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SMR.1580 - 14

CONFERENCE ON FUNDAMENTAL SYMMETRIES AND FUNDAMENTAL CONSTANTS

15 - 18 September 2004

ON THE WAY TO TESTING CPT WITH ANTIHYDROGEN

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Germano Bonomi CERN (*)

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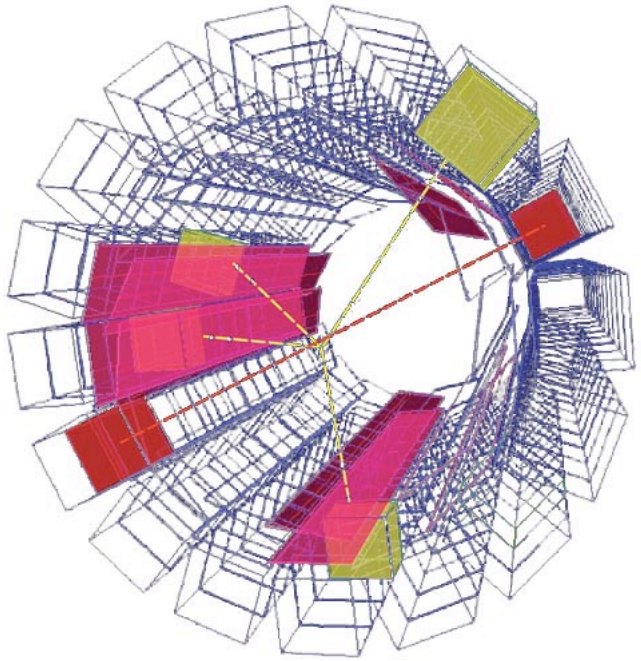
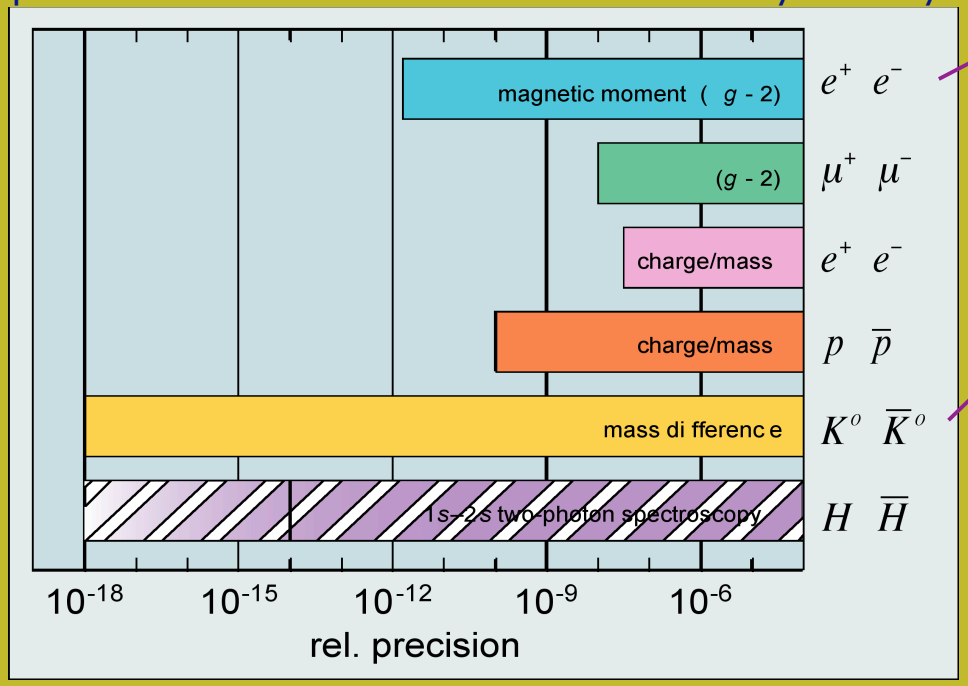


ATHENA
COLLABORATION

On the way to testing CPT with antihydrogen

antihydrogen production long term goal - CPT

CPT transform an elementary particle into its antiparticle: this predestines antimatter for tests of CPT symmetry



in specific models CPT may be broken without affecting the gyromagnetic moment [1]

assumes the validity of the standard model which does not contain a mechanism to violate CPT [2]

Antihydrogen is a complete system (not a single particle)

→ a perfect system for direct CPT test

1) Using same experimental methods of hydrogen spectroscopy, high precision comparison of the two system may be achieved

2) Antihydrogen is a mostly electromagnetic system (weak interaction, or parity violating, effects are small and the same for hydrogen and antihydrogen) → comparison is less model dependent

[1] R. Bluhm, V. A. Kostelecky and N. Russell, Phys. Rev. Lett. 79 (1997) 1432
D. Colladay and V.A. Kostelecky Phys. Rev. D 55 (1997) 6760
[2] E. Shabalin, Phys. At. Nuclei 57 (1994) 1862

antihydrogen production long term goal - WEP

Weak Equivalence Principle (WEP): gravitational acceleration of a falling object is independent of its composition

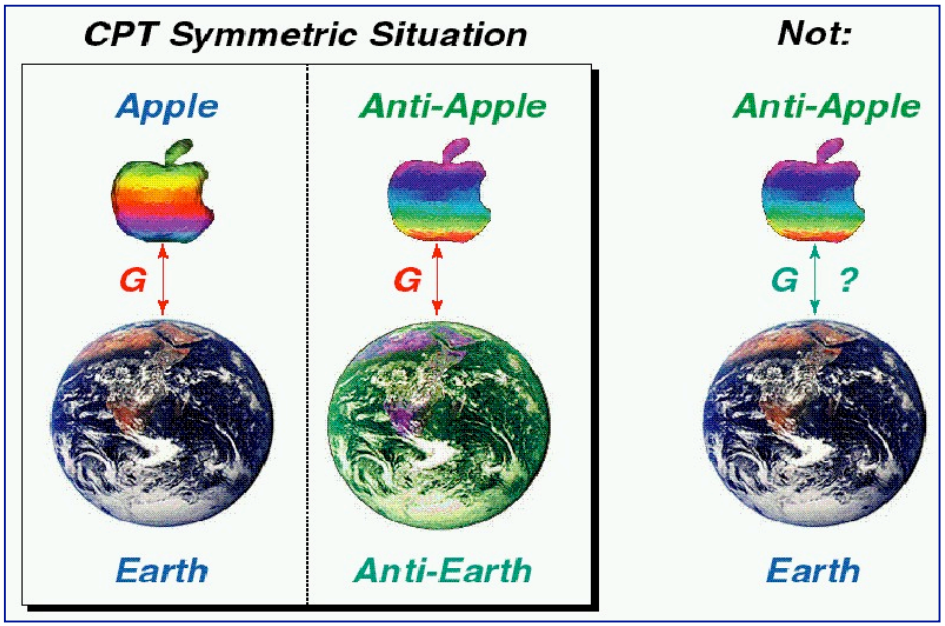
composite objects of ordinary matters have shown equal gravitational acceleration to one part in 10^{12}

arguments against "antigravity" have been given by numerous authors (see [1])

but no experimental test of the WEP has been performed with particles and antiparticles

Antihydrogen is a **neutral system free from** problems associated with **electromagnetic interactions**

→ perfect for a direct test of gravitational interaction of antimatter with the Earth field



[1] M. M. Nieto and T. Goldman, Phys. Rep. 205 (1991) 221

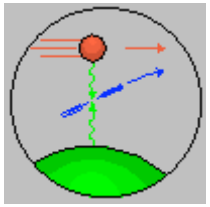
History of antihydrogen

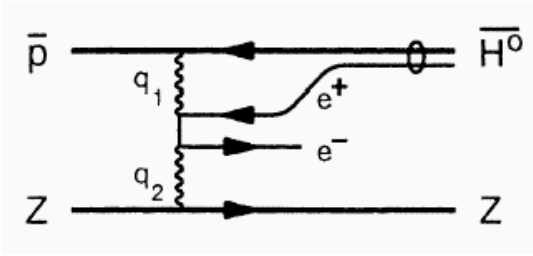
Prehistory

- 1928: Dirac equation "suggests" the existence of antimatter
- 1932: Anderson discover the antielectron
- 1955: Segre and Chamberlain discover the antiproton
- 1956: Piccione (et al.) discover the antineutron
- 1965: Lederman and Zichichi observe the first antinucleus

History

- 1996: PS210 @ CERN (First **9** antihydrogen)
- 1997: E862 @ Fermilab (other 99 antiatoms)



