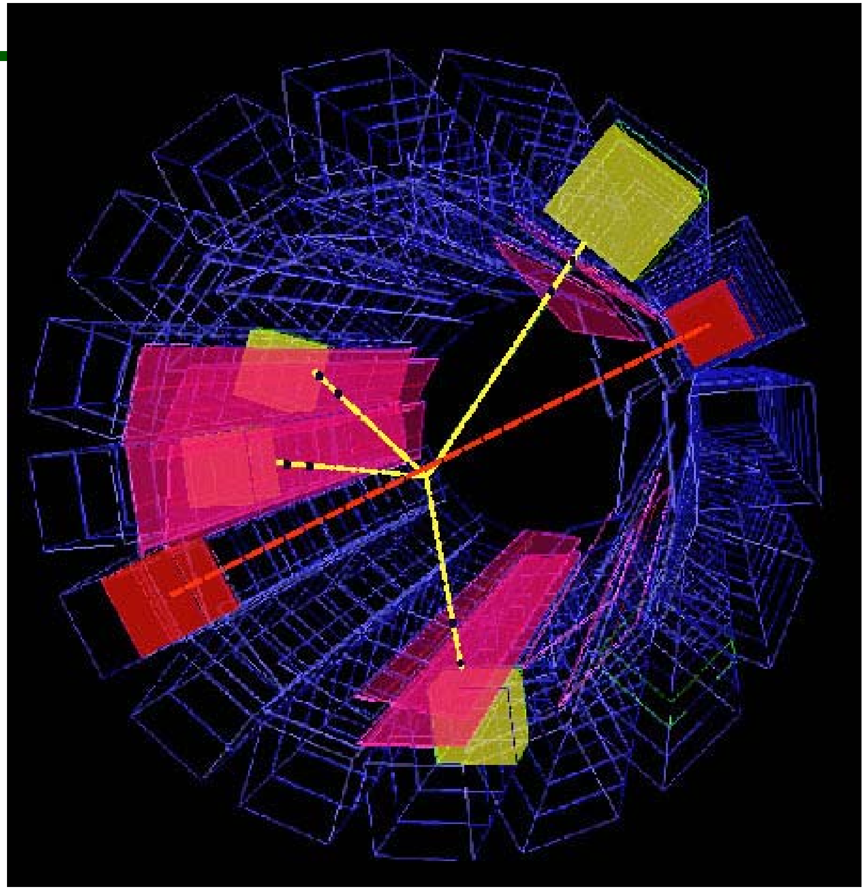
CERN

25 January 2005

ATHENA

Study of the Anti-hydrogen production mechanisms

Overview of the results



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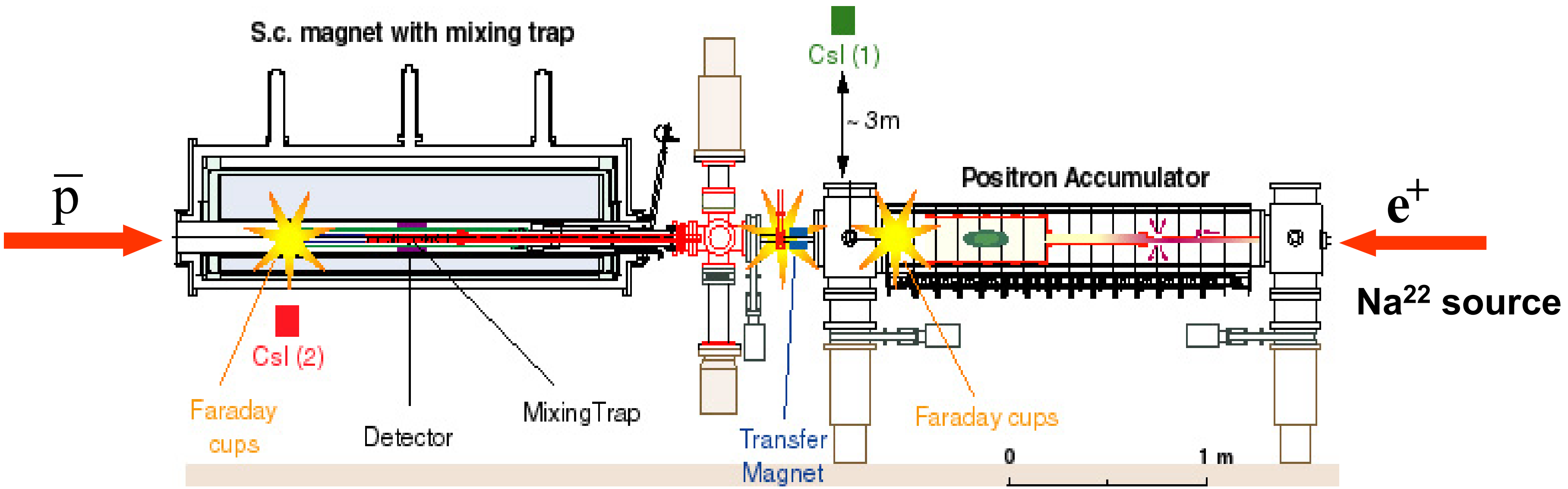
ATHENA main results

1) "Production and detection of cold antihydrogen atoms" Nature 419 2002 456
2) "Positron plasma diagnostic and temperature control for antihydrogen production" Phys. Rev. Lett. 91 2003 05501
3) "Complete non destructive diagnostic of non neutral plasmas based on the detection of the electrostatic modes" Phys. Plasmas 10 2003 3056
4) " The ATHENA antihydrogen apparatus" NIM A 518 (2004) 679
5) "Three dimensional annihilation imaging of trapped antiprotons" Phys. Rev. Lett 92 (2004) 065005
6) "High rate production of antihydrogen" Phys. Lett. B 578 (2004) 23
7) "Dynamics of antiproton cooling in a positron plasma during antihydrogen formation" Phys. Lett. B 590(2004)133
8) "Antihydrogen production temperature dependence" Phys. Lett. B 583 (2004) 59
9) "Spatial distribution of Cold Antihydrogen Formation " accepted on Phys. Rev. Lett.
10) "Transfer, Stacking and Compression of Positron Plasmas" submitted

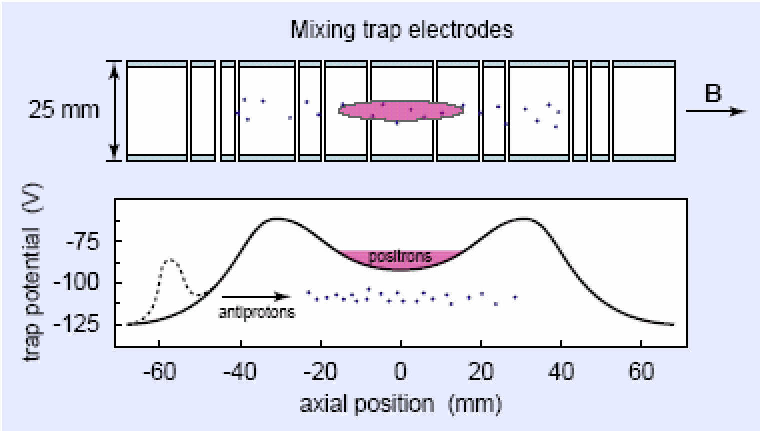
- dependence of the antihydrogen formation on plasma dimensions, temperature and density
- identification of the main recombination mechanisms (radiative vs 3body)
- to enhance radiative recombination by laser radiation

