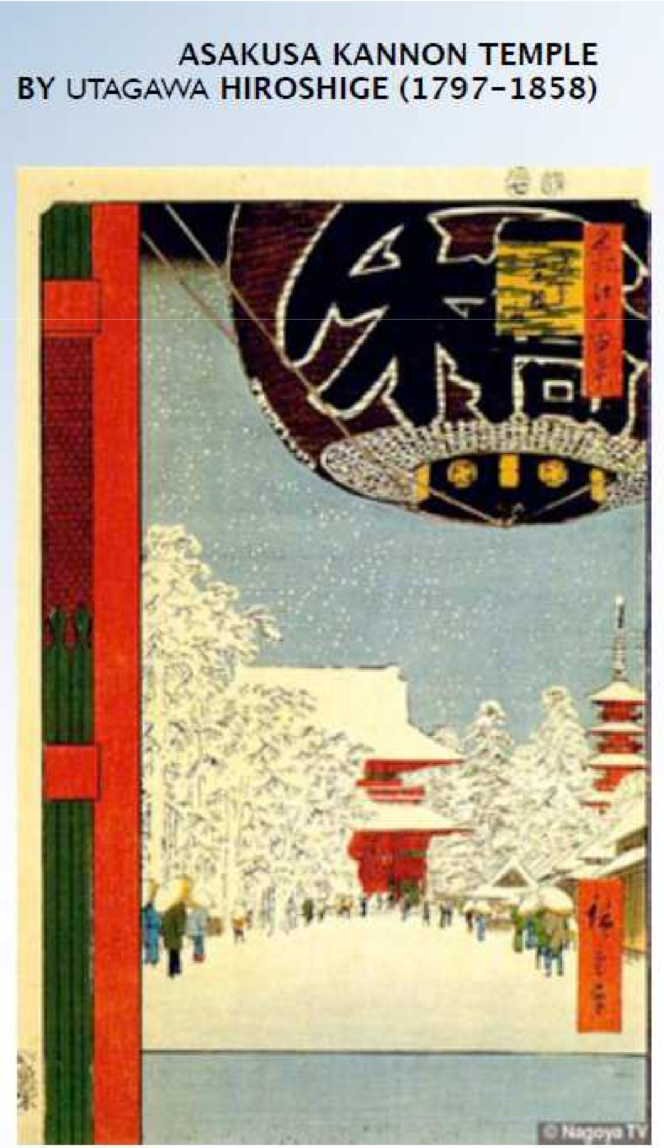
CERN, 1211 Genève, Switzerland

Dipartimento di Ingegneria dell'Informazione, Università di Brescia
& Istituto Nazionale di Fisica Nucleare, Gruppo Collegato di Brescia, 25133 Brescia, Italy

Department of Physics, Tokyo University of Science, Tokyo 162-8601, Japan

Graduate School of Advanced Sciences of Matter, Hiroshima University, Hiroshima 739-8530, Japan

ASACUSA



Atomic **S**pectroscopy **A**nd **C**ollisions **U**sing **S**low **A**ntiprotons

Spokesperson: R. Hayano

Not only antihydrogen

- $\bar{p}He$ laser spectroscopy : $m_{\bar{p}}$ vs. m_p
- $\bar{p}He$ microwave spectroscopy : $\mu_{\bar{p}}$
- $\bar{p}A$ collision : formation and ionization cross section
- $\bar{p}N$ collision : in flight annihilation cross section
- $\bar{p}e^+ = \bar{H}$ beam microwave spectroscopy :

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

1 Institute of Physics, Graduate School of Arts and Sciences, University of Tokyo, Tokyo 153-8902, Japan
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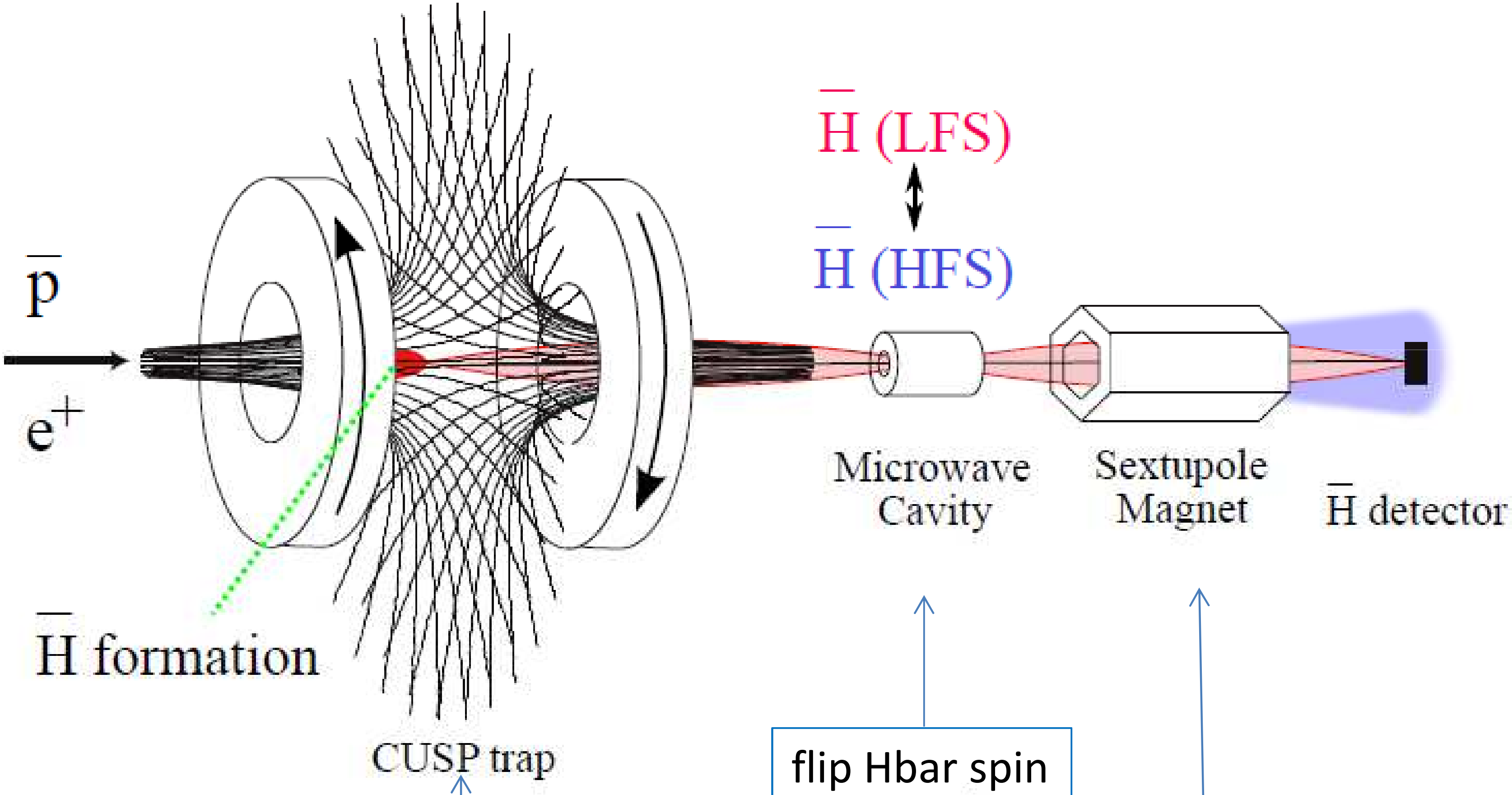
8 Graduate School of Advanced Sciences of Matter, Hiroshima University, Hiroshima 739-8530, Japan

