Stefan Meyer Institute
for
Subatomic Physics

ASACUSA
Collaboration

Microwave Spectroscopy of the Hyperfine Structure with Antiprotonic ^{4}He & ^{3}He

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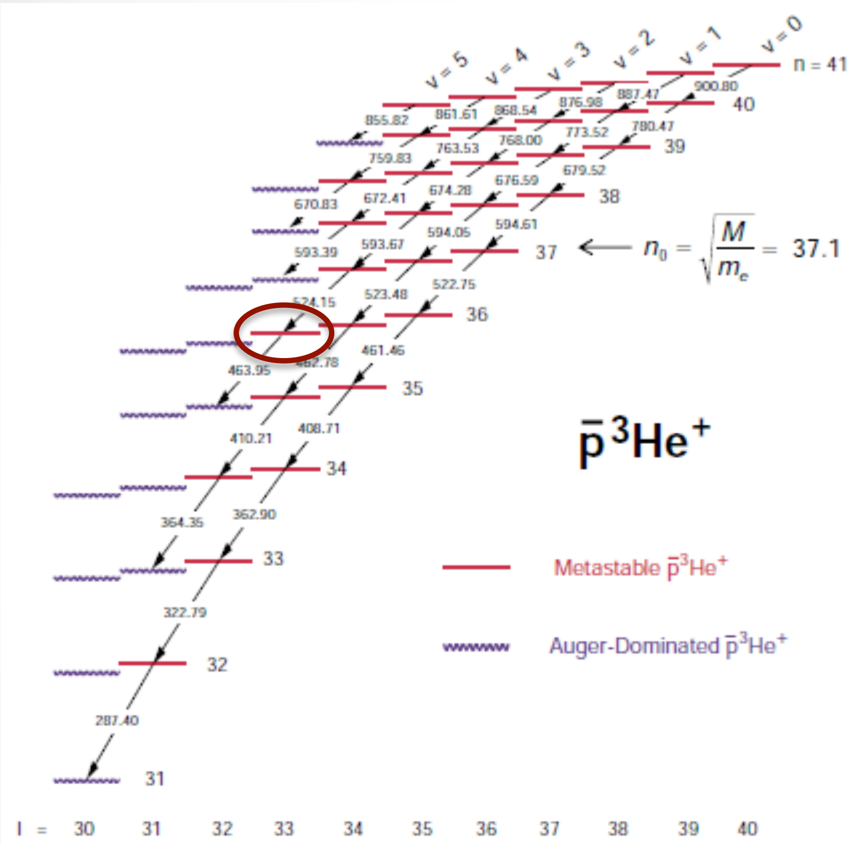
of Sciences

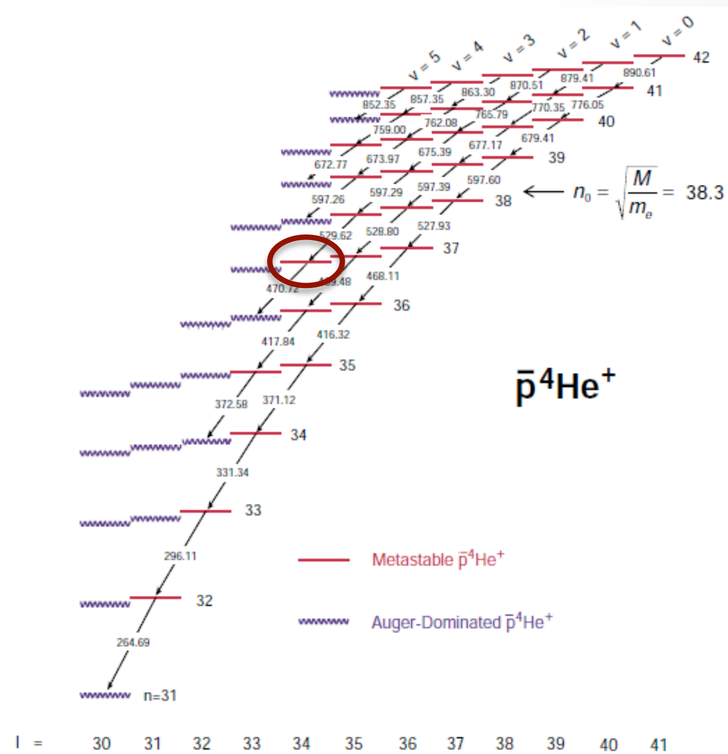
Outline

- Hyperfine Structure of $\overline{p}\,^4He$ & $\overline{p}\,^3He$
- Laser-Microwave-Laser Technique
- The Experimental Setup
- Where did we start..?
- A new Laser System
- $\overline{p}\,^4He$ - new Value for $\overline{p}$ Magnetic Moment
- $\overline{p}\,^3He$ - what's different?
- Final Achievements with $\overline{p}\,^3He$

Antiprotonic Helium



➡ <u>3% in metastable states</u>
Auger effect & Stark decay suppressed
lifetime ~ 1.5 microseconds