ATHENA overview



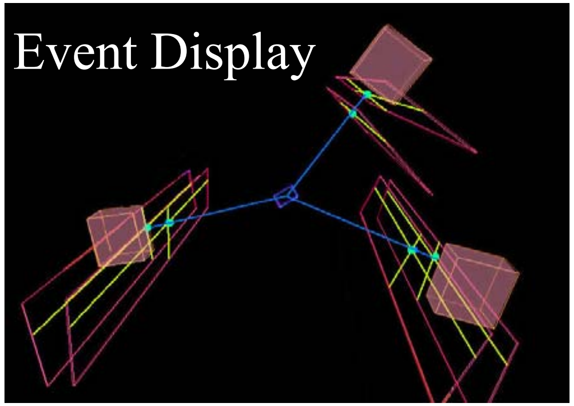
- Transfer positrons from accumulator into mixing trap ($\varepsilon \sim 50$ %)
- Positrons cool by synchrotron radiation at B=3T: 75 million cold positrons
- Non-destructive diagnostics gives plasma parameters:

  R = 2.0 mm L = 32 mm $n = 2 \cdot 10^8$ cm^{-3}
- Positrons life time ~ many hours
- Caught antiprotons: 10 000 (3 AD shots), cooling by electrons in 20 s
- Annihilation detection by the antihydrogen detector
- No positron heating: cold mixing (Hbar production)@15 K
- Controlled positron heating: hot mixing (background)

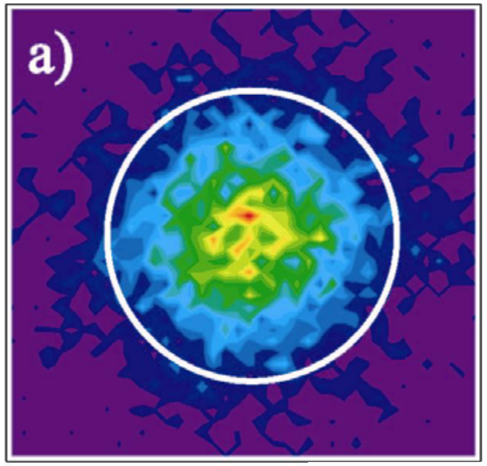


From the ATHENA detector

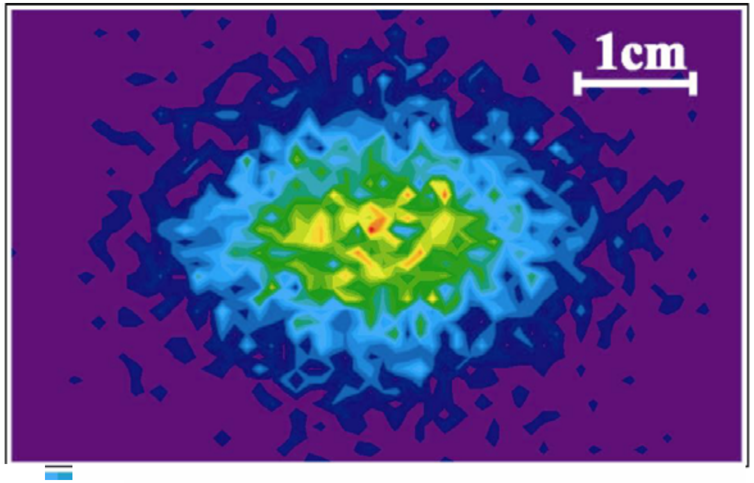
Athena Collaboration, Phys. Rev. Lett. **92**, 065005 (2004)