Scheme of the measurement



confine pbars and e^{+} ;
select Hbar spin state

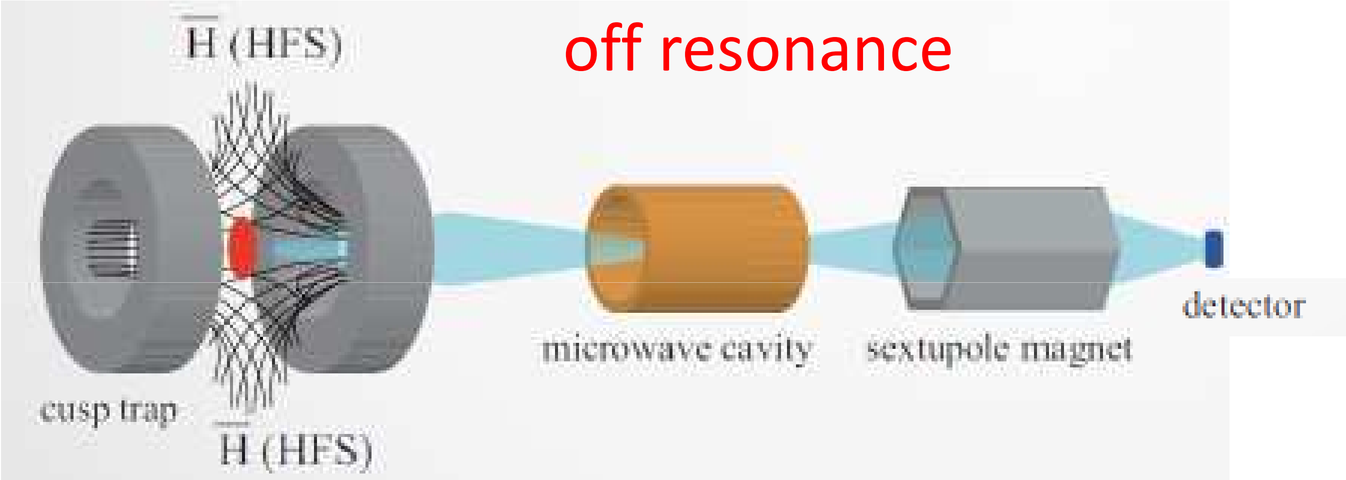
flip Hbar spin

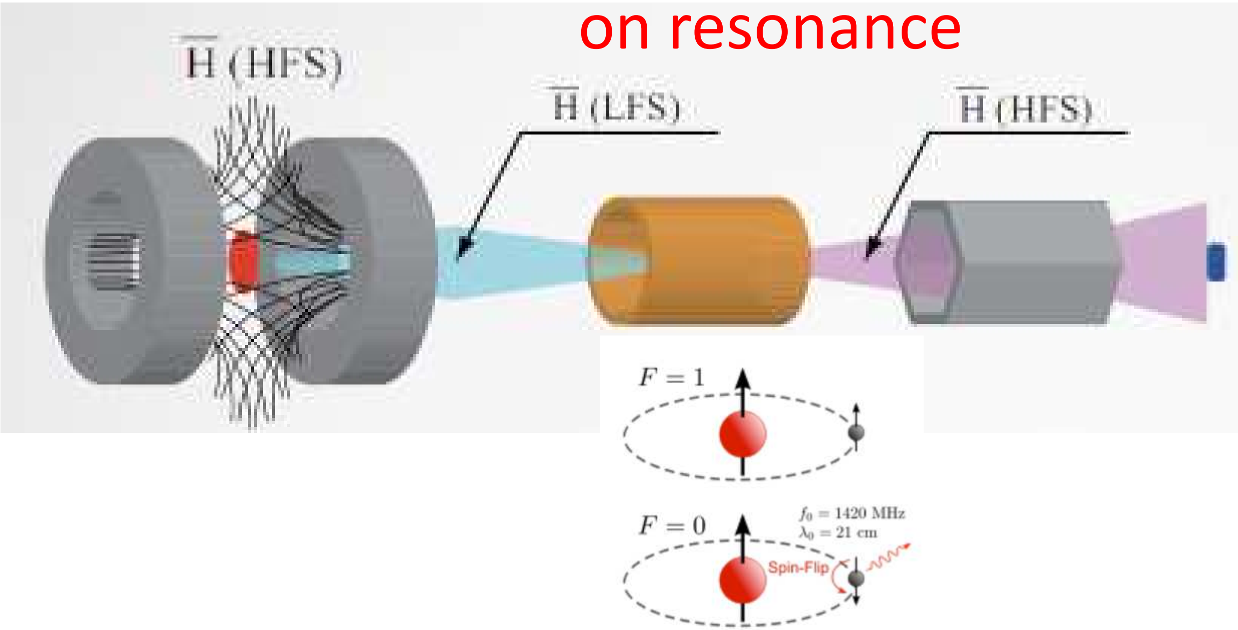
select spin state

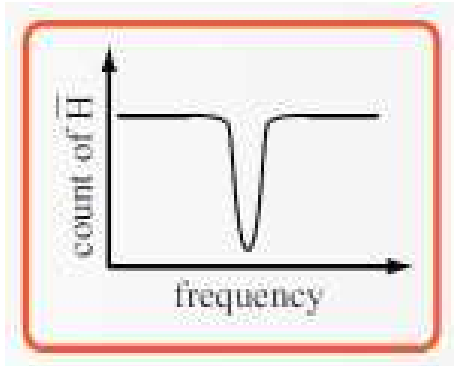
HFS-states: de-focused
LFS-states: focused

B and **E** axially symmetric

Scheme of the measurement



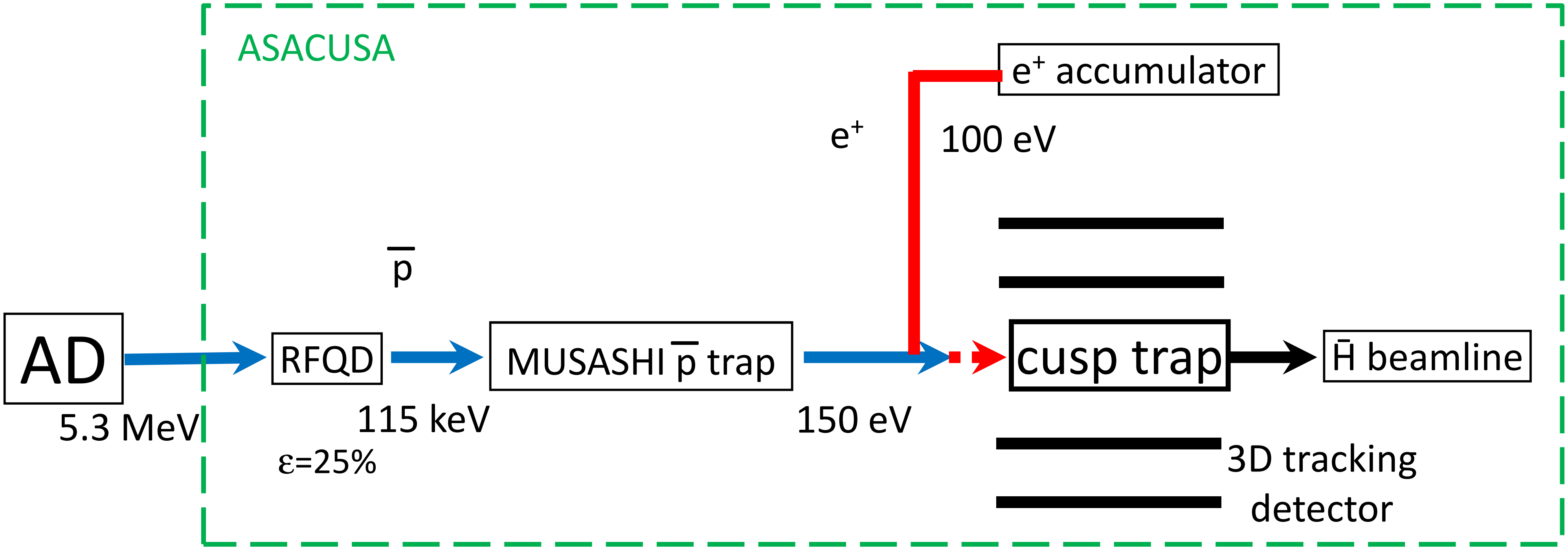




"Disappearance Mode"

Scheme of the experimental set-up

2012



$\bar{p}$:

deceleraled by RFQD

e- cooling, accumulation (3–5 AD shots), compression in MUSASHI

pulse extraction from MUSASHI

transfer of 3 10^5 to the cusp trap

guided by magnetic fields

e^+:

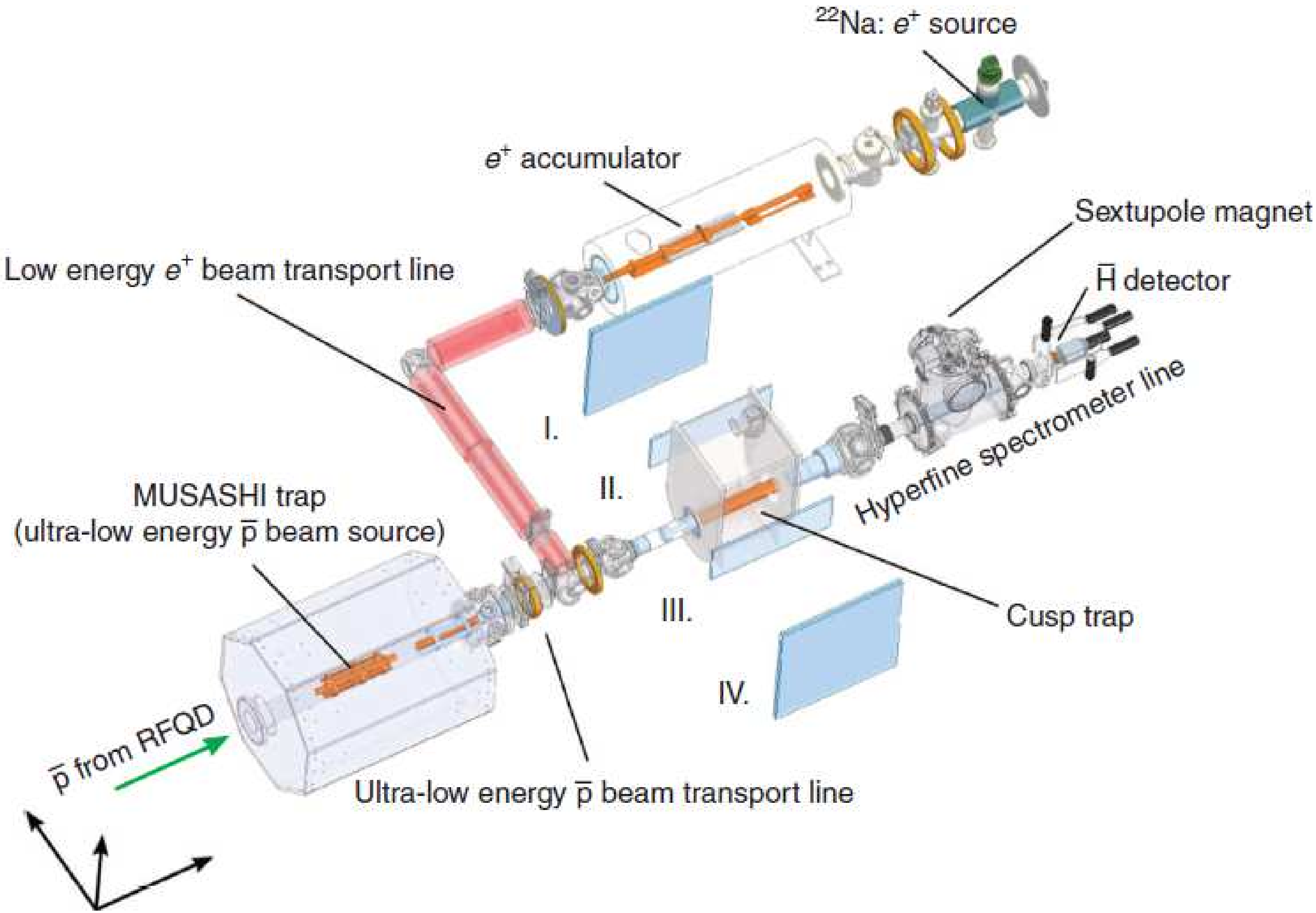
^{22}Na source (0.6 GBq), Ne moderator, N_2 gas moderator, MRE

accumulation (10–100 stacks)

