Recent results from ATHENA

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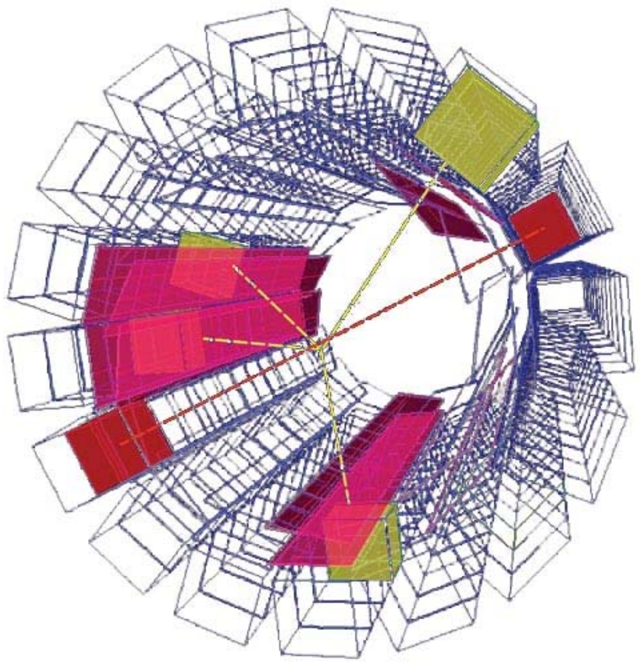
Motivation

First Production of Cold Antihydrogen

Recent Results

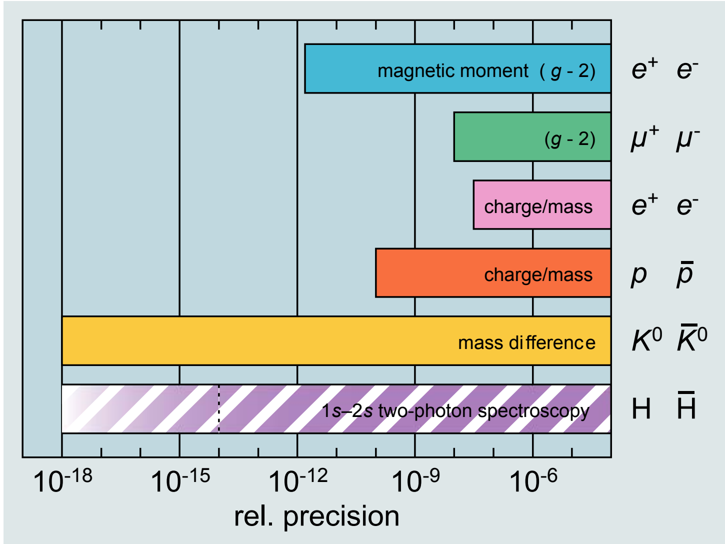
Outlook



Fundamental Tests with Antihydrogen

- CPT theorem
  - Laws of physics invariant under simultaneous charge, spatial, and time inversion
  - Assumptions: point-like particles, flat 4-D spacetime, etc.
  - Not necessarily valid at Planck scale: Quantum gravity, strings, extra dimensions
  - Recent theories suggest possibility of CPT violation
    [R. Bluhm *et al.*, PRD **57** (1998) 3932; O. Bertolami *et al.*, PLB **395** (1997) 178; etc., etc.]
  - Implies that H and $\bar{\mathrm{H}}$ have the same mass, lifetime, etc.
  - Comparison of H–$\bar{\mathrm{H}}$ spectrum offers direct CPT test

- Current precision of CPT tests:



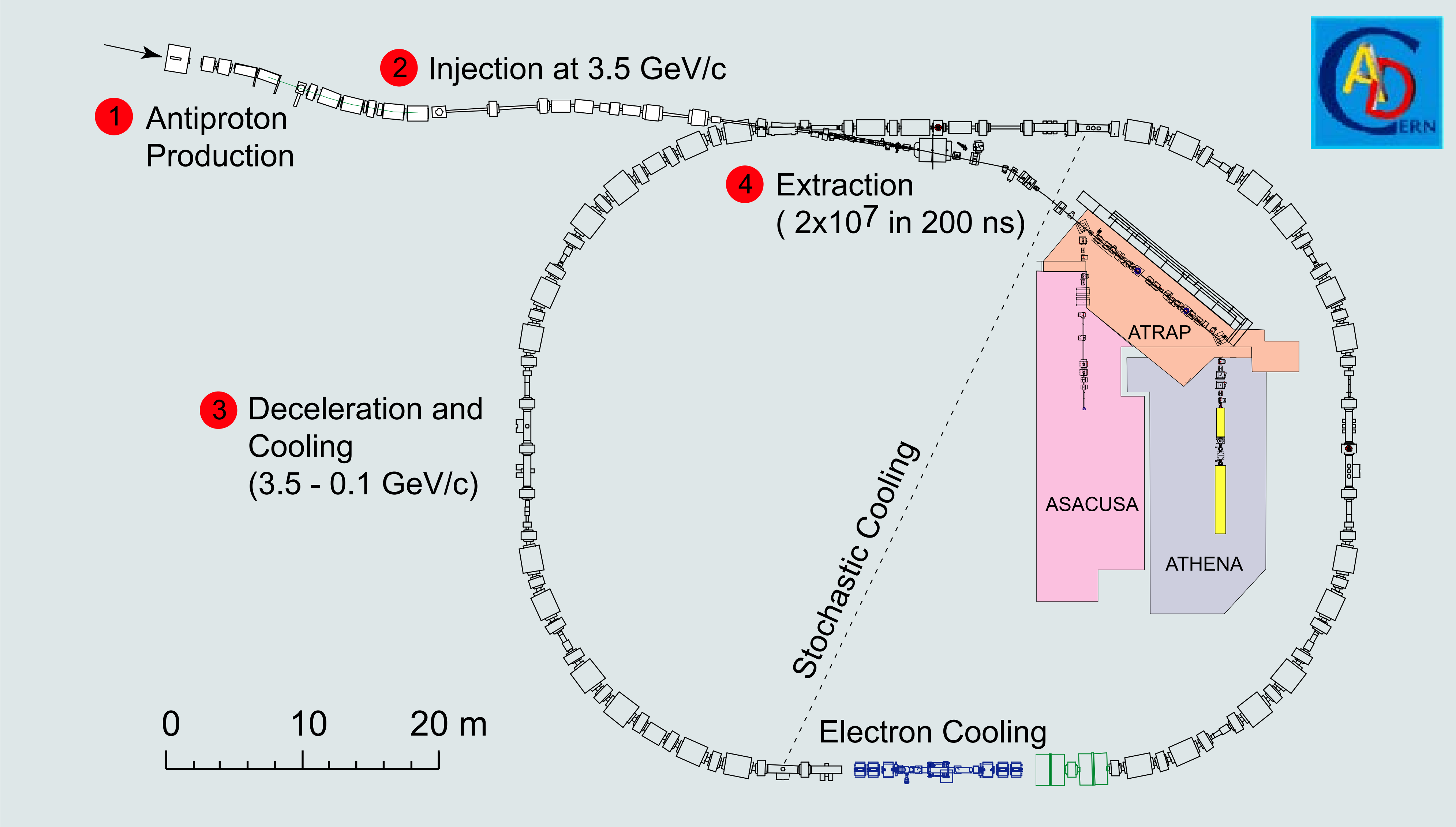
- Hydrogen 1*s* –2*s* transition freq. can be measured to very high precision today:

  ν = 2 466 061 413 187 103(46) Hz

  [M. Niering *et al.*, PRL **84** (2000) 5496]

- Gravity Tests
  - Equivalence principle (GR): Gravitational pull shifts transition lines
  - Spectra of H and $\bar{\mathrm{H}}$ are expected to react in the same way to changes in this pull (*e.g.* earth's elliptical orbit)
- High-precision tests require confined $\bar{\mathrm{H}}$ atoms $\Rightarrow$ need *cold* $\bar{\mathrm{H}}$

Antiproton Decelerator

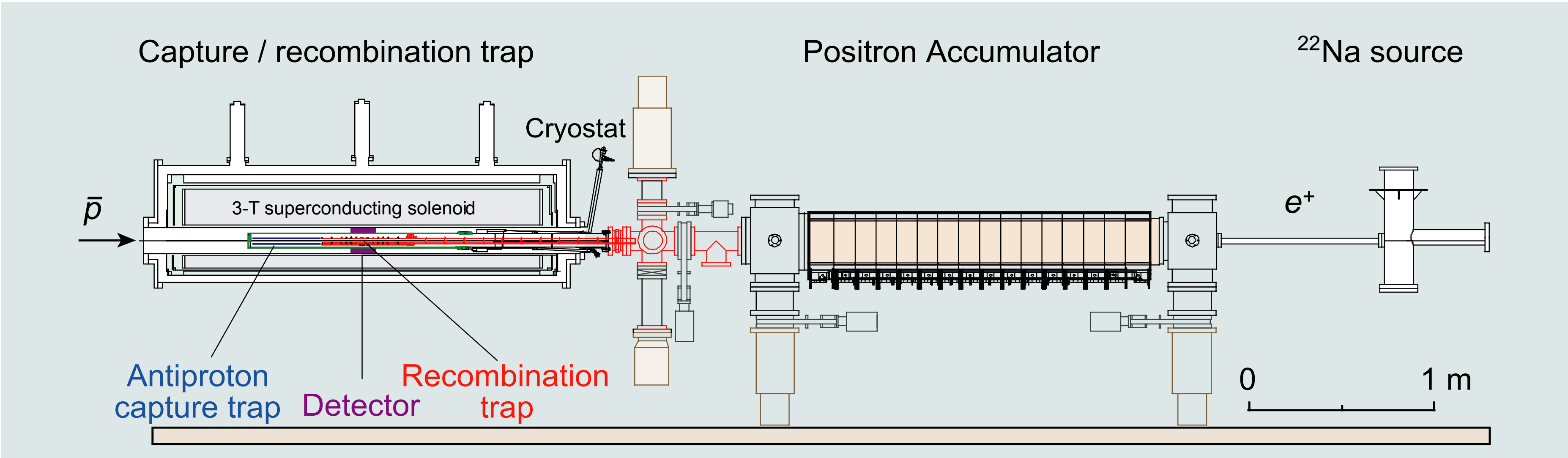


Overview of the ATHENA Apparatus

Antiproton capture trap
- Deceleration and capture of antiprotons
- Penning trap in 3-T field at 15 K
- Cooling and accumulation in e^- plasma

