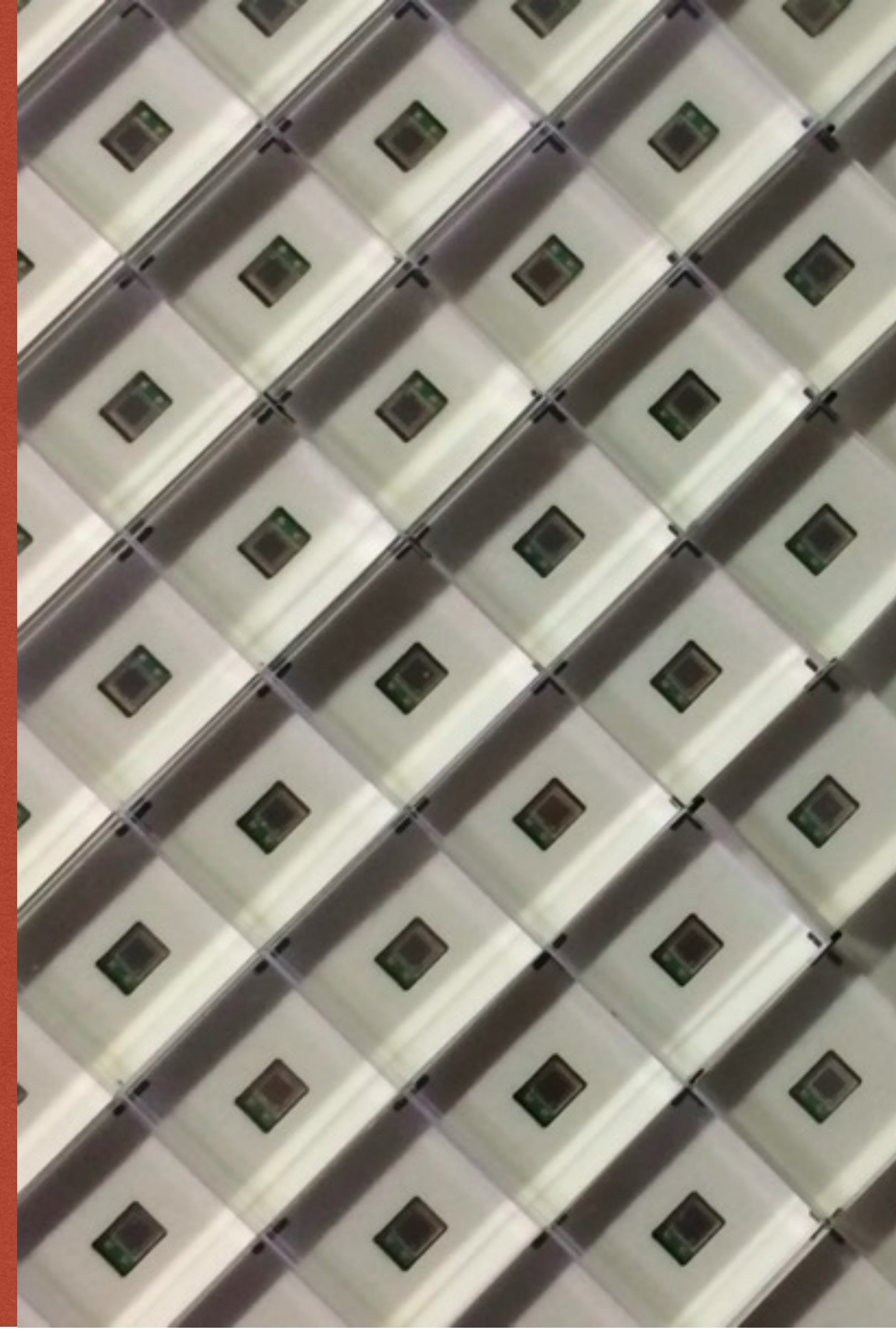
Precision Laser Spectroscopy of the Ground State Hyperfine Splitting in Muonic Hydrogen



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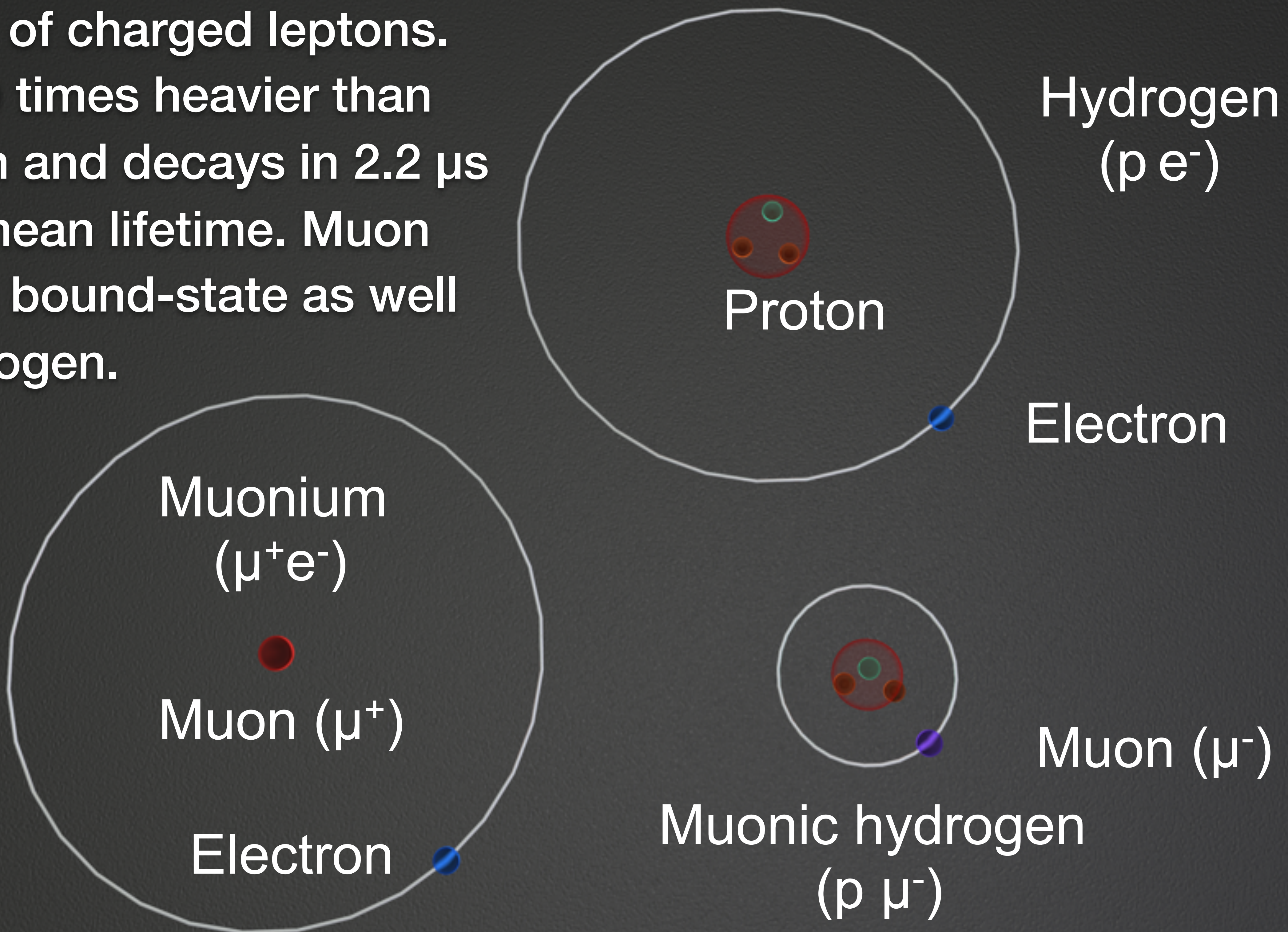
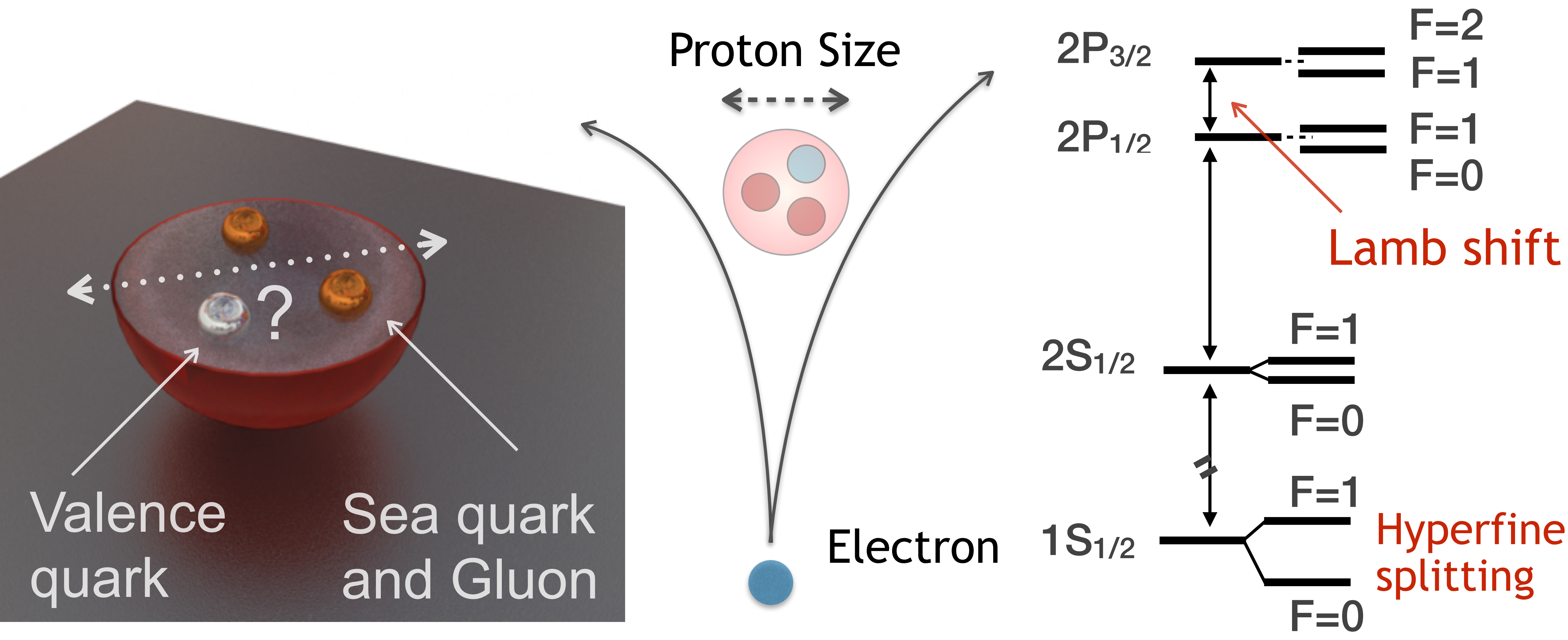
Exotic Atoms Involving Muon

Muon is the 2nd generation particle of charged leptons. It is 200 times heavier than electron and decays in 2.2 μs of the mean lifetime. Muon forms a bound-state as well as hydrogen.



