Laser spectroscopy of antiprotonic helium and pionic helium atoms at CERN and PSI

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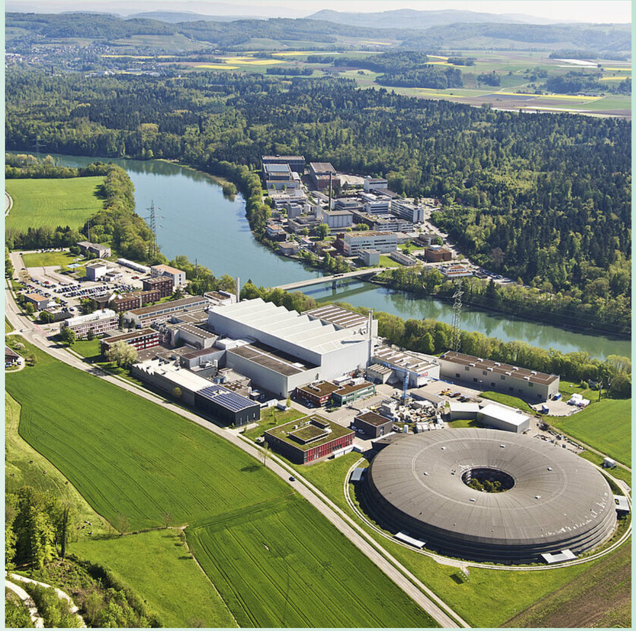
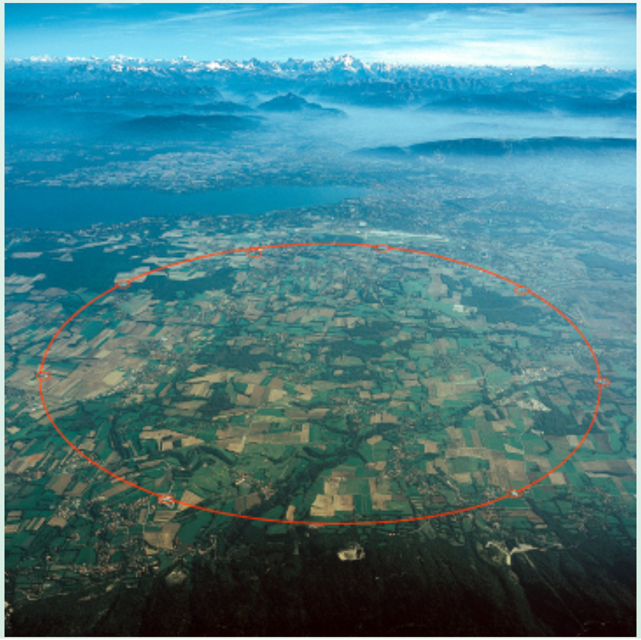
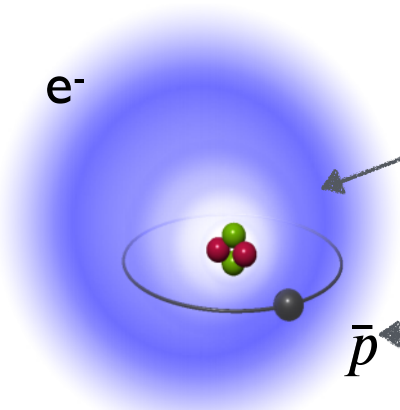
D. Barna[2], A. Dax[3], L. Venturelli[4]
ASACUSA and PiHe collaborations



ICHEP-2022
July 8th, 2022



Fundamental three-body, long-lived Rydberg helium atoms (antimatter and mesonic counterparts of HD+ molecular ions)

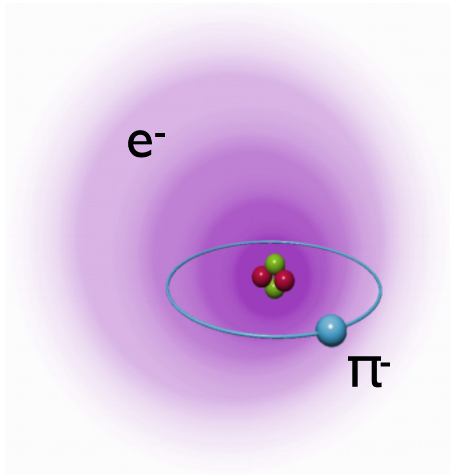


$\bar{p}He^+$: metastable antiprotonic helium atom.

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

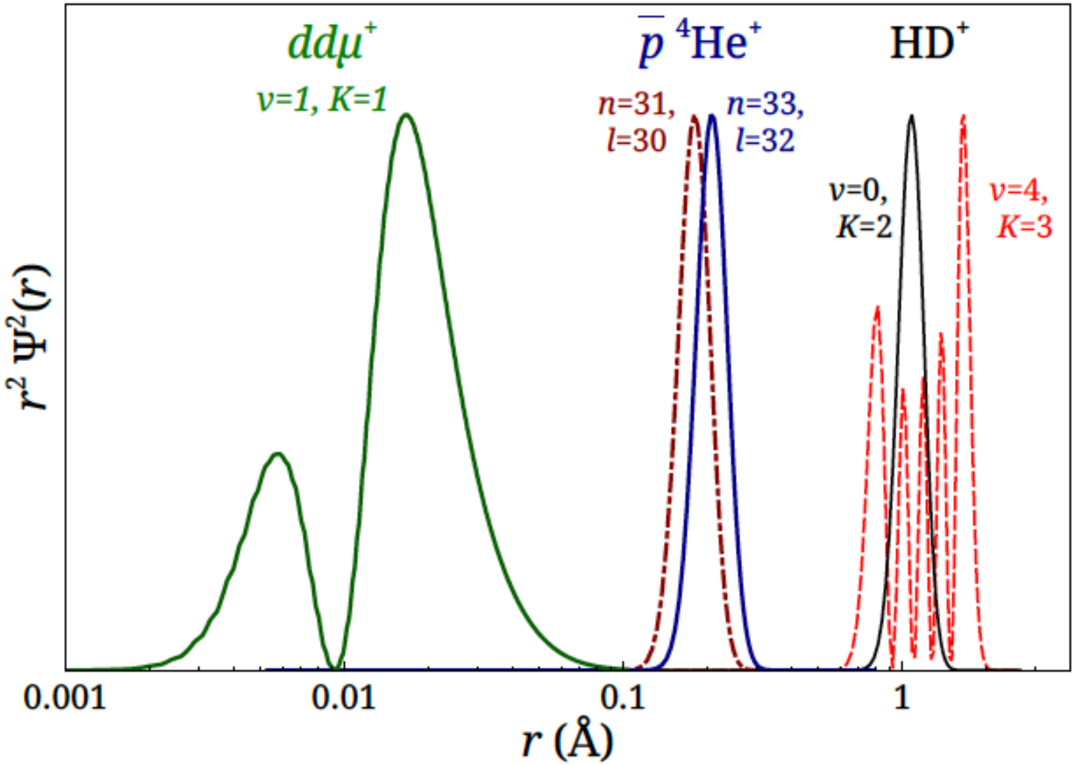
Antiproton in a circular Rydberg orbital n=38, l=n-1 with diameter of 100 pm.

- Localized away from the nucleus.
- The electron protects the antiproton during collisions with helium atoms.
- Mean lifetime $\tau \approx 4\ \mu s$



πHe^+: metastable pionic helium atom, negative pion in n=l-1=17 orbital, lifetime $\tau \approx 7$ ns.

Antiprotonic helium atoms, the longest-living hadron-antihadron system known



Lasers probe potential V(r) at Angstrom distances between antiproton, alpha particle, and electron very precisely.

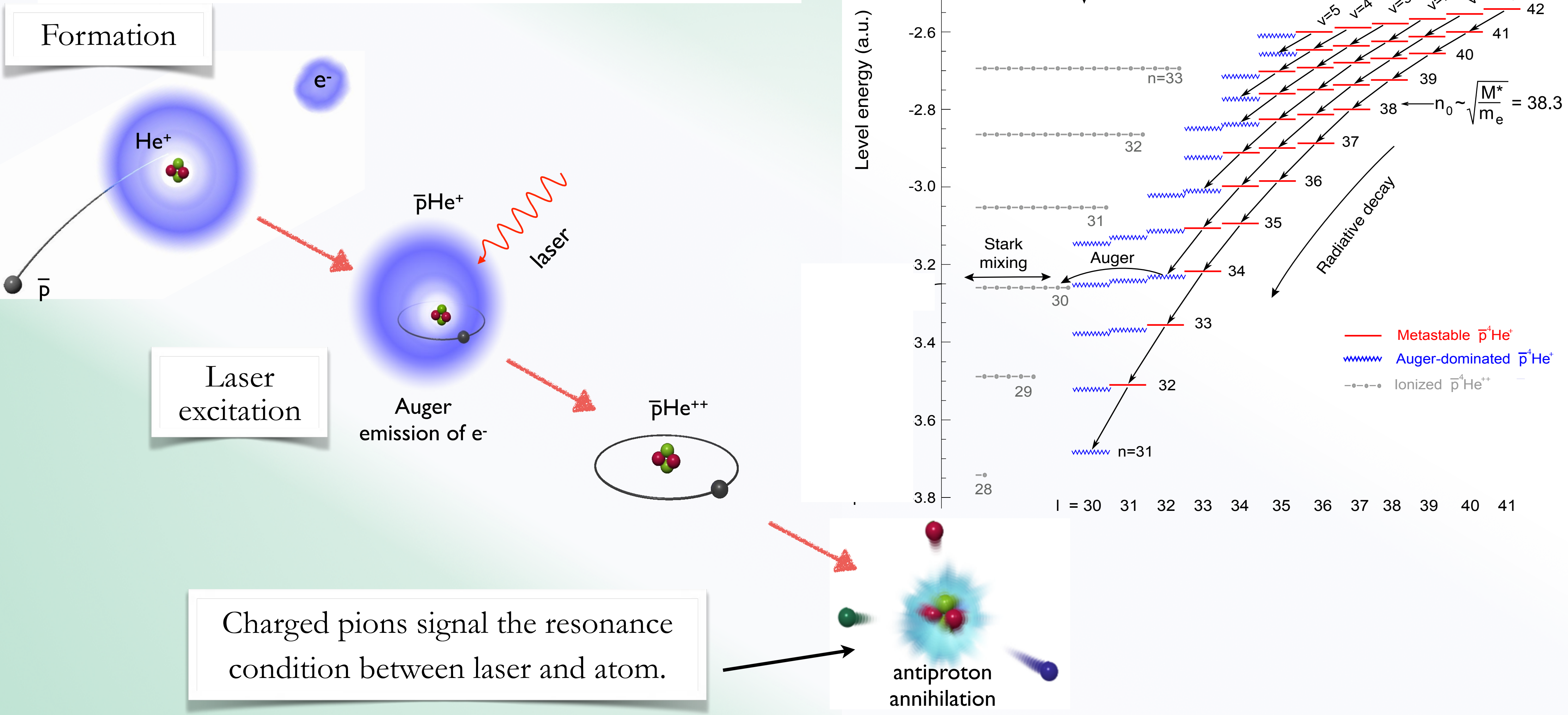
Standard Model V(r) can be theoretically calculated to extraordinary precision.

