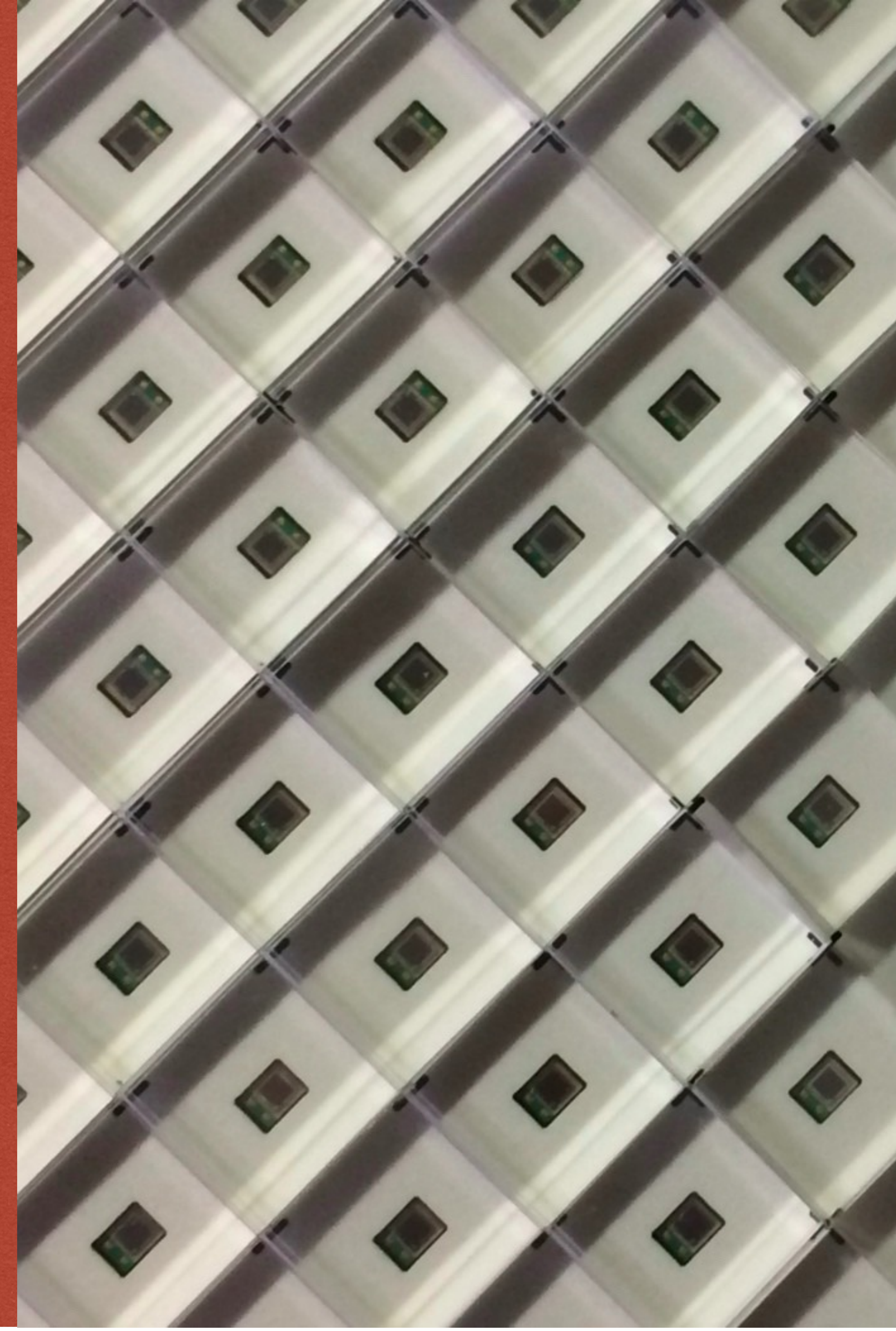
Laser spectroscopy of the hyperfine splitting in muonic hydrogen atom by a measurement of decay electron asymmetry



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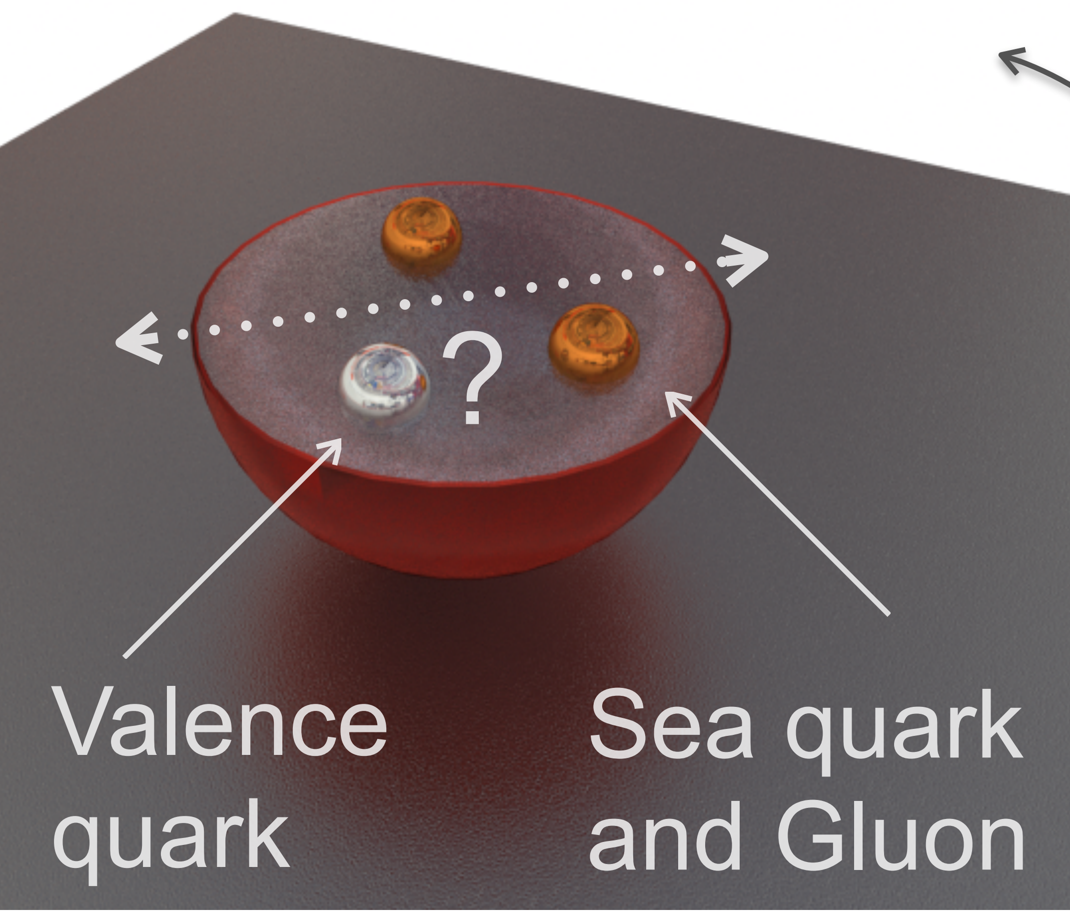
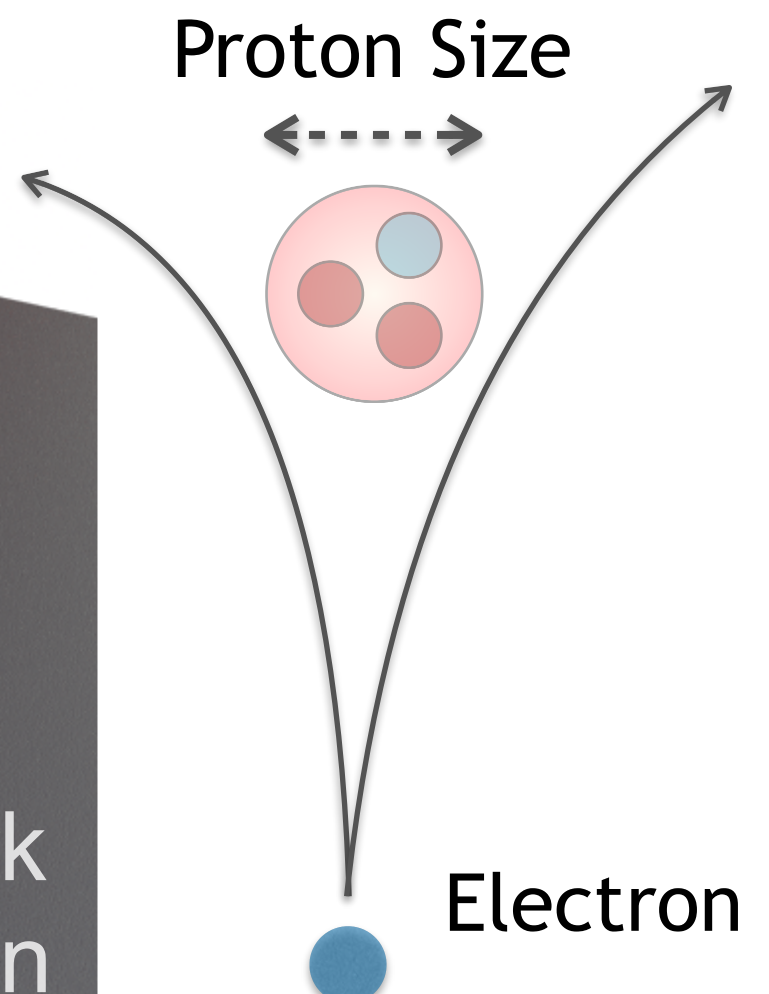
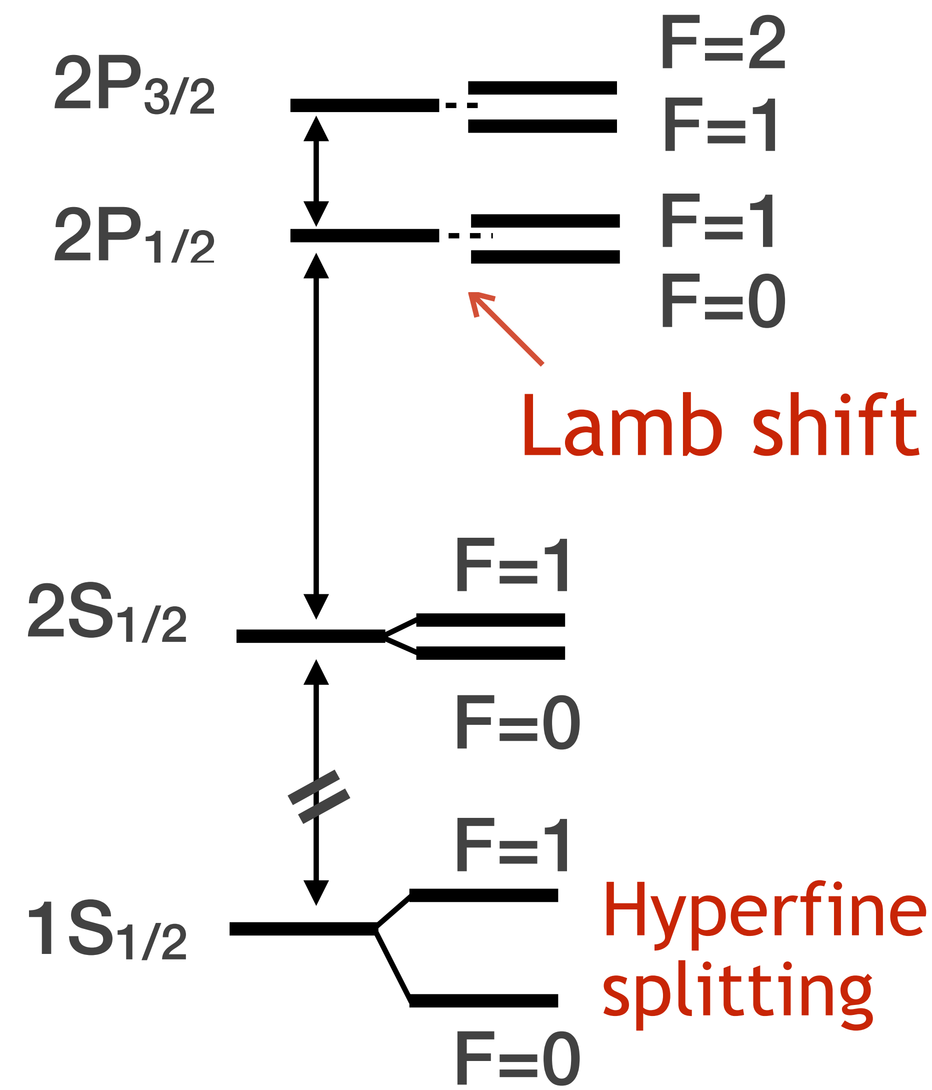
How Large is the Proton?

- 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.



