CONSUNTIVI SCIENTIFICI (BRESCIA)

Luca Venturelli
Università di Brescia
INFN-Pavia

ASACUSA Italia (per 2015)

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 Univ.			50
Leali Marco	assoc			x	100
Lodi Rizzini Evandro	assoc				
Mascagna Valerio		Assegnista			…
Venturelli Luca	assoc	Prof. Associato			100

+ collaboratori Universita' dell'Insubria-Como INFN Trieste

Attività teorica (per 2015)

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

Attività teorica

1) Fisica medica e ambientale : ricerca sugli effetti di lungo periodo da contaminazioni interne di Diossido di Torio radioattivo ; ritrattamento dell’amianto

A.Bianconi, "Bonifiche e sistemi di smaltimento alternative alla discarica", invited talk relativo ai sistemi di ritrattamento dell'amianto al convegno "Una vita in polvere" agli Spedali Civili di BS.

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.

A.Bianconi ed Egle Tomasi-Gustafsson, Periodic interference structures in the time-like proton form factor, Phys. Rev. Lett. 114, 232301 (2015).
A.Bianconi ed Egle Tomasi-Gustafsson, Phenomenological analysis of near threshold periodic modulations of the proton timelike form factor. Phys. Rev. C 93, 035201 (2016)

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, "Adaptation of a generator to TMD analysis" al convegno "TMDe2015", settembre 2015, ICTP Trieste.

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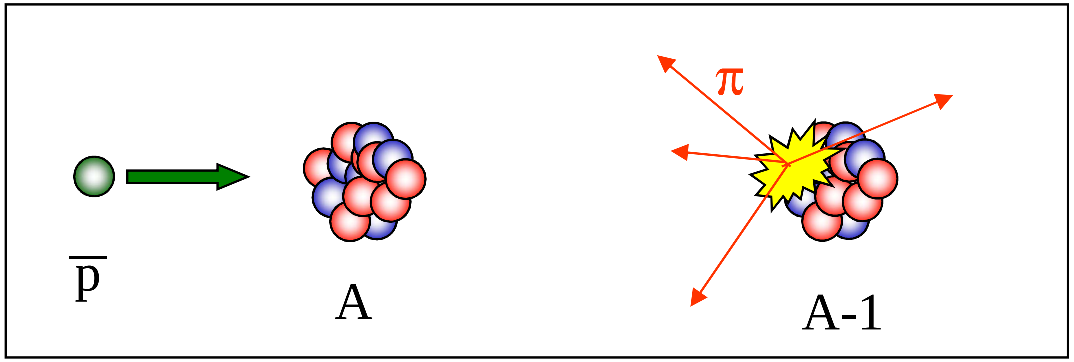
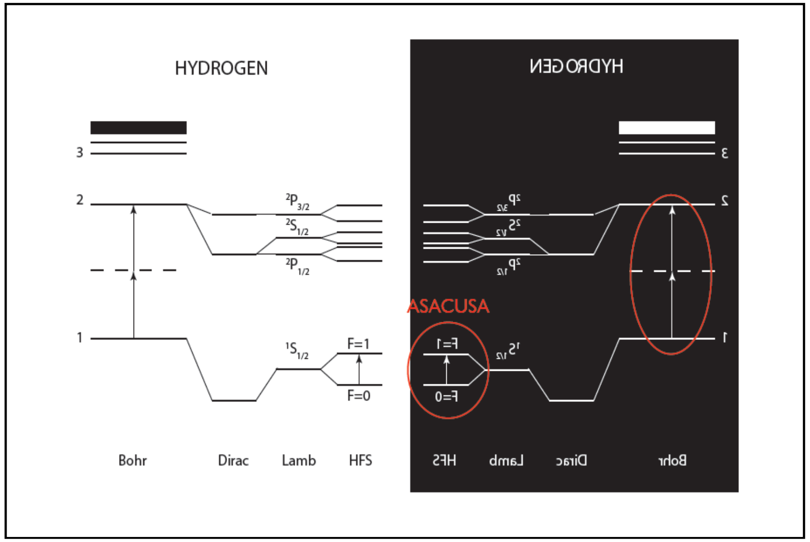
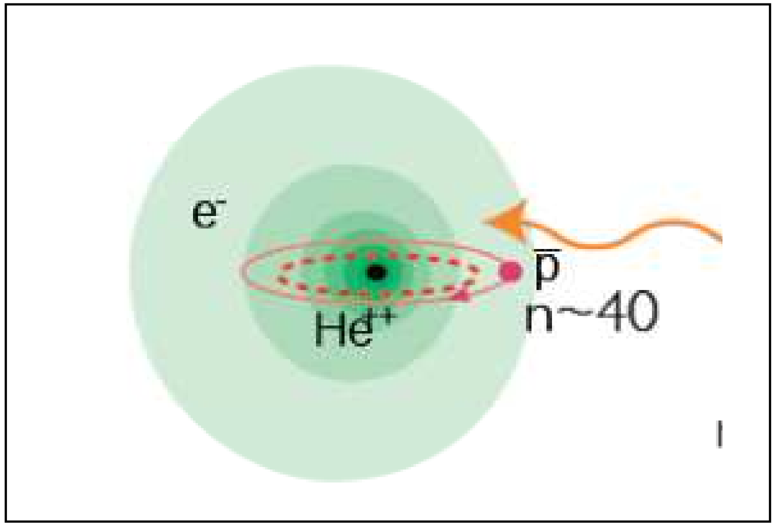


π
p̄
A
A-1



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⁻
He⁺⁺
p̄
n~40

Publications

	Titolo	Rivista	Cit.	INFN	Tot	Ratio	CIVR	Hi-Q
1	The development of the antihydrogen beam detector and the detection of the antih... ISI ID della pubblicazione: **WOS:000366407000092**	J PHYS CONF SER, **635-**, 022061 (2015)	0	3	28	11%	0%	NO
2	Scintillating bar detector for antiproton annihilations measurements ISI ID della pubblicazione: **WOS:000360770700009**	HYPERFINE INTERACT, **233-1-3**, (2015)	0	7	7	100%	0%	NO
3	First measurement of the antiproton-nucleus annihilation cross section at 125 keV ISI ID della pubblicazione: **WOS:000360770800012**	HYPERFINE INTERACT, **234-1-3**, (2015)	1	7	16	44%	0%	NO
4	Experimental access to Transition Distribution Amplitudes with the PANDA experim... ISI ID della pubblicazione: **WOS:000360439700001**	EUR PHYS J A, **51**, 107 (2015)	0	55	535	10%	0%	NO

5	The ASACUSA CUSP: an antihydrogen experiment	Hyperfine Interactio, -, (2015)	0	4	33	12%	12%	Nuclear Physics	NO

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

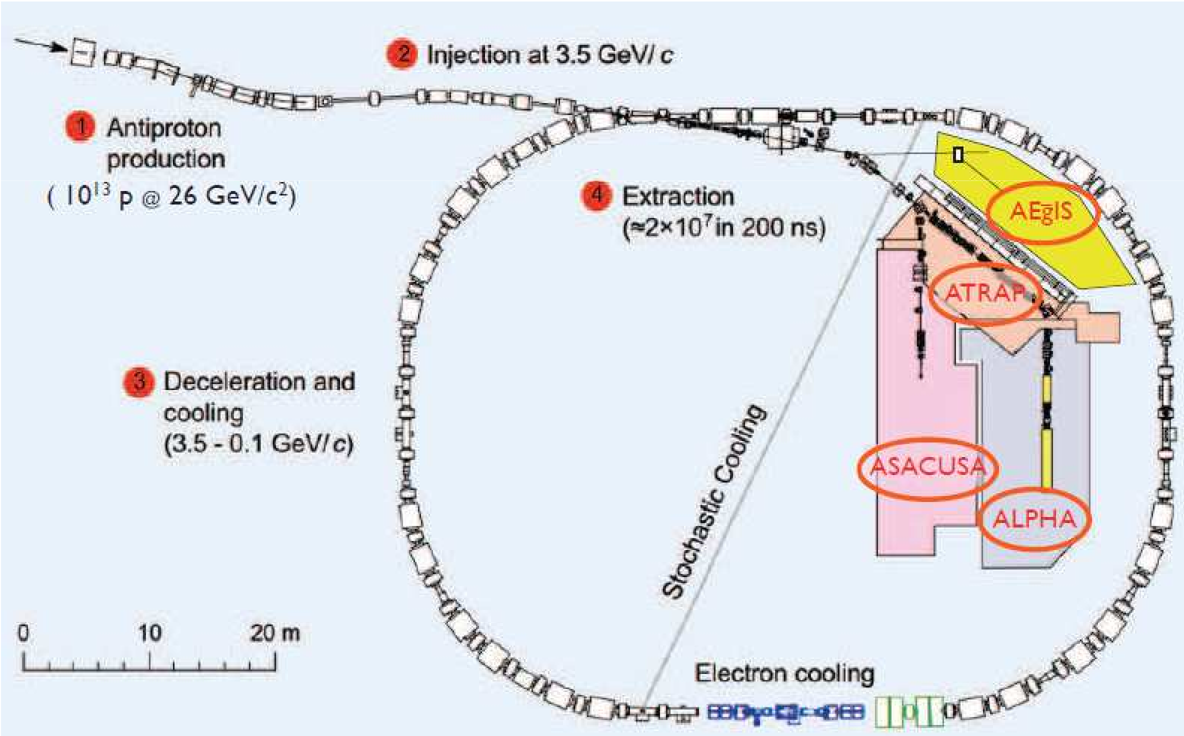
Asakusa, Tokyo

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.

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

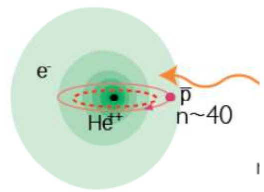
- ATHENA (ended), ACE (ended), GBAR (future)

ASACUSA Experiments

Studies of *CPT symmetry* by atomic spectroscopy

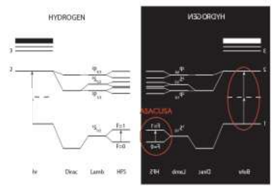
1) • laser spectroscopy of antiprotonic helium :
→ Antiproton mass

6 weeks



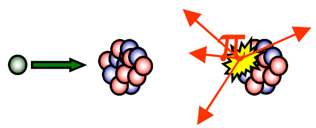
2) • Microwave spectroscopy of antihydrogen :
→ Ground-state hyperfine structure

5 weeks



Nuclear collisions with antiprotons

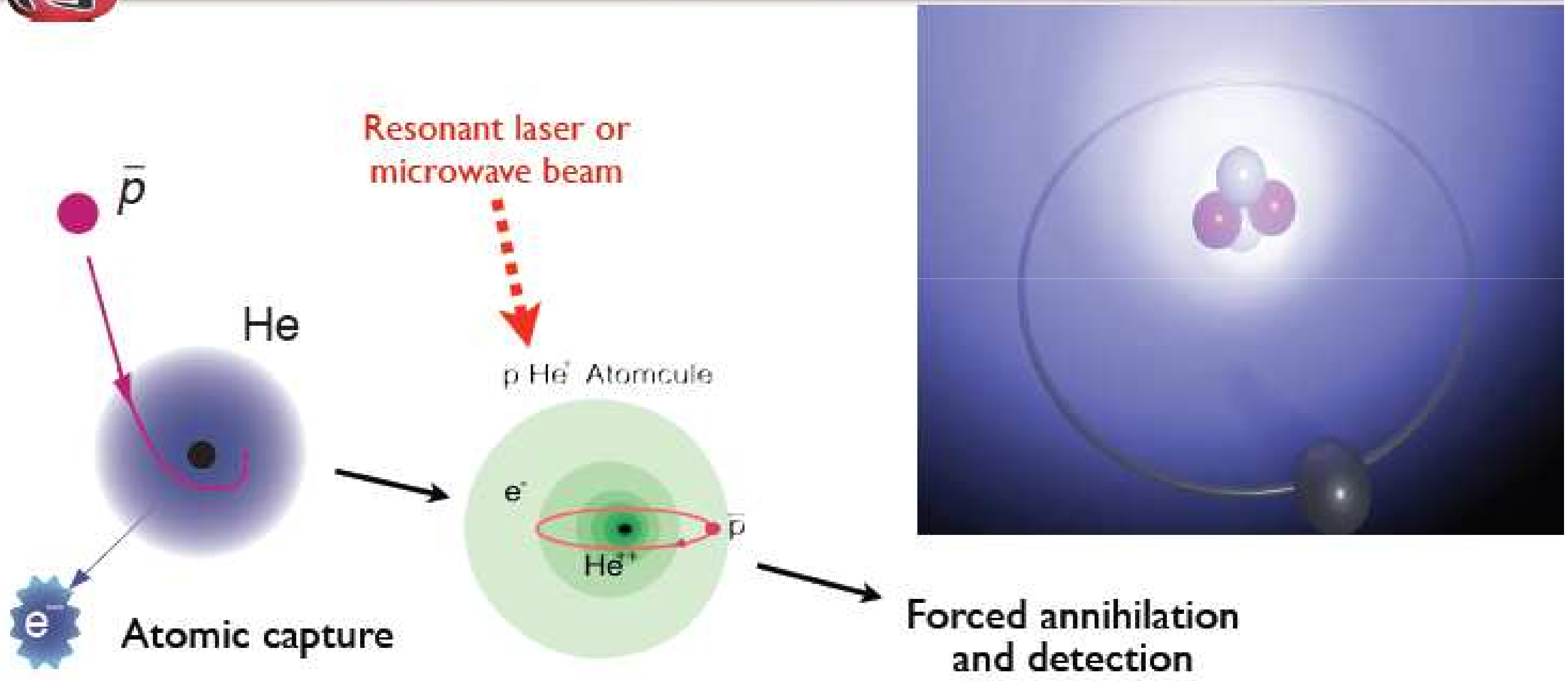
3) • total annihilation cross-section σ.



2 weeks

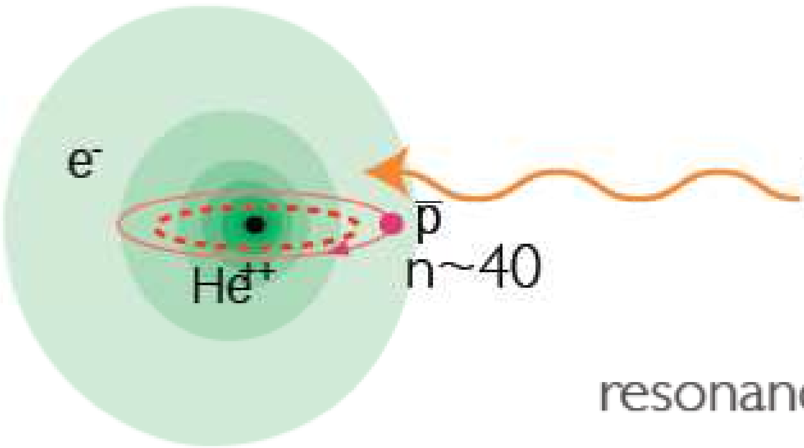
1. $\bar{p}$He laser spectroscopy

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



resonance detection via $\bar{p}$ annihilation

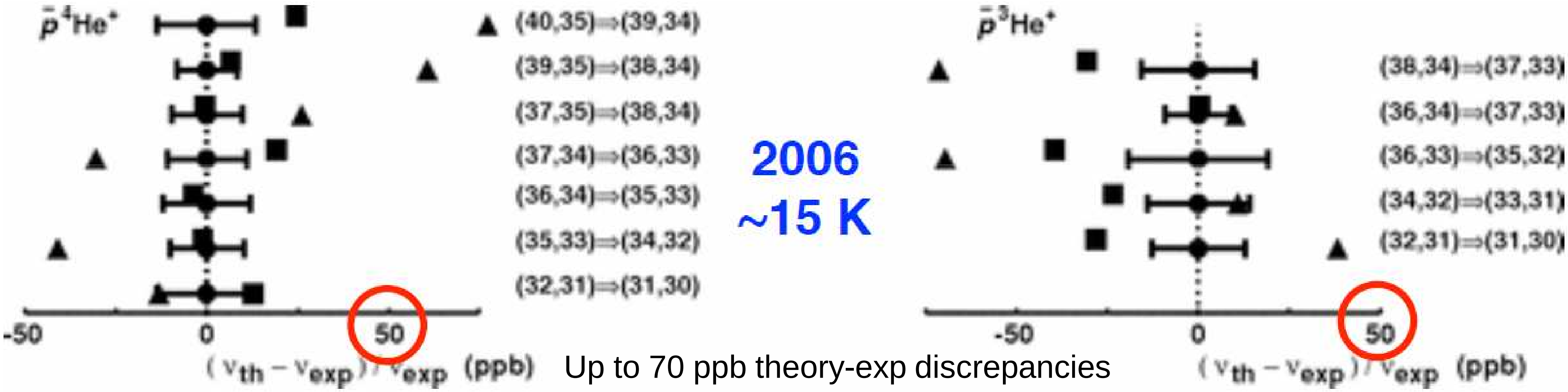
Frequency

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

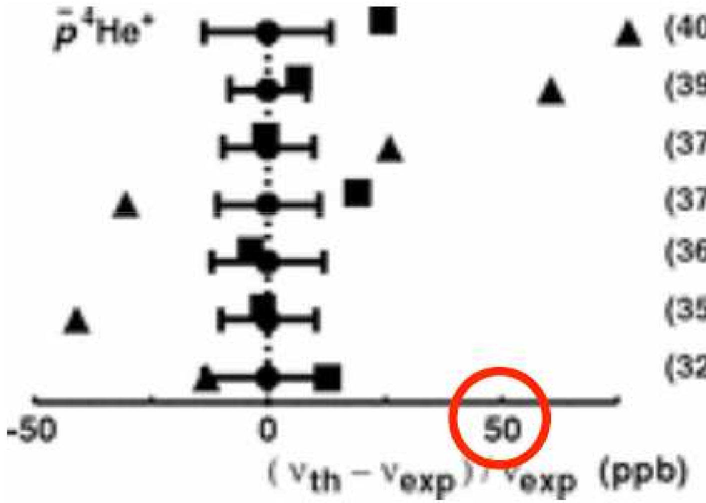
$\bar{p}$ (p) - e mass ratio

Theory

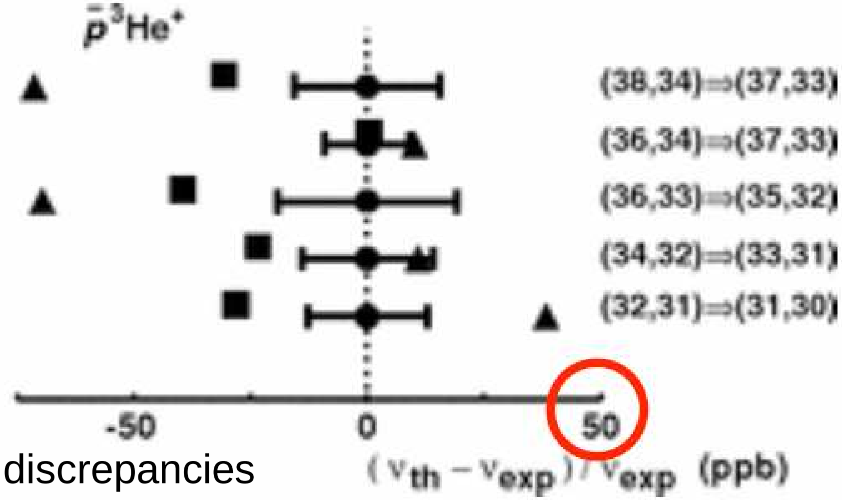
ASACUSA single photon (final)



