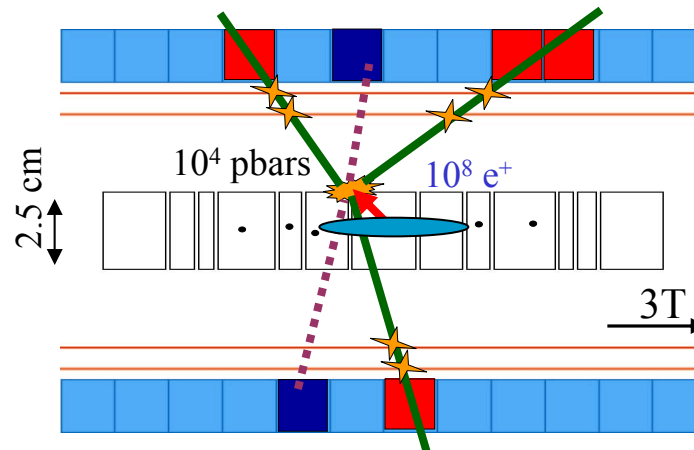
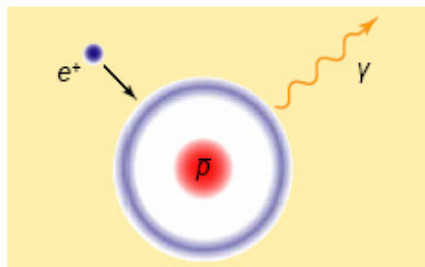
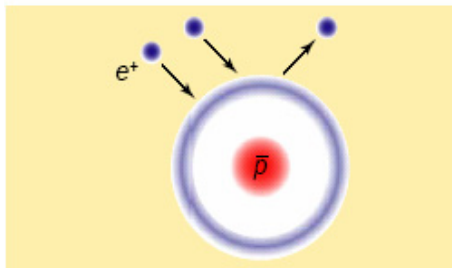


# “The mechanisms of antihydrogen formation”

E.Lodi Rizzini, L.Venturelli, N.Zurlo, ... (ATHENA Collaboration)



Presented by L.Venturelli  
Brescia University & INFN (Italy)



# Antihydrogen Experiments

## Hot Hbars:

relativistic

- 1996: PS210 @ CERN (First 10 antihydrogen)
- 1997: E862 @ Fermilab (other 100 antiatoms)

## Cold Hbars:

$10^2$  K

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

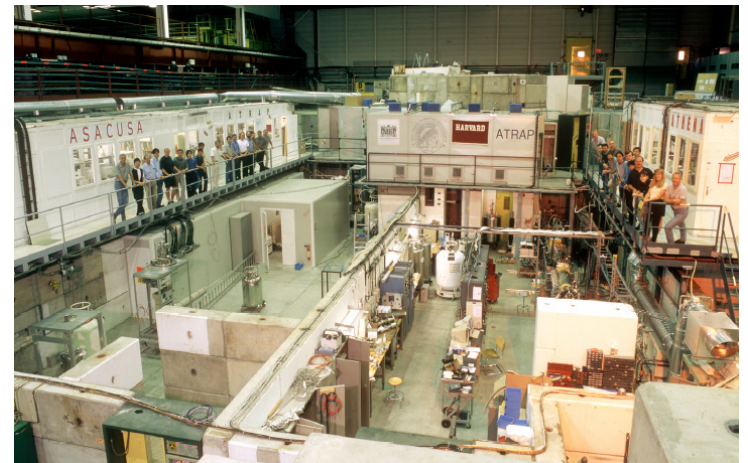
## - Now

@ CERN-AD, 3 Collaborations are working towards **antihydrogen spectroscopy**: Atrap (AD-2), Asacusa (AD-3), Alpha (AD-5)

see Cesar's talk

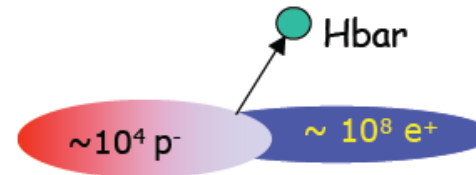
They need:

- enough # of Hbars
- very cold Hbars
- Hbars in low n states
- magnetic trapping

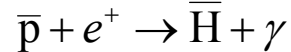


# Antihydrogen production mechanisms:

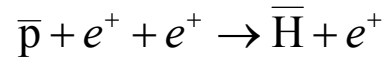
Reference procedure to produce Hbars is the **overlapping** of pbars and e+



The **expected Hbar formation mechanisms** are:



(1) Radiative recombination (**2-BR**)



(2) 3-body recombination (**3-BR**)

Hbar productions **rates** of (1) and (2) **depend differently** on the e+ plasma parameters (e+ plasma density, temperature, ...)

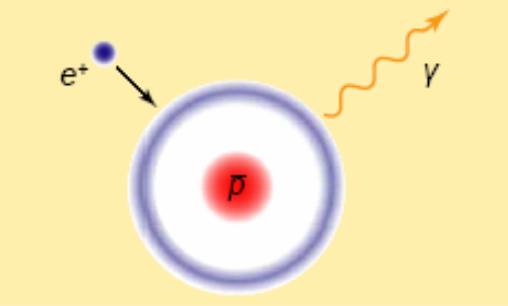
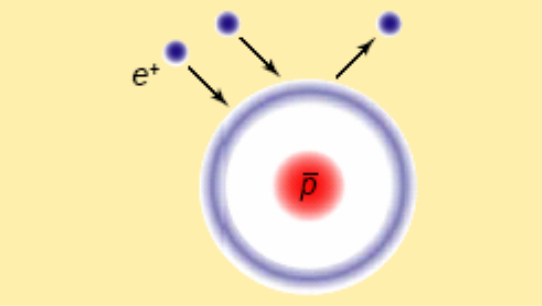
**Hbars** produced in (1) and (2) have **different characteristics** (binding energy, ...)

