CONSUNTIVI SCIENTIFICI
GRUPPO COLLEGATO di BRESCIA

Luca Venturelli

Università di Brescia

INFN Gruppo Collegato di Brescia

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				
Ferroni Matteo	assoc	Ricercatore			50
Leali Marco	assoc			x	100
Lodi Rizzini Evandro	assoc				
Mascagna Valerio		Assegnista			…
Venturelli Luca	assoc	Prof. Associato			100
Zurlo Nicola	assoc	Ricercatore			100

Marca Alessandro		tecnico informatico			100

+ collaboratori Universita' dell'Insubria-Como INFN Trieste

Attività teorica (per 2014)

cognome nome		TIPO	Ricercatori	Tecnologi	FTE
Bianconi Andrea	assoc	Prof.Associato			30

Attività teorica

1) Fisica medica: ricerca sugli effetti di lungo periodo da contaminazioni interne di Diossido di Torio radioattivo.

A.Bianconi: "Thorotrast and in vivo thorium dioxide: Numerical simulation of 30 years of a radiation absorption by the tissues near a large compact source",
European Journal of Medical Physics (Physica Medica), 30, 489-496 (2014)

intervento al 21esimo convegno SIRR (Società Italiana Ricerca Radiazioni):
A.Bianconi, "Eventi in cui un nucleo cellulare, posizionato per decenni accanto ad una sorgente interna di Torio, viene colpito da due o più particelle a entro intervalli di tempo di ordine 1 s".

2) Fattori di forma time-like del protone, collaborazione con E.Tomasi-Gustafsson del CEA-Saclay su esperimenti di annichillazione elettrone-positrone in p-pbar o viceversa. In particolare sono stati rianalizzati alcuni dati dell'esperimento Babar.

(pubblicazione su PRL, ma nel 2015).

3) Deep Inelastic Scattering ed eventi Drell Yan (urto ad alta energia protone-antiprotone oppure pione-protone, in entrambi i casi con produzione inclusive di una coppia elettrone-positrone).

Invited talks a congressi (in particolare: A.Bianconi, "MC at intermediate energies and including transverse polarizations", al convegno "Studies of 3D Structure of Nucleon (INT-14-55W) 2014, Institute of Nuclear Theory, Seattle)

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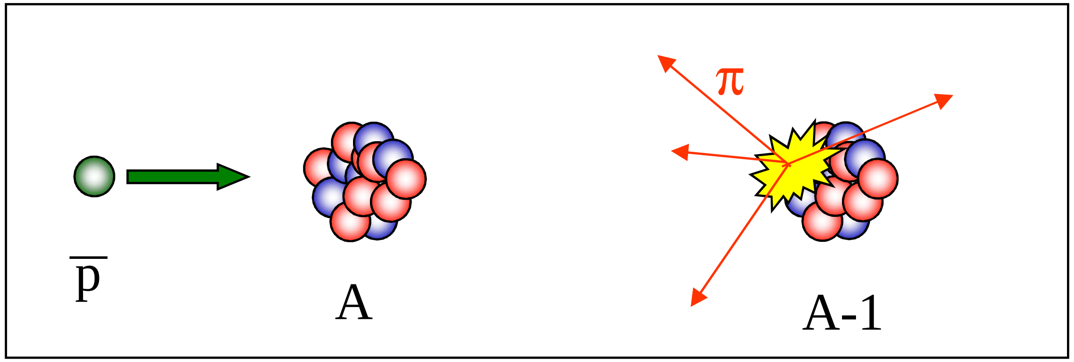
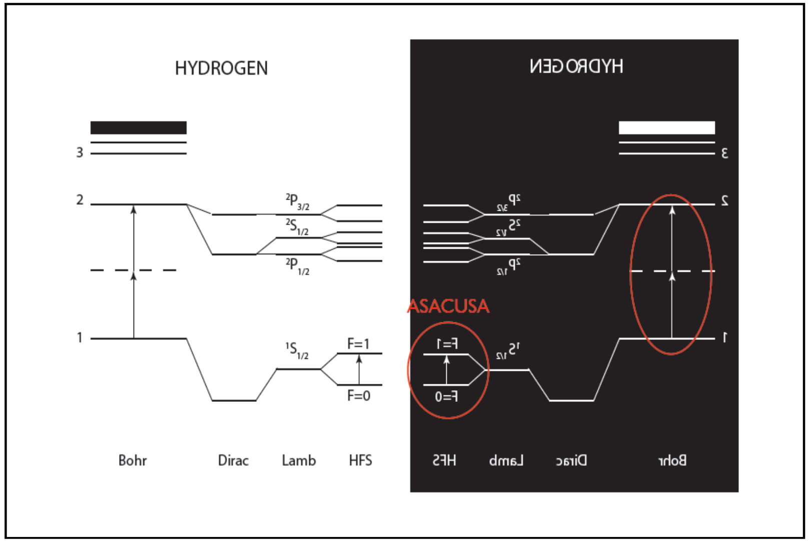
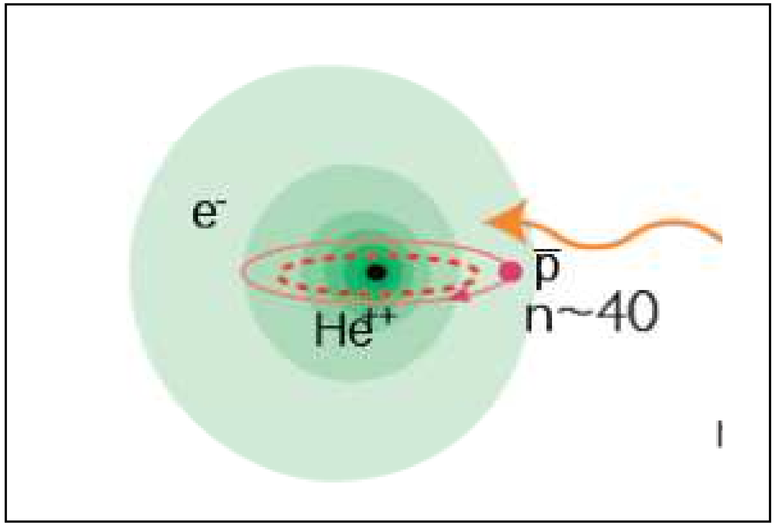

π
p̄
A
A-1


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


e-
p̄
He++
n~40

Publications and talks

ISI

	Titolo	Rivista
1	Antihydrogen formation mechanisms ISI ID della pubblicazione: **WOS:000342463600046**	INPC 2013 - INTERNATIONAL NUCL, **66-**, 05015 (2014)
2	Beam Diagnostics for Measurements of Antiproton Annihilation Cross Sections at U... ISI ID della pubblicazione: **WOS:000342463600134**	INPC 2013 - INTERNATIONAL NUCL, **66-**, 09020 (2014)
3	Antiproton-to-electron mass ratio determined by two-photon laser spectroscopy of... ISI ID della pubblicazione: **WOS:000342463600051**	INPC 2013 - INTERNATIONAL NUCL, **66-**, 05020 (2014)
4	Near-infrared laser spectroscopy of antiprotonic helium atoms ISI ID della pubblicazione: **WOS:000342463600041**	INPC 2013 - INTERNATIONAL NUCL, **66-**, 05010 (2014)
5	Experimental results on antiproton-nuclei annihilation cross section at very low energies ISI ID della pubblicazione: **WOS:000342463600115**	INPC 2013 - INTERNATIONAL NUCL, **66-**, 09001 (2014)
6	A source of antihydrogen for in-flight hyperfine spectroscopy ISI ID della pubblicazione: **WOS:000331084200031**	NAT COMMUN, **5-**, 3089 (2014)
7	Enhancement of annihilation cross sections by electric interactions between the ... ISI ID della pubblicazione: **WOS:000346246700001**	EUR PHYS J A, **50-12**, 182 (2014)

Non-ISI

	Titolo	Rivista
1	Experimental investigation of ≈130 keV kinetic energy antiprotons annihila...	Hyperfine Interactio, -, (2014)
2	Modelling the behavior of the positron plasma temperature in antihydrogen experimentation	Hyperfine Interactio, **228-**, (2014)
3	Towards a spin polarized antihydrogen beam	Hyperfine Interactio, -, (2014)

Talks

	Speaker	Conference	Contr. Title	Type	Place
1	Venturelli L.	*20th International Conference on Pa...*	The First Cold Beam of Antihydrogen Atoms from a Cusp Trap	par	Hamburg
2	Venturelli L.	*5th International Conference on Exo...*	First measurements of the antiproton-nucleus annihilation cross section at ...	par	Vienna
3	Mascagna V.	*5th International Conference on Exo...*	Scintillating bar detector for antiproton annihilations detection	pos	Vienna

ASACUSA

Atomic Spectroscopy And Collisions Using Slow Antiprotons

- 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

Asakusa, Tokyo

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

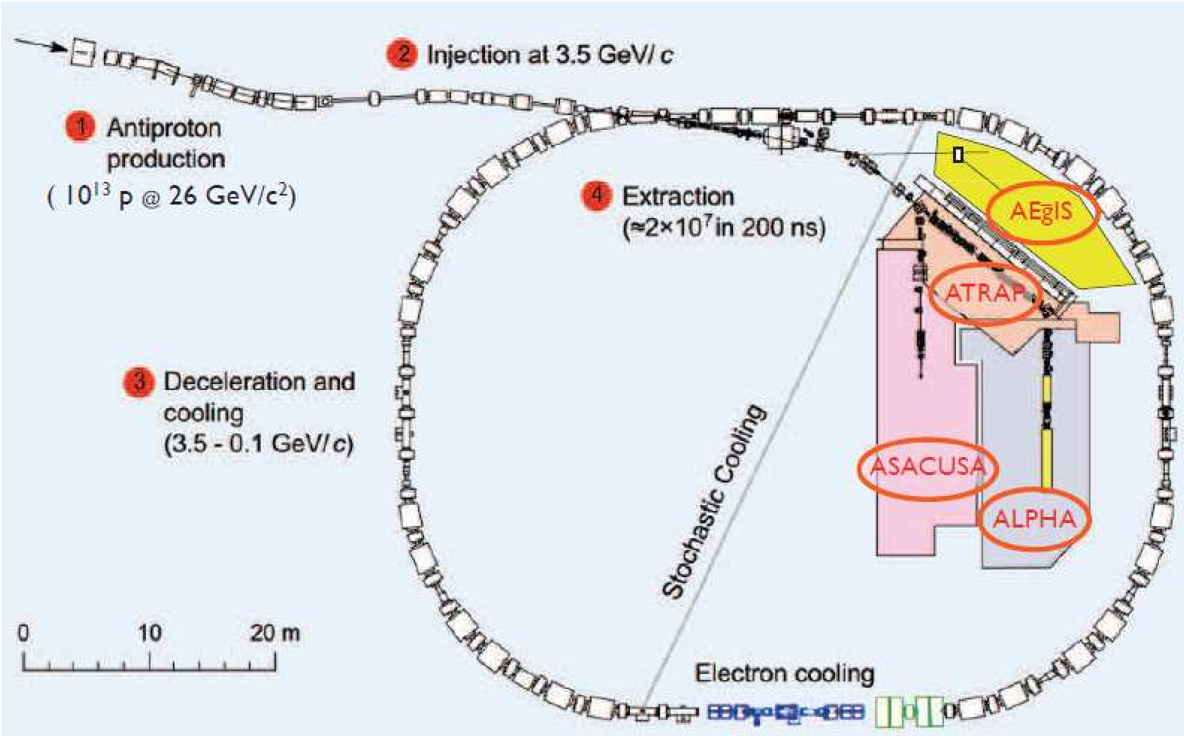
Aghai Khozani, H.[1], Barna, D.[2,6], Caradonna, P.[3], Corradini, M.[4], Dax, A.[2], Diermaier, M.[3], Federmann, S.[3], Friedreich, S.[3], Hayano, RS.[2], Higaki, H.[5], Hori, M.[1], Horvath, D.[6], Kanai, Y.[5], Knudsen, H.[7], Kobayashi, T.[2], Kuroda, N.[5], Leali, M.[4], Lodi-Rizzini, E.[4], Malbrunot, 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)

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)

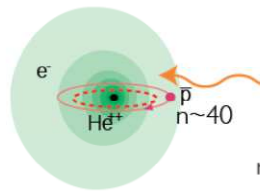
Experiments: - (2015) ALPHA, ATRAP, ASACUSA, AEgIS, BASE

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

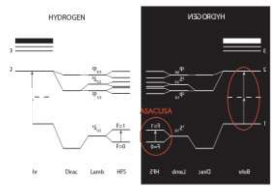
ASACUSA Experiments

Studies of *CPT symmetry* by atomic spectroscopy

1) • laser spectroscopy of antiprotonic helium :
→ Antiproton mass

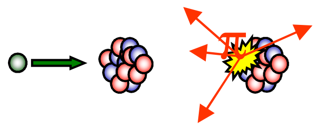


2) • Microwave spectroscopy of antihydrogen :
→ Ground-state hyperfine structure



Nuclear collisions with antiprotons

3) • total annihilation cross-section σ.

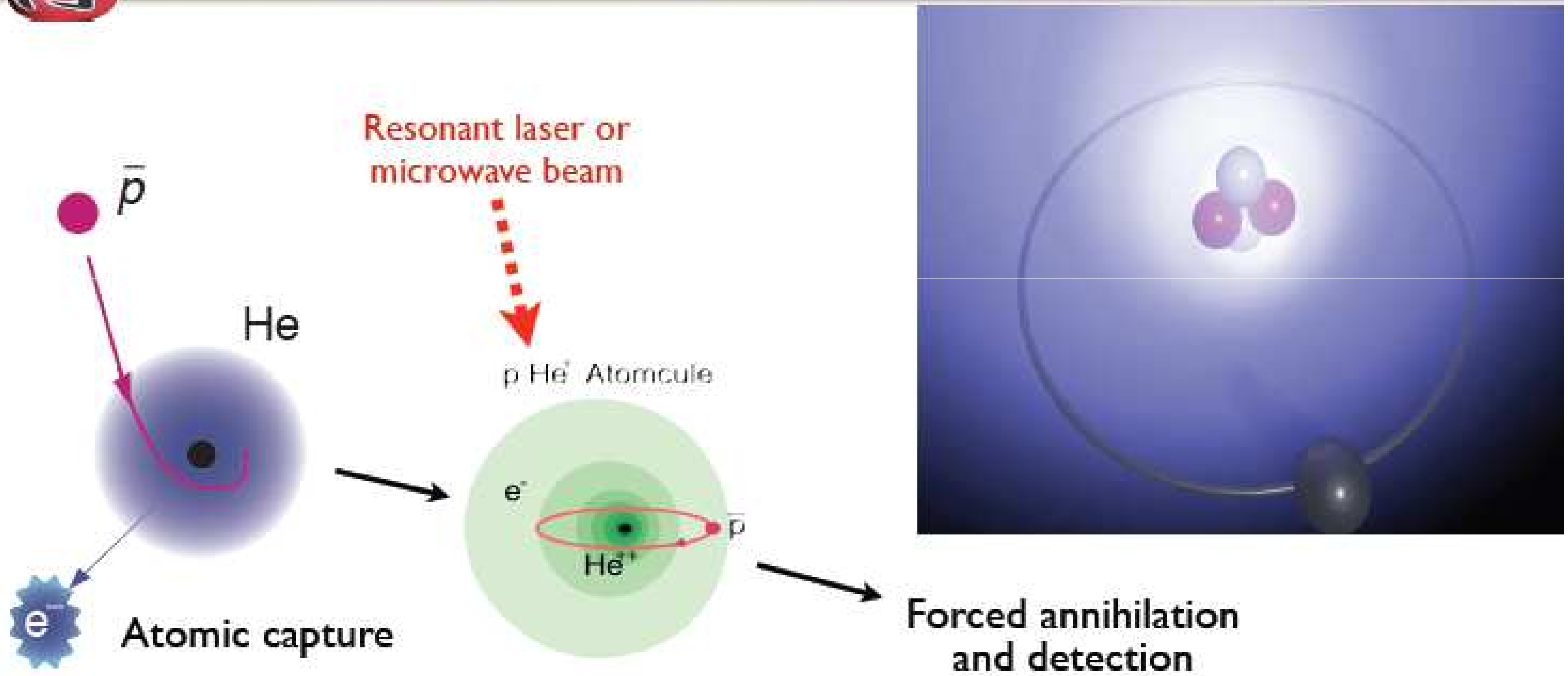


No beam during 2013 (CERN Long Shutdown 1)

2014: short beamtime with AD problems

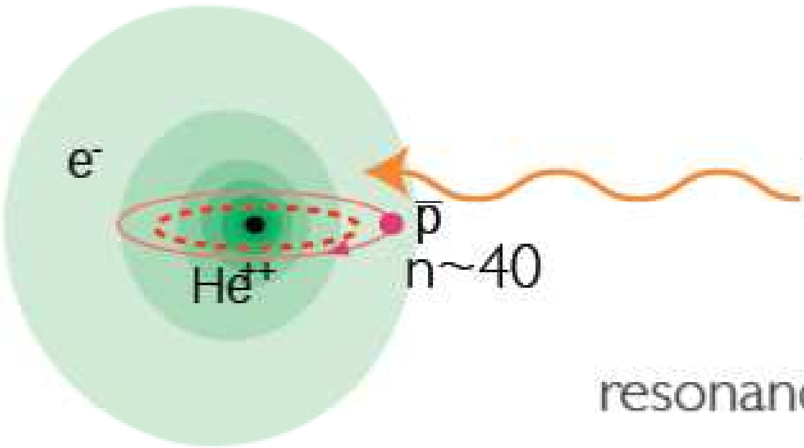
1. $\bar{p}$He laser spectroscopy

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

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

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

Theory

Korobov

2014: Difficulties of AD startup after LS1

- Sep. 29 First beam. No deceleration….
- Oct. 1 RFQD amplifier pulse not in synchronization with AD.
- Oct. 2 Meeting with RF specialists (AD timing system changed)
- Oct. 3 RFQD timing problem intervention
- Oct. 4 Almost no beam (6h loss), RFQD timing problem solved, 30% empty, fluctuations, no efficiency in deceleration.

- Oct. 5 Some transport to target, huge fluctuations.
- Oct. 6 First antiprotonic helium, almost no resonance signal.
- Oct. 7 No beam, PSB problem, power glitch
- Oct. 8 No beam, e-cooler does not work at 300 MeV/c.
- Oct. 9 New beam tuning, almost no deceleration.

- Oct. 10 Realized transfer line changed (due to ELENA+BASE).
- Oct. 11 Started to tune quad values through RFQD.
- Oct. 12-13 Continue quad tuning through RFQD.
- Oct. 14-15 First attempt at spectroscopy scans.
- *Oct. 16 Fire, power cut*
- Oct. 20 Beam recovery (end of our scheduled beam).
- Oct. 21-22 Some hours obtained from ATRAP+BASE.

AD Schedule 2014 (Version 1.3 Aug 12th, 2014)

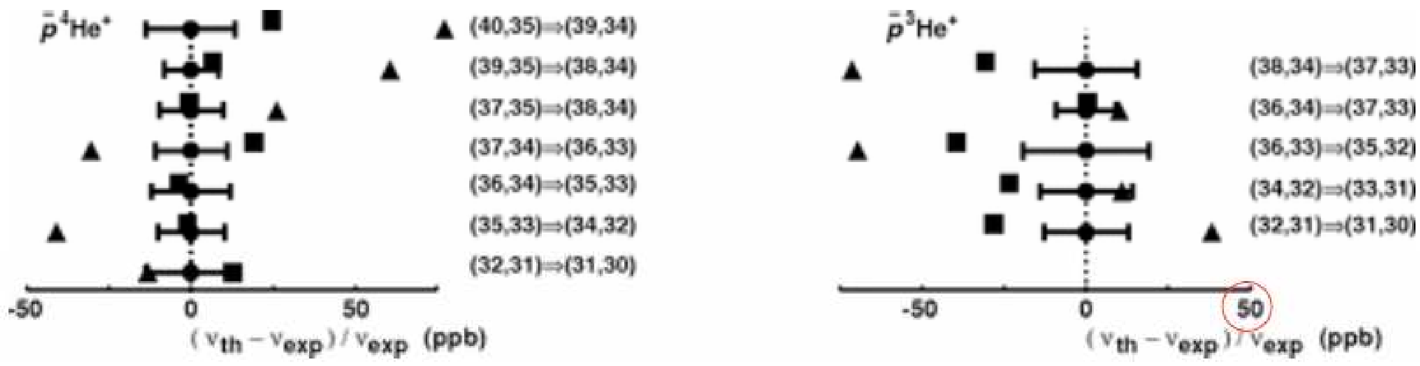
	Wk	Mon			Tue			Wed			Thu			Fri			Sat			Sun		
Jul 28 - Aug 3	31																					
Aug 4 - Aug 10	32	AD setting up																				
Aug 11 - Aug 17	33																					
Aug 18 - Aug 24	34	Setup extraction to experiments																				
Aug 25 - Aug 31	35	07-15	15-23	23-07	AD3	AD6	AD5	AD3	AD6	AD5	AD3	AD6	AD5	AD3	AD6	AD5	AD3	AD6	AD5	AD3	AD6	AD5
Sept 1 - Sept 7	36	AD8	AD3	AD6	AD8	AD3	AD6	AD8	AD3	AD6	AD8	AD3	AD6	AD8	AD3	AD6	AD8	AD3	AD6	AD8	AD3	AD6
Sept 8 -Sept 14	37	AD2	AD8	AD3	AD2	AD8	AD3	AD2	AD8	AD3	AD2	AD8	AD3	AD2	AD8	AD3	AD2	AD8	AD3	AD2	AD8	AD3
Sept 15 - Sept 21	38	AD5	AD2	AD8	AD5	AD2	AD8	AD5	AD2	AD8	AD5	AD2	AD8	AD5	AD2	AD8	AD5	AD2	AD8	AD5	AD2	AD8
Sept 22 - Sept 28	39	AD6	AD5	AD2	AD6	AD5	AD2	AD6	AD5	AD2	AD6	AD5	AD2	AD6	AD5	AD2	AD6	AD5	AD2	AD6	AD5	AD2
Sept 29 - Oct 5	40	AD3	AD6	AD5	AD3	AD6	AD5	AD3	AD6	AD5	AD3	AD6	AD5	AD3	AD6	AD5	AD3	AD6	AD5	AD3	AD6	AD5
Oct 5 - Oct 12	41	AD8	AD3	AD6	AD8	AD3	AD6	AD8	AD3	AD6	AD8	AD3	AD6	AD8	AD3	AD6	AD8	AD3	AD6	AD8	AD3	AD6
Oct 13 - Oct 19	42	AD2	AD8	AD3	AD2	AD8	AD3	AD2	AD8	AD3	AD2	AD8	AD3	AD2	AD8	AD3	AD2	AD8	AD3	AD2	AD8	AD3
Oct 20 - Oct 26	43	AD5	AD2	AD8	AD5	AD2	AD8	AD5	AD2	AD8	AD5	AD2	AD8	AD5	AD2	AD8	AD5	AD2	AD8	AD5	AD2	AD8
Oct 27 - Nov 2	44	AD6	AD5	AD2	AD6	AD5	AD2	AD6	AD5	AD2	AD6	AD5	AD2	AD6	AD5	AD2	AD6	AD5	AD2	AD6	AD5	AD2
Nov 3 - Nov 9	45	AD3	AD6	AD5	AD3	AD6	AD5	AD3	AD6	AD5	AD3	AD6	AD5	AD3	AD6	AD5	AD3	AD6	AD5	AD3	AD6	AD5
Nov 10 - Nov16	46	AD8	AD3	AD6	AD8	AD3	AD6	AD8	AD3	AD6	AD8	AD3	AD6	AD8	AD3	AD6	AD8	AD3	AD6	AD8	AD3	AD6
Nov 17 - Nov 23	47	AD2	AD8	AD3	AD2	AD8	AD3	AD2	AD8	AD3	AD2	AD8	AD3	AD2	AD8	AD3	AD2	AD8	AD3	AD2	AD8	AD3
Nov 24 -Nov 30	48	AD5	AD2	AD8	AD5	AD2	AD8	AD5	AD2	AD8	AD5	AD2	AD8	AD5	AD2	AD8	AD5	AD2	AD8	AD5	AD2	AD8
Dec 1 - Dec 7	49	AD6	AD5	AD2	AD6	AD5	AD2	AD6	AD5	AD2	AD6	AD5	AD2	AD6	AD5	AD2	AD6	AD5	AD2	AD6	AD5	AD2
Dec 7 -Dec 14	50	AD3	AD6	AD5	AD3	AD6	AD5	AD3	AD6	AD5	AD3	AD6	AD5	AD3	AD6	AD5	AD3	AD6	AD5	AD3	AD6	AD5
		AD physics stop December 15th 8AM. Potential AD4 (ACE) run in week 50, subject to Research Board approval.																				

AD MD (7:00-15:00) or Injector Stop 8h   Injector MD (7:00-19:00)

AD2 (ATRAP)   AD3 (ASACUSA)   AD4 (ACE)   AD5 (ALPHA)   AD6 (AEGIS)   AD8 (BASE)

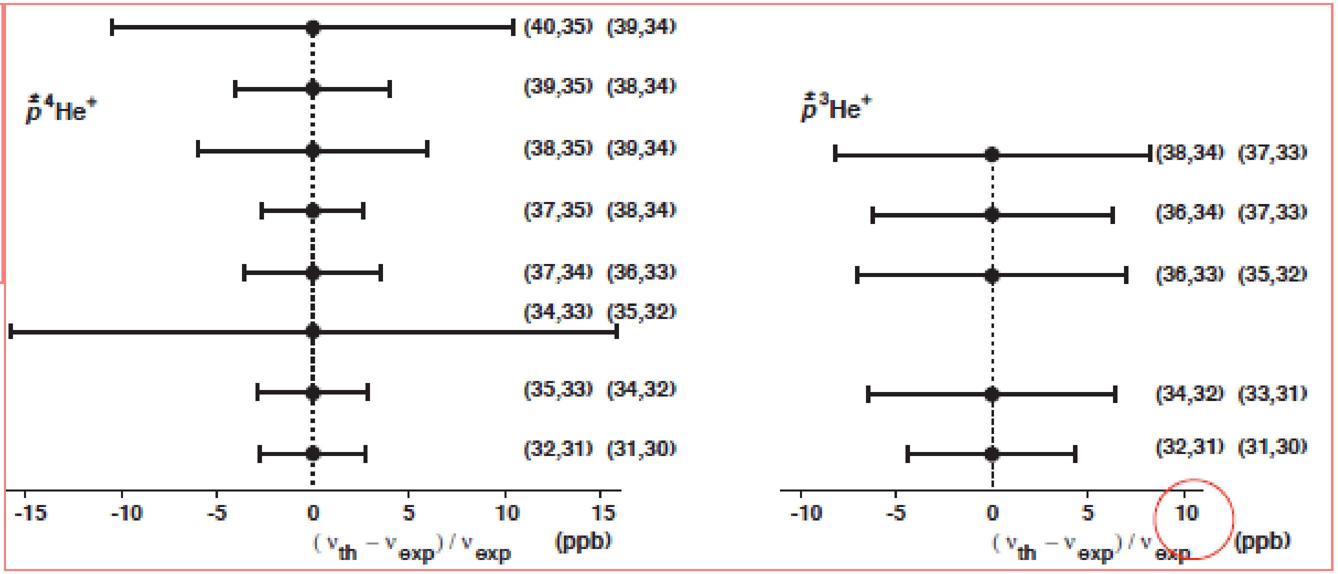
2012-2014 Results (1-photon resonance)

