International Conference on Muon Catalyzed Fusion and Related Topics

μCF - 07

Dubna, 18 - 21 June 2007

JOINT INSTITUTE FOR NUCLEAR RESEARCH

JINR

The Hyperfine Structure of Antiprotonic Helium and the Antiproton Magnetic

Eberhard Widmann

ÖAW Austrian Academy of Sciences

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ASACUSA Collaboration @ CERN-AD

Asakusa Kannon Temple
by Utagawa Hiroshige (1797-1858)

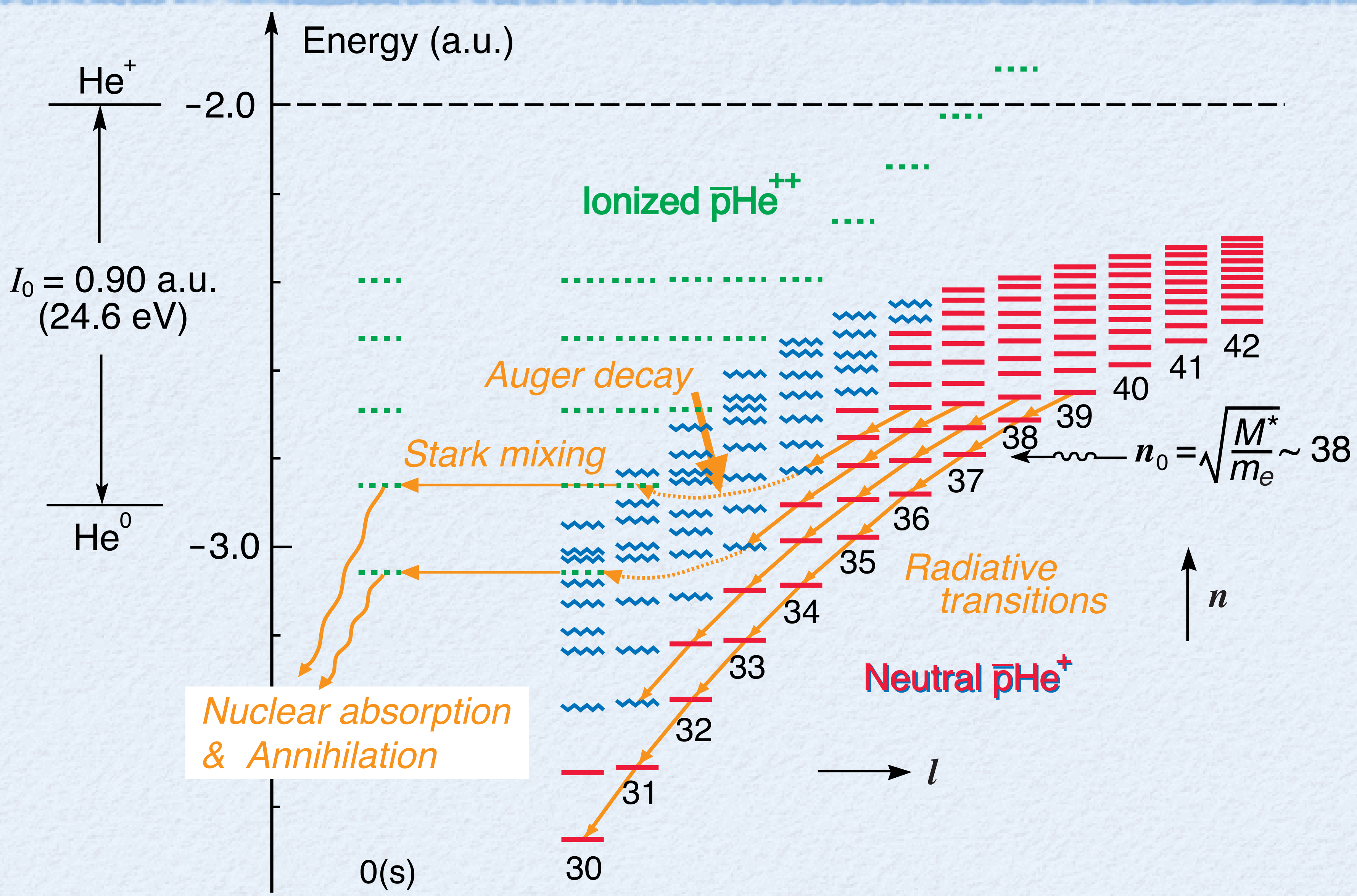
Spokesman: R.S. Hayano, University of Tokyo

Atomic **S**pectroscopy **A**nd **C**ollisions **U**sing **S**low **A**ntiprotons

- University of Tokyo, Japan
  - College of Arts and Sciences, Institute of Physics
  - Faculty of Science, Department of Physics
- RIKEN, Saitama, Japan
- SMI, Austria
- Aarhus University & ISA, Denmark
- Niels Bohr Institute, Copenhagen, Denmark
- Max-Planck-Institut für Kernphysik, Heidelberg, Germany
- KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
- University of Debrecen, Hungary
- Brescia University & INFN, Italy
- University of Wales, Swansea, UK
- The Queen's University of Belfast, Ireland

~ 44 members

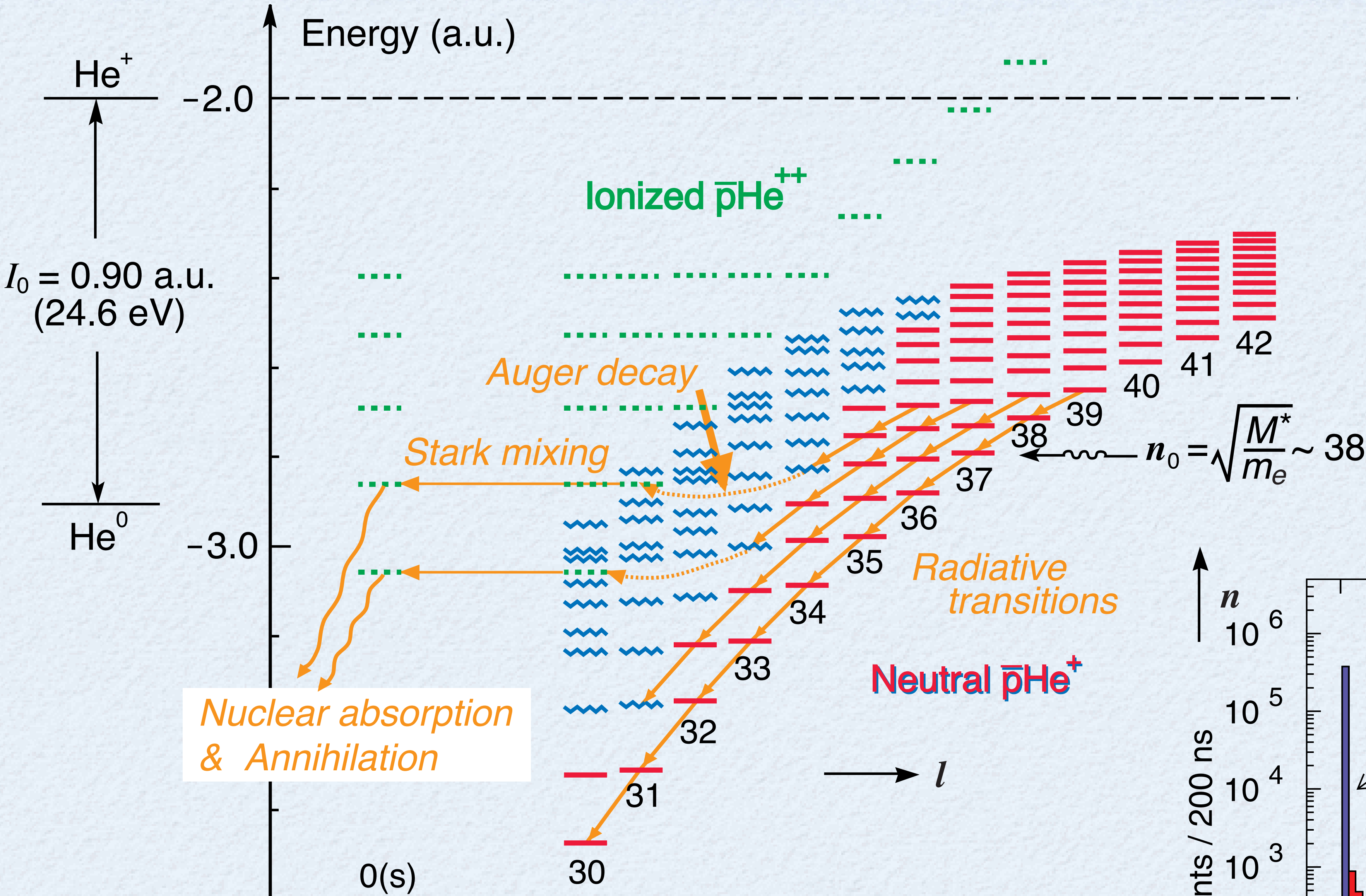
$\bar{p}He^+$ "atomcule" - a naturally occurring trap for antiprotons



Metastable states
$\tau \sim \mu s$

short-lived states
(Auger decay)
$\tau \leq 10$ ns

p̄He+ "atomcule" - a naturally occurring trap for antiprotons



Metastable states
τ~ μs

short-lived states
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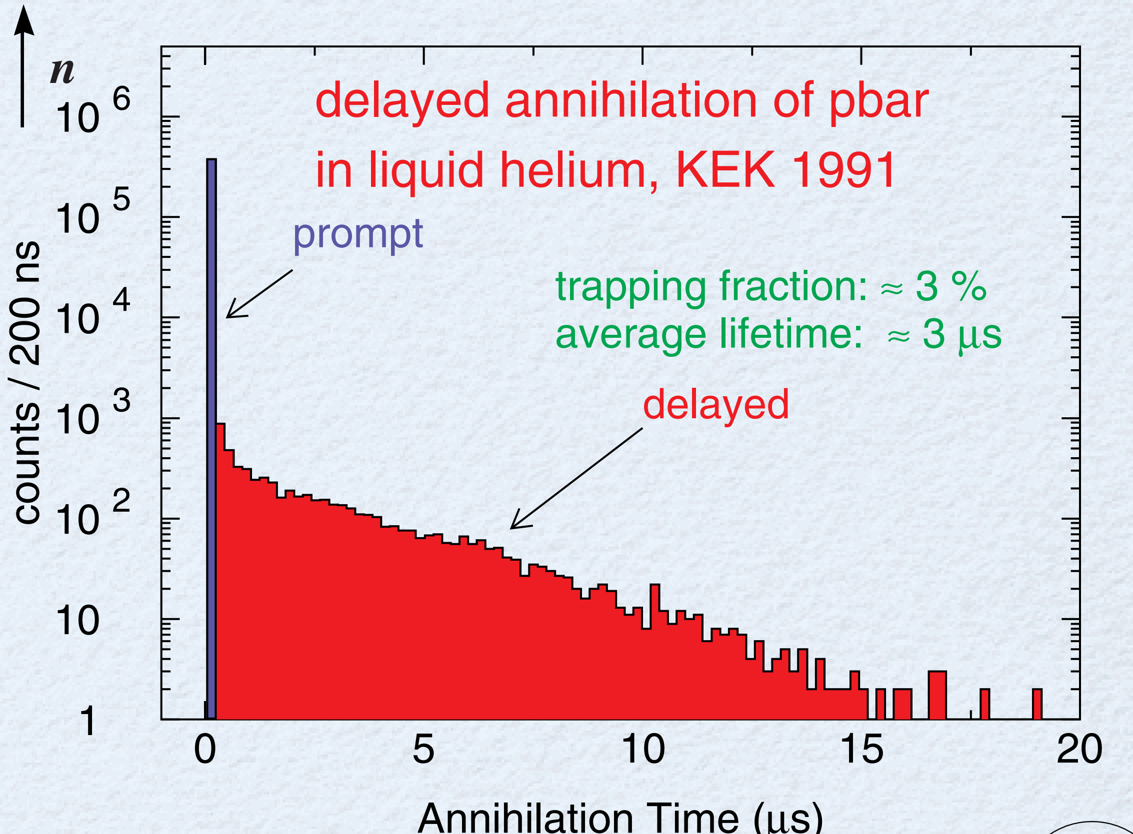
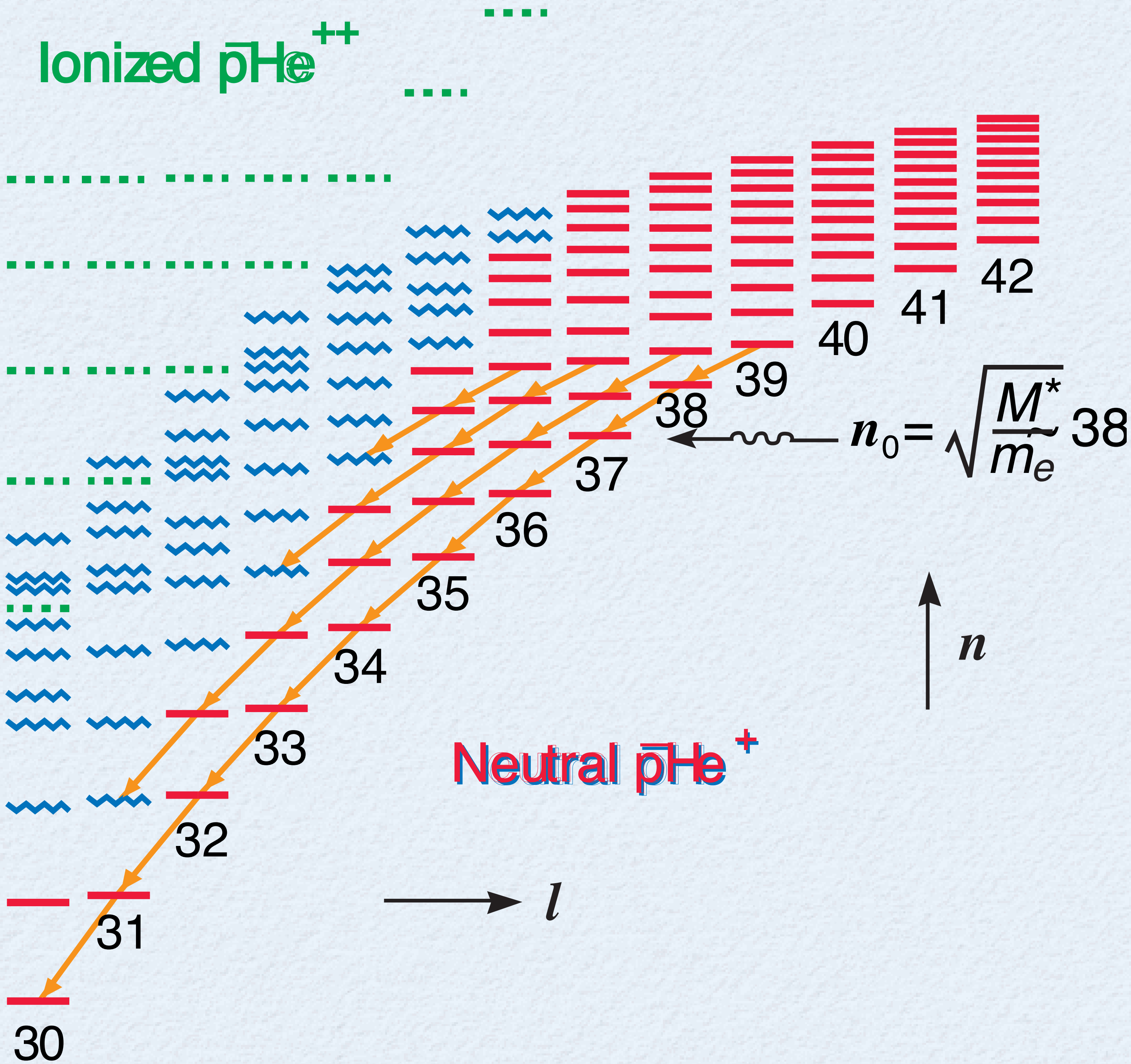
τ ≤ 10 ns



possibility of precision spectroscopy

Precision Spectroscopy



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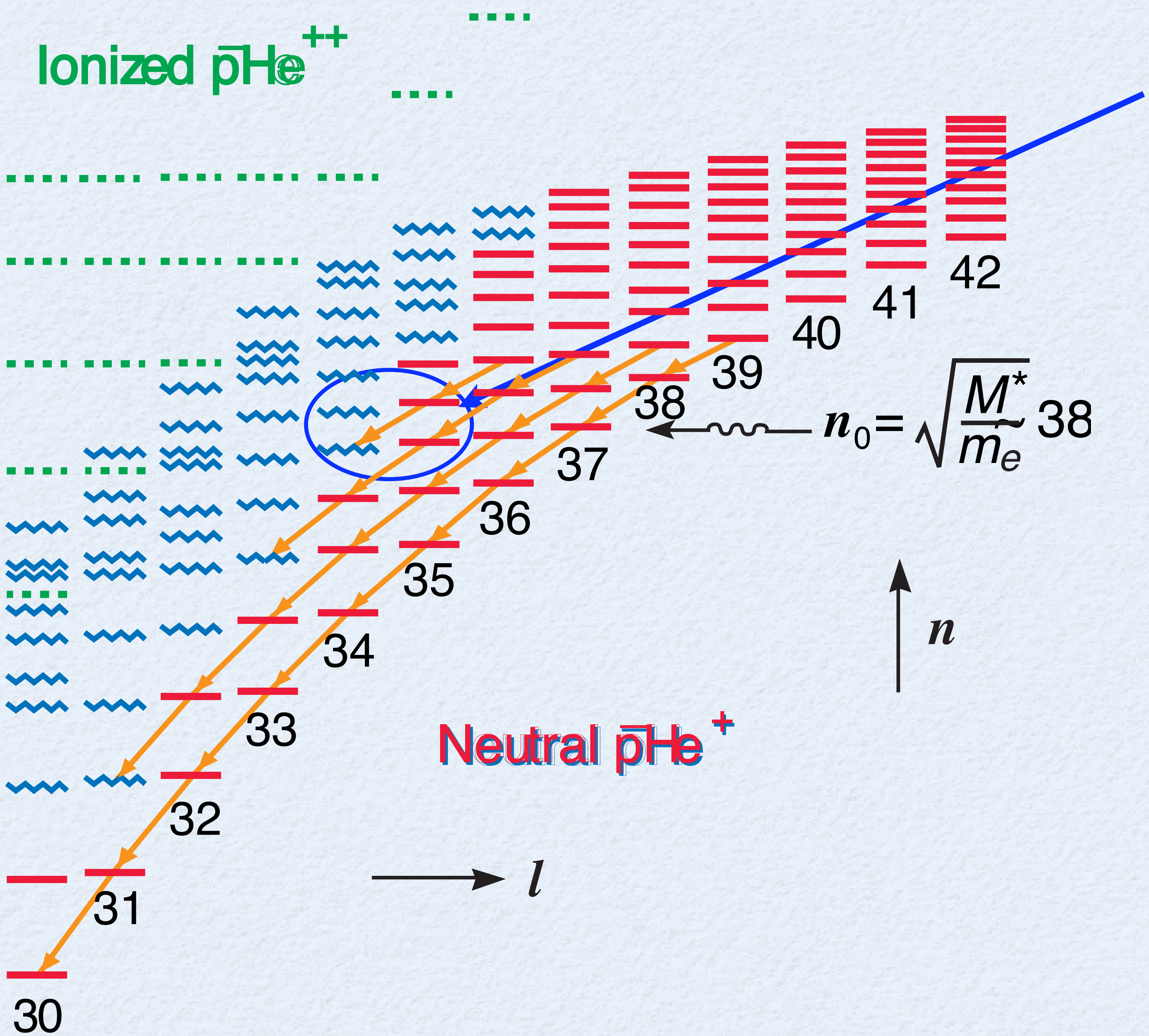
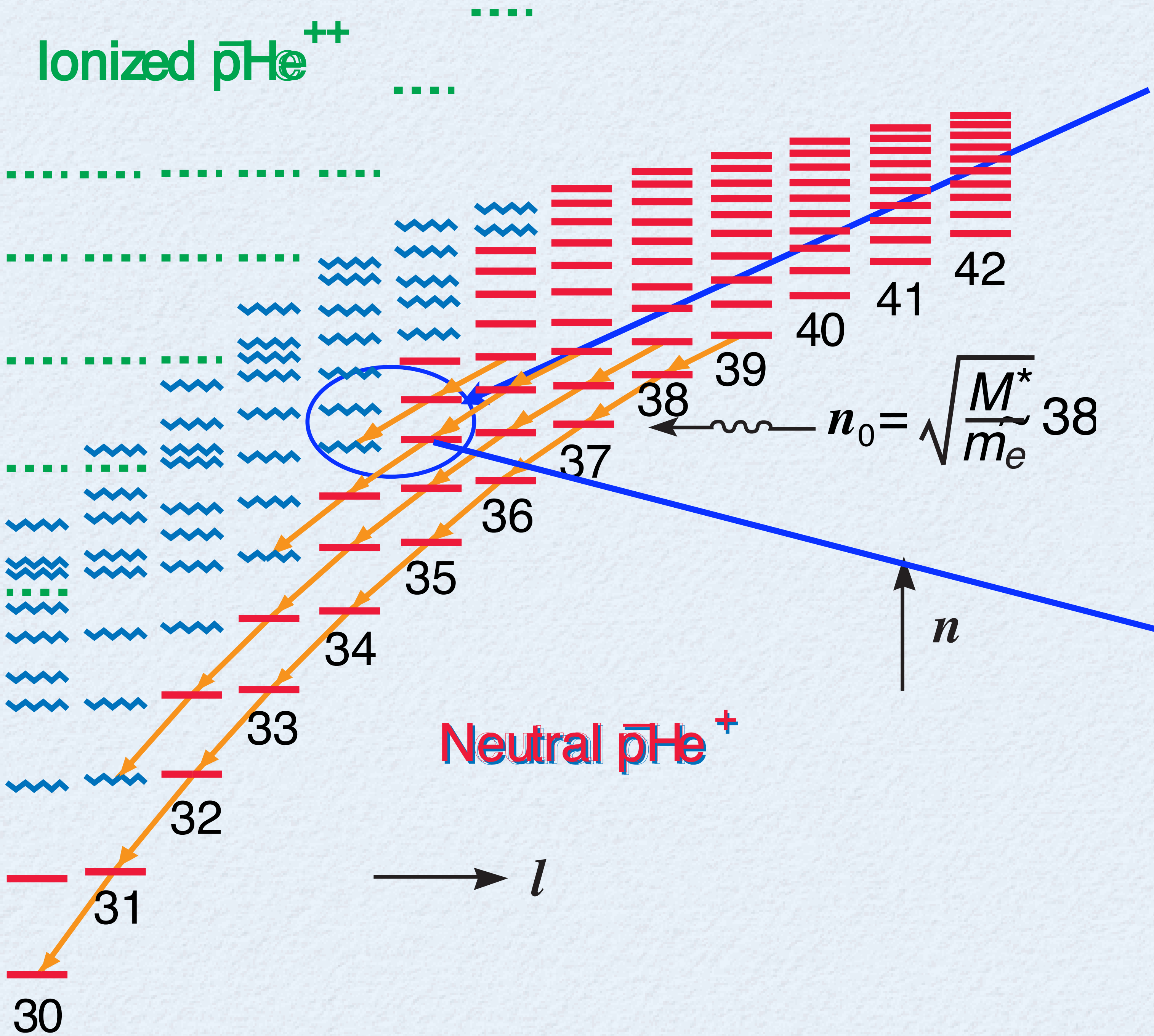