- Non-relativistic QED have begun to determine the atomic transition frequencies of HD^+ and $\overline{p}He^+$ with 10^{-11} scale precision by including $m\alpha^7$ scale QED corrections.
- Same level of theoretical precision as two-body atoms, often less sensitive to nuclear effects.

Therefore high sensitivity to rich physics:

- CPT
- High order QED
- Antiproton-to-electron mass ratio
- Fifth forces
- Contributions from spin-0/1 exotic bosons (axions etc.)

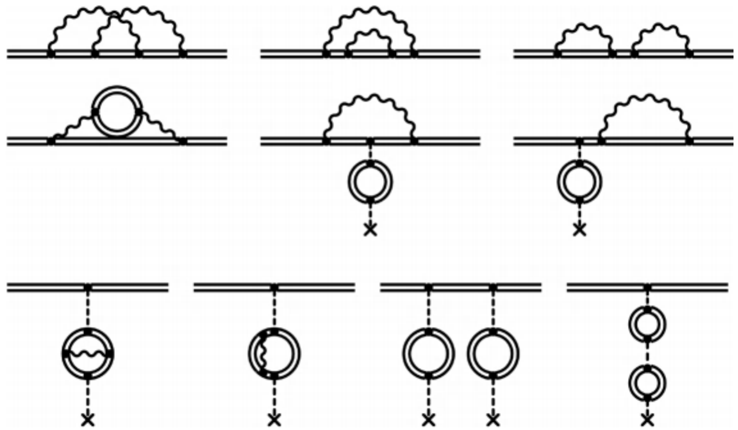
Laser spectroscopy allows us to measure the transition frequencies of the atom and compare them with QED calculations



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).



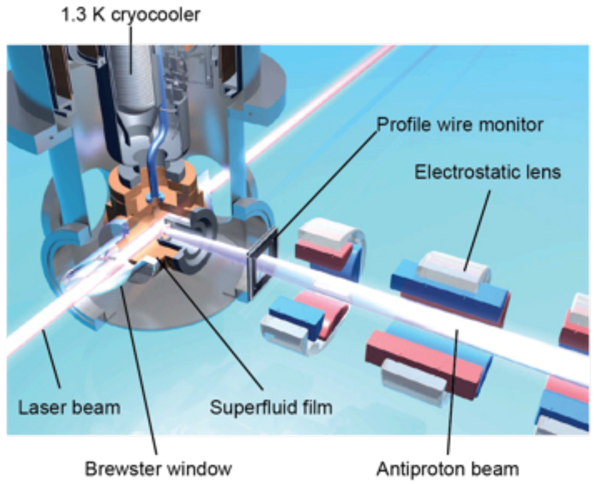
2 145 054 858.100(200) MHz

Experimental precision

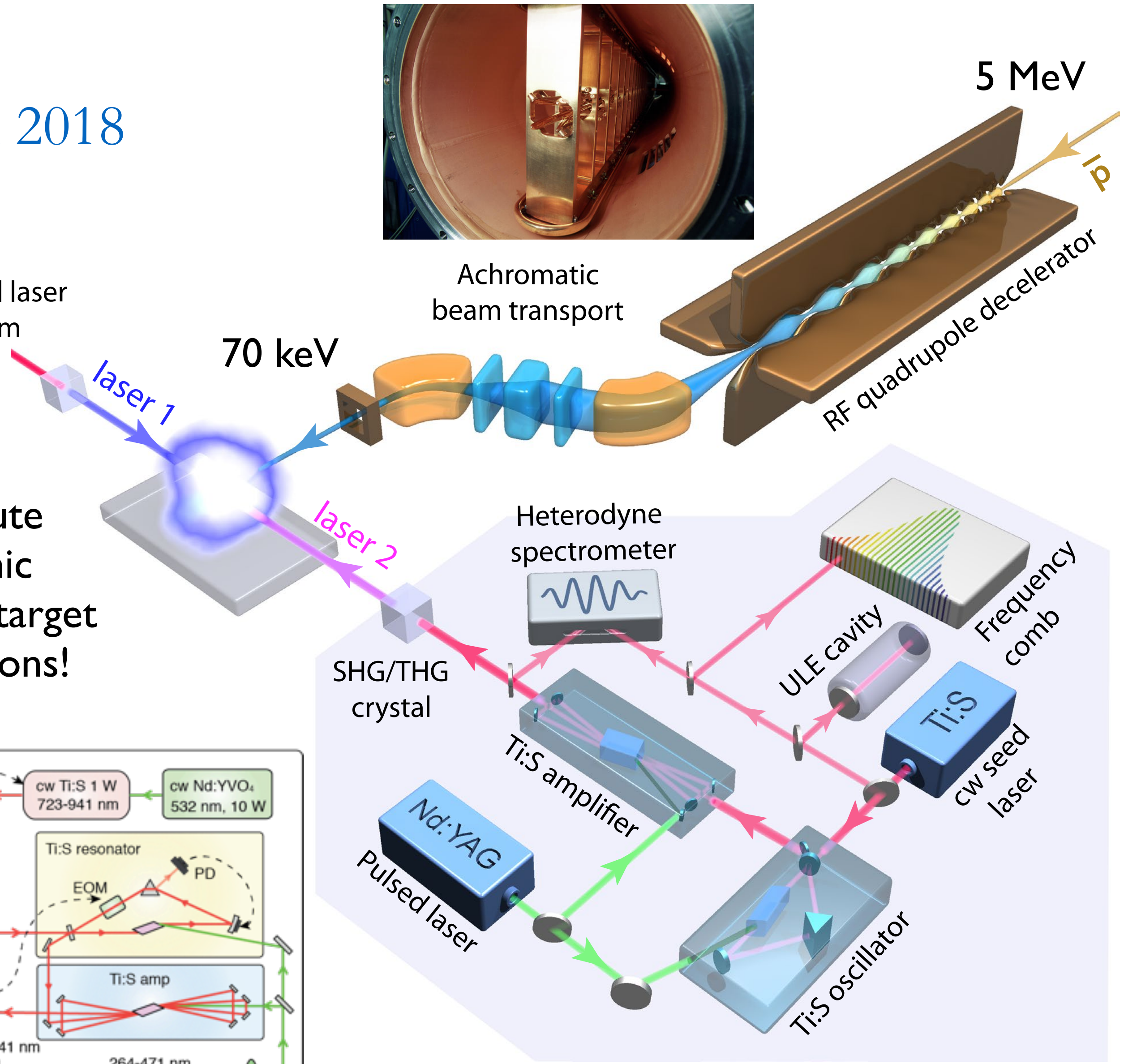
Uncertainty due to $m\alpha^7$ QED on this digit

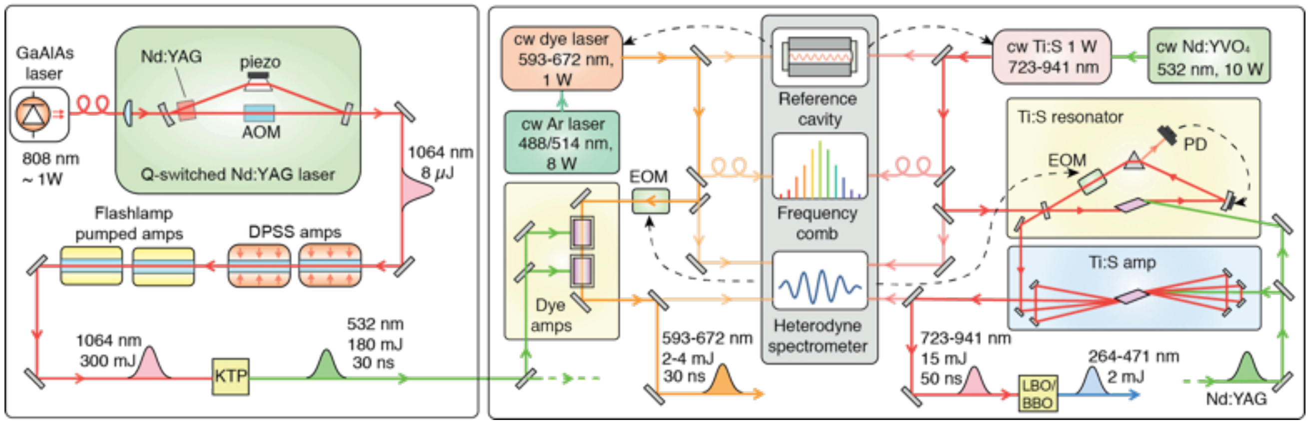
Uncertainty due to helium charge radius

Experimental setup until end 2018



Very dilute cryogenic helium gas target few collisions!