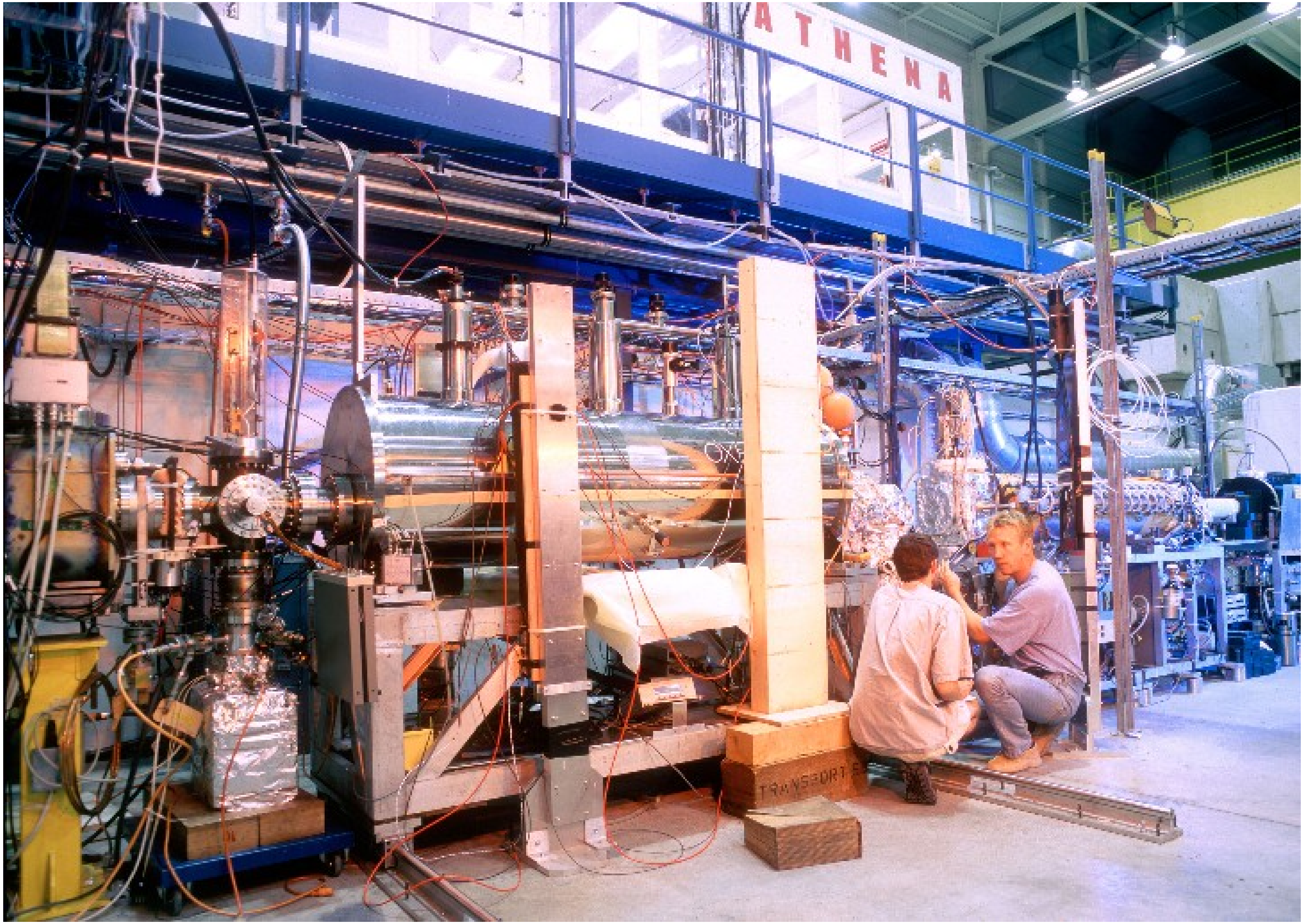
^{22}Na source
- Positron production via $^{22}Na(\beta^+)^{22}Ne$ at 5.5 K

Positron accumulator
- Penning trap in 0.14-T field at 300 K



Recombination trap
- Antihydrogen production
- Nested Penning trap in 3-T field at 15 K

