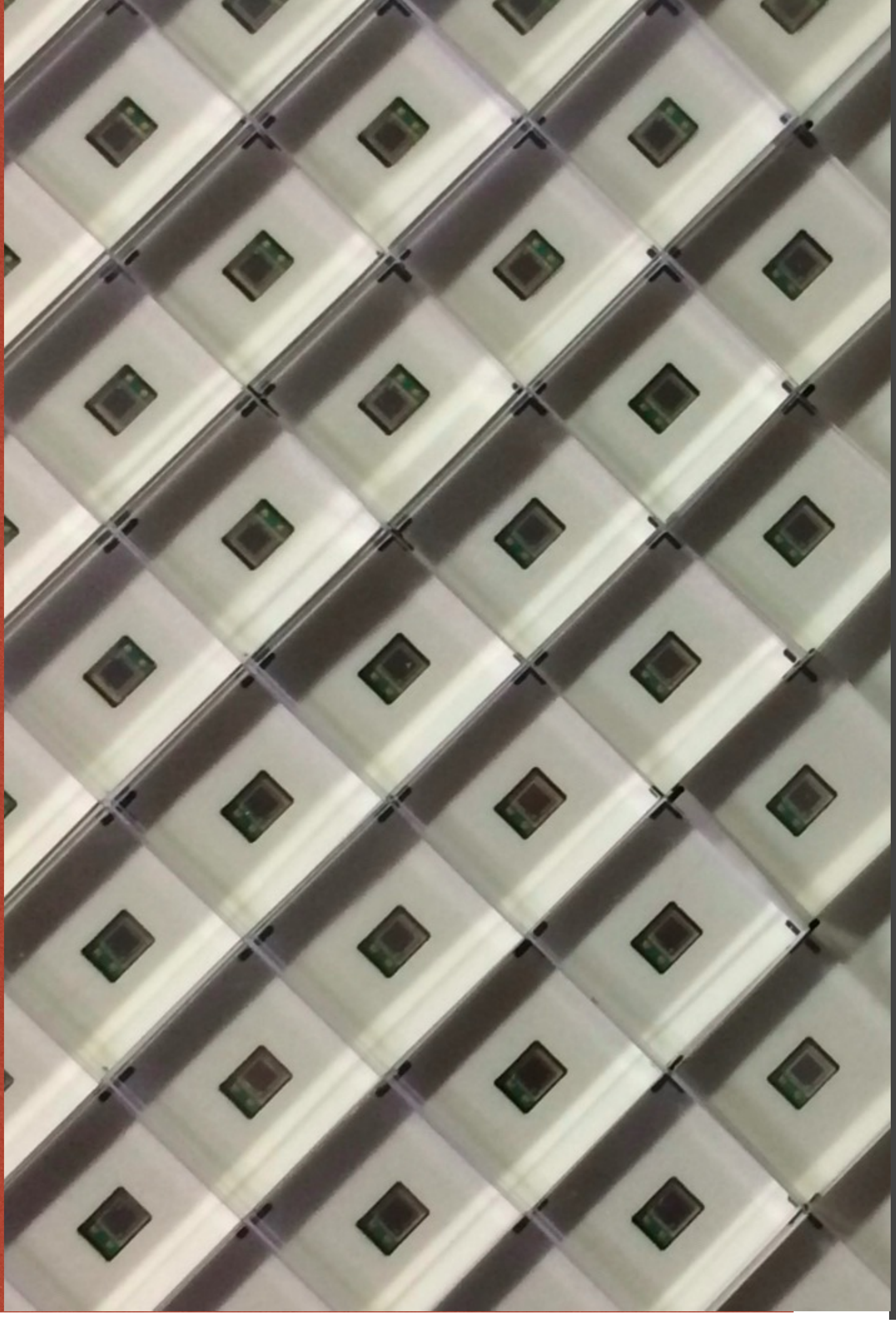
Precision Spectroscopy of Exotic Atoms Involving Muon



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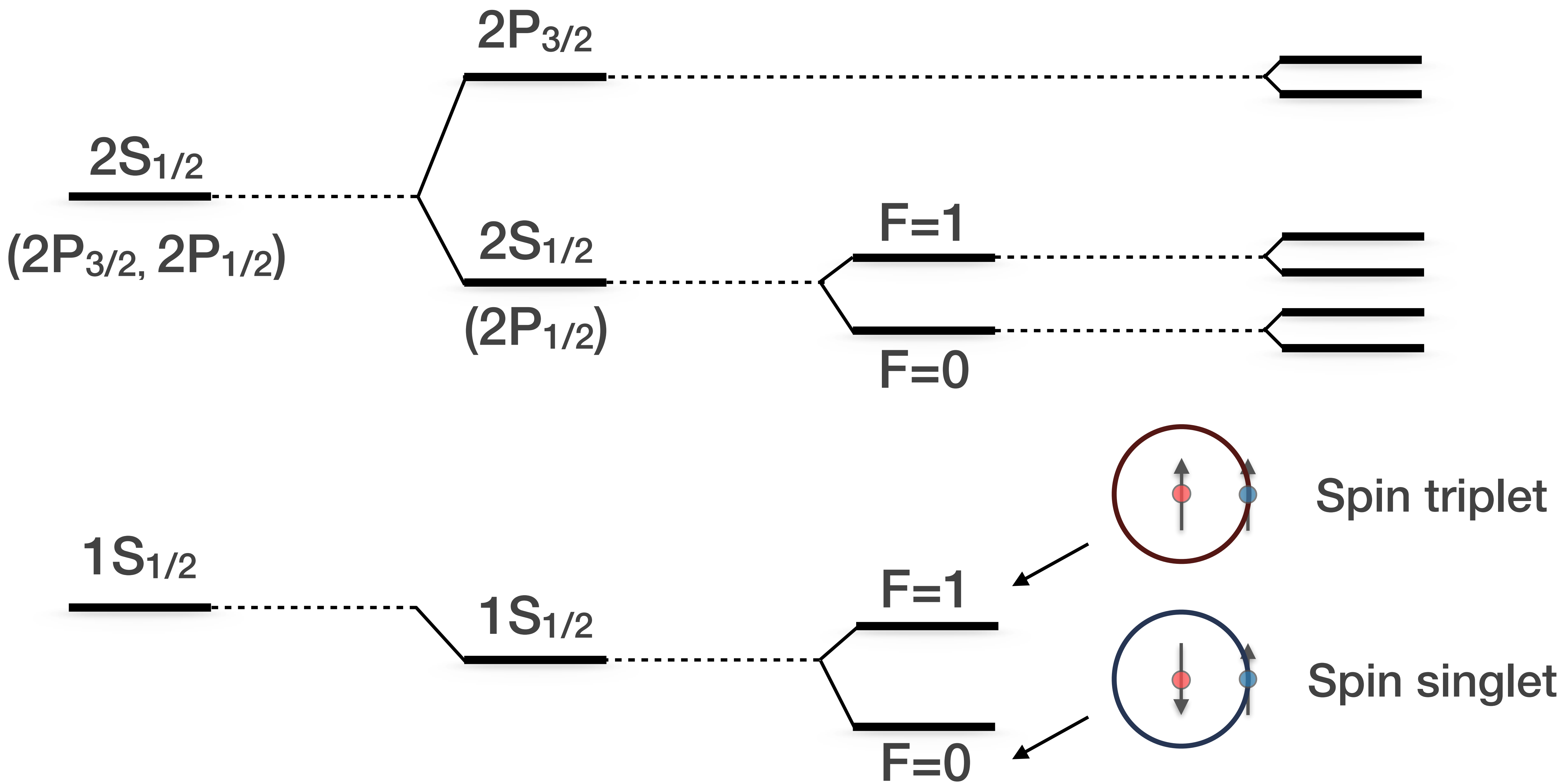
2018/08/16

Spectroscopy of H-Like Atoms



<u>Lyman series (1906)</u>
Bohr model (1913)

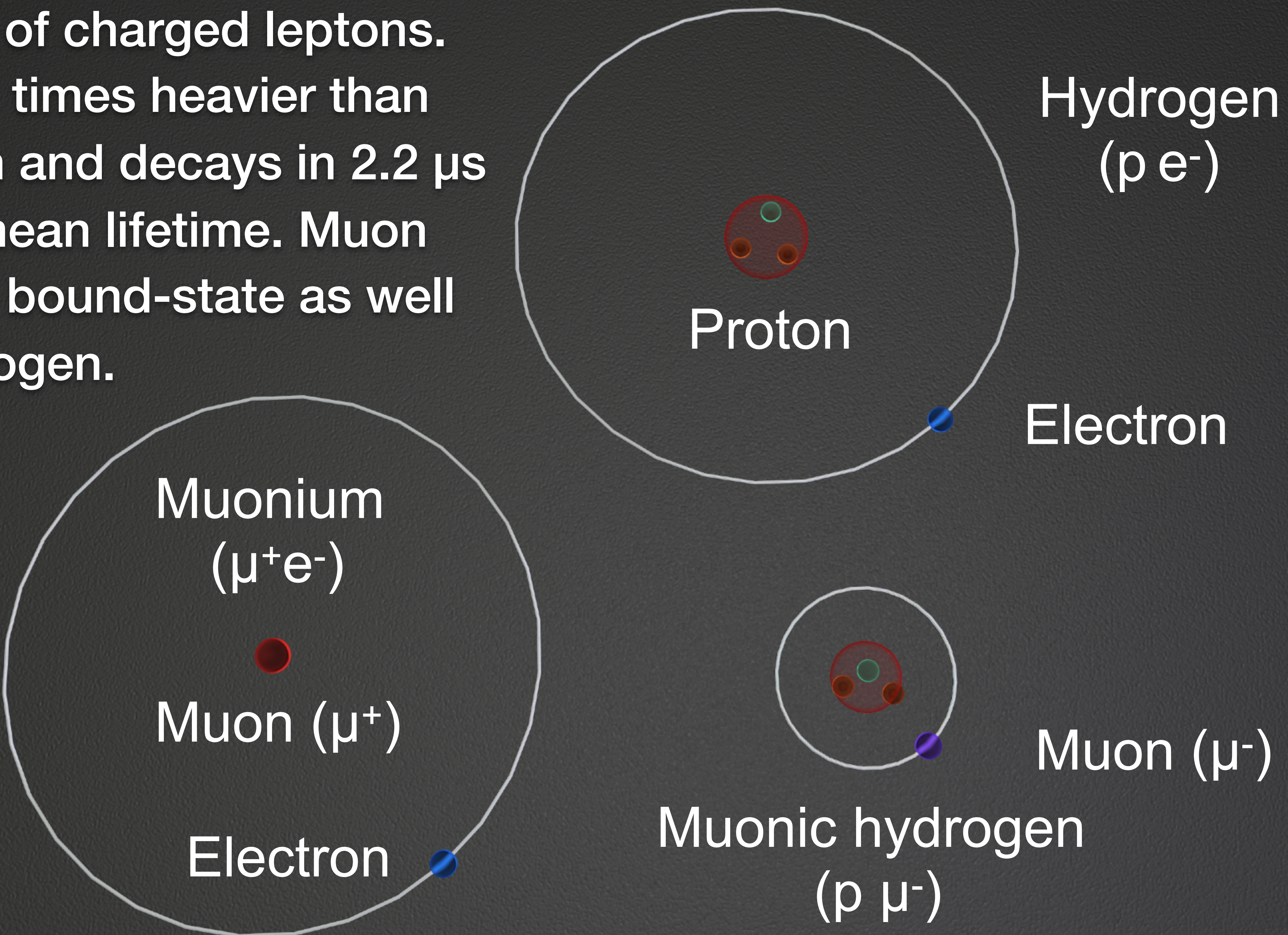
<u>Hyperfine structure (1881)</u>
Nuclear magnetic moment (1924)

<u>Fine structure (1887)</u>
Sommerfelt-Bohr model (1916)

<u>Lamb shift (1947)</u>
QED (1949)

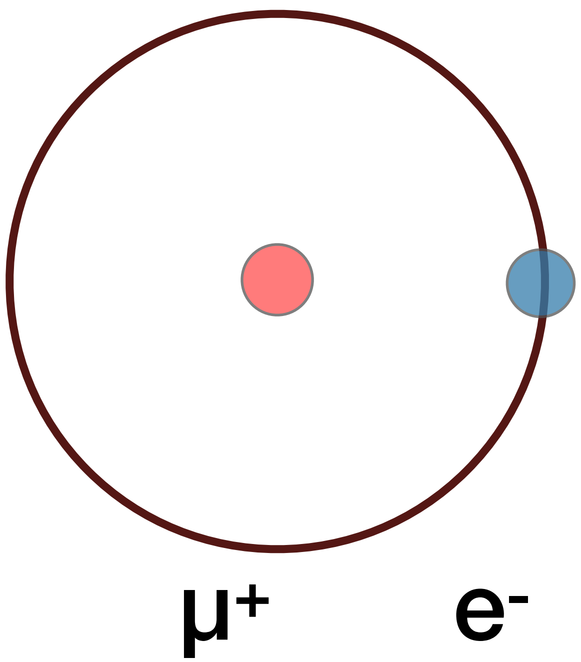
Exotic Atoms Involving Muon

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.

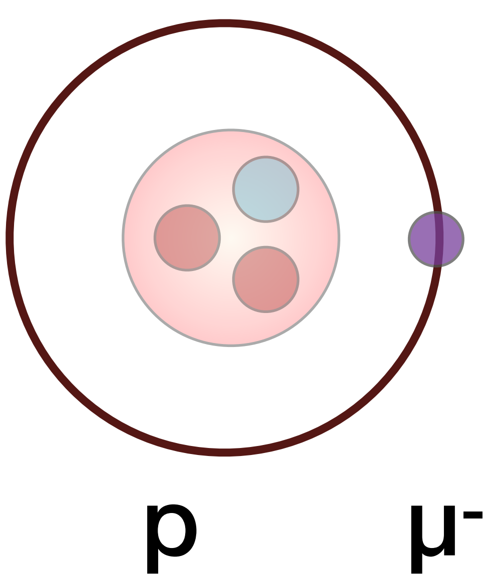


Spectroscopy of Muonic Systems

- What can we extract from muonic atom spectroscopy?
  - Fundamental constants, QED, Nuclear physics…



- Muon magnetic moment (HFS, μ_μ/μ_p)
- Muon mass (1S-2S, m_μ/m_e)
- Muon charge (1S-2S, q_μ/q_e)
- Fine structure constant (HFS)
- Bound-state QED theory