The **knowledge of (1) and (2)** is crucial for the best optimization of the creation of Hbars **for spectroscopy**

Not yet solved

# Features of the Hbar production mechanisms:

## Naive expectations

	Radiative Recombination	Three-Body Recombination
Principle		
Temperature depend.	$\propto T^{-2/3}$	$\propto T^{-9/2}$
e <sup>+</sup> density dependence	$\propto n_e$	$\propto n_e^2$
Final internal states	$n < 10$	$n \gg 10$
Expected rate (in Athena) (*)	some 10 Hz	High ( $\gg 10\text{Hz}$ )

(\*) Assuming complete overlapping of  $10^4$  pbars with e<sup>+</sup> plasma ( $n_{e^+} = 2 \cdot 10^8 \text{ cm}^{-3}$  @ 15K)

# What we experimentally know

Not-exhaustive

Atrap

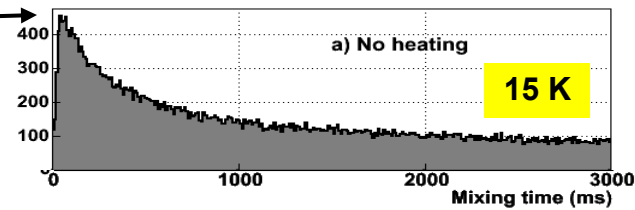
- detected Hbars with  $n$  about 60

~~2-BR~~

Athena

- Maximum Hbar production rate (per cycle) =  $440 \pm 40$  Hz

~~2-BR~~



- no increase in Hbar formation from laser stimulation in  $n=11$

~~2-BR~~

- Results from temperature dependence (2 different experiments) → ...

~~3-BR~~

... →

Results from **temperature dependence** (1st experiment) M. Amoretti et al., PLB (2004)

■ Hbar production decreases when temperature increases (still present @ room temperature)

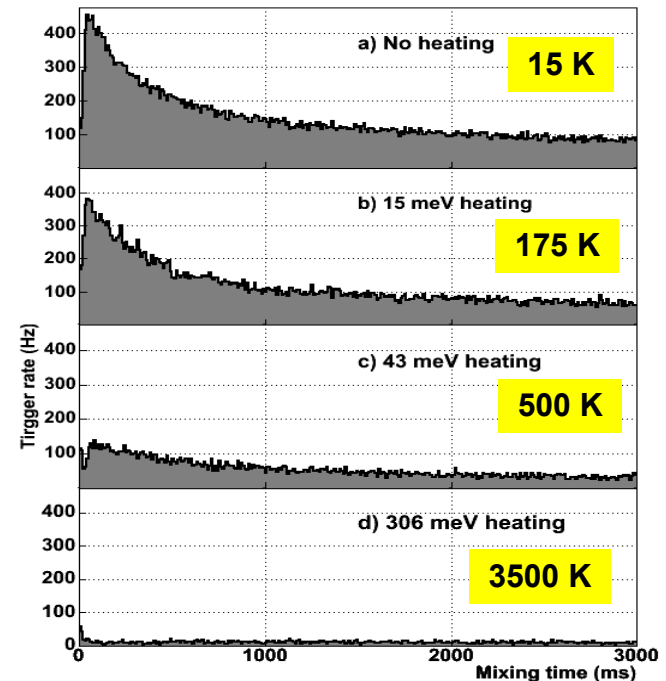
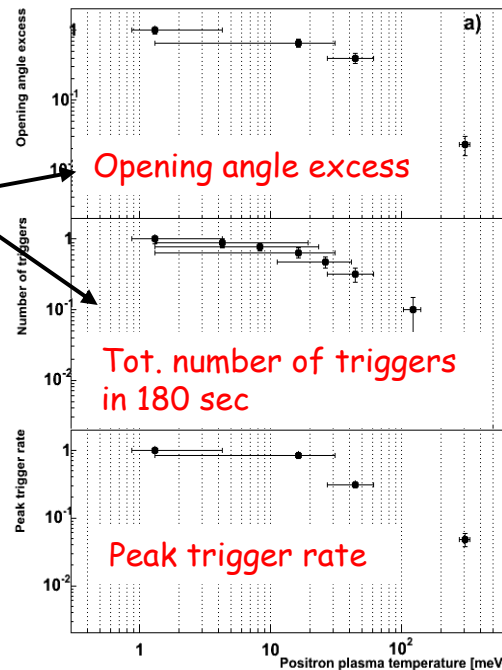
■ No power law reproduces the data.

However best fit:  $T^{-0.7 \pm 0.2}$

~~3-BR~~

■ No simple mixing of 2-BR and 3-BR

Proportional to the total number of detected hbar in a mixing cycle



... →

Results from **temperature dependence** (2nd experiment) M.C.Fujiwara et al., PRL in press