2006



Up to 70 ppb
theory-exp discrepancies

2012
|
2014



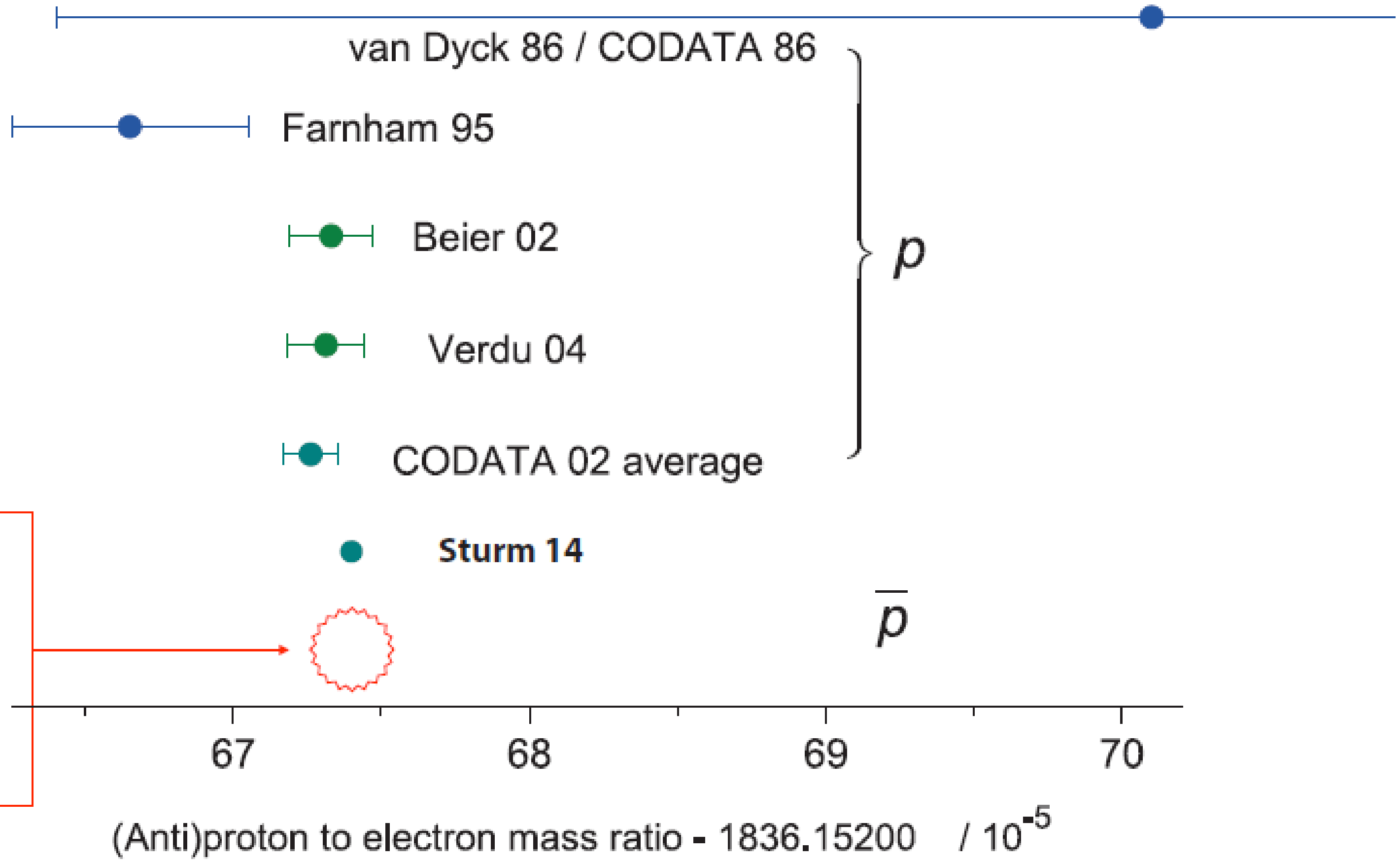
COMPLETED

←2014

←2014

Exp precision 1.3-5 higher; theory-exp agreement improved 5-10 x

ASACUSA antiproton to electron mass ratio



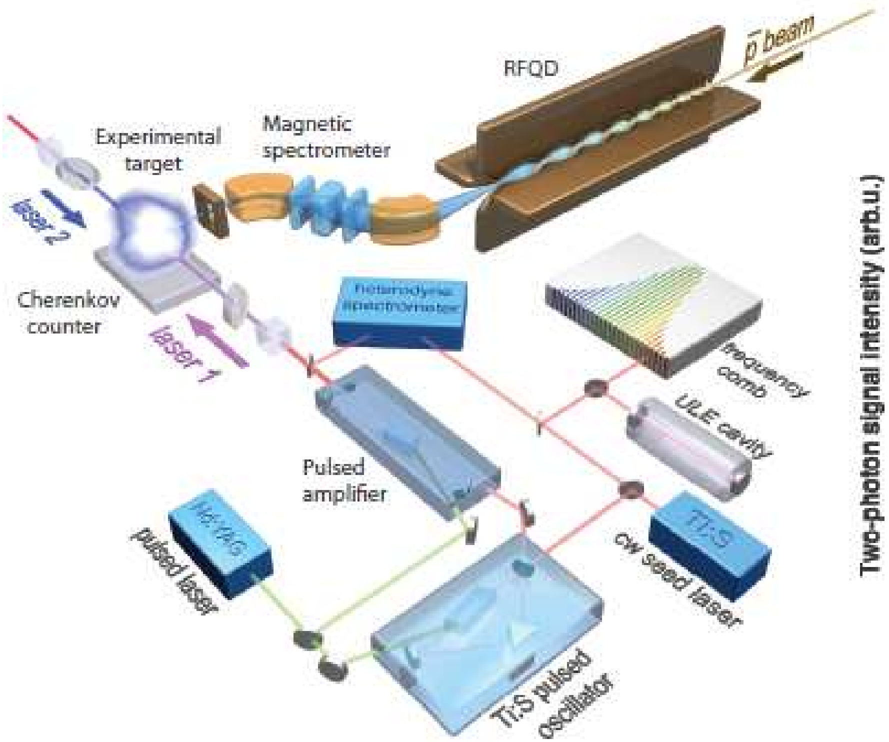
ASACUSA preliminary data not shown

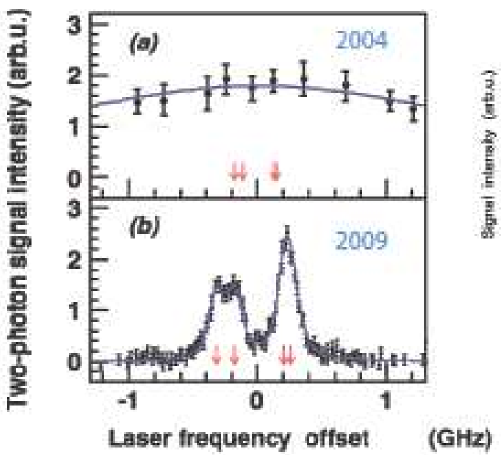
consistent with Strum 14, error bar ~ Verdu 04

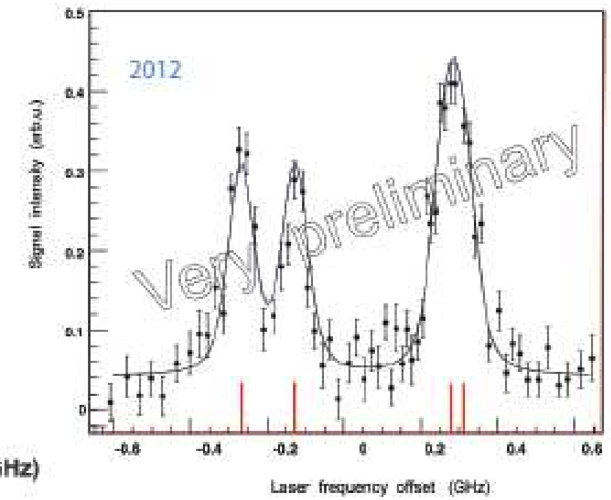
To be published

2015 (and beyond): 2-photon exp at 1.5 K

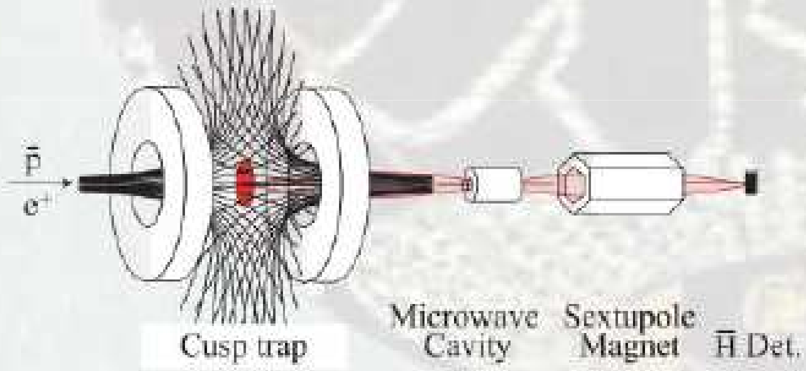
Goal: 300 ppt







2. Towards $\bar{H}$ Spectroscopy



- 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

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

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

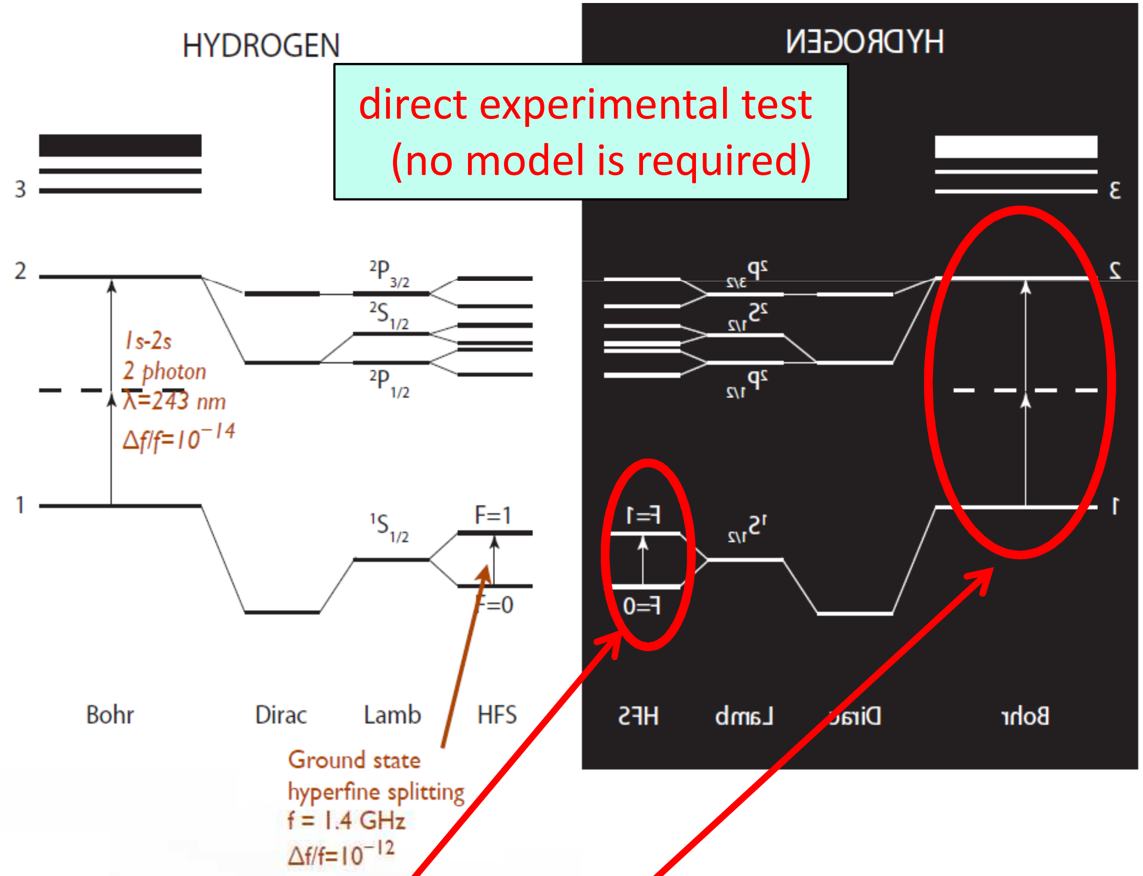
Lorentz Invariance Violating terms

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)

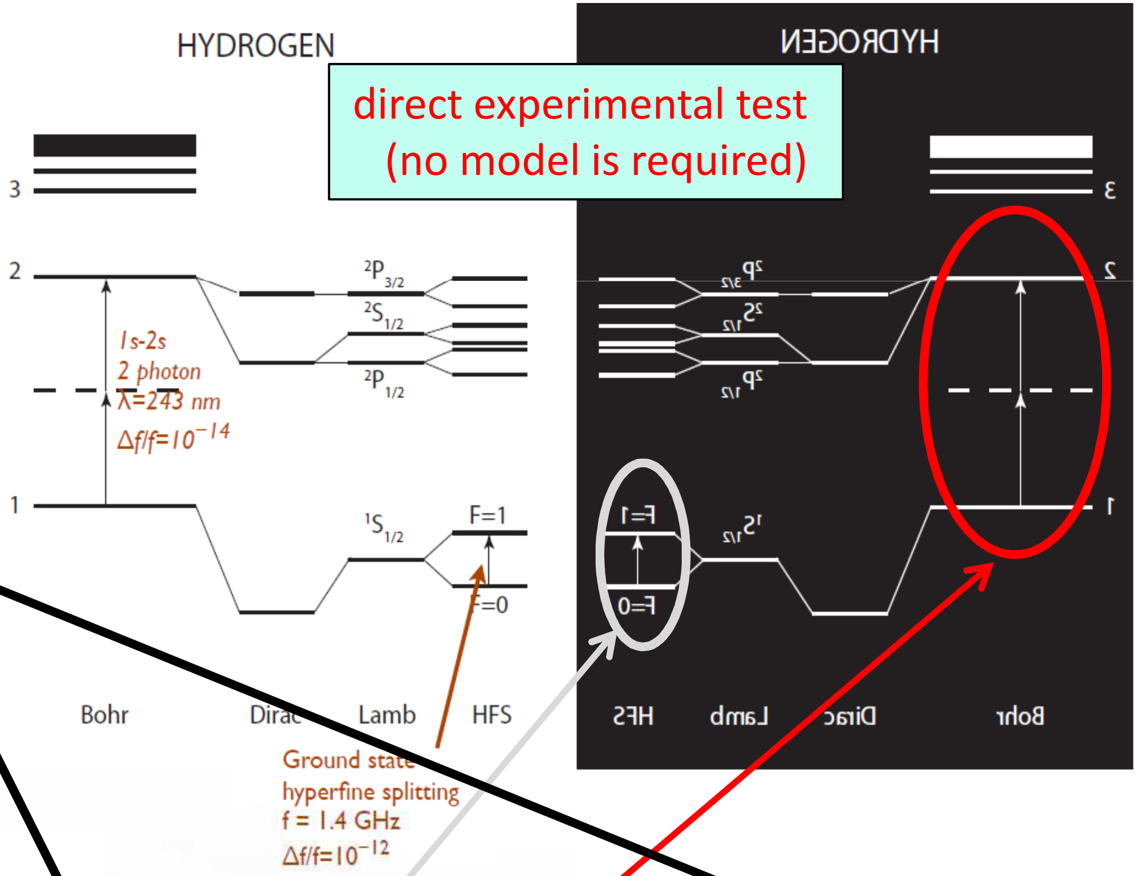
Plans for antihydrogen:

- 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



ALPHA
ATRAP

Plans for antihydrogen:

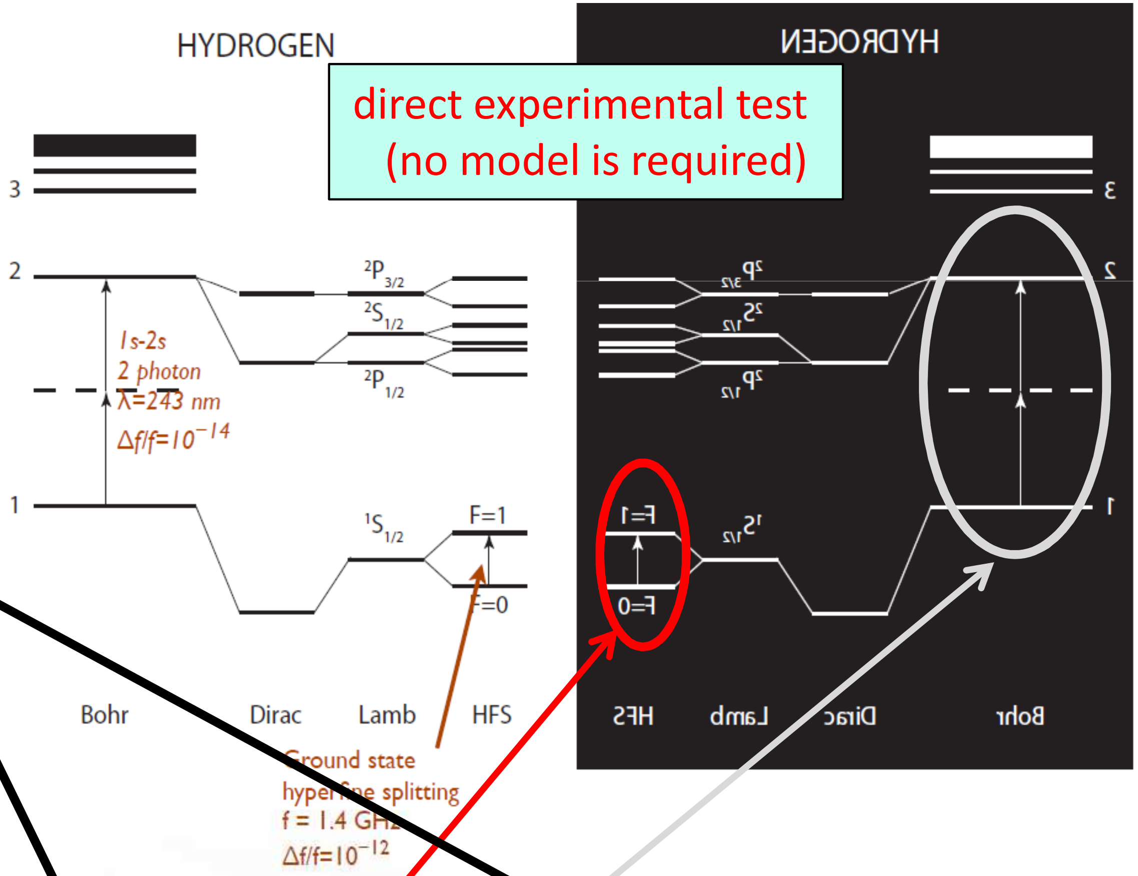
- measurements:
  - Hyperfine splitting of ground state
  - **1S-2S transition**

- 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

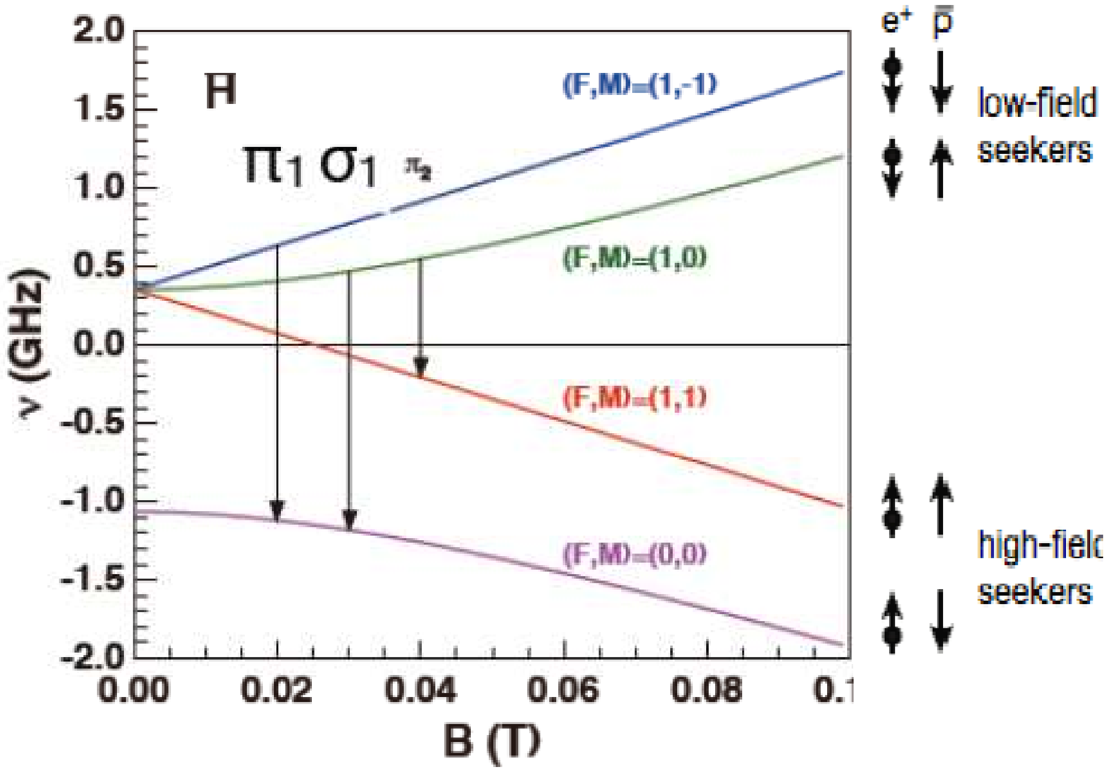
Plans for antihydrogen:

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

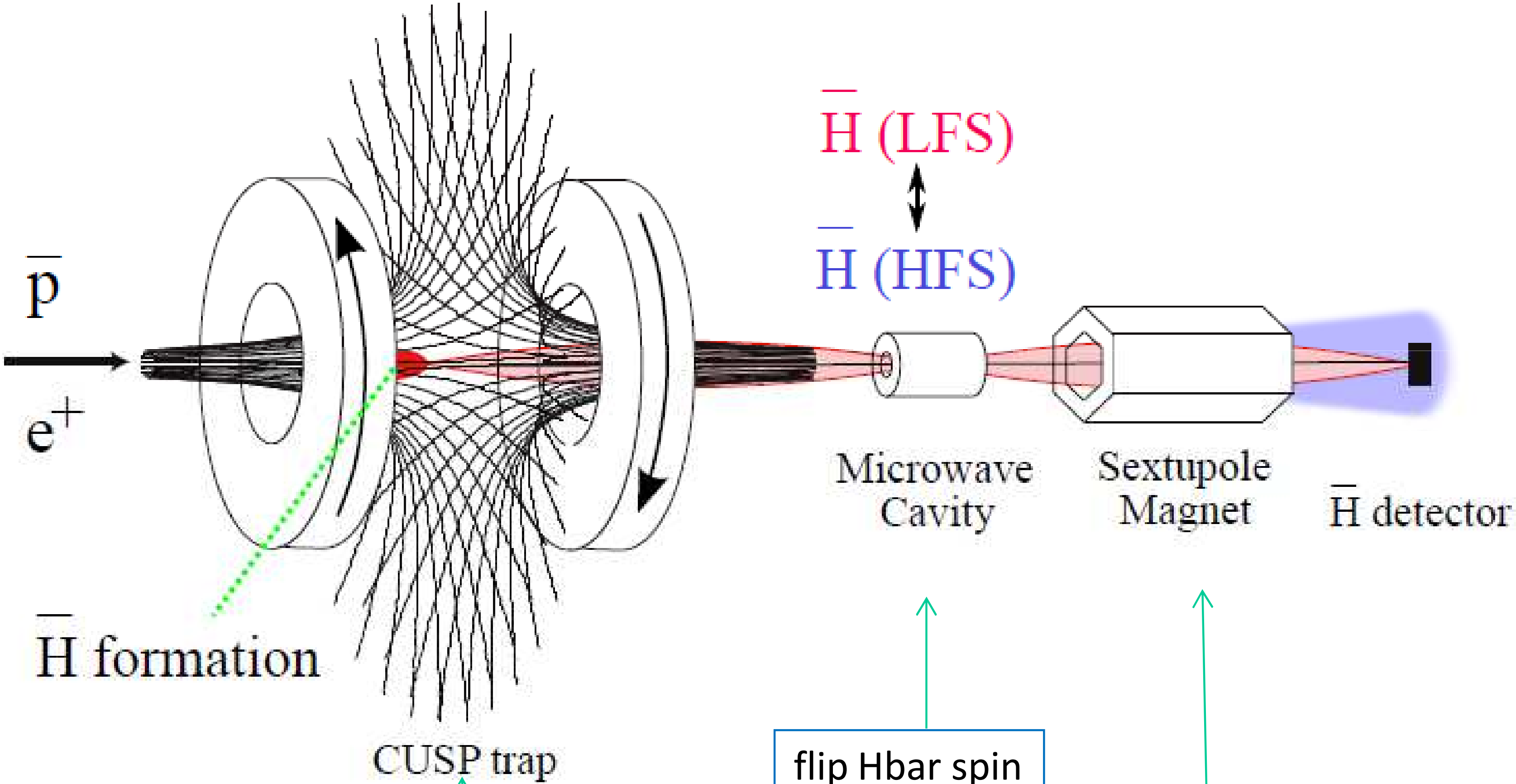
- methods: - Antihydrogen trapping
  - Antihydrogen beam

Method

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



Scheme of the measurement



flip Hbar spin

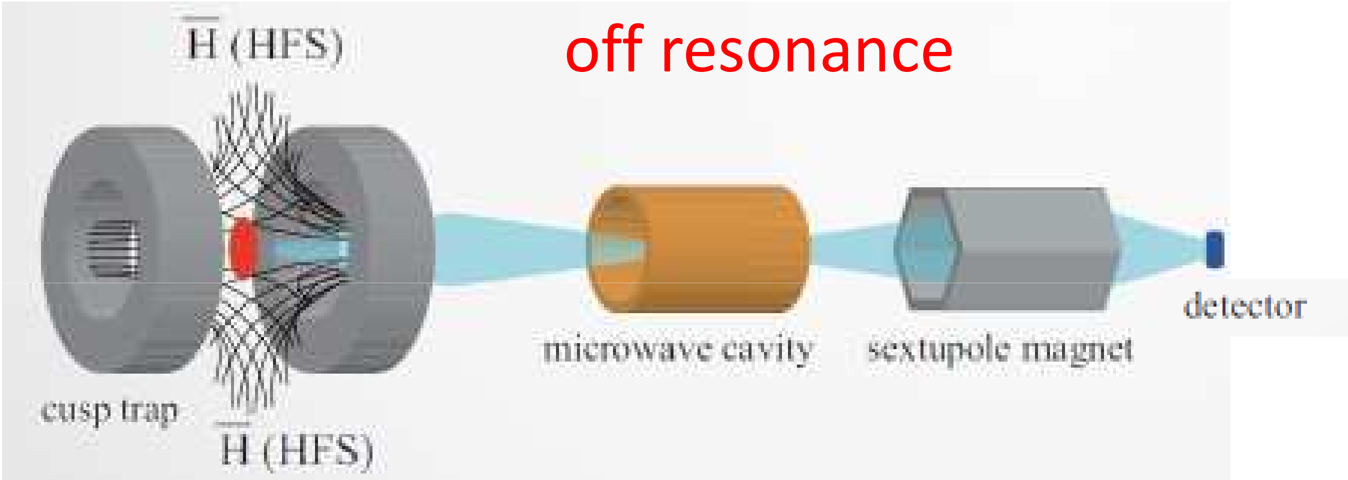
confine pbars and e^+ ;
select Hbar spin state

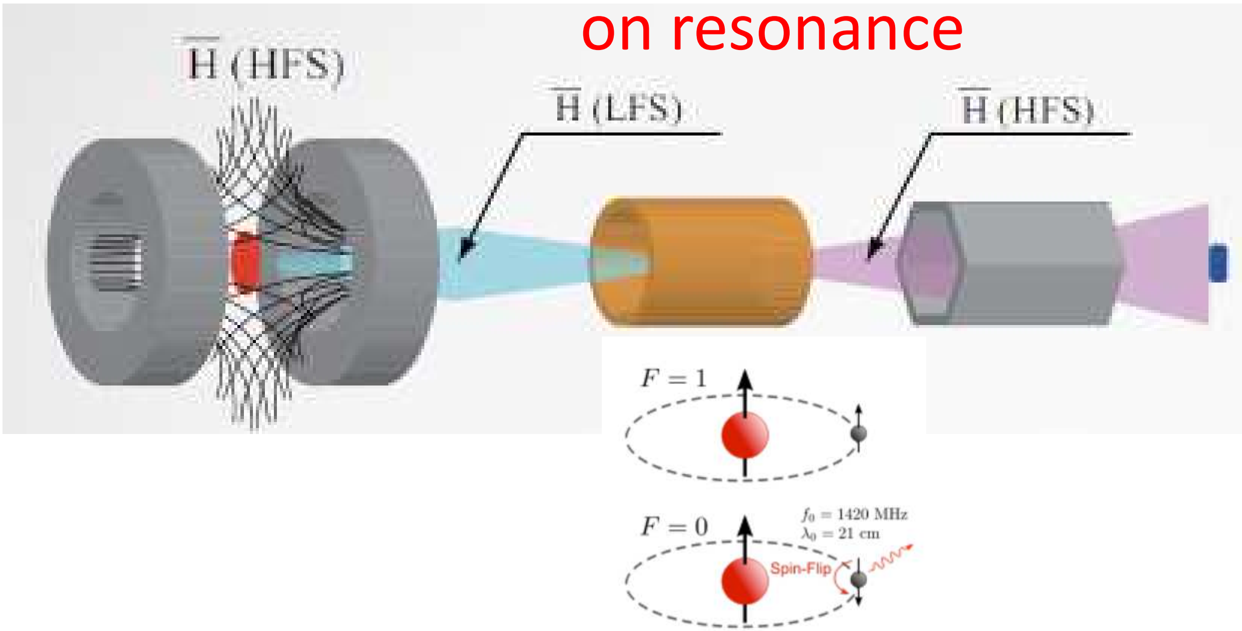
select spin state

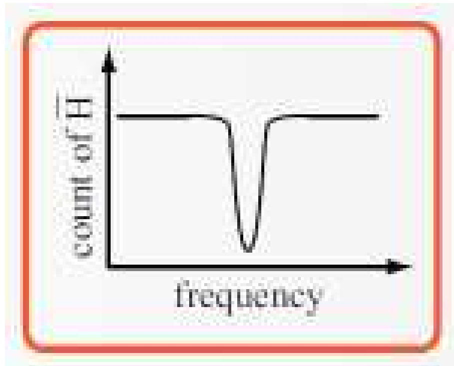
HFS-states: de-focused
LFS-states: focused