Detector

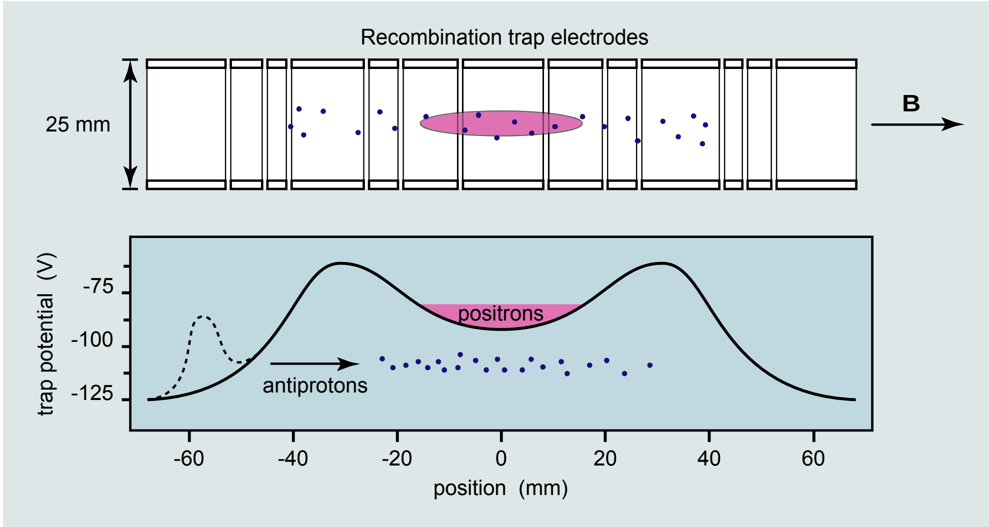

ATHENA
TRANSPORTS

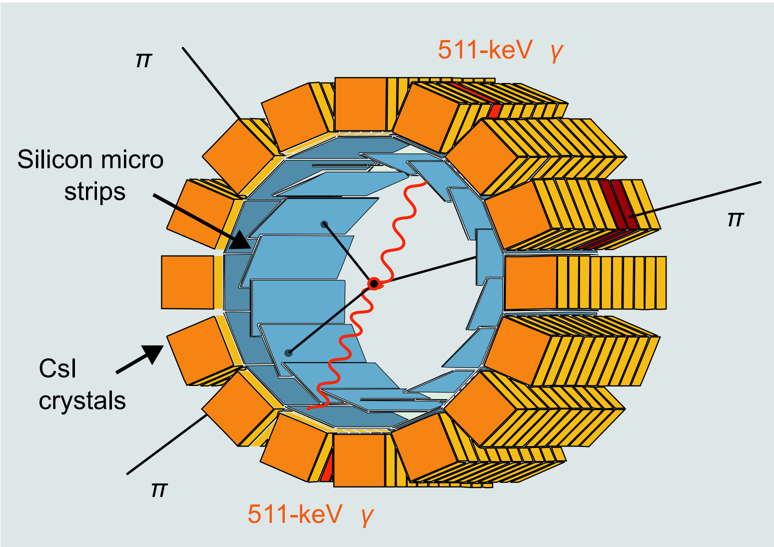
Recombination Trap and Detector

Recombination trap

Nested Penning trap at 15 K in 3-T field

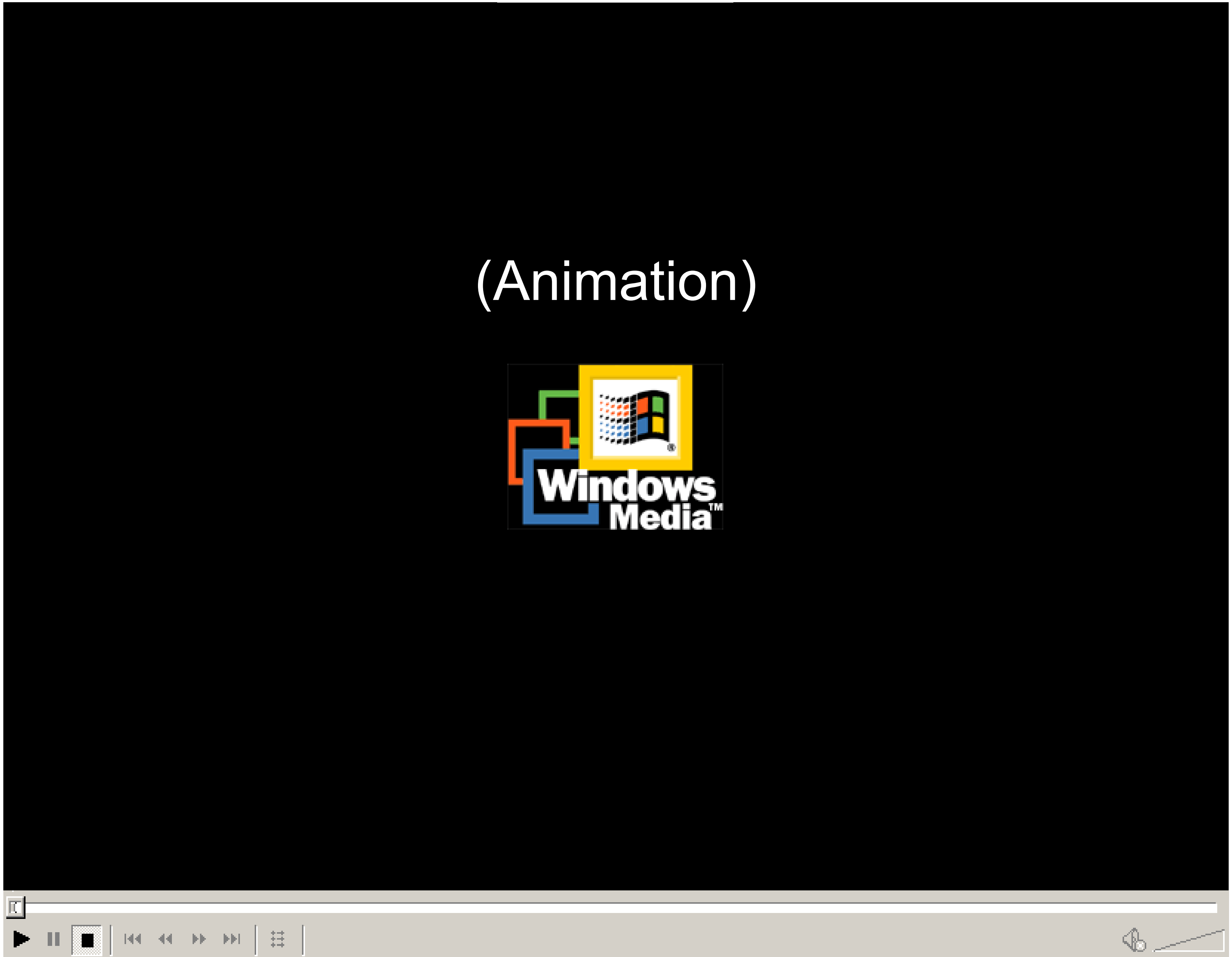
1. Fill positron well in mixing region with 10^8 e^+
2. Launch 10^4 $\bar{p}$ into mixing region
3. Continuously monitor production during 70-s mixing cycle
4. Repeat cycle every 250 seconds





