The First Cold Beam of Antihydrogen Atoms from a Cusp Trap

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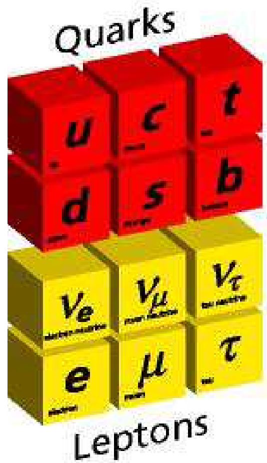
Antihydrogen

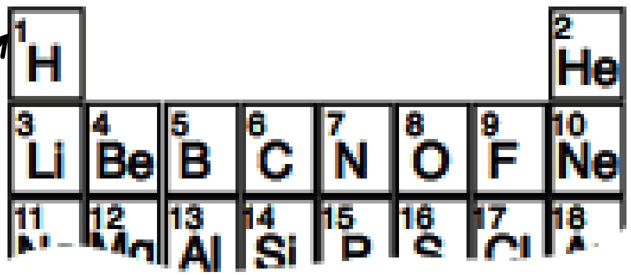
Antihydrogen is the bound state of an antiproton and a positron

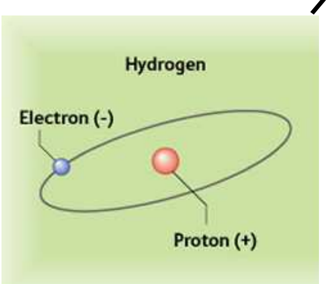
Matter

particles

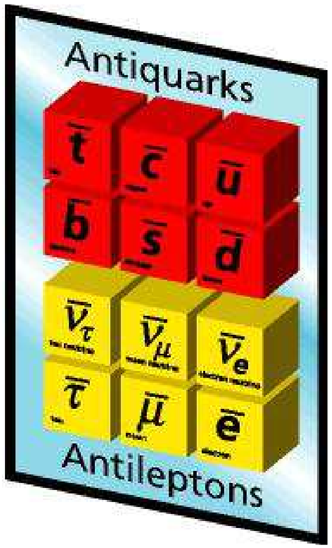


elements



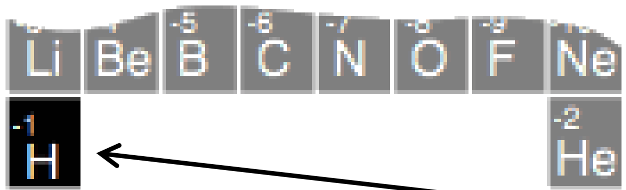


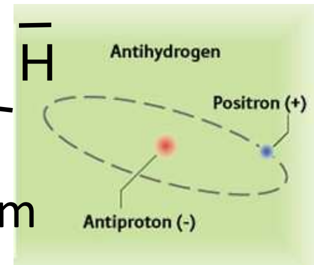
Anti-matter



antiparticles

anti-elements

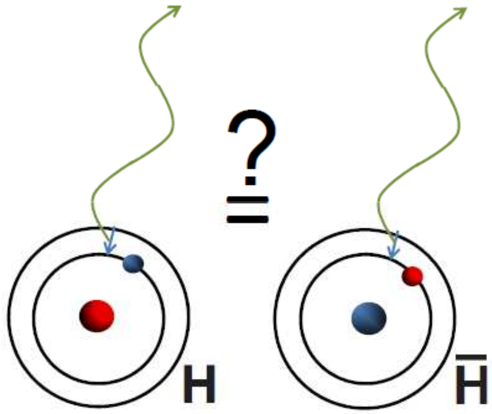




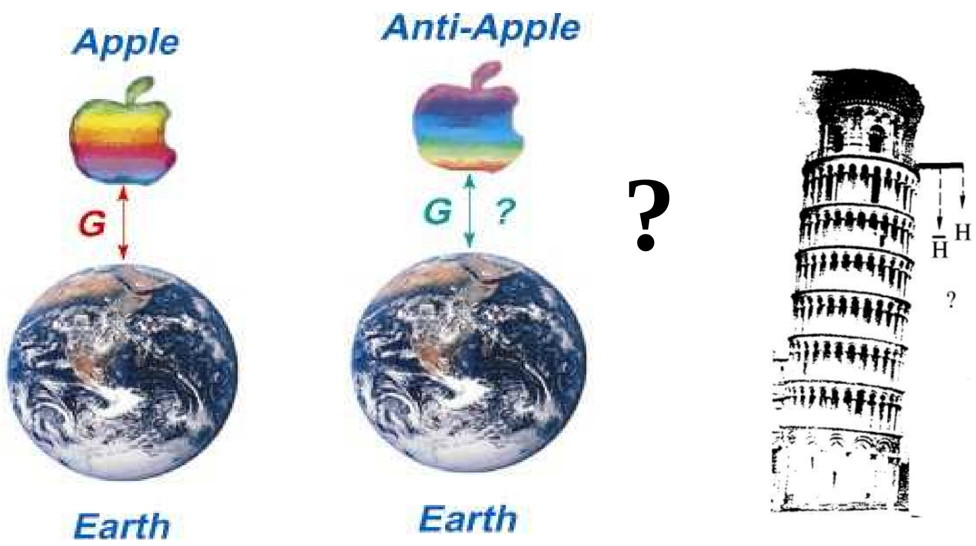
Antihydrogen is the simplest atom consisting entirely of antimatter

Why study antihydrogen

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



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

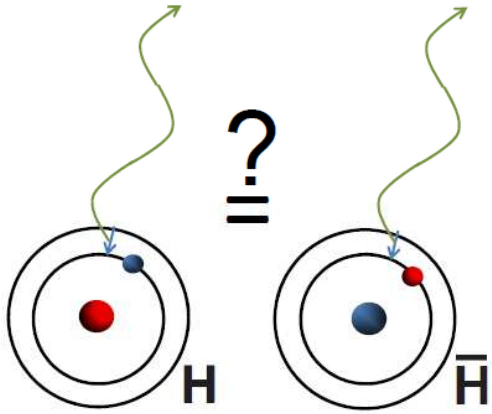


Impossible with charged antiparticle

only with neutral system → $\bar{H}$

Why study antihydrogen

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



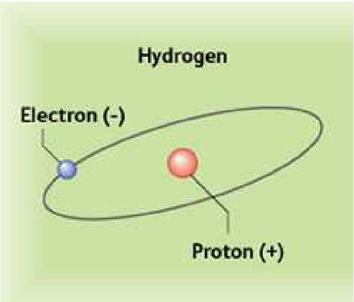
2) Measurement of the gravitational behaviour of antimatter→ test of WEP

antiparticle

utral system → $\bar{H}$

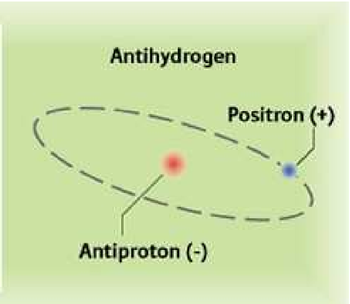
Not discussed here

Antihydrogen: what is it known?



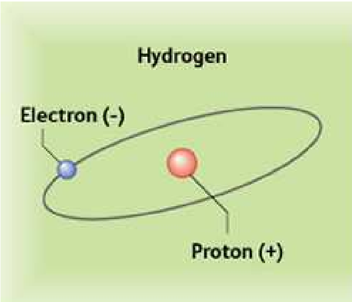
Hydrogen

Antihydrogen

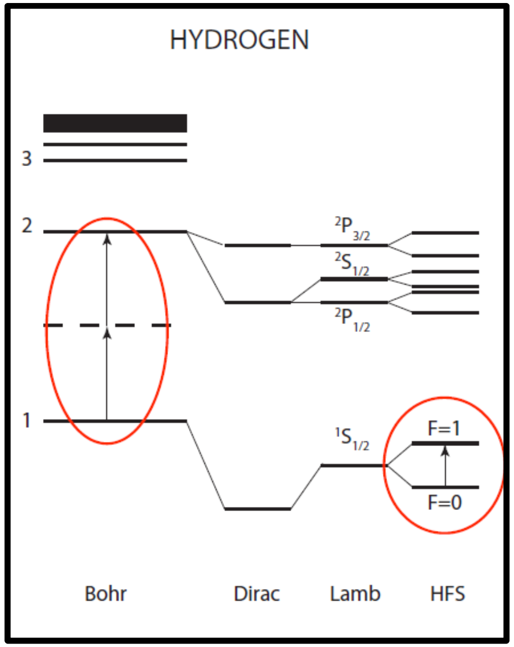


$\bar{H}$

Antihydrogen: what is it known?



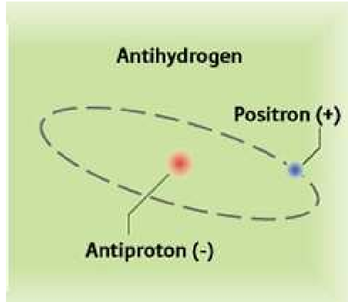
Hydrogen



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}	$1420\,405\,751.7667(9)$	6.3×10^{-13}	$(3.5\pm0.9)\times10^{-6}$

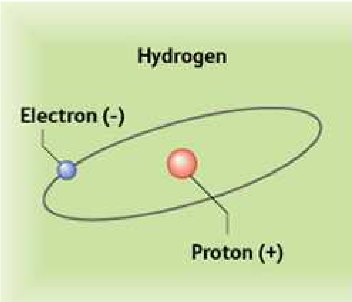
Antihydrogen



$\bar{H}$

Antihydrogen: what is it known?

Hydrogen



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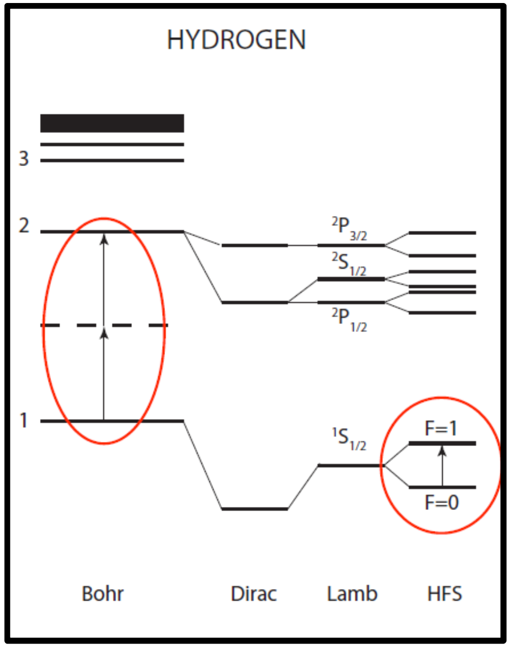

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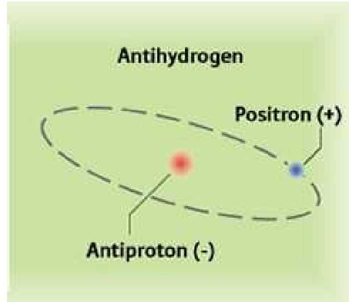
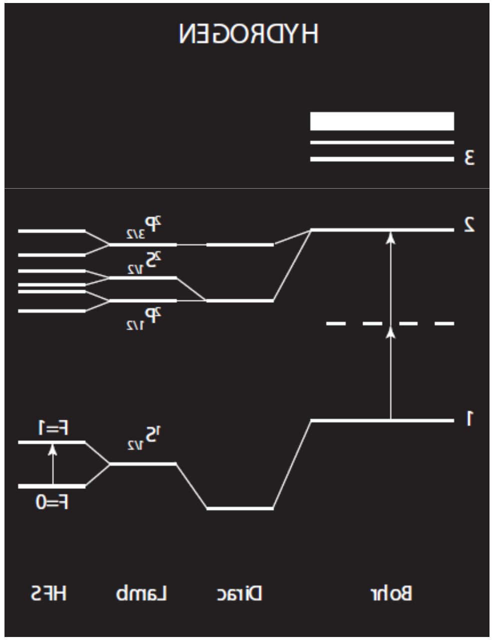
Antihydrogen



$\bar{H}$



← Expected from CPT

significant milestones achieved

→ see Fujiwara's talk

But

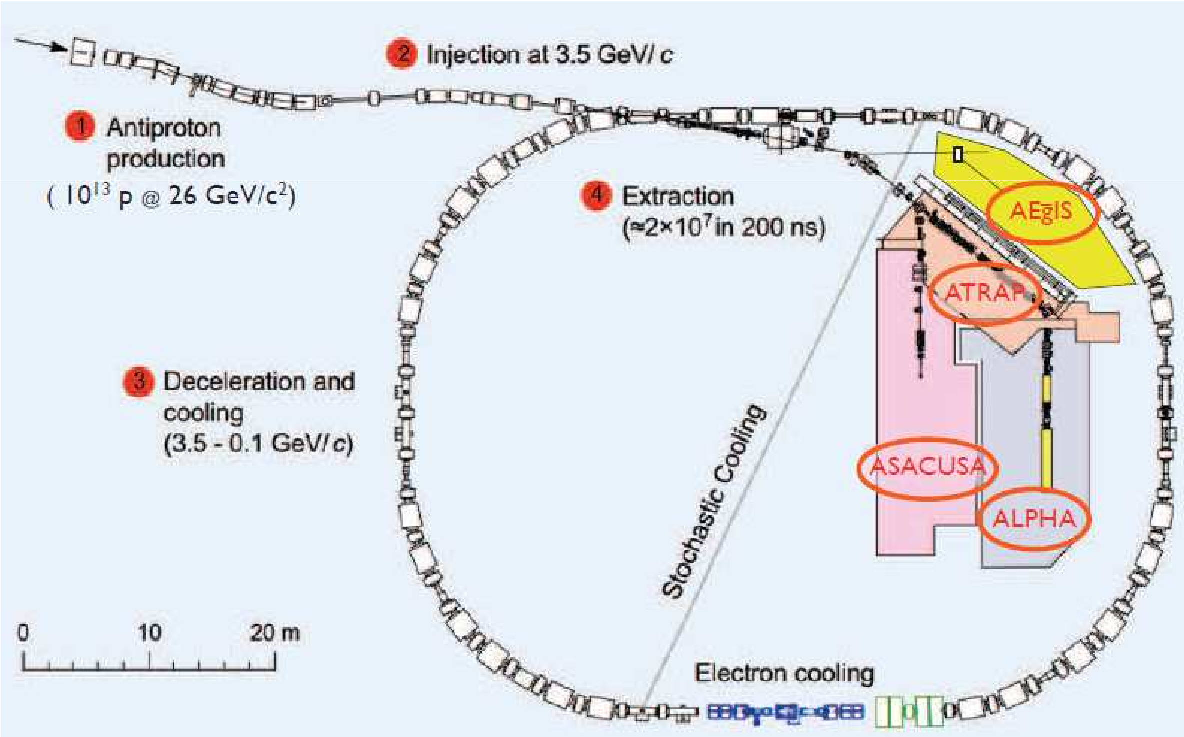
no precise measurement so far

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 :