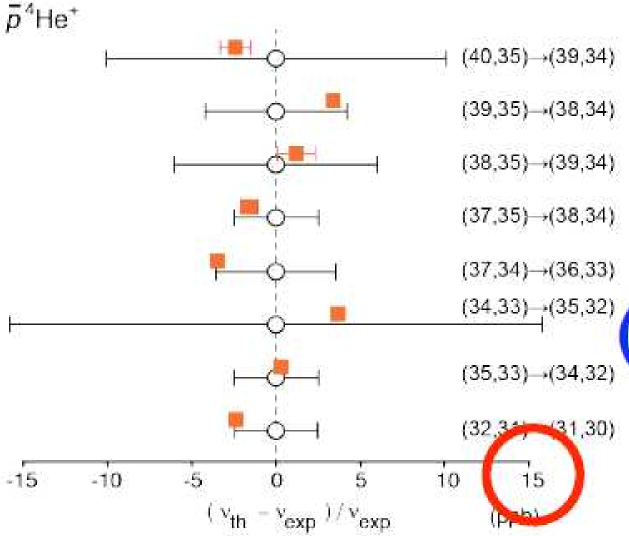
ASACUSA single photon (final)



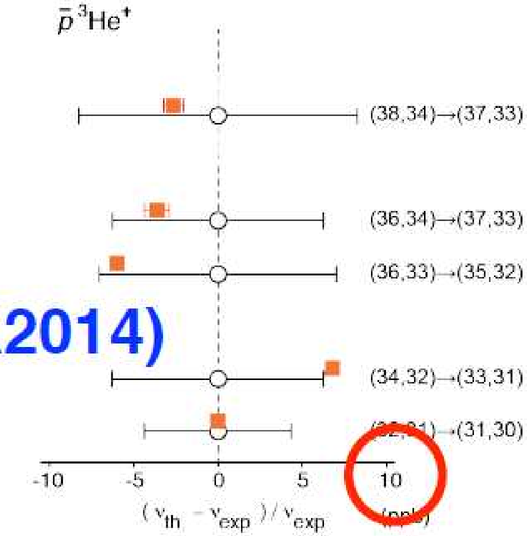
2006
~15 K



Up to 70 ppb theory-exp discrepancies

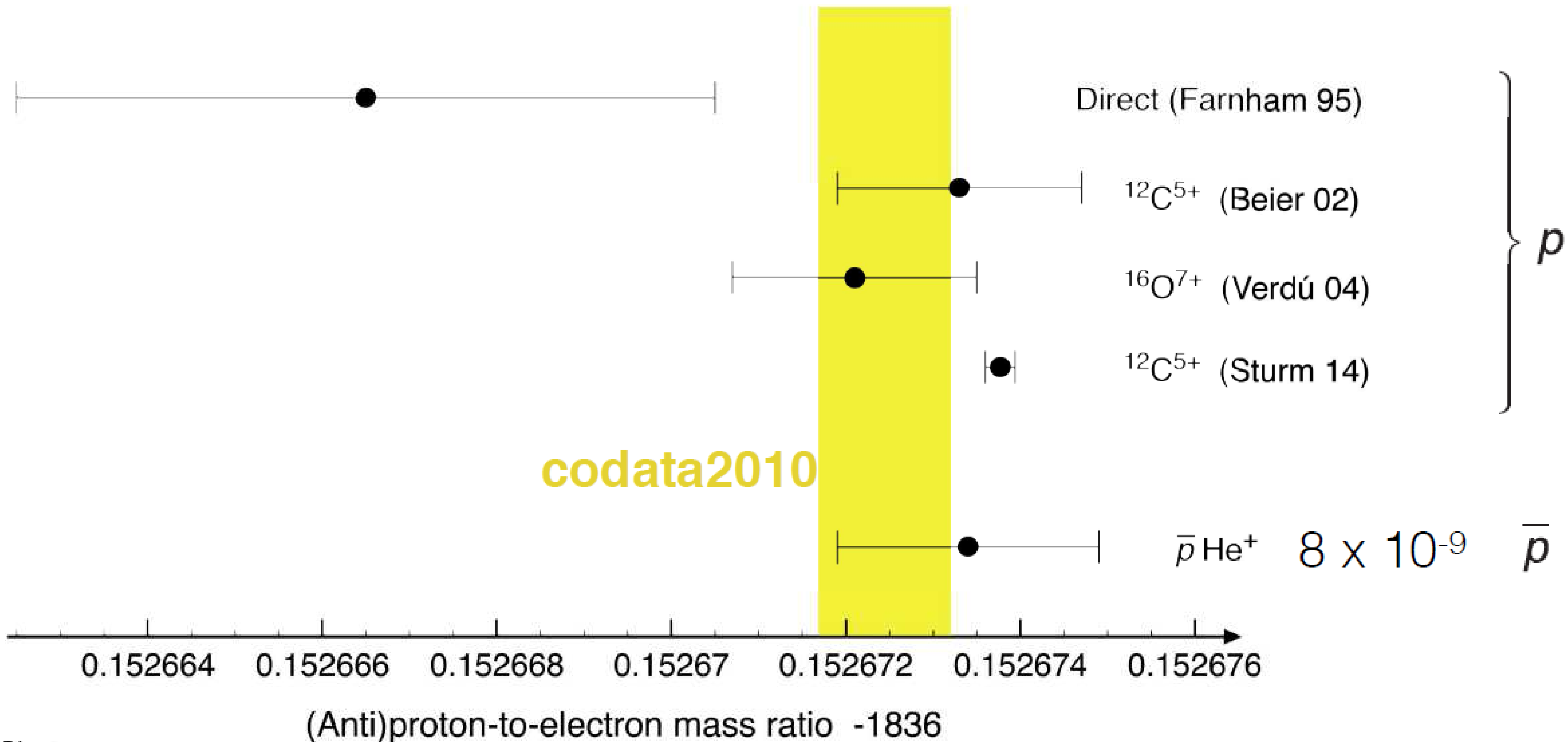


2015
~1.5K
(contributed to CODATA2014)



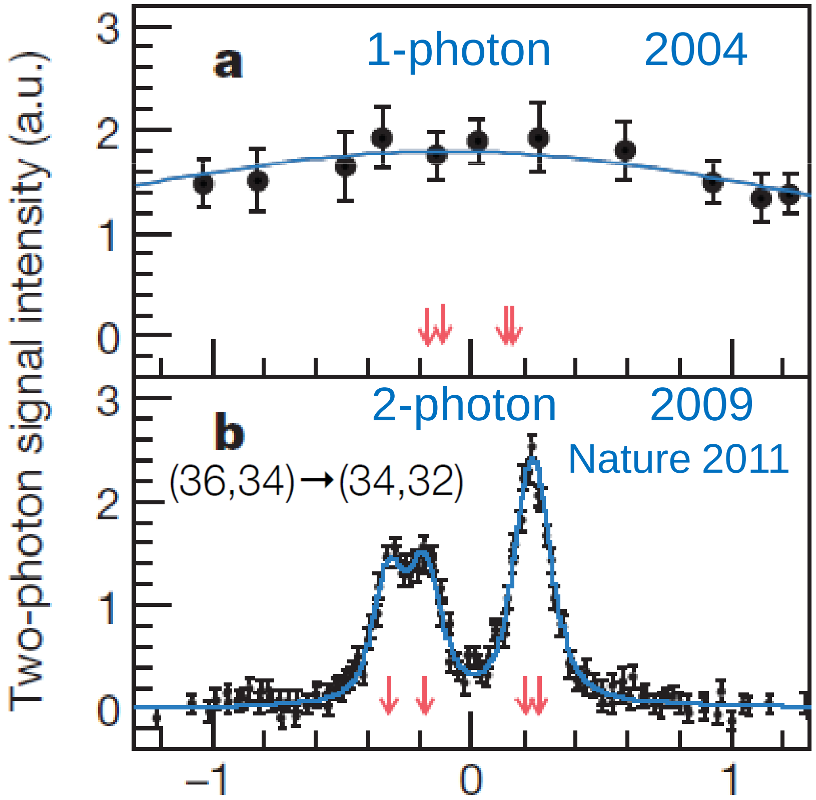
Exp precision 1.3-5 higher; theory-exp agreement improved 5-10 x

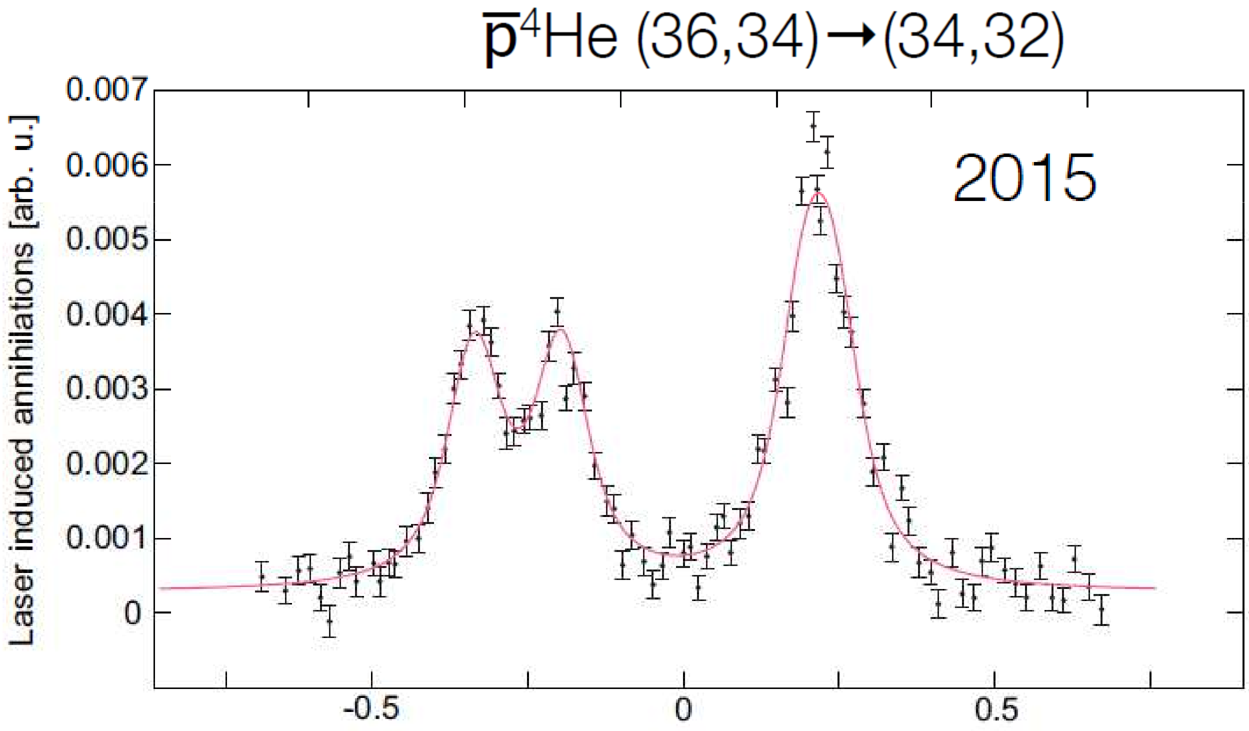
ASACUSA antiproton to electron mass ratio



To be published

2-photon experiment at 1.5 K





- New frequency comb improved experimental stability
- Leak in target→higher temperature
  → slight deterioration of resolution
  (will be fixed in 2016)

2016: continuation of 2-photon exp at 1.5 K

$\bar{p}^4He$

(n,l)=(36,34)→(34,32)

(n,l)=(31,30)->(30,29)

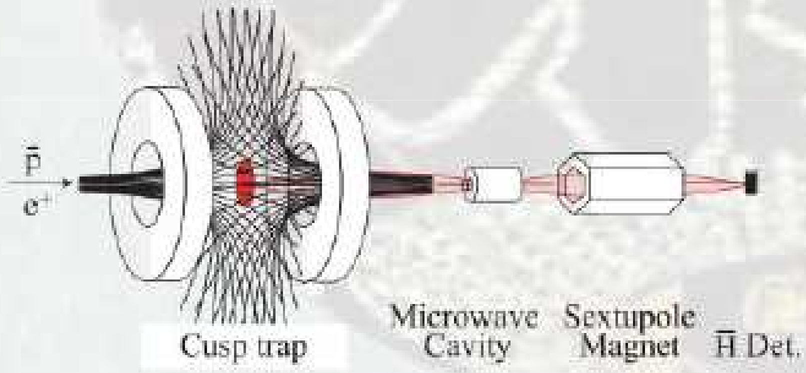
$\bar{p}^3He$

(n,l)=(30,29)->(29,28)

Goal: antiproton-to-electron mass ratio $<3\times10^{-10}$

($<1 \times 10^{-10}$ at ELENA)

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

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

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

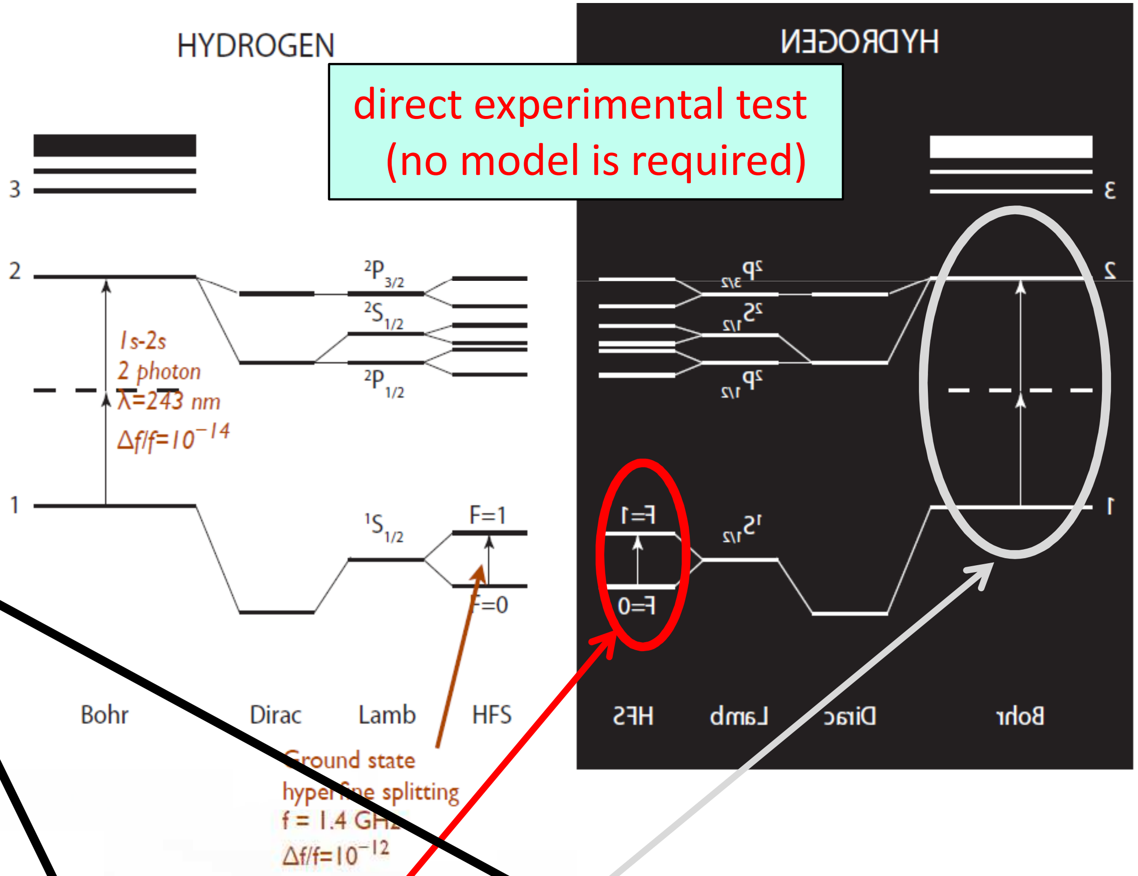
Lorentz Invariance Violating terms

a & b parameters have energy dimensions

No quantitative prediction

Antihydrogen for CPT test

matter-antimatter precise comparison by means of spectroscopy



ASACUSA

Plans for antihydrogen:

- measurements: **- Hyperfine splitting of ground state**

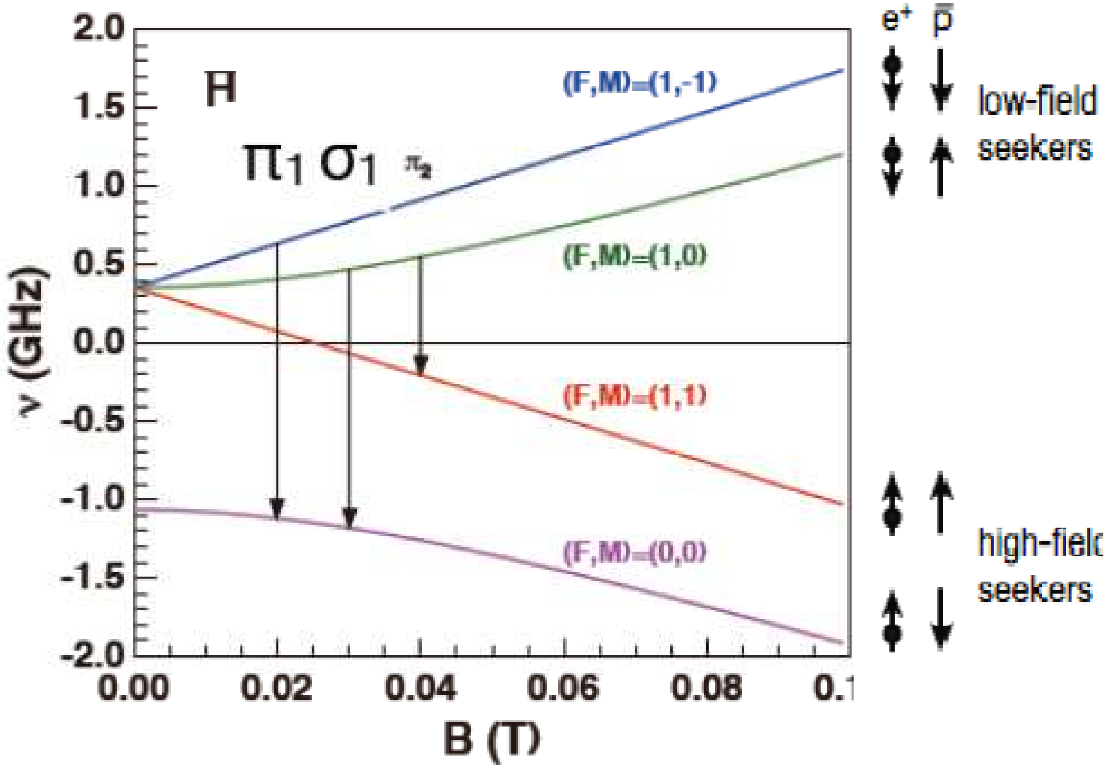
  - 1S-2S transition

- 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



Antihydrogen GSHFS Spectroscopy in 2015

1. transportation of 20 eV $\bar{p}$s to the double-cusp trap
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3. synthesis of $\bar{H}$ atoms - formation rate ~15 %
4. $\bar{H}$ transport and detection
5. σ_1 hyperfine frequency of ordinary H atoms measured to <10 ppb