transfer of 3 10^7 every 10 min to the cusp

Experimental set-up

2012



Experimental set-up

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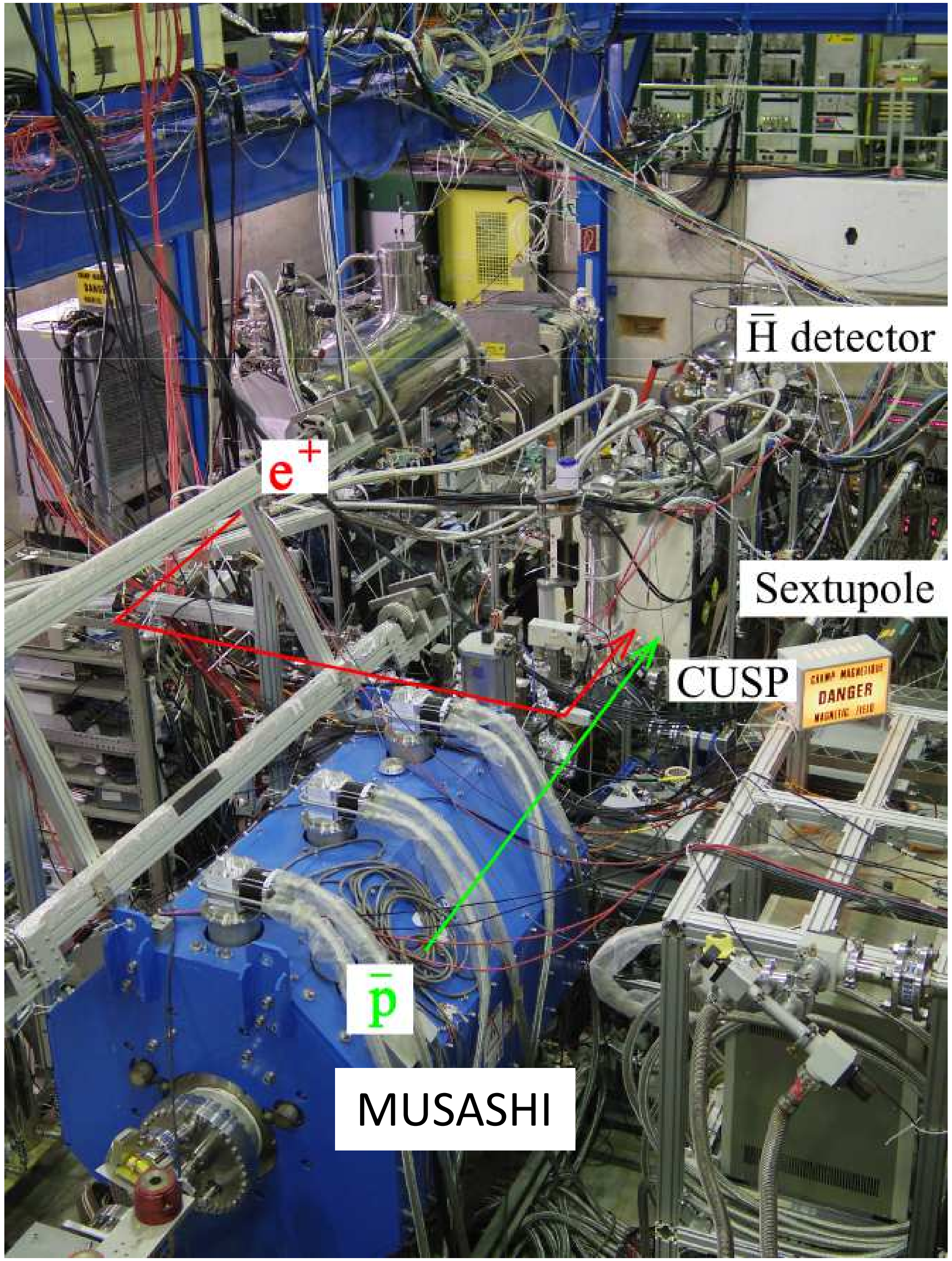

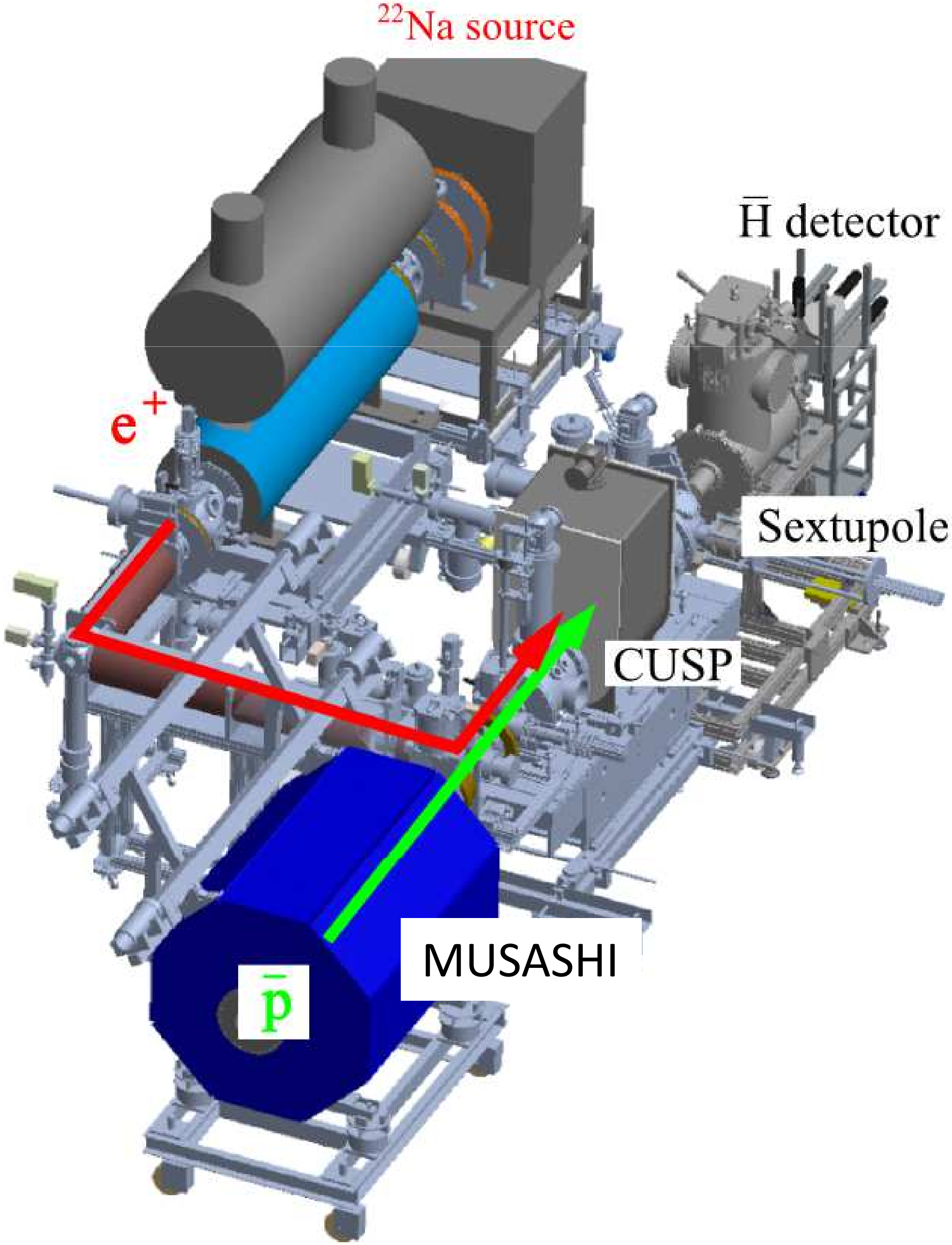

ASACUSA – CUSP TRAP

- Hbar production in 2010
- Hbar beam in 2012 (published in 2014)
- Lots of improvements during LS1
- H spectroscopy in 2014
- Analysis of 2014 Hbar data in progress

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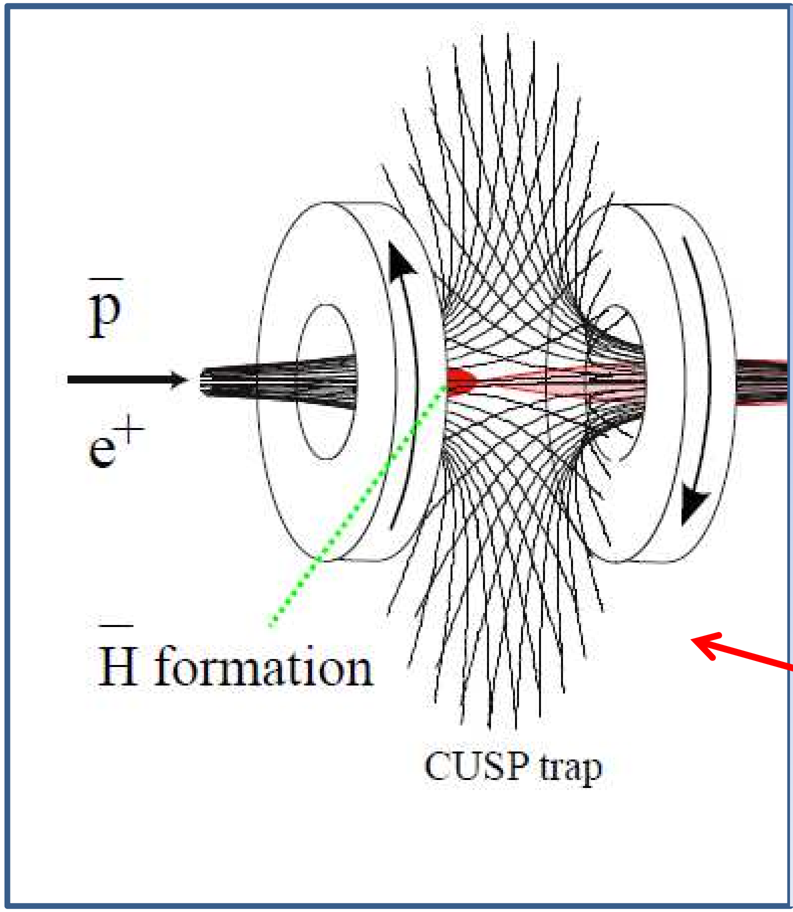
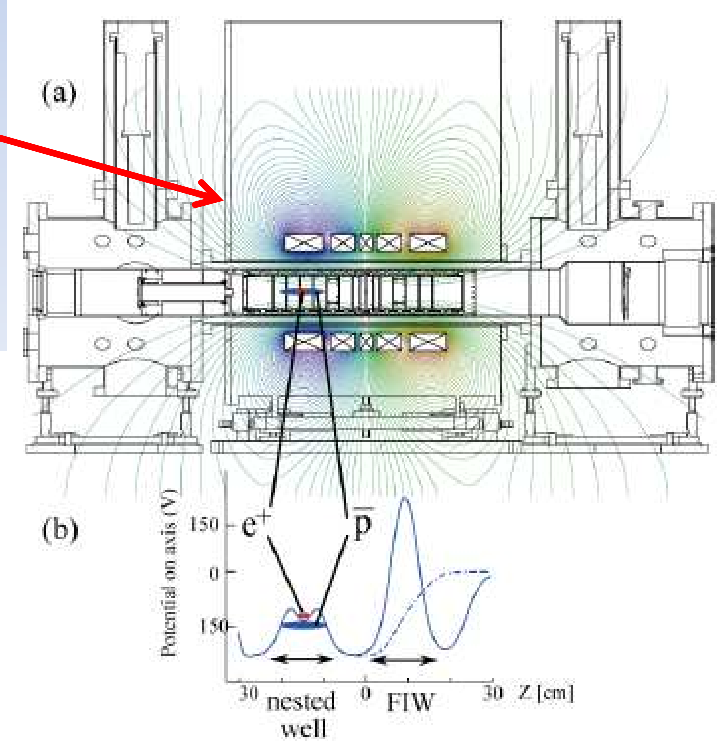
Antihydrogen formation





Y. Enomoto et al.
Phys. Rev. Lett 243401, 2010

First antihydrogen production in a "cusp trap"

$\bar{H}$ production in the “cusp” trap

Physics World reveals its top 10 breakthroughs for 2010

Dec 20, 2010 25 comments

It was a tough decision, given all the fantastic physics done in 2010. But we have decided to award the *Physics World* 2010 Breakthrough of the Year to two international teams of physicists at CERN, who have created new ways of controlling antiatoms of hydrogen.