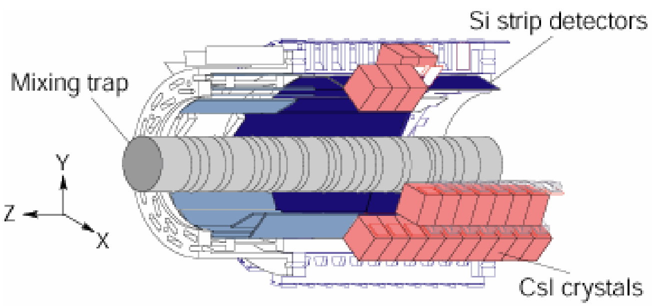


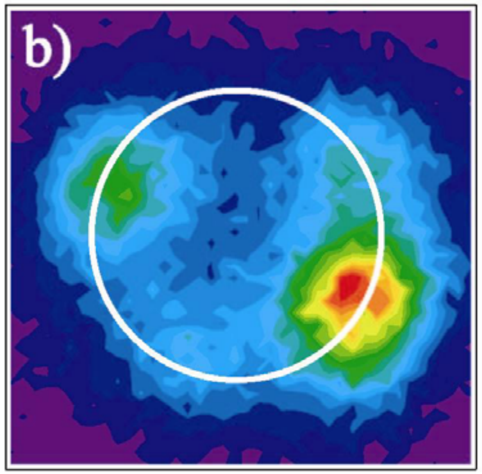
XY projection



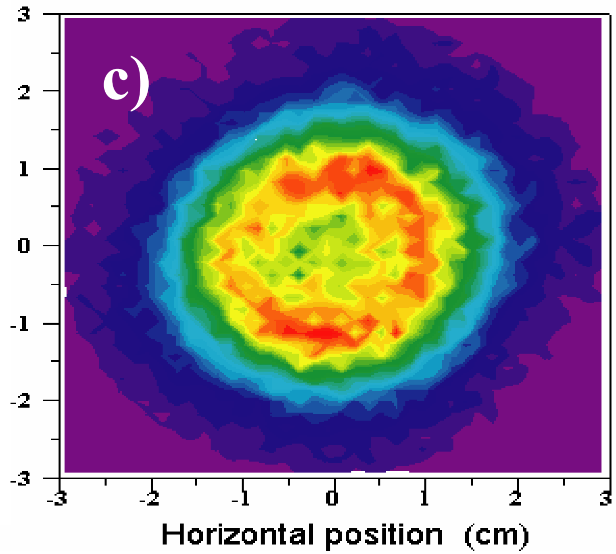
ZY projection



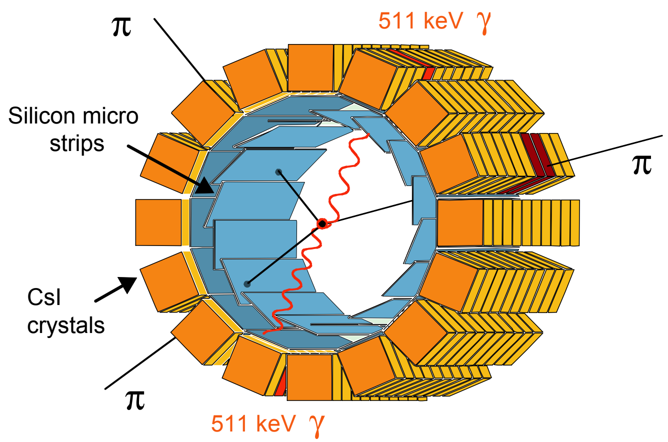




X-Y projection

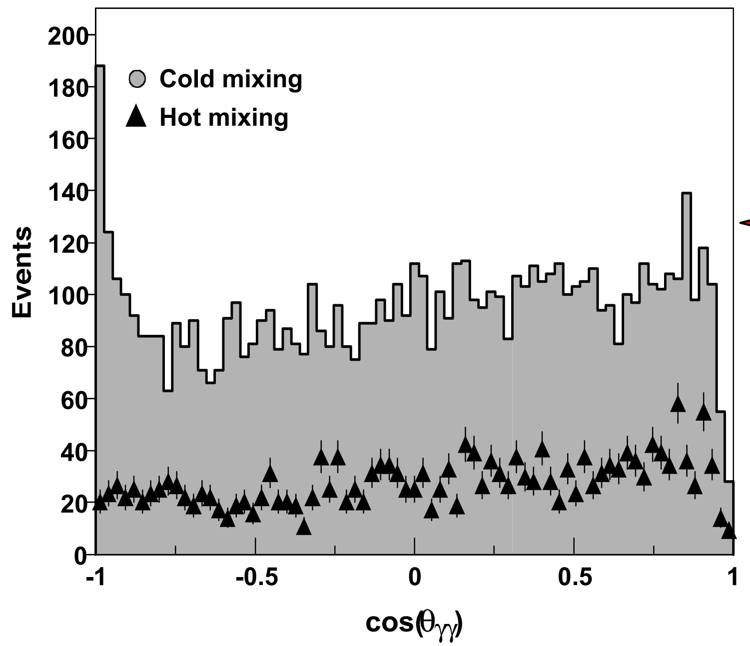


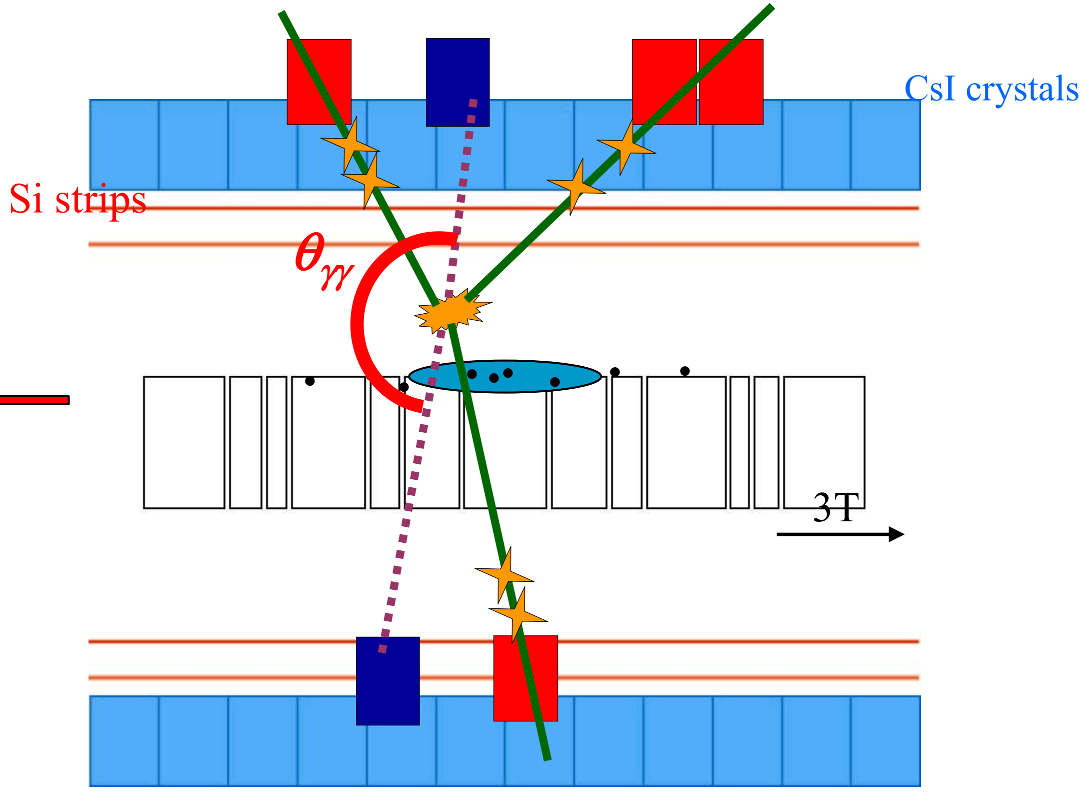
Opening angle distribution



Vertex rec. eff.:	50%
Position resolution (σ):	4 mm
Silicon trigger efficiency:	(85 +-10)%
Photon energy resolution:	24% (FWHM) @ 511KeV
Photon detection efficiency:	20%