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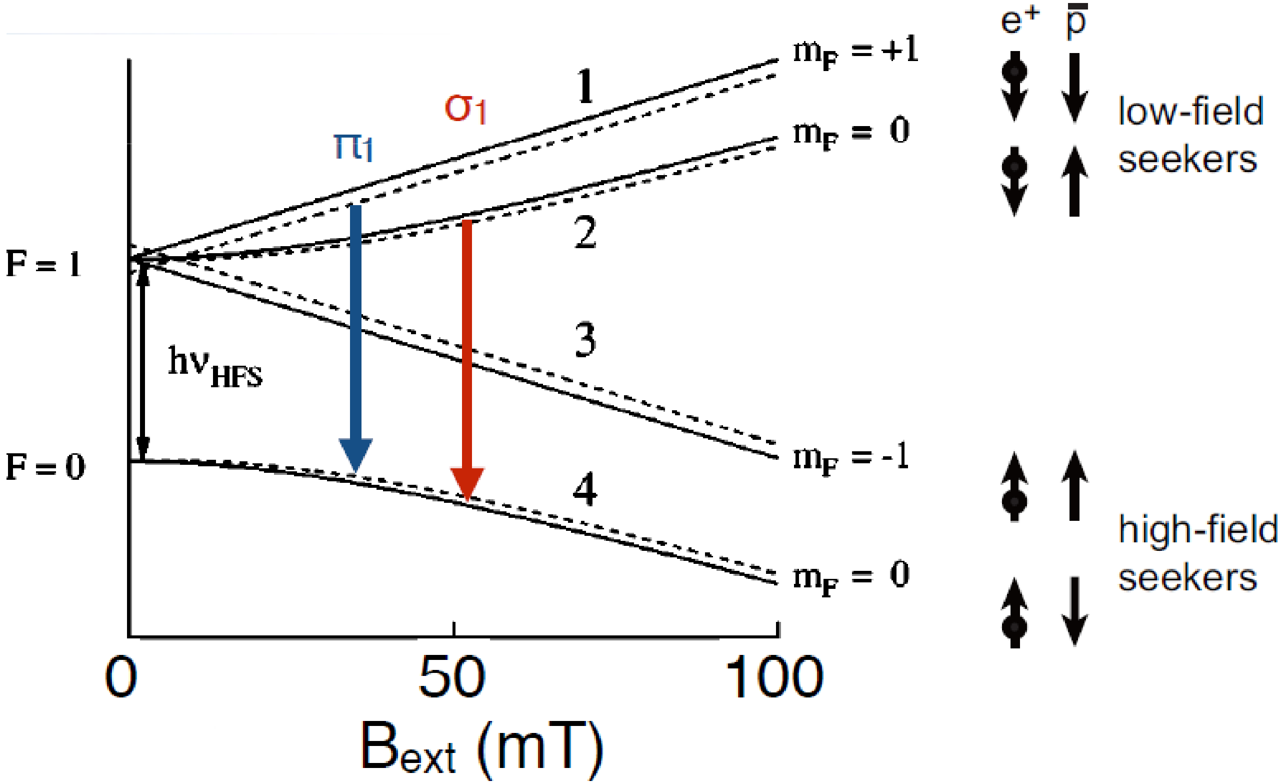
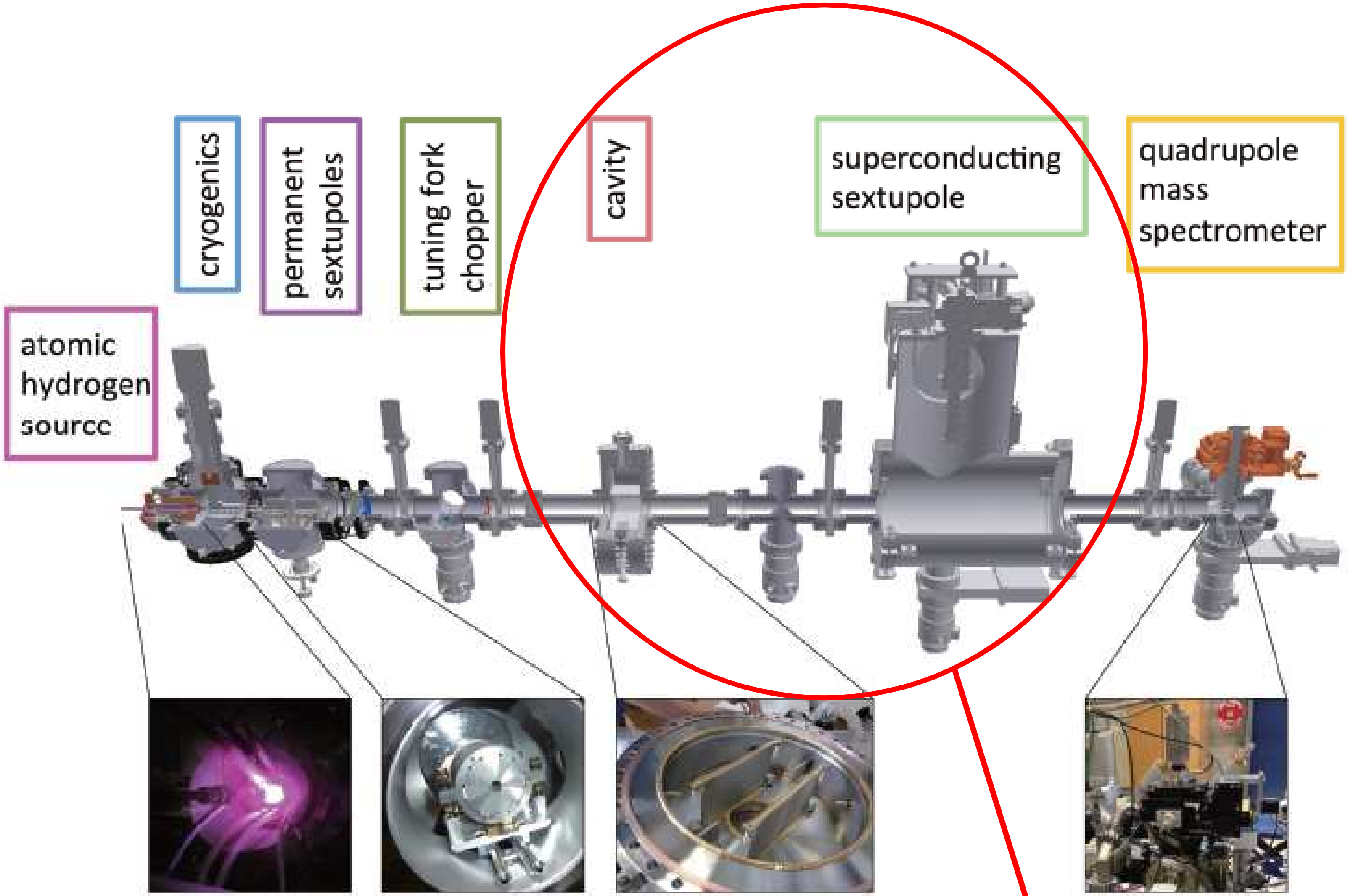
Two accessible transitions, σ_1 & π_1

σ_1 - less sensitive to B_{ext}

π_1 - more sensitive to B_{ext}
& possible CPTV effects



The hydrogen setup



Same as for Hbar

hydrogen σ_1 measured

- Best beam value up to date

$$\nu = 1420.40573(5)\,\text{MHz}$$

$$\frac{\Delta\nu}{\nu} = 3.5 \times 10^{-8}$$

Kusch, Phys. Rev. 100, 4, (1955)

- Maser experiments

$$\nu = 1420.405751768(1)\,\text{MHz}$$

$$\frac{\Delta\nu}{\nu} = 7 \times 10^{-13}$$

N.F. Ramsey et al., Quantum Electrodynamics, World Scientific, Singapore, 1990, p. 673

preliminary results:

ν = 1 420.405 7… MHz
statistical error ~3 Hz
systematic error ~2 Hz

rel. precision: < 3 ppb

factor >10 better than Kusch et al.

Performed by E.Widmann group (SMI)

soon to be published

precision π_1 measurement planned in 2016

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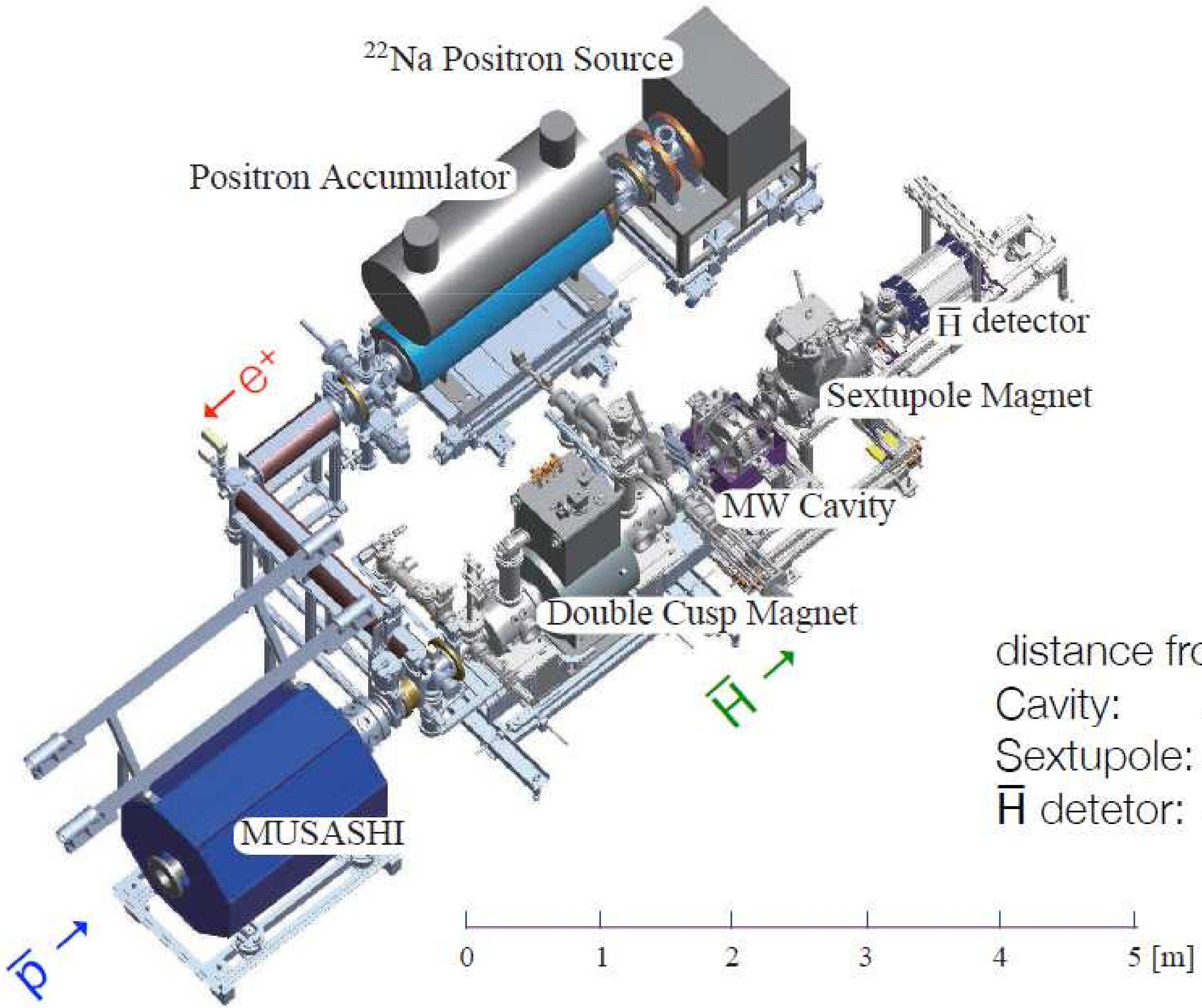


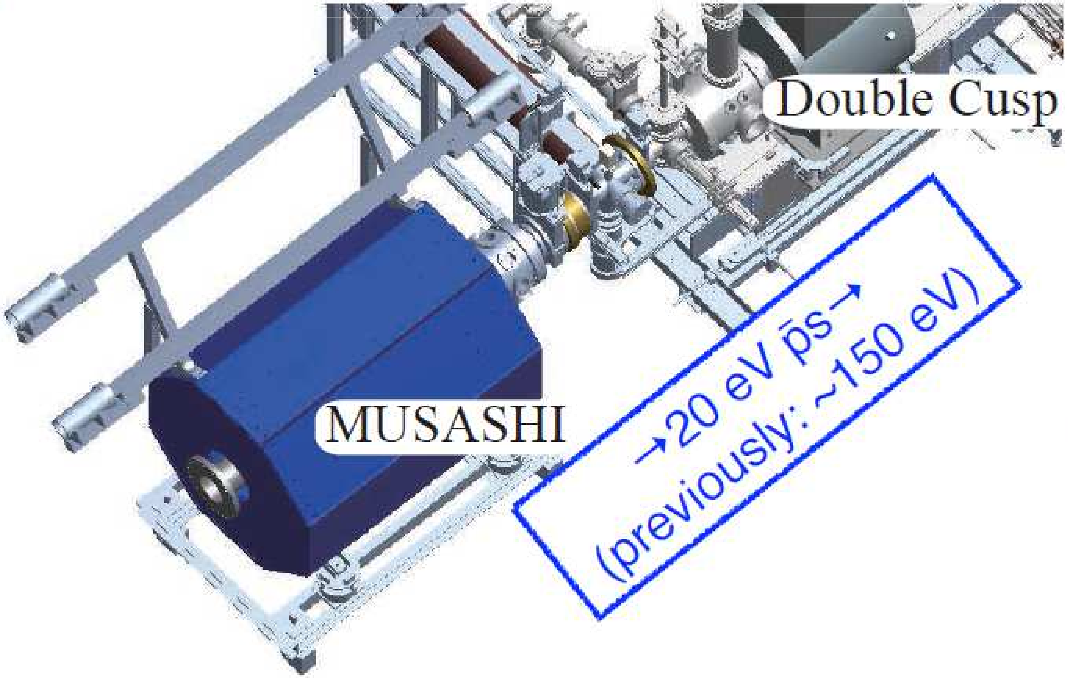
distance from the mixing position

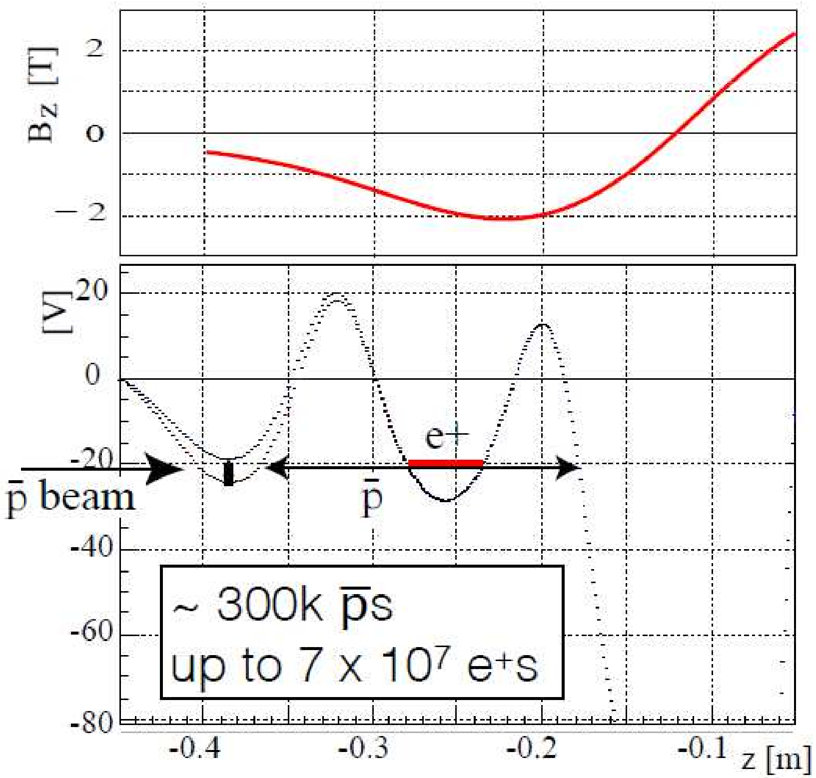
Cavity: +1840mm

Sextupole: +2628mm

H̄ detetor: +3739mm

minimize energy deposition to the e^+ plasma





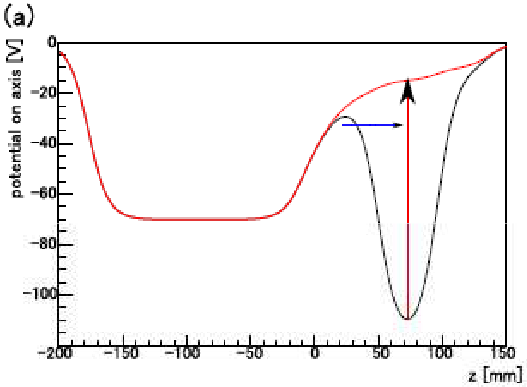
optimizing $\overline{p}$-extraction scheme

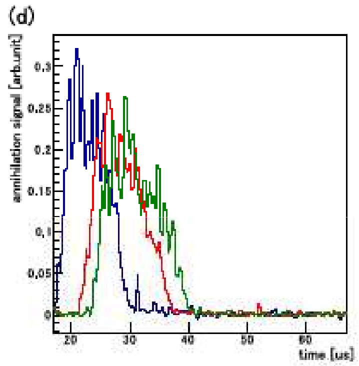
potential in the $\overline{p}$ catching trap