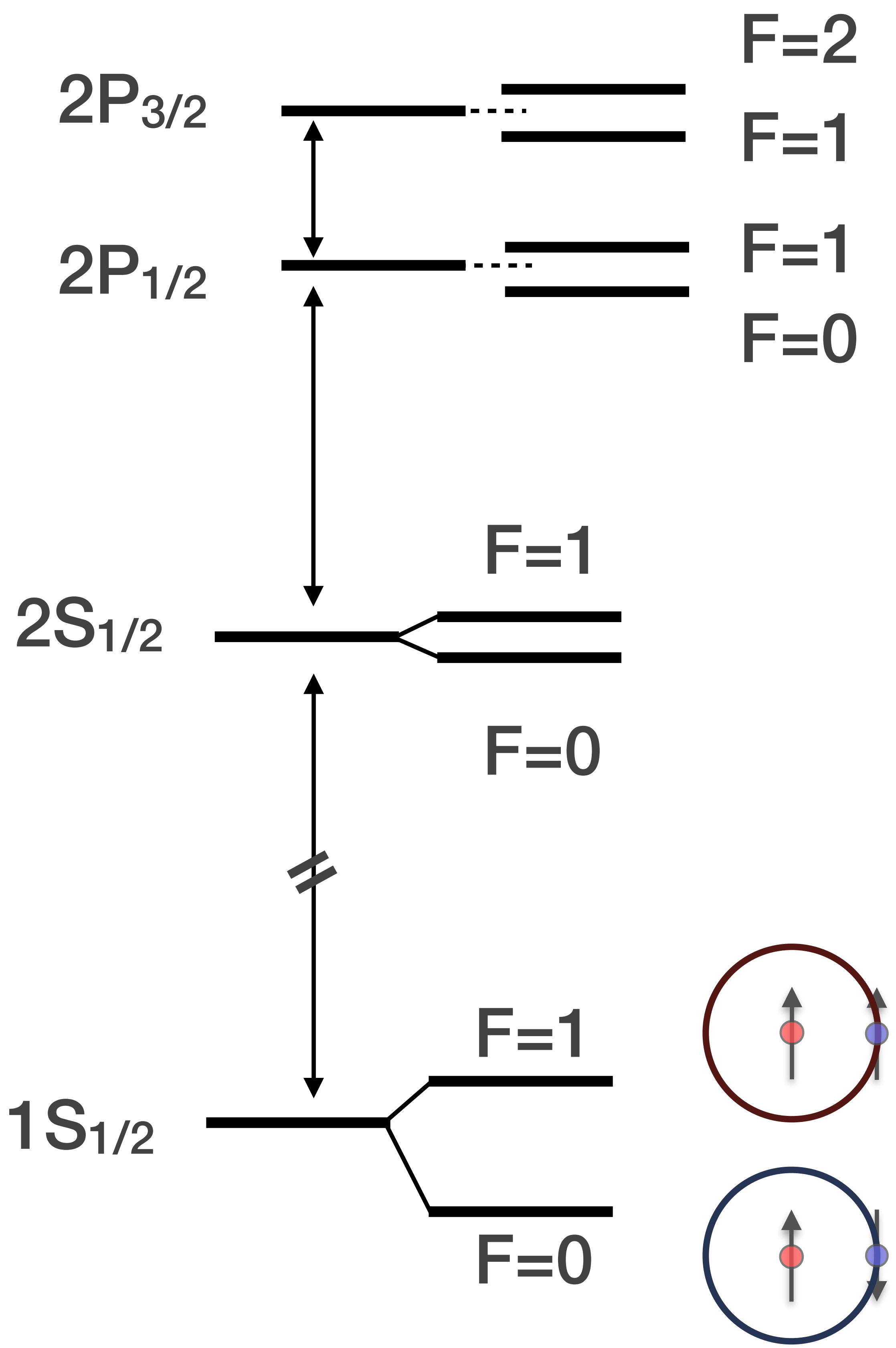


Electron-proton scattering



Atomic spectroscopy

Muonic Hydrogen Spectroscopy

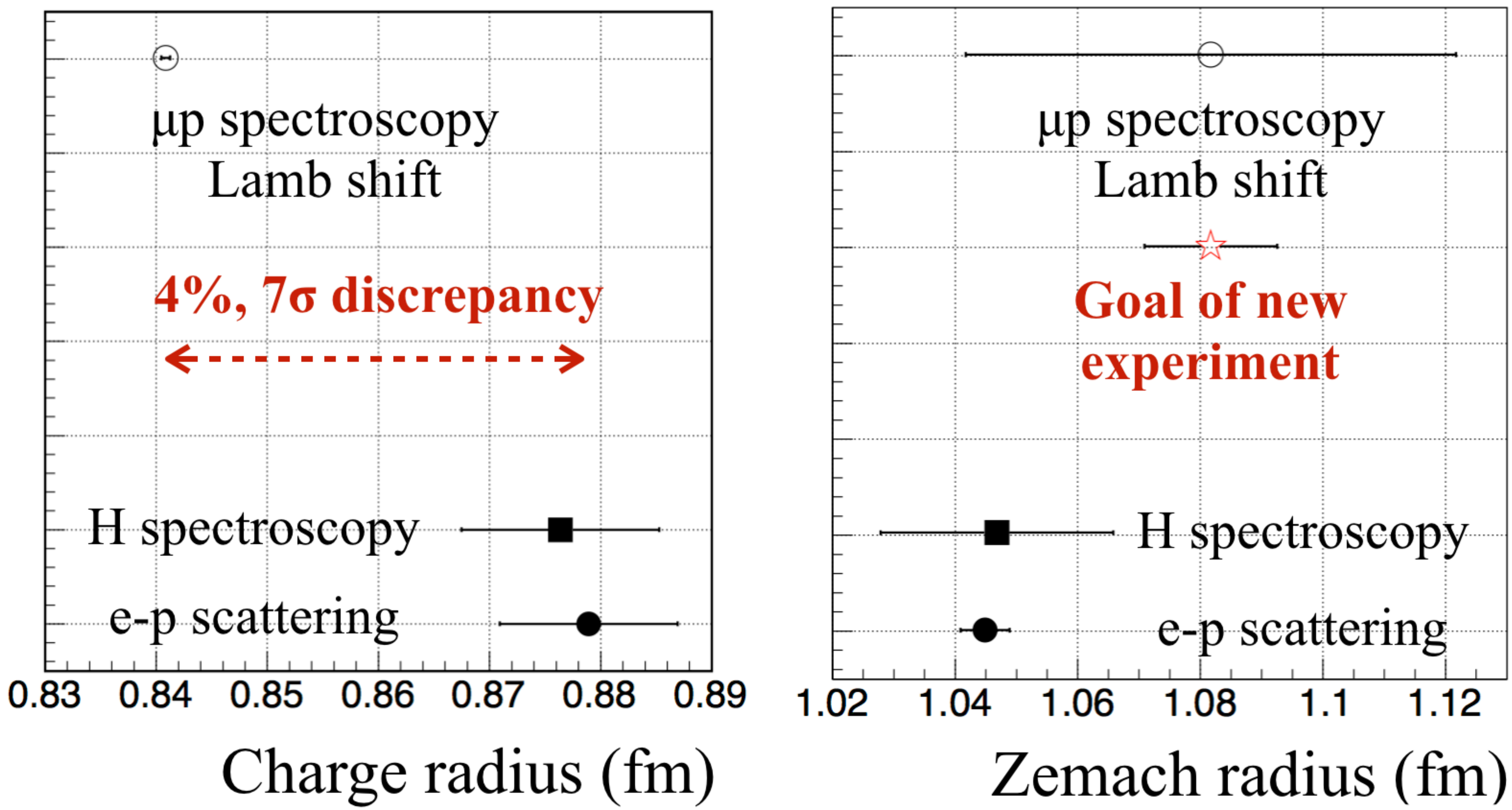


Lamb Shift : 206 meV=6 μm
Finite size effect 3.7 meV
-> Charge Radius
(Experiment at PSI)

2S-HFS : 23 meV=54 μm
(Indirectly obtained by two Lamb shifts)

1S-HFS : 183 meV=6.8 μm
Finite size effect 1.3 meV
->Zemach Radius
(Our experiment)

Proton Radius Puzzle

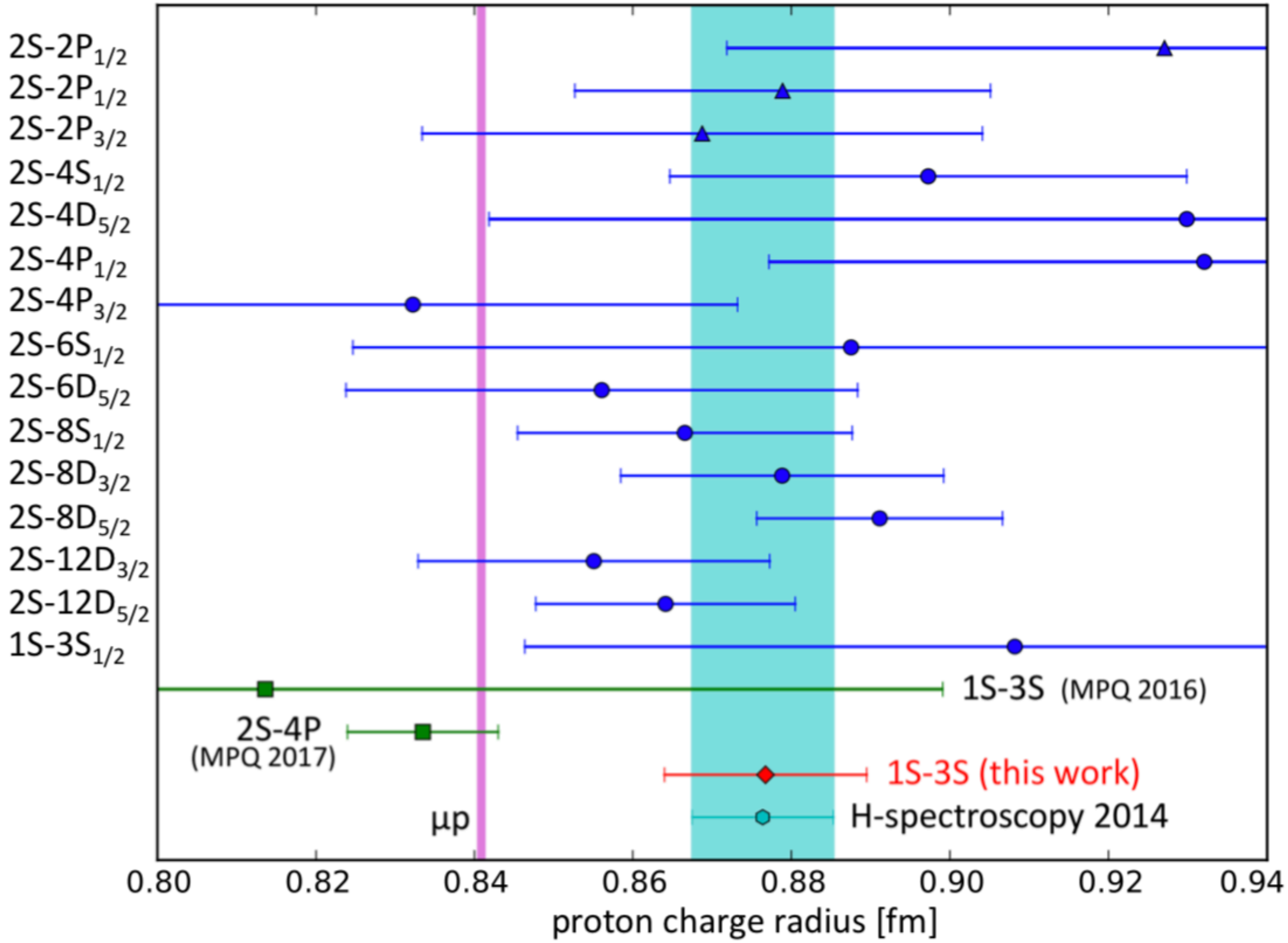


There is no definitive interpretation of the puzzle and new, independent experiment is needed.

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

Antognini *et al*., Science 339, 417 (2013). J. C. Bernauer *et al*., Phys. Rev. C 90 015206 (2014). M. O. Distler et al., Phys. Lett. B696 (2011) 343. A. V. Volotka *et al*., Eur. Phys. J. D33, 23 (2005).

Latest Hydrogen Results



Proton charge radius puzzle is not a simple problem between electronic and muonic measurements.

Hélène Fleurbaey *et al.*, Phys. Rev. Lett. **120**, 183001 (2018).