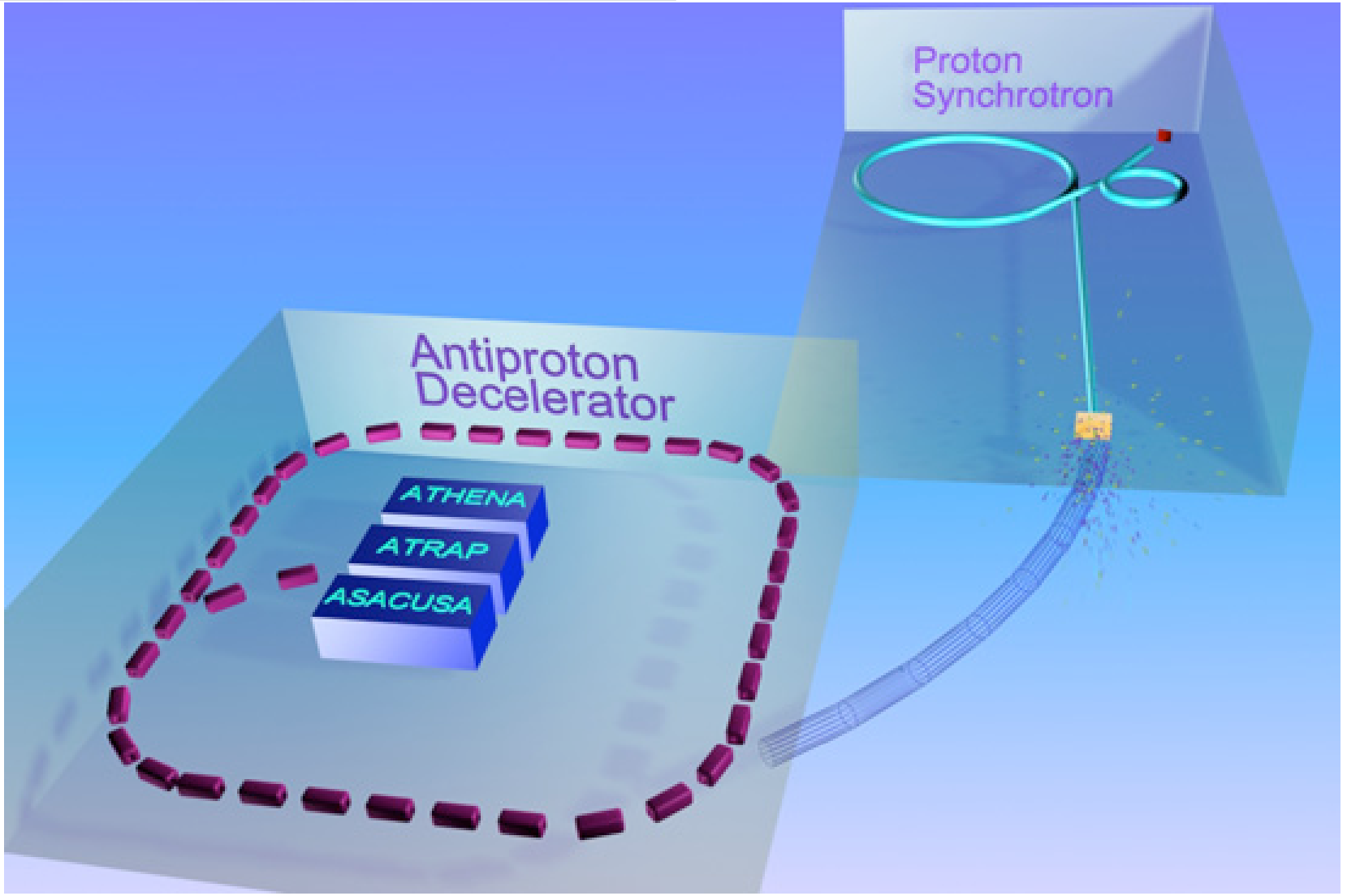


LEAR → AD

Present

- 2002 September: Athena @ CERN (First **50000** cold antihydrogen atoms)
- 2002 November: Atrap @ CERN (other cold antiatoms)

Antiproton Decelerator (AD) at CERN



the ATHENA collaboration

Univ. of Aarhus, Denmark

Univ. of Brescia, Italy

Univ. of Genova, Italy

CERN, Geneva, Suisse

Univ. of Pavia, Italy

Univ. of Rio, Brazil

Univ. of Swansea, Wales (UK)

Univ. of Tokyo, Japan

Univ. of Zurich, Suisse

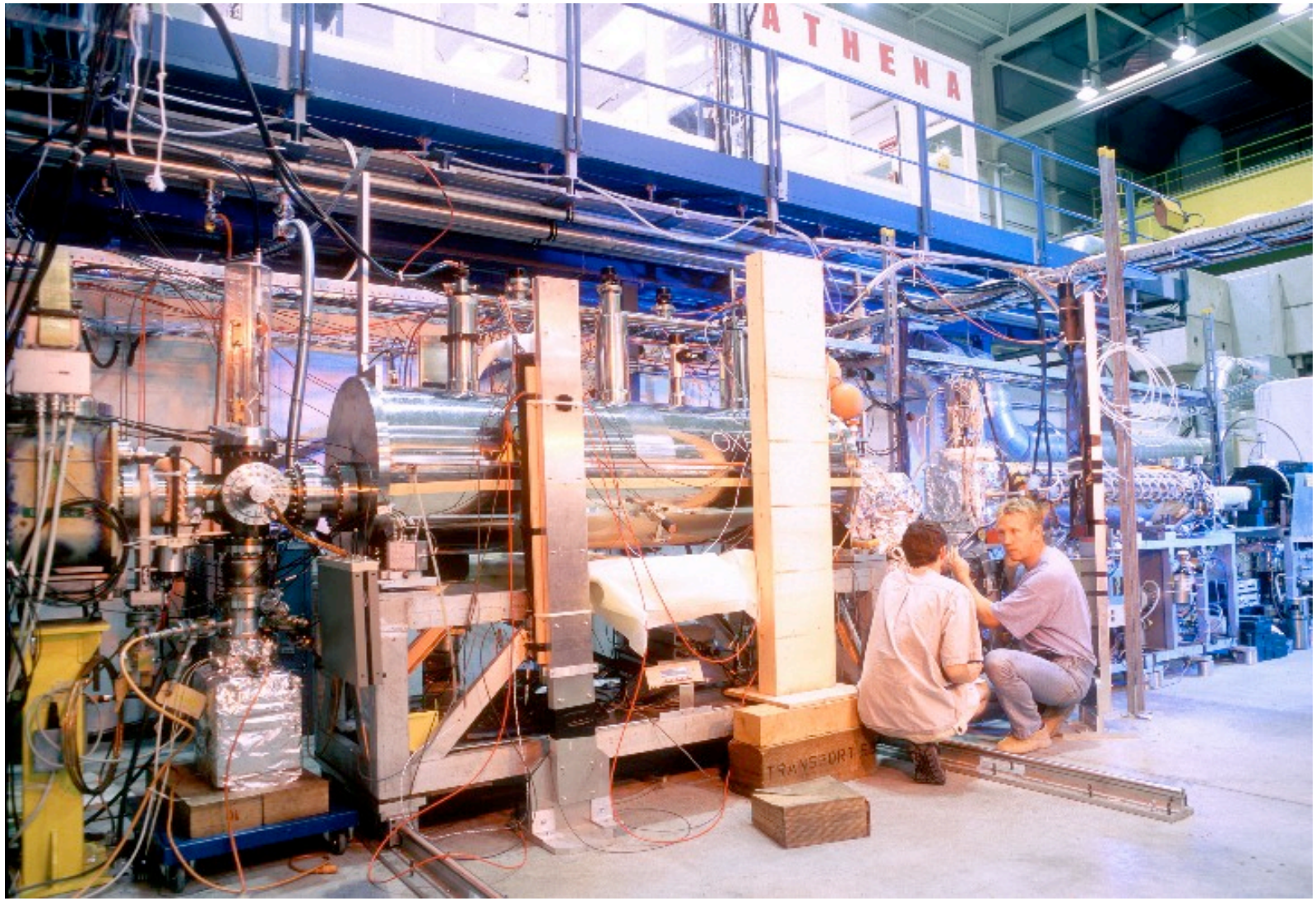
INFN, Italy

Riken, Japan

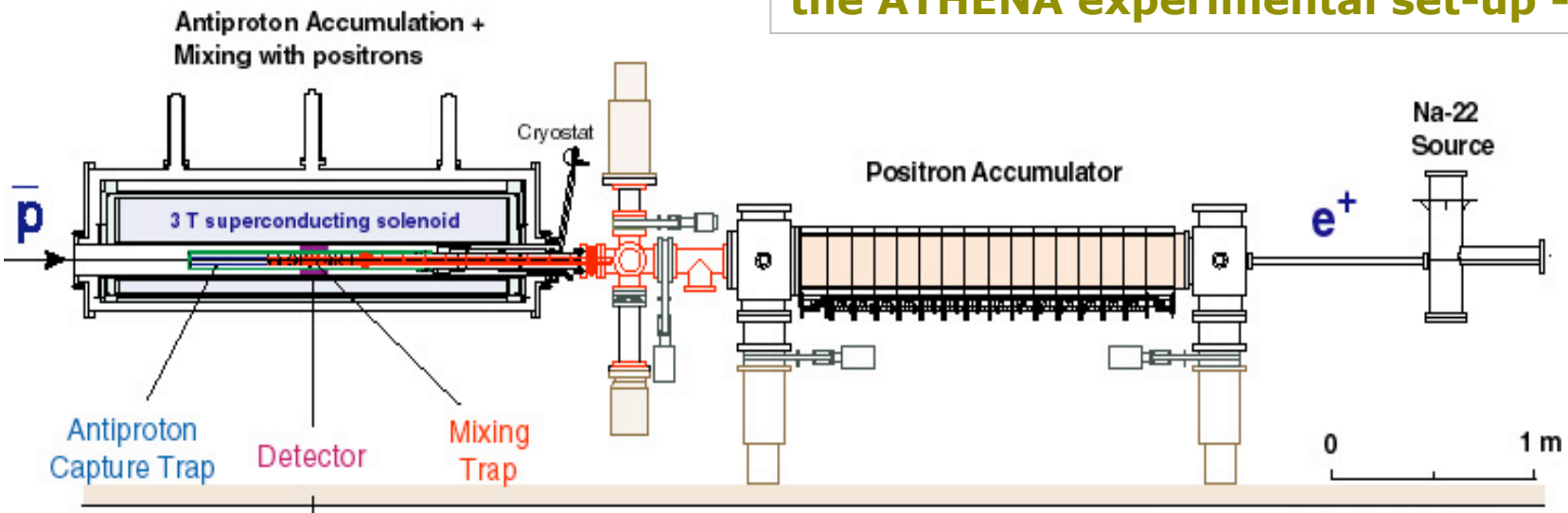
Expertise from very different fields:
Plasma, Atomic, Particle Physics …
Cryogenics, Vacuum, Detectors …..