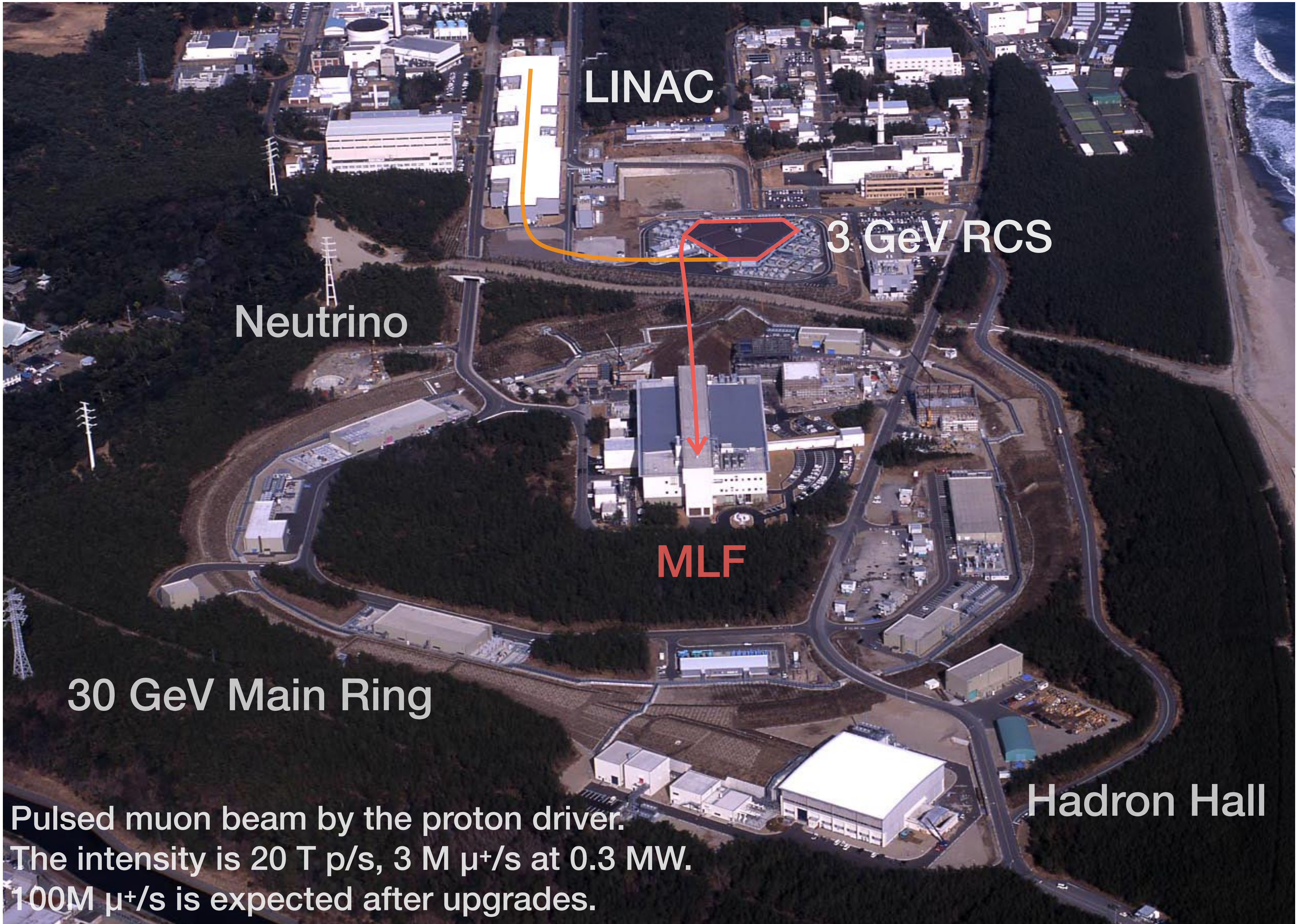
- Proton charge radius (Lamb shift)
- Proton Zemach radius (HFS)
- Proton polarizability (HFS, Lamb shift)
- Rydberg constant (Lamb shift)
- Bound-state QED theory (Sternheim interval)

- Today's talk covers two different muonic systems.

	Muonium (μ^+e^-) MuSEUM	Muonic Hydrogen (μ^-p) 2014MS04
HFS (1S)	4.463 GHz	44.23 THz
	Microwave	Mid-IR Laser

- At J-PARC,
  - Microwave spectroscopy of muonium is ongoing.
  - Laser spectroscopy of muonic hydrogen is in preparation.
- Two experiments have different energy scales and motivations, however, the measurement principle is similar.

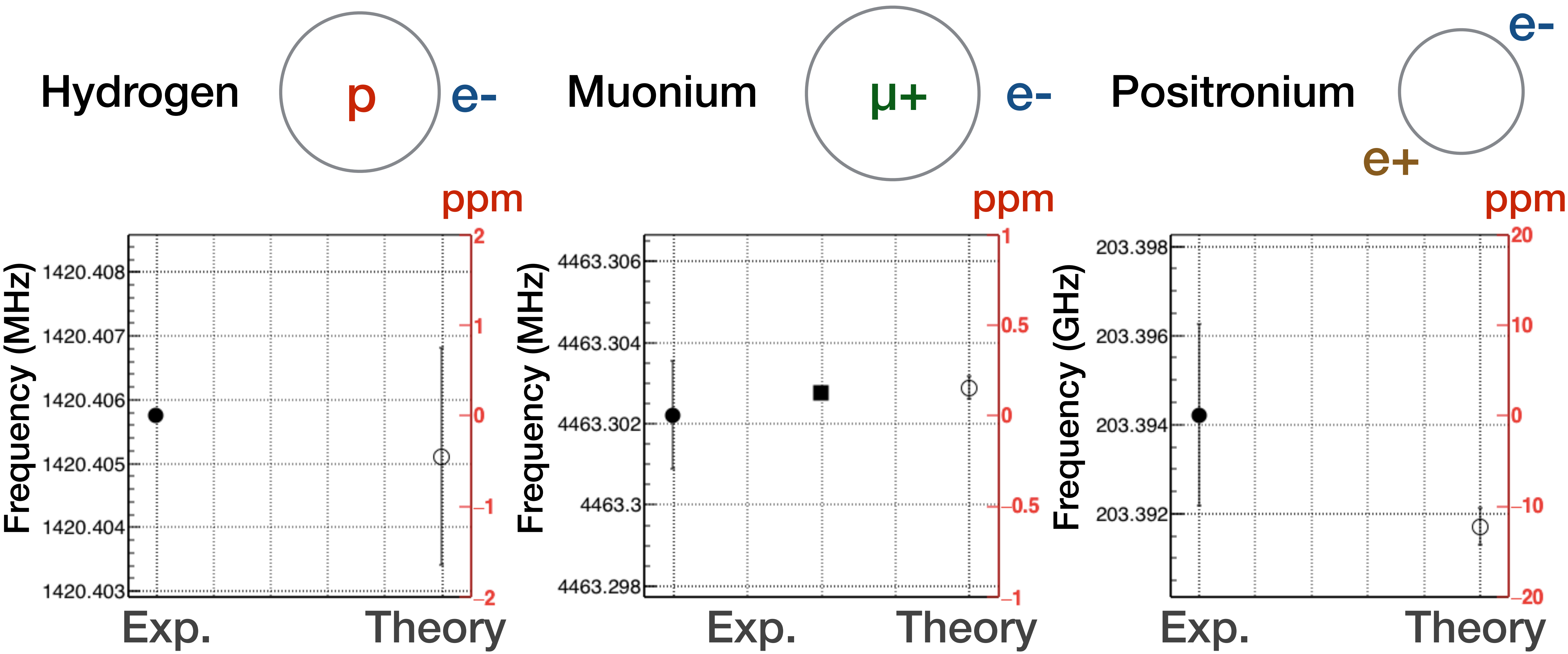
J-PARC



Pulsed muon beam by the proton driver.
The intensity is 20 T p/s, 3 M μ^+/s at 0.3 MW.
100M μ^+/s is expected after upgrades.

Muonium HFS

Hyperfine Splitting of H-Like Atoms



- Hyperfine splitting (HFS) in ground-state hydrogen-like atoms:
  - (left) hydrogen; (center) muonium; (right) positronium.
- Muonium provides the most precise theory/experiment comparison.
  - Experiment: 12 ppb W. Liu et al., PRL, 82, 711 (1999).
  - Theory: 63 ppb D. Nomura and T. Teubner, Nucl. Phys. B 867 (2013).

Precision Test of Bound-State QED

- **Theoretical prediction of muonium HFS**

$$\Delta\nu_{\mathrm{Mu}} = 4\ 463\ 302\ 868(271)\ \mathrm{Hz}$$

- **Contributions from each sector**

$$\Delta\nu_{\mathrm{Mu\ (QED)}} = 4\ 463\ 302\ 700\ (271)\ \mathrm{Hz}$$

$$\Delta\nu_{\mathrm{Mu\ (QCD)}} = 232.7\ (1.4)\ \mathrm{Hz}$$

$$\Delta\nu_{\mathrm{Mu\ (EW)}} = -65\ \mathrm{Hz}$$

- **Theoretical uncertainty**

Term	Contribution (Hz)	Major source
Radiative correction	5	Uncalculated contribution
Recoil correction	64	Constant term
Radiative recoil correction	55	Constant term
Hadronic correction	1.4	Vacuum polarization
Total	85	

- **Remaining uncertainties are arising from errors in physical constants (fine structure constant, Rydberg constant, and muon mass).**

D. Nomura and T. Teubner, Nuclear Physics B 867 (2013) 236-243.

Muon-to-Electron Mass Ratio

- By comparing the theoretical expression and experimental result of the muonium HFS, the muon-to-electron mass ratio can be extracted.

$$\nu_{\text{theory}} = \frac{16}{3}\alpha^2 c R_\infty \frac{m_e}{m_\mu}\left[1+\frac{m_e}{m_\mu}\right]^{-3} + \delta(\alpha,\ m_e/m_\mu)$$

- The muon-to-electron mass ratio is one of the necessities to the experimental determination of the muon anomalous magnetic moment (muon *g*-2).

$$a_\mu(\text{Exp.}) = 11\ 659\ 208.9(6.3)$$

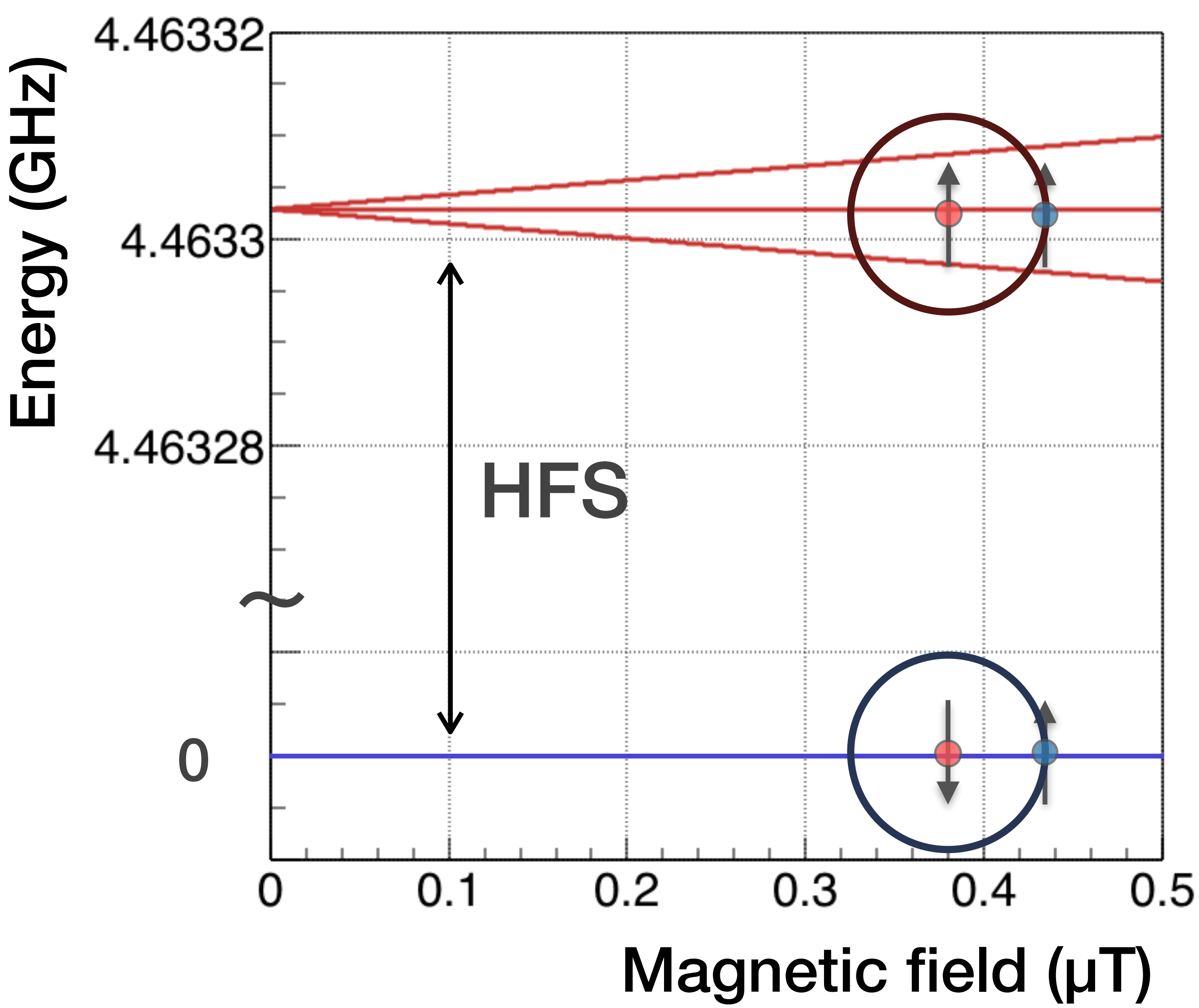
$$a_\mu(\text{Theory}) = 11\ 659\ 181.8(4.9)$$

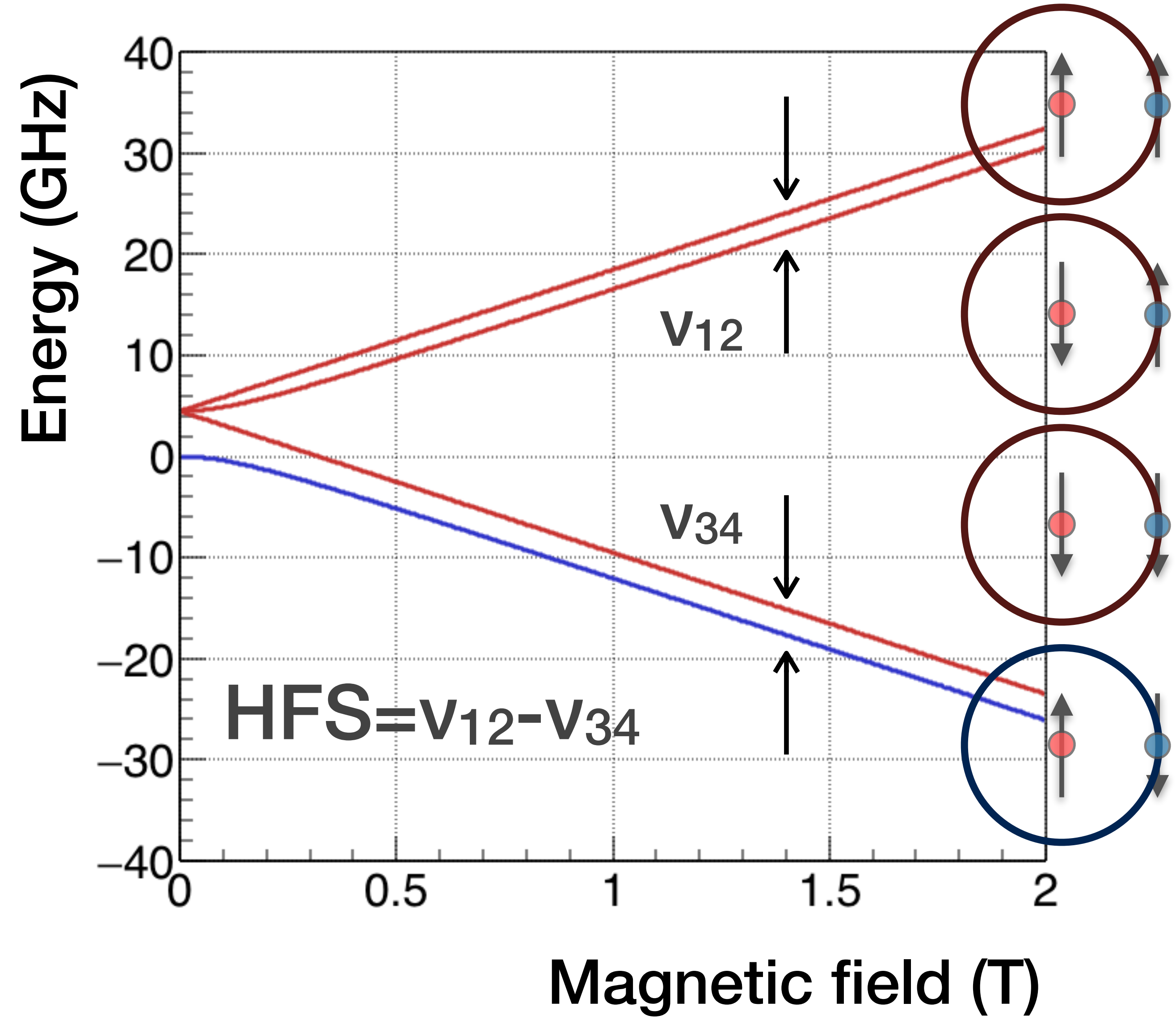
$$a_\mu = \frac{g_e}{2}\frac{\omega_a}{\omega_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}$$

P. J. Mohr, D. B. Newell, and B. N. Taylor, "CODATA2014", Rev. Mod. Phys. 88, 035009 (2016).

G.W. Bennett *et al*., Phys. Rev. D73, 072003 (2006). K. Hagiwara *et al*., JPHGB G38, 085003 (2011).