B and **E** axially symmetric

Scheme of the measurement

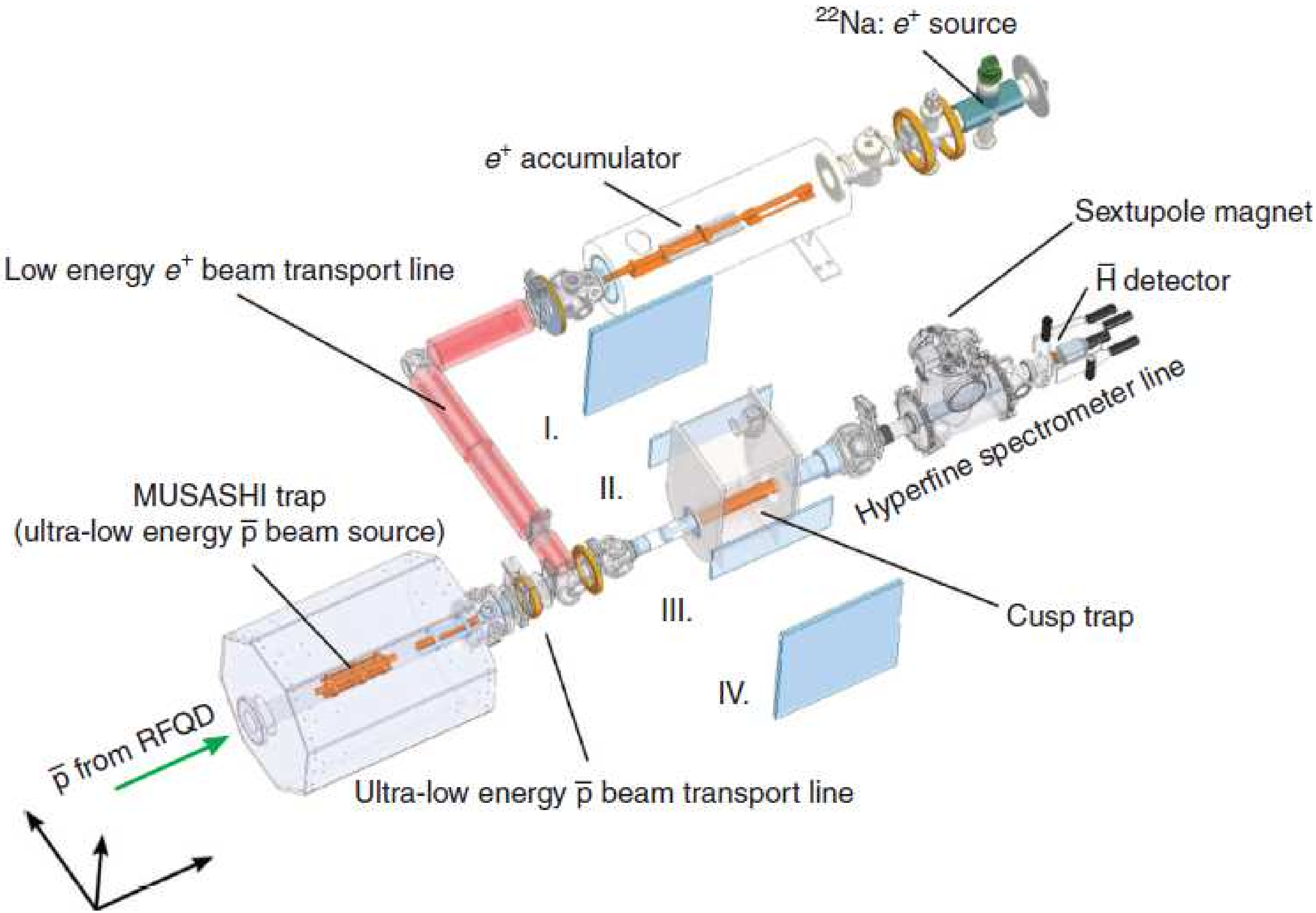




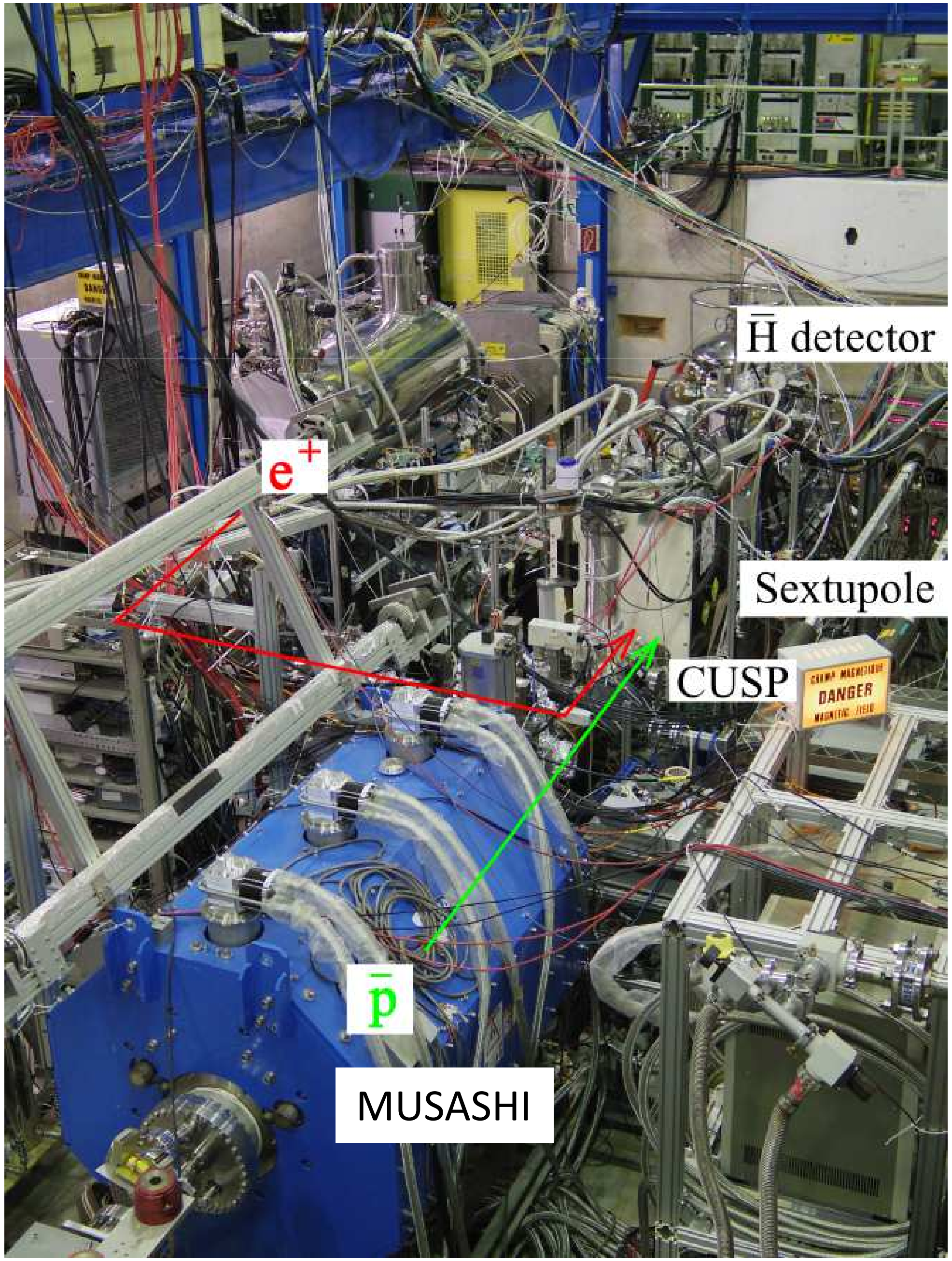


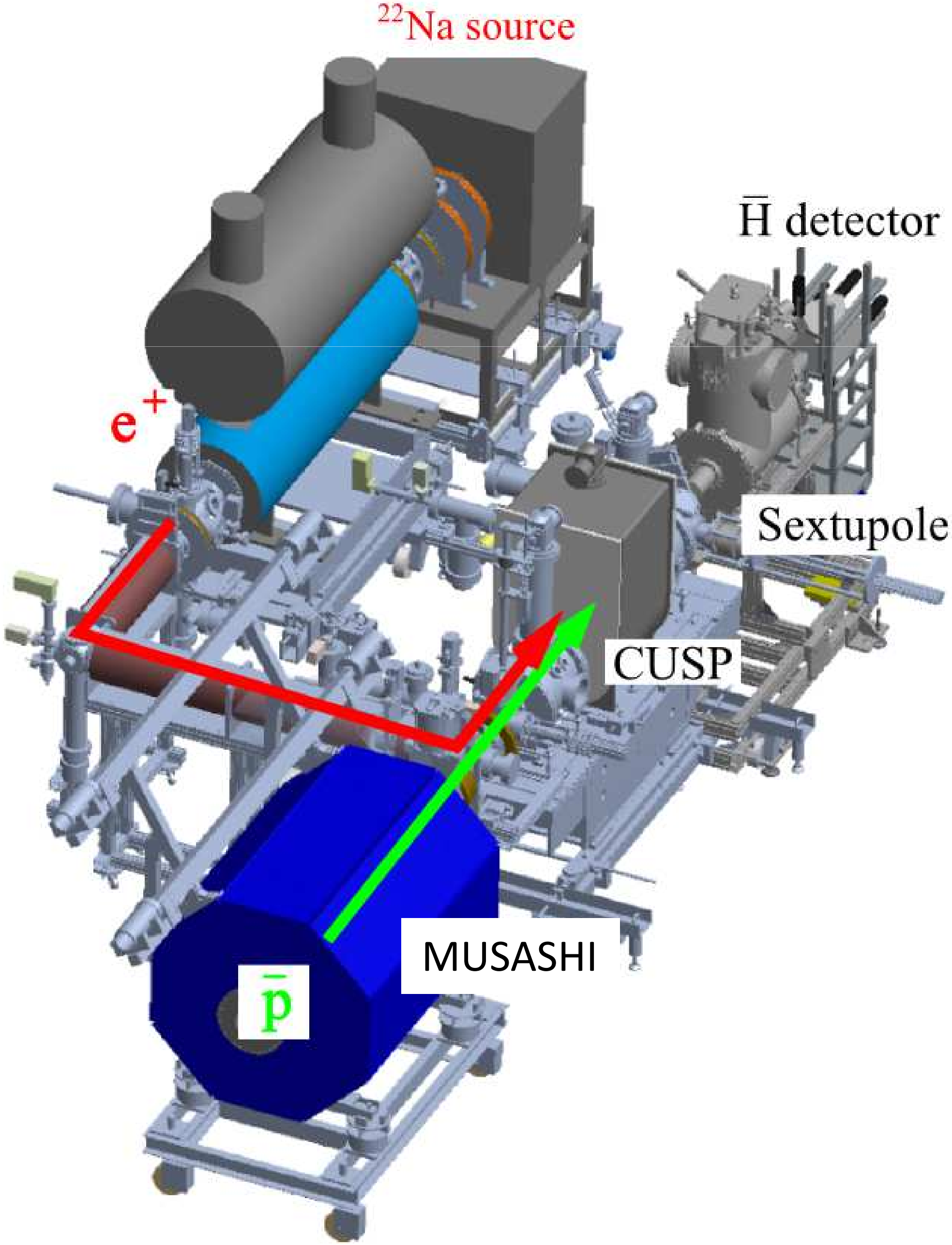
“Disappearance Mode”

experimental set-up

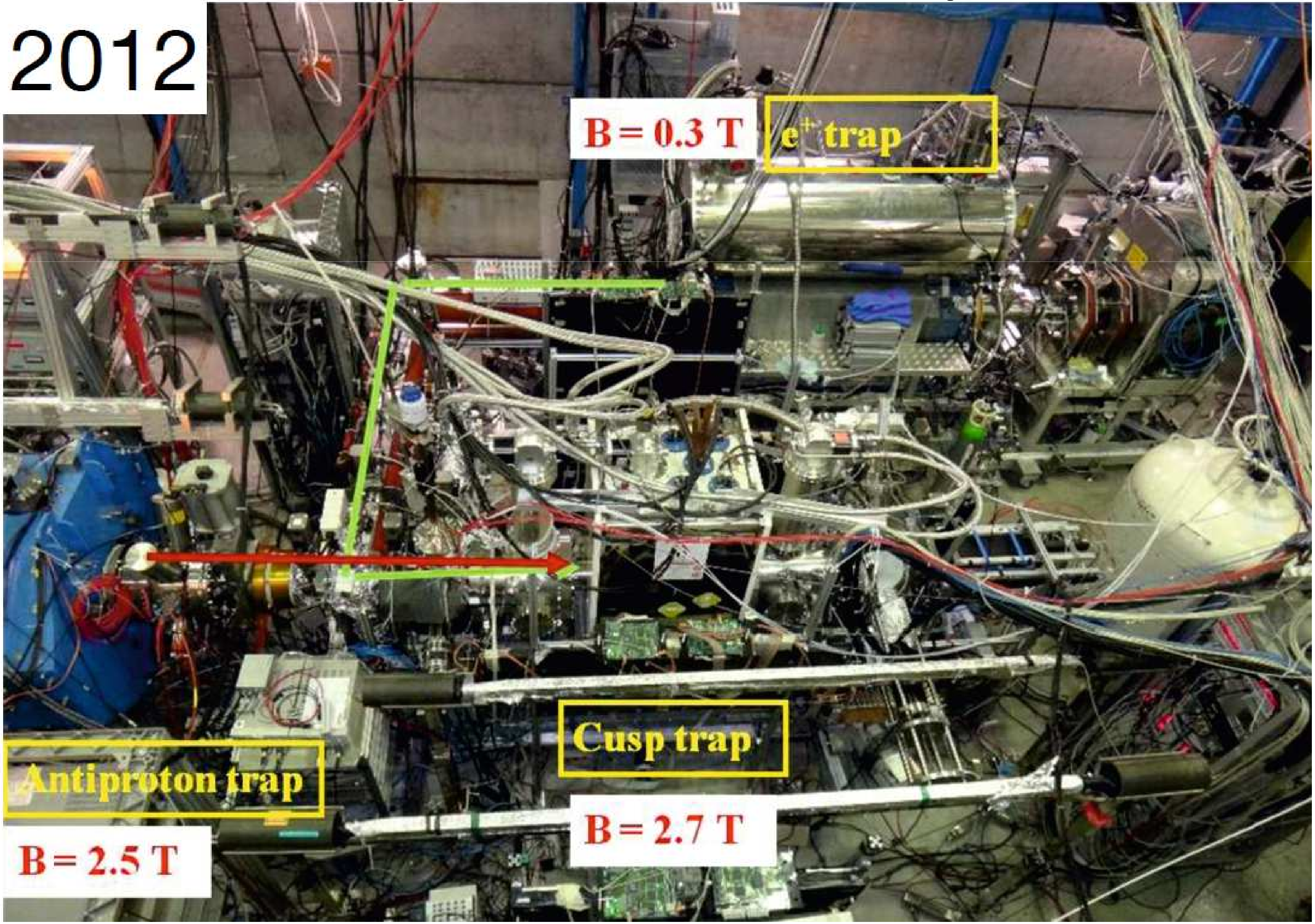


experimental set-up





experimental set-up



ASACUSA – CUSP TRAP

- Hbar production in 2010
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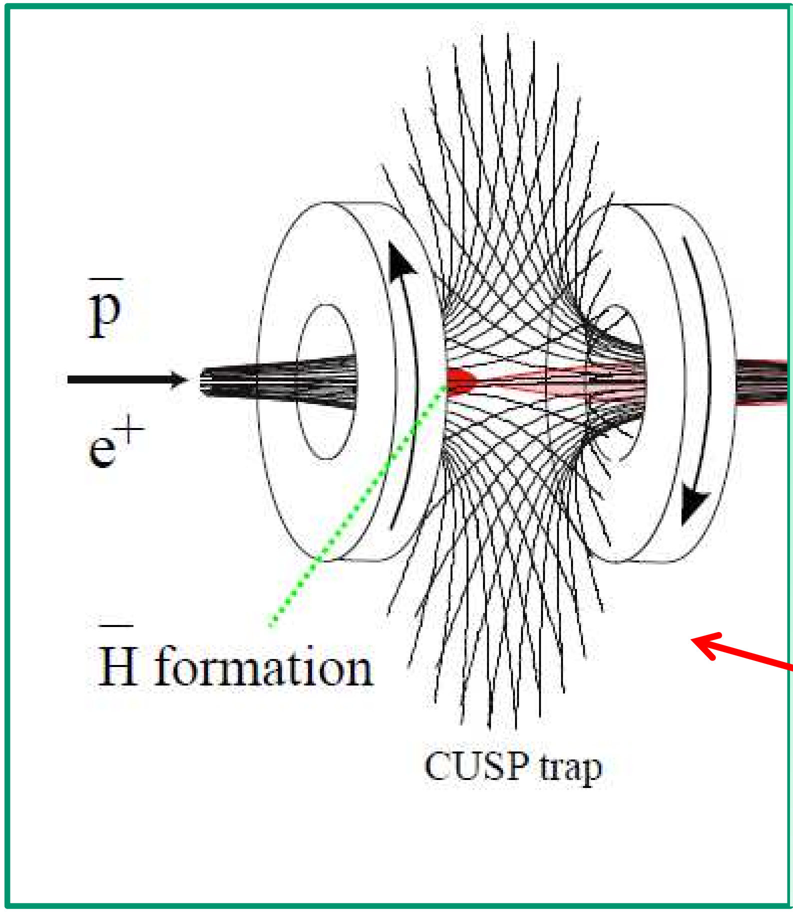
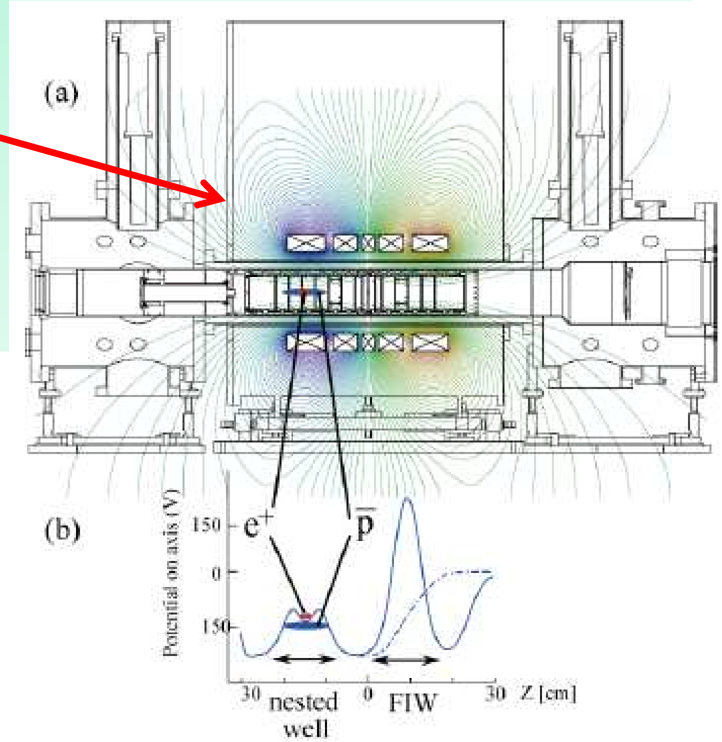
Antihydrogen formation





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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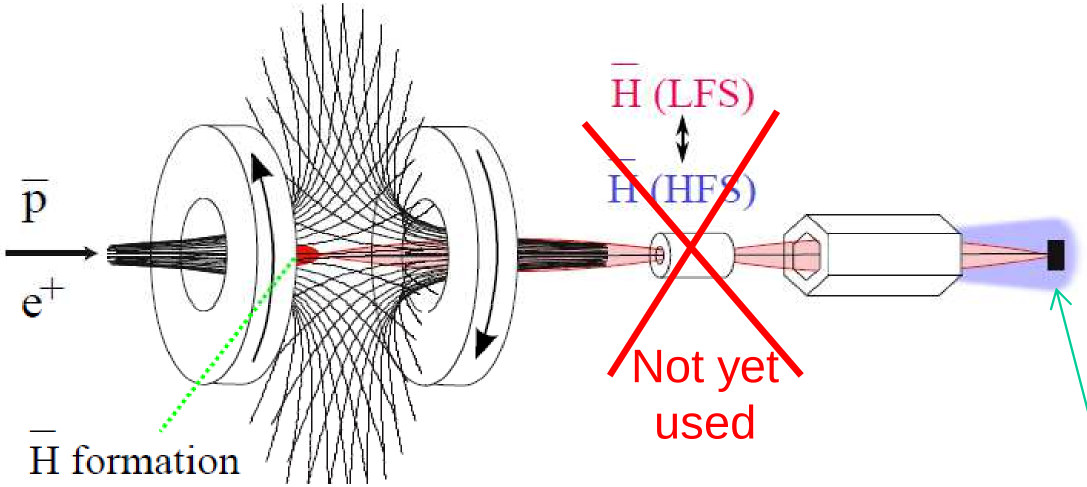
Antihydrogen beam



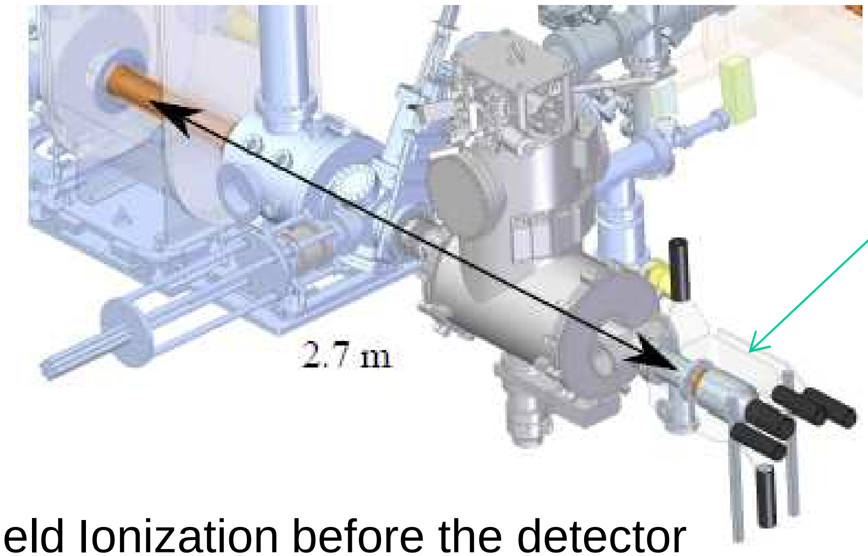
nature COMMUNICATIONS

ARTICLE

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]

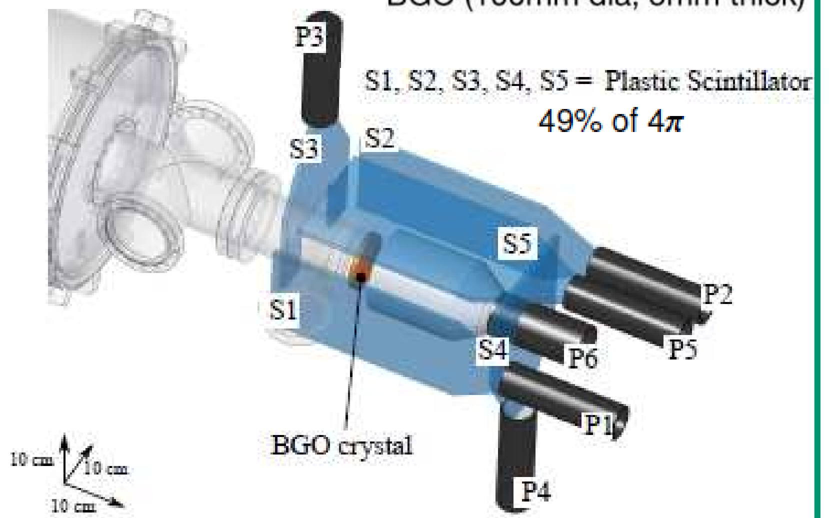


Field Ionization before the detector

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

Hbar detector

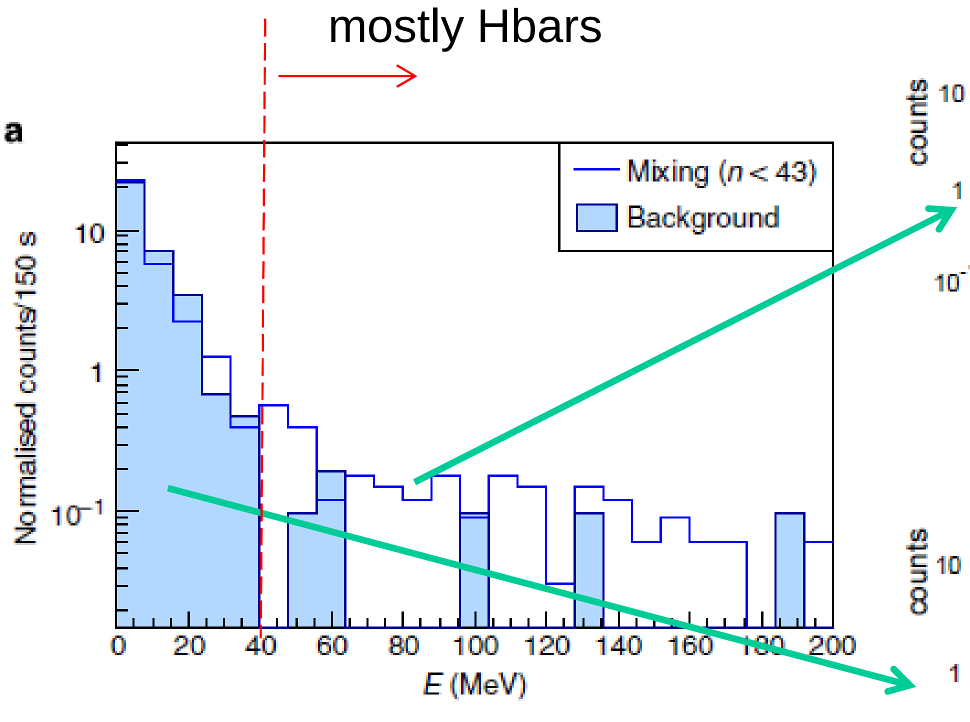
plastic +
BGO (100mm dia, 5mm thick)

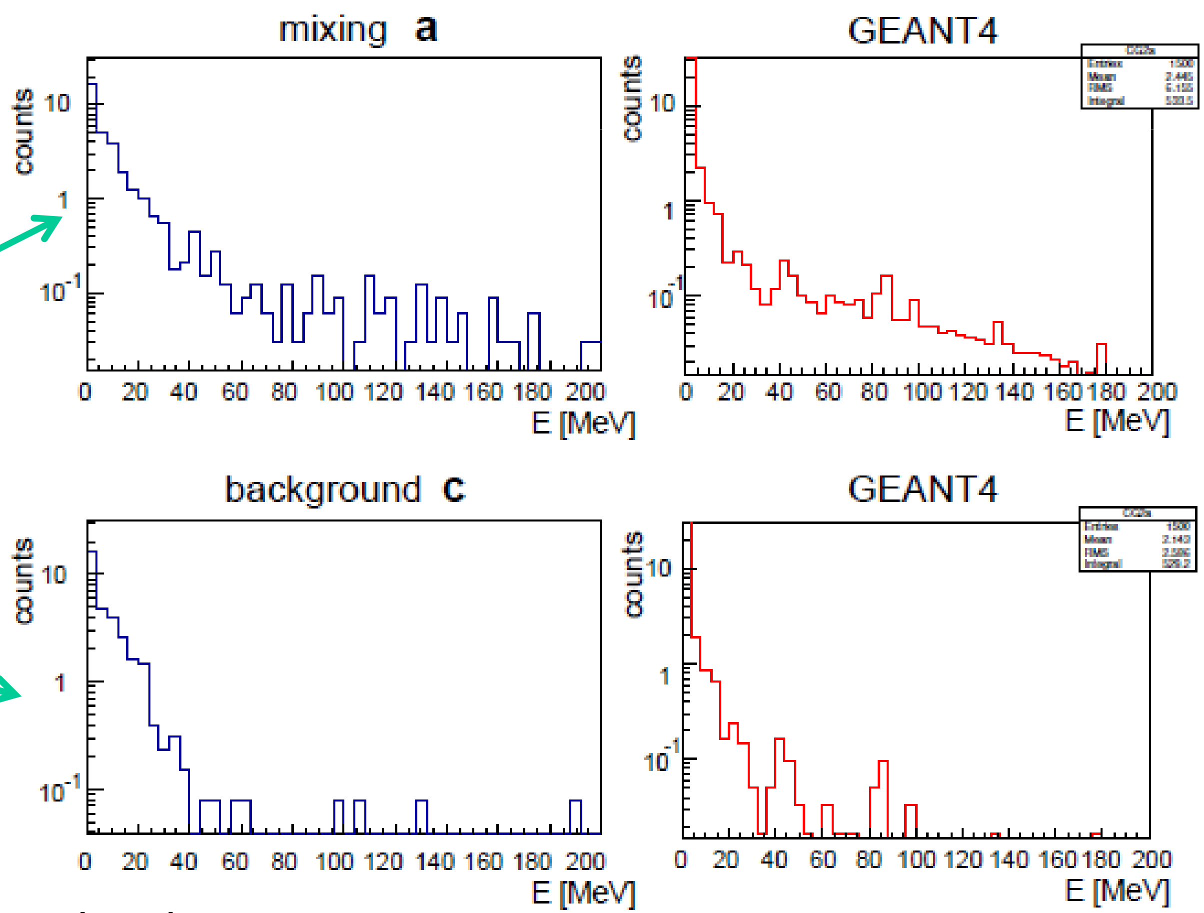


BGO measures energy deposition by Hbar annih.

coincidence: BGO AND (>1 S)

Energy deposition in the BGO





Unshaded histo → pbar-e+ mix

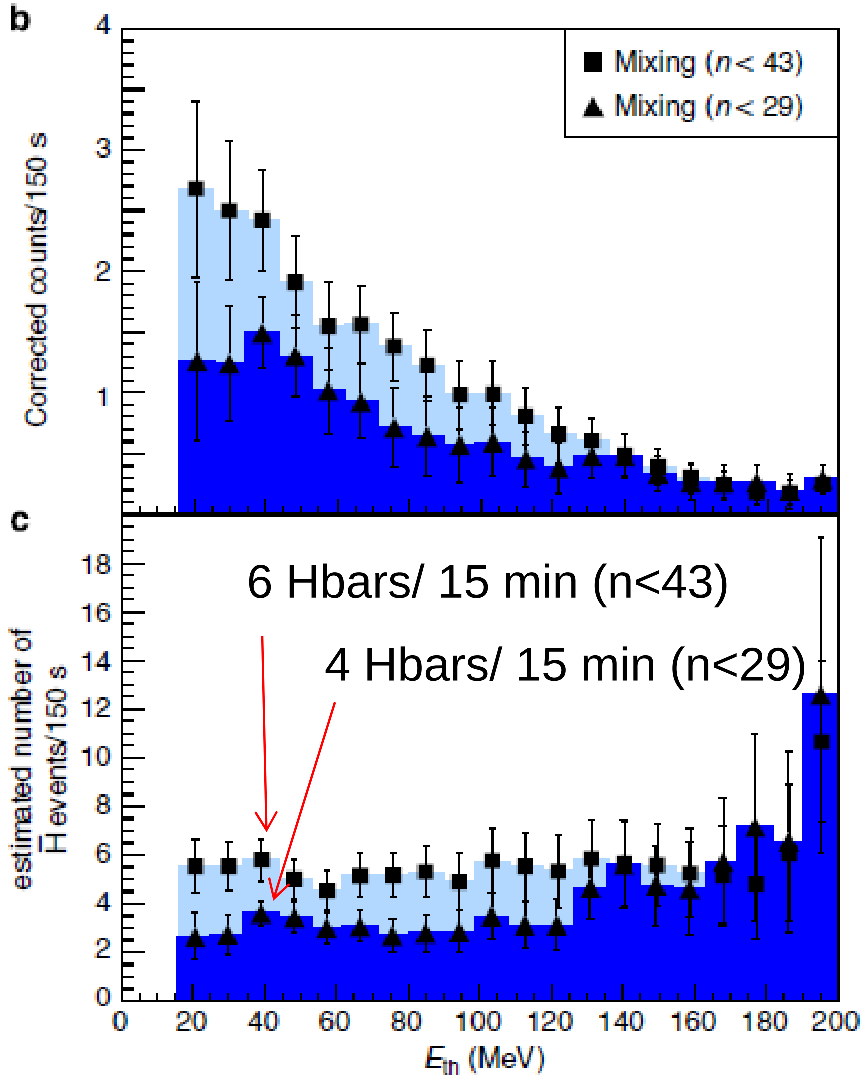
Shaded histo → pbar-e- mix (background run)

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

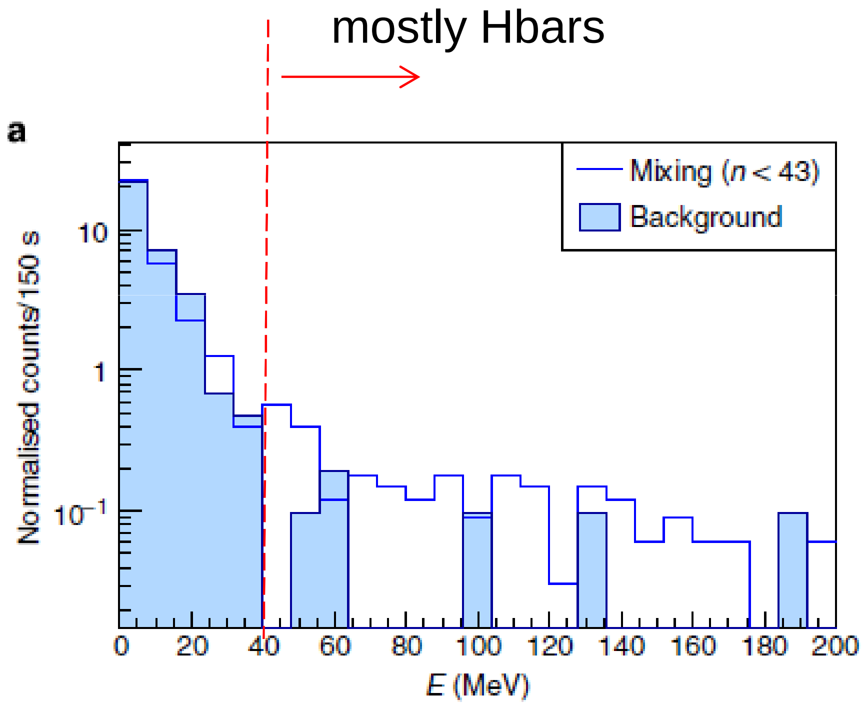


Table 1 | Summary of antihydrogen events detected by the antihydrogen detector.