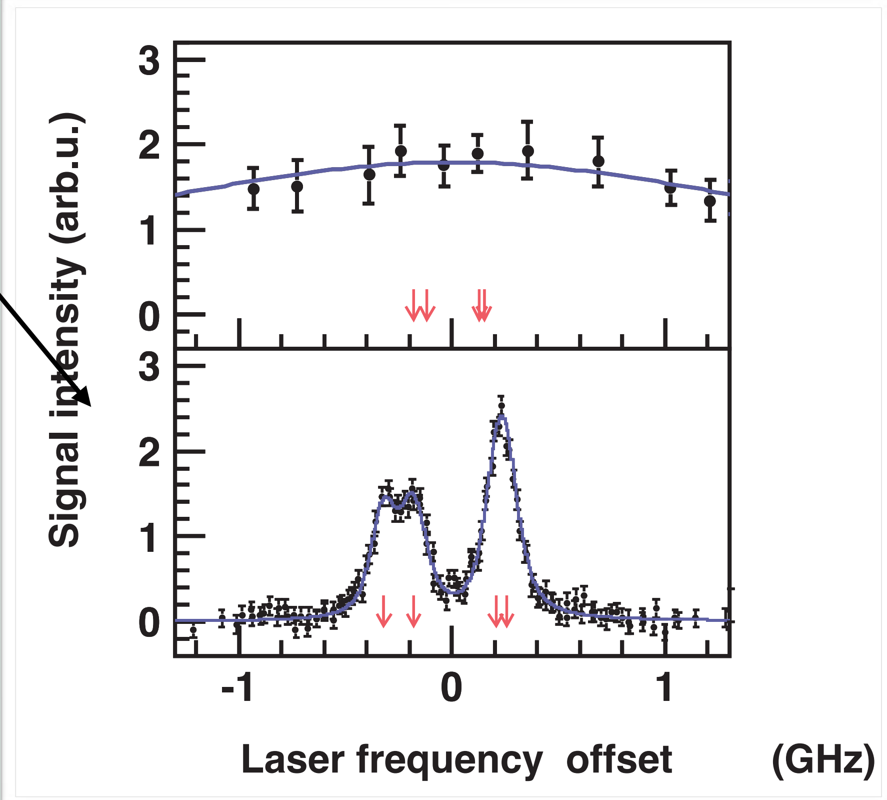


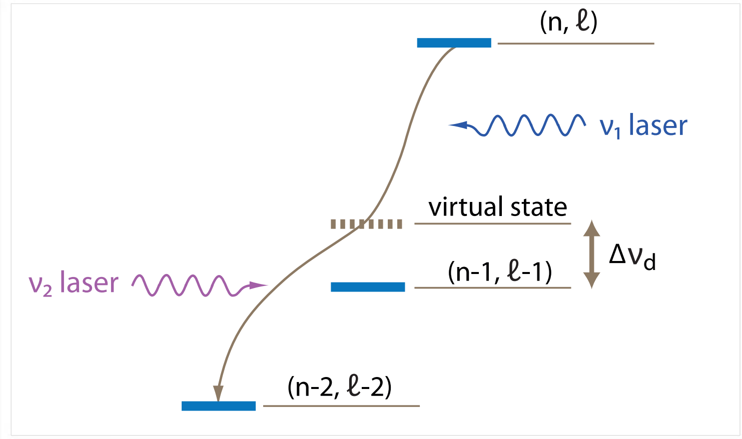


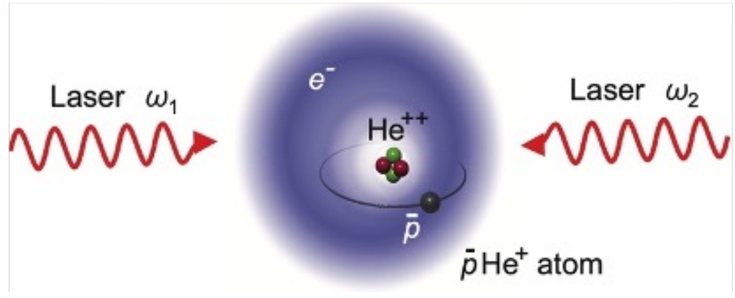
Sub-Doppler two-photon spectroscopy

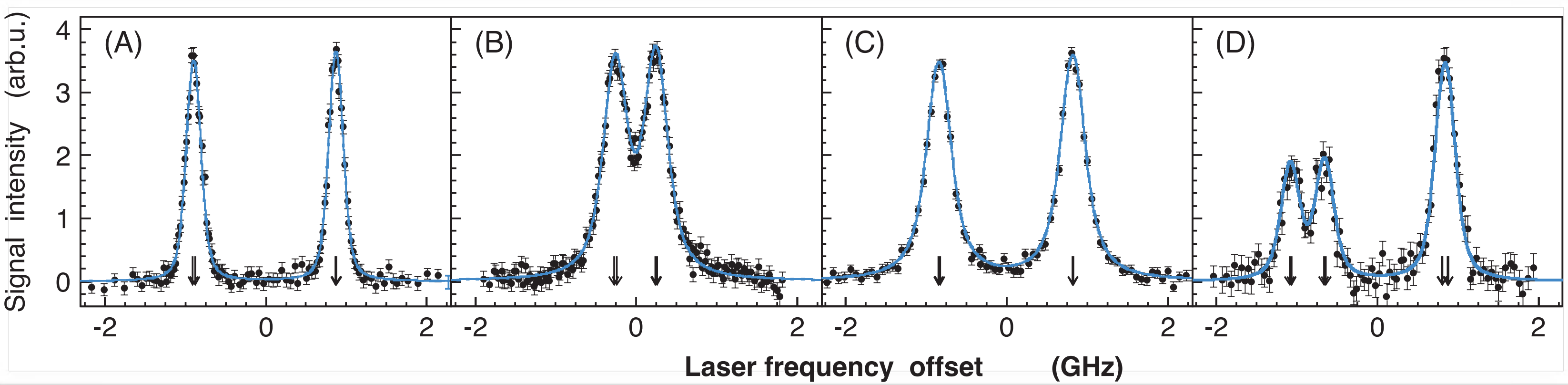
Nature 475, 484 (2011)

Science 354, 610 (2016)

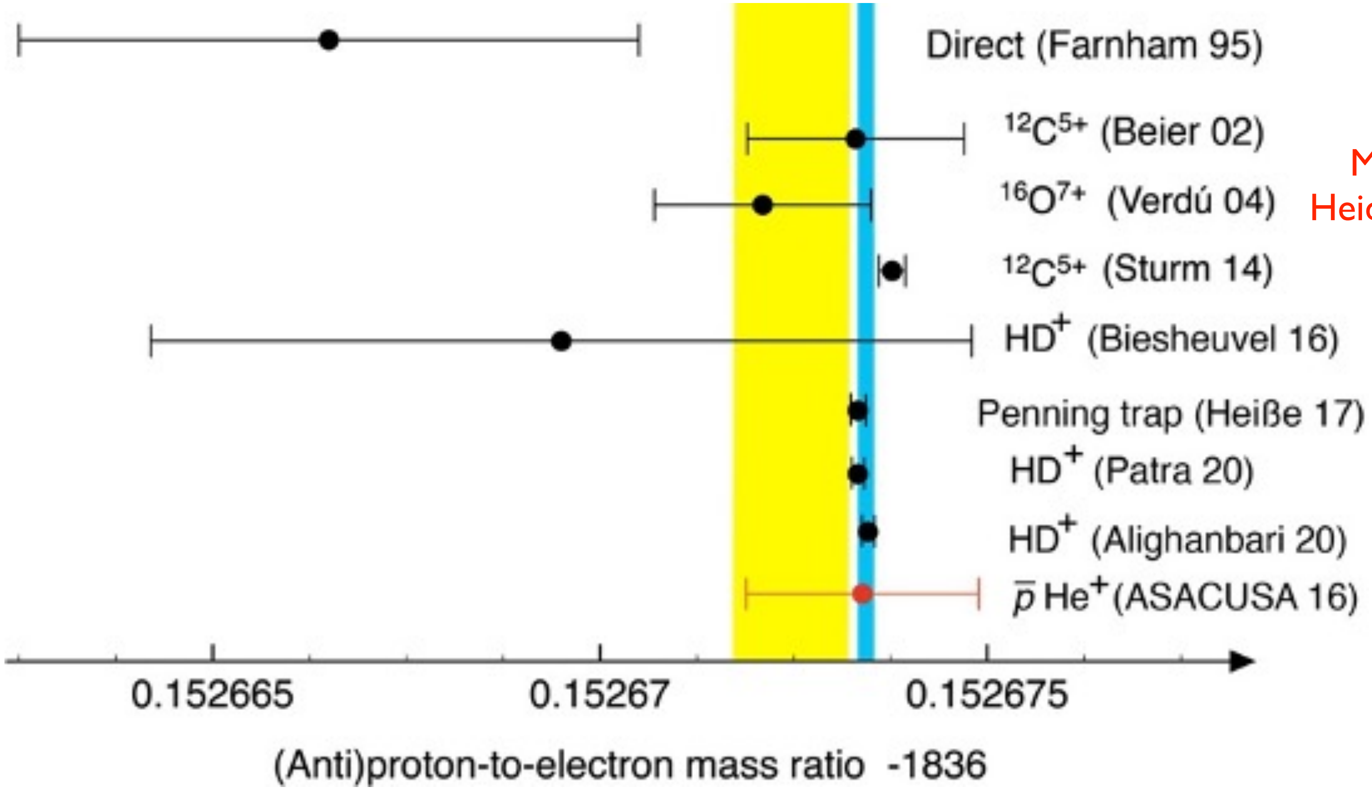








(Anti)proton to electron mass ratio



Mainz-Heidelberg-GSI

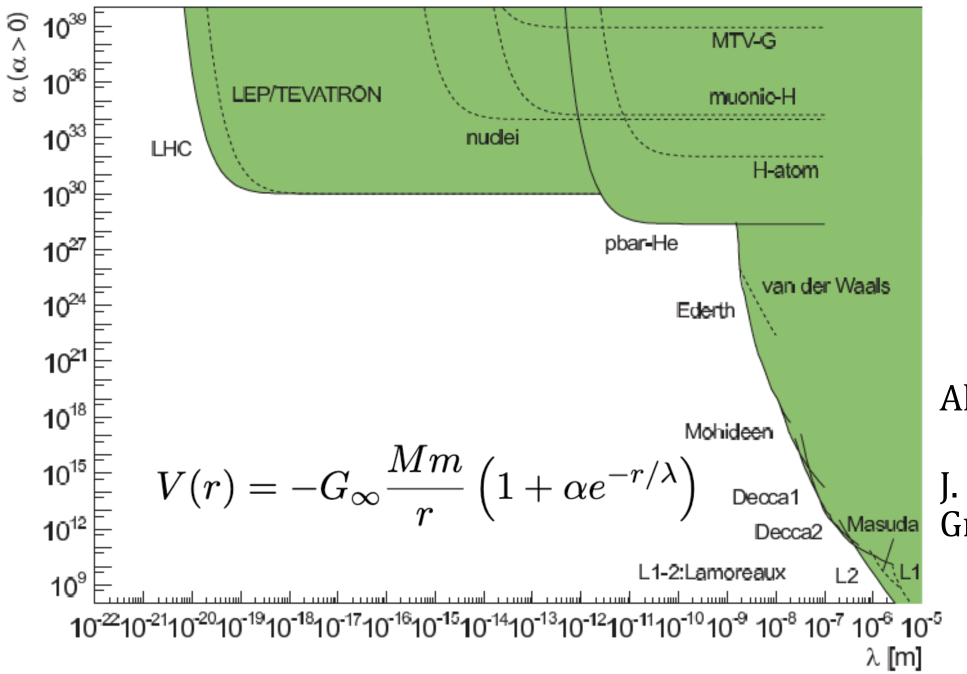
Antiproton-to-electron mass ratio

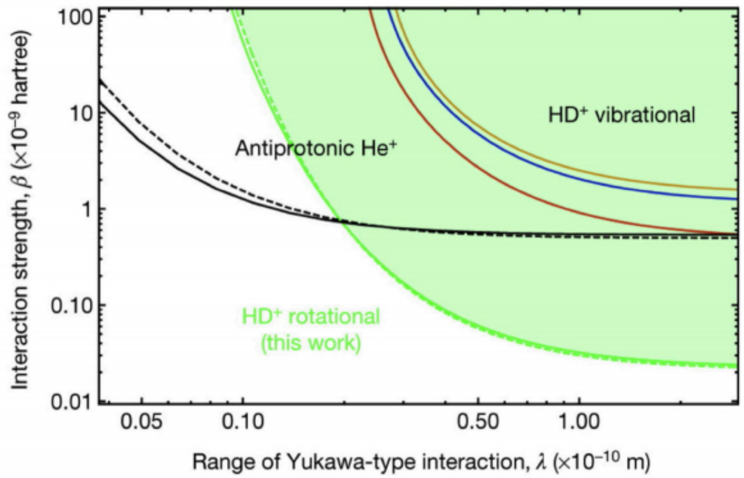
1836.1526734 (15)

Science 354, 610 (2016)

- Consistency test of CPT invariance in a hadron-antihadron system (compared to antihydrogen which is an antihadron-antilepton bound state)
- Combined with the cyclotron frequency Q/M of antiprotons in a Penning trap compared to much higher precision by TRAP and BASE collaborations, antiproton and proton masses and charges to 5×10^{-10}
- $\overline{p}He^{+}$ and HD^{+} are among the 3-body atoms most precisely calculated by QED.