How Large is the Proton?

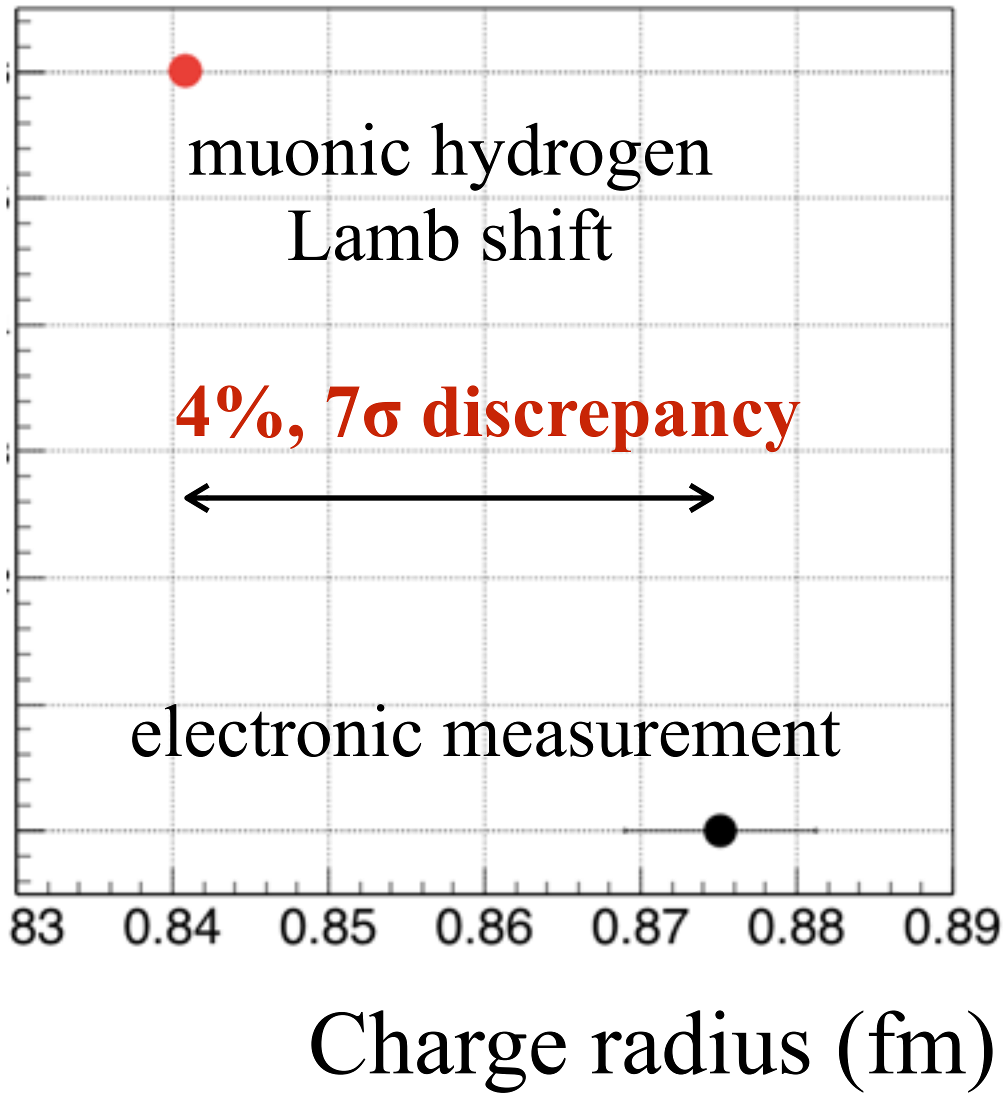
- The proton is a fundamental constituent of the world.
- However, its internal structure has not been fully understood.
- Internal structure of the proton is described by the electric/magnetic form factors, *i.e*. the charge/magnetic radii.
- Two methods are known; scattering and spectroscopy.

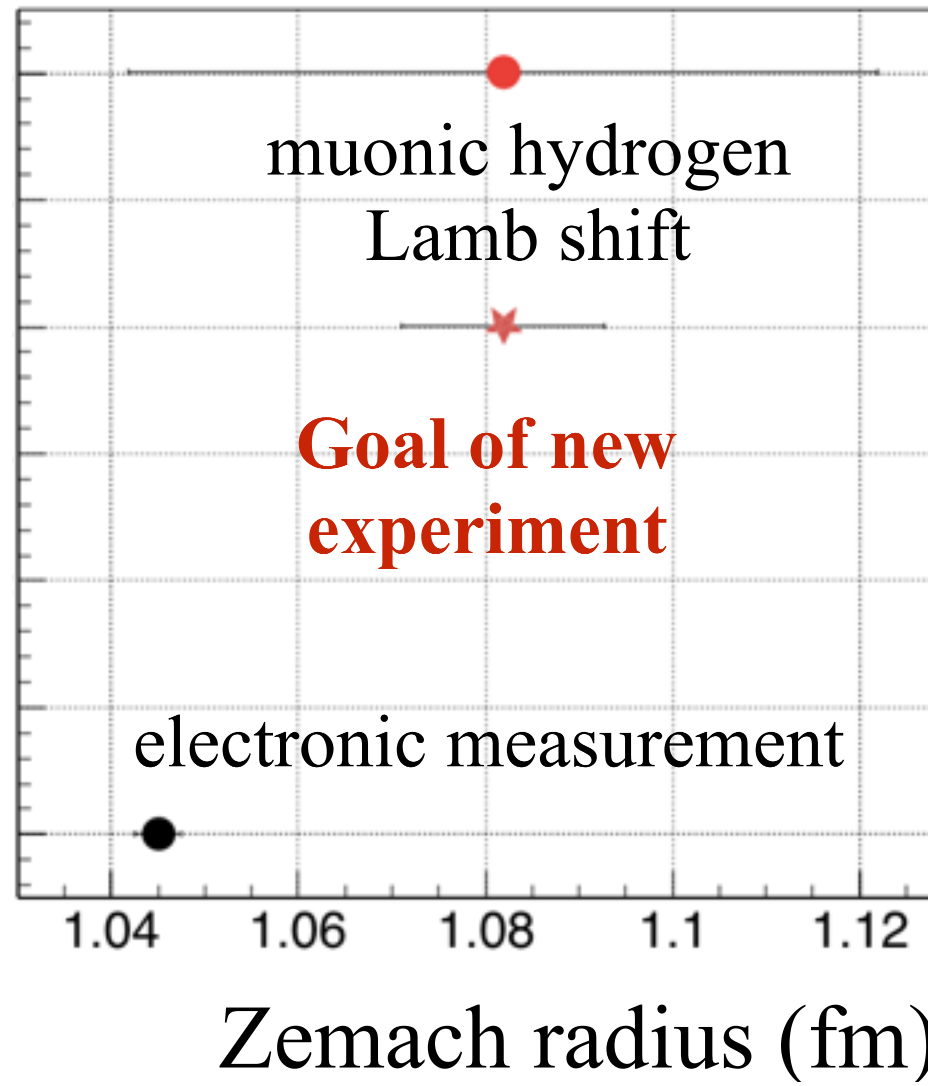


Electron-proton scattering

Atomic spectroscopy

Proton Radius Puzzle





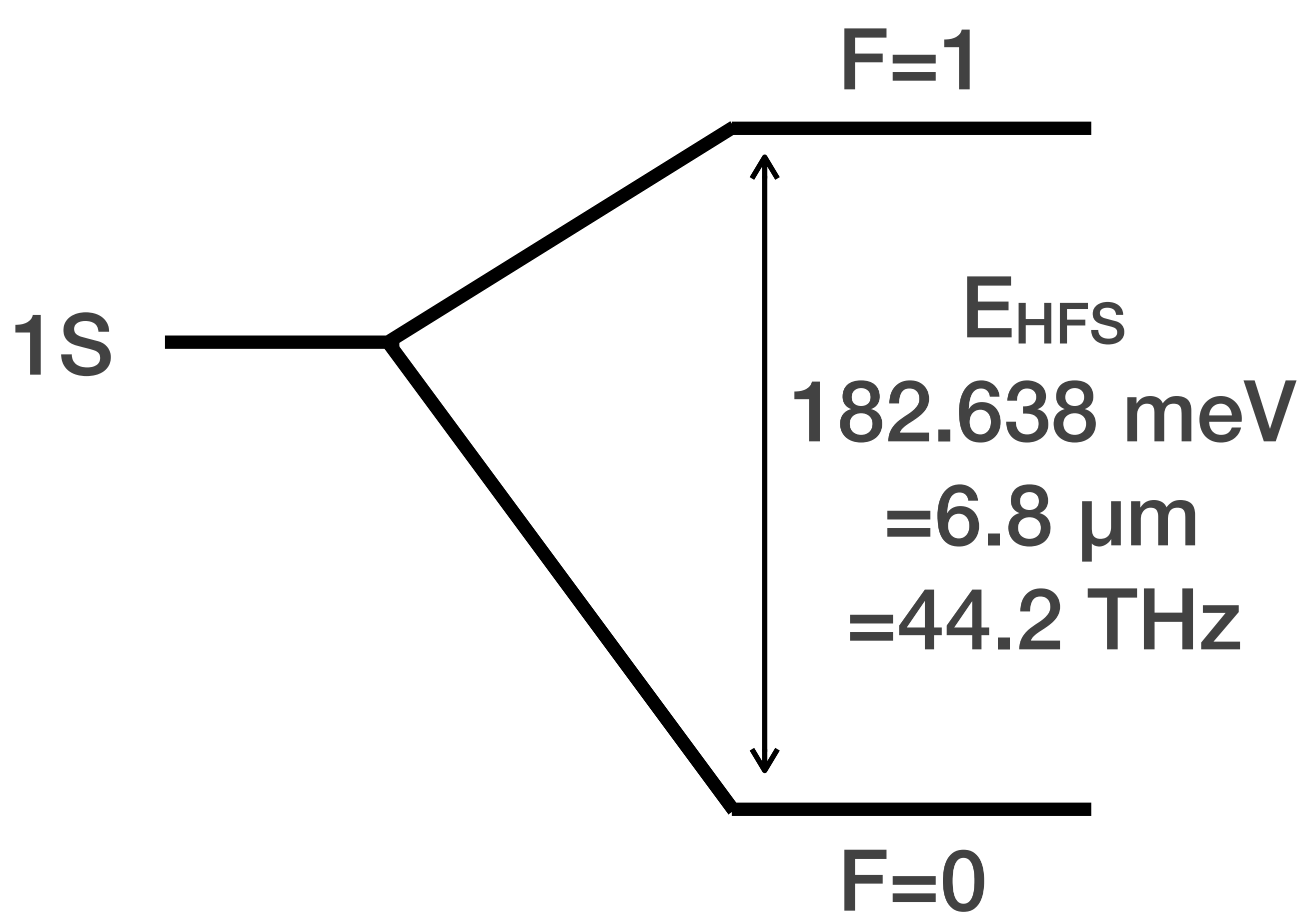
There is no definitive interpretation of the puzzle and new, independent experiment is needed.