- pairs of metastable - short-lived state
  - laser spectroscopy
  - forced annihilation
  - determine mass, charge of antiproton

Precision Spectroscopy



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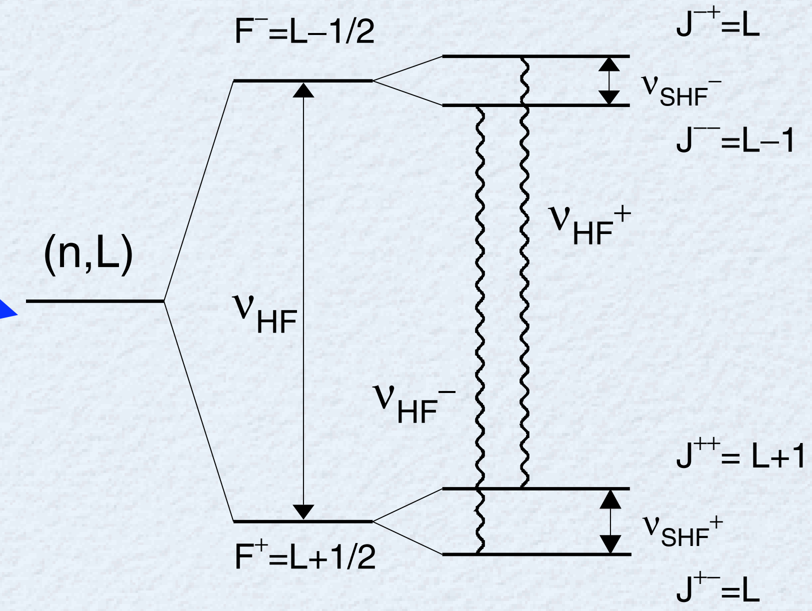
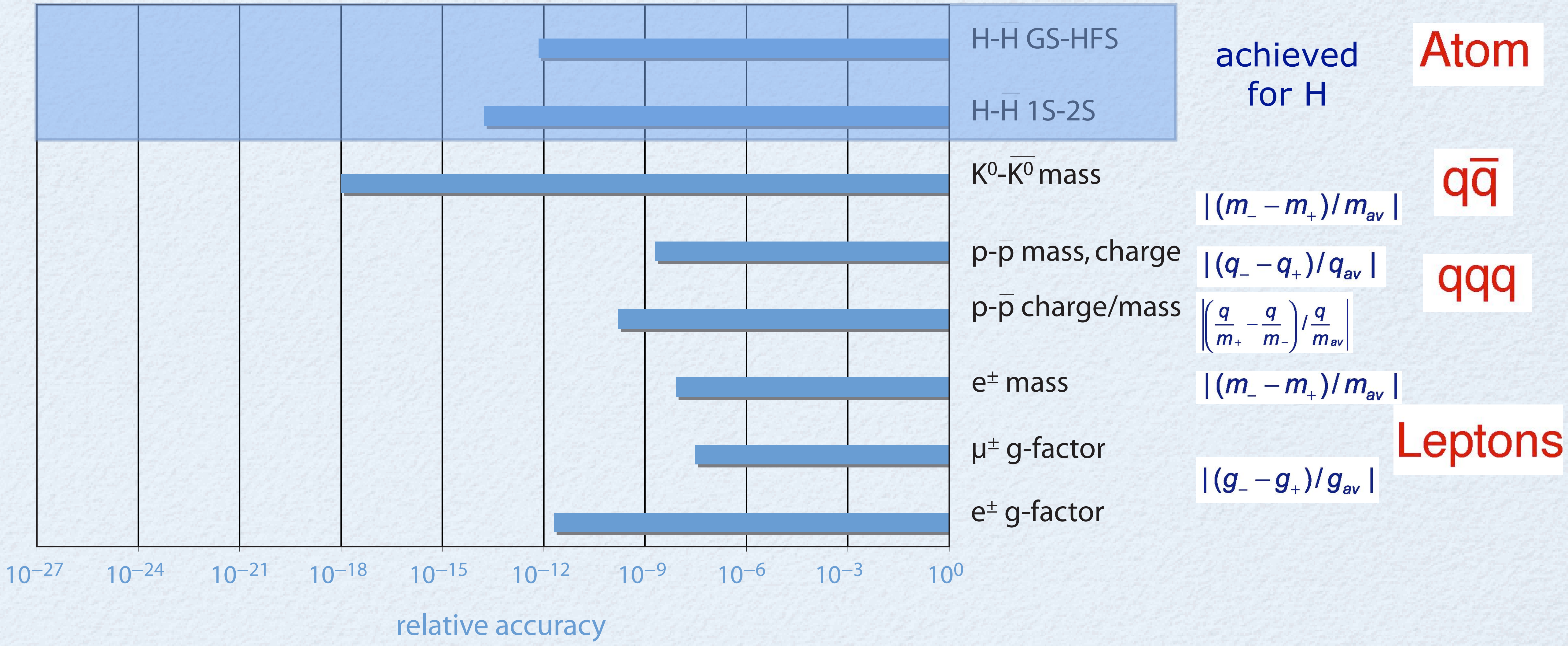


- hyperfine structure
  - magnetic moment of antiproton

CPT TESTS - PDG

- *Tests of particle/antiparticle symmetry properties*

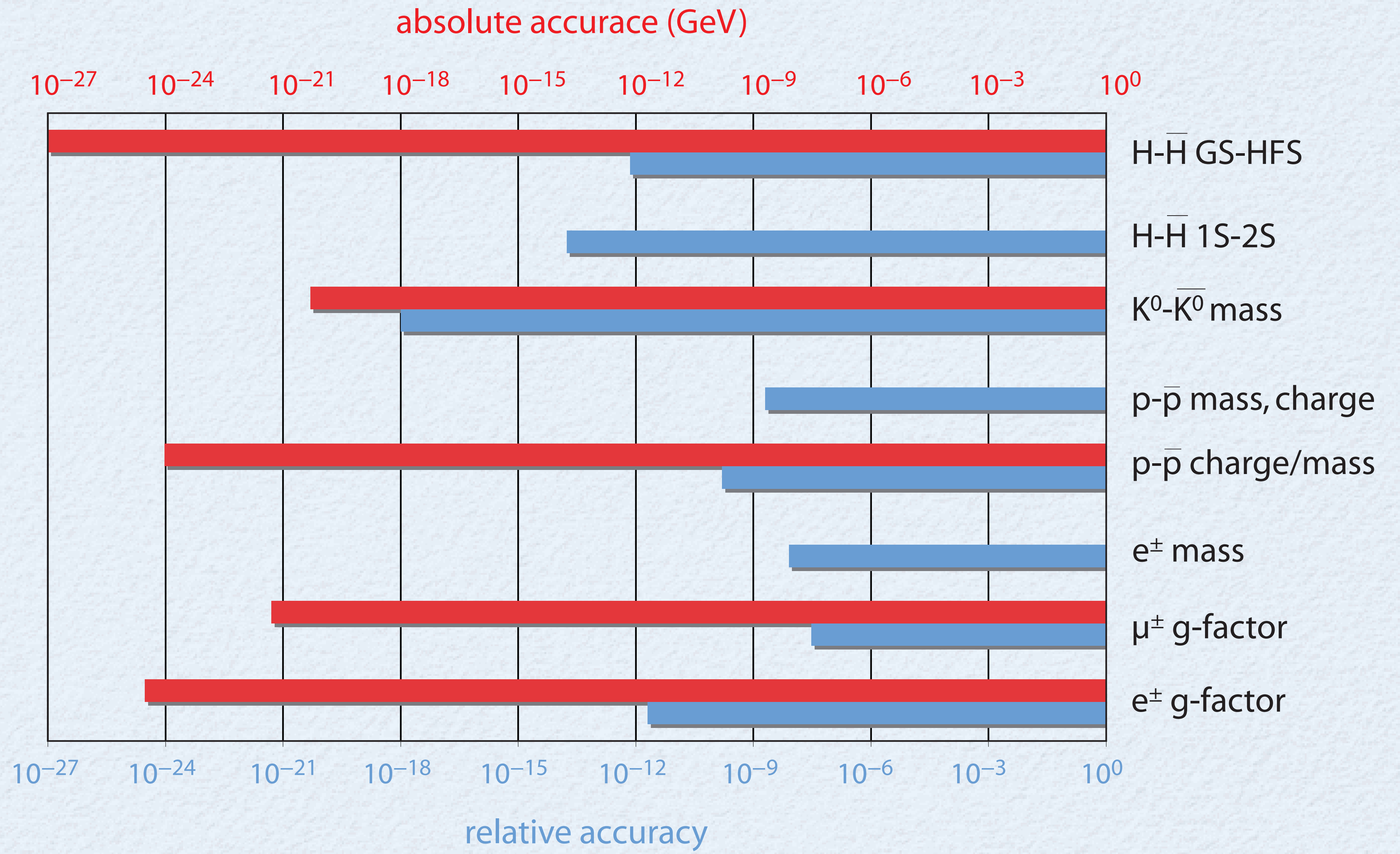


- *Inconsistent definition of figure of merit: comparison difficult*
- *Pattern of CPT violation unknown (P: weak interaction, CP: mesons)*

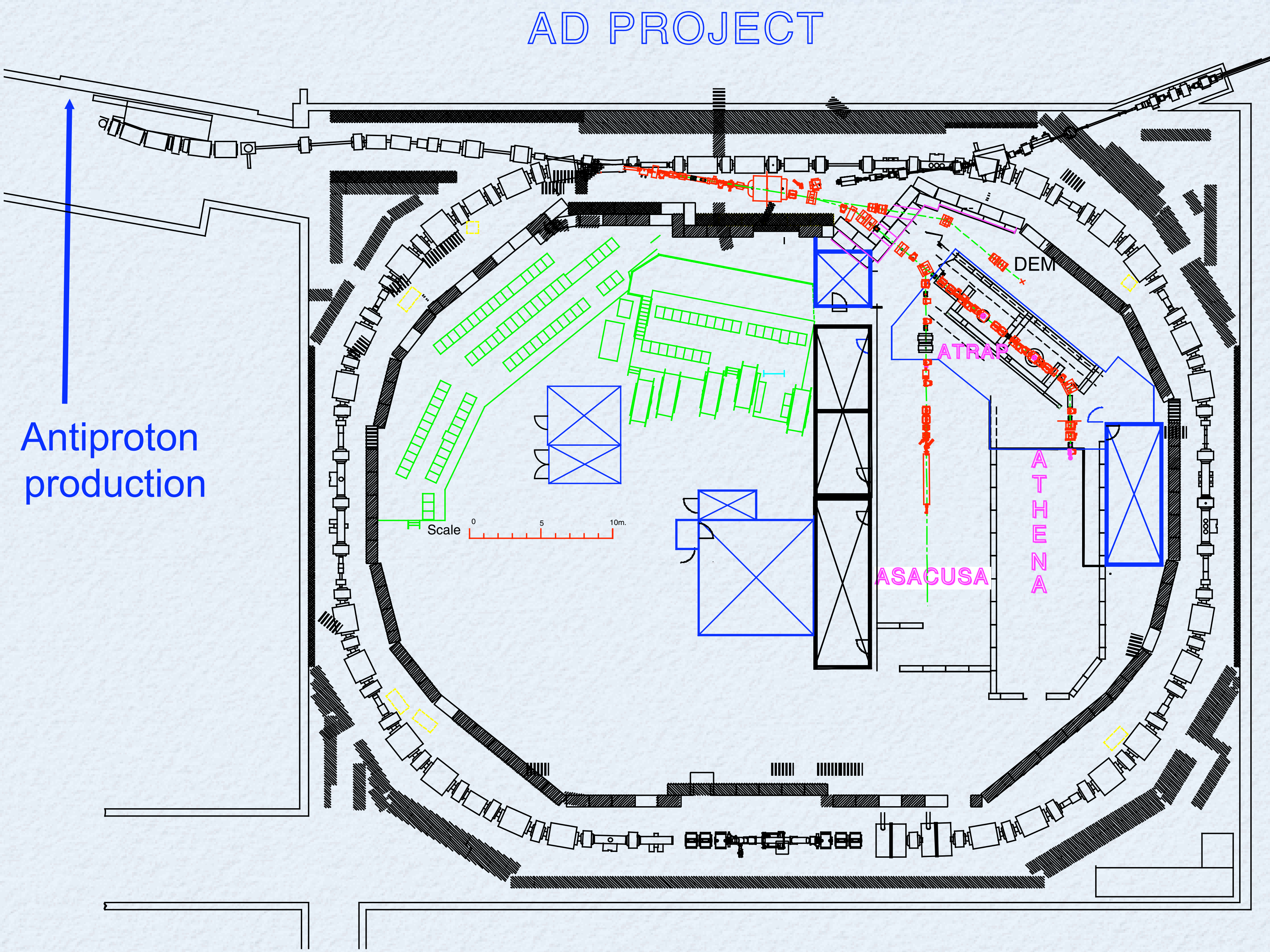
CPT test - systematic comparison

- Standard Model Extension: V.A. Kostelecky et al.
  - parameters of extended Dirac equ: dimension of energy

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



Antiproton Decelerator @ CERN

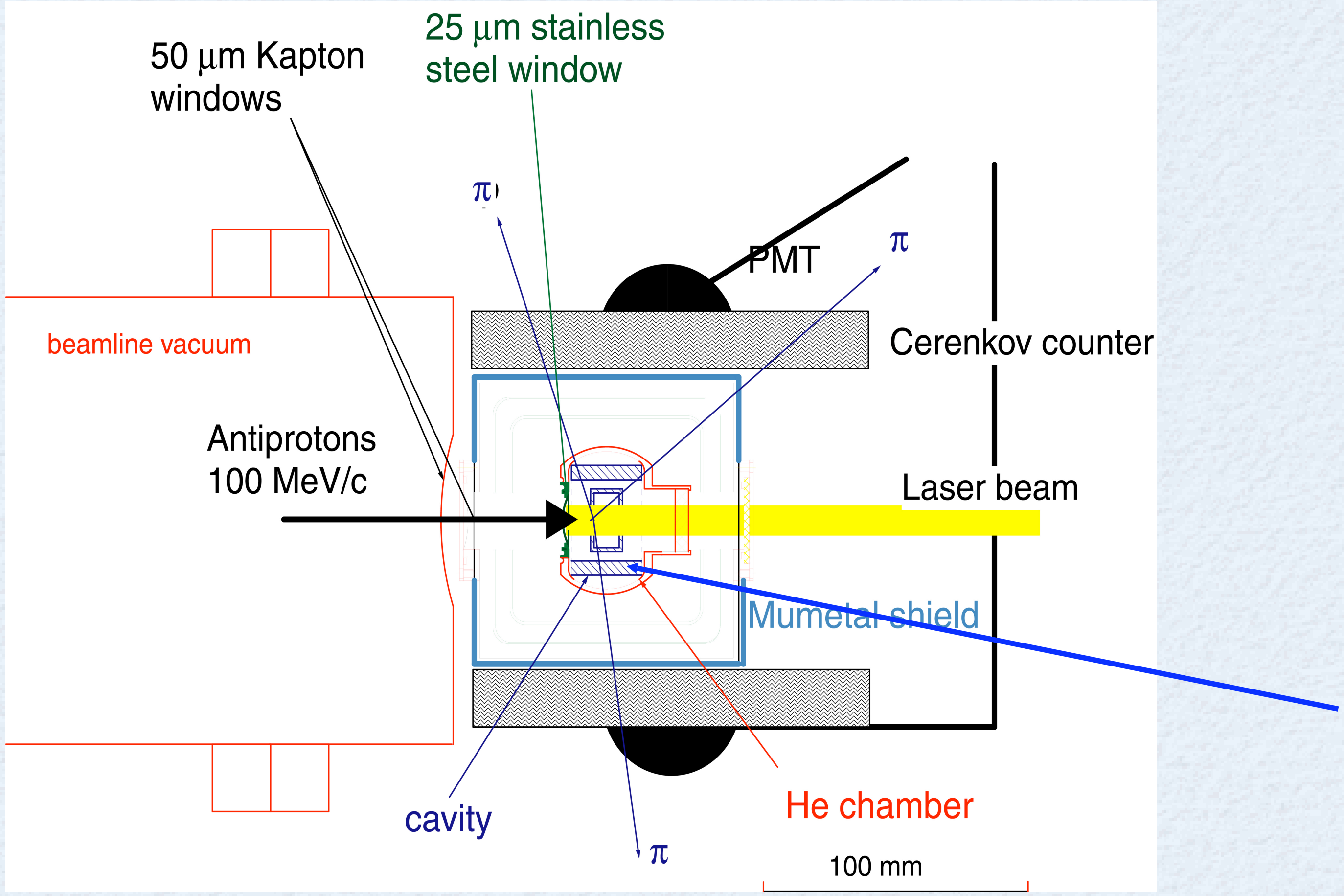


- AD
- Modification of the AC ring
- 1 ring for 3 tasks
  - Antiproton capture
  - deceleration
  - cooling
- start operation in 2000

Experimental setup at AD

Analog Measurement of Delayed Annihilation using Cerenkov counters and digital oscilloscope

TOP VIEW



5.3 MeV antiprotons are stopped in ~ 6 K 0.5 – 3 bar He gas

Microwave cavity 12.91 GHz:
28.8 mm diameter, 24.5 mm length

ÖAW

Experimental Setup at AD

Analog Measurement of Delayed Annihilation using Cerenkov counters and digital oscilloscope

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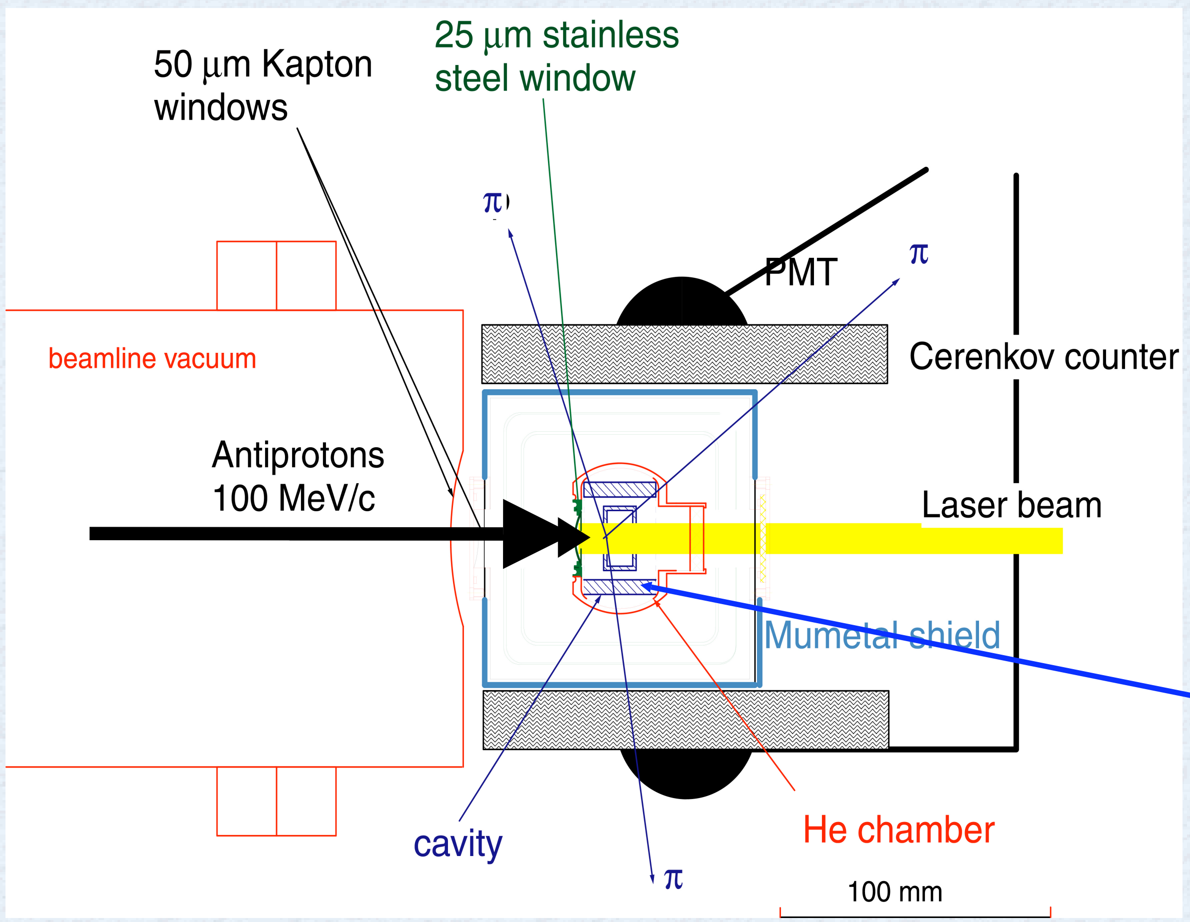