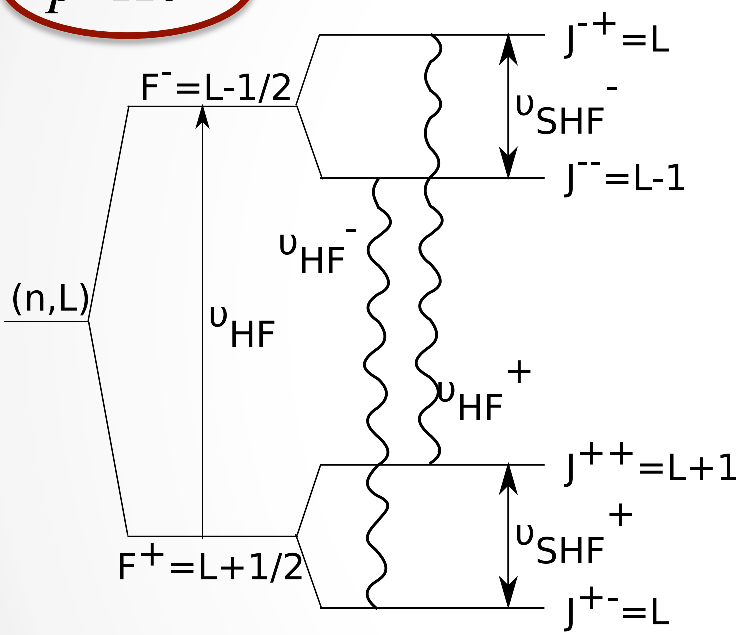


➡ parent state highly populated

Hyperfine Structure

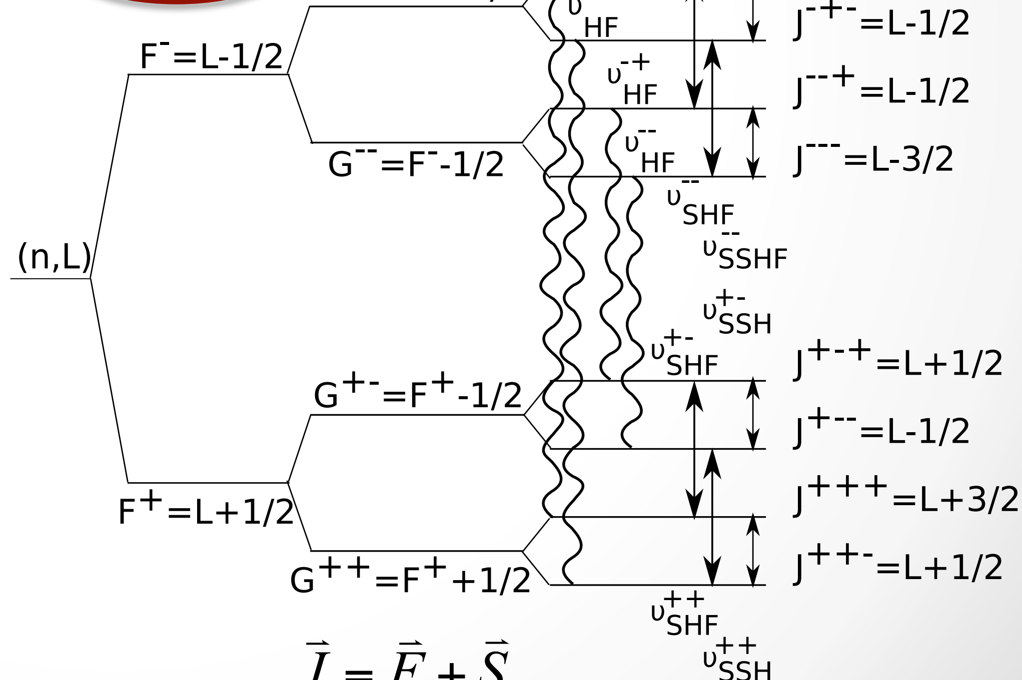
$$\vec{F} = \vec{L} + \vec{S}_e$$

$\bar{p}\,^4He^+$



➡ interaction of e^- and $\bar{p}$ magnetic moment
no nuclear spin

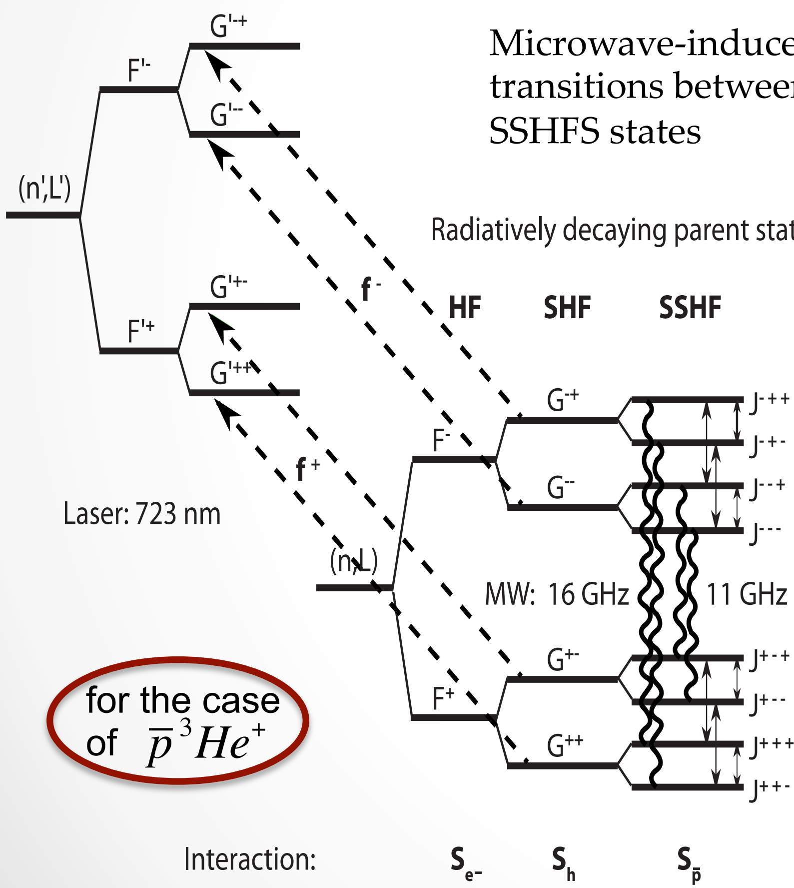
$\bar{p}\,^3He^+$



e^- and $\bar{p}$ magnetic moment
➡ also couple with
nuclear magnetic moment

$$\vec{G} = \vec{F} + \vec{S}_h \qquad \vec{J} = \vec{G} + \vec{S}_{\bar{p}} \qquad \vec{J} = \vec{F} + \vec{S}_{\bar{p}}$$