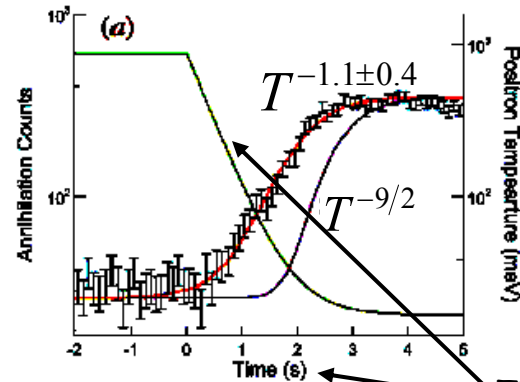
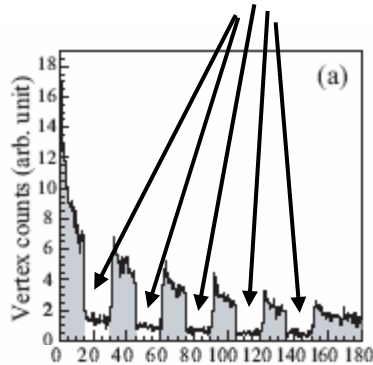
■ best fit

$$T^{-1.1 \pm 0.4}$$

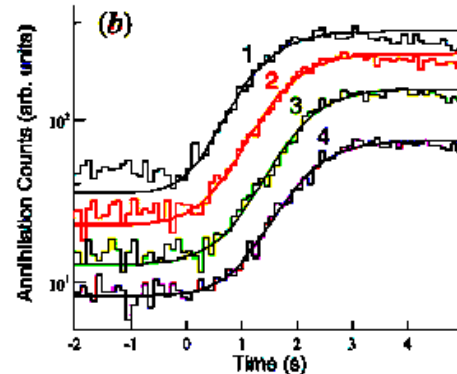
~~3-PR~~

In agreement with the 1st exp. result

Periodic heating of e+ plasma



Time ⇔ e+ temperature



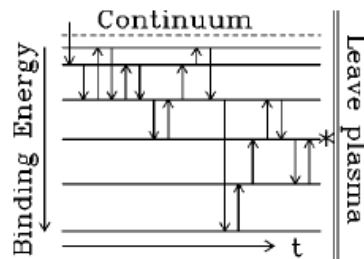
The results appear to be in contradiction

N.B.

The detected Hbars are the ones that survive to the re-ionization (due to  $e^+$  and trap potentials)

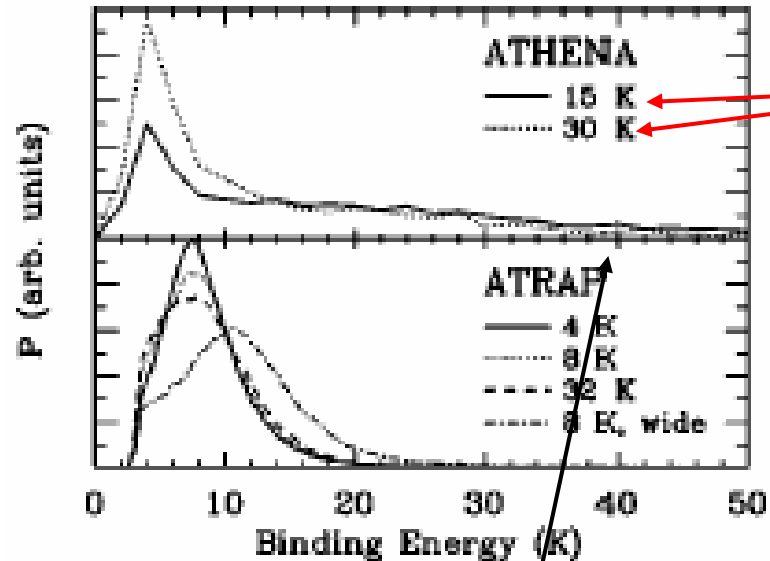
### 3-body Monte Carlo for ATHENA

F.Robicheaux PRA 2004



Different results between MC and naive expectations since:

- pbars repeatedly cross  $e^+$  plasma;
- Hbar formation is a multistep process;
- reionization.



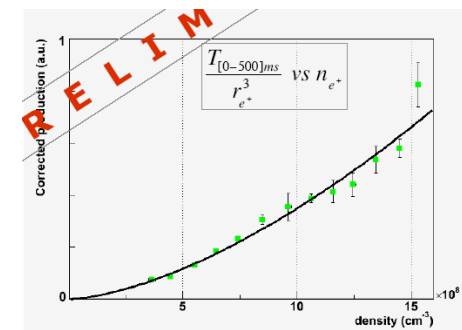
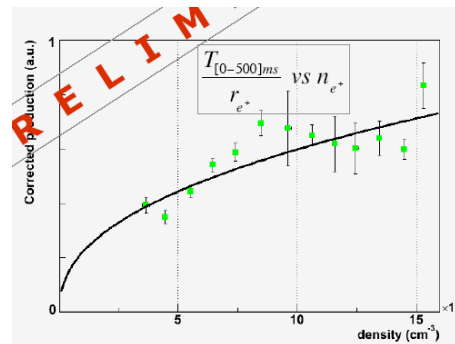
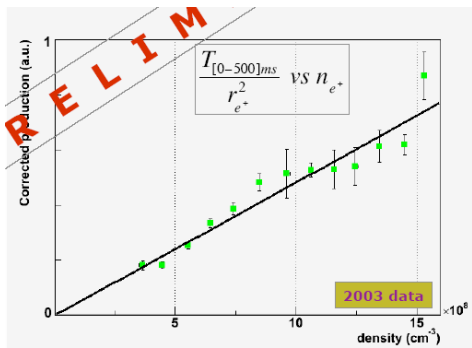
Doubling T the # of detected hbars decreases of a factor 2.5 only (instead of 20 with  $T^{-9/2}$ )

FIG. 3. The probability  $P$  for a  $\bar{H}$  atom to have binding energy. All ATHENA simulations are for an  $e^+$  density of  $2.5 \times 10^8 \text{ cm}^{-3}$  and an extent of 32 mm along the magnetic field. All ATRAP simulations are for an  $e^+$  density of  $4 \times 10^7 \text{ cm}^{-3}$ ; three simulations are for an extent of 0.4 mm along the magnetic field and one for an extent of 1.6 mm. To survive a 25 V/cm field, an atom needs a binding energy greater than  $\sim 40$  K.