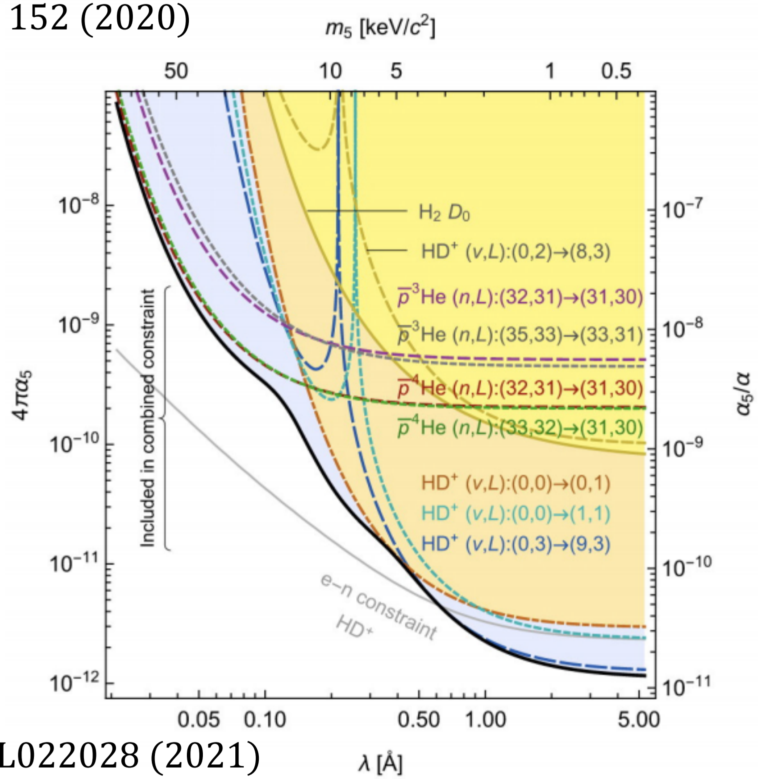
Bounds on the 5th force at 10^{-11} to 10^{-9} m length scales





Alighanbari et al., Nature 581, 152 (2020)

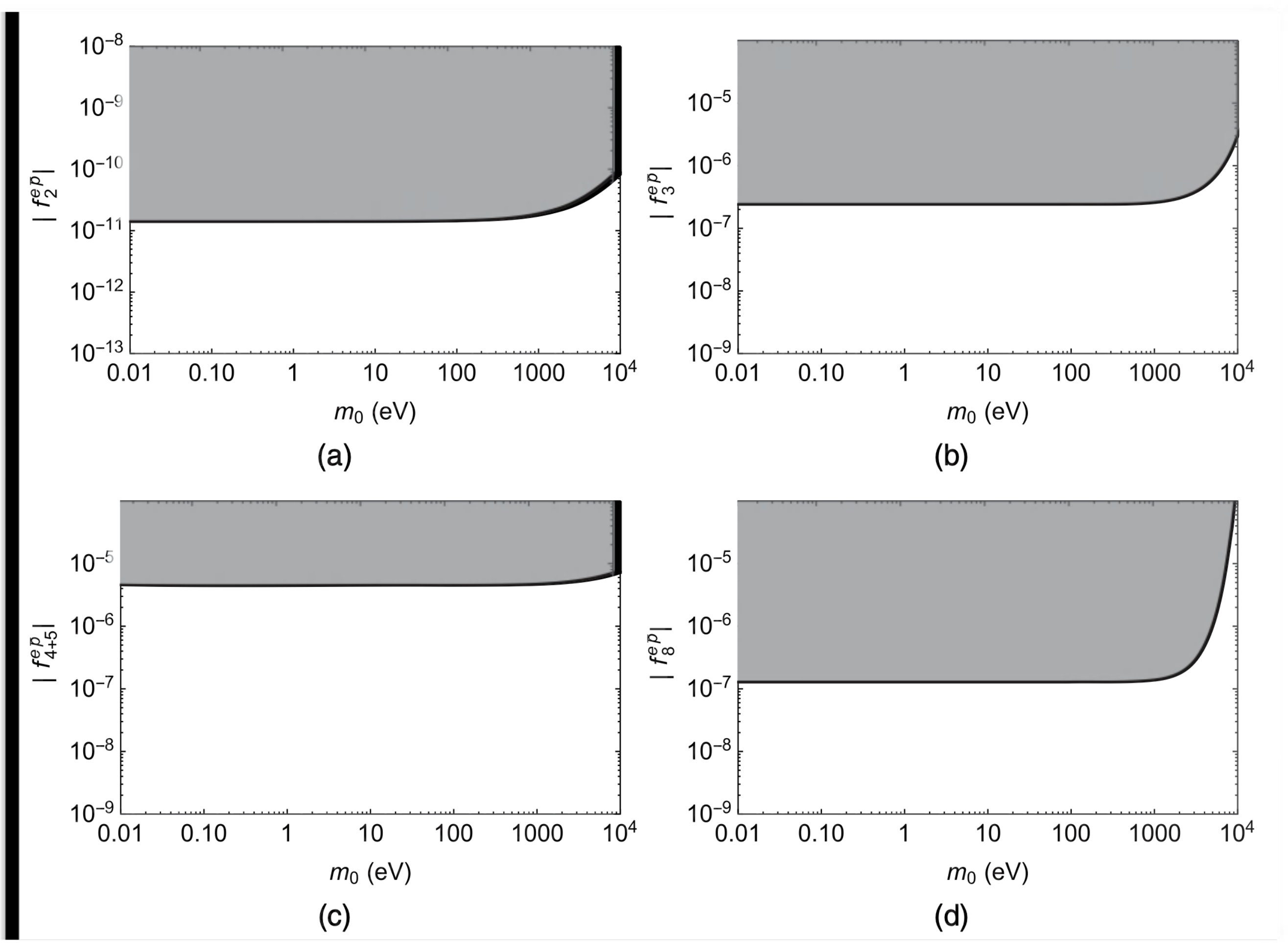
J. Murata et al. Class Quantum Grav. 32, 033001 (2015)



- Inverse square law of gravity has been "proven" to a sensitivity of 10^{-10} in lunar ranging experiments.
- Inverse square law of gravity has not been tested at length scales <100 μm. Only upper limits that are many orders of magnitude larger than the Newtonian force exist.
- $\bar{p}He^+$ constrains Yukawa-like part of potential to $\alpha<10^{28}$ times the Newtonian one. Complementary to HD^+.

Germann et al., Phys. Rev. Research 3, L022028 (2021)

Bounds on couplings between antiprotons and axions or other spin-0 or 1 bosons

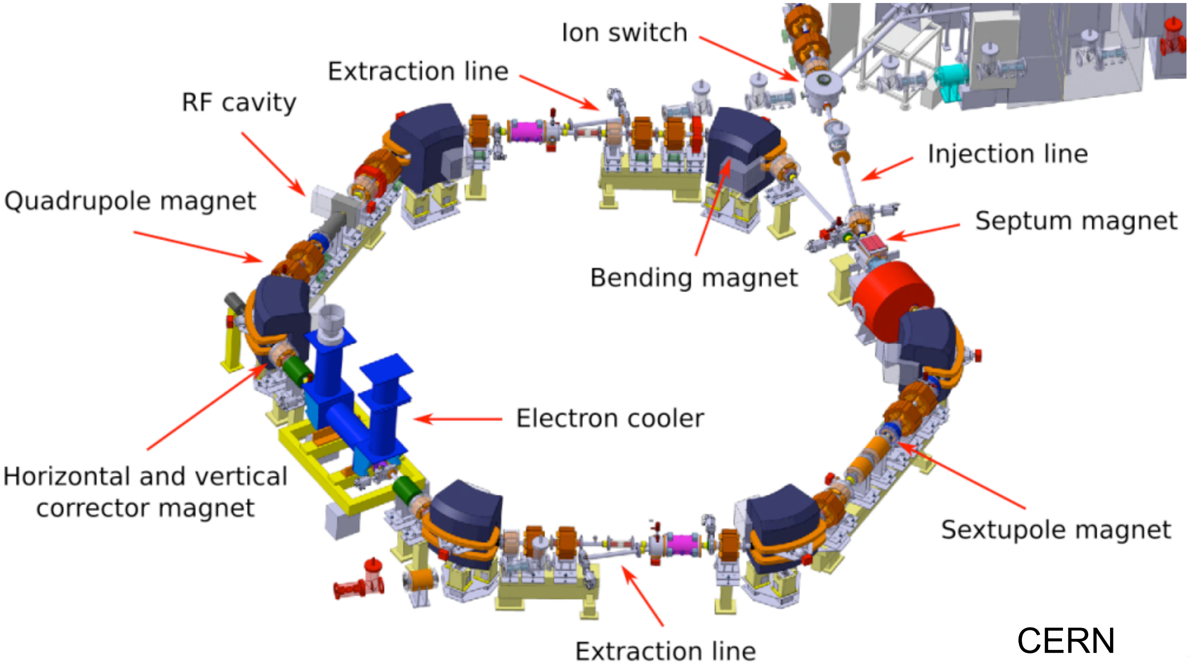


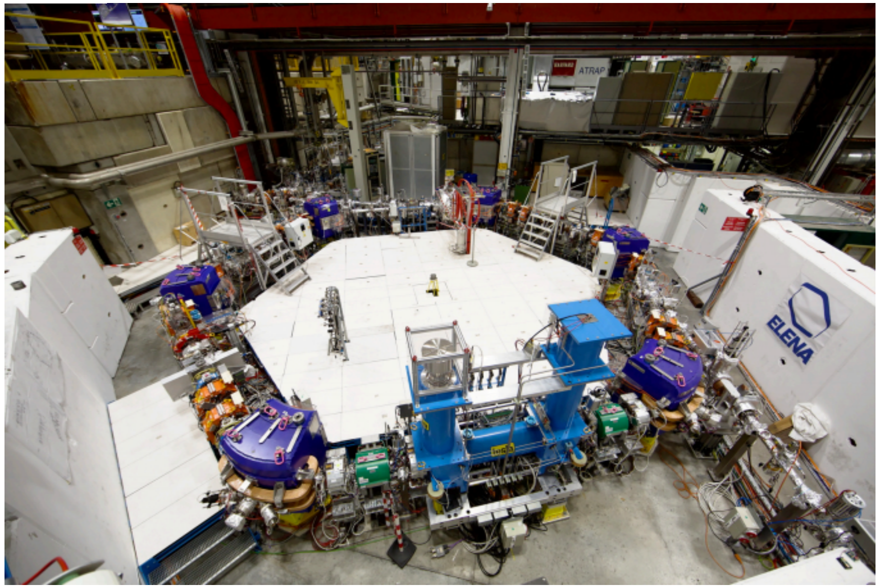
Our experiments provide constraints on exotic velocity and spin-dependent, semi-leptonic forces that may arise between antihadrons and electron due to axions or other spin=0 or 1 bosons.

