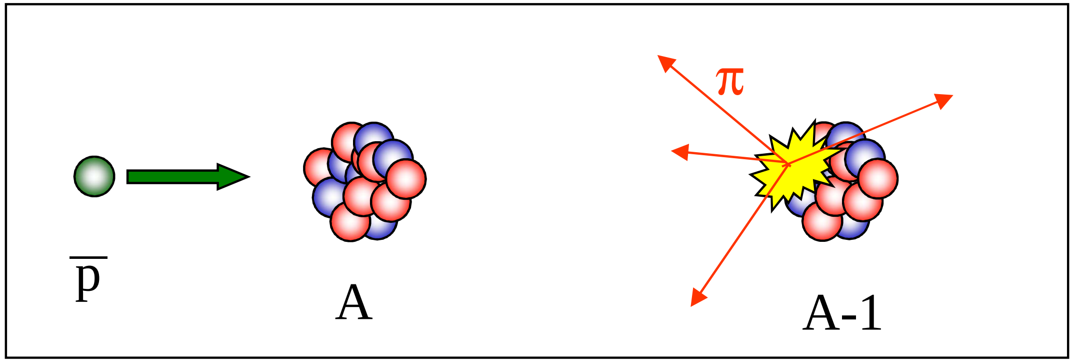
CONSUNTIVI SCIENTIFICI GRUPPO COLLEGATO di BRESCIA

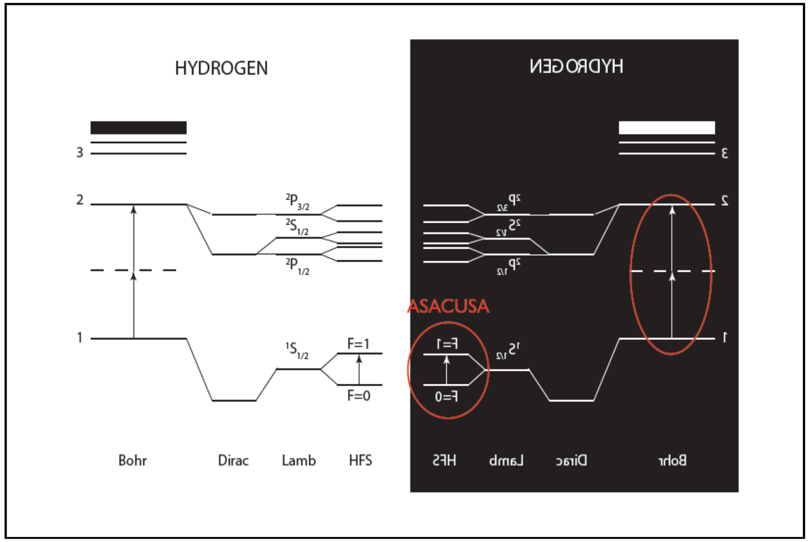
Luca Venturelli

Università di Brescia & INFN Gruppo Collegato di Brescia

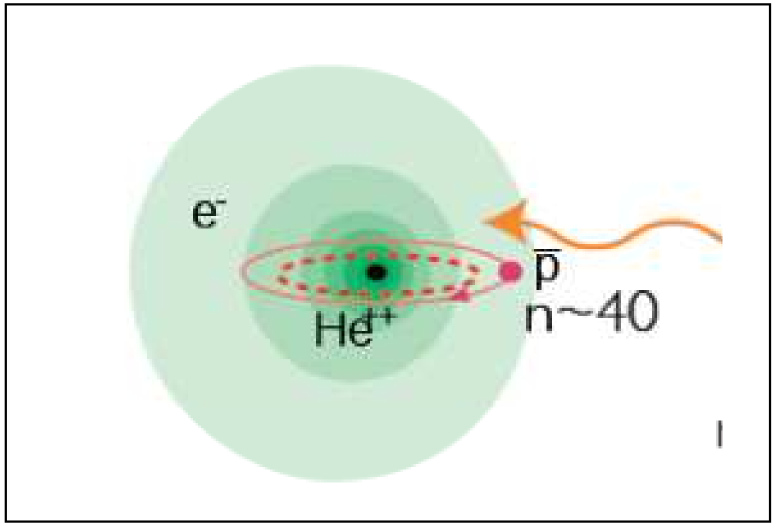
ASACUSA



π
$\bar{p}$
A
A-1



HYDROGEN
3
2
1
$^2P_{3/2}$
$^2S_{1/2}$
$^2P_{1/2}$
$^1S_{1/2}$
F=1
F=0
ASACUSA
Bohr
Dirac
Lamb
HFS



e^-
$\bar{p}$
He^{++}
n~40

ASACUSA

Atomic Spectroscopy And Collisions Using Slow Antiprotons

Asakusa, Tokyo

- Austria - SMI Vienna
- Denmark - University of Aarhus
- Germany - Max-Planck Institute for Quantum Optics
- Hungary - KFKI Budapest, ATOMKI Debrecen
- Italy - INFN Brescia
- Japan - University of Tokyo, RIKEN Saitama
- United Kingdom - University of Swansea, Queens University of Belfast

7 countries, 10 institutions, 40 researchers
Started in 1997 by merger of PS194, PS205, etc. collaborations.
Members active in CERN's antiproton programme since >20 years.

$\bar{p}$He & $\bar{H}$ spectroscopy
→CPT, fundamental const.

100 keV $\bar{p}$s (RFQD)
100 eV $\bar{p}$s ("MUSASHI" trap)

ASACUSA

Atomic Spectroscopy And Collisions Using Slow Antiprotons

Aghai Khozani, H.[1], Barna, D.[2,6], Caradonna, P.[3], Corradini, M.[4], Dax, A.[2], Diermaier, M.[3], Federmann, S.[3], Friedreich, S.[3], Hayano, RS.[2], Higaki, H.[5], Hori, M.[1], Horvath, D.[6], Kanai, Y.[5], Knudsen, H.[7], Kobayashi, T.[2], Kuroda, N.[5], Leali, M.[4], Lodi-Rizzini, E.[4], Malbrunot, C.[3], Mascagna, V.[4], Massiczek, O.[3], Matsuda, Y.[5], Michishio, K.[5], Mizutani, T.[5], Murakami, Y.[2], Murtagh, D.[5], Nagahama, H.[5], Nagata, Y.[5], Otsuka, M.[5], Sauerzopf, C.[3], Soter, A.[1], Suzuki, K.[3], Tajima, M.[5], Todoroki, K.[2], Torii, H.[5], Uggerhoj, U.[7], Ulmer, S.[5], Van Gorp, S.[5], Venturelli, L.[4], Widmann, E.[3], Wunscheck, B.[3], Yamada, H.[2], Yamazaki, Y.[5], Zmeskal, J.[3], Zurlo, N.[4]

1. Max-Planck-Institut für Quantenoptik (DE), 2. The University of Tokyo (JP), 3. Stefan Meyer Institute (AT), 4. Universita' di Brescia, and INFN, Gruppo Collegato di Brescia, (IT), 5. RIKEN, and The University of Tokyo, Komaba (JP), 6. KFKI (HU), 7. University of Aarhus (DK)

ASACUSA Italia (per 2014)

cognome nome		TIPO	Ricercatori	Tecnologi	FTE
Artoni Maurizio	assoc	Prof.Associato			30
Bianconi Andrea	assoc	Prof.Associato			70
Corradini Maurizio	assoc	Ricercatore			100
Ferroni Matteo	assoc	Ricercatore			50
Leali Marco	assoc			x	100
Lodi Rizzini Evandro	assoc				
Mascagna Valerio		Assegnista			100
Venturelli Luca	assoc	Prof. Associato			100
Zurlo Nicola	assoc	Ricercatore			100

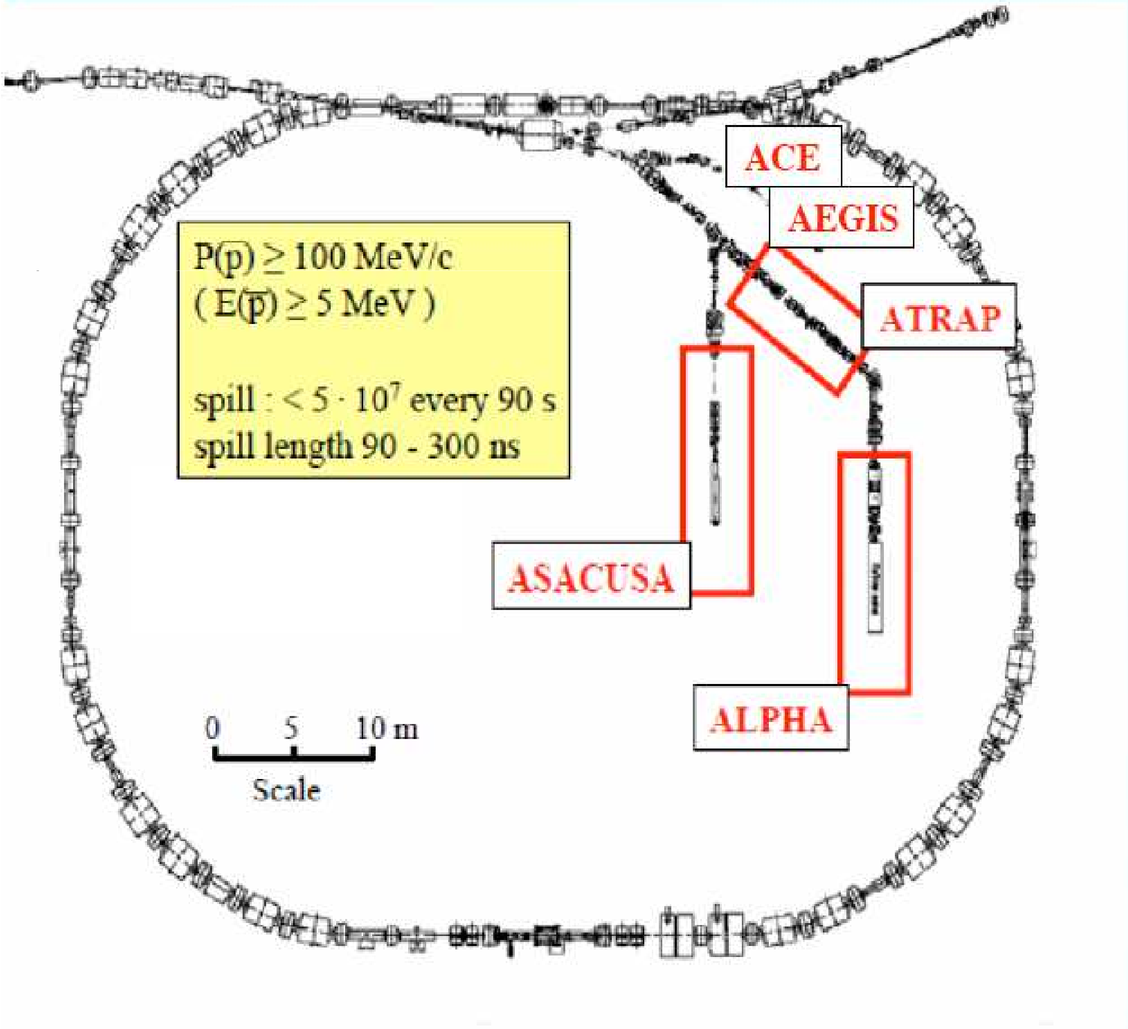
tecnico

Marca Alessandro	tecnico informatico	100

+ collaboratori Universita' dell'Insubria-Como INFN Trieste

	Titolo	Rivista	C
1	Experimental apparatus for annihilation cross-section measurements of low energy... ISI ID della pubblicazione: **WOS:000318321300003**	NUCL INSTRUM METH A, **711-**, (2013)	
2	Sub-Doppler Two-Photon Laser Spectroscopy of Antiprotonic Helium and the Antipro... ISI ID della pubblicazione: **WOS:000322489800021**	FEW-BODY SYST, **54-7-10**, (2013)	
3	Observation of the 1154.9 nm transition of antiprotonic helium ISI ID della pubblicazione: **WOS:000328275700005**	JOURNAL OF PHYSICS B-ATOMIC MO, **46-24**, 245004 (2013)	
4	Thorotrast: Analysis of the time evolution of its alpha activity concentration, ... ISI ID della pubblicazione: **WOS:000330144700013**	PHYSICA MEDICA-EUROPEAN JOURNA, **29-5**, (2013)	
5	Towards the Production of Anti-hydrogen Beams ISI ID della pubblicazione: **WOS:000317068200014**	NON-NEUTRAL PLASMA PHYSICS VII, **1521-**, (2013)	
6	Two-photon laser spectroscopy of antiprotonic helium and the antiproton-electron... ISI ID della pubblicazione: **WOS:000327656000033**	11TH CONFERENCE ON THE INTERSE, **1560-**, (2013)	

Antiproton Decelerator (AD) @ CERN



- **Started operation** July 6, **2000**

  Antiproton capture, deceleration, cooling 100 MeV/c (5.3 MeV)
- **Pulsed extraction**
- **Many Experiments**
  - ASACUSA
  - ATRAP
  - ALPHA
  - AEGIS
  - Free Fall
  - ~~PAX~~
  - ACE
  - .....

Antiprotonic atom formation and spectroscopy;
Antihydrogen formation and spectroscopy;
Atomic collisions;
Nuclear collisions

- **Request for more and better antiproton beams**
  - To speed up progress
  - To boost accuracy

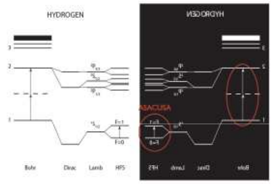
⇒ **ELENA**

AD is the only low-energy $\bar{p}$ source

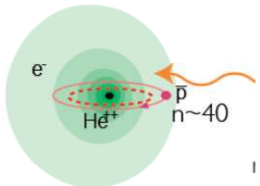
Goals

Studies of *CPT symmetry* by atomic spectroscopy

1) • Microwave spectroscopy of antihydrogen :
→ Ground-state hyperfine structure with 10^{-6} precision.

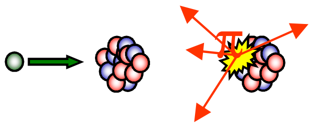


2) • Two-photon laser spectroscopy of antiprotonic helium :
→ Antiproton mass with $<10^{-10}$ precision.



Nuclear collisions with antiprotons

3) • total annihilation cross-section σ at 5 MeV completed. 0.1 MeV ongoing.

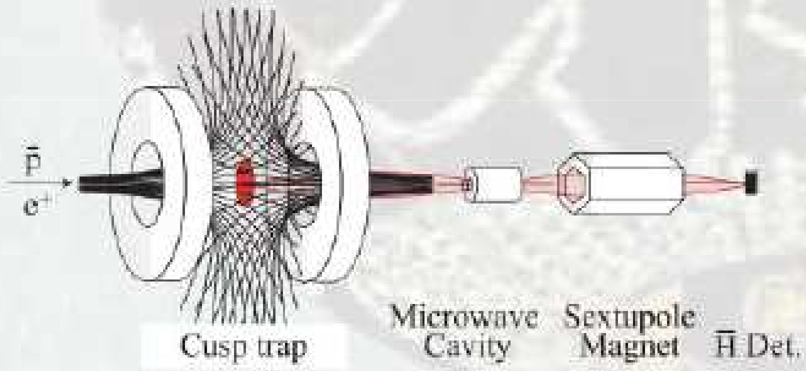


No beam during 2013 (CERN Long Shutdown 1)

→ Analysis of 2012 data

→ Improvements for next data acquisitions

1. Towards $\bar{H}$ Spectroscopy



$\bar{H}$ production demonstrated in 2010
$\bar{H}$ beam development started in 2011
$\bar{H}$ reached 2.7m downstream in 2012
Lots of improvements in 2013

Why study antihydrogen?

- Precise matter-antimatter comparison → CPT test
- Measurement of the gravitational behavior of antimatter → WEP test

CPT

CPT invariance is inside the Standard Model

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

  - particles/antiparticles: equal mass, lifetime; equal and oppositye charge and magnetic moment
  - atoms/antiatoms: identical energy levels

Standard Model can be extended with CPT violation

CPT violation in Standard Model Extension

Indiana group, Kostelecky et al. (since 1997)

CPT Violating terms

$$(i\gamma^\mu D_\mu - m - a_\mu\gamma^\mu - b_\mu\gamma_5\gamma^\mu - \frac{1}{2}H_{\mu\nu}\sigma^{\mu\nu} + ic_{\mu\nu}\gamma^\mu D^\nu + id_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0$$

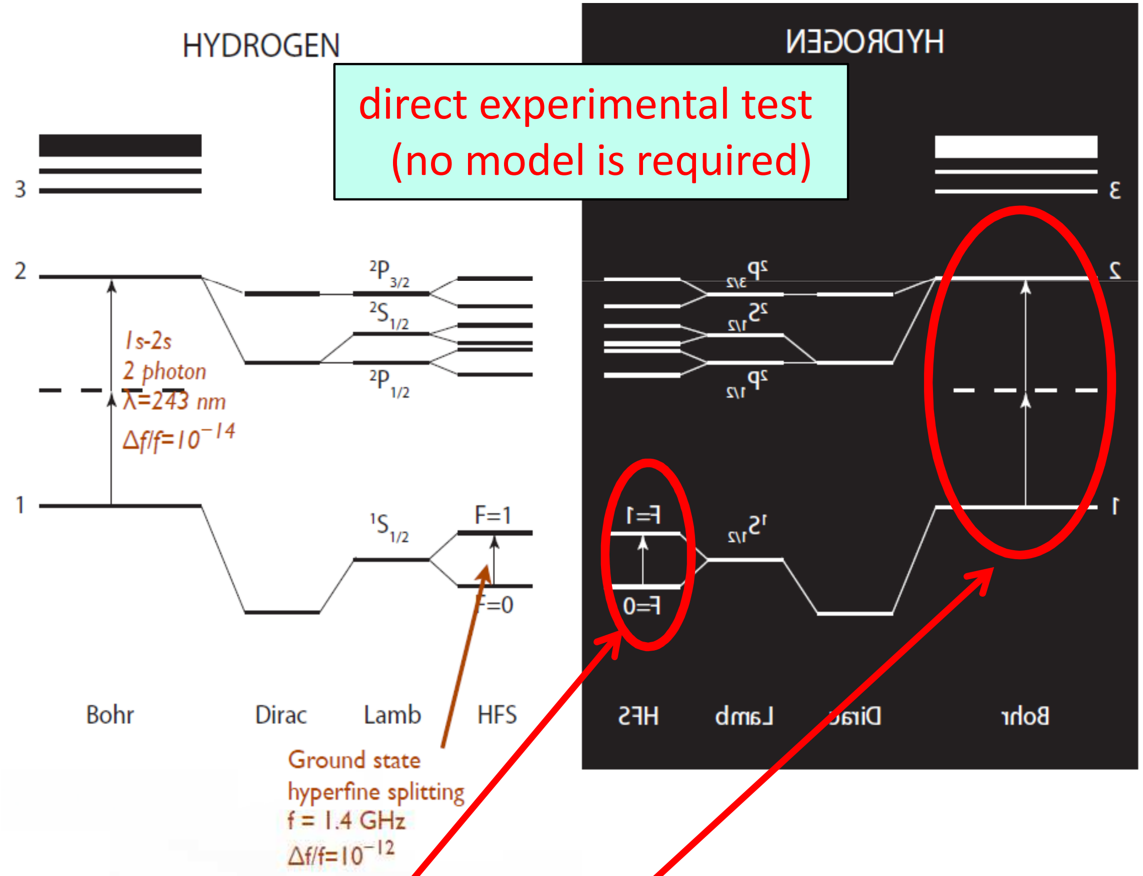
Lorentz Invariance Violating terms

a & b parameters have energy dimensions

No quantitative prediction

Antihydrogen for CPT test

matter-antimatter precise comparison by means of spectroscopy



direct experimental test
(no model is required)

Plans for antihydrogen:

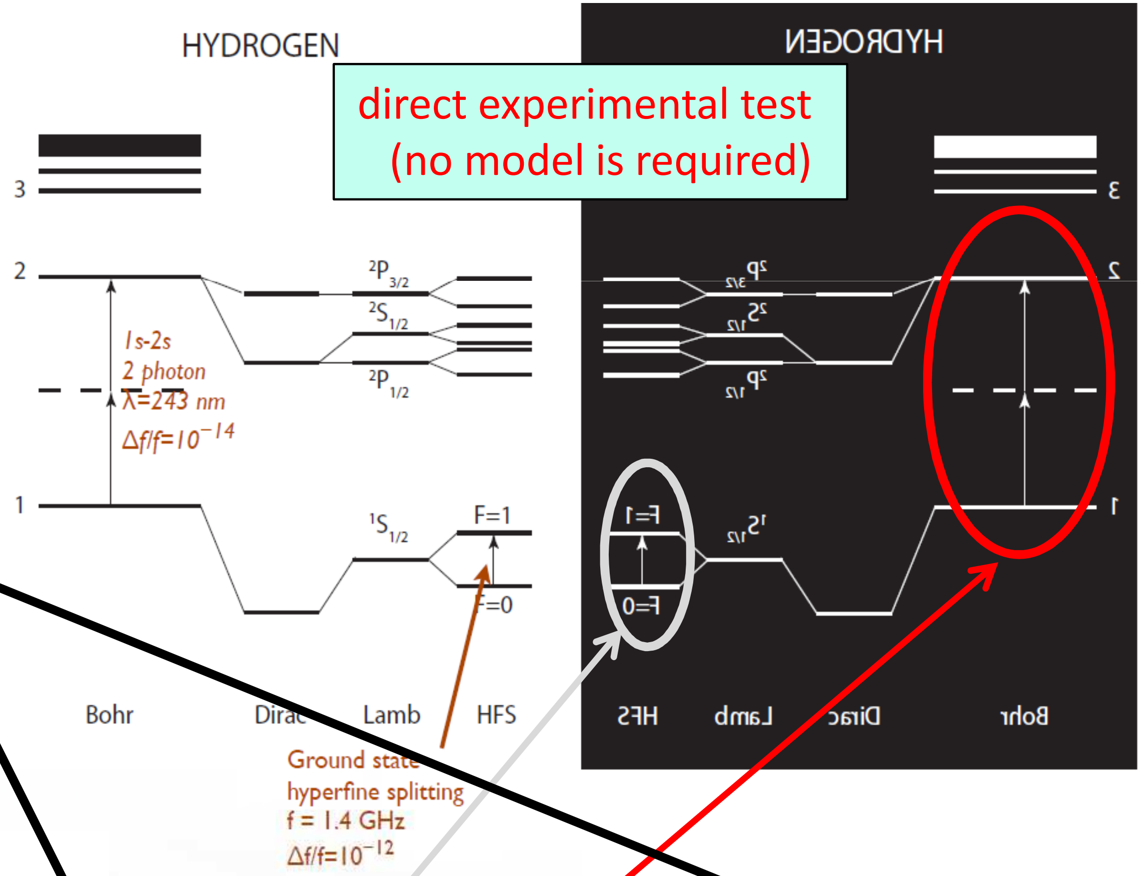
- measurements:
  - Hyperfine splitting of ground state
  - 1S-2S transition

- methods:
  - Antihydrogen trapping
  - Antihydrogen beam

Antihydrogen for CPT test

matter-antimatter precise comparison by means of spectroscopy

direct experimental test
(no model is required)



ALPHA
ATRAP

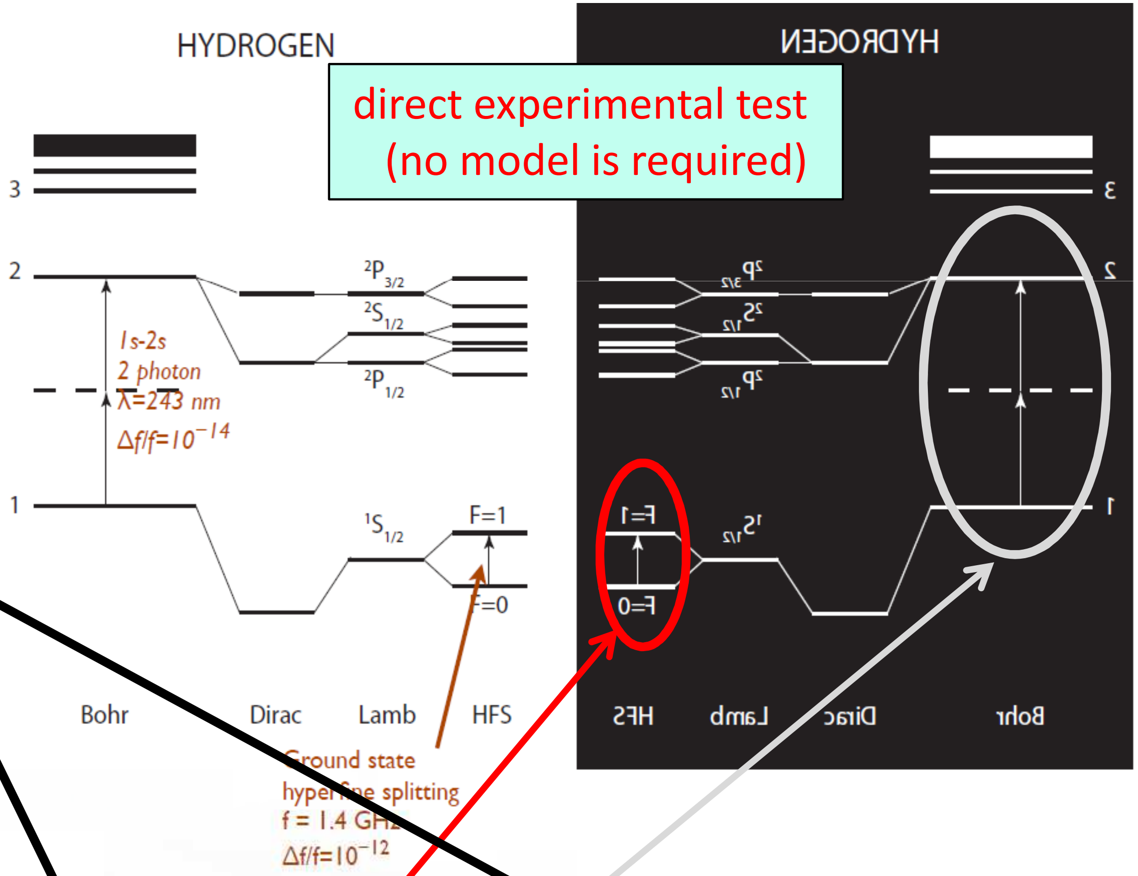
Plans for antihydrogen:

- 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



direct experimental test
(no model is required)

ASACUSA

AEGIS

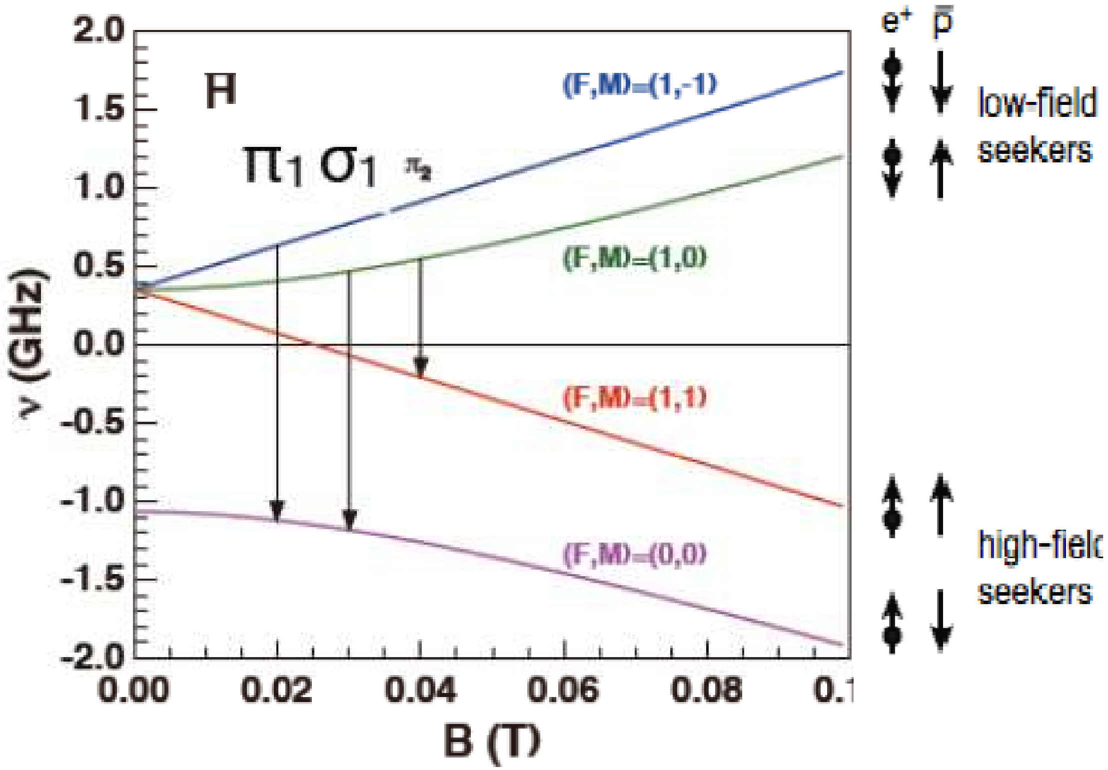
Plans for antihydrogen:

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

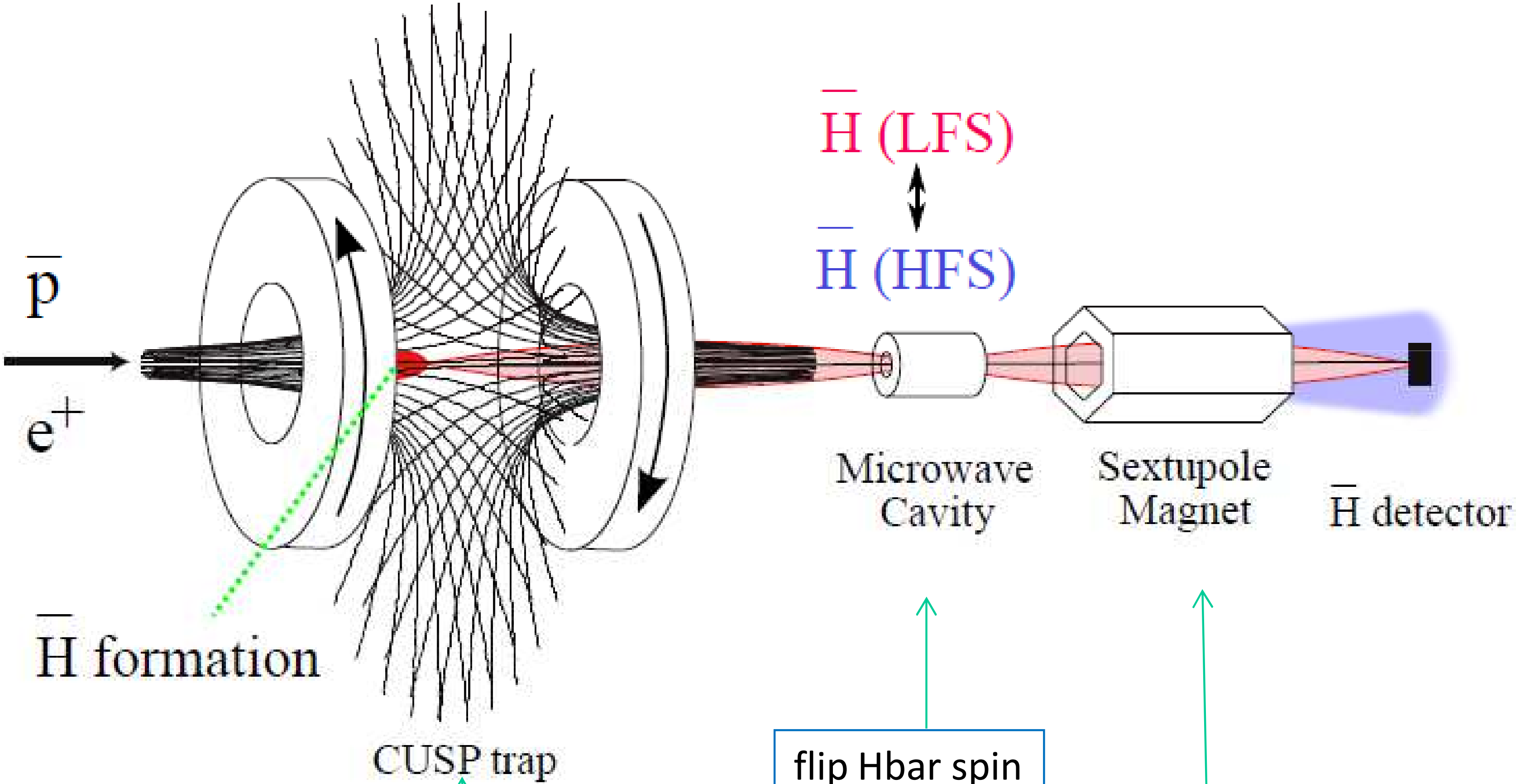
- methods: - Antihydrogen trapping
  - **- Antihydrogen beam**

Method

- (anti)atomic beam
- measure σ_1 at several B's, extrapolate to B = 0
- achievable precision $\lesssim 10^{-6}$ for T $\leq$ 100 K
- > 100 $\bar{H}$/s in 1S state needed



Scheme of the measurement



flip Hbar spin

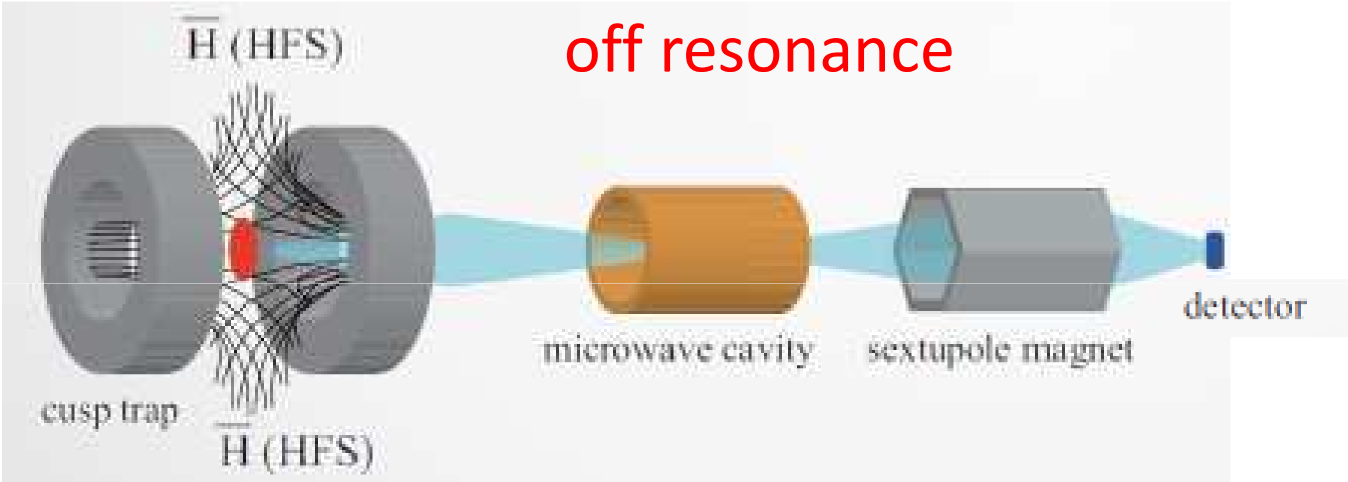
confine pbars and e^+ ;
select Hbar spin state

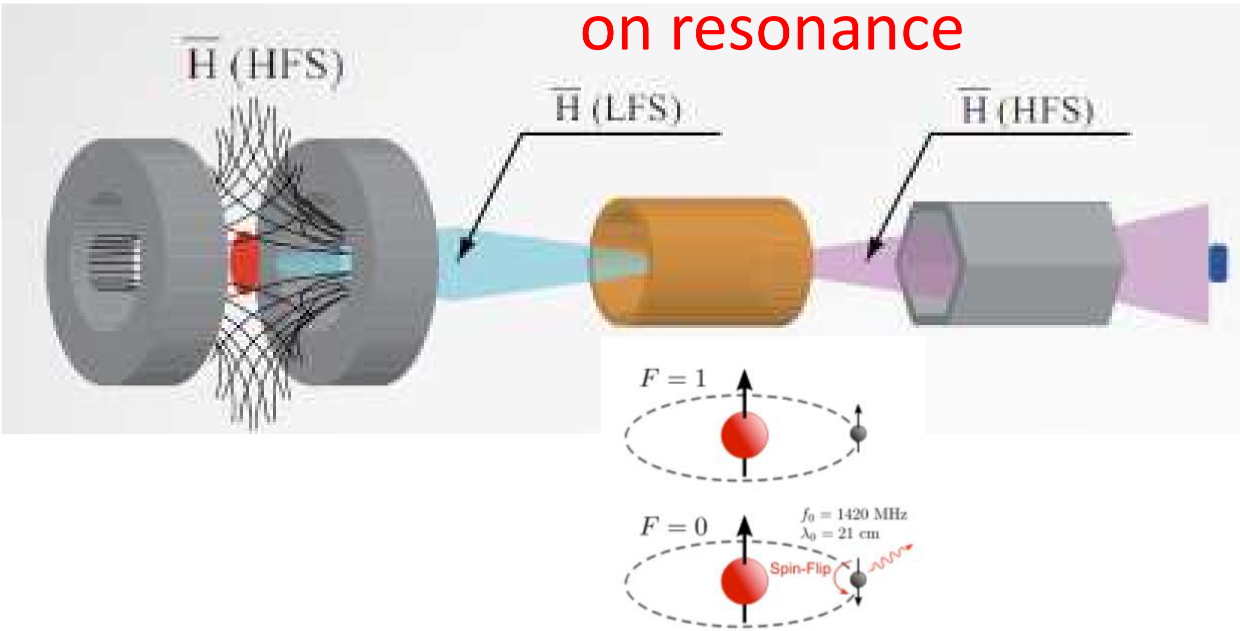
select spin state

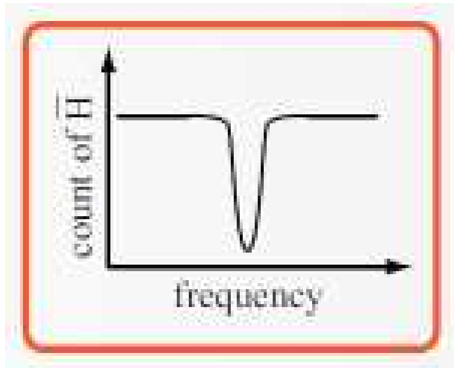
HFS-states: de-focused
LFS-states: focused

B and **E** axially symmetric

Scheme of the measurement

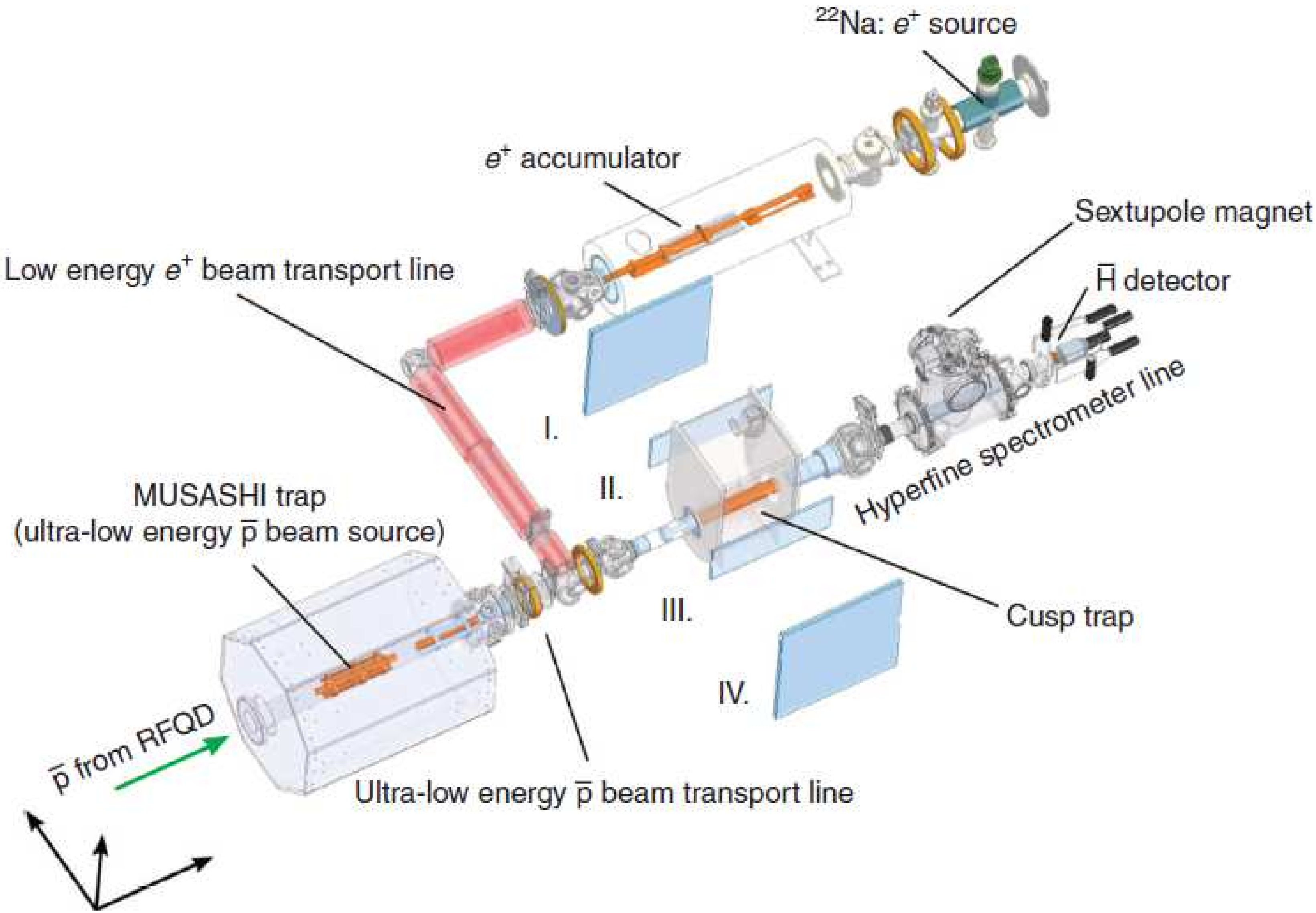




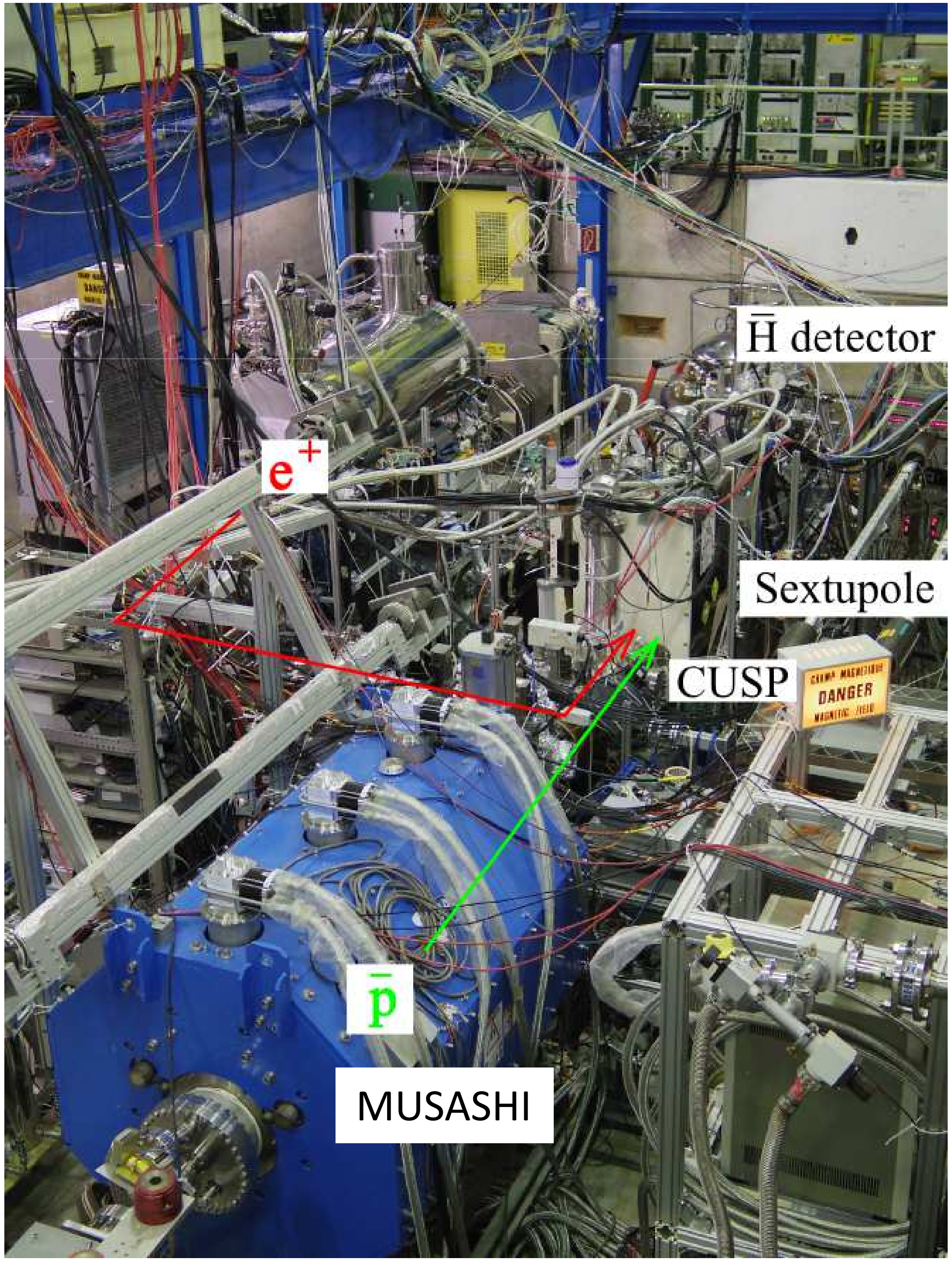


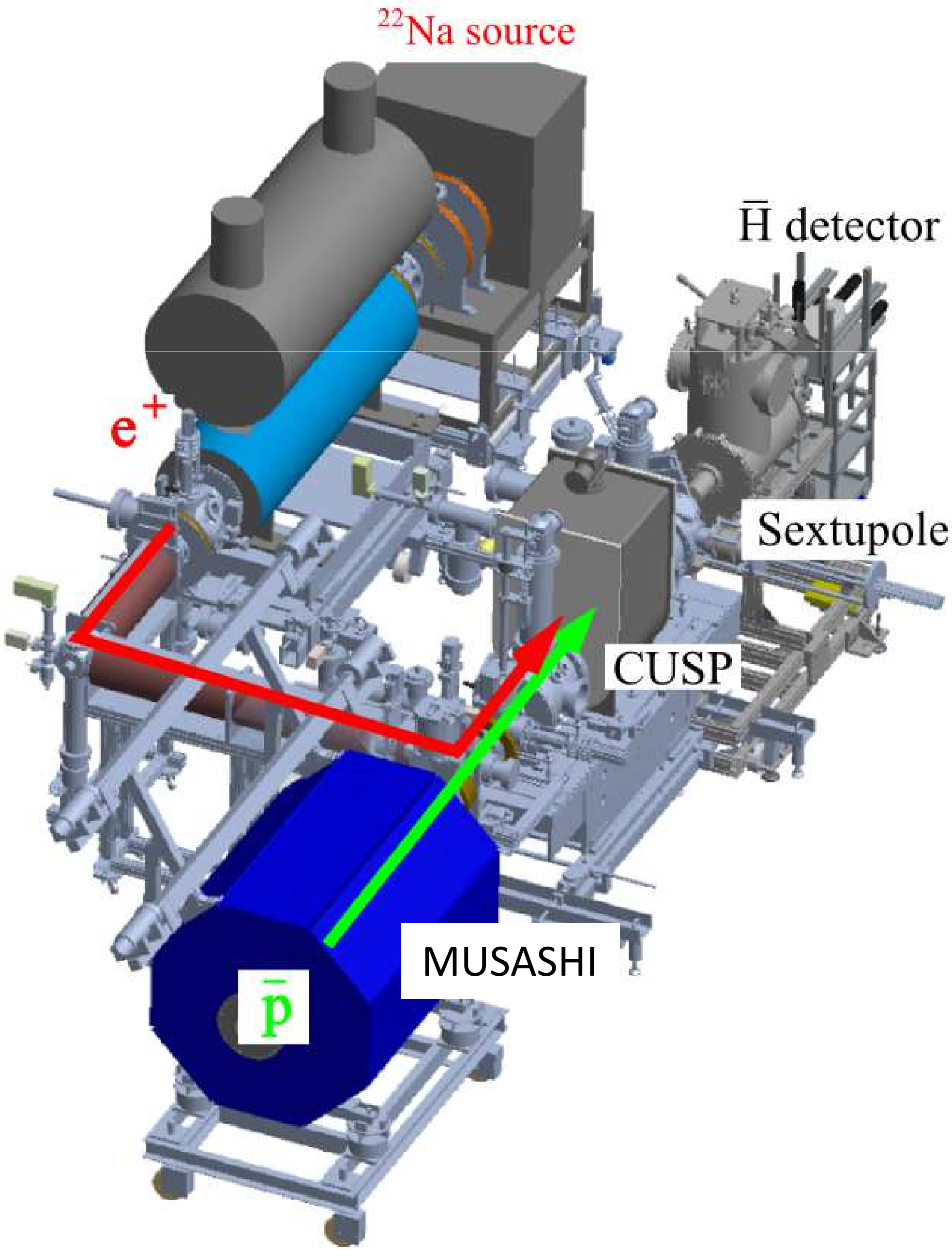
"Disappearance Mode"