What about the  $e^+$  density dependence?

Athena

A tentative already done (see Int.Nucl.Conference 2004 Goteborg) ...  
...but the results depend on the radial distribution of the pbars cloud



NOW new analysis ... ->

# ATHENA Collaboration @ CERN-AD

• Worked @ Cern-AD (Antiproton Decelerator) during 2000-2004



Univ. of Aarhus, Denmark



Univ. of Brescia, Italy



CERN, Geneva, Suisse



Univ. of Genova, Italy



Univ. of Pavia, Italy



Univ. of Rio, Brazil



Univ. of Swansea, Wales (UK)



Univ. of Tokyo, Japan



Univ. of Zurich, Suisse



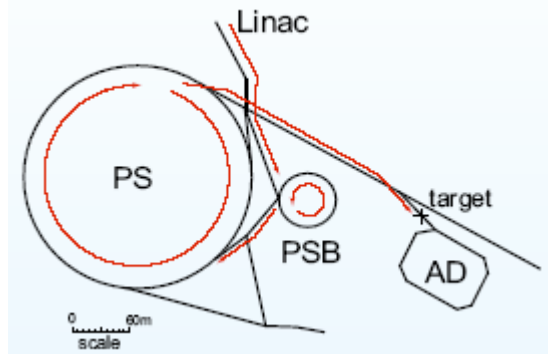
INFN, Italy



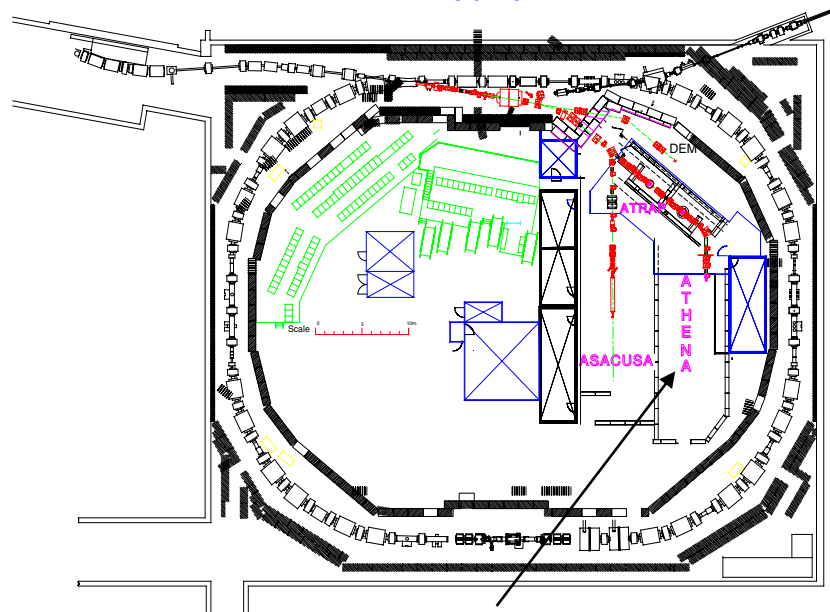
Riken, Japan

~ 40 members

# Antiproton Decelerator (AD) at CERN



AD PROJECT



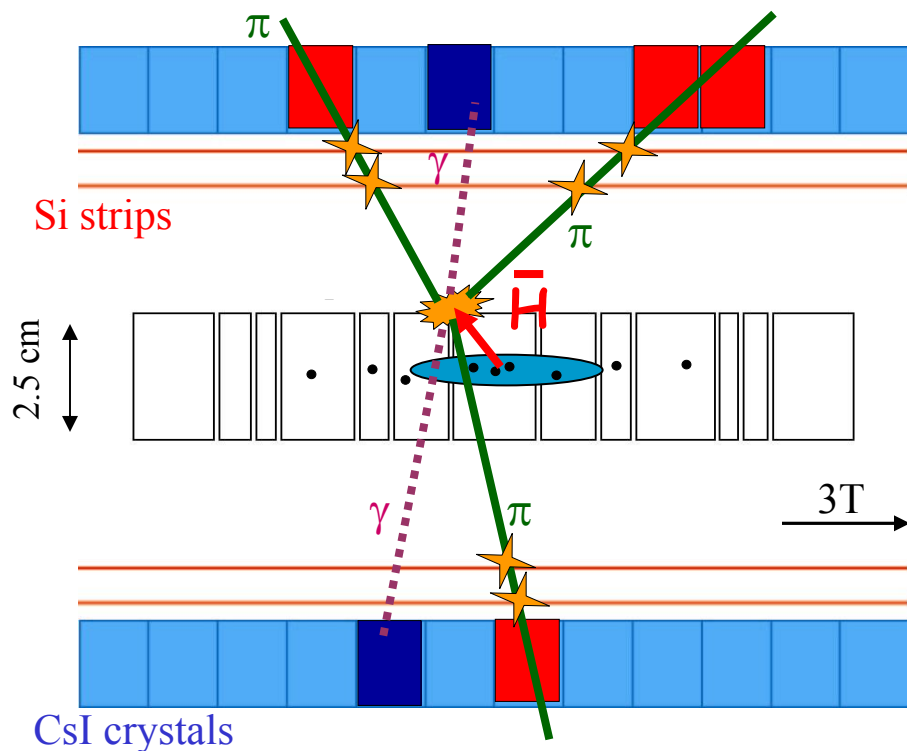
ATHENA experimental area

- Antiproton production, capture, deceleration, cooling
  - 100 MeV/c (5.3 MeV)
- **Pulsed** extraction
  - $2-4 \times 10^7$  antiprotons per pulse of 100 ns length
  - 1 pulse / 85 seconds
- Antiprotonic atom/ion formation and spectroscopy;  
Antihydrogen formation and spectroscopy;  
Atomic collisions;  
Nuclear collisions
- In operation 2000-2004 and restarted in 2006