	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	—

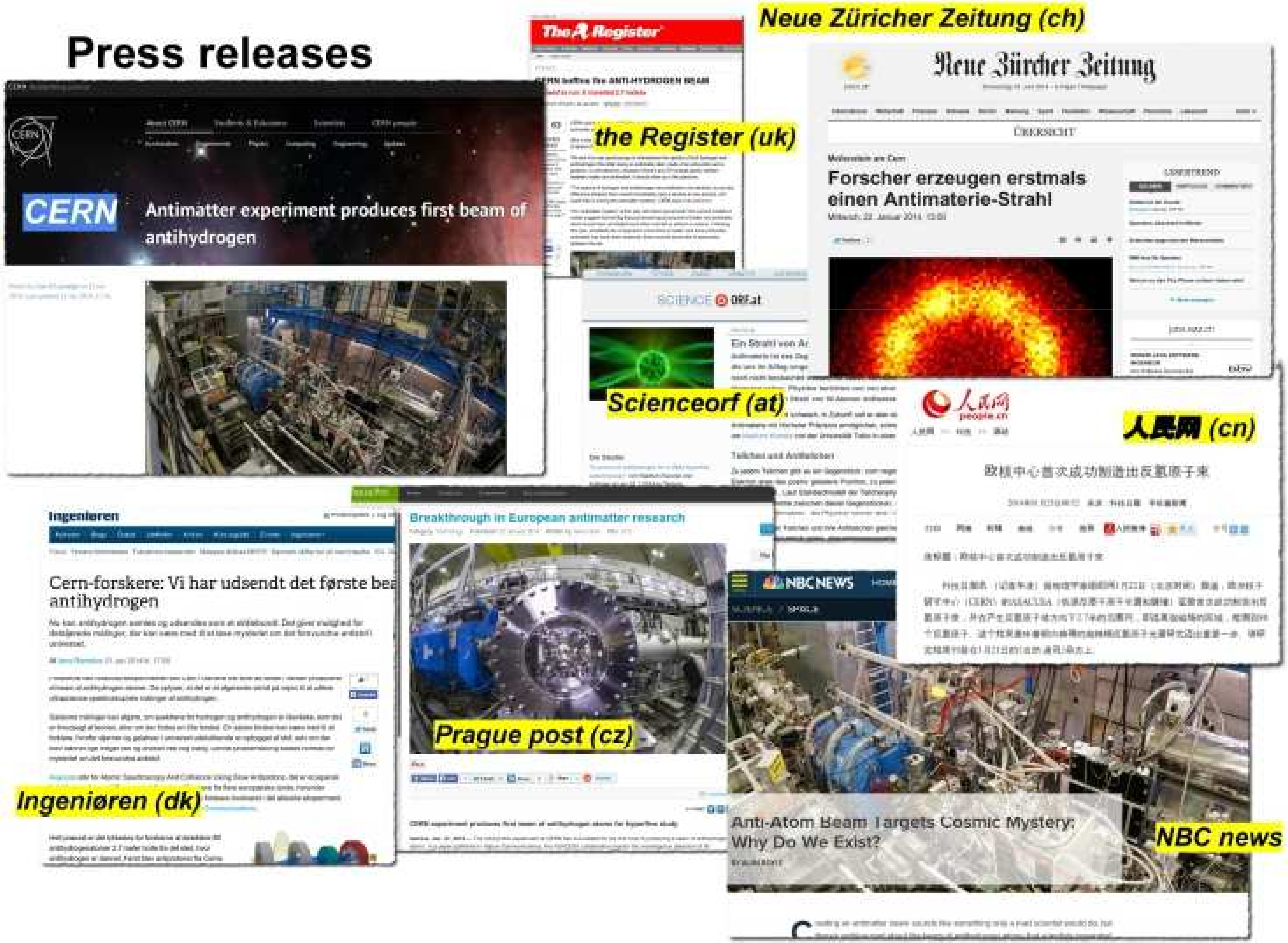
Antihydrogens (n<43) detected with 5 σ significance 2.7 m far from their production region

➔ Antihydrogen beam has been produced

25 Hbars/hour (n<43)

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

Press releases



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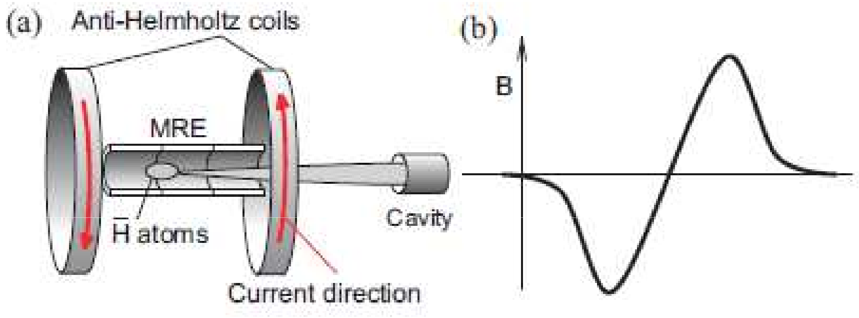
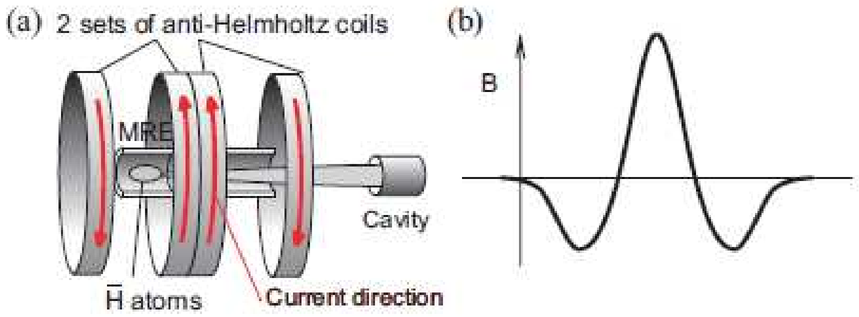
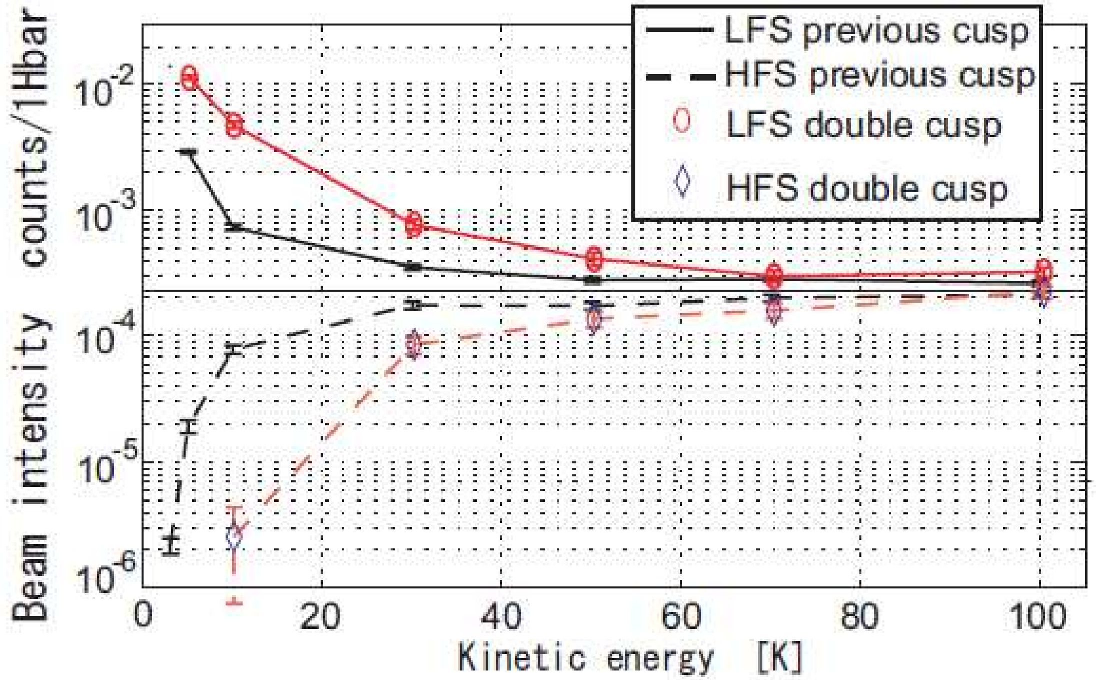
Recent improvements

-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 field ionizer
-Installation and successful operation of a new Hbar 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

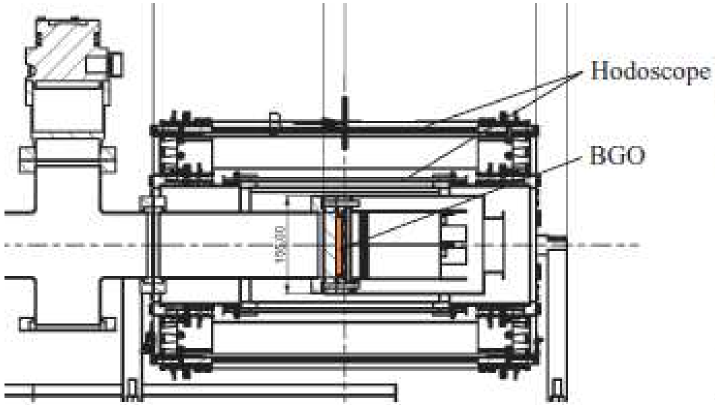


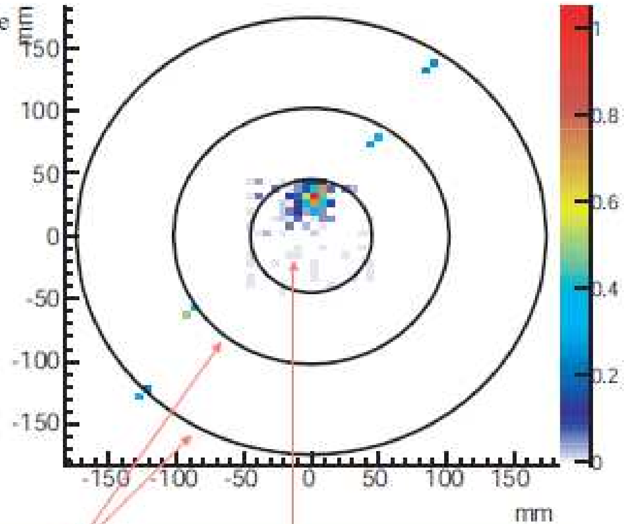


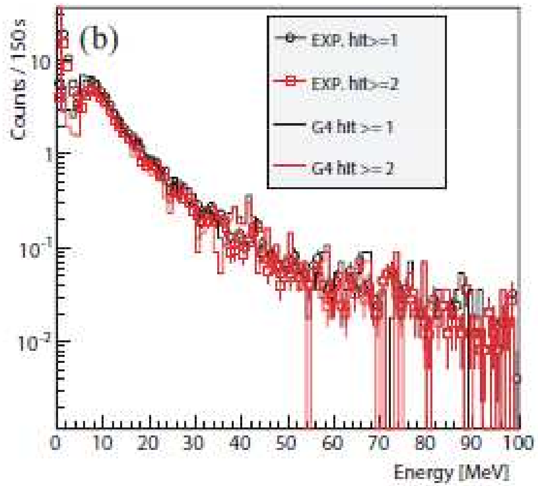


Higher Hbar beam intensity

new antihydrogen detector







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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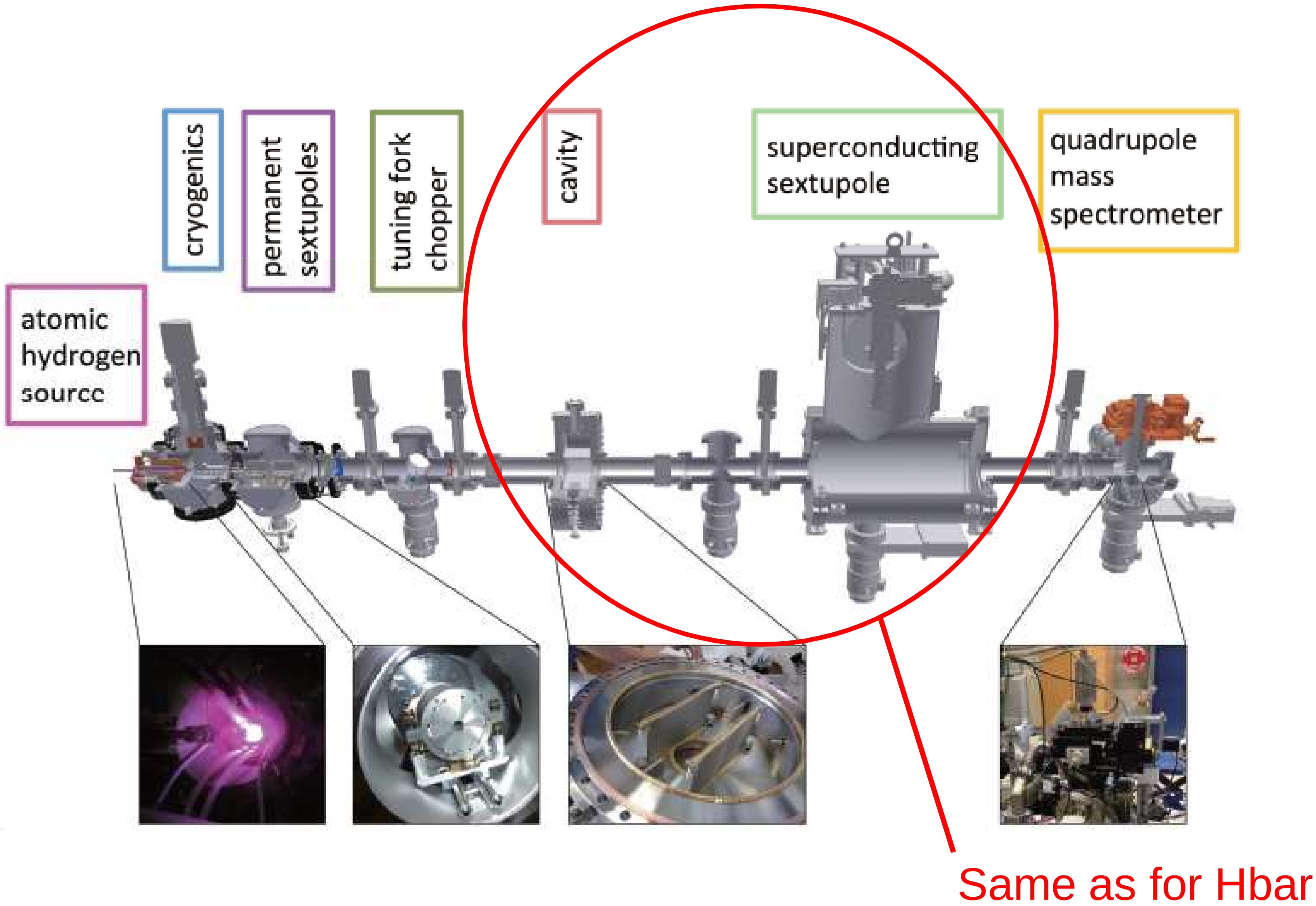
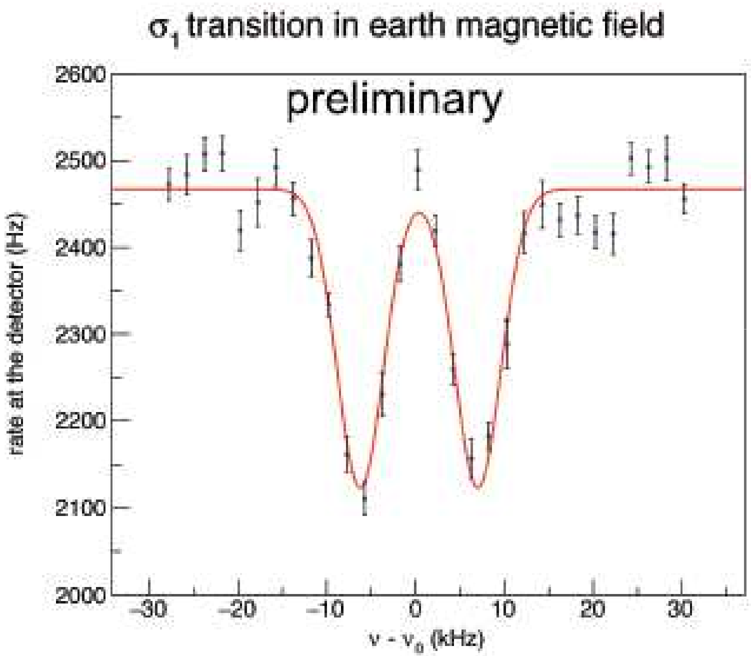
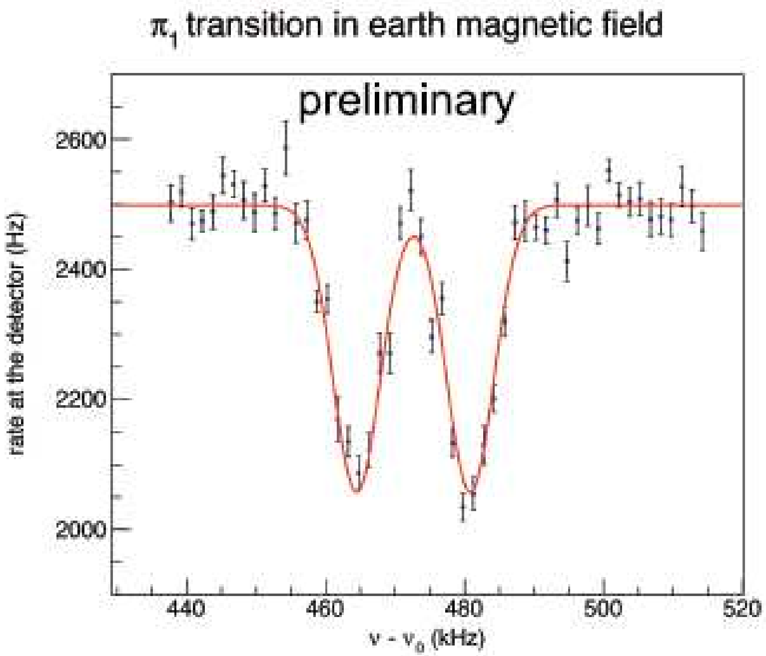
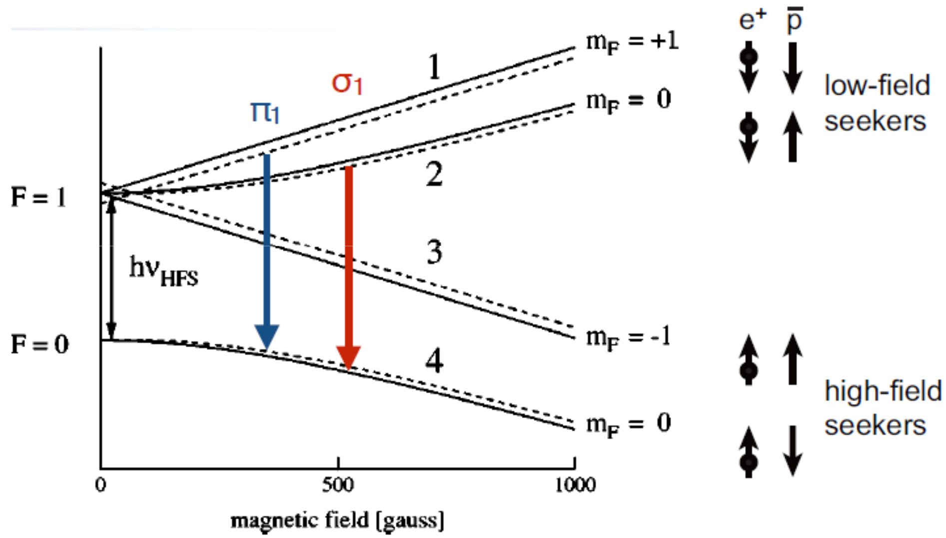
The hydrogen setup



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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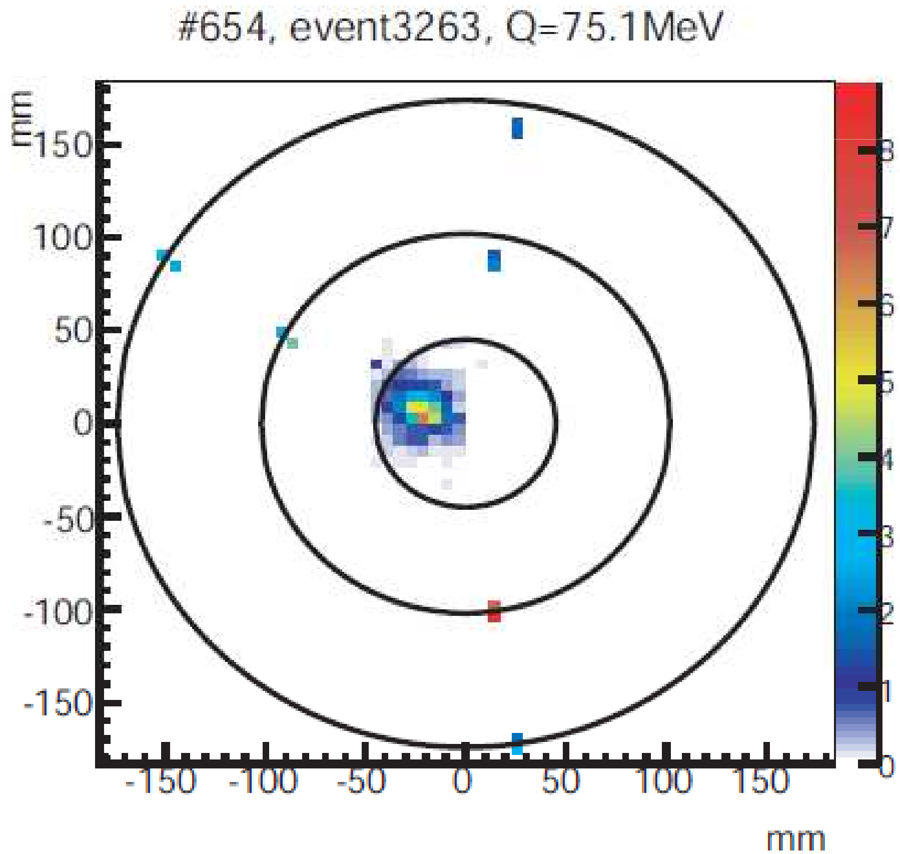
2014 Hbar data analysis

- in progress

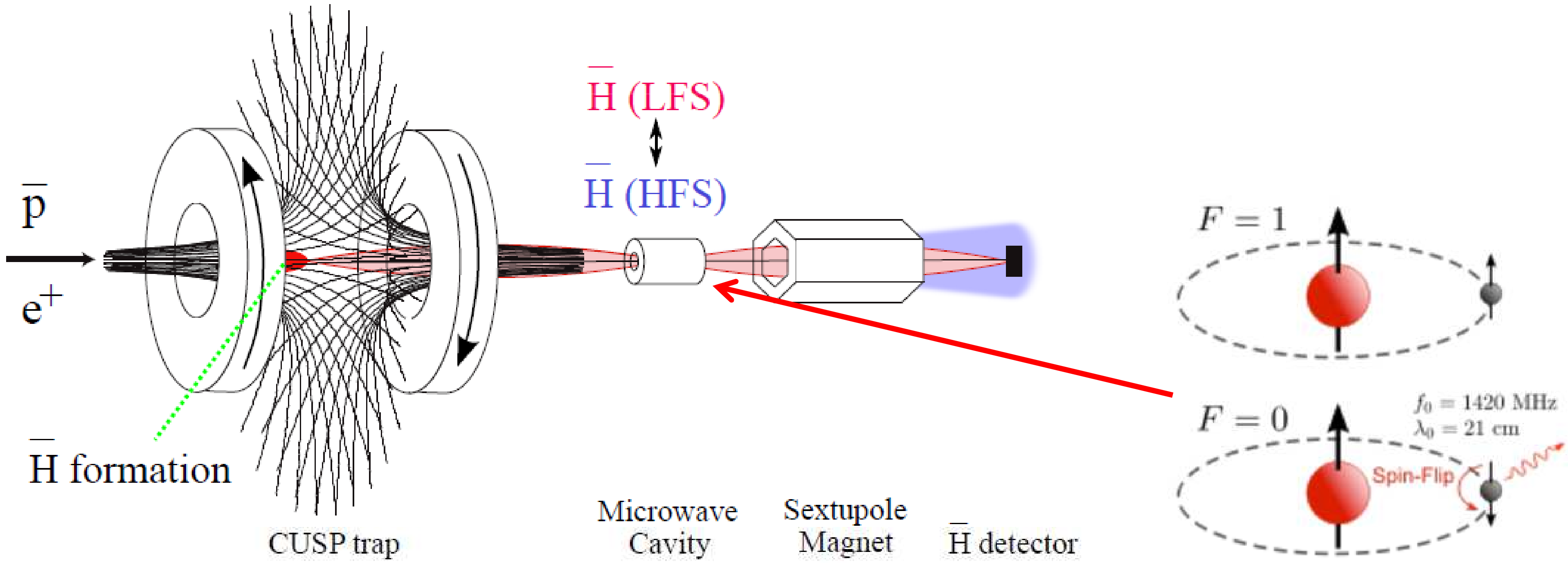


Hbar (n<12) candidate observed @3.4 m

Next steps

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

Perform the measurement

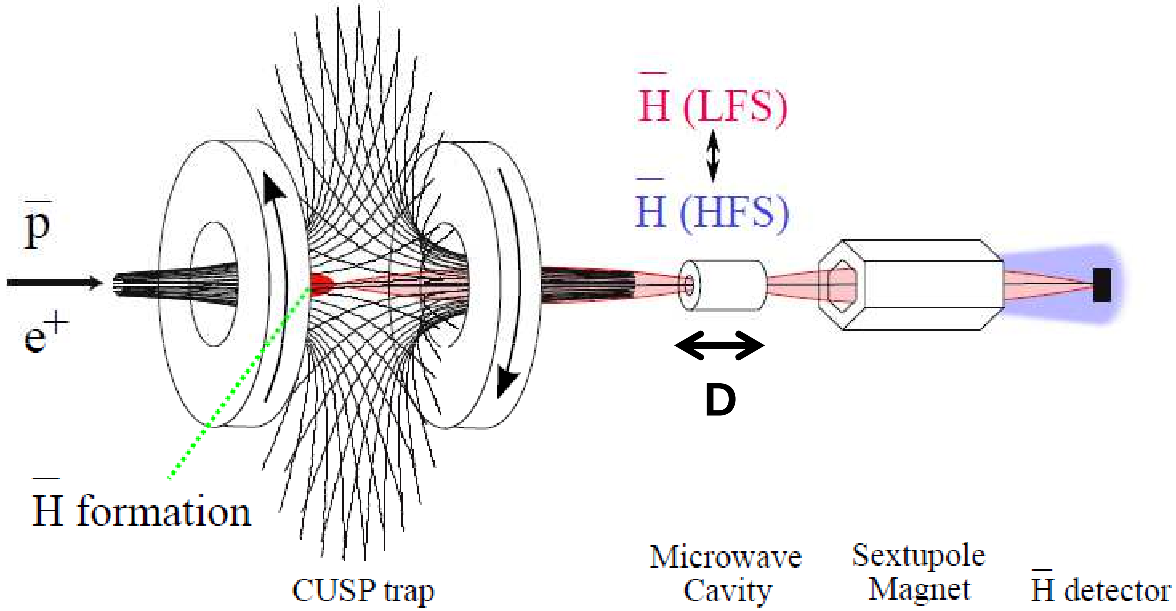


Achievable resolution:

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

Expectation

Rabi method



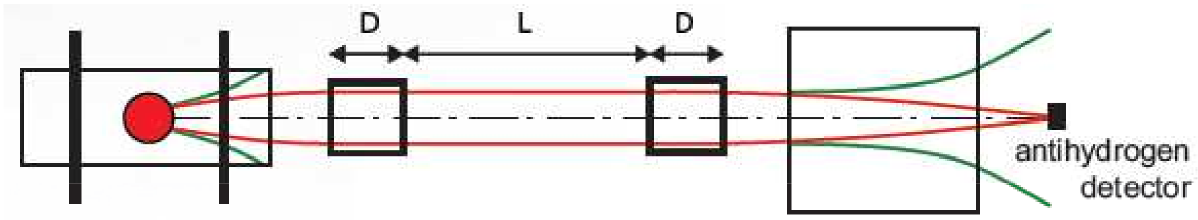
D=10 cm, v=1 km/s (100K)
1/T=10 kHz → linewidth resolution $\delta\nu$ (FWHM) = 0.8/T → $\delta\nu$ / ν =8x10^{-6}
→ Resonance center resolution = 10^{-7}

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):



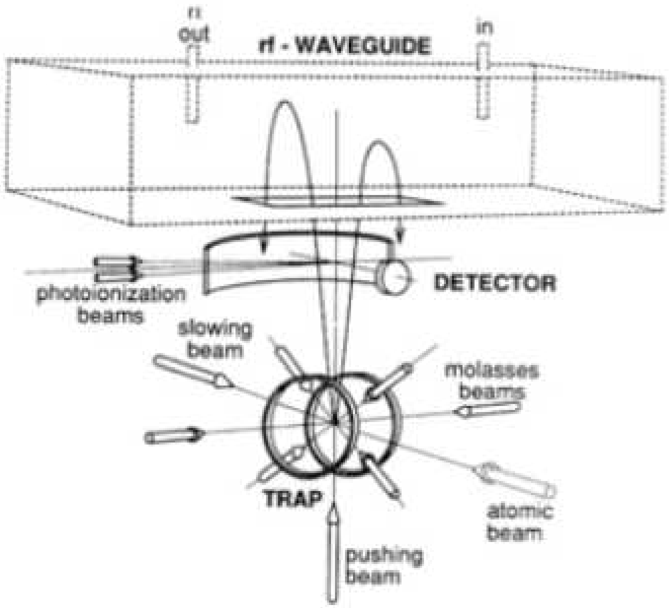
Linewidth reduced by D/L

Antihydrogen fountain:

-trapping and laser cooling

- Ramsey method with L=1m

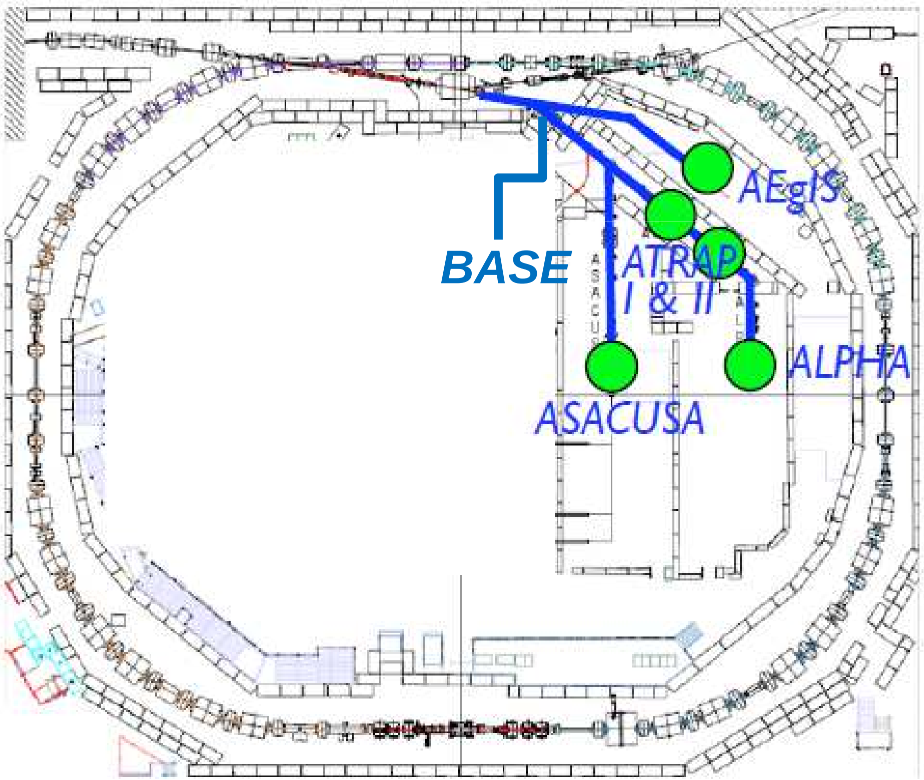
Δf ~3 Hz, $\Delta f/f \sim 2x10^{-9}$



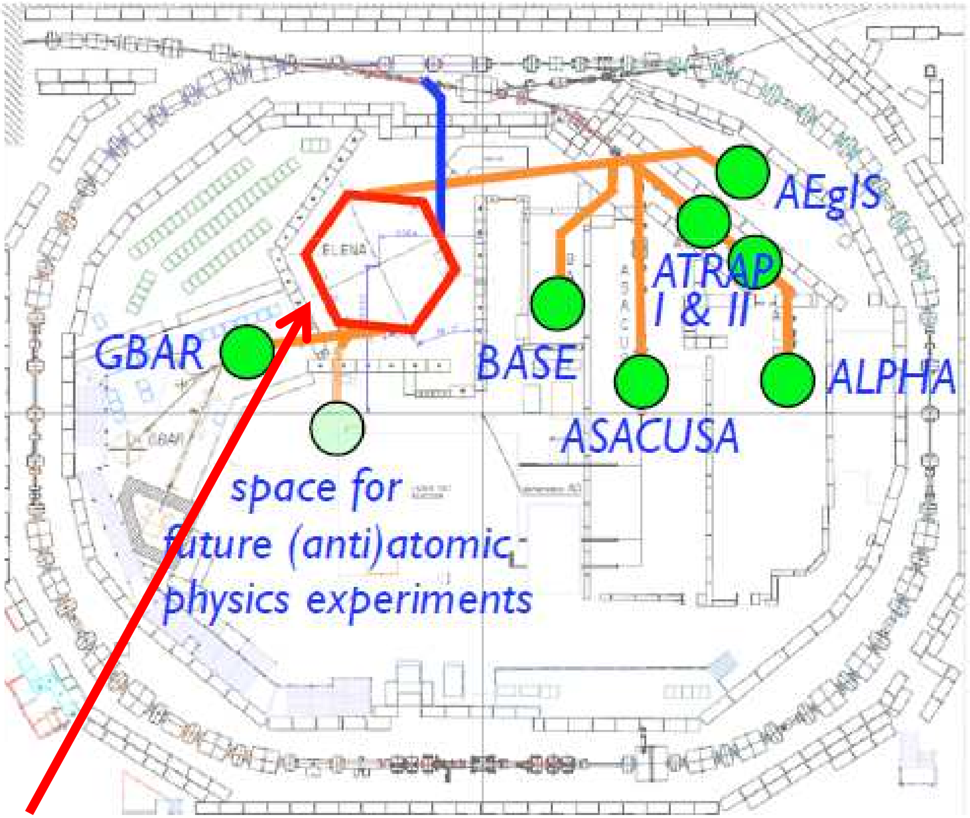
<-- AEGIS

Future

2015



2017 →



ELENA decelerator:

5.3 MeV → 100 keV

x 100 pbars trapping efficiencies

4 experiments can run in parallel

3. Collision experiments

Nuclear Physics @ AD

p̄-A annihilations σ

- @ 5.3 MeV (Ni, Sn, Pt)

PLB 2011 & NIMA 2013

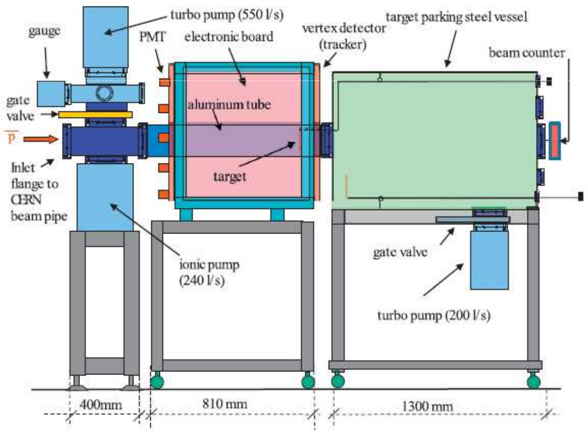
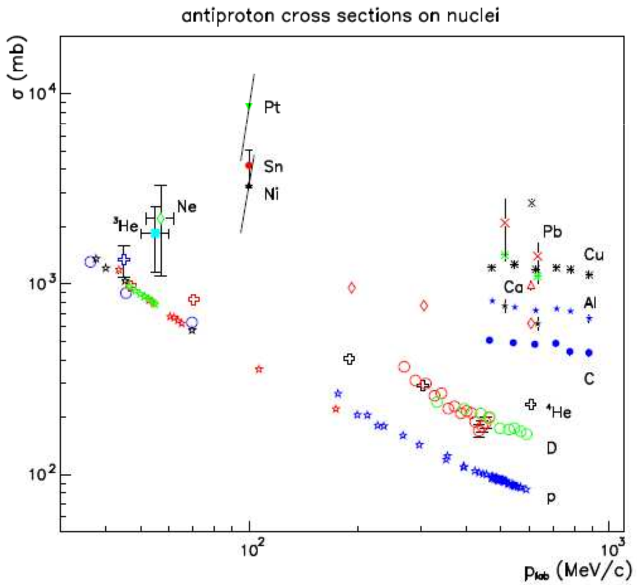
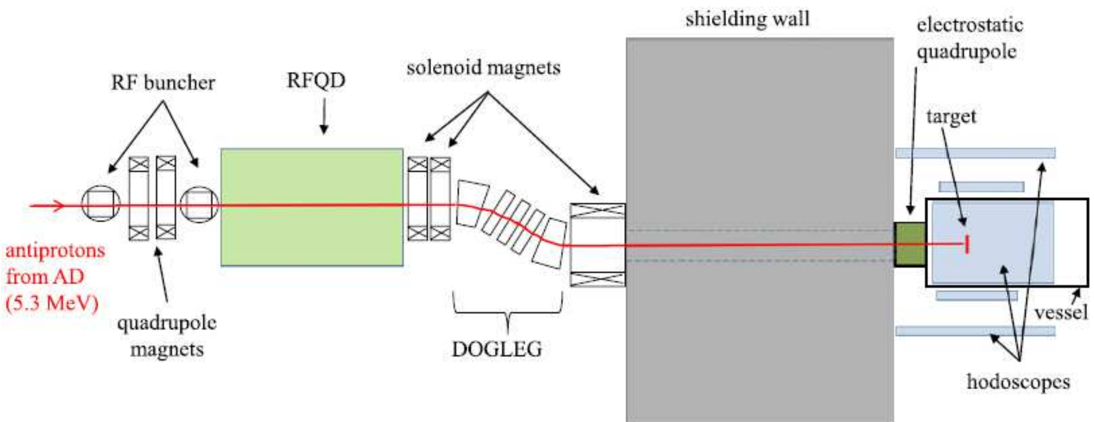


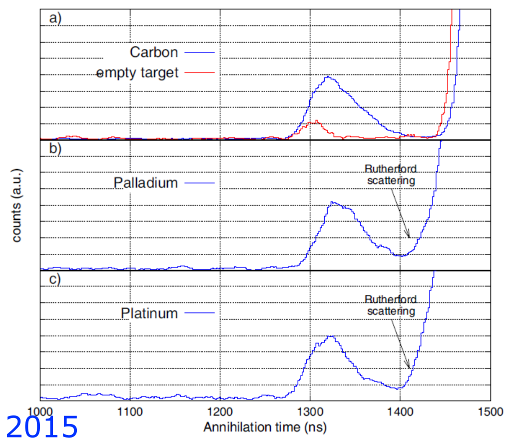
Fig. 1. Experimental setup.



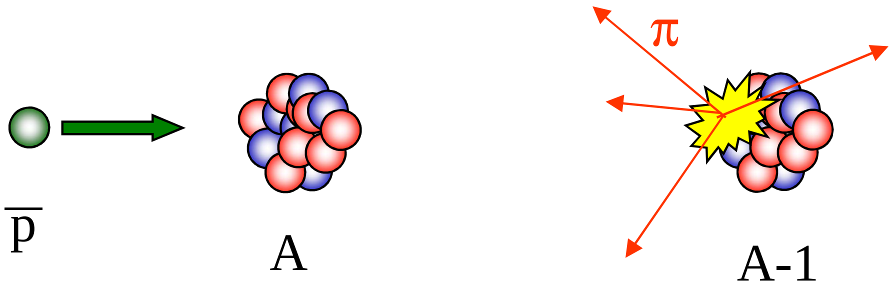
- @ 130 keV (C, Pd, Pt)

EPJ+ 2012





Antiproton annihilations σ at 5.3 MeV



Physics motivations

Some topics of interest:

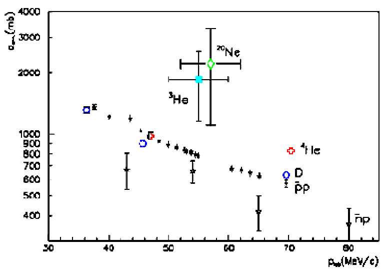
- Cosmology: matter-antimatter asymmetry in the Universe

  (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.)

- Search of resonances
- Determine the interaction parameters
- Probe the external region of nucleus

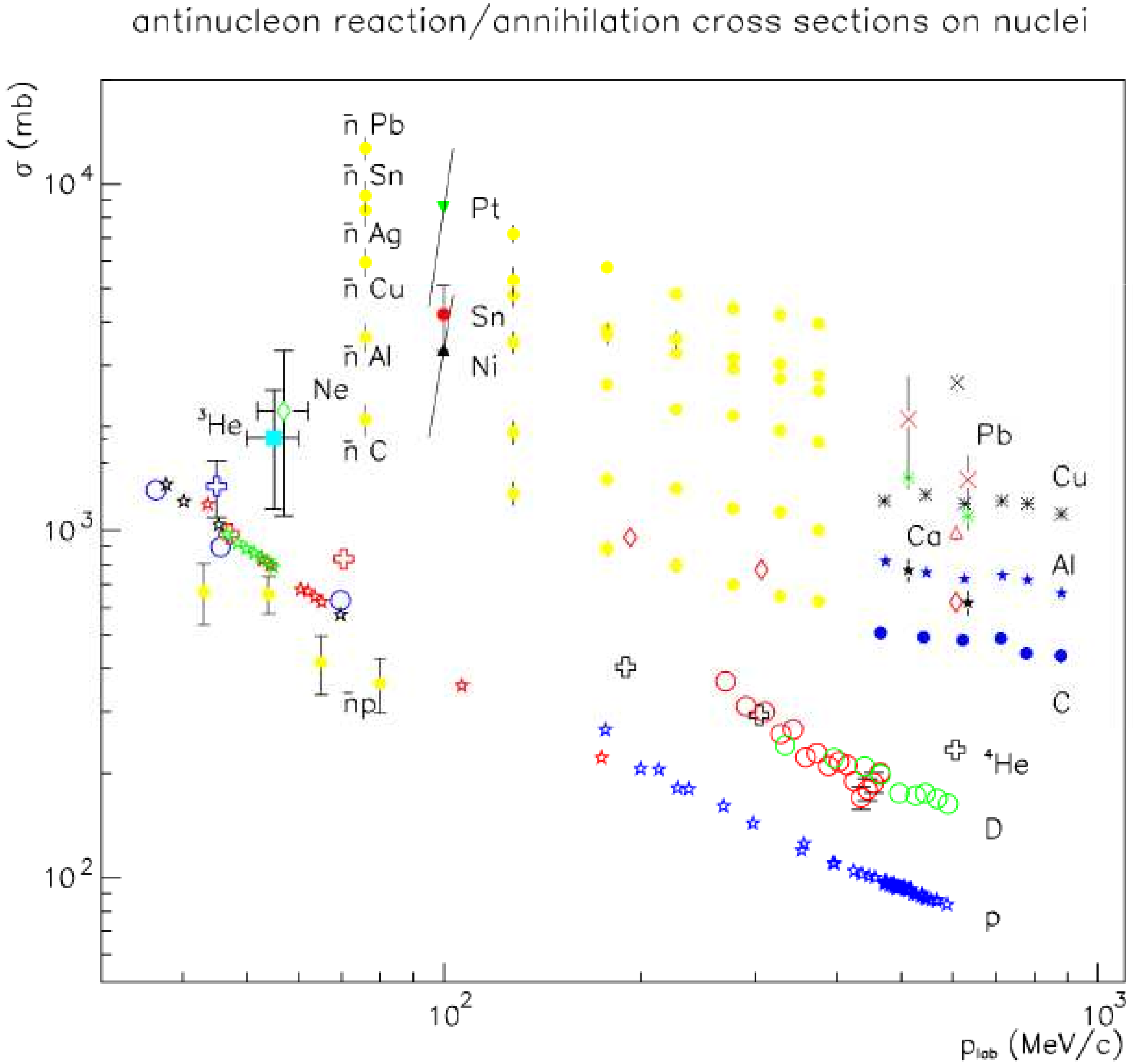
  (both potential models and phenomenological analyses state that the annihilations occur in a thin region placed just outside the nuclear volume: neutron/proton ratio or the extraction energy of the peripheral nucleons can be determined)

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



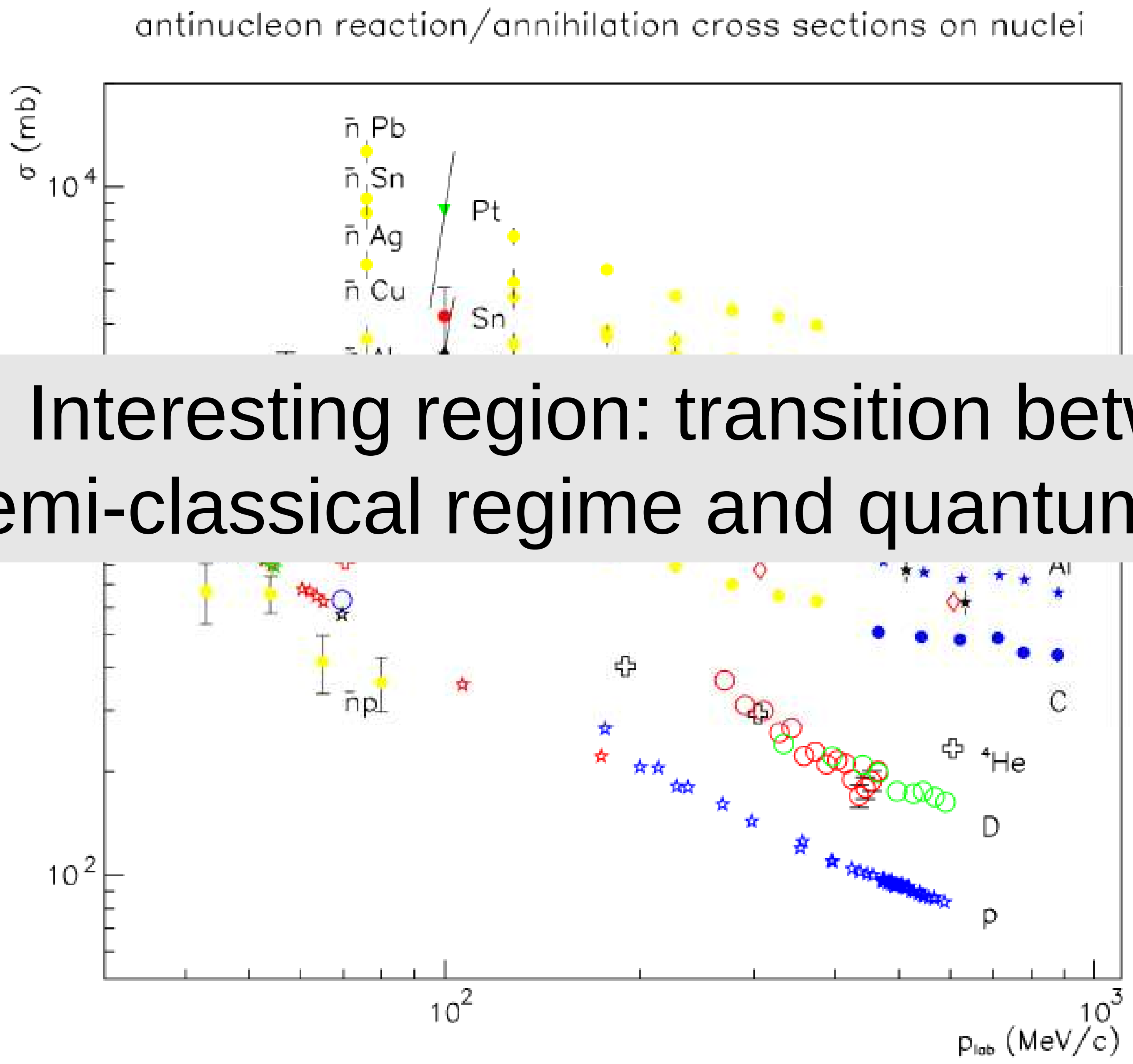
- Reversed nbar to pbar behaviour for σ_{ann} at 5 MeV on Sn
- …the region below 0.5-1 MeV is completly unexplored

Existing data



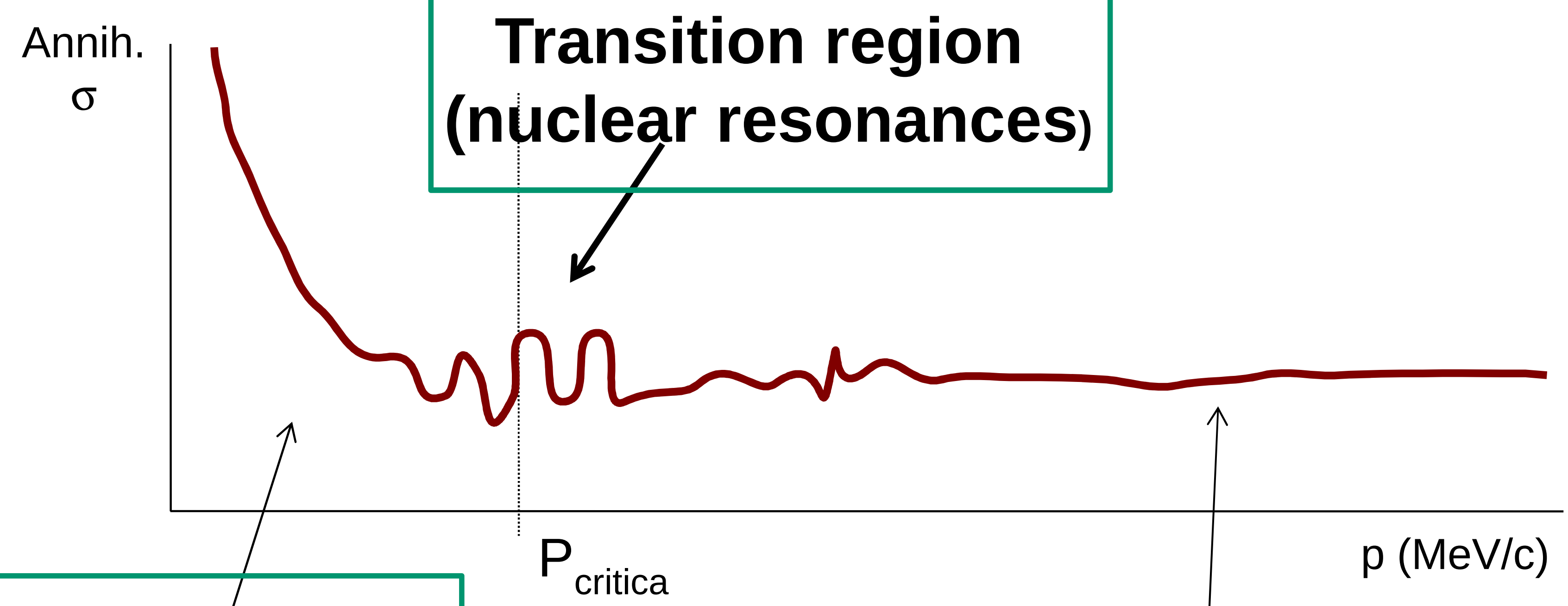
Nbar data in yellow

Existing data



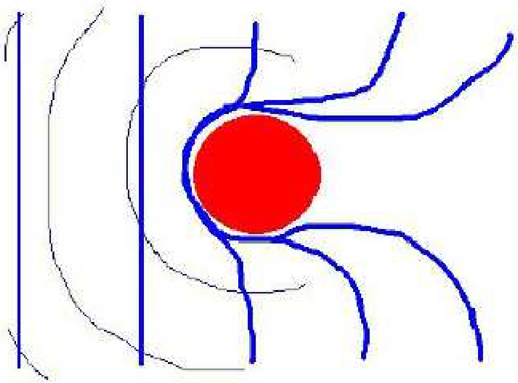
Nbar data in yellow

Interesting region: transition between semi-classical regime and quantum regime



For nbar;
$\sigma(p) = A + B/p$
For pbar;
$\sigma(p) = A + B/p + C/p^2$

Quantum regime



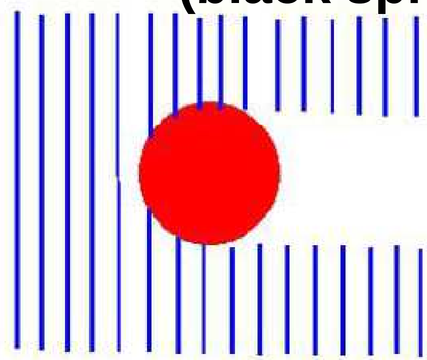
Wavelength ≥ target size

l

• 10-20 MeV/c for heavy nuclei
• 200 MeV/c for light nuclei

$\sigma(p) =$ cost

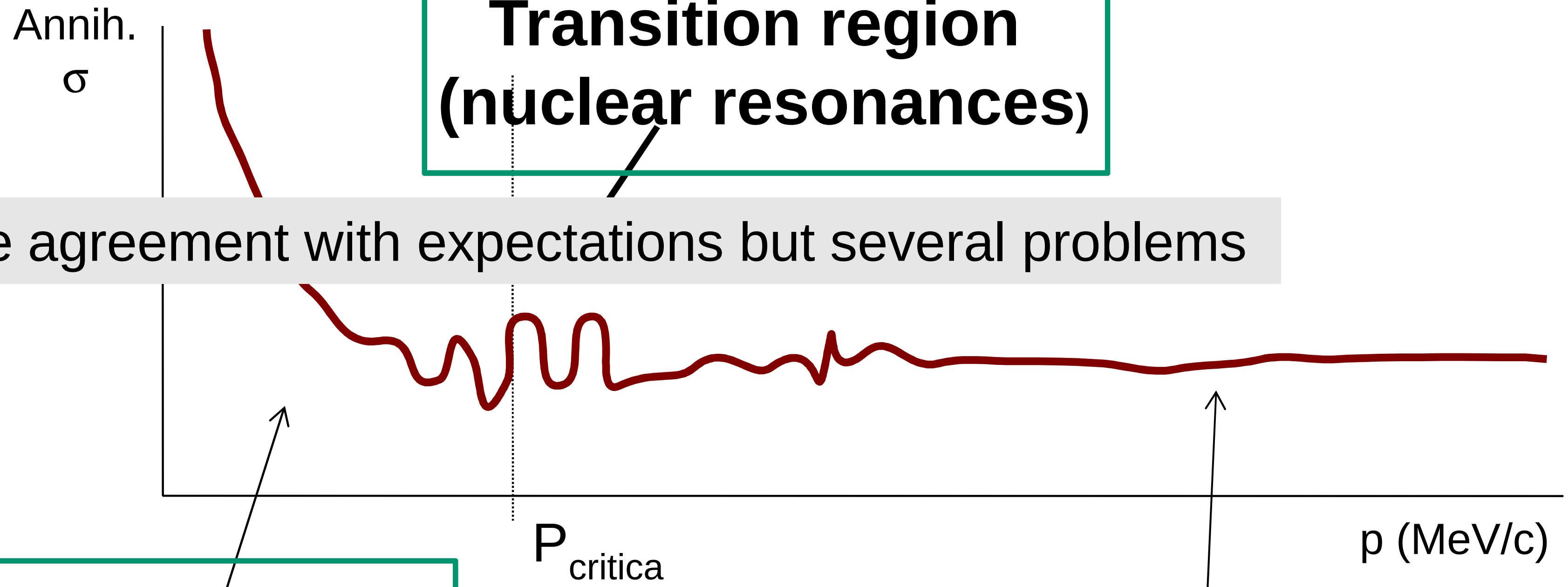
Semi-classical (black sphere)



Wavelength << target size

Transition region (nuclear resonances)

Some agreement with expectations but several problems



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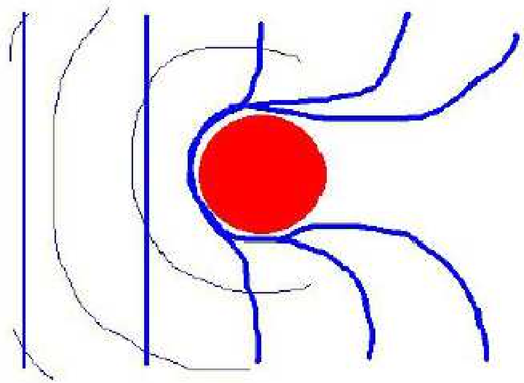
Quantum regime



Wavelength ≥ target size

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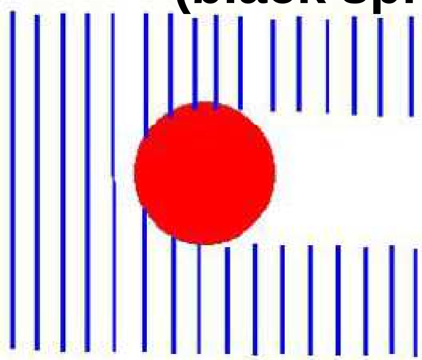


Wavelength << target size

1° problem: any resonance?