experimental set-up

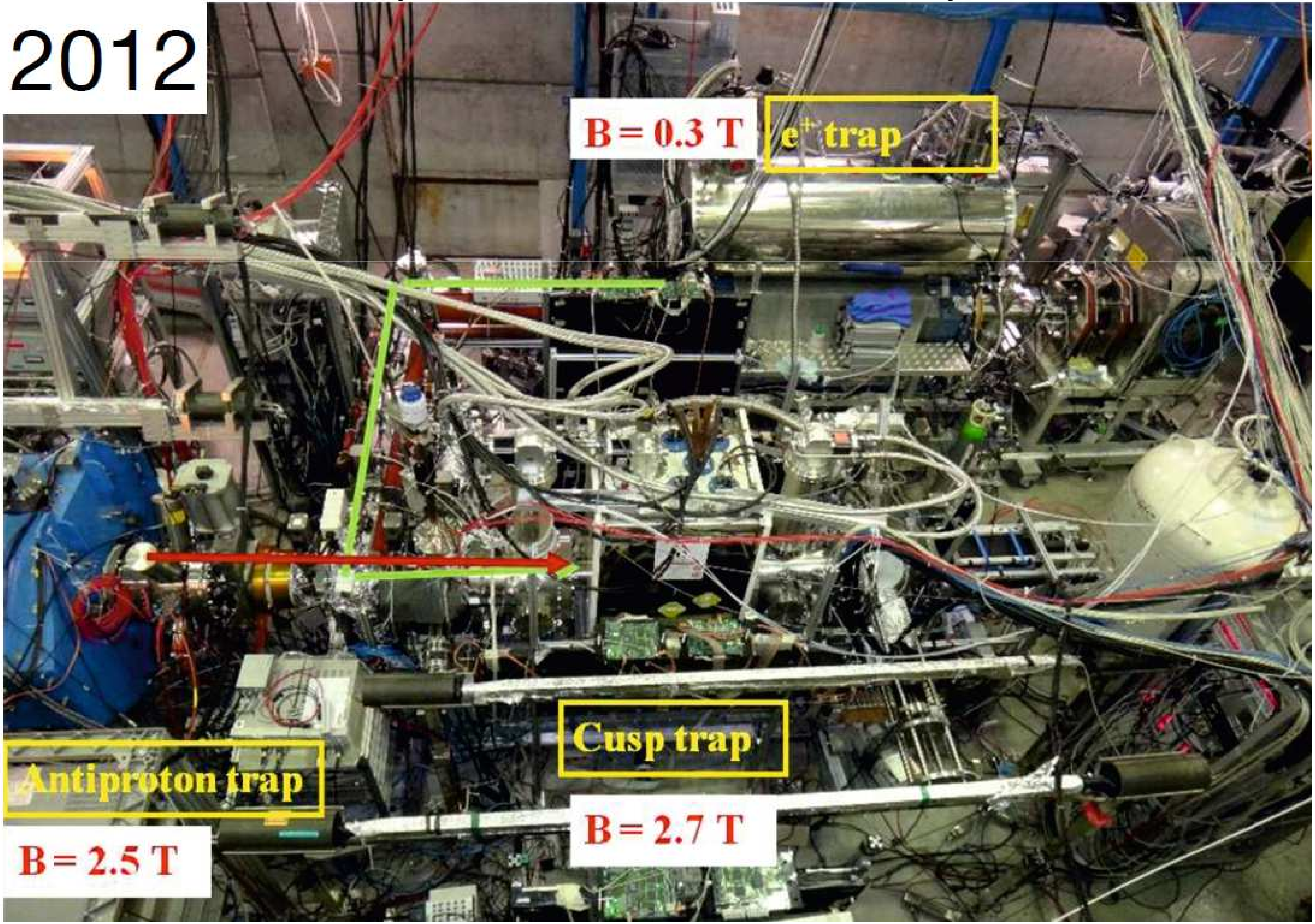


experimental set-up

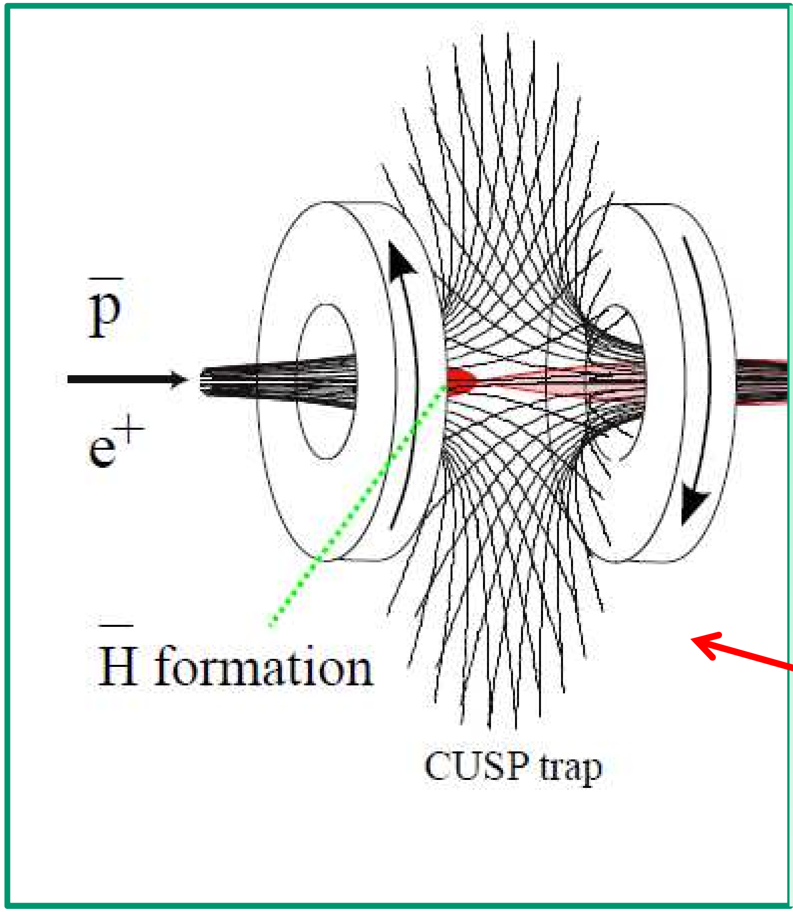


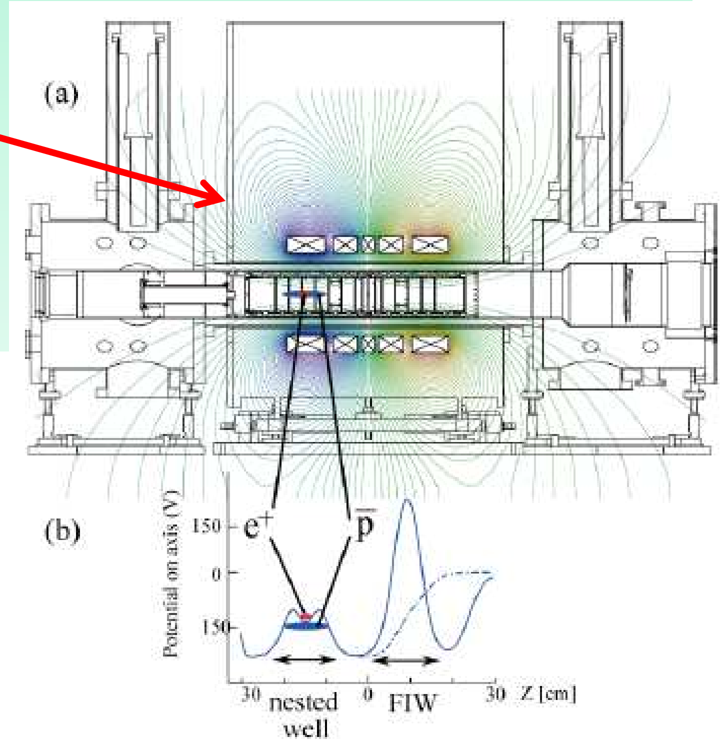


experimental set-up



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

ASACUSA

Tracking detector

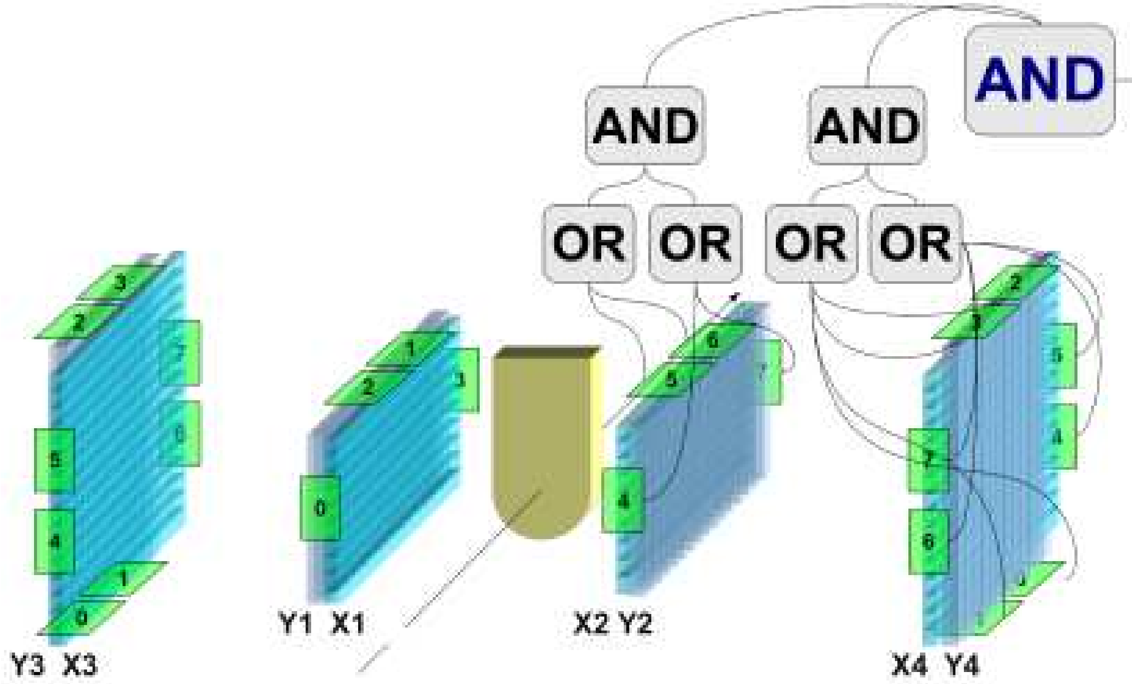
- Scintillator bars 15 mm × 15 mm

  960 mm in length
- $\Omega/4\pi$ = 6.6% + 8.6%

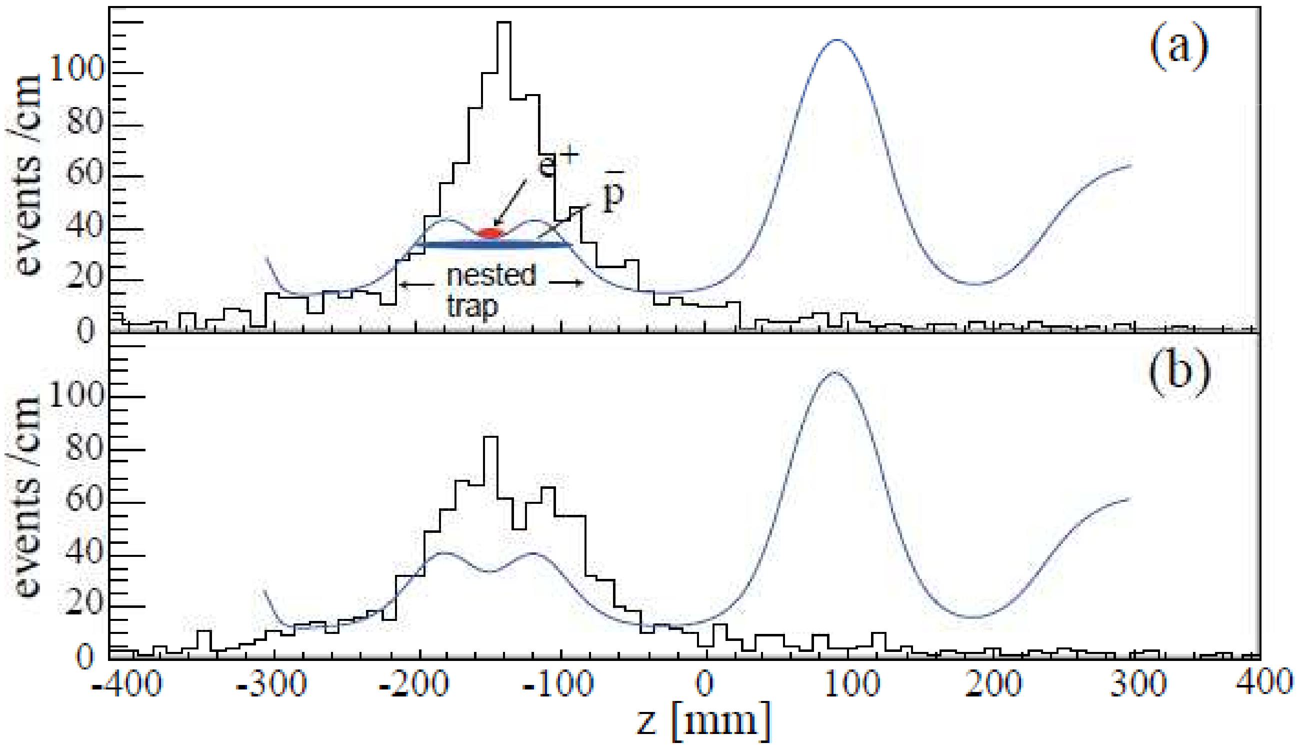
  for each side
- for $\pi^{\pm}$ multiplicity 3

  ⇒ 39%
- double coincidence

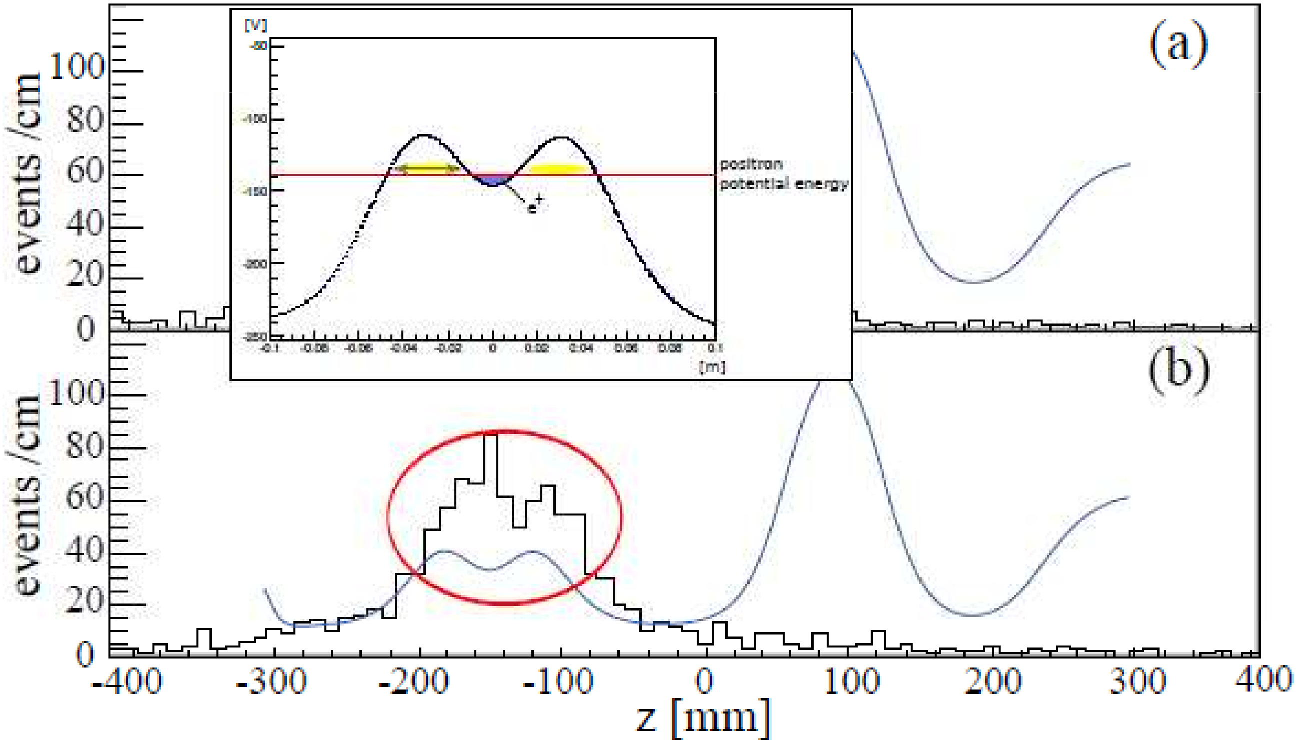
  ⇒ 3.3%



Annihilations vertices



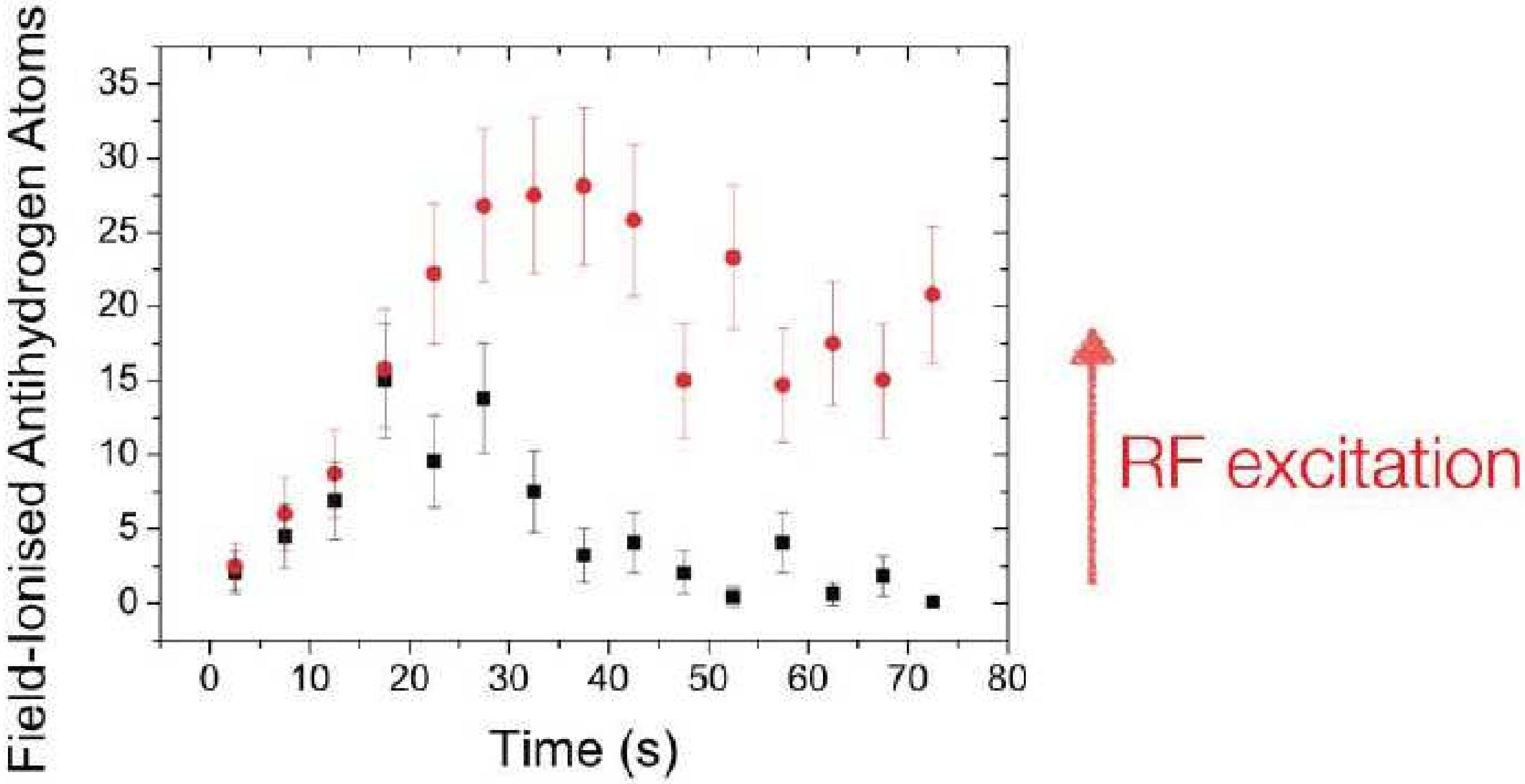
Annihilations vertices



Increase antihydrogen production

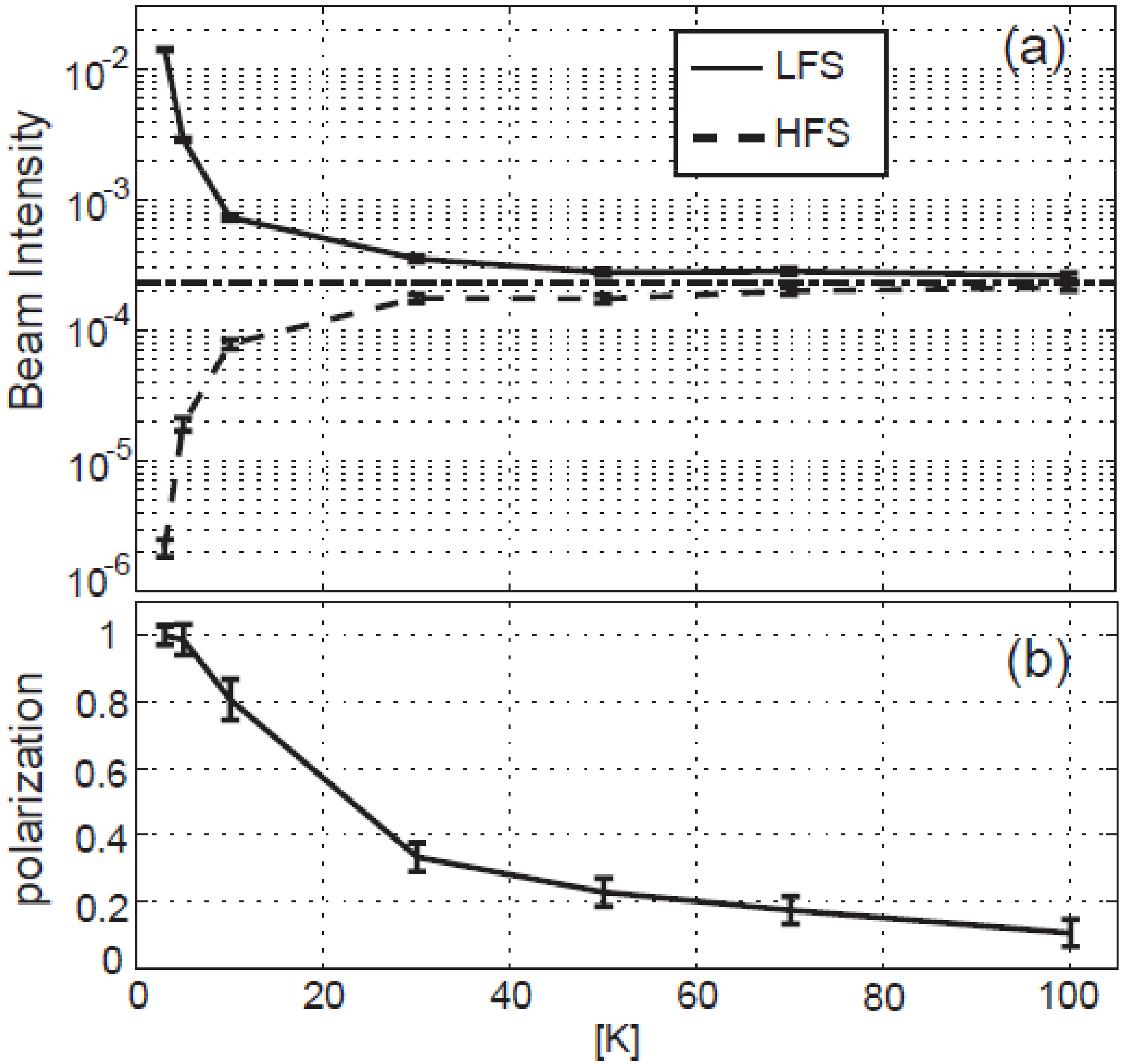
3×10^5 $\bar{p}$ mixed with 3×10^7 e^+

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

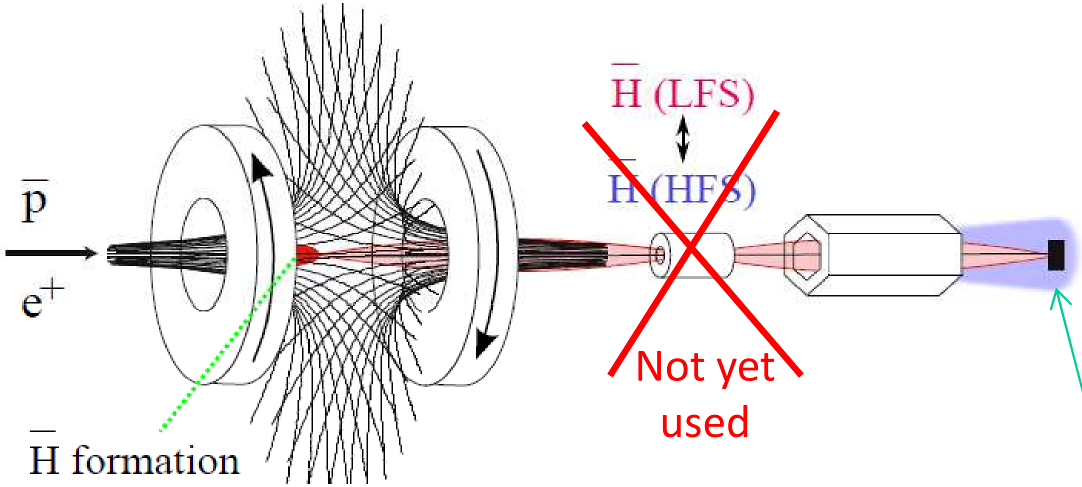


Antihydrogen beam

expected polarization of antihydrogen beam



Antihydrogen beam



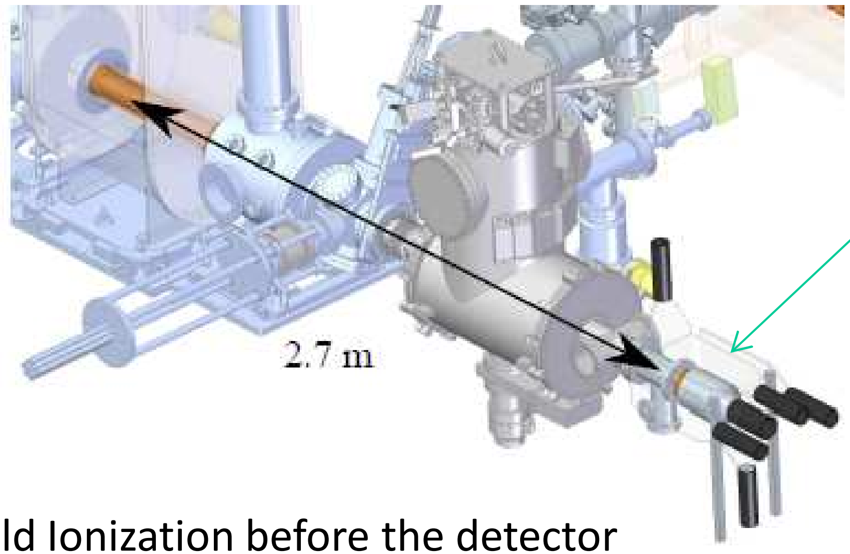
nature COMMUNICATIONS

ARTICLE

Received 25 Jun 2013 | Accepted 11 Dec 2013 | Published 21 Jan 2014 DOI: 10.1038/ncomms4089 OPEN

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]

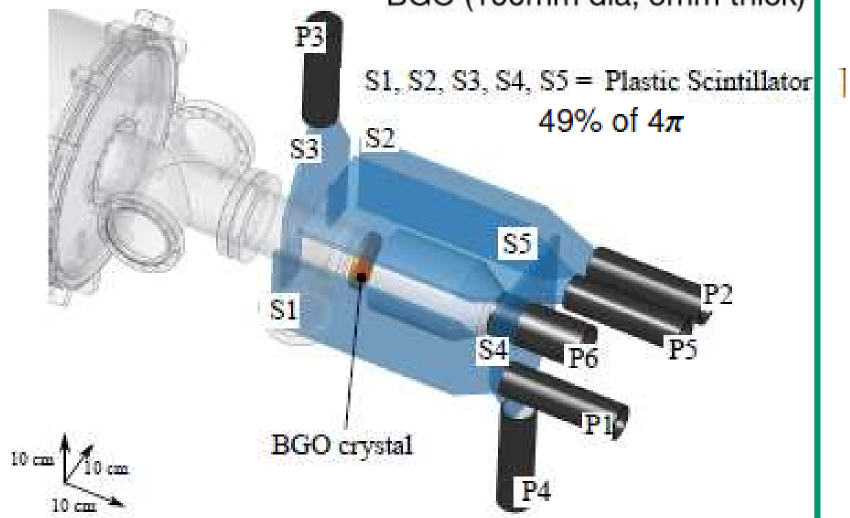


Field Ionization before the detector

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

Hbar detector

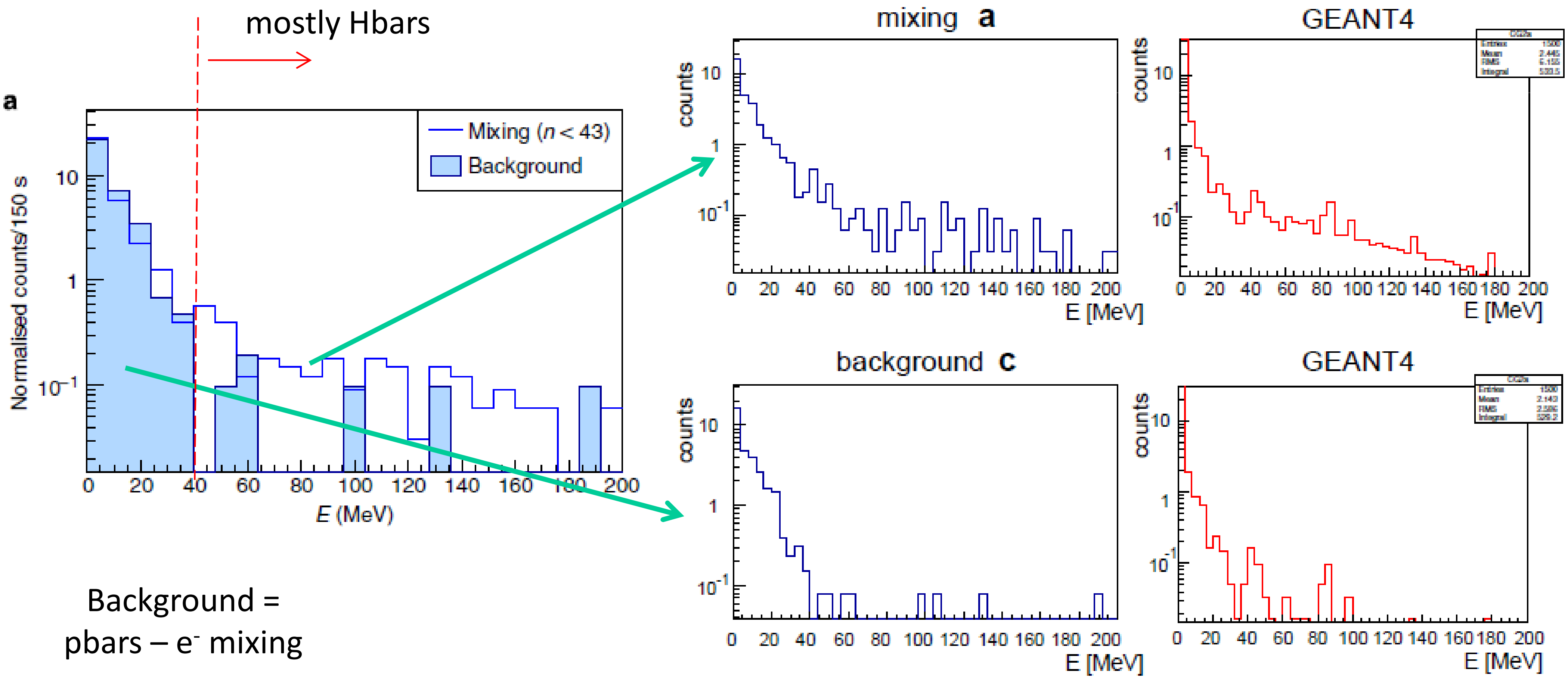
plastic +
BGO (100mm dia, 5mm thick)



BGO measures energy deposition by Hbar annih.

coincidence: BGO AND (>1 S)

Energy deposition in the BGO



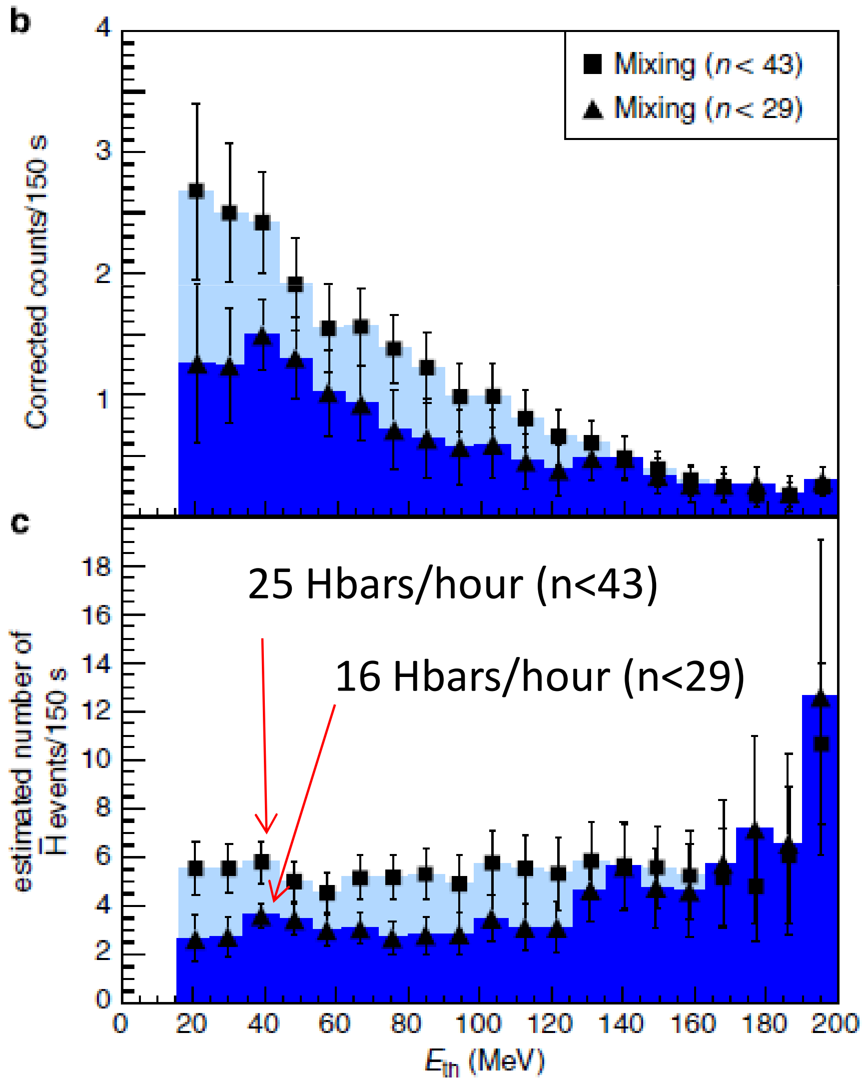
Background =
pbars – e⁻ mixing

Antihydrogens reaching the BGO

a-c (see previous slide)