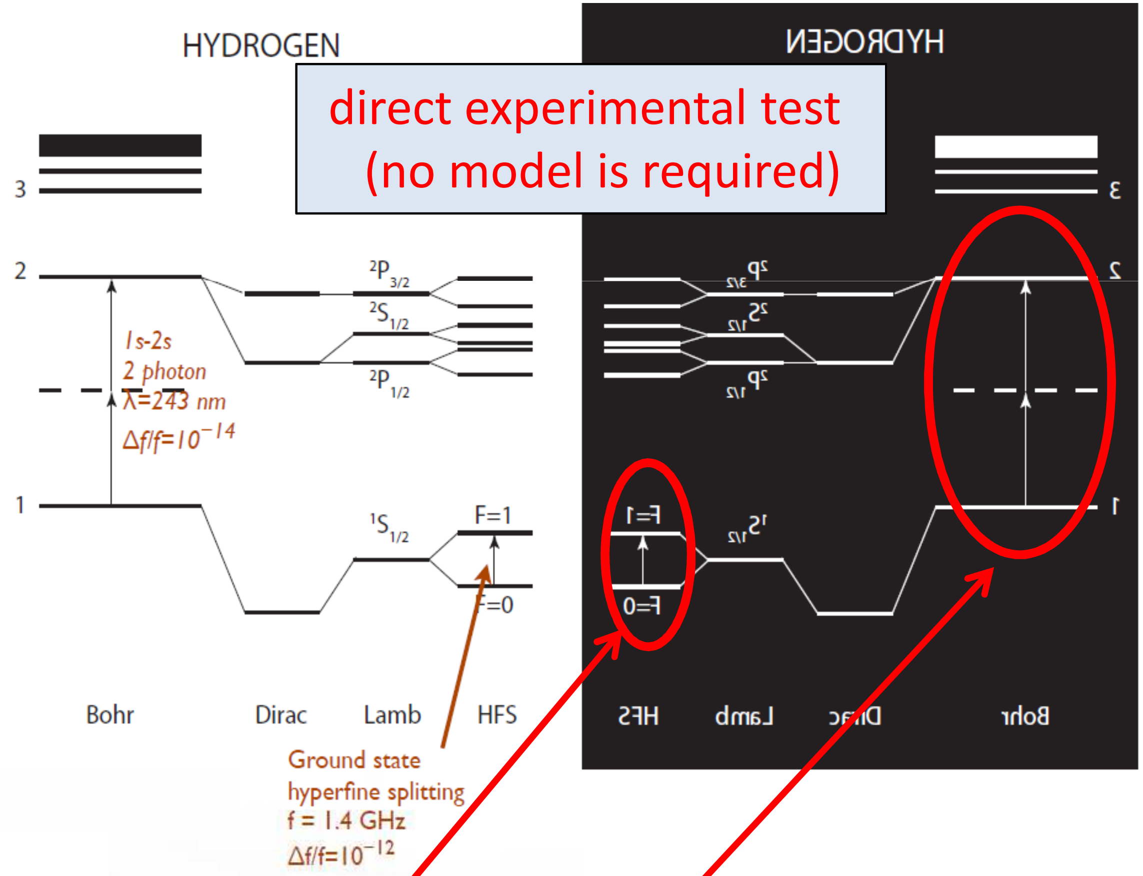
- 2-4 10^7 antiprotons per bunch
  (150-300 ns length)
- 1 bunch/ 100 s
- Energy = 5.3 MeV (100 MeV/c)

Experiments: - (2014) ALPHA, ATRAP, ASACUSA, ACE, AEgIS, BASE

- ATHENA (terminated), GBAR (future)

Antihydrogen for CPT test

matter-antimatter precise comparison by means of spectroscopy



direct experimental test (no model is required)

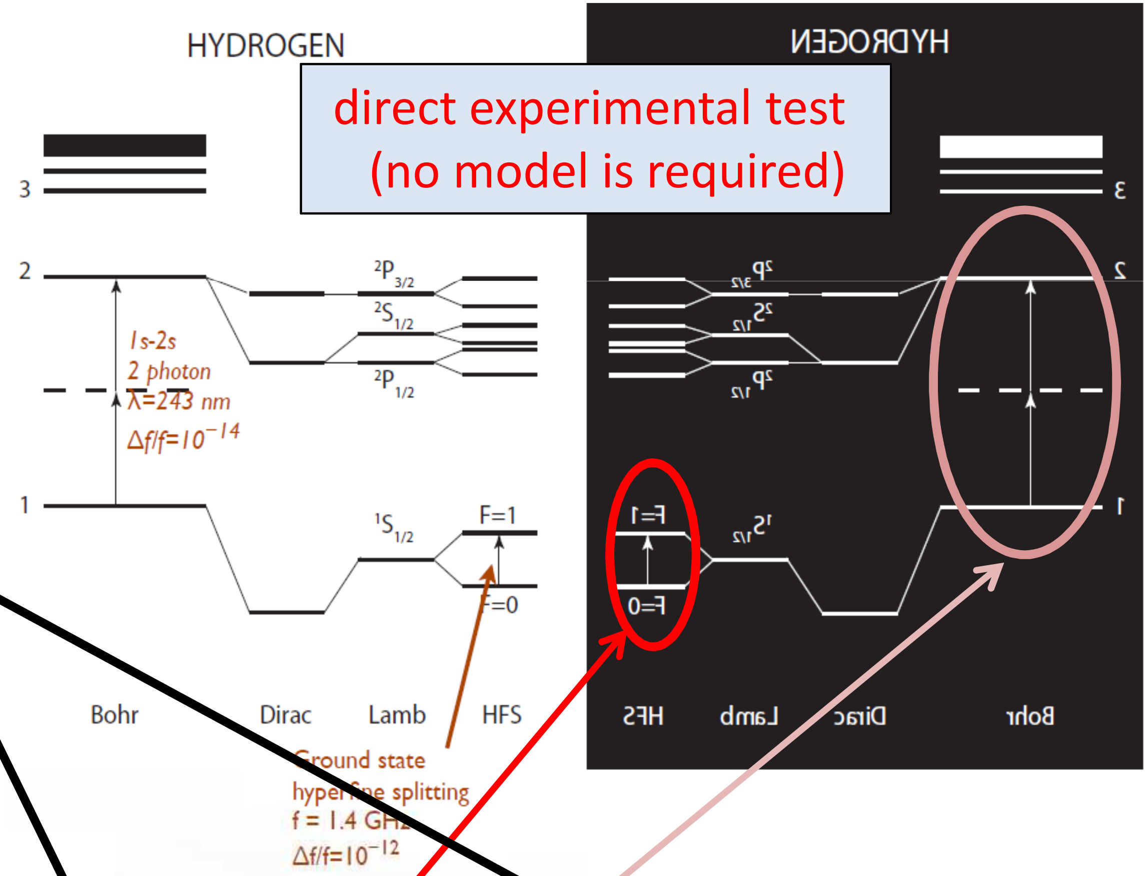
Plans for antihydrogen:

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

- methods:
  - Antihydrogen trapping
  - Antihydrogen beam

Antihydrogen for CPT test

matter-antimatter precise comparison by means of spectroscopy



ASACUSA

AEGIS

Plans for antihydrogen:

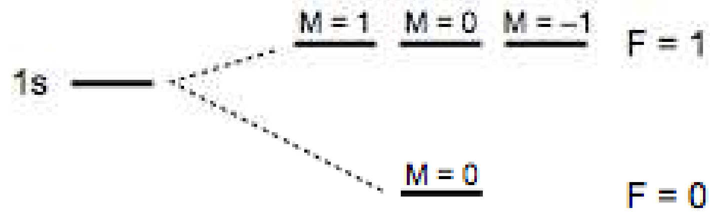
- measurements: **- Hyperfine splitting of ground state**
  - 1S-2S transition

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

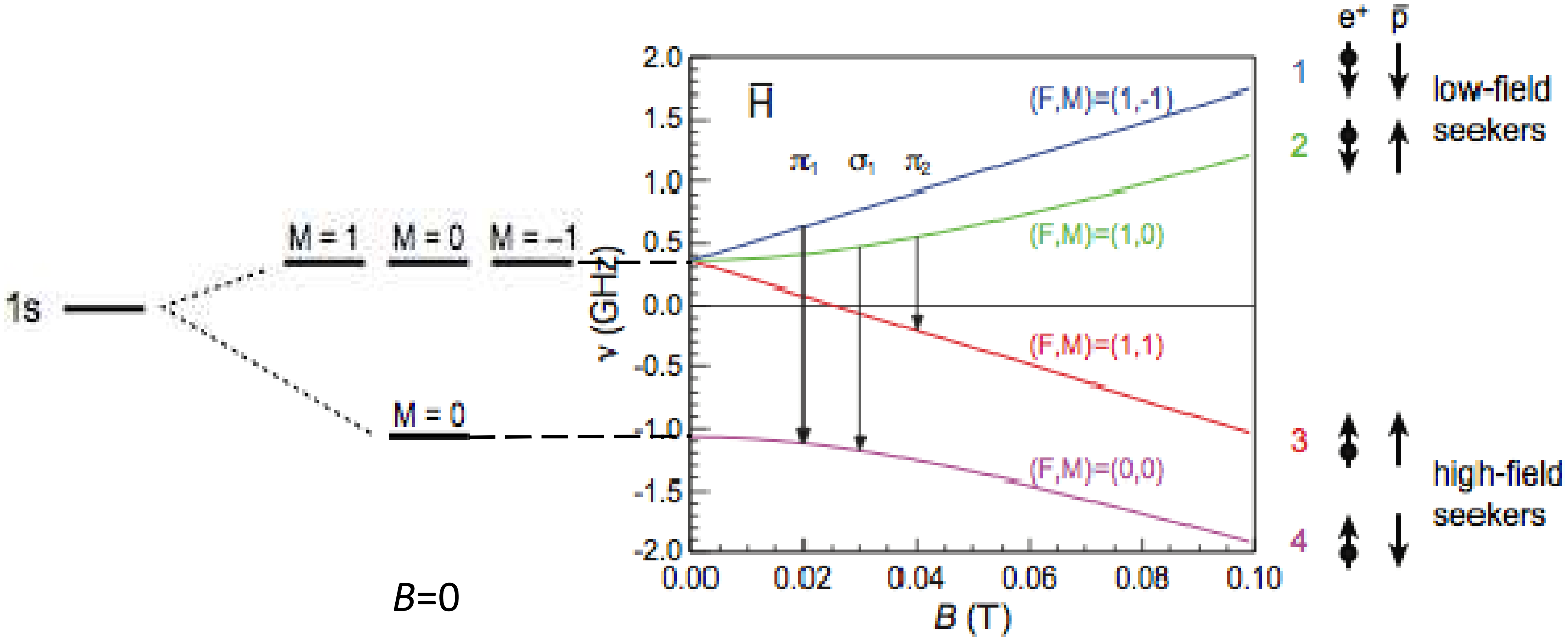
- ν_{HF} is proportional to the (anti)proton magnetic moment $\mu_{\bar{p}}$ (5 ppm 2012 Gabrielse, previously 0.3%)
- δ: higher-order QED & strong interaction corrections: ~10^{-3}
- Theoretical uncertainty on δ: ~10^{-6}

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 (μ < 0)

Energy decreases for (*F*, *M*) = (1, 1) and (0, 0): high-field seekers (μ > 0)

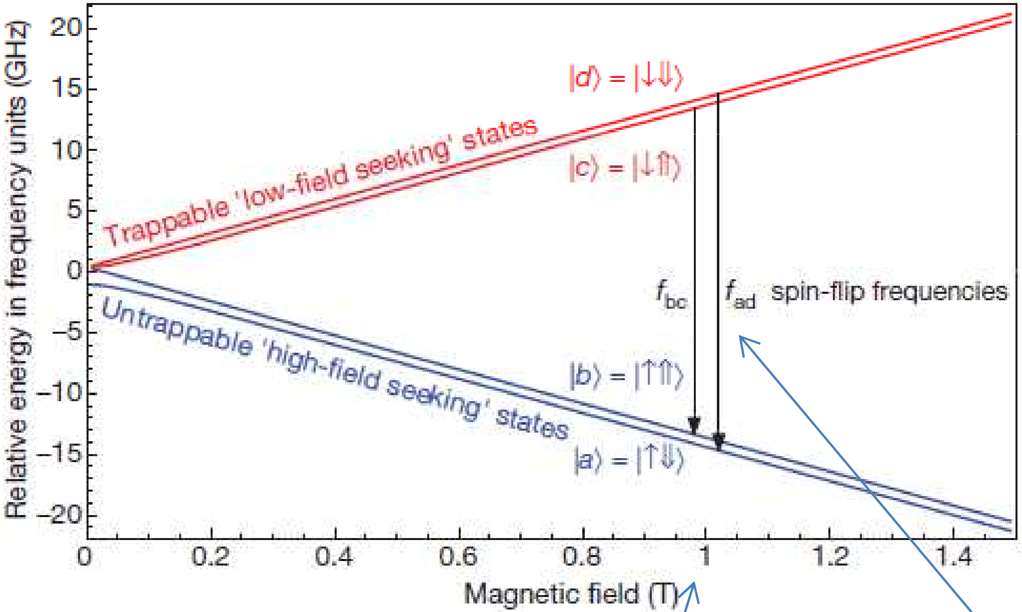


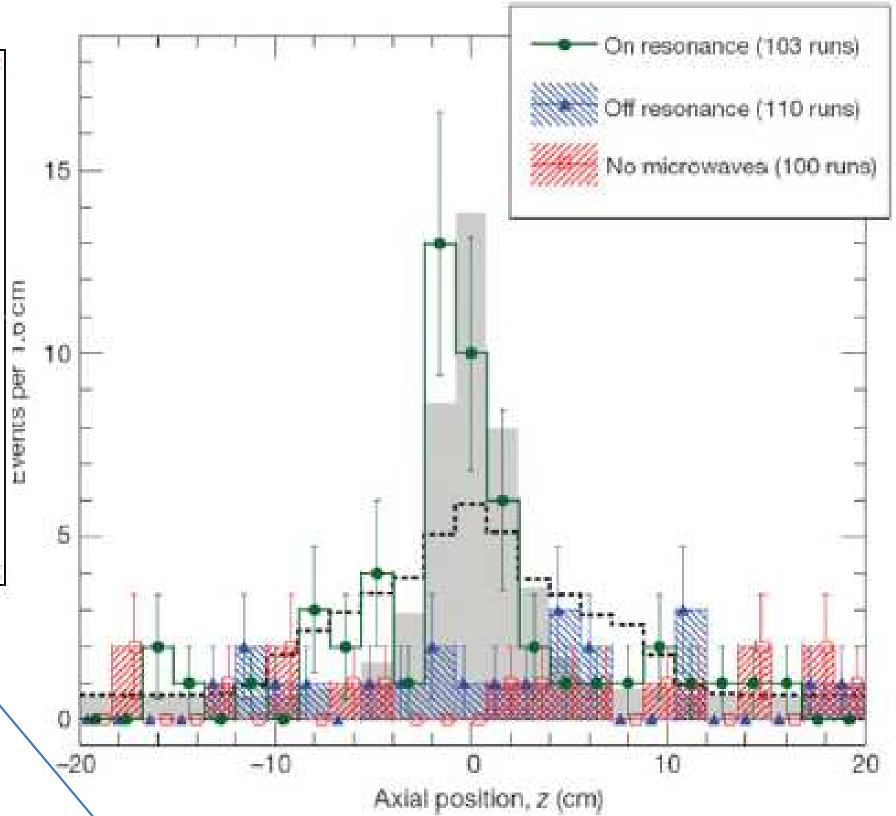
Antihydrogen GS-HFS measurement

- 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

ASACUSA

ASAKUSA KANNON TEMPLE
BY UTAGAWA HIROSHIGE (1797-1858)