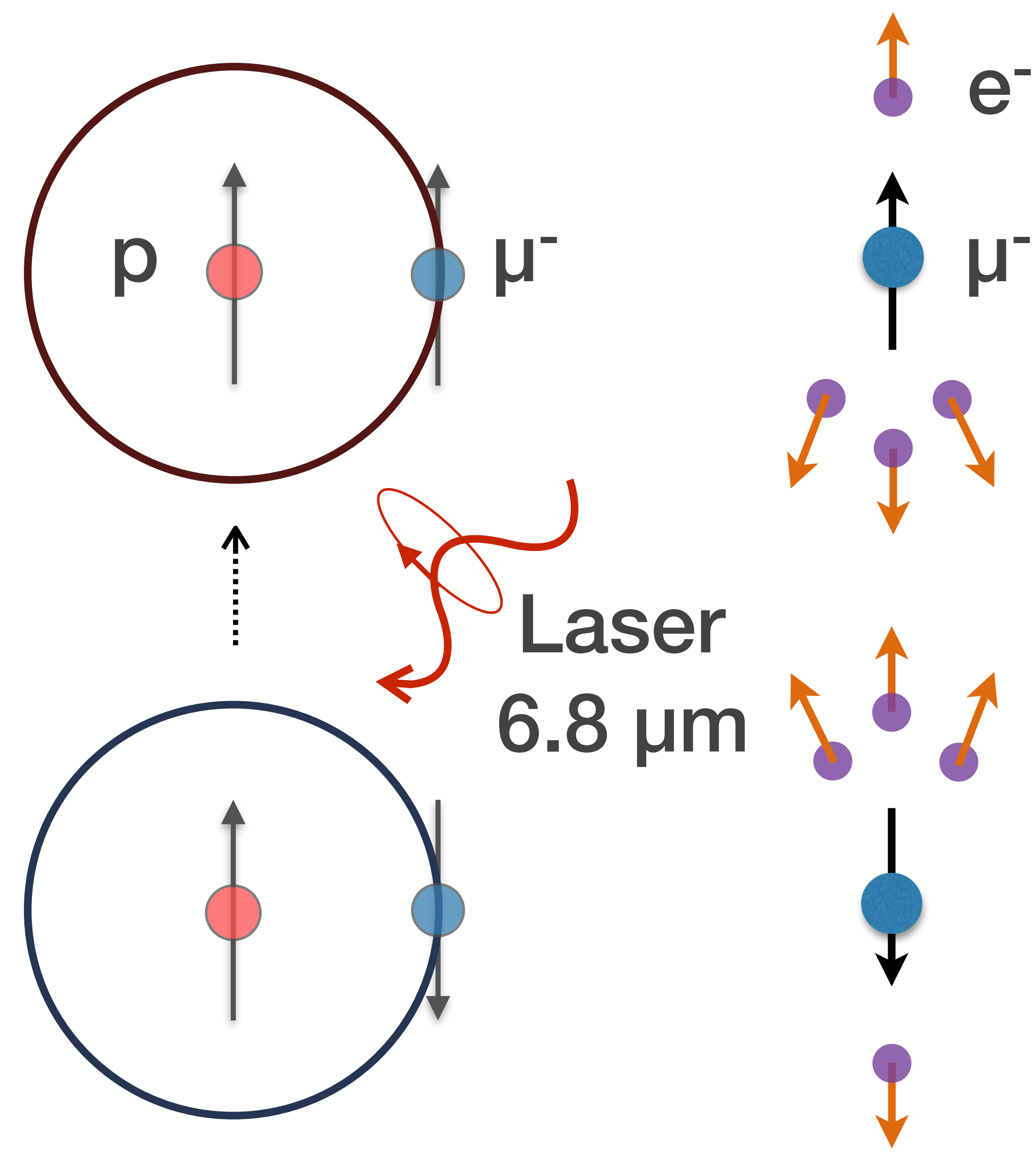
Our goal is a factor of three improvement; 1% precision.

R. Pohl *et al*., Nature 466, 213 (2010). A. Antognini *et al*., Science 339, 417 (2013).
J. C. Bernauer *et al*., PRL. 105 (2010). M. O. Distler et al., Phys. Lett. B 696, 343 (2011).

Muonic Hydrogen HFS

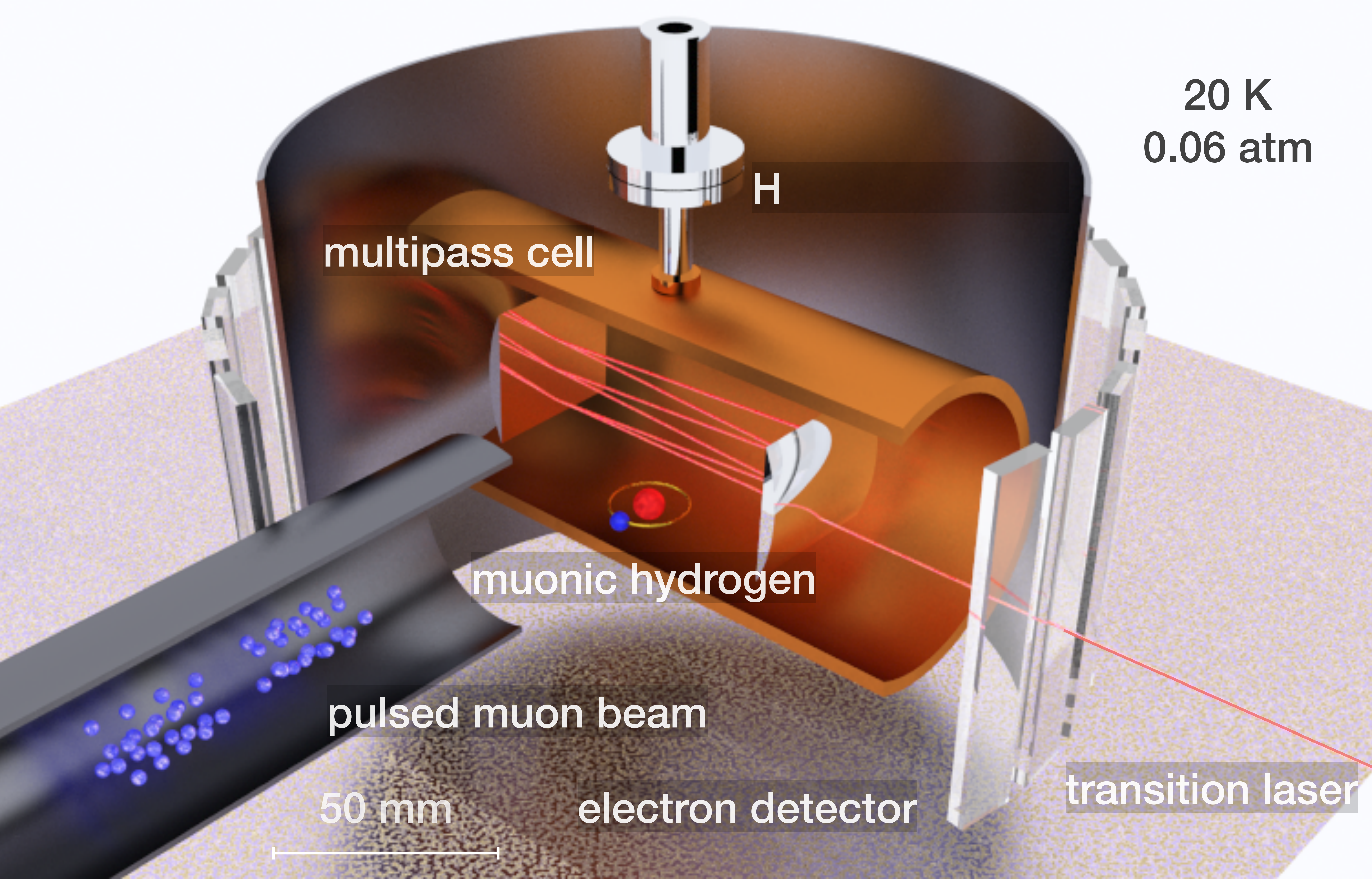
- μp hyperfine splitting (HFS) transition is induced by a circularly polarized laser light.
- HFS contains a contribution from the finite size effect of the proton. Hence, the proton Zemach radius can be extracted.