Integration from E_{th} to 200 MeV

After detection efficiency correction (from GEANT)



80 Hbars detected

Improvements in 2013

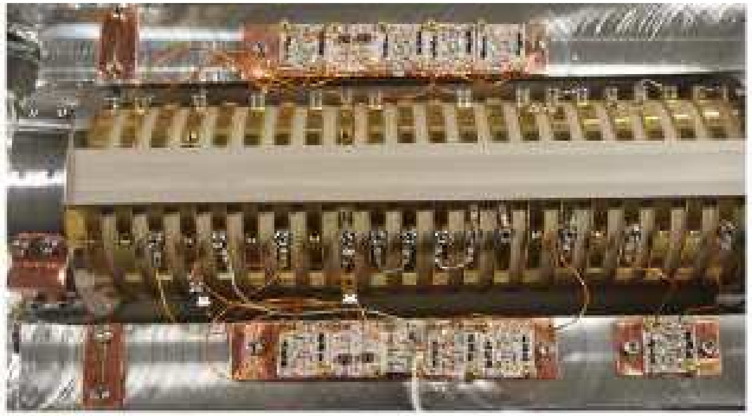
- Positron Accumulator (more e^+s for the 2014 run)
- Improved e^+ transport
- Sextupole & cavity

More e$^+$ for the 2014 run

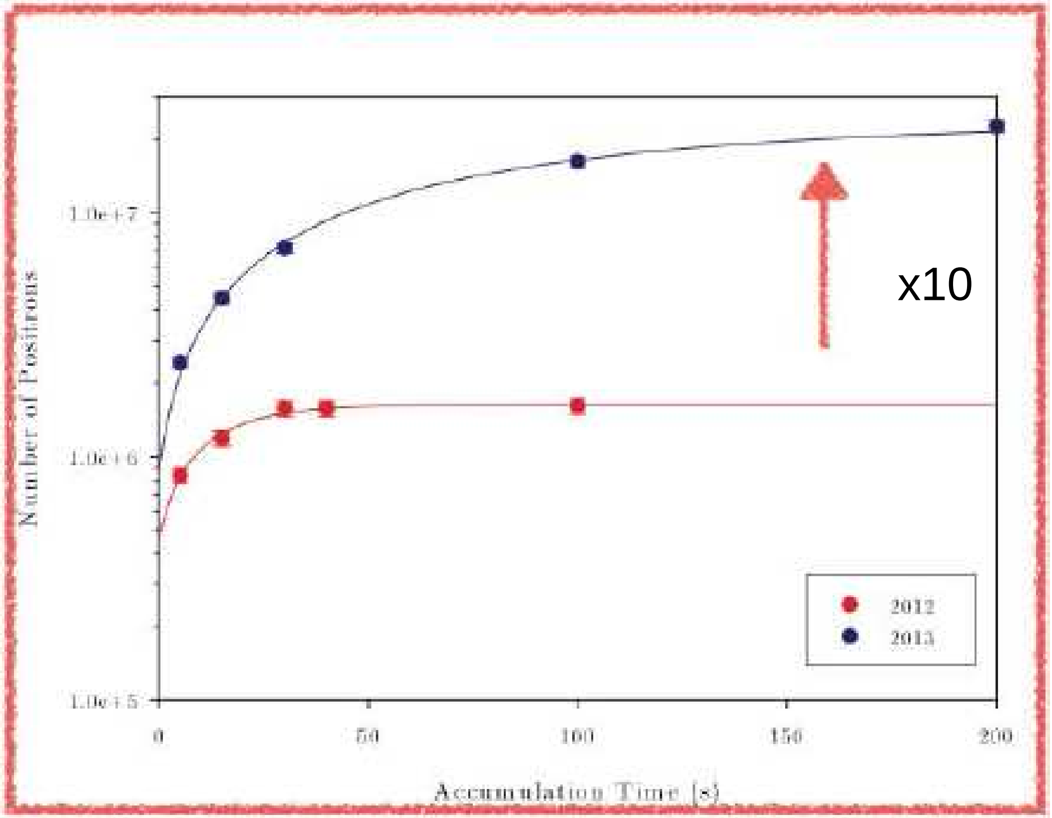
Electrode noise reduced (longer lifetime)

A new ^{22}Na source 0.65 GBq→1.84 GBq

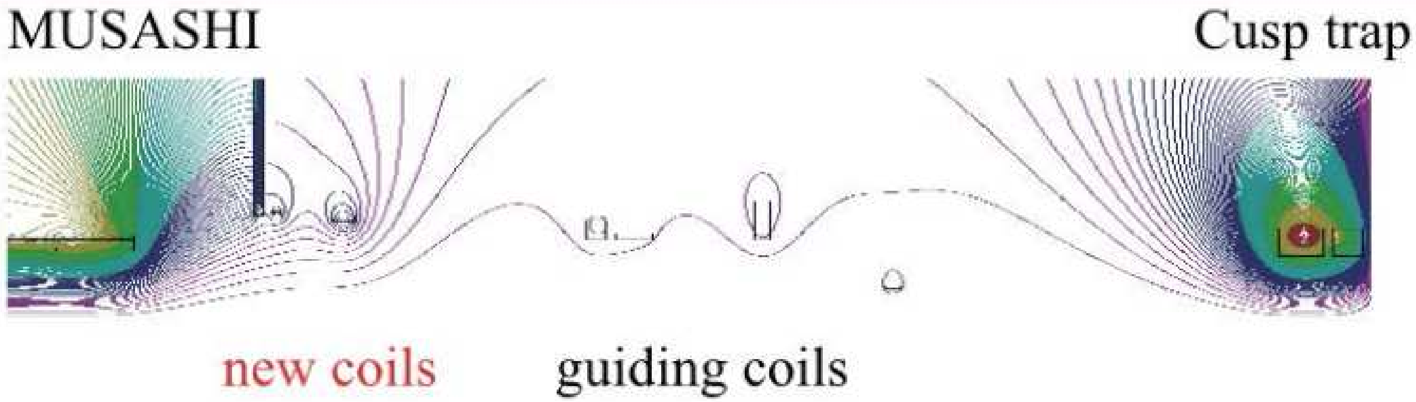
Magnetic field 0.3 T→ 1 T (longer lifetime, less transport loss)



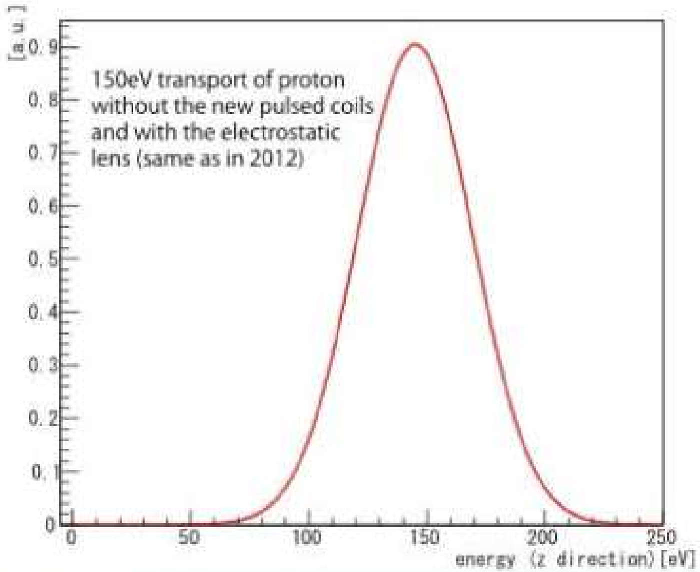
new filters added to the
e$^+$ accumulator electrodes

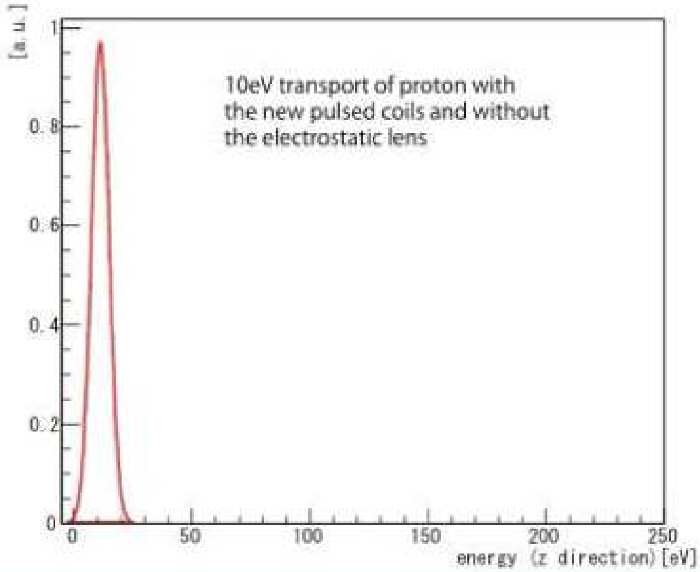


new $\bar{p}$ injection scheme



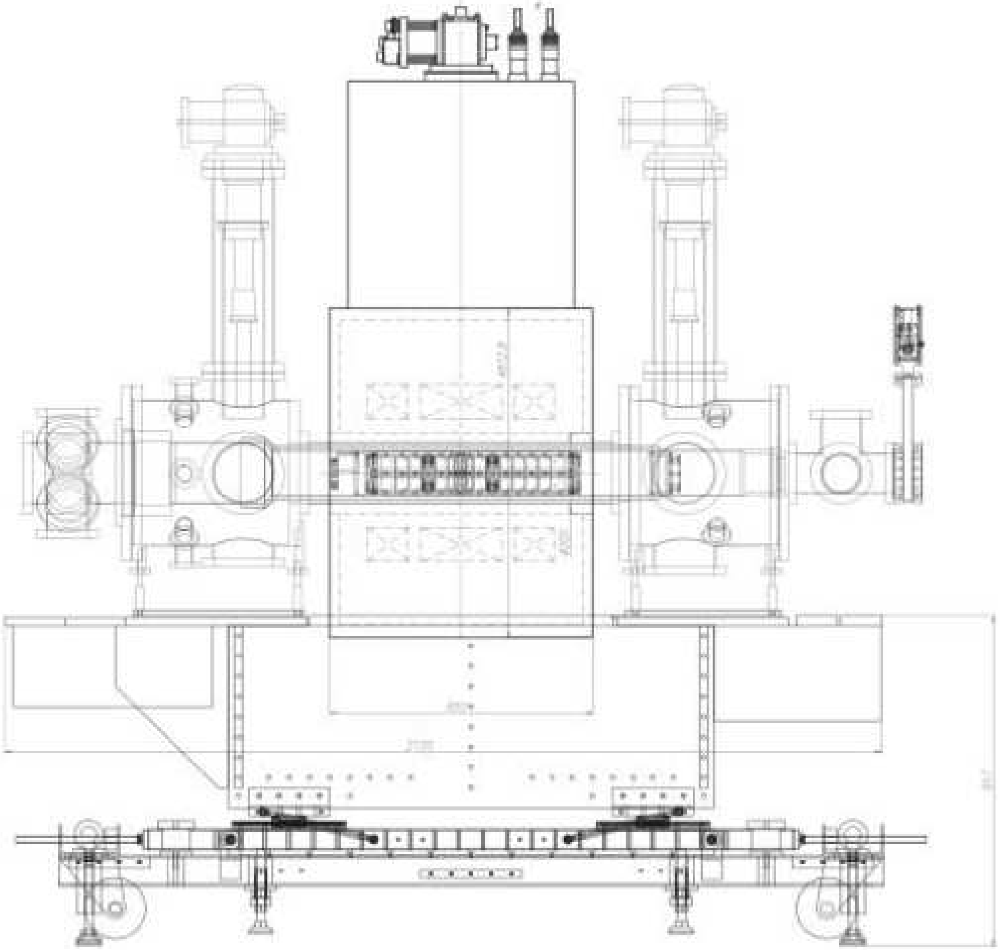
injection at 150 eV with electrostatic lens (energy spread 24 eV FWHM) → injection at 10 eV with guiding coils (no lens)





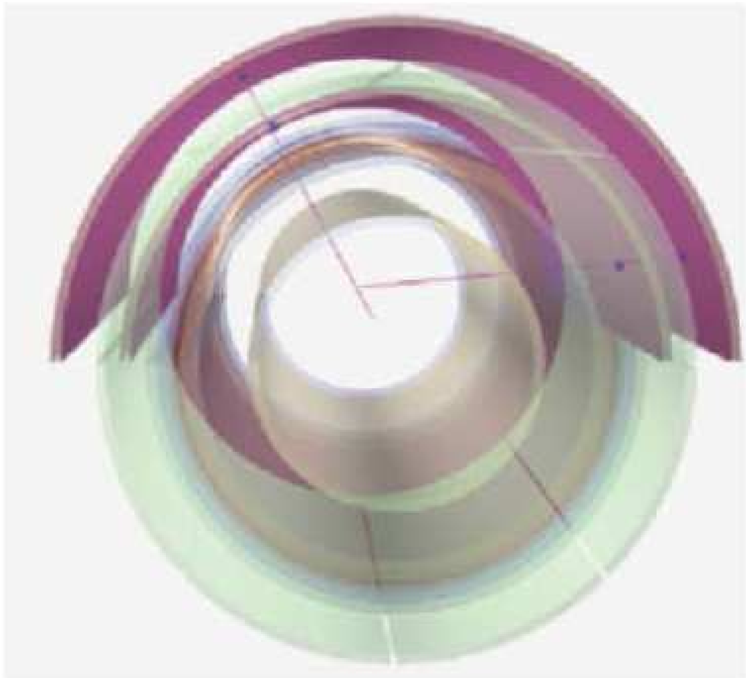
new “double cusp” magnet & detector

1. improve the focusing power
2. higher spin-polarization of antihydrogen



multilayer micromegas detector for

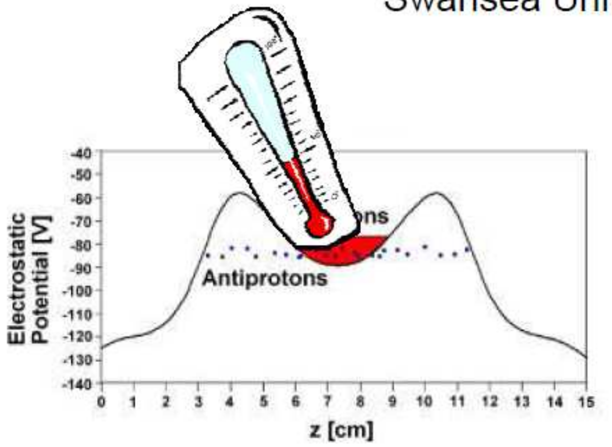
$\bar{H}$ diagnostics



Modelling the behavior of the positron plasma temperature in antihydrogen experiments

Evandro Lodi Rizzini, Valerio Mascagna, Luca Venturelli, Nicola Zurlo
Università di Brescia & INFN-Italy

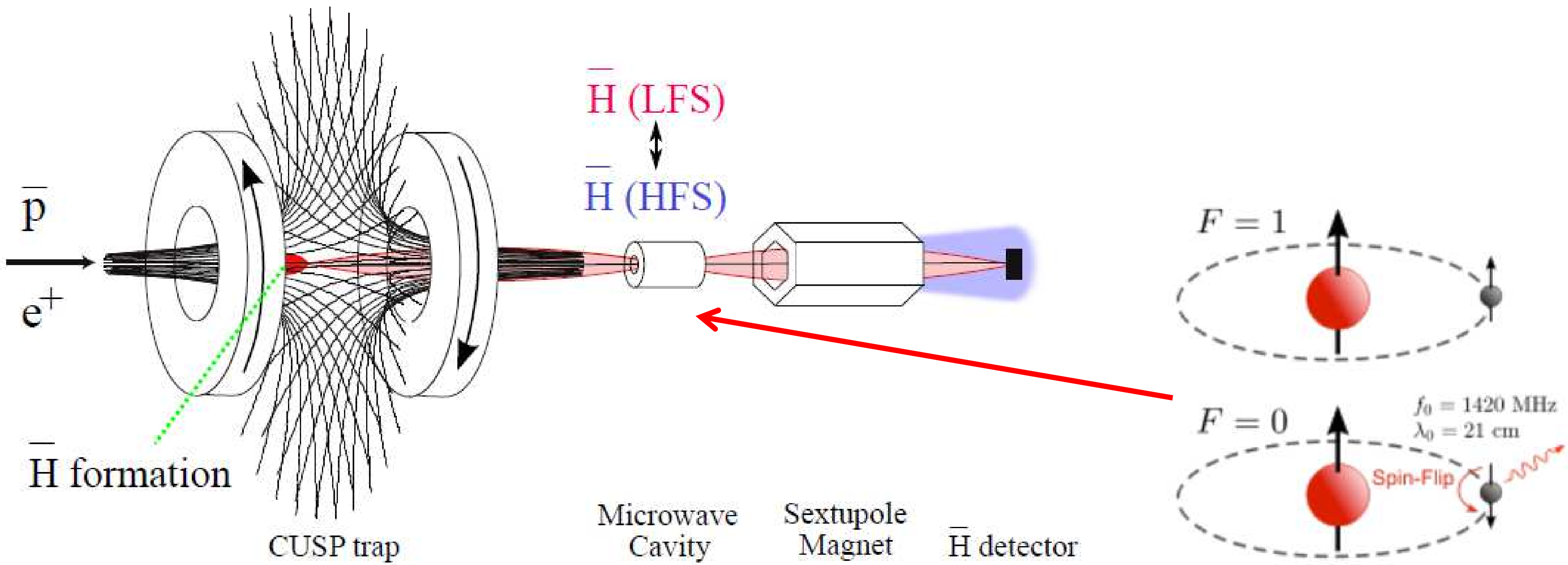
Michael Charlton
Swansea University-Wales-UK



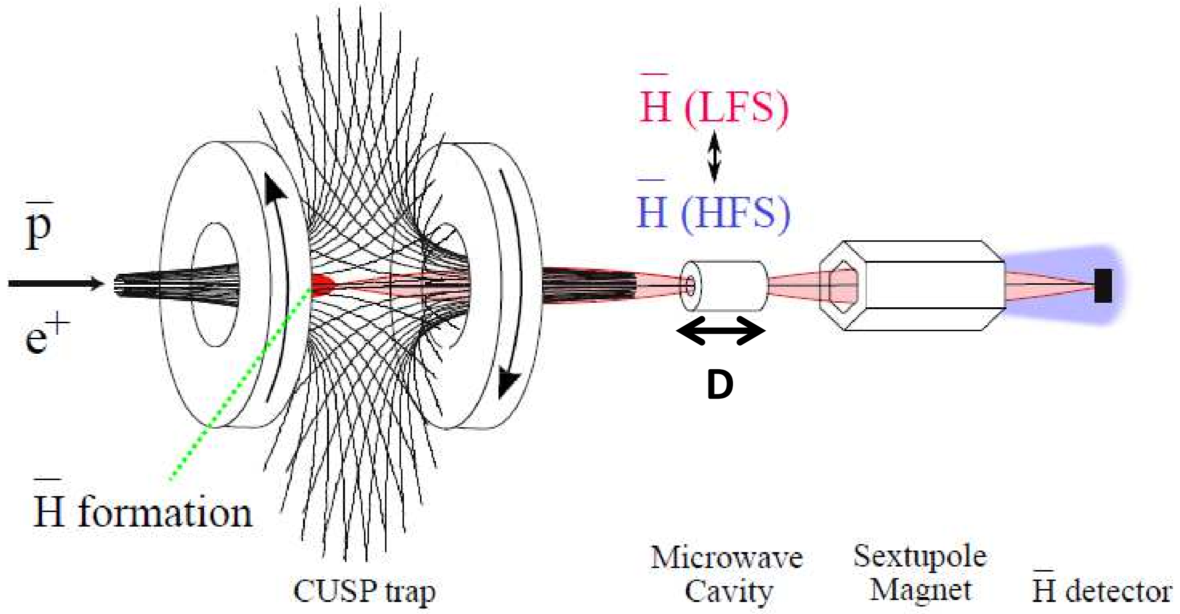
Next steps

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

Introduce MW cavity



Expectations



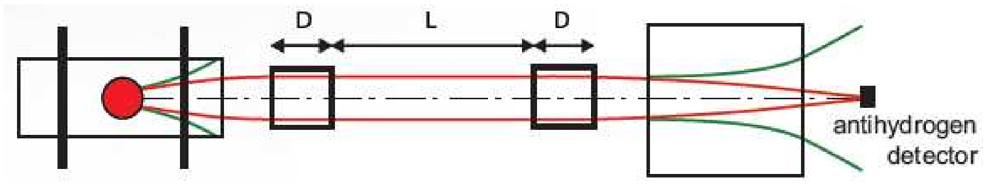
D=10 cm, v=1 km/s
1/T=10 kHz → Df/f=$7x10^{-6}$
→ s=$7x10^{-7}$

Achievable resolution:

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

- 100 Hbar/s in 1S state needed (in 4 π)→ event rate=1/min.

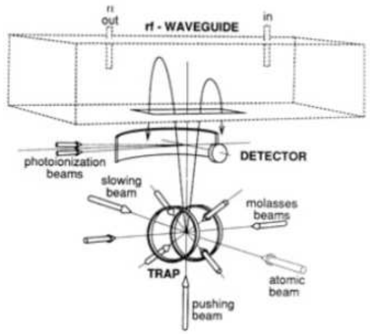
1° improvement (Ramsey):



Linewidth reduced by D/L

Antihydrogen fountain:

<-- AEGIS



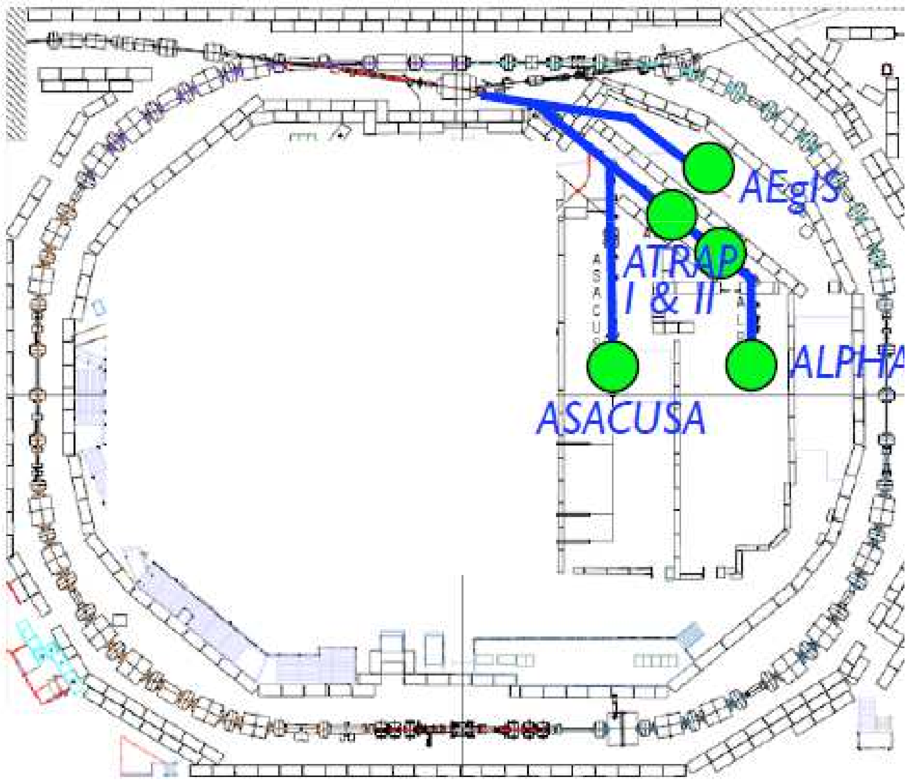
-trapping and laser cooling

- Ramsey method with L=1m

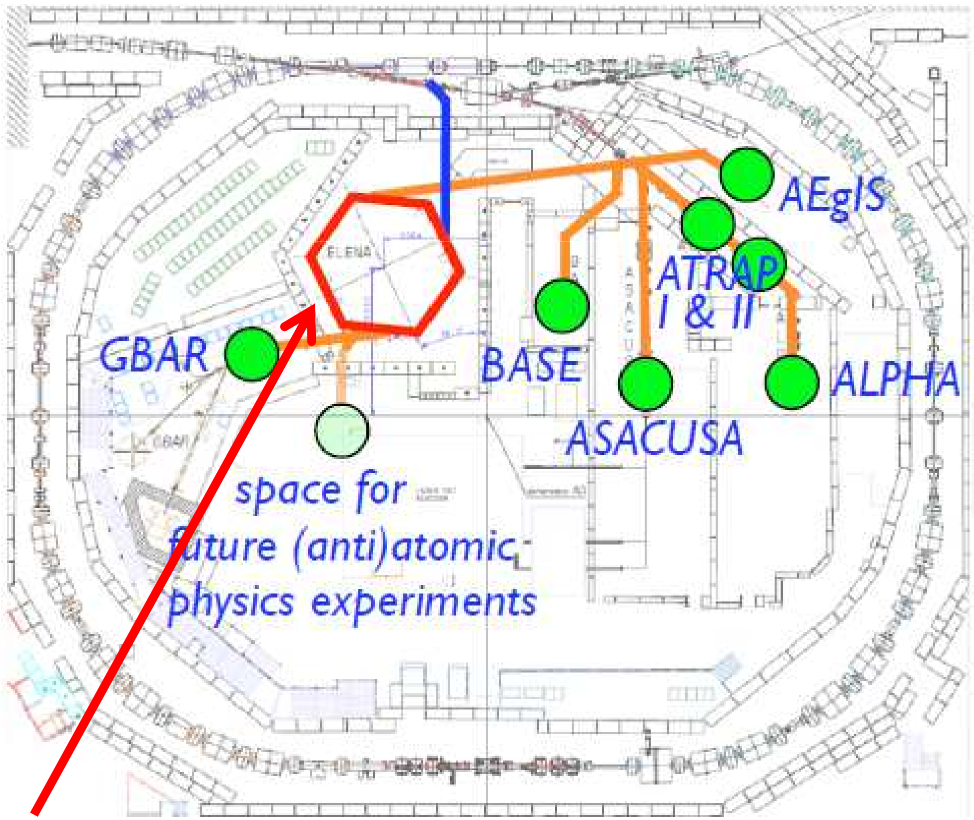
Δf ~3 Hz, $\Delta f/f$ ~ $2x10^{-9}$

Future

2014



2017 →



ELENA decelerator:

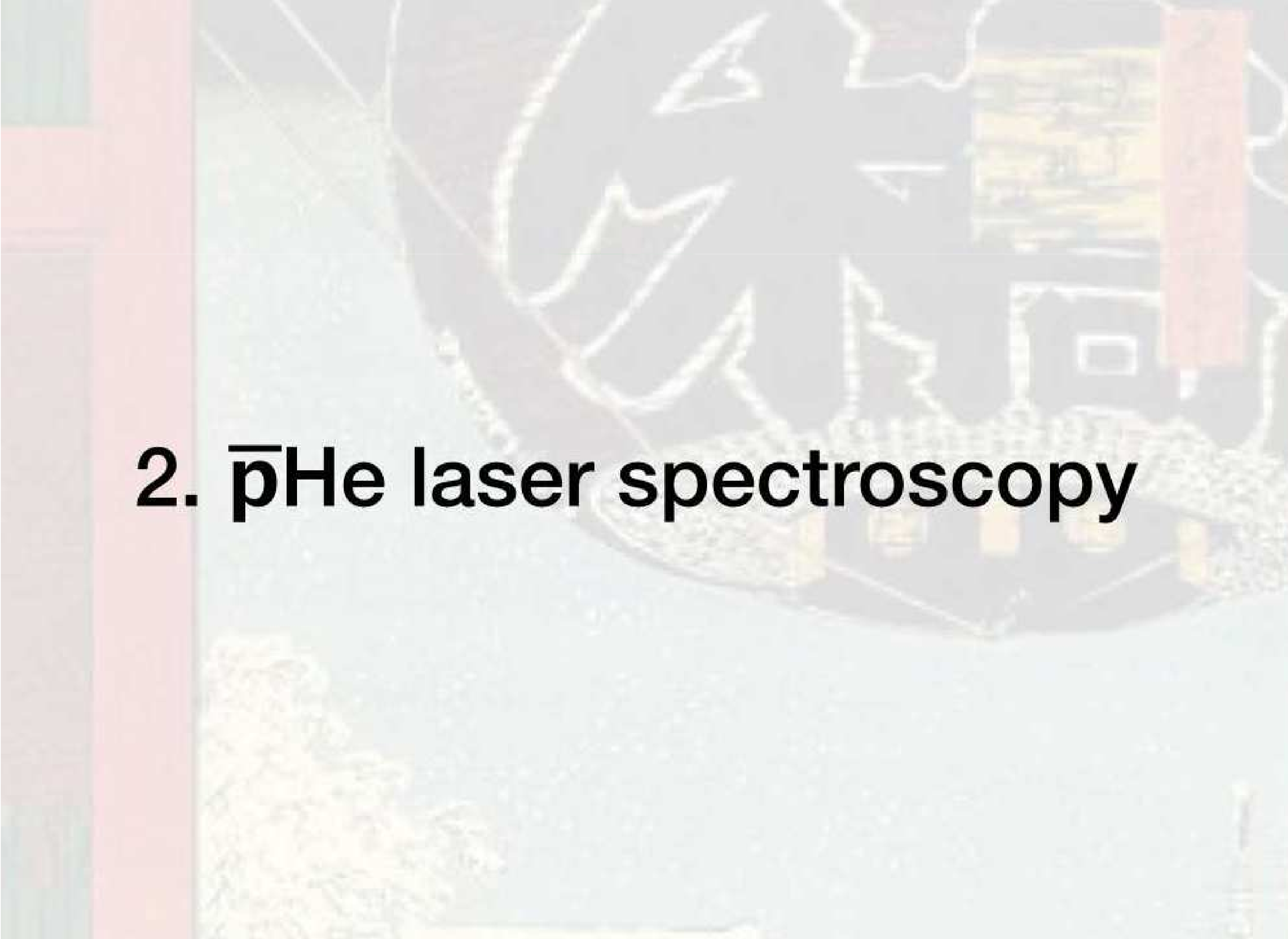
5.3 MeV → 100 keV

x 100 pbars trapping efficiencies

4 experiments can run in parallel

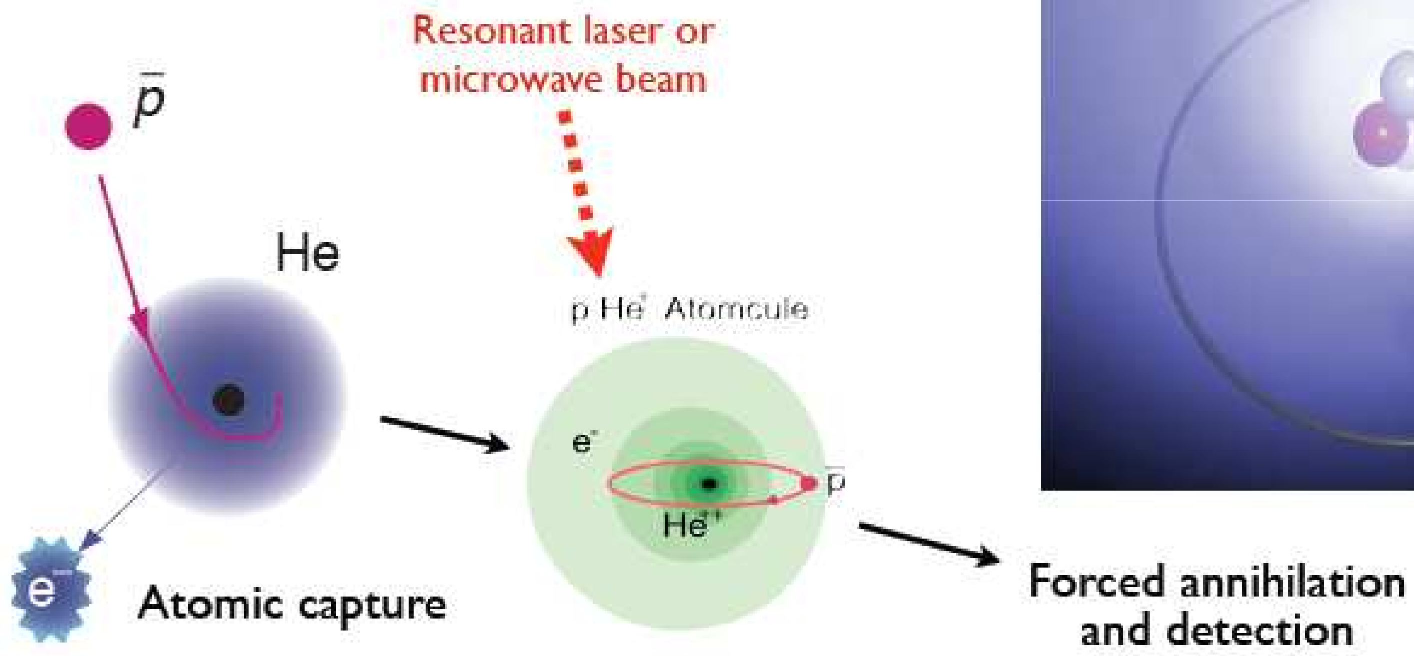
$\overline{H}$ summary

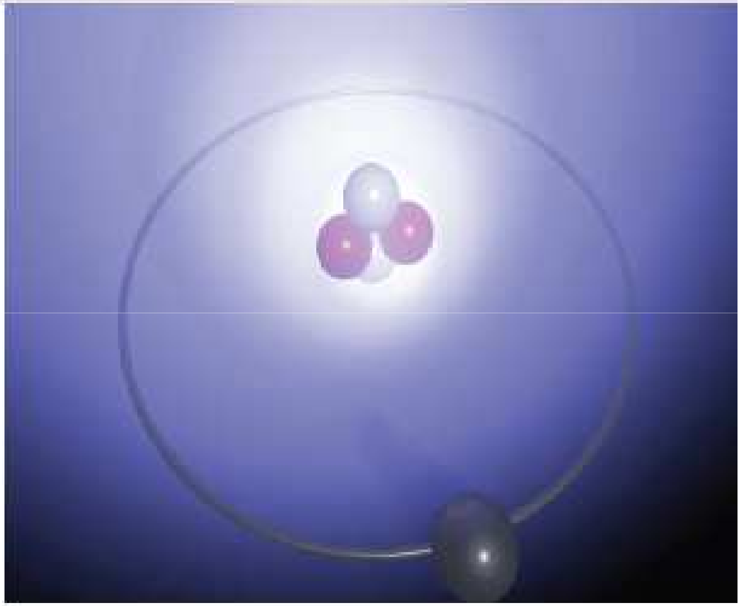
- In 2012
  - $\overline{H}$ yield x 10 (compared to 2010)
  - ~25 $\overline{H}$s /hour reach downstream of the sextupole
- in 2013-2014
  - x10 more e+ accumulated (compared to 2012)
  - improved $\overline{p}$ injection scheme (e+ heating 1/10)
  - Double Cusp Magnet & Micromegas Tracking detector to be installed in 2014
  - polarized cold hydrogen beam will characterize the sextuple & cavity in 2014
  - GEANT4 simulation code with the neutral-atom tracking



2. $\bar{p}$He laser spectroscopy

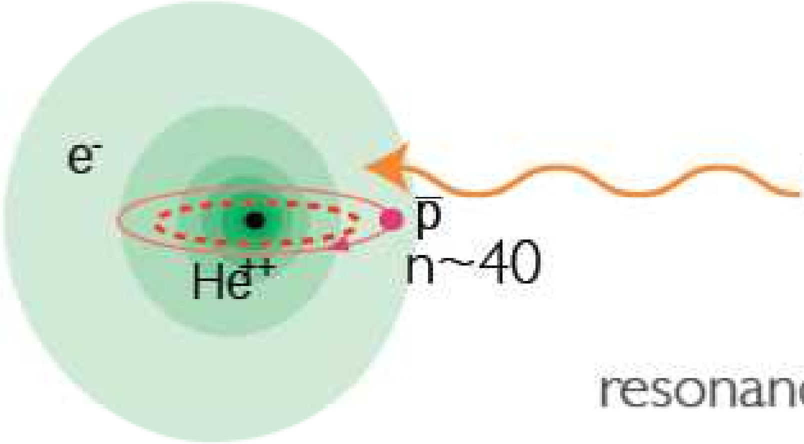
Spectroscopy of antiprotonic helium





- 3-body atom made of antiproton, He, and electron.
- Survives for >10 microseconds.
- >1 billion atoms synthesized per day.
- Amenable to high-precision laser and microwave spectroscopy.

$\bar{p}$He laser spectroscopy contributes to m_p/m_e



laser pulse changes the $\bar{p}$ orbit

resonance detection via $\bar{p}$ annihilation

Frequency

$$\nu_{n,\ell\to n',\ell'} = Rc\,\frac{m^*_{\bar{p}}}{m_e} Z^2_{\mathrm{eff}} \left(\frac{1}{n'^2} - \frac{1}{n^2}\right) + QED$$

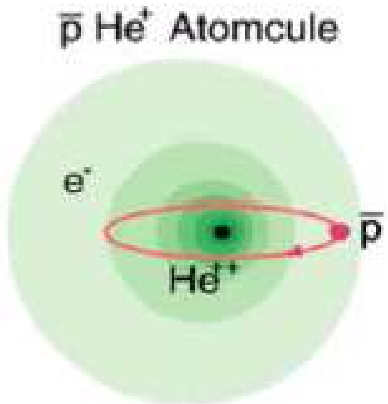
$\bar{p}$ (p) - e mass ratio

Theory

Korobov

$\bar{p}$He laser spectroscopy & comparison with QED calculation yields

- ν_{exp} (2-photon laser) to 2.3-5 x 10^{-9}



- Antiproton-to-electron mass ratio to 1.3 x 10^{-9}.
  → Dimensionless fundamental constant.
  (3 times lower than proton-to-electron mass ratio)

- Assuming CPT invariance, the electron mass in u. to 1.3 x 10^{-9}
  → One of the data points used in CODATA2010 average.

- Combined with cyclotron frequency of antiprotons by TRAP collaboration, comparison of antiproton and proton mass and charge to 7 x 10^{-10}
  → Consistency test of CPT invariance in PDG2014.

p̄He laser spectroscopy

M. Hori et al., Nature 475, 484 (2011).

+ L.Venturelli, N.Zurlo

Now in CODATA

CERN Press Release

CERN experiment weighs antimatter with unprecedented accuracy

PR10.11
28.07.2011

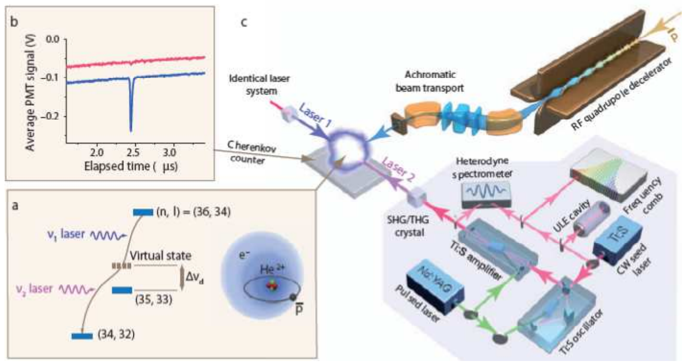
Geneva, 28 July 2011. In a paper published today in the journal Nature, the Japanese-European ASACUSA experiment at CERN[1] reported a new measurement of the antiproton's mass accurate to about one part in a billion. Precision measurements of the antiprot… mass provide an important way to investigate nature's apparent preference for matter over antimatter.

"This is a very satisfying result," said Masaki Hori, a project leader … the ASACUSA collaboration. "It means that our measurement of th… antiproton's mass relative to the electron is now almost as accurat… as that of the proton."

Ordinary protons constitute about half of the world around us, ourselves included. With so many protons around it would be natu… to assume that the proton mass should be measurable to greater … today's result, this remains true but only just. In future experimen… accuracy of the antiproton mass measurement to far better than t… the mass of protons and antiprotons would be a signal for new phy… could be different for matter and antimatter.

To make these measurements antiprotons are first trapped inside … with a laser beam. The laser frequency is then tuned until it cause… within the atoms, and from this frequency the antiproton mass ca…

p̄He sub-Doppler 2-photon spectroscopy



2012

REVIEWS OF MODERN PHYSICS, VOLUME 84, OCTOBER–DECEMBER 2012

CODATA recommended values of the fundamental physical constants: 2010*

Peter J. Mohr,† Barry N. Taylor,‡ and David B. Newell§

National Institute of Standards and Technology, Gaithersburg, Maryland 20899-8420, USA

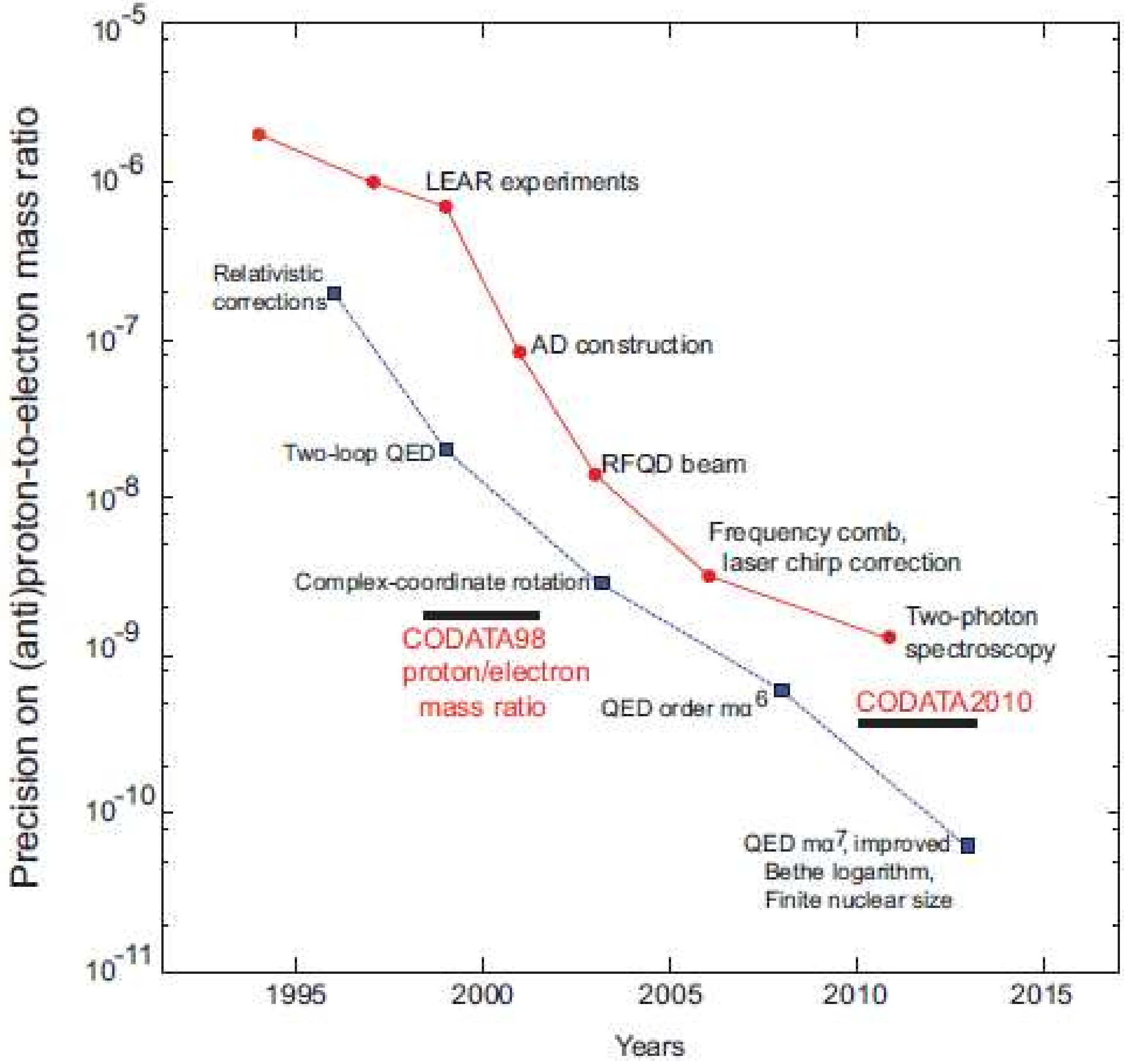
(published 13 November 2012)

This paper gives the 2010 self-consistent set of values of the basic constants and conversion factors of physics and chemistry recommended by the Committee on Data for Science and Technology (CODATA) for international use. The 2010 adjustment takes into account the data considered in the 2006 adjustment as well as the data that became available from 1 January 2007, after the closing date of that adjustment, until 31 December 2010, the closing date of the new adjustment. Further, it describes in detail the adjustment of the values of the constants, including the selection of the final set of input data based on the results of least-squares analyses. The 2010 set replaces the previously recommended 2006 CODATA set and may also be found on the World Wide Web at physics.nist.gov/constants.

DOI: 10.1103/RevModPhys.84.1527 PACS numbers: 06.20.Jr, 12.20.−m

IV. ATOMIC TRANSITION FREQUENCIES

Measurements and theory of transition frequencies in hydrogen, deuterium, antiprotonic helium, and muonic hydrogen provide information on the Rydberg constant, the proton and deuteron charge radii, and the relative atomic mass of the electron.



Precision on (anti)proton-to-electron mass ratio
Years
LEAR experiments
AD construction
RFQD beam
Frequency comb, laser chirp correction
Two-photon spectroscopy
Relativistic corrections
Two-loop QED
Complex-coordinate rotation
QED order mα6
QED mα7, improved Bethe logarithm, Finite nuclear size
CODATA98 proton/electron mass ratio
CODATA2010

Theory improvements in 2013

Korobov 2013

1: Nonrelativistic Bethe logarithm calculated by complex-coordinate rotation method to 7 digits of precision.

$$\beta(L,v) = \frac{\langle \mathbf{J}(H-E_0)\ln((H-E_0)/R_\infty)\,\mathbf{J}\rangle}{\langle [\mathbf{J},[H,\mathbf{J}]]/2\rangle} \qquad \mathbf{J} = \sum_a Z_a \mathbf{p}_a/m_a$$

$$E_{se}^{(3)} = \alpha^3 \frac{4}{3}\left[\ln\frac{1}{\alpha^2} - \beta(L,v) + \frac{5}{6} - \frac{3}{8}\right] \langle Z_{\rm He}\delta(\mathbf{r}_{\rm He}) + Z_{\bar{p}}\delta(\mathbf{r}_{\bar{p}})\rangle\,,$$

V.I. Korobov, recently submitted to Phys. Rev. A

2: Complete set of QED terms of order $m\alpha^7$ evaluated.

Theoretical precision: 1×10^{-10}

20x better than 2011 experiment

50x-200x better than 2006 single-photon experimental precision.

Experimental strategy

12 single-photon transitions measured in 2006

Tried to remeasure this as precisely as possible using much improved techniques in 2012.

Studied all kinds of systematic effects.

Experimental precision improved by 1.5-5x.

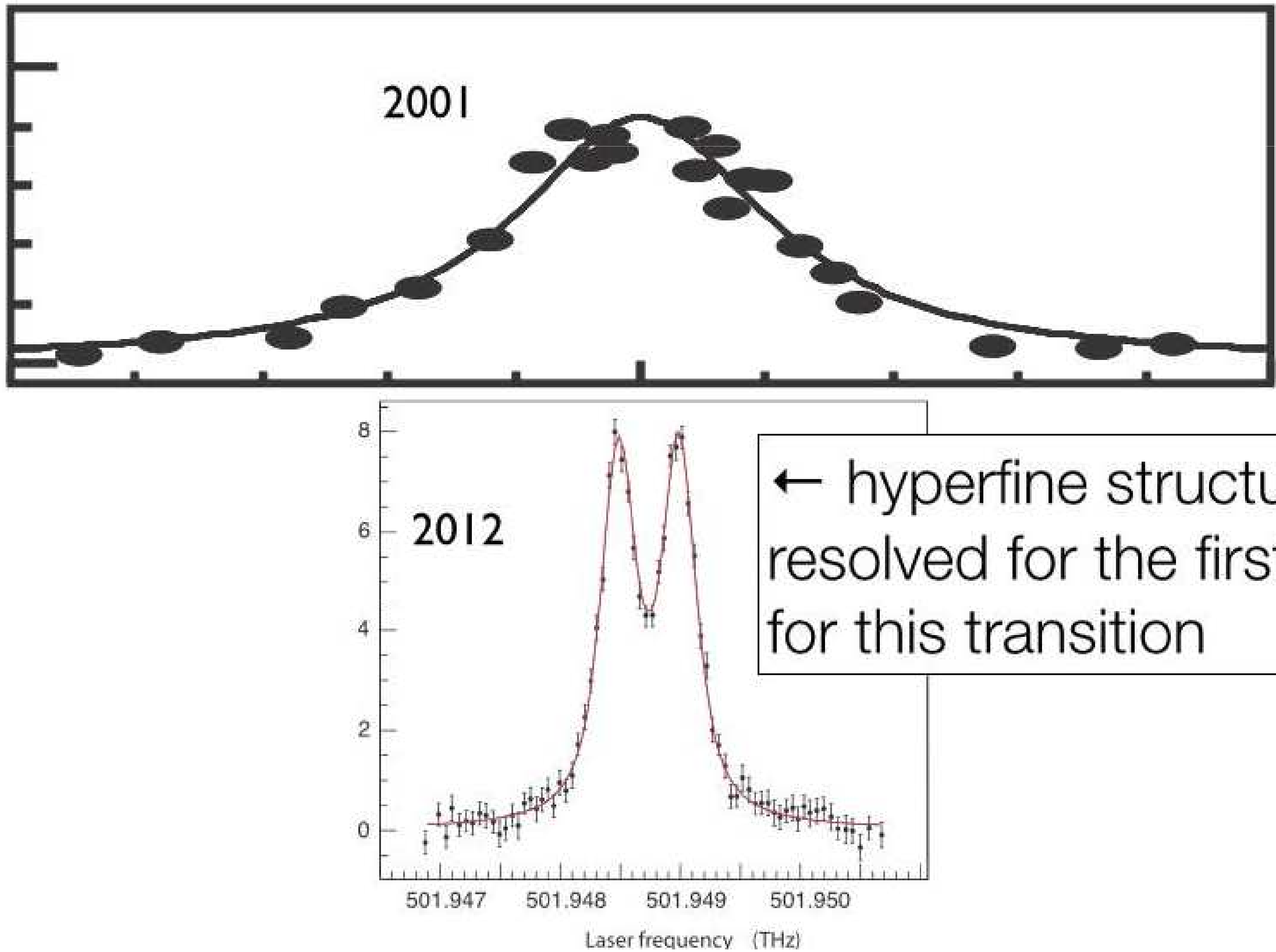
+

3 two-photon transitions measured in 2011

Will try to remeasure these as precisely as possible in >2014

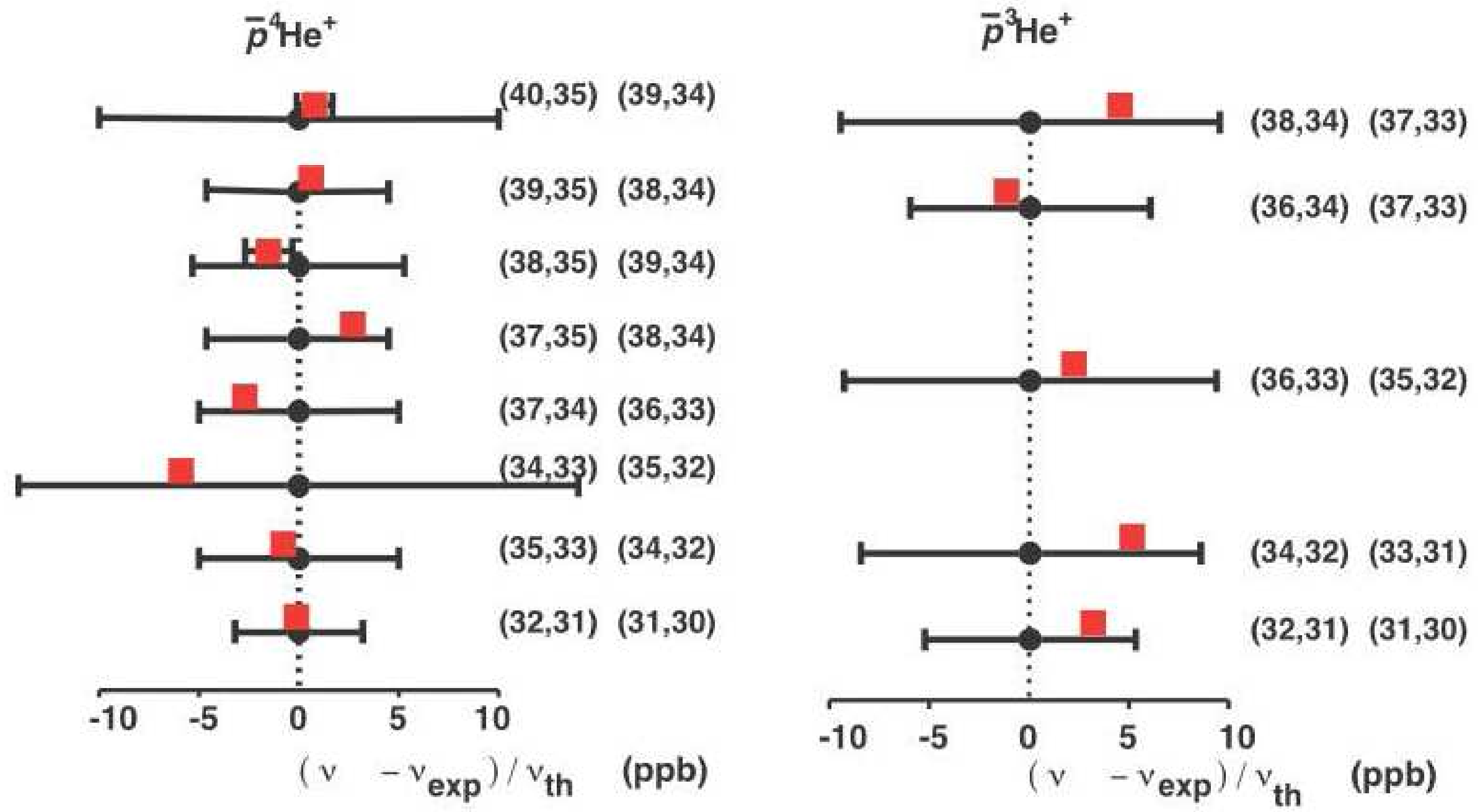
improvement in 1-photon resolution at 1.5K

597-nm line, 2012



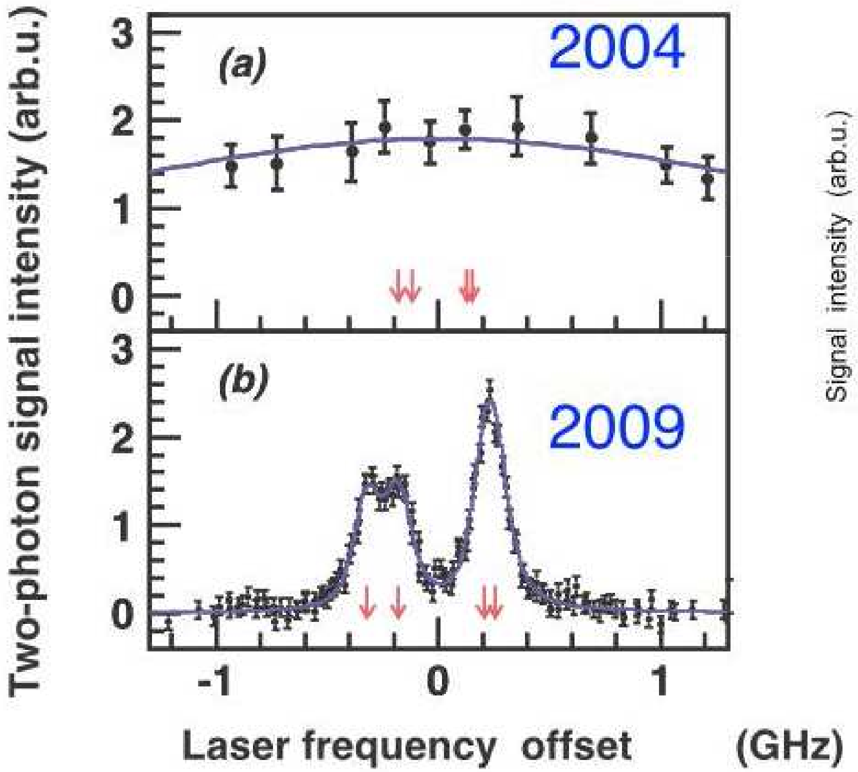
← hyperfine structure resolved for the first time for this transition

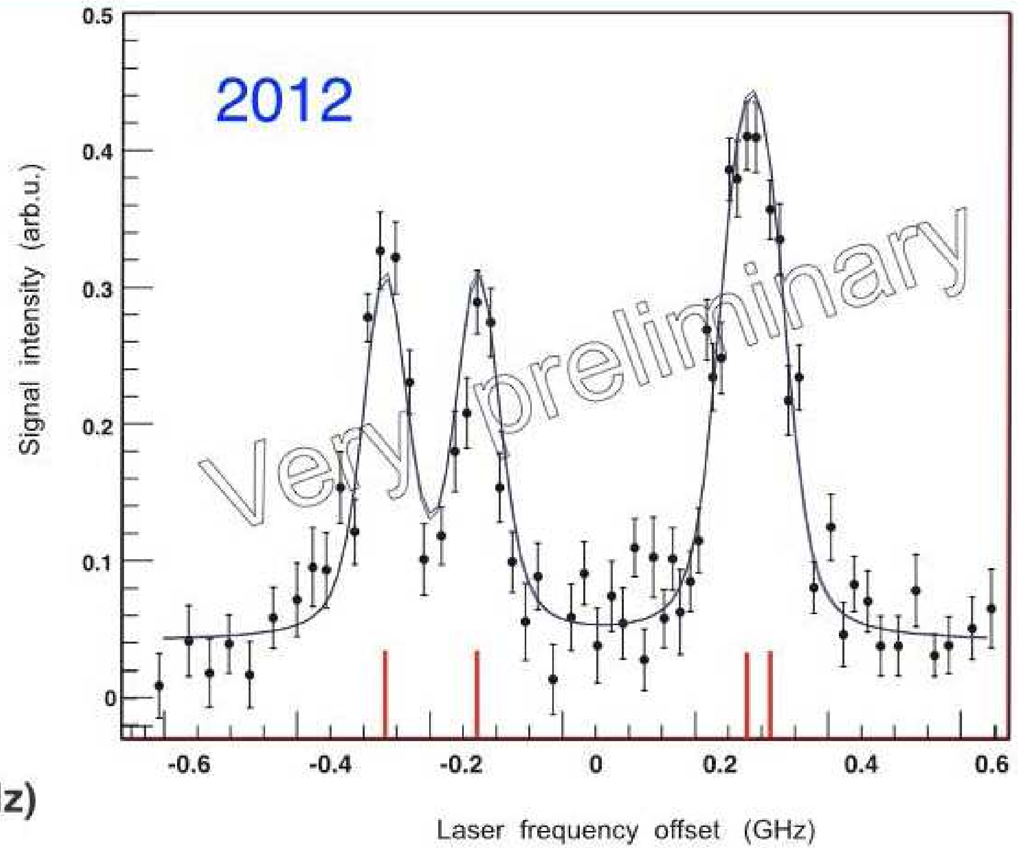
1-photon (2012) + theory (Korobov 2013)



Single-photon precision 3 ppb level agreement in best case. As good as two-photon spectroscopy.

