Laser spectroscopy of antiprotonic helium

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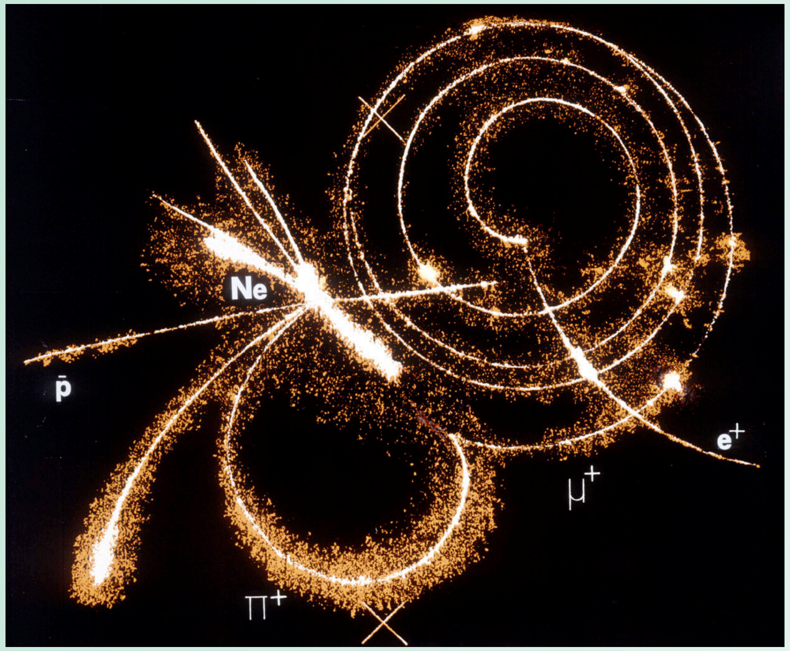
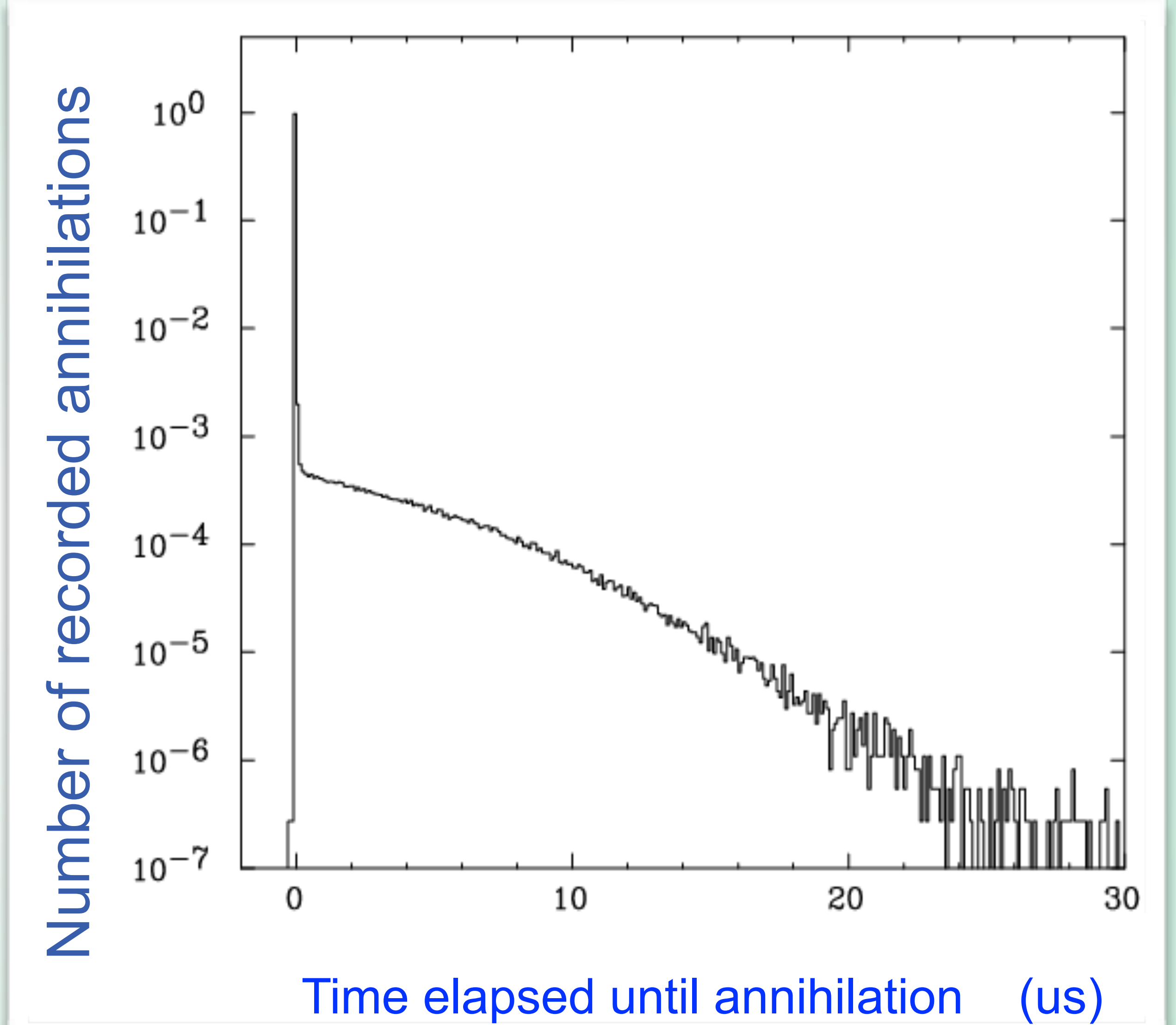
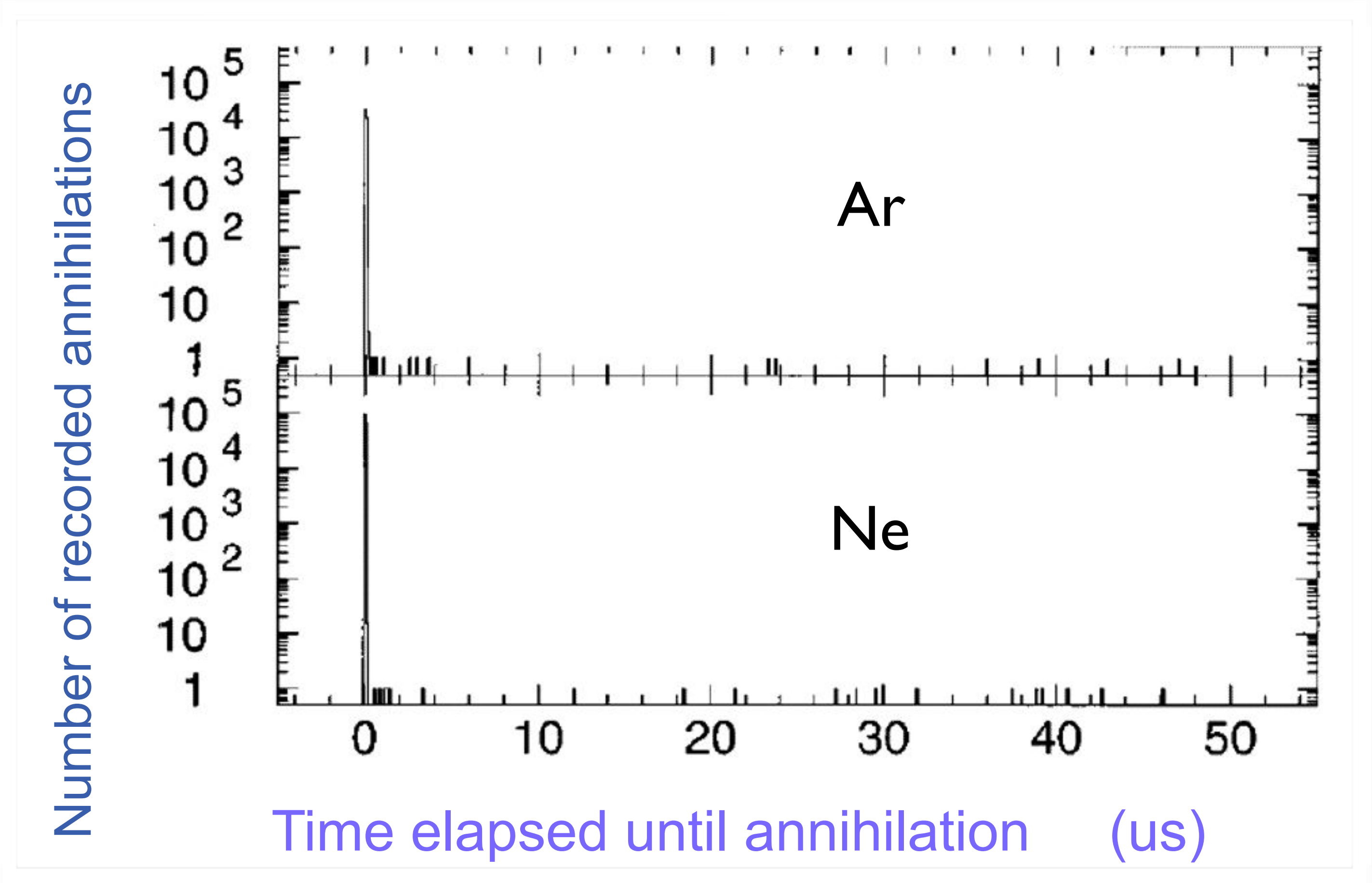
Moriond 2017

Long-lived antiprotons in helium

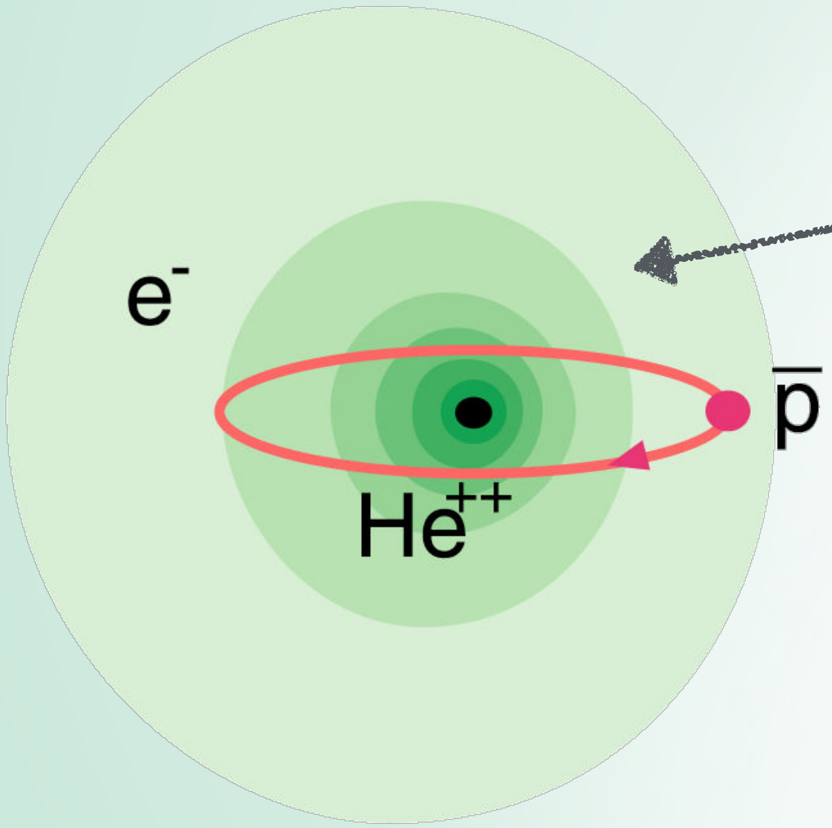






PS205 experiment (1993)

Metastable antiprotonic helium ($\bar{p}He^+$)



$\tau \sim 4\ \mu s$

Electron in 1s orbital. Attached with 25-eV ionization potential. Auger emission suppressed.