Shared glory at CERN as antihydrogen research takes the gong

The ALPHA collaboration announced its findings in late November, which involved trapping 38 antihydrogen atoms (an antielectron orbiting an antiproton) for about 170 ms. This is long enough to measure their spectroscopic properties in detail, which the team hopes to do in 2011.

Just weeks later, the ASACUSA group at CERN announced that it had made a major

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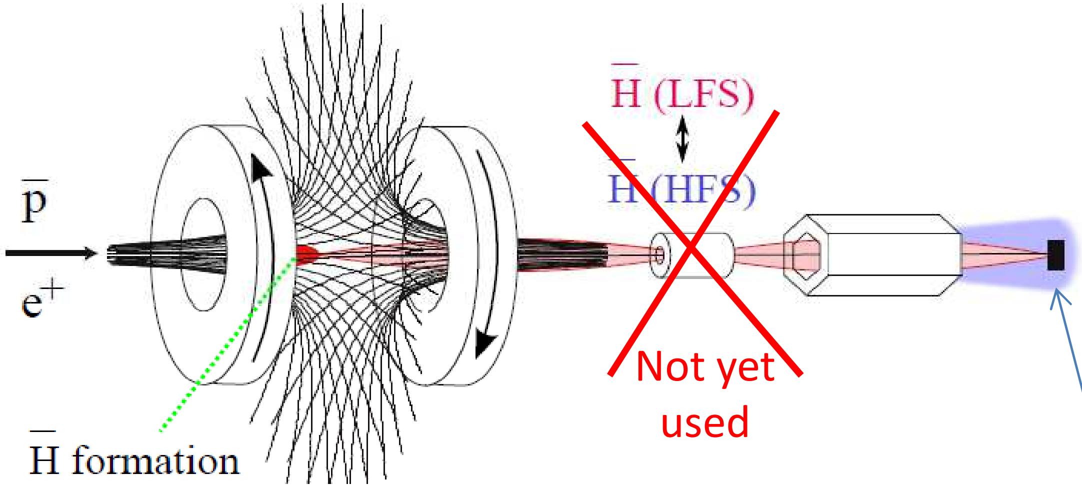
Antihydrogen beam



nature COMMUNICATIONS

ARTICLE

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A source of antihydrogen for in-flight hyperfine spectroscopy

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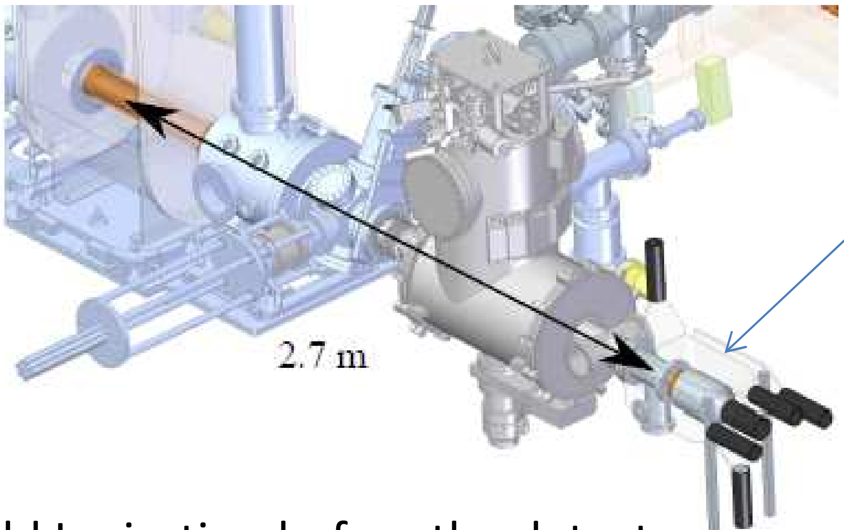
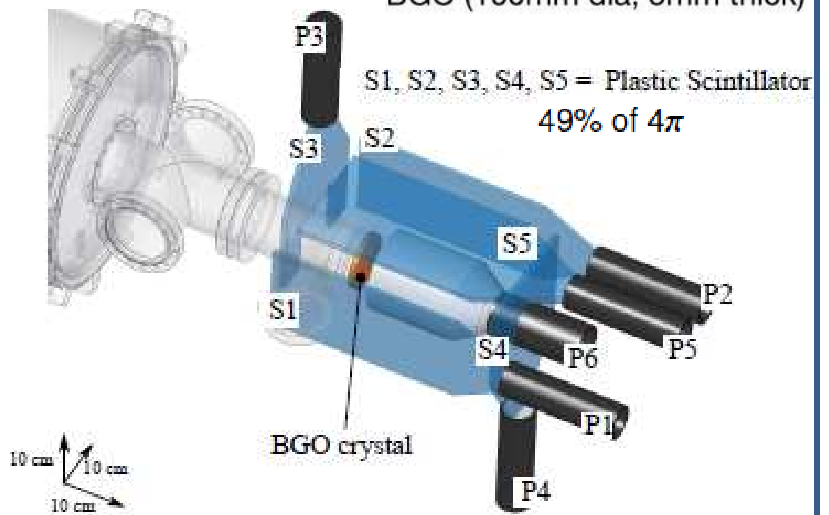


Field Ionization before the detector

→ Only Hbars with n<43 (or n<29) reach the detector

Hbar detector

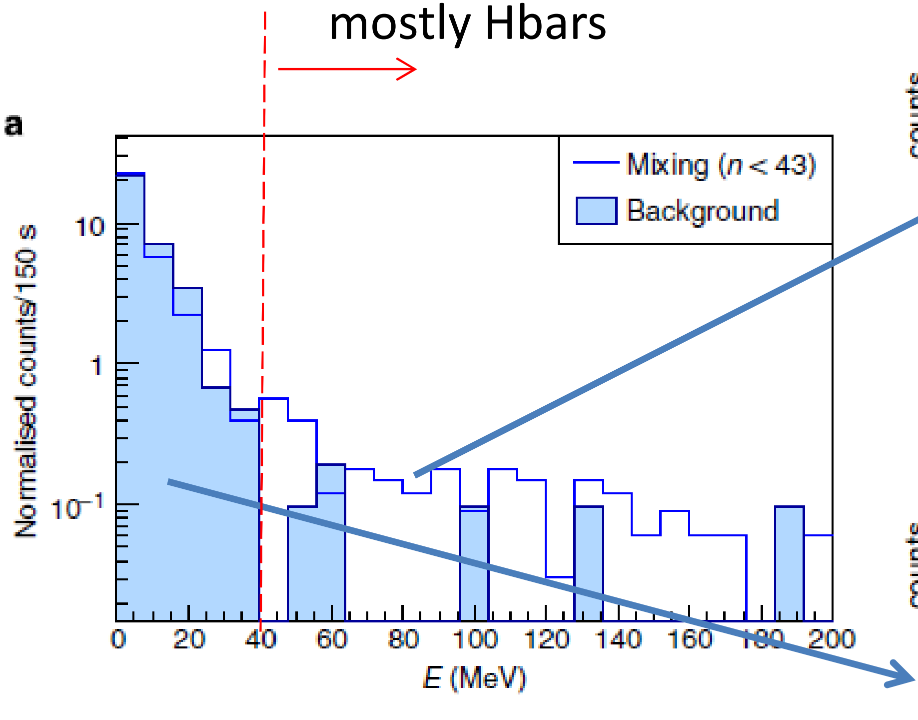
plastic +
BGO (100mm dia, 5mm thick)

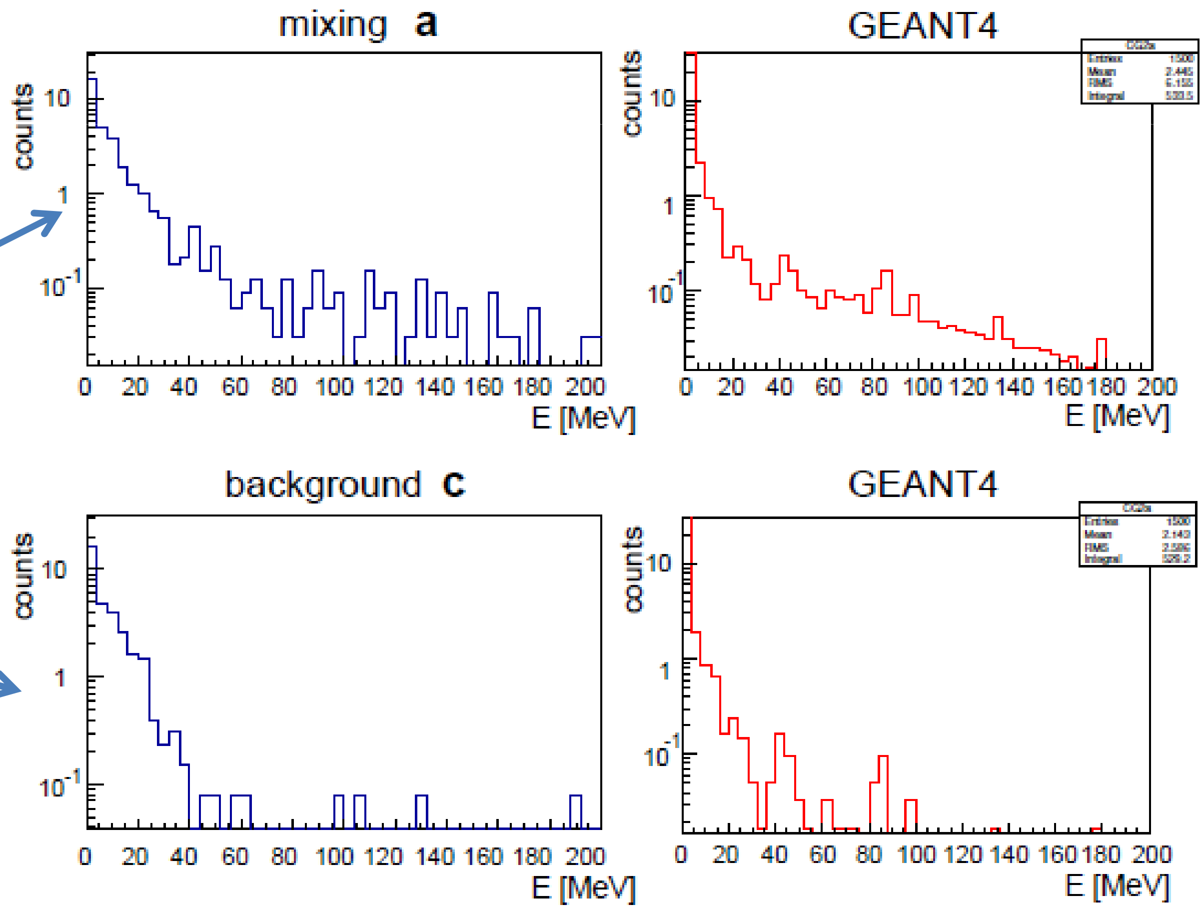


BGO measures energy deposition by Hbar annih.

coincidence: BGO AND (>1 S)