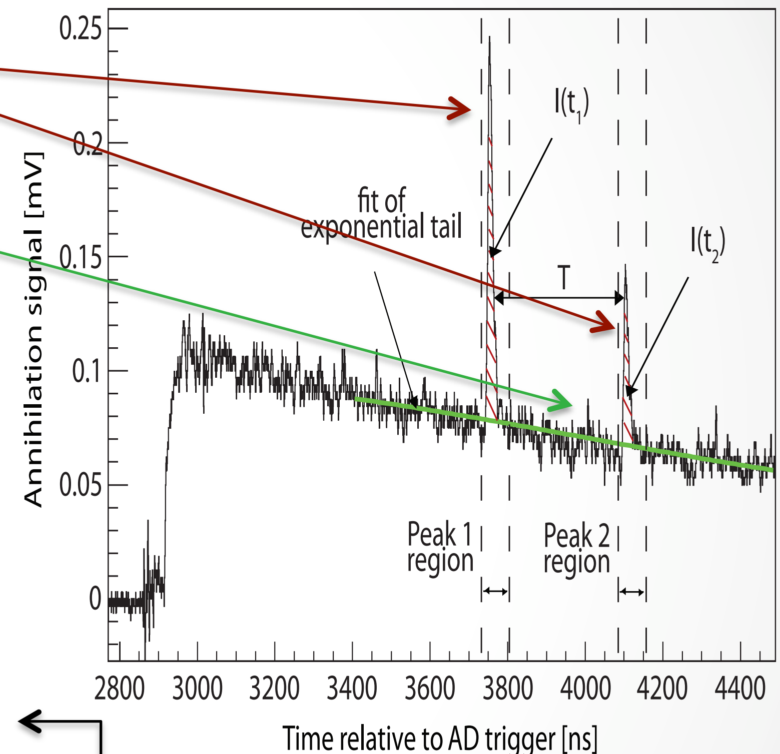
Laser-Microwave-Laser Technique



for the case of $\bar{p}\,{}^3He^+$

Laser-induced annihilations

Microwave-induced transitions between SSHFS states

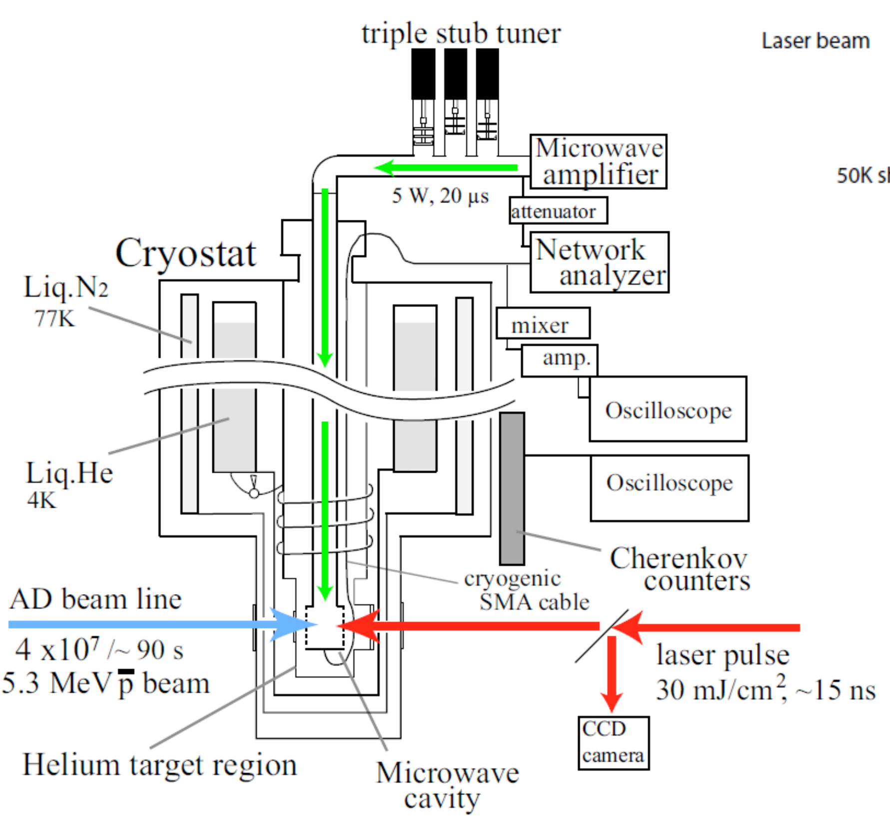


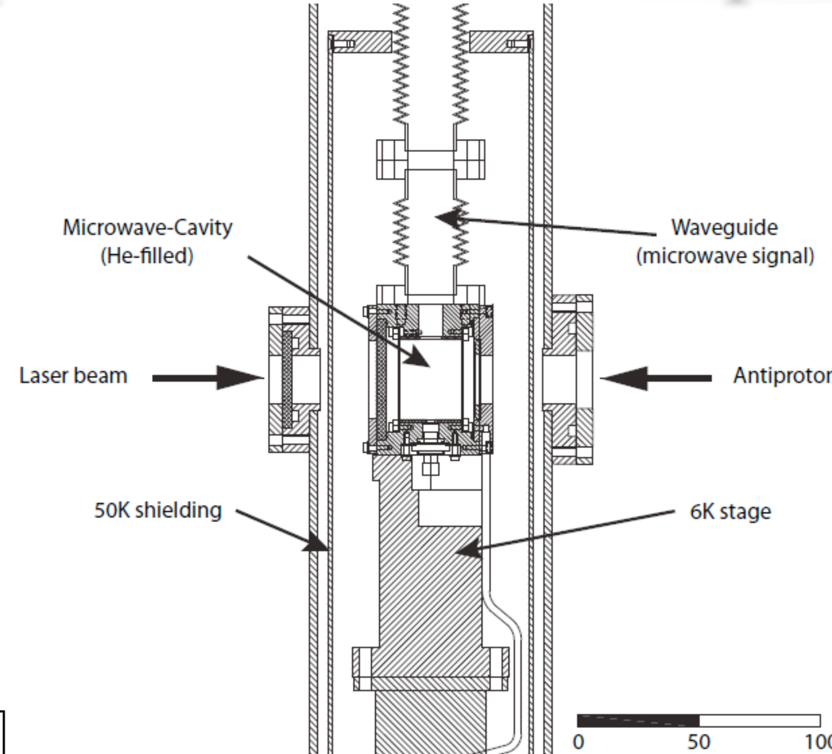
prompt peak due to immediate annihilations in the helium target (Auger decay cut off)

The Experimental Setup

Old cryostat:

two thermal shields
- 77 K (liquid nitrogen)
- 6 K (liquid helium)