Antiproton in a 'circular' Rydberg orbital n=38, l=n-1 with diameter of 100 pm.

- Localized away from the nucleus.
- The electron protects the antiproton during collisions with helium atoms.

Precision measurements of $\bar{p}He^+$ transition frequencies and companions with QED calculations yields:

Antiproton-to-electron mass ratio to precision of 8×10^{-10}

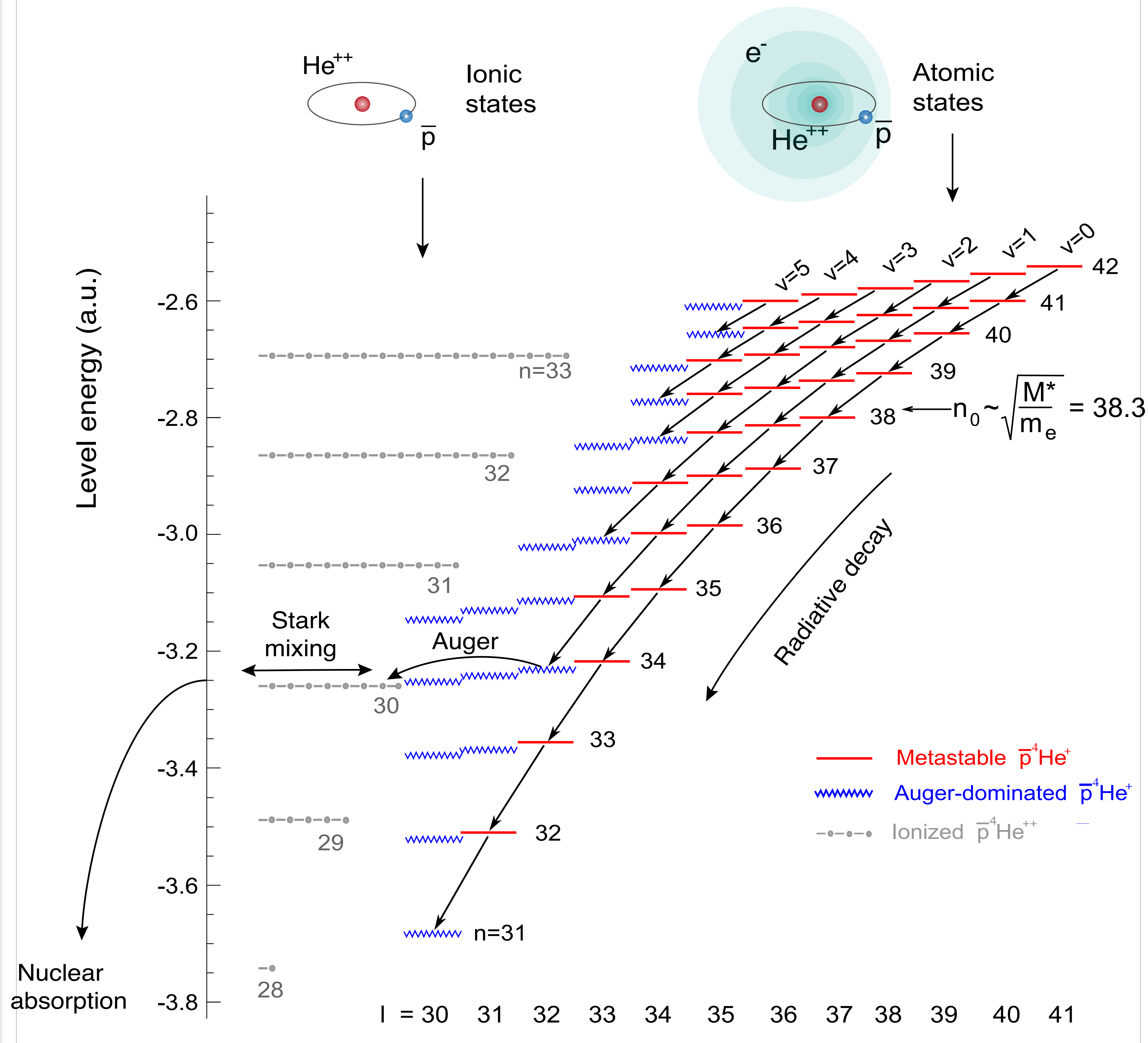
Assuming CPT invariance, **electron mass** to 8×10^{-10}

Combined with the cyclotron frequency of antiprotons in a Penning trap by TRAP and BASE collaborations, antiproton and proton masses and charges to 5×10^{-10}

→ Consistency test of CPT invariance

Bounds on the 5th force at the sub-A length scale……

Energy levels of $\bar{p}He^+$



Calculated two-photon transition frequency (n,l)=(36,34)→(34,32)

Non-relativistic energy	1 522 150 208.13 MHz
$m\alpha^4$ order corrections	-50320.64
$m\alpha^5$ order corrections	7070.28
$m\alpha^6$ order corrections	113.11
$m\alpha^7$ order corrections	-10.46(20)
$m\alpha^8$ order corrections	-0.12(12)
Transition frequency	1 522 107 060.3(2)
Uncertainty from alpha charge radius	+/-0.007
Uncertainty from antiproton charge radius	< 0.0007

Korobov, Hilico, Karr, *PRL* 112, 103003 (2014).

Korobov, Hilico, Karr, PRA 89, 032511 (2014).

Korobov, Hilico, Karr, *PRA* 87, 062506 (2013).

One-loop self-energy correction in atomic units for two-center system

$$\Delta E^{(7)}_{\rm se} = \frac{\alpha^5}{\pi}\Bigg\{\mathcal{L}(Z,n,l) + \left(\frac{5}{9}+\frac{2}{3}\ln\left[\frac{1}{2}\alpha^{-2}\right]\right)\left\langle 4\pi\rho\, Q(E-H)^{-1}Q\, H_B\right\rangle_{\rm fin_{au}}$$

$$+2\left\langle H_{so}\, Q(E-H)^{-1}Q\, H_B\right\rangle + \left(\frac{779}{14400}+\frac{11}{120}\ln\left[\frac{1}{2}\alpha^{-2}\right]\right)\left\langle \boldsymbol{\nabla}^4 V\right\rangle_{\rm fin_{au}}$$

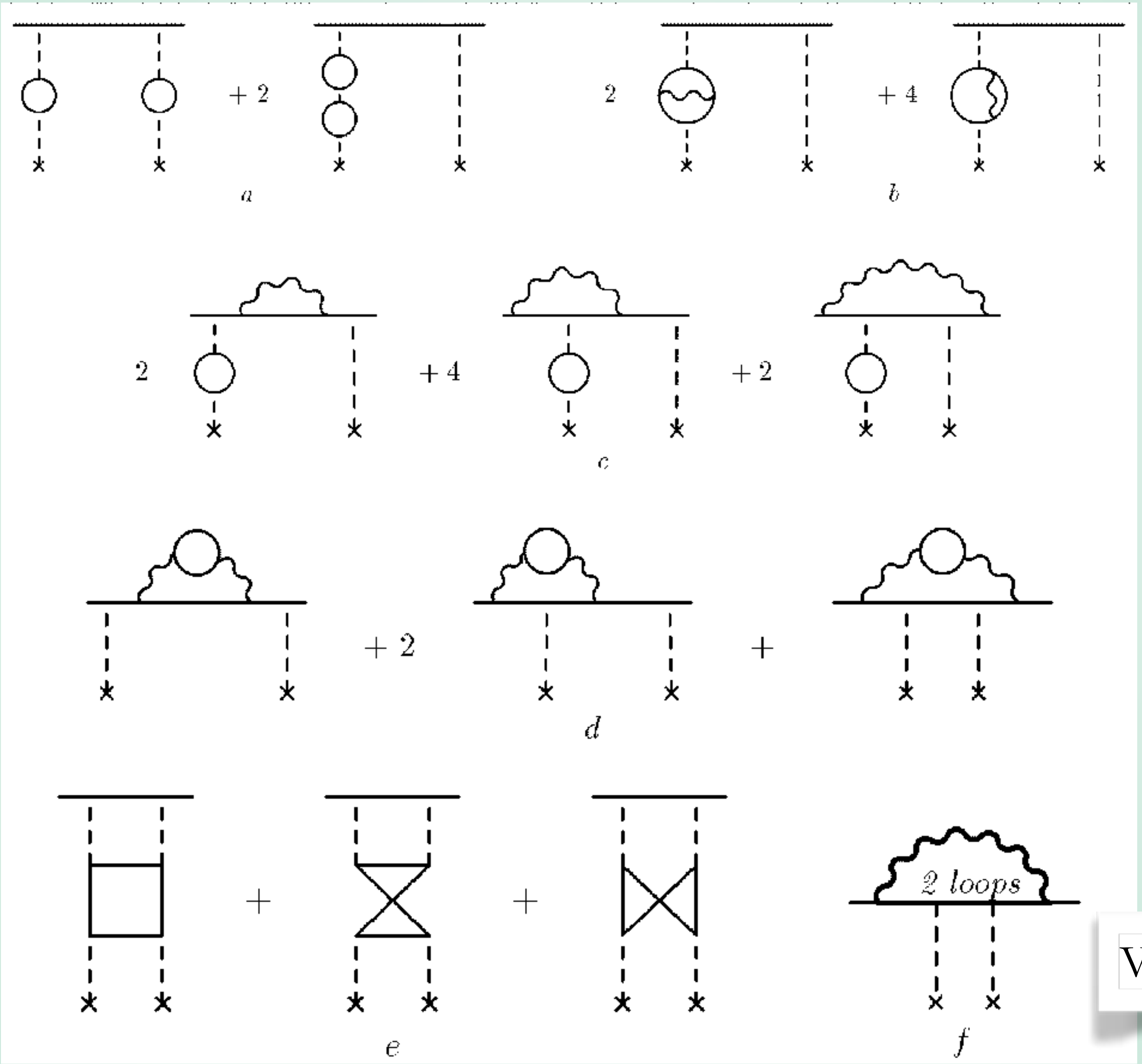
$$+\left(\frac{23}{576}+\frac{1}{24}\ln\left[\frac{1}{2}\alpha^{-2}\right]\right)\left\langle 2i\sigma^{ij}p^i\boldsymbol{\nabla}^2 V p^j\right\rangle$$

$$+\left(\frac{589}{720}+\frac{2}{3}\ln\left[\frac{1}{2}\alpha^{-2}\right]\right)\left\langle(\boldsymbol{\nabla}V)^2\right\rangle_{\rm fin_{au}} + \frac{3}{80}\left\langle 4\pi\rho\,\mathbf{p}^2\right\rangle_{\rm fin_{au}} - \frac{1}{4}\left\langle \mathbf{p}^2 H_{so}\right\rangle$$

$$+Z^2\left[-\ln^2[\alpha^{-2}] + \left[\frac{16}{3}\ln 2 - \frac{1}{4}\right]\ln[\alpha^{-2}] - 0.81971202(1)\right]\langle\pi\rho\rangle\Bigg\}$$