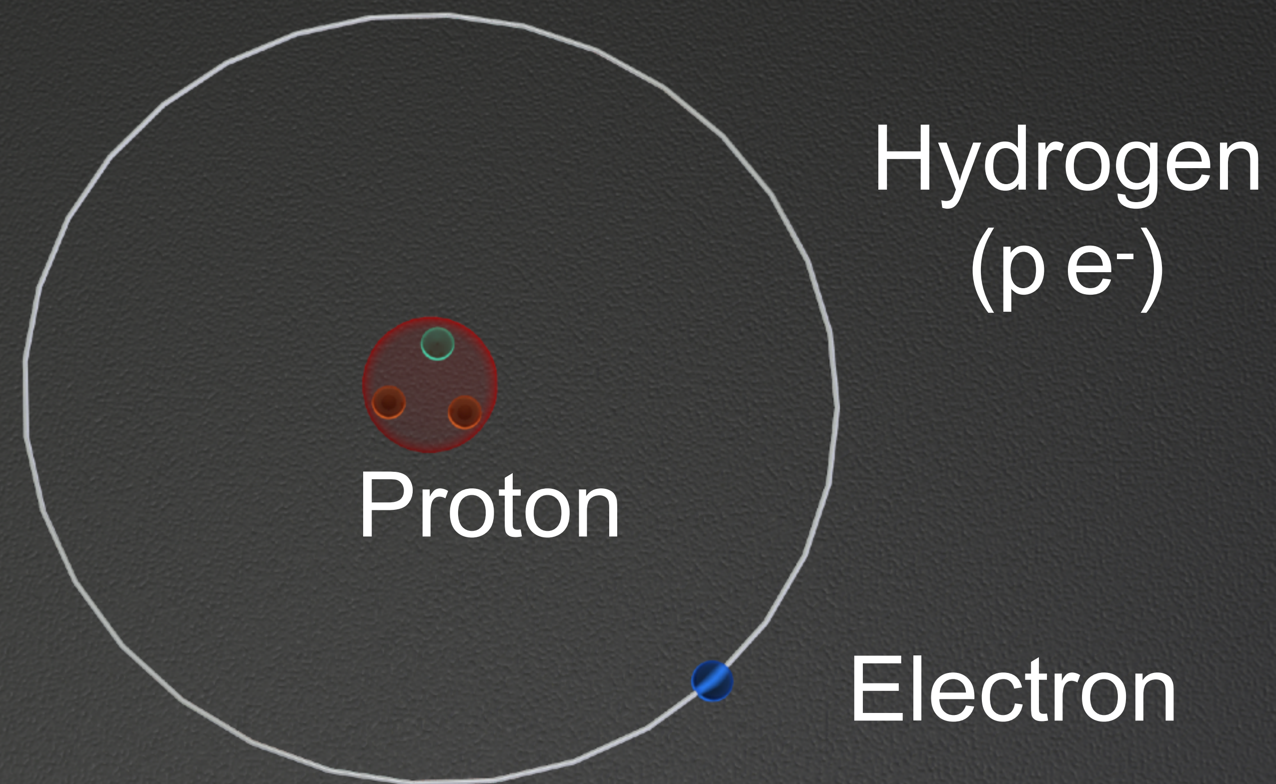
Sternheim Interval

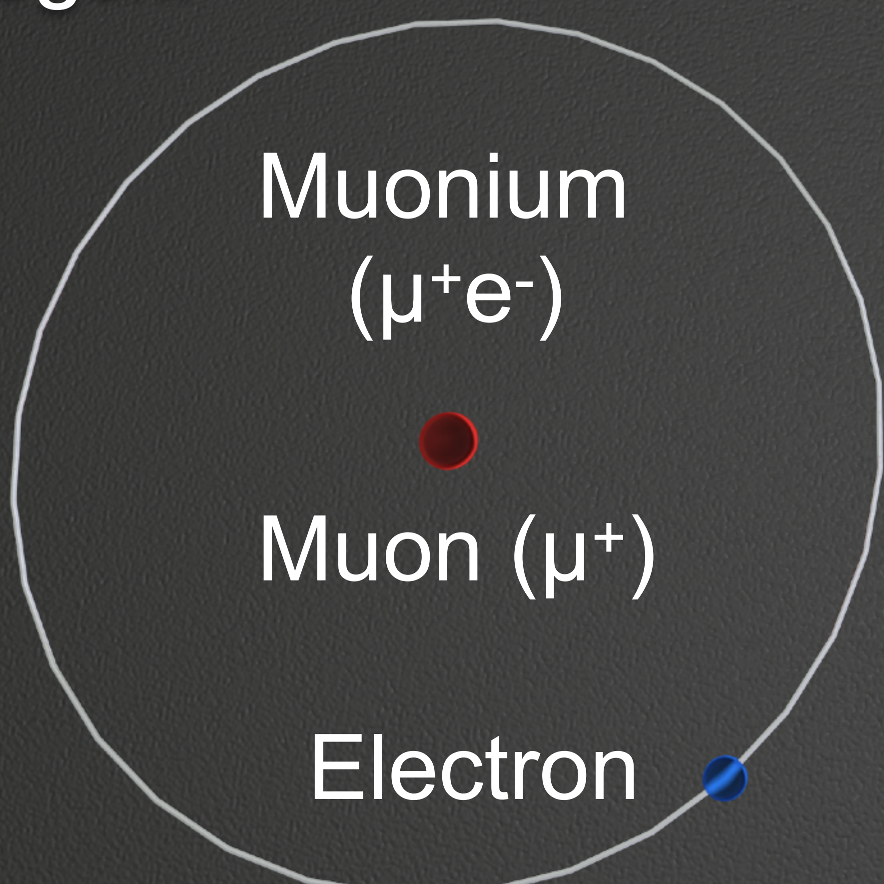
- When the ground-state hyperfine splitting is precisely measured, we can obtain the Sternheim interval
  - $\Delta E_{12} = 8\Delta E(2S) - \Delta E(1S)$.
- This interval is precisely calculated because it does not contain the proton structure terms up to $O(\alpha^5)$.
- We can test the bound-state QED theory by measuring $\Delta E(1S)$.
- Theory predicts $\Delta E_{12} = -0.12$ meV with a precision of ppm.

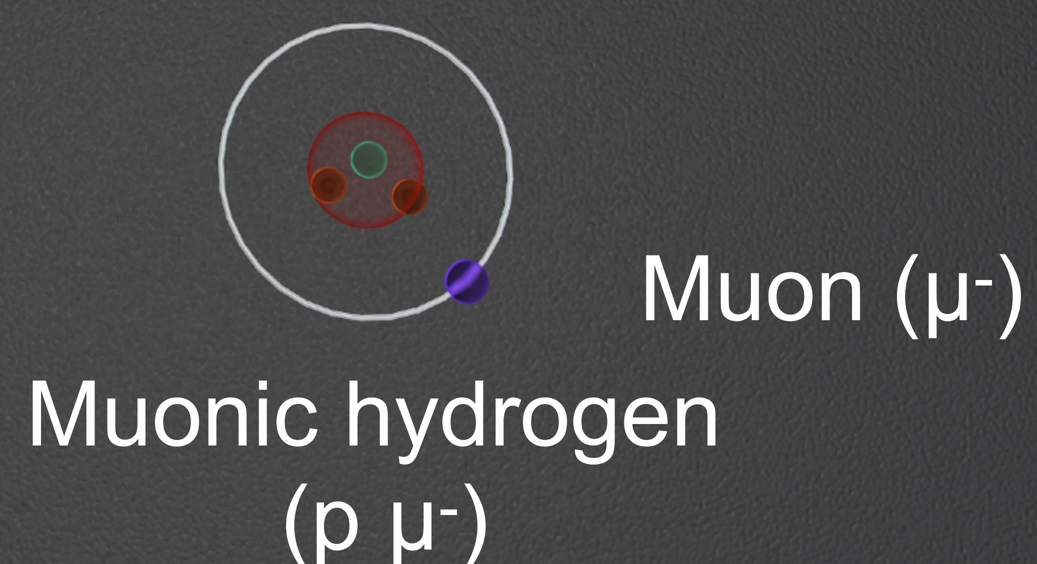
M. Sternheim, Phys. Rev. 130, 211 (1963).
A. P. Martynenko, Phys. Rev. A 71, 022506 (2005).

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.



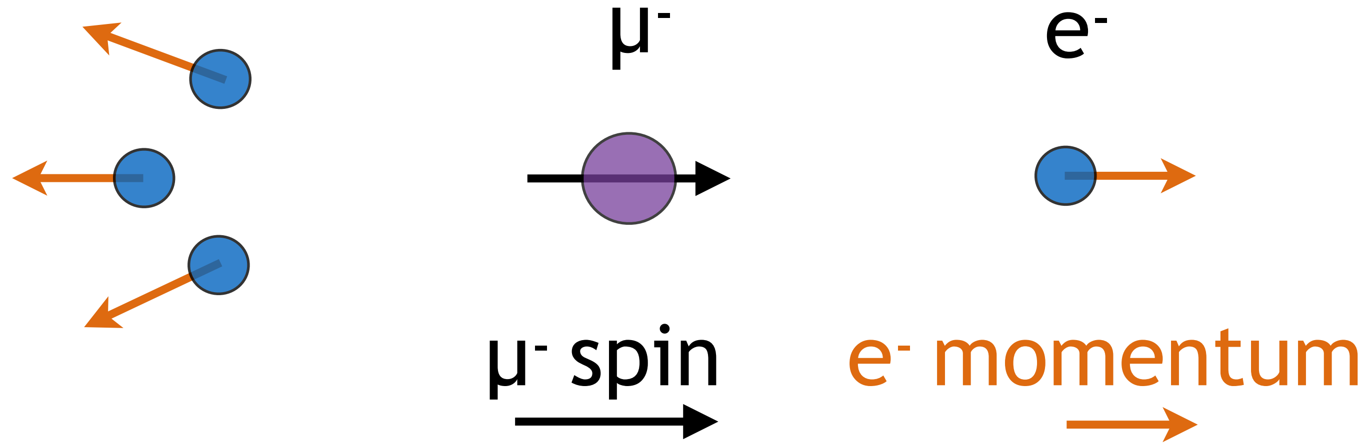




Muon Decay

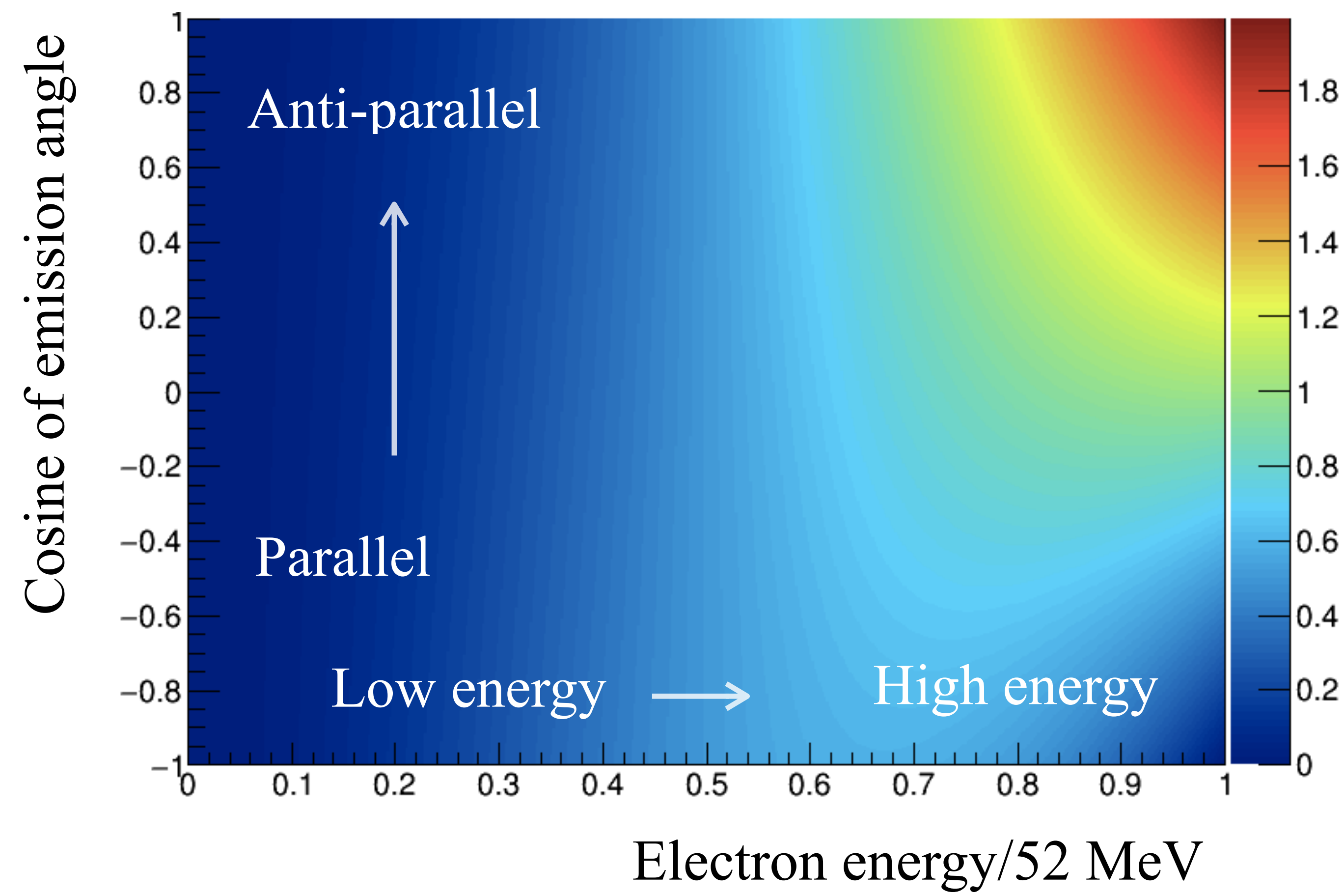
- Muon decay: $\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu}_e$ (neutrinos are invisible)

More electrons in anti-parallel to muon spin



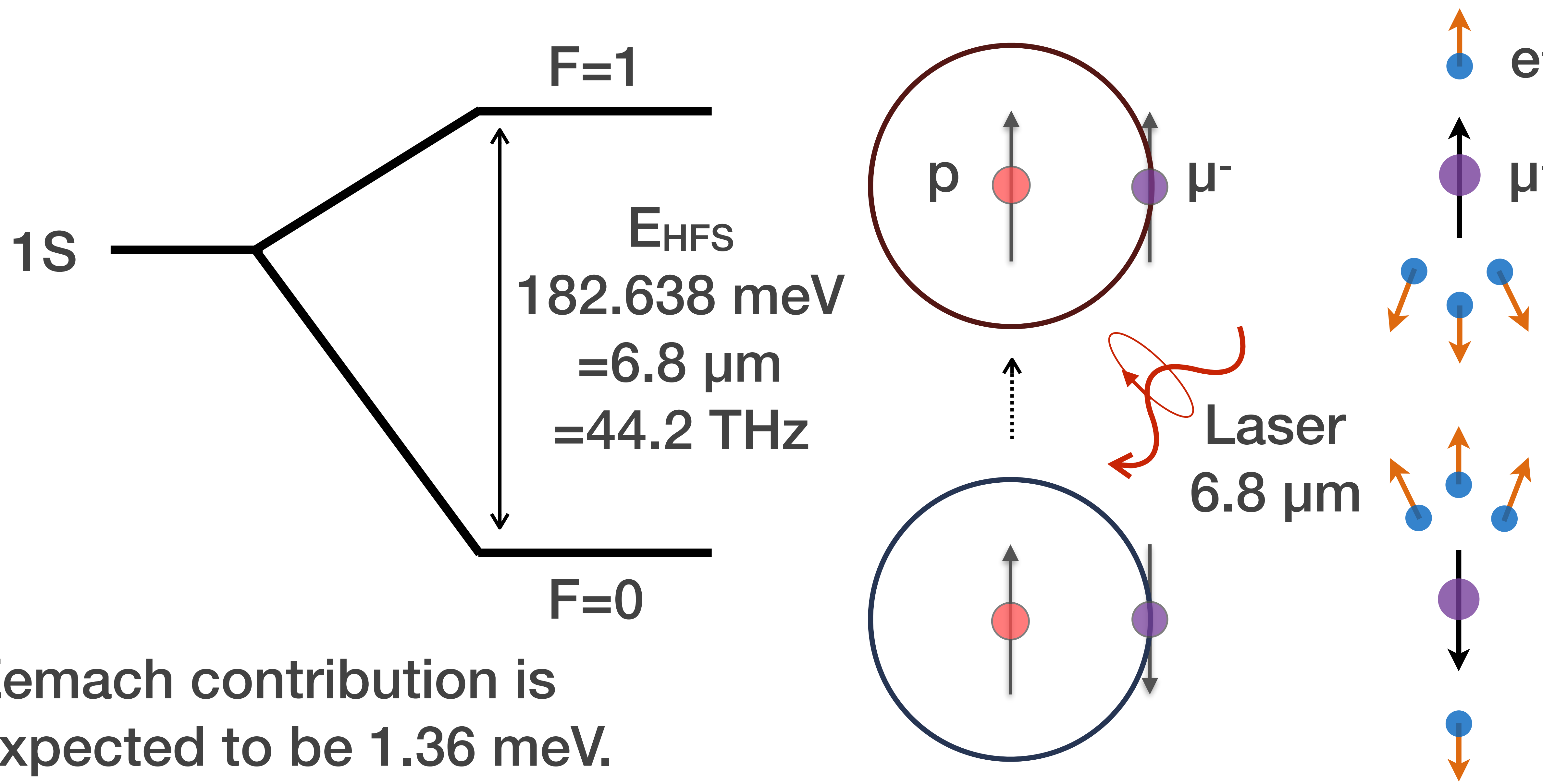
Less electrons in parallel to muon spin

- **Muon is a self-analyzing particle.**
- The parity violating muon decay causes the correlation between muon spin and electron direction.