$\overline{p}$ time distribution downstream

$\overline{p}$ trapping

$\overline{p}$ extraction



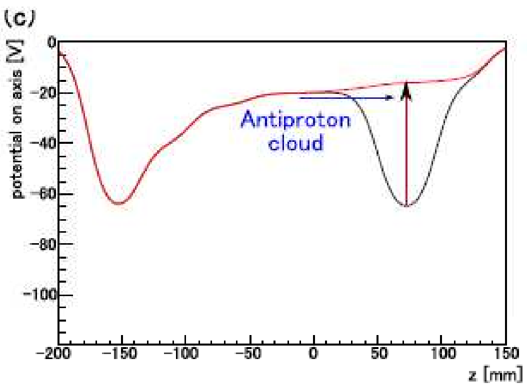


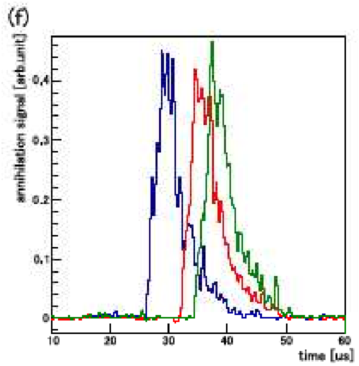
1.5 m

1.9 m

2.1 m

20 eV→



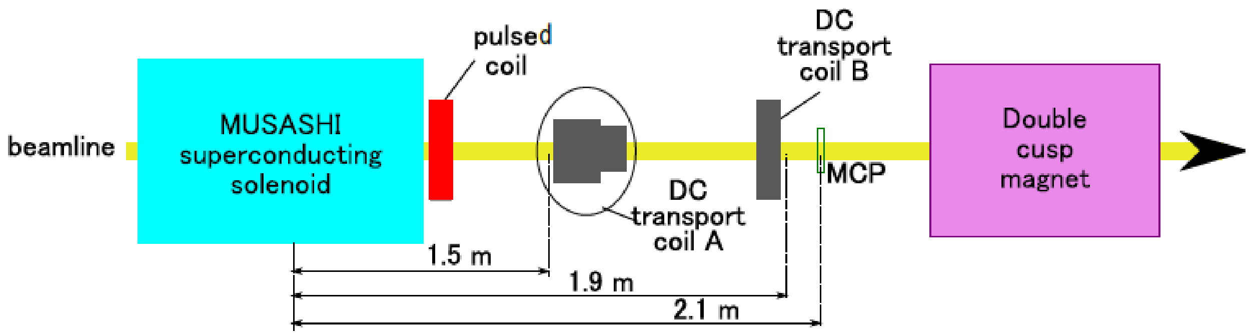


1.5 m

1.9 m

2.1 m

estimated $T_{\overline{p}} \sim 1eV$



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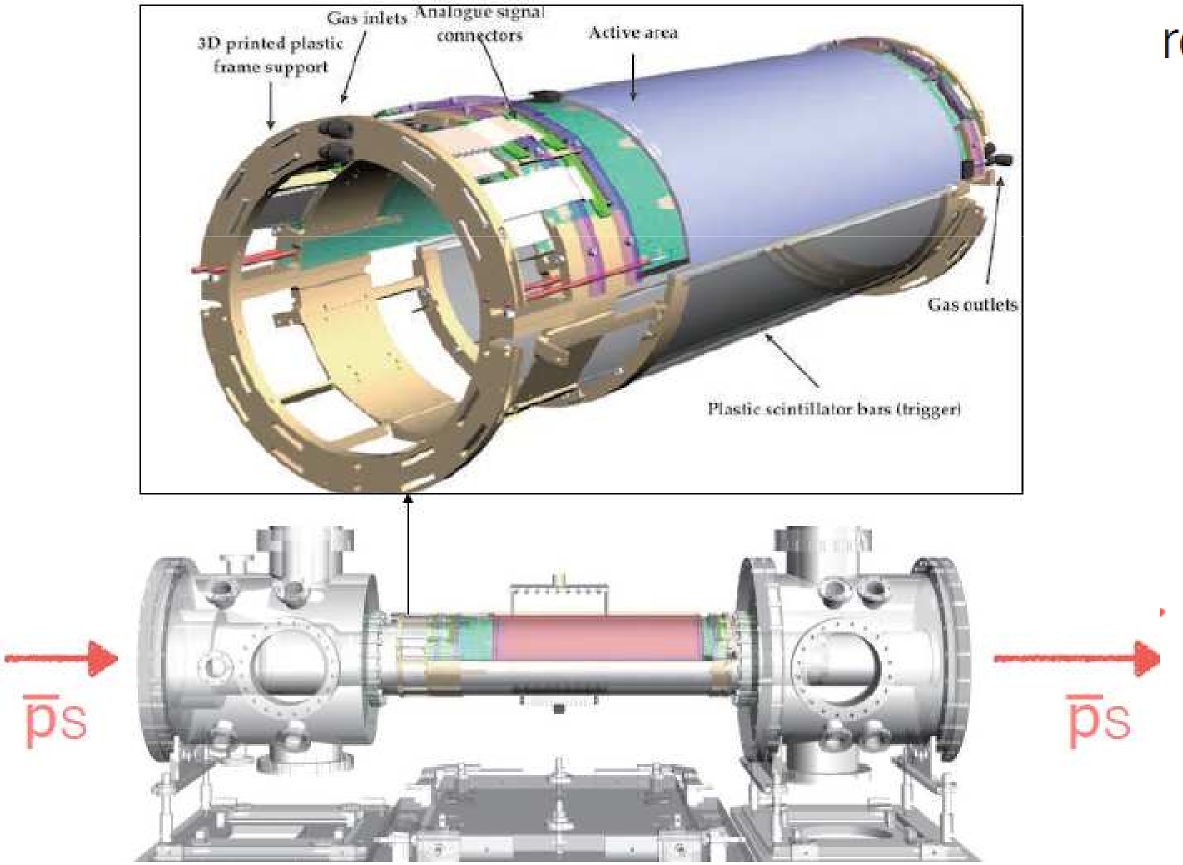
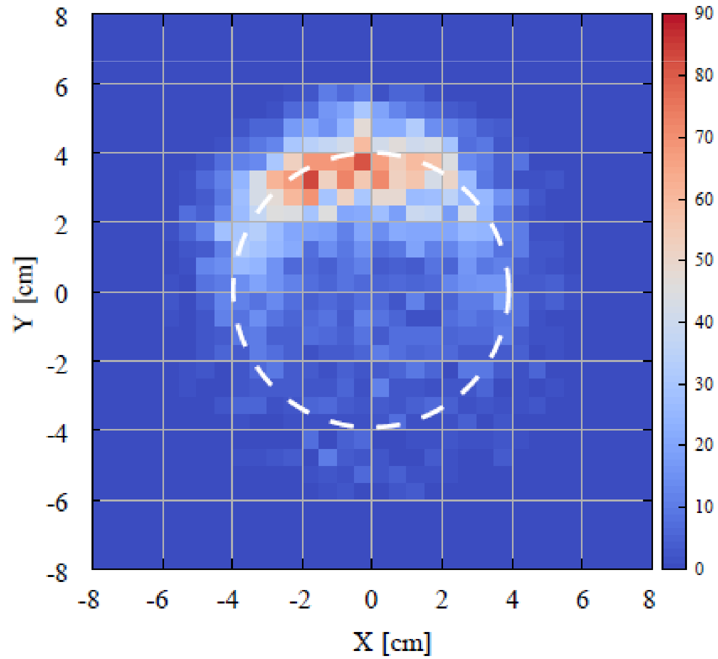
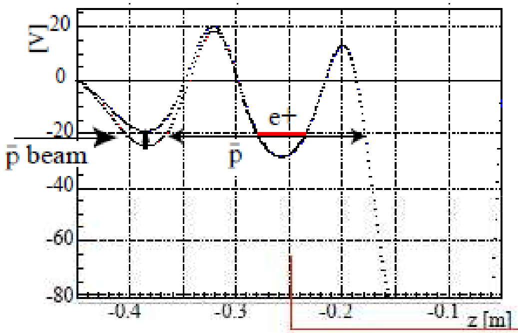
micromegas around the 2-cusp vacuum tube

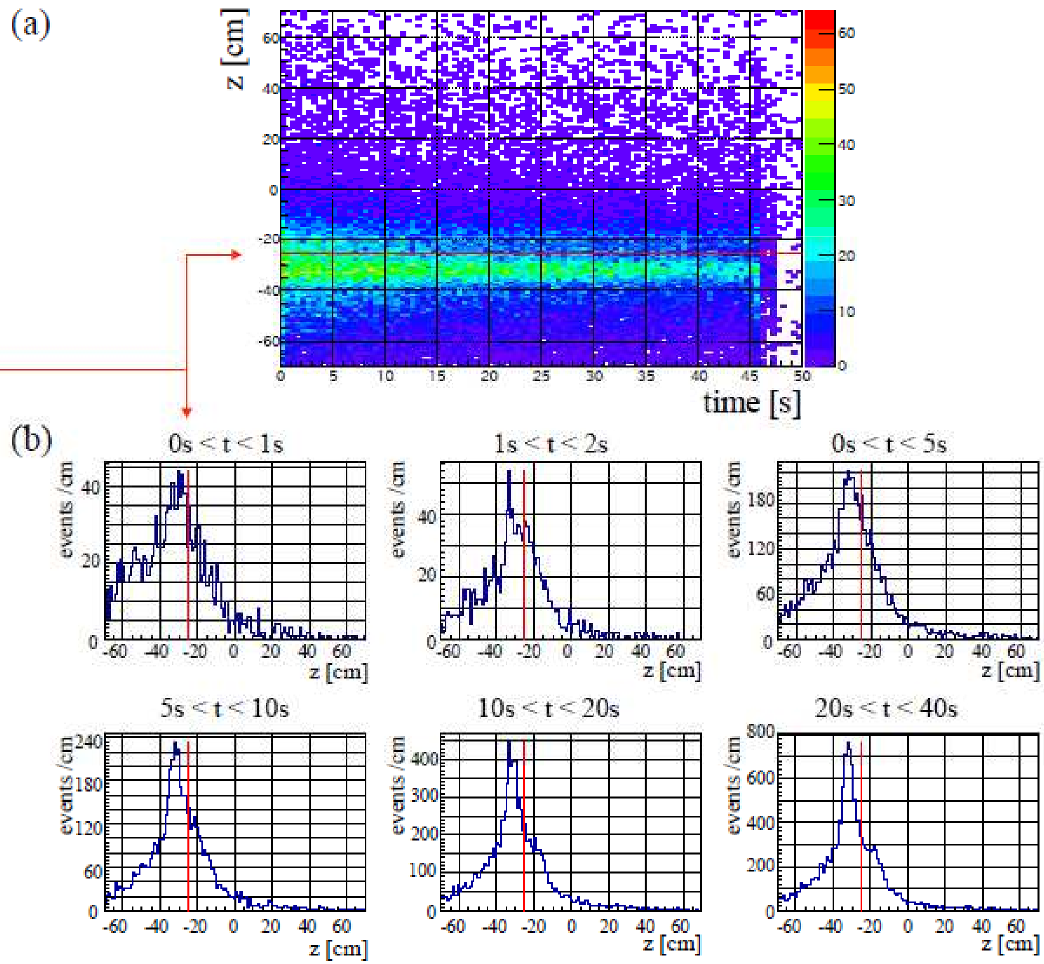


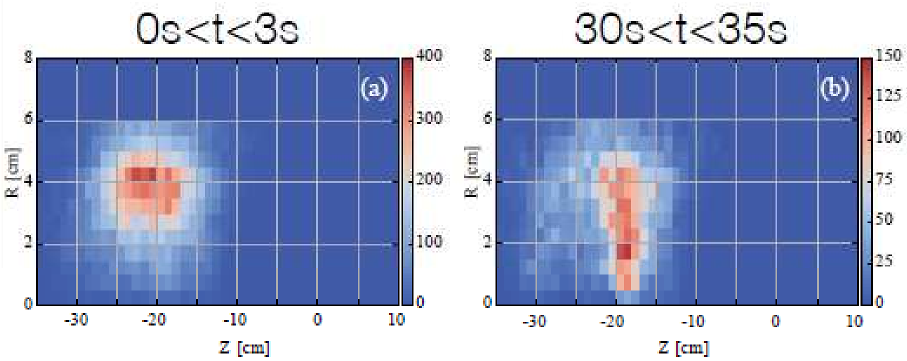
reconstructed annihilation x-y vertices with slow-extracted p̄s



time evolution of annihilation positions during $\overline{p}$-e^+ mixing







R-Z distributions

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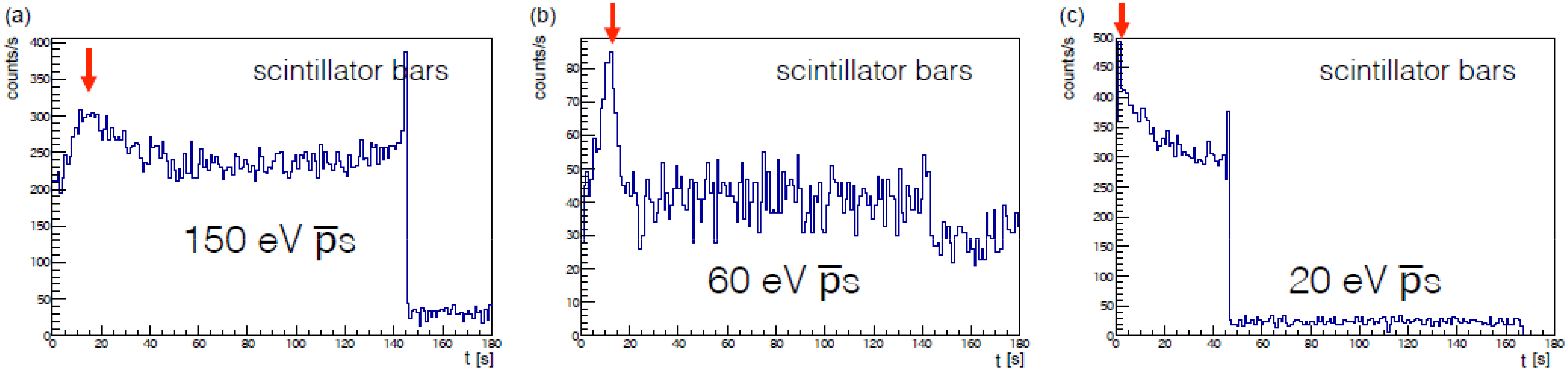
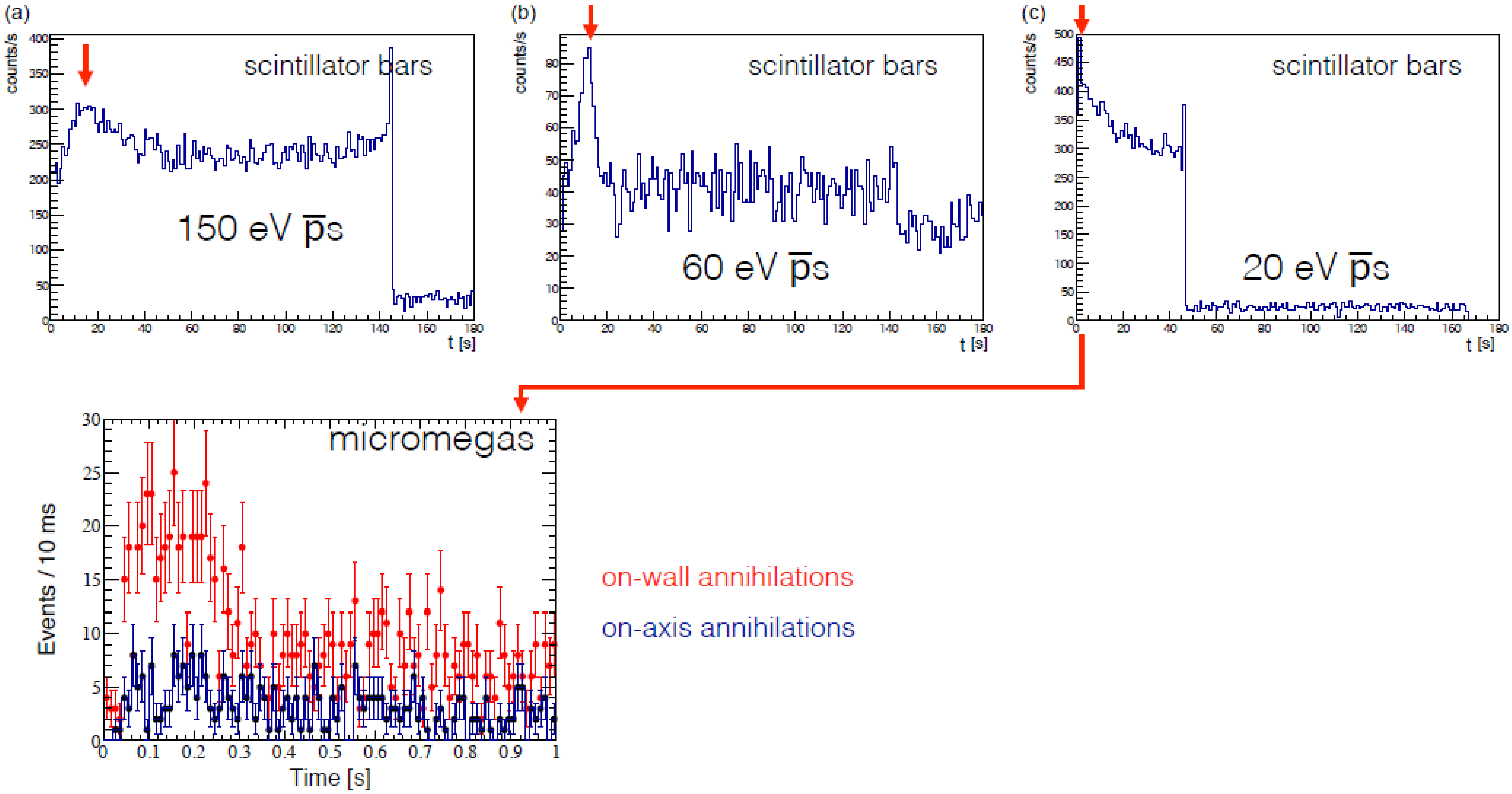
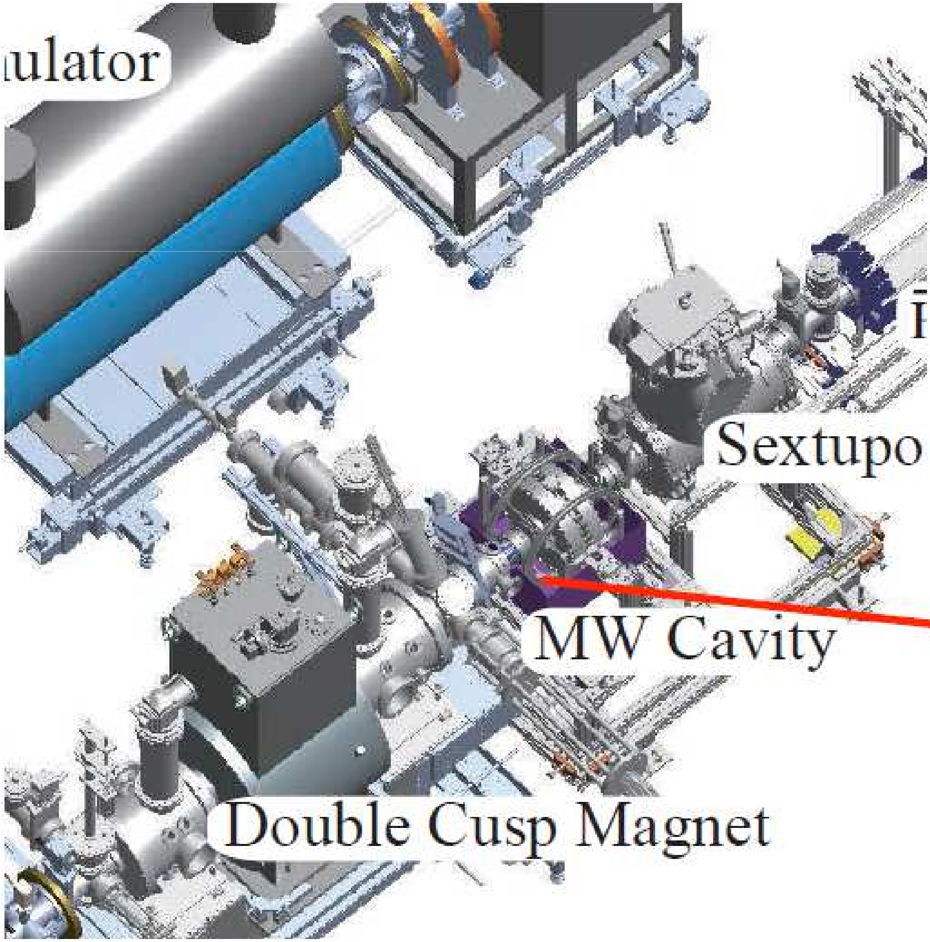
with 20 eV $\overline{p}$s - high $\overline{H}$ formation rate in early times