V.I. Korobov, J.-P. Karr, L. Hilico

Two-loop QED contributions



V.I. Korobov

Theoretical precision compared to other atoms

Antiprotonic He (n,l)=(33,32)→(31,30)

2 145 054 858.100(200) MHz

(Korobov 2014)

Experimental precision

Uncertainty due to $m\alpha^7$ QED on this digit

Uncertainty due to helium charge radius (to be improved by muHe experiment)

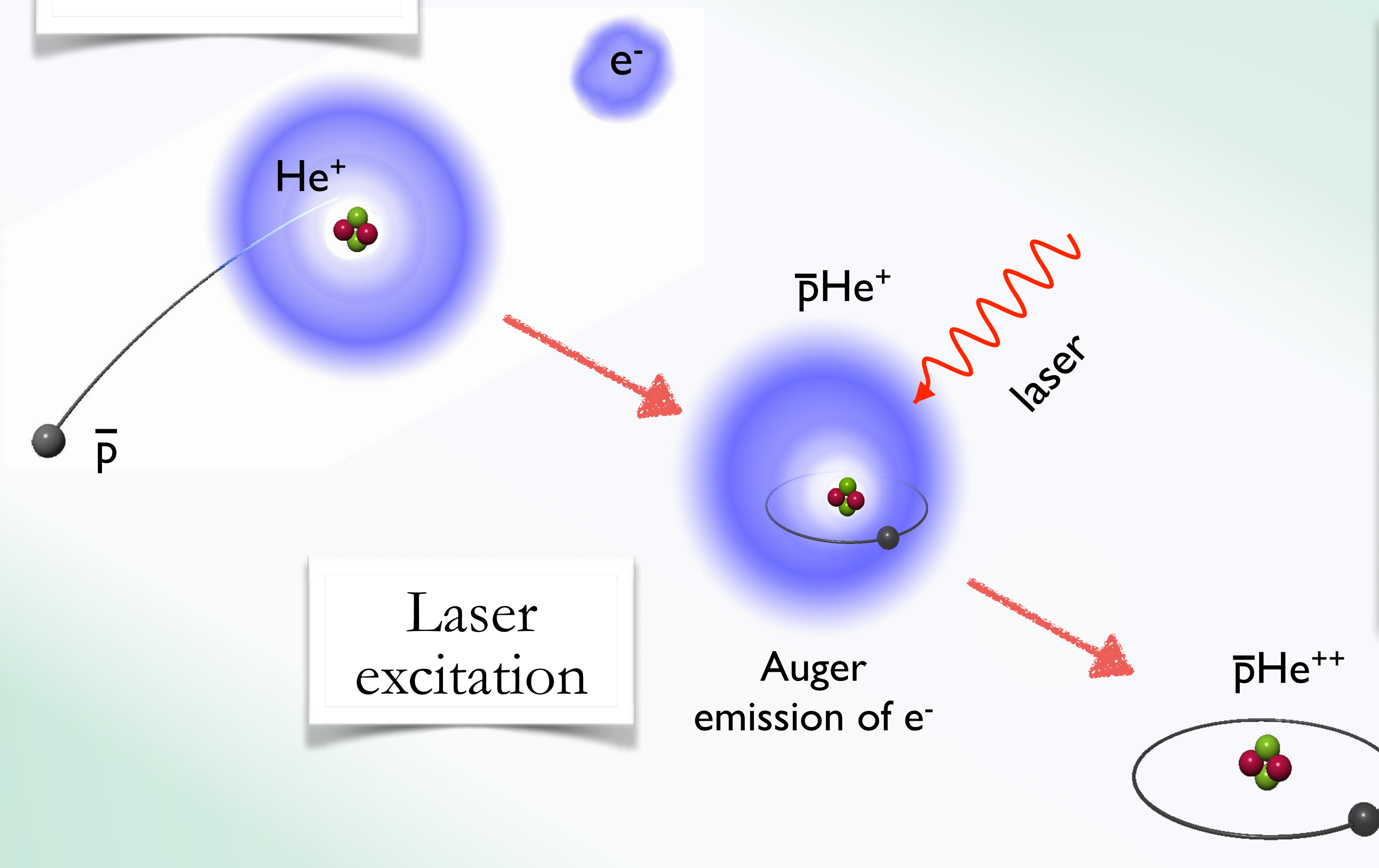
Hydrogen 1s-2s

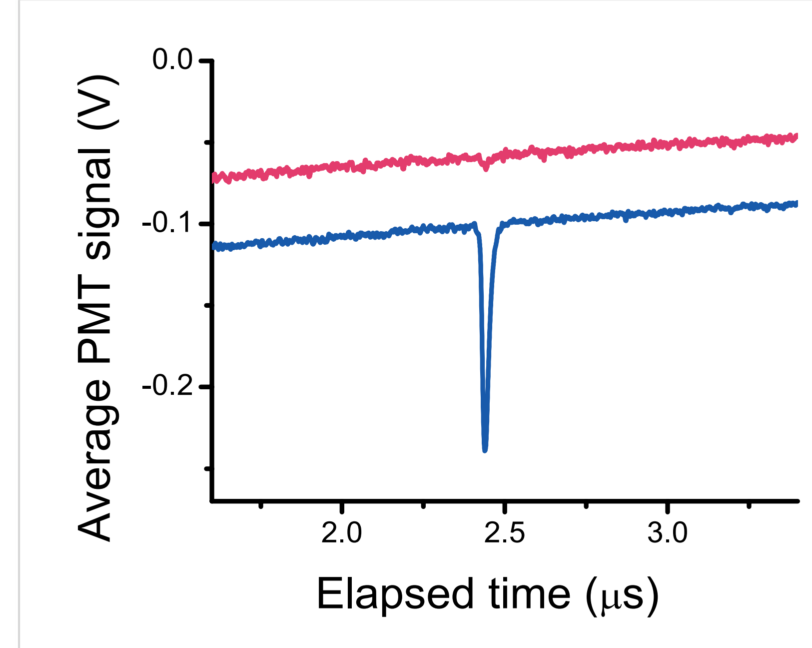
2 466 061 413.18 MHz

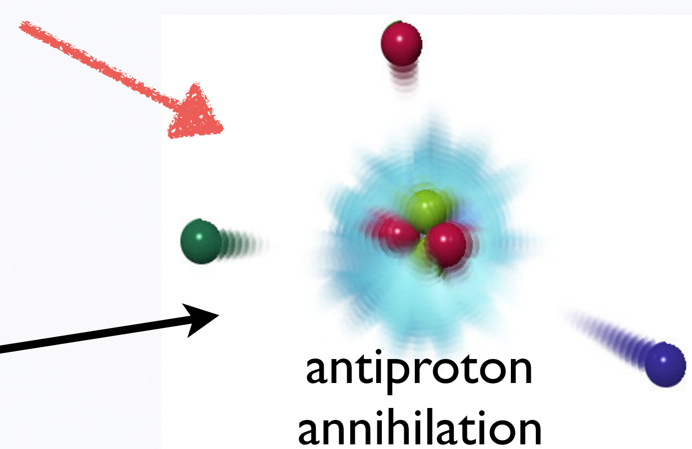
(Parthey *et al.* 2014)