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



# How ATHENA worked



- $10^4 \bar{p}$  &  $10^8 e^+$  are mixed in Penning trap
- $\bar{H}$  form and fly away
- $\bar{H}$  annihilate on trap wall

Offline selection of  $\bar{H}$  annihilation:

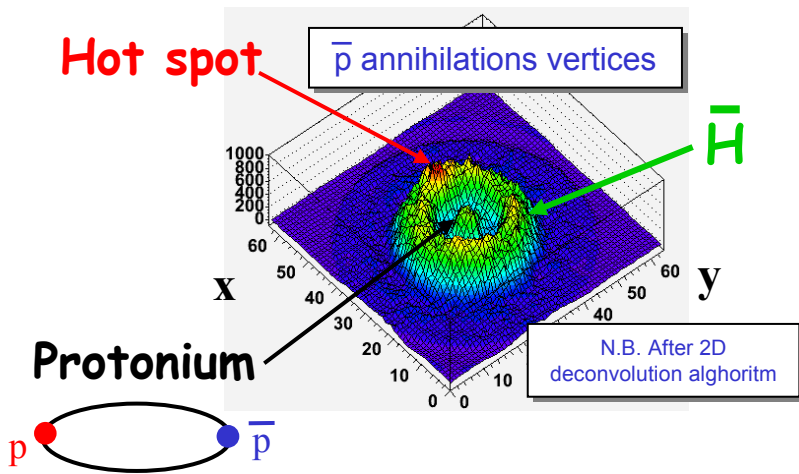
Coincidence in space & time ( $<5\mu s$ ) of:

- $\bar{p}$  annihilation (charged pion vertex)
- $e^+$  annihilation (2 back-to-back 511 keV  $\gamma$ )

# New Data Analysis

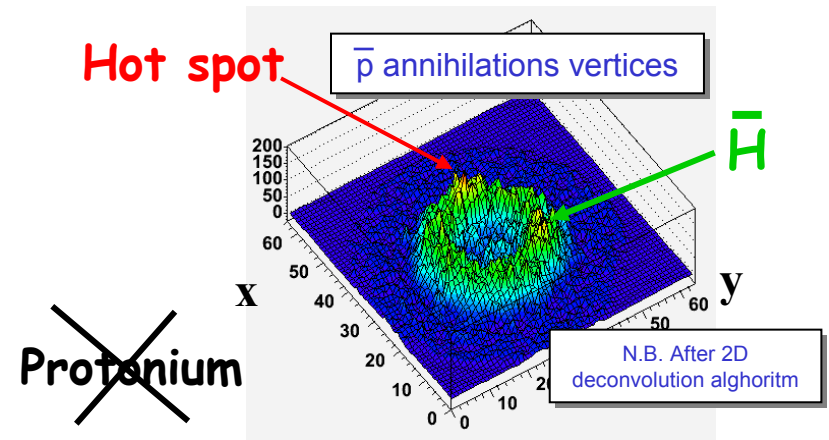
Preliminary

Previous data analyses based on  
 "Cold Mixing Data" (CM)  
 (standard conditions for  $\bar{H}$  production)



Some difficulties to disentangle  
 signal ( $\bar{H}$ ) from background  
 (protonium, Hot Spots)

New data analysis uses mainly  
 "Electron through Positron Data" (ETP)



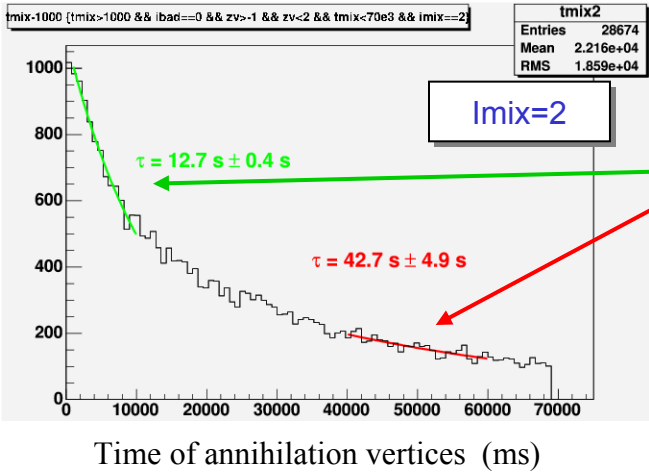
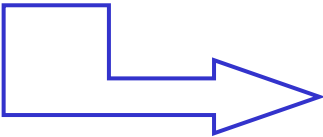
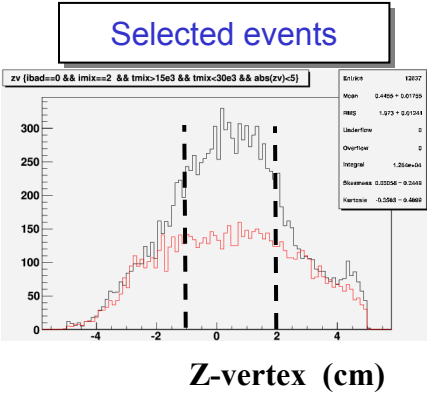
Less background (no protonium)

ETP: continuous mixing and  $e^+$  stacking  
 mix  $e^+$  and antiprotons and cool new  
 antiprotons at the same time  
 stack 10  $e^+$  shots in the mixing trap