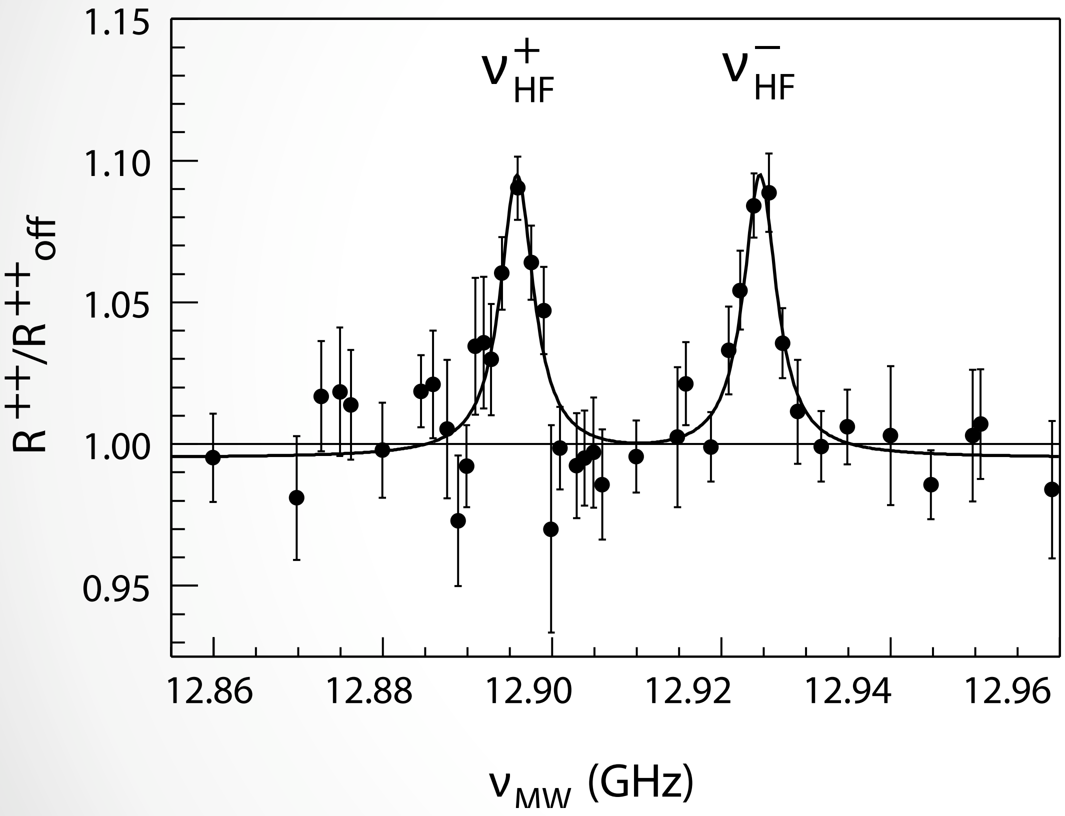




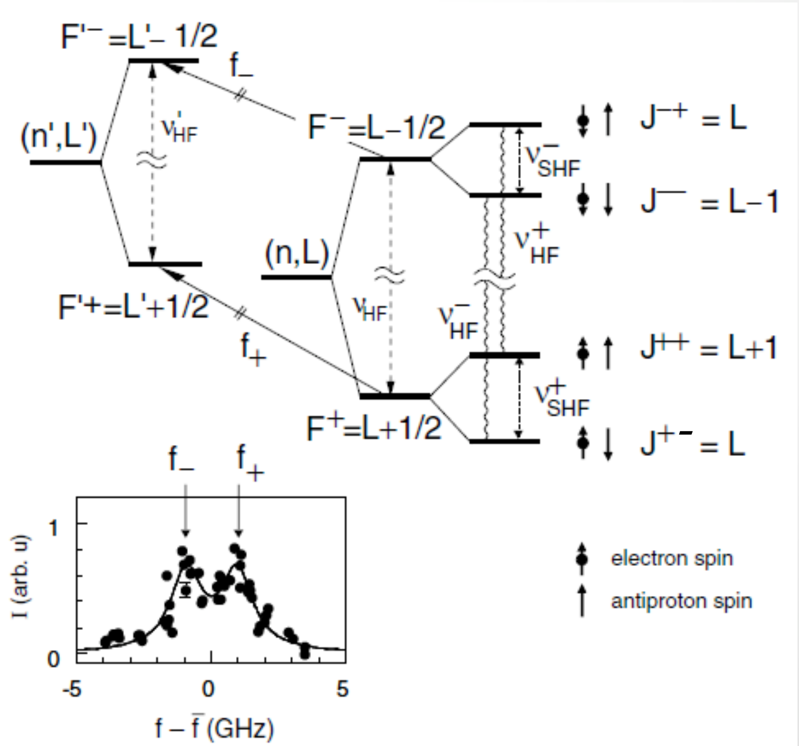
Compressor-cooled Cryostat:

- ✓ no liquid He or N_2
- ✓ cool-down to ~6K

Where did we start..?



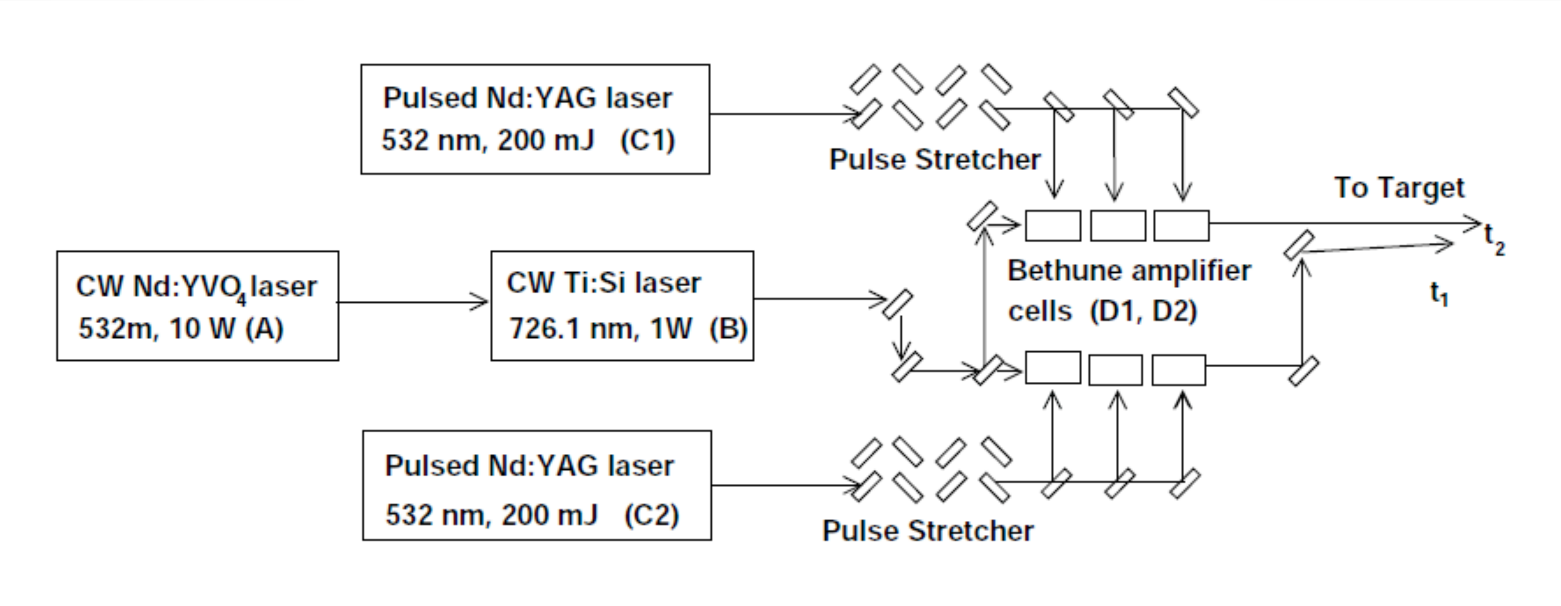
First microwave scan with new laser-microwave-laser resonance method!