Uncertainty due to proton charge radius on these digits

Laser spectroscopy method



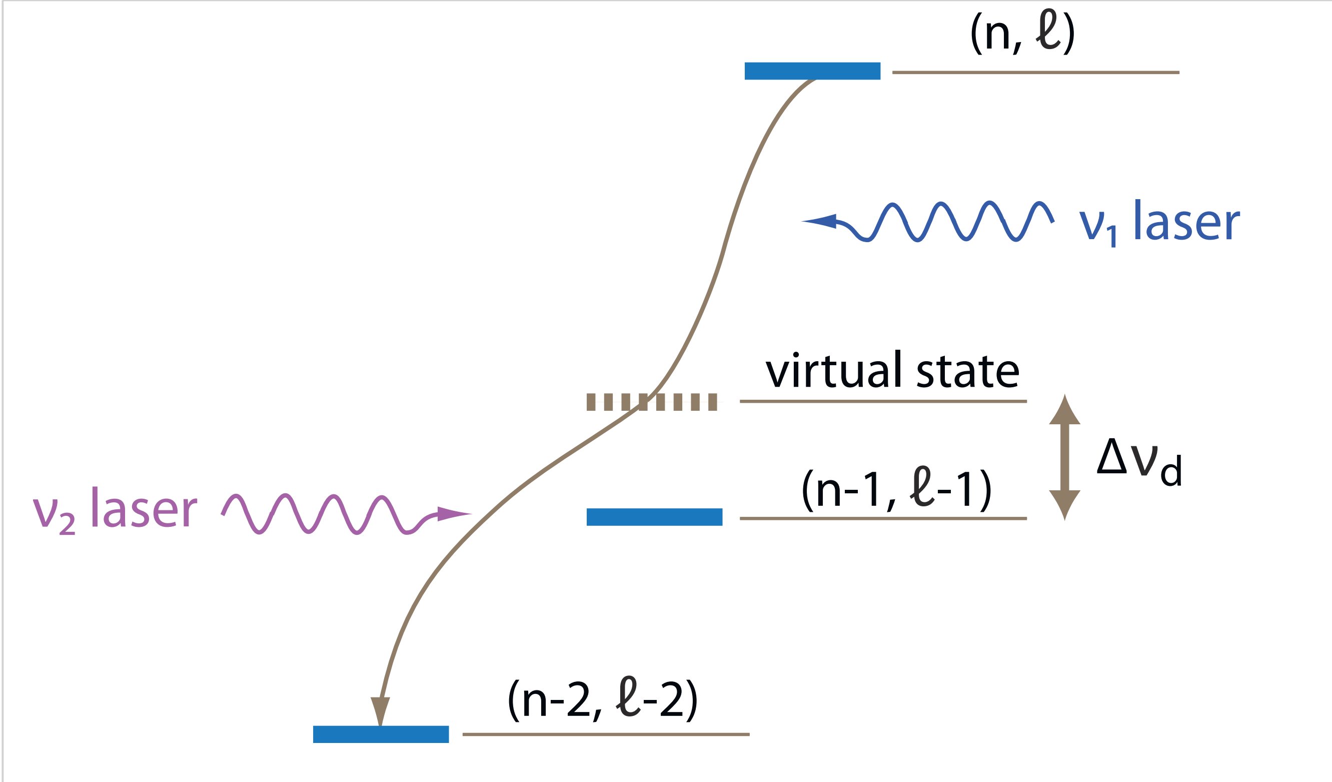


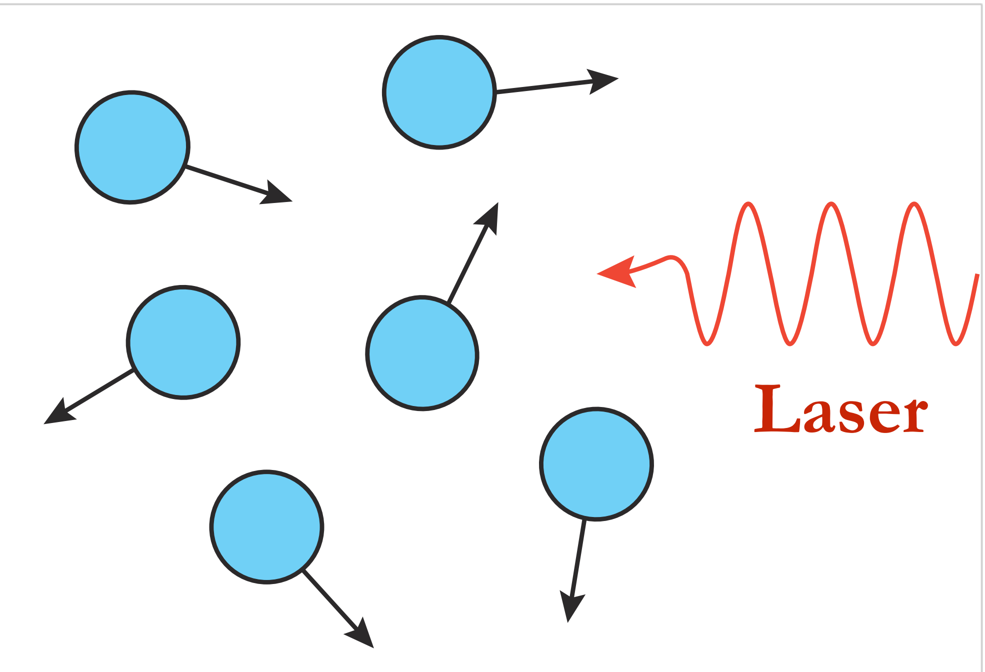


Charged pions signal the resonance condition between laser and atom.

Sub-Doppler two-photon spectroscopy

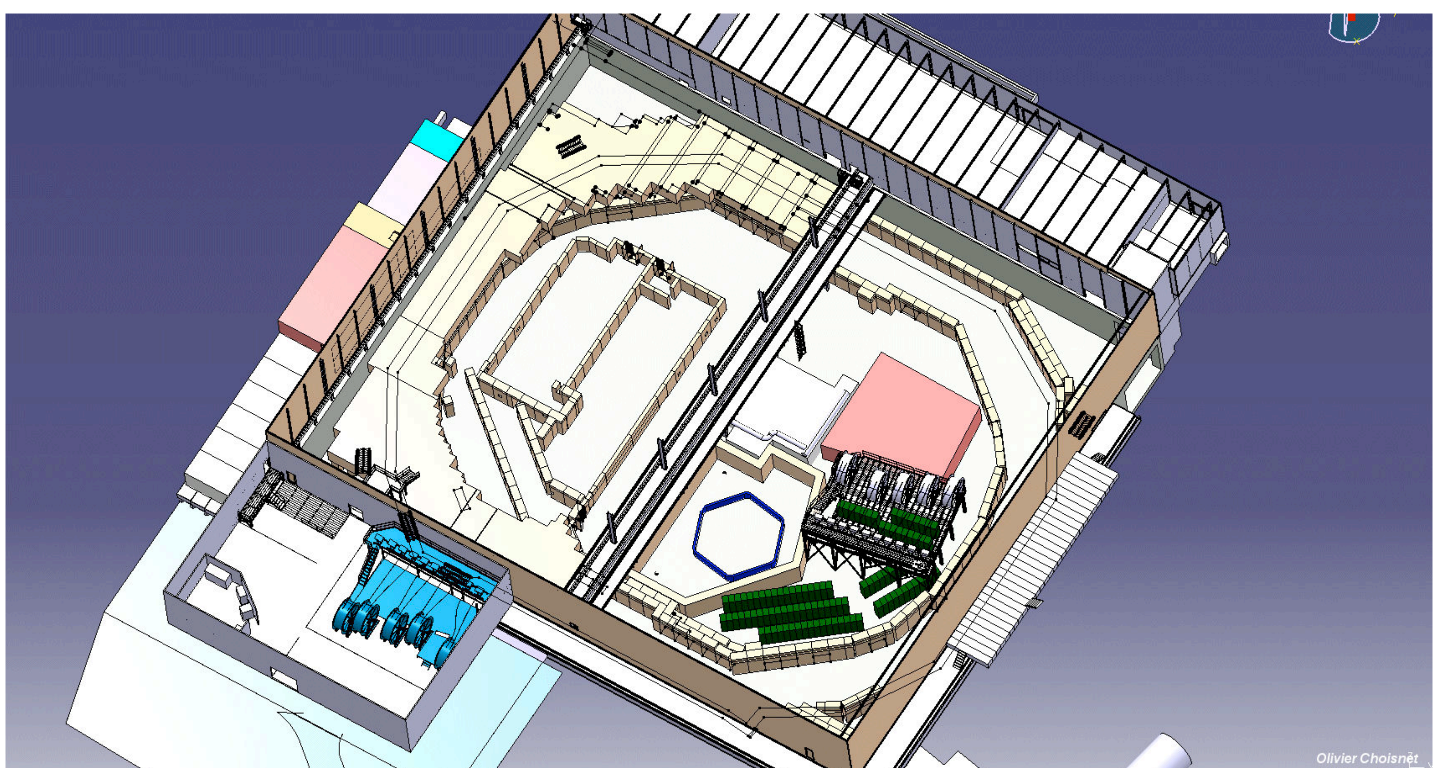
We reduced broadening using two-photon excitation of antiproton with counter-propagating laser beams of unequal wavelength.





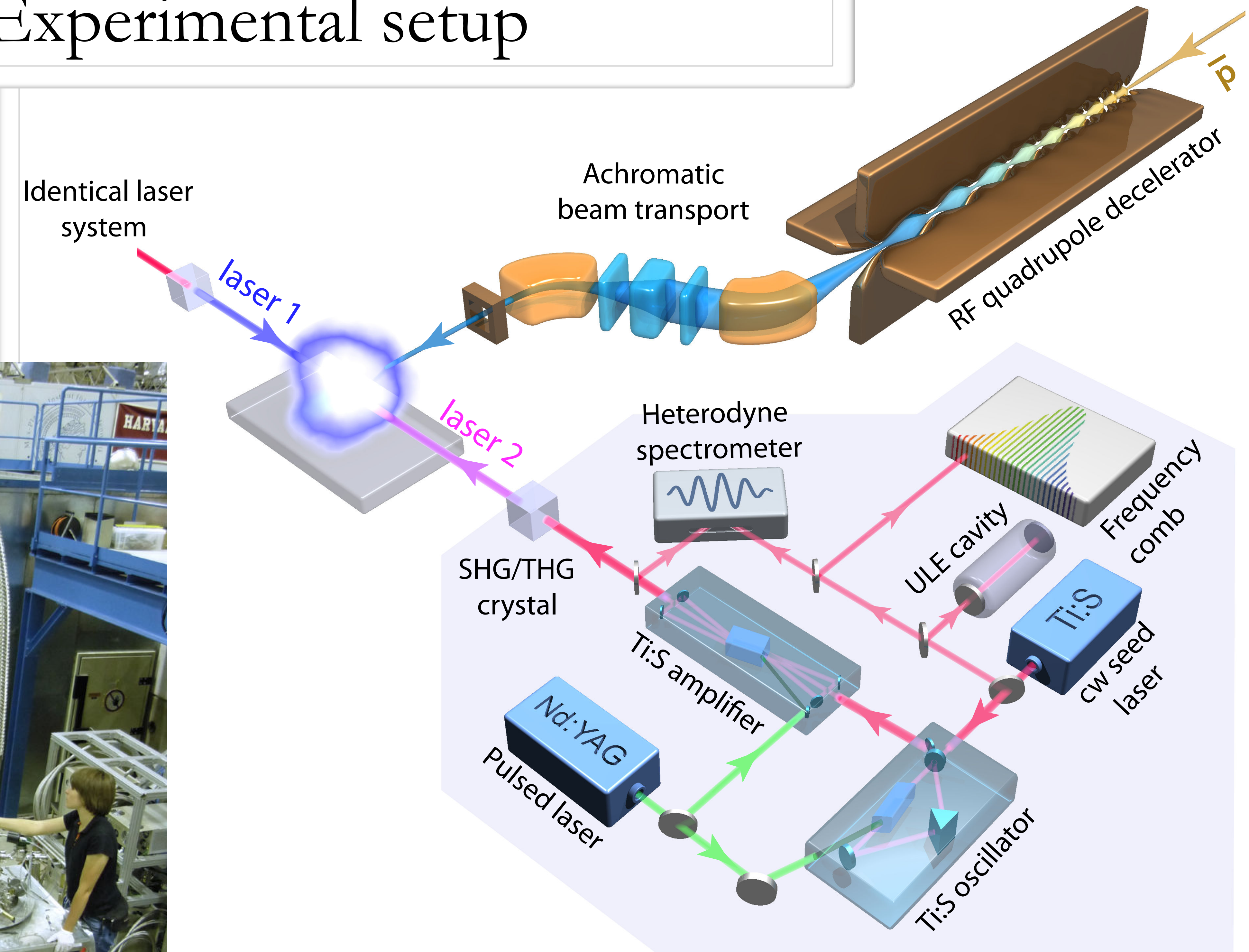
By tuning virtual intermediate state of antiproton within 10 GHz of a real state, transition probability enhanced by >1000x.