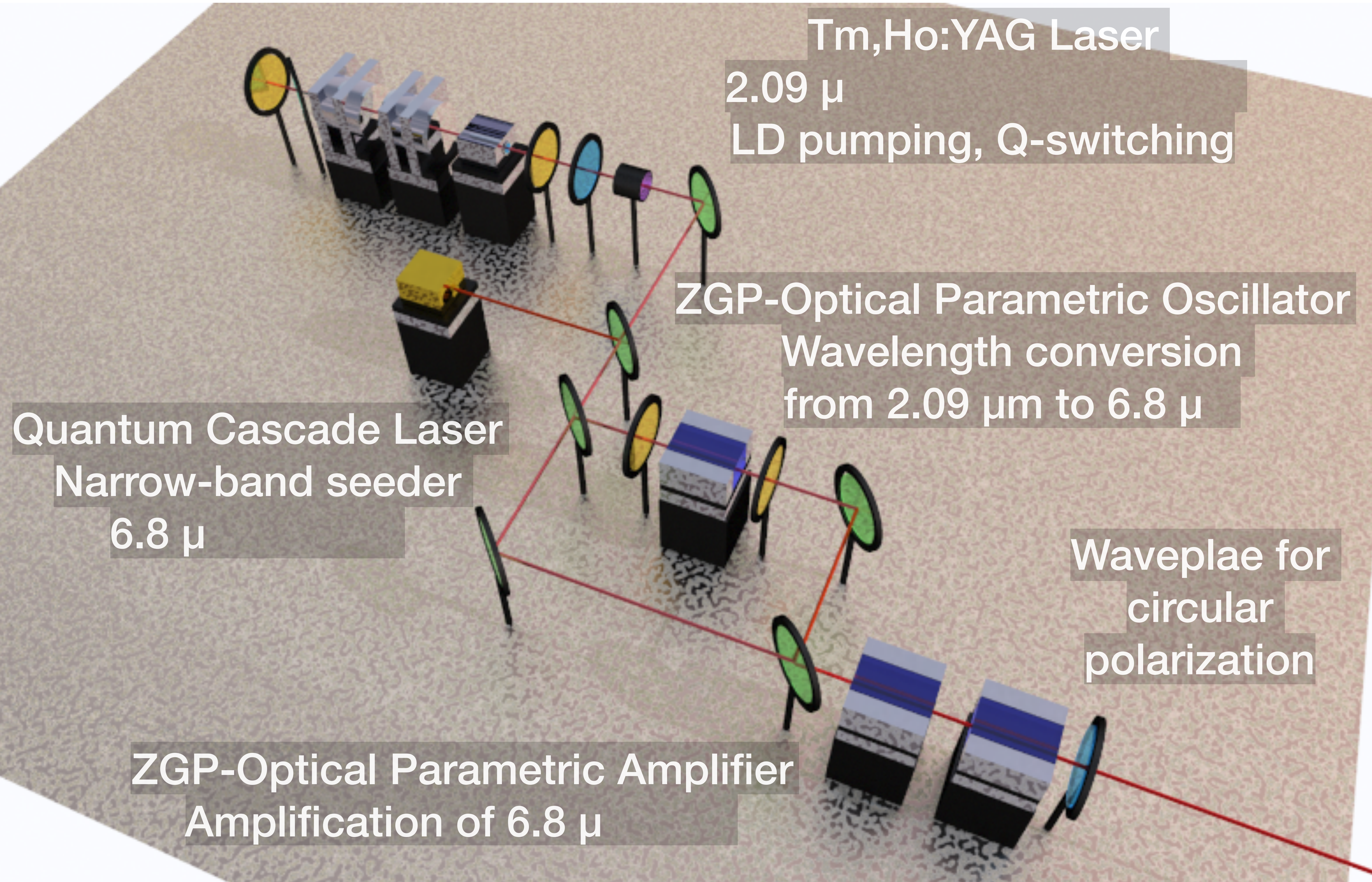


Zemach contribution is expected to be 1.36 meV.