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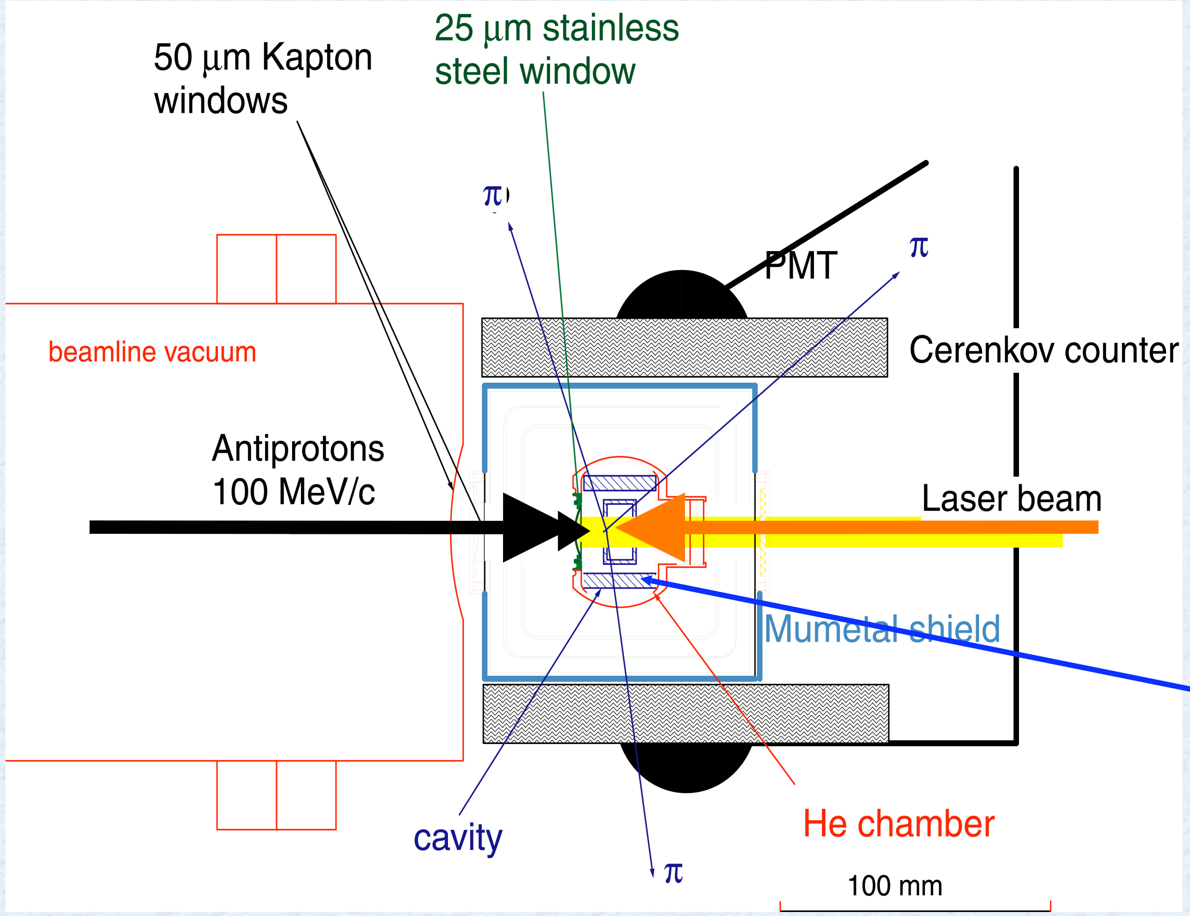

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EXPERIMENTAL SETUP AT AD

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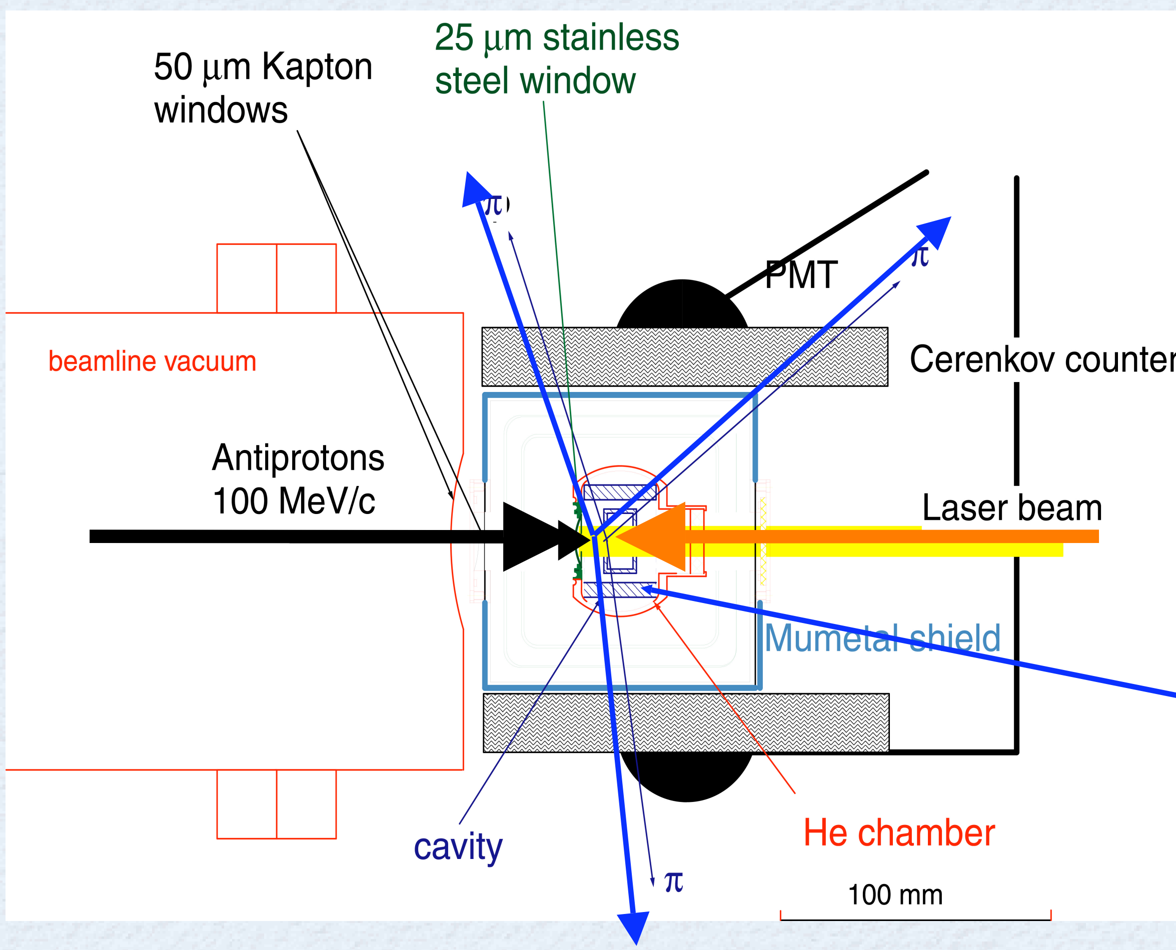

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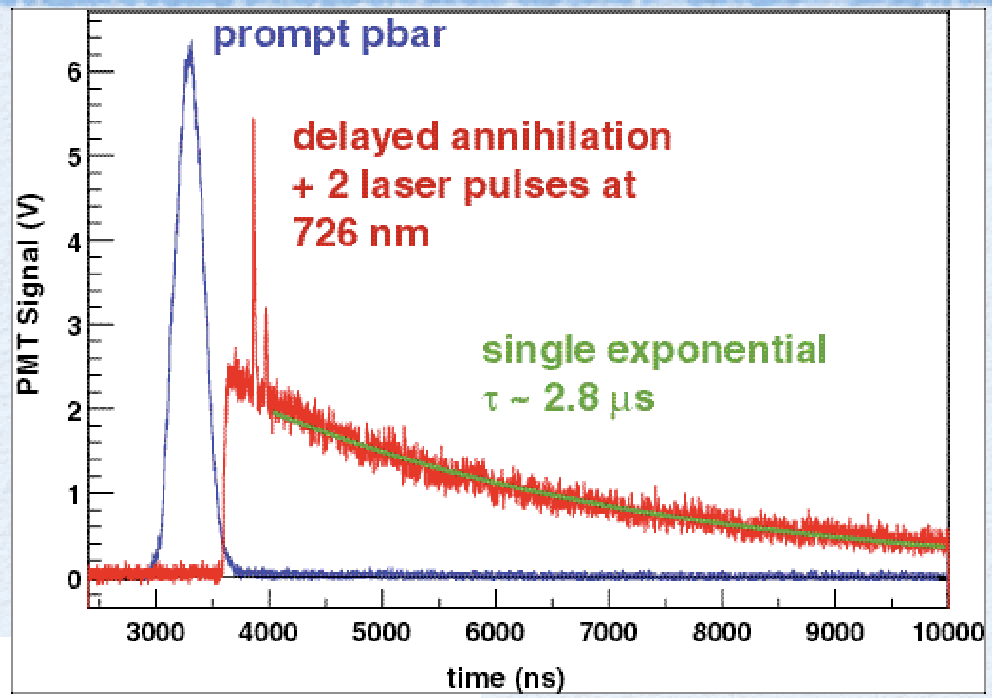

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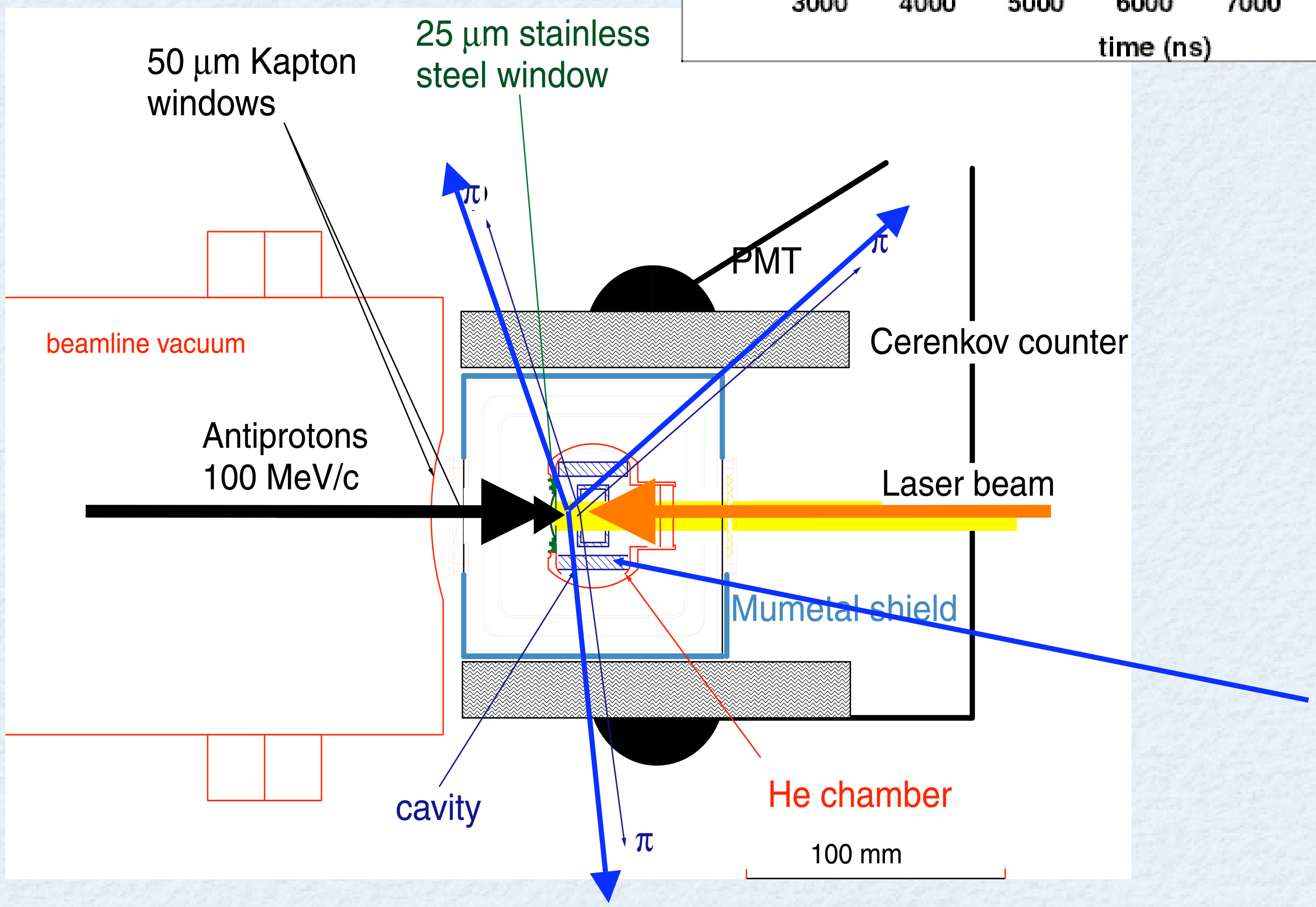

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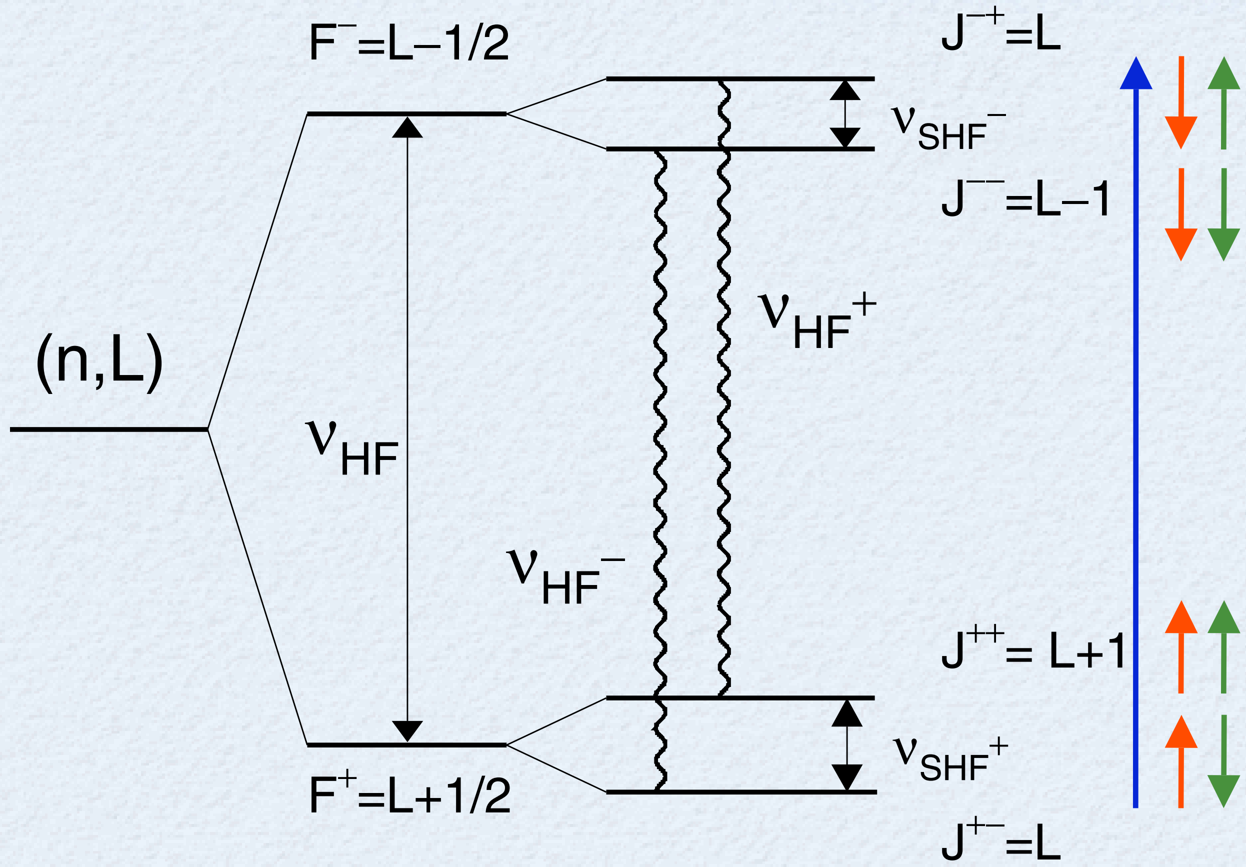
HYPERFINE STRUCTURE OF $\bar{p}{}^4He^+$



- *interactions of magnetic moments:*
  - electron: $\vec{\mu}_e = g\mu_B \vec{S}_e$
  - pbar: $\vec{\mu}_{\bar{p}} = [g_s(\bar{p})\vec{S}_{\bar{p}} + g_l(\bar{p})\vec{L}_{\bar{p}}]\mu_N$
- *"Hyperfine" splitting HFS:*

  $$\vec{L}_{\bar{p}} \cdot \vec{S}_e$$

  - dominant because of large L
- *"Superhyperfine" splitting*

  $$\vec{S}_{\bar{p}}$$

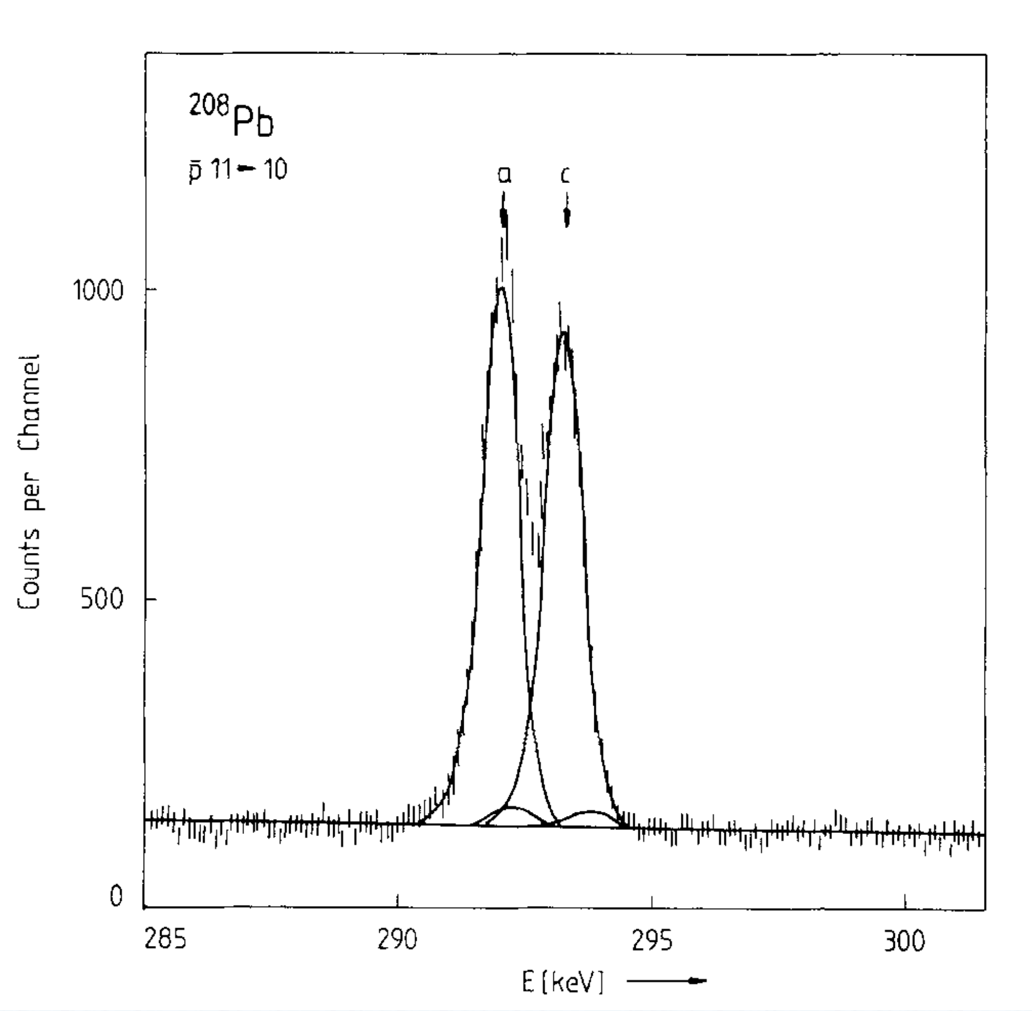
- *HFS: 10 … 15 GHz*
- *SHFS: 0.1 … 0.3 GHz*

ν_{SHF} sensitive to magnetic moment of pbar

(known to 3×10^{-3})

ν_{HF} tests ***orbital*** angular moment: g_l

Current knowledge of μp̄



- Kreissl, Daniel, v. Egidy, Hartmann et al. PRC 37 (1988) 557
- fine structure of x-Rays of antiprotonic lead
  - ^{208}Pb to avoid HFS
- results (PDG):