The magnitude of the coupling constants for four types of possible spin- and velocity-dependent potentials arising between antiprotons and electrons, carried out by Krakow-Mainz-LMU-Sydney-Hayward-Gatchina-St. Peterburg-Berkeley collaboration

Filip Ficek et al., Phys. Rev. Lett. 120, 183002 (2018).

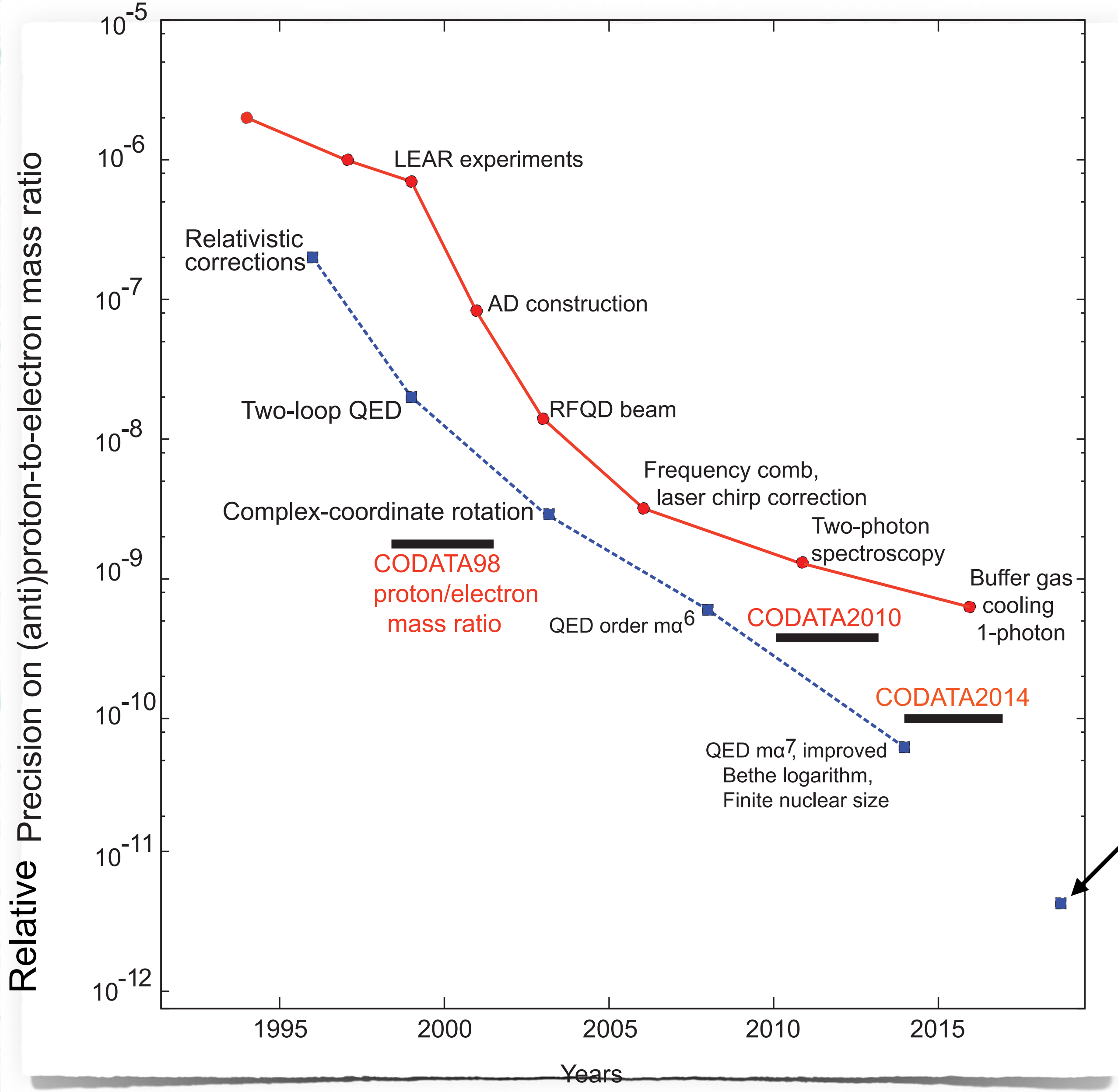
ELENA Extra Low Energy Antiproton Ring





CERN

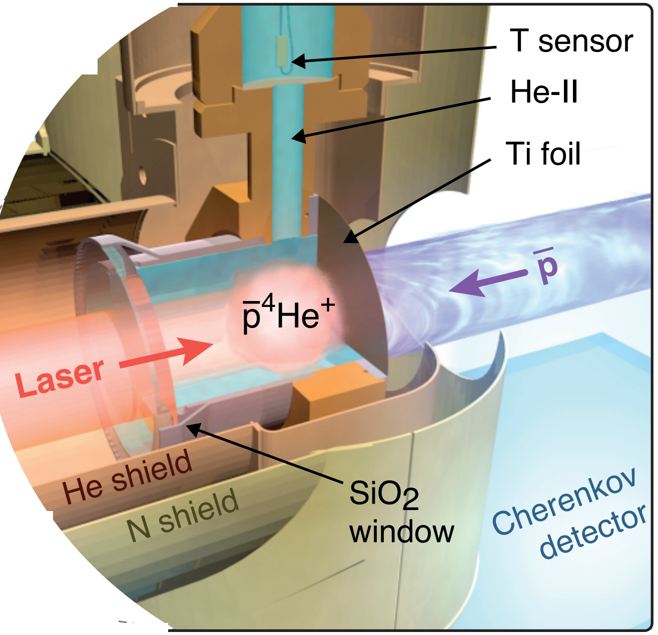
- Circumference 30 m magnetic synchrotron. Decelerates and electron-cools 20 million antiprotons to kinetic energy 100 keV. Increases the number of antiprotons that can be trapped per unit time by potentially two orders of magnitude.
- Circulates 4 antiproton pulses that can be extracted to multiple users simultaneously, increasing the range of possible experimental users.
- Will lead to a factor >20 increase in the annual data collection and a factor 2-6 increase in the signal-to-noise ratio for antiprotonic helium experiments, enabling the spectroscopy of very narrow resonances.

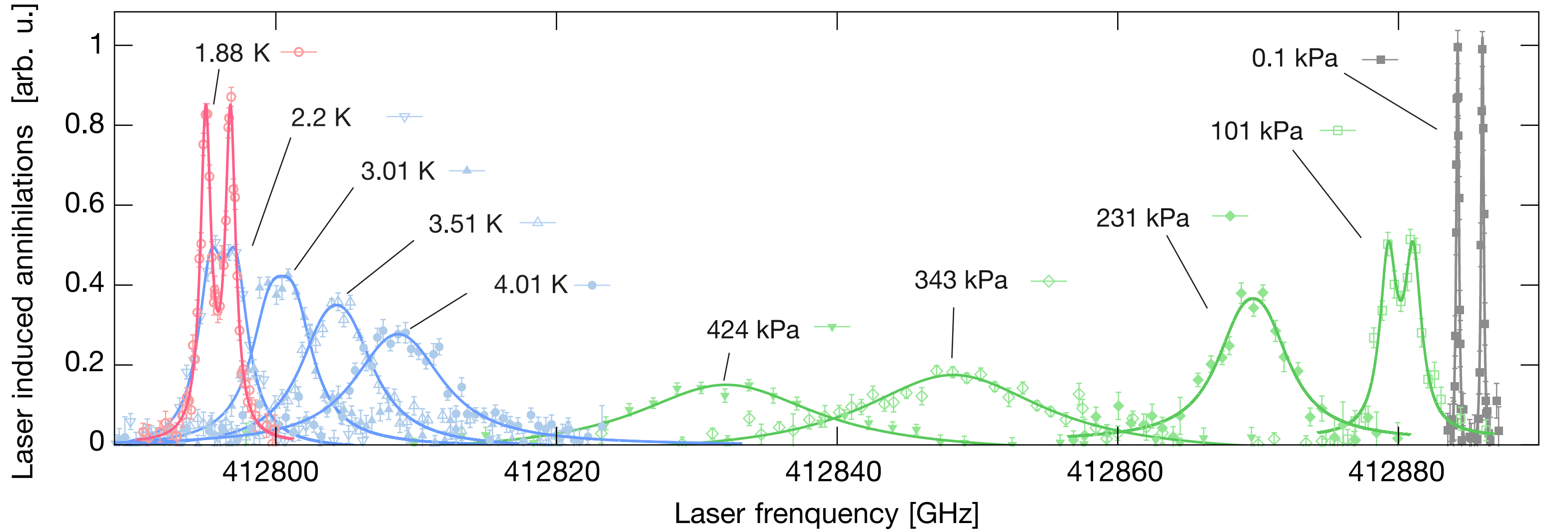


Using this beam, we aim to improve the precision of the antiprotonic helium spectroscopy by factor 100x.

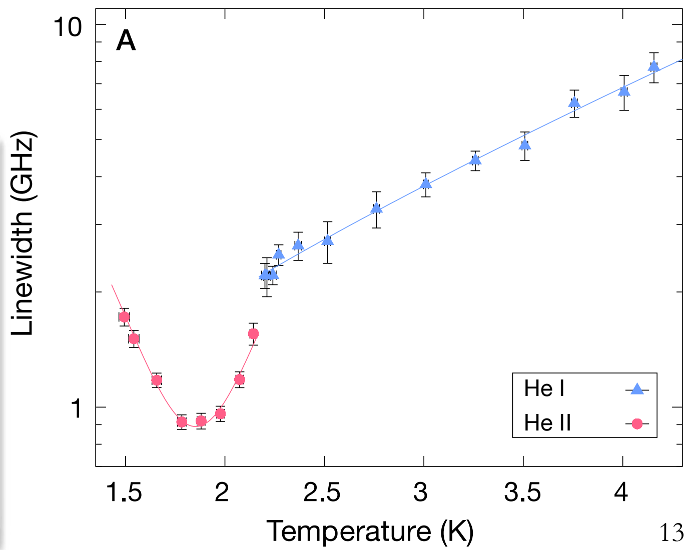
Two-loop self-energy corrections: Extremely difficult theoretical problem to solve in **all** orders of Zα. Will in several years limit the theoretical precision on $\bar{p}He^+$, HD^+, H_2^+ and $^{12}C^{5+}$ ion used to determine the proton-to-electron mass ratio, and the electron mass.