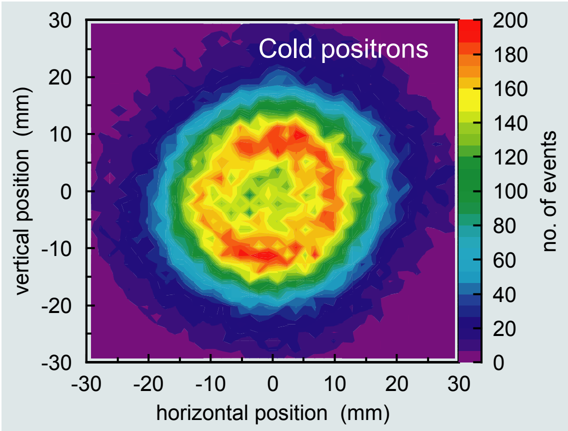
Antihydrogen detector

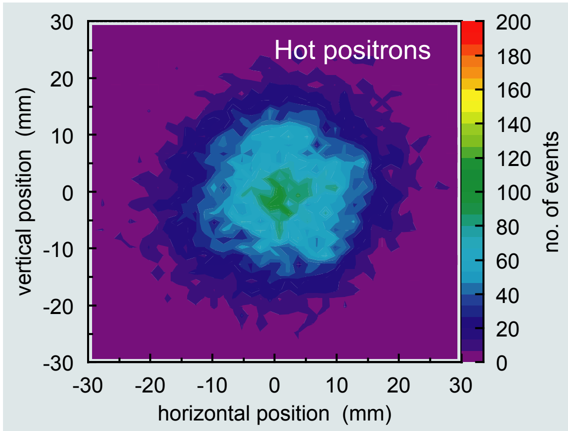
- Compact design (radial thickness ≈ 30 mm)
- Large solid angle (> 70%)
- High granularity (≈ 8000 strips, 192 crystals)
- Reconstruct vertex from tracks of charged particles
- Identify pairs of 511-keV γ rays
- Time and space coincidence


(Animation)
Windows Media

First Production of Cold Antihydrogen (2002)