Preliminary

# Vertex time distributions

ETP Data

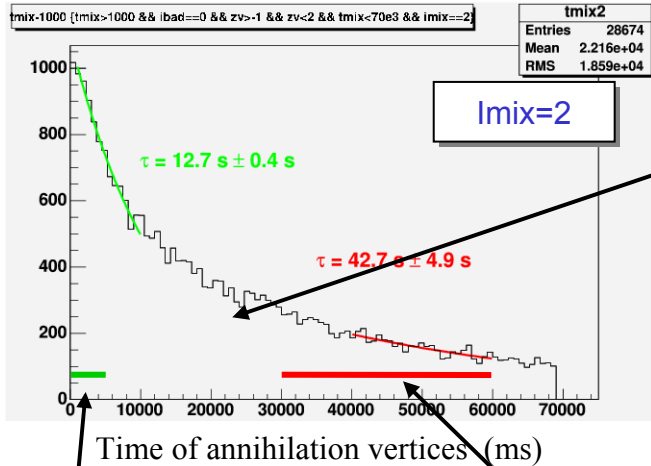


Different slopes

- why different slopes in different time intervals?
- do the different slopes correspond to different Hbar production mechanisms (2-BR, 3-BR)?

# Data analysis 1/2

Preliminary



$$N_{\bar{H}}^{\text{det}} = (N_{\bar{H}}^{\text{det}})_{3BR} + (N_{\bar{H}}^{\text{det}})_{2BR}$$

$$(N_{\bar{H}}^{\text{det}})_{3BR} \div \epsilon_{3BR} n_{e^+}^2 N_{\bar{p}}^{\text{int}} \Delta t \quad \text{3-body}$$

$$(N_{\bar{H}}^{\text{det}})_{2BR} \div \epsilon_{2BR} n_{e^+} N_{\bar{p}}^{\text{int}} \Delta t \quad \text{2-body}$$

$N_{\bar{H}}^{\text{det}}$  = detected Hbars # in  $\Delta t$   
 $\epsilon$  = detection efficiency  
 $n_{e^+}$  = Positrons #/cm<sup>3</sup>  
 $N_{\bar{p}}^{\text{int}}$  = # of pbars interacting with positrons in  $\Delta t$

assumed to be constant in  $\Delta t$

in  $\Delta t_1 = (1,5)s$

$$N_{\bar{H}}^{\text{det}}(\Delta t_1) = c_1 n_{e^+}^2 + c_2 n_{e^+}$$

3-BR      2-BR

in  $\Delta t_2 = (30,60)s$

$$N_{\bar{H}}^{\text{det}}(\Delta t_2) = c_3 n_{e^+}^2 + c_4 n_{e^+}$$

3-BR      2-BR

We call

$$R \equiv \frac{N_{\bar{H}}^{\text{det}}(\Delta t_1)}{N_{\bar{H}}^{\text{det}}(\Delta t_2)} = \frac{c_1 n_{e^+}^2 + c_2 n_{e^+}}{c_3 n_{e^+}^2 + c_4 n_{e^+}}$$

If  $c_4 n_{e^+} \gg c_3 n_{e^+}^2$  (i.e. if 2-BR is dominant in  $\Delta T_2$ ) then

$$R \approx \frac{c_1}{c_4} n_{e^+} + \frac{c_2}{c_4}$$

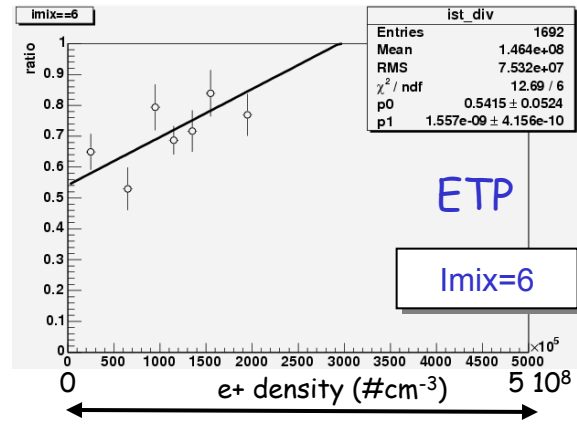
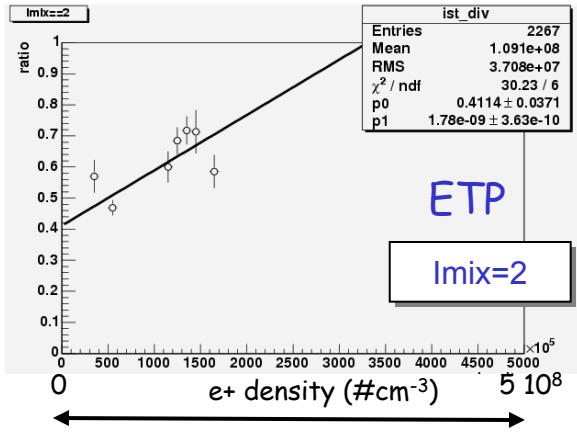
# Data analysis 2/2

Preliminary

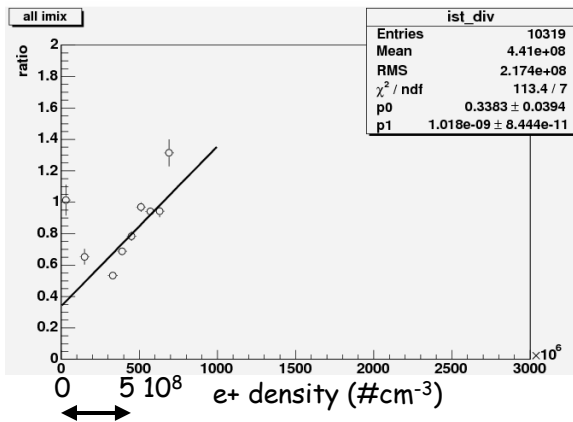
Verification of

$$R \approx a n_{e^+} + b$$

by fitting it to the data



Also with Cold Mix Data



	b	a
ETP imix=2	0.4 ± 10%	1.8 E-9 ± 20%
ETP imix=6	0.5 ± 10%	1.6 E-9 ± 20%
Cold Mix	0.3 ± 10%	1.0 E-9 ± 20%