the ATHENA experimental hall

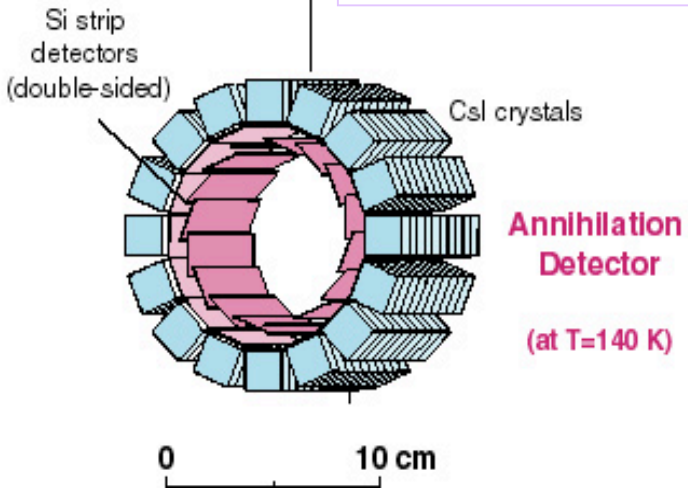
the ATHENA experimental set-up - I

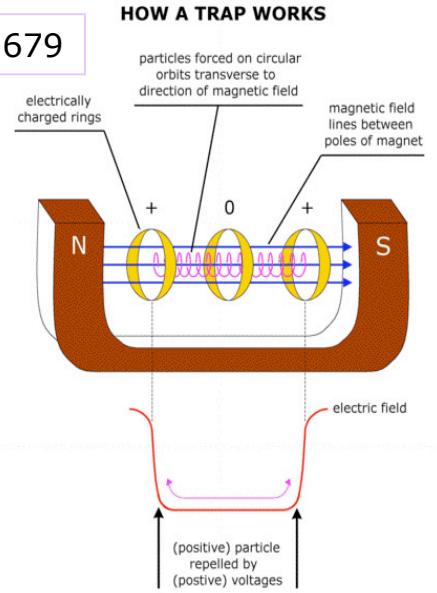


the ATHENA experimental set-up - II

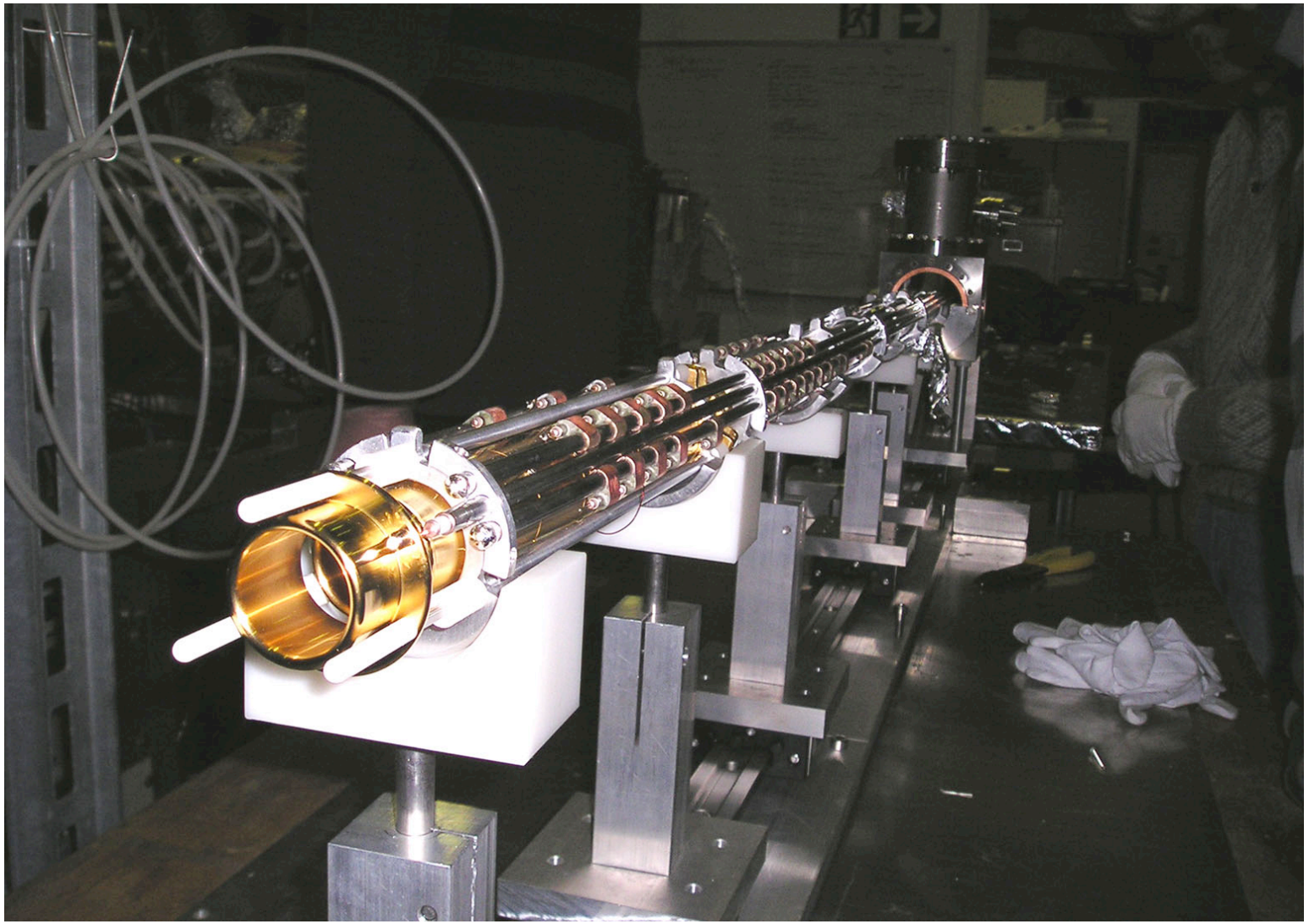


M. Amoretti et al., Nucl. Instr. & Meth. A 518 (2004), 679



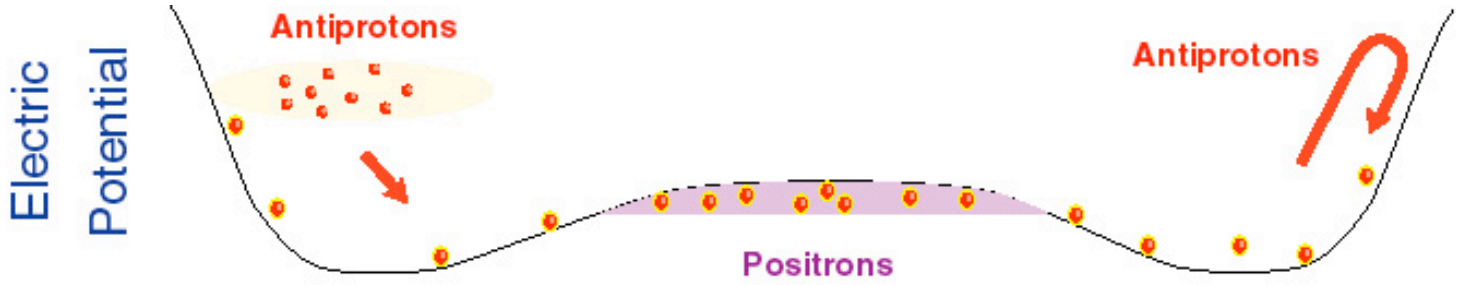


the ATHENA experimental set-up - III

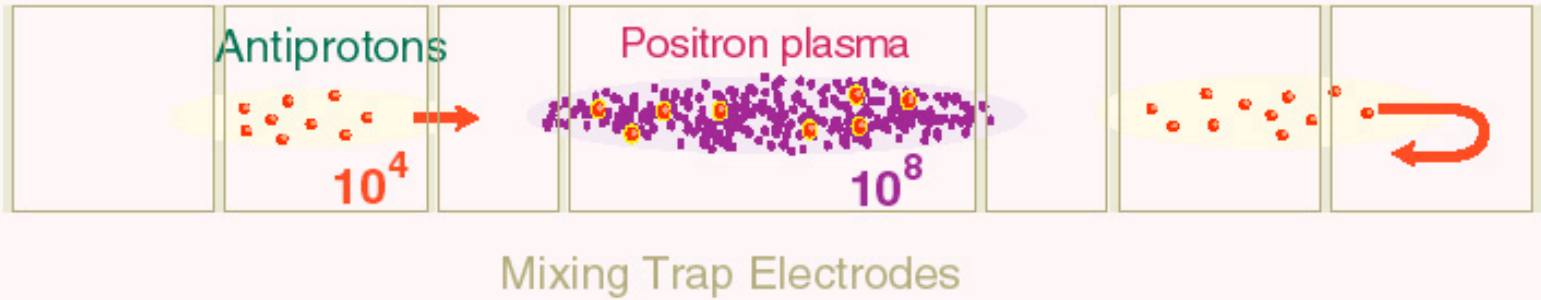


the mixing cycle

details on cooling process: M. Amoretti et al., Phys. Lett. B 590 (2004), 133



Scheme proposed by G. Gabrielse et al. - Phys.Lett. A129, 38 (1988)



the antihydrogen signal

THE MIXING CYCLE

1 Fill positron well in mixing region with [40-70]·10^6 positrons

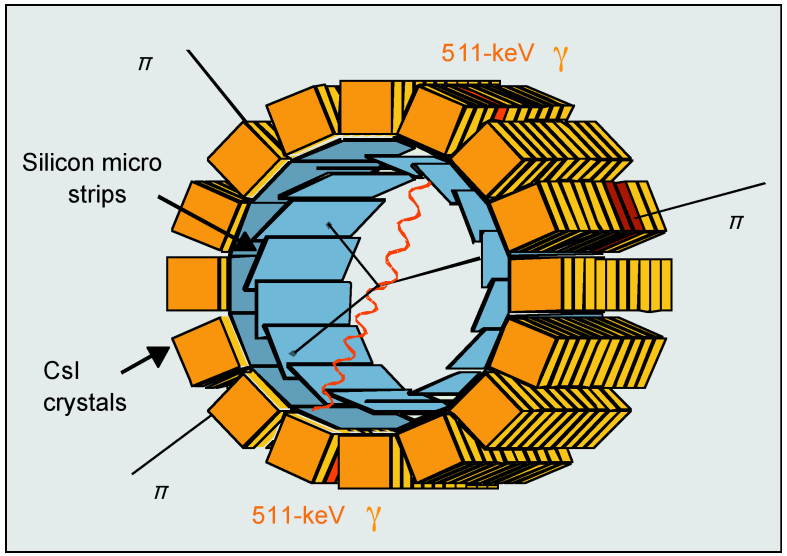
2 Launch 10^4 antiprotons into mixing

3 Mixing time 70 sec (Detector monitoring)

4 Repeat cycle every 3 minutes

when antihydrogen is formed:

- it escapes the mixing region (being neutral)
- it annihilates on the trap walls
- space-time coincidence of antiproton & positron annihilations

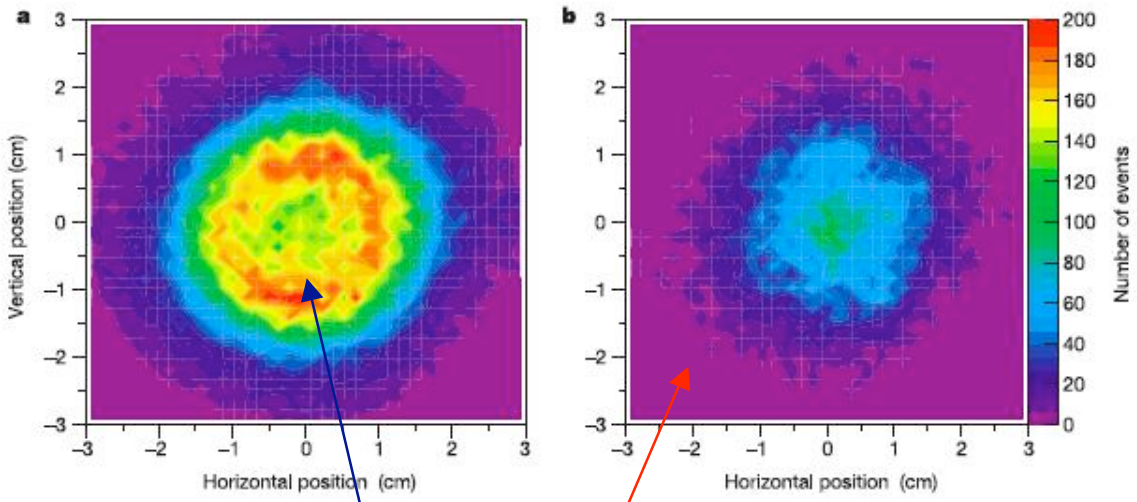


the movie (mov)

the movie (avi)

antihydrogen !!!!!!!!!!

FIRST COLD ANTIHYDROGEN PRODUCTION (2002)
M. Amoretti et al., Nature 419 (2002) 456
M. Amoretti et al., Phys. Lett. B 578 (2004) 23

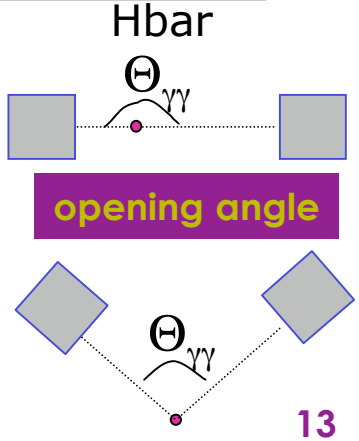


SIGNAL ANALYSIS:
opening angle
xy vertex distribution
radial vertex distribution

65 % +/- 10% of annihilations are due to antihydrogen

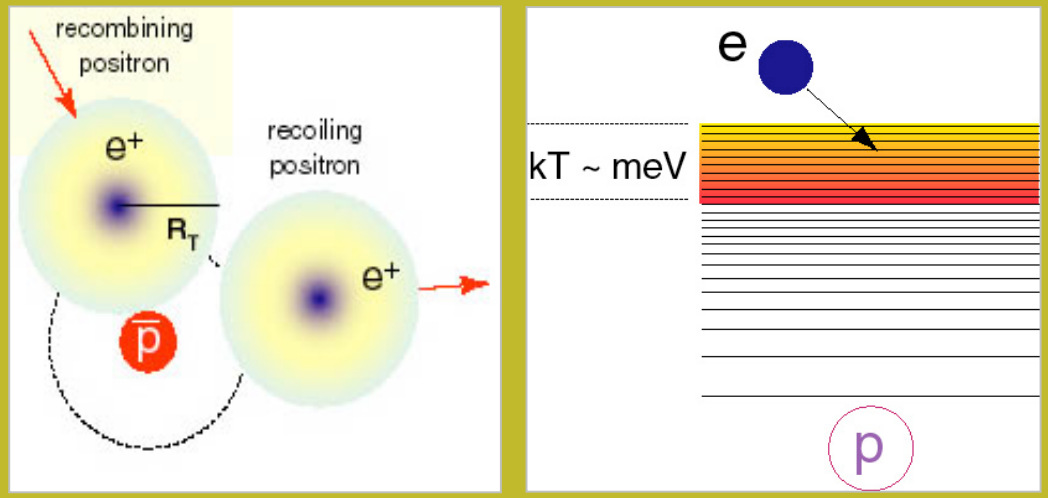
between 2002 & 2003 about 2 millions antihydrogen atoms have been produced

that's about 3×10^{-15} mg .. or .. 1000 Giga years for a gram

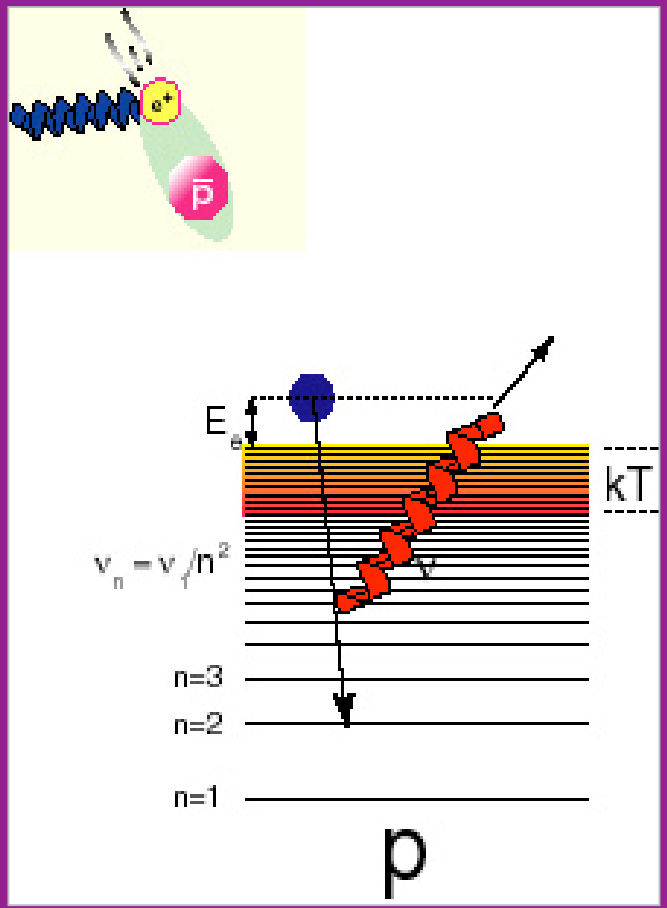


combination processes[1] - models

Three-body (re)combination process[2]

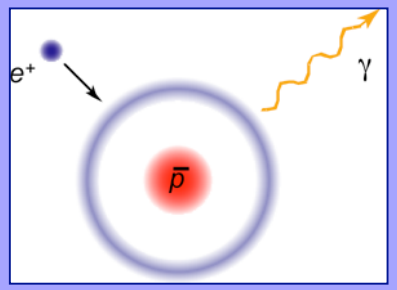


Spontaneous radiative (re)combination process[3]

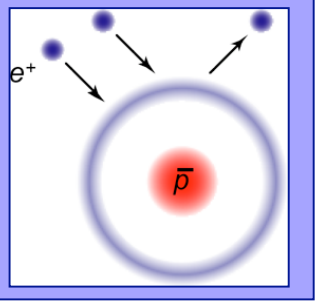


[1] *M.H. Holzscheiter, M. Charlton, Rep. Prog. Phys.* ***62*** *(1999) 1*
[2] *P. Mansback, J.C. Keck, Phys. Rev.* ***181*** *(1969) 275*
[3] *H.A. Bethe, E.E. Salpeter, Quantum Mechanics of One- and Two-Electron Systems, Springer, Berlin (1957)*

combination processes - predictions



	Radiative	Three-body
T dependence	$T^{-0.63}$ (see ref. 1)	$T^{-9/2}$ (see ref. 2)
density dependence	ρ	ρ^2
Final state	n < 10	n >> 100
Stability (re-ionization)	high	low
Expected rates (*)	~ 40 Hz	~ 10^5



(*) Assuming 10^4 pbars, ~ 2 x 10^8 cm^{-3} e^+ density and complete overlap at 15 K