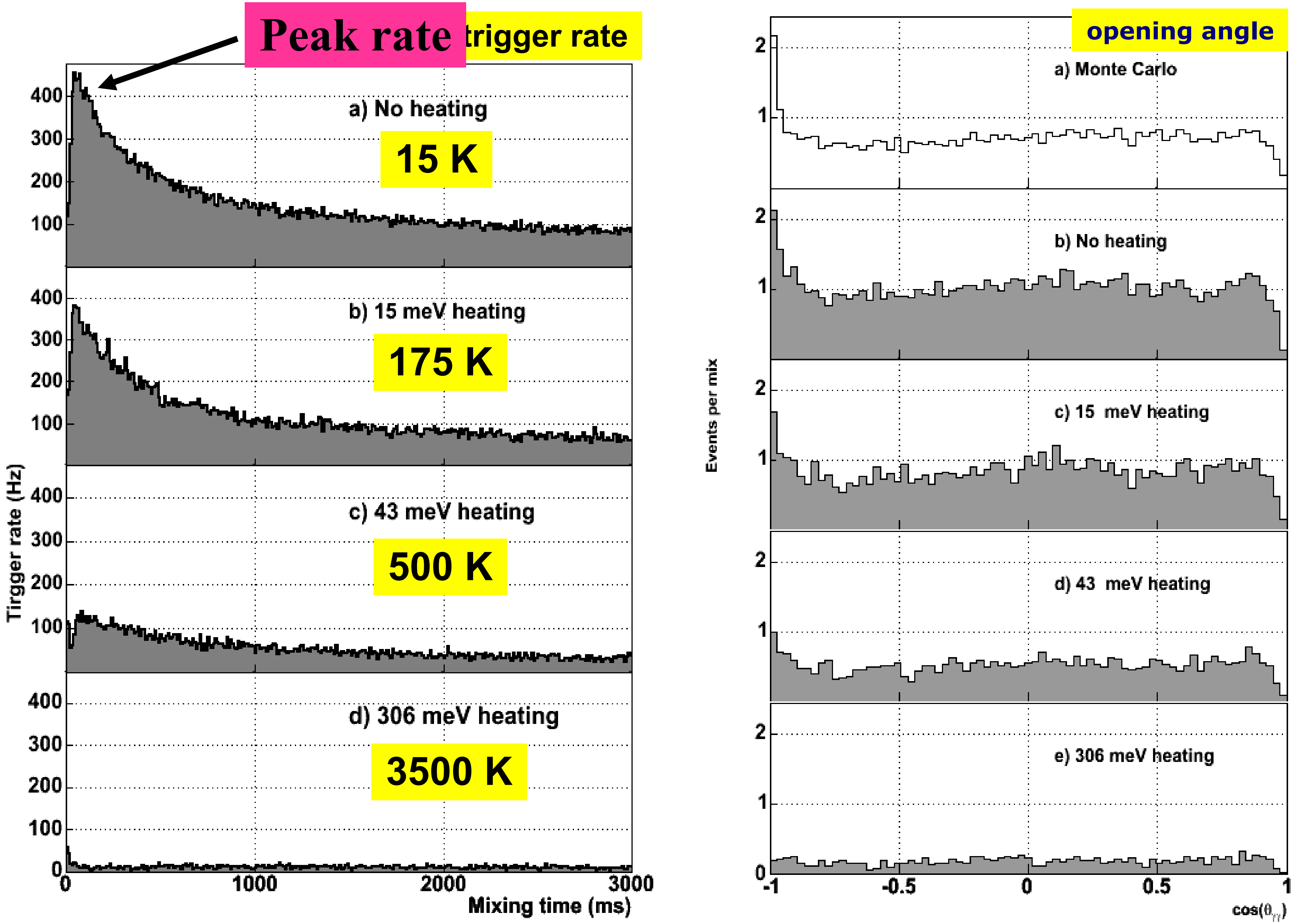
Opening angle distribution



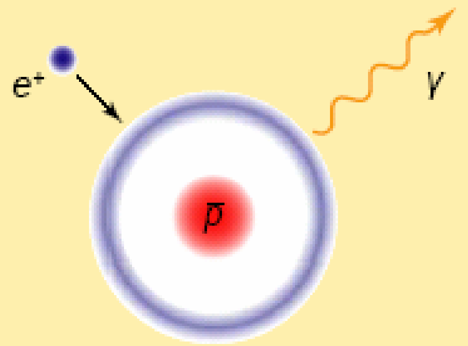
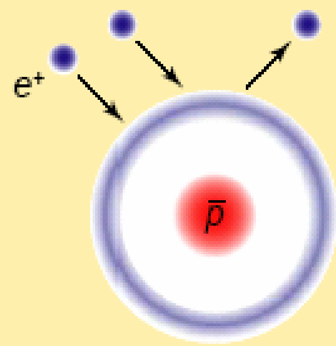


Amoretti et al.,(ATHENA coll.)***Nature*** 419 (2002) 456

$\bar{H}$ production in ATHENA



(Re)combination mechanisms

	Radiative Recombination	Three-Body Recombination
Principle		
Temperature depend.	$\propto T^{-2/3}$	$\propto T^{-9/2}$
e^+ density dependence	$\propto n_e$	$\propto n_e^2$
Final internal states	$n < 10$	$n >> 10$
Expected rates	few 10 Hz	unknown

[J. Stevefelt *et al.*, PRA **12** (1975) 1246] [M. E. Glinsky *et al.*, Phys. Fluids B **3** (1991) 1279]

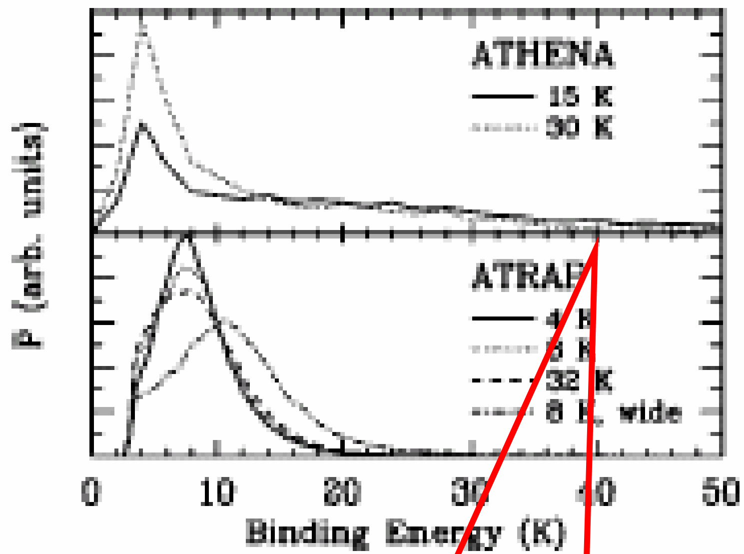
Predicted 2-body annihilation peak rate (first 10 ms):

$$R_{rad} = N_{\bar{p}}\, n_{e^+} \left[\frac{m}{2\pi kT}\right]^{3/2} \int v\, \sigma_{rad}(v)\, e^{-mv^2/2kT}\, d^3v$$ **< 40 Hz**

Observed:
440 ± 40 Hz

A 3-body MC for the ATHENA trap

F. Robicheaux PHYSICAL REVIEW A 70, 022510 (2004)



Plasma dimensions are crucial for the recombination!!

FIG. 3. The probability P for a $\bar{H}$ atom to have binding energy. All ATHENA simulations are for an e^+ density of 2.5×10^8 cm^{-3} and an extent of 32 mm along the magnetic field. All ATRAP simulations are for an e^+ density of 4×10^7 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 ~40 K.

Standard antihydrogen production

Antihydrogen balance sheet:

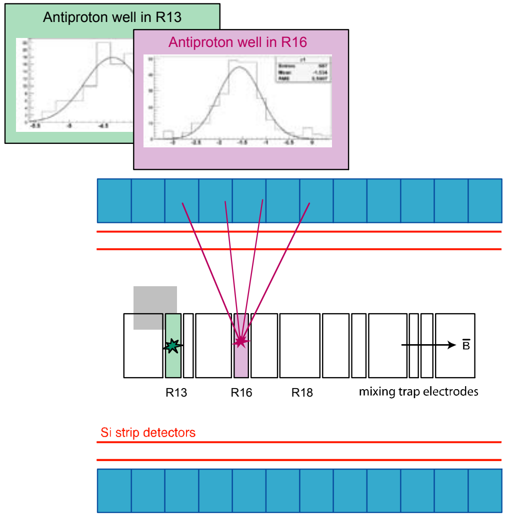
	Cold Mixing 2002	Cold Mixing 2003	
Total no. of cycles	341	416	
Cycle duration	180 s	70 s	
Total mixing time	61 400 s	29 100 s	
Injected $\bar{p}$ *	2 924 000	5 065 000	
Produced $\bar{H}$ *	494 000	704 000	
Production efficiency*	16.9%	13.9%	**33%**
Avg. $\bar{H}$ production rate	8.0(4) Hz	24.2(1.3) Hz	
Signal $\bar{H}$ fraction	65(5)%	74(3)%	

* 5% relative uncertainty

Data are in qualitative agreement with three body recombination

M.E.Glinsky &T.M.O'Neil, Phys.Fluids B 3(1991)1279,
F.Robicheaux & D.Hanson PRA 69(2004)010701,
F.Robicheaux, PRA 70(2004)022510