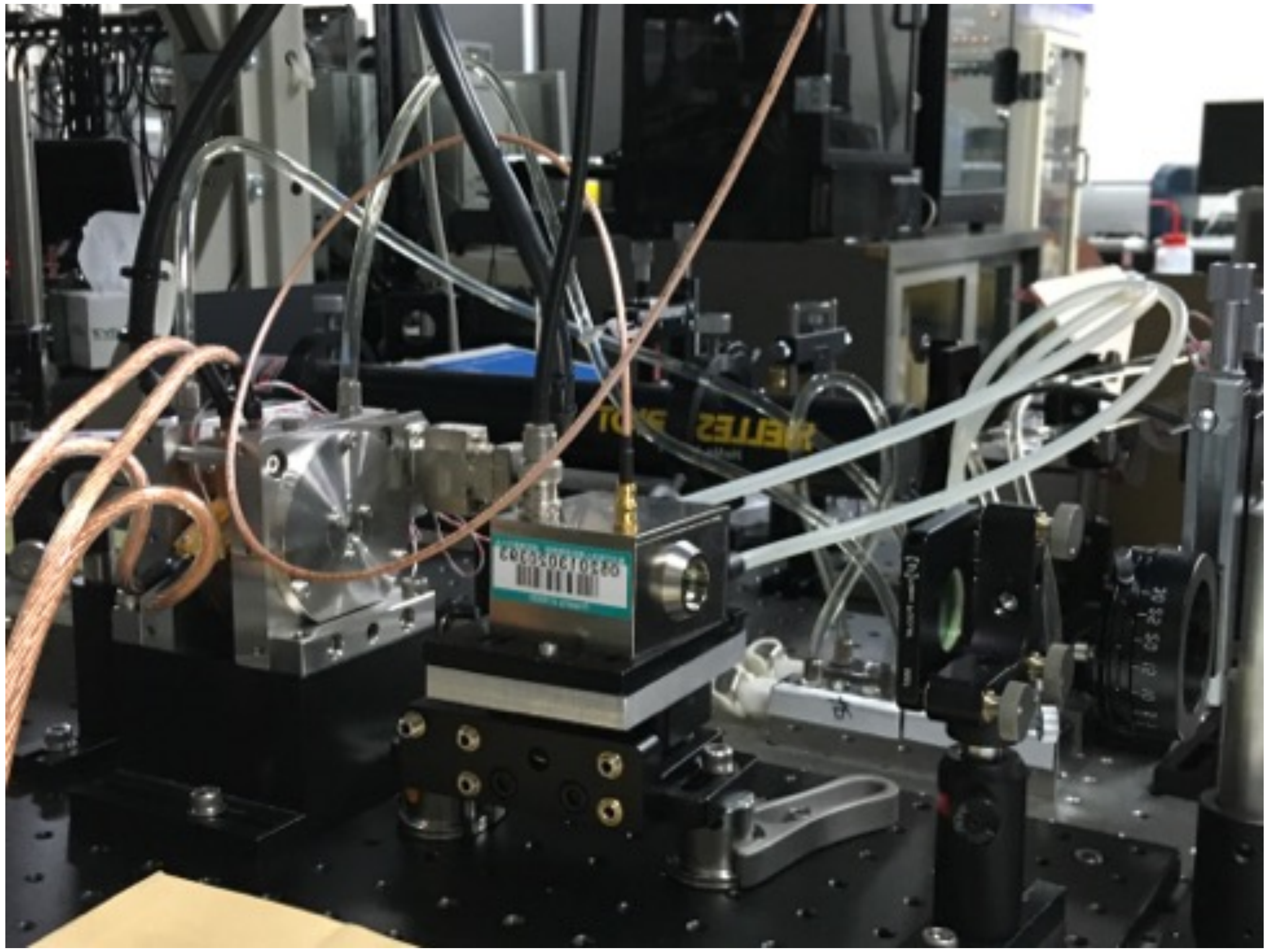
New μp 1S-HFS Measurement

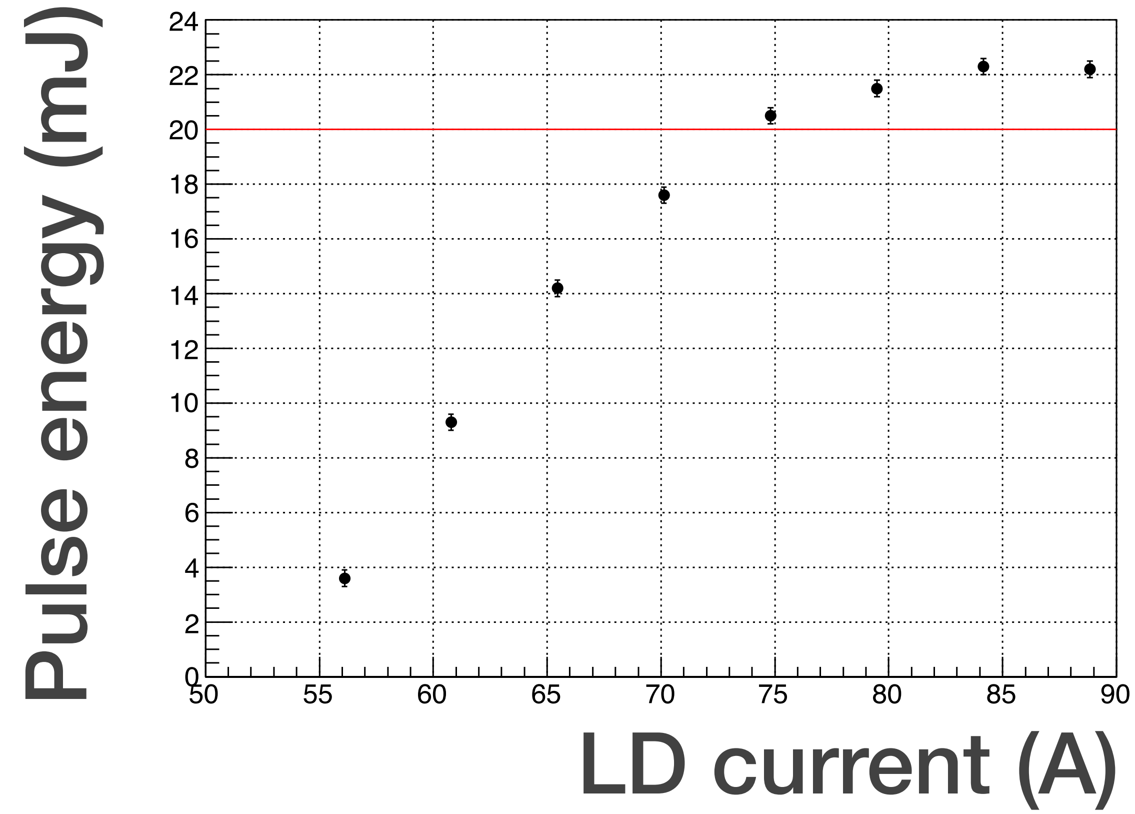


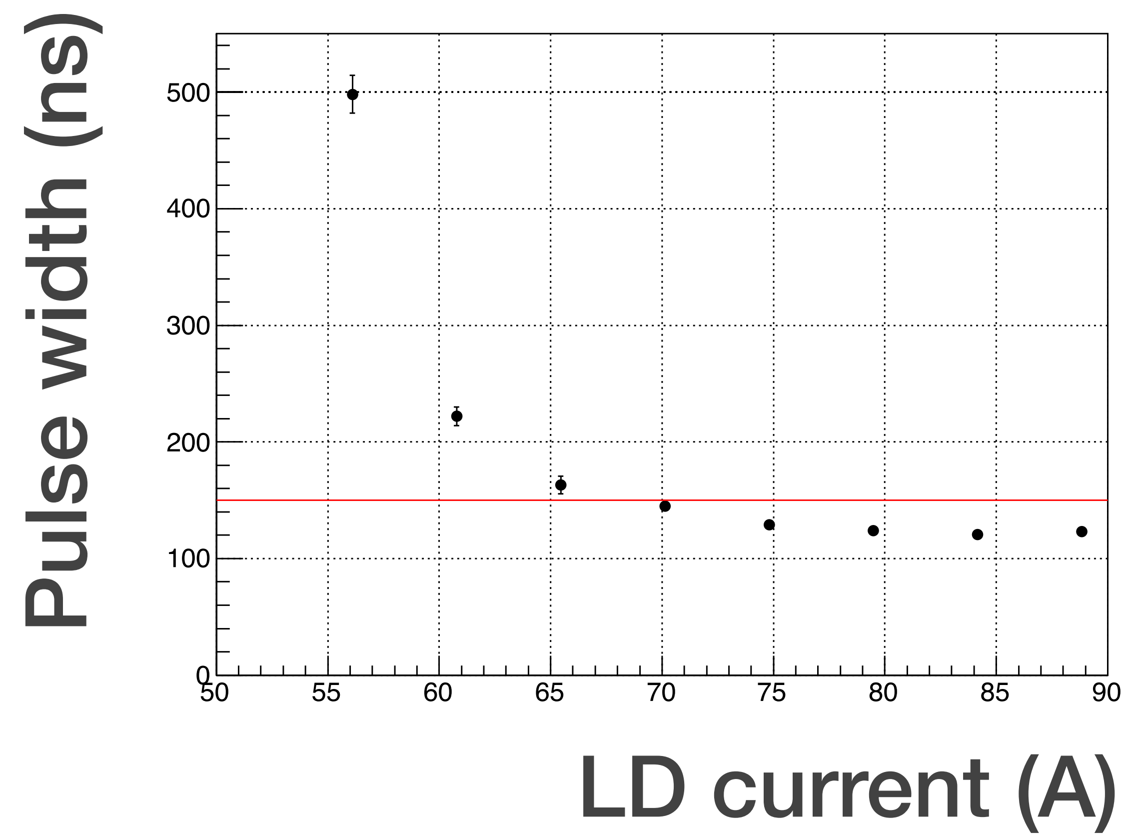
Laser System



Laser Development



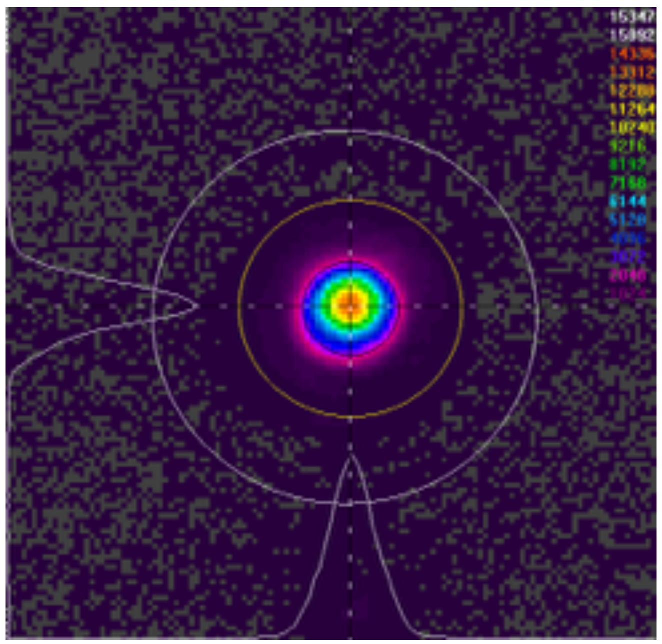




- 2.09 µm light is necessary for 6.8 µm light generation via OPO
- 20 mJ of pulse energy and 150 ns of pulse width are required
- LD pumped Q-switching Tm,Ho:YAG laser was developed and it satisfies the requirements

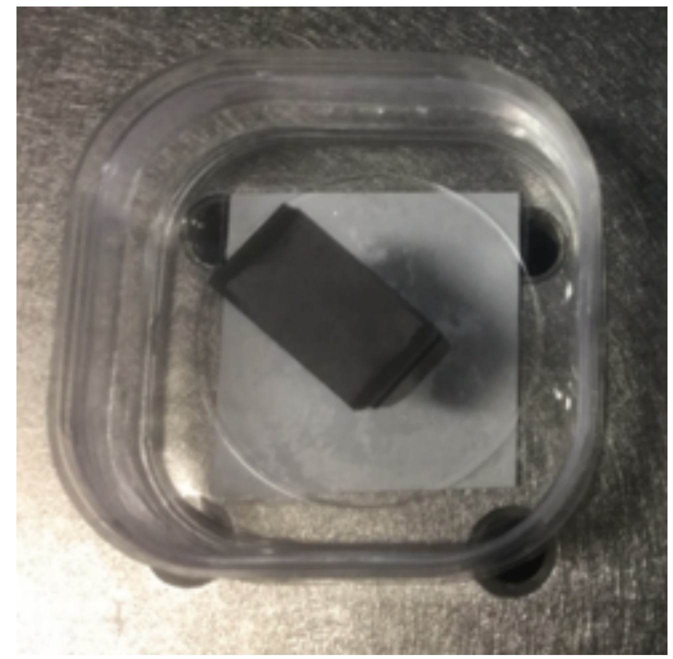
Laser Development (con’d)

- Beam profile



1σ~0.5 mm for both X and Y

- ZGP-OPO/OPA

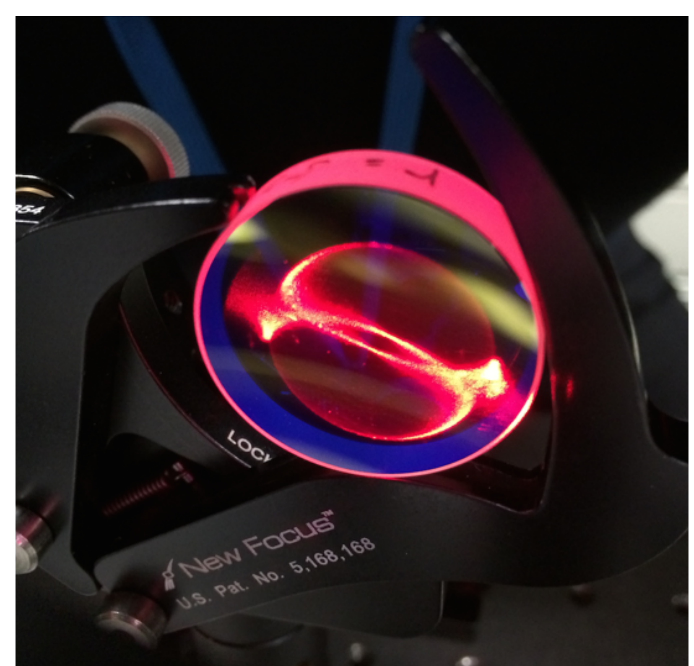


Demonstrated by using Cr,Zn:Se laser. Conv. eff. ~13%

- QCL

Manufacturing is in progress.

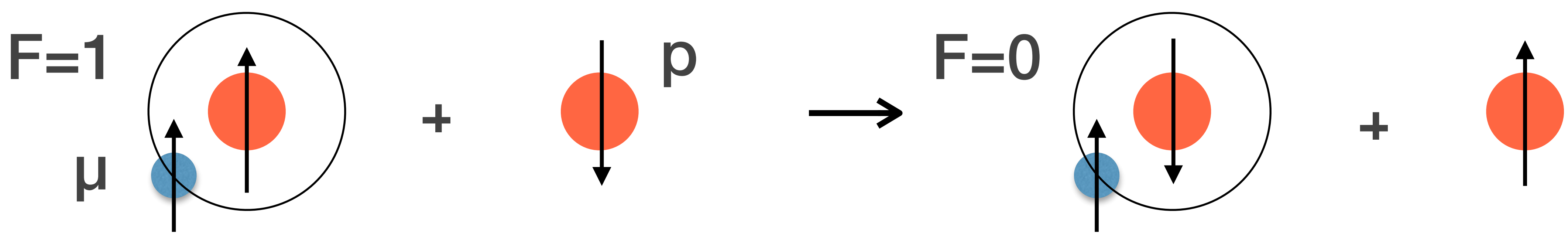
- Multi-pass cell

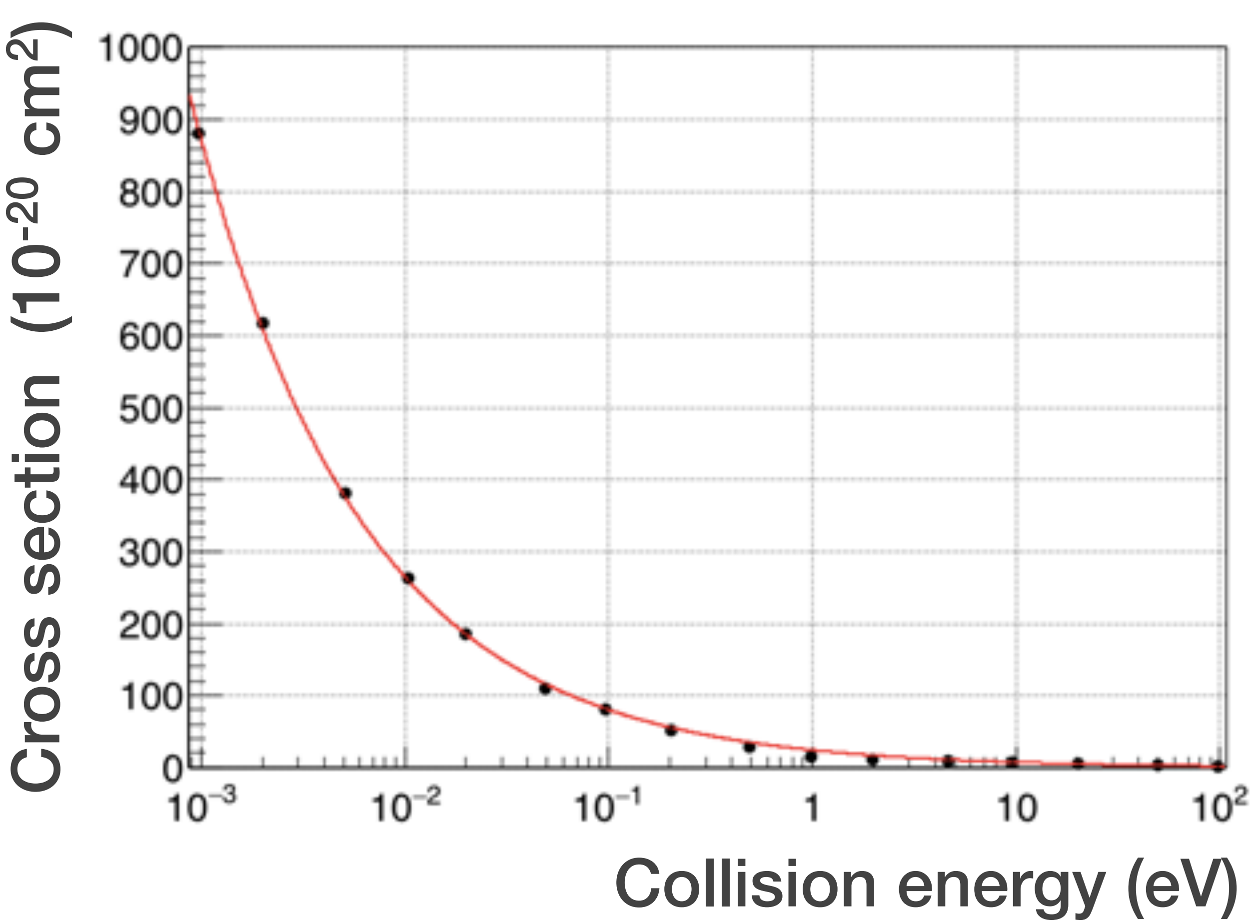


Prototypes for coating optimization are under development.