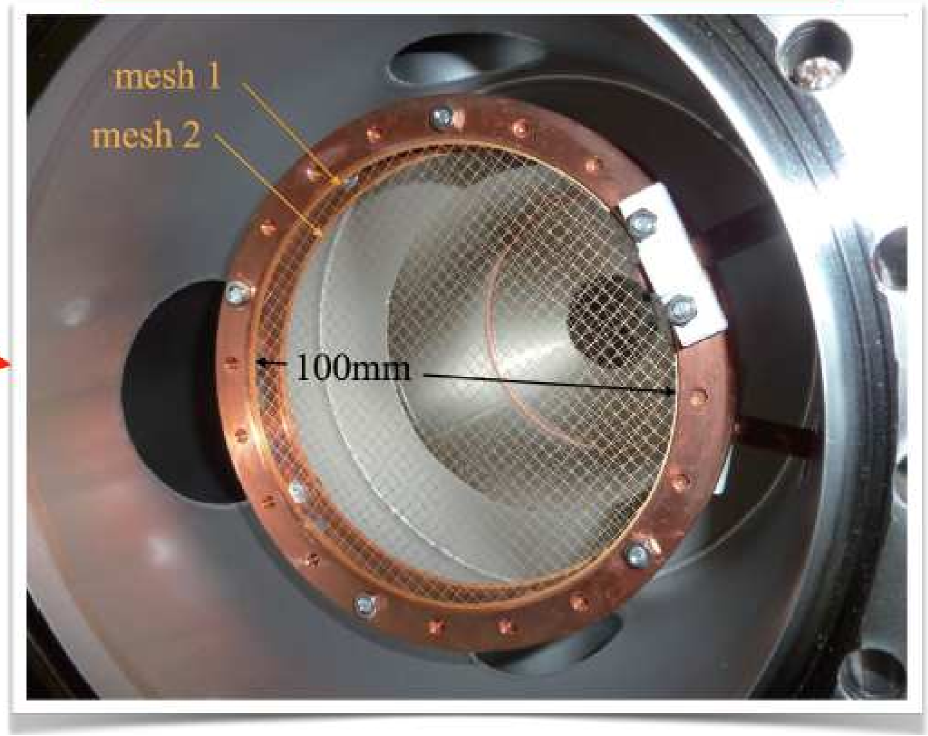
with 20 eV $\bar{p}$s - high $\bar{H}$ formation rate in early times



Field ionizer chamber between cusp & cavity



±8.7 kV → 17.4 kV/cm
→ n ≥ 12 ionized



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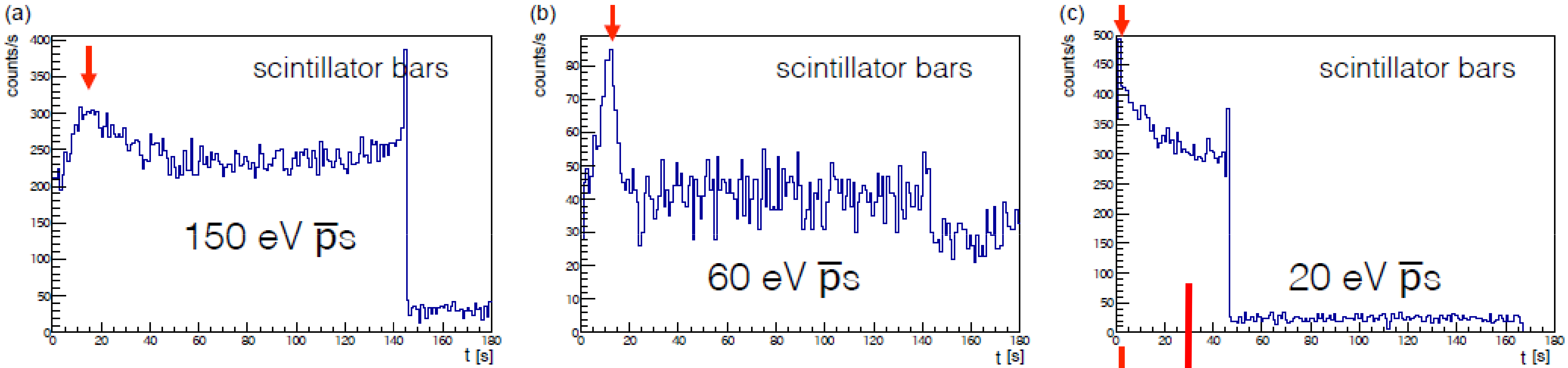

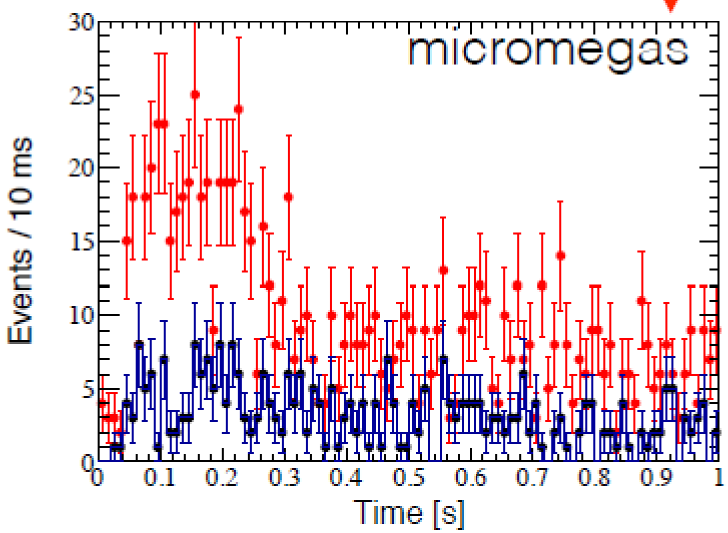

on-wall annihilations

on-axis annihilations

- The total number of field-ionized $\overline{H}$s ~ 390 (in 40 s)
- $\overline{p} \rightarrow \overline{H}$ efficiency ~16% (assuming isotropic emission)

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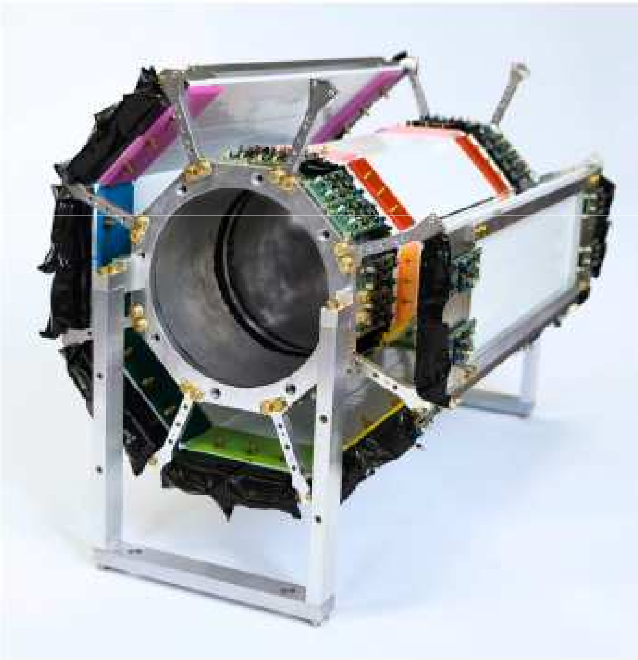
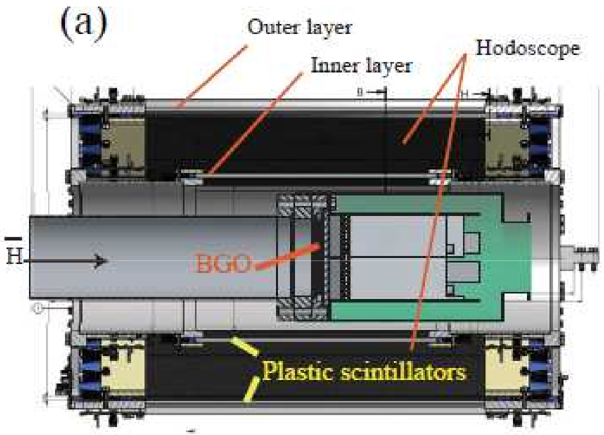
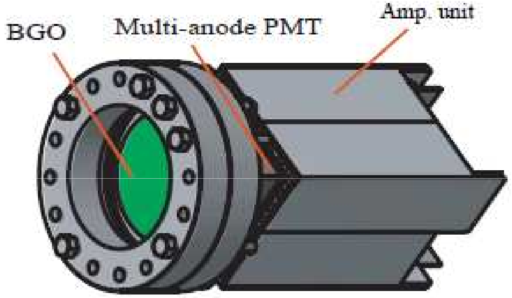
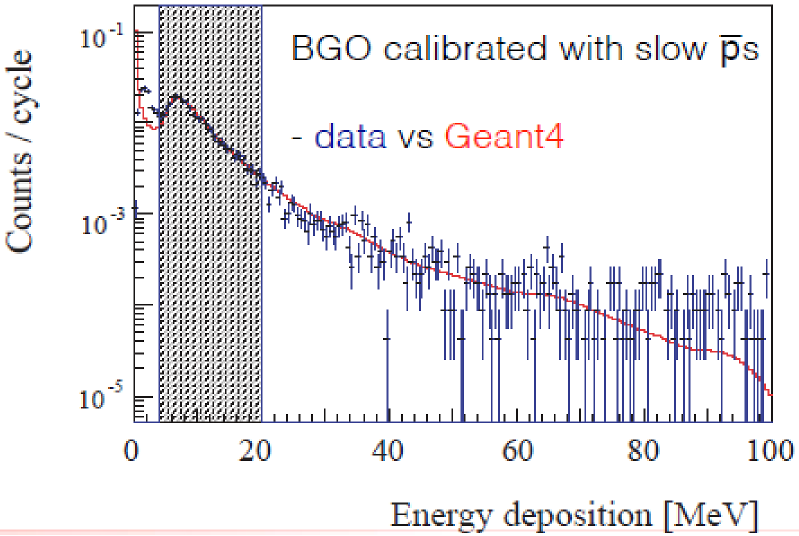
$\bar{H}$ detector @ 3.7m (Solid angle ~0.004%)



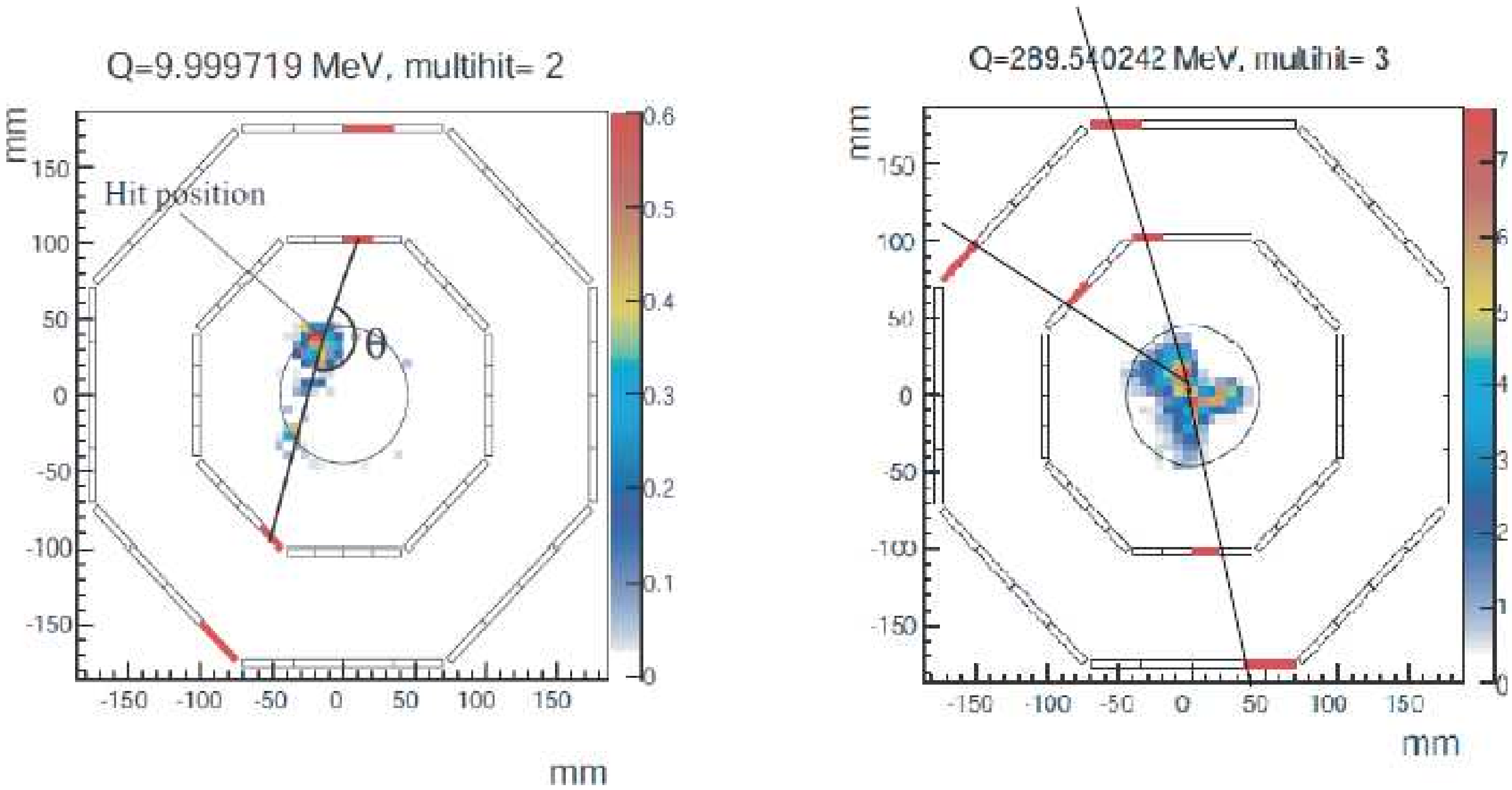






cosmic vs $\overline{H}$ ($\overline{p}$)

BGO energy deposit and hodoscope opening angle



$\overline{H}$ GSHFS Spectroscopy: 2015 summary

1. $\overline{H}$ atom formation rate ~15 % with 300k $\overline{p}$s at 20 eV & $7x10^7$ e^+s

2. $\overline{H}$ detection scheme perfected

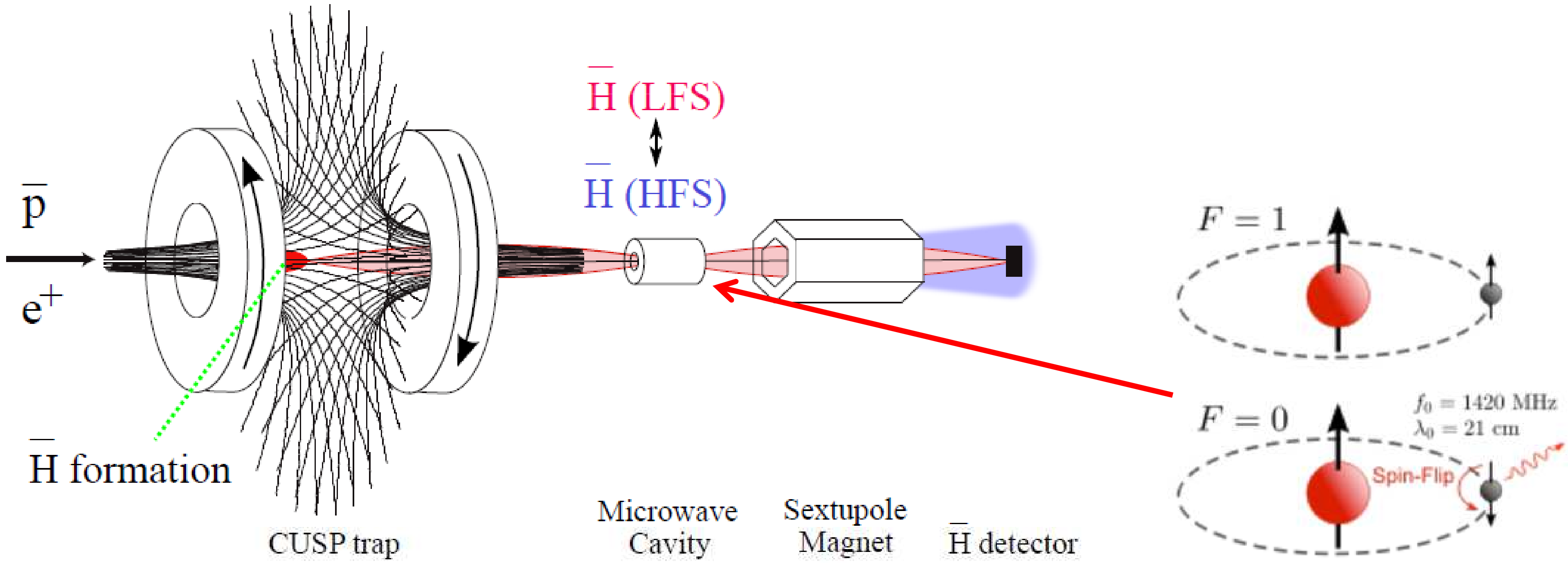
3. σ_1 hyperfine frequency of ordinary H atoms measured to <10 ppb

4. Currently, ~1 $\overline{H}$ detected / mixing cycle (~15 min)
   x10 $\overline{H}_{gs}$ rate needed for spectroscopy

Next steps

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

Perform the measurement

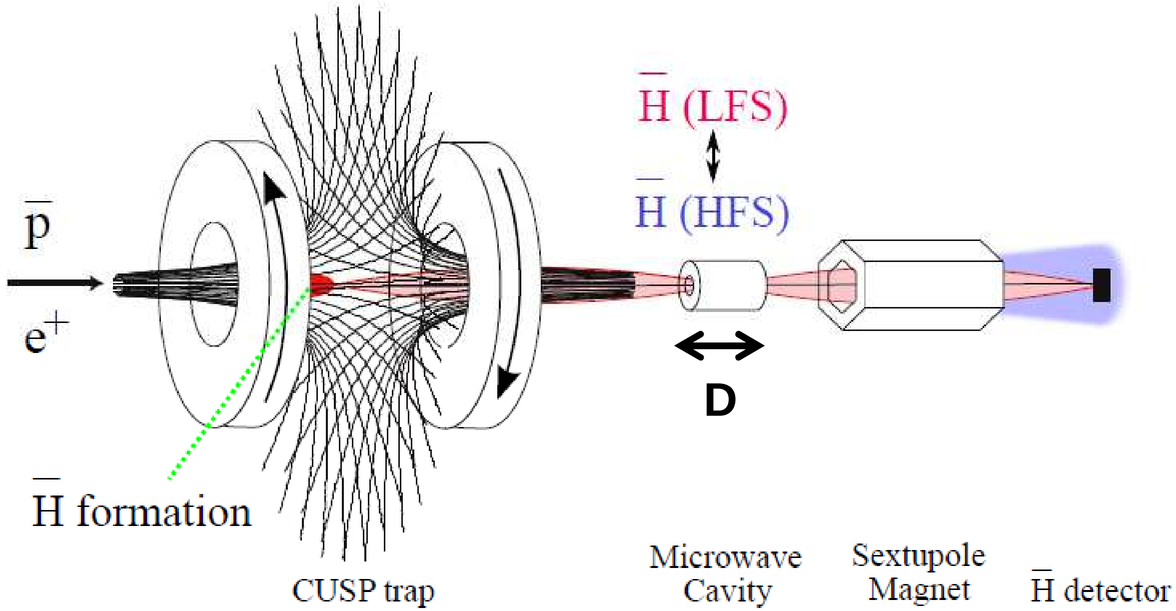


Achievable resolution:

- 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 → $\delta\nu / \nu = 8\text{x}10^{-6}$

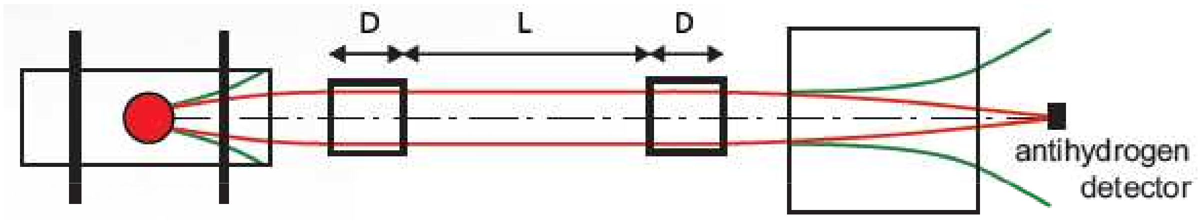
→ Resonance center resolution = 10^{-7}

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):