The Antihydrogen Z-distibution



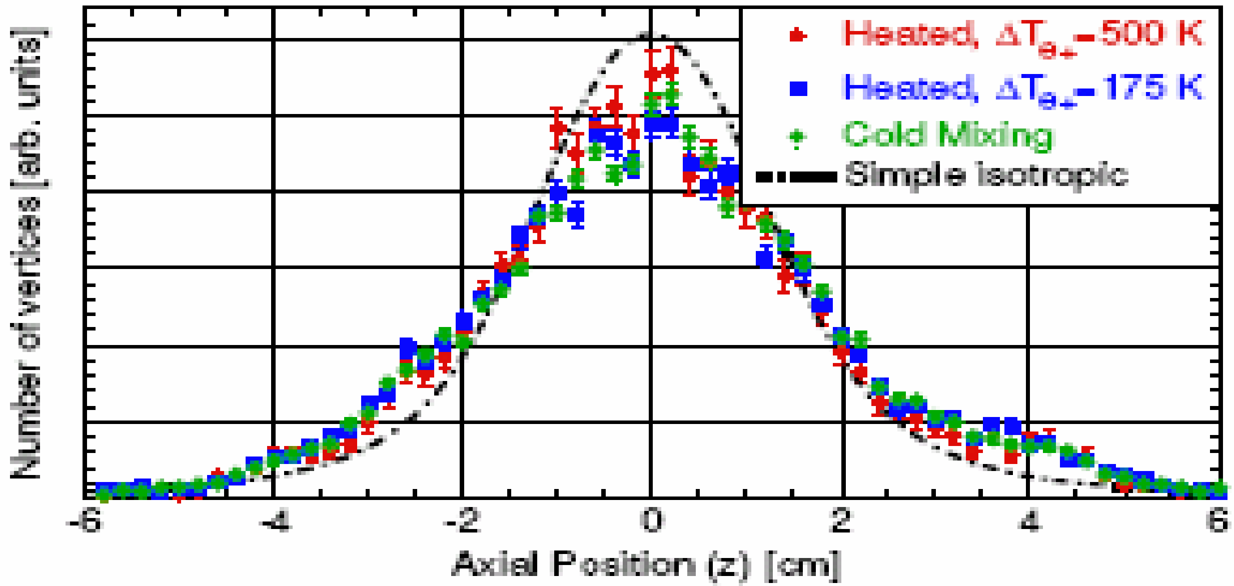


FIG. 2: Axial $\bar{\mathrm{H}}$ distributions for cold mixing and mixing with e^+ heated by two different amounts (hot mixing subtracted, xy-cut applied). The dot-dashed line is a simple calculation of isotropic emission from the e^+ plasma volume. The distributions have been normalized to the same area.

The Z-distribution

- **is independent of the plasma temperature**
- **is slightly enhanced in the axial direction**

The $\bar{\mathrm{H}}$ formation occurs from $\bar{\mathrm{p}}$ not in thermal equilibrium

The Antihydrogen velocity

By assuming the $\bar{p}$ capture from the rotating plasma (80 kHz) we obtain

$$T_{\parallel} = (10 \pm 2)\, T_{\perp}$$

By neglecting this effect we obtain

$$T_{\parallel} = (2.3 \pm 0.3)\, T_{\perp}$$

Assuming a plasma temperature of 15 K:

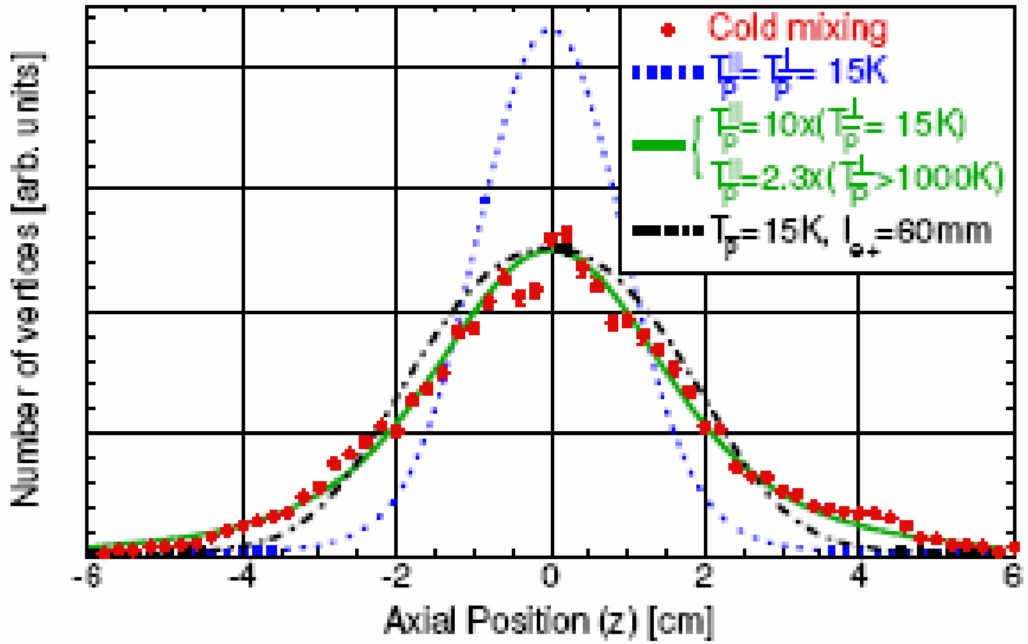


FIG. 3: Comparison of the axial distribution from cold mixing with a number of calculated distributions. Standard e^+ plasma parameters and $E \times B$ rotation were used except for the dot-dashed curve where $l_{e^+} = 60$ mm. Homogeneous formation in the plasma was assumed.