Collisional Hyperfine Quenching

- Collisional quenching of the HFS triplet state
  - Inelastic scattering μp(F=1)+p -> μp(F=0)+p
  - Only theoretical predictions are known and no measurement had been performed

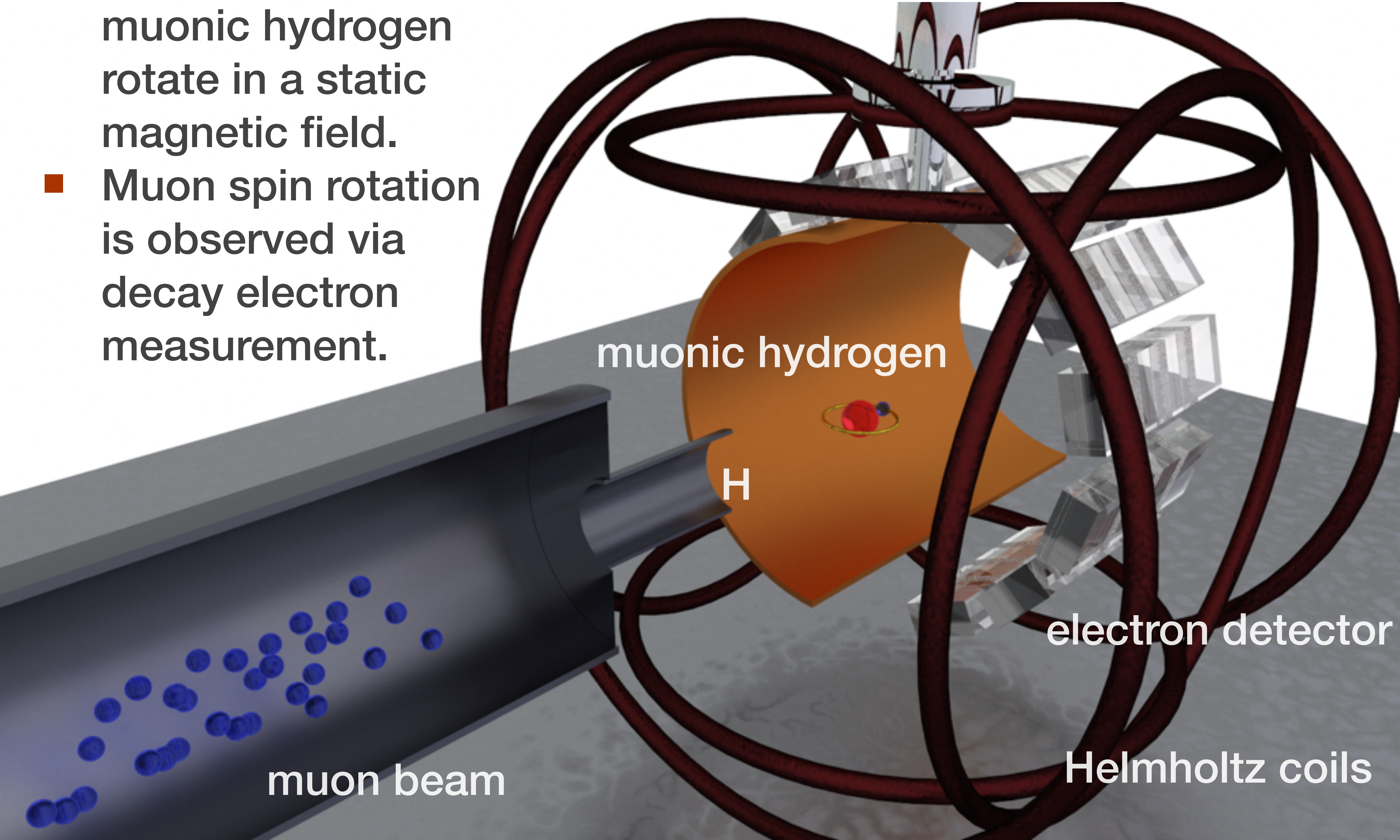




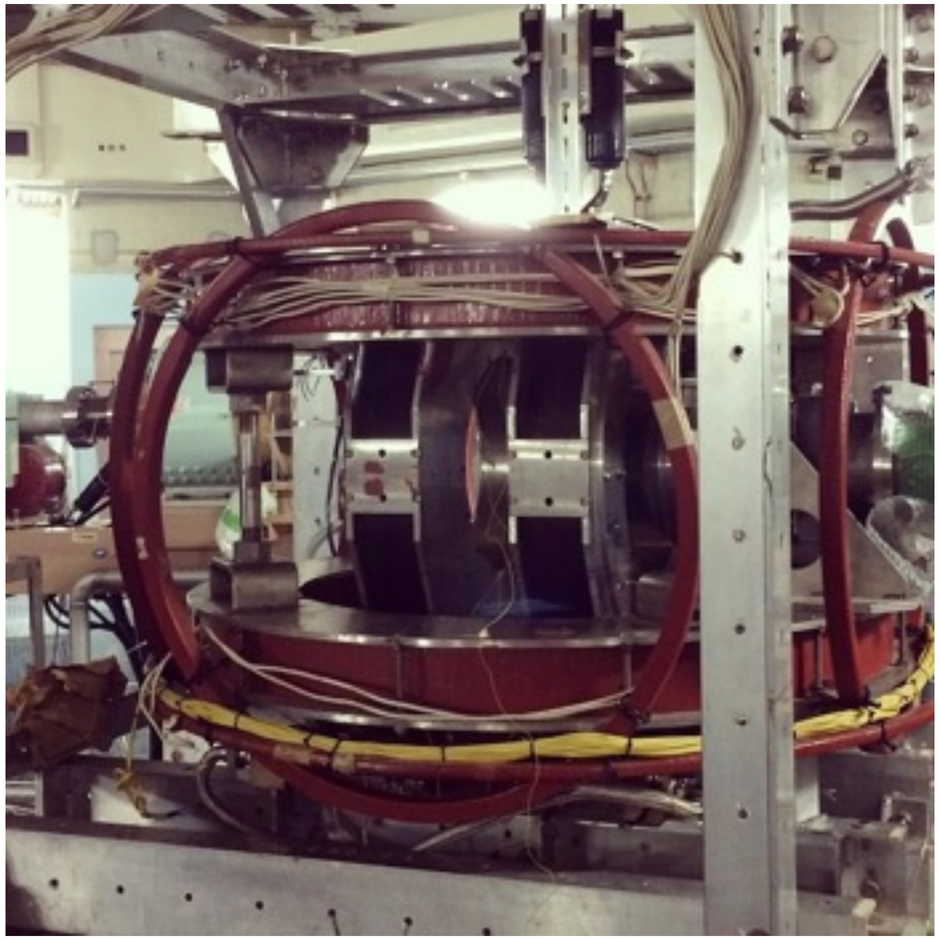
- Quenching rate depends on collision energy (gas temperature) and gas pressure
- Expected lifetime at 20 K, 0.06 atm is 50 ns
- J.S. Cohen, PRA 43, 3460 (1991)
- A new experiment for direct measurement of the quenching rate was proposed

Quenching Rate Measurement

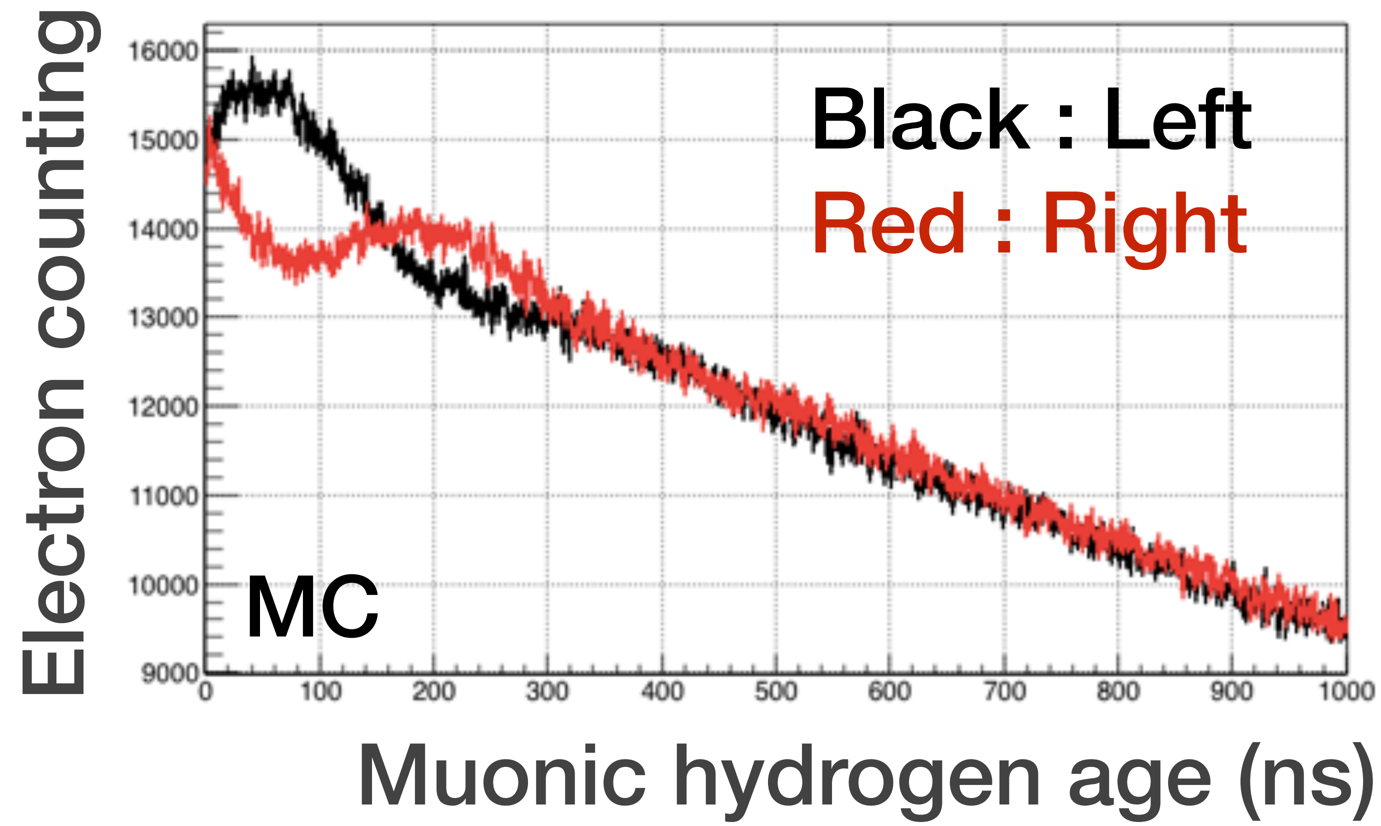
- Only munos in F=1 muonic hydrogen rotate in a static magnetic field.
- Muon spin rotation is observed via decay electron measurement.