Direct and Indirect Measurements





- Two independent methods for the hyperfine splitting measurement
  - Direct measurement at “zero” magnetic field (ZF, in progress).
  - Indirect measurement in a high magnetic field (HF, in preparation).
- Our goal is ten-fold of improvements in both ZF and HF experiments.

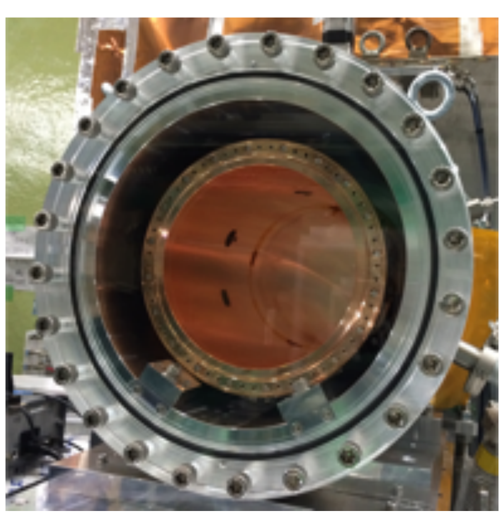
MuSEUM Experiment

- Muonium Spectroscopy Experiment Using Microwave
  - Zero field: Demonstration at existing beamline.
  - High field: Highest precision experiment at dedicated beamline under construction.

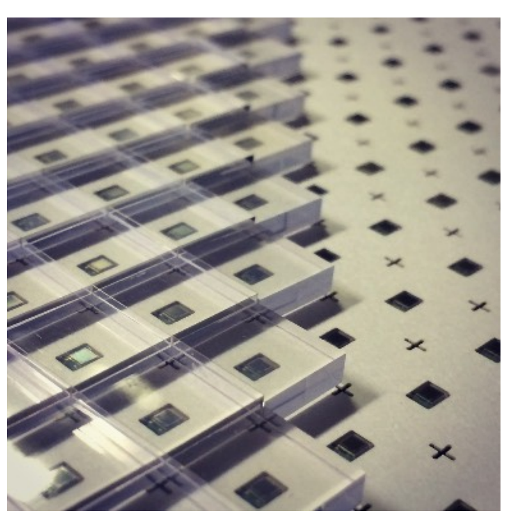
2011 2013 2015 2017 2019

ZF: R&D | 1st ZF | 2nd ZF | 3rd ZF | 4th ZF?

HF: Proposal Submitted | R&D | New Beamline Construction | 1st HF?