$$< v_{\parallel} > \approx 1100 \pm 100 \text{ m/s}$$

Accepted on PRL

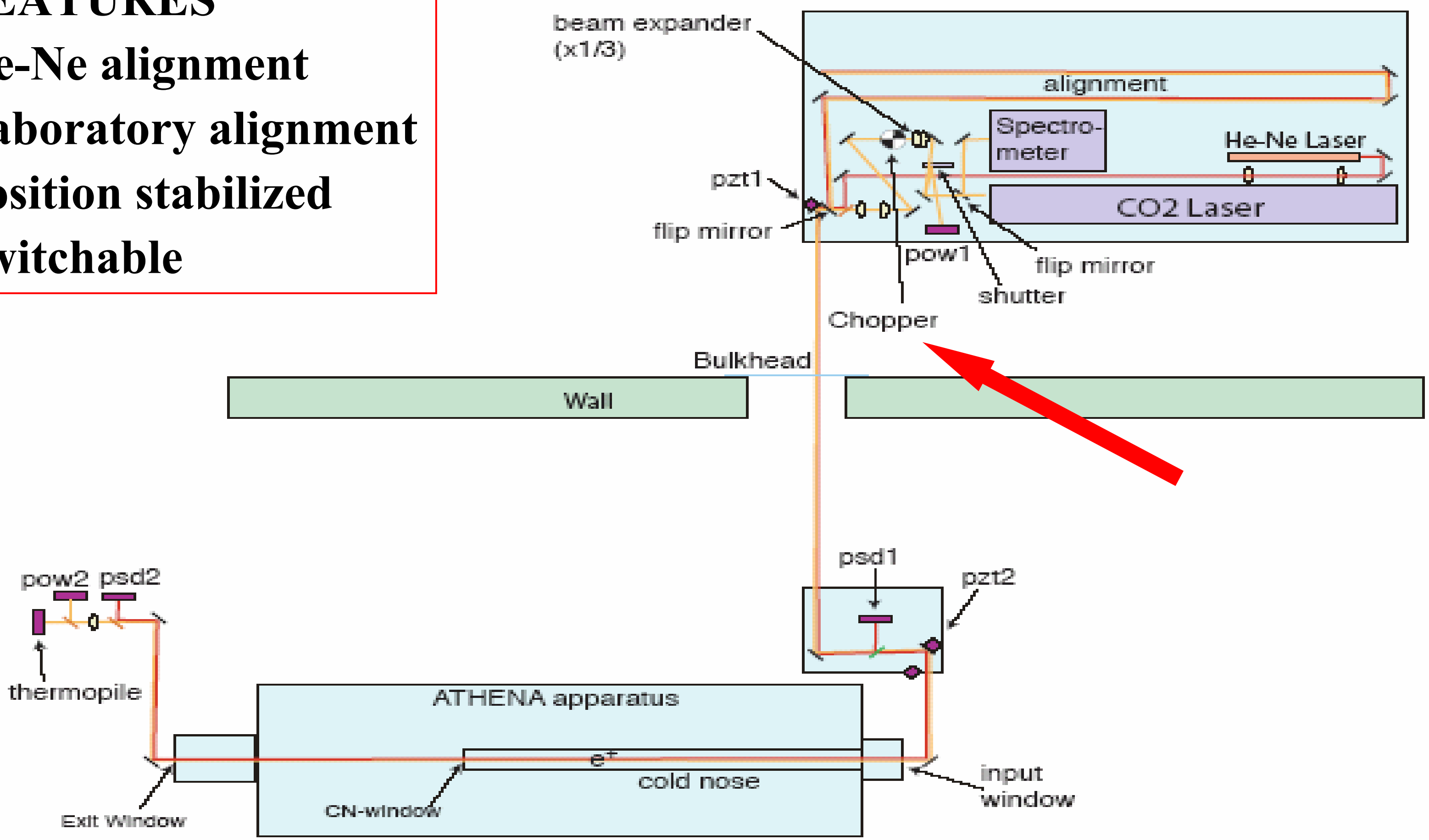
(model dependent result)

Laser runs (2004)

- We used a CO_2 laser to stimulate the radiative transition from the continuum to the n= 11 state
- Wavelength: tunable $9.5<\lambda<11.2$ μm. Used 10.96 μm (tried also 9.6 μm)
- Laser beam: power 15-30 W, waist of 2 mm, peak intensity 160 W/cm^2 at a 10 Watt power in the mixing region
- Recombination rate is not affected by the finite Doppler width for T=15K nor by the laser band width (100 MHz)
- Expected stimulated rate: > 60 Hz

The laser set-up

FEATURES
He-Ne alignment
Laboratory alignment
Position stabilized
Switchable



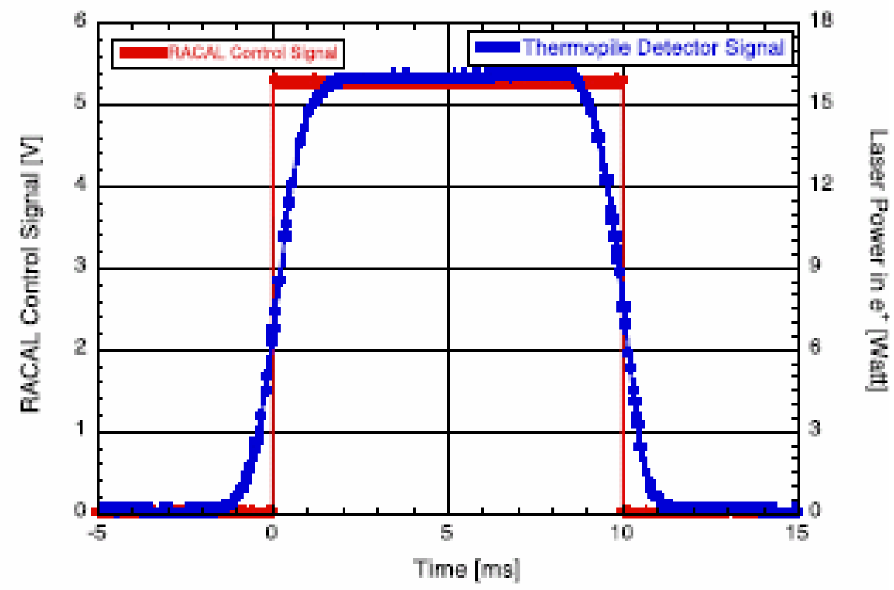
PZT: mirrors, POW: laser power meters
PSD: position sensitive detectors for He-Ne (feedback for PZT)

The ON-OFF technique

- **With the laser we measure a slight increase in temperature and no vacuum deterioration**
- **To assure the same conditions in the on-off laser measurements, the comparison has been made in the same run, by chopping the beam at a frequency of 25 Hz, with triggers recorded by DAQ**
- **In the following we will compare standard the Cold Mix runs with these laser runs in the 20 ms on-off mode**