Condensed-matter effects observed for antiprotonic helium atoms suspended in bulk superfluid helium





A. Soter et al. Nature 603, 411 (2022)



- Very narrow (<1 GHz) resonances at wavelength 726 nm (n,l)=(37,35) → (38,34) observed for atoms suspended in superfluid and liquid helium.
- Sudden narrowing of the resonance line observed when the liquid surrounding the atom transitions to the superfluid state. Due to phonon-atom interactions?
- Possibilities to use antiprotons to probe condensed matter effects?

Physics motivation for πHe^+ laser spectroscopy

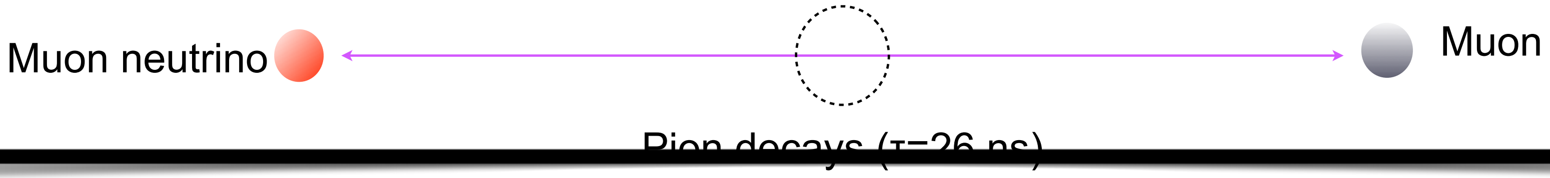
- Definitive evidence for the existence of three-body metastable πHe^+ It would be the first laser excitation and spectroscopy of an atom containing a meson.
- As the ^4He nucleus and pion are spin-0 bosons, there is no spin-spin hyperfine structure. The atomic energy levels obey the Klein-Gordon equation $\mathscr{L} = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2} m^2 \phi^2$ + etc. as opposed to the hydrogen atom etc. which behaves according to the Dirac equation $\mathscr{L}_{QED} = \bar{\psi}\left(i\gamma^\mu \partial_\mu - m\right)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - q\bar{\psi}\gamma^\mu \psi A_\mu$
- Precise determination of the π^- mass at a level of ≦10^{-8} precision may in principle become possible.
- May allow us to set upper limits on exotic forces coupling to mesons as in antiproton case.
- Improvement on the direct laboratory limit of the muon antineutrino ν_μ mass by using the kinematical formula,

$$p_\mu^2 + m_\mu^2 = \left(m_\pi^2 + m_\mu^2 - m_{\nu\mu}^2\right)^2 / 4m_\pi^2$$

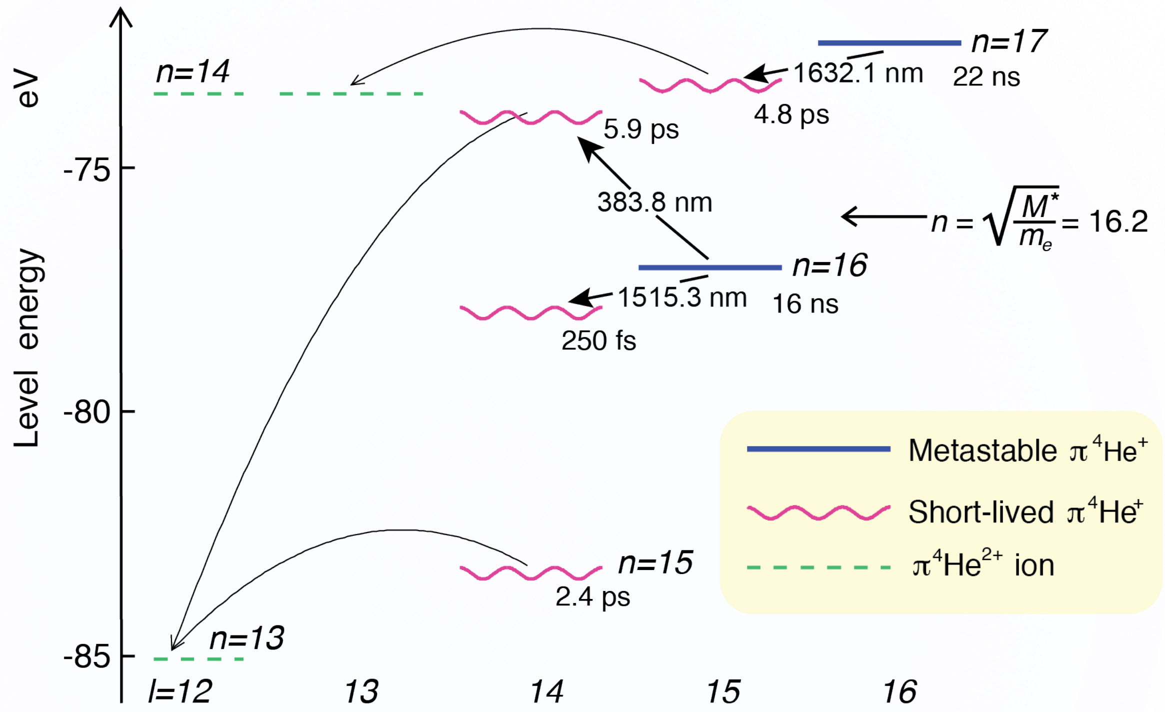
p_μ: 29.79200(11) MeV/c

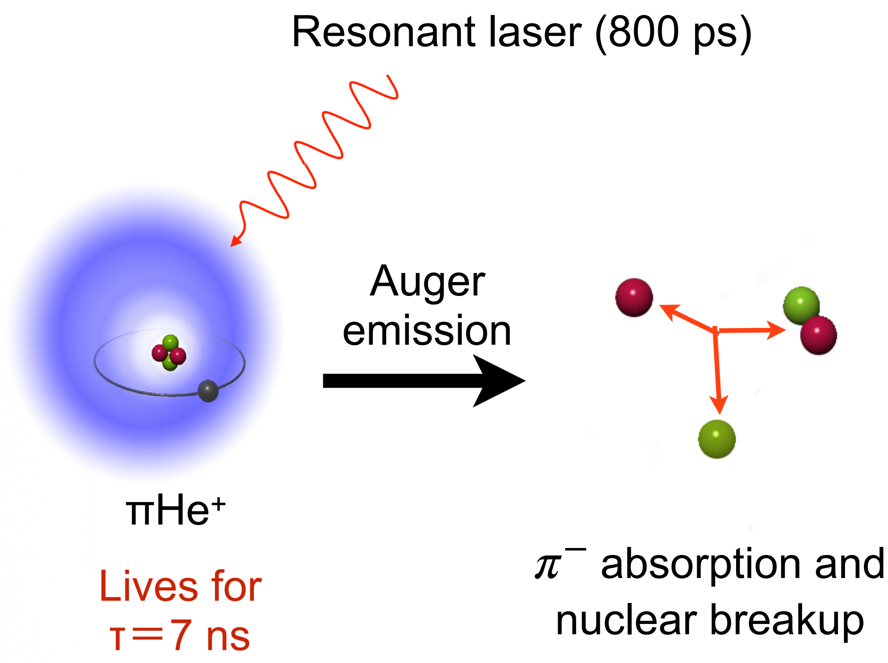
m_μ: 105.6583668(38) MeV

PRD 53, 6065 (1996).
Best value <1 eV obtained from neutrino oscillation experiments



Laser spectroscopy of πHe+



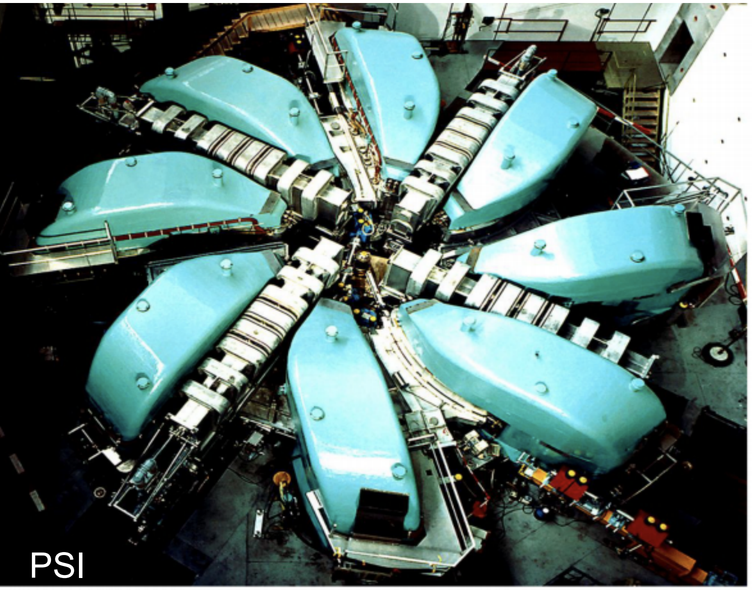


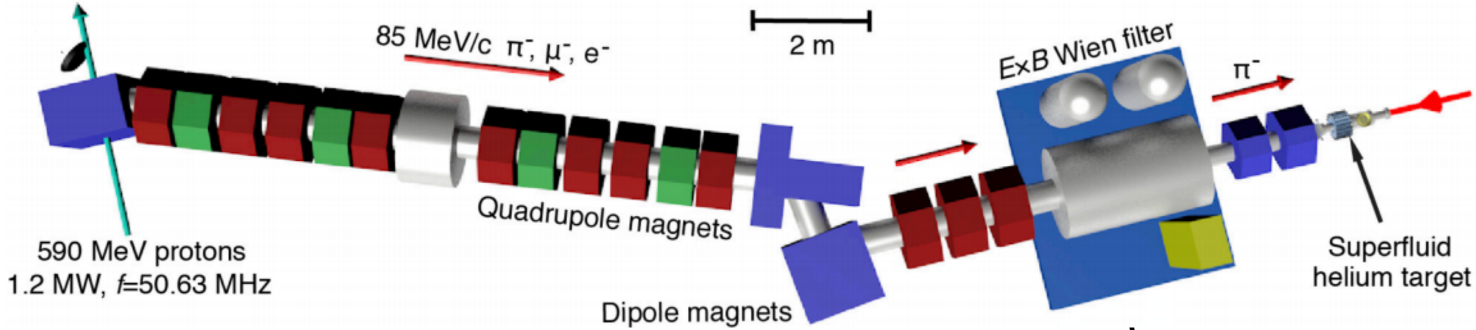
- When the laser is in resonance with the atom, the nucleus absorbs the pion and breaks up.