Published in 2002:

E. Widmann, J. Eades, T. Ishikawa, J. Sakaguchi, T. Tasaki, H. Yamaguchi, R.S. Hayano, M. Hori, H.A. Torii, B. Juhász, D. Horváth and T. Yamazaki, Hyperfine Structure of Antiprotonic Helium Revealed by a Laser-Microwave-Laser Resonance Method, Phys. Rev. Lett. 89 (24), 2002

A new Laser System



Advantages over previous system:

- ✓ narrow linewidth $\Gamma = 100\,MHz$
- ✓ single mode, high shot-to-shot stability
- ✓ Long pulse length (more than 10ns)
- ✓ Unlimited time difference between the two laser pulses

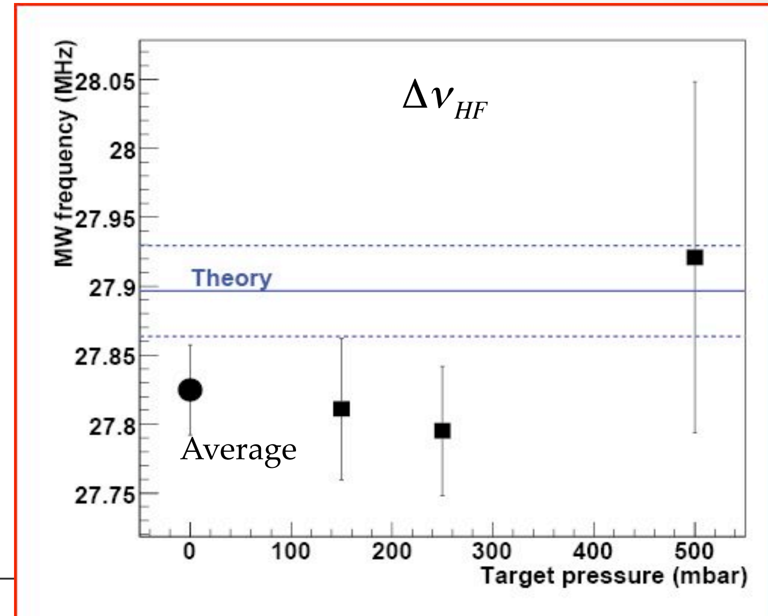
$\bar{p}\,{}^4He^+$

New Value for the $\bar{p}$ Magnetic Moment

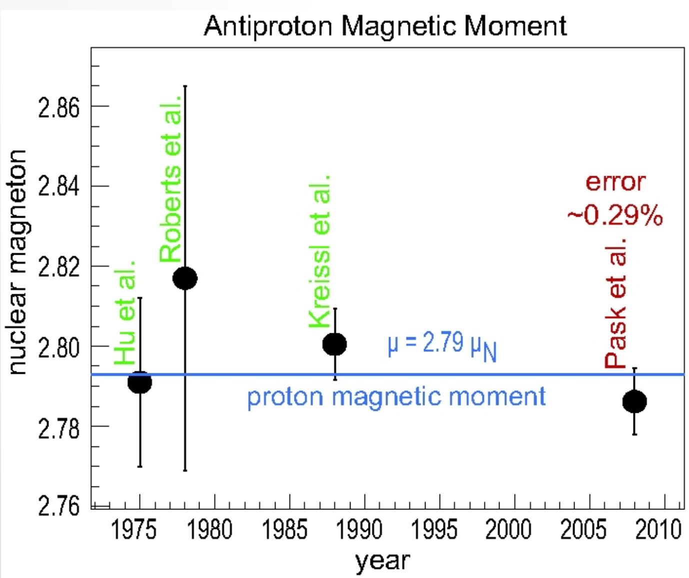
$\bar{p}$ MAGNETIC MOMENT References History since 1980

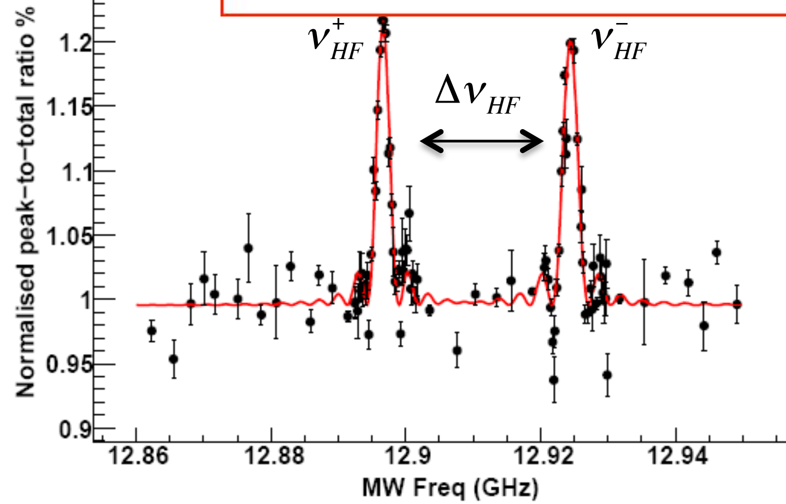
A few early results have been omitted.