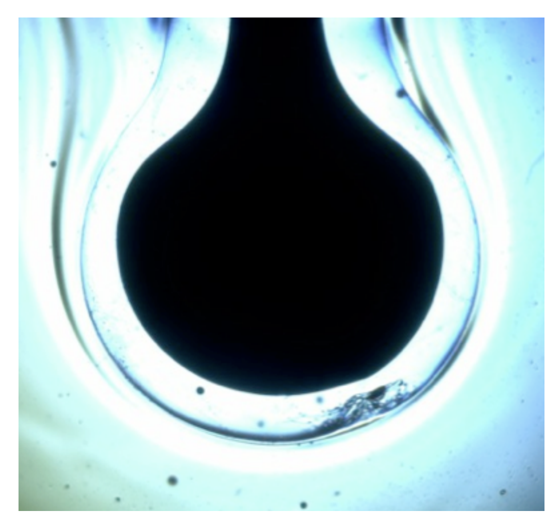


RF Cavity

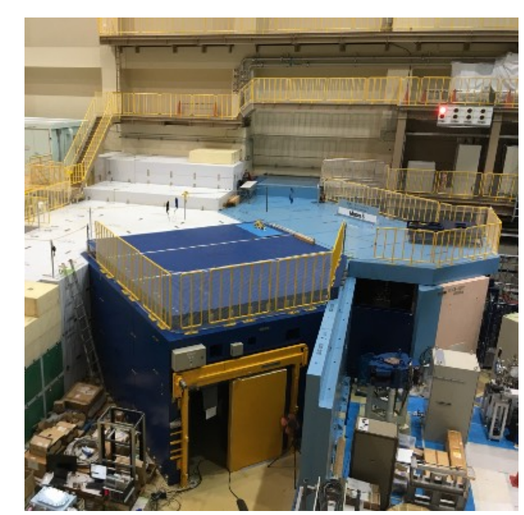


Detector

Magnet



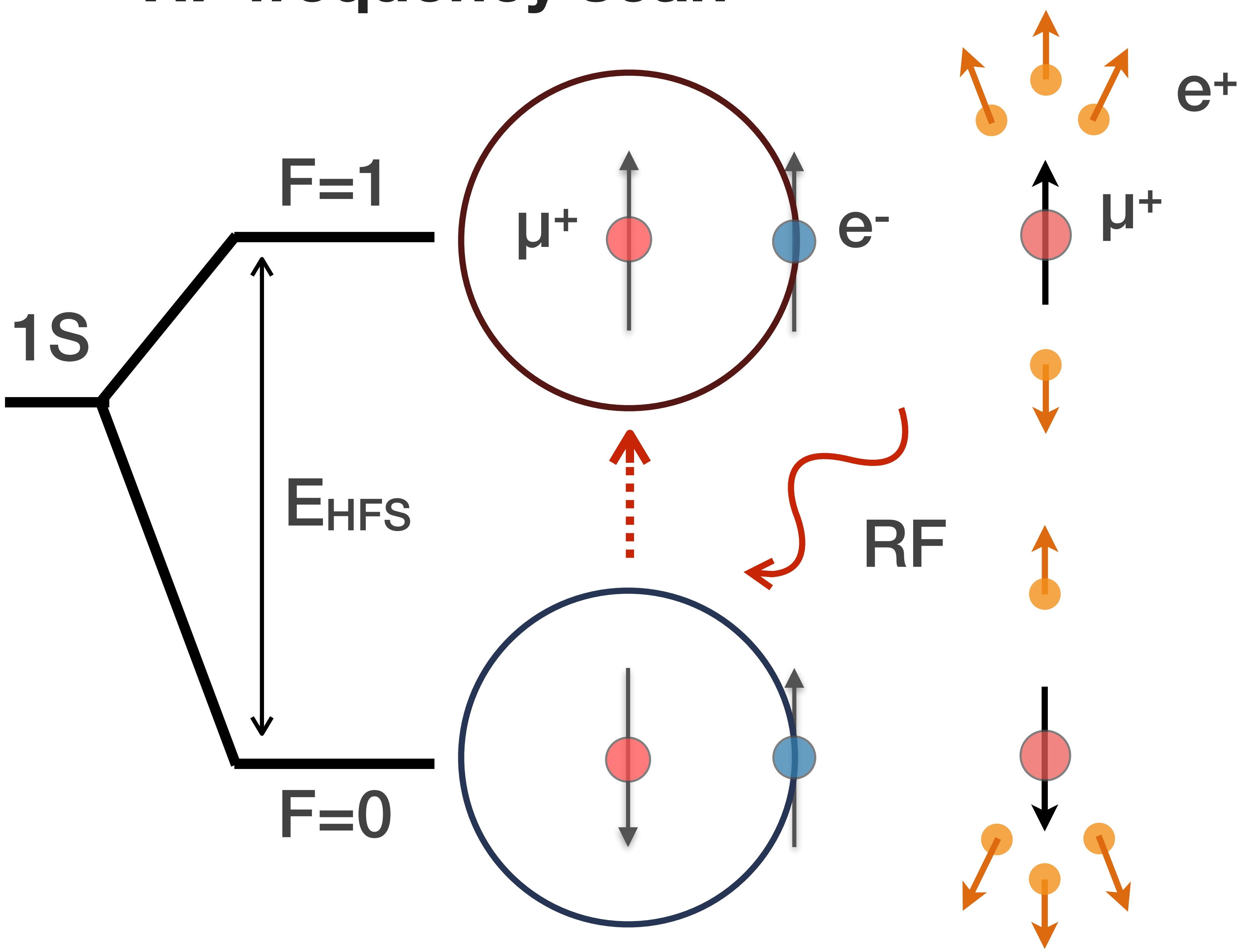
Field probe

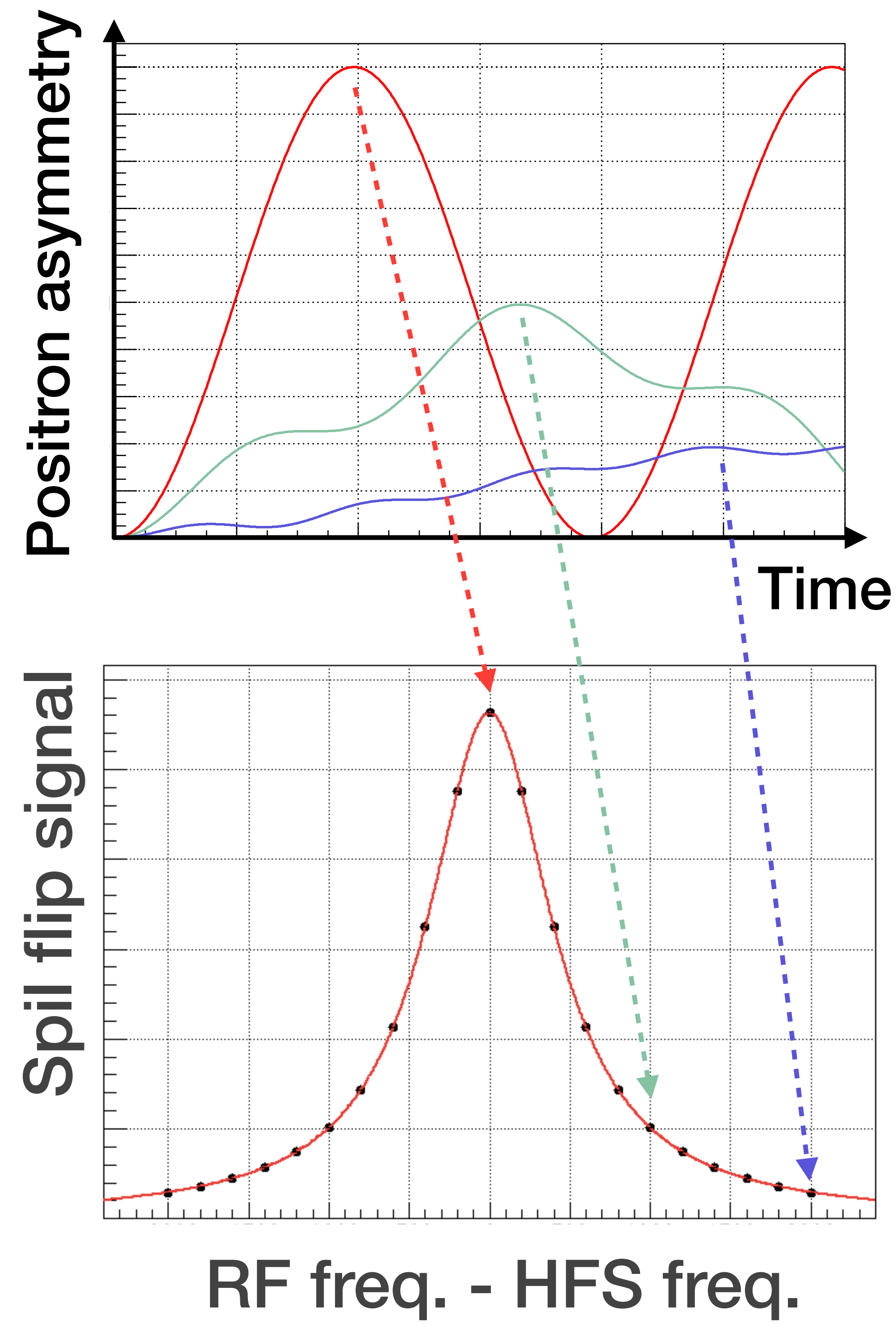


New beamline

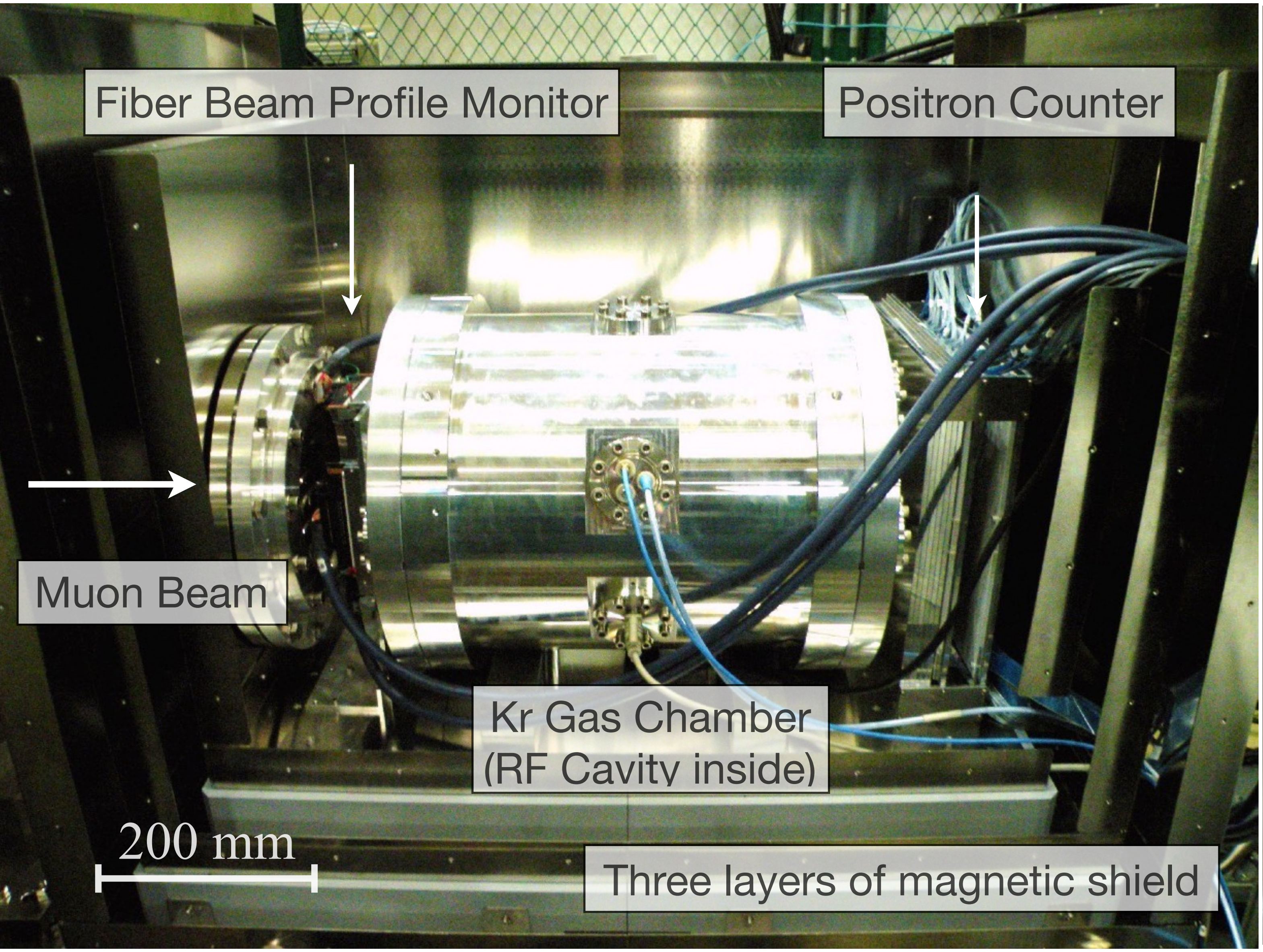
Experimental Principle/Procedure

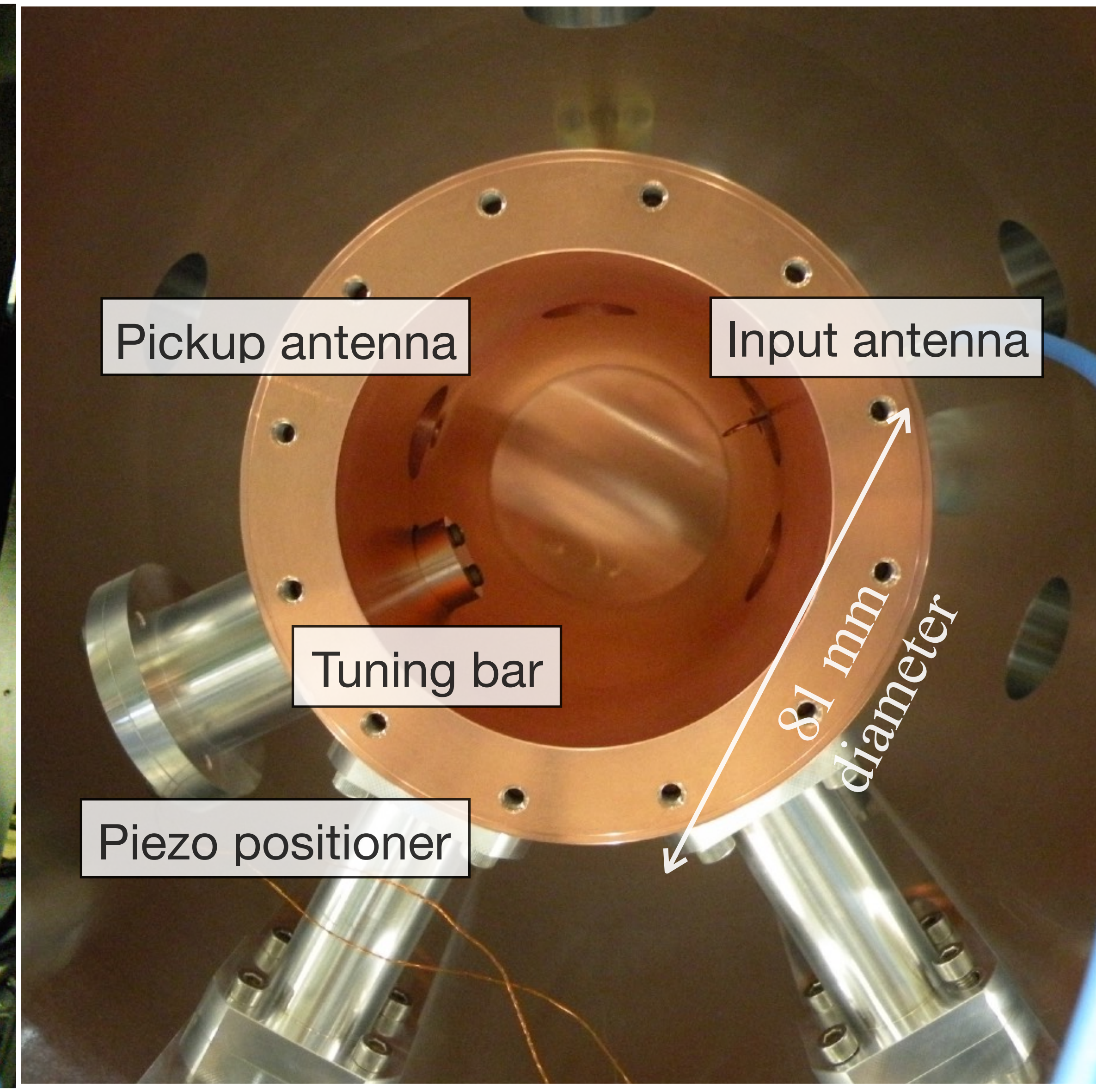
- **RF induced hyperfine transition and muon spin flip**
- **Parity violating muon decay**
- **Decay positron angular asymmetry**
- **RF frequency scan**





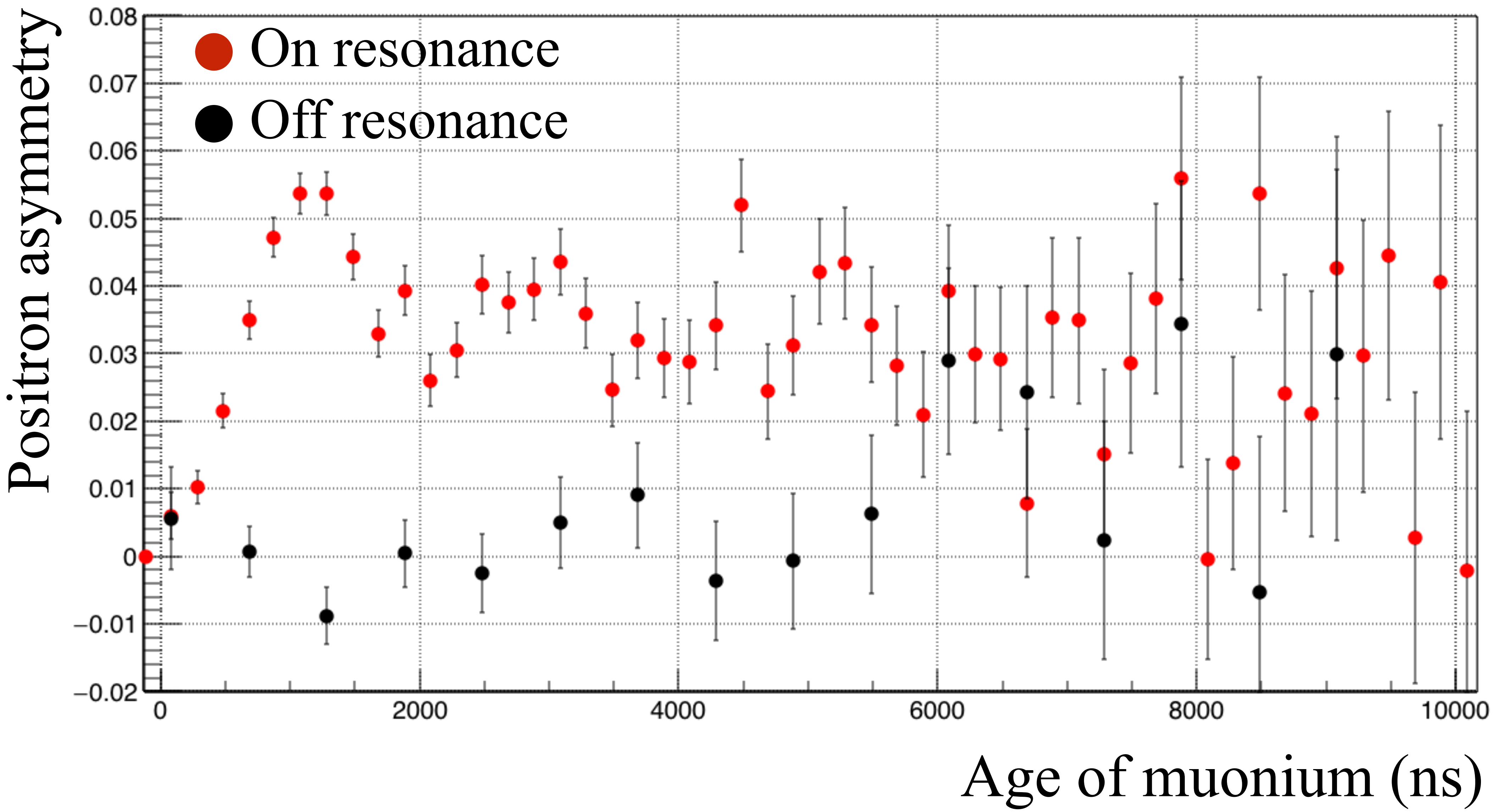
Experimental Setup





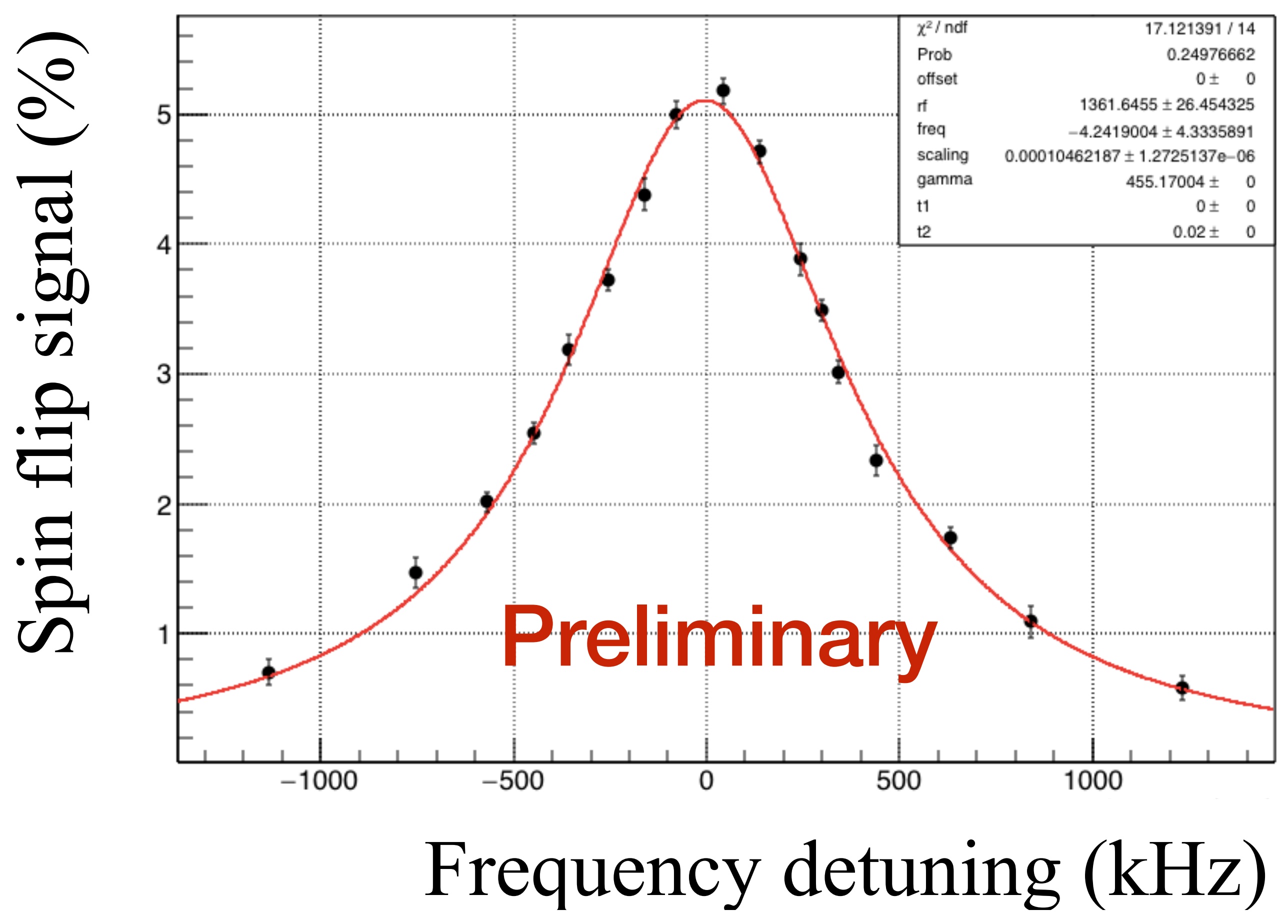
- **Experimental setup for the resonance measurement at J-PARC MLF MUSE D2 beamline: (left) the magnetic shield, gas chamber, beam profile monitor, and positron counter; (right) the microwave cavity inside the gas chamber.**

Muonium Spin Flip Signal



- **Oscillating muonium spin flip signal was observed.**
- **Time integration of the asymmetry gives a data point in the resonance line shape (next page).**

Muonium HFS Result (2017 Feb.)



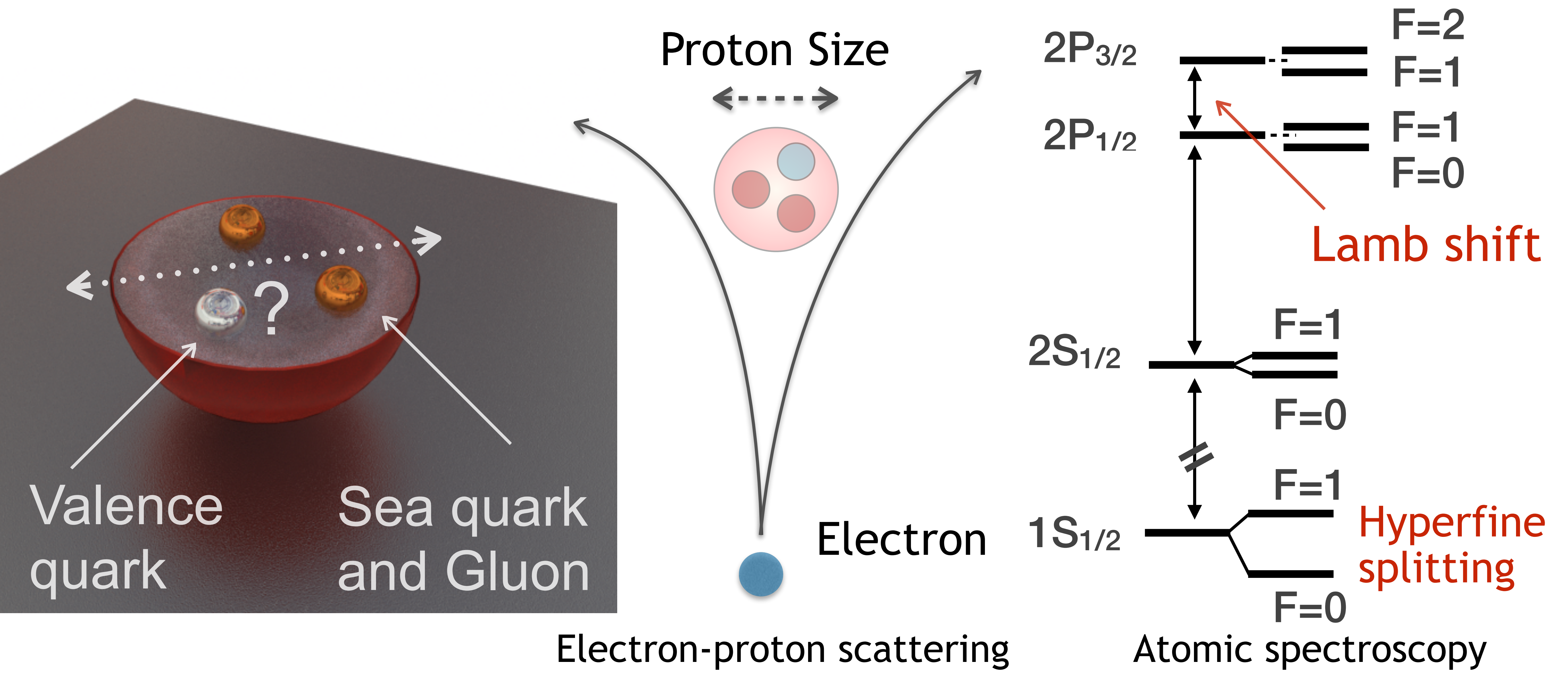
Result of the second resonance measurement in Feb. 2017 after some improvements in apparatuses. Statistical uncertainty was 4 kHz and this precision is comparable to that of the precursor experimental case.