No resonance detected with antinucleons

Resonance in nbar-p?

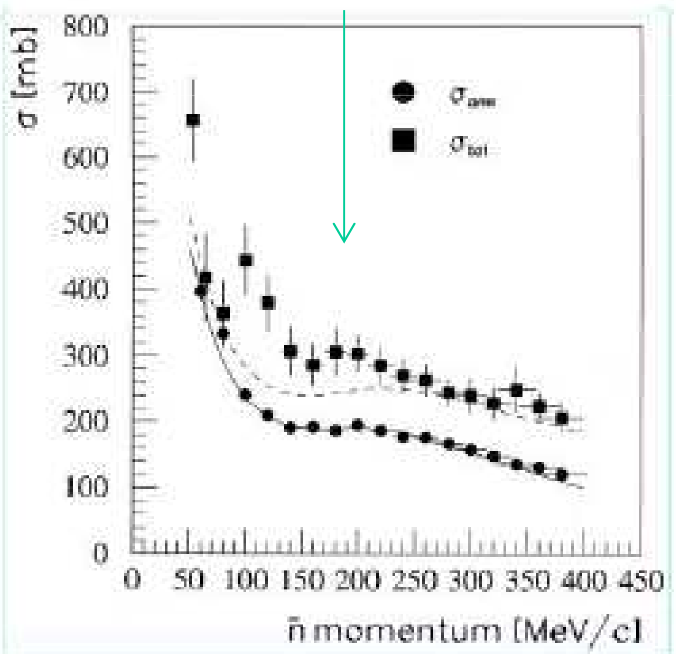


Fig. 4. Experimental values of the total (■: present work) and annihilation (●: Ref. [8]) $\bar{n}p$ cross sections. The solid curve represents the calculation of $\sigma_{ann}(\bar{n}p)$ performed in Ref. [8], the dotted one the calculation of $\sigma_T(\bar{n}p)$ by using the same parameters.

Resonance only subthreshold in e+e-

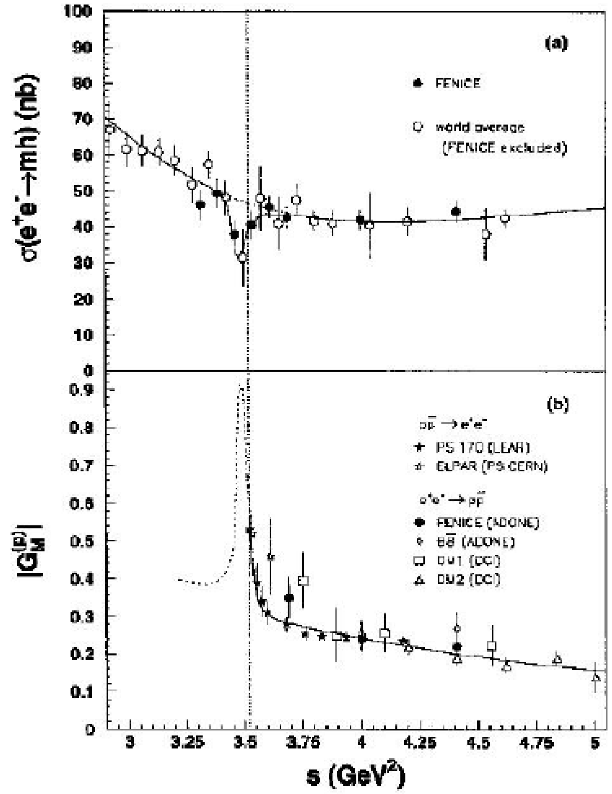
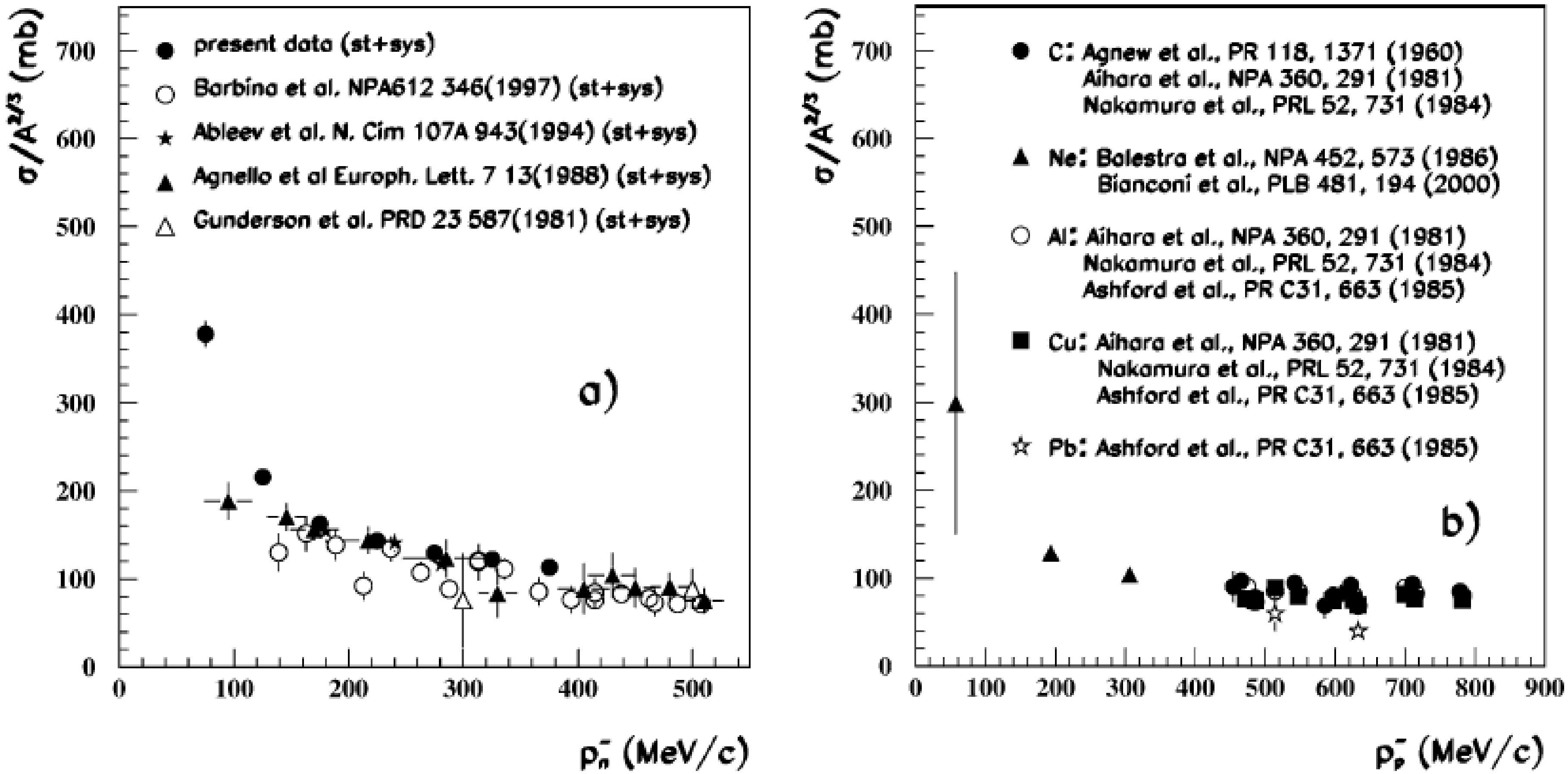


Figure 1.7: (a) Total $e^+e^- \to$ *hadrons* cross section, systematics is also included in the error bars; (b) proton time-like Form Factor. The solid curves are the best fit assuming the interference with a resonance below the $\bar{N}N$ threshold (the dashed curve in (a) is the expectation without). From [16].

2° problem: annih. sigma too high

At 300-400 MeV/c annih. sigma for pbar and nbar are similar (as expected) but are 2 times what expected by optical potential



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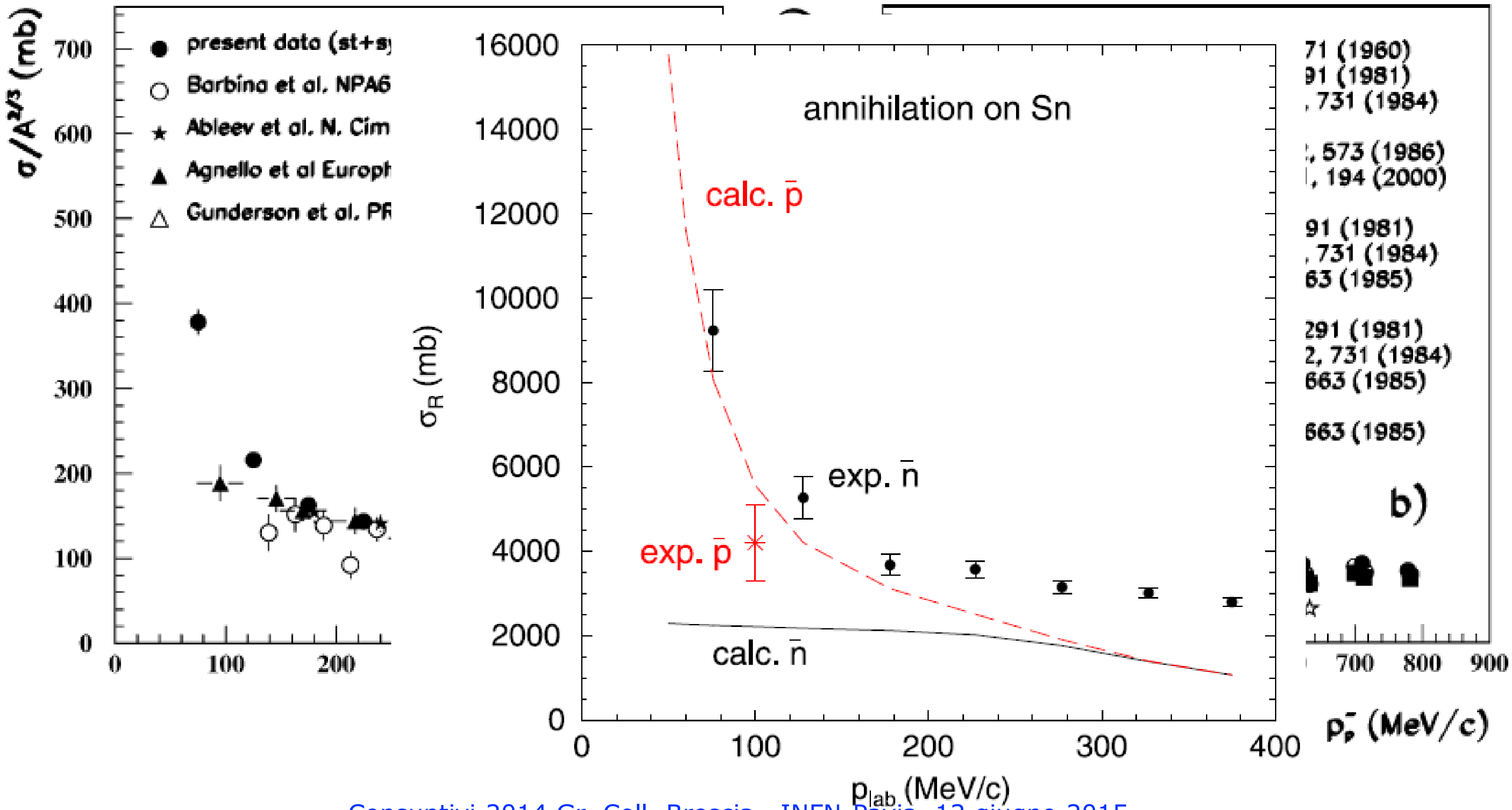
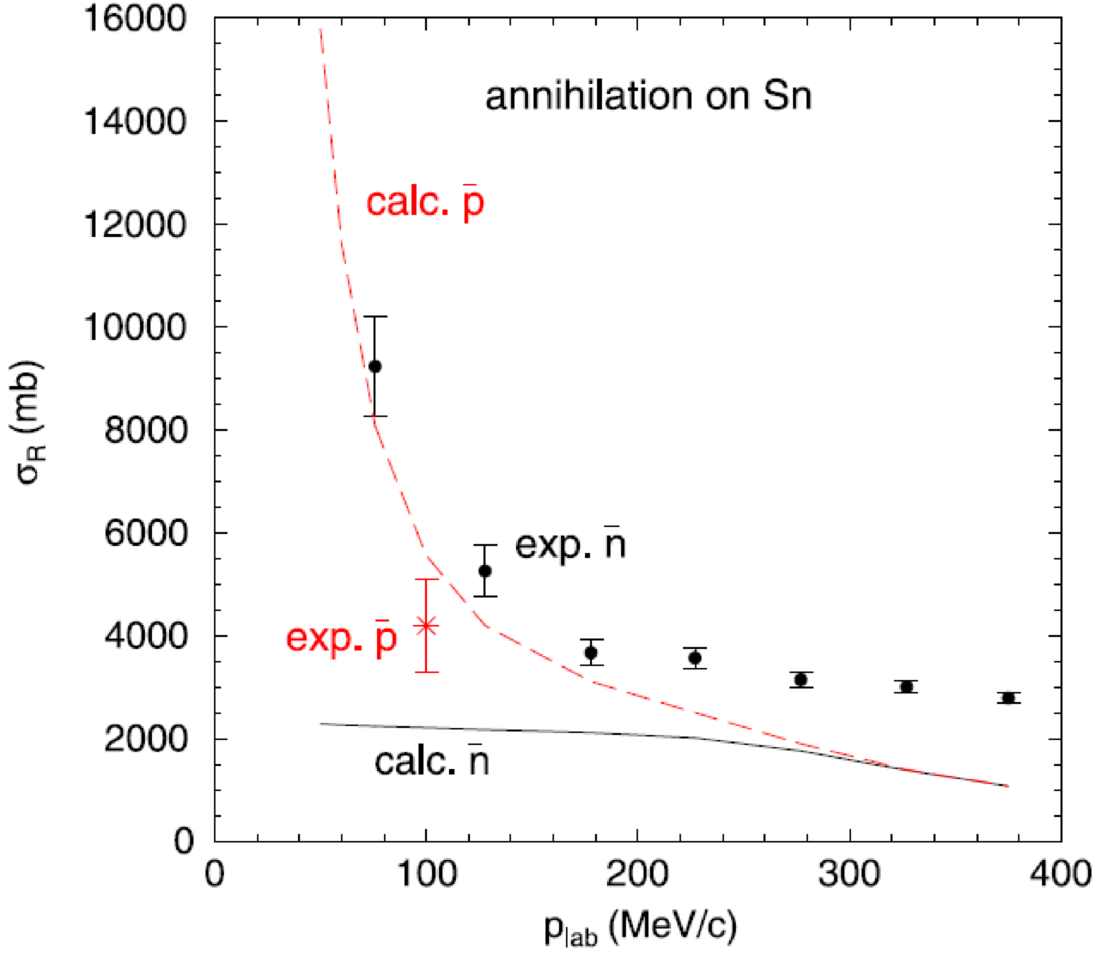


3° problem: nbar sigma rises steeper than pbar sigma

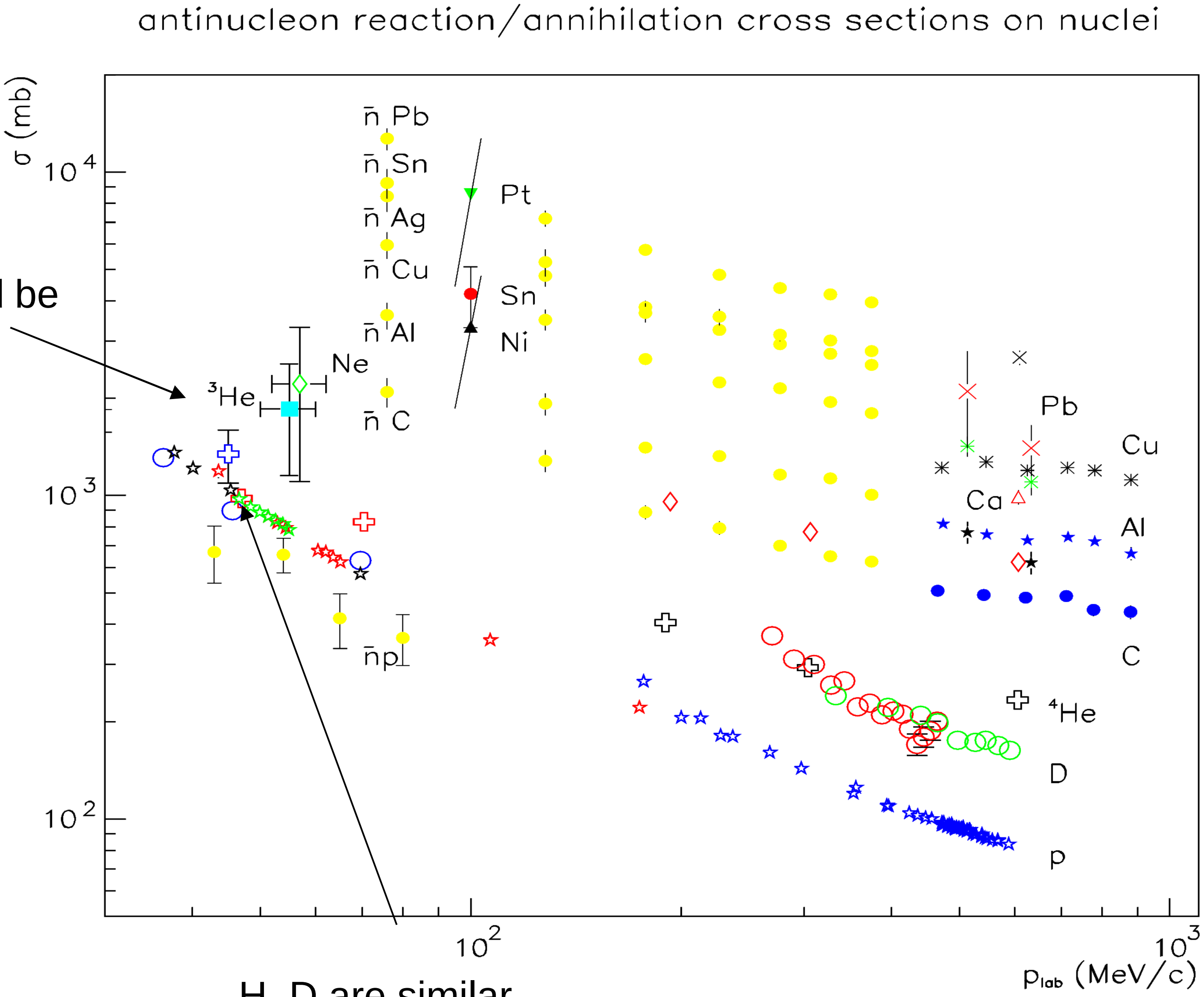


See Friedman's talk at EXA 2014

No clear explanation with short-range interactions

4th problem: “inversion” (sigma on light nuclei cross each other)

Neon should be twice He3

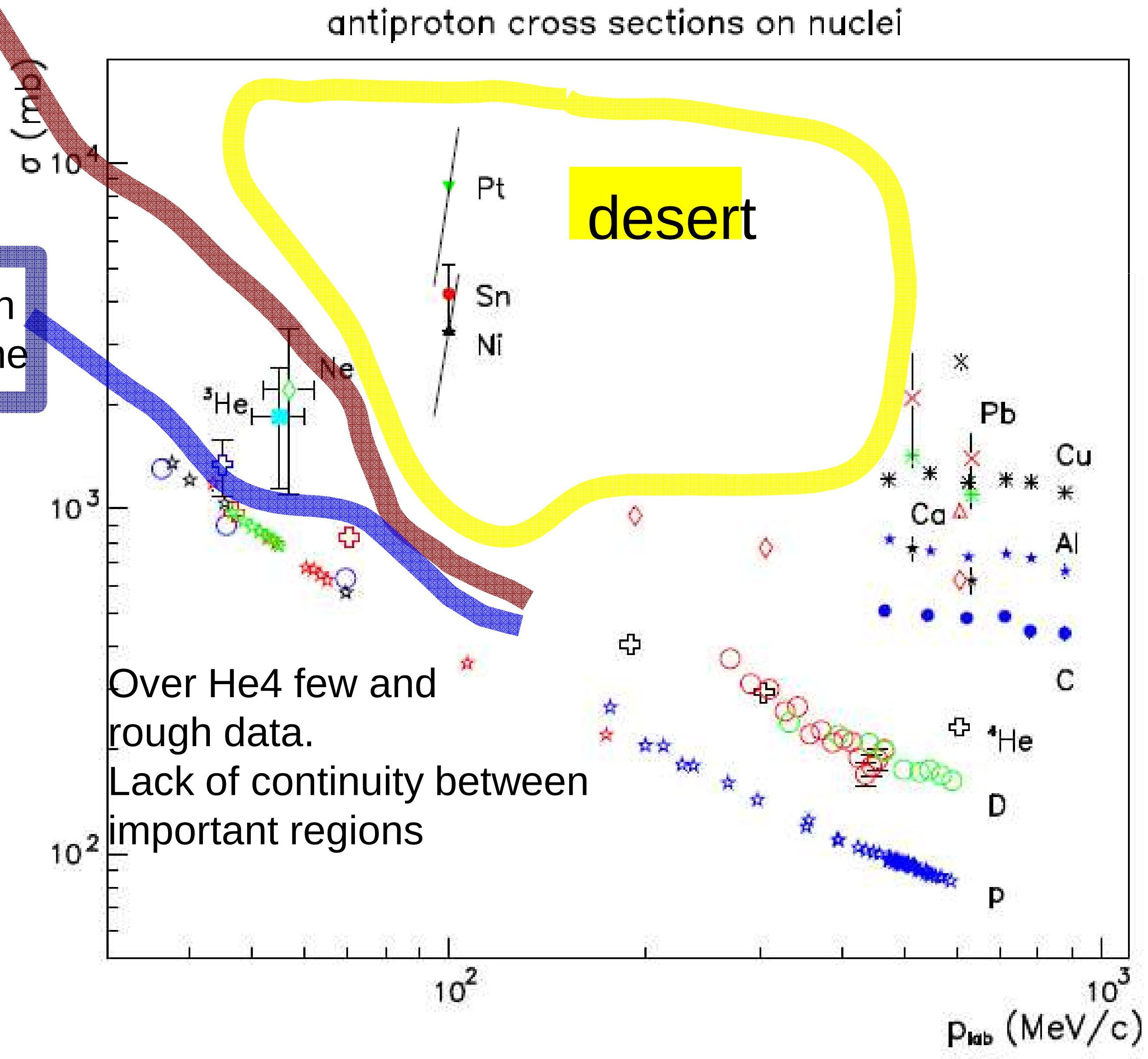


H, D are similar

Antiproton data

light / heavy gap

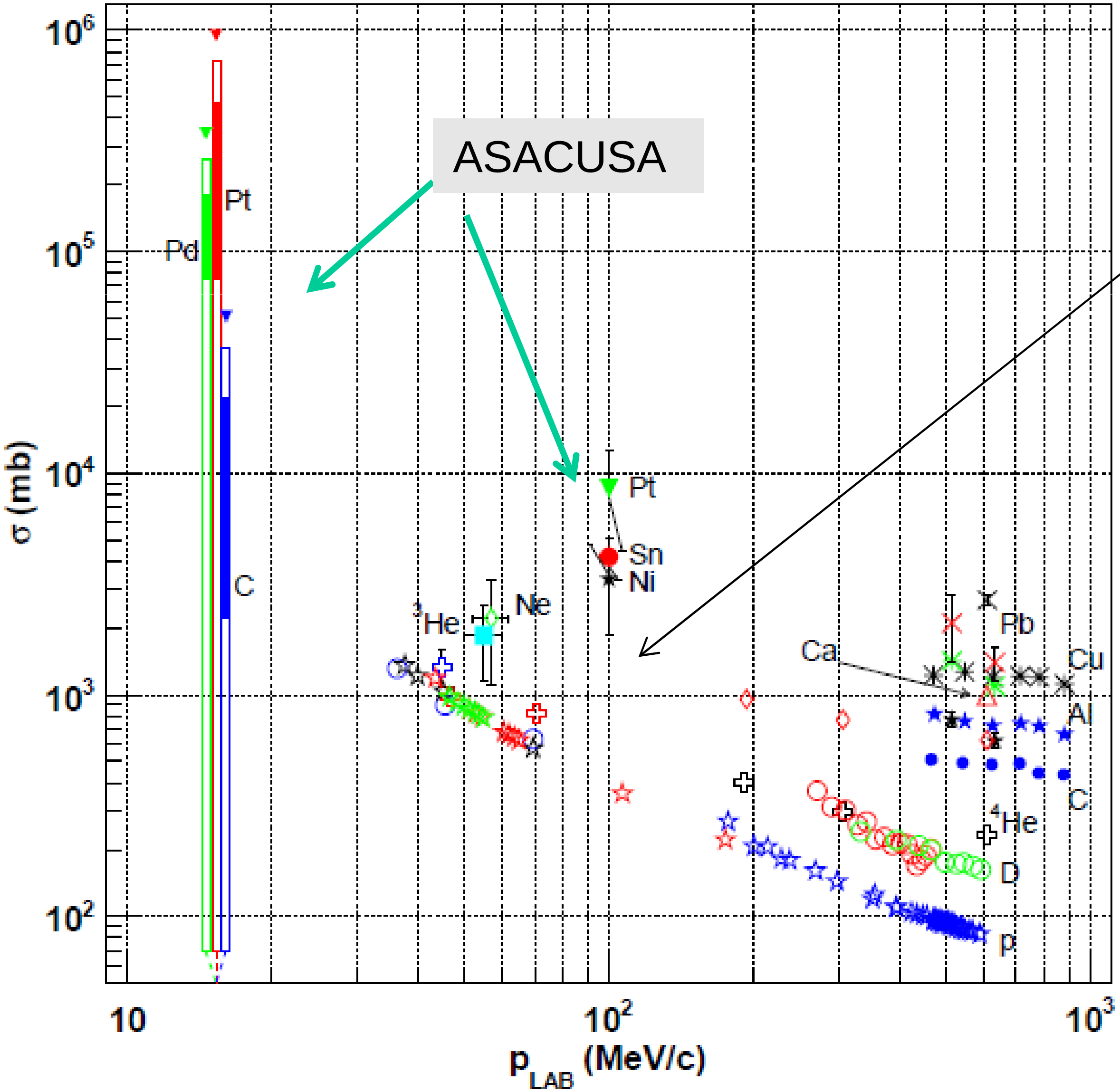
Precision borderline



Over He4 few and rough data.
Lack of continuity between important regions

Experimental data needed

Existing data



We want to measure carbon at 5.3 MeV

Why carbon?