VALUE (μ_N)	DOCUMENT ID		TECN	COMMENT
−2.793±0.006	OUR AVERAGE			
−2.7862±0.0083	PASK	09	CNTR	$\bar{p}$ He$^+$ hyperfine structure
−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



Published in Physics Letters B in 2009:
T. Pask, D. Barna, A. Dax, R. S. Hayano, M. Hori, D. Horvath, S. Friedreich, B. Juhasz, O. Massiczek, N. Ono, A. Soter, E. Widmann, Antiproton magnetic moment determined from the HFS of $\bar{p}$He$^+$, Phys. Lett. B 678, Issue 1, 6, 2009



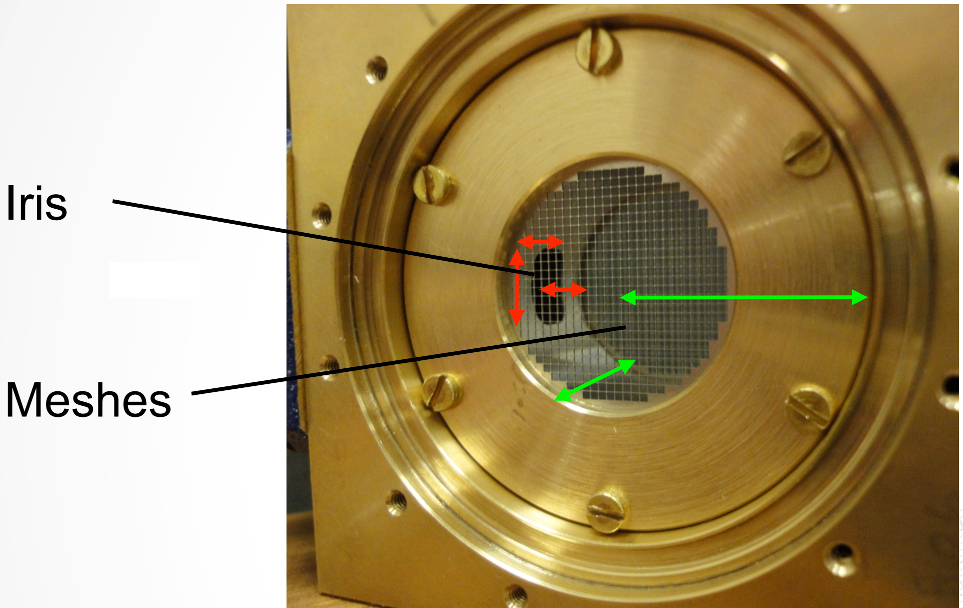


$\bar{p}\,^3He$ - what's different?

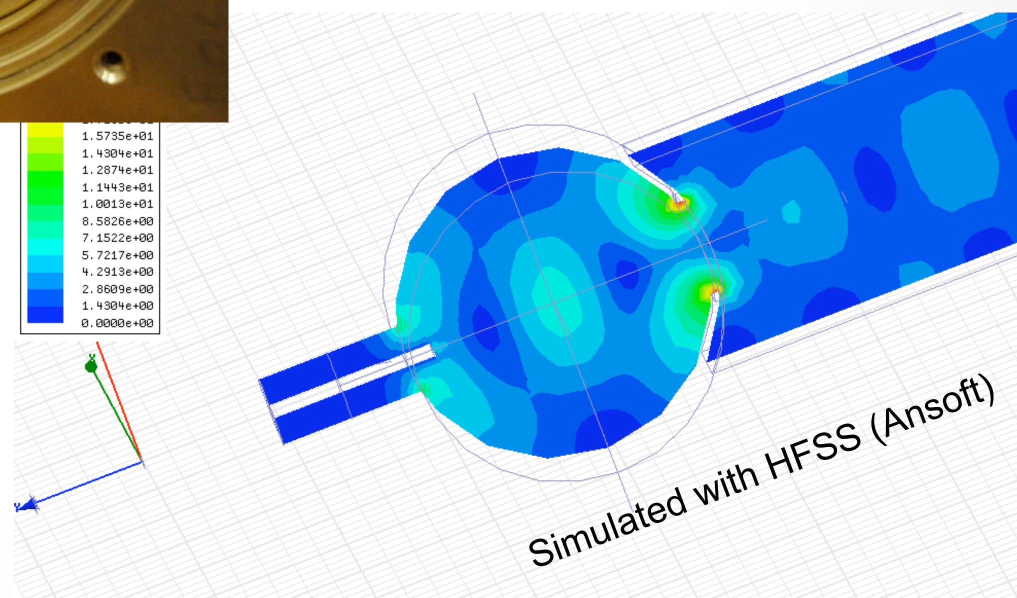
- Microwave Spectroscopy with $\bar{p}\,^4He^+$:
  - precise determination of antiproton magnetic moment
  - test of CPT invariance
- With $\bar{p}\,^3He^+$:
  - more rigurous test of QED theory
  - new cryostat
  - microwave cavities for the new SSHF transition frequencies

..no improvement in precision achievable..

..the microwave apparatus..