Muonic Hydrogen HFS

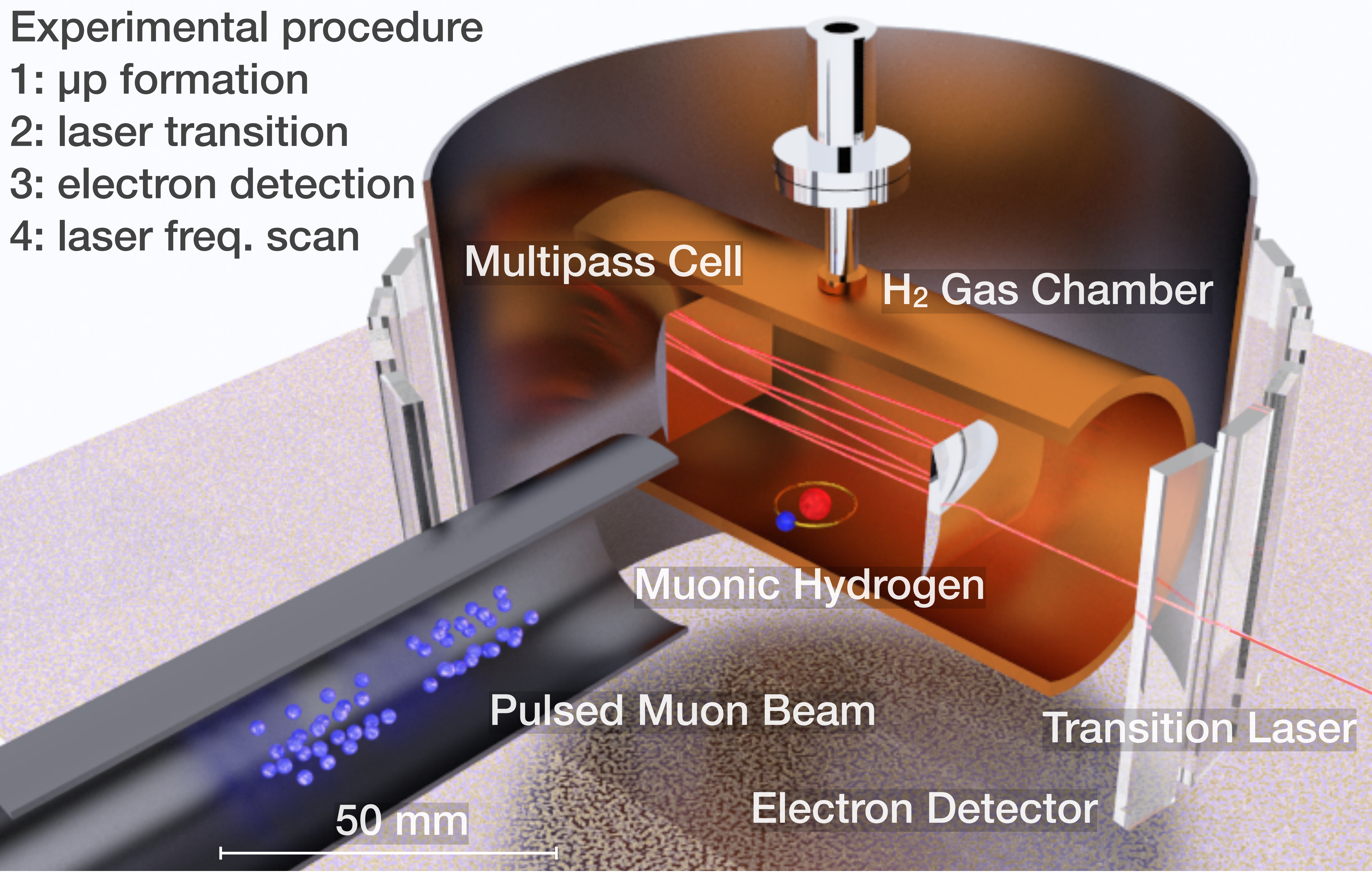
- μp hyperfine splitting (HFS) transition is induced by a circularly polarized laser light having a wavelength of 6.8 μm.
- **HFS contains a contribution arising from the finite size effect of the proton. Hence, the proton Zemach radius can be extracted.**



Zemach contribution is expected to be 1.36 meV.

Experimental Overview

Experimental procedure
1: μp formation
2: laser transition
3: electron detection
4: laser freq. scan



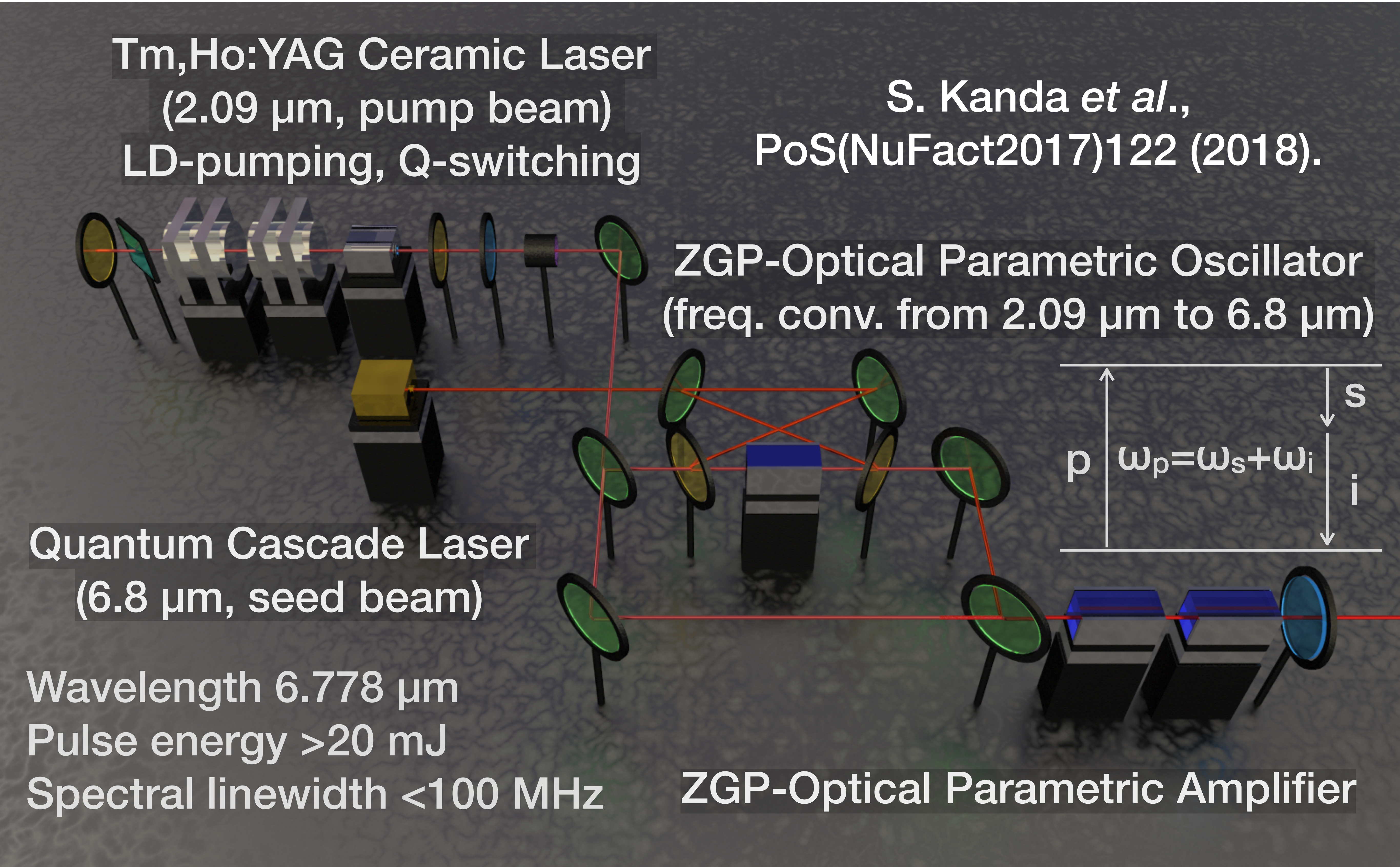
Experimental Facility: J-PARC

What is Difficult?

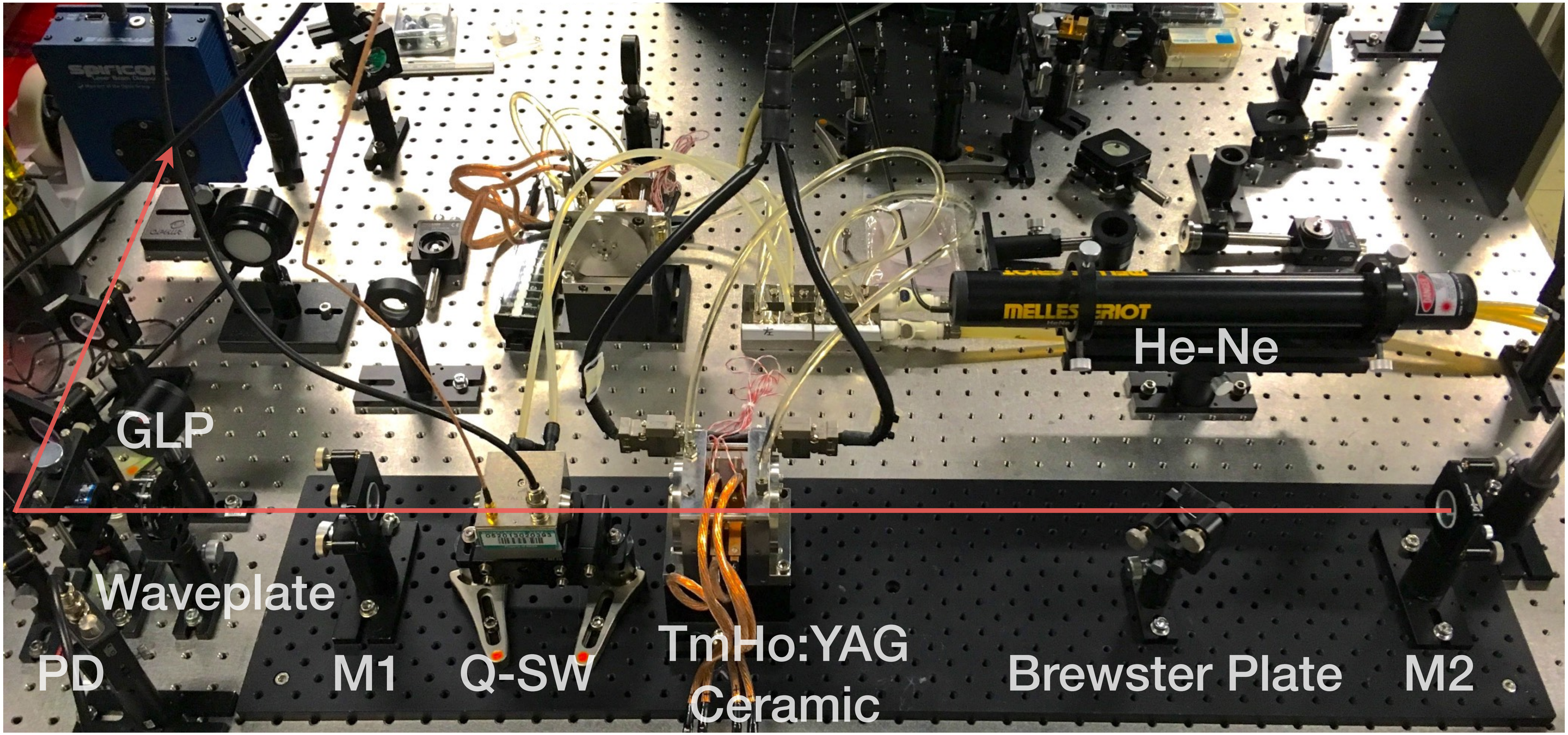
- High-performance transition laser is required
  - High pulse energy > 20 mJ
  - Narrow spectral linewidth < 100 MHz
  - Necessity of a new development

- HFS triplet state is de-excited in a short lifetime
  - Collisional hyperfine quenching
  - Inelastic scattering $\mu p(F=1)+p \rightarrow \mu p(F=0)+p$
  - Polarization lifetime ~ 50 ns at 20 K, 0.06 atm