(36,34)-(34,32) 2-photon trial at 1.5 K in 2012

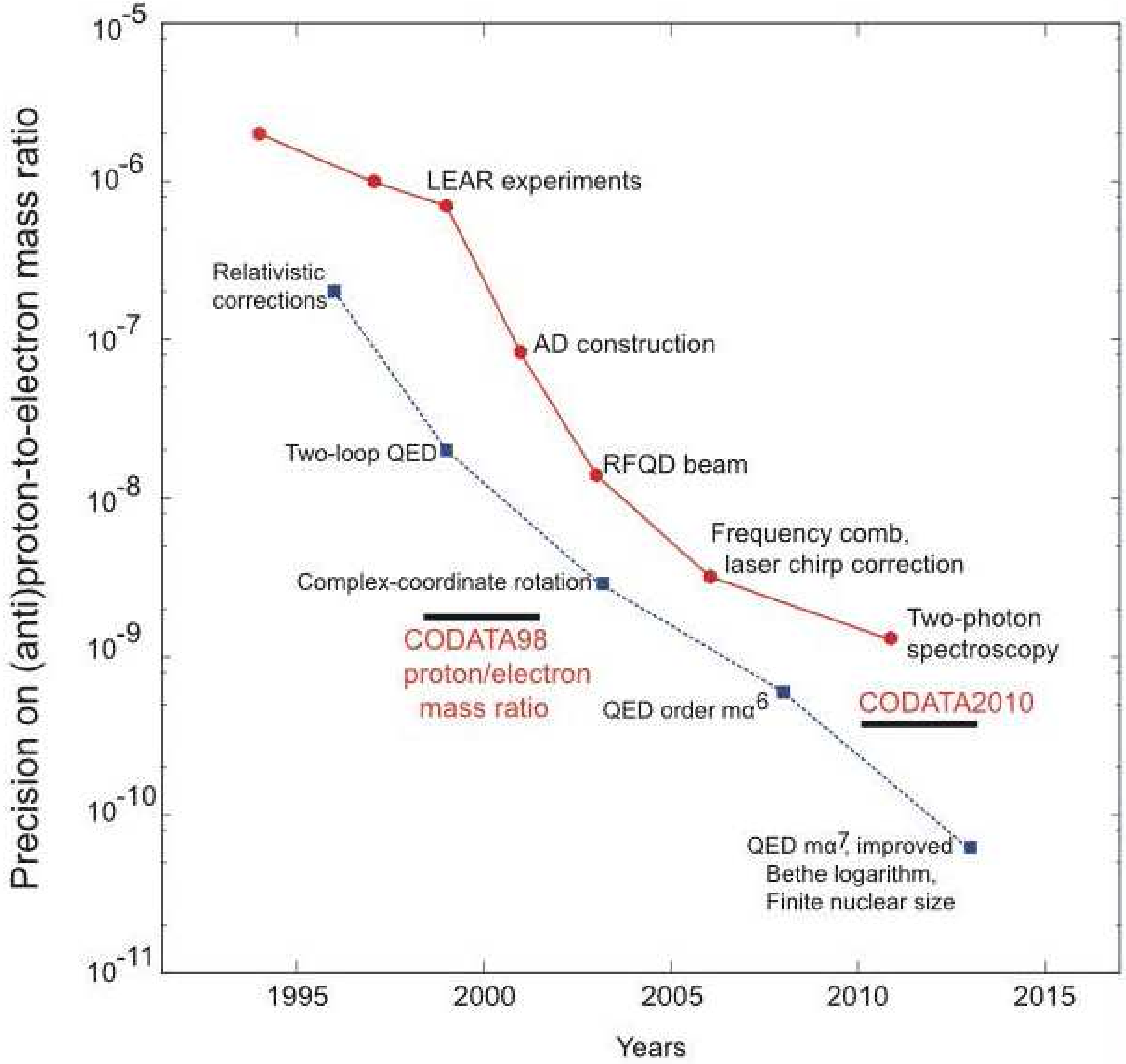




Reduction of residual Doppler broadening, by cooling atom to T=1.5 K via gas buffer cooling. Experimental precision should improve by >3x compared to before.

$\bar{p}$He summary

- New theoretical calculations achieve precision of 1 x 10^{-10}
- re-measured single photon transitions - exp-theory agree
- 2-photon resolution x3 better than in 2011



3. Collision experiments

Nuclear Physics @ AD

p̄-A annihilations s

- @ 5.3 MeV done (Ni, Sn, Pt)

PLB 2011 & NIMA 2013

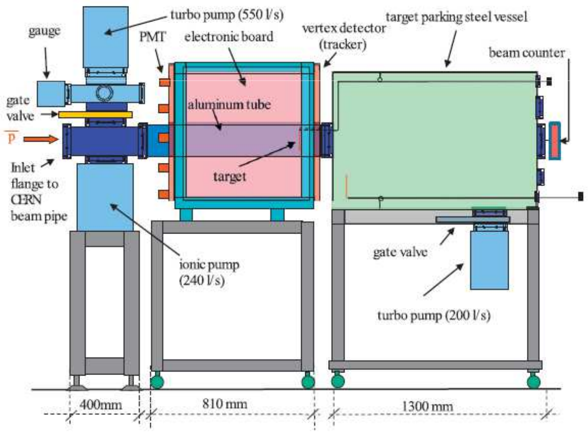
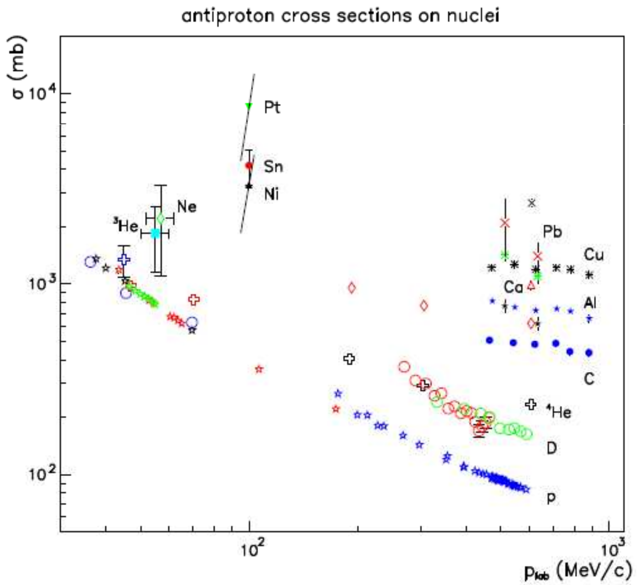
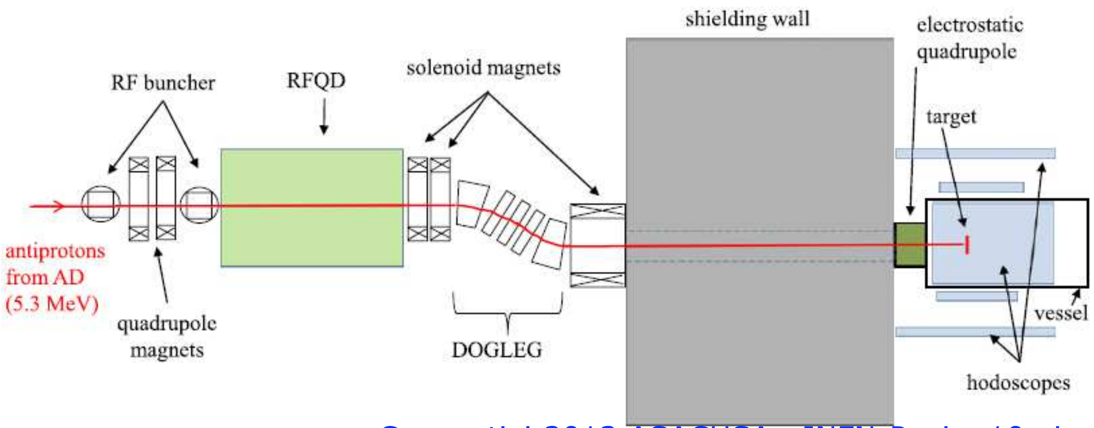
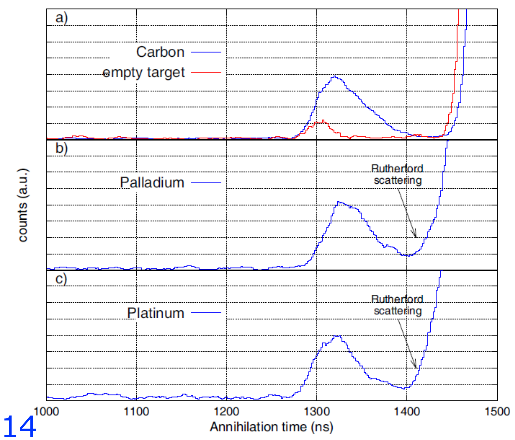


Fig. 1. Experimental setup.



- @ 130 keV in progress



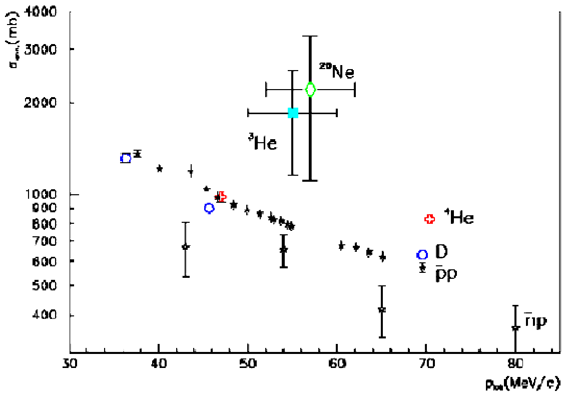


Physics motivations

- Cosmology: matter-antimatter asymmetry in the Universe

  (One possibility is that antimatter is distributed non-homogeneously in the Universe within the so-called "islands" of antimatter . In the border region between matter and antimatter, the role of annihilation is important.)

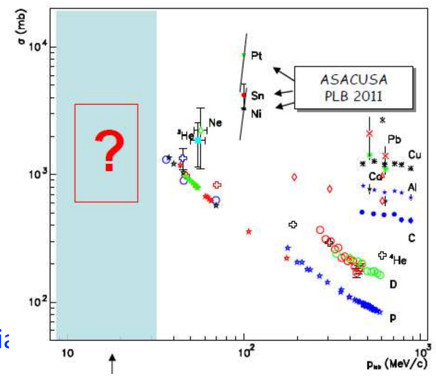
- Saturation: s_{ann} (pbarA) does not increase with A as expected



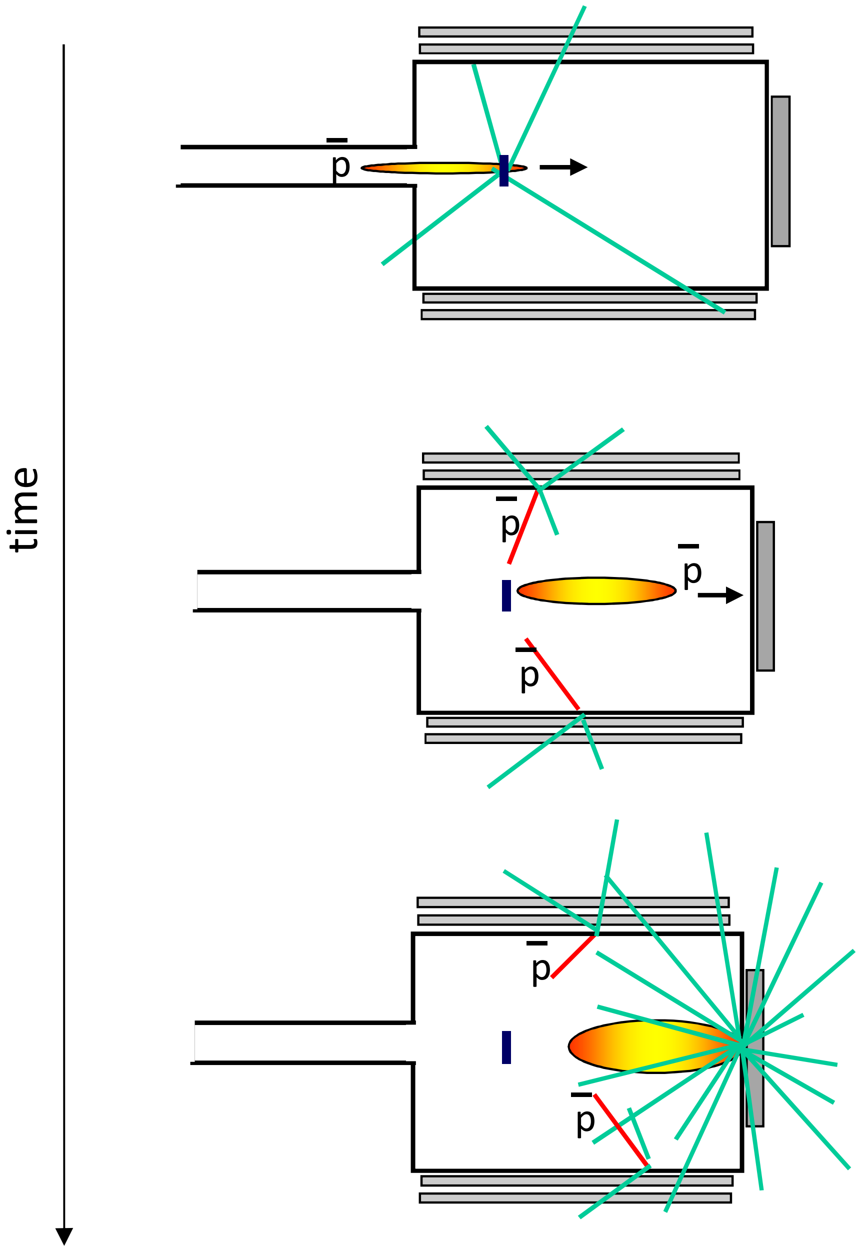
- Probe the external region of nucleus

  (both potential models and phenomenological analyses state that the annihilations occur in a thin region placed just outside the nuclear volume: neutron/proton ratio or the extraction energy of the peripheral nucleons can be determined)

- …completly unexplored region



Method of the annihilation s measurement



$$\sigma_{ann}(\bar{p}A) \div \frac{N_{events}}{N_{beam}}$$

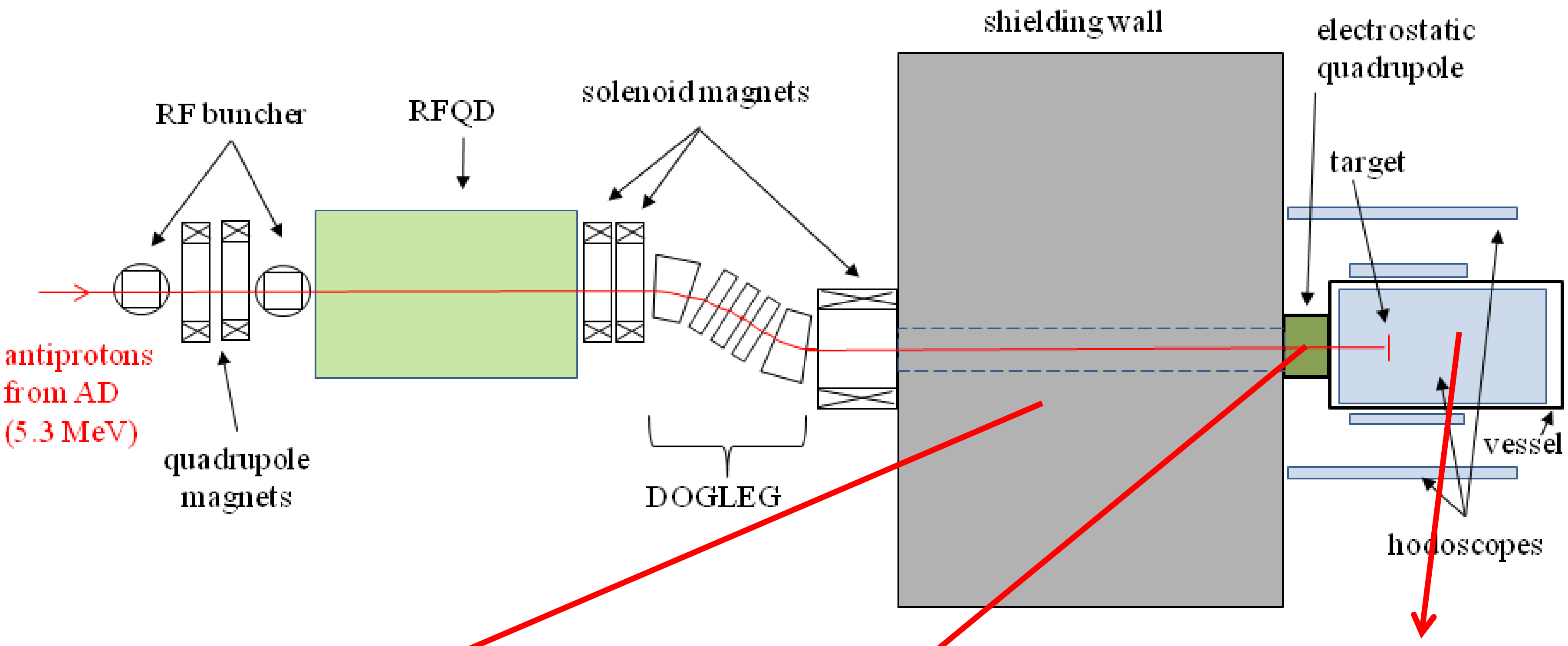
counted by Vertex detector (N_{events})

counted by Beam monitor & by Rutherford annihilations (N_{beam})

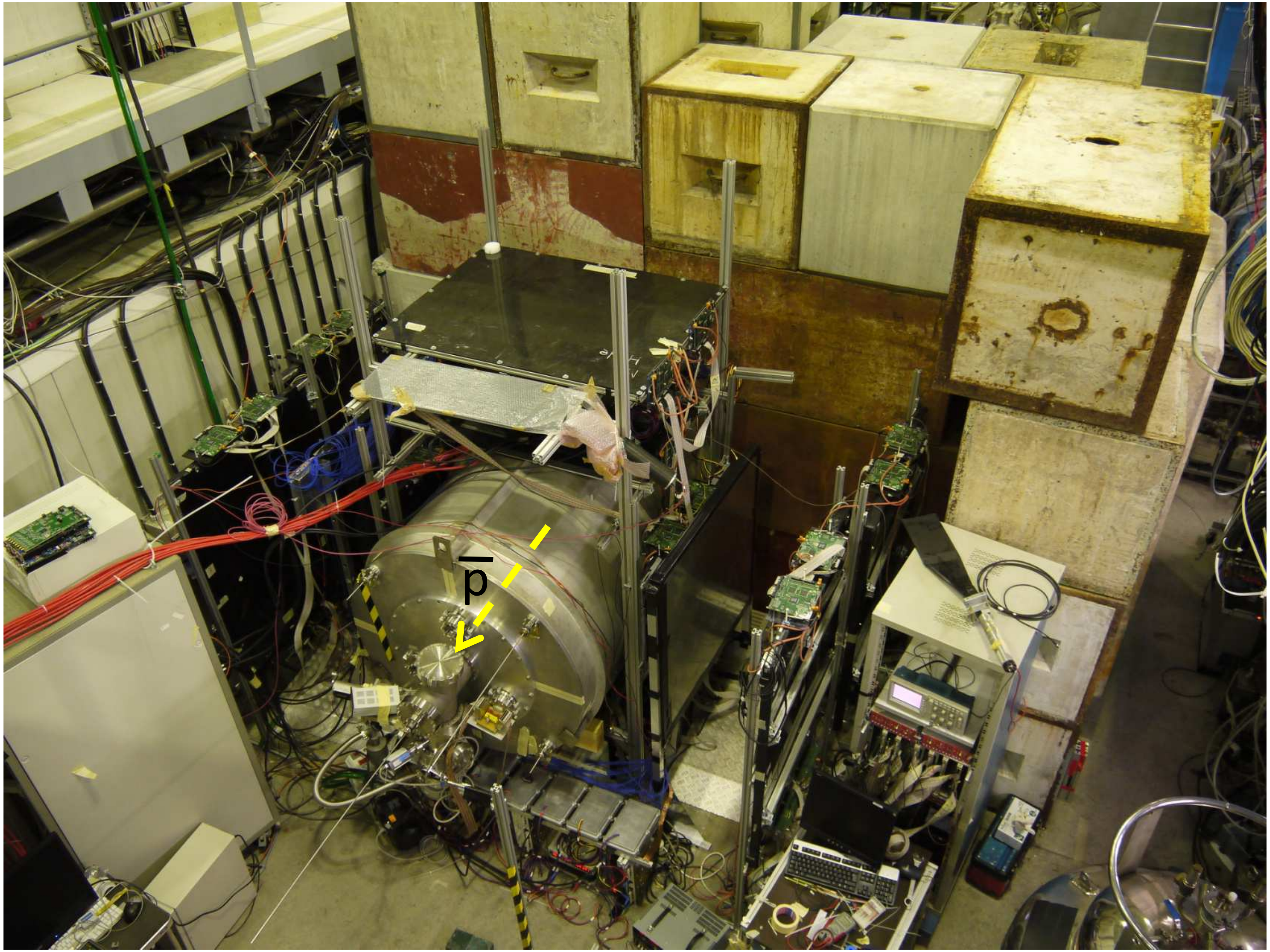
To separate signal from background:

- Beam chopper to reduce the pbar shot lenght
- Slits along the beam-line to reduce halo
- Long & large vessel
- Ultra-thin targets
- Thick wall to screen detector from p->m->e

Experimental set-up

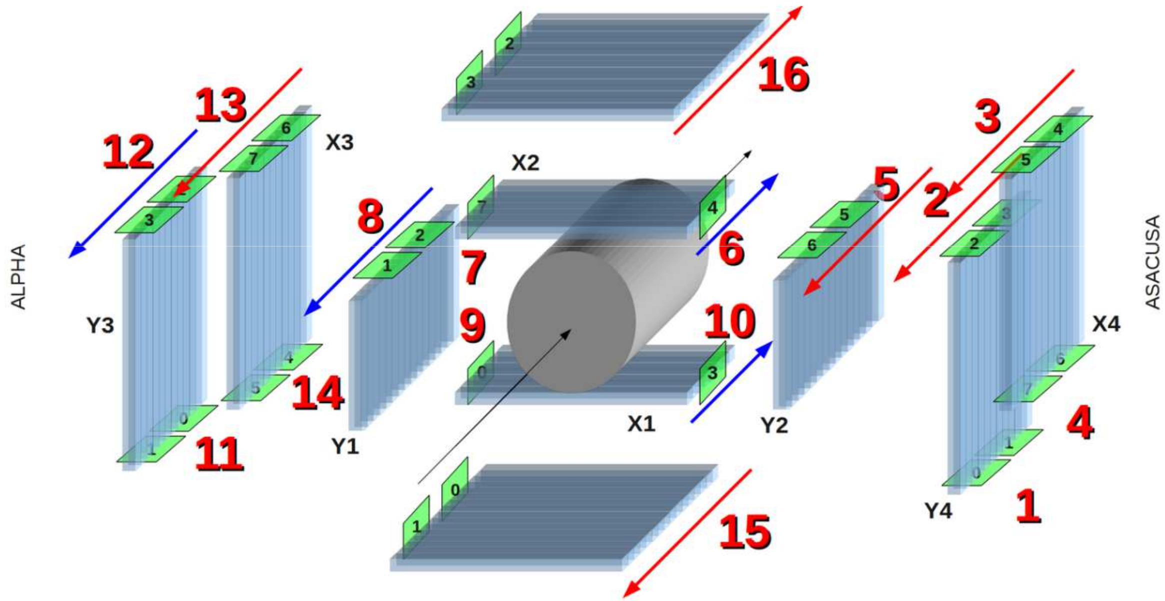


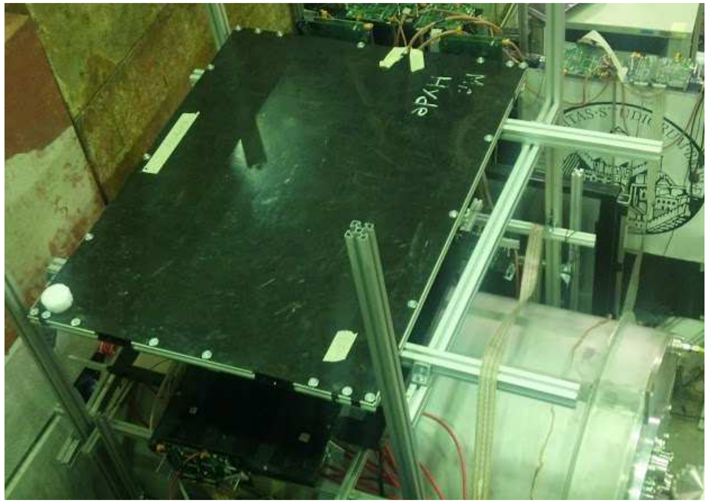
Experimental set-up



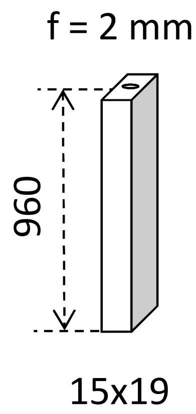
Detectors 1/2

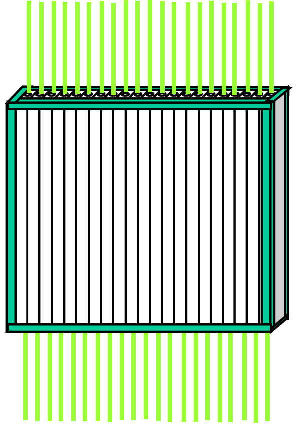
"Brescia detector"