	Uncertainty
Statistics	4333 Hz
Atomic collisional shift	46 Hz
RF power drift	26 Hz
Gas impurity	12 Hz
Beam profile	9.8 Hz
Gas pressure fluctuation	6 Hz
Detector pileup	2 Hz
Beam intensity	0 Hz
Magnetic field	0 Hz

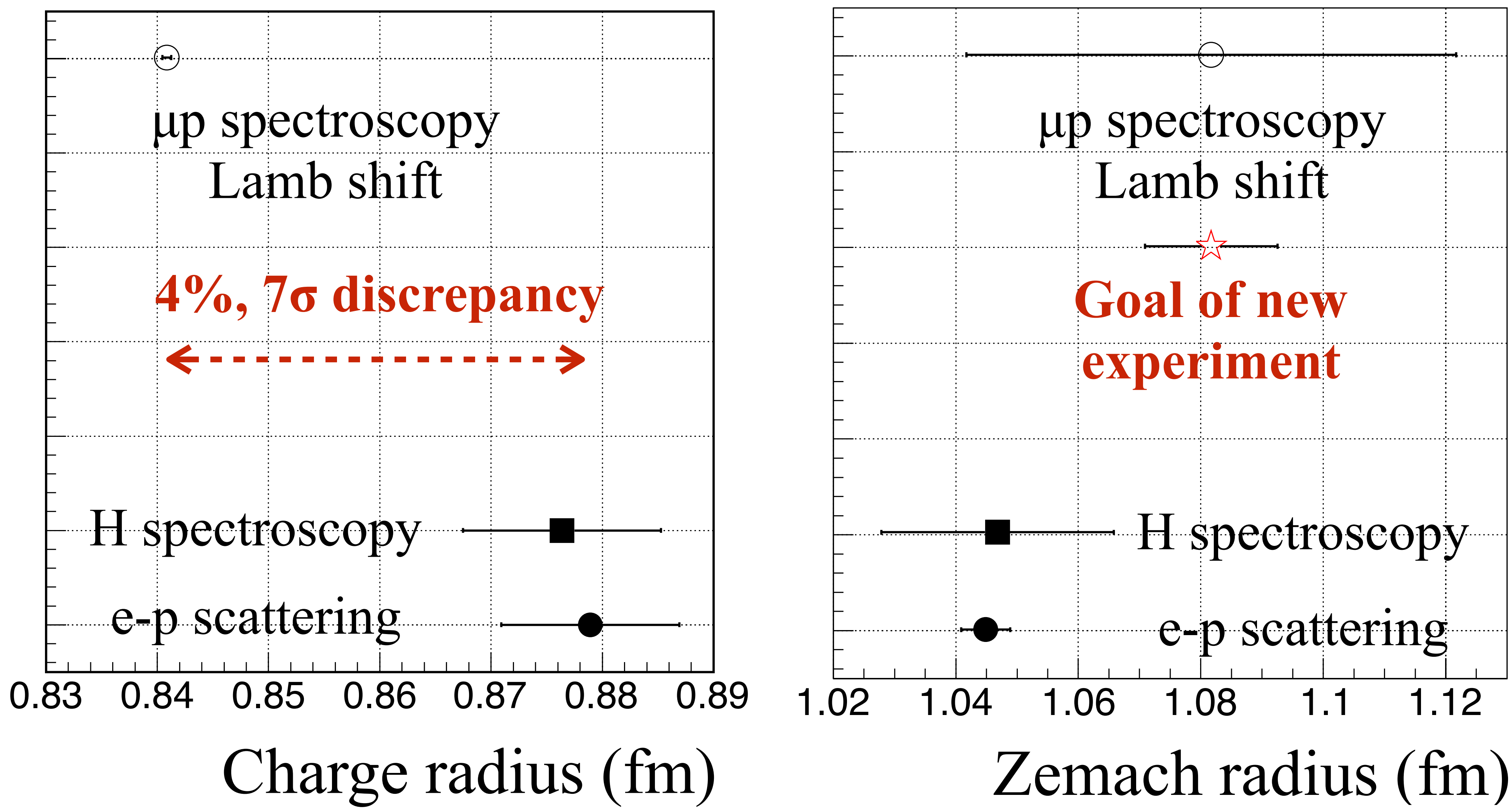
Muonic Hydrogen HFS

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.



Proton Radius Puzzle



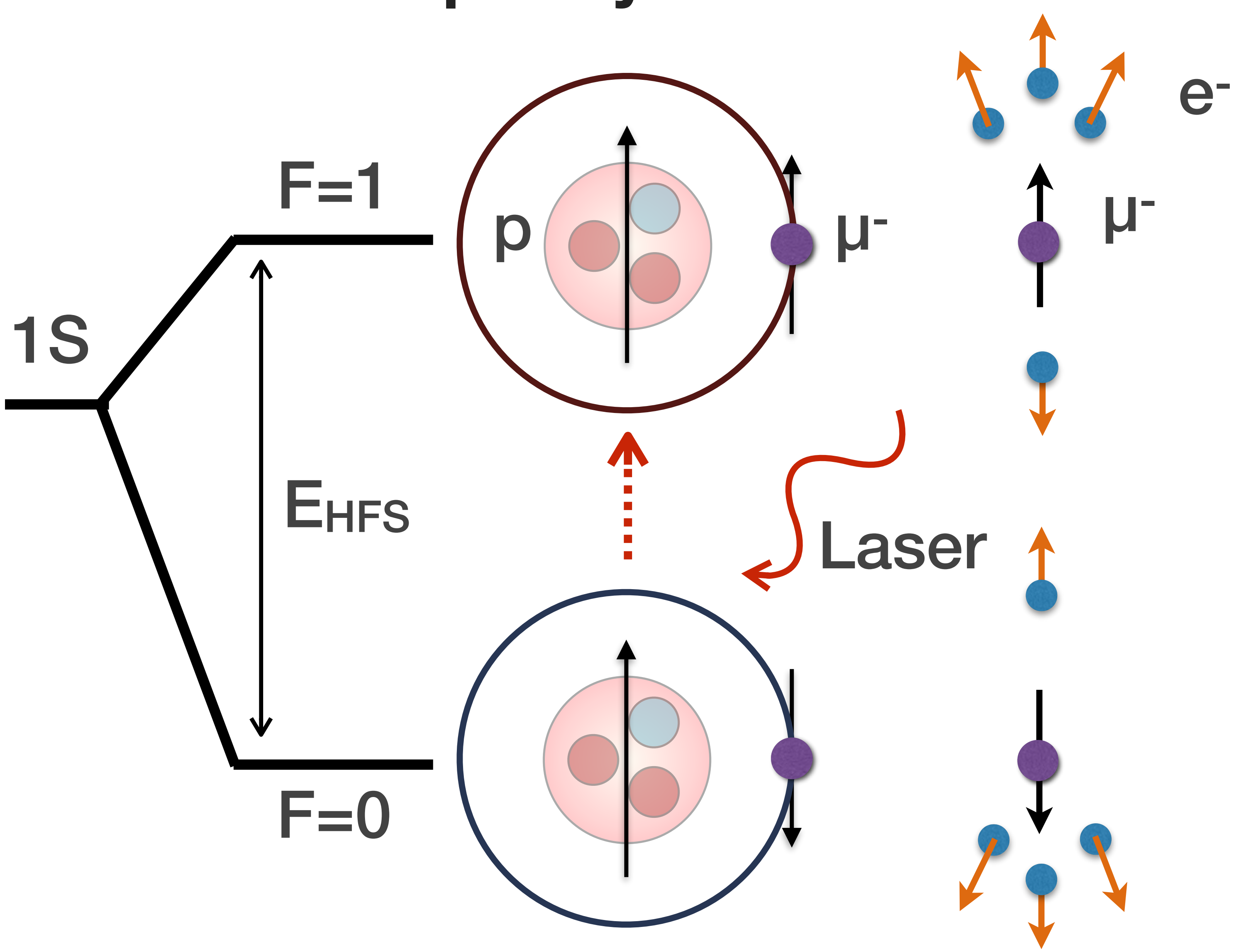
There is no definitive interpretation of the puzzle and new, independent experiment is needed.

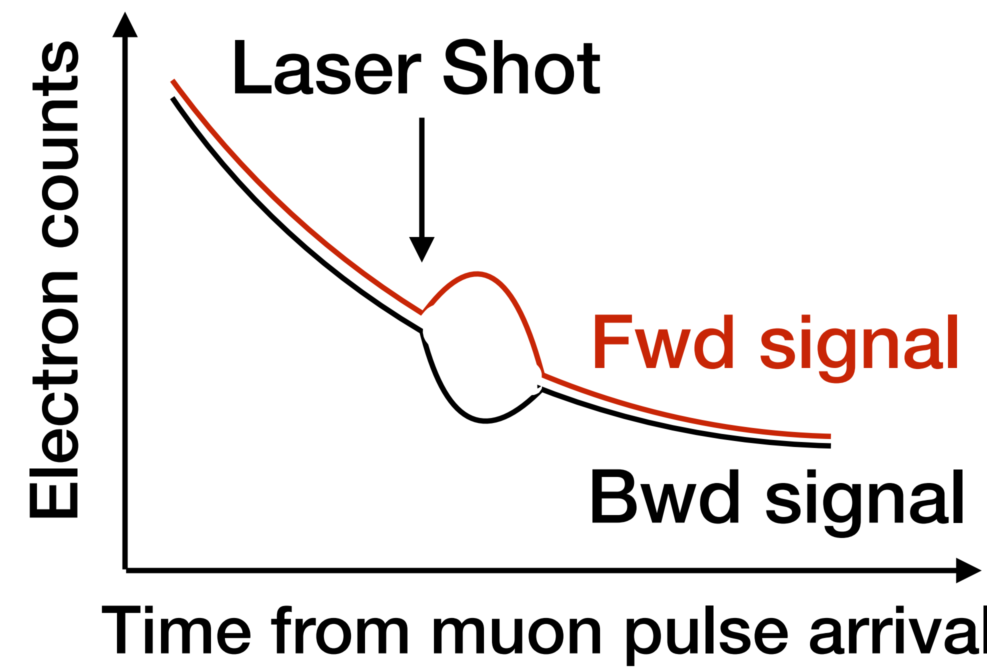
Our goal is a factor of three improvement; 1% precision.

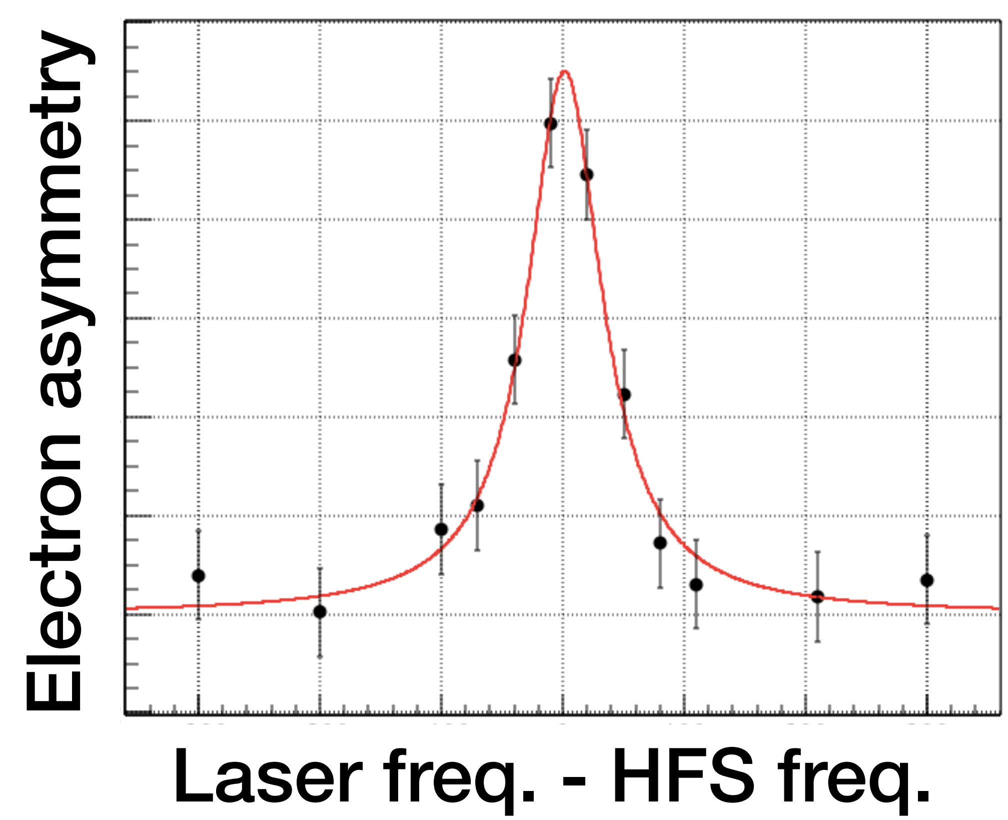
R. Pohl *et al*., Nature 466, 213 (2010). A. Antognini *et al*., Science 339, 417 (2013).
J. C. Bernauer *et al*., Phys. Rev. C 90 015206 (2014). A. V. Volotka *et al*., Eur. Phys. J. D33, 23 (2005).