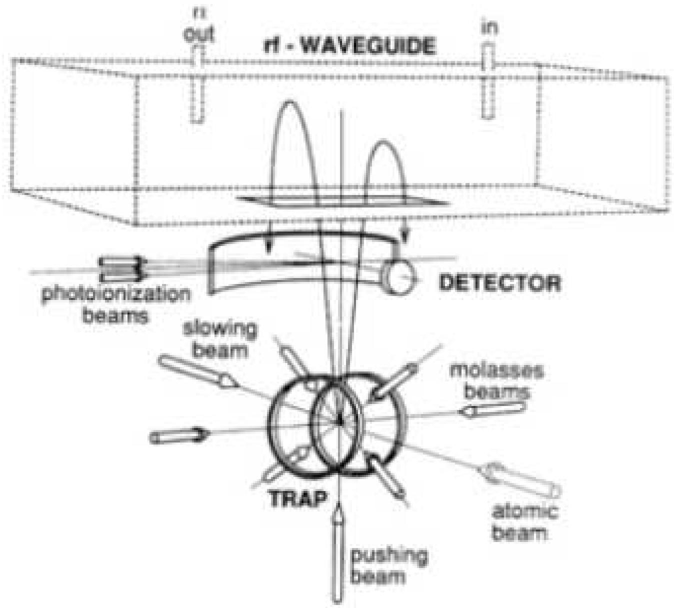
Linewidth reduced by D/L

Antihydrogen fountain:

-trapping and laser cooling

- Ramsey method with L=1m

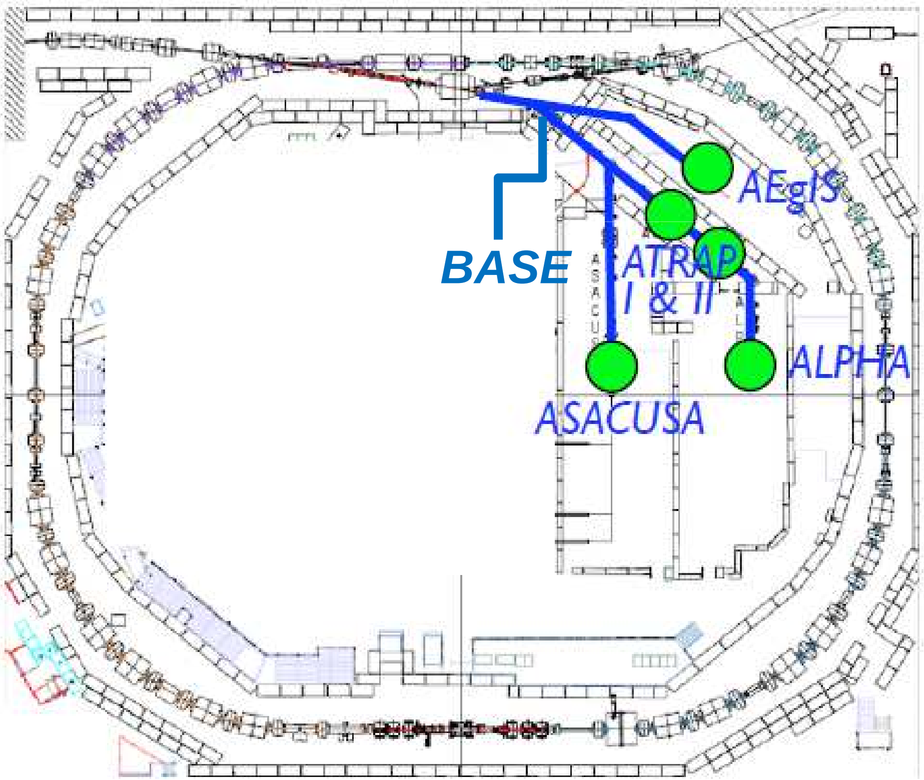
$\Delta f \sim 3$ Hz, $\Delta f/f \sim 2\text{x}10^{-9}$



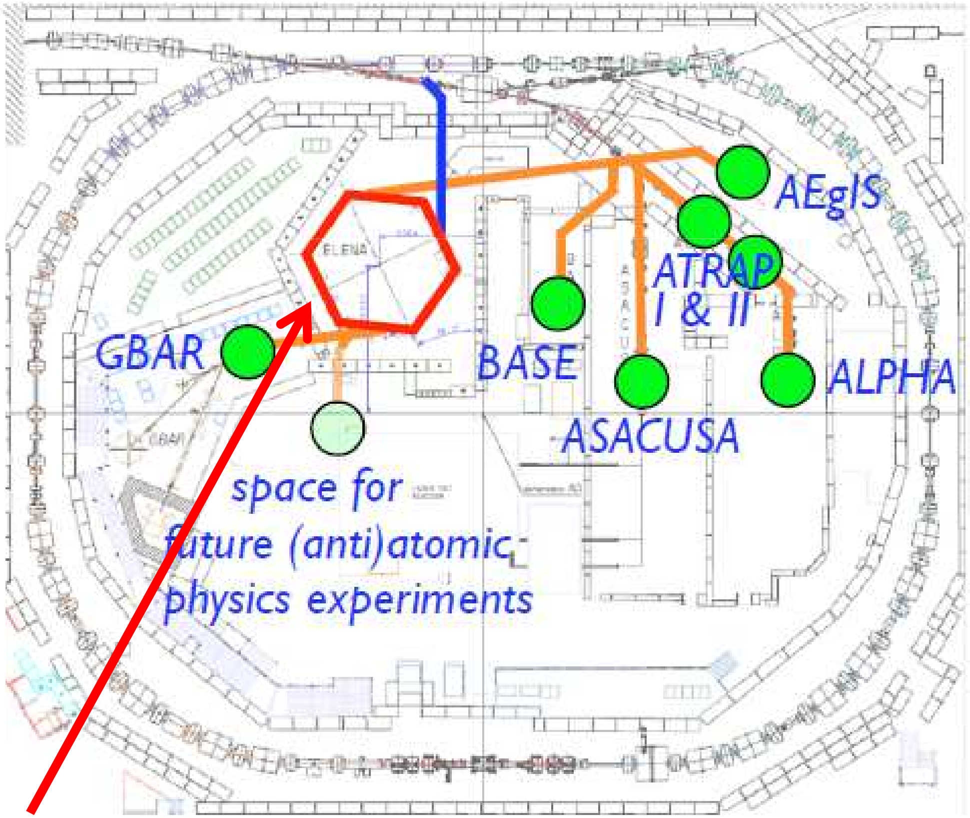
<-- AEGIS

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 collisions with antiprotons

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

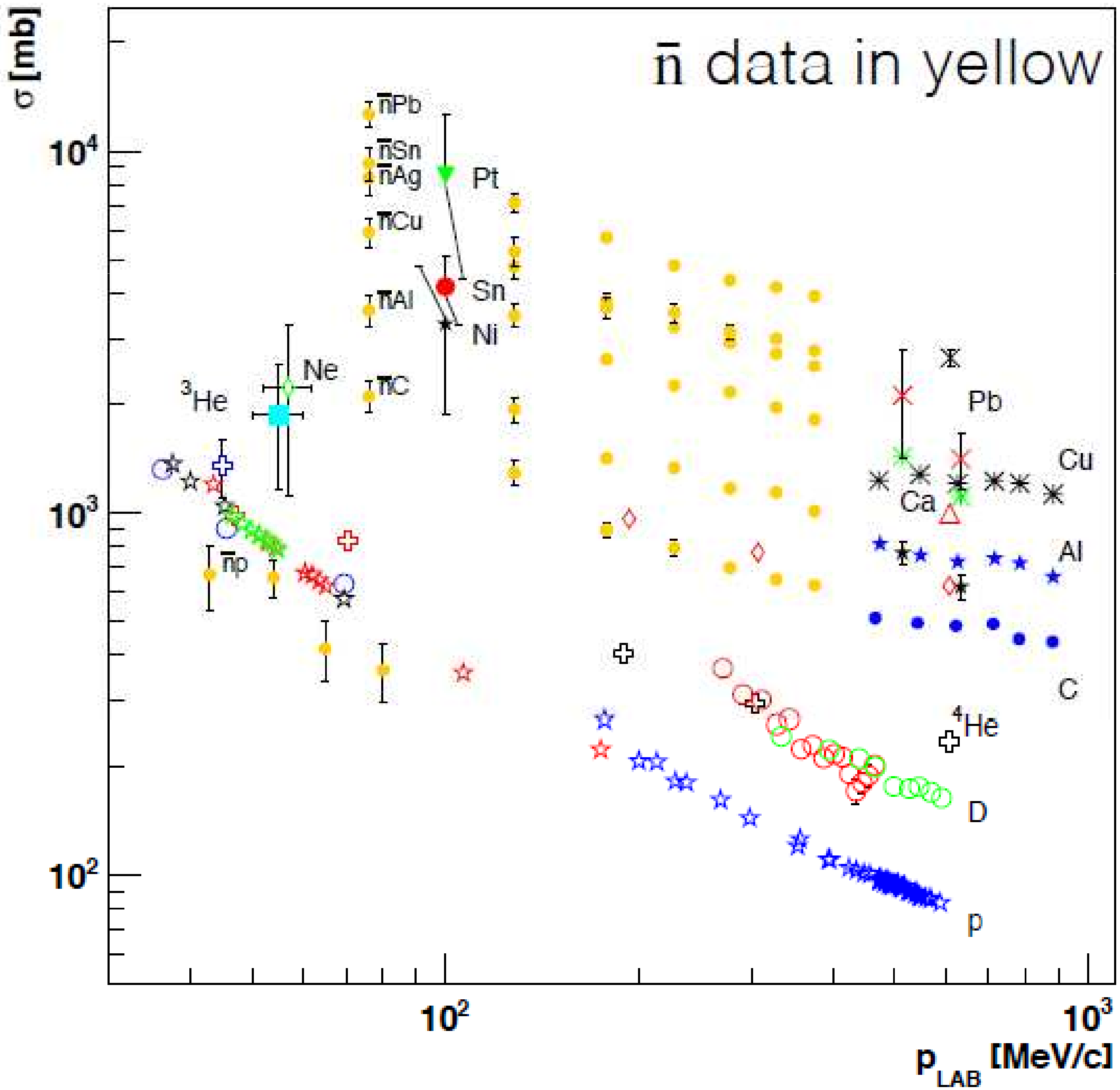
  (both potential models and phenomenological analyses state that the annihilations occur in a thin region placed just outside the nuclear volume: neutron/proton ratio or the extraction energy of the peripheral nucleons can be determined)

- …

Existing data

2011

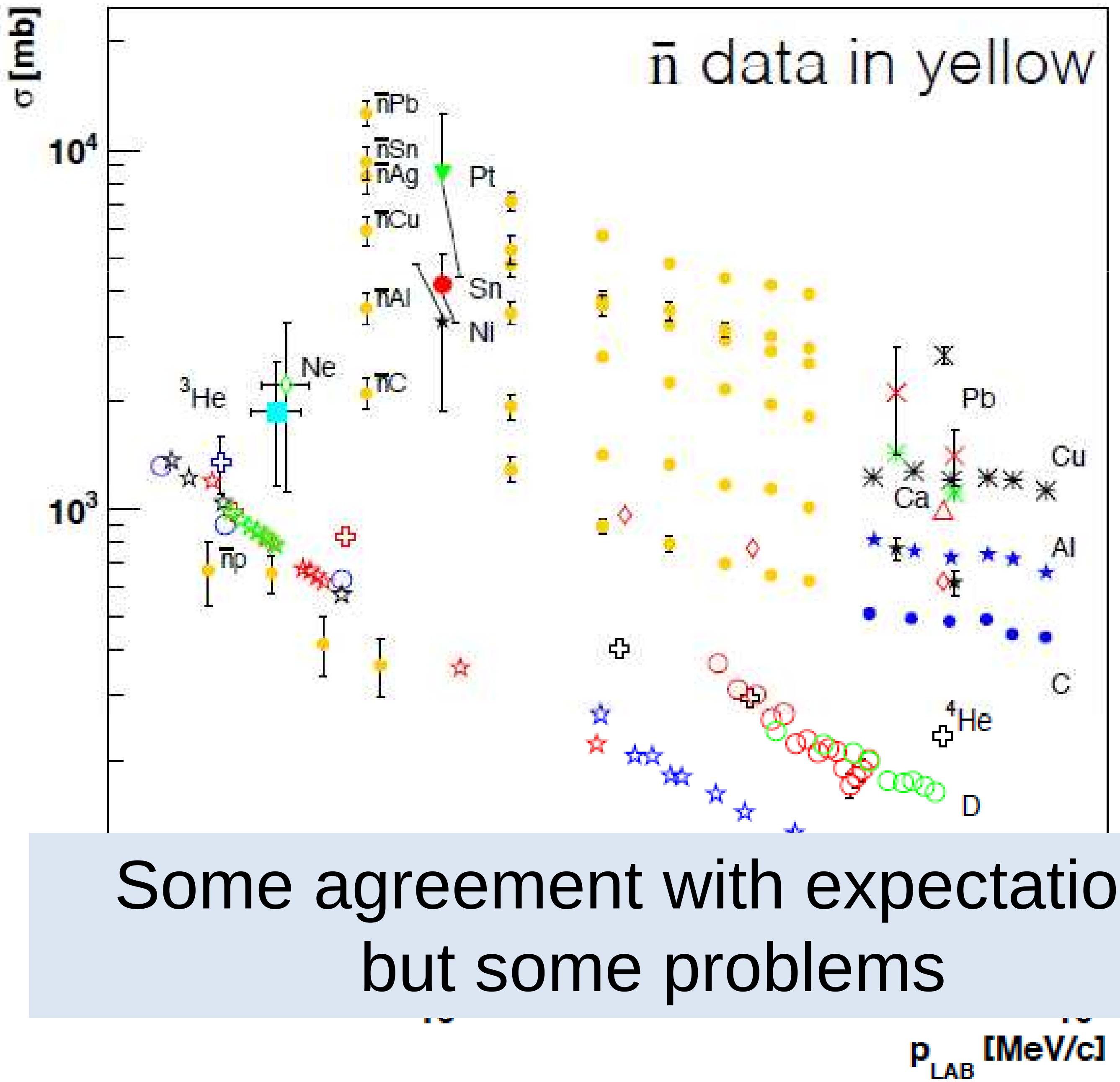
Antinucleon annihilation σ on nuclei



Existing data

2011

Antinucleon annihilation σ on nuclei



Some agreement with expectations
but some problems

Some problems

1°) No resonance detected.

2°) "inversion" (σ_{ann}'s on light nuclei cross each other at 50 MeV/c)

3°) exp. σ_{ann}'s are too high compared to the expectations

At 300-400 MeV/c σ_{ann} for pbar and nbar are similar (as expected) but are higher than what expected from optical potential

4°) nbar σ_{ann} looks like pbar σ_{ann} also at very low energy

At very low energy it is expected:

$$\sigma_{ann}(\overline{p}A) > \sigma_{ann}(\overline{n}A)$$ due to the Coulomb attraction by nucleus

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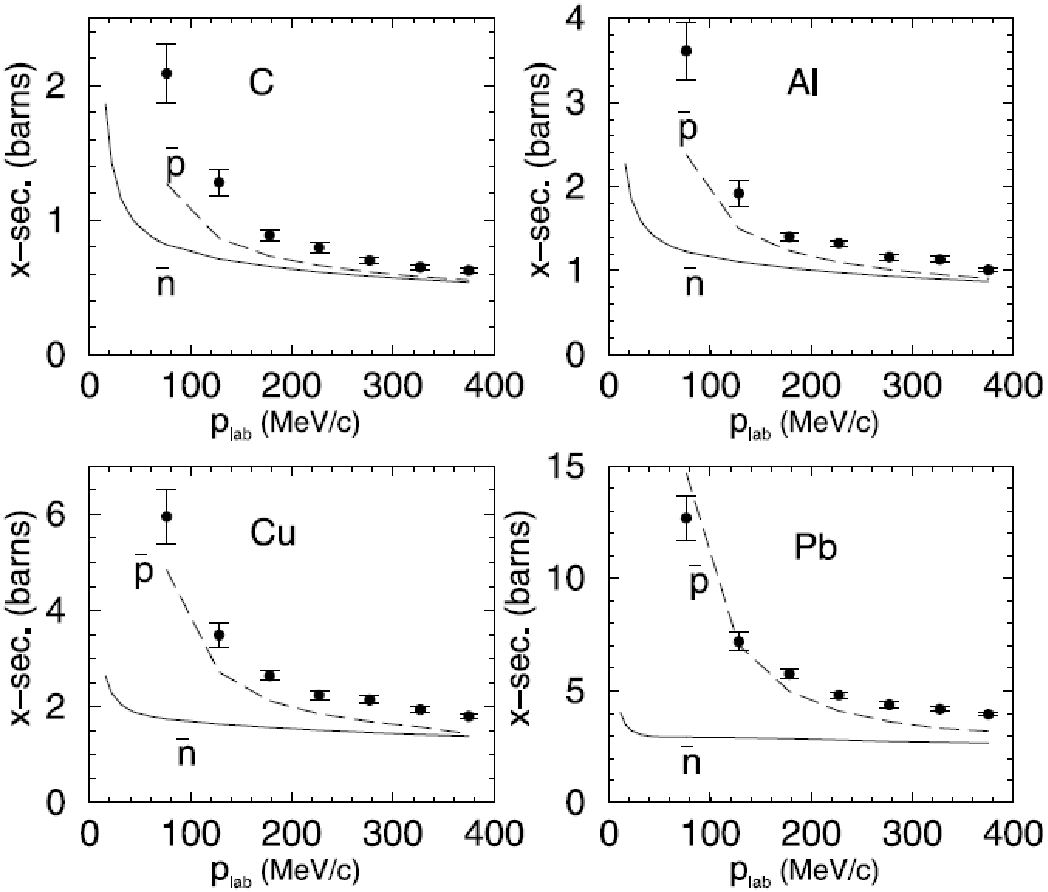
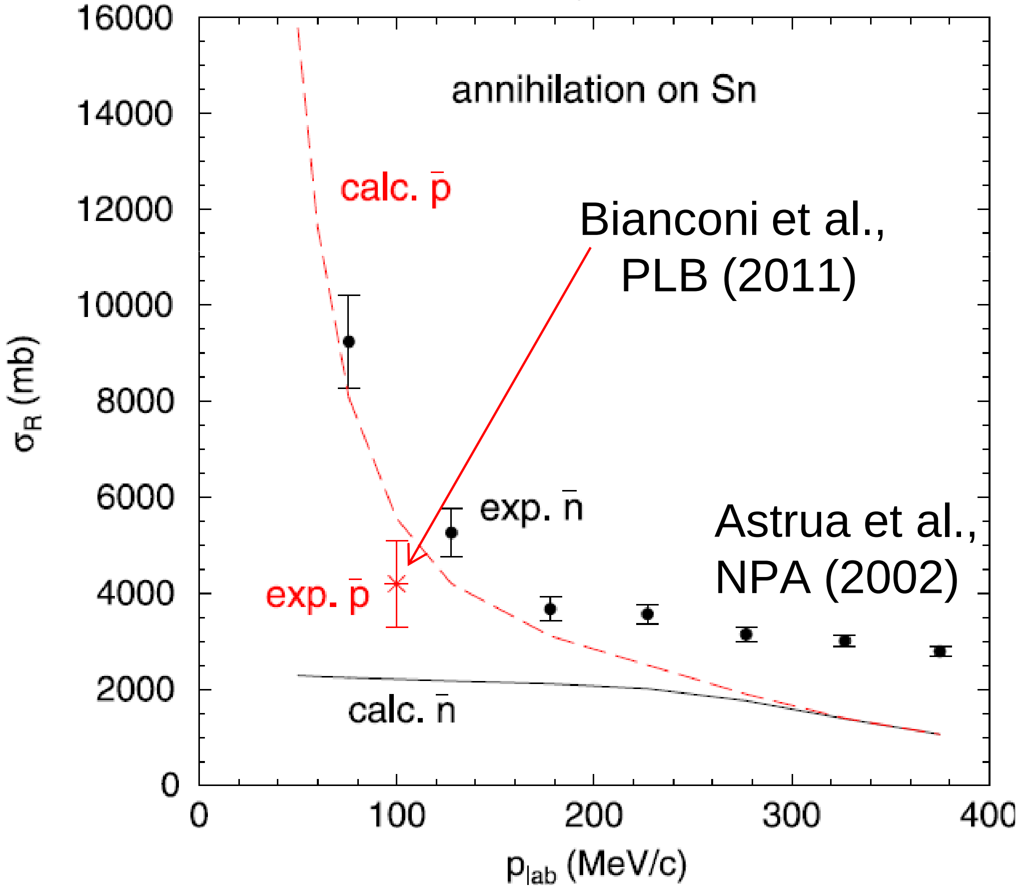
nbar σ_{ann} looks like pbar σ_{ann} at very low energy ← problem