Atomic **S**pectroscopy **A**nd **C**ollisions
Using **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]

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5 CERN, 1211 Genève, Switzerland
6 Dipartimento di Ingegneria dell'Informazione, Università di Brescia & Istituto Nazionale di Fisica Nucleare, Gruppo Collegato di Brescia, 25133 Brescia, Italy
7 Department of Physics, Tokyo University of Science, Tokyo 162-8601, Japan
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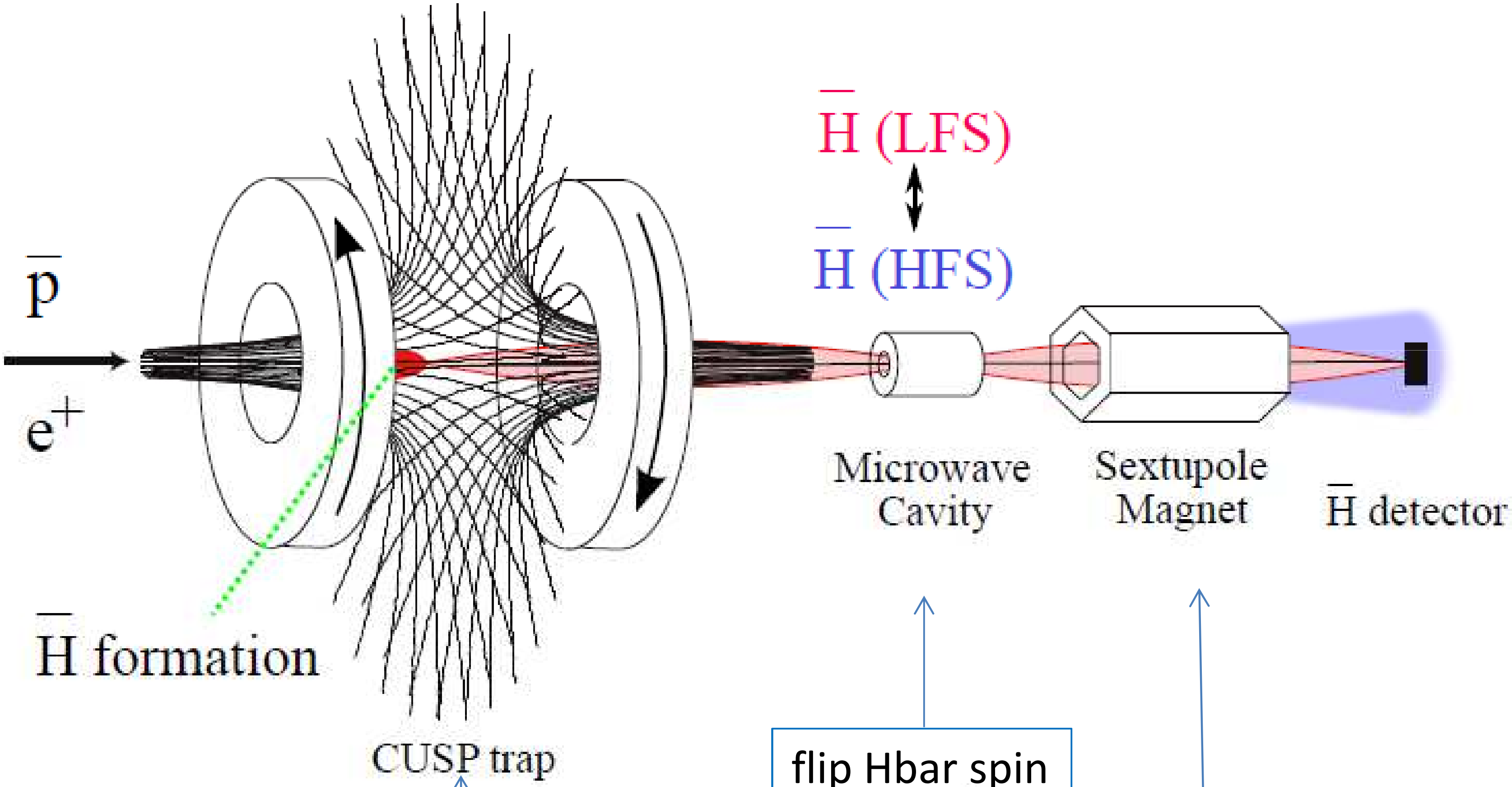
Scheme of the measurement



confine pbars and e^+ ;
select Hbar spin state

flip Hbar spin

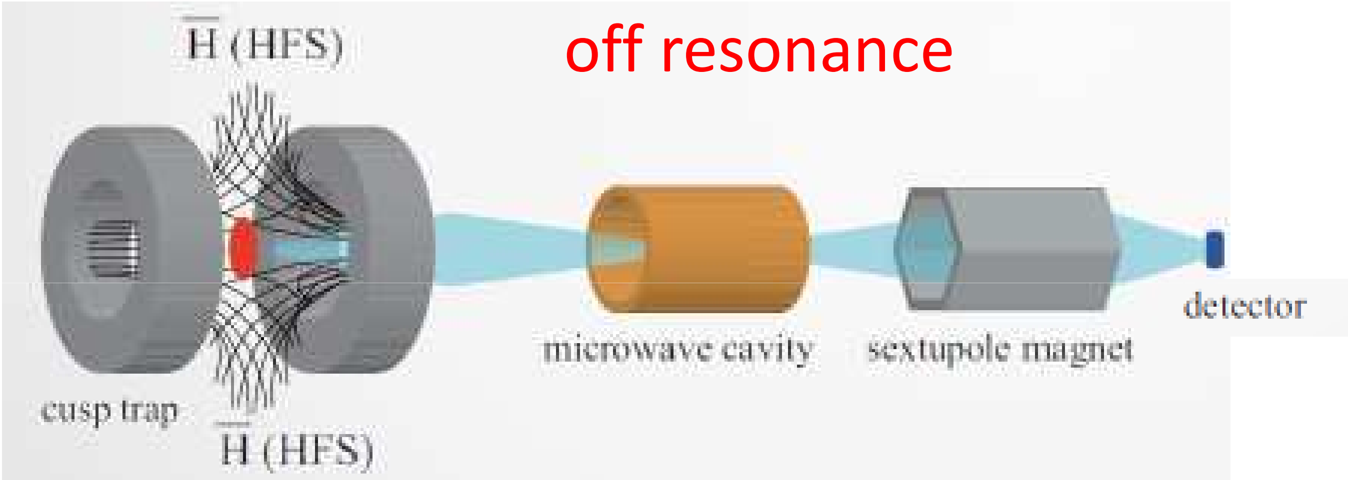
select spin state

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

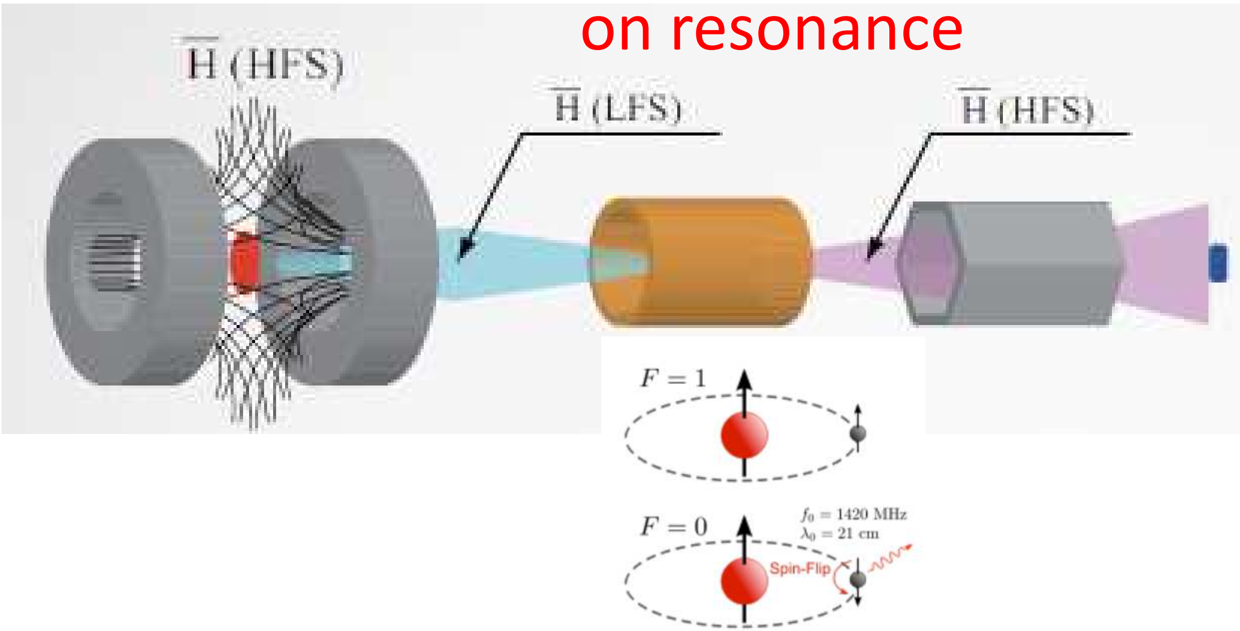
B and **E** axially symmetric

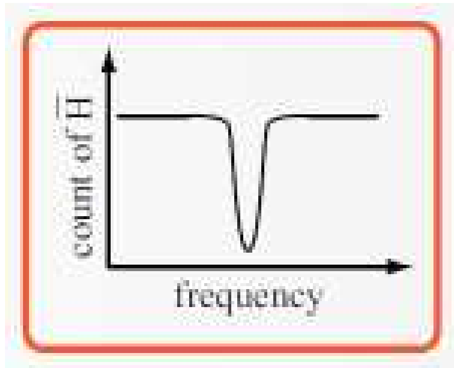
Scheme of the measurement

off resonance



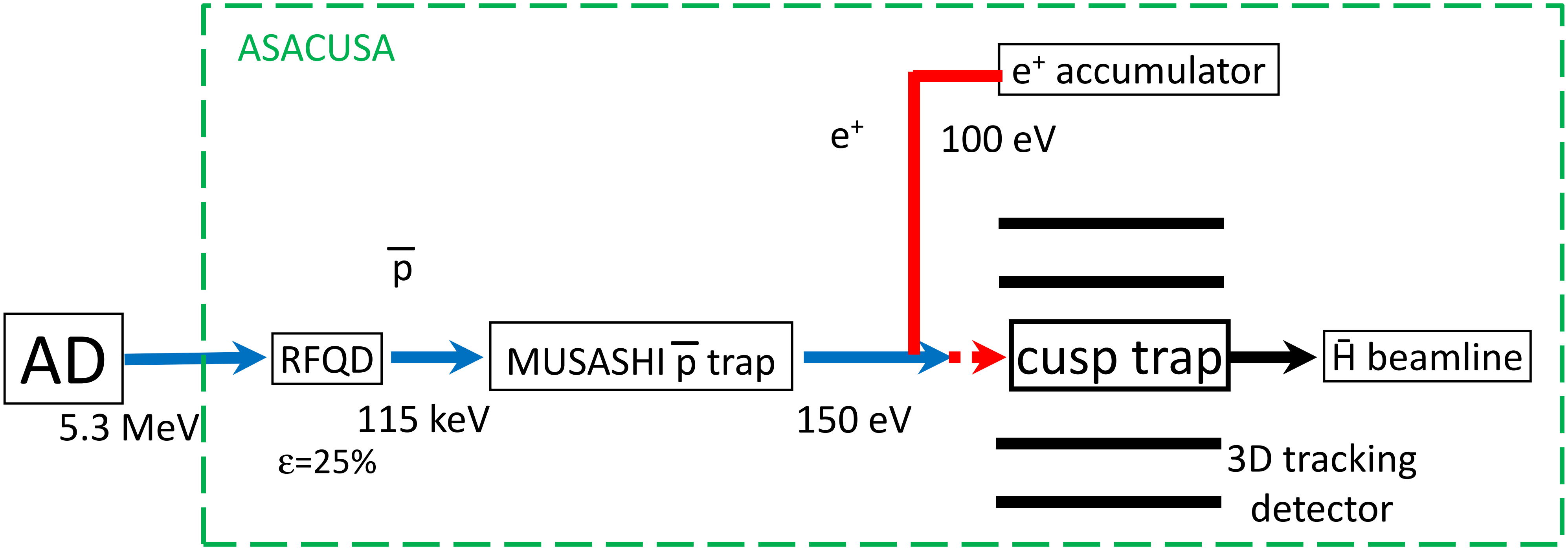
on resonance





“Disappearance Mode”