Laser System

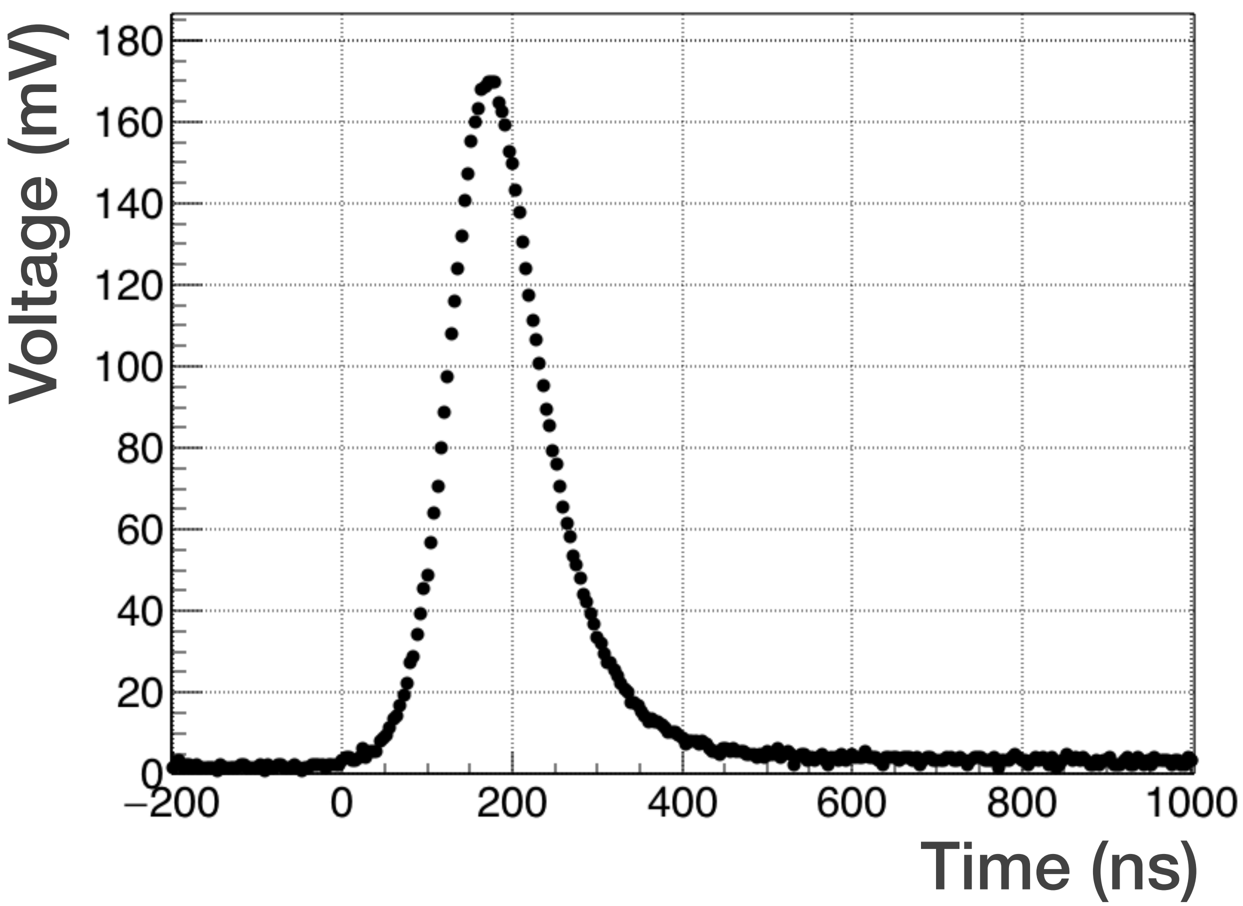


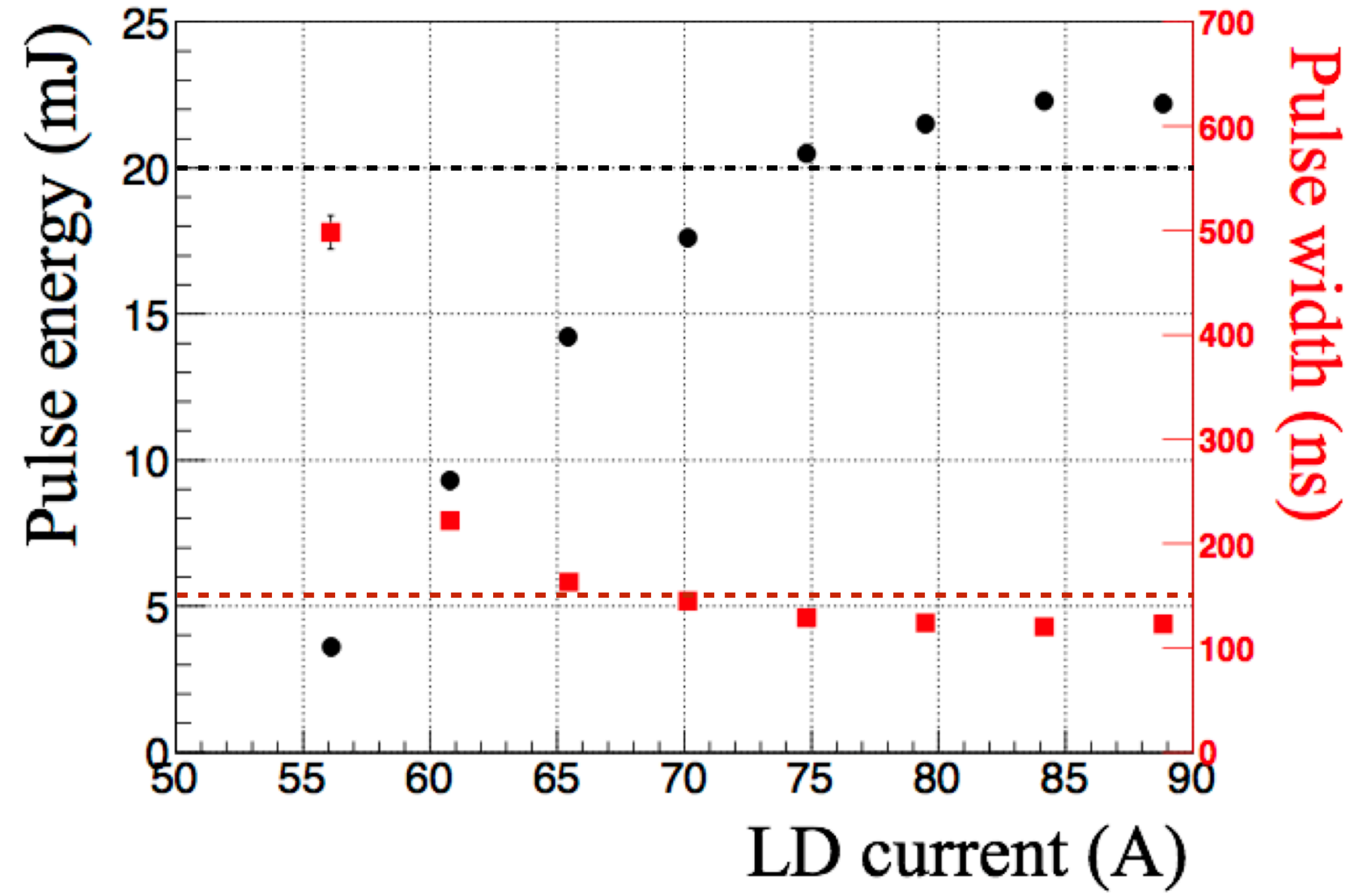
TmHo:YAG Laser Development



- 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).

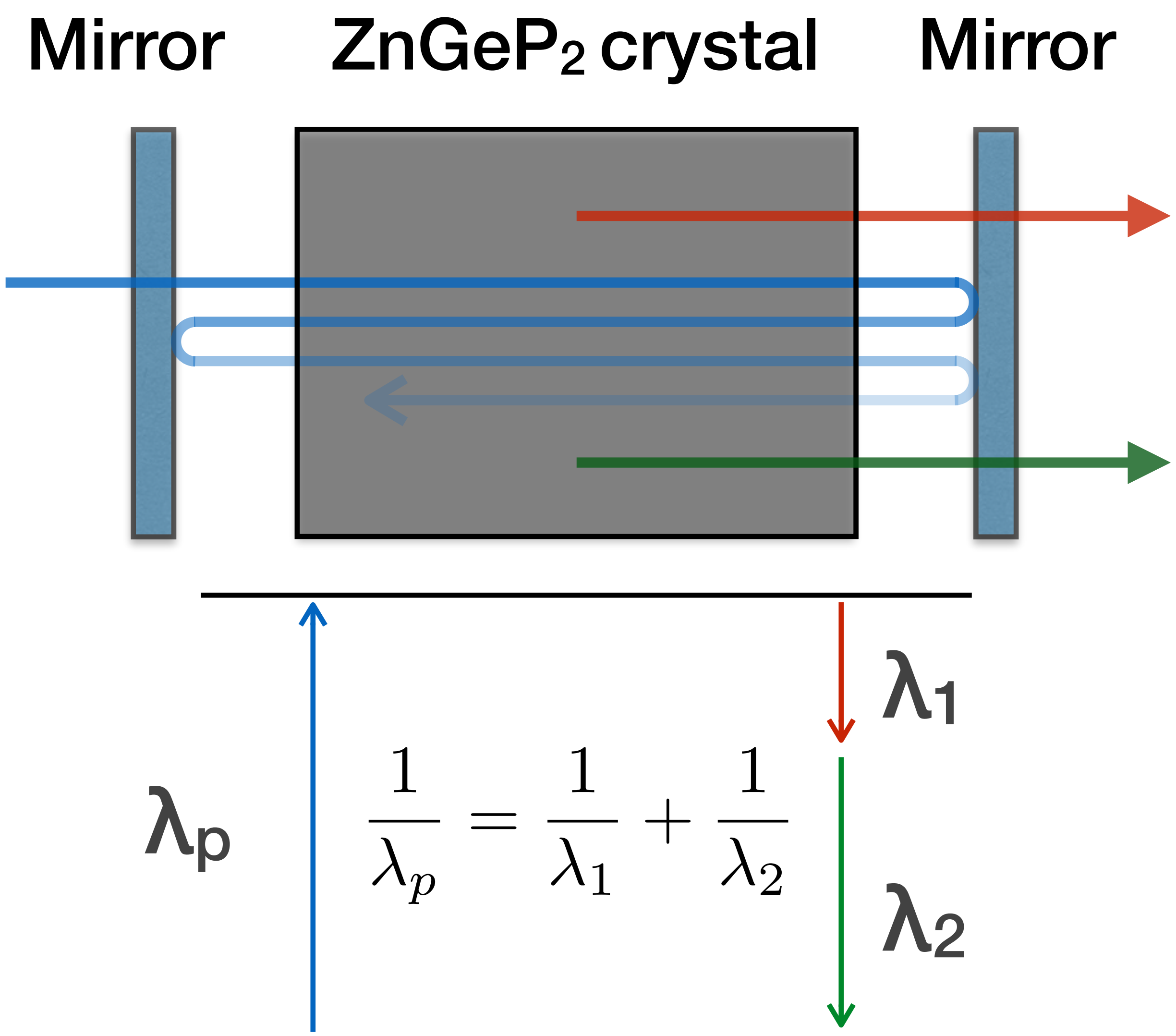
Tm,Ho:YAG Ceramic Laser

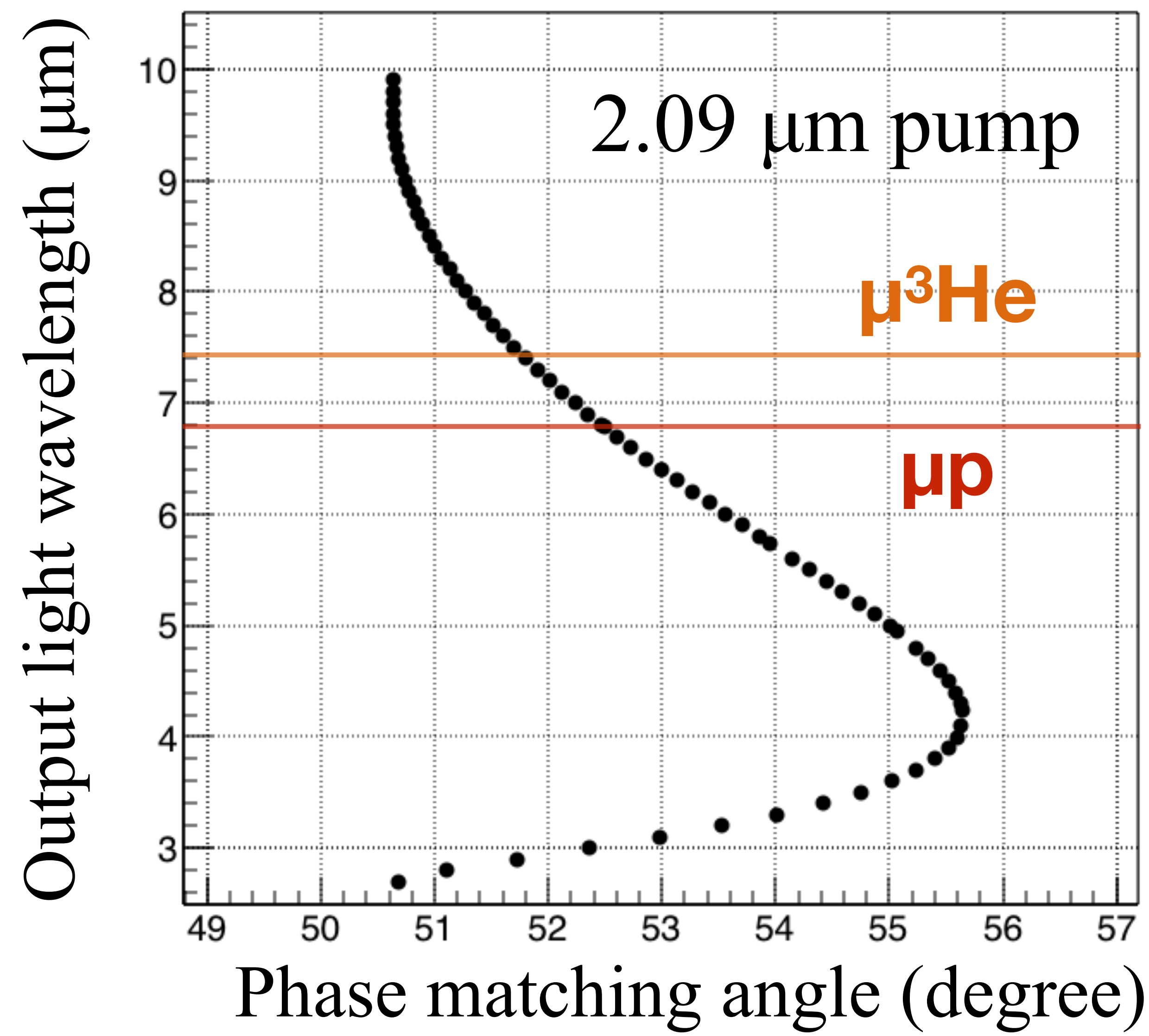




- 2.09 μm light is necessary for 6.8 μm light generation via OPO.
- LD pumped, Q-switching, Tm^{3+},Ho^{3+} co-doped YAG ceramic laser was developed.
- Sufficient performance as a pumping beam for ZGP-OPO was achieved (E>20 mJ, Width<150 ns).