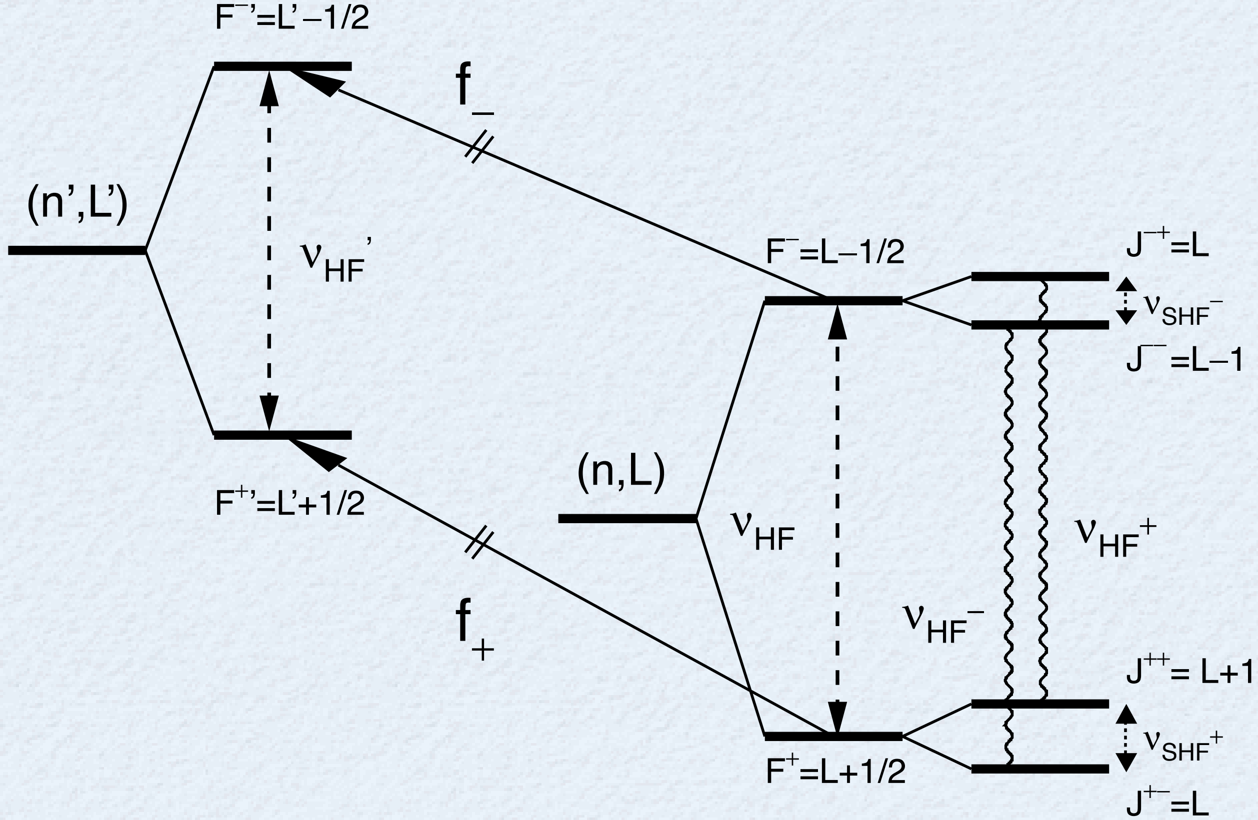
$\bar{p}$ MAGNETIC MOMENT

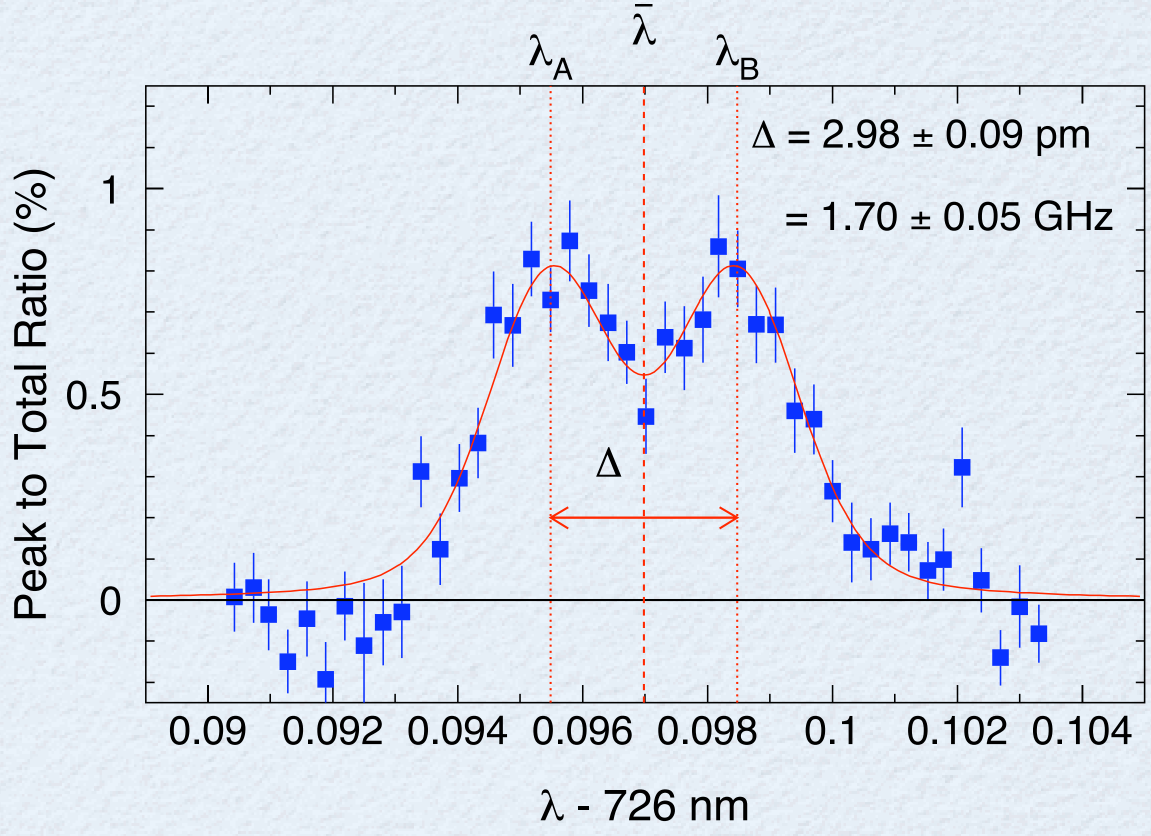
A few early results have been omitted.

0.3%!! →

VALUE (μ_N)	*DOCUMENT ID*		*TECN*	*COMMENT*
−2.800 ±0.008 OUR AVERAGE				
−2.8005±0.0090	KREISSL	88	CNTR	$\bar{p}$ ^{208}Pb 11→ 10 X-ray
−2.817 ±0.048	ROBERTS	78	CNTR	
−2.791 ±0.021	HU	75	CNTR	Exotic atoms

1st observation of HFS in a laser transition





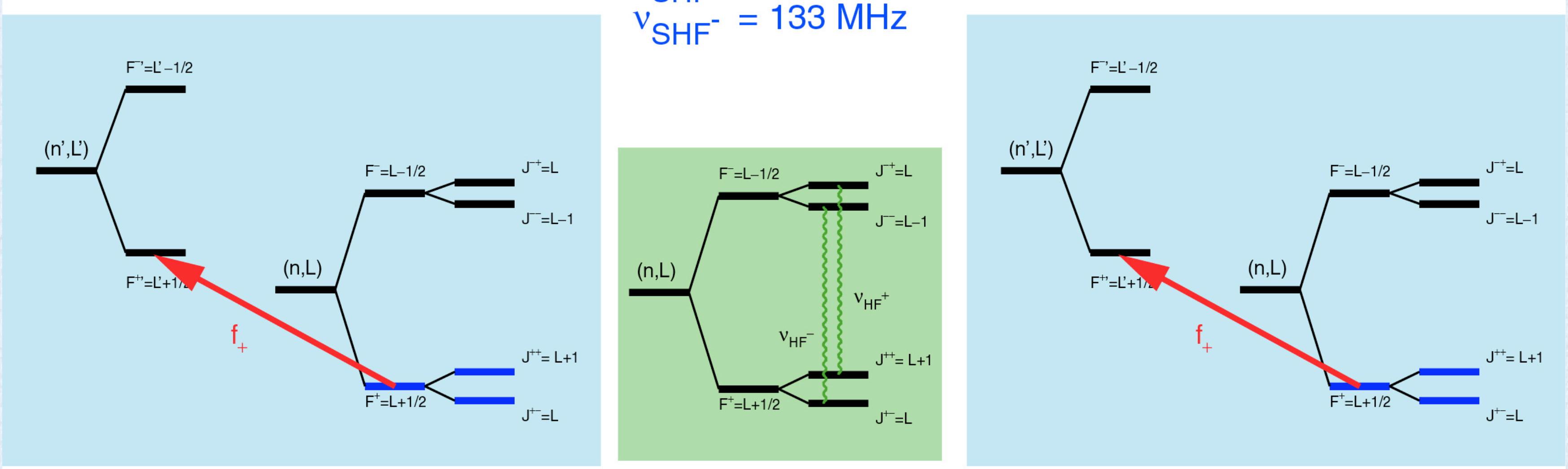
LEAR, E. W. et al. PLB 404 (1997) 15-19

- 1.75 GHz is difference of HF splitting of (37,35) and (38,34) state
- SHFS transitions cannot be observed due to Doppler broadening & laser bandwidth

Laser-Microwave-Laser Resonance Experiment

Parameters of (37,35) state:

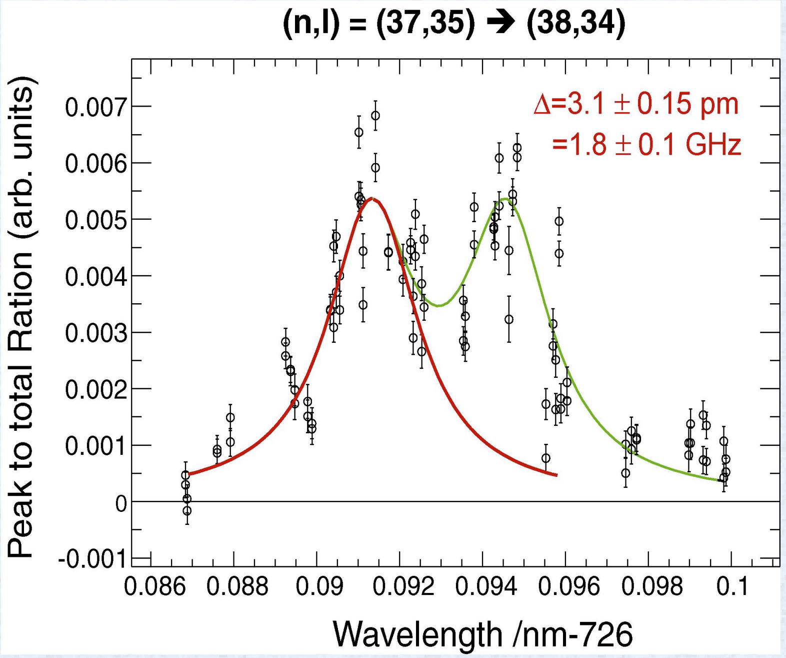
ν_{HF} = 12.91 GHz
ν_{SHF^+} = 161 MHz
ν_{SHF^-} = 133 MHz



Step 1: depopulation of F$^+$ doublet with f$_+$ laser pulse

Step 2: equalization of populations of F$^+$ and F$^-$ by microwave

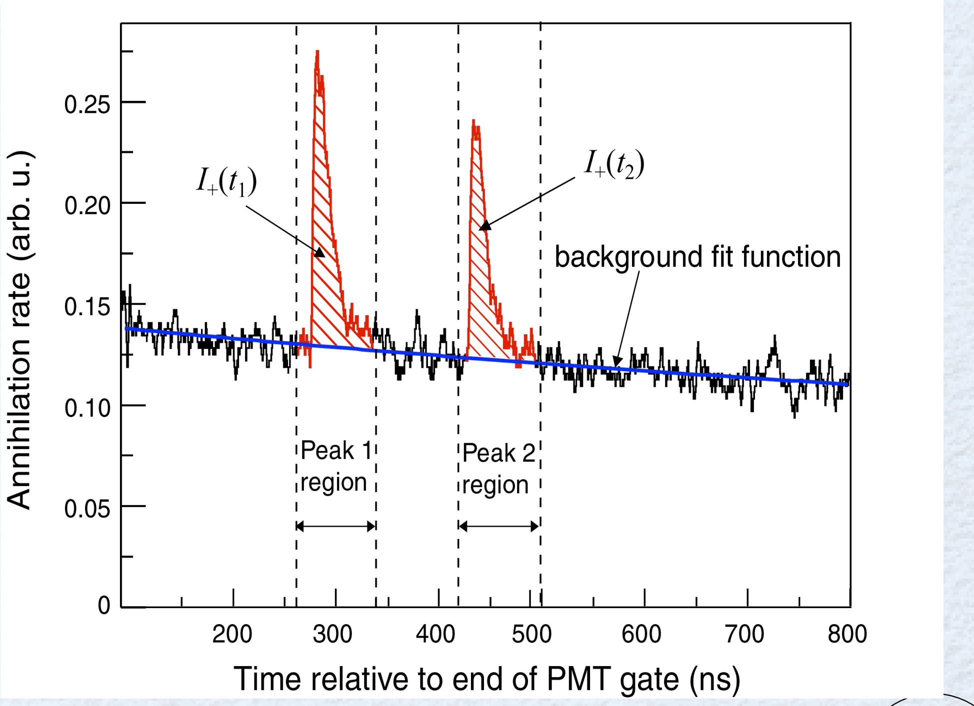
Step 3: probing of population of F$^+$ doublet with 2nd f$_+$ laser pulse



Laser scan

Time spectrum with 2 laser pulses

$$R^{++}(\nu_{MW}) = \frac{I_+(t_2)}{I_+(t_1)}$$



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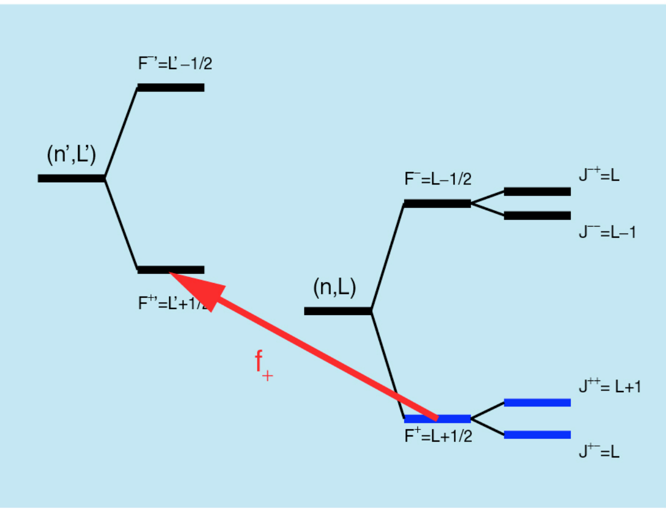

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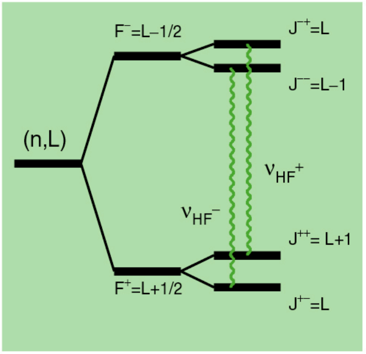

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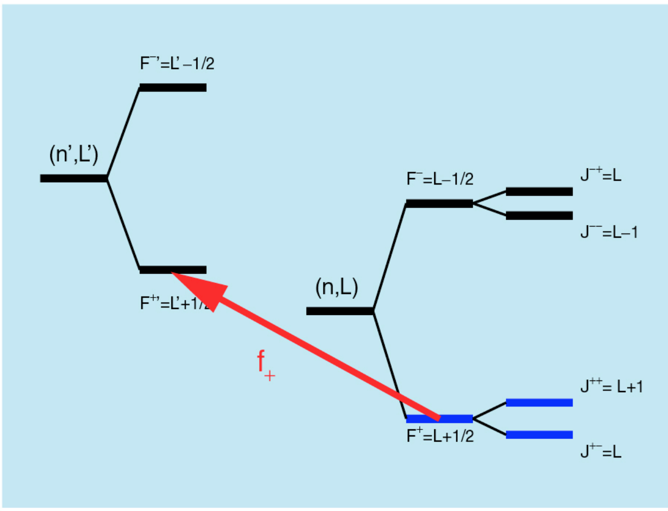
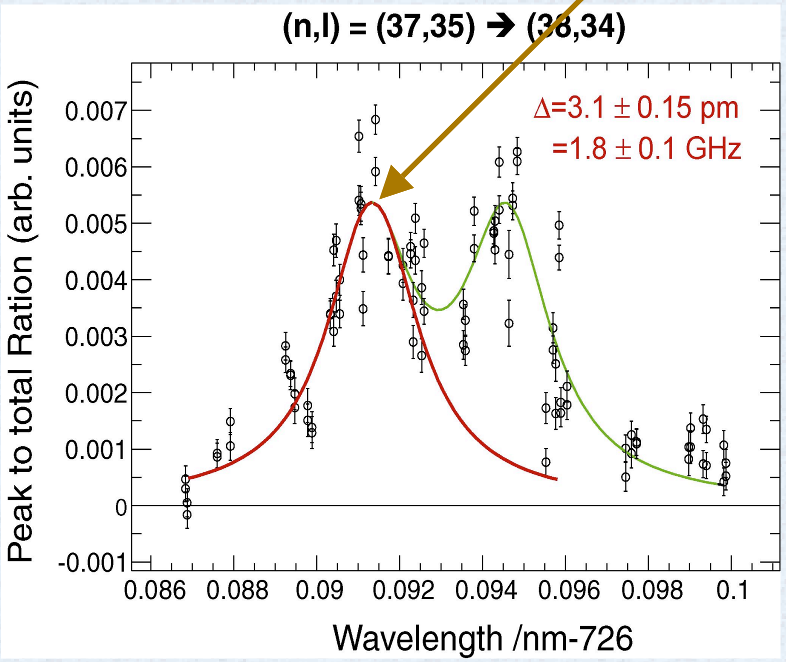


Step 3: probing of population of F$^+$ doublet with 2nd f_+ laser pulse



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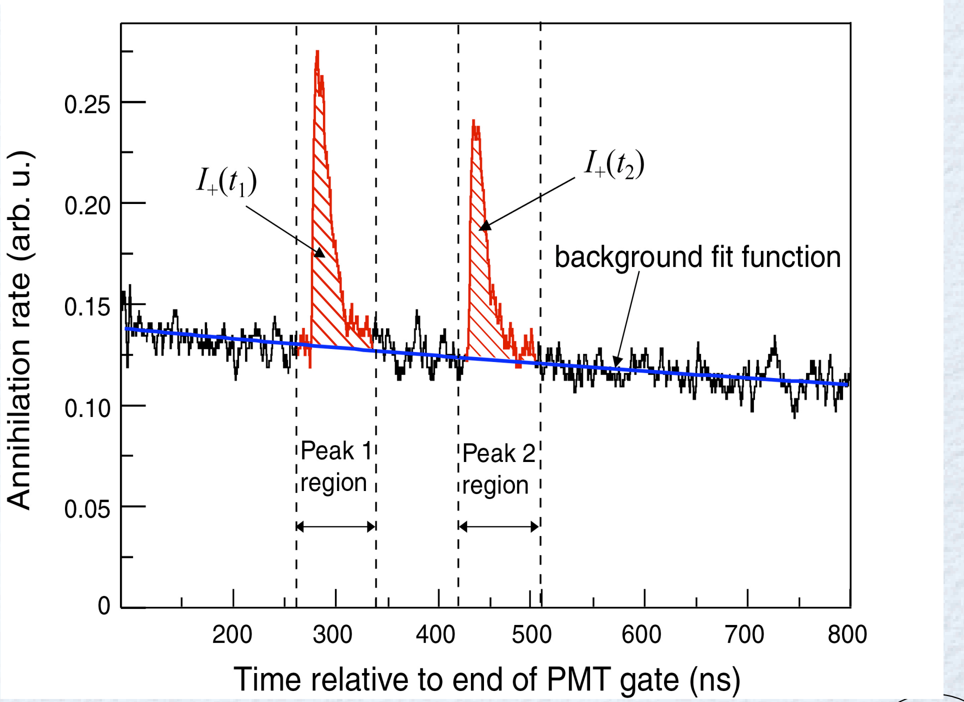

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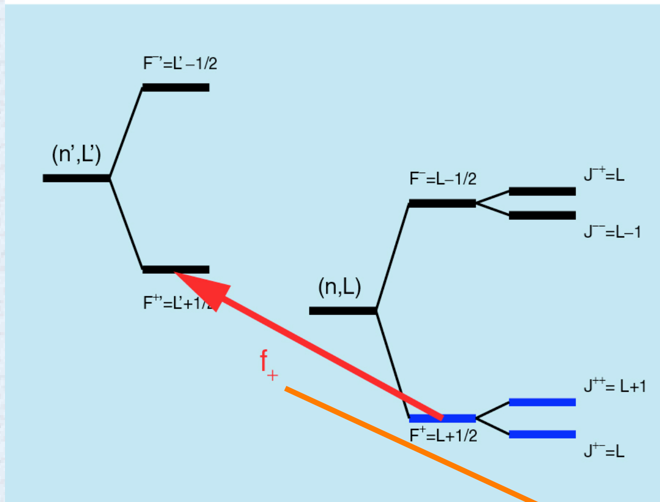