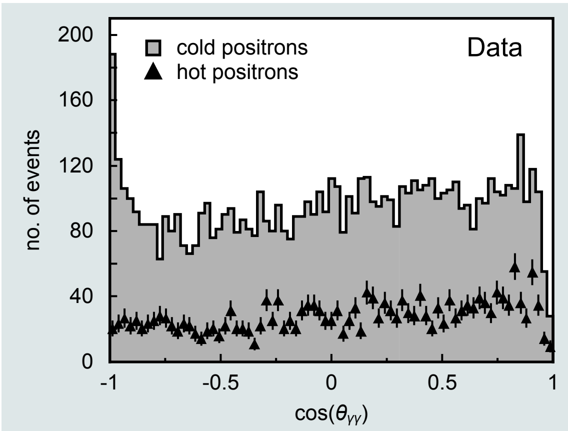
Spatial annihilation distribution

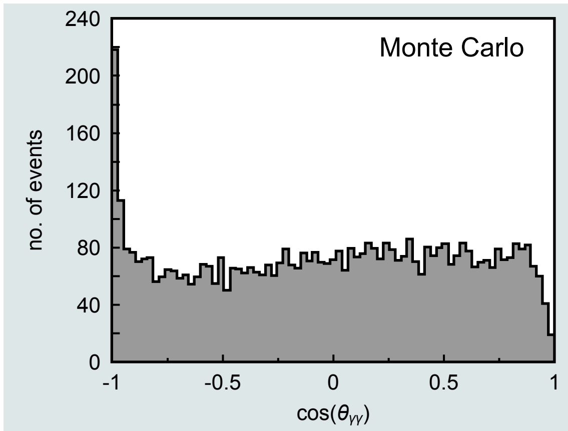




- Neutral $\bar{H}$ atoms annihilate on trap walls
- Heating of positrons suppresses $\bar{H}$ production
- Initial production rate of several 100 Hz observed

Opening angle distribution

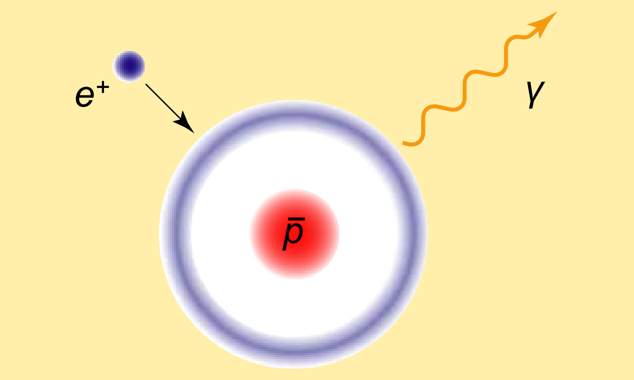
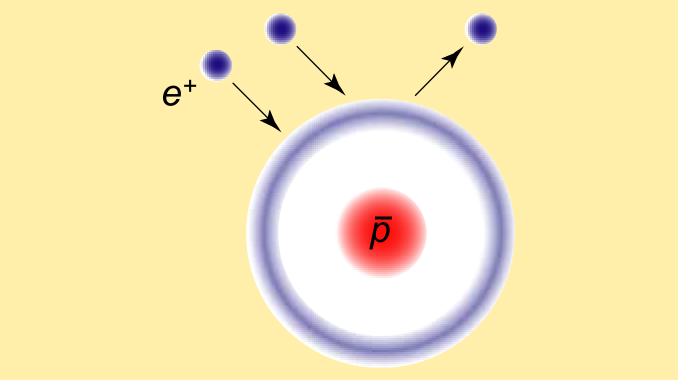




- Excess of back-to-back 511-keV photons

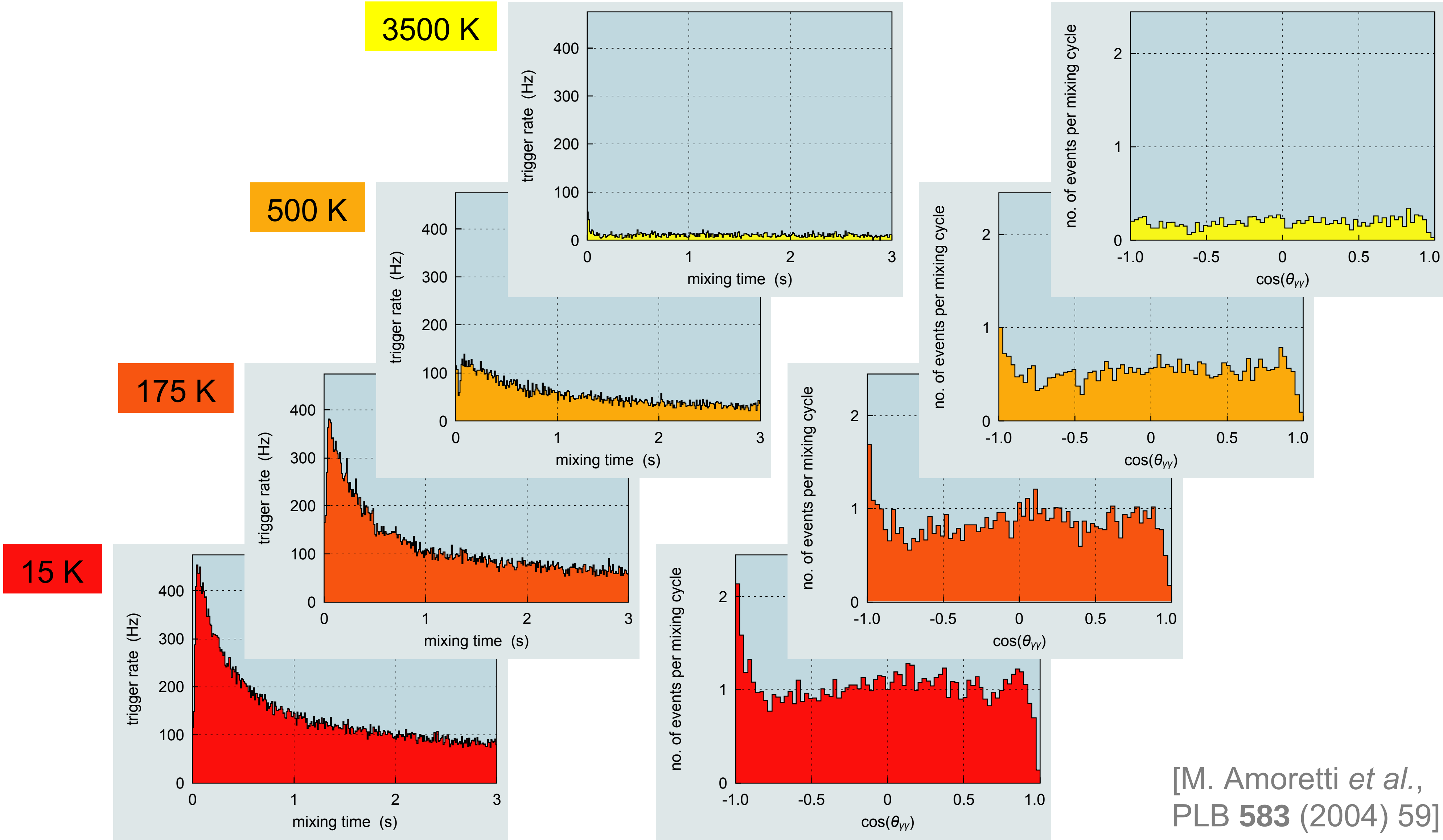
[M. Amoretti *et al.*, Nature **419** (2002) 456]