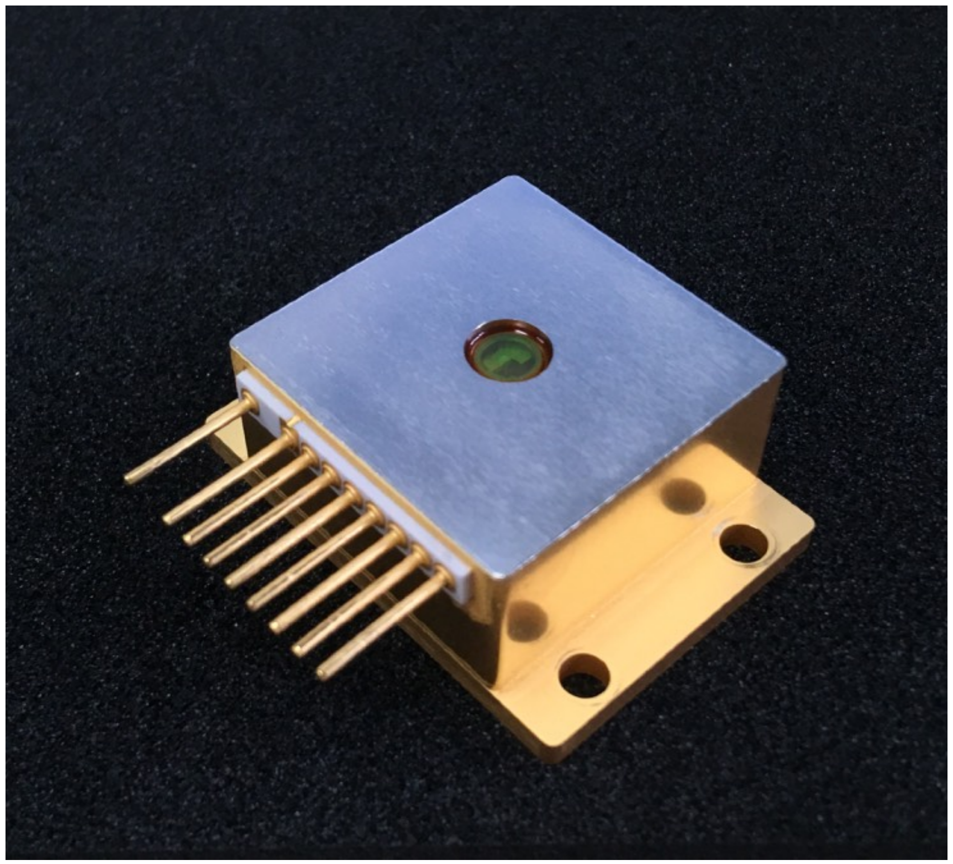
Optical Parametric Oscillation

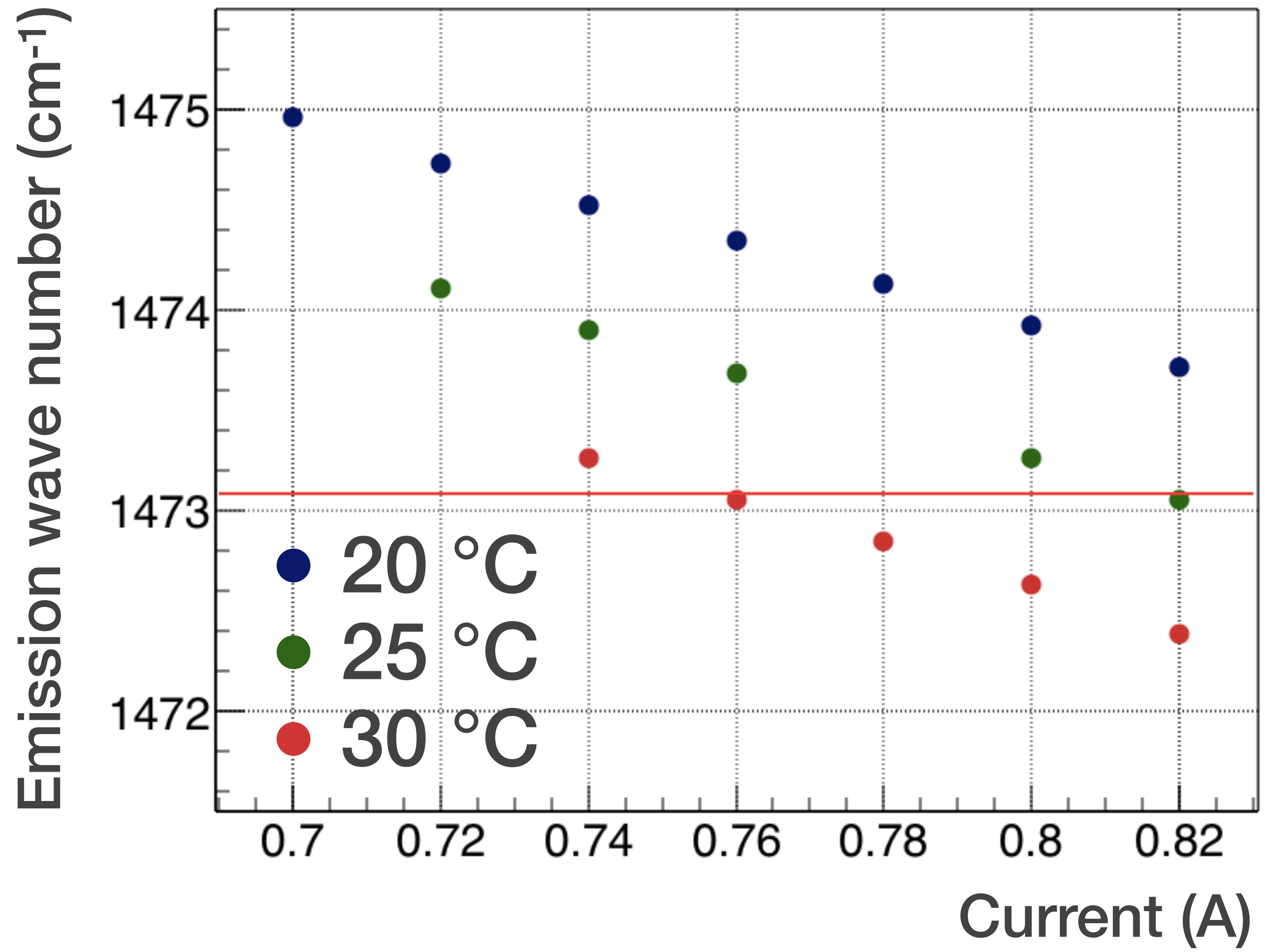




- Optical parametric oscillator provides two lower frequency lights from a pumping light via non-linear optical effect.
- ZGP is an optimum from viewpoints of the damage threshold and non-linear optical coefficient.
- All-solid mid-infrared light source covers both μp 1S-HFS and μHe 2S-HFS at the same time by just changing of the crystal angle.

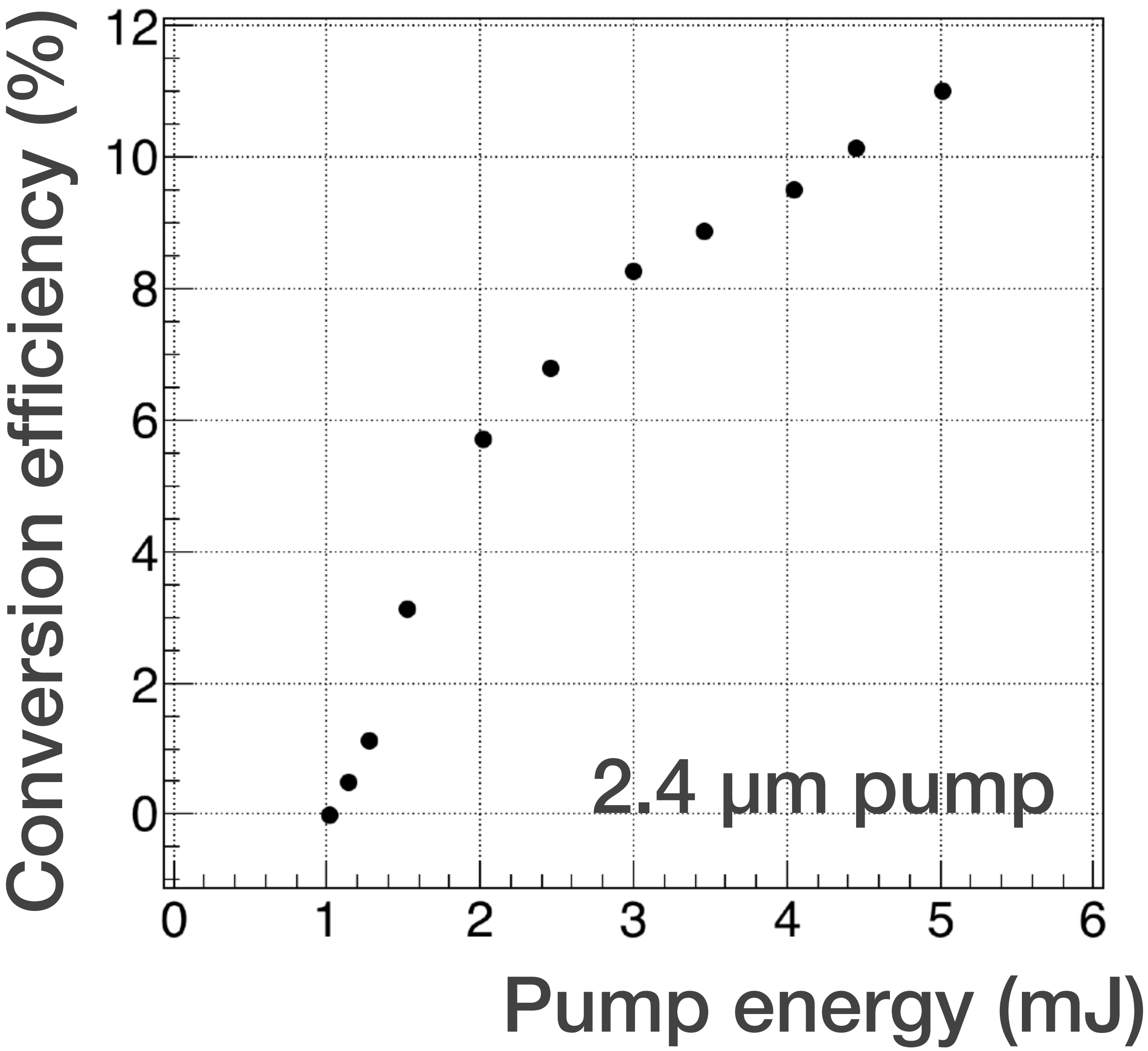
QCL-Seeded ZGP-OPO

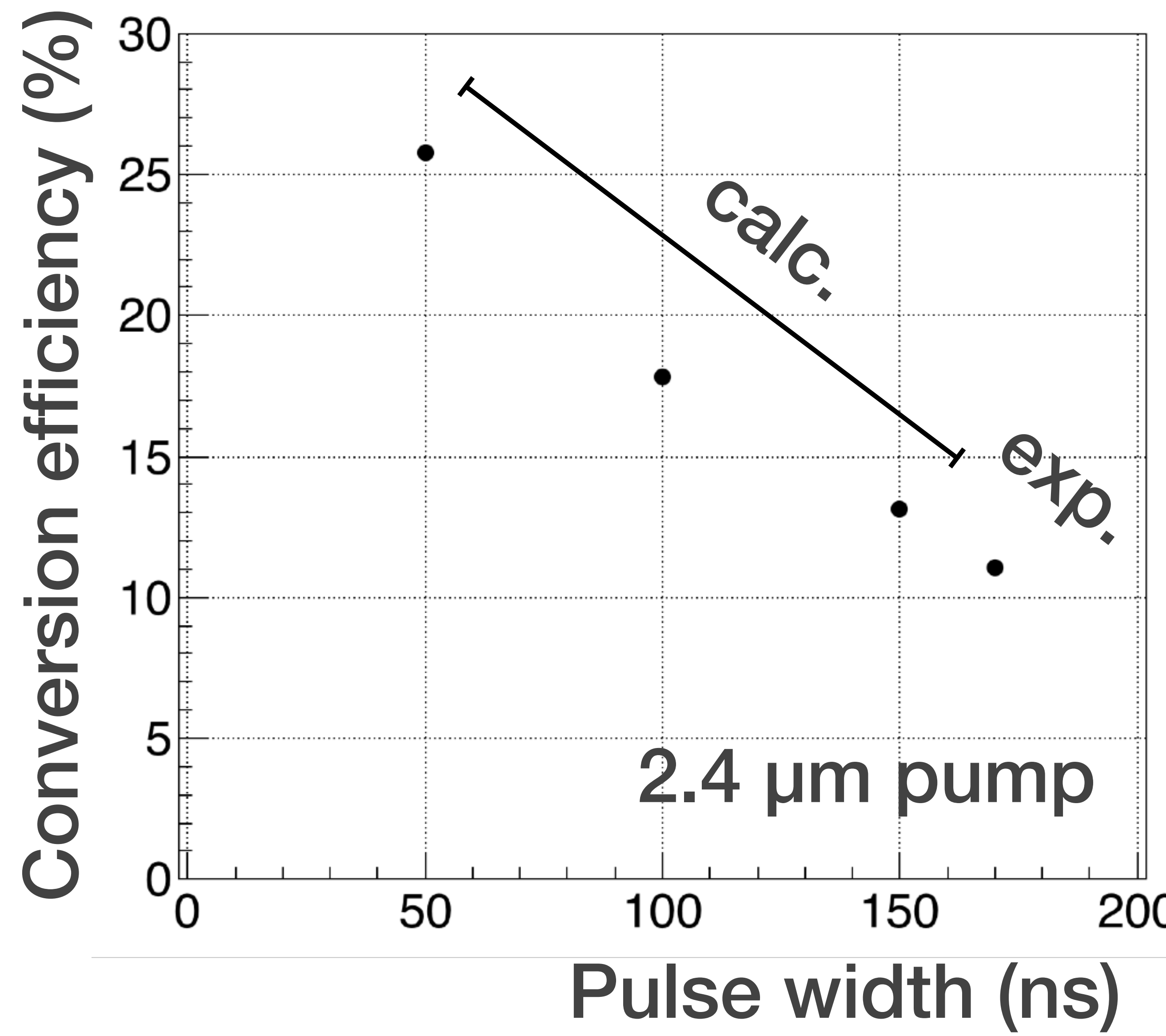




- Quantum cascade laser (QCL) for a seeder was developed.
- Oscillation at 1473.03 cm^{-1} = 6.778 μm was confirmed.
- Radiant output power was 25 mW at 6.778 μm (high enough).
- Spectral linewidth measurement is in preparation.