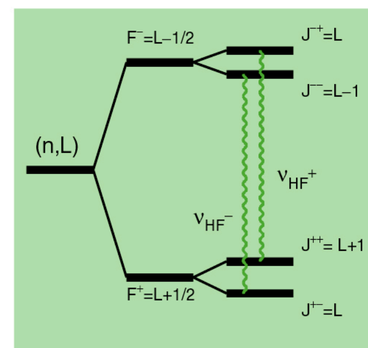

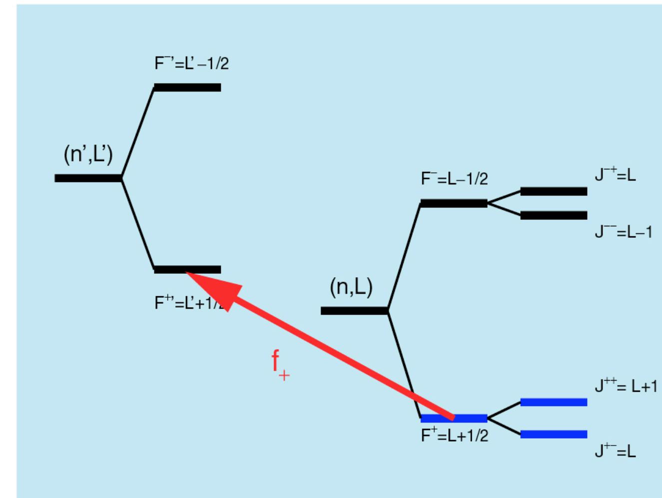

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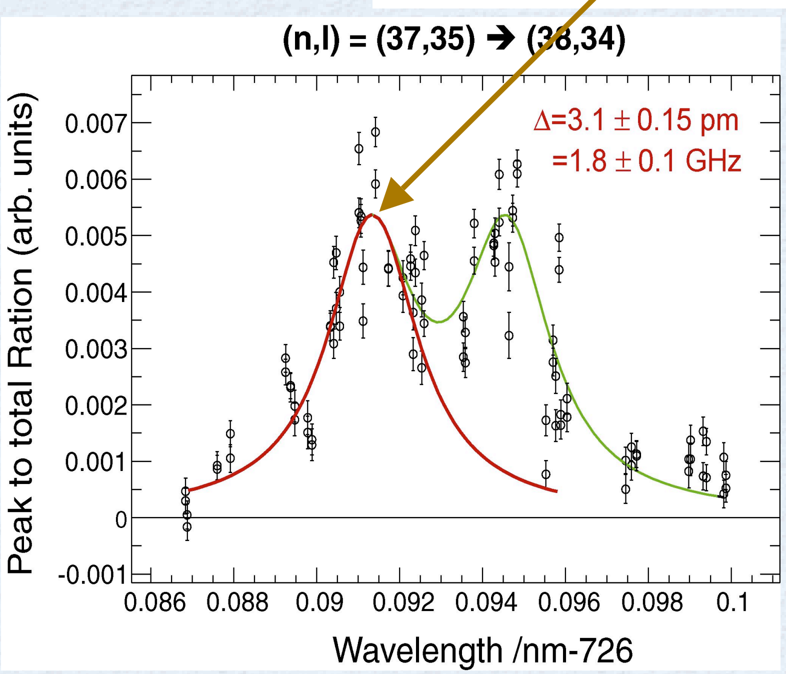

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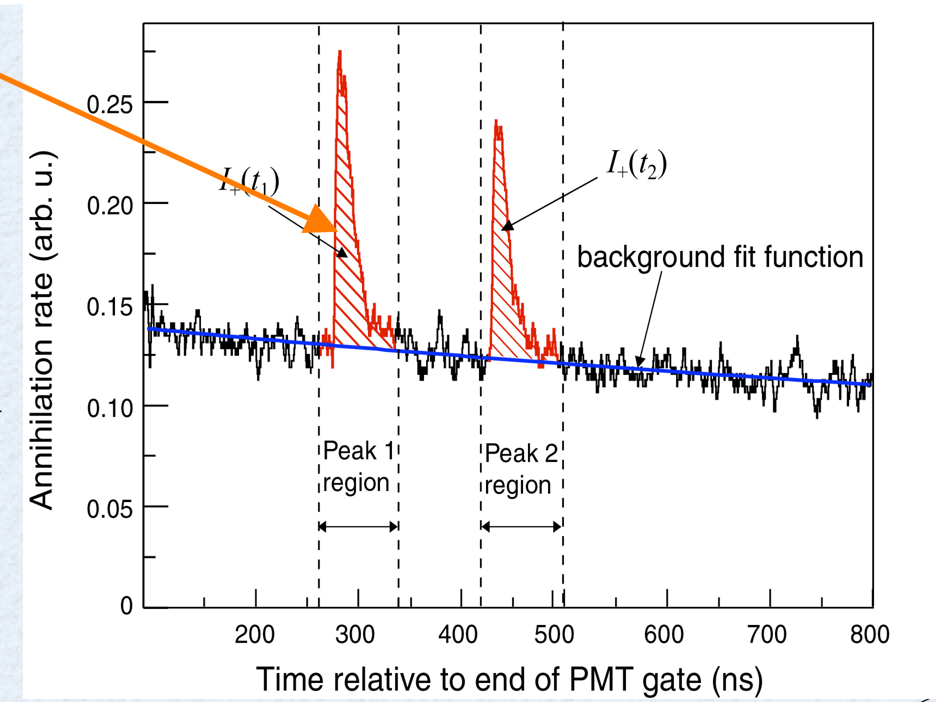

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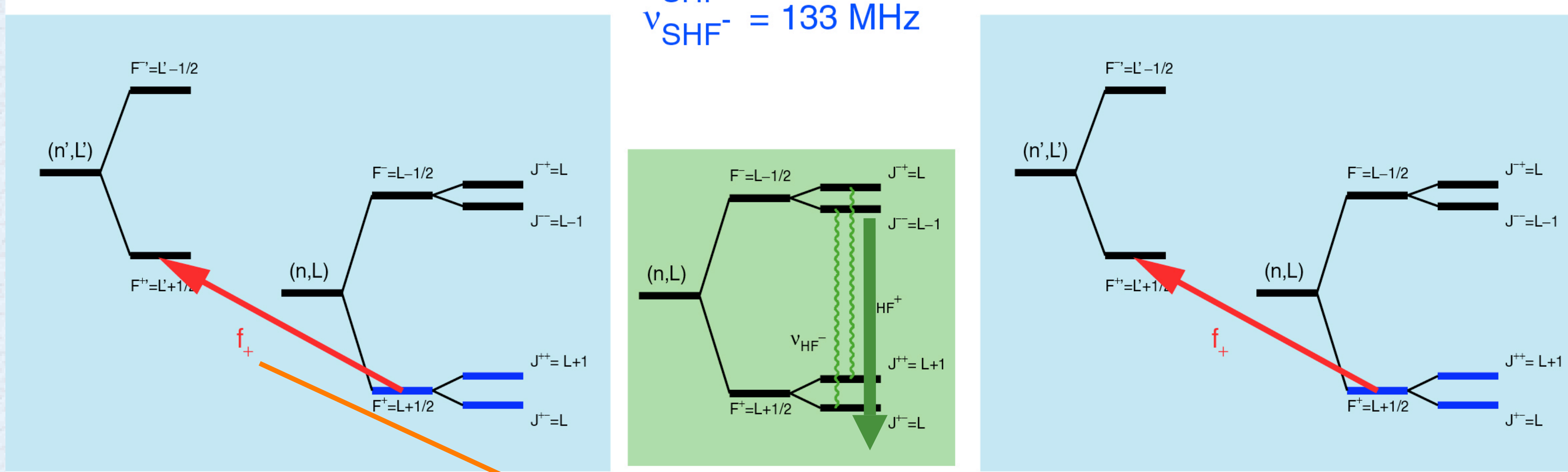

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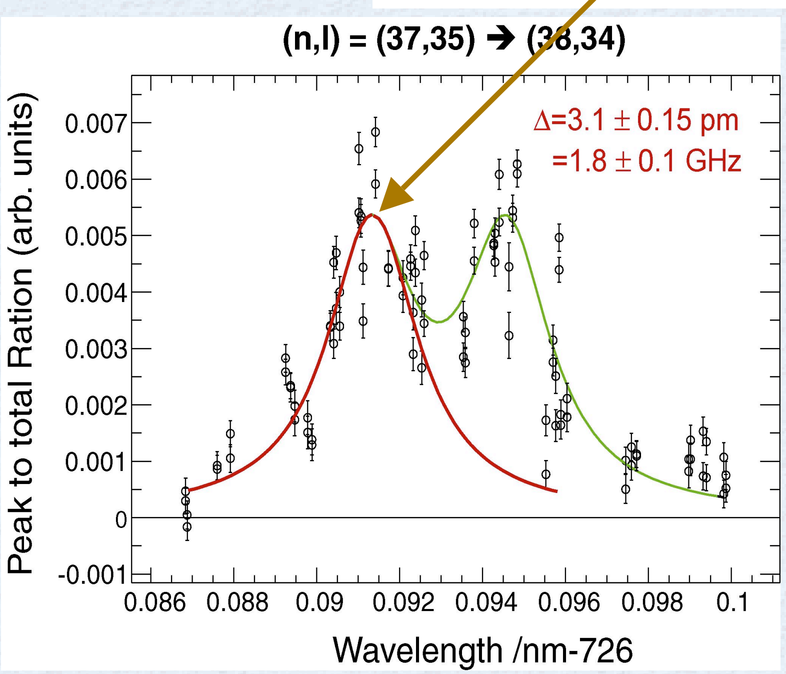

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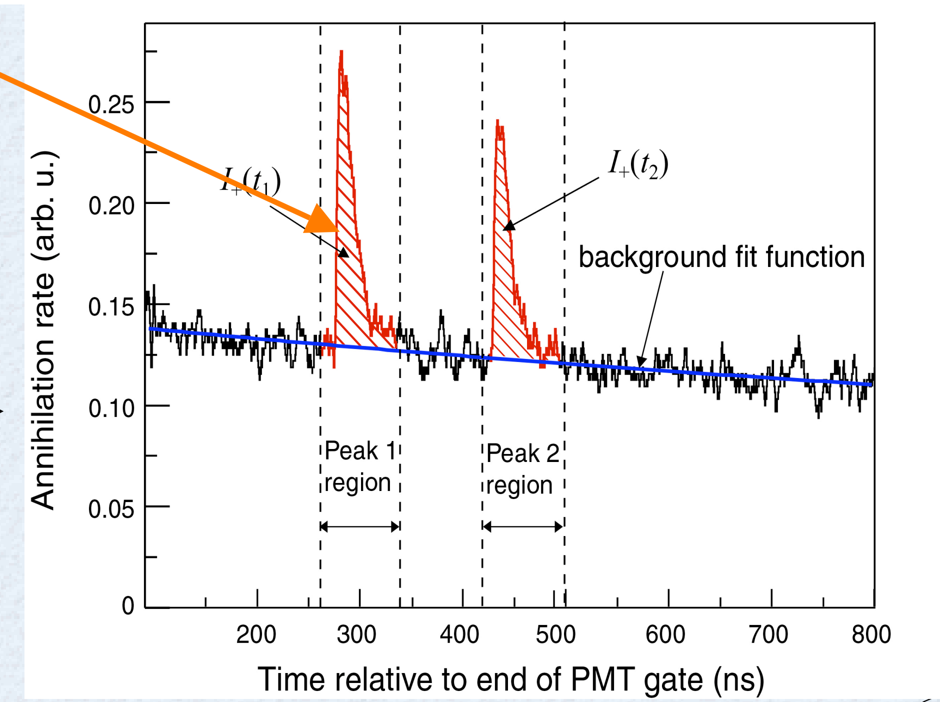

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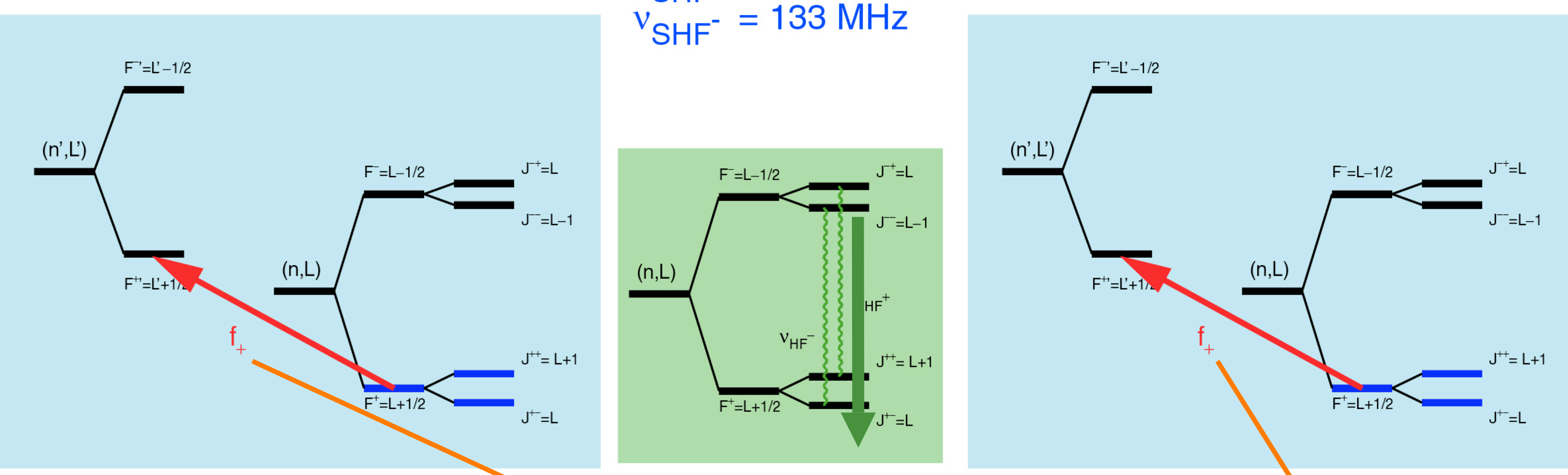

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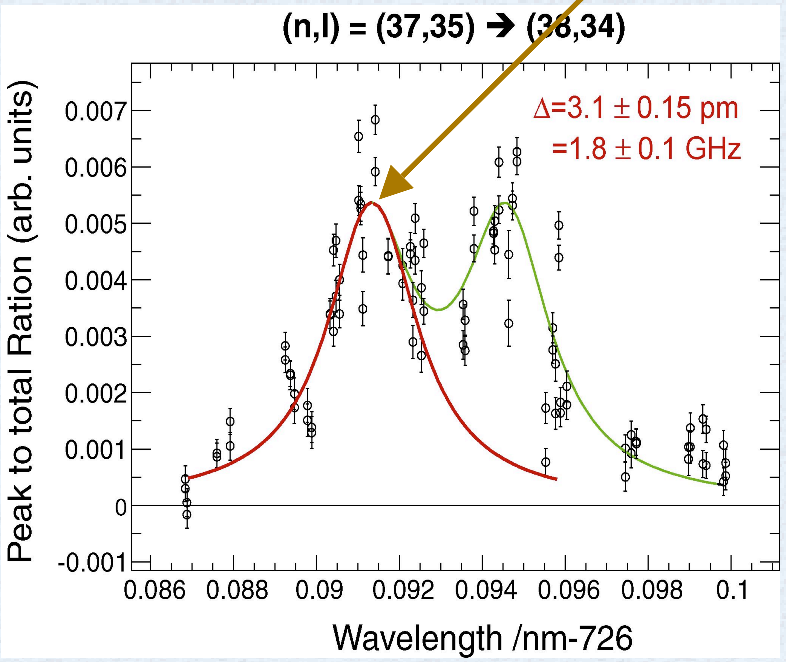

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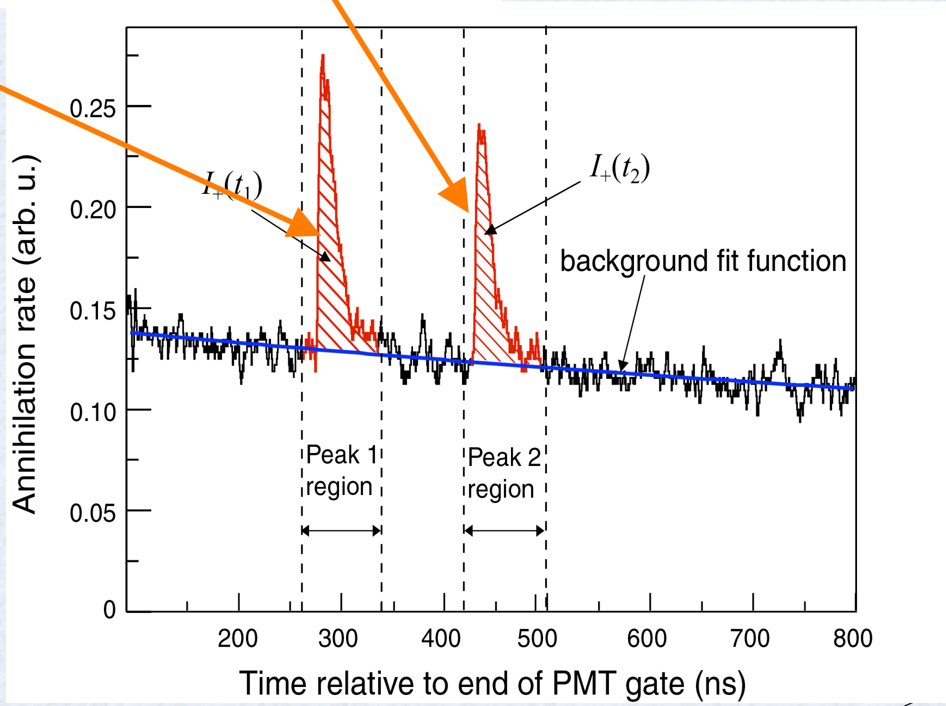
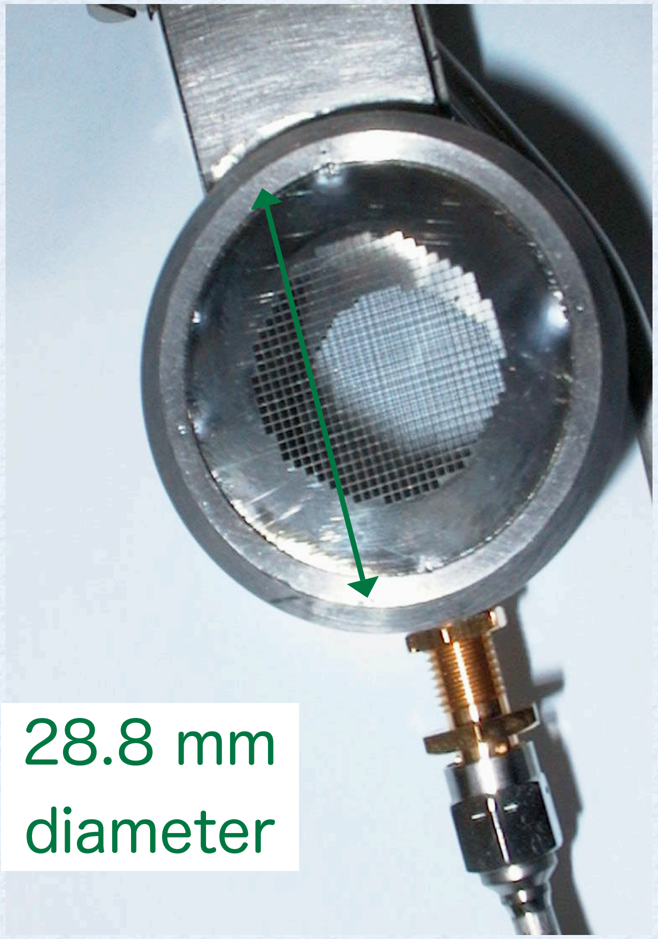
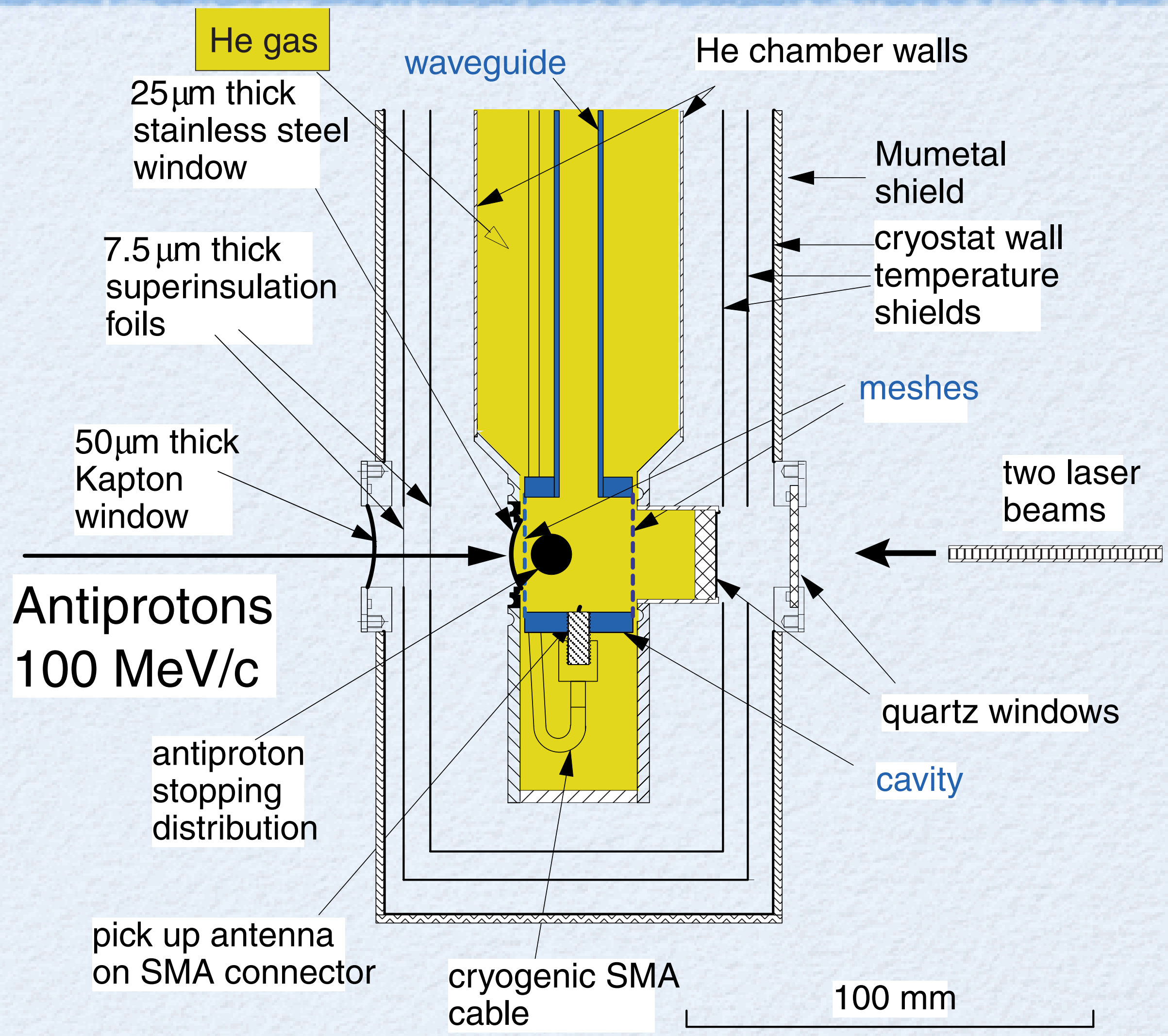