- To have pbar-nbar comparison at same energy
- to fill the gap between light nuclei and heavy nuclei

Experiments at low energies

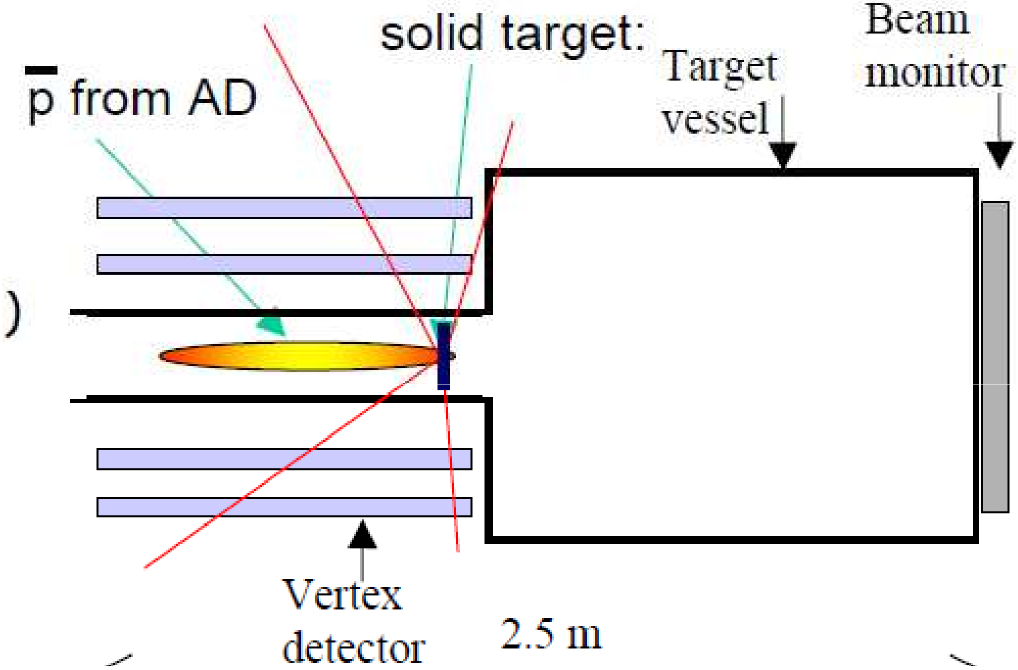
target	$\bar{p}$ atoms	$\bar{p}$ ann.	$\bar{p}$ scatt.	$\bar{n}$ ann.
C	+*		+	+
O	+*			
Ne		+		
Al				+
Ca	+		+	
Fe	+			
Ni	+	+		
Cu				+
Zr	+			
Ag				+
Cd	+			
Sn	+	+		+
Te	+			
Pt		+		
Pb	+		+	+
data	90	7	88	6

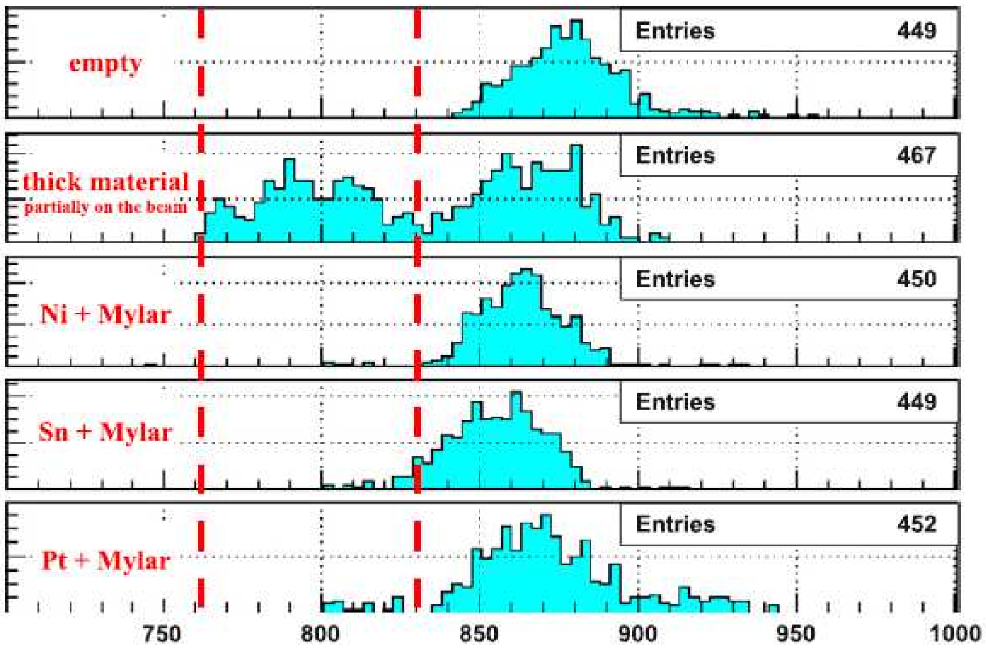
Friedman, EXA 2014

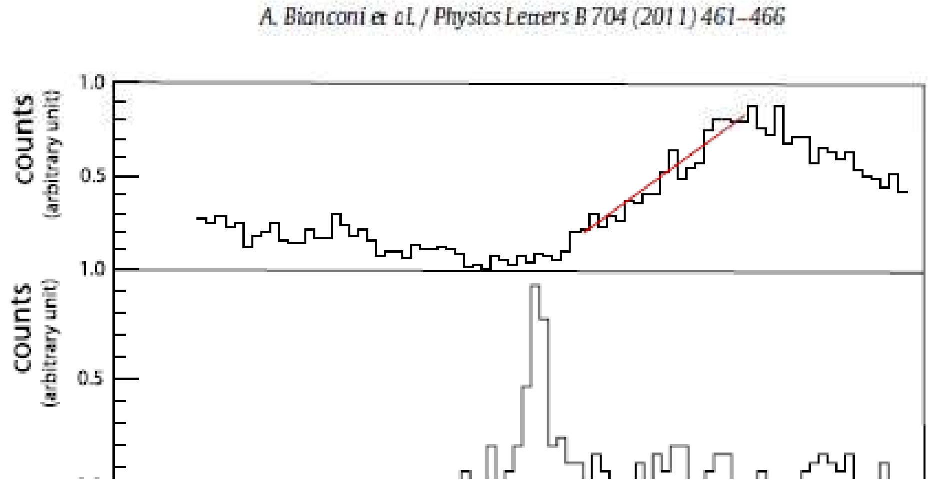
*pre-LEAR data.

Fill the gaps! [NPA 925 (2014) 141]

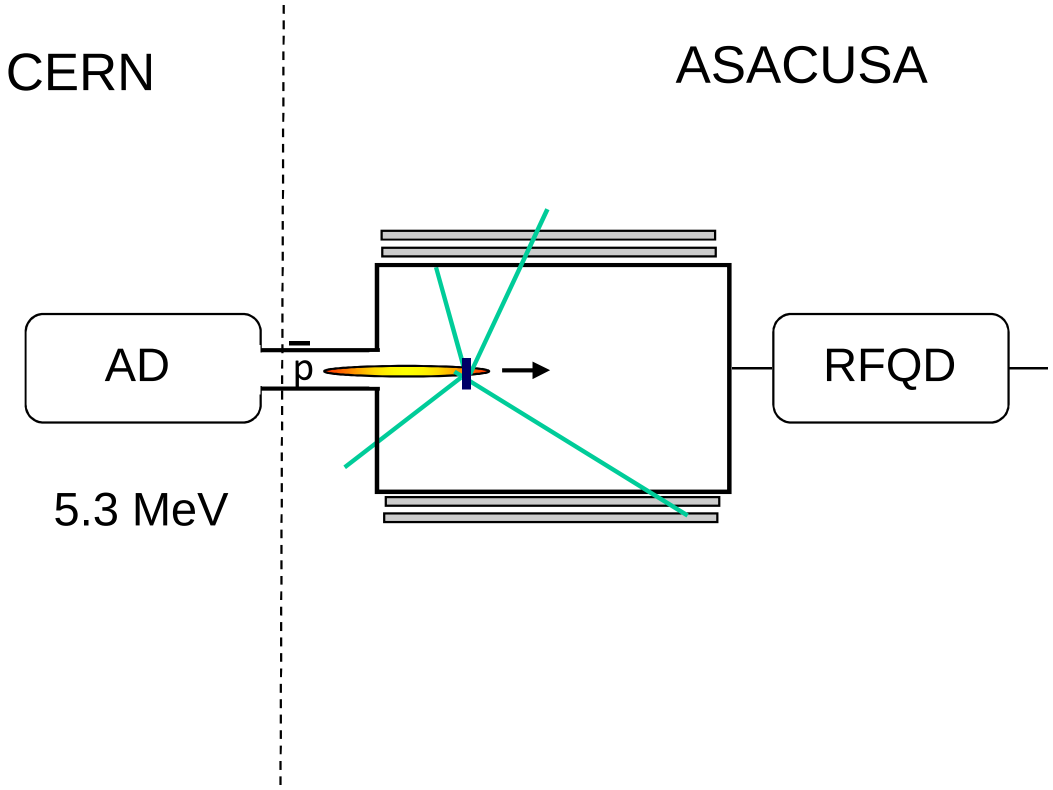
Old measurement technique at 5.3 MeV



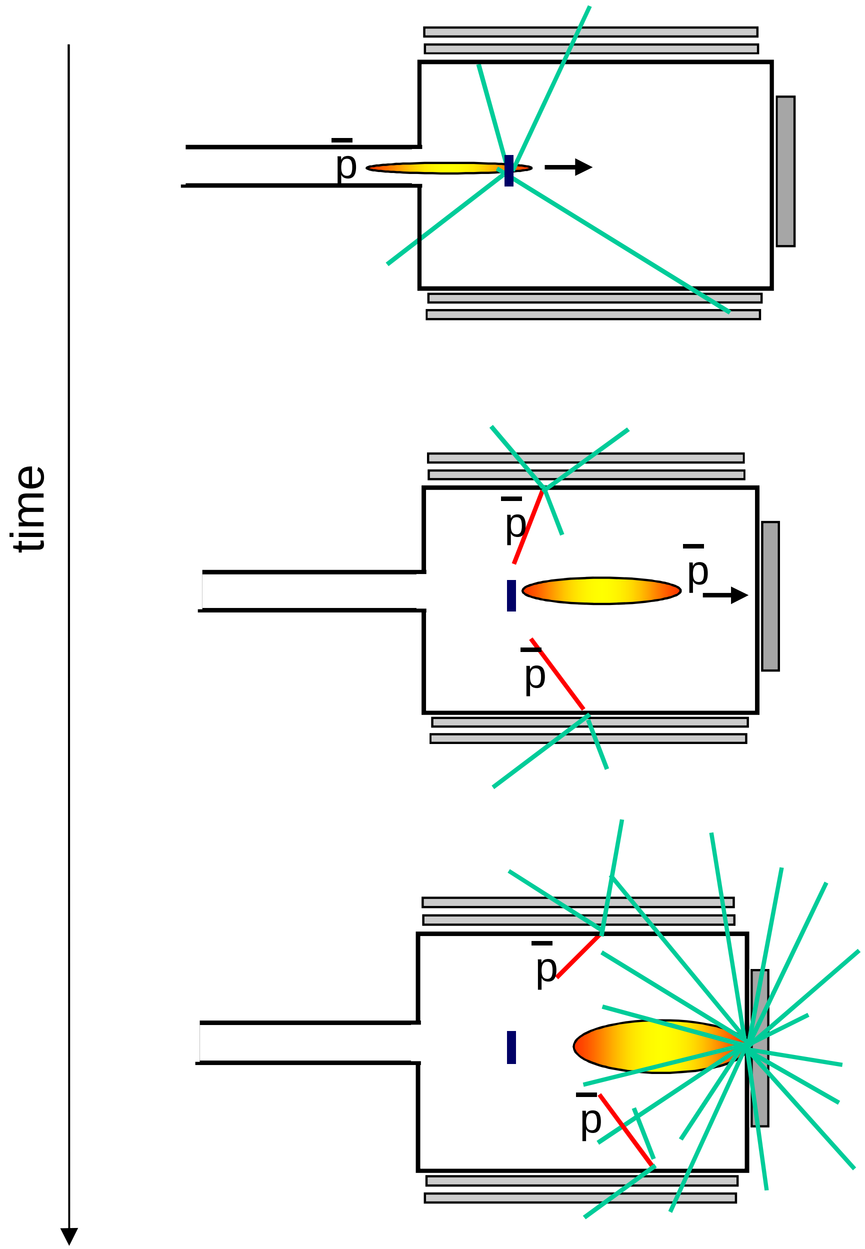




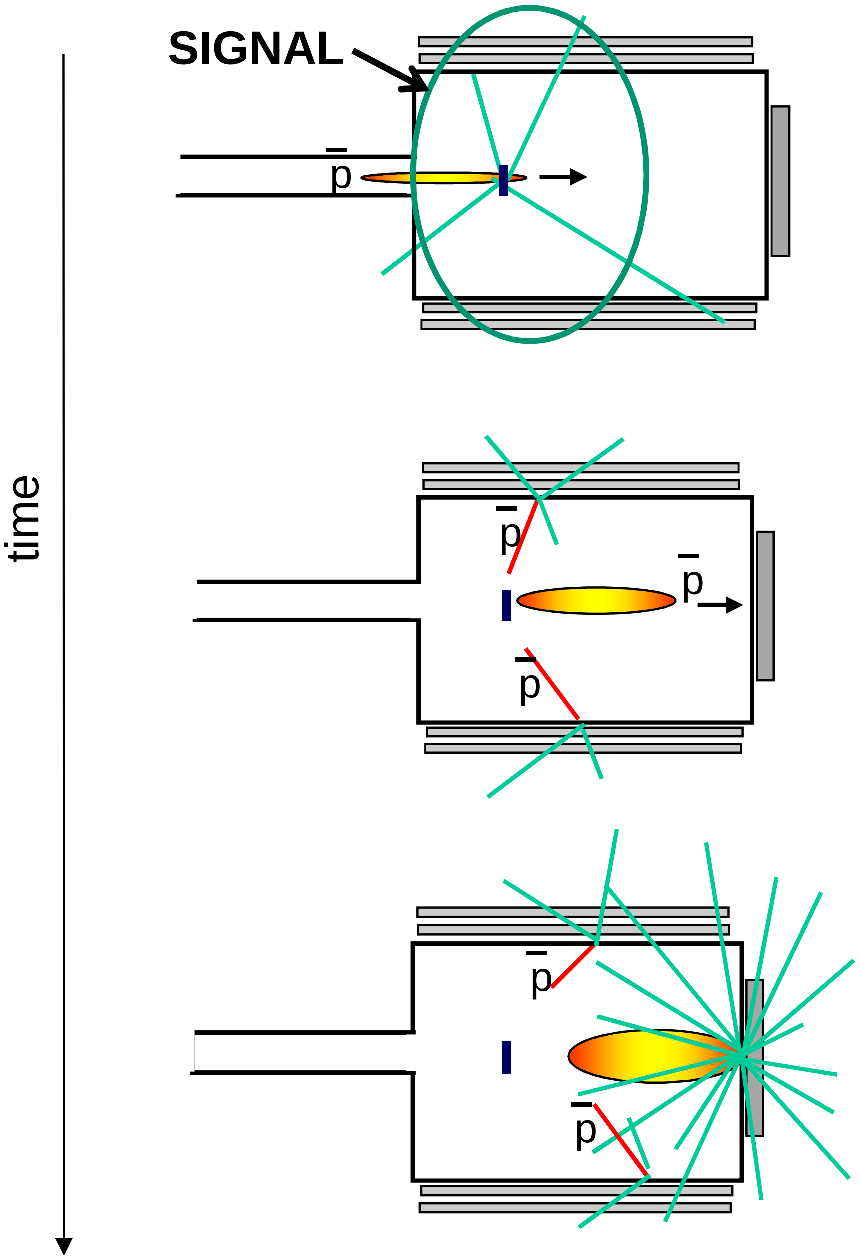
DESIGN OF THE 2015 EXPERIMENT



Technique of the annihilation σ measurement

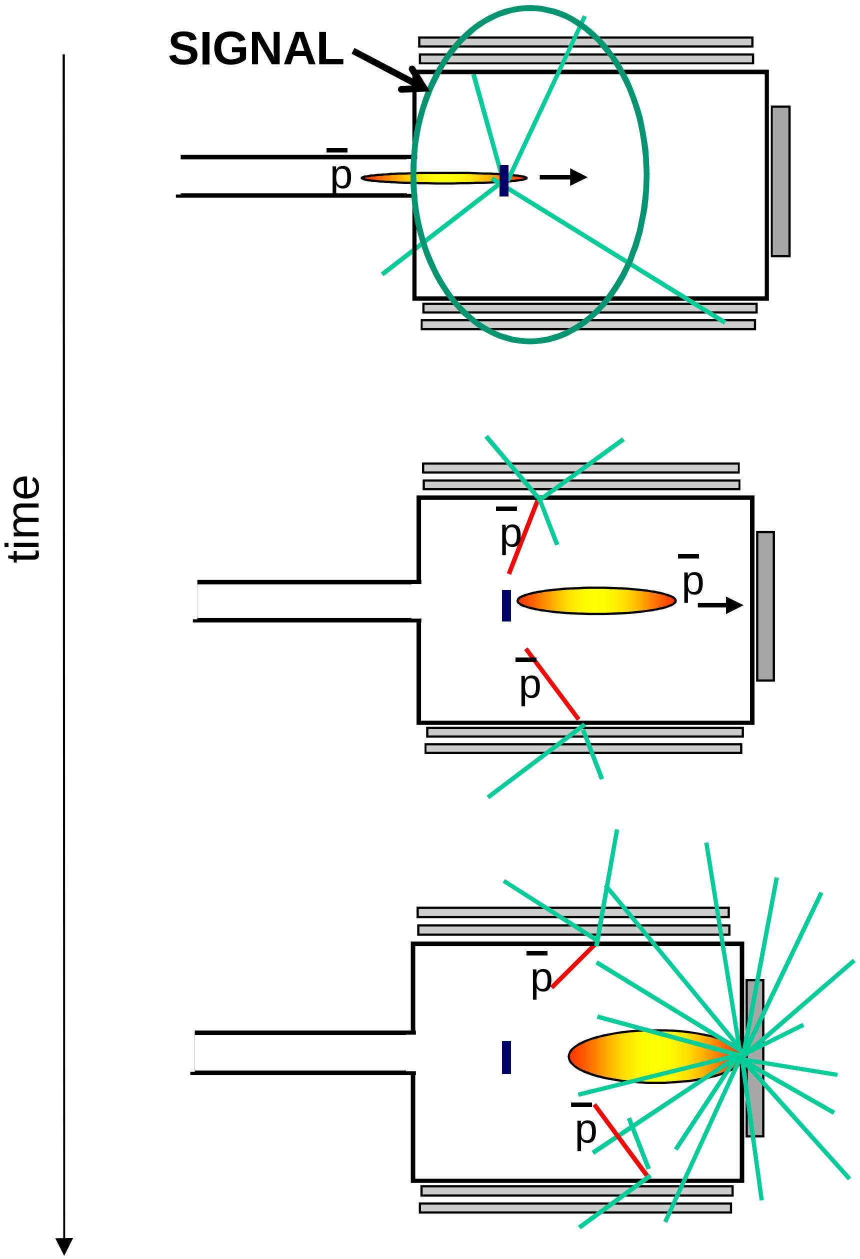


Technique of the annihilation σ measurement

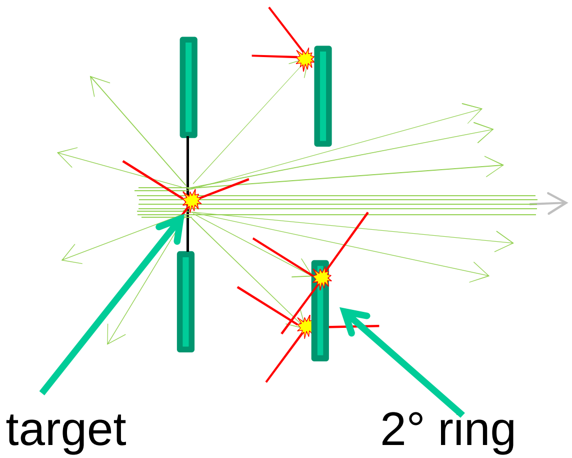


$$\sigma_{ann}(\bar{p}A) \propto \frac{N_{events}}{N_{beam}}$$

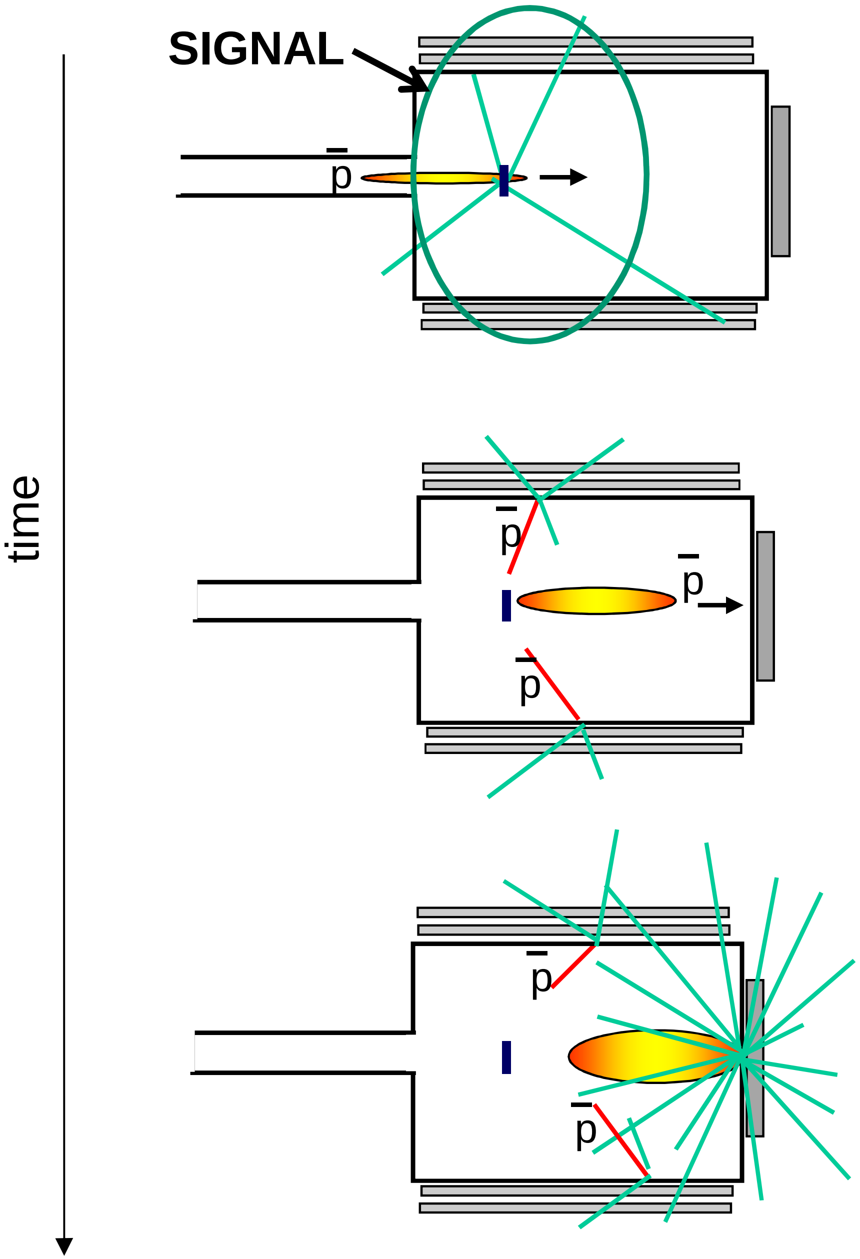
Technique of the annihilation σ measurement



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



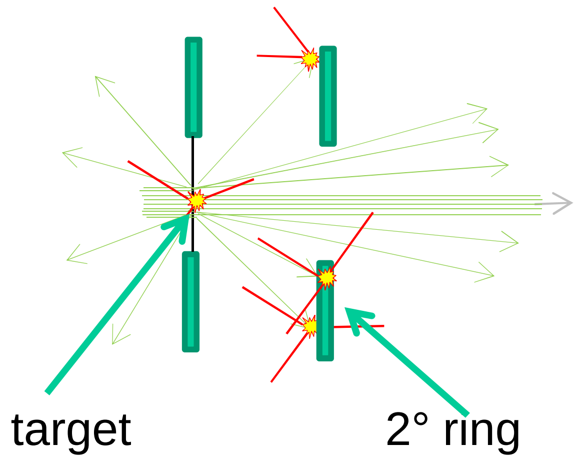
Technique of the annihilation σ measurement