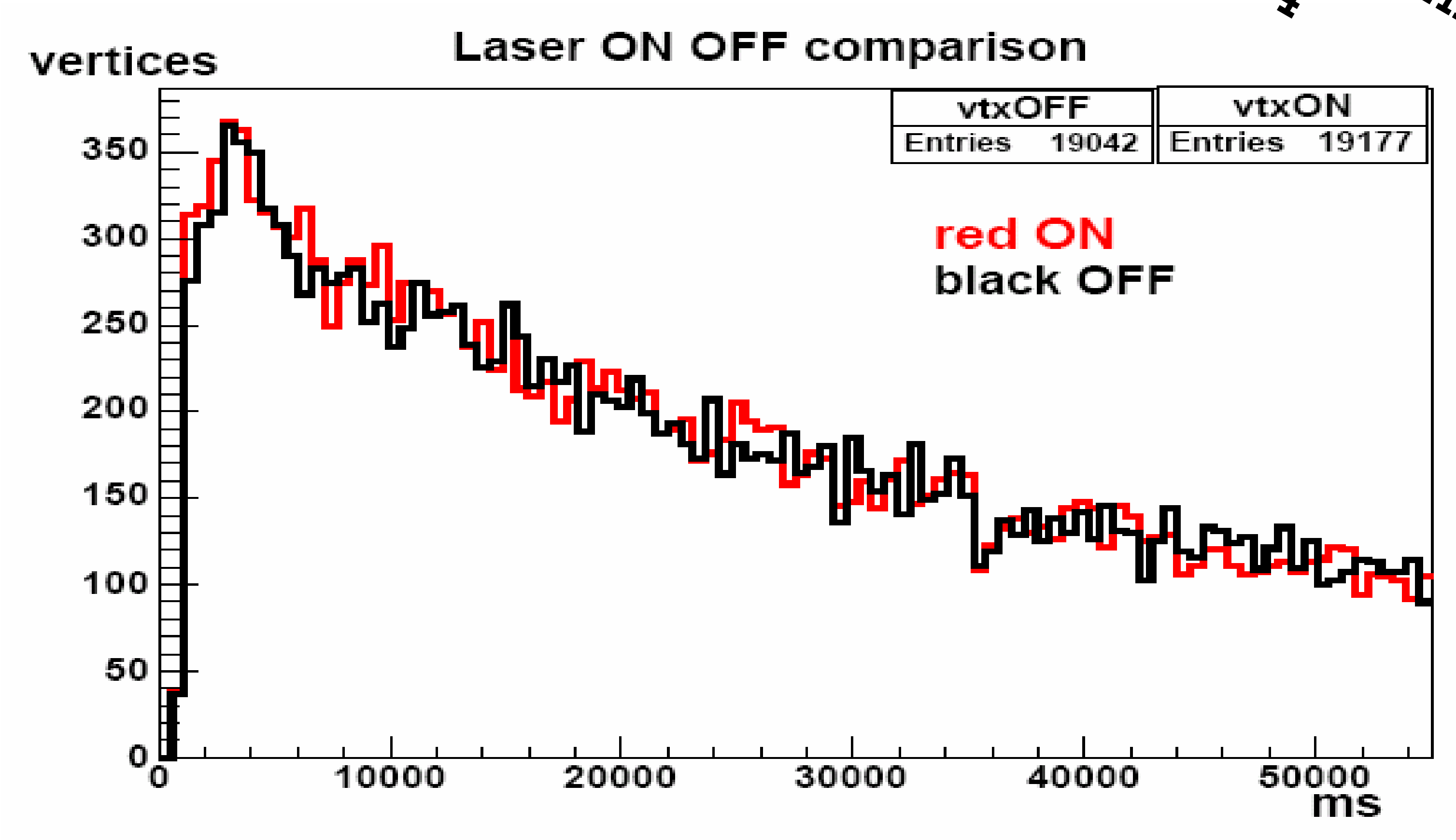
Power in the set-up

Control signal



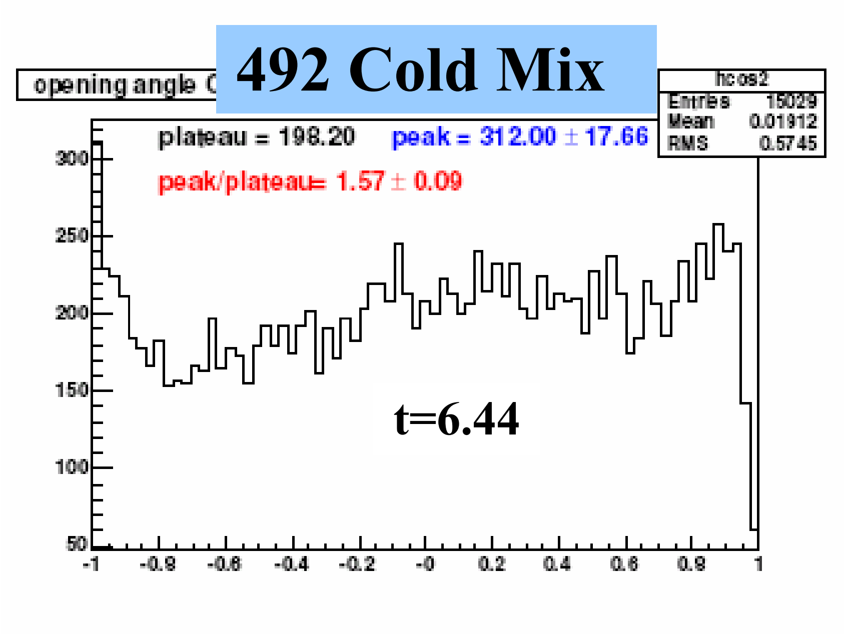
Trigger rate

Preliminary 2004



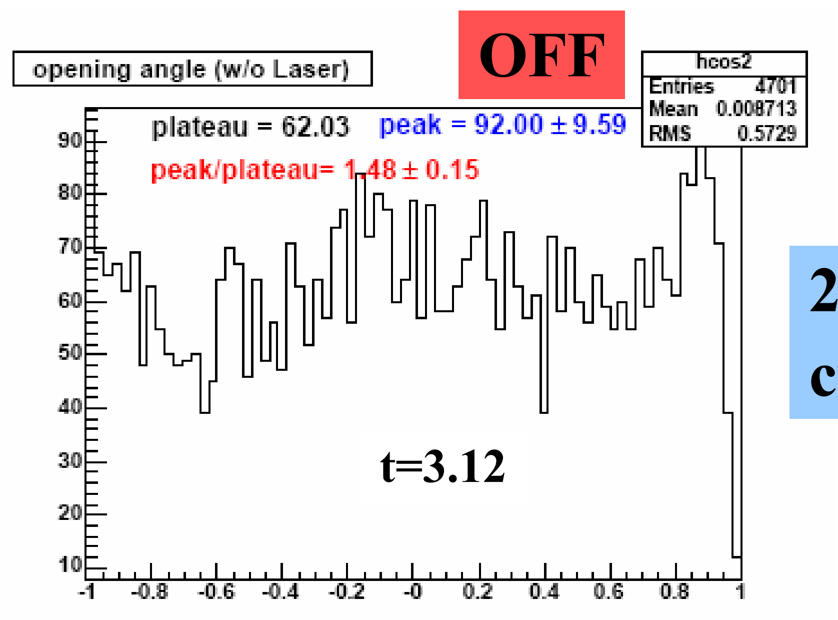
These data have to be analyzed also as a function of the plasma conditions and transfer parameters. The work is in progress