Measurement Principle

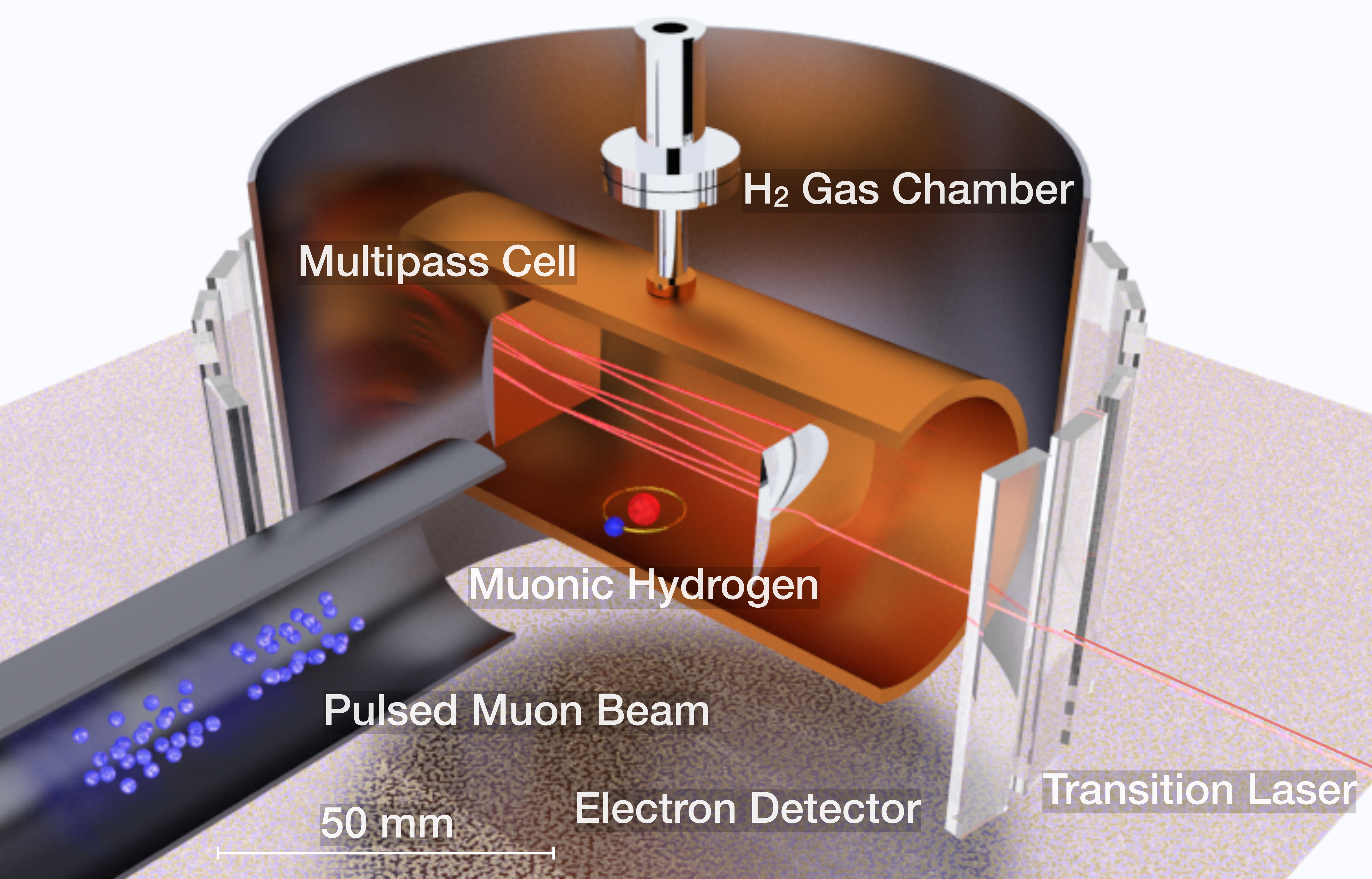
- **Laser induced hyperfine transition and muon spin flip**
- **Parity violating muon decay**
- **Decay electron angular asymmetry**
- **Laser frequency scan**



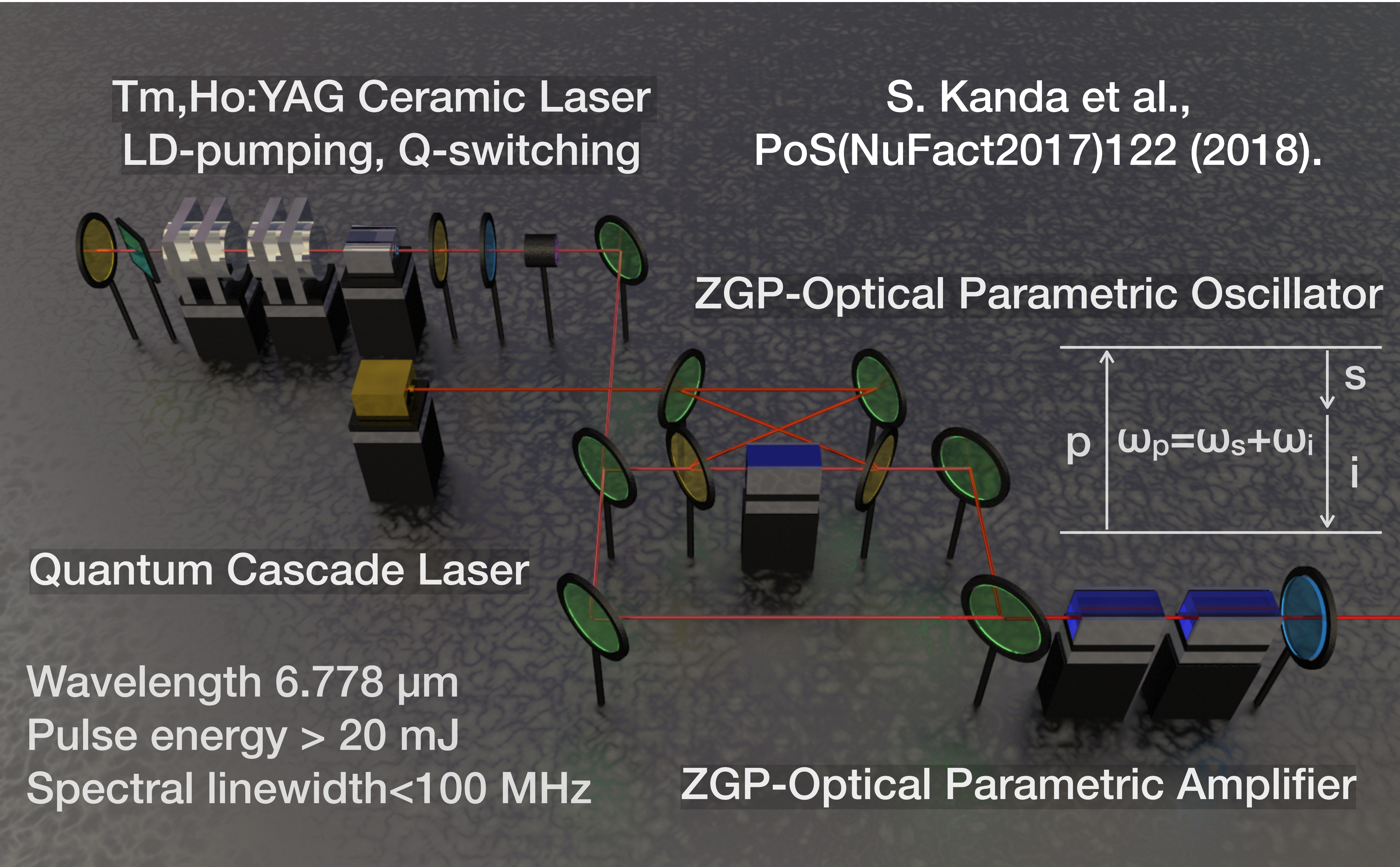




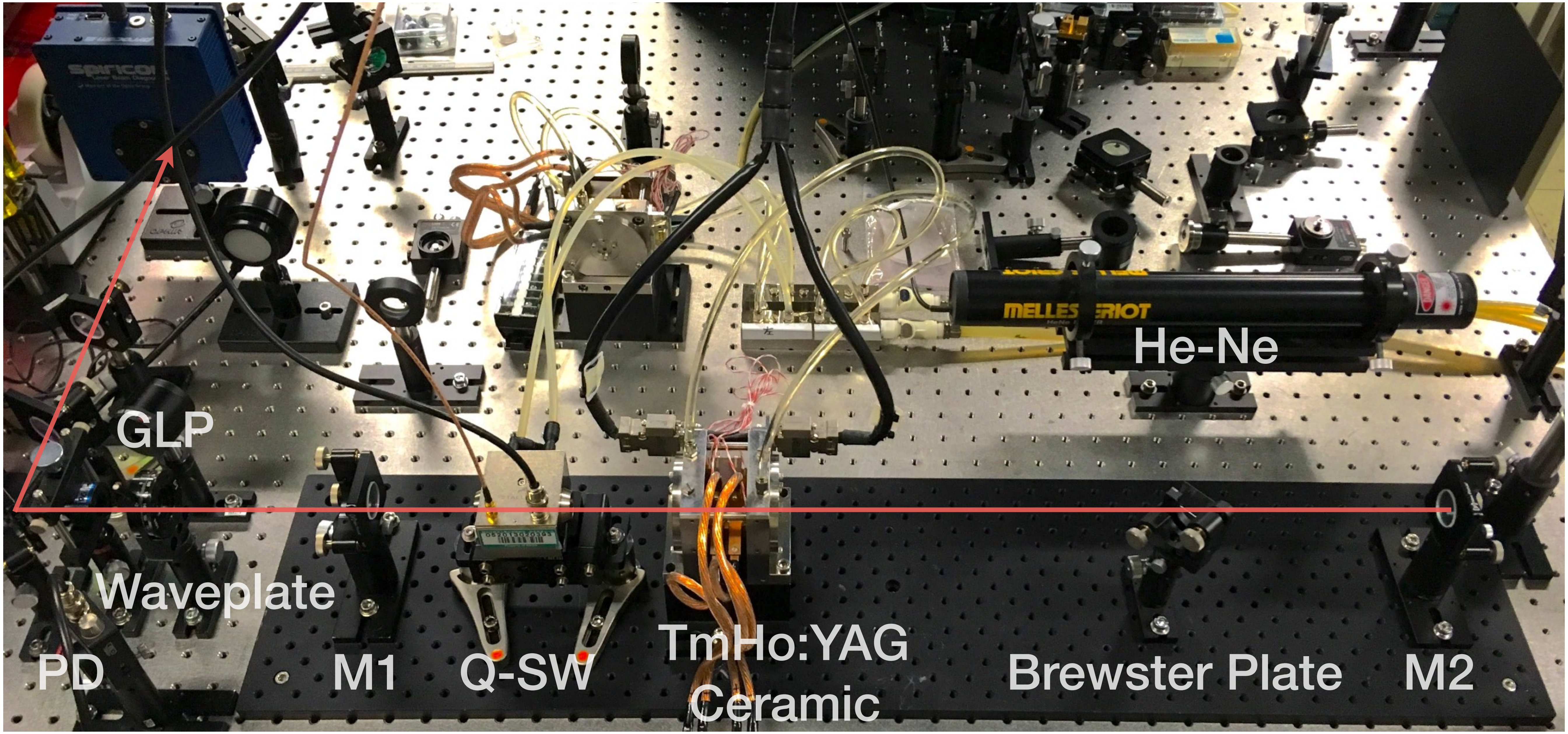
Experimental Setup



Laser System



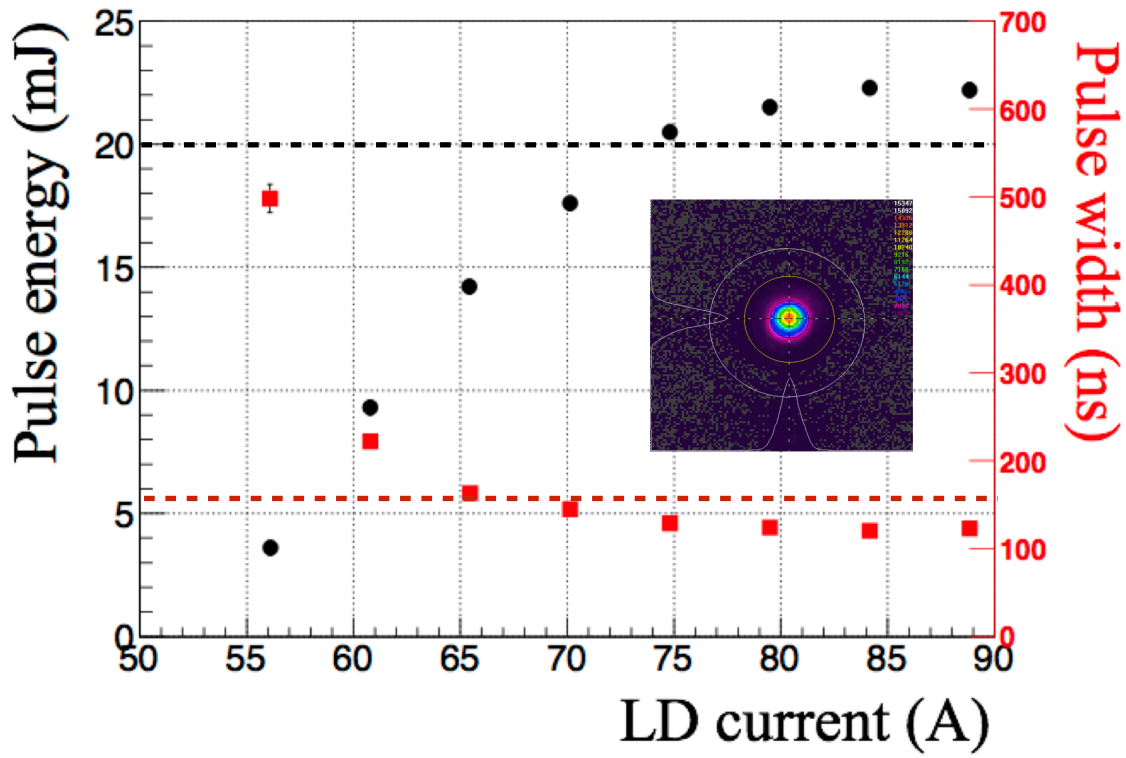
Laser Development in RIKEN



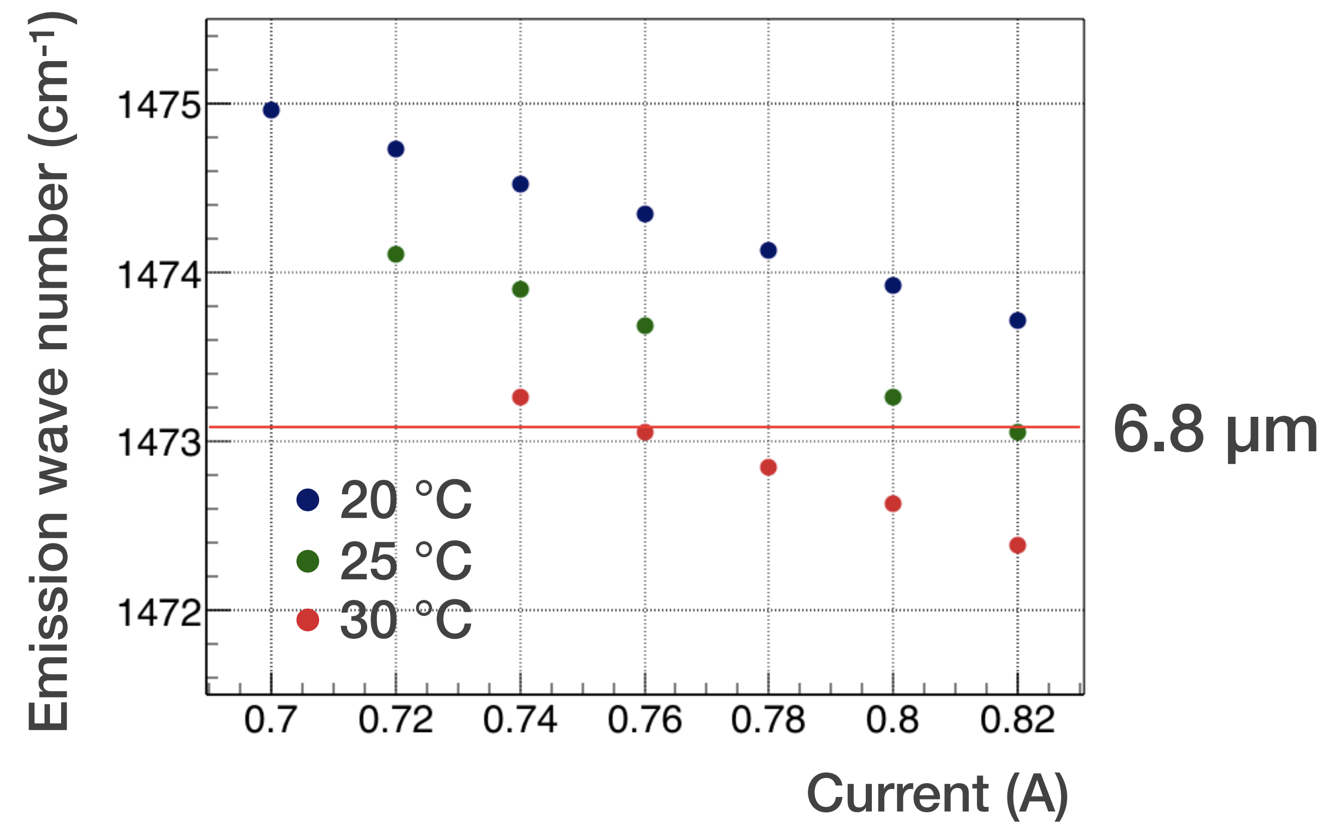
- Tm,Ho:YAG ceramic laser was developed and its performance was evaluated by using a diode photo detector, an energy meter, and a beam profiler.
- Reference : H. Hazama, M. Yumoto, T. Ogawa, S. Wada, and K. Awazu, “Mid-infrared tunable optical parametric oscillator pumped by a Q-switched Tm, Ho:YAG ceramic laser,” Proc. SPIE 7197, 71970J (2009).