ZGP-OPO with 2.4 μm pump





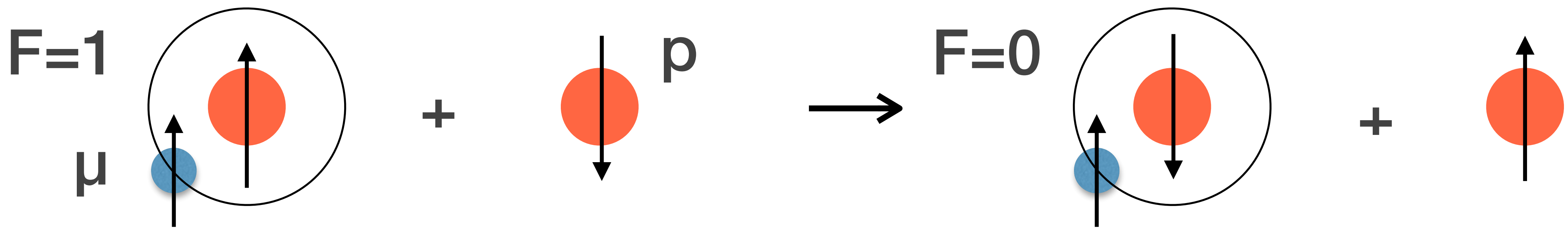
- **The ZGP-OPO was demonstrated with Cr:ZnSe laser (2.4 μm).**
- **Similar performance is expected with 2.09 μm pump.**
- **The conversion efficiency of 13% or above is achievable.**

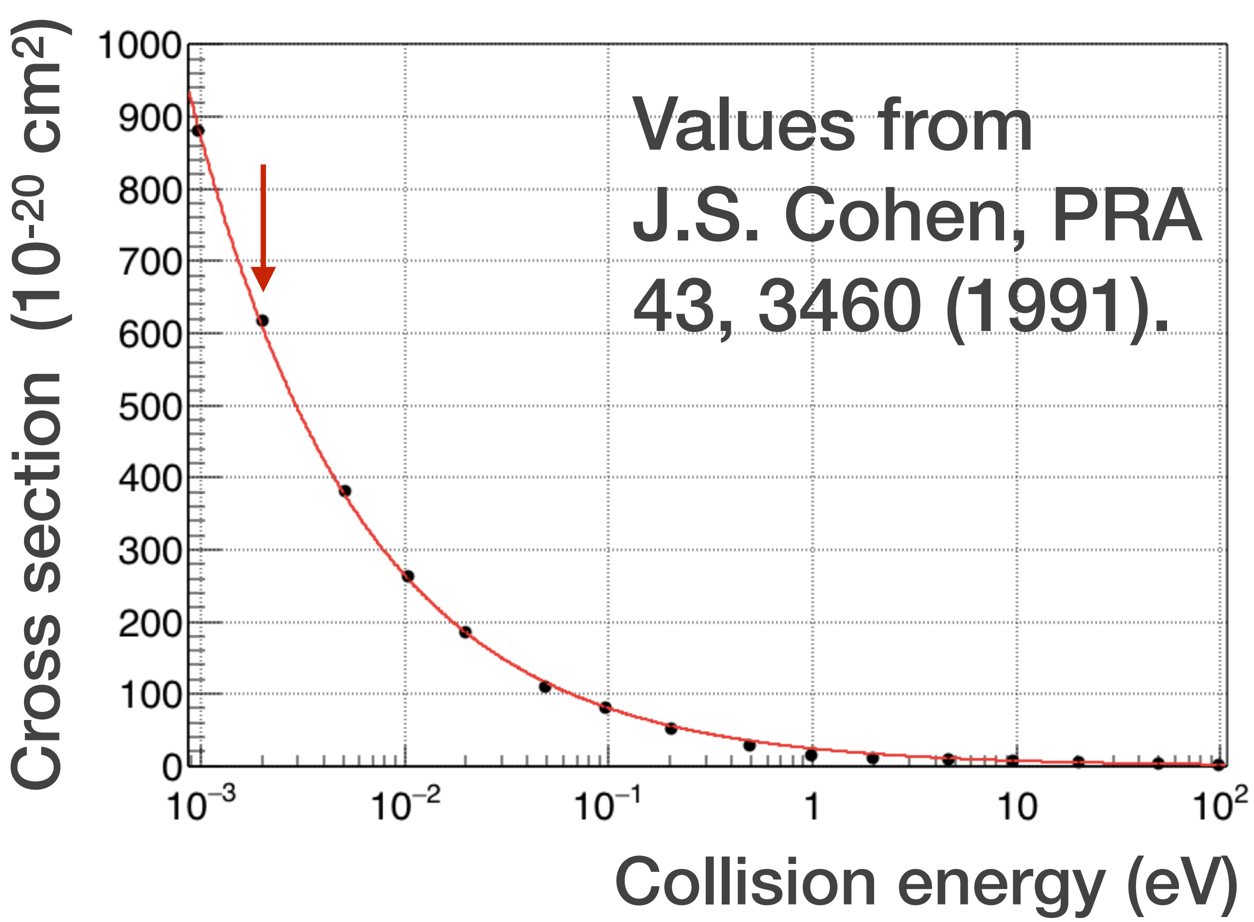
What is Difficult? (reprise)

- High-performance transition laser is required
  - High pulse energy > 20 mJ
  - Narrow spectral linewidth < 100 MHz
  - Necessity of a new development
- HFS triplet state is de-excited in a short lifetime
  - Collisional hyperfine quenching
  - Inelastic scattering μp(F=1)+p->μp(F=0)+p
  - Polarization lifetime ~ 50 ns at 20 K, 0.06 atm

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.

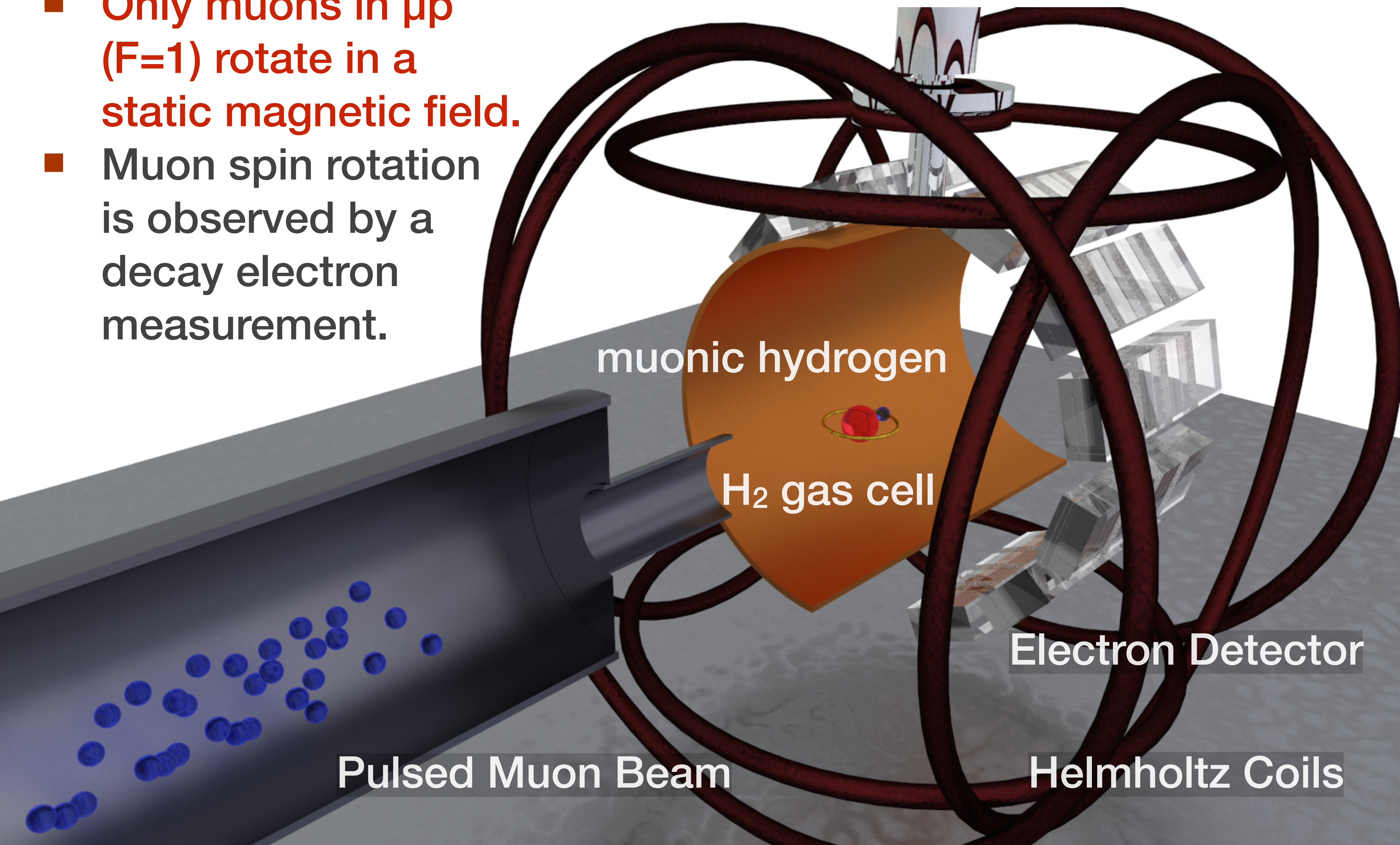




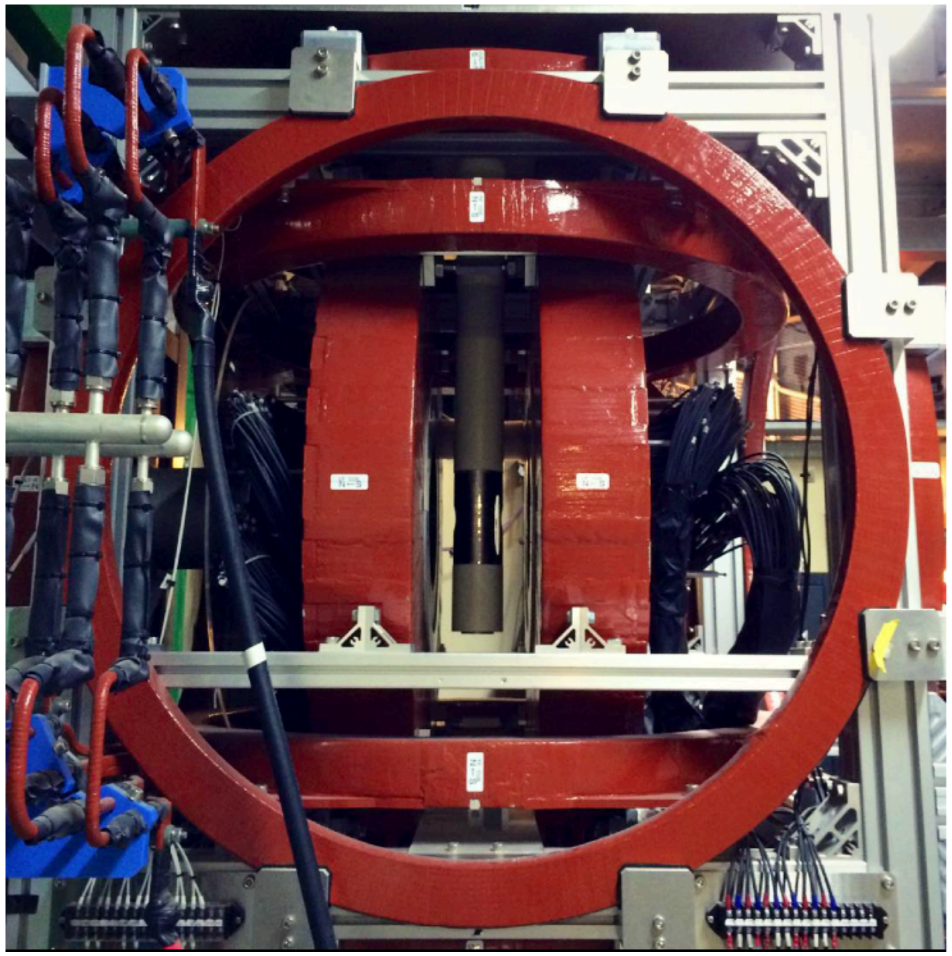
- Quenching rate depends on collision energy (gas temperature) and gas pressure.
- Expected lifetime at 20 K, 0.06 atm is approximately 50 ns.
- A new experiment for direct measurement of the quenching rate was proposed.