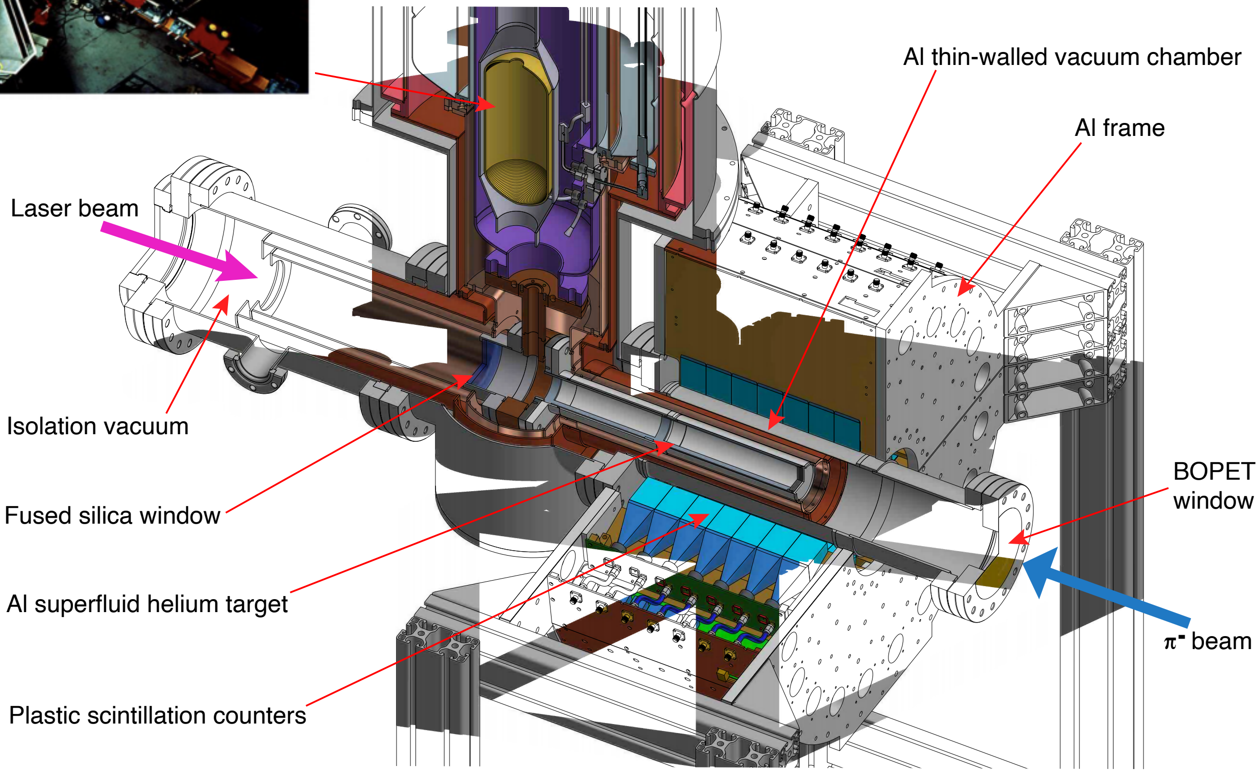
  πHe^+ + laser $\rightarrow p + n + n + n,\quad d + n + n,$ or $t + n$ detect these fission products.

- High backgrounds (relative yield >10^3) from decay electrons, nuclear fission, and contamination in the particle beam.
- Ultra low-rate experiment: 2-3 events per hour. Must accumulate data for months.

Experimental setup

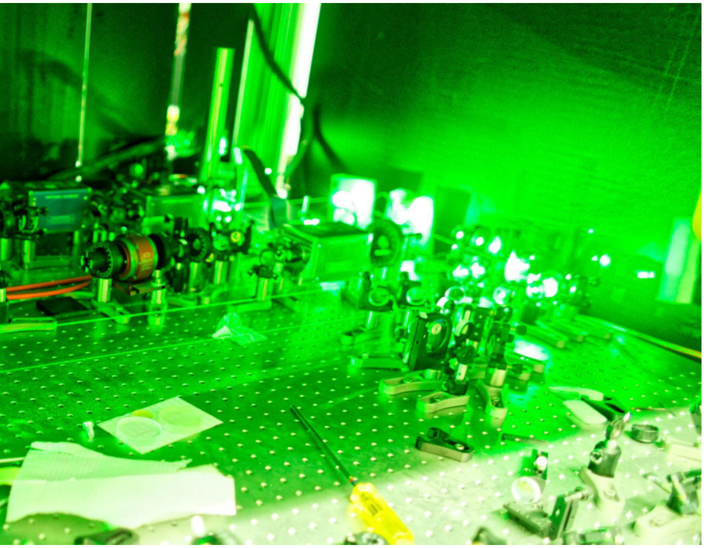


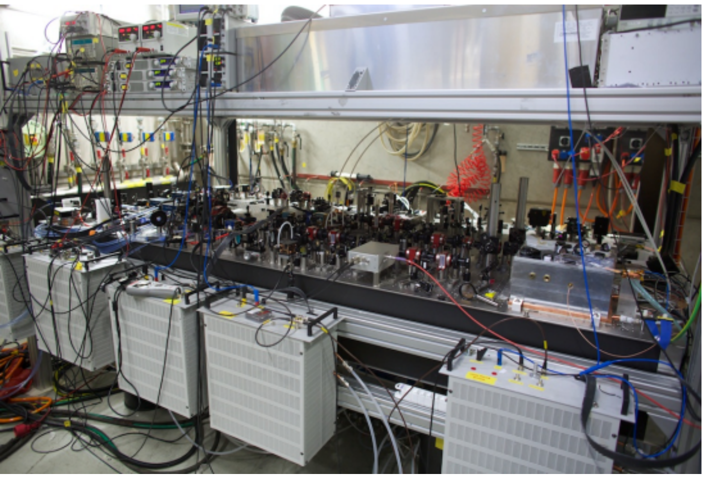


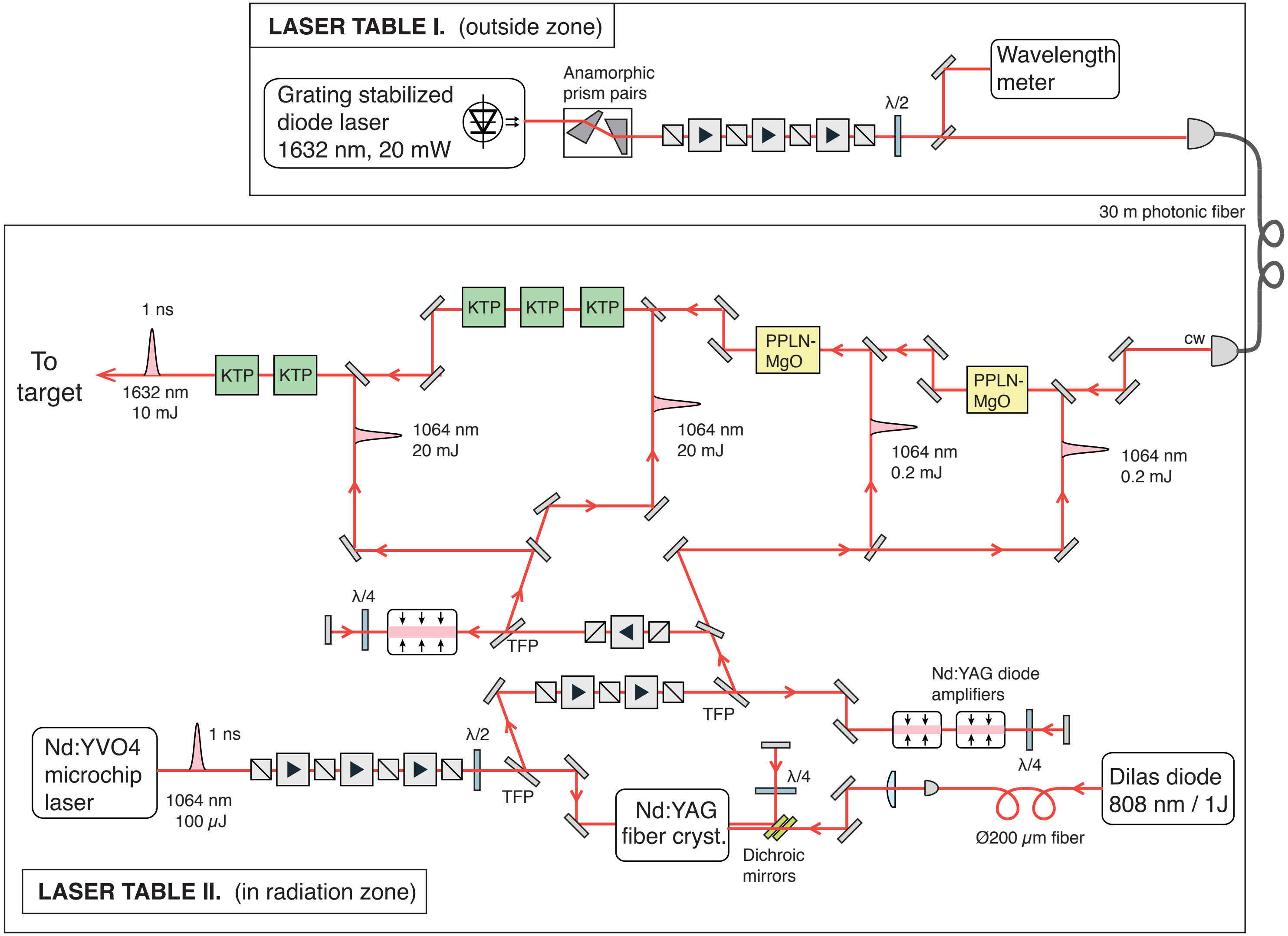


Wien filter ΔV=550 kV

1515-1633 nm / 800 ps / 10 mJ tunable optical parametric generator + amplifier with a firing timing jitter of <1 ns.