Development Highlights

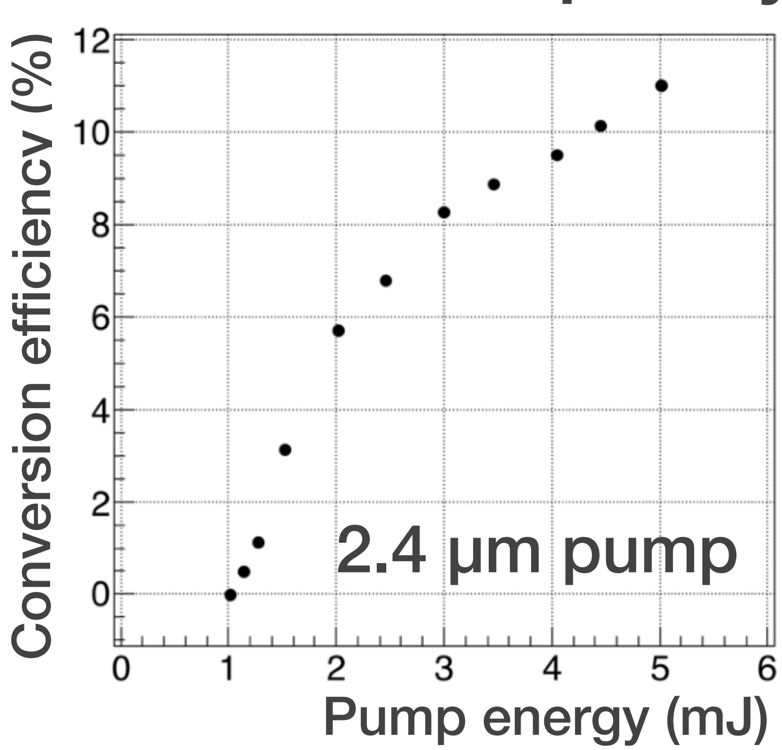
- Tm,Ho:YAG for pump beam

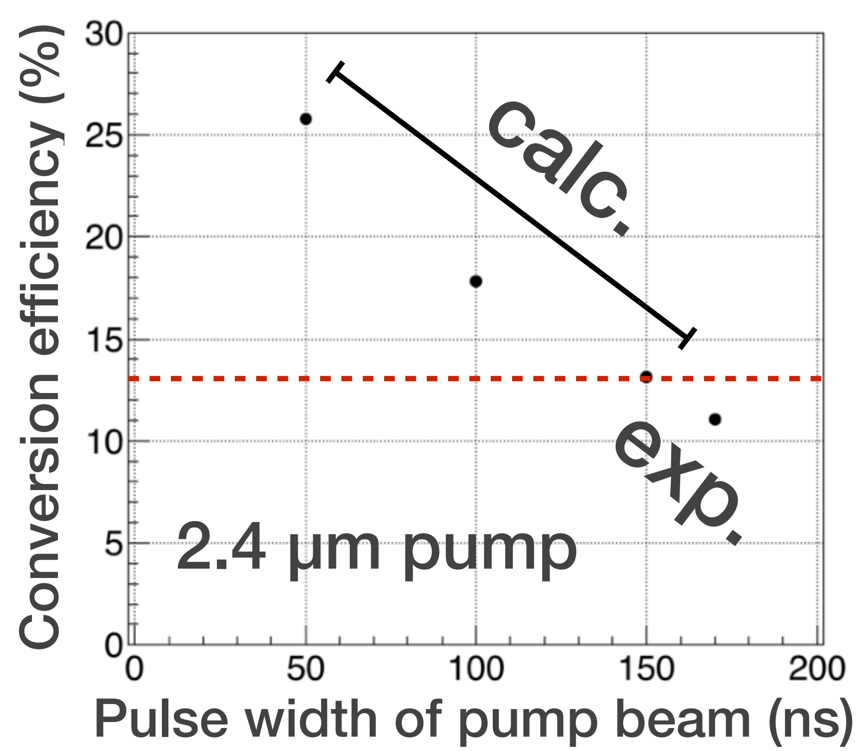


- QCL for seed beam



- OPO for frequency conversion

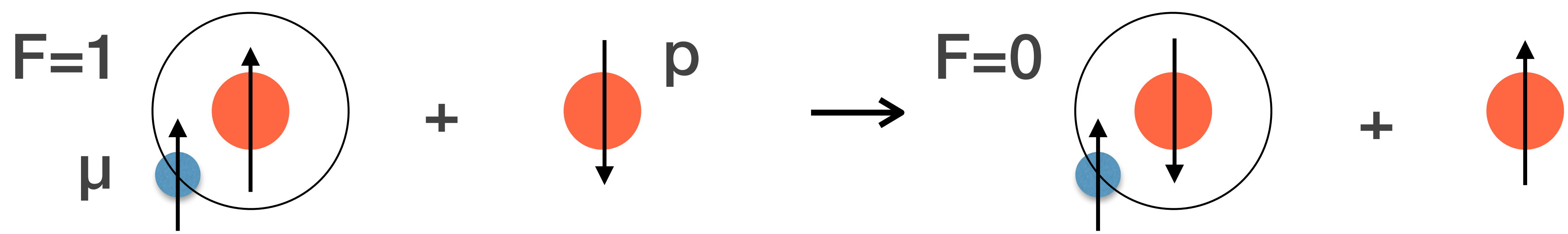


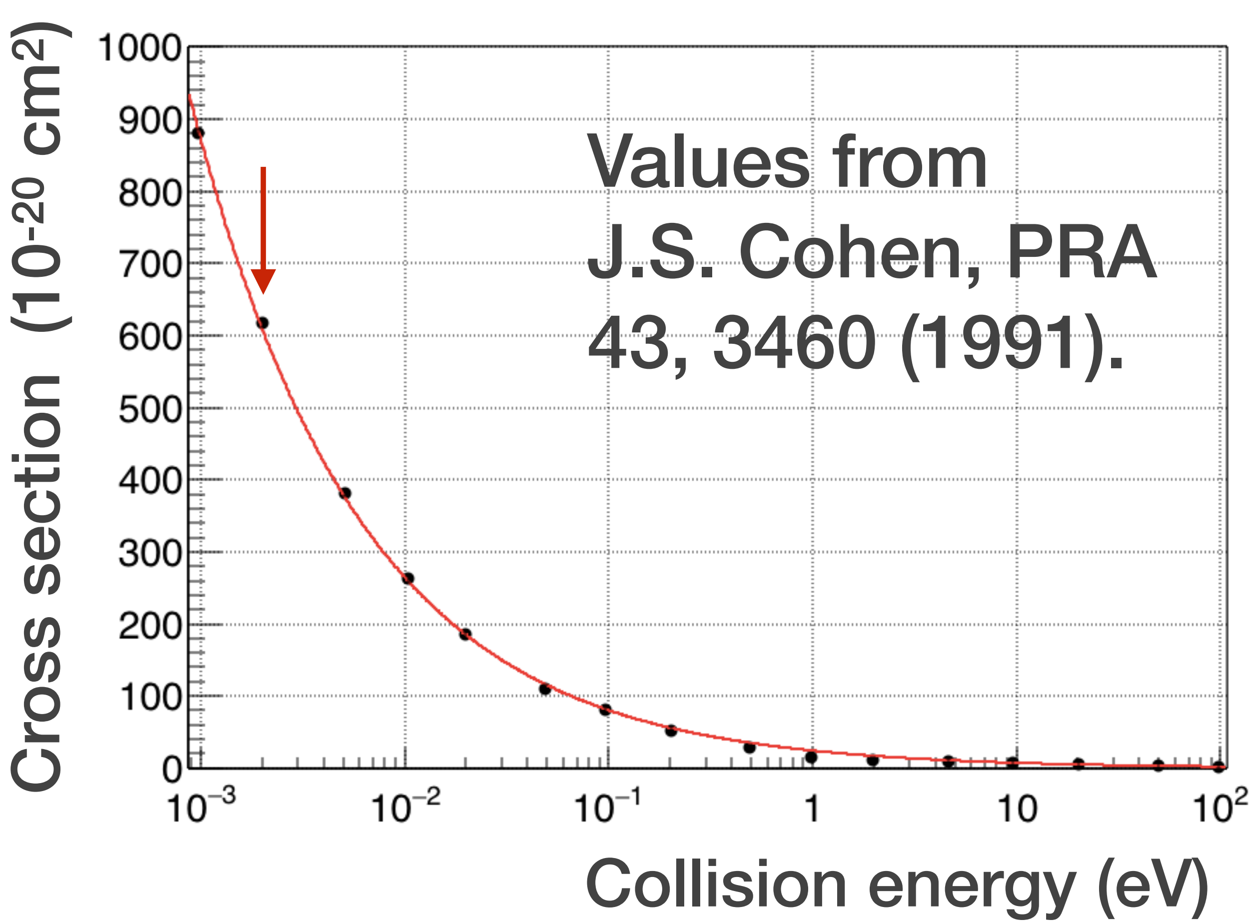


- Pump beam: Requirements were satisfied.
- Seed beam: Oscillation was confirmed at 6.778 μm. Linewidth is to be evaluated.
- OPO: To be improved a little.
- Next step: Development of the multi-pass cell.

Collisional Hyperfine Quenching

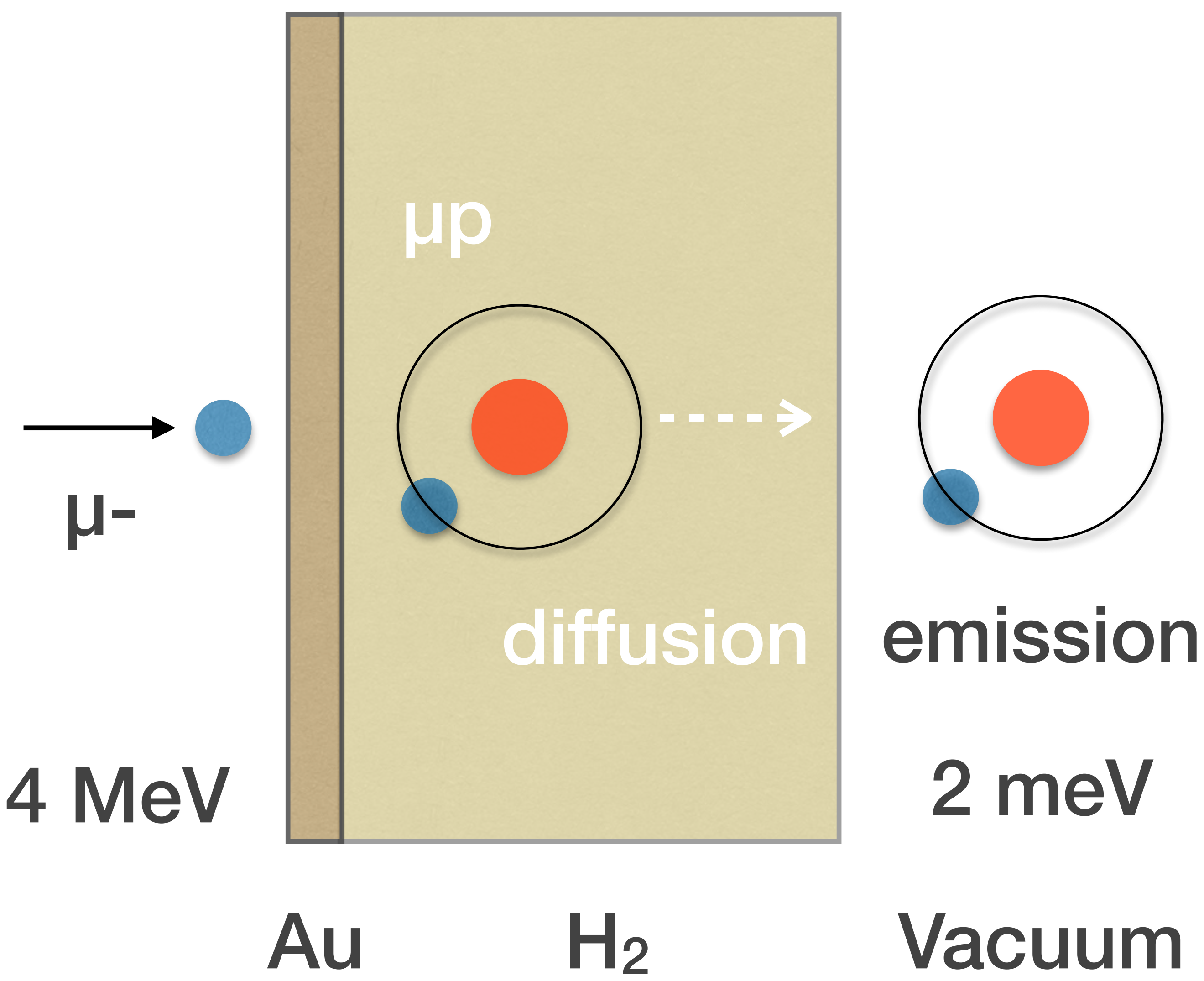
- Collisional quenching of the HFS triplet state
  - Inelastic scattering μp(F=1)+p -> μp(F=0)+p
  - Only theoretical predictions are known and no measurement had been performed.