Similar values

⇒  $R \div n_{e^+}$  at least for  $n_{e^+} < 2 \cdot 10^8 \text{ cm}^{-3}$

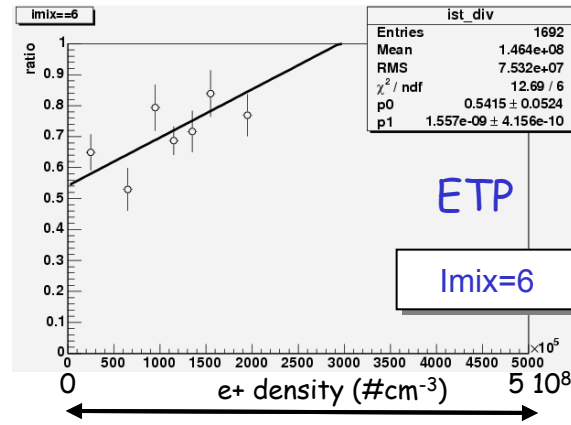
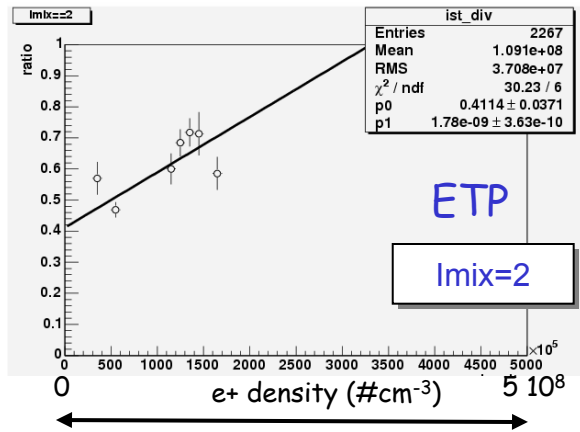
# Data analysis 2/2

Preliminary

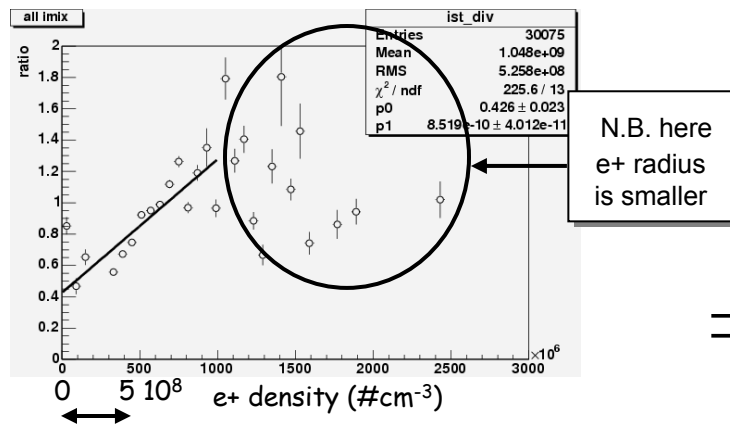
Verification of

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Also with Cold Mix Data



	b	a
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Similar values

⇒  $R \approx n_{e^+}$  at least for  $n_{e^+} < 2 \cdot 10^8 \text{ cm}^{-3}$

# Rates

Preliminary

Athena

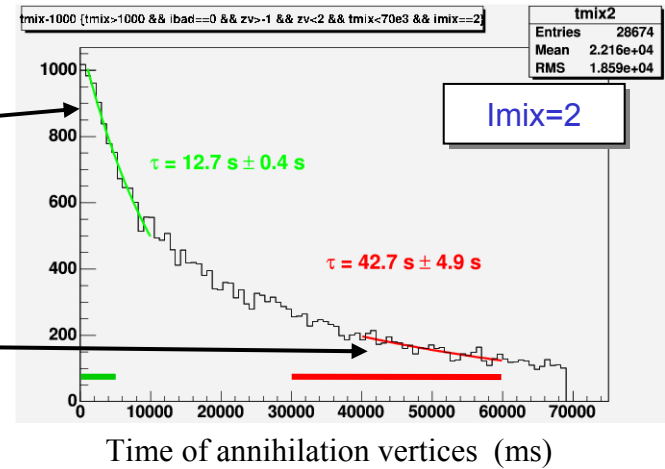
The measured R (ratio) values agree with the hypothesis that:

- @ early times (first seconds)

3-BR dominates

- @ late times (> tens seconds)

2-BR dominates



*What about the rates?*

The measured rates:

Mean value, not the peak

sample	rate in the first second (Hz)	rate after 40 seconds (Hz)
ETP	85	15
standard	95	17

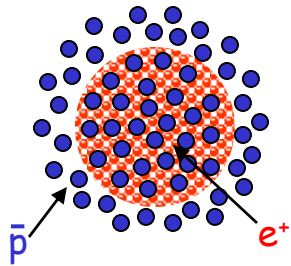
To be increased by 2 due to the detector efficiency

Rates @ late times are consistent with 2-BR expectations

# (Possible) explanation

Preliminary

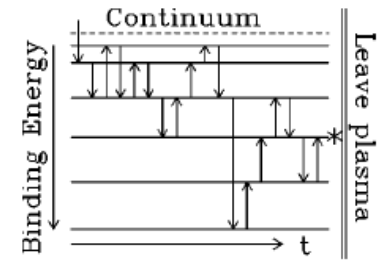
## @ early times ( $\Delta t_1$ )