Highlighted by Friedman NPA 2014

Only nbar data (from Astrua et al., NPA (2002))



Nbar and pbar data

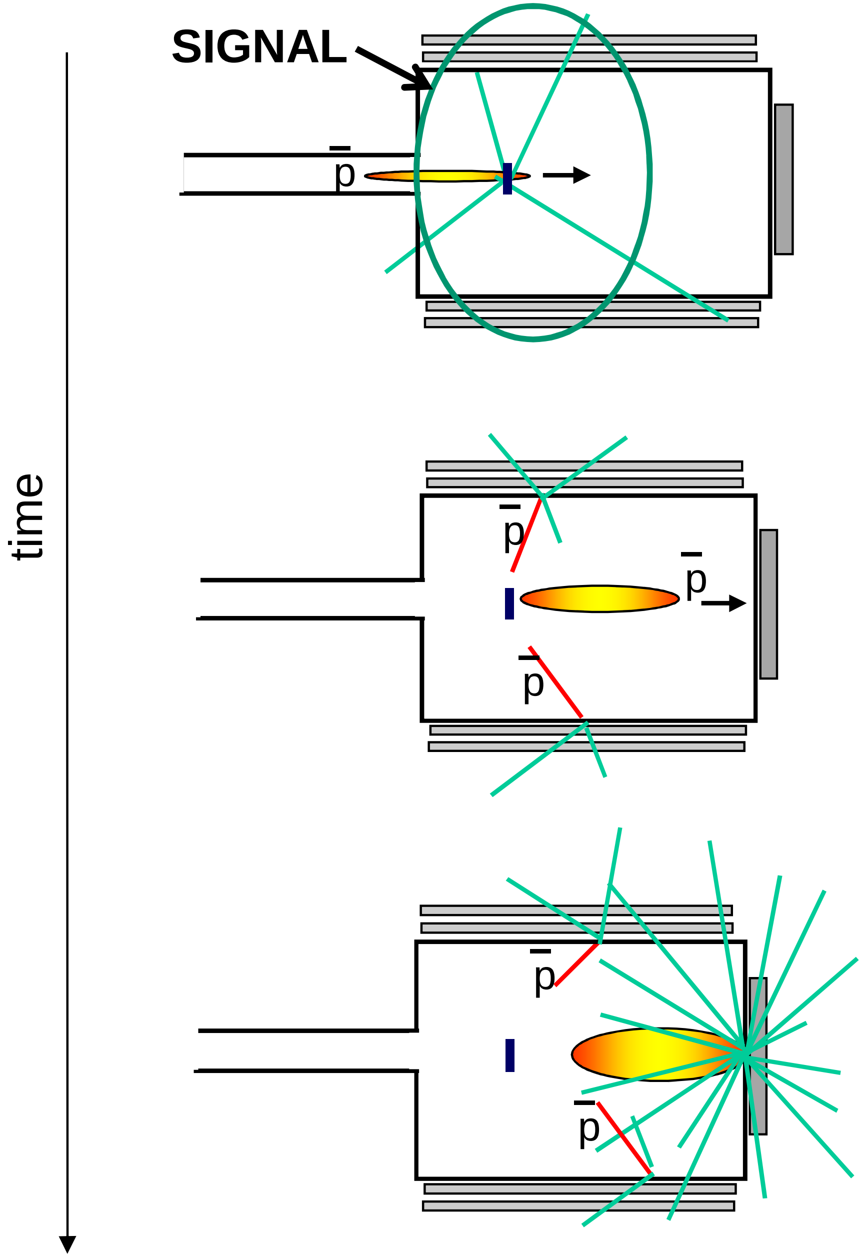


Calculations based on optical potential (Friedman) which fits well antiprotonic atoms

More antiproton data are needed for direct data-to-data comparisons

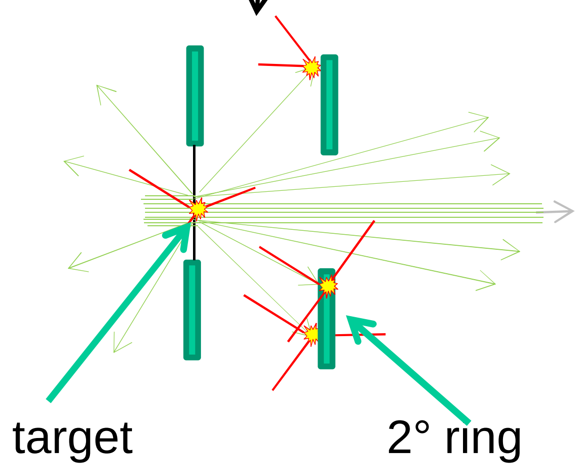
New (2015) measurement of pbar σ_{ann} performed by ASACUSA

Technique of the σ_{ann} measurement



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

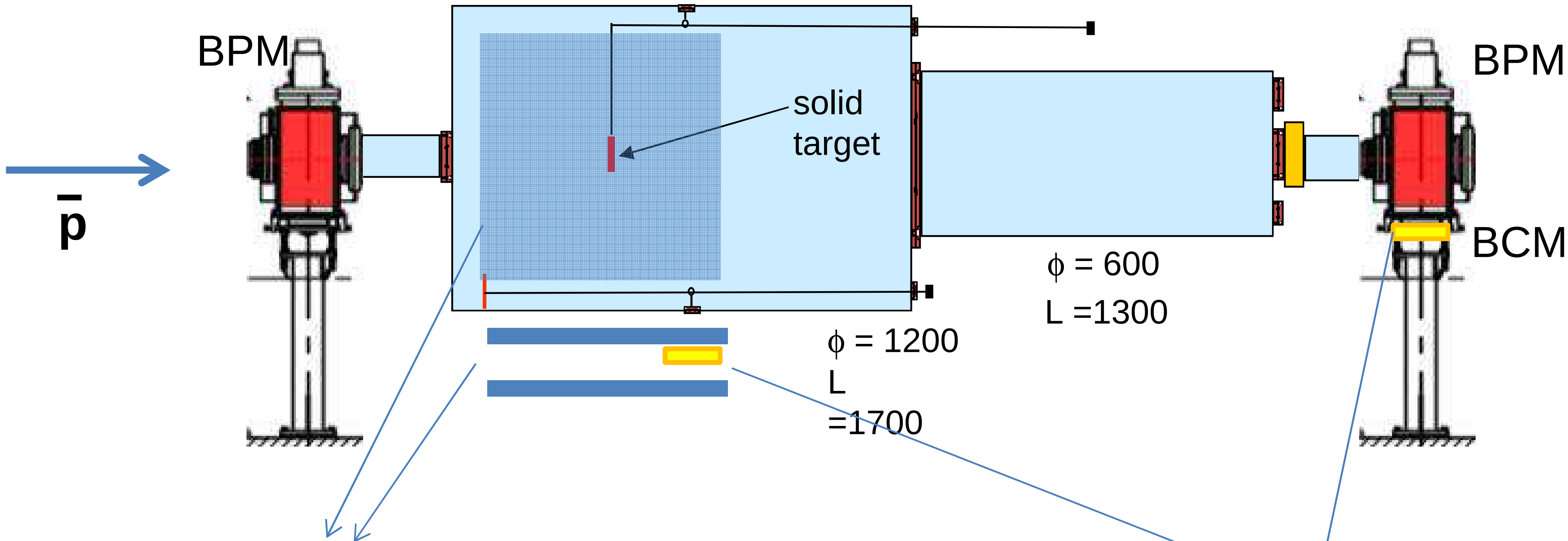
Time to separate signal from BCK



2° ring to calibrate (Rutherford) the beam counter

σ_{ann} is independent from detector efficiency (same detector to count N_{events} and N_{beam})

σ_{ann} set-up

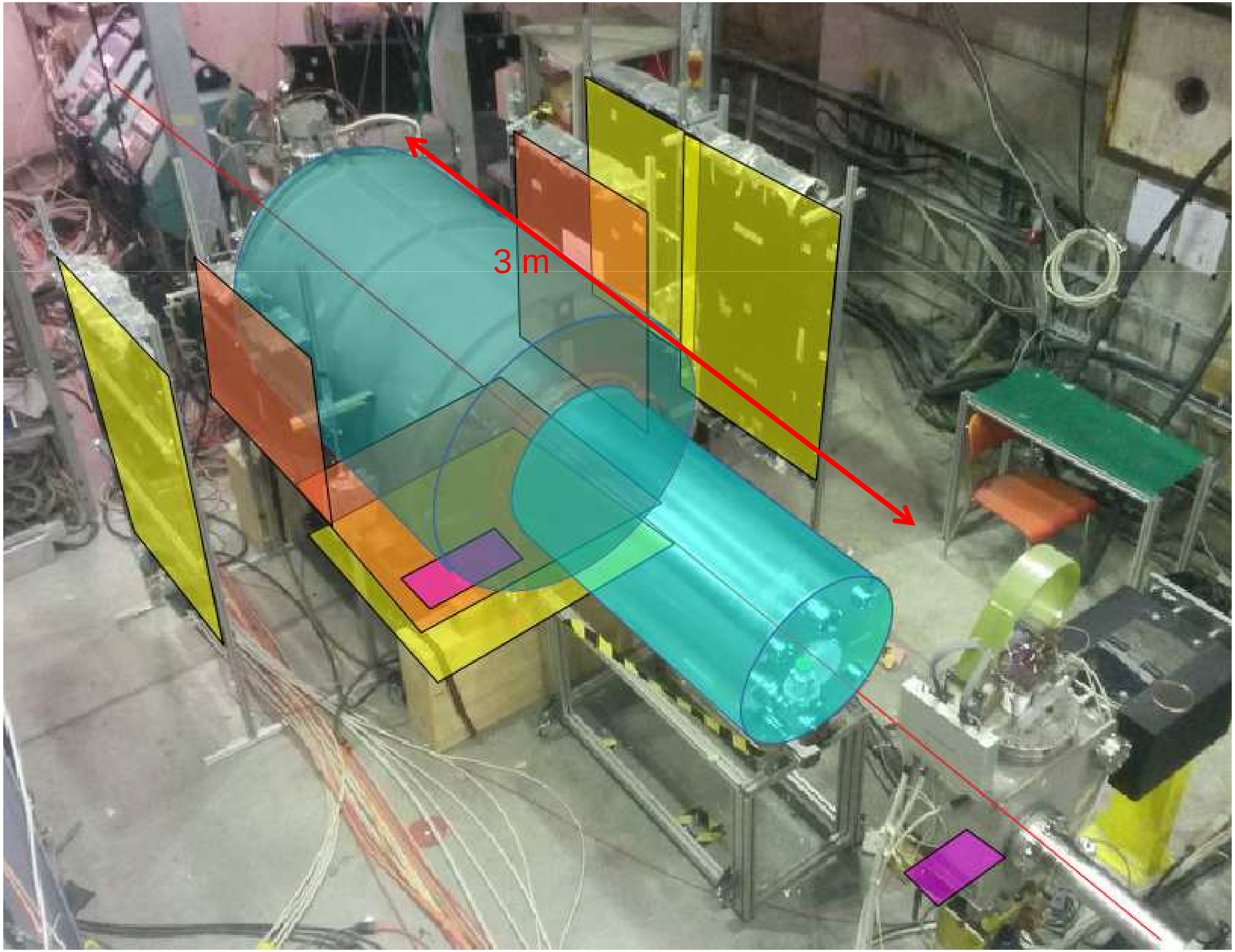


Scintillaror bars module

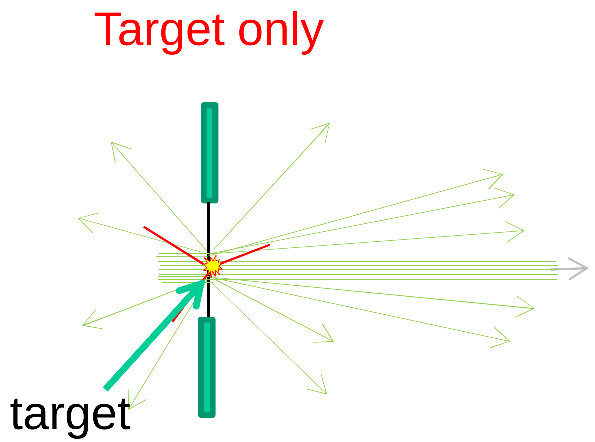
Carbon targets: 700 nm, 1000 nm
radius =5 cm