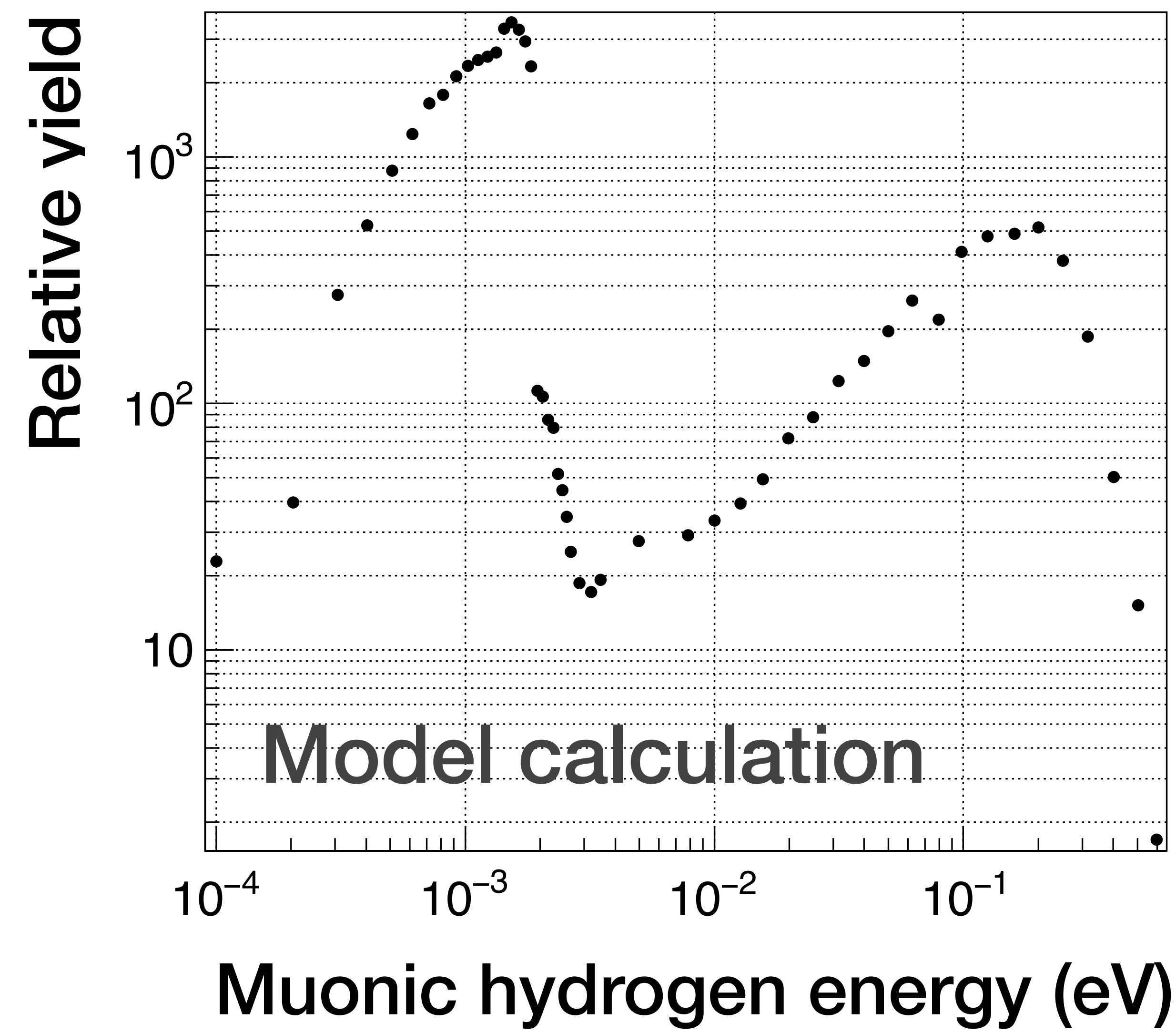




- Quenching rate depends on collision energy (gas temperature) and gas pressure.
- Expected lifetime at 20 K, 0.06 atm is approximately 50 ns.
- A new experiment for direct measurement of the quenching rate will be performed.

Alternative Idea: μp in vacuum





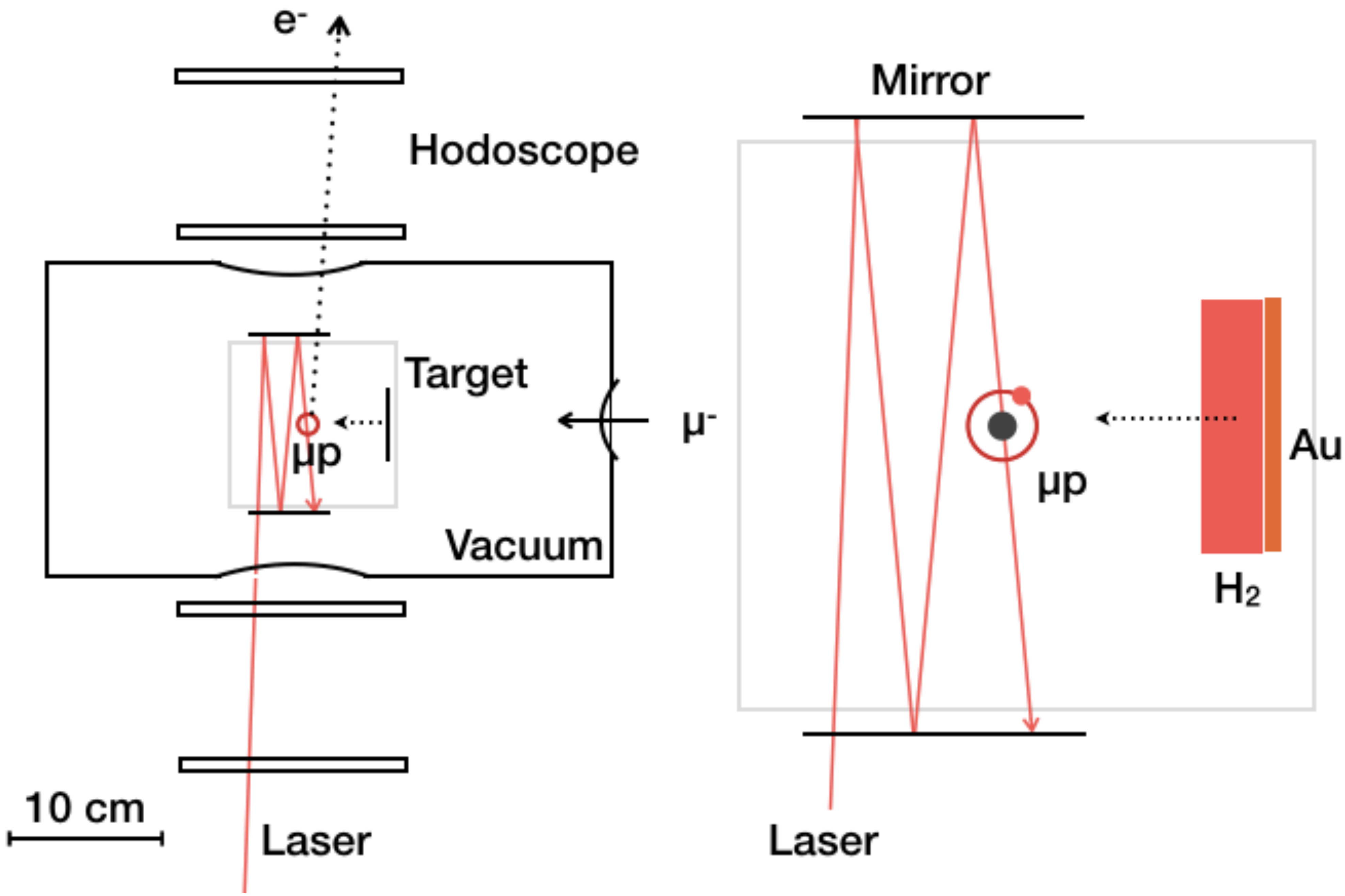
Slow muonic hydrogen is emitted from solid hydrogen thin film.

Emission energy has two components: 2 meV and 0.2 eV.

Slow μp yield is approximately 0.5% of incident muons.

Theory: A. Adamczak, Hyperfine Interact. 119, 23 (1999).
Experiment: J. Woźniak *et al.*, Phys. Rev. A 68, 062502 (2003).

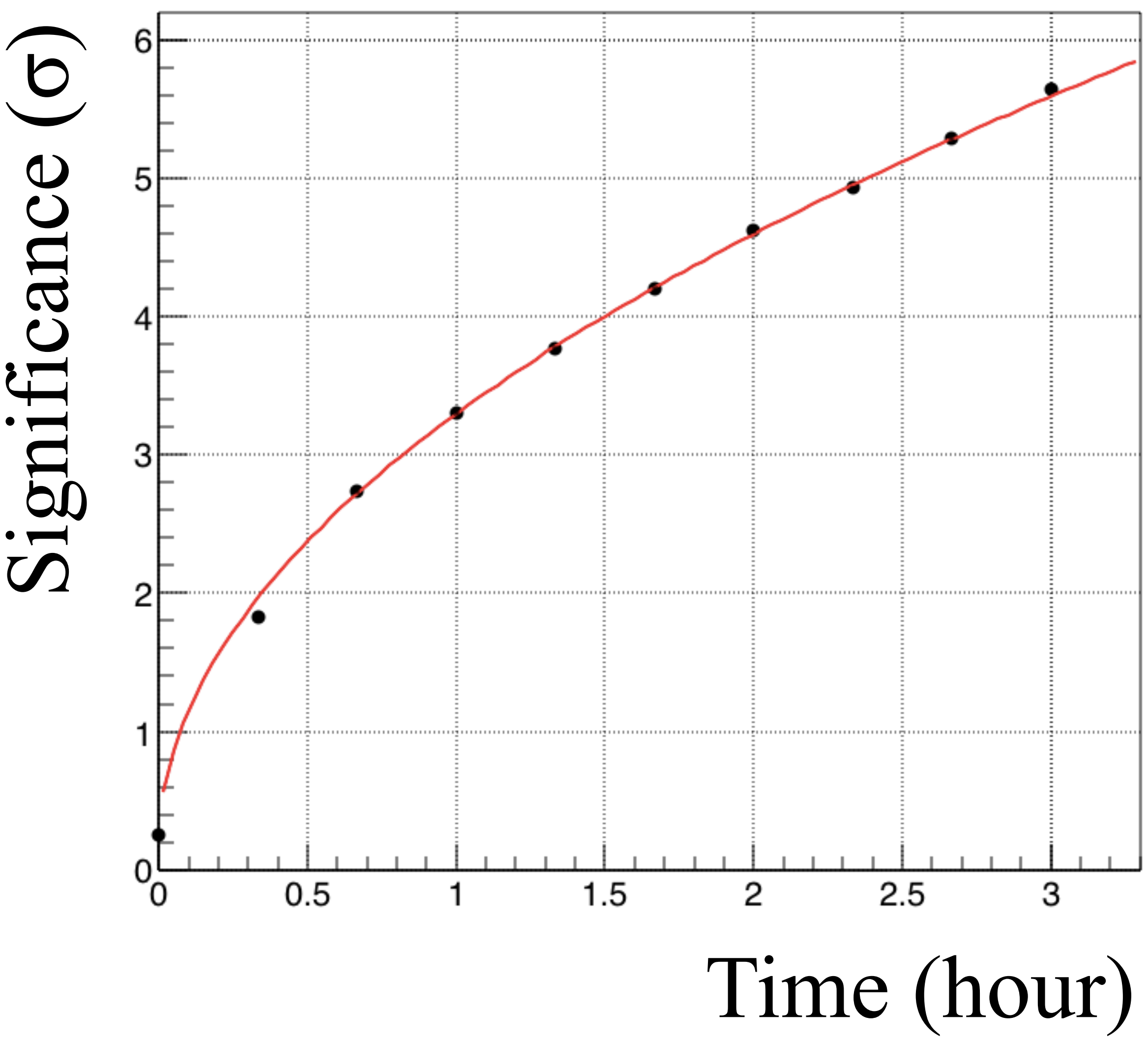
In-Flight Spectroscopy



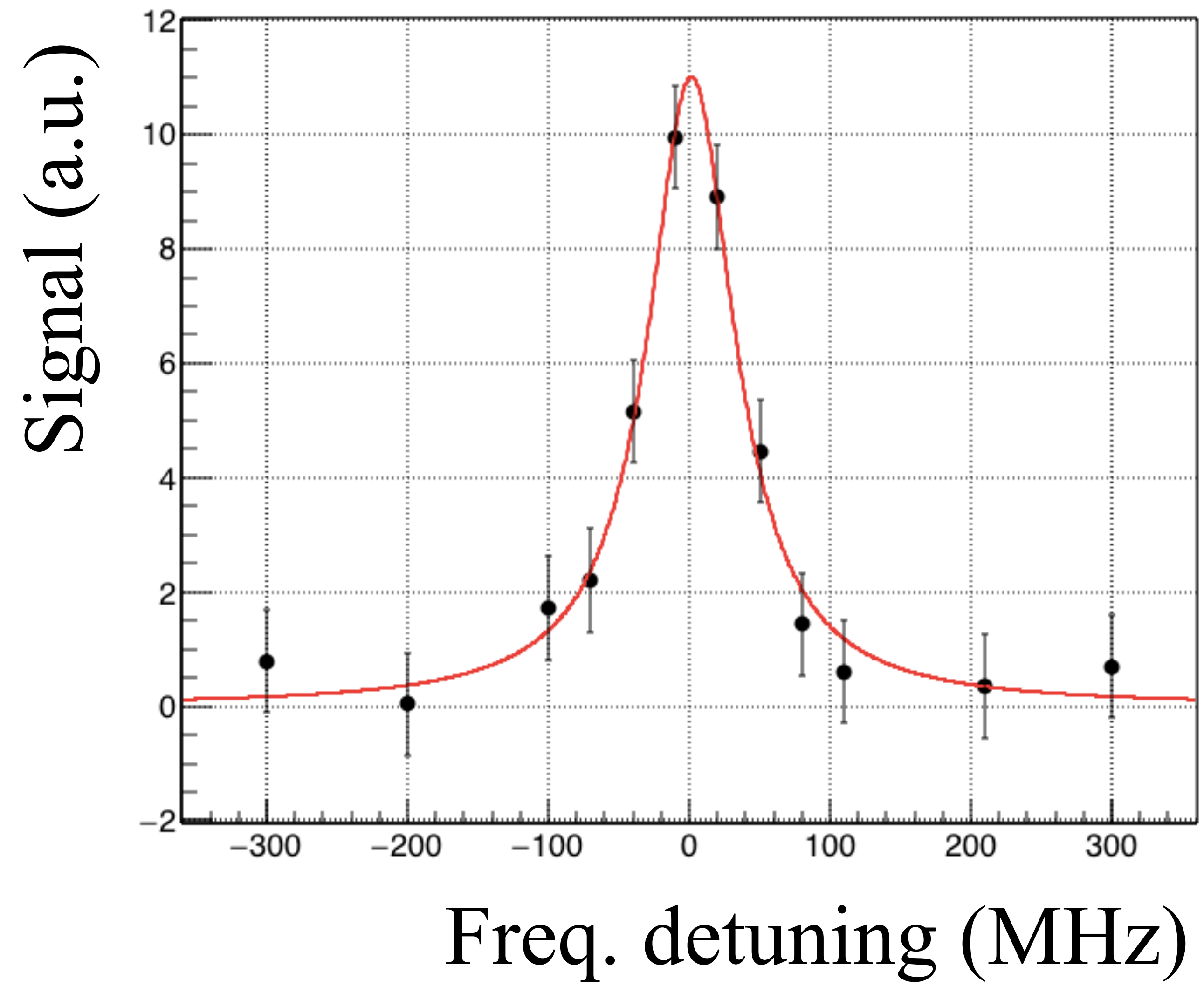
- In-flight spectroscopy is free from the collisional quenching.
- Systematics will be dominated by the Doppler effect.
- Experimental proposal was submitted to J-PARC.

Statistical Significance

Statistics on resonance



Laser frequency scan



- **The laser pulse energy of 20 mJ and the beam intensity of 3.5x10^5 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

[Muonium HFS]

- Muonium HFS is a powerful probe for a stringent test of the bound-state QED theory.
- The muonium HFS was successfully observed and studies for the high field experiment are ongoing.

[Muonic Hydrogen HFS]

- “Proton Radius Puzzle” is one of the most important unsolved problem in sub-atomic physics.
- We are preparing for a new measurement of the HFS in ground-state muonic hydrogen atom.