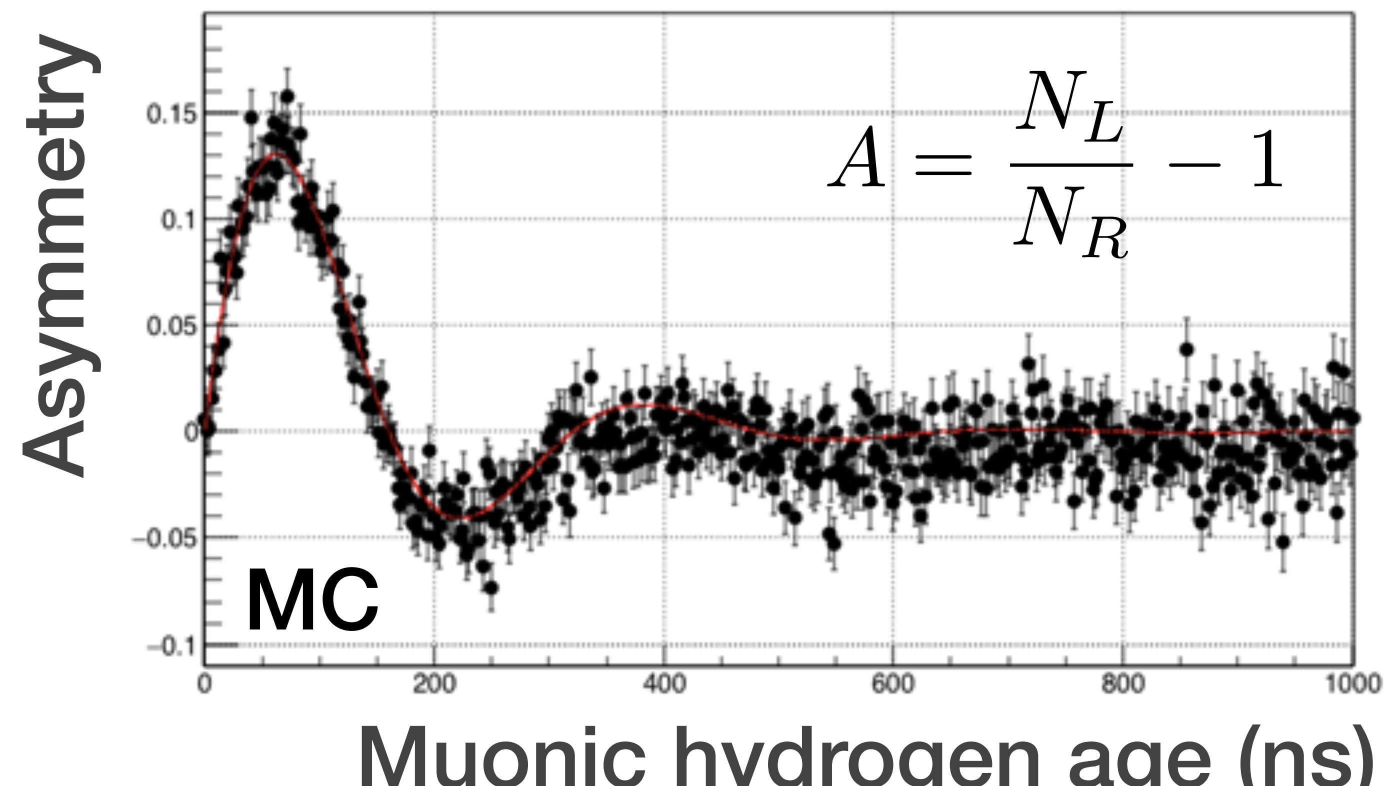


Quenching Rate Measurement

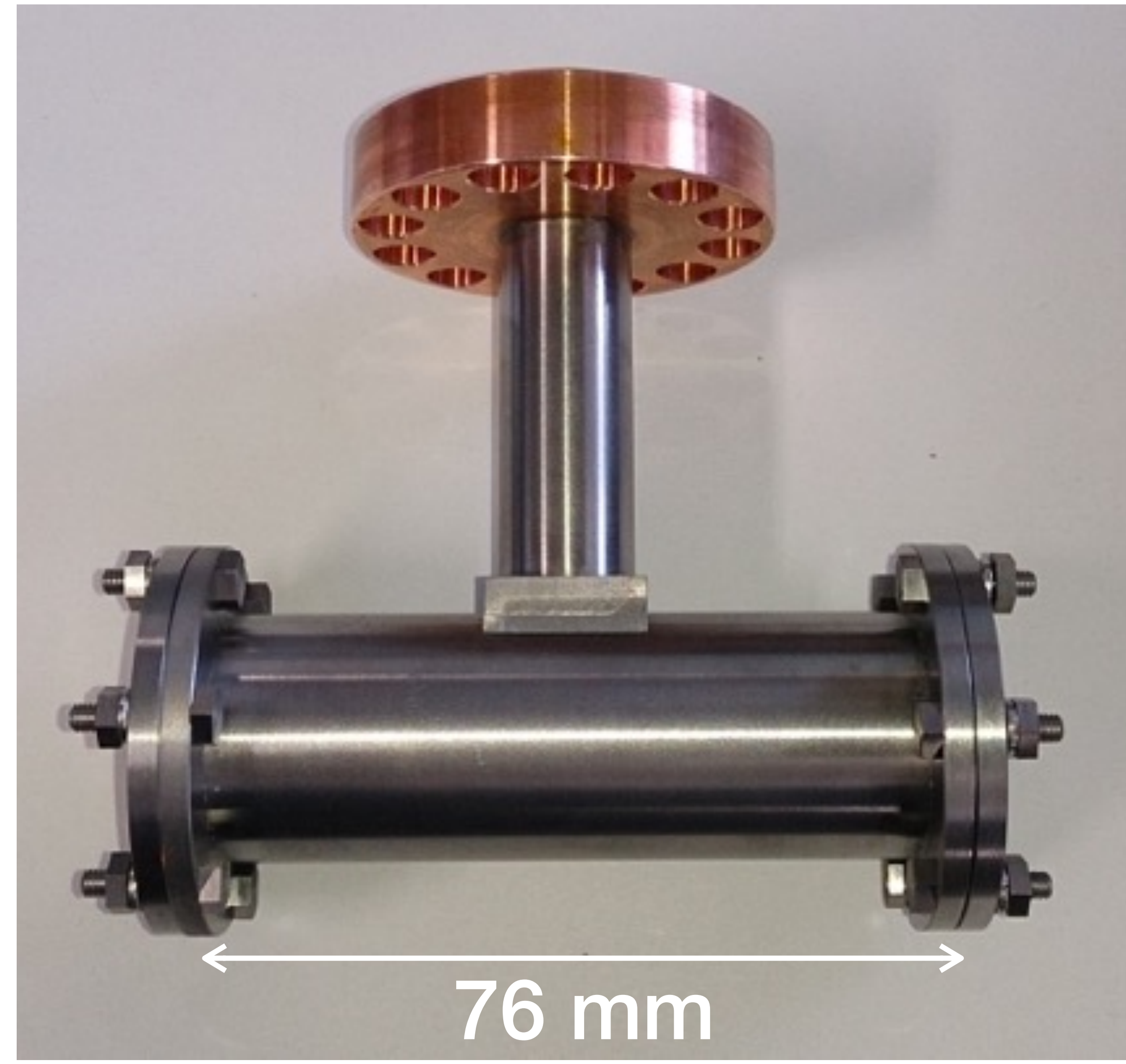


- A transverse field of 600 Gauss is applied in the exp.
- Left/Right electron angular asymmetry is measured.
- Experimental proposal E527 and budget request to RCNP were approved.