Energy deposition in the BGO





Unshaded histo → pbar-e+ mix

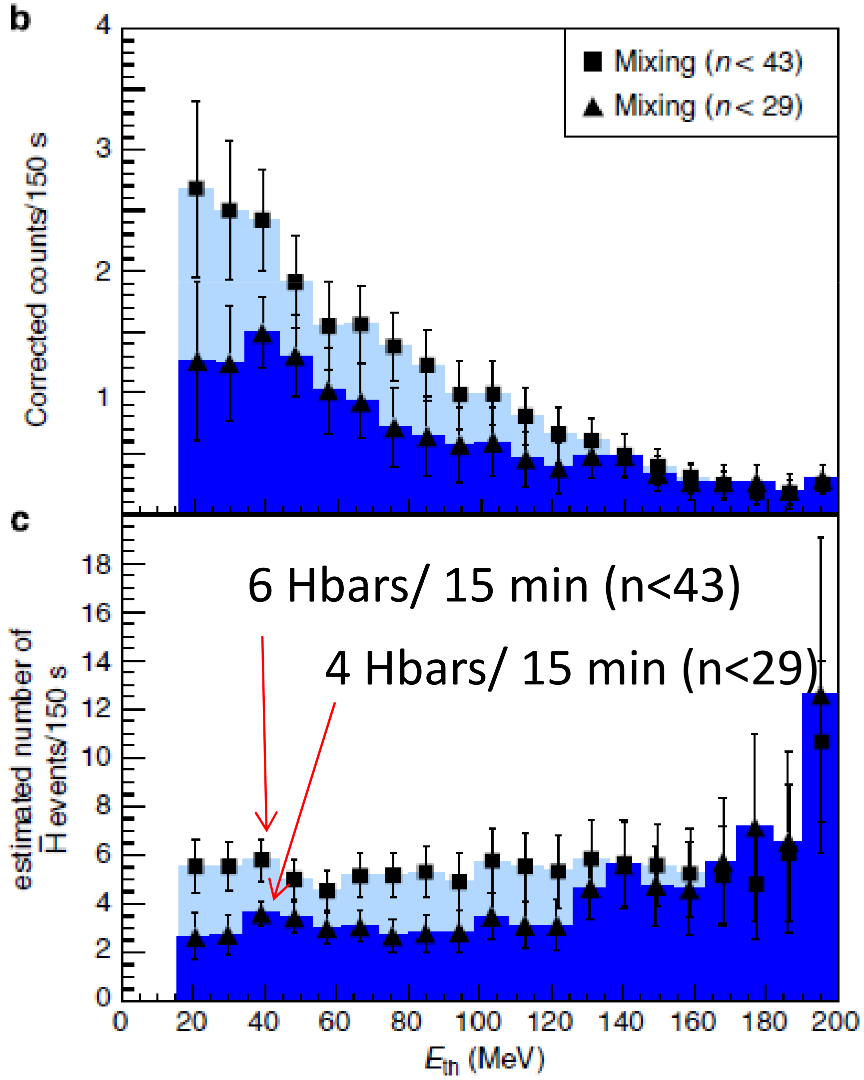
Shaded histo → pbar-e- mix (background run)

Antihydrogens reaching the BGO

a-c (see previous slide)

Integration from E_{th} to 200 MeV

After detection efficiency correction (from GEANT)



Detected antihydrogen atoms

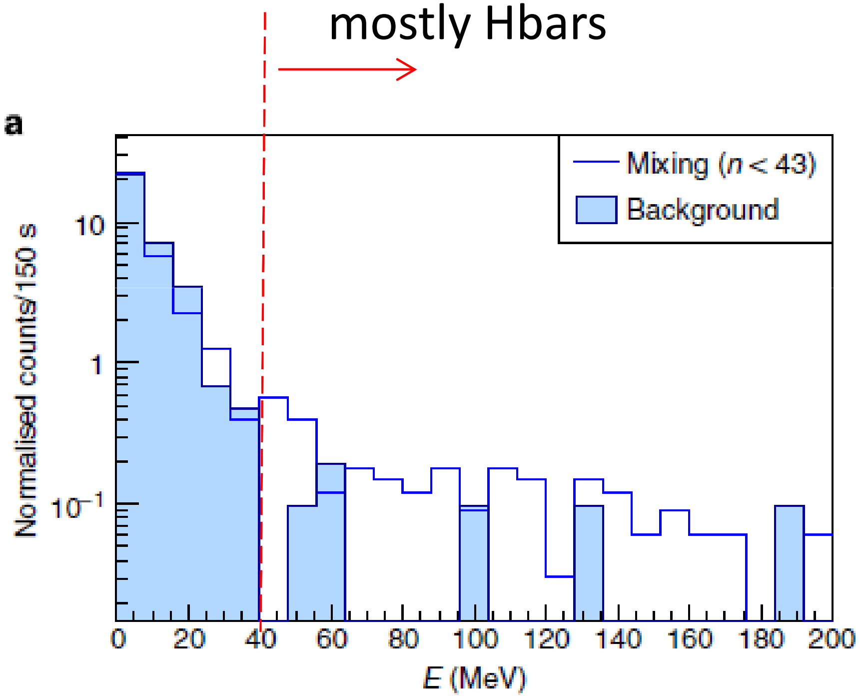


Table 1 | Summary of antihydrogen events detected by the antihydrogen detector.

	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	—

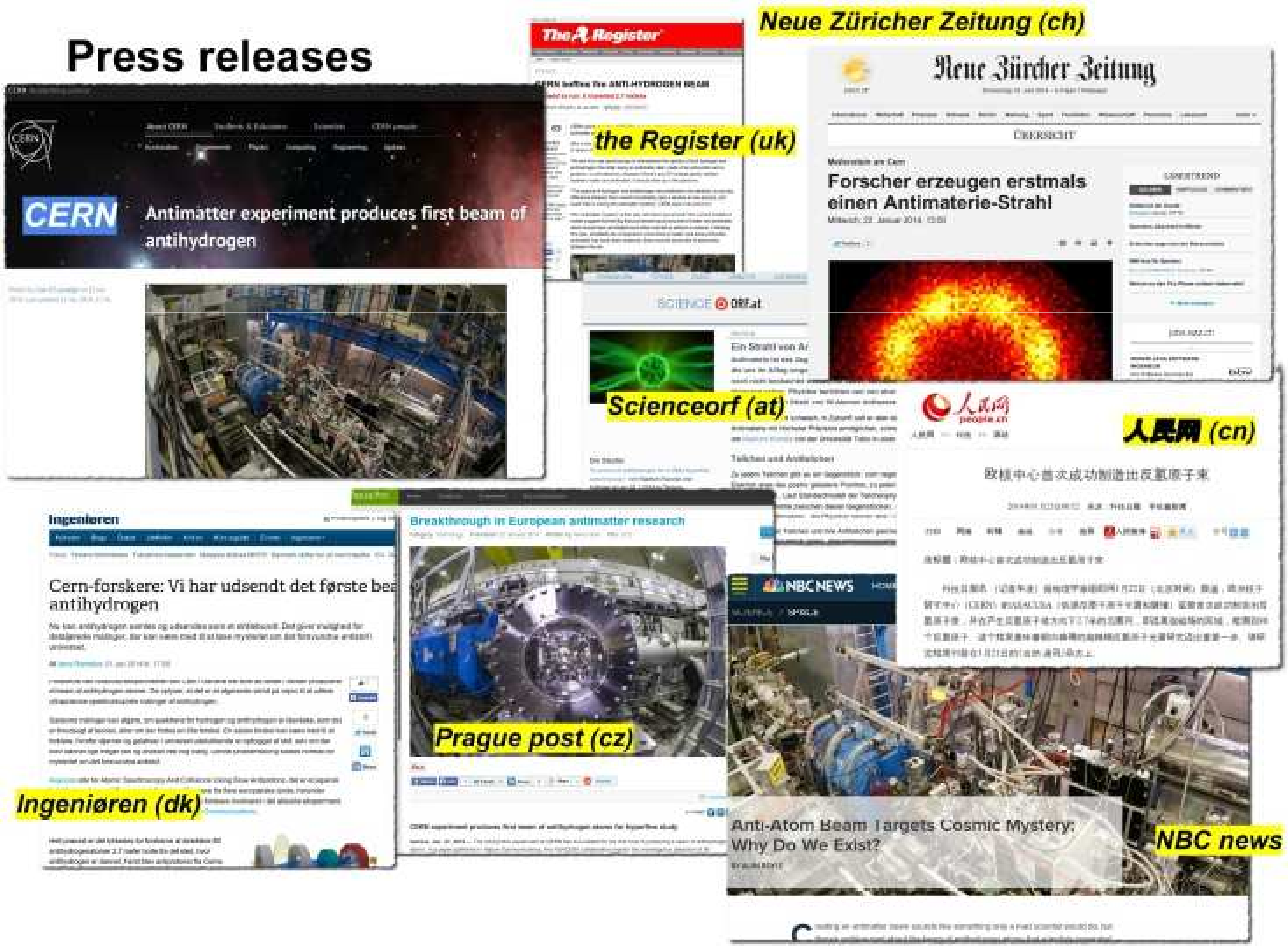
Antihydrogens (n<43) detected with 5 σ significance 2.7 m far from their production region

➔ Antihydrogen beam has been produced

25 Hbars/hour (n<43)

16 Hbars/hour (n<29) ← significant fraction in lower n

Press releases



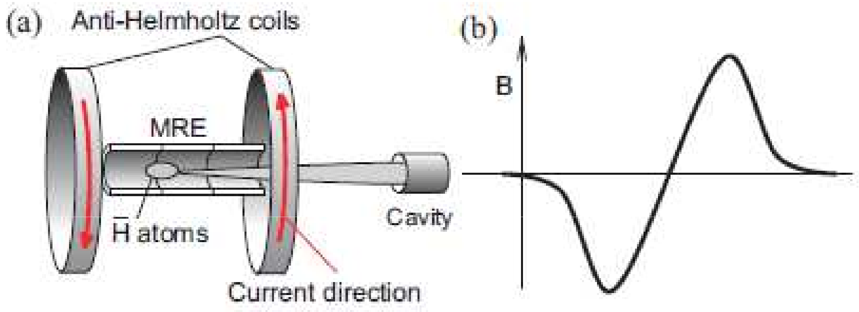
ASACUSA – CUSP TRAP

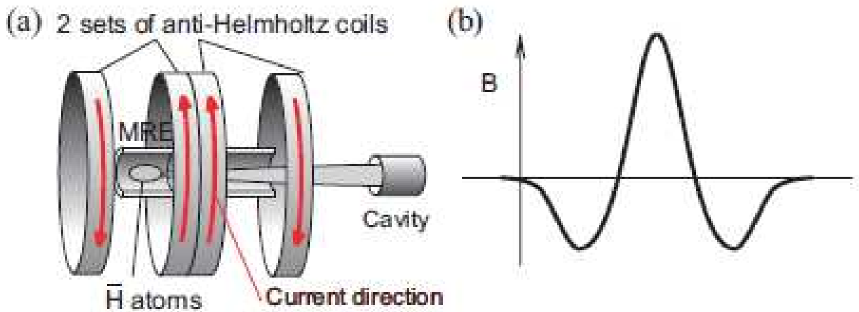
- Hbar production in 2010
- Hbar beam in 2012 (published in 2014)
- Lots of improvements during LS1
- H spectroscopy in 2014
- Analysis of 2014 Hbar data in progress