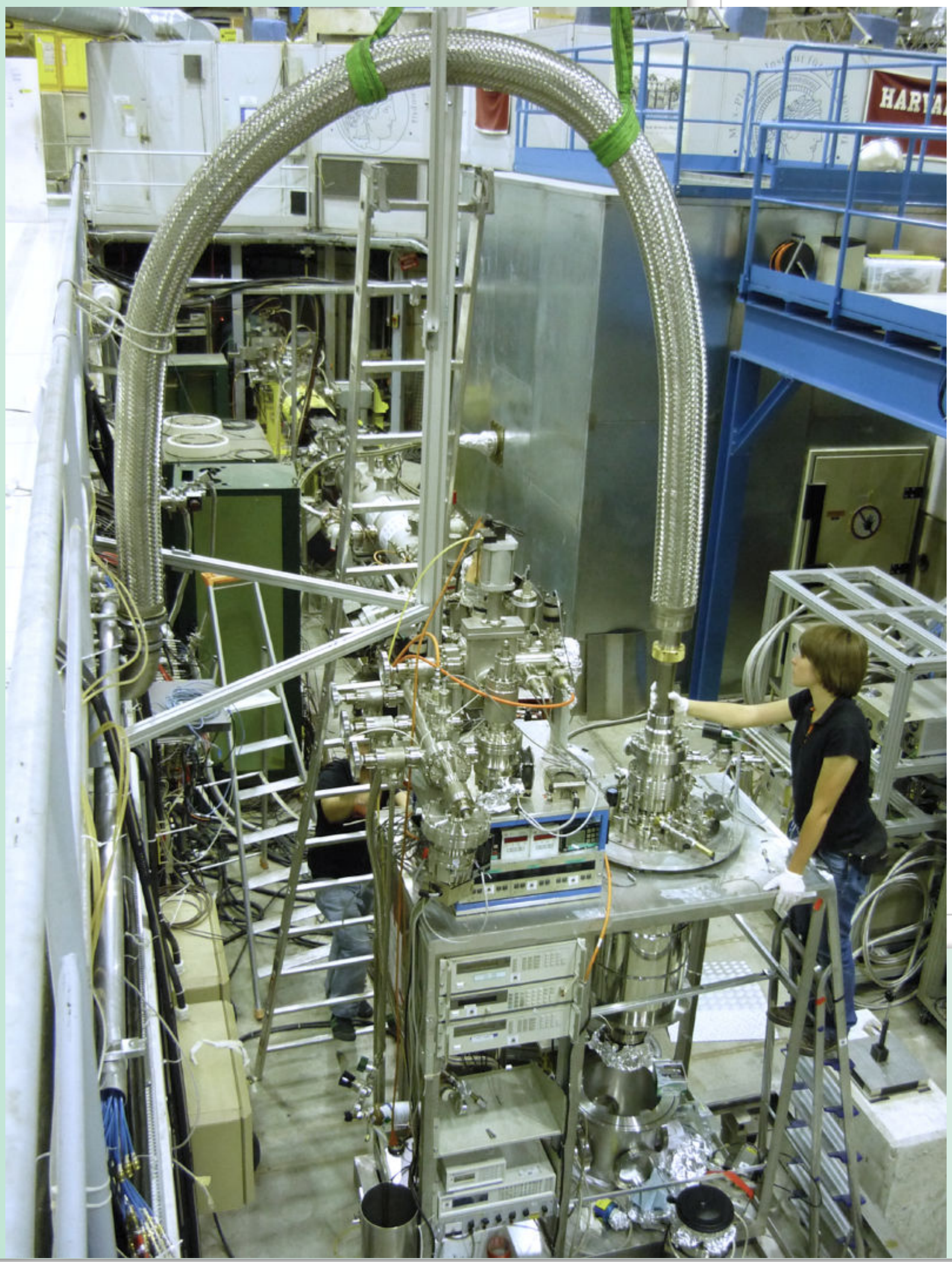
CERN Antiproton Decelerator



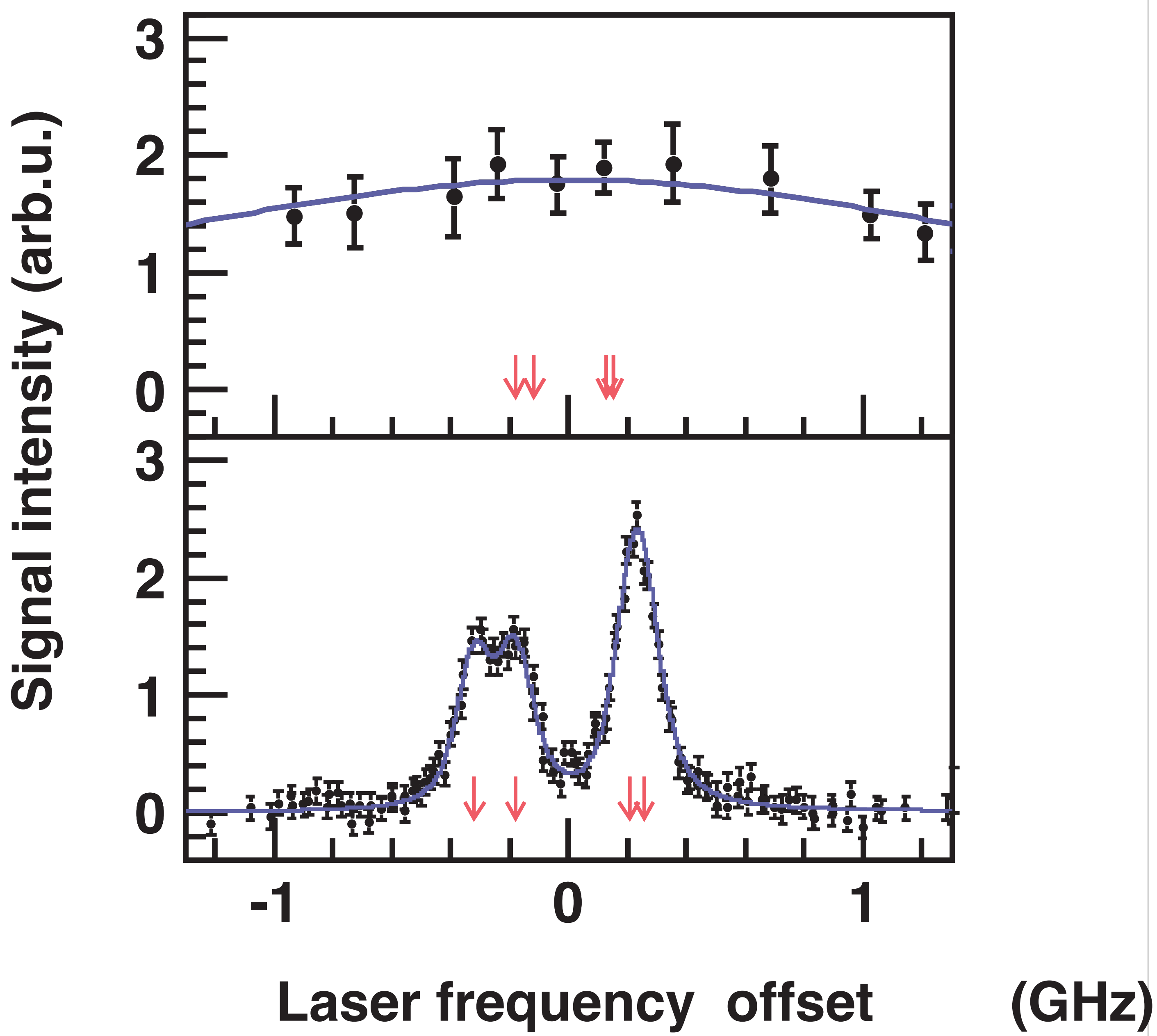
A beam of 3 million antiprotons of kinetic energy 5.3 MeV are provided every minute to ATRAP, ALPHA, AEGIS, ASACUSA, BASE, (GBAR)

Experimental setup





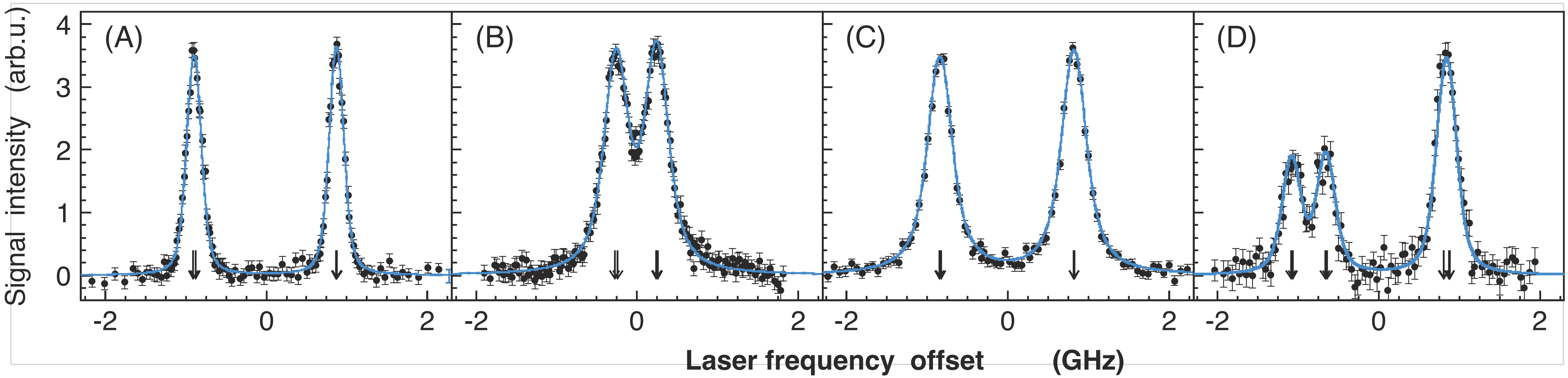
Two-photon spectroscopy results



Single-photon spectroscopy of (n,l)=(36,34)-(35,33)