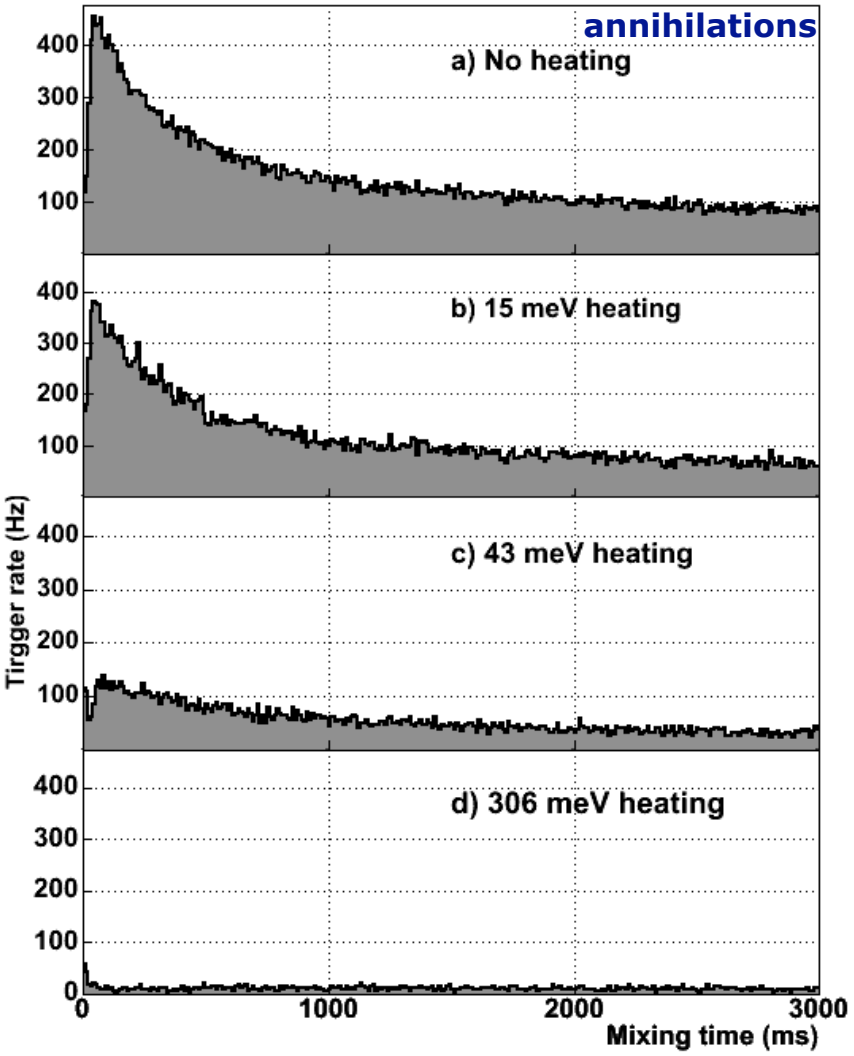
[1] J. *Stevefelt, J. Boulmer, J.F. Delpech, Phys. Rev. A* ***12*** *(1975) 1246.*
[2] *M.E. Glinsky, T.M. O'Neil, Phys. Fluids B* ***3*** *(1991) 1279.*

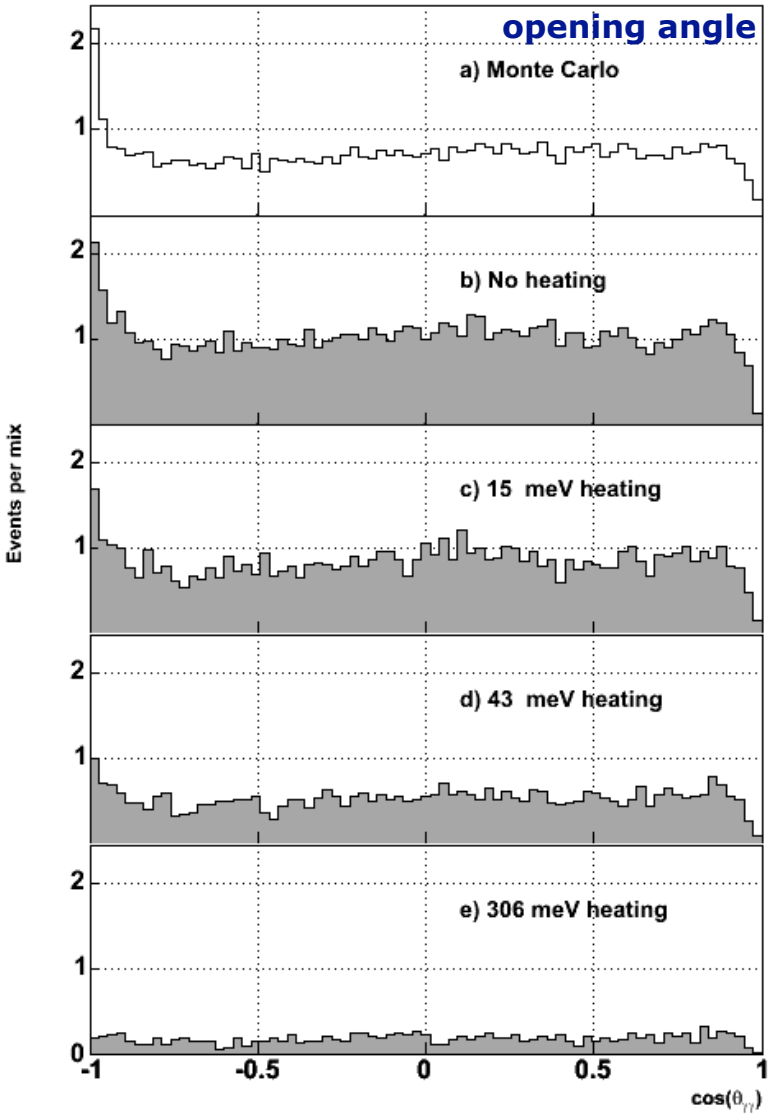
combination processes - experimental

How can we extract information about the predominant combination process?

1) Studying the antihydrogen production **dependence on the positron temperature**
2) Studying the antihydrogen production **dependence on the positron density**

temperature dependence I





we are able to change the temperature (and to measure its increase) of the positron plasma!

temperature dependence II

0 antihydrogen production decreases with temperature

1 antihydrogen production still present @ room temperature

2 antihydrogen production doesn't scale as power laws (best -0,7± 0.2)

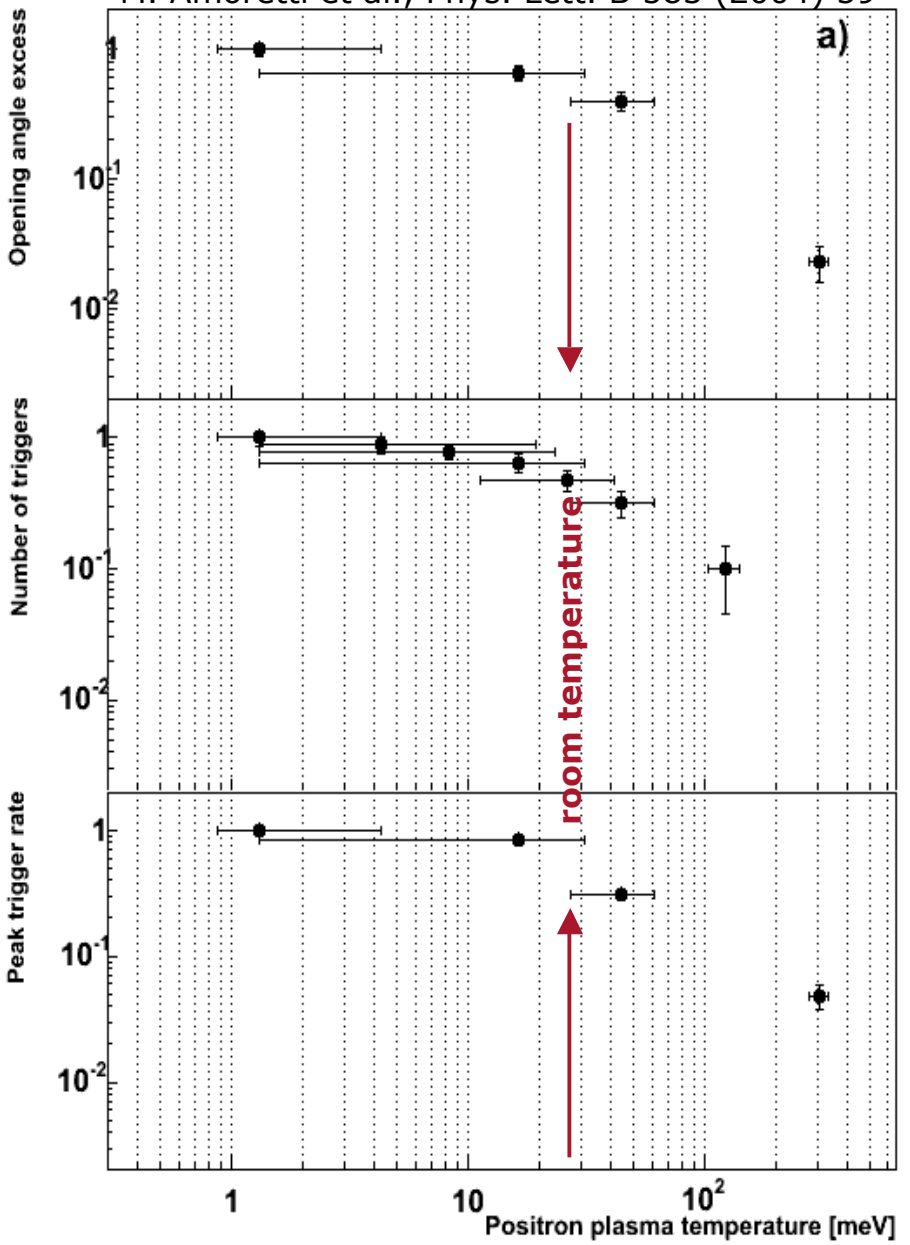
3 the turn-over at low T excludes naïve $T^{-9/2}$ three-body scaling

4 radiative predictions are 10-20 times smaller compared to peak production of > 400 Hz

WARNING:
the detected antihydrogen atoms are the ones that survive ionization (due to plasma and electrodes potentials)

complex interplay between production & ionization is not yet completely understood