Microwave cavity for HFS measurement

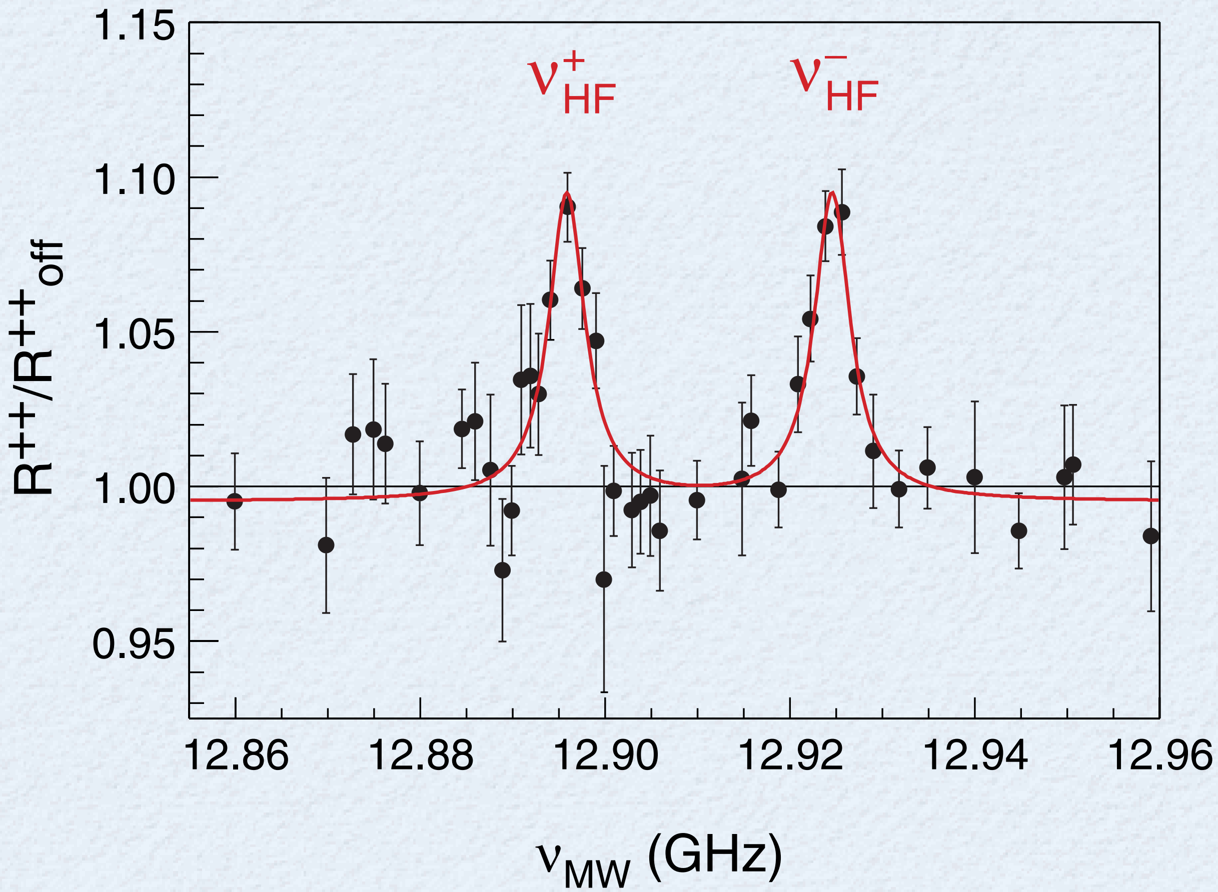




- cavity for 13 GHz at < 10 K to reduce Doppler broadening
- Meshes to allow pbar and laser light to enter

- low Q (~100) to avoid mechanical tuning
- tuning via synthesizer and stub tuner

First observation of HFS transition



- Experimental accuracy: ~ 3 x 10^{-5}

ν_{HF}^{+}	12.895 96(34) GHz	27 ppm
ν_{HF}^{-}	12.924 67(29) GHz	23 ppm

- E.W. et al. PRL 89 (2002) 243402

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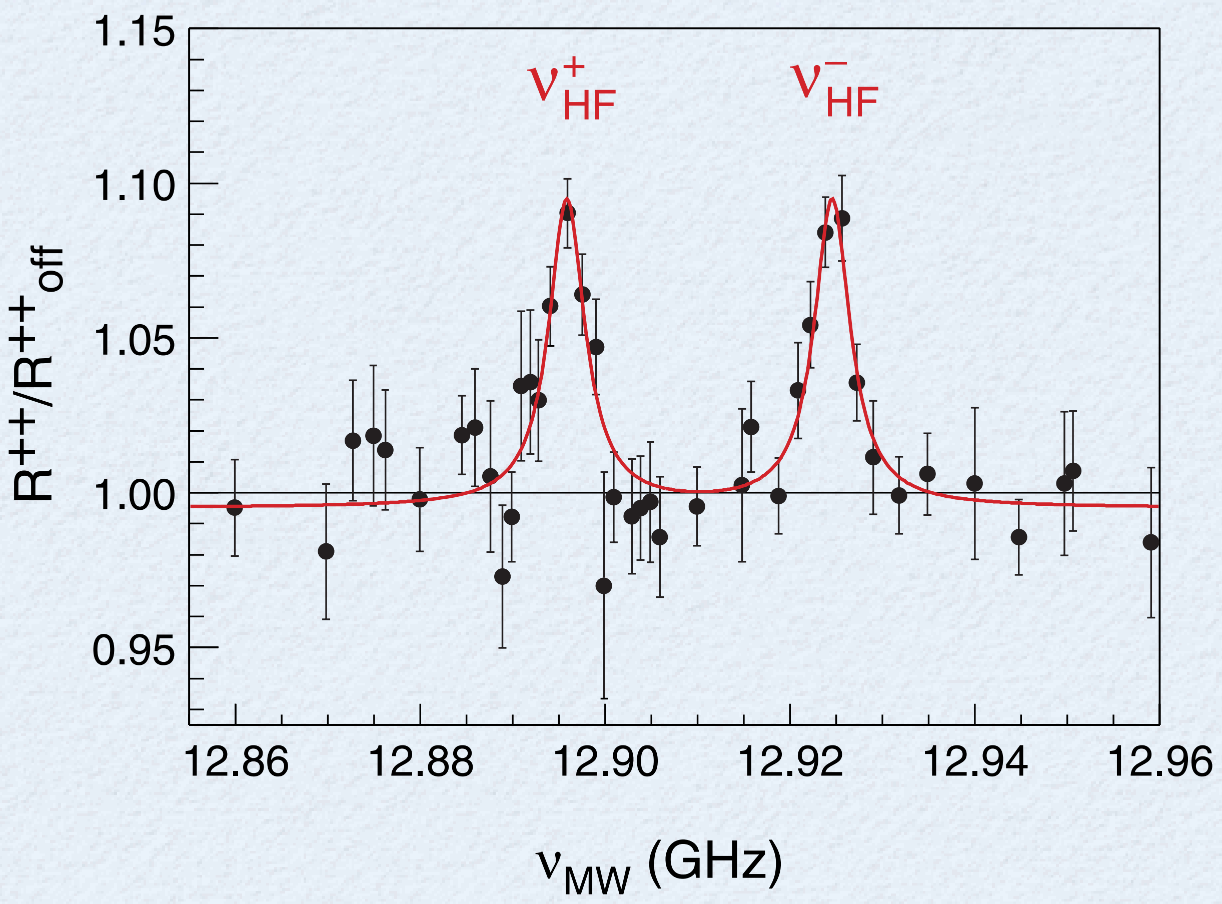

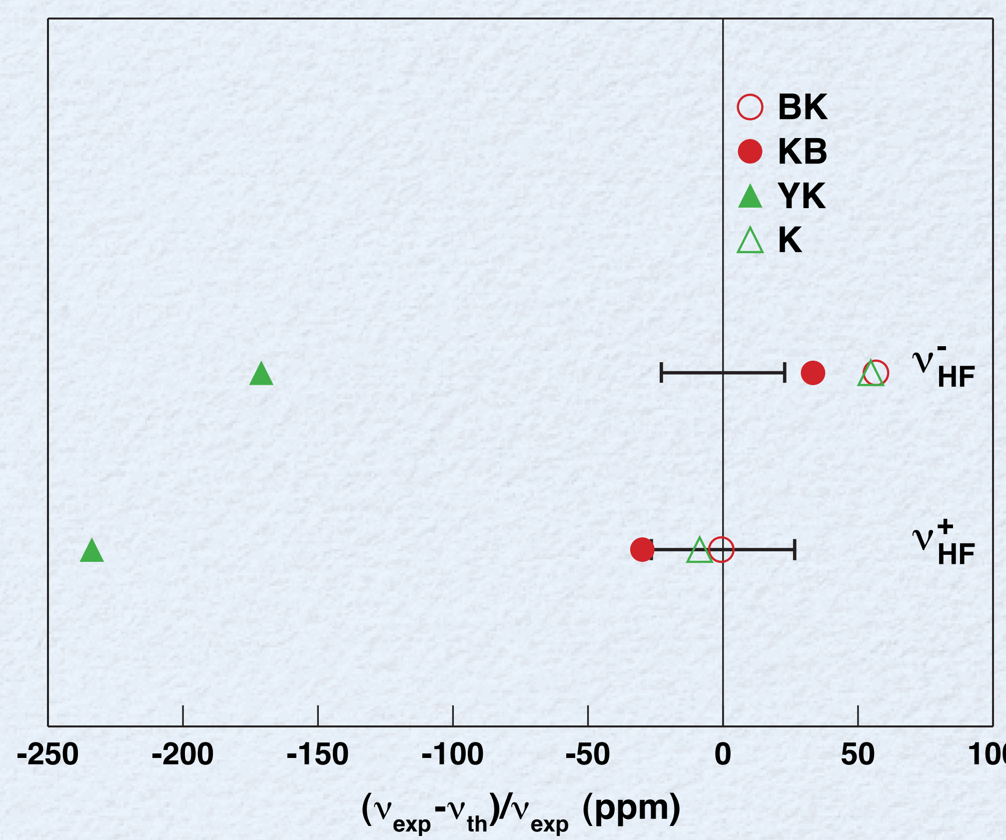

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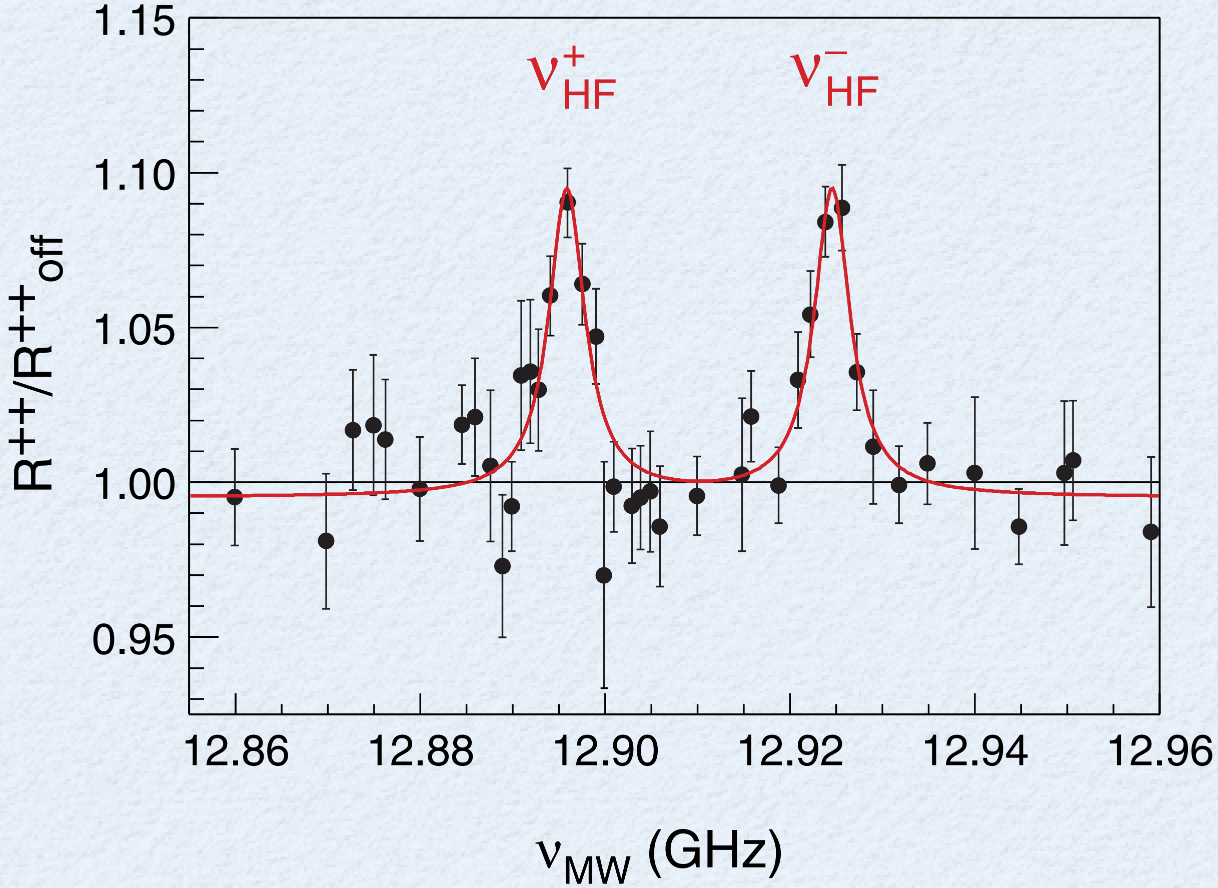

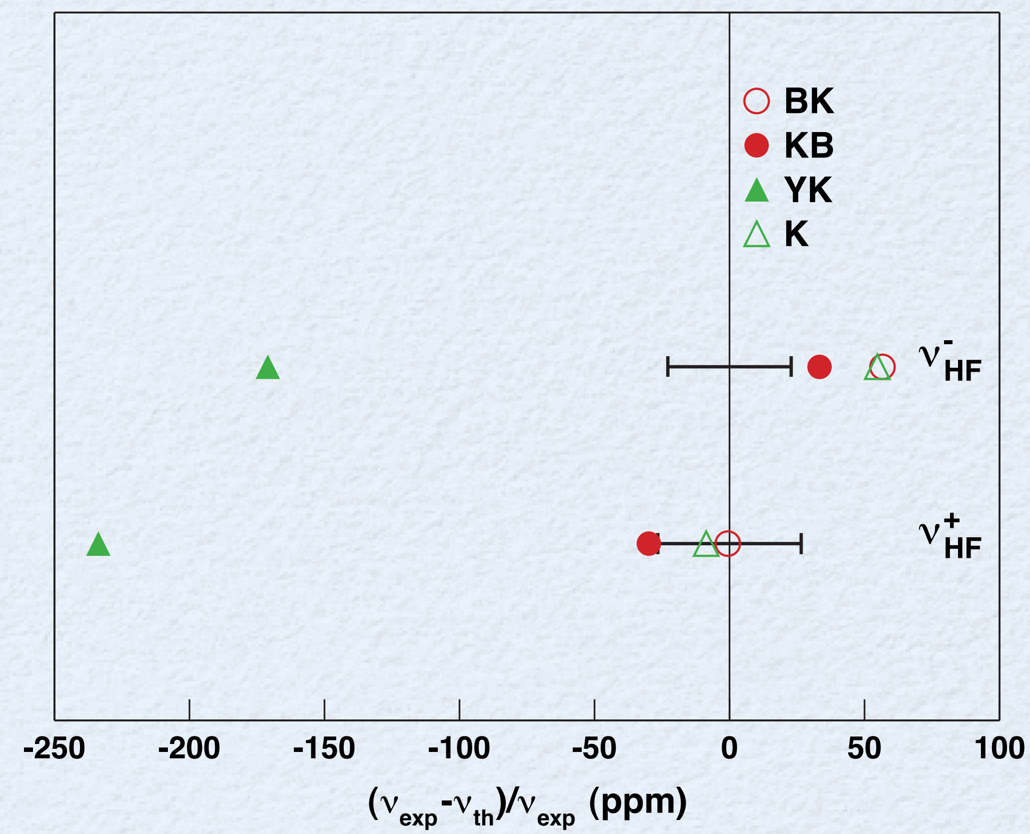

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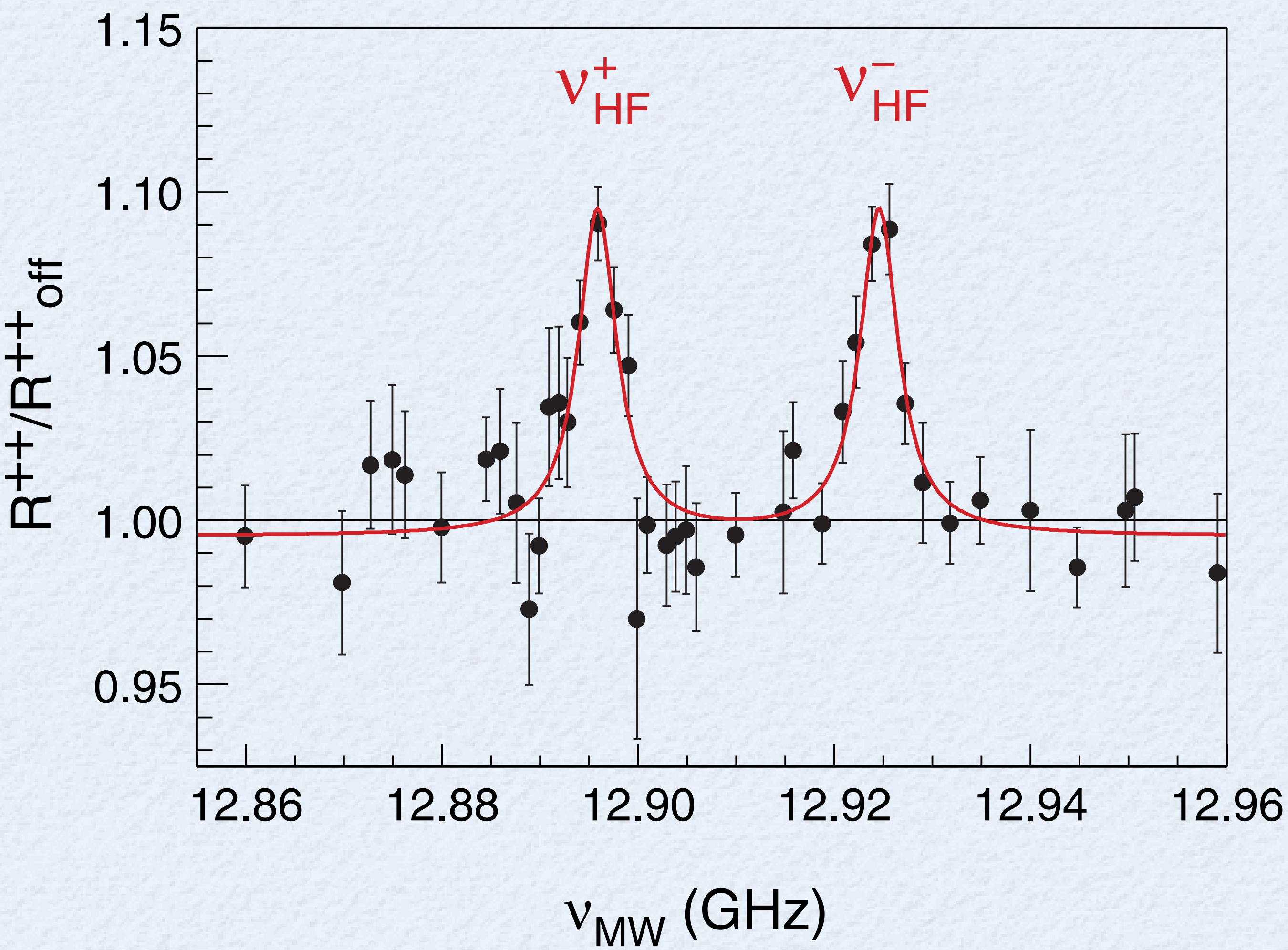
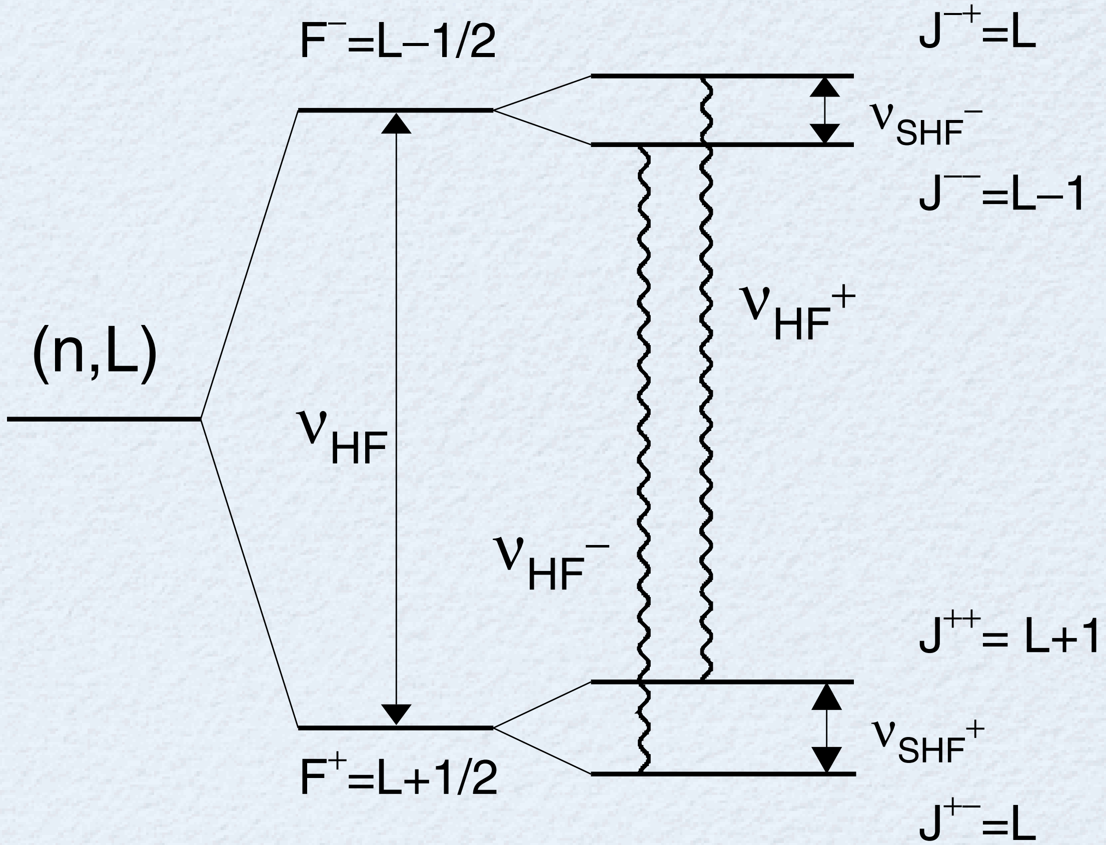
- *Comparison to theory favours most recent results of both groups*
  - *Korobov & Bakalov JPB 34 L519 2001*
  - *Kino et al. Proc. APAC 2001*
- *Difference < 6×10^{-5}*
- *Corresponds to theoretical uncertainty*
  - Omission of terms $O(\alpha^2) \sim 5 \times 10^{-5}$