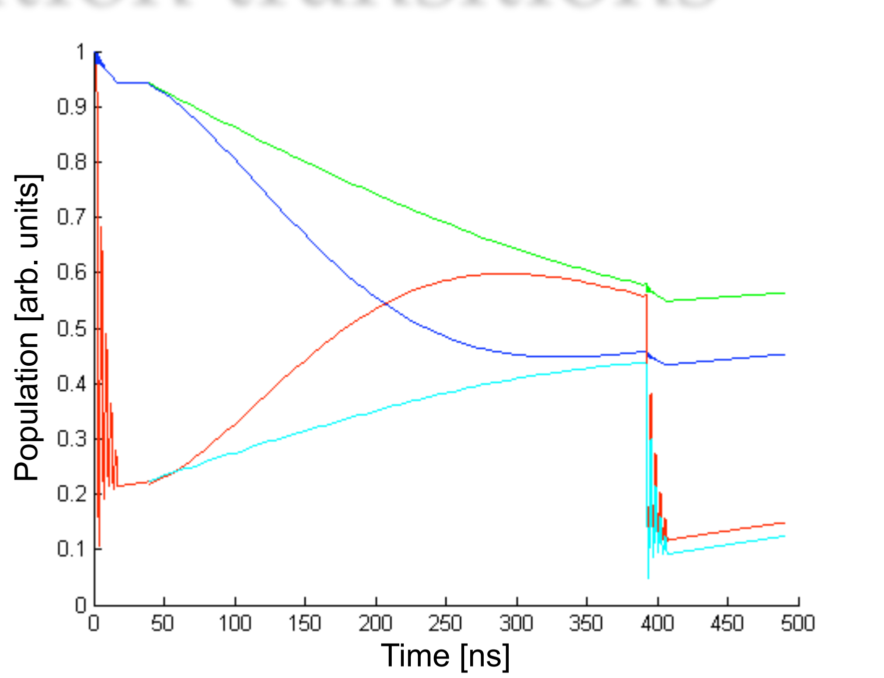


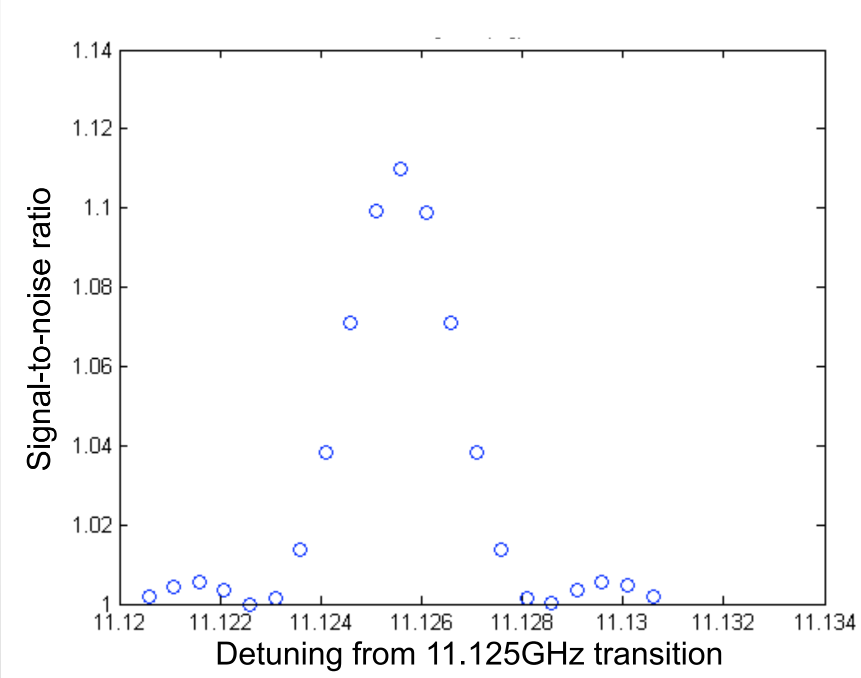
- ✓ correct field mode
- ✓ fixed central frequency
- ✓ measurements over frequency range ~100MHz
  equal magnetic field strength



Simulations of the laser- and MW-induced population transitions

- microwave-induced (de)population of states (for 11.125 GHz transition)