Scheme of the experimental set-up



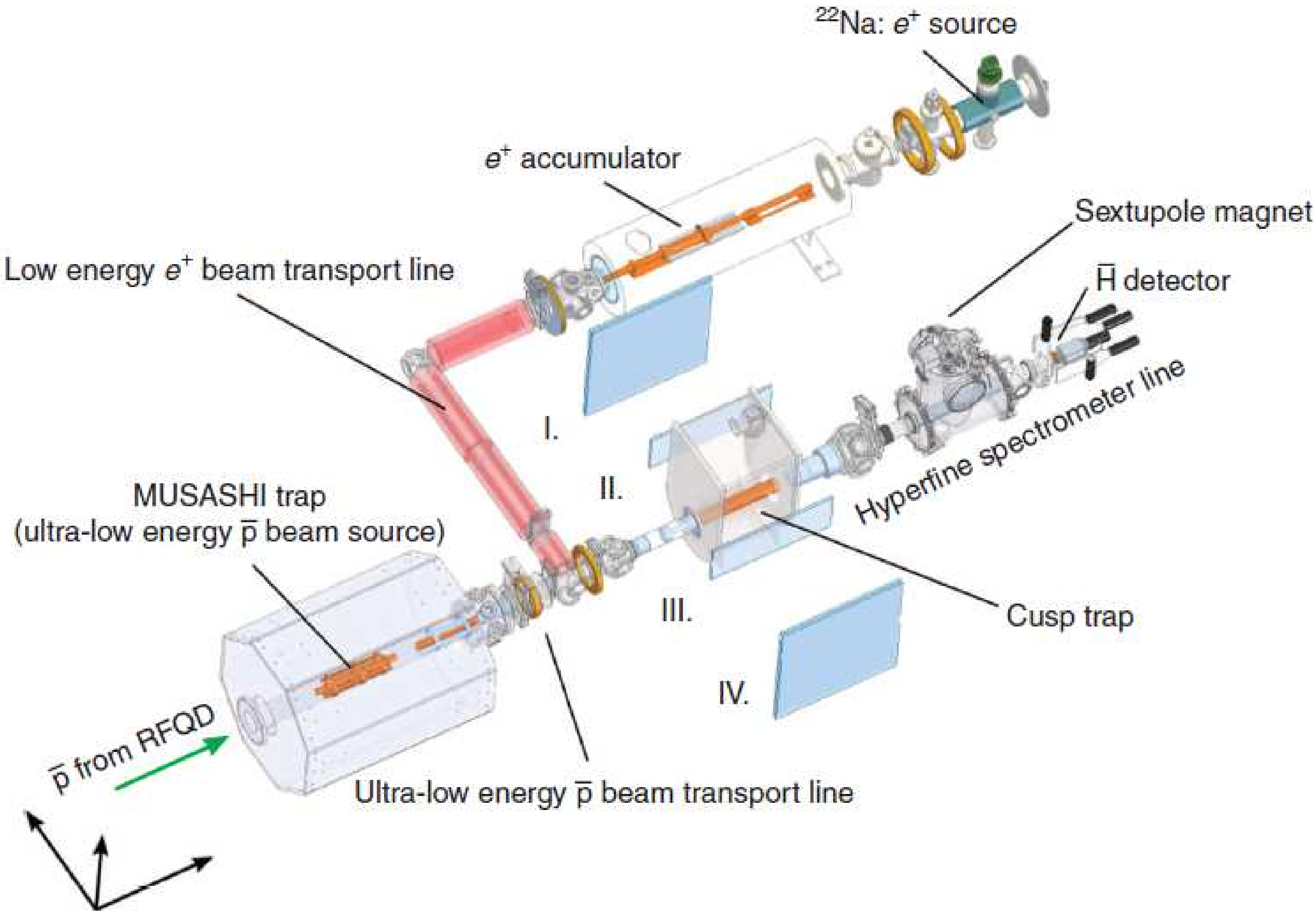
$\bar{p}$:

- decelerated 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

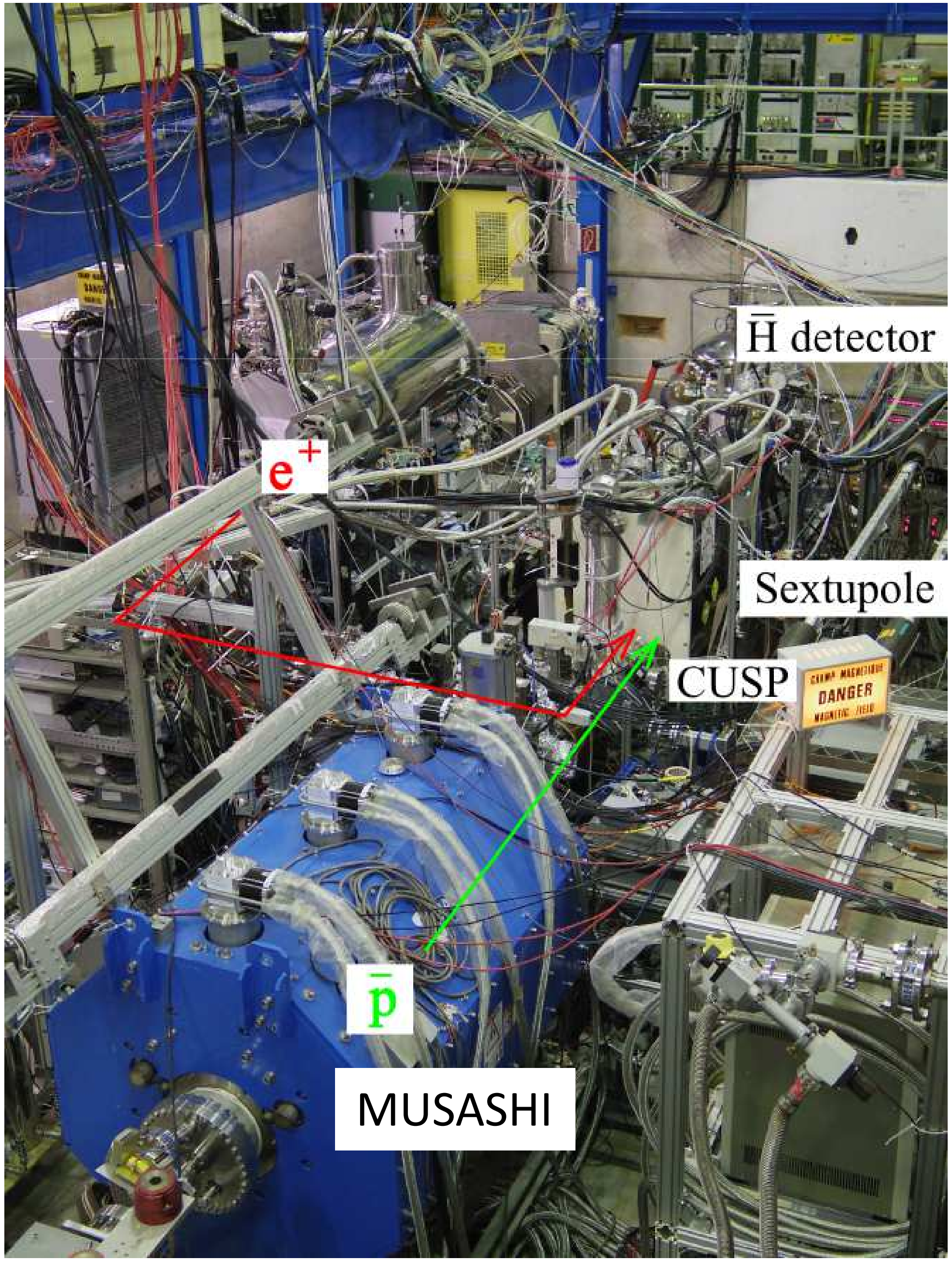
e^+:

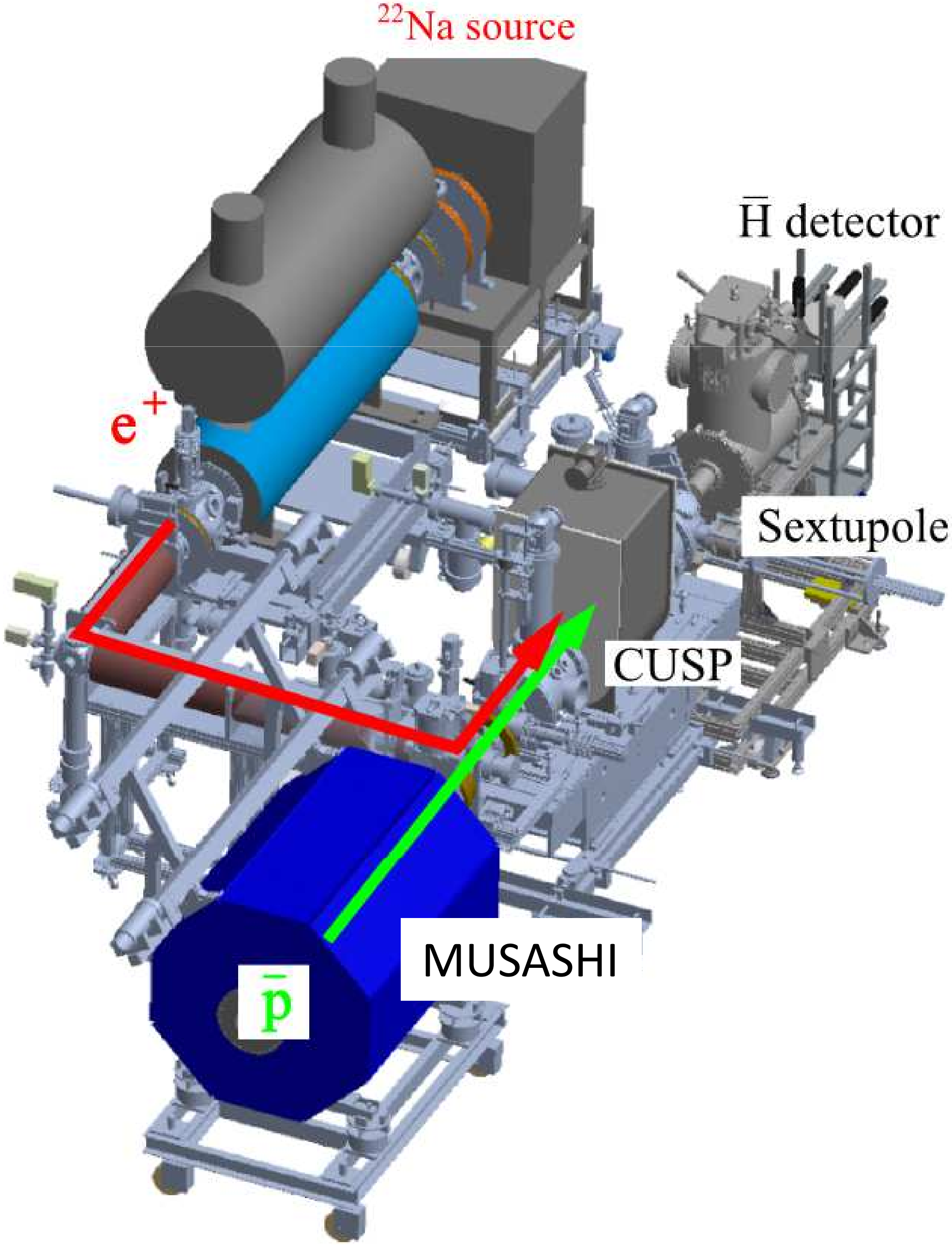
- ^{22}Na source (0.6 GBq), Ne moderator, N_2 gas moderator, MRE
- accumulation (10–100 stacks)
- transfer of 3 10^7 every 10 min to the cusp