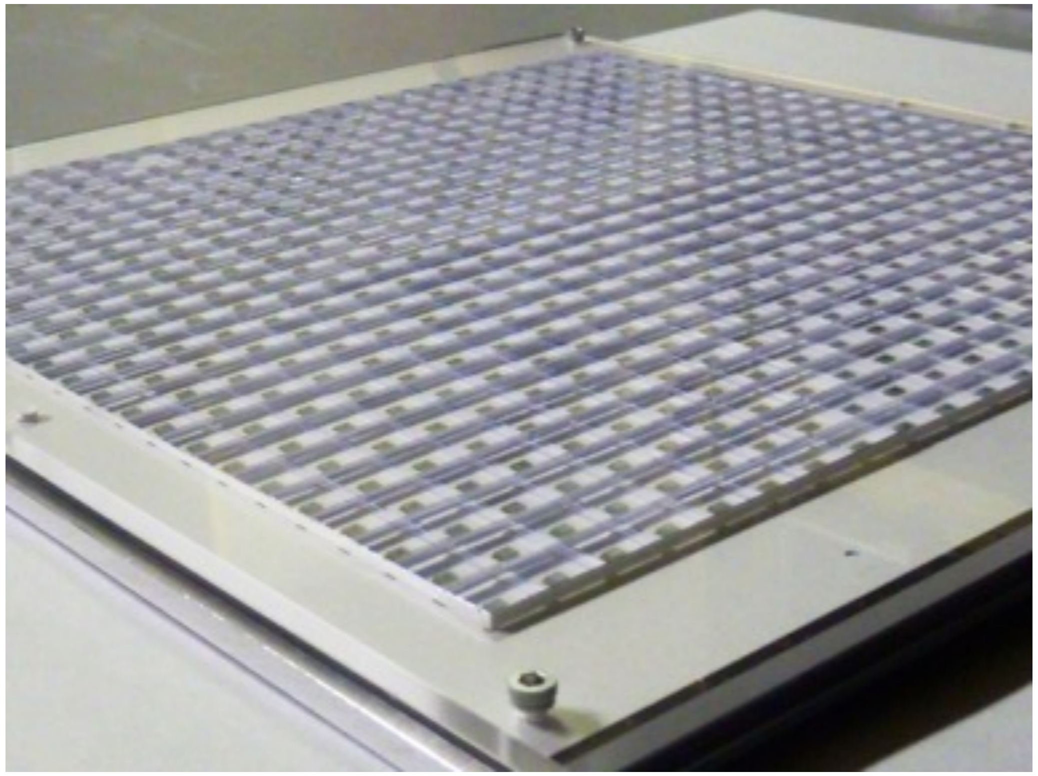


Hydrogen Gas Target System

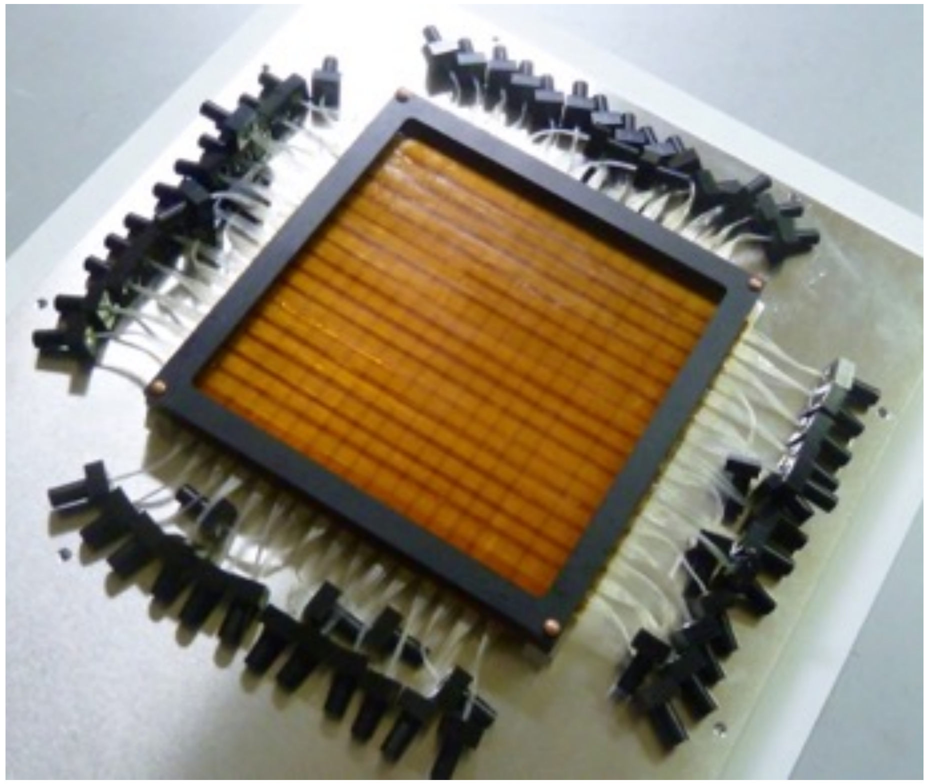


- Temperature is controlled by using a GM cryostat.
- Gas temperature ranges from RT to 20 K.
- Gas density is monitored by a baratron pressure gauge.
- Target cell is made of tungsten for background suppression.

Particle Detectors



Electron detector
Segmented scintillation counter with SiPM readout



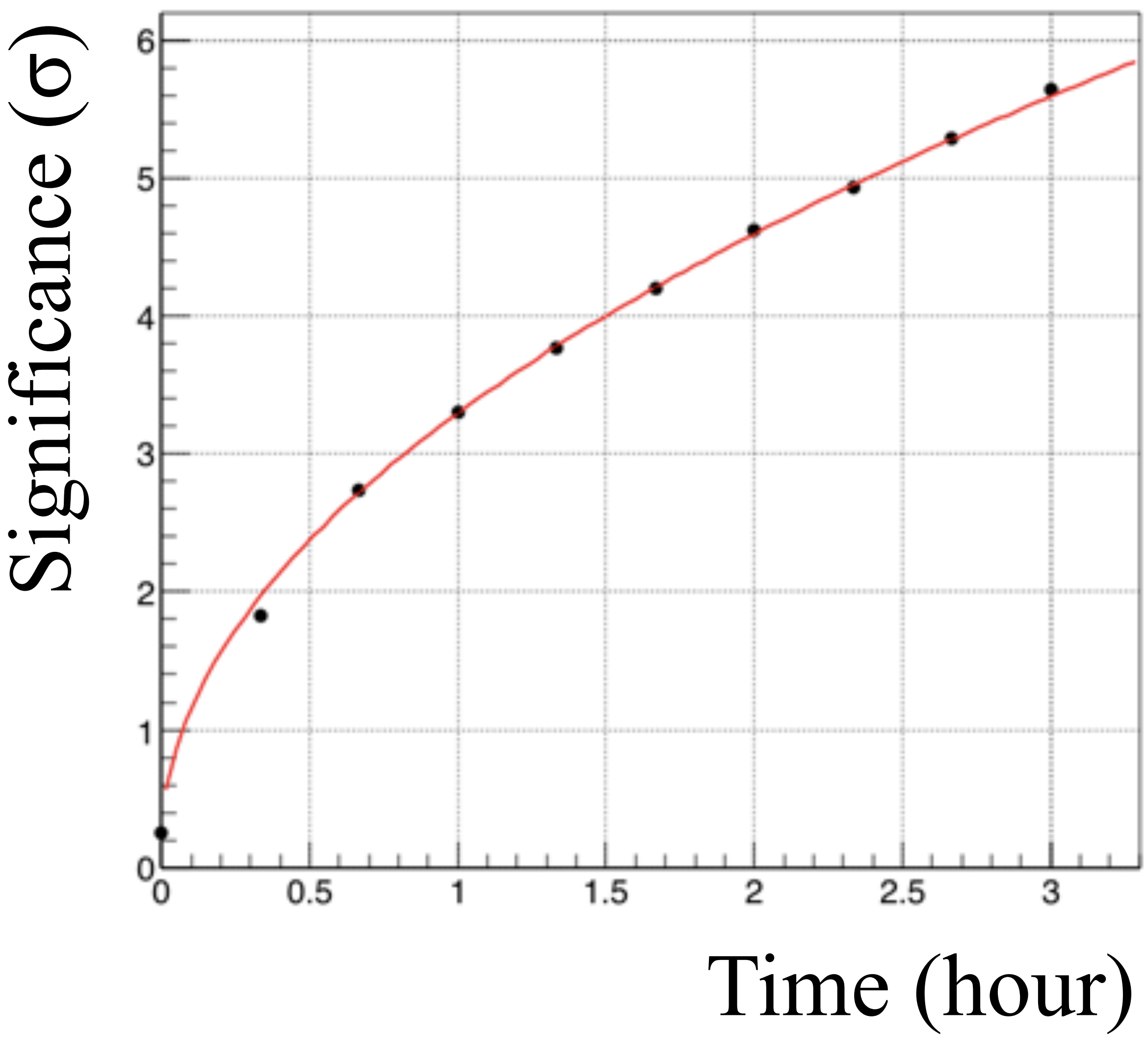
Muon detector
Thin scintillating fiber hodoscope

- **Particle detectors were developed for the muonium HFS experiment and demonstrated by the highest intensity pulsed beam at J-PARC.**

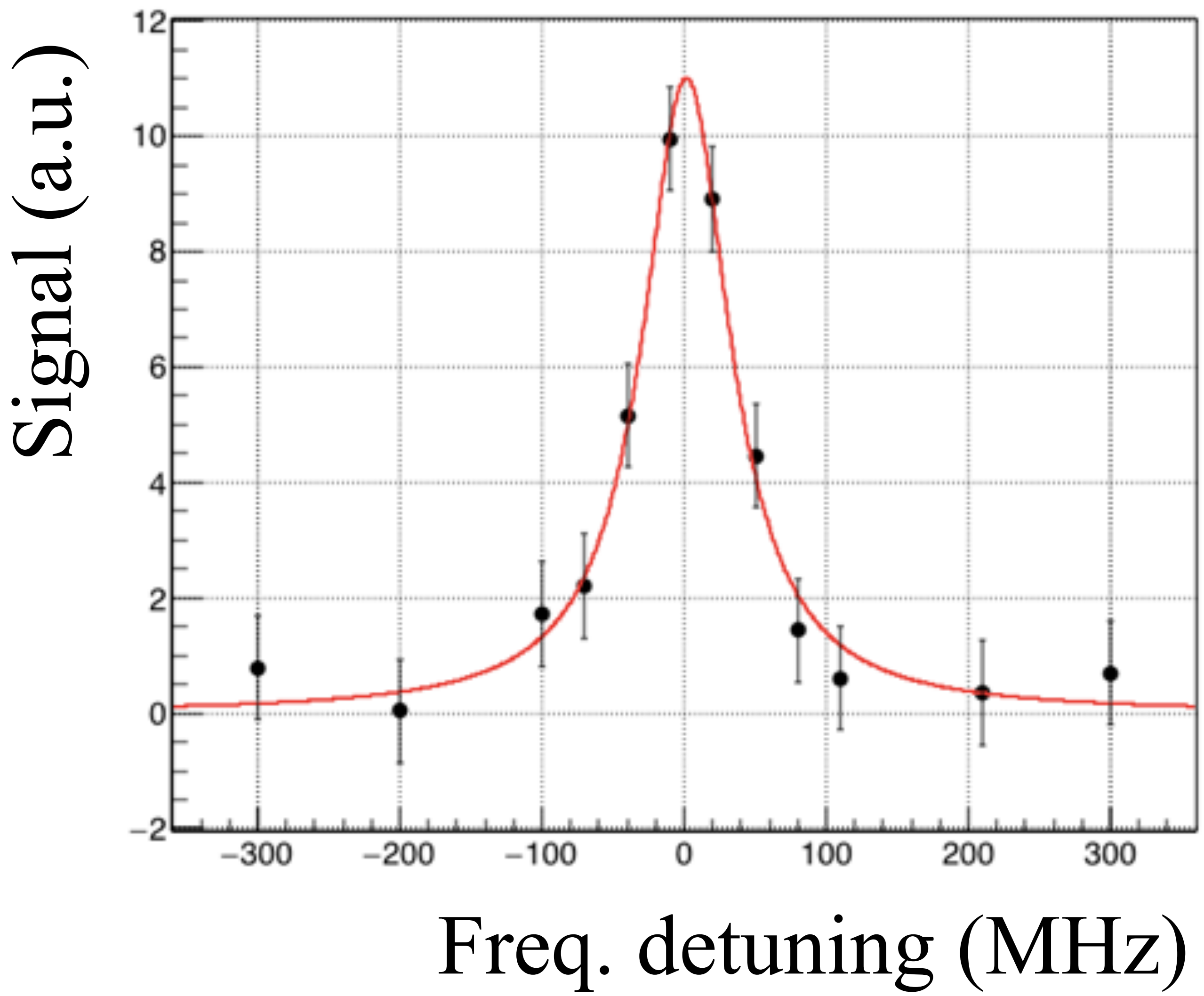
S. Kanda for the MuSEUM Collaboration, Proceedings of Science, PoS(INPC2016)170 (2017).
S. Kanda for the MuSEUM Collaboration, Proceedings of Science, PoS(PhotoDet2015)036 (2016).
S. Kanda for the MuSEUM Collaboration, RIKEN APR Vol. 48 (2016).

Statistical Significance

Statistics on resonance



Laser frequency scan



- **The laser pulse energy of 20 mJ and the beam intensity of 3.5×10^5 muon/s give 3σ significance in an hour**
- **At J-PARC, two weeks of measurement is enough for HFS resonance spectroscopy with 2 ppm uncertainty.**

Summary and Outlooks

- "Proton Radius Puzzle" is one of the most important unsolved problem in sub-atomic physics.
- We proposed a new measurement of the HFS in muonic hydrogen atom.
- Two obstacles and solutions for them:
    - HFS transition is forbidden and difficult to occur
        - Development of an intense laser system
    - Fast quenching of the triplet state
        - Direct measurement of triplet lifetime is planned
        - (Nuclear spin polarized target is under study)
- Two years for development, one year for measurement