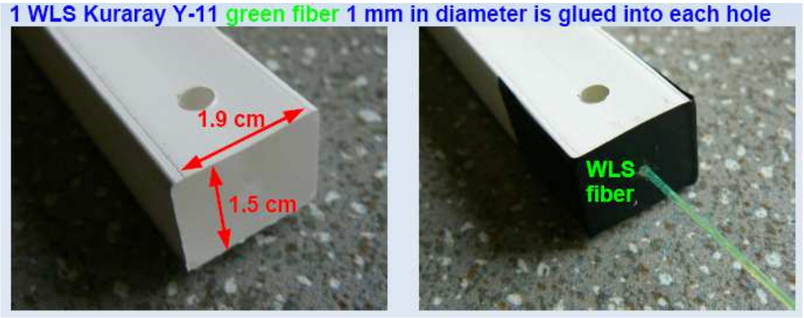
Modules of different dimensions (total number of scintillator bars = 500)





62 bars -> two 64-ch multi-anode PMTs

Scintillator bar



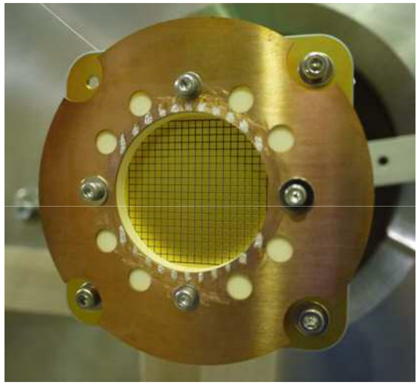
Antiproton beam monitors

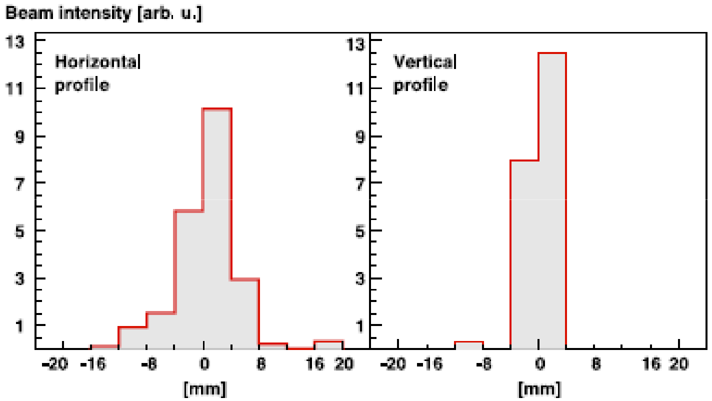
- Beam position monitor

-Secondary emission electron detector

-Placed (& removable) at the target position

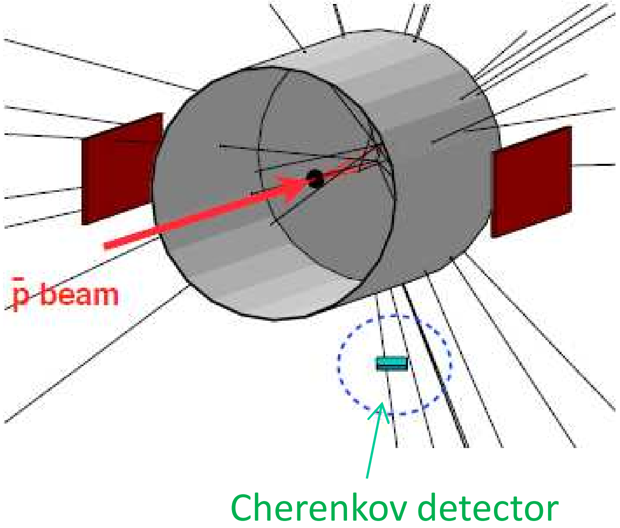
- Resolution 4 mm

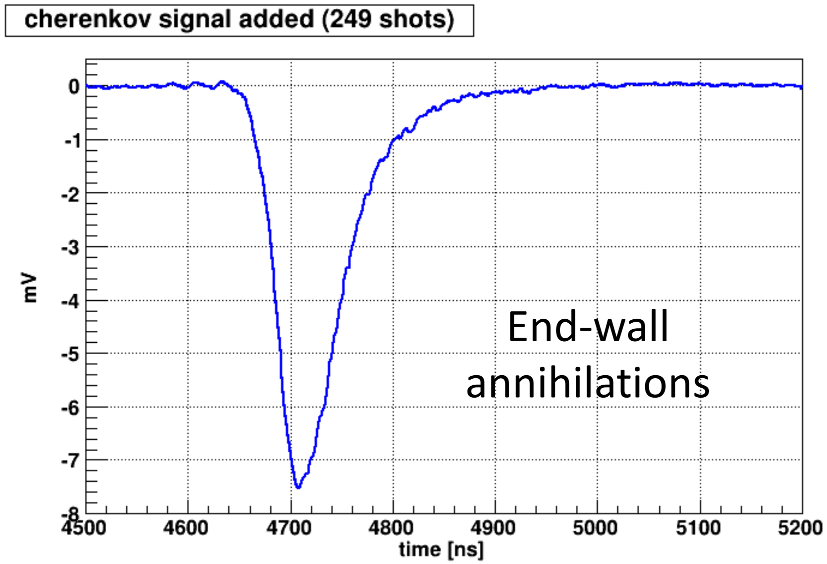




- Beam intensity monitor

- Cherenkov detector





Targets

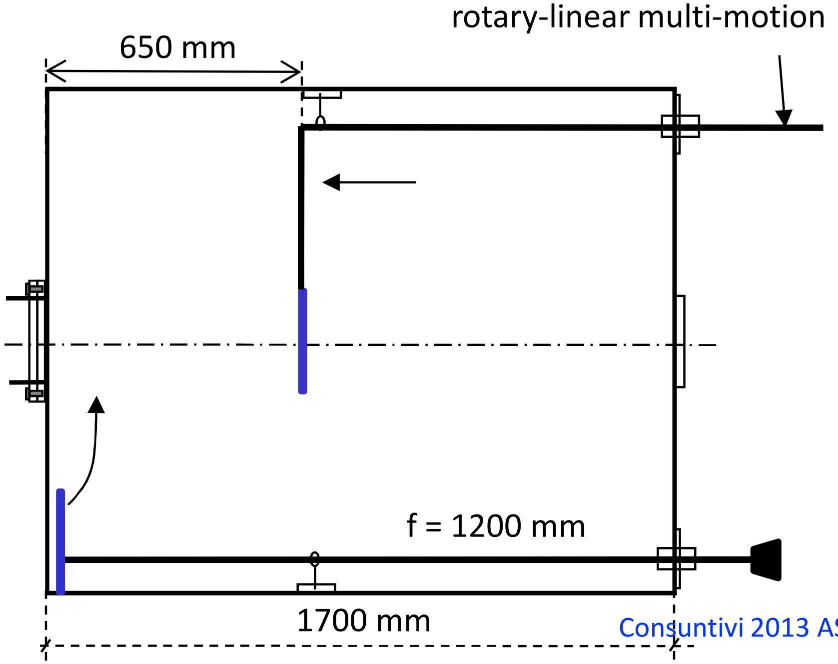
Ultra-thin targets:

- carbon foil (70 nm)
- carbon foil (70 nm) + Pd (20 nm)
- carbon foil (70 nm) + Pt (5 nm)

Made @ TUM

Steel ring frame: $\Phi_{int} = 8\,\text{cm} \quad \Phi_{ext} = 13\,\text{cm}$

target parking vessel

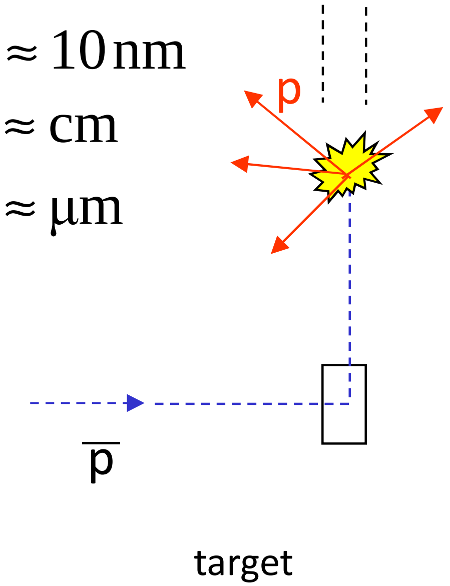


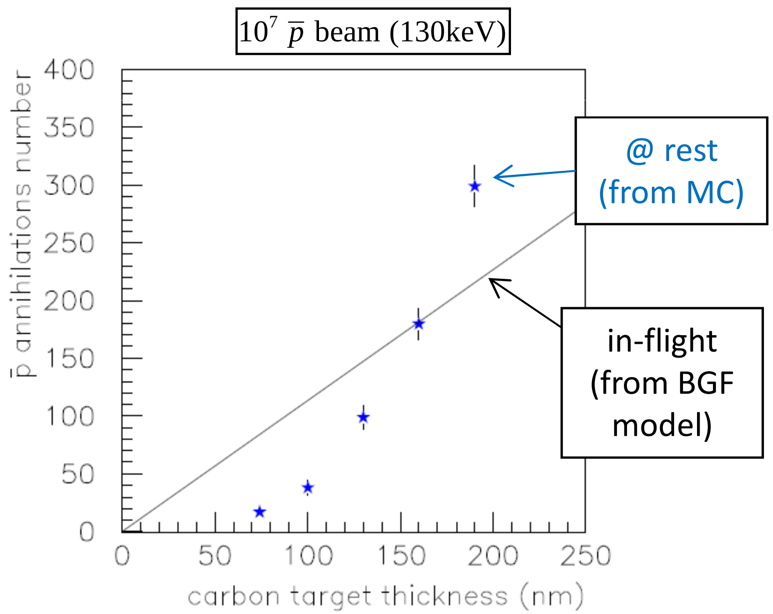
Why ultra-thin targets?

antiprotons scattered at $\approx 90^{\circ}$ will stop in the target

Scale dimensions:

Target thickness	$\Delta x \approx 10\,\text{nm}$
Target radius	$D \approx \text{cm}$
antiproton range (@100keV)	$R \approx \mu\text{m}$





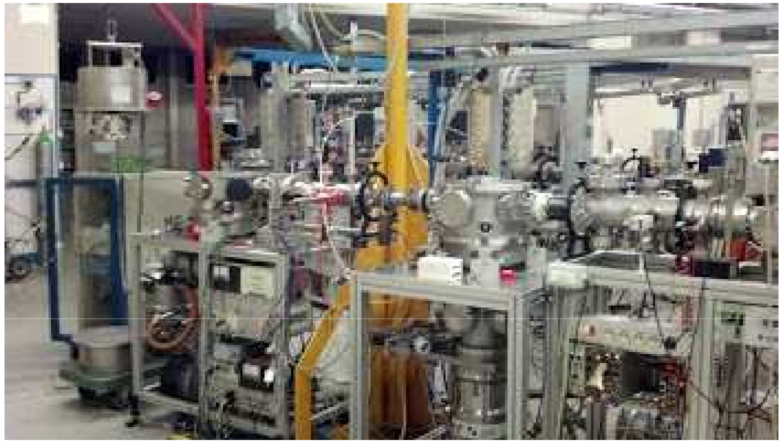
For C target (70 nm) the expected pbars @ rest are much less than in-flight annihilations

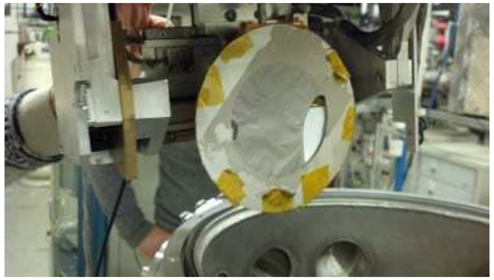
⇒ very thin targets needed

Targets measurements @ LNL

Rutherford Back Scattering measurement:

2 MeV Alpha scatterd at 165° ; spot 1x1 mm^2





C+Pd

	nominal µg/cm^2	nominal 1E15 at/cm^2	measured 1E15at/cm^2	measured nm
Pd	24	135.8	**139** (+- 4)	20.4 (ρ=21.45 g/cm^3)
C	16	803	**720** (+- 35)	71.7 (ρ=2 g/cm^3)

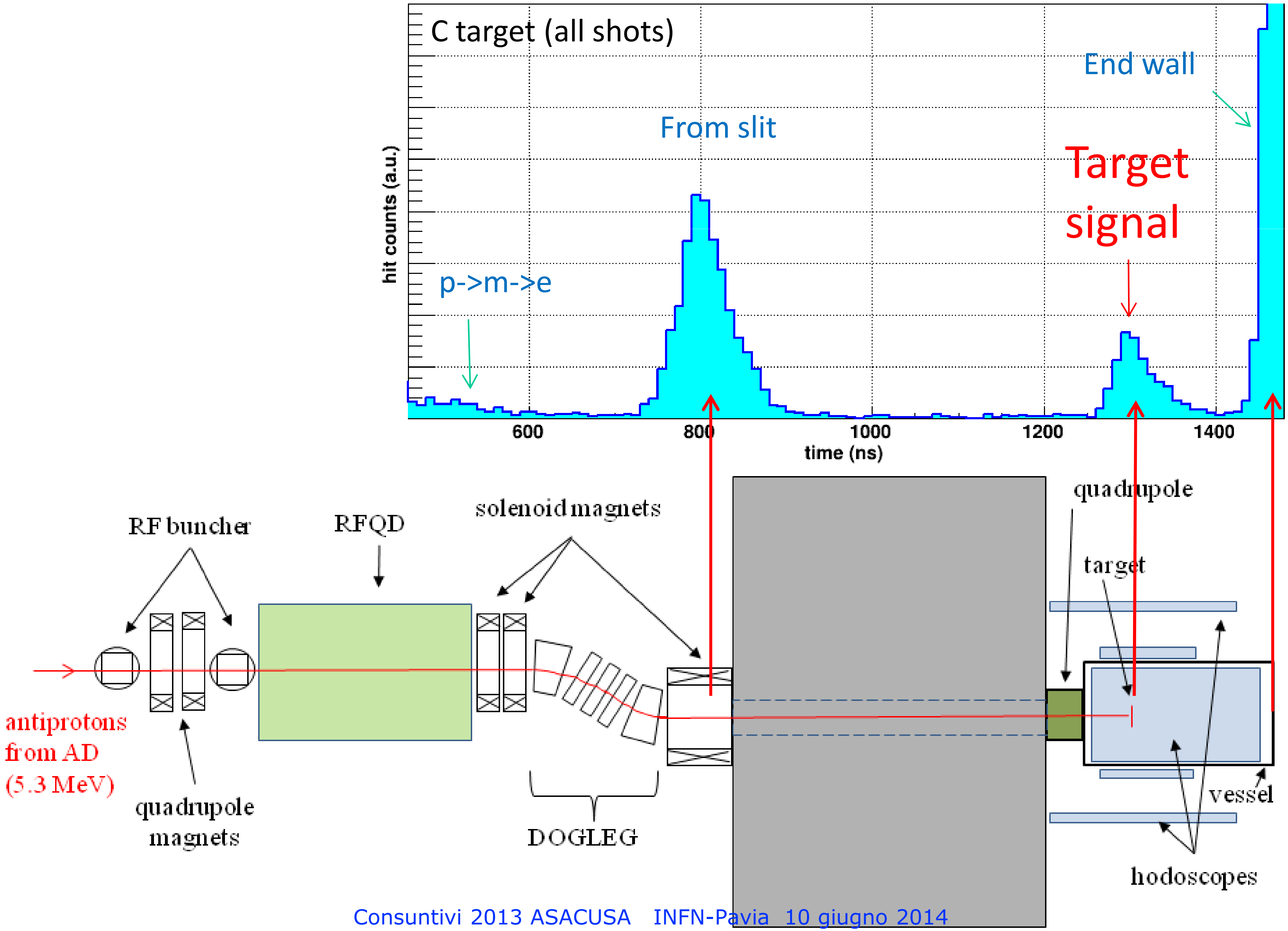
C+Pt

	nominal µg/cm^2	nominal 1E15 at/cm^2	measured 1E15 at/cm^2	measured nm
Pt	10.7	33	**43.8** (+-3%)	6.62 (ρ=21.45g/cm^3)
C	16	803	**768** (+-5%)	76.5 (ρ=2 g/cm^3)

C target not measured (destroyed)

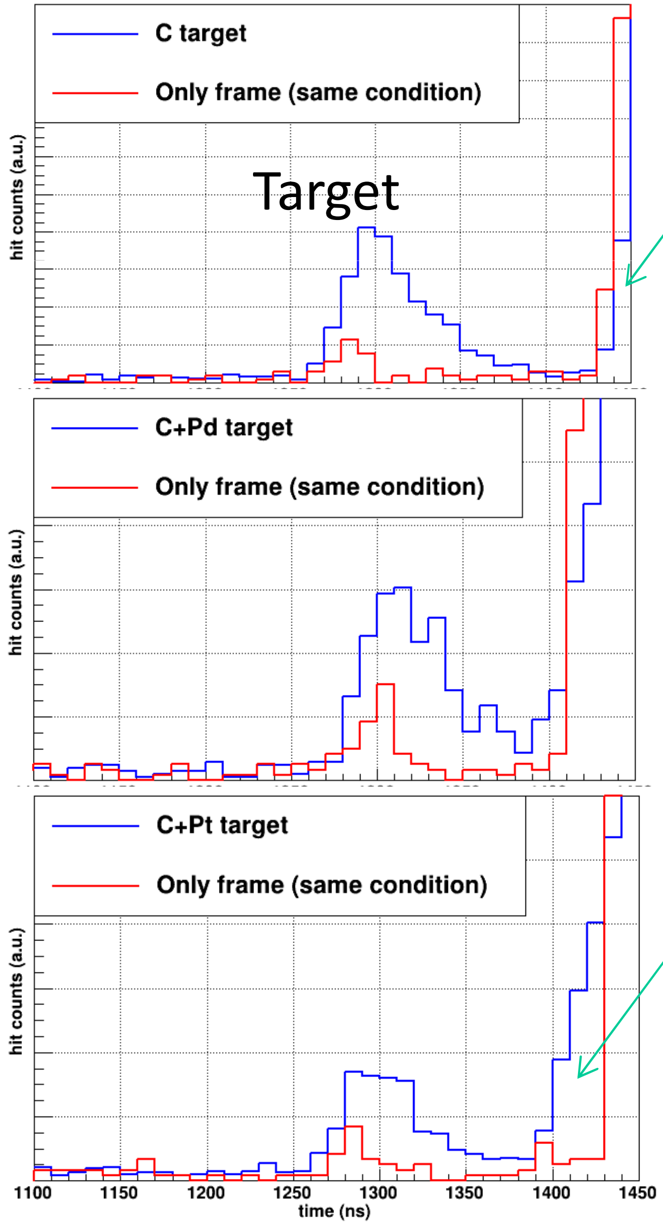
Good thickness uniformity (better than 5%)

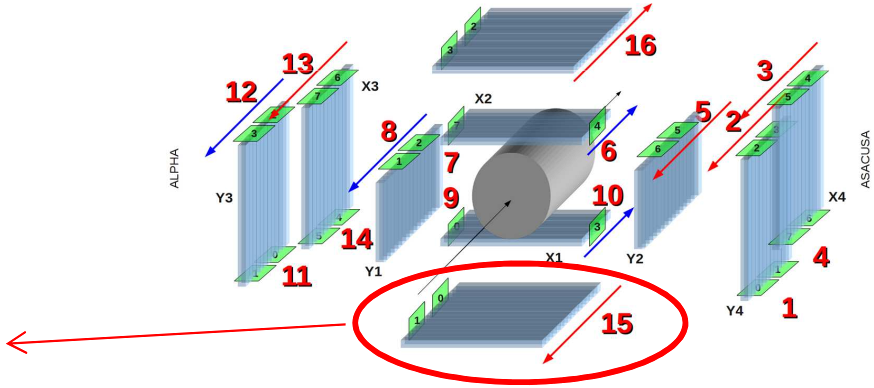
The raw data 1/3



The raw data 2/3

"Brescia detector"

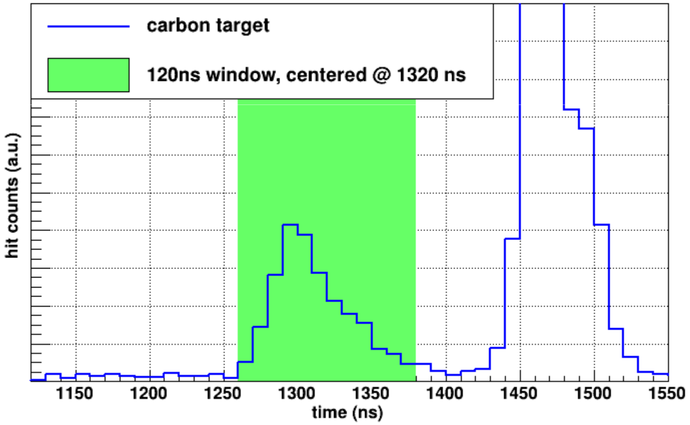


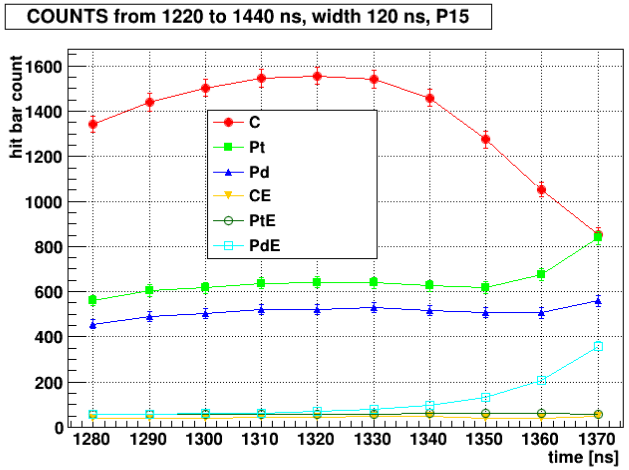


Data analysis

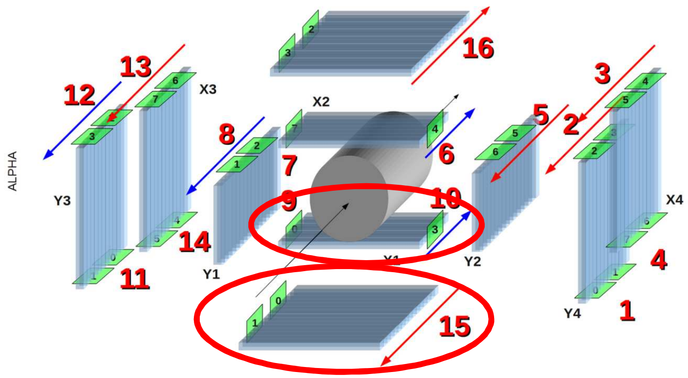
"Brescia detector"

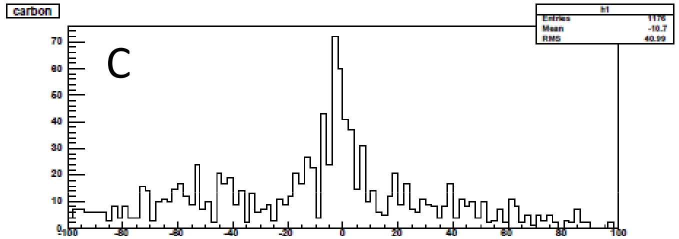
Only time info

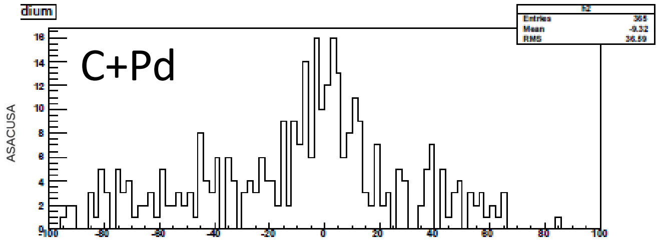


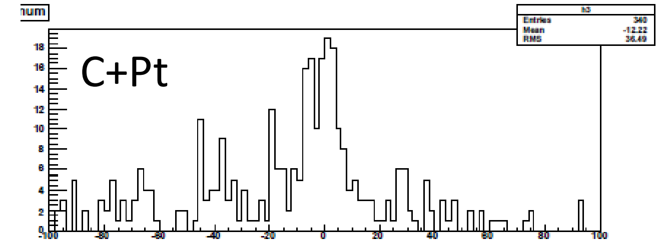


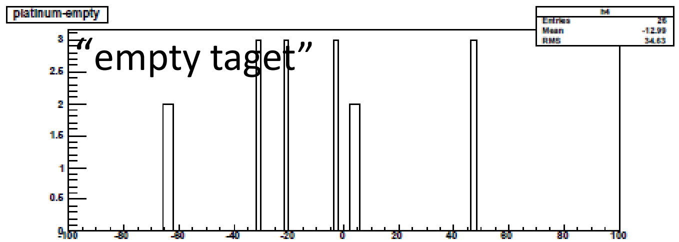
Vertex reconstruction









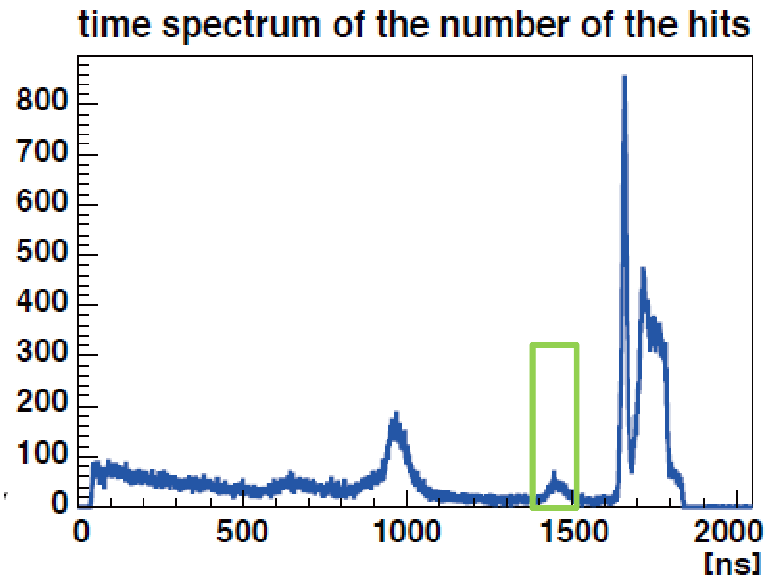


Consistent results

Data analysis

"MPQ/Tokyo detector"

Only time info



	Total hits		
	Brescia (1 mod.)	MPQ/Tokyo	Ratio
bare-C	1556	4010	2.6
C+Pd	523	1490	2.8
C+Pt	643	2000	3.1
Acceptance (W)	6%	16%	2.7

Results from BS-detector and MPQ/Tokyo detector are consistent

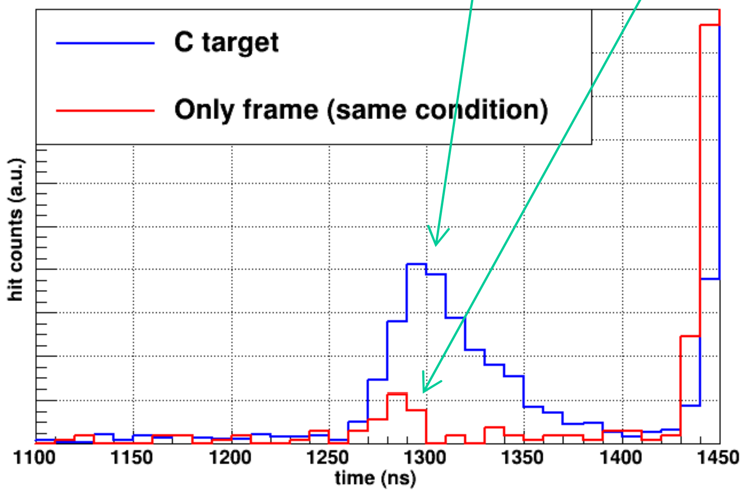
Data analysis

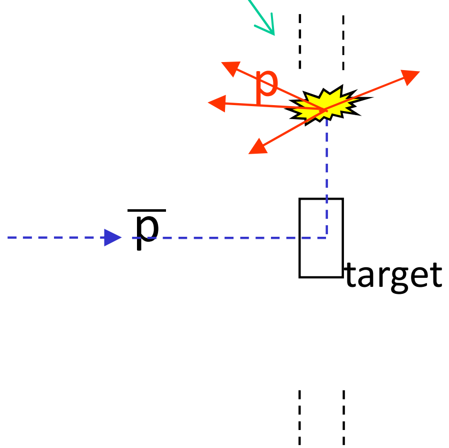
$$\sigma_{ann}(\bar{p}A) \div \frac{\mathrm{N}_{\mathrm{events}}}{\mathrm{N}_{\mathrm{beam}}}$$

In-flight annihilations

$$N_{\mathrm{events}} = N_{\mathrm{tot}} - N_{\mathrm{halo}} - N_{\mathrm{rest}}$$

from Monte Carlo

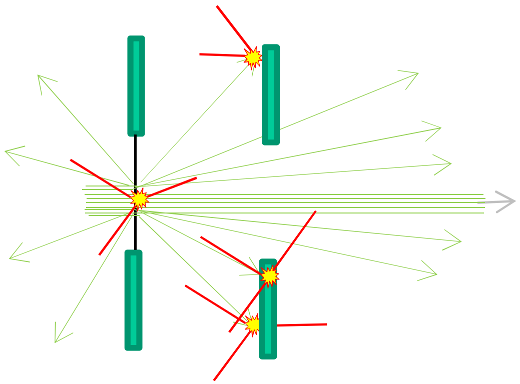


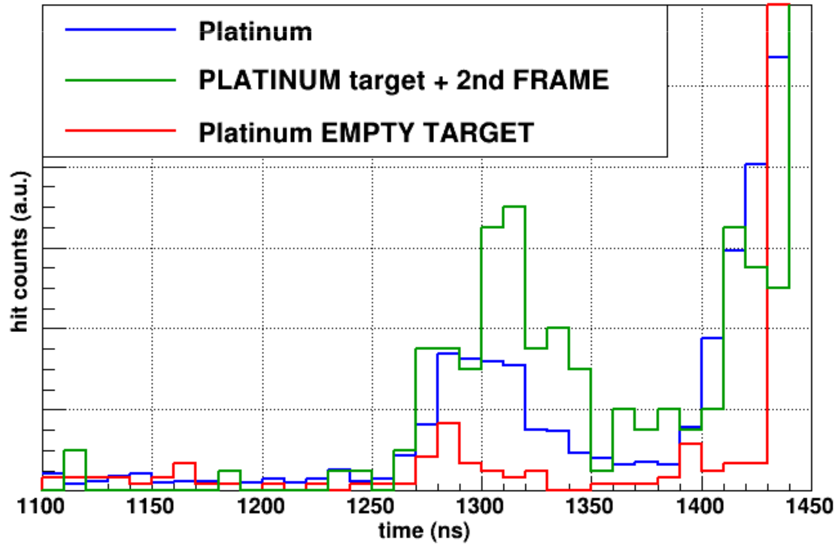


Beam intensity measurement

Cherenkov detector → relative measurement of the pbar beam intensity

Cherenkov signal normalized to the signal from Coulomb-scattered pbars on a 2° frame
→ absolute pbar beam intensity





Assuming prong multiplicity (k)=6, solid angle(W)=6%, detector efficiency (e)=0.9
the beam intensity is 7 x 10^4 pbars per shot (in the C+Pt day)

N.B. $$\sigma_{ann}(\bar{p}A) \div \frac{N_{events}}{N_{beam}}$$ is independent from k, W, e

same detector

Carbon target

Problems with bare-C target data

	Normalized hits/shot	
C	5.8 +-0.1	← Too many in respect to the others
C+Pd	1.98+-0.06	
C+Pt	1.81+-0.08	

- The carbon films had similar thicknesses (even if bare-C not measured)

-same results in different days

-same results with different detectors

- Beam halo on the frame is very unlikely (checked during run)

-large dusts on the bare-C target?