Experimental set-up

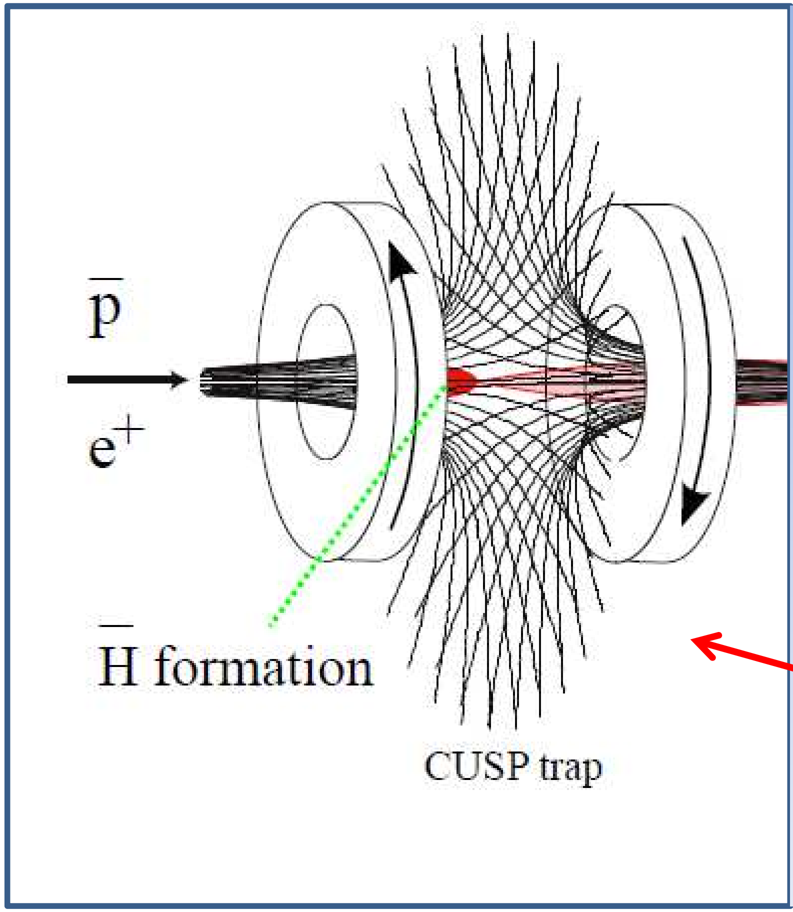


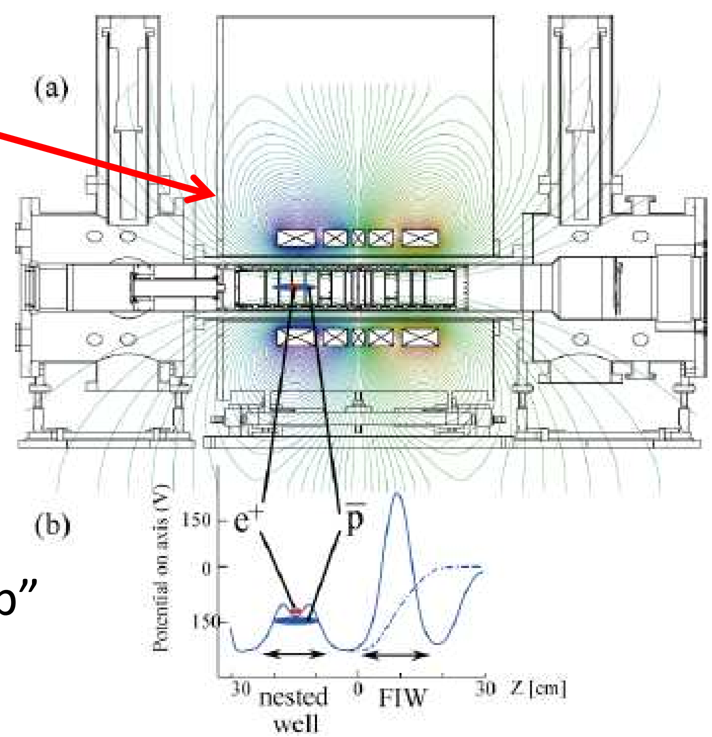
Experimental set-up





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

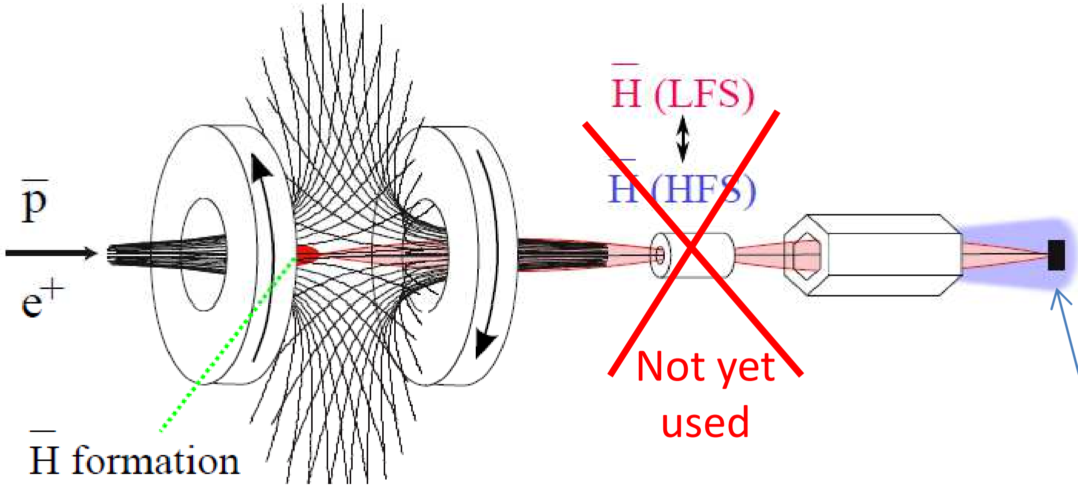
It was a tough decision, given all the fantastic physics done in 2010. But we have decided to award the *Physics World* 2010 Breakthrough of the Year to two international teams of physicists at CERN, who have created new ways of controlling antiatoms of hydrogen.

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

Antihydrogen beam



nature COMMUNICATIONS

ARTICLE

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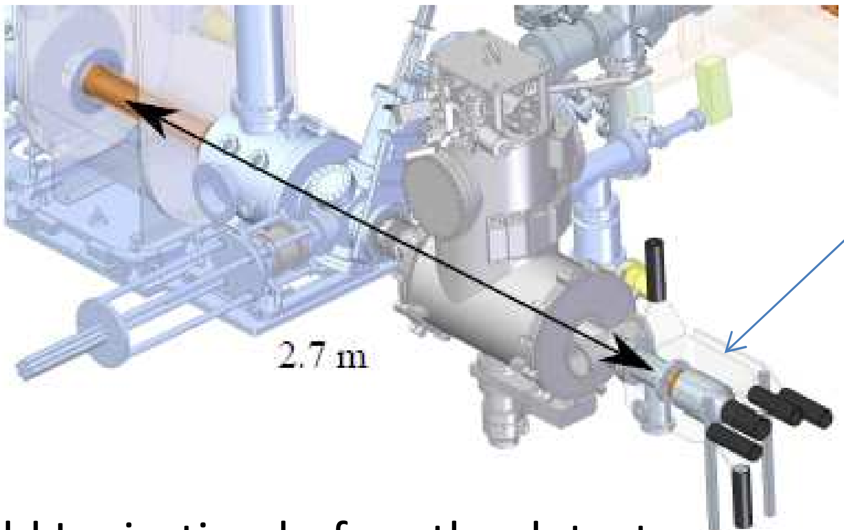
A source of antihydrogen for in-flight hyperfine spectroscopy

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]

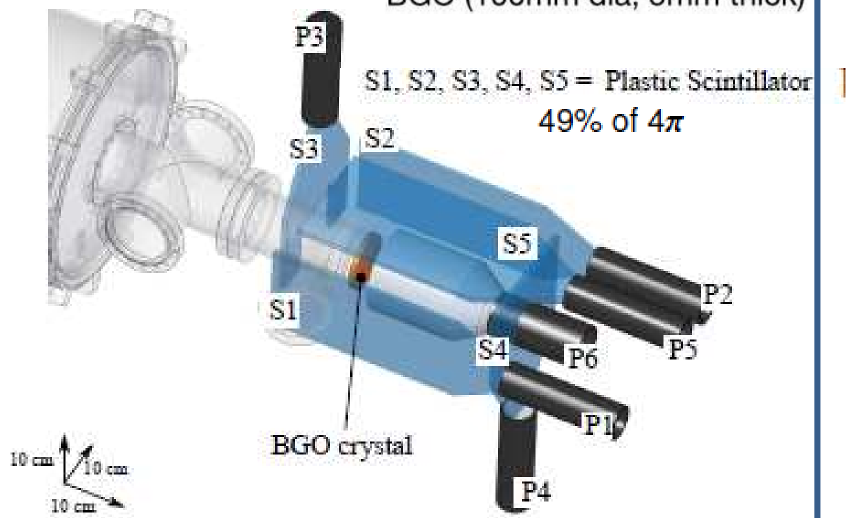


Field Ionization before the detector

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

Hbar detector

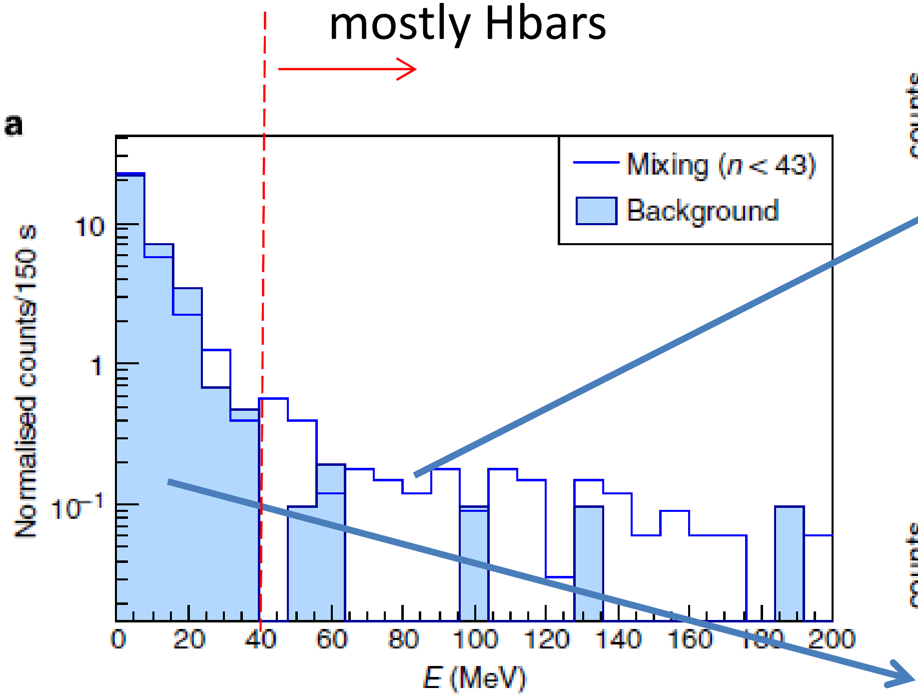
plastic +
BGO (100mm dia, 5mm thick)

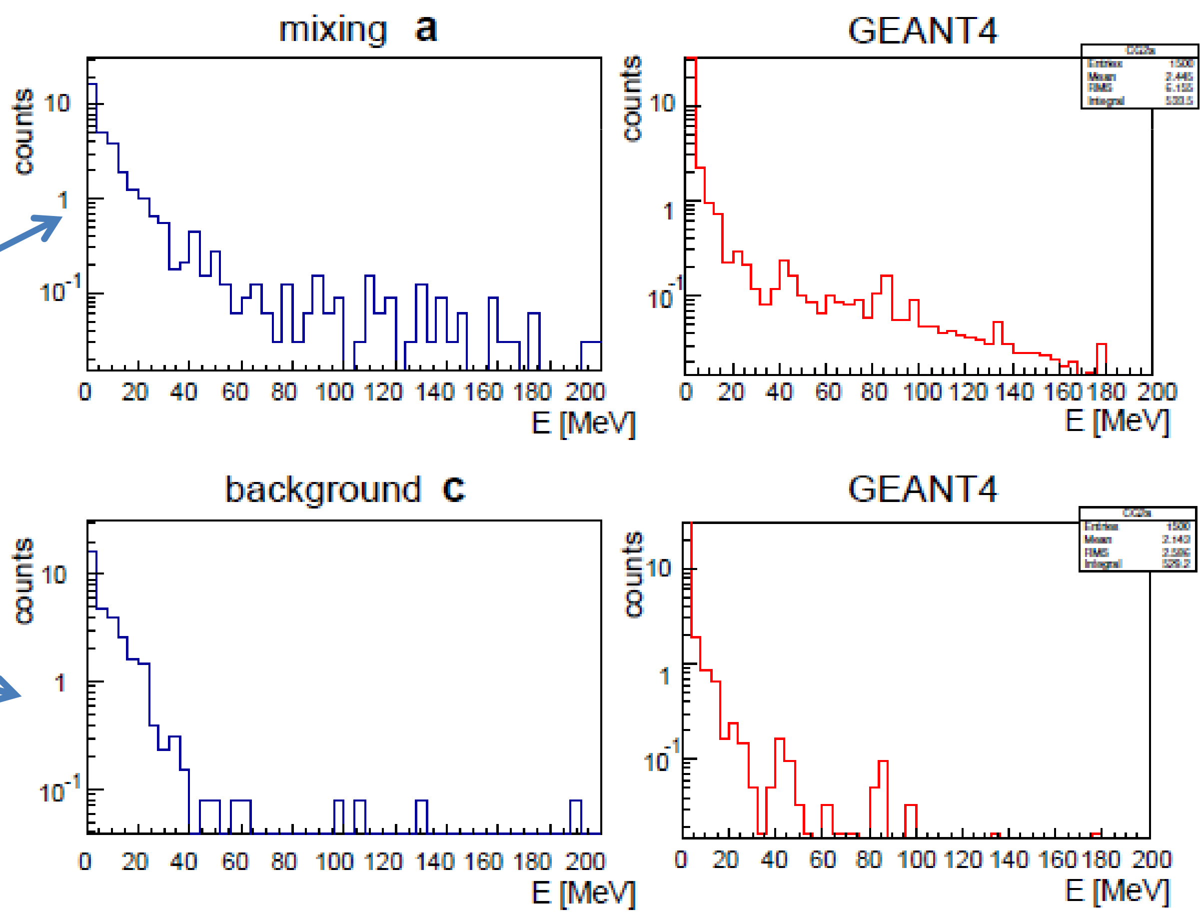


BGO measures energy deposition by Hbar annih.

coincidence: BGO AND (>1 S)

Energy deposition in the BGO





Unshaded histo → pbar-e+ mix

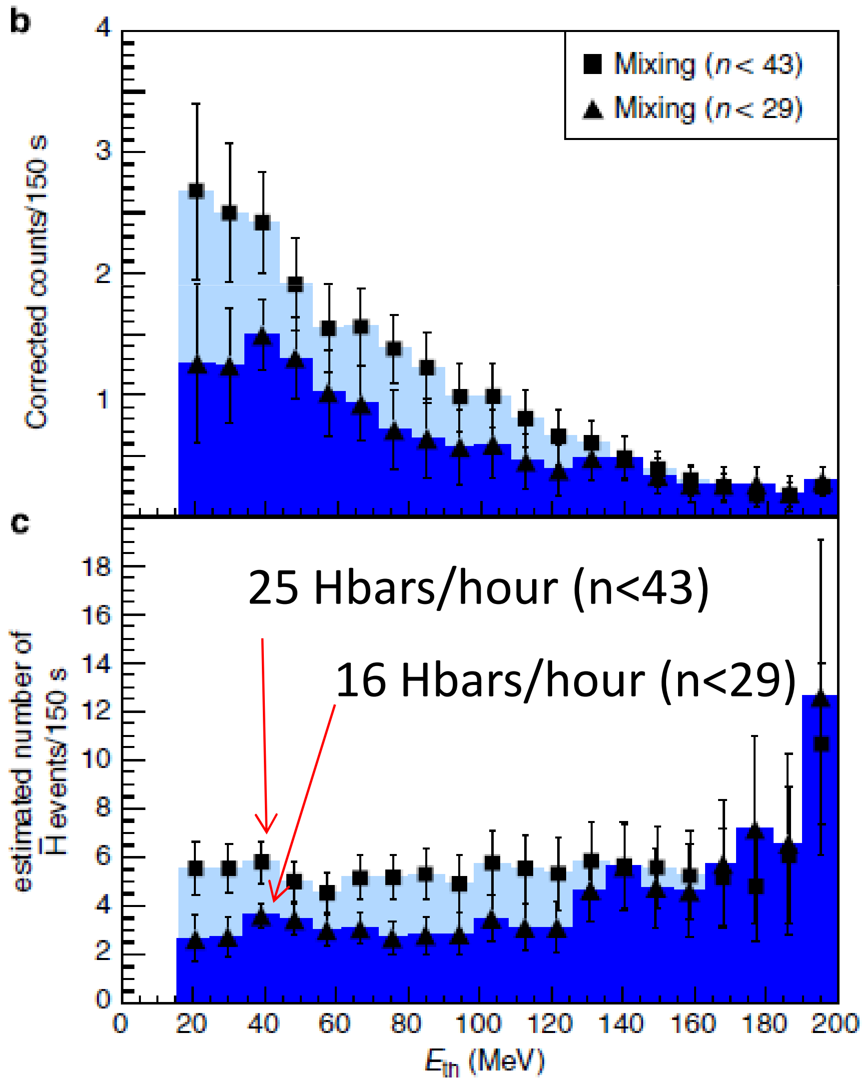
Shaded histo → pbar-e- mix (background run)