M. Amoretti et al., Phys. Lett. B 583 (2004) 59



density dependence I

positrons
N = number — **(measured dumping the e^+s)**

n = density
α= r/2L — **non destructive method**

r = radius

$$r = \sqrt[3]{\frac{3}{4\pi}\frac{N}{n\alpha}}$$

WARNING
In plasma physics the density is indicated with **n**

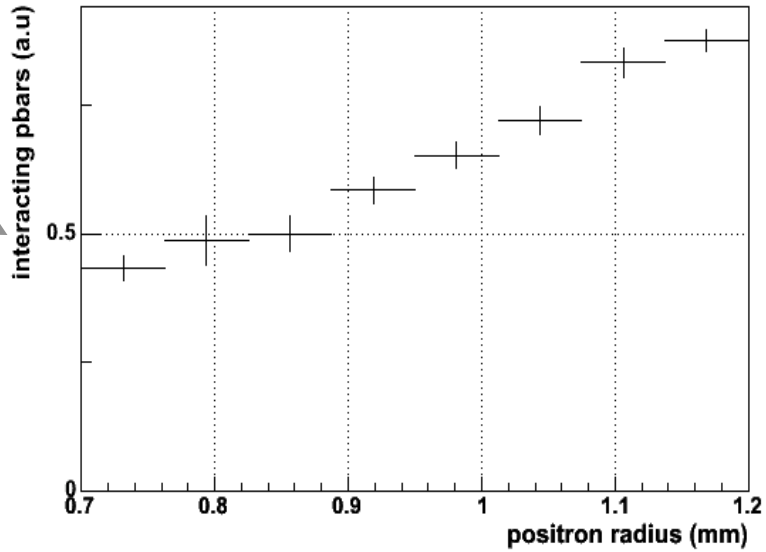
The positron plasmas characteristics were varied during the 2003 data taking:

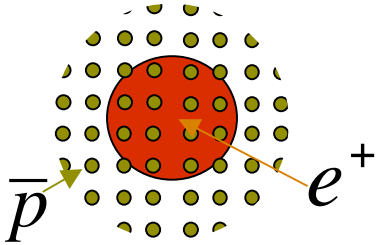
→ **$n \subseteq [3\text{-}16]\ 10^8\ cm^{-3}$**

in principle we have all the ingredients to study the density dependence

Problem 1: antiproton radius > positron radius

the number of antiprotons that interacted (after 70 s. of mixing) depends on the positron plasma radius





density dependence II

$$R_{\bar{H}} \propto N_{\bar{p}} \cdot n_{e^+}^{\beta} \Rightarrow R_{\bar{H}} \propto r_{e^+}^{m+2} \cdot n_{e^+}^{\beta}$$

$$N_{\bar{p}} = \int_0^{r_{e^+}} \sigma_{\bar{p}} \pi r dr$$

$$with\ \sigma_{\bar{p}} = kr^m \Rightarrow N_{\bar{p}} \propto r_{e^+}^{m+2}$$

Definitions

- $R_{\bar{H}}$ = antihydrogen production rate
- $N_{\bar{p}}$ = interacting antiprotons
- n_{e^+} = positron plasma density
- β = scaling parameter
- r_{e^+} = positrons radius
- $\sigma_{\bar{p}}$ = antiprotons radial density

Problem 2: antiproton radial density is unknown

as proxy for antihydrogen production rate we use the number of trigger in the first 500 ms after the start of mix

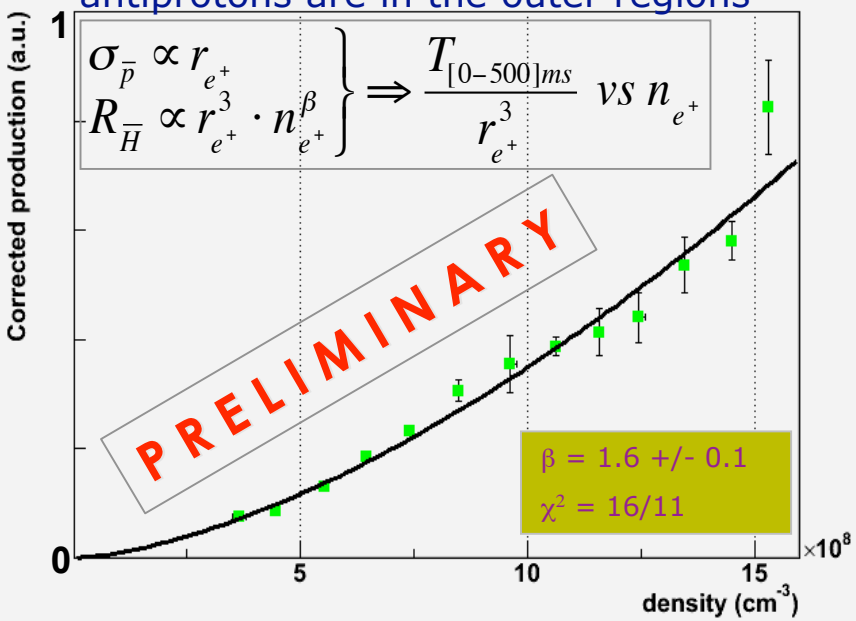
we have not been able to deduce the antiproton radial density yet
we can make assumptions ⇒

is too premature to draw any conclusion about the density dependence

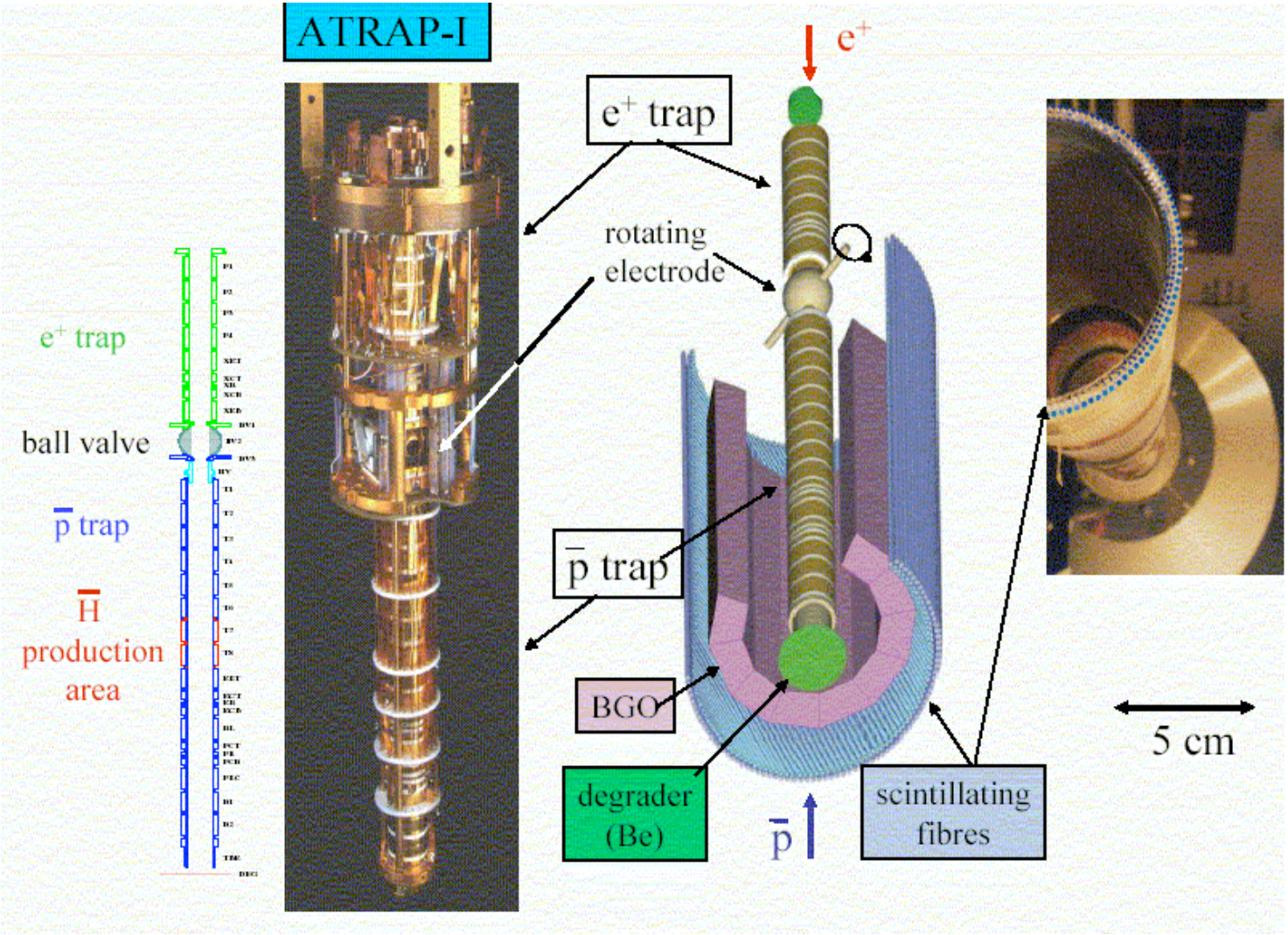
WORK IN PROGRESS
UNCERTAIN but PROMISING