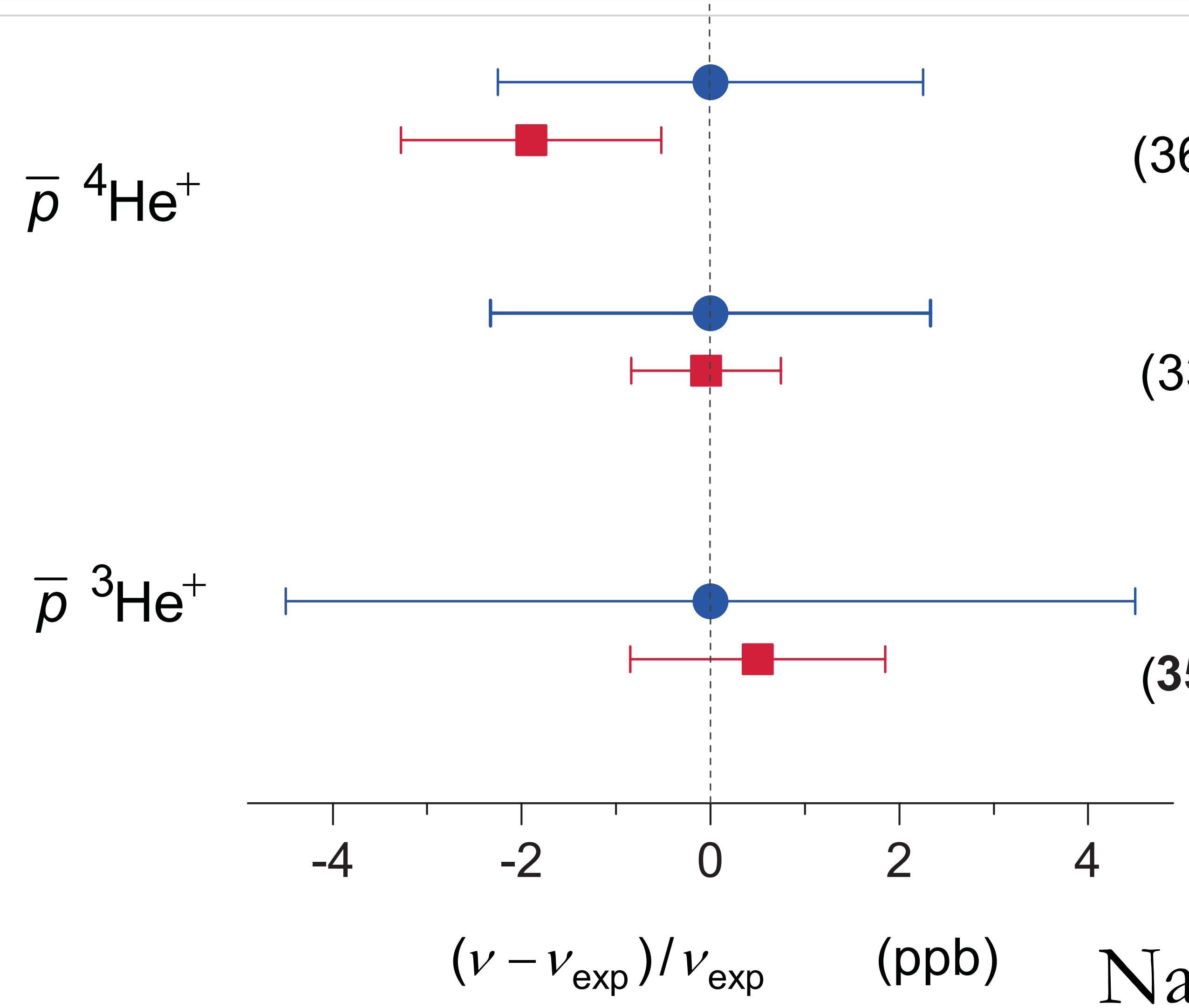
Two-photon spectroscopy (n,l)=(36,34)-(34,32)

Reduction of Doppler width by buffer gas cooling



- Cooled 2×10^{9} $\bar{p}He^{+}$ atoms to ~1.5 K
- Experiment took over 4 years of data.
- Resolved hyperfine structure in single-photon resonance

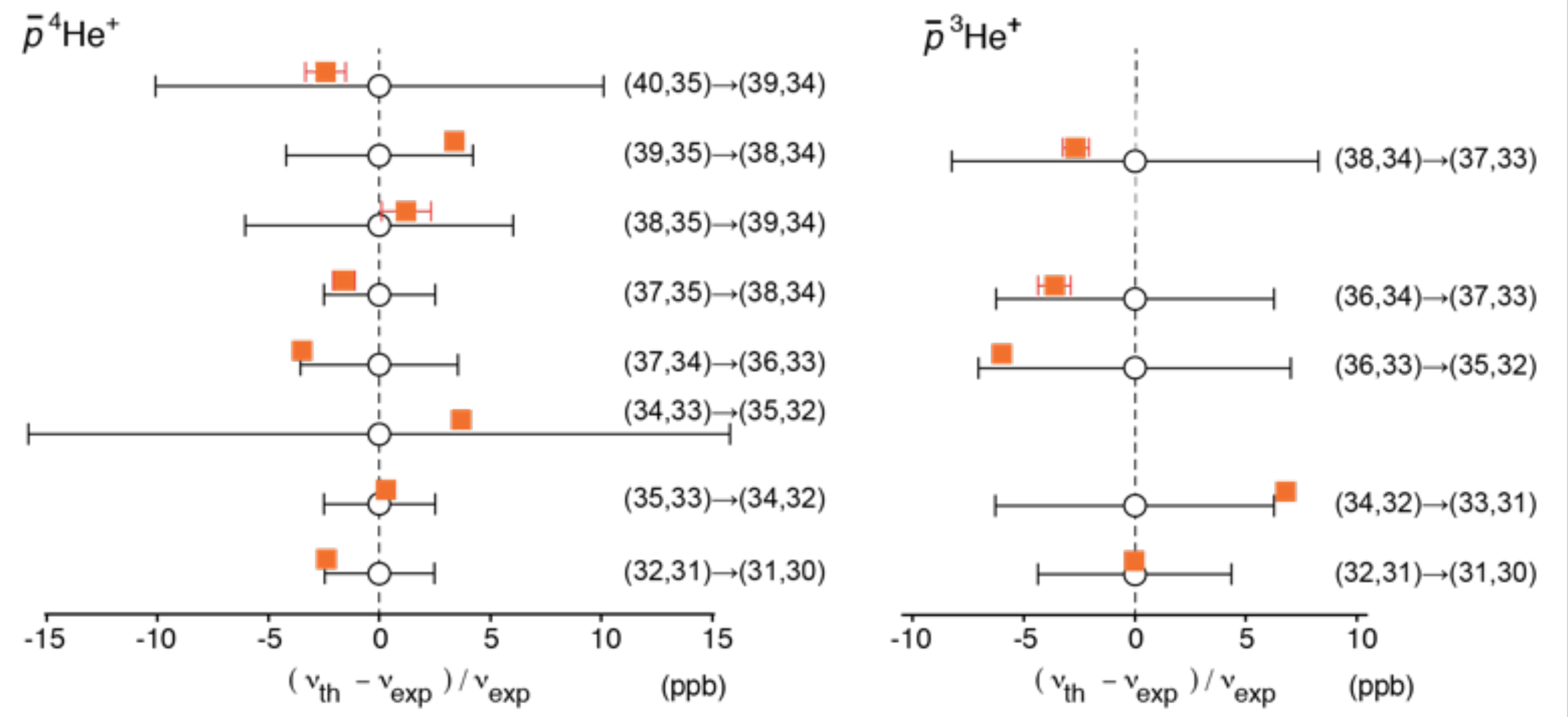
Experiment-theory 2-photon comparison



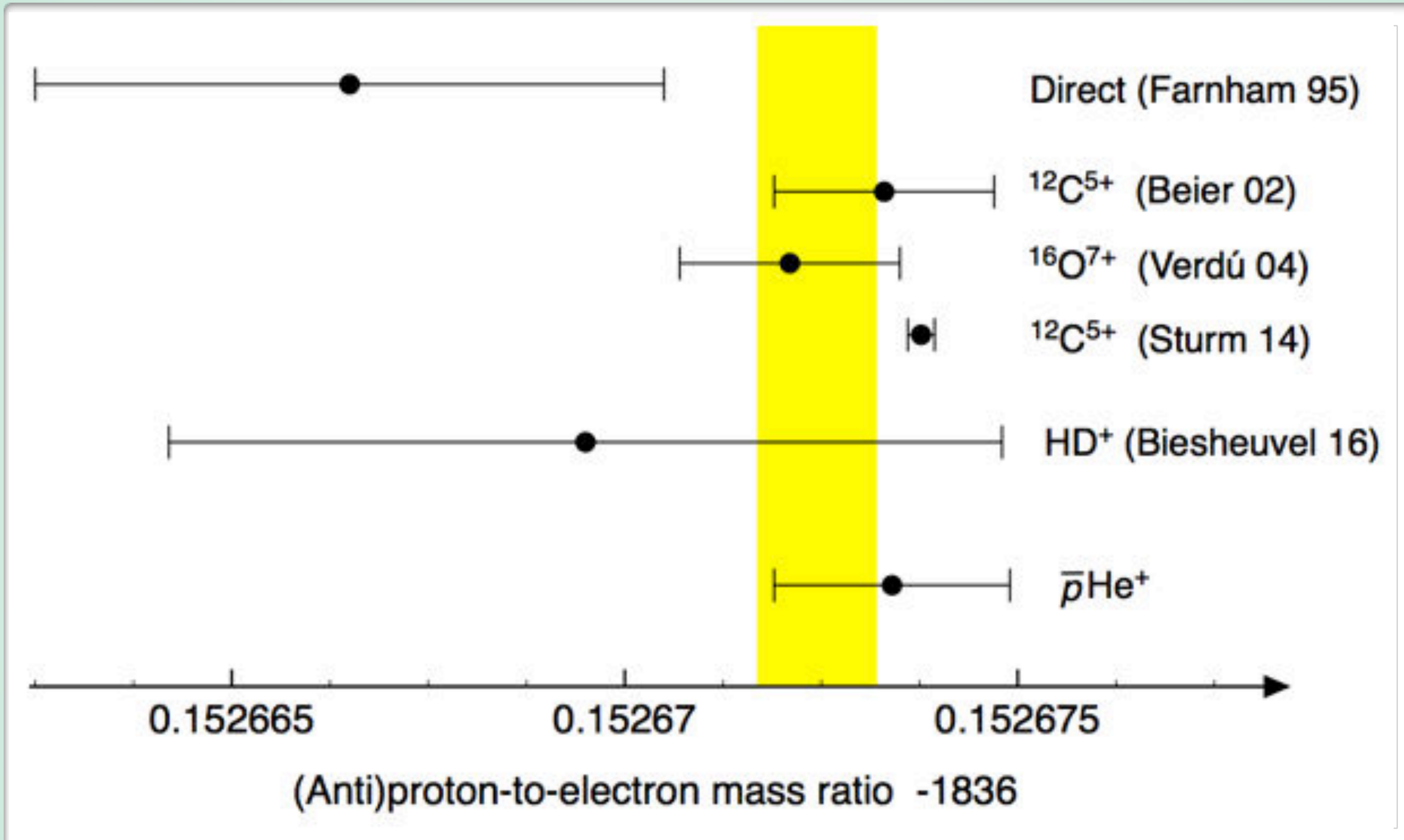
Nature 475 484 (2011)

Theory	1 522 107 060.3(2)	MHz
Experiment	1 522 107 062(4)(3)(2)	MHz

Comparison between experimental and theoretical transition frequencies of 13 single-photon resonances