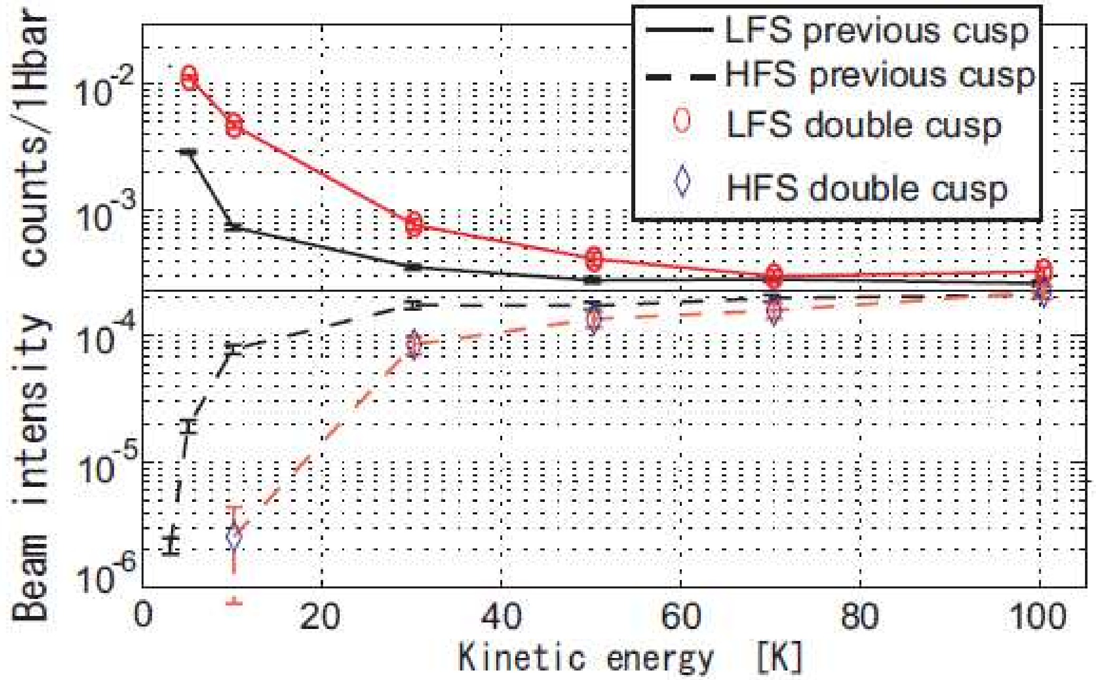
Recent improvements

-Installation and successful operation of a new double cusp magnet
-Installation and successful operation of a new multi-ring electrodes (MRE)
-Installation and successful operation of a new Asacusa Micromegas
-Installation and successful operation of a new eld ionizer
-Installation and successful operation of a new H detector consisting of a BGO disc with 2D read-out and a double layered hodoscope
-An order of magnitude faster positron accumulation as compared to 2012
-Stable manipulation of positron plasma in the double cusp magnet
-Successful transport of 60eV antiproton beam
-Detection of H atoms 3.4 m downstream from the nested well (including candidates in the ground state)

cusp → 2-cusp

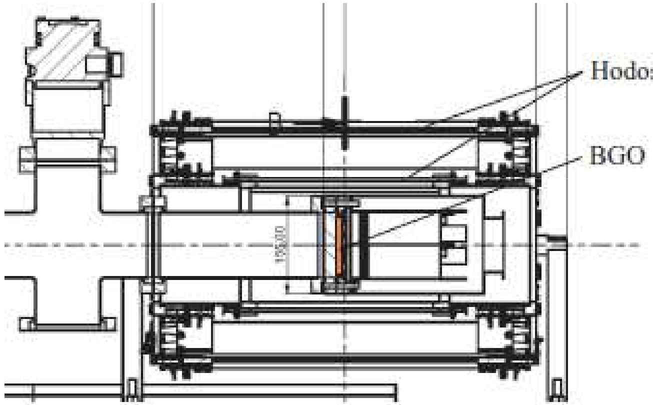




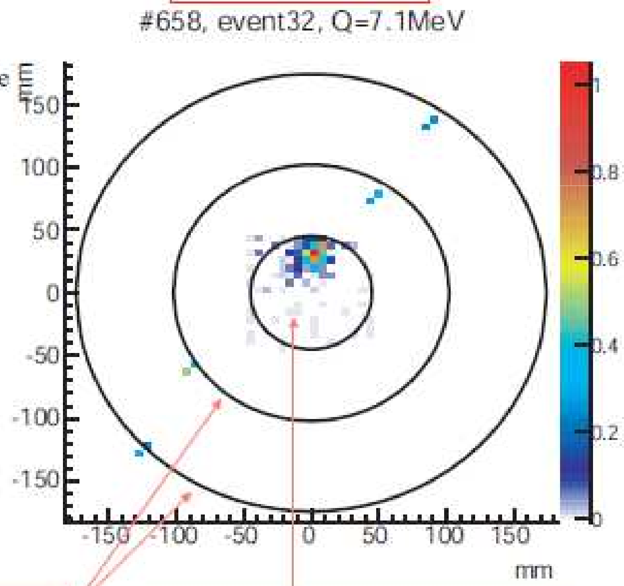


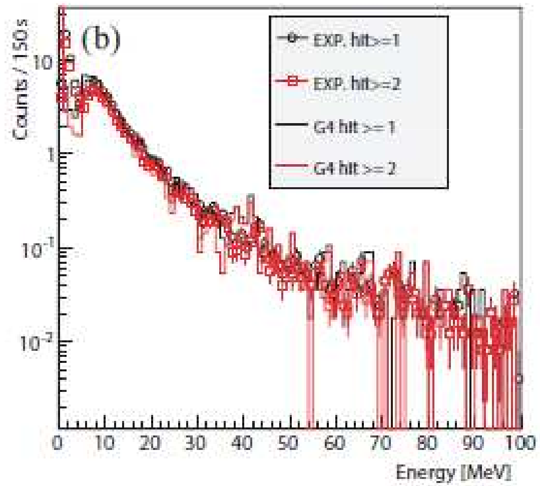
Higher Hbar beam intensity

new antihydrogen detector



cosmic event





Hodoscope:
inner d=200mm, t=5mm 32 bars
outer d=350mm, t=5mm 32 bars
readout - SiPMs

BGO:
d=90mm, t=5mm
readout - 4xMAPMTs

BGO energy deposit (cosmic) measured vs Geant4

Placed @3.4 m (solid angle = 0.004%)

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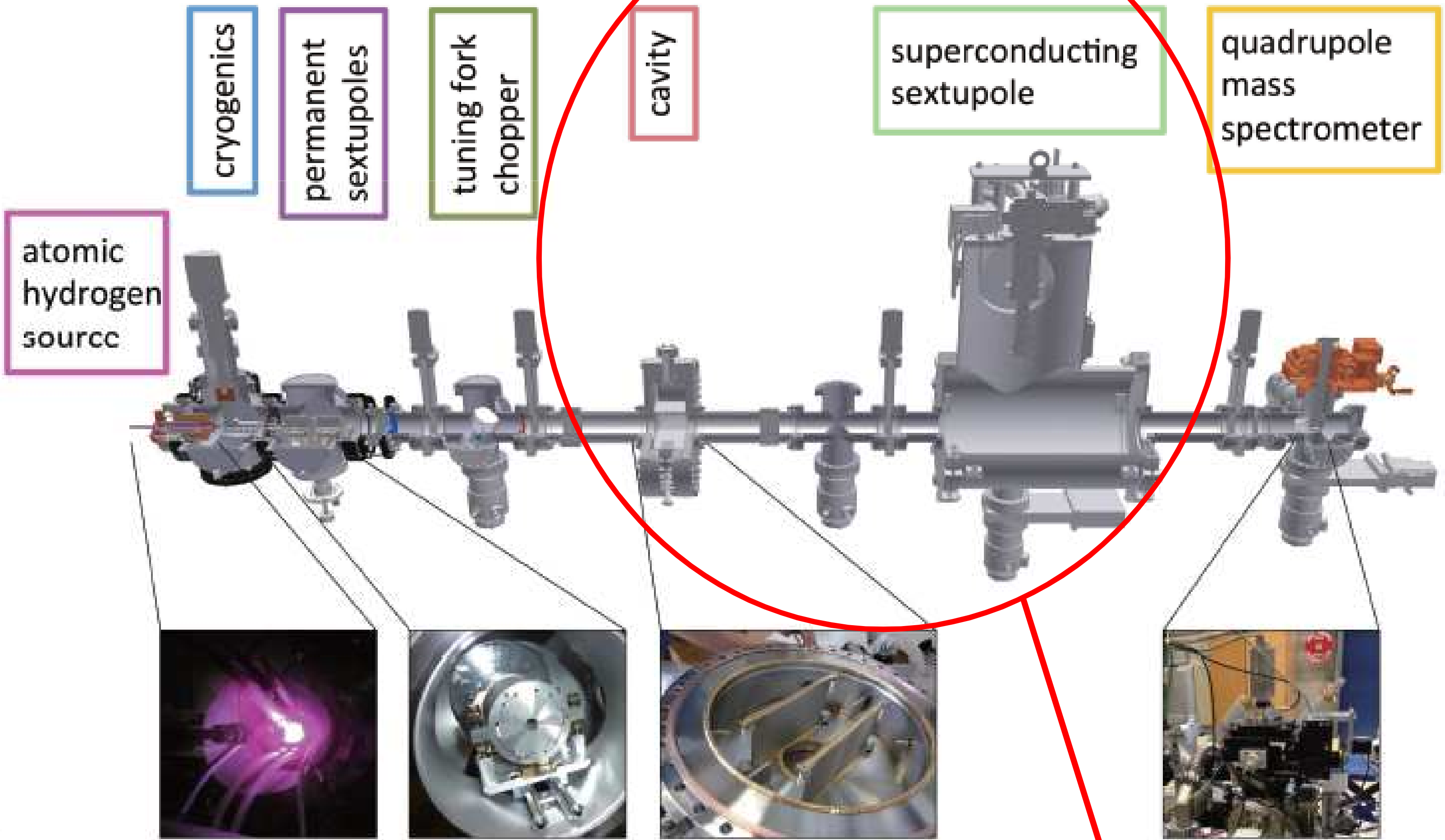
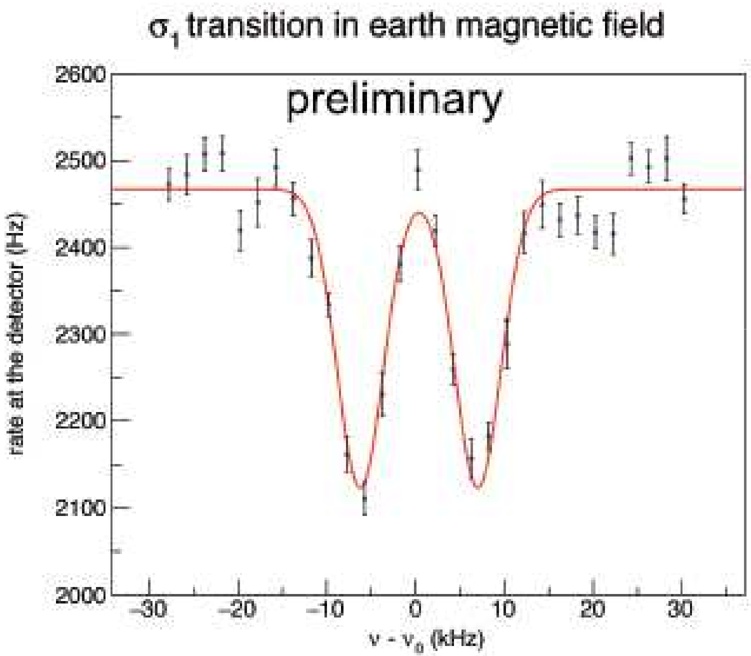
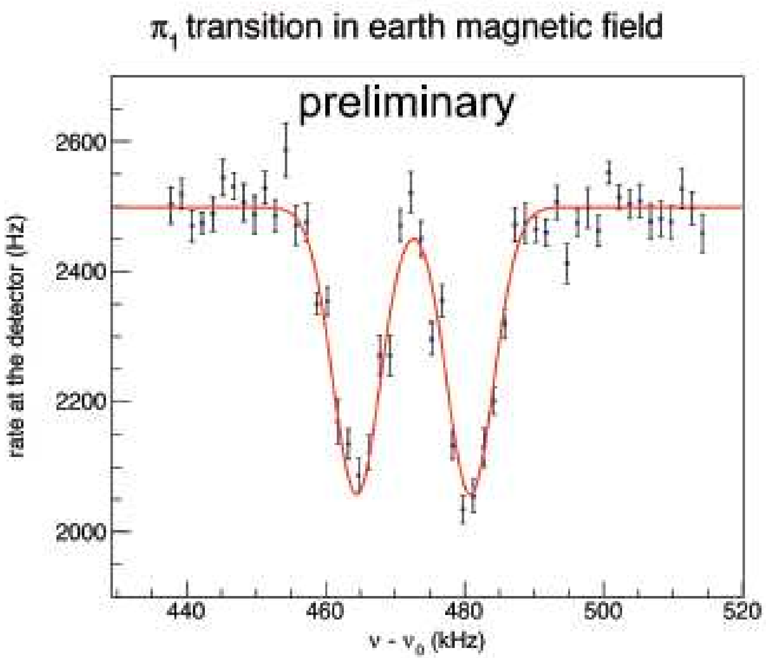
The hydrogen setup