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

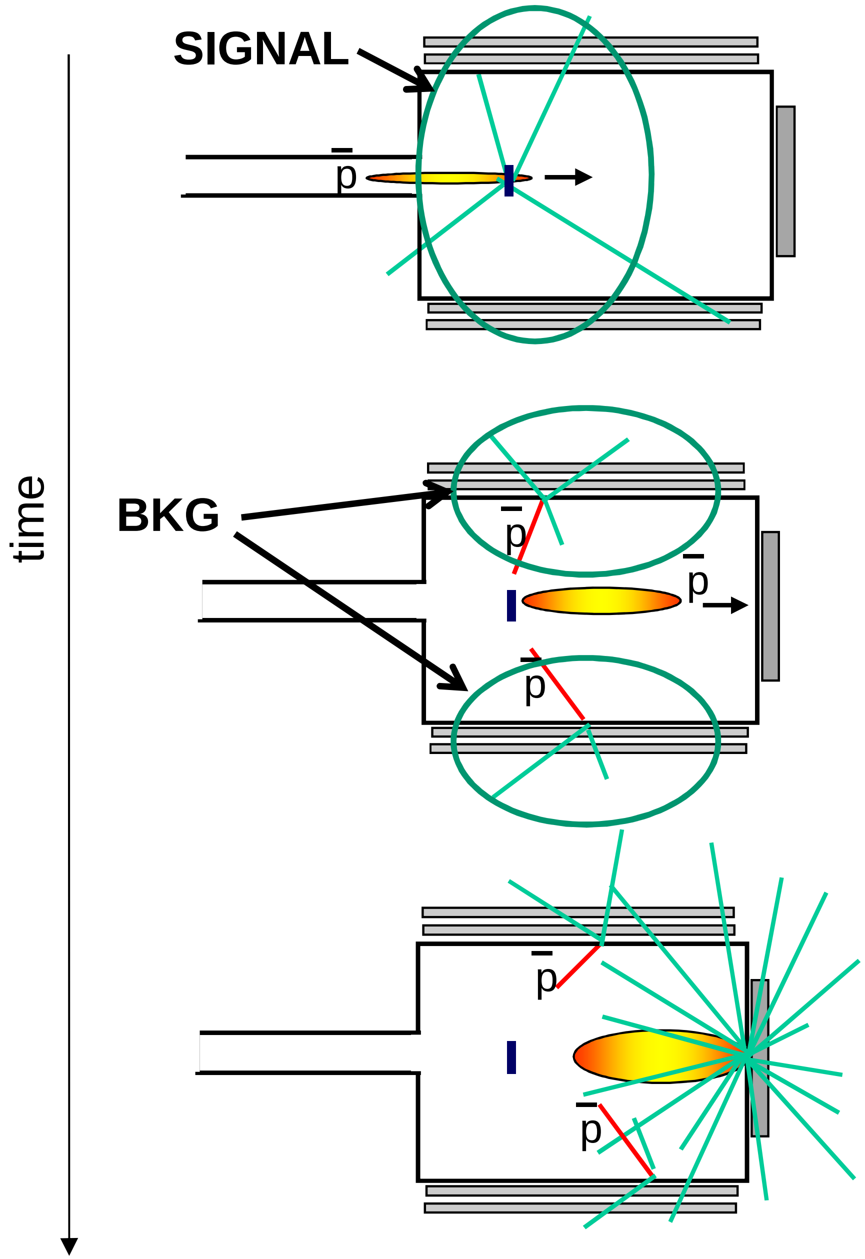
same detector

➔ σ_{ann} is independent from detector efficiency

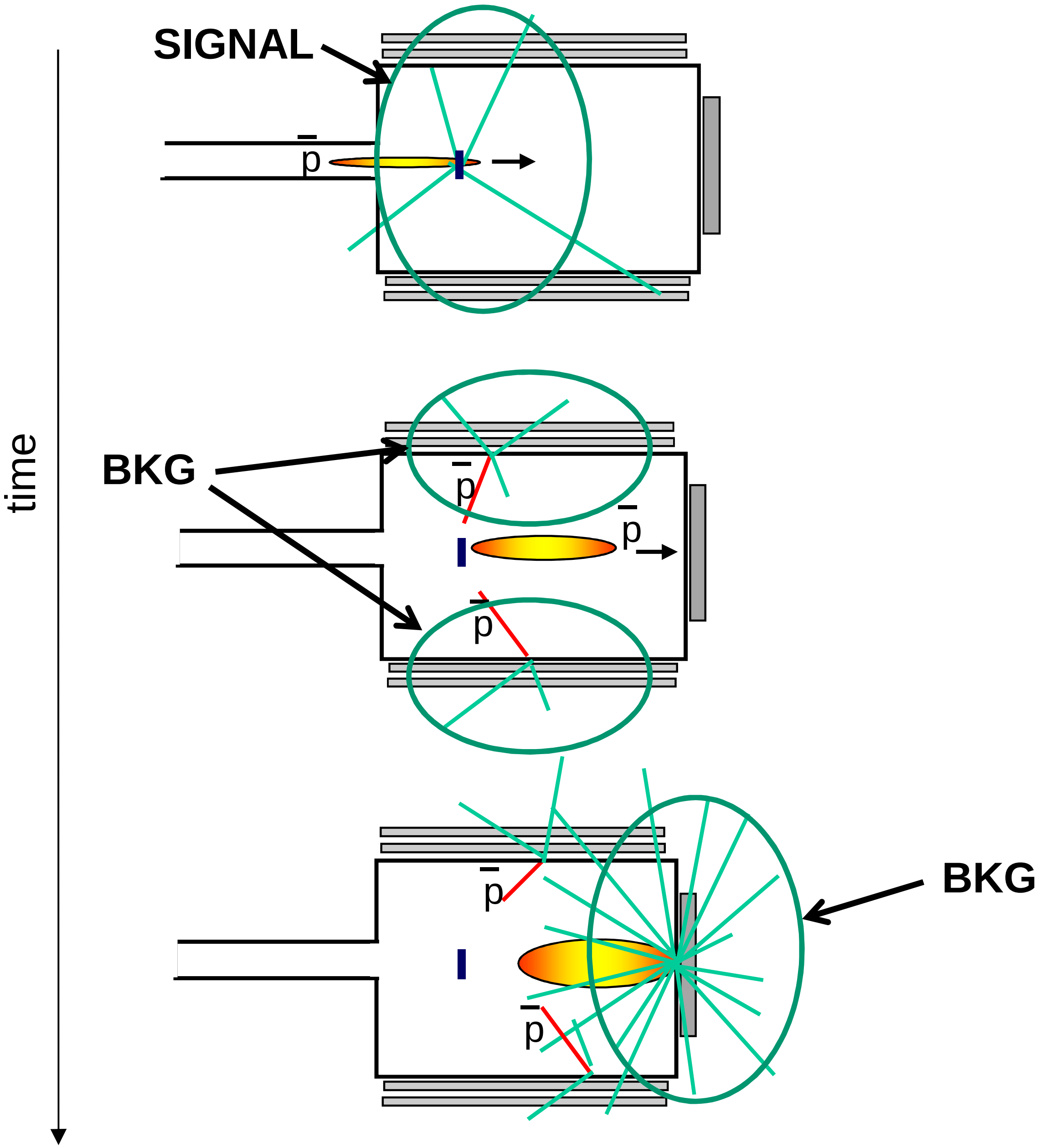


Technique already used @130 keV

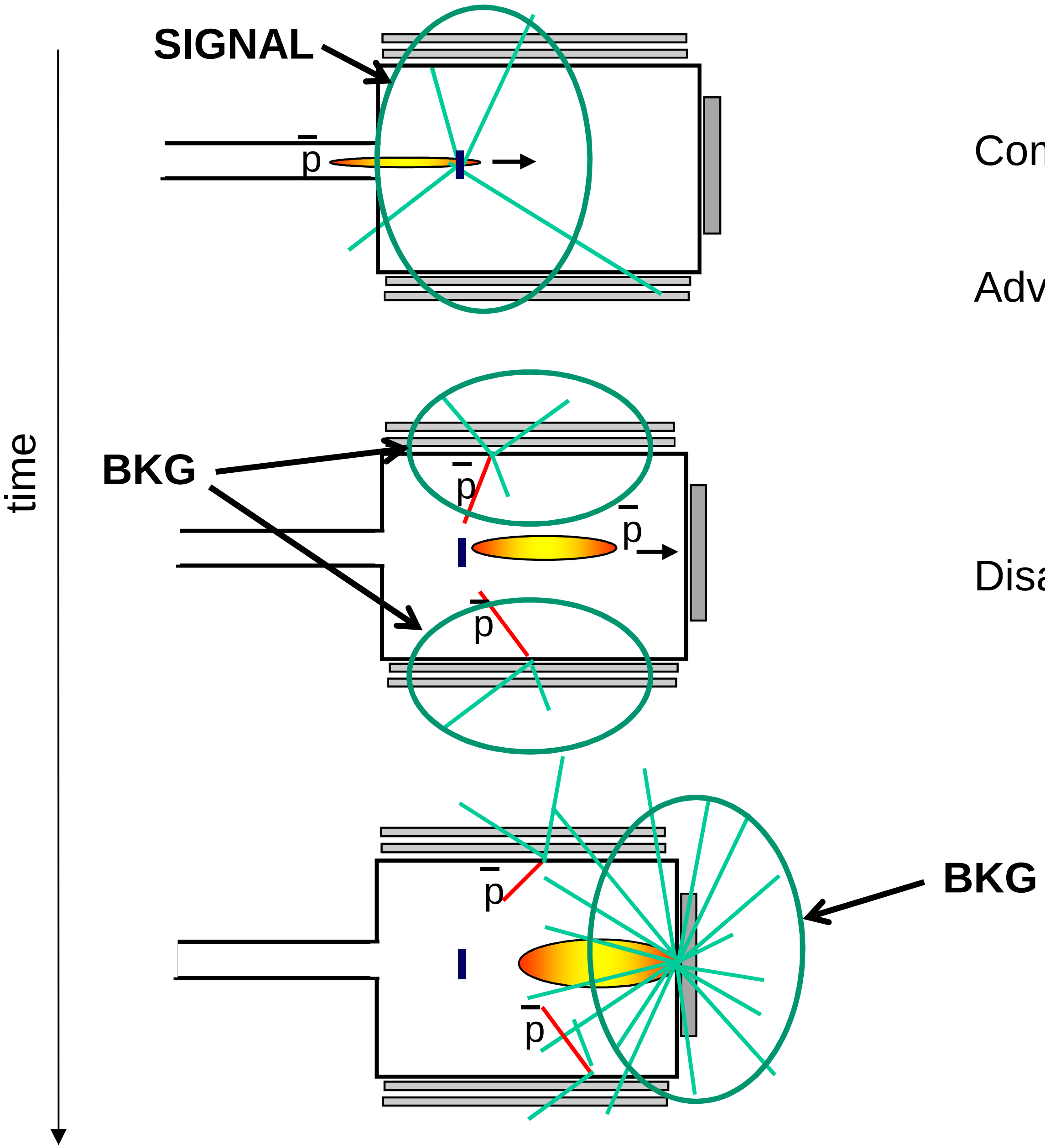
Technique of the annihilation σ measurement



Technique of the annihilation σ measurement



Technique of the annihilation σ measurement



Compared to 130 keV experiment:

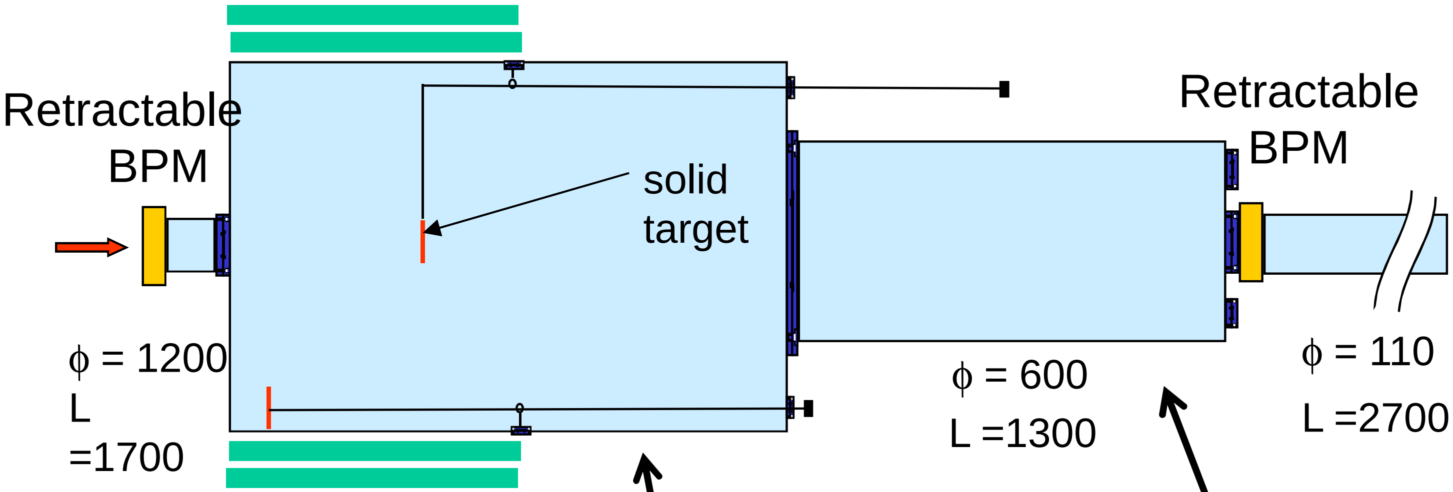
Advantages:

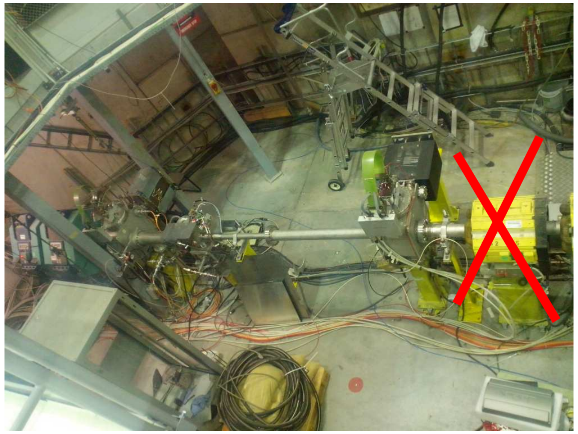
- thicker target
- no π-μ-e bkg
- less Rutherford sigma
- no RFQD-DOGLEG

Disadvantages:

- faster pbars (3cm/ns)
- Nuclear scatt. bkg

Set-up





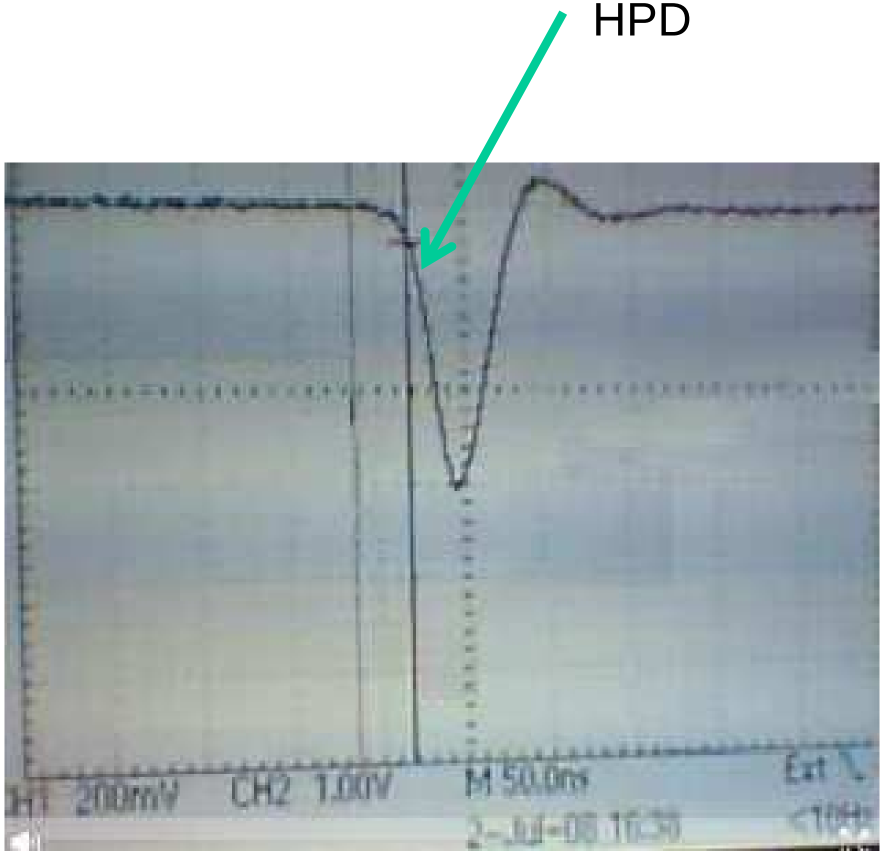
Yellow quadrupoles to be removed

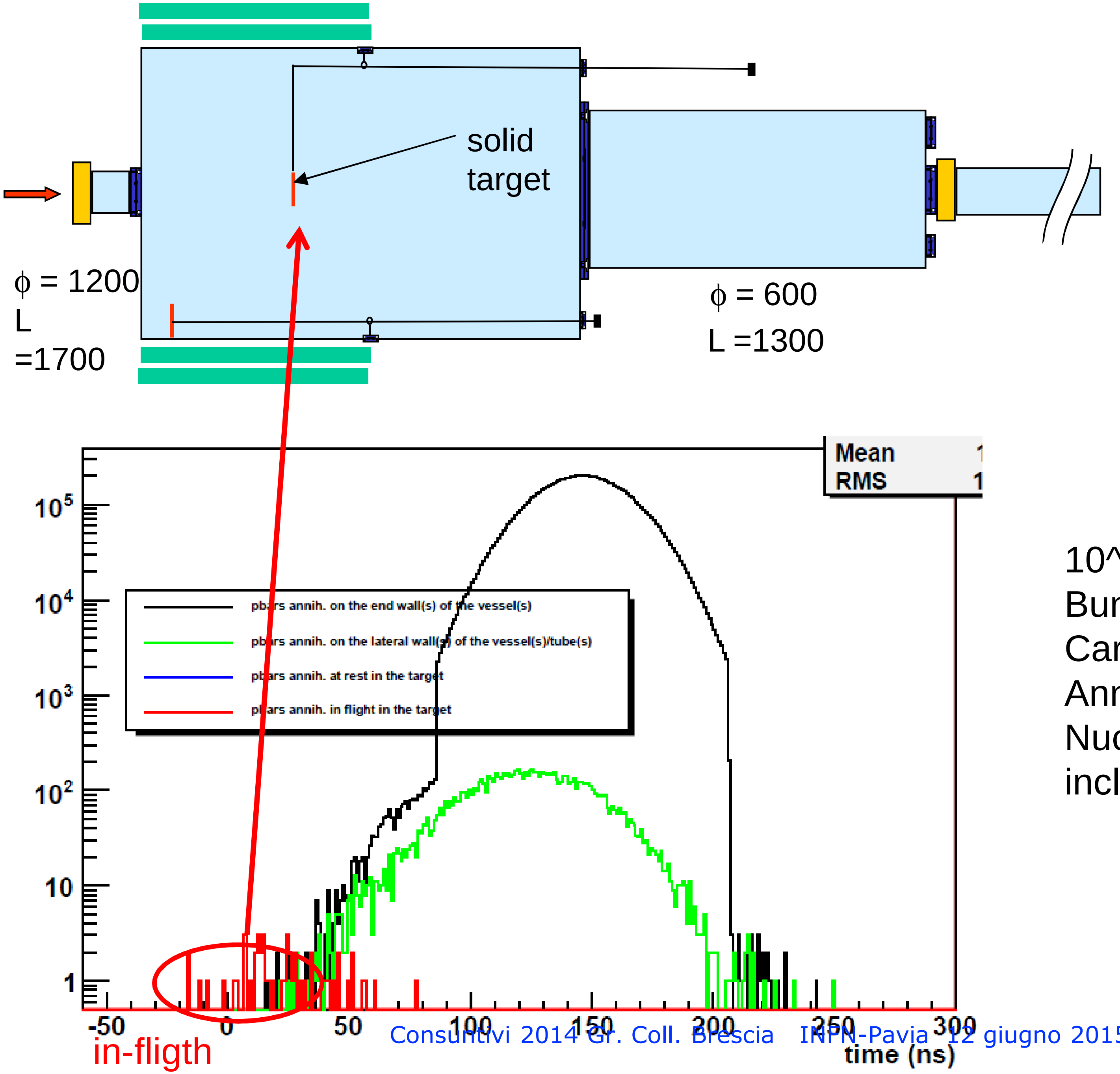
SIMULATIONS

To evaluate background contamination:

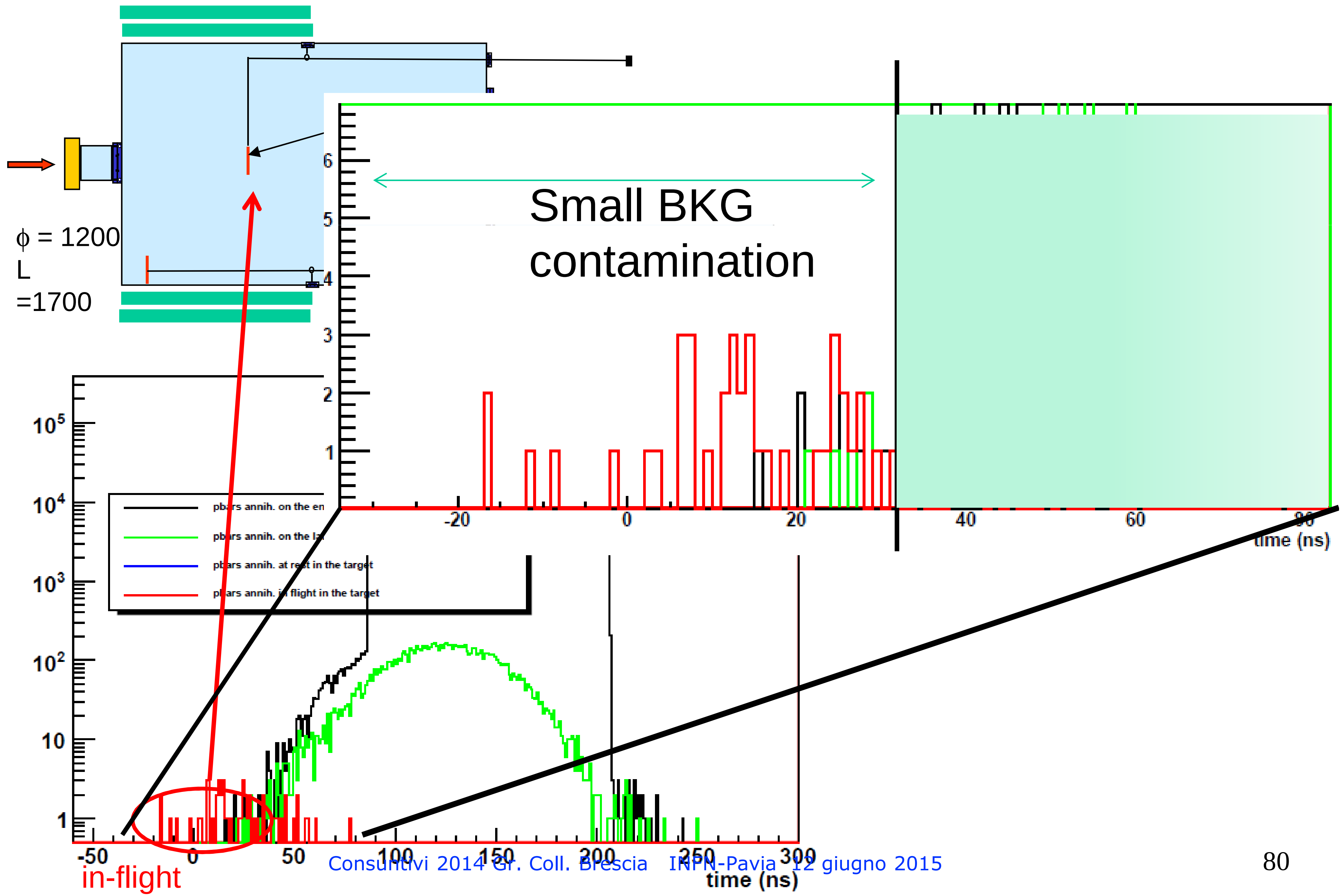
• downstream pbar annihilations (end wall+lateral walls…)
• Nuclear+Rutherford (lateral wall)
• etc.

pbar beam:
on axis with Gaussian time distribution
(FWHM=50ns, truncated to +-3 σ –>Δt=130 ns)



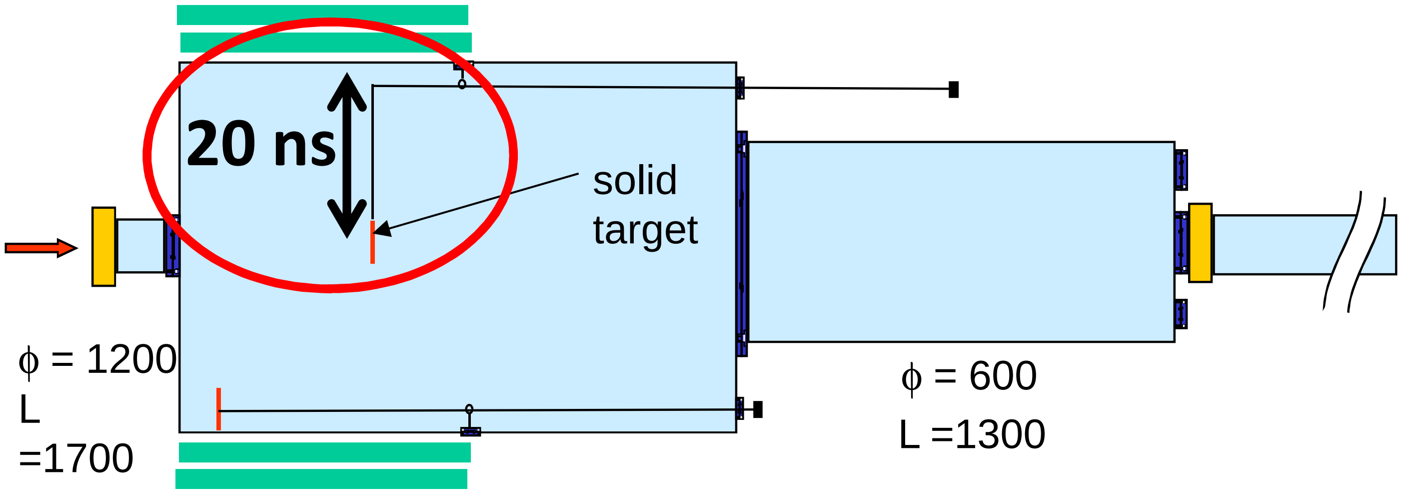


10^7 pbars
Bunch length=50 ns (FWHM)
Carbon target (700 nm)
Annihilation σ = 1 b
Nuclear elastic events not included



ϕ = 1200
L
=1700
Small BKG
contamination
time (ns)
pbars annih. on the en
pbars annih. on the la
pbars annih. at rest in the target
pbars annih. in flight in the target
time (ns)
in-flight

HOW TO SEPARATE SIGNAL FROM BKG



Exploit the (at least) 20 ns delay

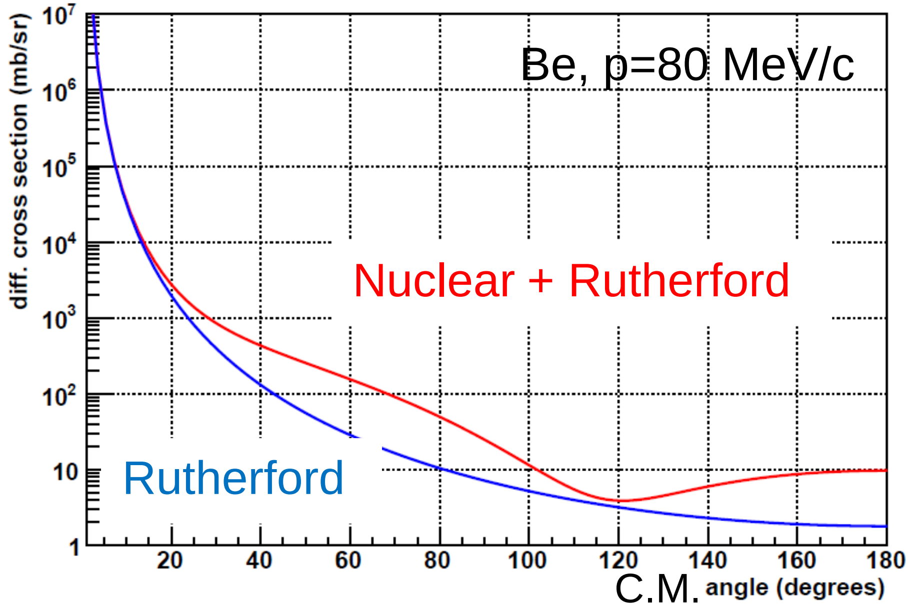
between signal from target and BKG from walls
due to Rutherford & Nuclear elastic scattering

Nuclear Elastic Scattering “background”

No data exist!

Calculation from Andrea Bianconi

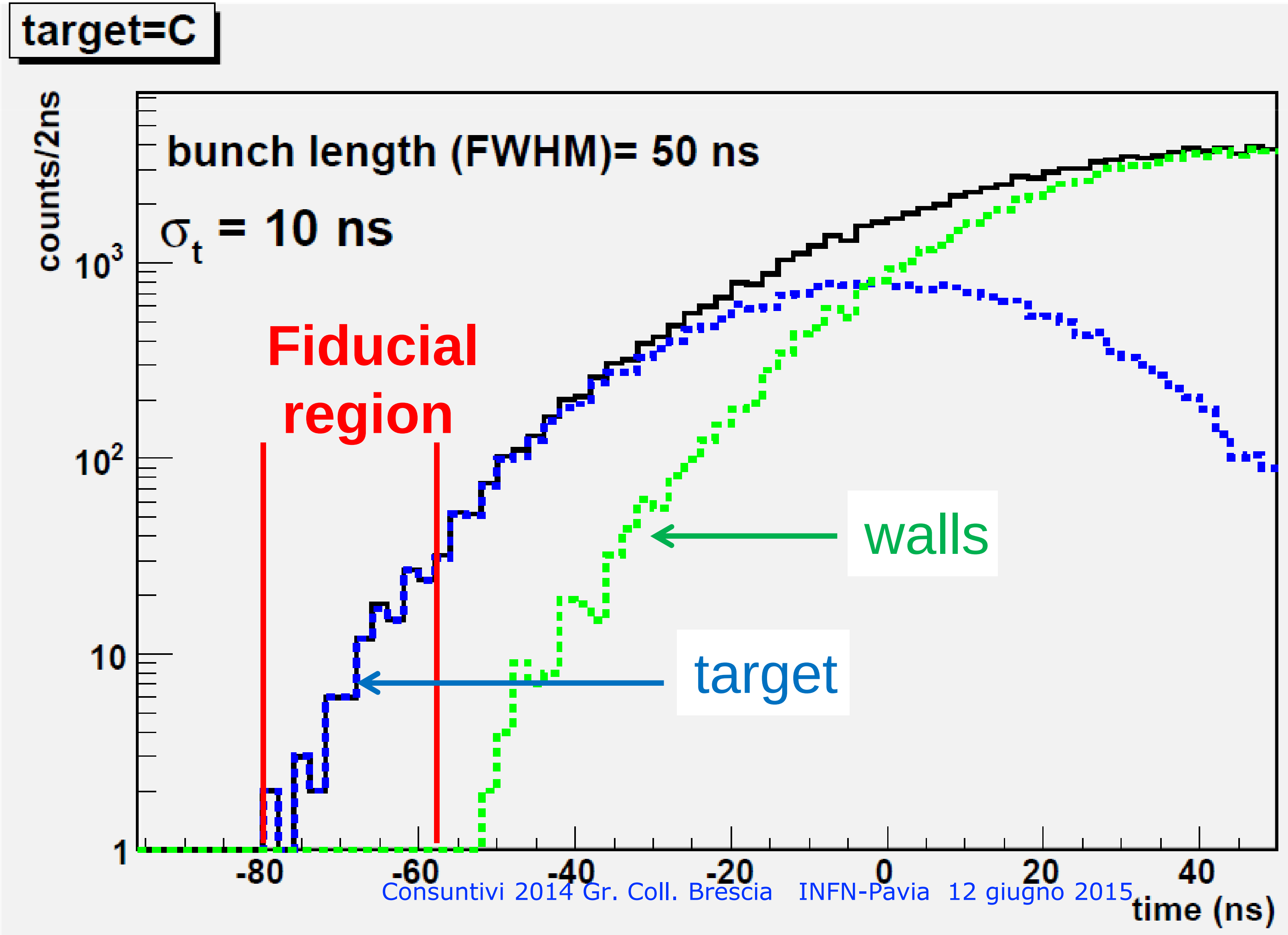
We use it (rescaled) just to check the analysis method



HOW TO SEPARATE SIGNAL FROM BKG

- signal (from target)
- BKG (Rutherford & Nuclear scattered pbars on the chambers walls)

Detector time resolution (σ_t)= 10 ns



Plan for 2015

Measurement of the absolute annihilation σ for C

- 1 week for beam steering and set-up optimization
- 1 week for C-target measurement → 1000 events

C-target: 500nm → 50 annih./10^7 pbars

few events in the fiducial region per spill;

Summary

In 2014, ASACUSA achieved:

- Installed and operated all elements necessary for $\bar{H}$ ground-state hyperfine spectroscopy.
- Detected $\bar{H}$ (n<12) candidates @3.4 m.

- Finished data taking and analysis for single-photon laser spectroscopy of $\bar{p}$He, cooled to ~1.5K.
- Plan to publish a new value for the antiproton-to-electron mass ratio soon (theory meanwhile reached a precision of 1.3×10^{-10}).

- Design of $\bar{p}$ annihilation σ measurement on carbon @5.3 MeV

- In 2015, ASACUSA plans to carry out

- $\bar{H}$ ground-state hyperfine spectroscopy

- higher-precision two-photon laser spectroscopy of $\bar{p}$He

- in-flight $\bar{p}$ annihilation σ measurement on carbon @5.3 MeV