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

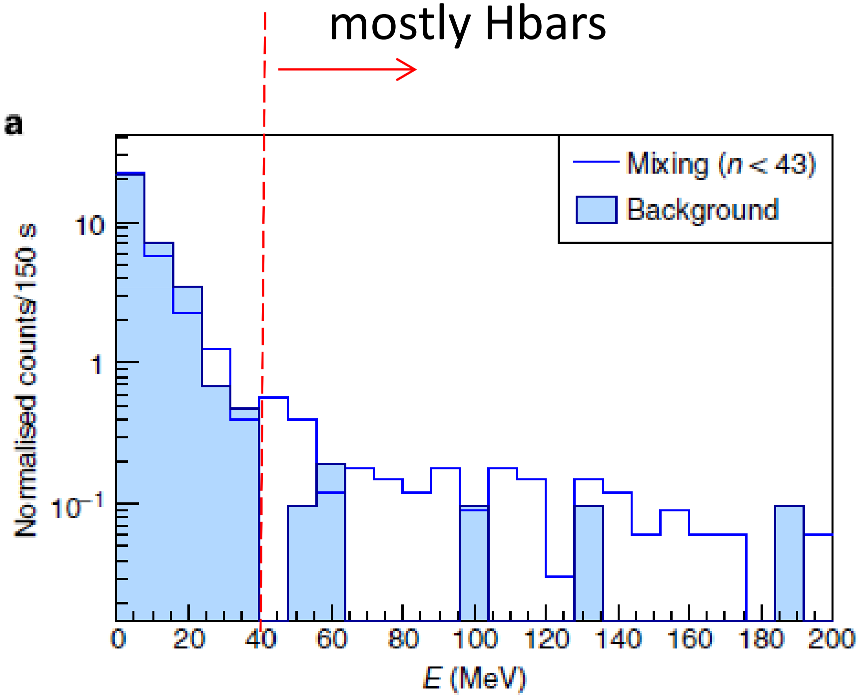


Table 1 | Summary of antihydrogen events detected by the antihydrogen detector.

	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	—

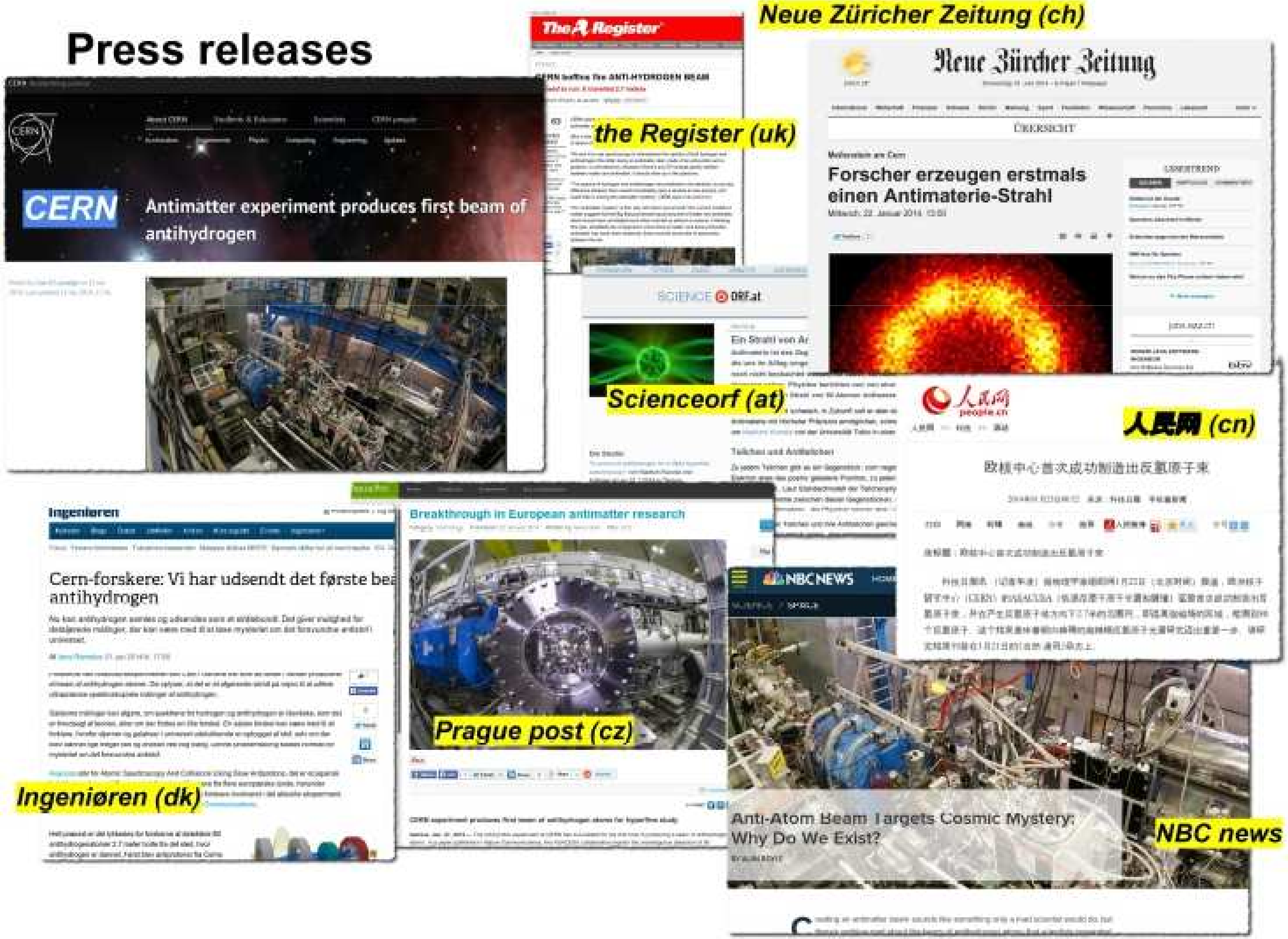
Antihydrogens (n<43) detected with 5 σ significance 2.7 m far from their production region

➔ Antihydrogen beam has been produced

25 Hbars/hour (n<43)

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

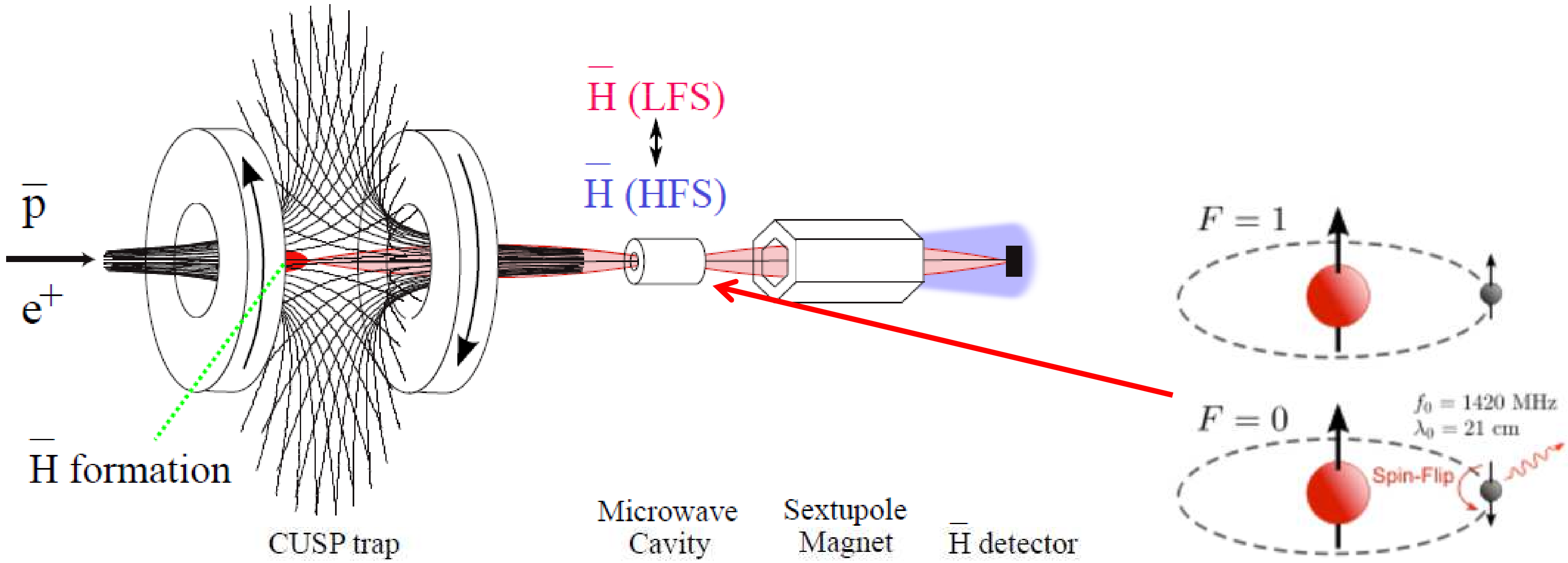
Press releases



Next steps

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

Introduce MW cavity

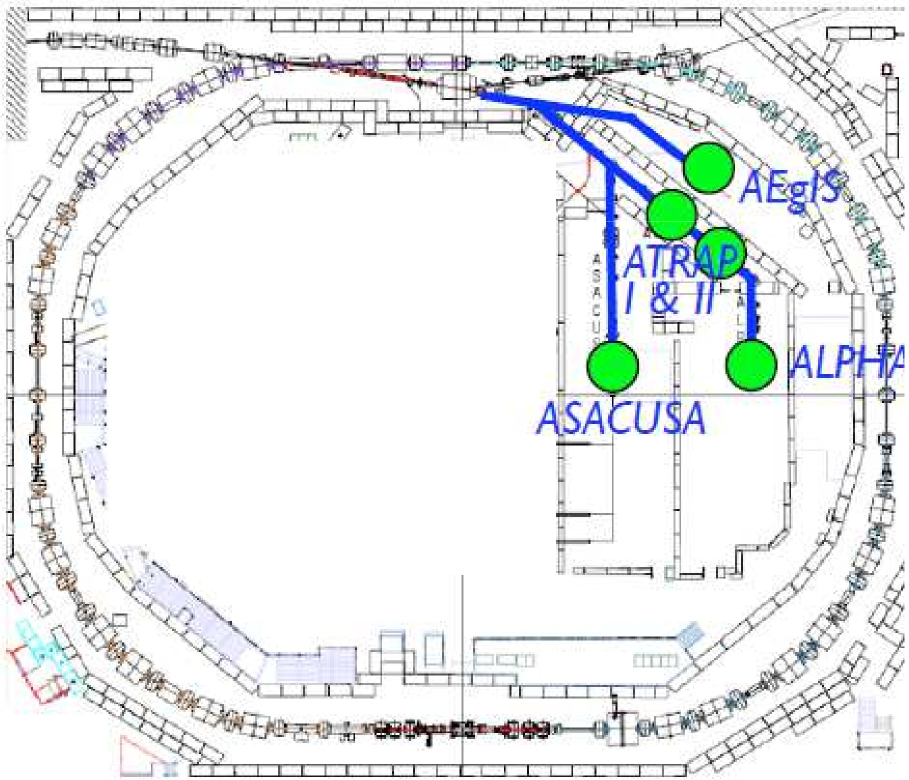


Achievable resolution:

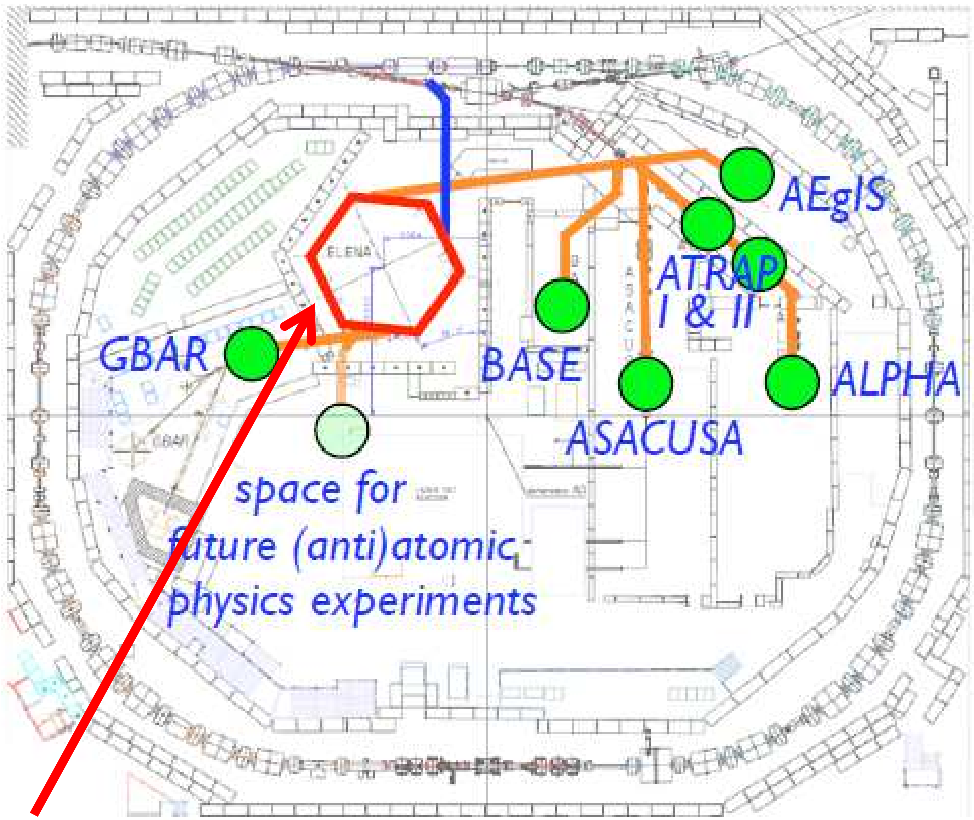
- better than 10^{-6} for T < 100 K → see Malbrunot's talk

Future

2014



2017 →



ELENA decelerator:

5.3 MeV → 100 keV

x 100 pbars trapping efficiencies

4 experiments can run in parallel

Summary

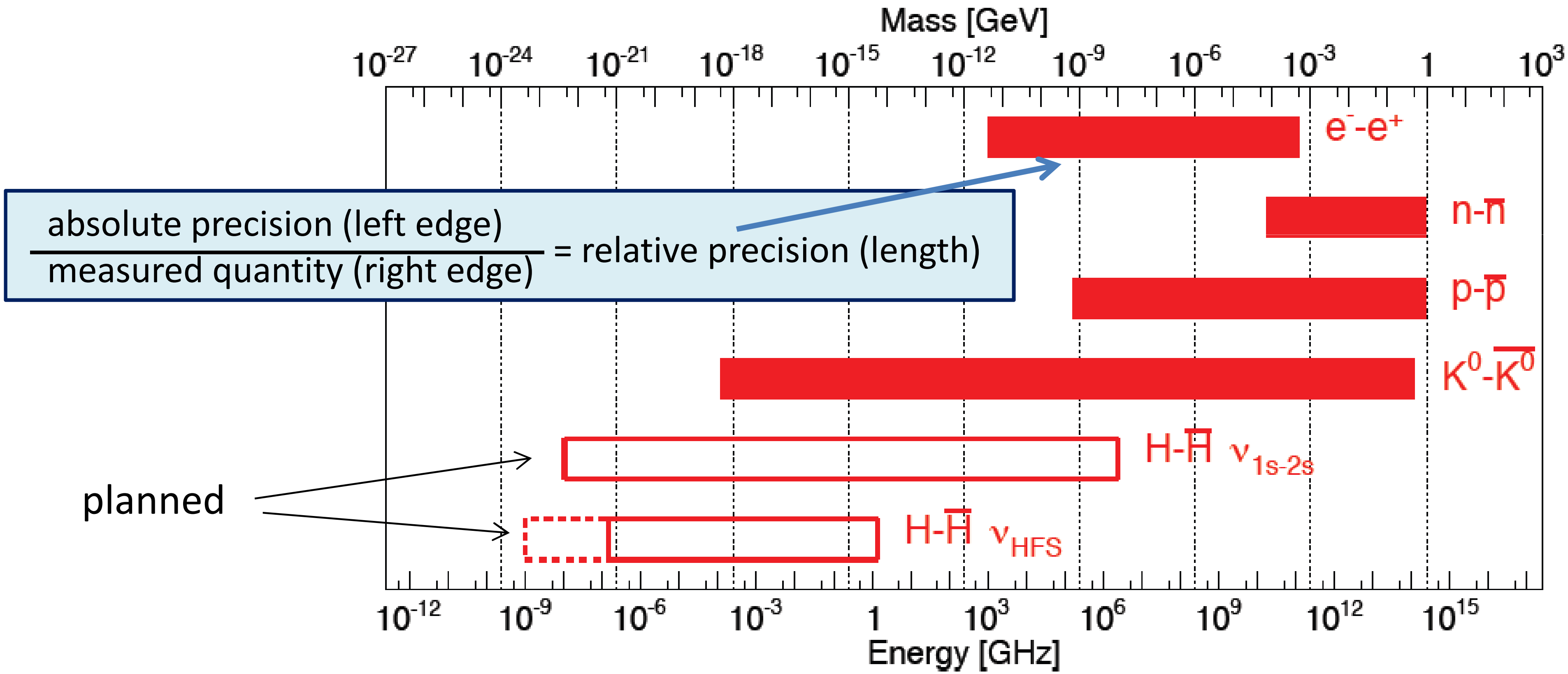
- Antihydrogen measurements promises high sensitive tests of CPT symmetry

- First cold beam of antihydrogen atoms produced by ASACUSA

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

- the present result together with those from the other AD experiments → spectroscopy era

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

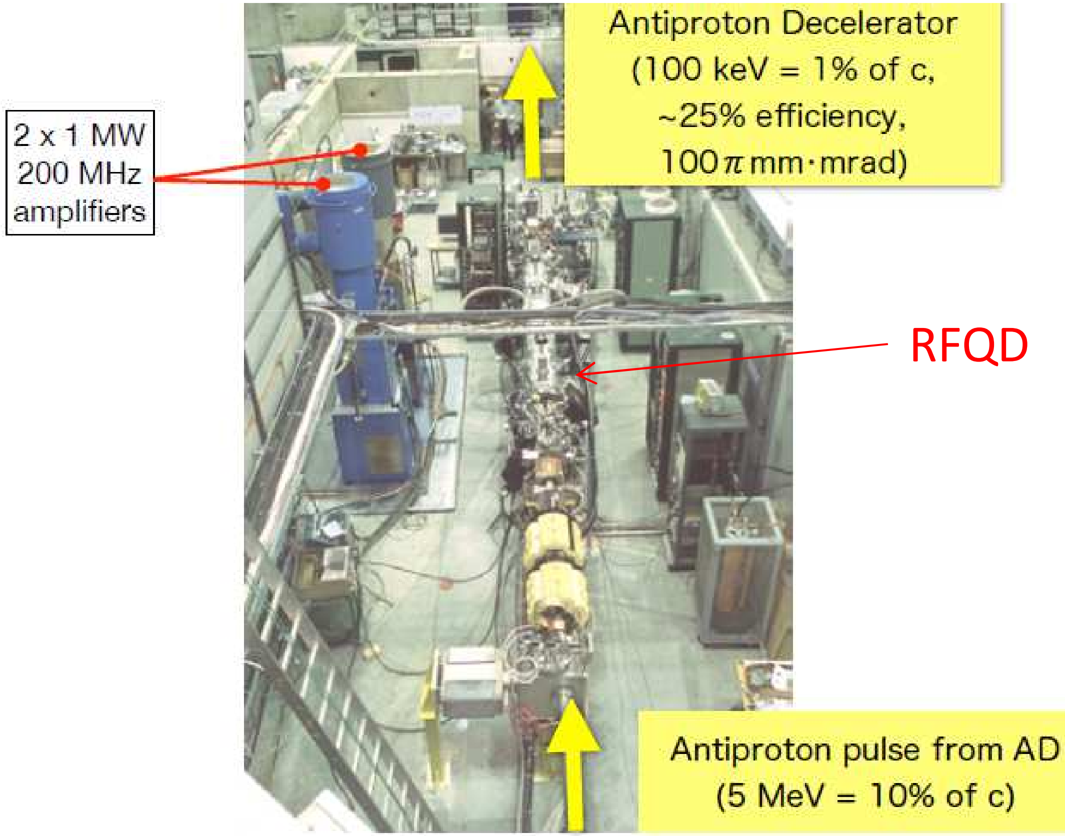
Where CPT violation might appear is unknown

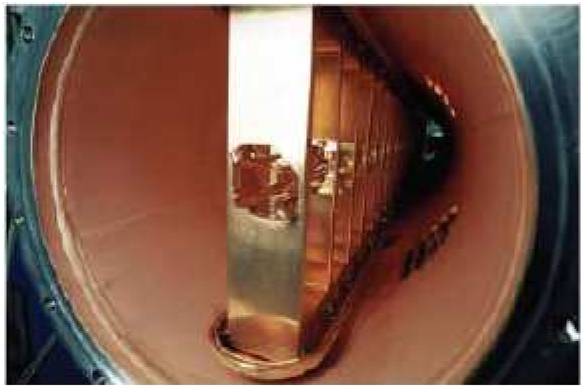
Radiofrequency Quadrupole Decelerator

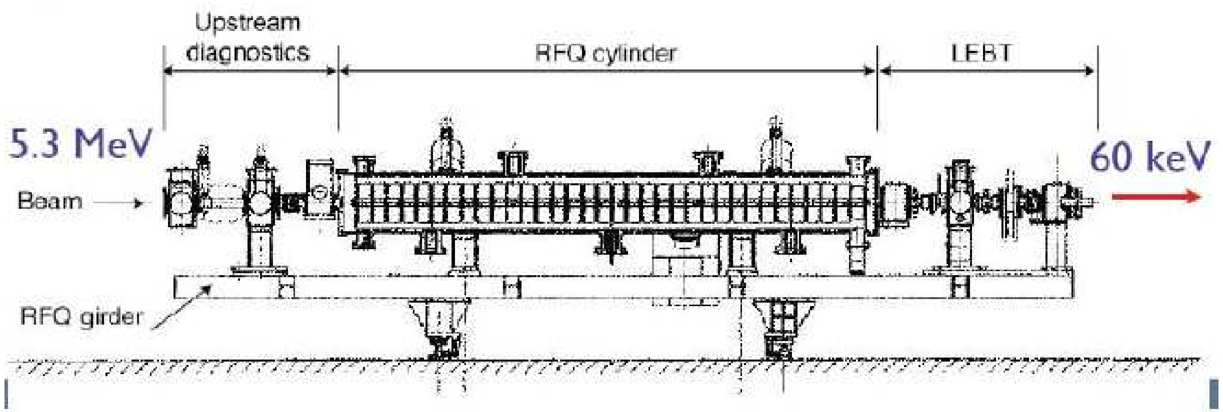
RFQD – inverse linac

Crucial part of ASACUSA.
Slows down antiprotons to E<100 keV.
Delivers >7 million antiprotons every 100 s.
Beam emittance > 100 pi mm mrad,
Energy spread > 10 keV.

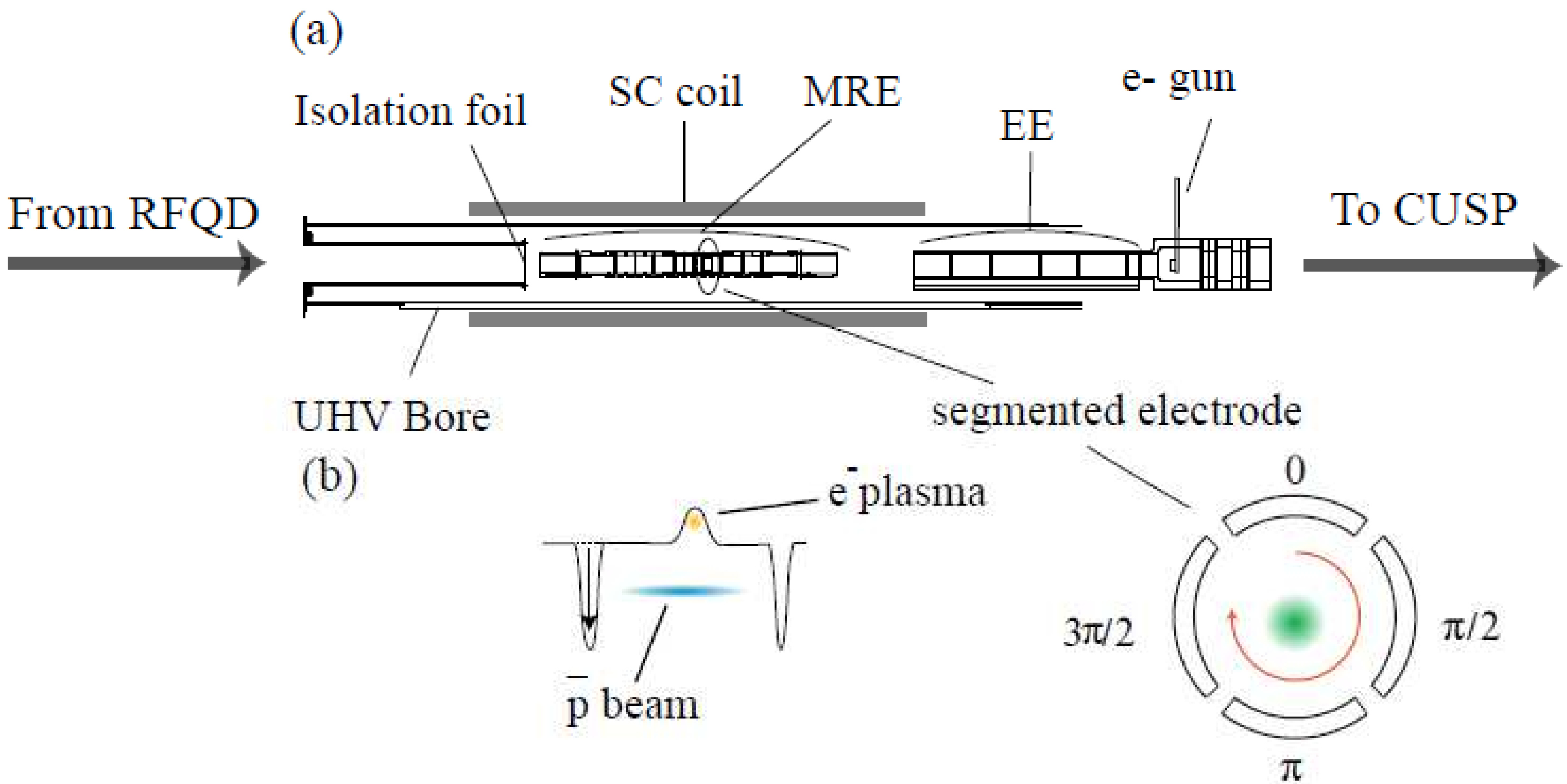
10-100-fold improvement of many parameters with new ELENA machine.