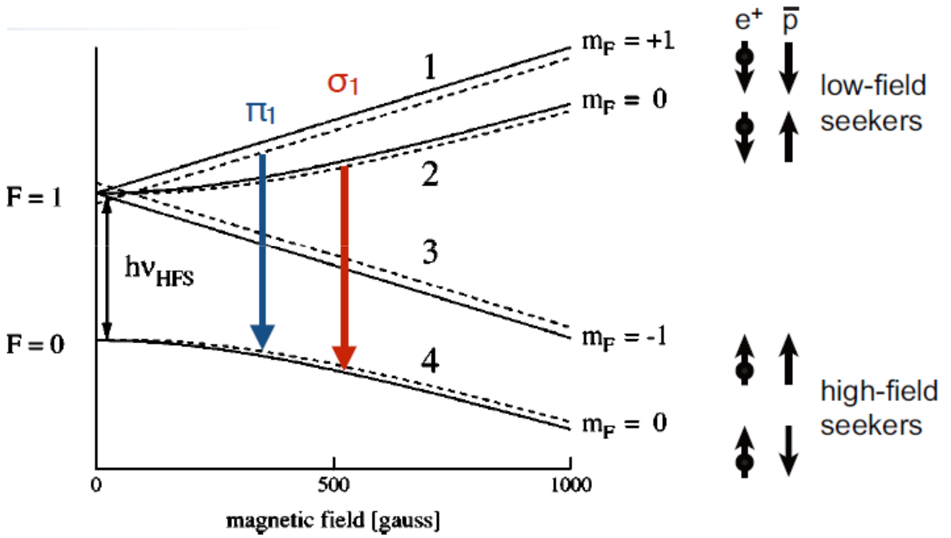


Same as for Hbar

hydrogen σ_1 and π_1 measured







- GS-HFS measured (zero-field extrapolation)
- precision better than 10 ppb (the best value for hydrogen in a Rabi-type experiment, to be published)

Performed by E.Widmann group (SMI)

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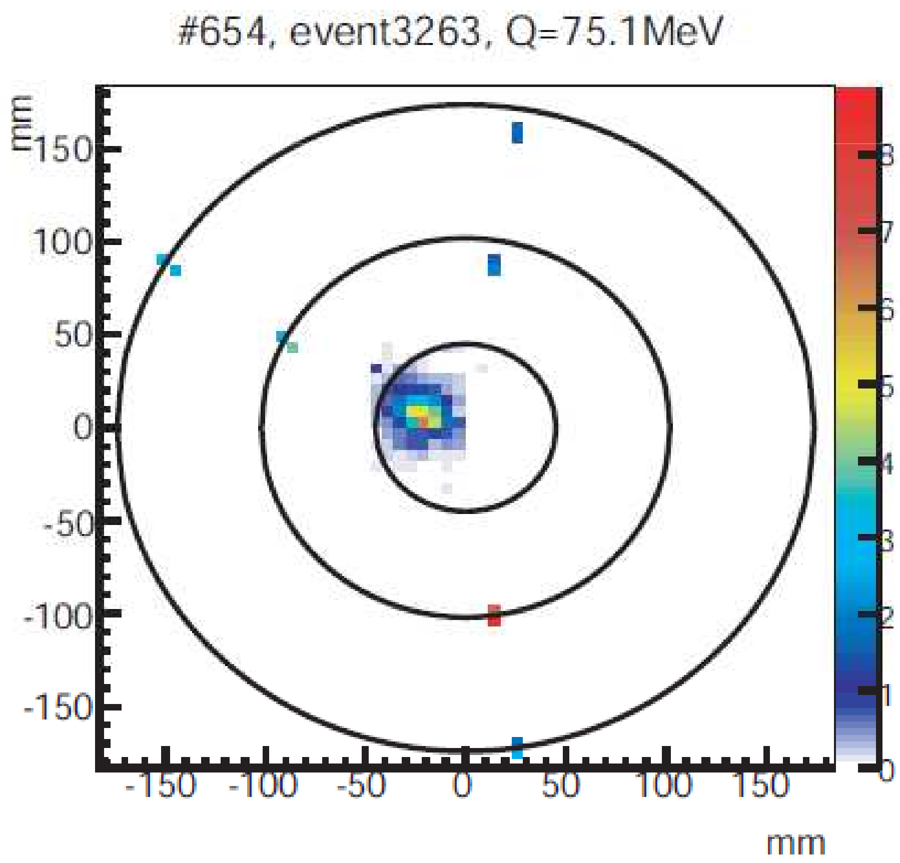
2014 Hbar data analysis

- in progress

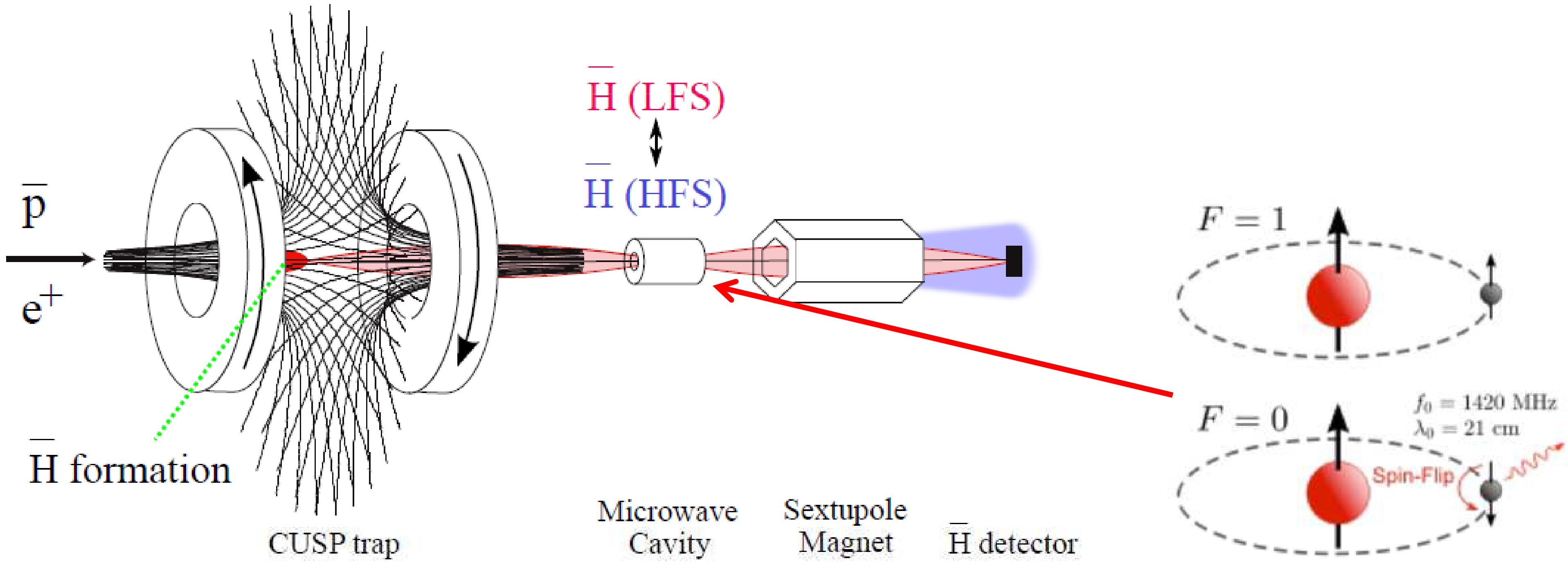


Hbar (n<12) candidate observed @3.4 m

Next steps

Study and improve the beam features (Hbar rate, temperature, n-states,…)