Many pbars well inside the e+ plasma

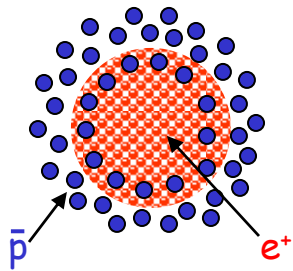
⇒ Relevant # of antihydrogens produced by 3-BR experience lot # of collisions and will be enough bounded to be detected

$$\Rightarrow \left(N_{\bar{H}}^{\text{det}}\right)_{3BR} \text{ Large} \quad \left(N_{\bar{H}}^{\text{det}}\right)_{3BR} \gg \left(N_{\bar{H}}^{\text{det}}\right)_{2BR}$$



F.Robicheaux  
PRA 2004

## @ late times ( $\Delta t_2$ )



Only few pbars well inside the e+ plasma (most of pbars are on the edge)

⇒ Antihydrogens produced by 3-BR easily re-ionize (not detected)

$$\Rightarrow \left(N_{\bar{H}}^{\text{det}}\right)_{3BR} \text{ small} \quad \left(N_{\bar{H}}^{\text{det}}\right)_{3BR} \ll \left(N_{\bar{H}}^{\text{det}}\right)_{2BR}$$

The radial evolution of pbars can be due to:

- centrifugal separation between pbars and e+ due to the different masses  
but in ATHENA it is expected to be slow (separation time = 1000 s)
- exhaustion of the central pbars (they have ben "used")

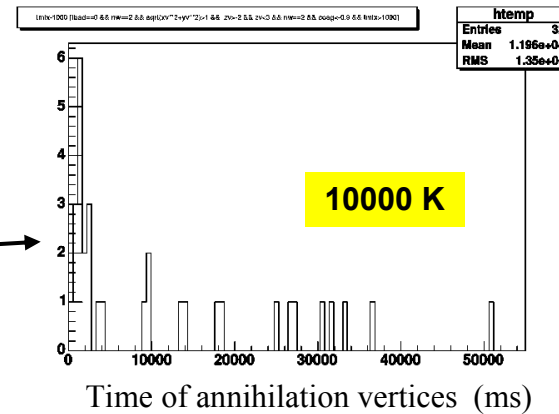
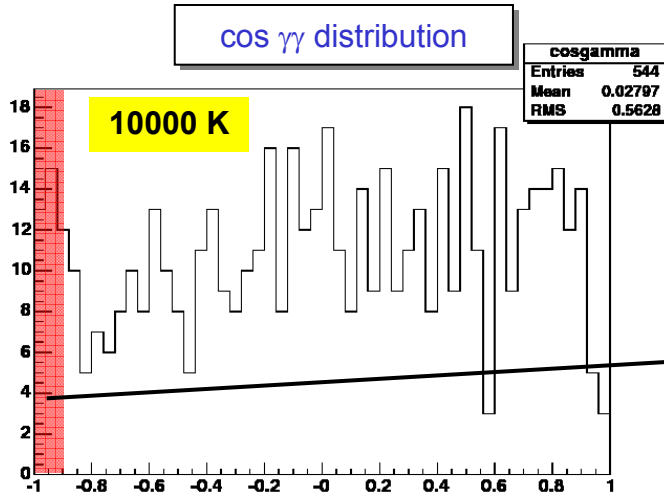
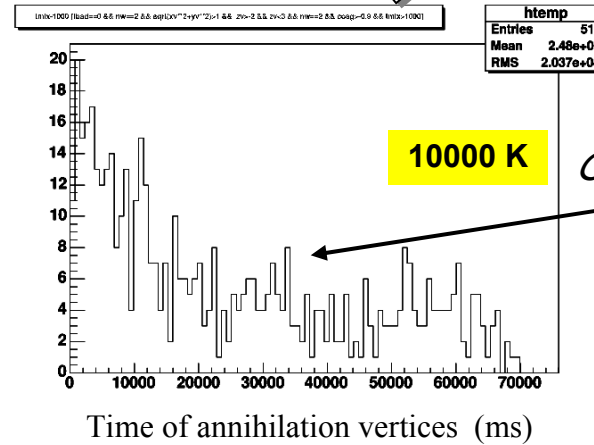
# Hot mixing data

Preliminary

Another topic...

Hbars produced @room temperature

Are antihydrogen produced @ 10 000 K ?



measured rate is 2 Hz

To be compared with 0.5 Hz from 2-BR expectation

## Next analysis improvement

- R (ratio) vs density with other data samples

- R (ratio) vs temperature  $(R = \frac{T^{-\frac{9}{2}}}{T^{-\frac{2}{3}}})$  ?

- Monte Carlo simulations

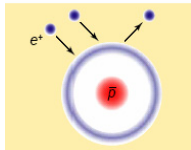
- Nature of the Hot Spot (are they consequence of the re-ionization?)

- ...

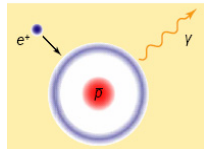
# Conclusions

- After the first cold Hbars detection, many efforts to understand the antihydrogen formation mechanisms have been done

- Preliminary analysis of the time evolution of antihydrogen annihilations vs  $e^+$  plasma density and rates estimations suggest that in Athena conditions:



3-body recombination dominates @ early-times (first seconds)



Radiative recombination dominates @ late-times (> tens seconds)

- More confirmations can come from the development of the analysis (Athena has a lot of useful data!)
- Information on the antihydrogen production mechanisms will be useful for the goal of precision spectroscopy of antihydrogen