Antiproton accumulator (MUSASHI)



RFQD→ foil → capture → cool with e- → compress → transport to CUSP

RFQD+MUSASHI → 5-50 more pbars than other experiments

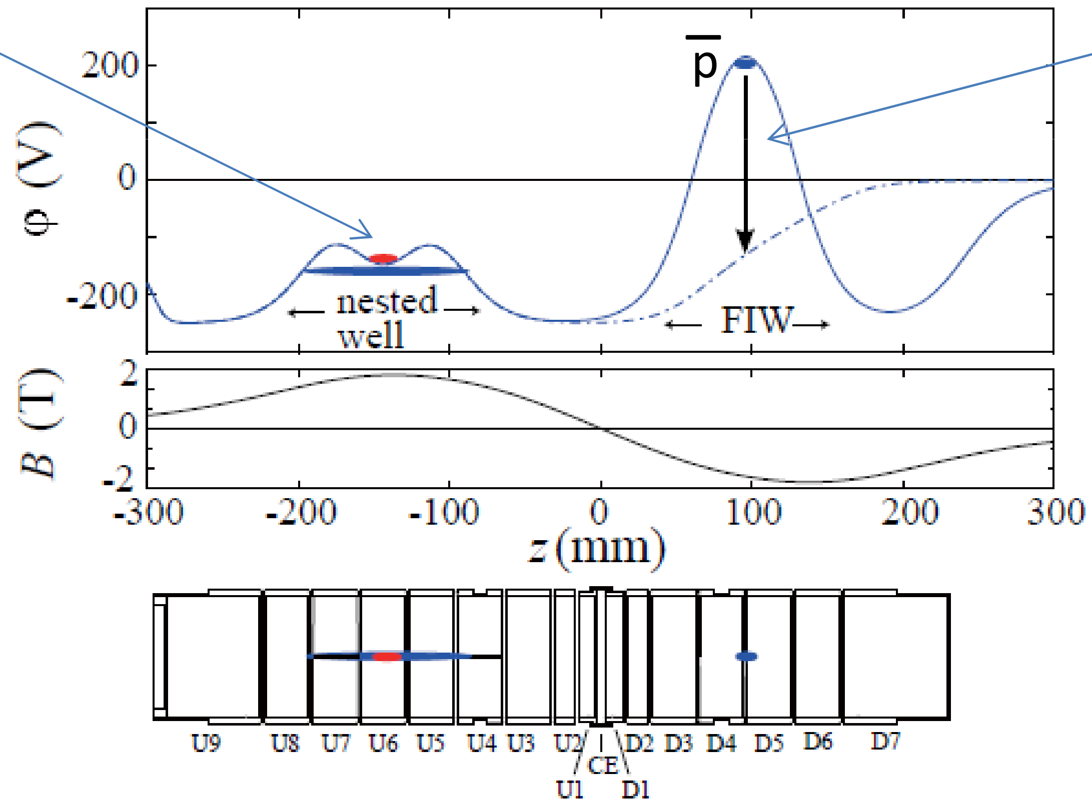
AD	5.3 MeV	$2.0–2.5 \times 10^7$/AD shot
RFQD	110 keV	$\sim 5 \times 10^6$/AD shot
trapped&cooled	$\lesssim 1$ eV	$0.5–0.8 \times 10^6$/AD shot
slow extraction	250 eV	$\leq 3.0 \times 10^5$/extraction
pulse (new optics)	150 eV	$\leq 1.5 \times 10^5$/extraction

3 AD shots per 1 MUSASHI extraction.

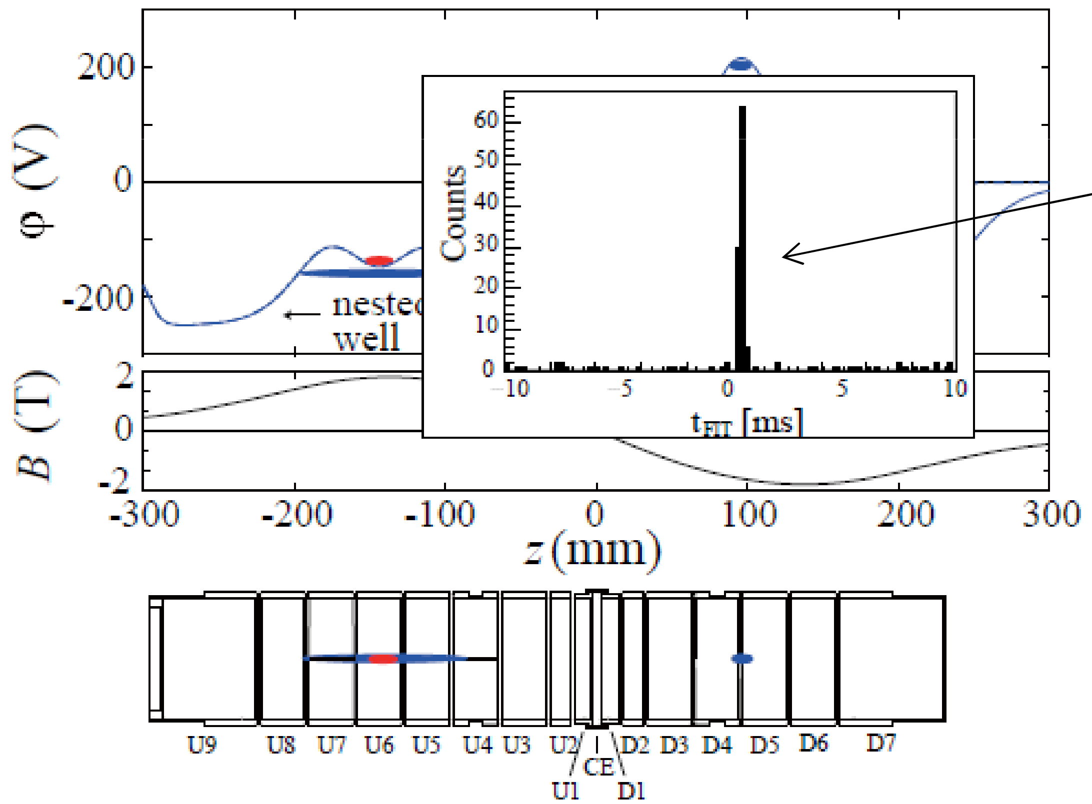
Antihydrogen formation

Hbar formation

Field Ionization of Hbar (→ pbar capture)



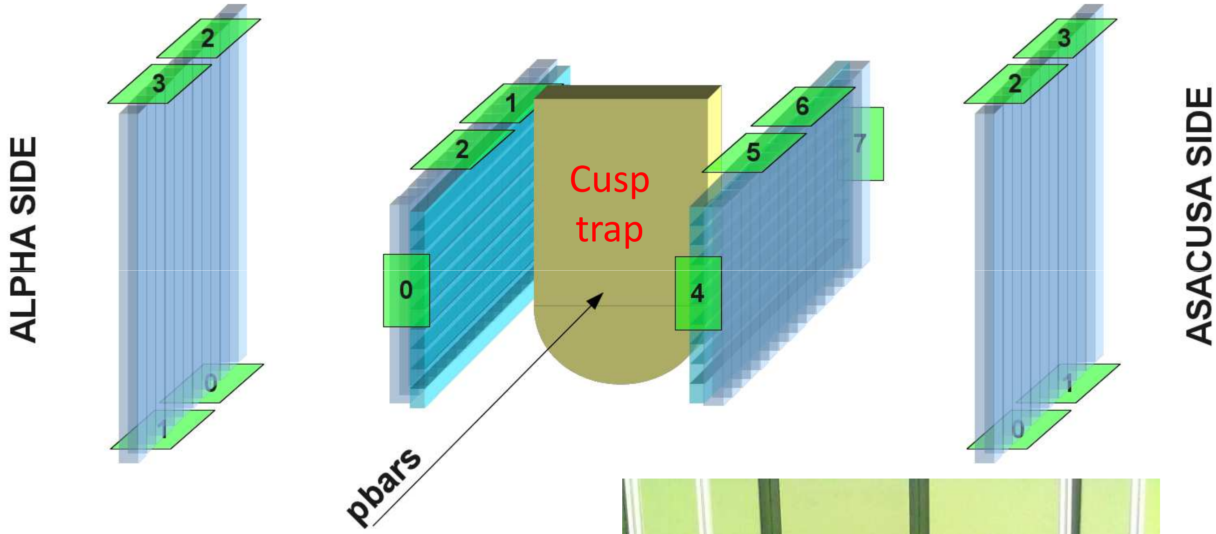
Antihydrogen formation



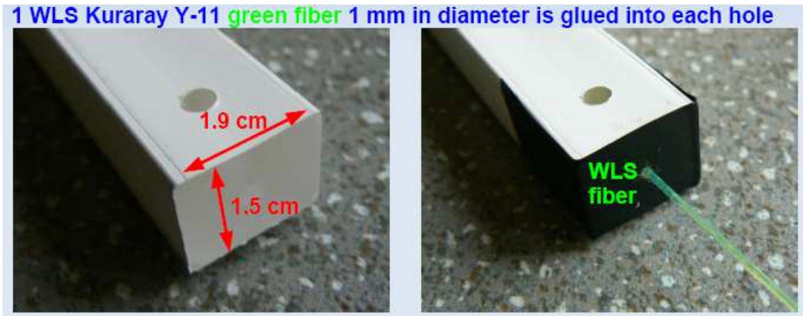
$\bar{p}$ annihilation signal

Tracking detector

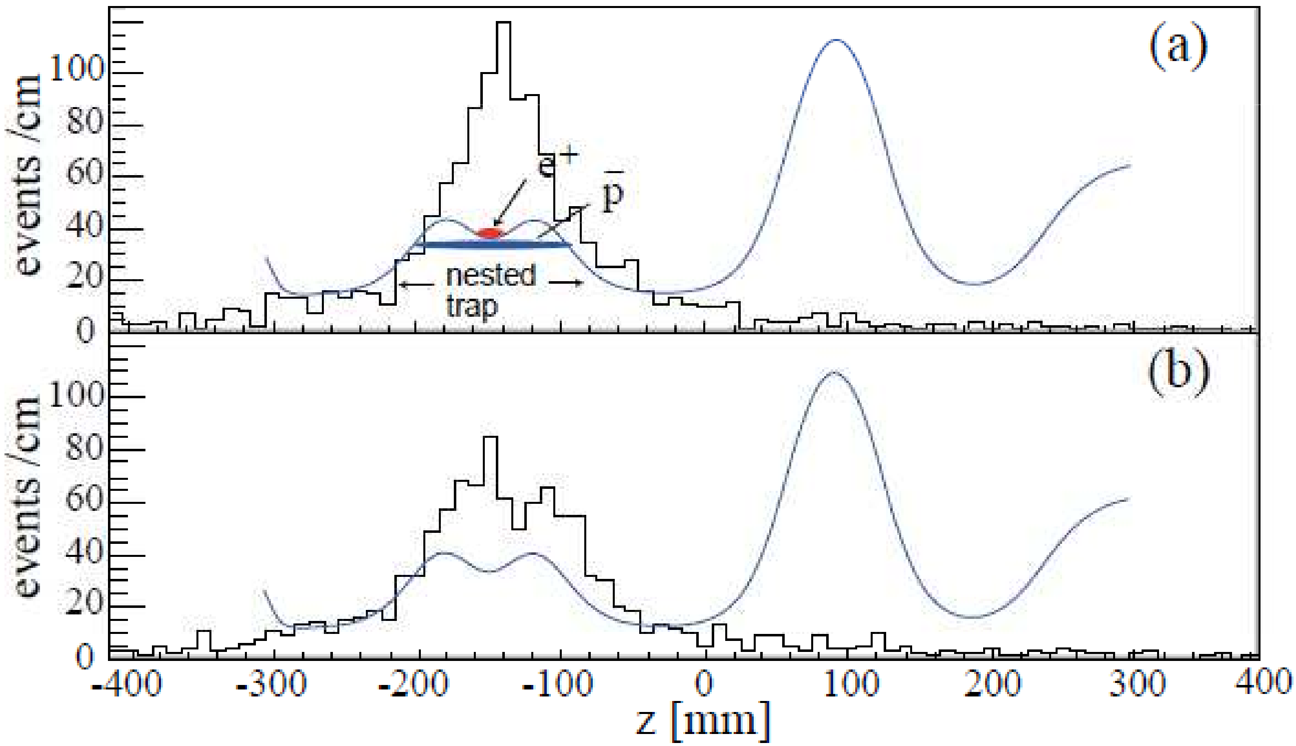
- Scintillator bars
  15 mm × 19 mm
  960 mm in length
- $\Omega/4\pi = 6.6\% + 8.6\%$
  for each side
- for $\pi^{\pm}$ multiplicity 3
  $\Rightarrow$ 39%
- double coincidence
  $\Rightarrow$ 3.3%



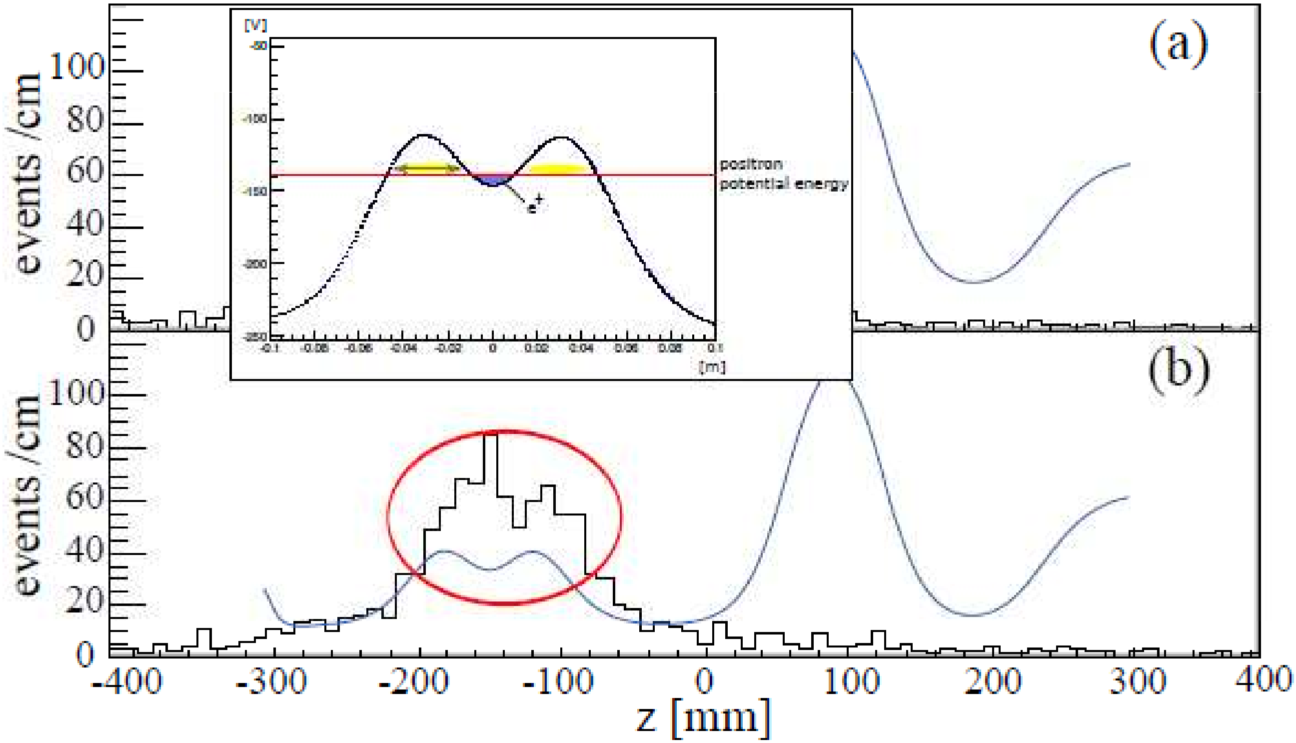
Scintillator bar



Annihilations vertices



Annihilations vertices



Increase antihydrogen production

3×10^5 $\bar{p}$ mixed with 3×10^7 e^+

Field Ionization for $n \gtrsim 39$: 75 $\bar{H} \Rightarrow$ 260 $\bar{H}$ (× 3.5)