Cherenkov detector

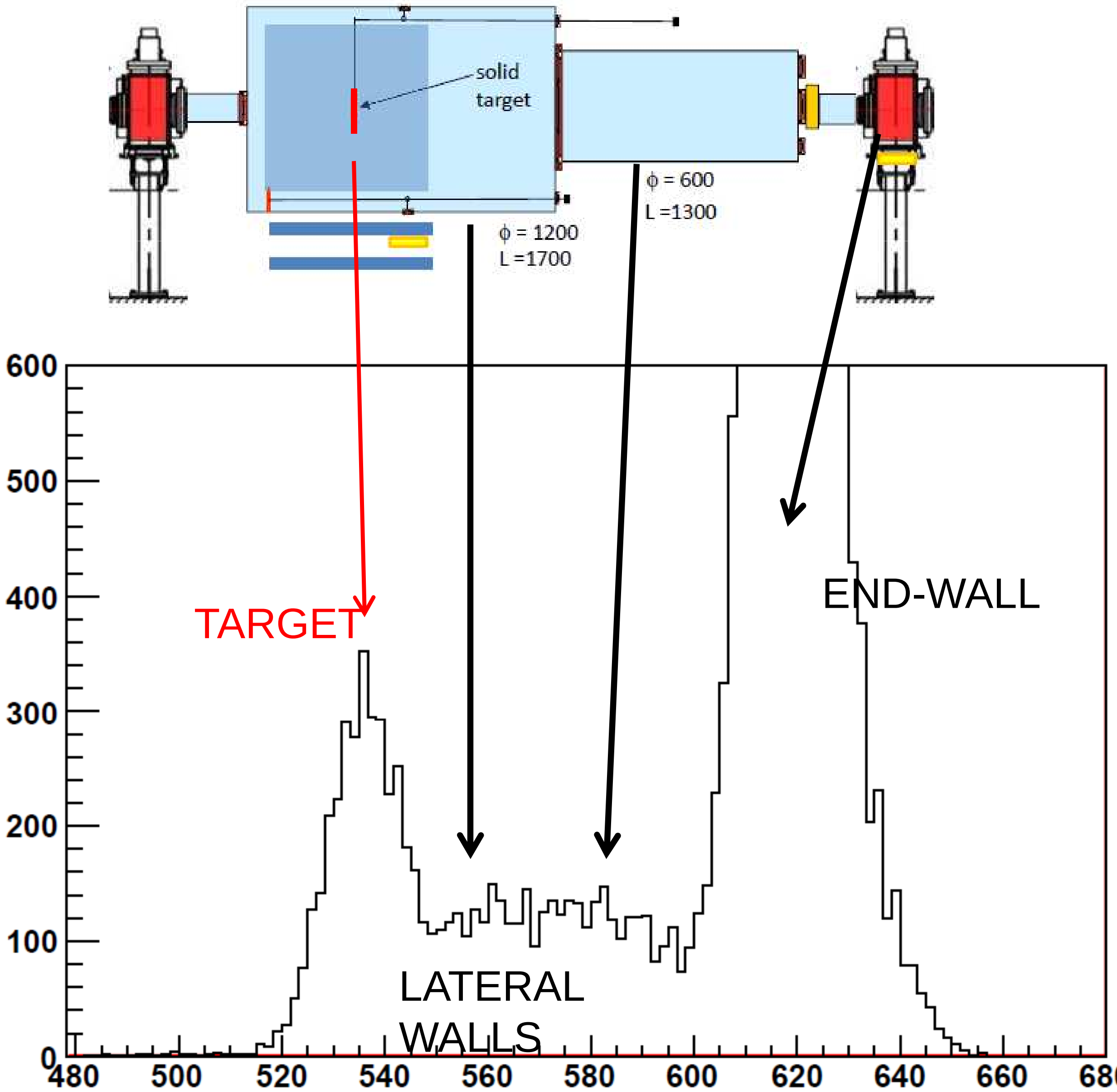
σ_{ann} set-up



$\bar{p}$ annihilation times

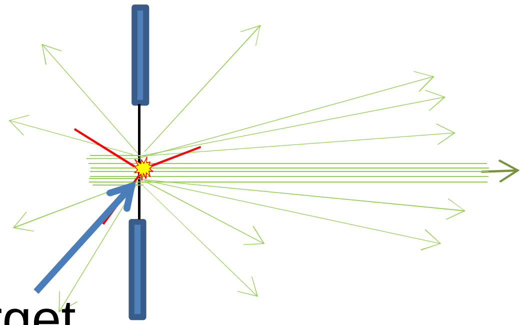


annihilations on the target clearly appear



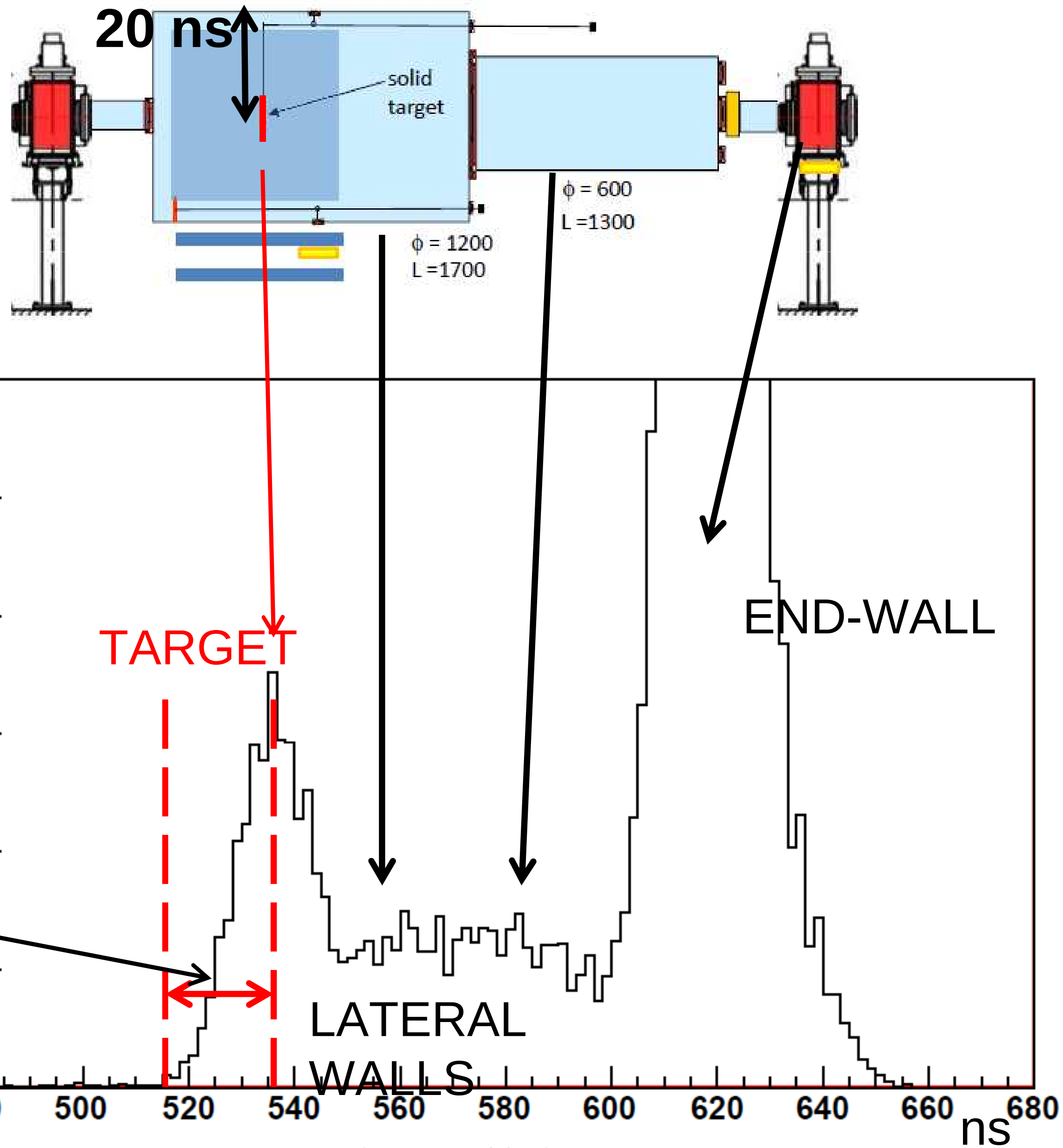
$\bar{p}$ annihilation times

Target only

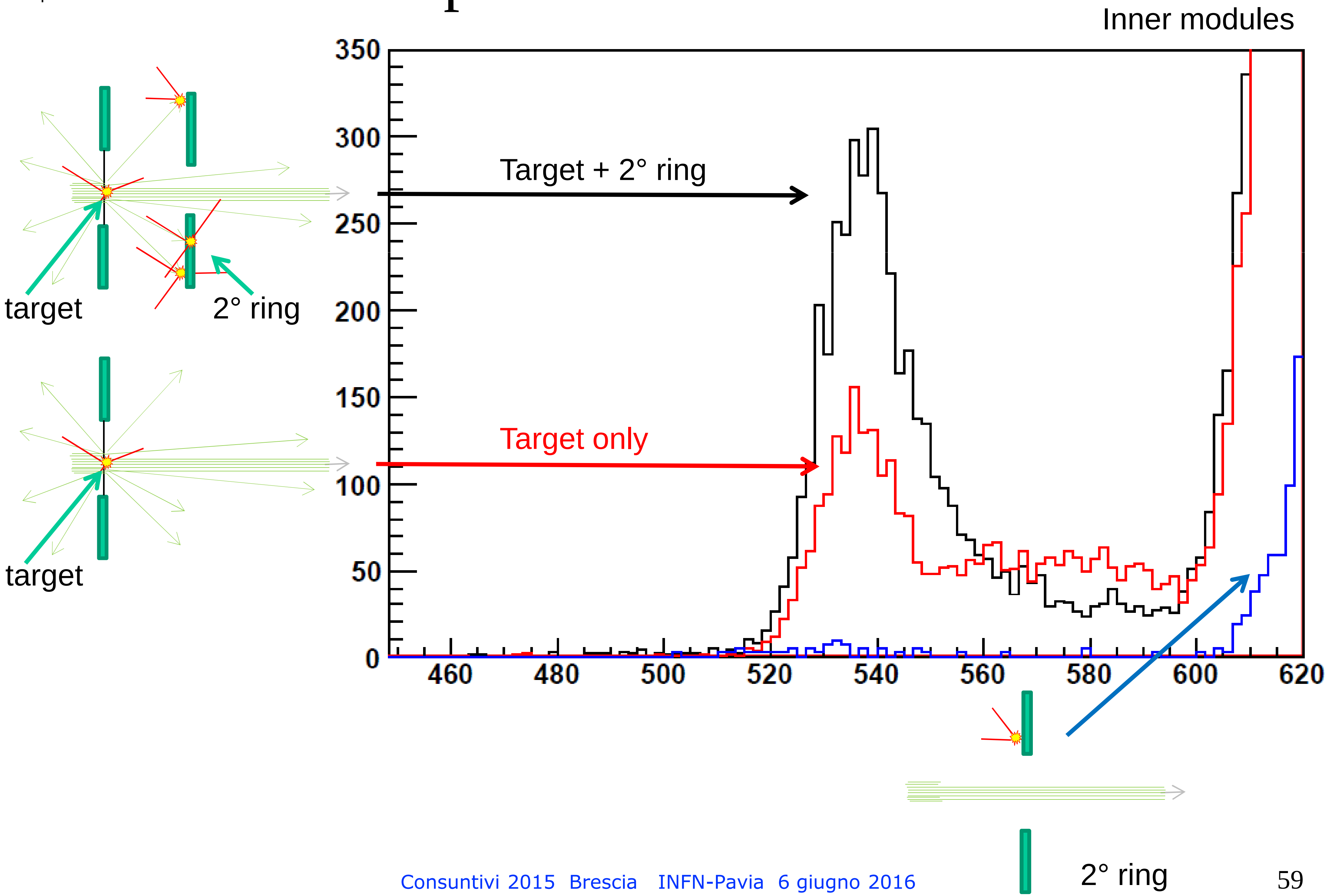


annihilation on the target clearly appears

The first 20-ns region is free from the annihilations on the walls



$\bar{p}$ annihilation times



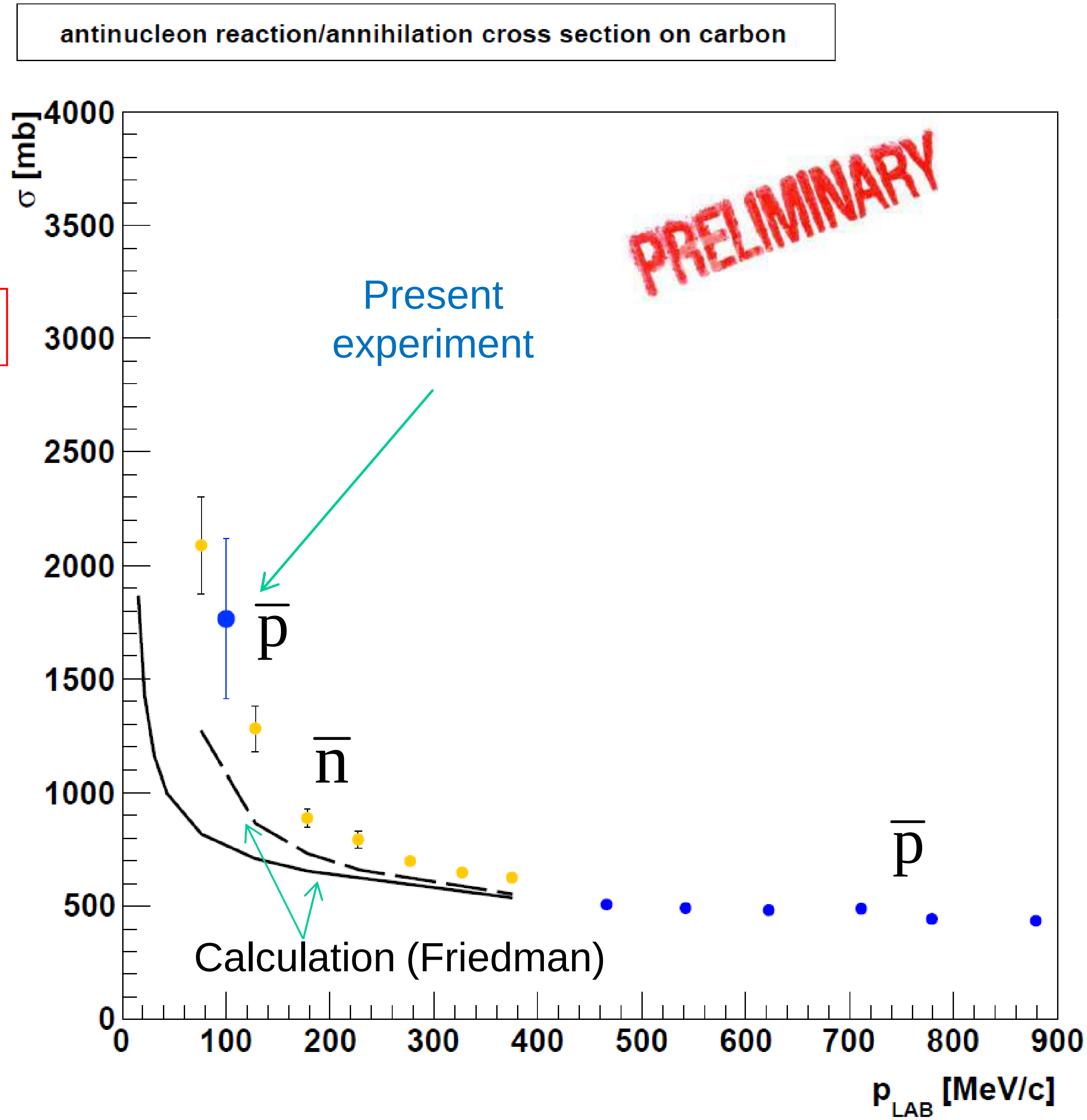
antiproton σ_{ann} on carbon at 5.3 MeV

Preliminary measurement

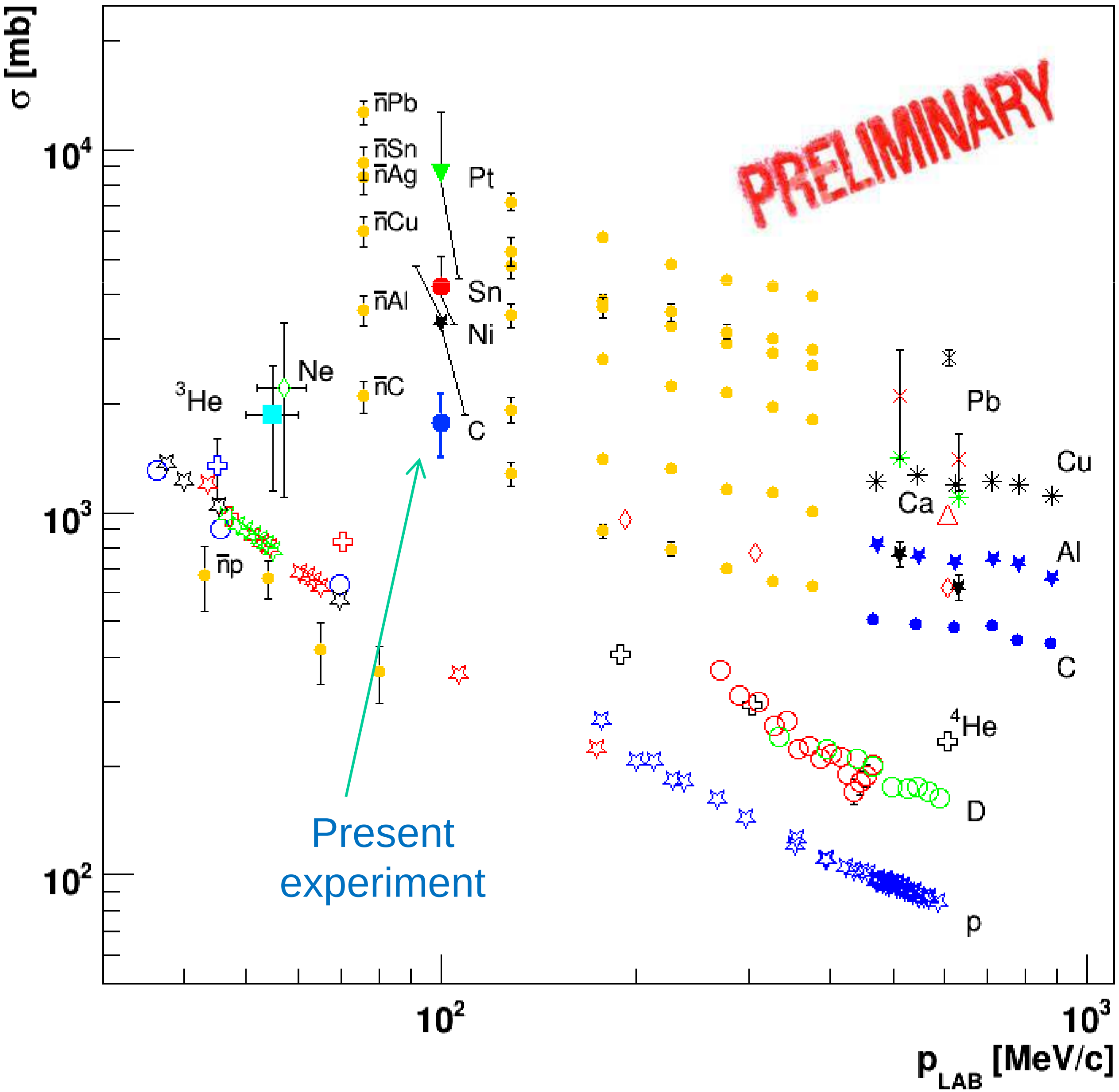
$$\sigma_{ann}(\bar{p} - C) = (1.75 \pm 0.35)\,\text{barn}$$

Expected final value with lower error (10%)

qualitatively agreement with the existing antineutron data.



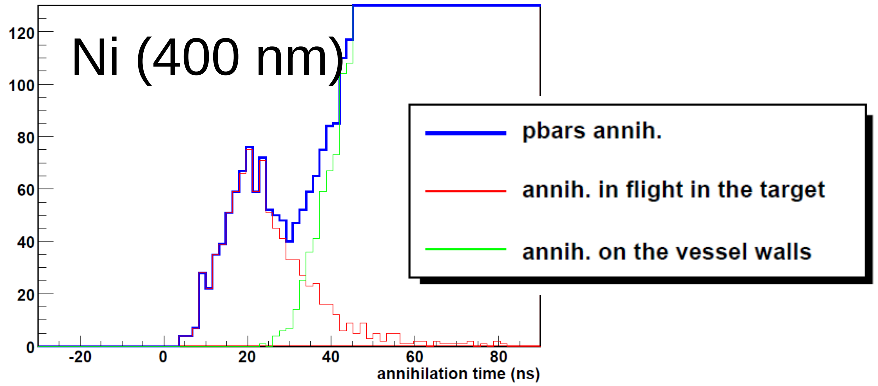
antinucleon reaction/annihilation cross section on nuclei



Possible extension of the measurement

At 5.3 MeV (AD)

- Monte Carlo simulations show that σ_{ann} measurements even with medium-heavy targets are feasible at AD with the present apparatus and technique



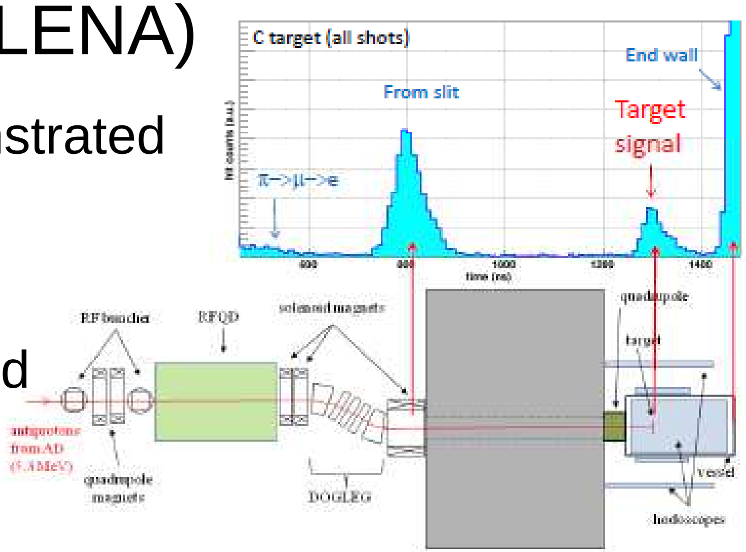
Signal (t<20 ns) well separated from BKG

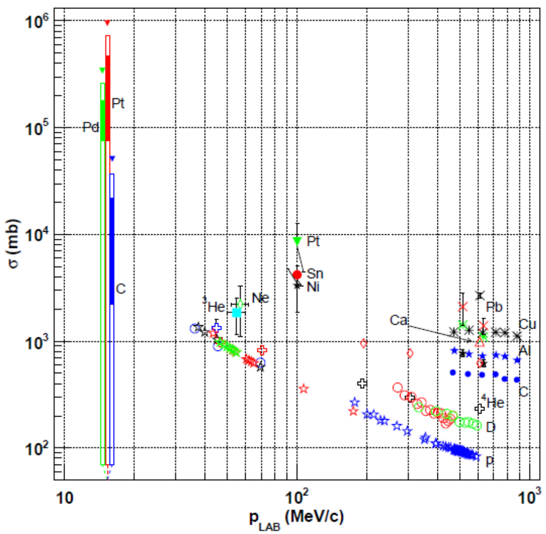
- Also pbar nuclear elastic σ could be measured (but more difficult)

At 0.1 MeV (AD-ELENA)

- Method already demonstrated with ASACUSA-RFQD .

Ultra-thin targets needed





Conclusions

Antiproton-C σ_{ann} measurement at 5.3 MeV has been performed by ASACUSA at the end of 2015

The result of a preliminary analysis shows a qualitatively agreement with the existing (antineutron) data.
The final result is expected to be more precise and could be used as a benchmark to understand the σ_{ann} (E, A) at low energies.

The present technique can be used even with heavier targets (if the 5.3 MeV antiproton beam will be available ...)

Measurements at lower energies (0.1 MeV) will be possible with ELENA, as already demonstrated by ASACUSA.

Summary

In 2015, ASACUSA achieved:

-Transfer of 20 eV pbars to the mixing trap: pbar-to Hbar conversion=15%
- hidrogen GSHFS measured (<10 ppb)

- Finished data taking and analysis for single-photon laser spectroscopy of $\bar{p}$He, cooled to ~1.5K.
- Started 2-photon spectroscopy of $\bar{p}$He at 1.5K

- Collected good data for $\bar{p}$ annihilation σ measurement on carbon @5.3 MeV

- In 2016, ASACUSA plans to carry out

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

- Continuation of 2-photon spectroscopy of $\bar{p}$He at 1.5K