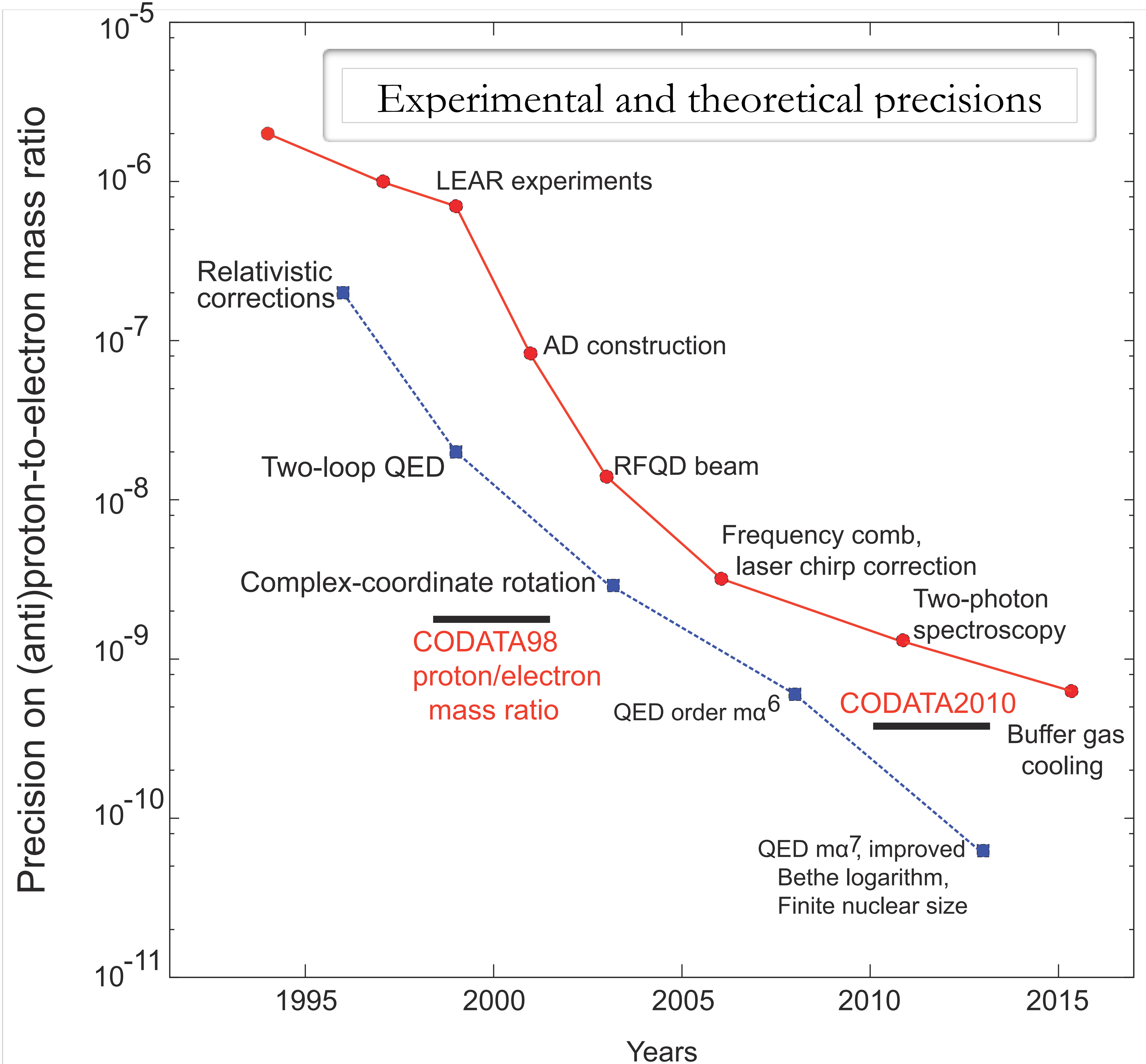


Antiproton-to-electron mass ratio 2016

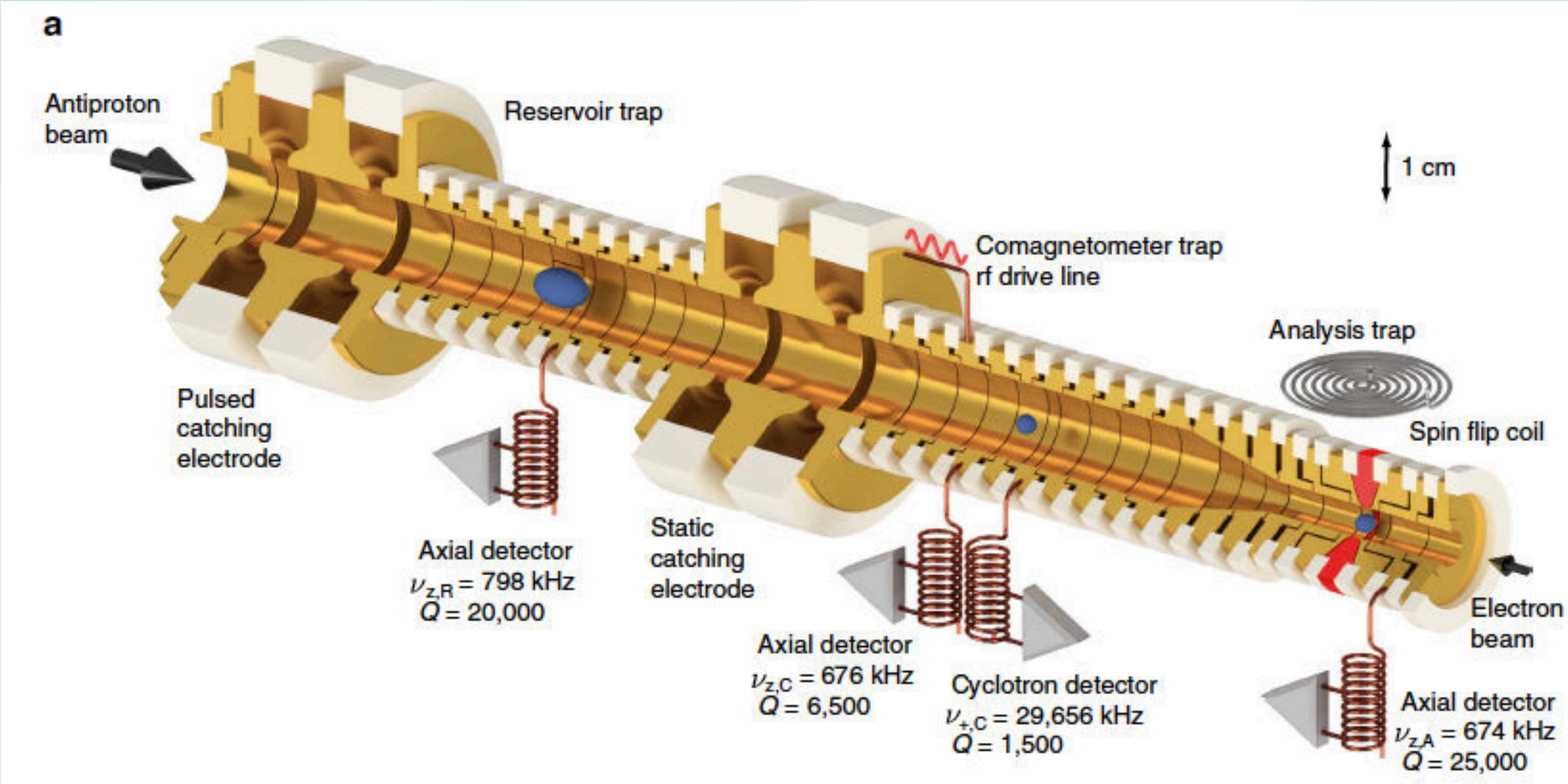


Antiproton-to-electron mass ratio 1836.1526734 (15)

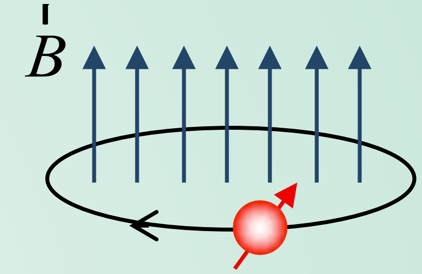
Science 354, 610 (2016)


Experimental and theoretical precisions
Precision on (anti)proton-to-electron mass ratio
10-5
10-6
10-7
10-8
10-9
10-10
10-11
LEAR experiments
Relativistic corrections
AD construction
Two-loop QED
RFQD beam
Frequency comb, laser chirp correction
Complex-coordinate rotation
Two-photon spectroscopy
CODATA98 proton/electron mass ratio
QED order mα6
CODATA2010
Buffer gas cooling
QED mα7, improved Bethe logarithm, Finite nuclear size
1995
2000
2005
2010
2015
Years