antiprotons are in the outer regions

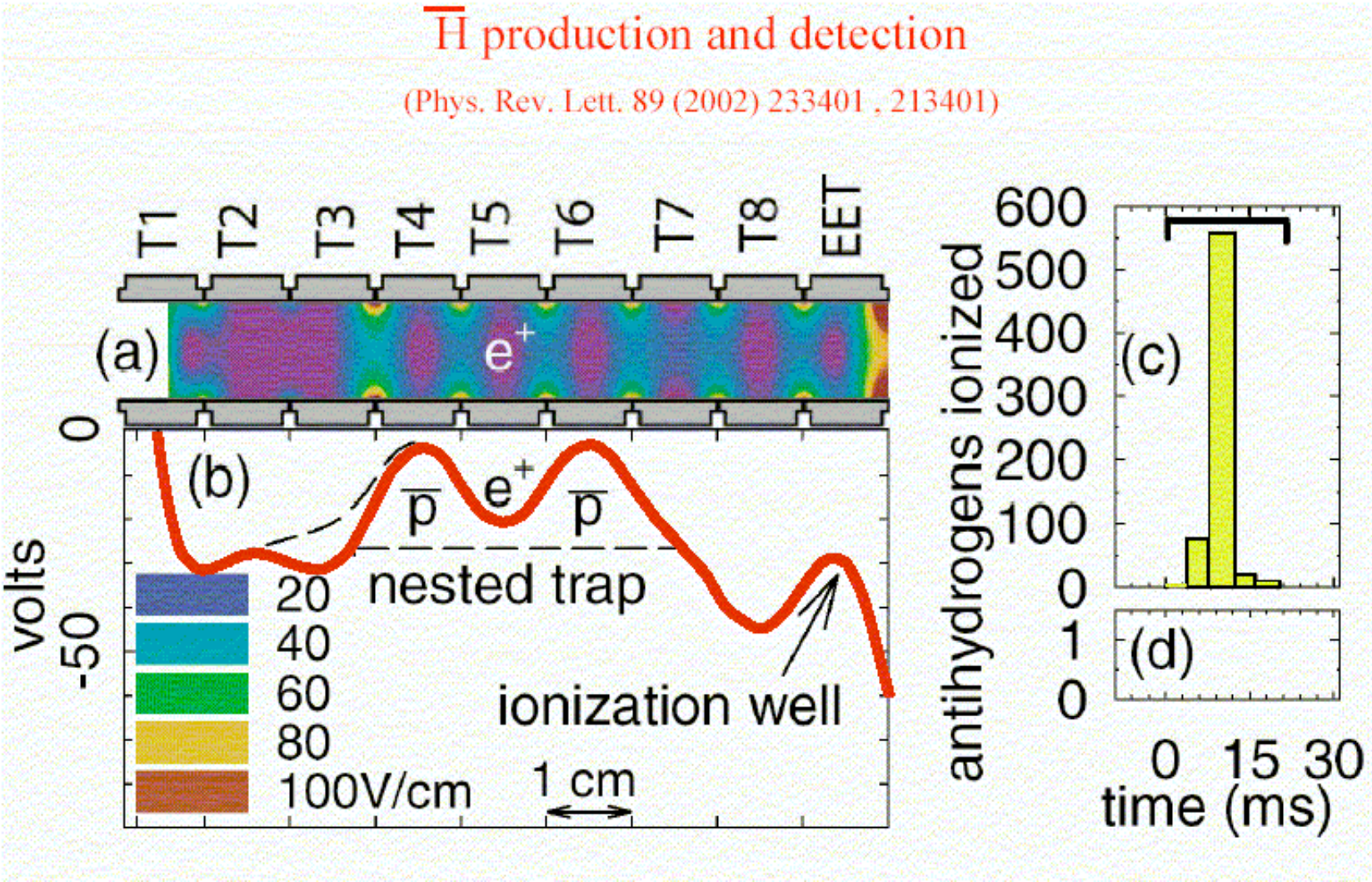
$$\left.\begin{aligned} \sigma_{\bar{p}} &\propto r_{e^+} \\ R_{\bar{H}} &\propto r_{e^+}^3 \cdot n_{e^+}^{\beta} \end{aligned}\right\} \Rightarrow \frac{T_{[0-500]ms}}{r_{e^+}^3} \; vs \; n_{e^+}$$



ATRAP I – from INPC04 Conference Presentation

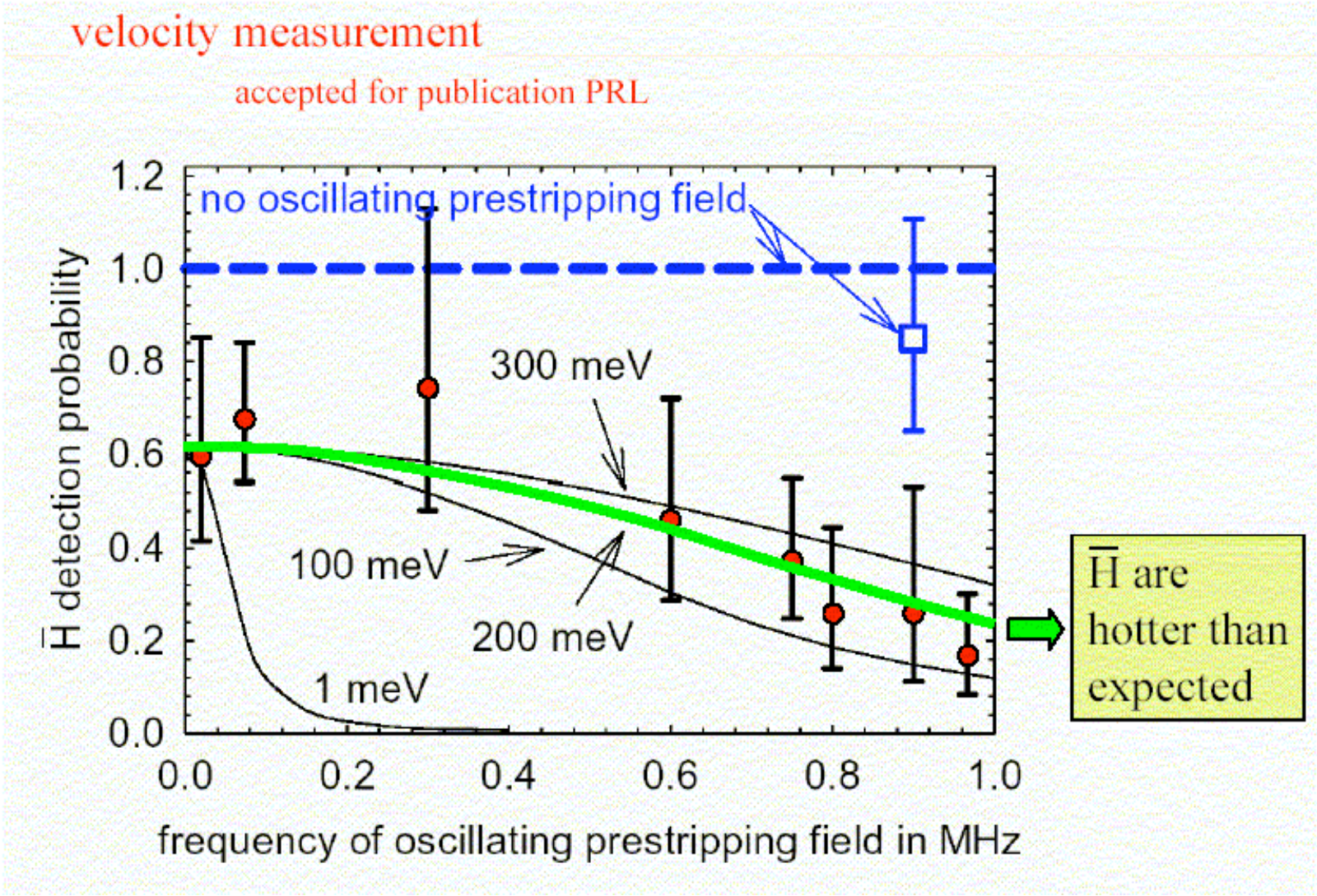


ATRAP II – from INPC04 Conference Presentation



This method also allowed a n-state analysis of the antihydrogen formed

ATRAP III – from INPC04 Conference Presentation



FUTURE - Overview

Challenges:

- **Confinement (and cooling) of neutral antihydrogen**
- **Antihydrogen/hydrogen spectroscopy with few atoms (*)**
- **Antimatter/matter gravity comparison**

(*) Present schemes for H spectroscopy require large numbers of atoms:
10^{10}-10^{13} (trap experiments), 10^{15}-10^{17} (beam experiments)

Only 10^3/min antihydrogen atoms are available now (in ATHENA)

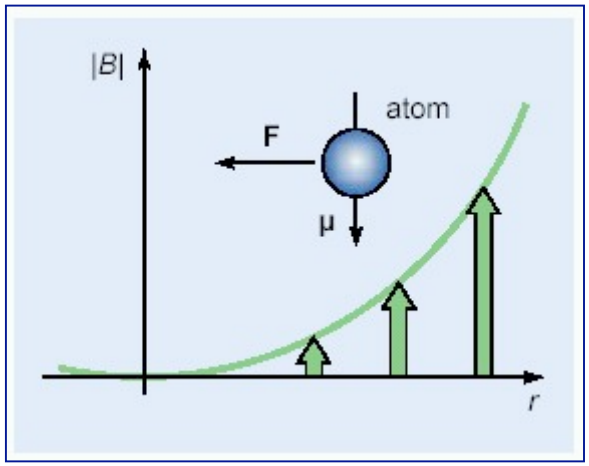
FUTURE – Confinement of Neutral Antihydrogen - I

- **Antihydrogen atoms are rare and expensive**
  current production of antiprotons: 3 x 10^7 every 100 s from AD
  current production of antihydrogen: ~ 10^3 every 3 min (in ATHENA)

Confinement of anti-atoms in neutral-particle magnetic trap

$$U = -\vec{\mu}\,\vec{B}$$

$$\vec{F} = -\vec{\nabla}U$$



Requirement:

- Confine both charged plasmas and neutral atoms
  - Preserve cylindrical symmetry (plasma confinement)
  - Magnetic field minimal in center (atom confinement)
  - Goal: Plasma lifetime of minutes

Solution:

Superpose radial magnetic multipole trap upon solenoidal field

FUTURE – Confinement of Neutral Antihydrogen - II

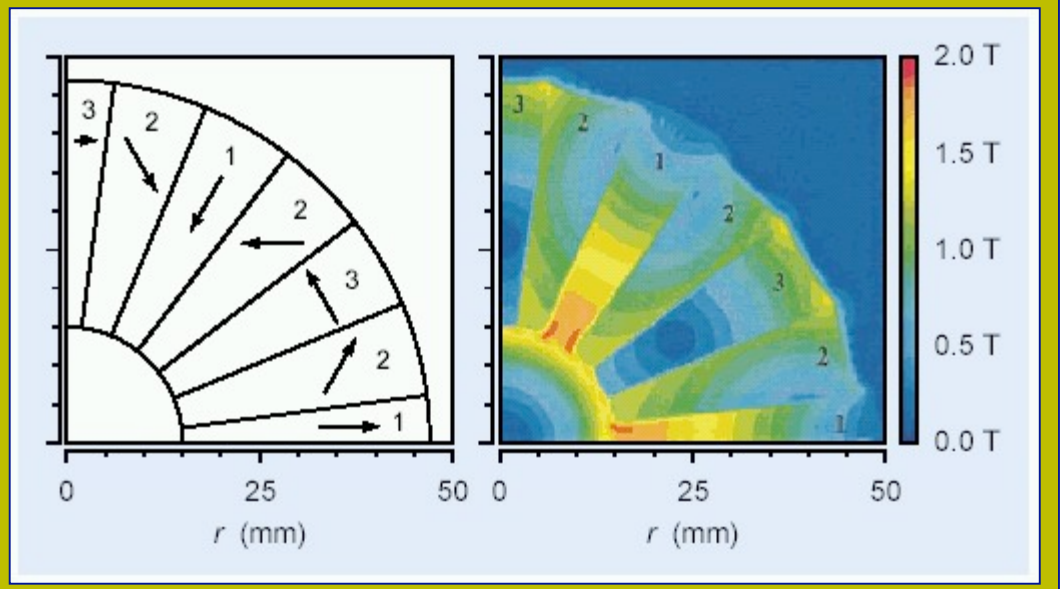
Radial quadrupole: Stable orbits for single particles
[T. Squires *et al.*, PRL **86** (2001) 5266]

***But*: No stable plasma orbits**
[E. P. Gilson & J. Fajans, PRL **90** (2003) 015001]

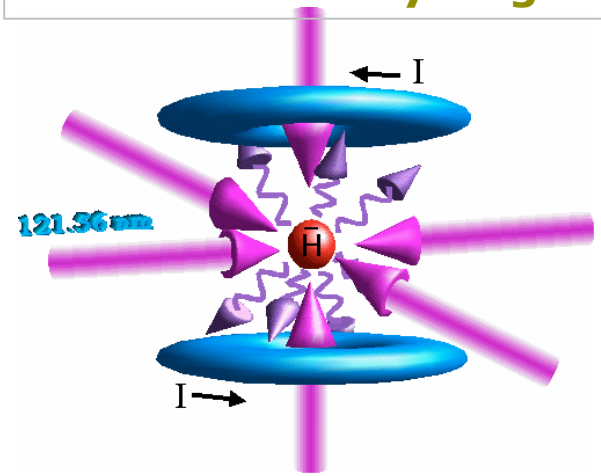
⇒ **Need higher multipole magnet (** $\vec{\nabla}^2\vec{B} \approx 0$ **near axis)**

Permanent magnet for plasma confinement studies:

- Sextupole magnet
  24 segments of NdFeB
- 1.69 T at pole tip
  (at r = 15 mm)
- Check plasma confinement with ordinary matter (e^-)




FUTURE – Antihydrogen spectroscopy



Laser cooling (down to 3 mK)

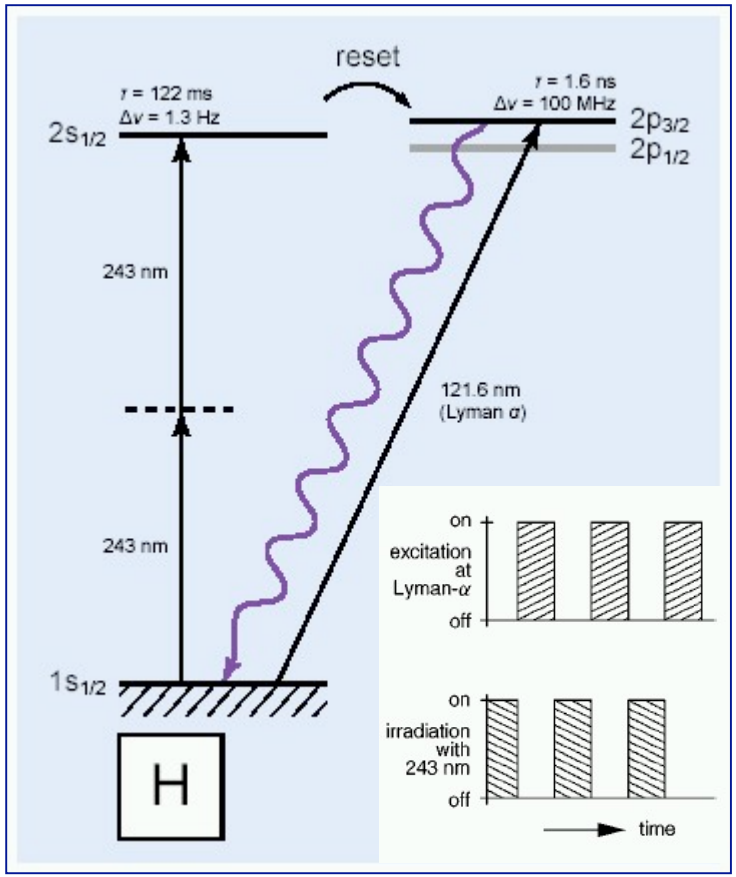
- Strong Lyman-α transition is excited
- Only atoms which travel toward the photons are selected (using Doppler effect) reducing their velocity (3m/s x γ)
- 6 laser beams are used to cool in all directions

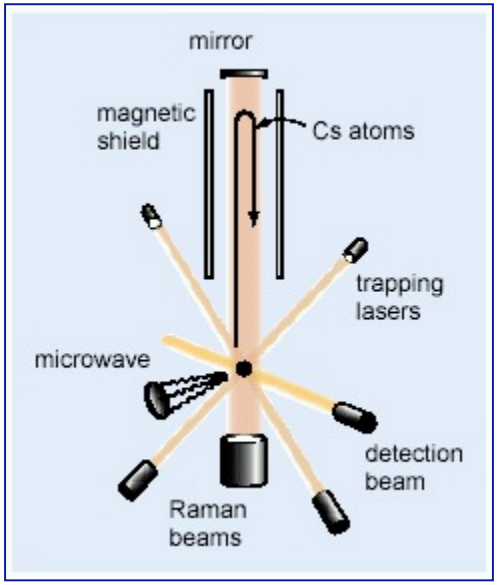
"Shelving" scheme:

- Strong Lyman-α transition is excited and fluoresces
- Metastable 2s state is populated by Doppler-free 2-photon excitation
- "Shelving" suppresses fluorescence
- 2s state is "reset" with microwave field
- Resolution (nat. linewidth): 4 x 10^{-6}

[J. Walz *et al.*, Hyp. Int. 127 (2000) 167]

Hyperfine structure is another possible Spectroscopy Measurement (ASACUSA)





FUTURE – Antimatter gravity tests

$$\Delta\Phi = \frac{\omega g T^2}{c}$$

Atomic fountain

Measurement of *g* by dropping atoms
- Requires ultracold atoms in MOT
- Used for ordinary-matter gravity tests

With 5_10^8 Cs atoms at $T \approx 1\ \_K$, $\Rightarrow\ \_g/g \approx 10^{-10}$ achieved

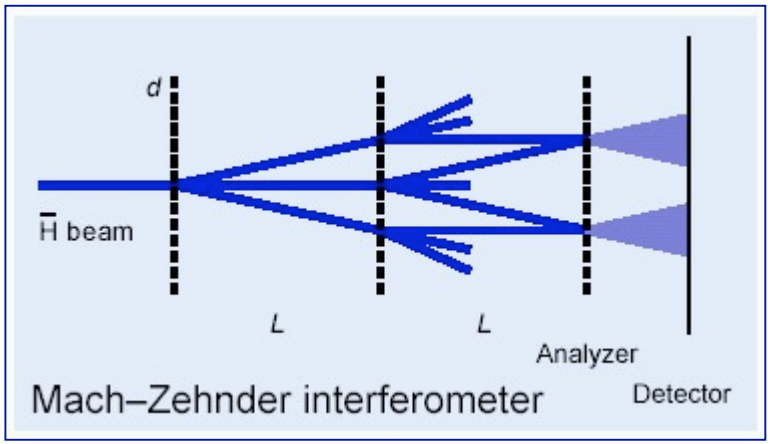
[A. Peters *et al.*, Nature **400** (1999) 849; Metrologia **38** (2001) 25]

Matter-wave interferometry

- Requires cold beam of antihydrogen
- Interference phase independent of: wavelength and spatial coherence

With **1 million** anti-atoms at $T = 4$ K, $d = 1\ \_m$, $L = 1$ m $\Rightarrow\ \_g/g \approx 10^{-4}$

[T. J. Philips, Hyp. Int. **109** (1997) 357]



$$\lambda = \frac{h}{p};\quad E = \frac{p^2}{2m_i} + m_g \bar{g} z$$

CONCLUSIONS

Antihydrogen & CPT

The first step toward CPT (and WEP) tests has been taken by ATHENA & ATRAP (2002) with the production of cold antihydrogen

Work is in progress to understand the involved processes and the properties of the produced antihydrogen (until November 2004 when AD will stop operation)

MEDIUM-TERM GOAL:

- Confinement of charged plasmas and neutral (anti)-atoms in the same trap
- Increase number of produced antihydrogen for a beam

LONG-TERM GOAL:

- Atomic spectroscopy on antihydrogen (CPT)
- Antimatter gravity tests with antihydrogen (WEP)

In the next days there will be an important meeting at Villar where CERN will define its future plans for fixed-target physics (and among others also the future of AD)