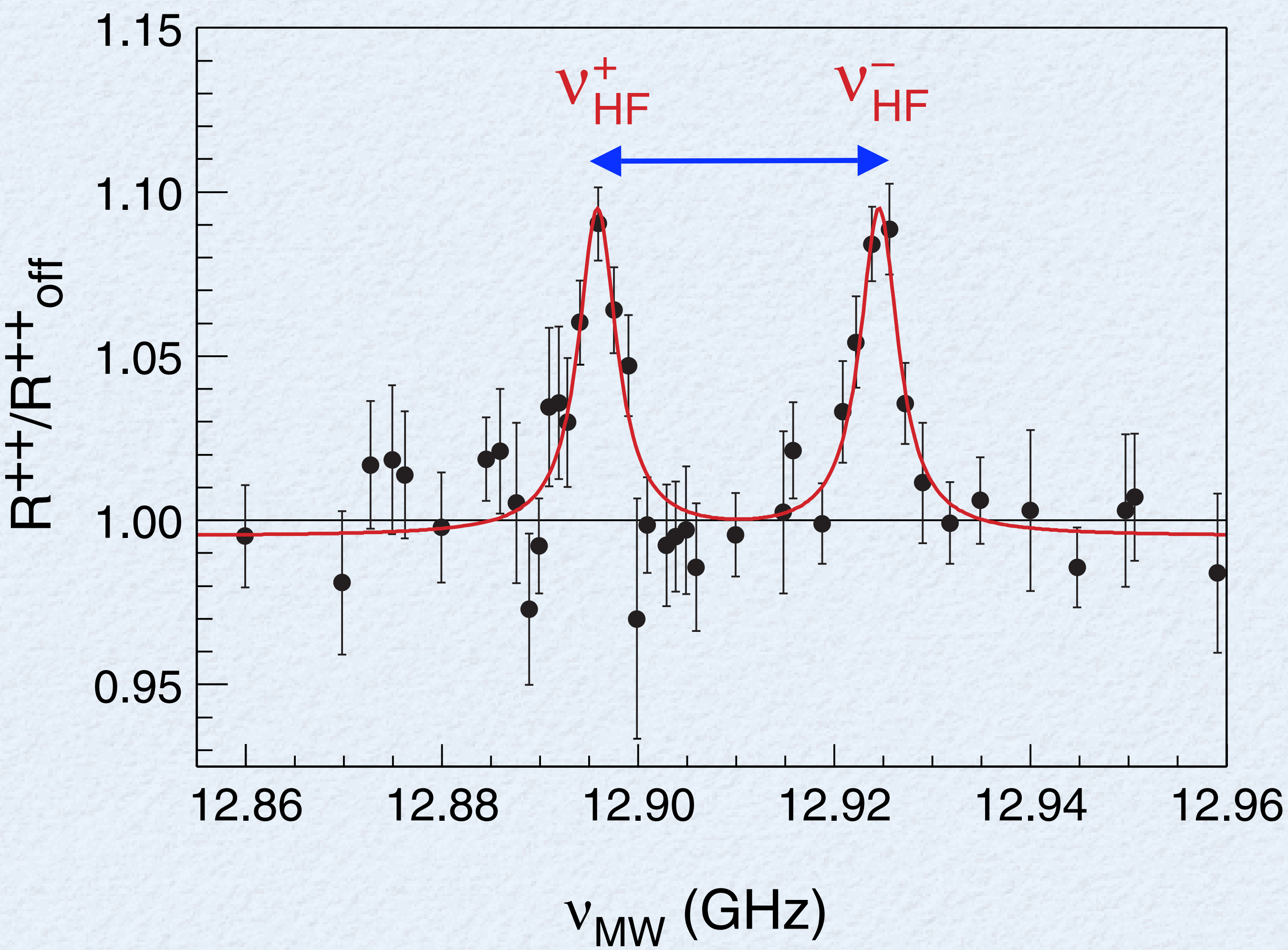
Determination of $\mu_{\bar{p}}$

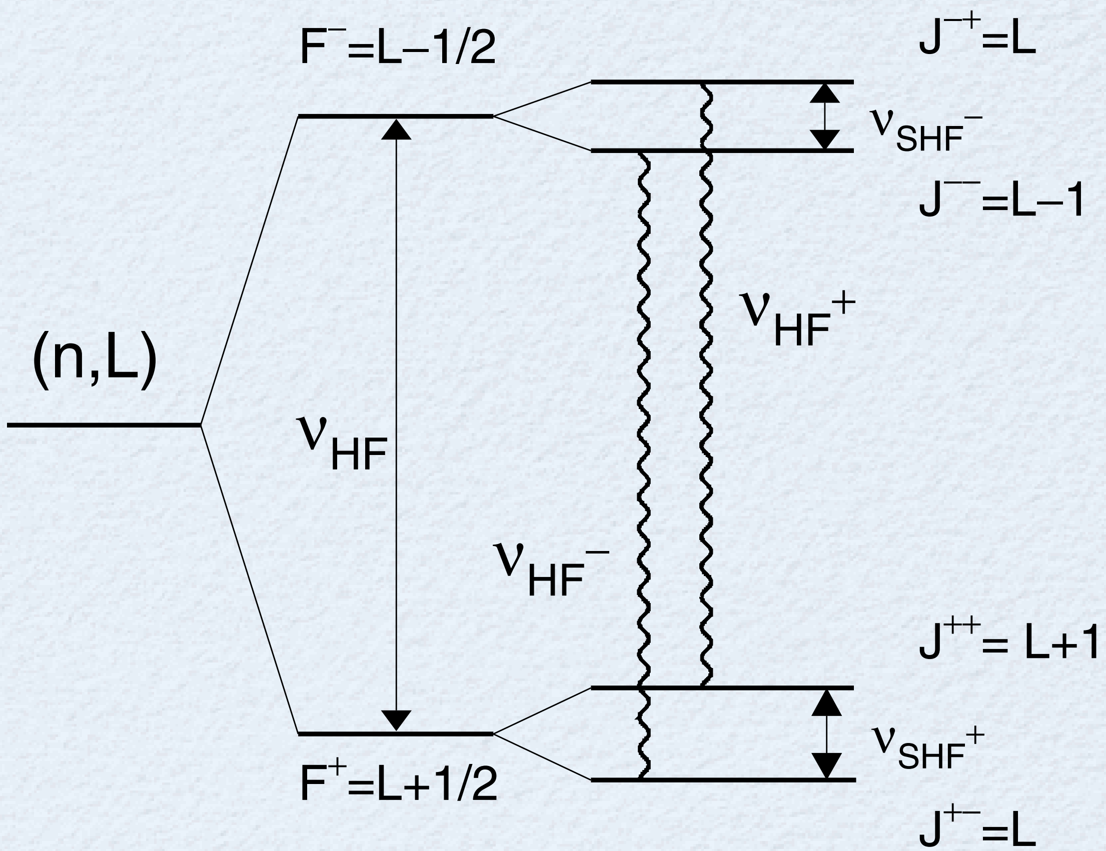




- ν_{SHF}^{+} , ν_{SHF}^{-} most sensitive, but impossible to measure (power requirement)
- $\Delta\nu_{HF} = \nu_{HF}^{-} - \nu_{HF}^{+} = \nu_{SHF}^{+} - \nu_{SHF}^{-}$: sensitive to $\mu_{\bar{p}}$
- sensitivity factors from theory *(D. Bakalov and E.W., PRA in print)*
  - $S(F,J) = \partial E_{nFLJ} / \partial \mu_{\bar{p}} \,|_{\mu_{\bar{p}} = -\mu_p}$
  - $S(\nu_{HF}^{+}) = S(F^{-}J^{--}) - S(F^{+}J^{+-})$

Determination of $\mu_{\bar{p}}$





- ν_{SHF}^+ , ν_{SHF}^- most sensitive, but impossible to measure (power requirement)
- $\Delta\nu_{HF} = \nu_{HF}^- - \nu_{HF}^+ = \nu_{SHF}^+ - \nu_{SHF}^-$: sensitive to $\mu_{\bar{p}}$
- sensitivity factors from theory *(D. Bakalov and E.W., PRA in print)*
  - $S(F,J) = \partial E_{nFLJ} / \partial \mu_{\bar{p}} \,|_{\mu_{\bar{p}} = -\mu_p}$
  - $S(\nu_{HF}^+) = S(F^-J^{--}) - S(F^+J^{+-})$

Improvements of $\mu_{\bar{p}}$

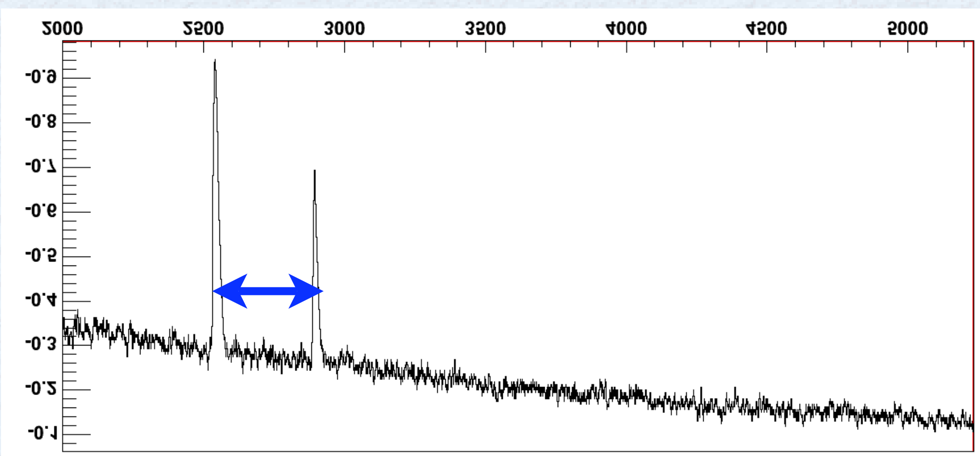
- error of known value of $\mu_{\bar{p}}$: $\delta_\mu = 3 \times 10^{-3}$
- limitation for $\bar{p}He^+$: theoretical accuracy
  - for $\Delta\nu_{HF}$: $\Delta_q \sim O(10^{-3})$ *conservative!*
  - max. improvement from ratio: factor $\Delta_q/\Delta_\mu = 3 - 9$
- (37,35): factor 3 improvement in $\mu_{\bar{p}}$: factor 10 in exp. accuracy

	(35,33)	(37,34)	(39,35)	(33,32)	(36,34)	(37,35)	(35,34)	(34,33)	(38,35)
$\Delta_q \times 10^4$	6	11	3	8	23	12	6	4	5
δ_μ kHz	180	90	270	510	50	90	210	360	190
Δ_q/Δ_μ	5.0	2.7	8.9	3.6	1.3	2.7	5.4	8.4	6.0
δ_{exp} kHz	36	33	30	142	38	33	39	43	32

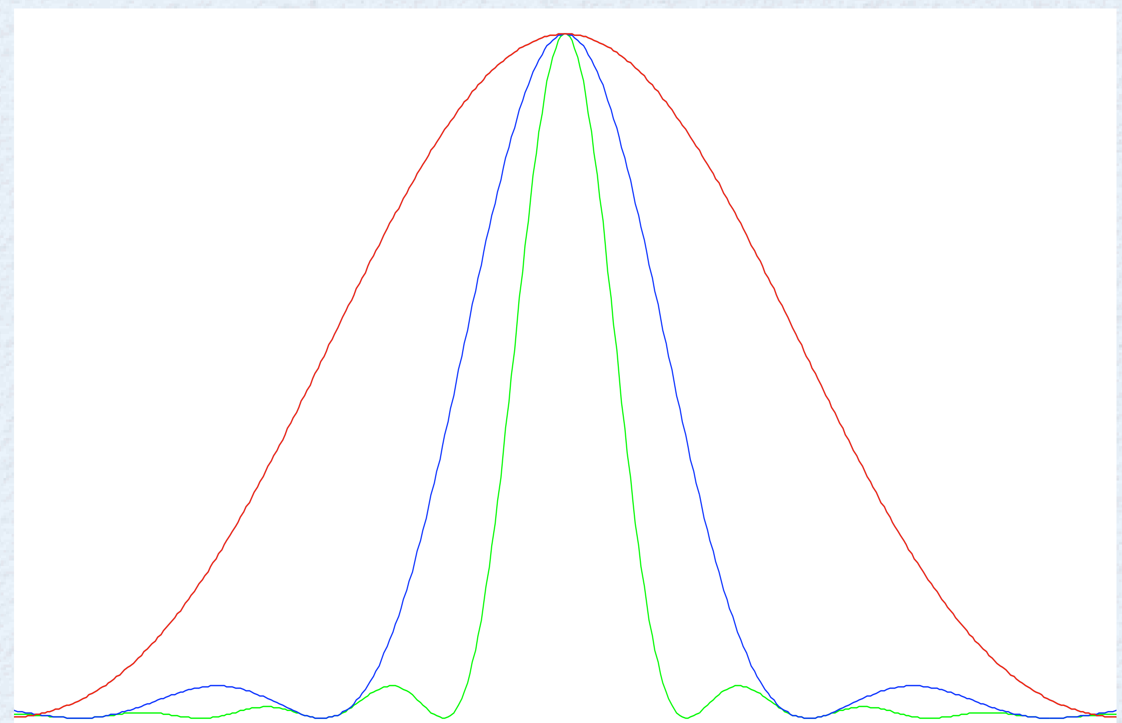
D. Bakalov & E.W., submitted

Reduction of Line Width

- possible sources of line width: ~ 6 MHz @ Δt=160 ns
  - collisional broadening
  - Fourier limit



- $\Delta f \approx 1/\Delta t$:
  - 160 ns: $\Delta f \approx$ 6 MHz
  - 350 ns: $\Delta f \approx$ 3 MHz



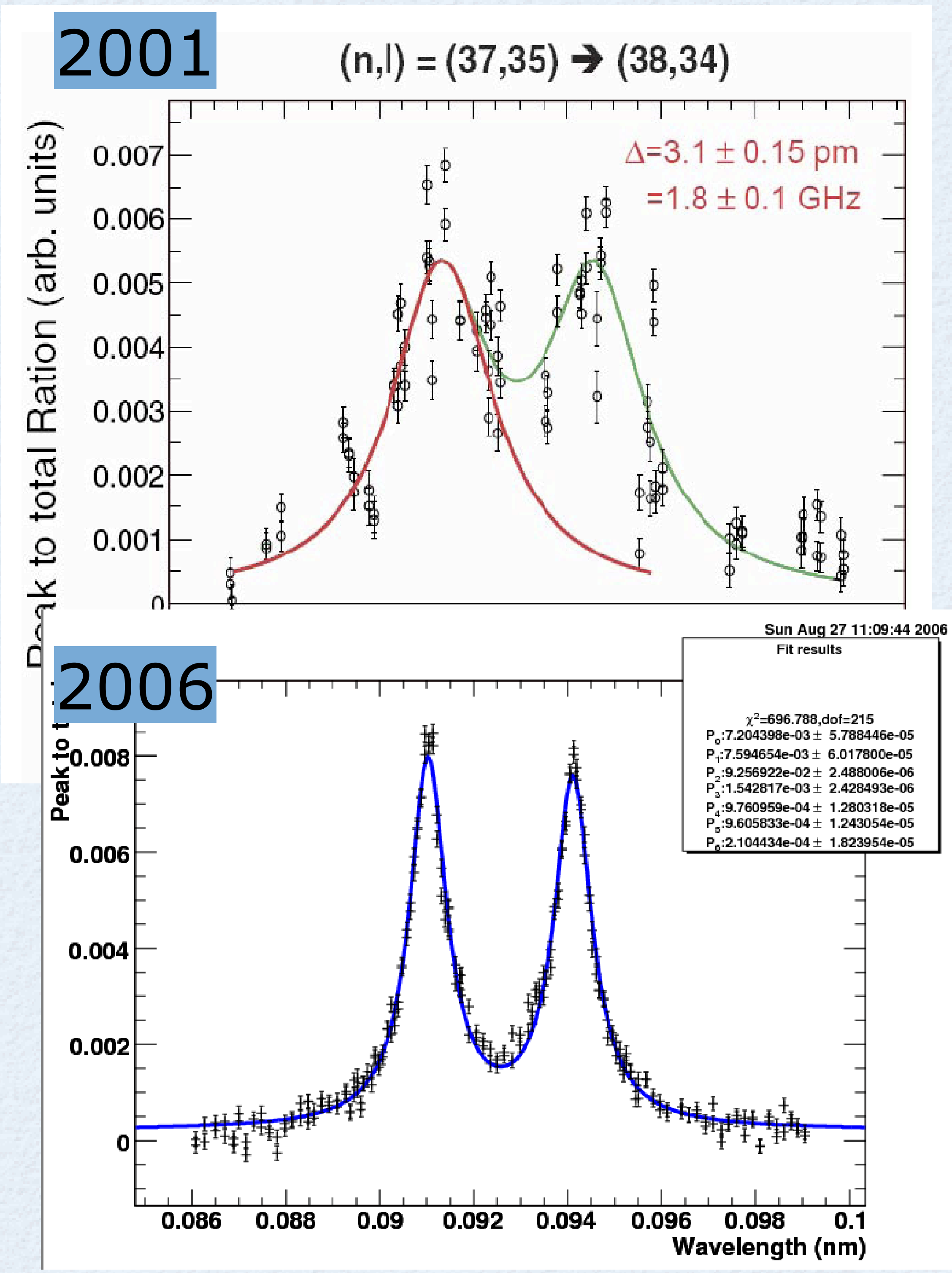
MW pulse length:

Red = 150 ns

Blue = 350 ns

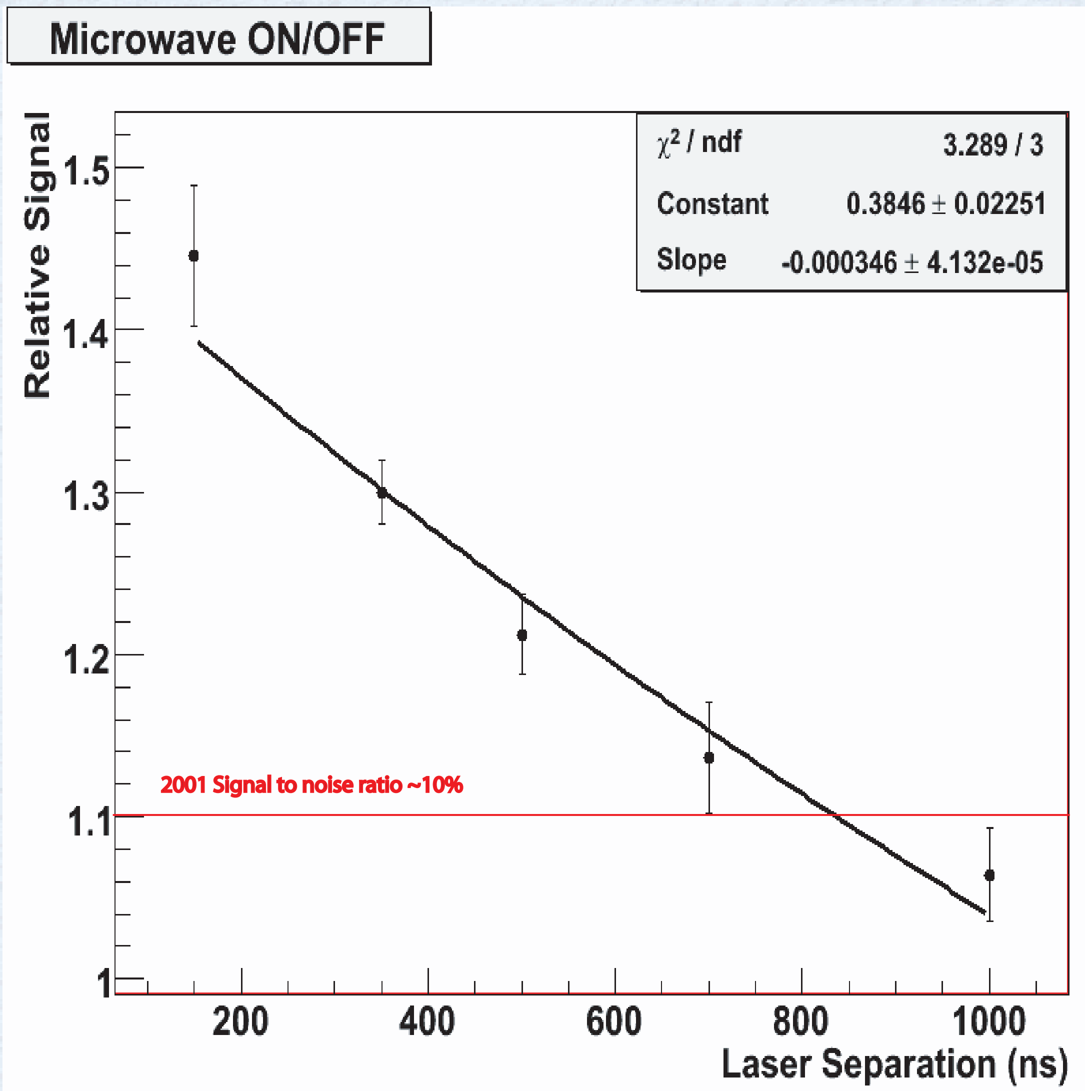
Green = 700 ns

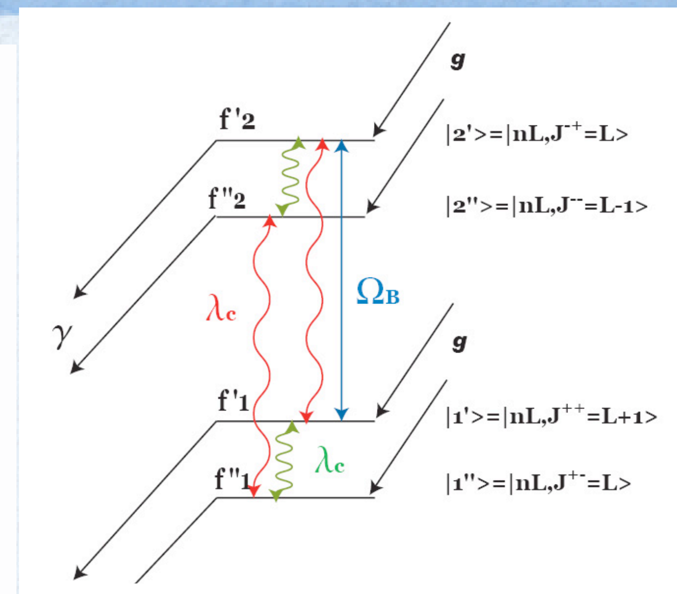
New measurements in 2006: laser scans

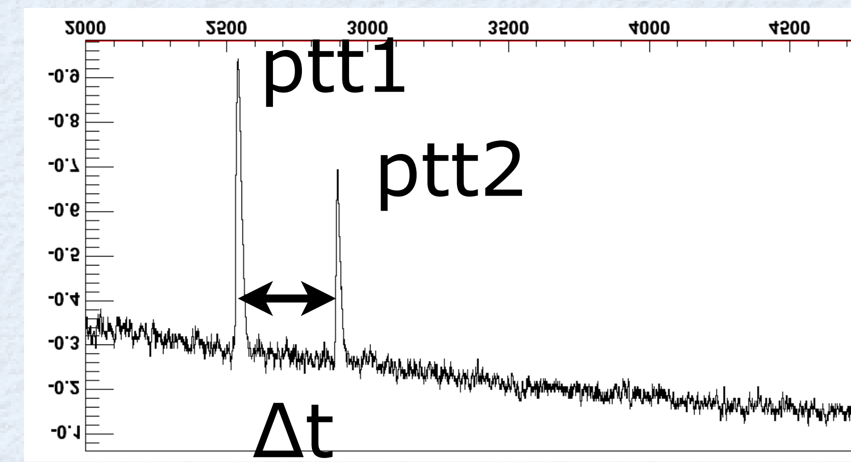


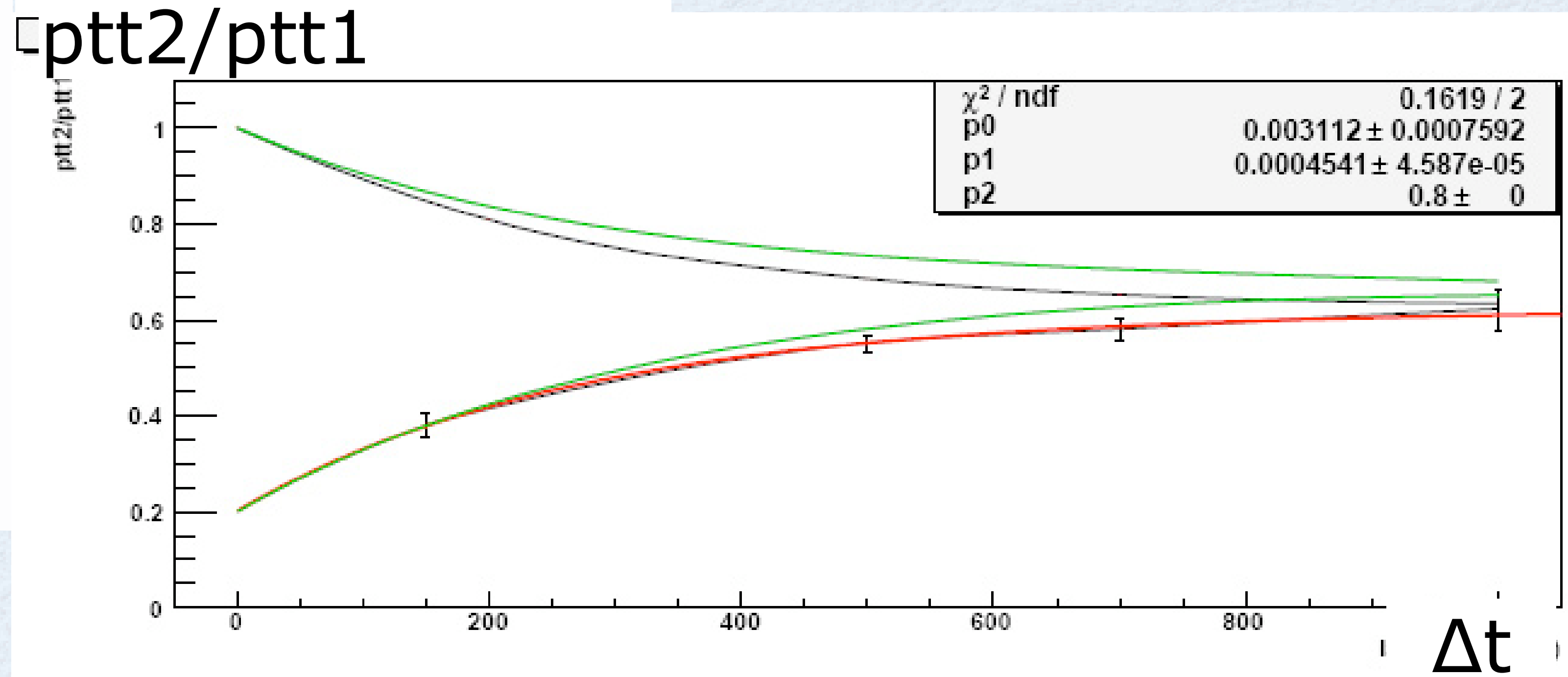
- improved laser system
  - laser band width < Doppler broadening
  - seeded by cw laser
    - much higher frequency stability
  - longer pulse length
    - higher depletion efficiency
    - higher signal-to-noise
- HF doublets completely separated
  - no cross talk
- first test experiments
  - factor ~5 improved accuracy (PRELIMINARY)

Collisional Relaxation





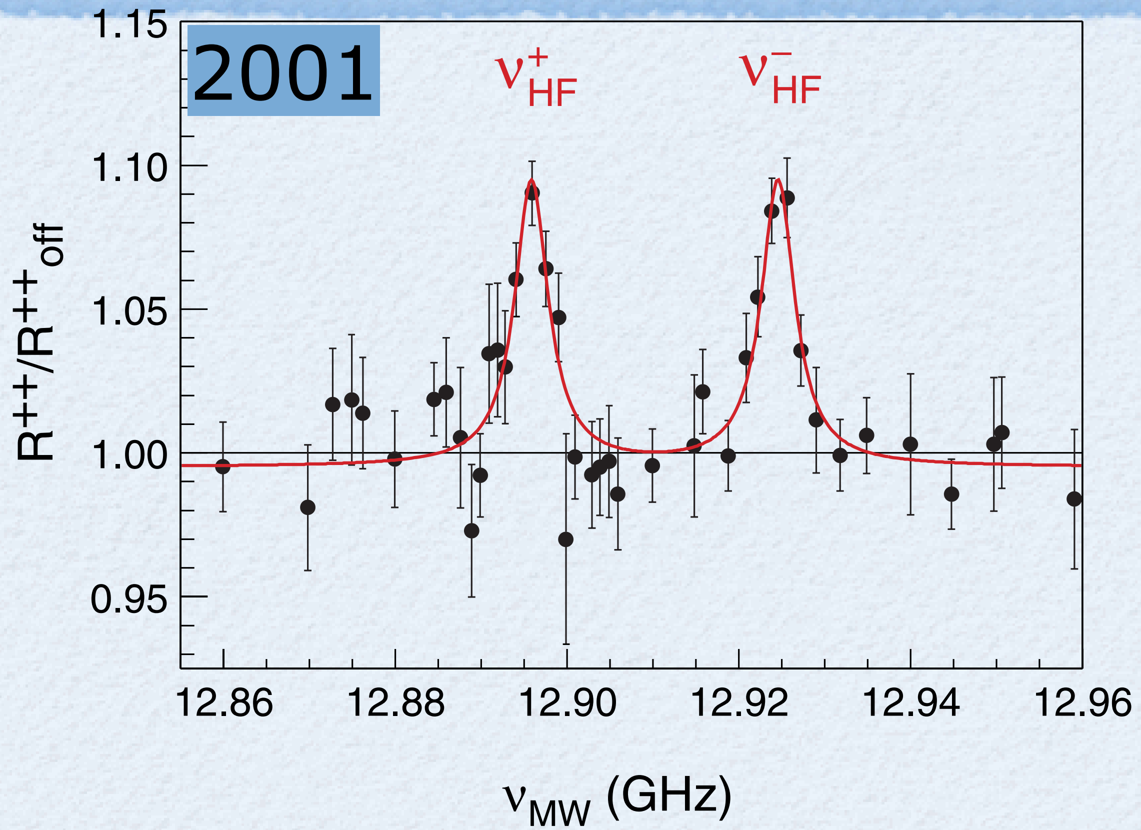


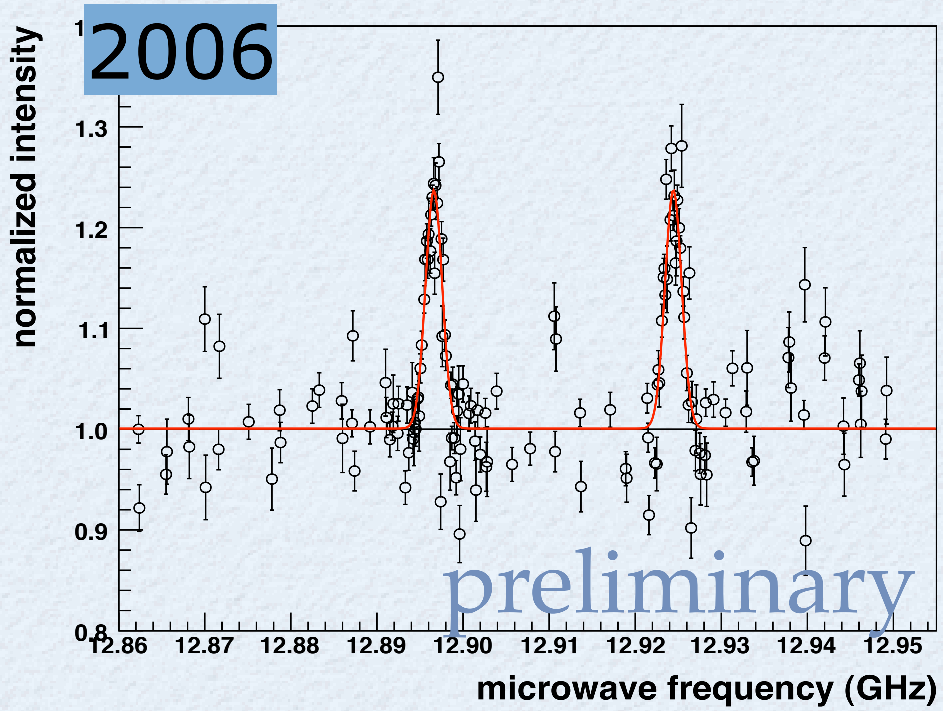


- relaxation time constant: τ_{exp} ~ 660 ± 69 ns
- theory τ_{max} ~ 325 ns

G.Ya. Korenman and S.N. Yudin, J. Phys. B **39**, 1473 (2006)

New measurements in 2006: microwave scans

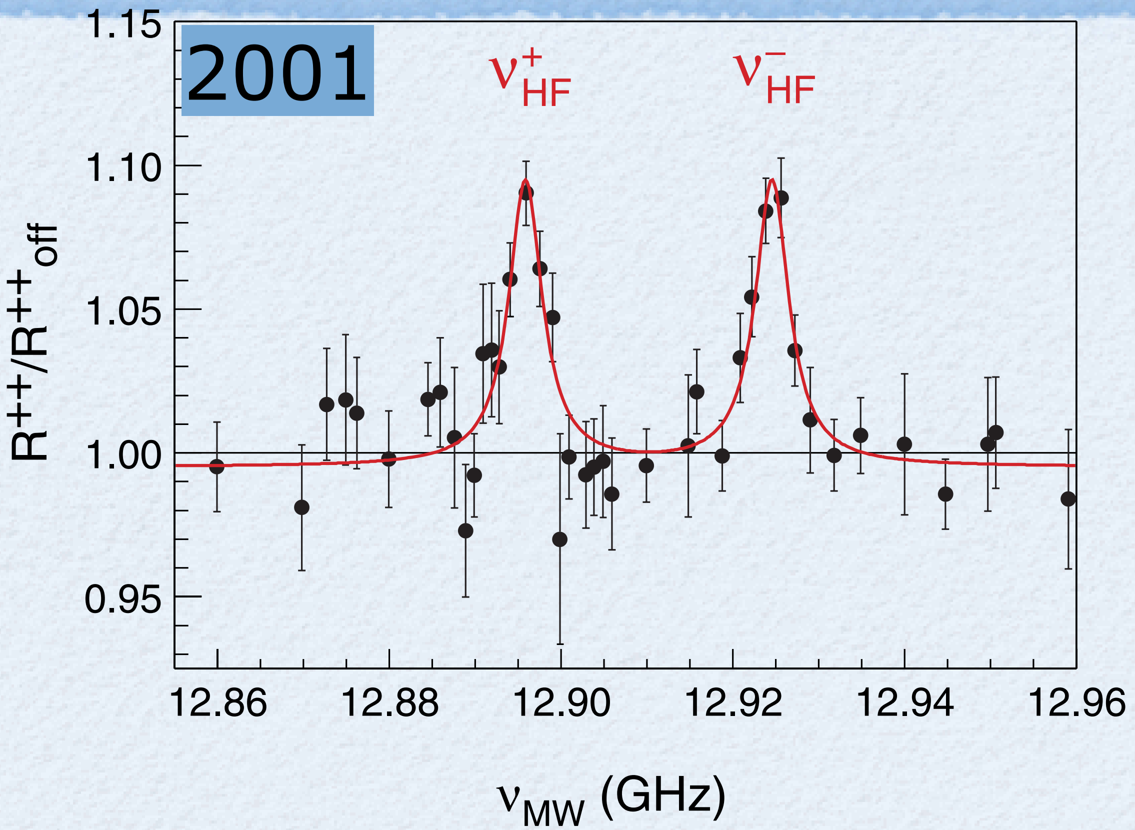




- ~ 3x narrower line width
- ~ 3x larger S/N
- ~ 5x better accuracy (PRELIMINARY)

- more systematic tests necessary (2007)
  - density dependence (very small according to theory)
  - MW power dependence

New Measurements in 2006: Microwave Scans



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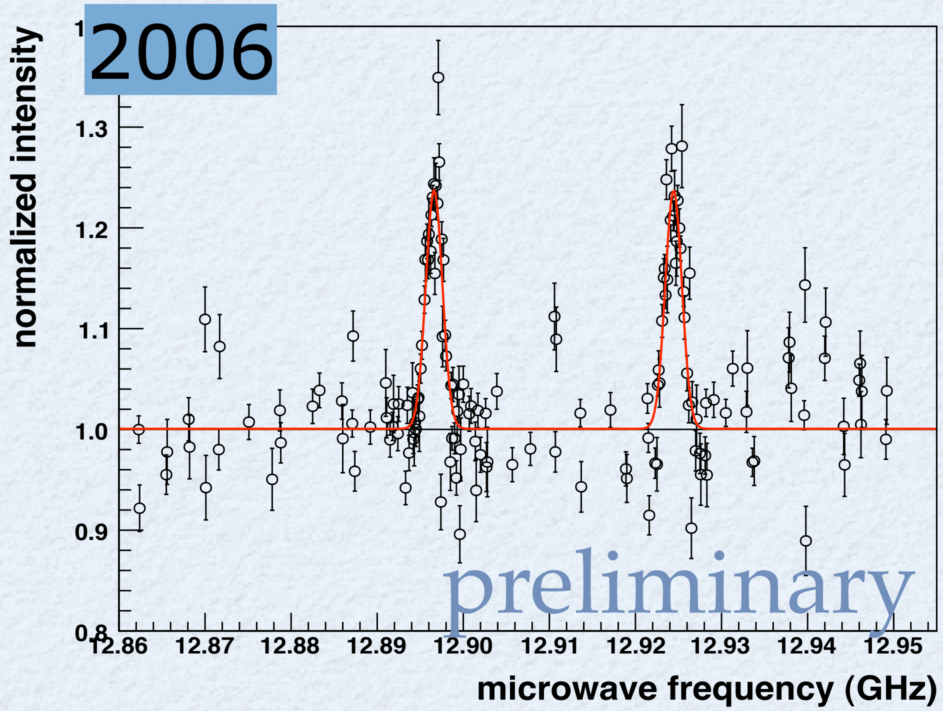

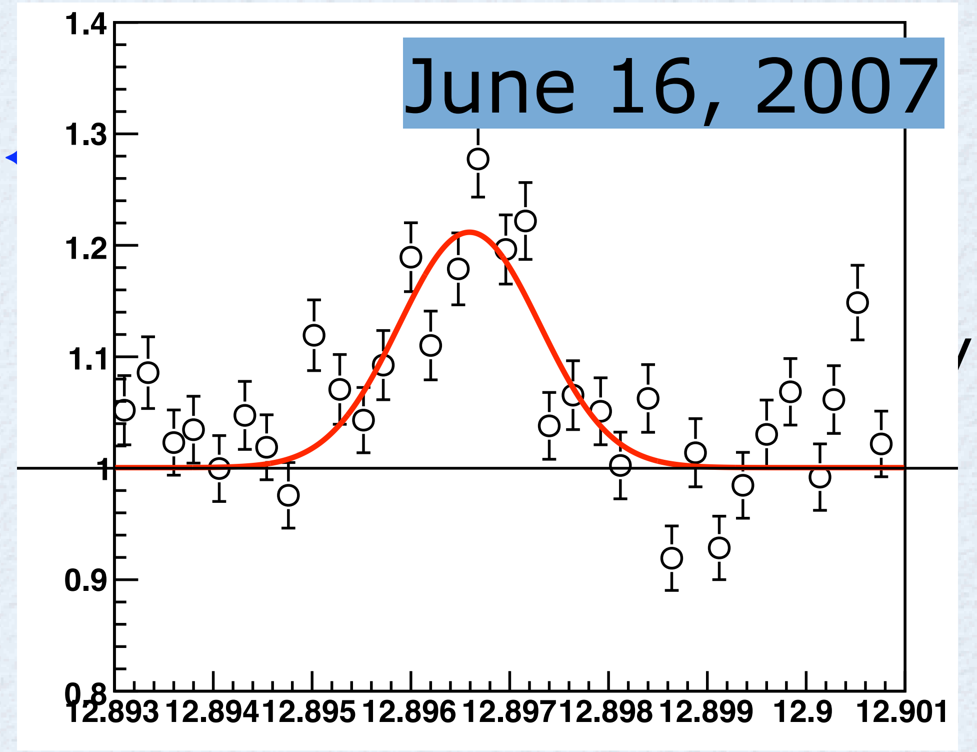

small

Summary & outlook

- antiprotonic helium offers one of best CPT tests in the hadronic sector
- big impact on development of 3-body bound-state QED
- many results for atomic (collision) physics
- further improvements expected
  - factor 3-9 possible over PDG for magnetic moment