Recombination Processes

	Radiative Recombination	Three-body Recombination
Principle		
Temperature Depend.	$T^{-2/3}$	$T^{-9/2}$
Cross-Section at 1 K	10^{-16} cm^2	10^{-7} cm^2
Stability (Re-ionization)	high	low
Final Internal States	$n < 10$	$n >> 100$
Expected Rates	few Hz	unknown

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

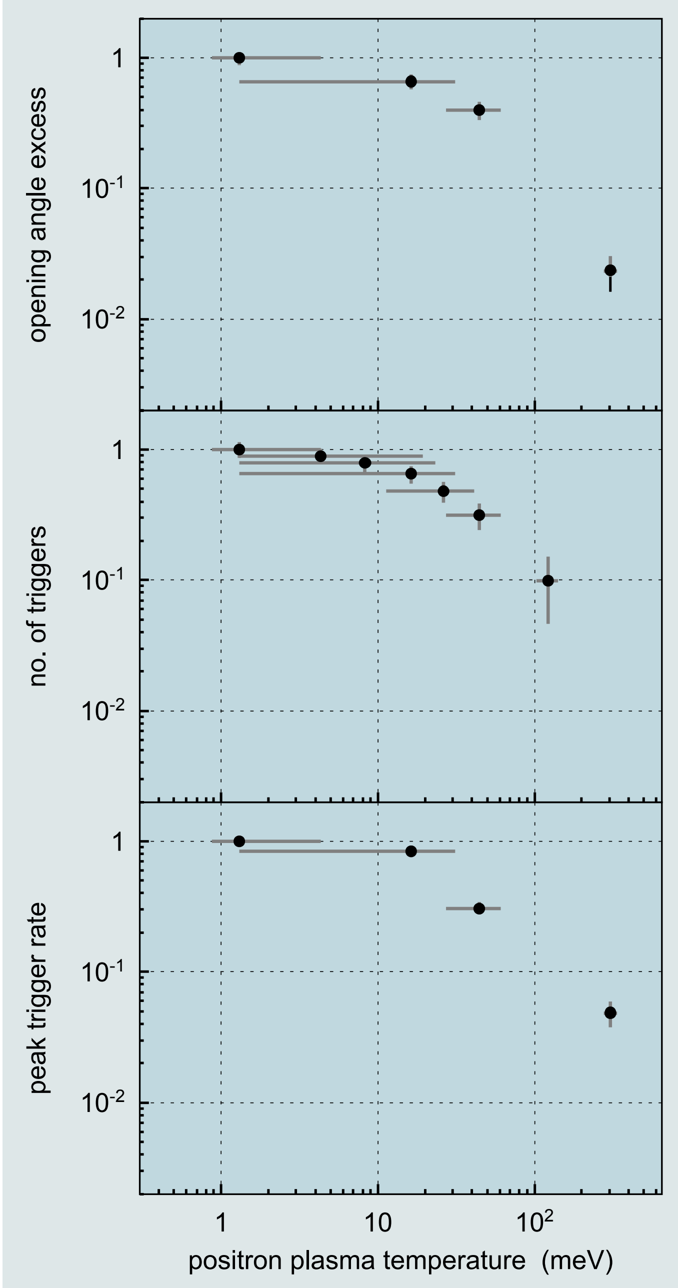
Temperature dependence of trigger rate and opening angle