Upper limits on pbar-nucleus annihilation cross-sections @130 keV

In 2012 data for 3 targets:

C

(C+Pd)

(C+Pt)

…but bare-C target was unreliable

Can we extract annih. cross-sections from (C+Pd) and (C+Pt) data?

Annihilation cross-section (s)

$$\begin{cases} N_{events}^{Pt+C} = N_{pbar}\left(\sigma_{Pt} n_{Pt} + \sigma_C n_C\right) & \text{for (Pt+C) target} \\ N_{events}^{Pd+C} = N_{pbar}\left(\sigma_{Pd} n_{Pt} + \sigma_C n'_C\right) & \text{for (Pd+C) target} \end{cases}$$

2 equations and 3 variables $\left(\sigma_C, \sigma_{Pd}, \sigma_{Pt}\right)$

It is possible to measure:

- relative s: $\frac{\sigma_{Pd}}{\sigma_C}, \frac{\sigma_{Pt}}{\sigma_C}, \frac{\sigma_{Pt}}{\sigma_{Pd}}$

- (lower & upper) limits for $\sigma_C, \sigma_{Pd}, \sigma_{Pt}$

Legenda:

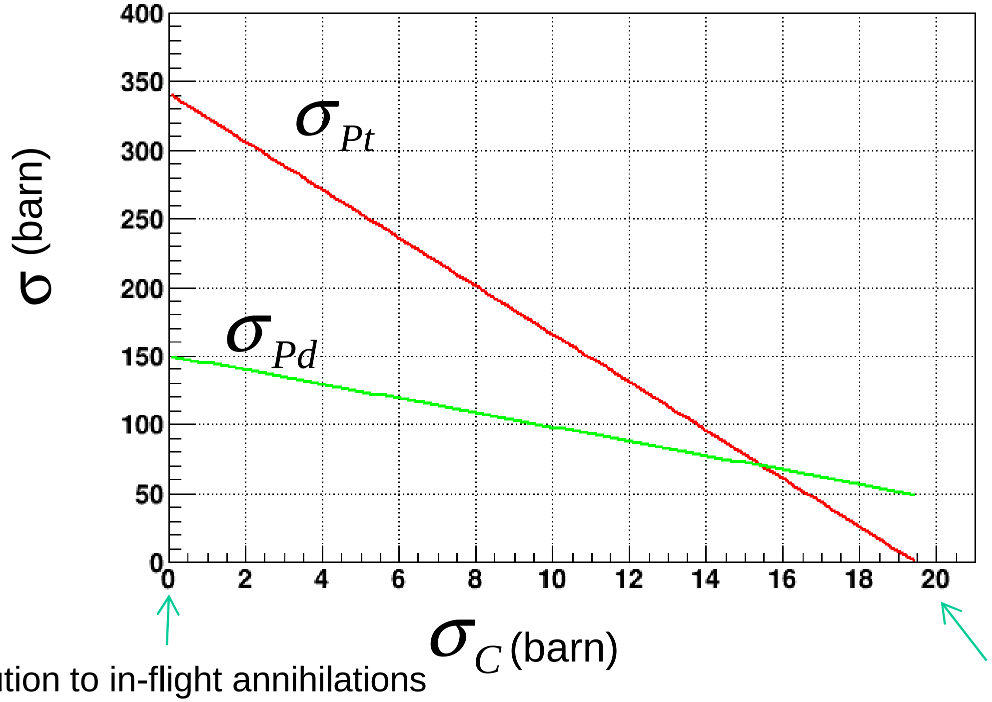
$N_{events}^{Pt+C}\left(N_{events}^{Pd+C}\right) =$ # of in-flight annihilations for Pt+C (Pd+C) target

$N_{pbar} =$ # of injected pbars

$n_X =$ Surface number density for X element ← RBS measurement @ Legnaro (Italy)

(lower & upper) limits for $\sigma_C, \sigma_{Pd}, \sigma_{Pt}$

From:
$$\begin{cases} \sigma_{Pt} = -\dfrac{n_C}{n_{Pt}}\sigma_C + \dfrac{N_{events}^{Pt+C}}{N_{pbar} n_{Pt}} \\ \sigma_{Pd} = -\dfrac{n'_C}{n_{Pt}}\sigma_C + \dfrac{N_{events}^{Pd+C}}{N_{pbar} n_{Pd}} \end{cases}$$
with the conditions $\sigma_C \geq 0$ $\sigma_{Pd} \geq 0$ $\sigma_{Pt} \geq 0$



For distance between (C+Pt) and 2°frame=1.25 cm

Contribution to in-flight annihilations from C-foil is negligible

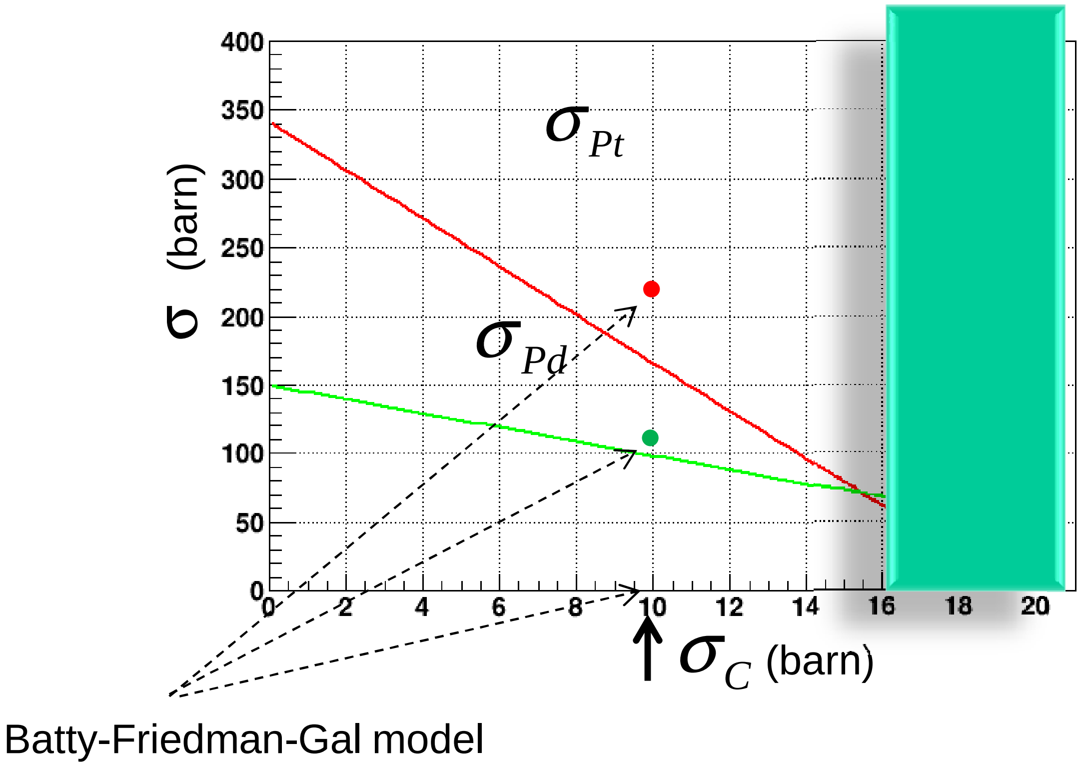
Mostly of in-flight annihilations are due to C-foil

more stringent (lower & upper) limits for σ_C, σ_{Pd}, σ_{Pt}

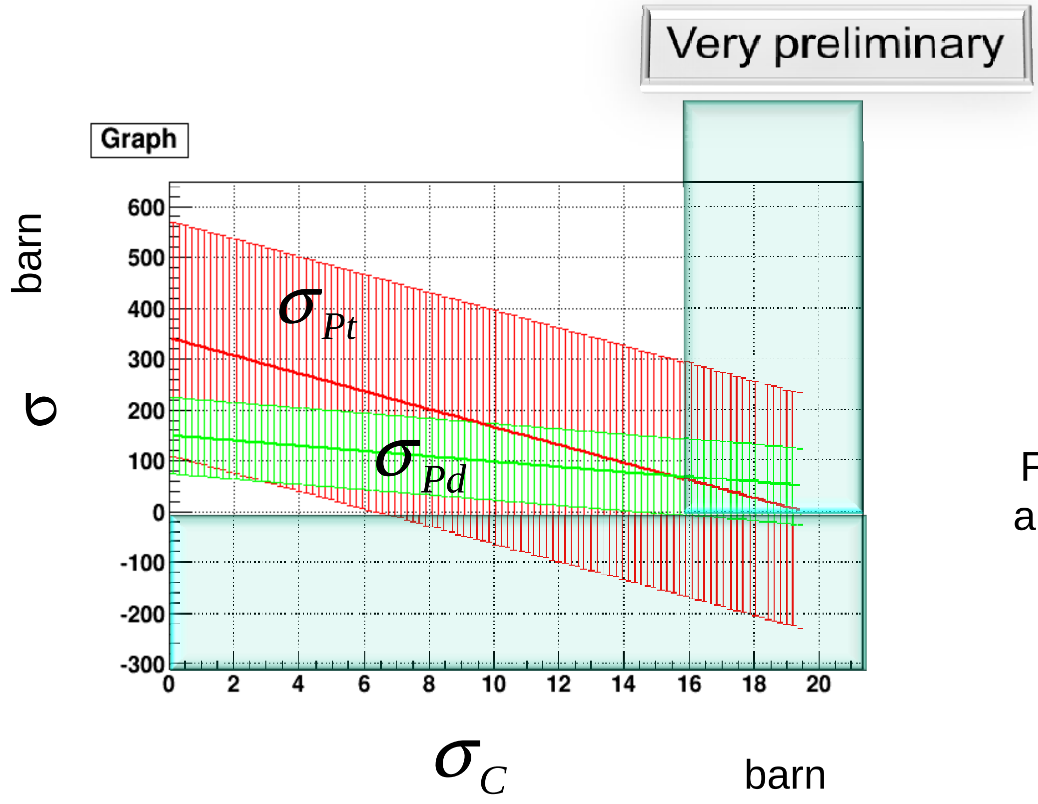
In addition if we assume:

$$\sigma_{Pt} \geq \sigma_{Pd} \geq \sigma_C$$

we can limit the ranges



(lower & upper) limits for σ_C, σ_{Pd}, σ_{Pt} + errors bands



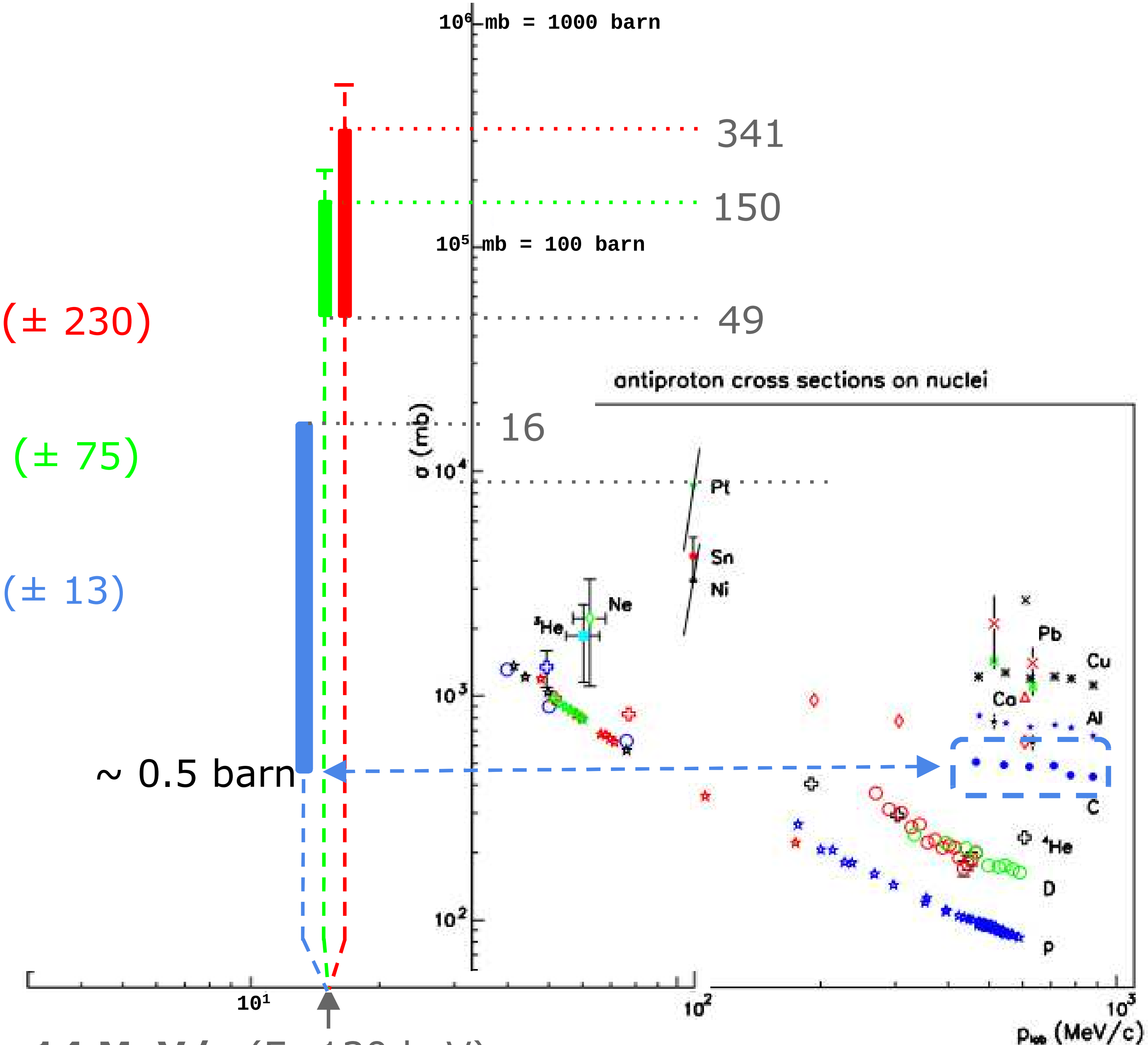
For distance between (C+Pt) and 2°frame=1.25(+-0.20) cm

@130 keV

$49 < \sigma_{Pt} < 341$ barn (± 230)

$49 < \sigma_{Pd} < 150$ barn (± 75)

$\sim 0.5 < \sigma_{C} < 16$ barn (± 13)

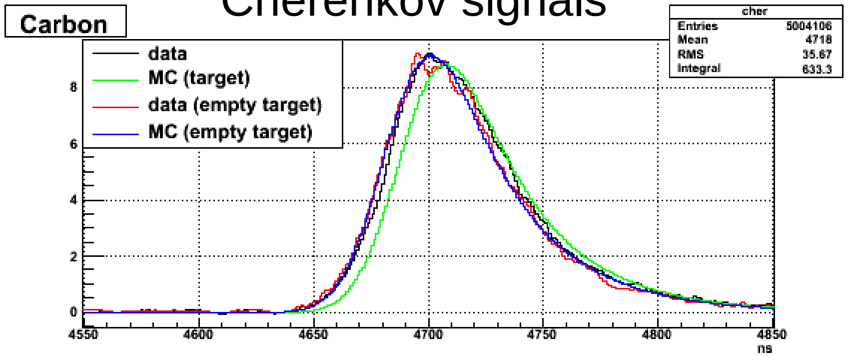


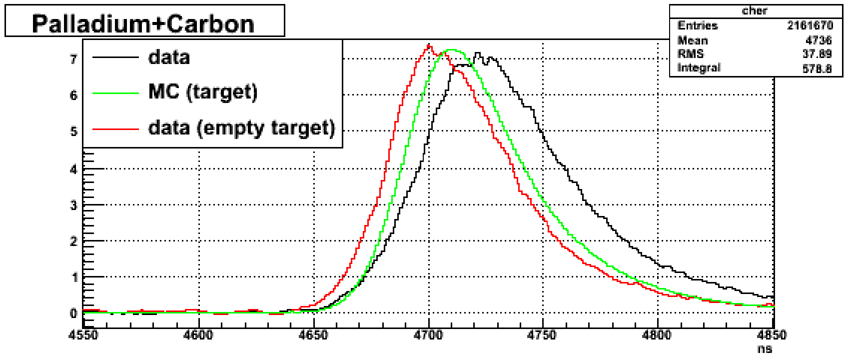
p = **14 MeV/c** (E=130 keV)

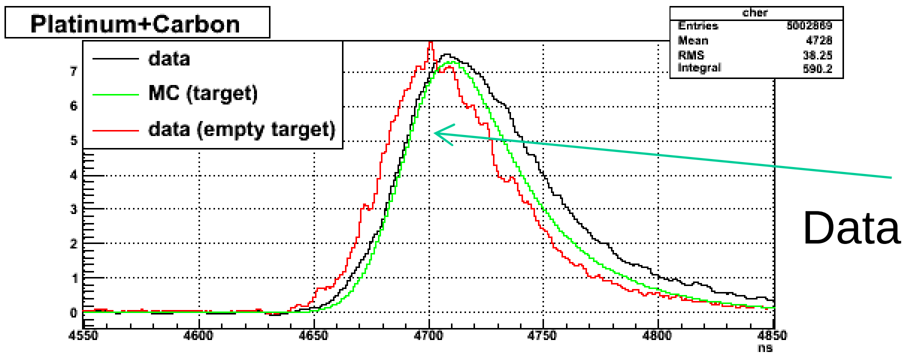
Energy loss

By product

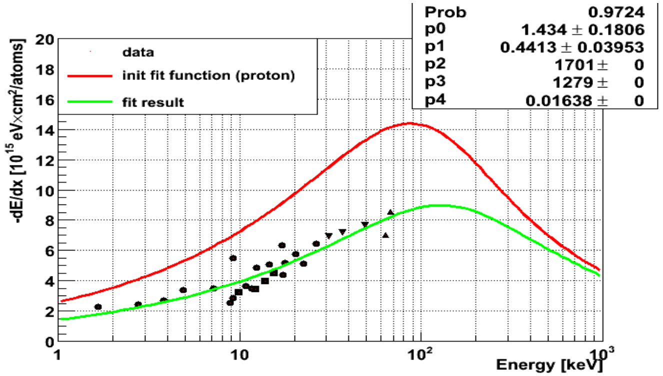
Cherenkov signals





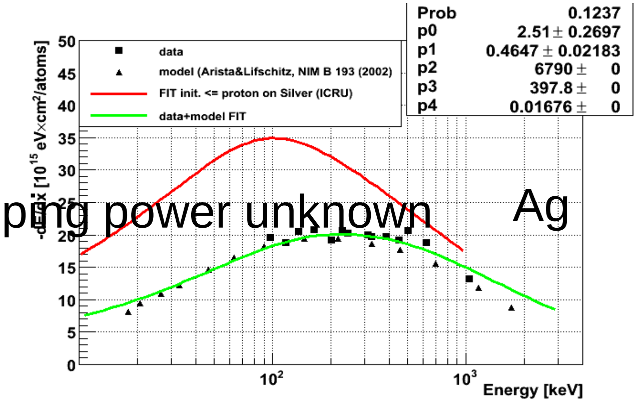


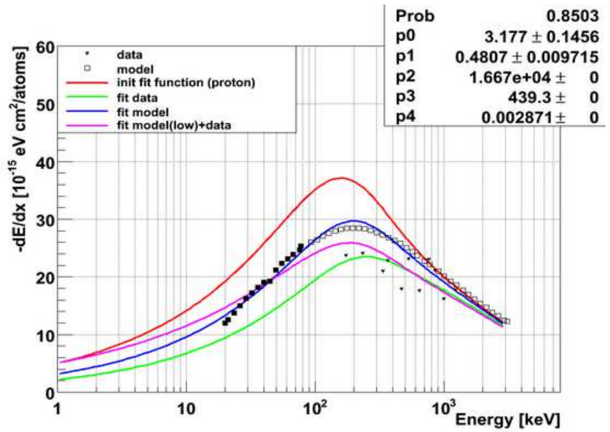
Data and simulations agree well



Pd stopping power unknown

Ag





Similar by using GEANT4

Improvements for next measurements

@ 130 keV

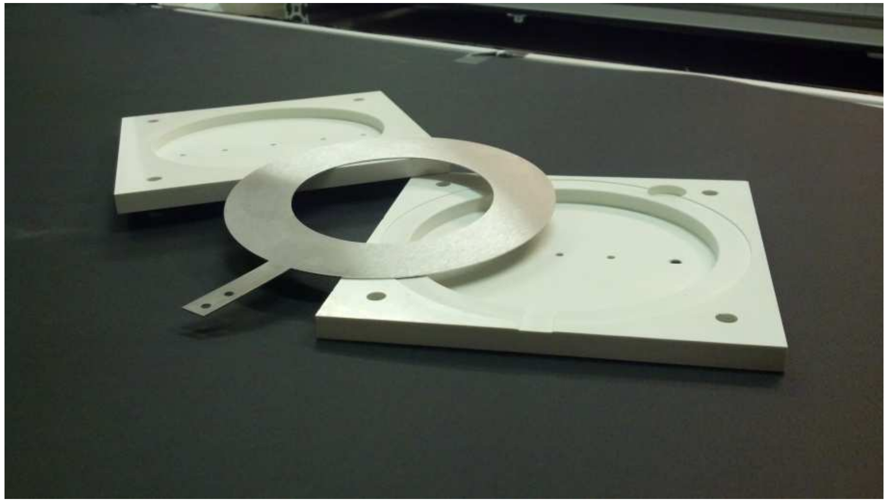
- Same apparatus
- Minor improvements:

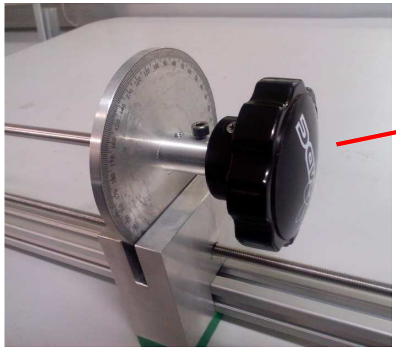
  -

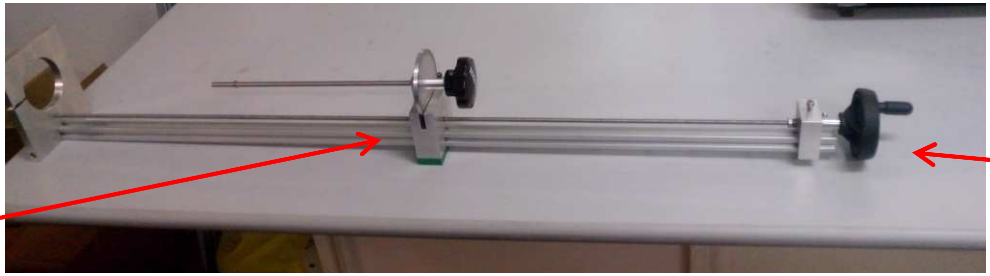
  - thicker wall

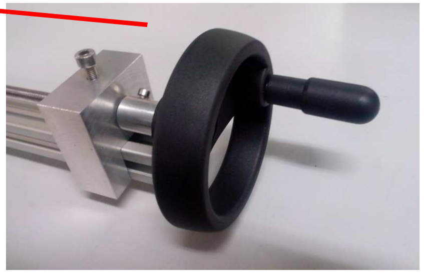
  - new target frames and boxes

  - new target positioning tool









Summary

1) Three targets used: C, C+Pd, C+Pt
2) Same results with 2 different and independent detectors (the MPQ/Tokyo detector and the Brescia detector).
3) good separation between signal and background
4) C- target was unreliable (too many events in respect to C+Pd and C+Pt targets)
5) the data acquired in different conditions are consistent (for example the only-frame data, the data with the 2nd frame. etc.)
6) if we exclude the carbon target, the other 2 targets give reasonable results:

   -it is possible to determine the upper limits for the pbar annihilation cross-sections (sigma) on carbon, palladium and platinum. Their values are 20, 150, 340 barn
   -If we assume that sigma_C < sigma_Pd < sigma_Pt the upper limit for sigma_C becomes 16 barn and we can give also lower limits for the other sigmas. They are 50 barn for both palladium and platinum.
   -The uncertainty on these values can be estimated to be around 60% (this is very preliminar)
   -If we assume sigma_C=10 barn (as predicted by Batty-Friedman-Gal) we have a good agreement between sigma_Pd and sigma_Pt values and the the Batty-Friedman-Gal's predictions.