Perform the measurement

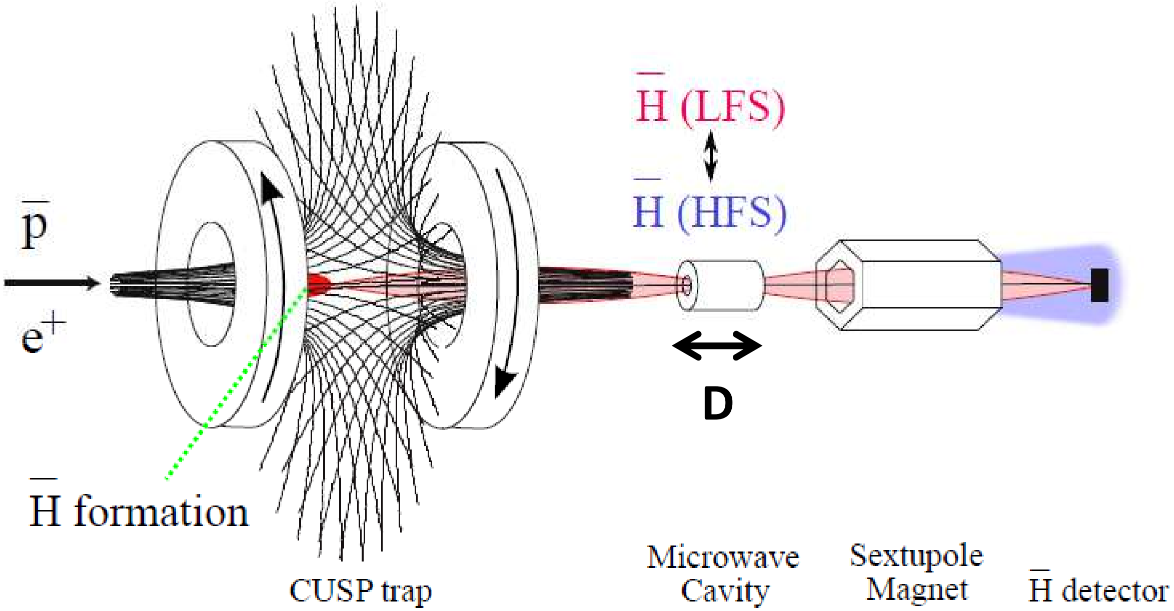


Achievable resolution:

- better than 10^{-6} for T < 100 K

Expectation

Rabi method



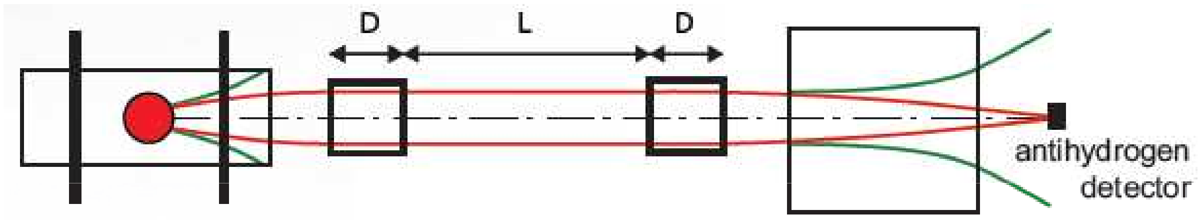
D=10 cm, v=1 km/s (100K)
1/T=10 kHz → linewidth resolution $\delta\nu$ (FWHM) = 0.8/T → $\delta\nu$ / ν =8x10^{-6}
→ Resonance center resolution = 10^{-7}

Achievable resolution:

- better than 10^{-6} for T < 100 K
- 100 Hbar/s in 1S state needed (in 4 π)→ event rate=1/min.

Future improvements

1° improvement (Ramsey separated oscillatory fields):



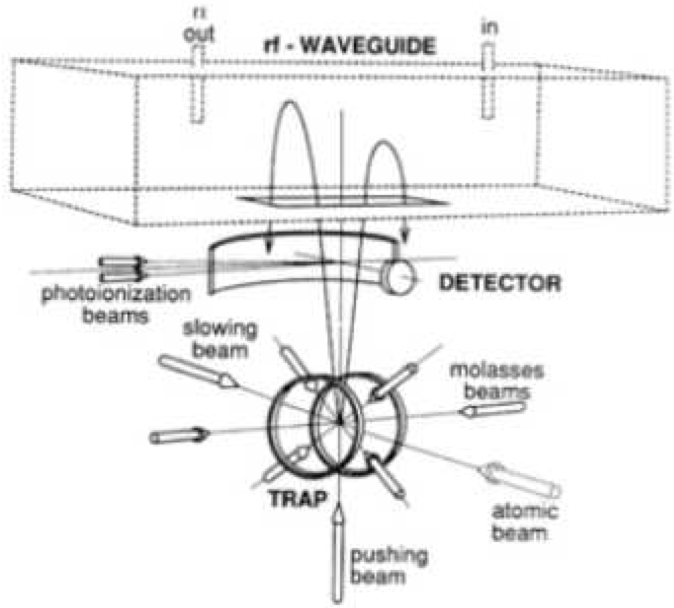
Linewidth reduced by D/L

Antihydrogen fountain:

-trapping and laser cooling

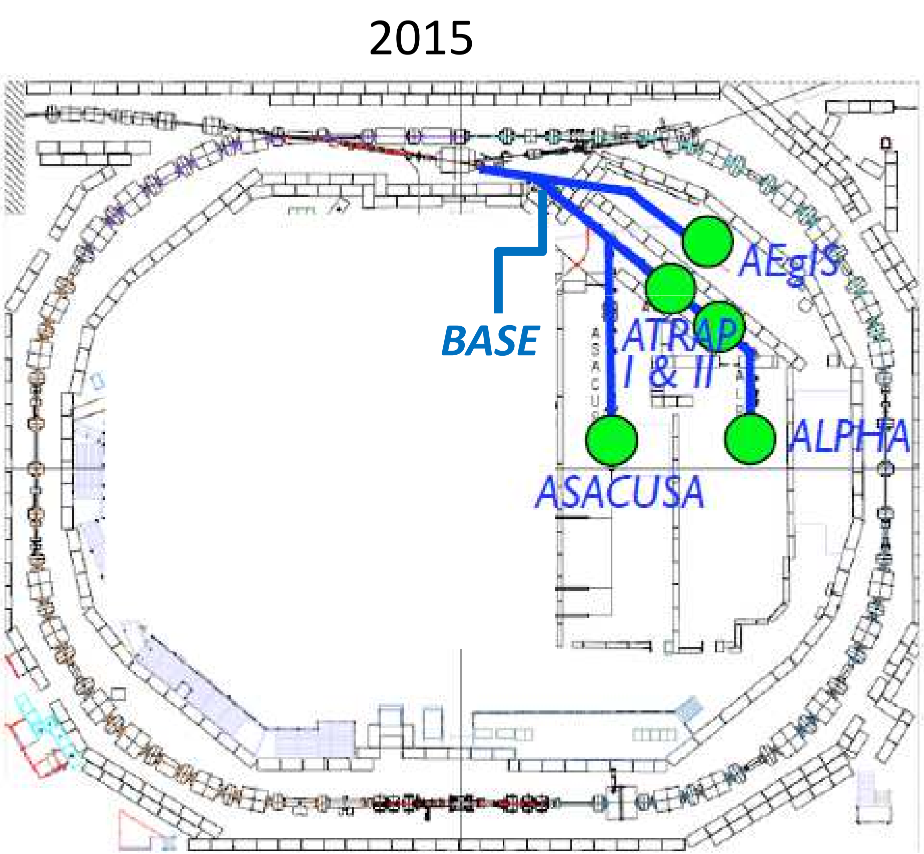
- Ramsey method with L=1m

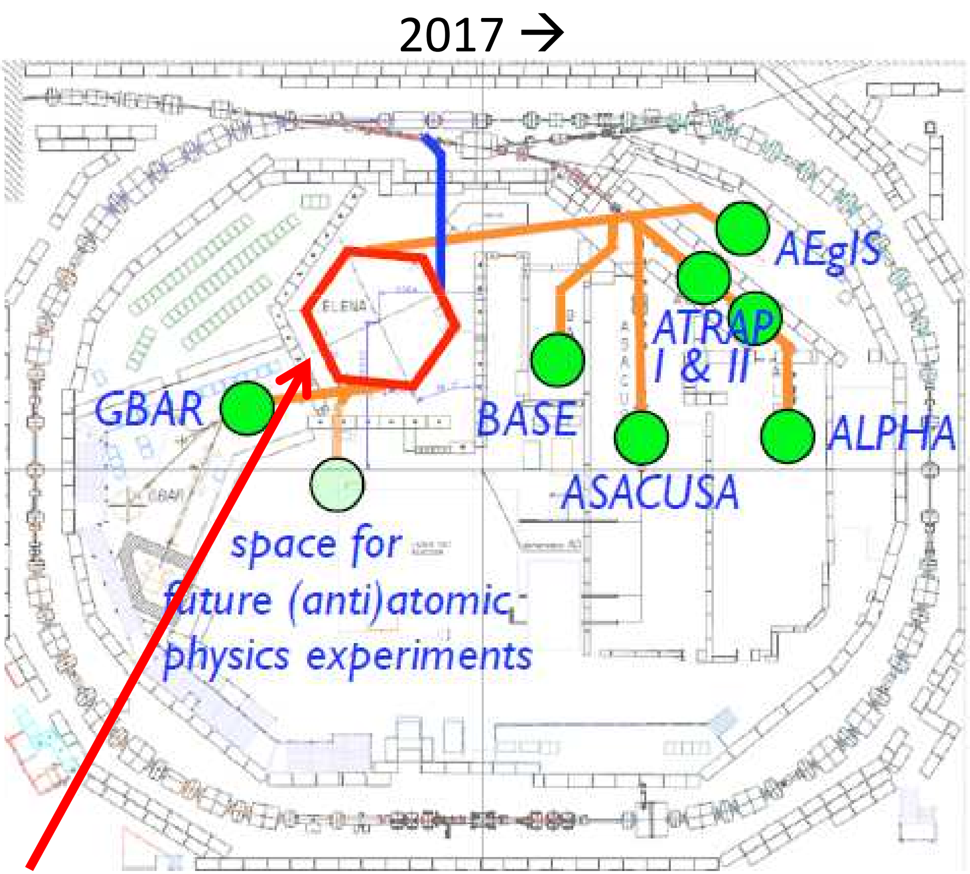
Δf ~3 Hz, $\Delta f/f \sim 2 \times 10^{-9}$



<-- AEGIS

Future





ELENA decelerator:

5.3 MeV → 100 keV

x 100 pbars trapping efficiencies

4 experiments can run in parallel

Summary

- Antihydrogen measurements promises high sensitive tests of CPT symmetry

- First cold beam of antihydrogen atoms produced by ASACUSA

- HFS measurement of hydrogen beam ($<10^{-8}$)

- beam features need to be investigated and improved (rate, temperature, n-states,…)

- the present result together with those from the other AD experiments $\rightarrow$ spectroscopy era