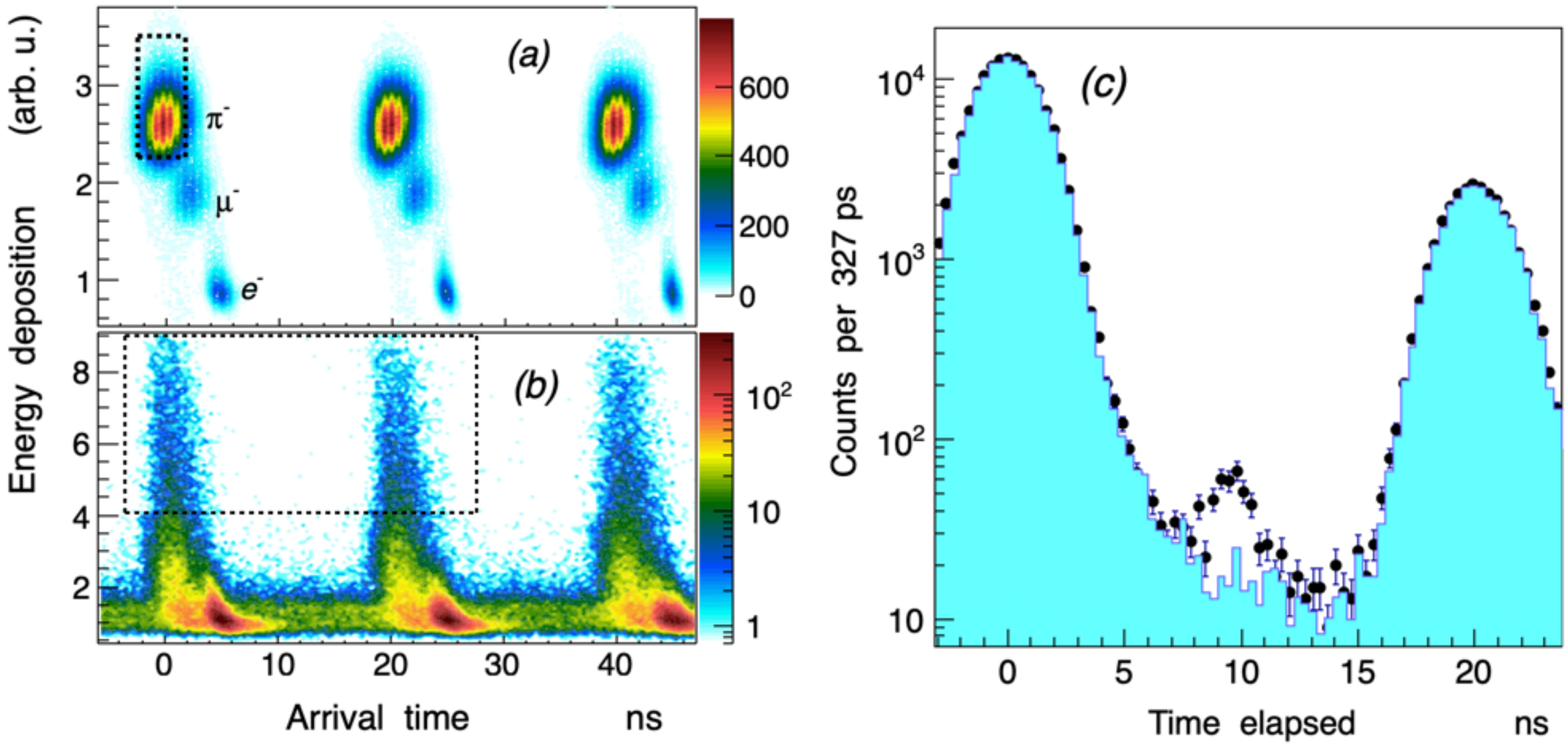






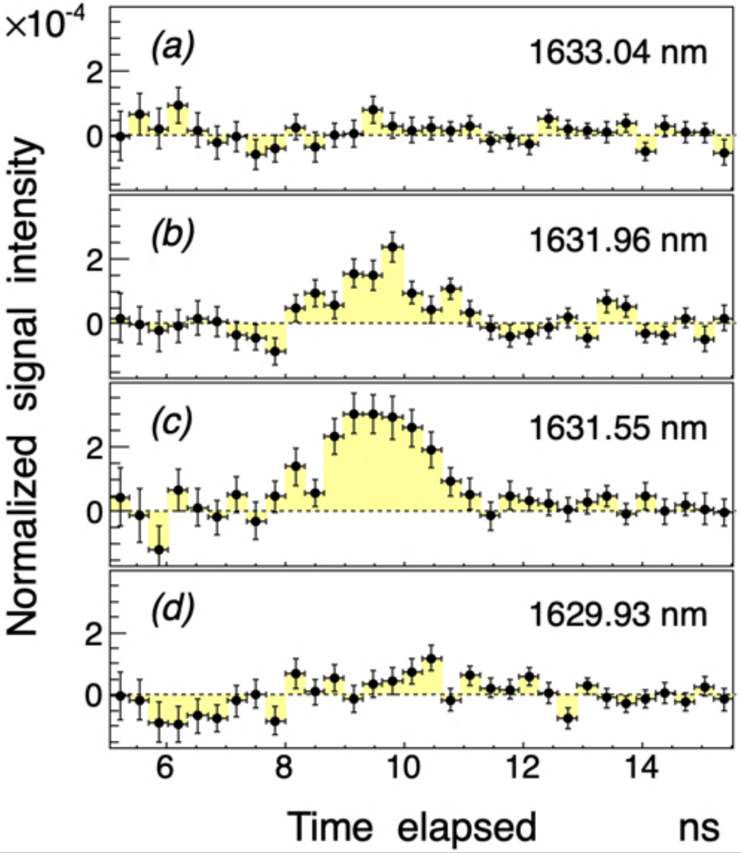
Masaki Hori

Analysis and signal isolation

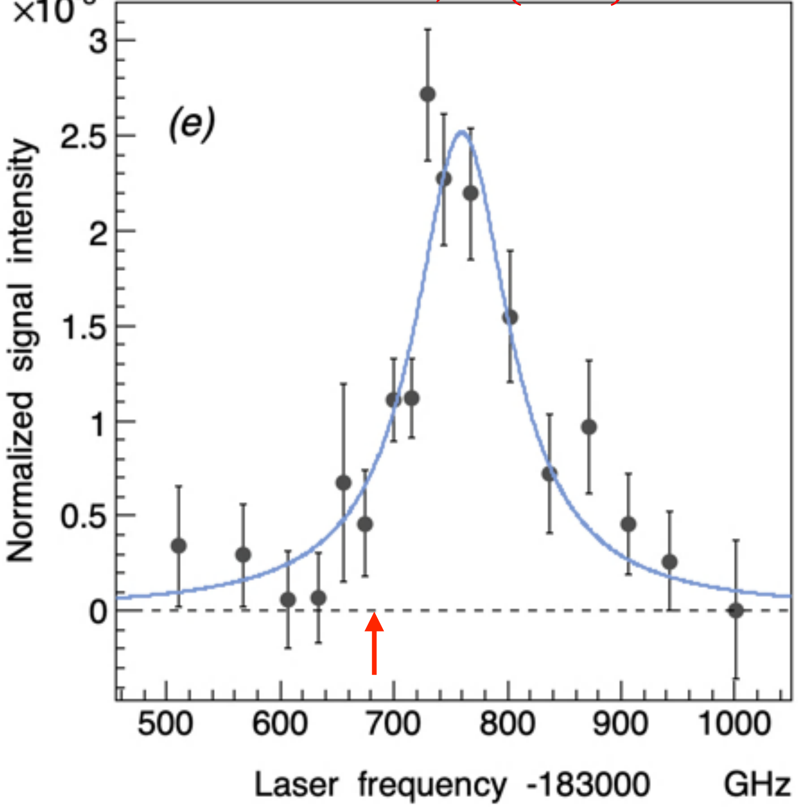


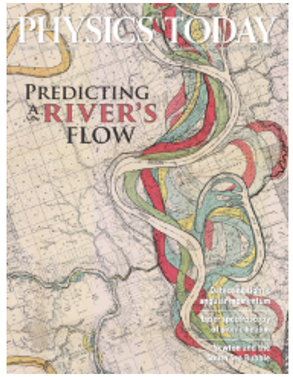
- Identify pions based on their arrival time and energy loss of 2.6 MeV in a 4.7 mm thick plastic scintillator placed at the entrance of the experimental target.
- Identify signal nuclear fragments by selecting events with a >20-25 MeV energy deposition in the 140 plastic scintillators. The scintillators were adjusted to a "magic thickness" of around 40 mm so that the background electrons could simply be rejected based on their much smaller 6-8 MeV energy deposition.

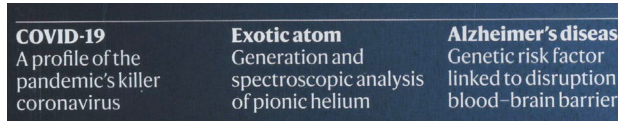
Experimental result



Nature 581, 37 (2020)







- By plotting the relative number of counts under the laser-induced peak as a function of laser frequency, we obtained the Lorentzian profile shown.
- Resonance centroid 183760(6)$_{STA}$(6)$_{SYS}$ GHz. The 6 GHz statistical uncertainty is due to the small number of detected atoms, the systematic uncertainty due to the selection of the Lorentzian fit function and the frequency modulation due to OPG and OPA processes.

Calculated transition frequency (n,l)=(17,16)→(16,15)

Non-relativistic energy	1 125 369 104.121(7) MHz
$\Delta E^{(2)}$ order corrections	-73281.2(9)
$\Delta E^{(3)}$ order corrections	10376.5(5)
$\Delta E^{(4)}$ order corrections	155.5(32)
$\Delta E^{(5)}$ order corrections	-15.5(31)
Transition frequency	1 125 306 339.4(45)

Z.-Da. Bai, V.I. Korobov, Z.-C. Yan, T.-Y. Shi, Z.-X. Zhong
Physical Review Letters 128, 183001 (2022)

"Once measurements reach the ppb level…. will improve the the value of the π- mass by 2-3 orders of magnitude."

Summary

- During the previous AD program we carried out sub-Doppler two-photon laser spectroscopy of antiprotonic helium atoms. We cooled 2×10^9 $\bar{p}He^+$ atoms to temperature T=1.5-1.7 K by utilizing buffer-gas cooling in cryogenic low-pressure helium gas, and measured 13 single-photon transitions to a fractional precision of 2.5-16 parts in 10^9. Comparisons with QED calculations yielded an antiproton-to-electron mass ratio $M_{\bar{p}}/m_e = 1836.1526734(15)$, which agrees with the proton-to-electron experimental value within 8×10^{-10}.
- ELENA facility will provide beams to achieve higher precision experiments using five laser beams.
- An "unexpected phenomenon" involving the narrowing of the spectral lines of antiprotonic helium embedded in superfluid helium to 2 ppm resolution was detected. The reason is not theoretically understood, but it allows us to study mesonic atoms in superfluid helium by laser spectroscopy.
- Using the above technique, laser spectroscopy of the transition $(n, \ell) = (17,16) \rightarrow (17,15)$ of metastable pionic helium was detected at PSI. This verified that the atom exists and constitutes the first excitation of an atom that includes a meson. Quantum optics techniques can now be used to study **mesons** and the method can probably be utilized for other mesons such as kaons that include the strange quark.
- By measuring such narrow resonances at various densities of a helium gas target, we may determine the transition frequency to much higher precision. This would lead to an improved charged pion mass "by up to 2 to 3 orders of magnitude".