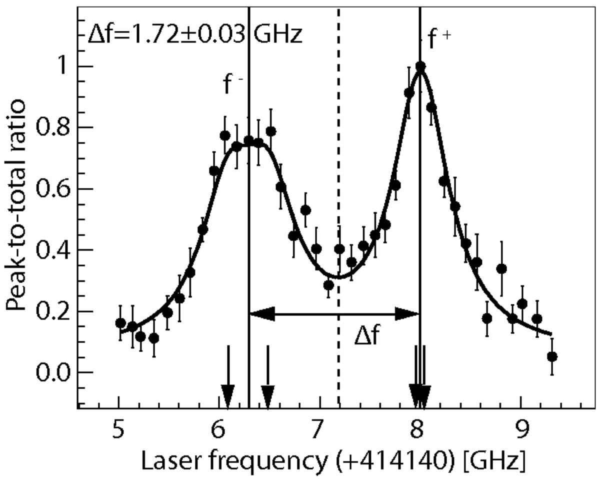


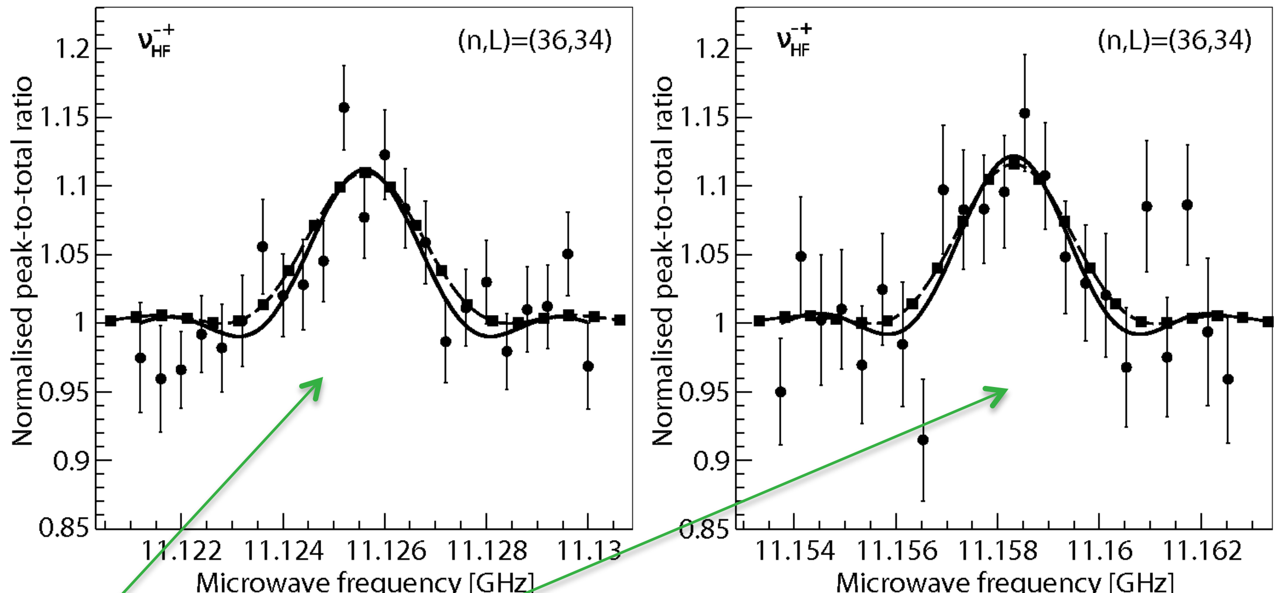
- by solving Bloch equations

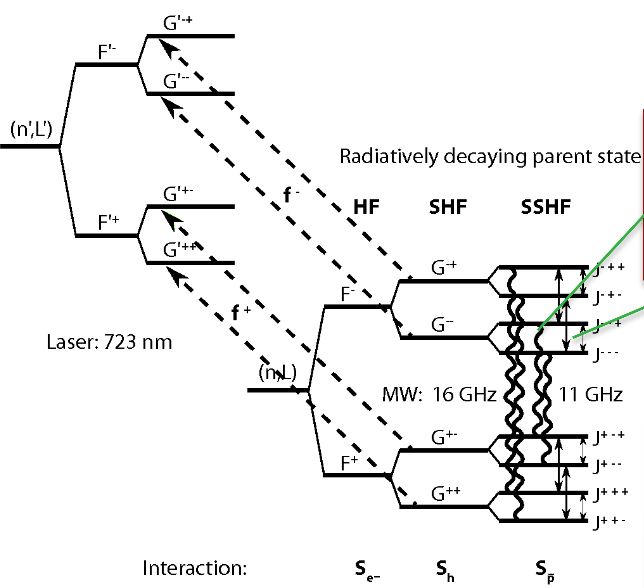
$$\frac{d}{dt}\rho = M\rho$$

M... 18x18 density matrix

Achievements with $\bar{p}\,^3He$





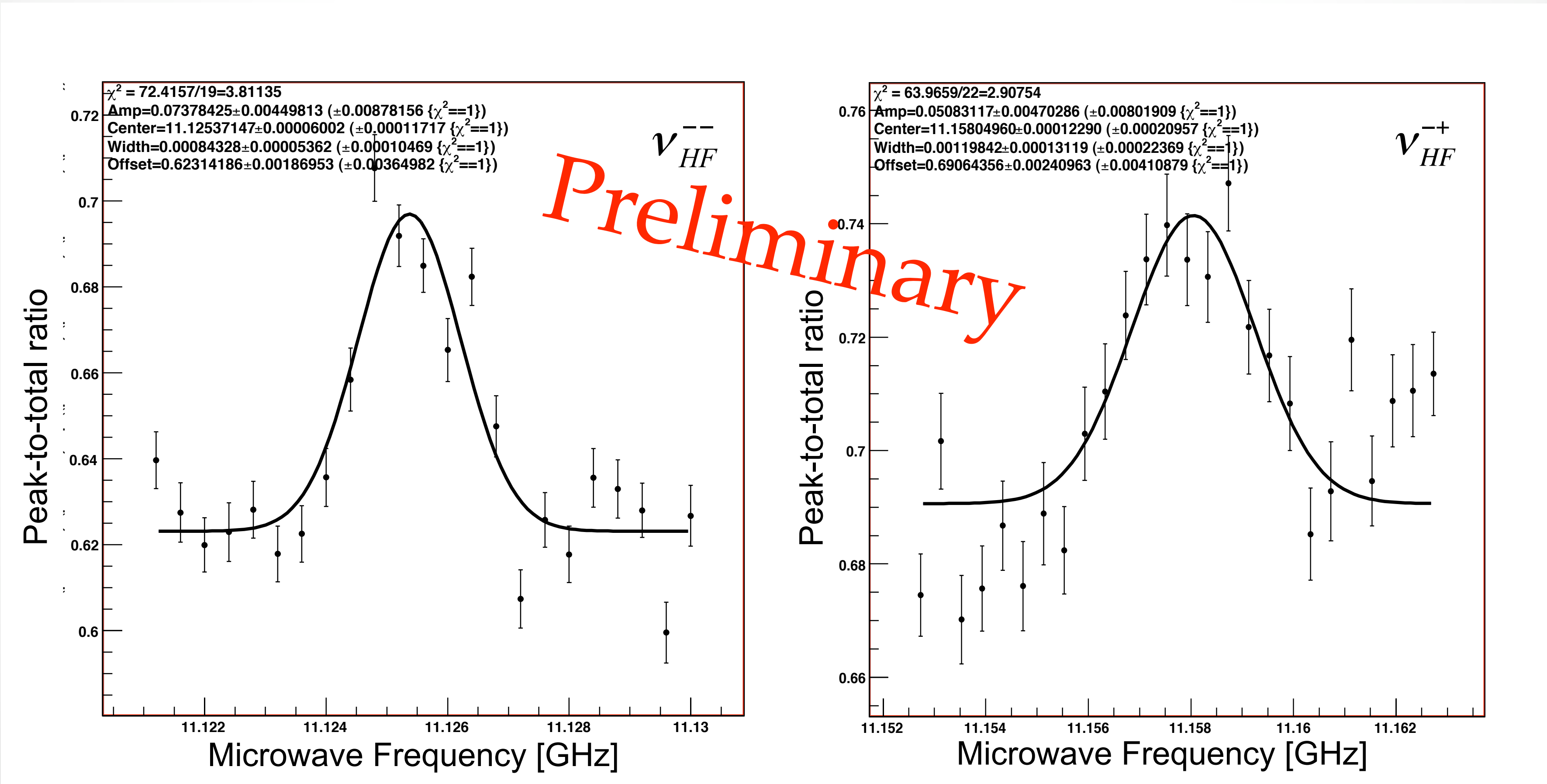


<u>Publication accepted in Physics Letters B</u>

First observation of two hyperfine transitions in antiprotonic ³He, S. Friedreich, D. Barna, F. Caspers, A. Dax, R.S. Hayano, M. Hori, D. Horváth, B. Juhász, T. Kobayashi, O. Massiczek, A. Sóter, K. Todoroki, E. Widmann, J. Zmeskal

	Experiment	Theory (Korobov)	Theory (Kino)
ν_{HF}^{--}	**11.12559(14)**	**11.12500(55)**	**11.12515(55)**
ν_{HF}^{-+}	**11.15839(18)**	**11.15773(55)**	**11.15756(55)**
$\Delta\nu_{HF}^{\pm}$	**0.03279(22)**	**0. 0327219(16)**	

..2011 Results for $\overline{p}\,{}^3He$



Summary

✧ Antiprotonic ^{4}He

final result for the antiproton magnetic moment:

$$\mu_s^{\bar p} = -2.7862(83)\mu_N$$

$\bar p$ MAGNETIC MOMENT	References	History since 1950	
A few early results have been omitted.			
VALUE (μ_N)	DOCUMENT ID	TECN	COMMENT
−2.793±0.006	OUR AVERAGE		
−2.7862±0.0083	PASK 09	CNTR	$\bar p$ He$^+$ hyperfine structure
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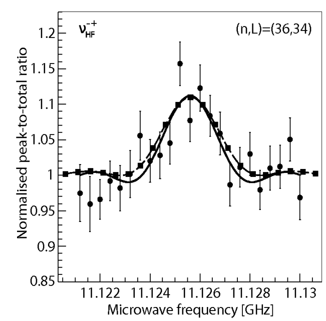
−2.817±0.048	ROBERTS 78	CNTR	
−2.791±0.021	HU 75	CNTR	Exotic atoms

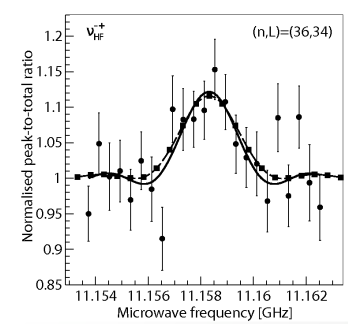
✧ Antiprotonic ^{3}He

first time observation of two transitions @ 11GHz:

$$\nu_{HF}^{--} = 11.12559(14) GHz$$

$$\nu_{HF}^{-+} = 11.15839(18) GHz$$





Acknowledgments

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THANK YOU.