Results: opening angle

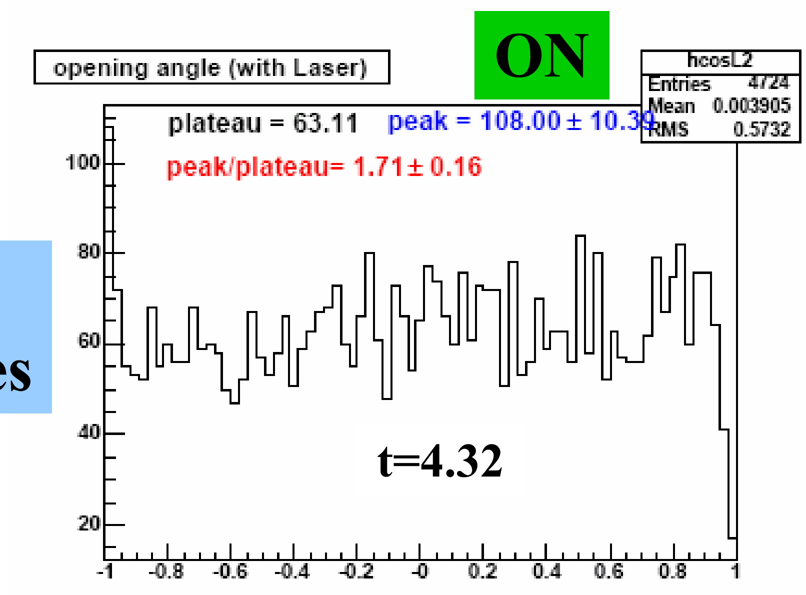


Preliminary 2004

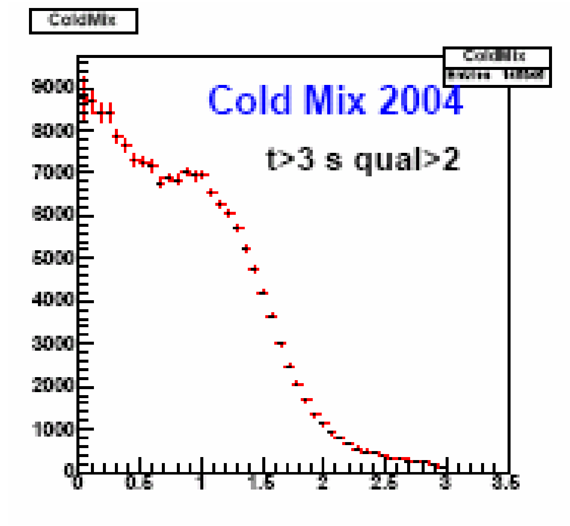
t=(peak-plateau)/σ_{peak}

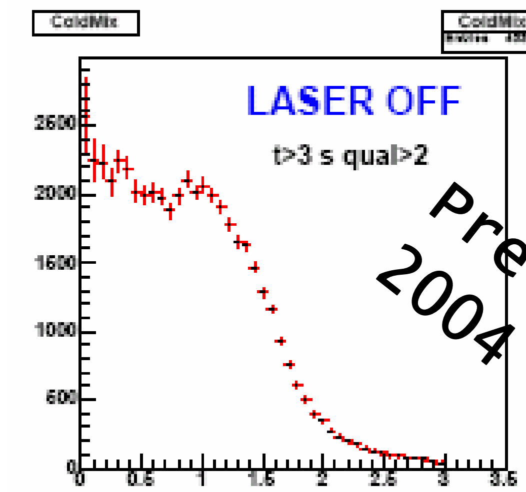


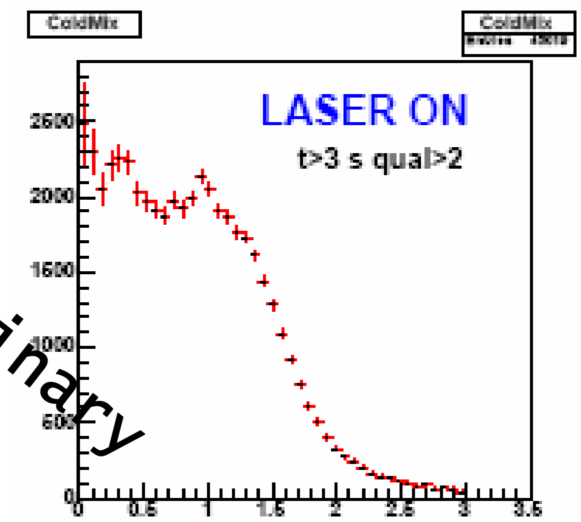
270 cycles

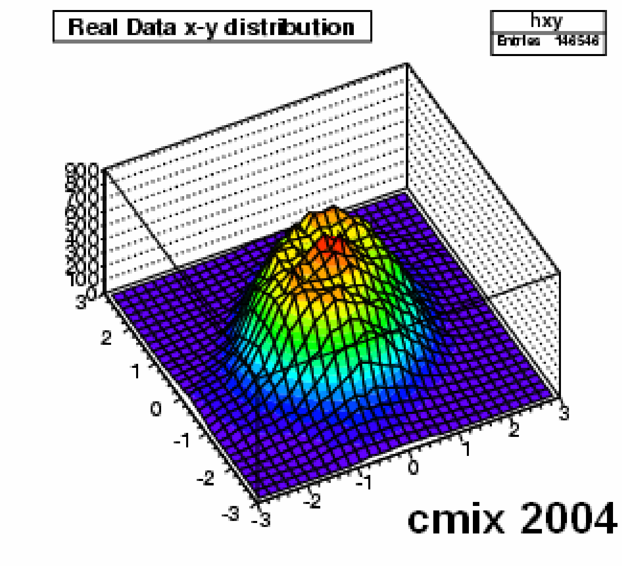


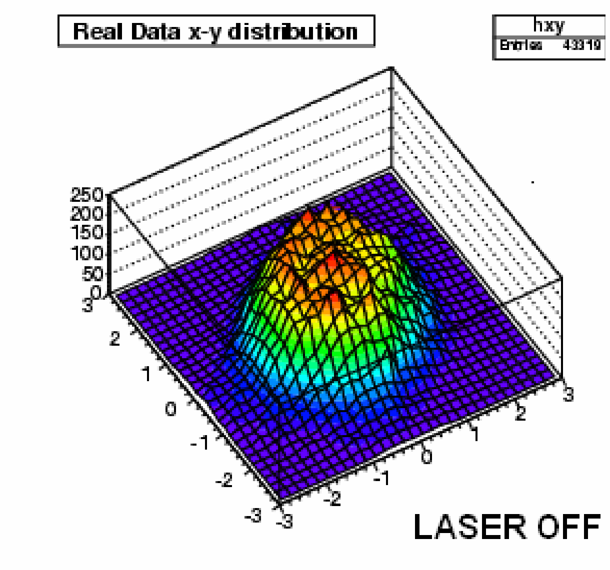
Radial distributions

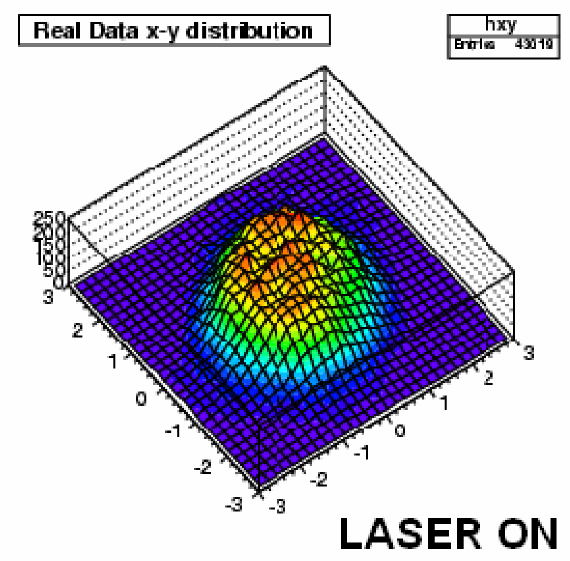












Conclusions

- ATHENA produced and detected the first antihydrogen atoms in 2002
- Many aspects of the dynamic of the mixing in the Penning trap have been clarified
- The dependence of the antihydrogen formation on the temperature, size and density of the positron plasma has been studied in detail (crucial issue)
- Now the conditions to routinely produce antiatoms at an average rate of 10-30 Hz for a minute are known

- The high production rate supports the 3-body process as the main mechanism of recombination.
- The spatial distribution of the antihydrogen atoms has been obtained an their axial velocity has been deduced
- The stimulation of the radiative 2-body recombination with a CO_2 laser from the continuum to n=11 has been performed in 2004 and preliminary results have been shown…..