[M. Amoretti *et al.*, PLB **583** (2004) 59]

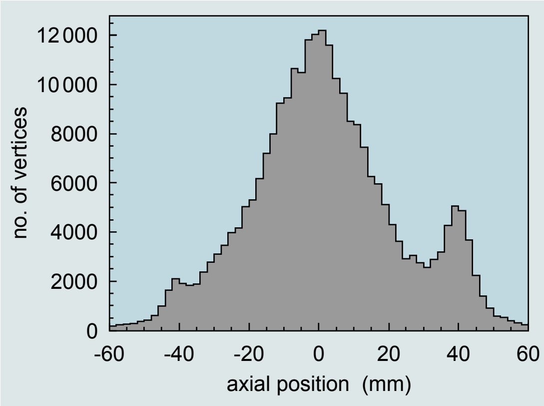
Detailed study of temperature dependence of $\bar{H}$ production

- Production levels off with increasing temperature
- Turnover for low temperatures is observed
- Best fit to data yields $T^{-0.7\pm0.2}$ behavior
- ...*but* three-body process is expected to be dominant for low temperatures
- ...*and* observed recombination rate is 20 times higher than predicted rate
- Note: Simple power laws must be corrected for overlap & effects due to high magnetic field

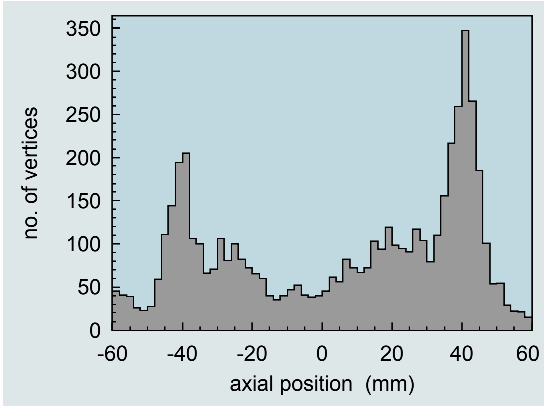


Spatial Distribution of Antihydrogen Emission

- Distribution in the radial plane is rotationally symmetric
- Axial distribution of $\bar{p}$ annihilations:



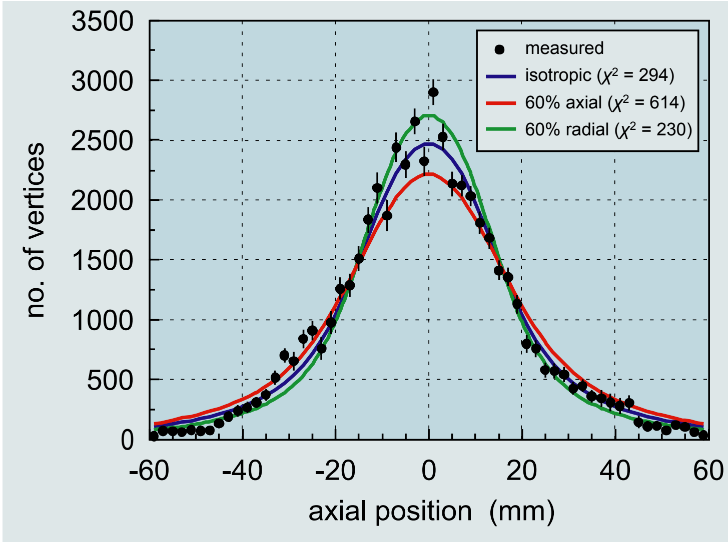
normal mixing



antiprotons only

$\Rightarrow$ antiproton loss is localized in z
(and also in θ) [M. C. Fujiwara et al., PRL, in press]

- Axial distribution of $\bar{p}$ annihilations



Fit reproduces data best for slight radial enhancement

- Observations:
  - Quasi-isotropy of emergence of $\overline{\mathrm{H}}$ suggests radiative recombination as dominant production mechanism
  - Antiproton transv. velocity is slightly larger than axial velocity $\Rightarrow$ thermal velocity small compared to radial velocity
  - Note: due to re-ionization, we are only sensitive to $n < 56$

Conclusion and Outlook

- ATHENA has produced ≈ 2 000 000 cold antihydrogen atoms in 2002–2003
- We have a growing understanding of the involved processes and $\bar{H}$ properties
- Short-term goals:
  - Use sideband cooling to center antiprotons radially
    $\Rightarrow$ improve overlap with positron plasma, produce $\bar{H}$ near axis
  - Laser-stimulated recombination of $\bar{H}$
    (constitutes a first spectroscopic measurement)
- Long-term goals:
  - Confinement of created $\bar{H}$ as prerequisite for precision studies
    (requires *very cold* $\bar{H}$)

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