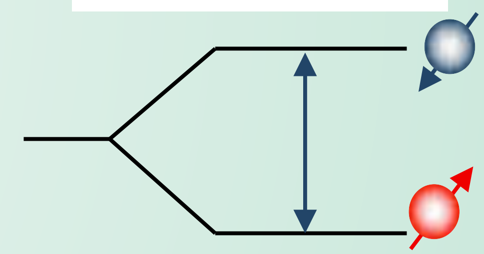
BASE and ATRAP recent results



$$\nu_c = \frac{e}{m} B$$



$$\nu_L = g \frac{e}{2m} B$$



Larmor frequency measured by continuous Stern Gerlach effect

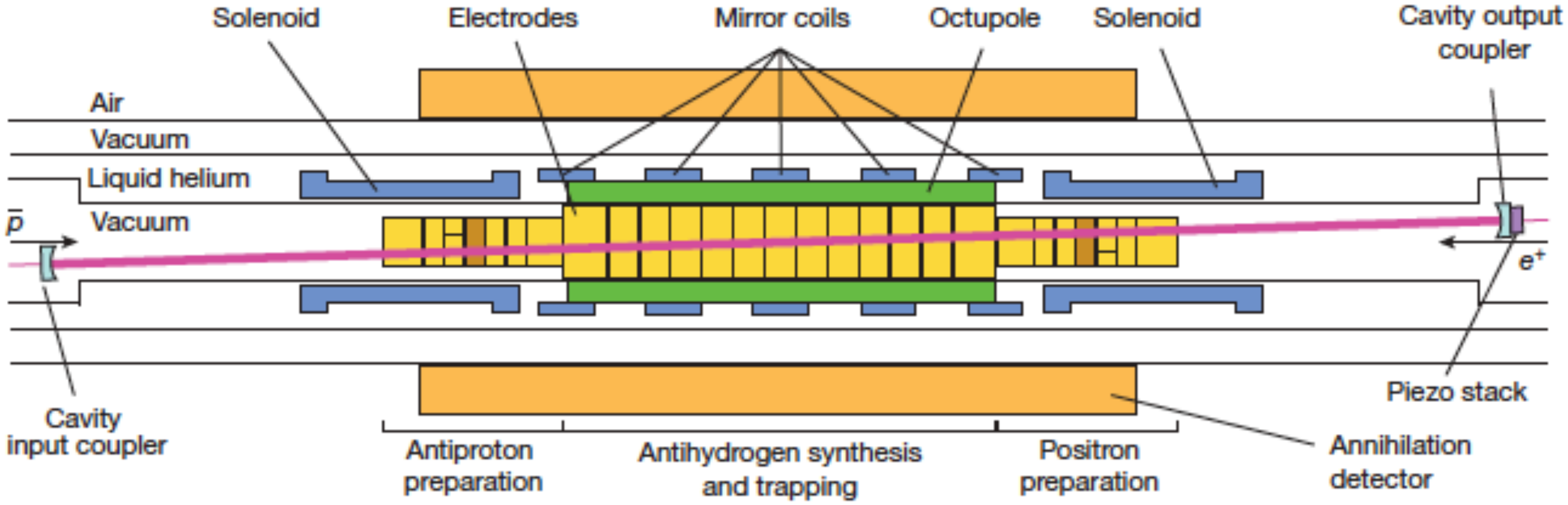
$$g_{\bar{p}} = 2.792845(12)$$

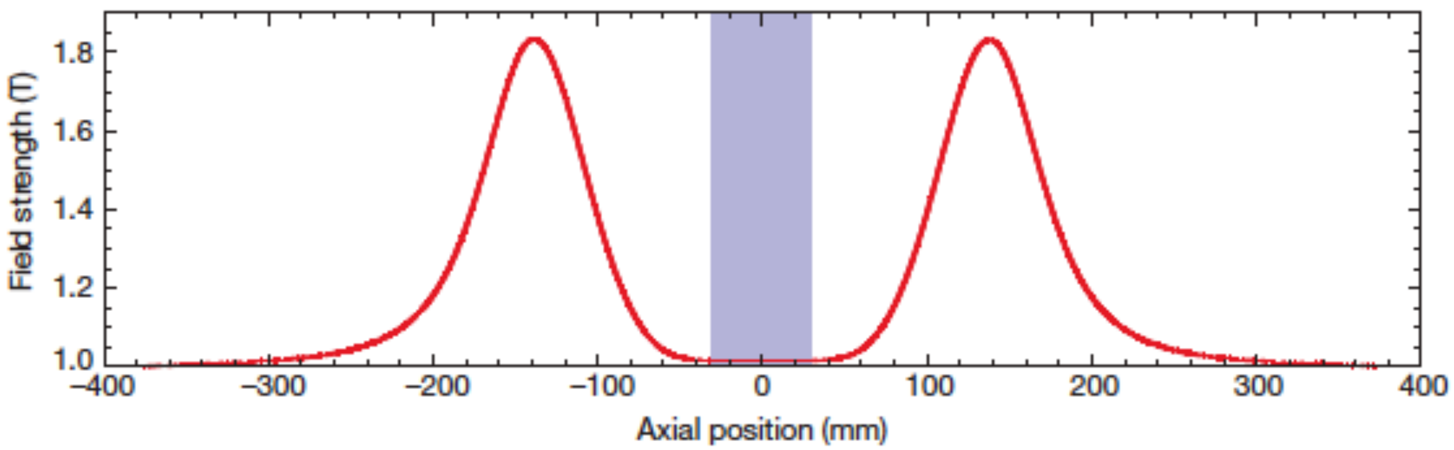
ATRAP collab. PRL 110, 130801 (2013)

$$g_{\bar{p}} = 2.792\,846\,5\,(23)$$

BASE collab. Nat. Comm. 8, 14084 (2017)
Nature 524, 196 (2015)

ALPHA 1s-2s laser spectroscopy @ 243 nm





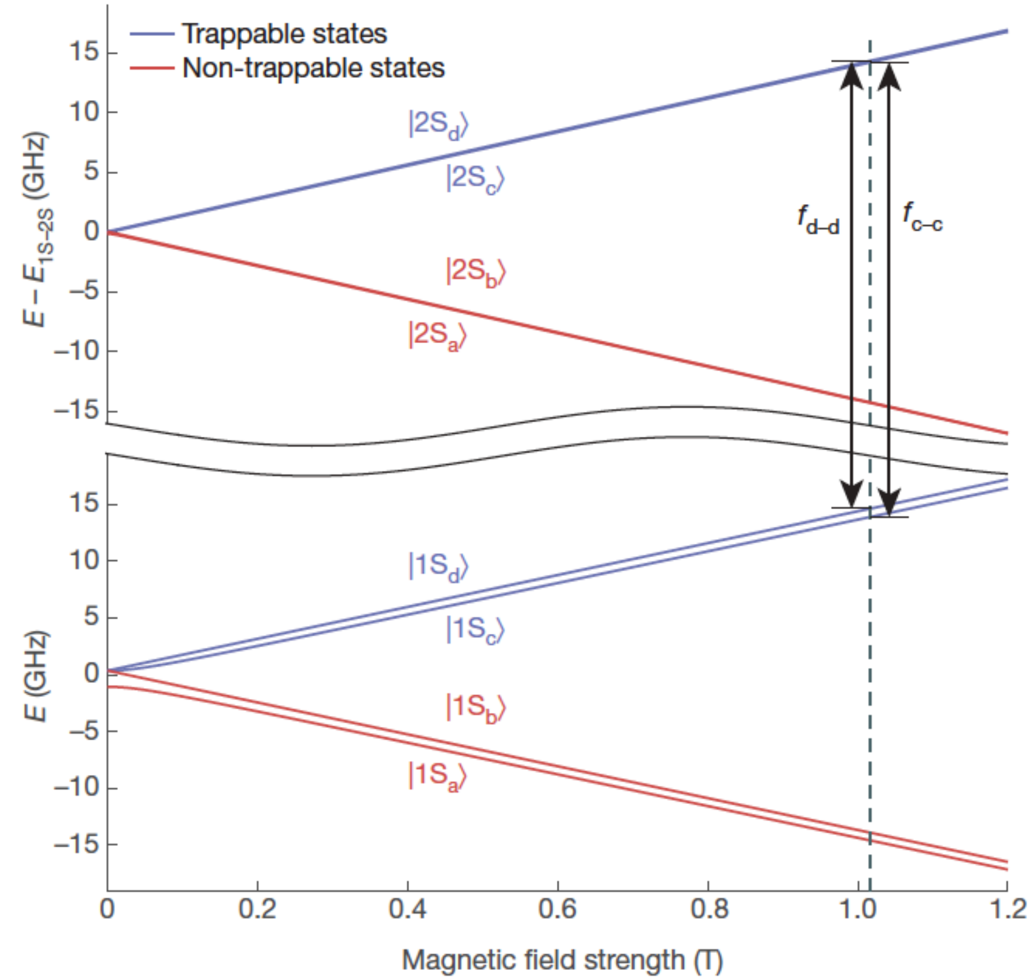


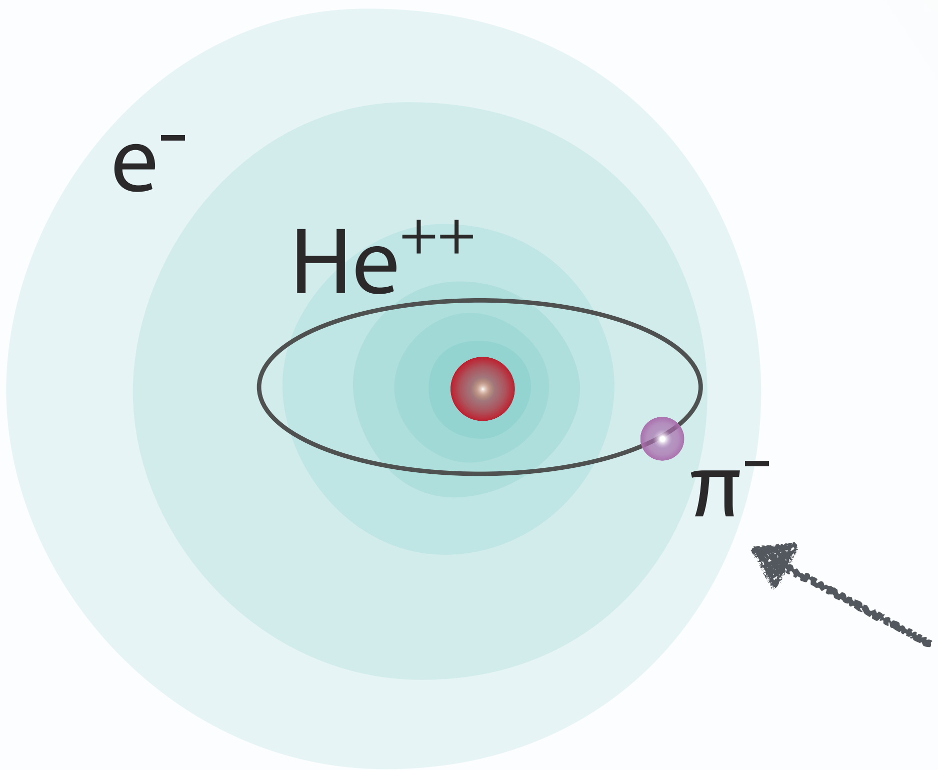
Table 1 | Events during the 1.5-s ramp down of the trap magnets

Type	Number of detected events	Background	Uncertainty
Off resonance	159	0.7	13
On resonance	67	0.7	8.2
No laser	142	0.7	12

Nature 541, 506 (2016)

ATRAP, AEGIS, ASACUSA-CUSP, GBAR also show lots of progress!

New experiment on pionic helium@PSI



$\tau \sim 7$ ns **!**

First laser spectroscopy of an atom containing a meson

Negative pion in a 'circular' Rydberg orbital n=16, l=n-1 with diameter of 100 pm.

- Localized away from the nucleus.
- The electron protects the antiproton during collisions with ordinary helium atoms.

Summary

- Sub-Doppler two-photon laser spectroscopy of antiprotonic helium atoms. Measured 3 two-photon transitions to a precision of 2.3 ppb.

- Collisional buffer gas cooling of antiprotonic helium atoms to T=1.5 K. Measured 13 single-photon transitions.

- Agreed with 3-body QED calculations. Determined the antiproton-to-electron mass ratio as 1836.1526734 (15).

- Laser spectroscopy of metastable pionic helium, experimental runs 2014-2015, observation of first laser induced pion transition……….

Backup slides

Datum	Error (MHz)
Experimental errors	
Statistical error, σ_{stat}	3
Collisional shift error	1
A.c. Stark shift error	0.5
Zeeman shift	<0.5
Frequency chirp error	0.8
Seed laser frequency calibration	<0.1
Hyperfine structure	<0.5
Line profile simulation	1
Total systematic error, σ_{sys}	1.8
Total experimental error, σ_{exp}	3.5
Theoretical uncertainties	
Uncertainties from uncalculated QED terms*	2.1
Numerical uncertainty in calculation*	0.3
Mass uncertainties*	<0.1
Charge radii uncertainties*	<0.1
Total theoretical uncertainty*, σ_{th}	2.1