Quenching Rate Measurement

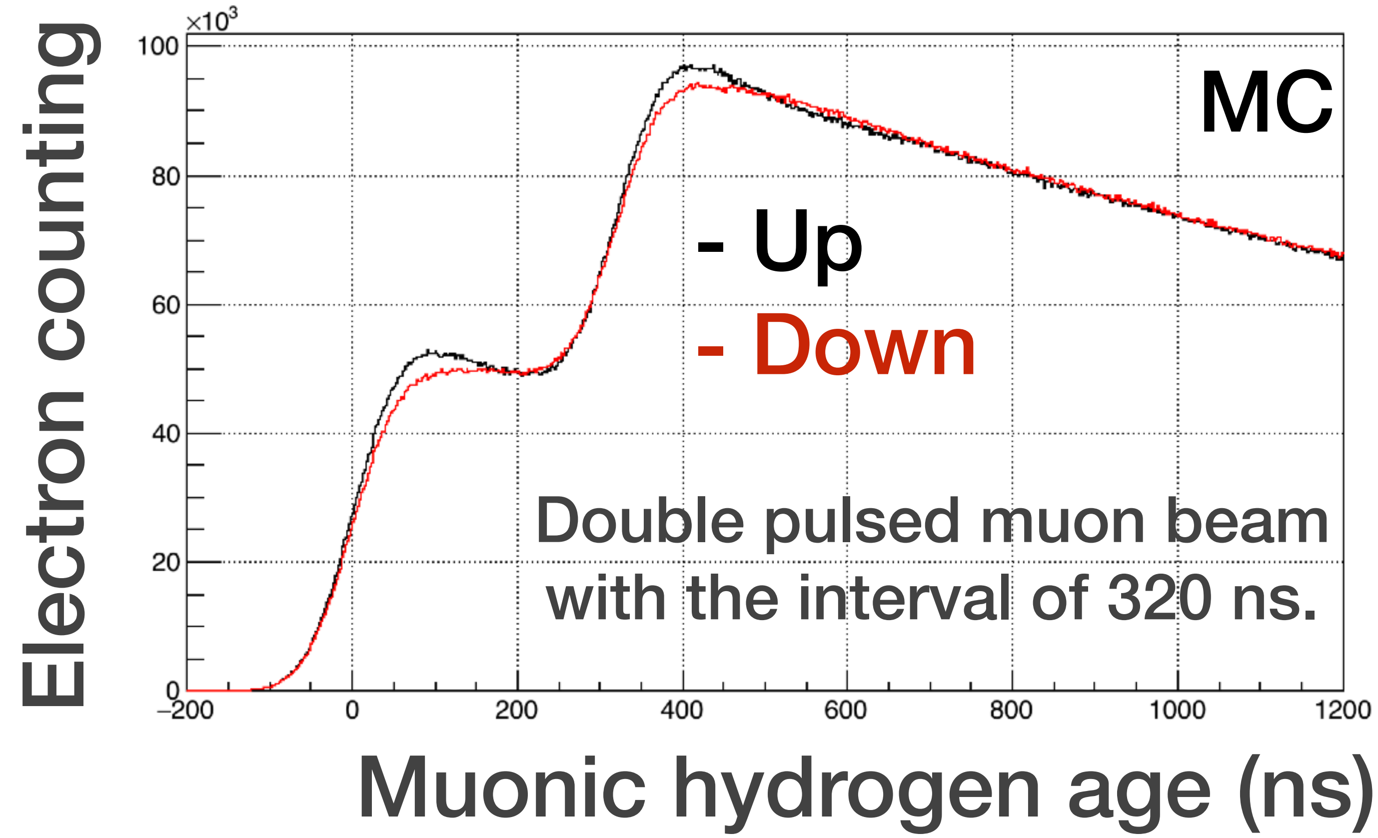
- Only muons in μp (F=1) rotate in a static magnetic field.
- Muon spin rotation is observed by a decay electron measurement.

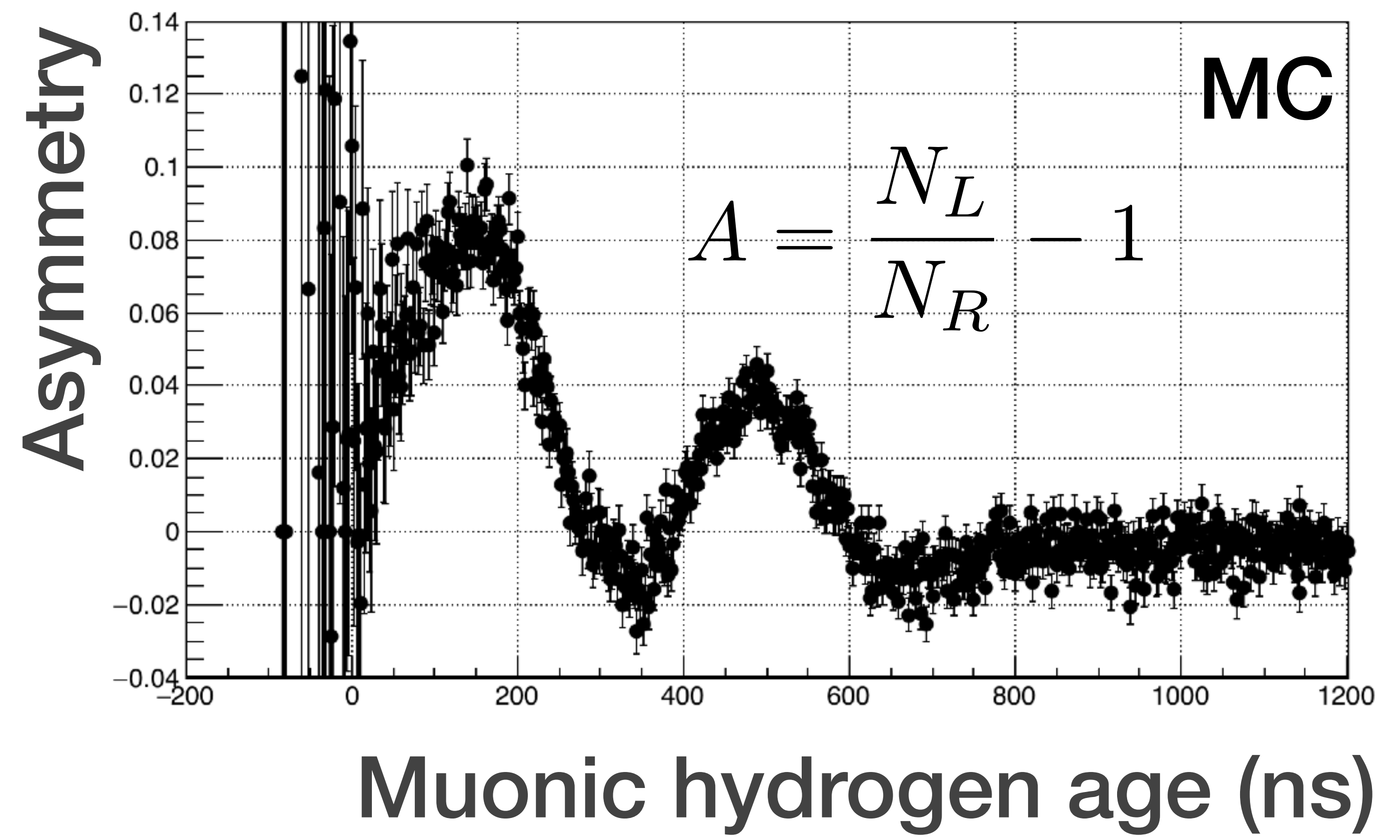


Muon Spin Rotation

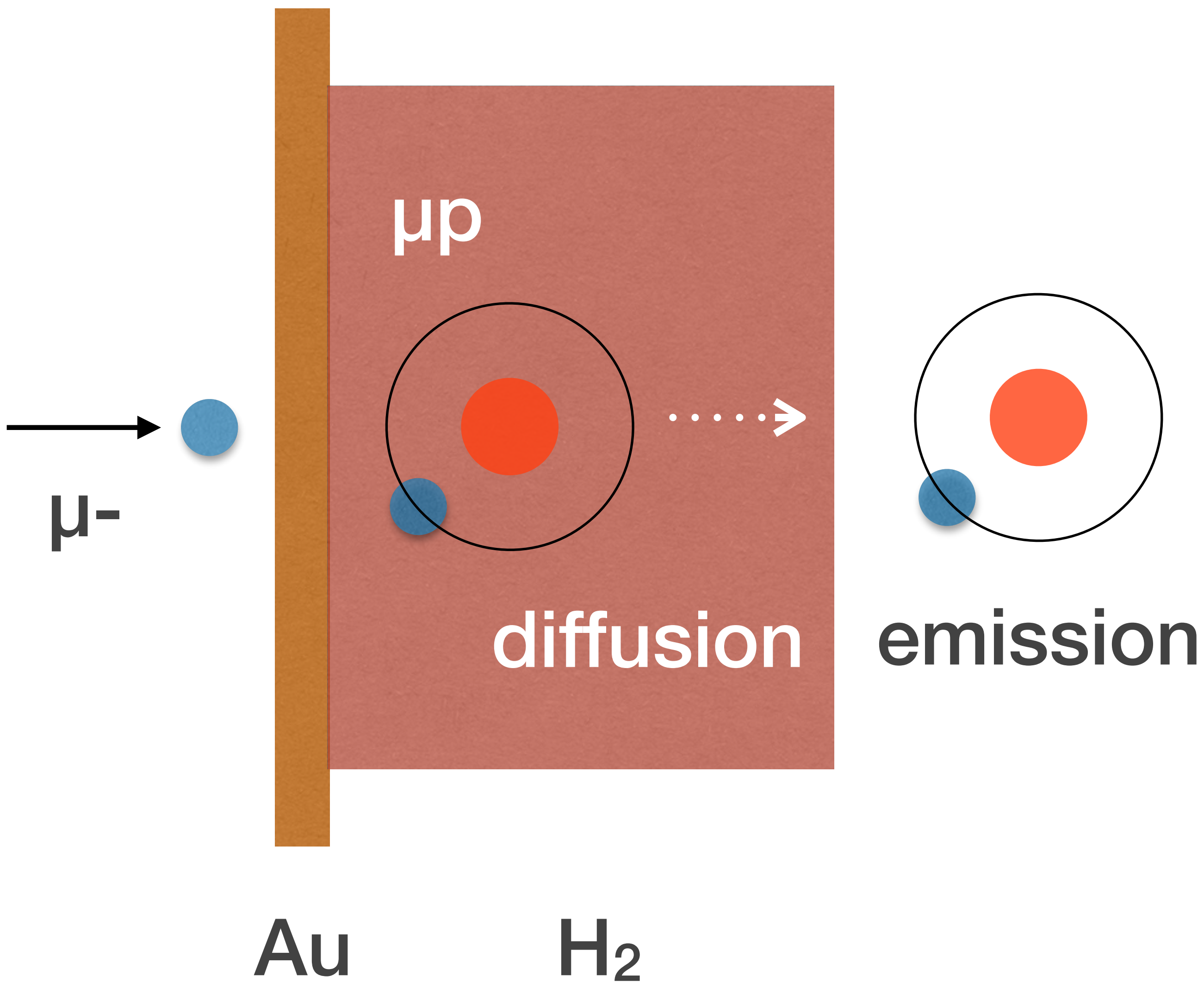


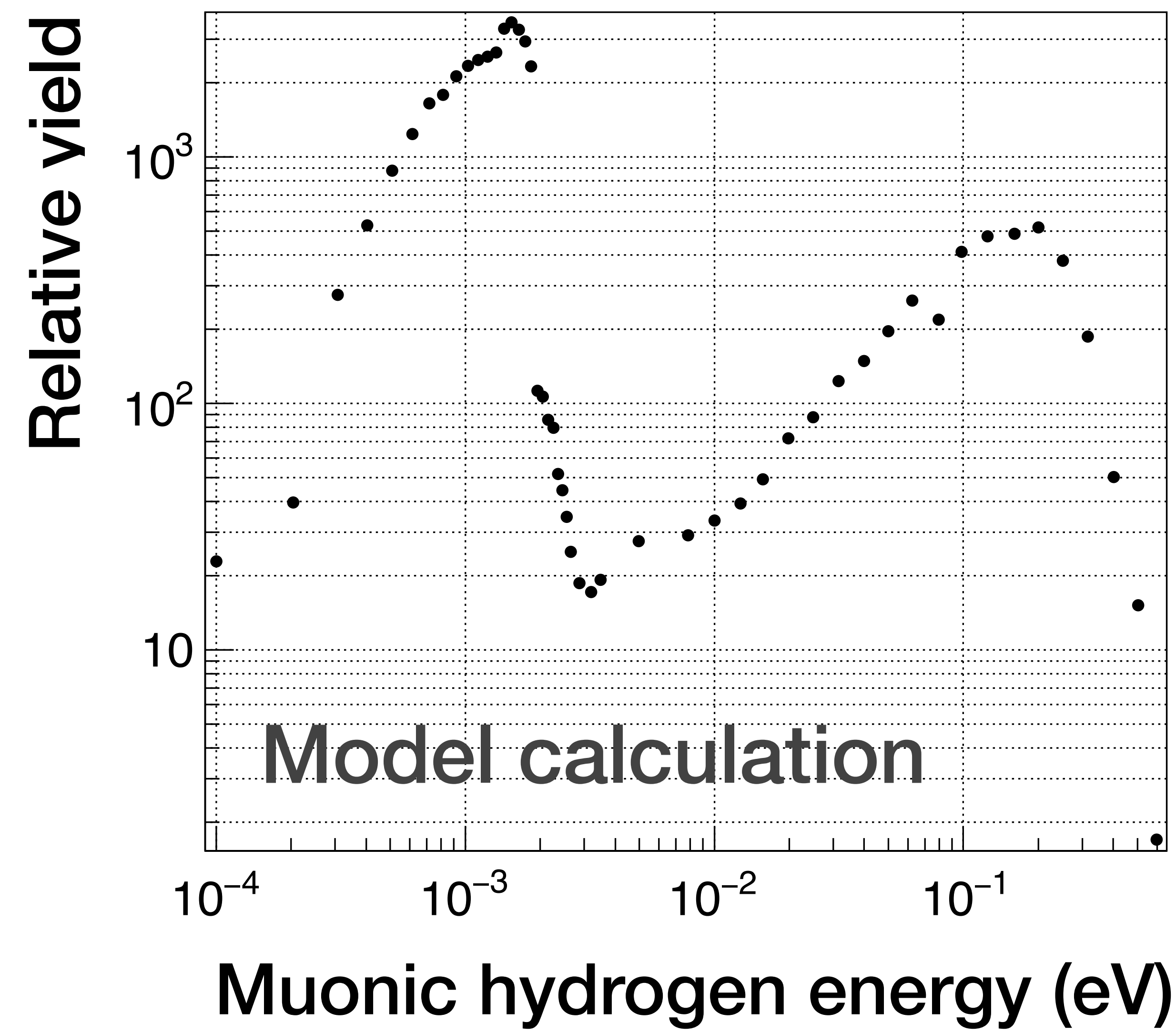
- A transverse field of 0.06 T is applied in the exp.
- Up/Down electron angular asymmetry is measured.
- Experimental proposal was approved by RAL in UK.





Alternative Idea: μp in vacuum





Slow muonic hydrogen is emitted from solid hydrogen thin film.

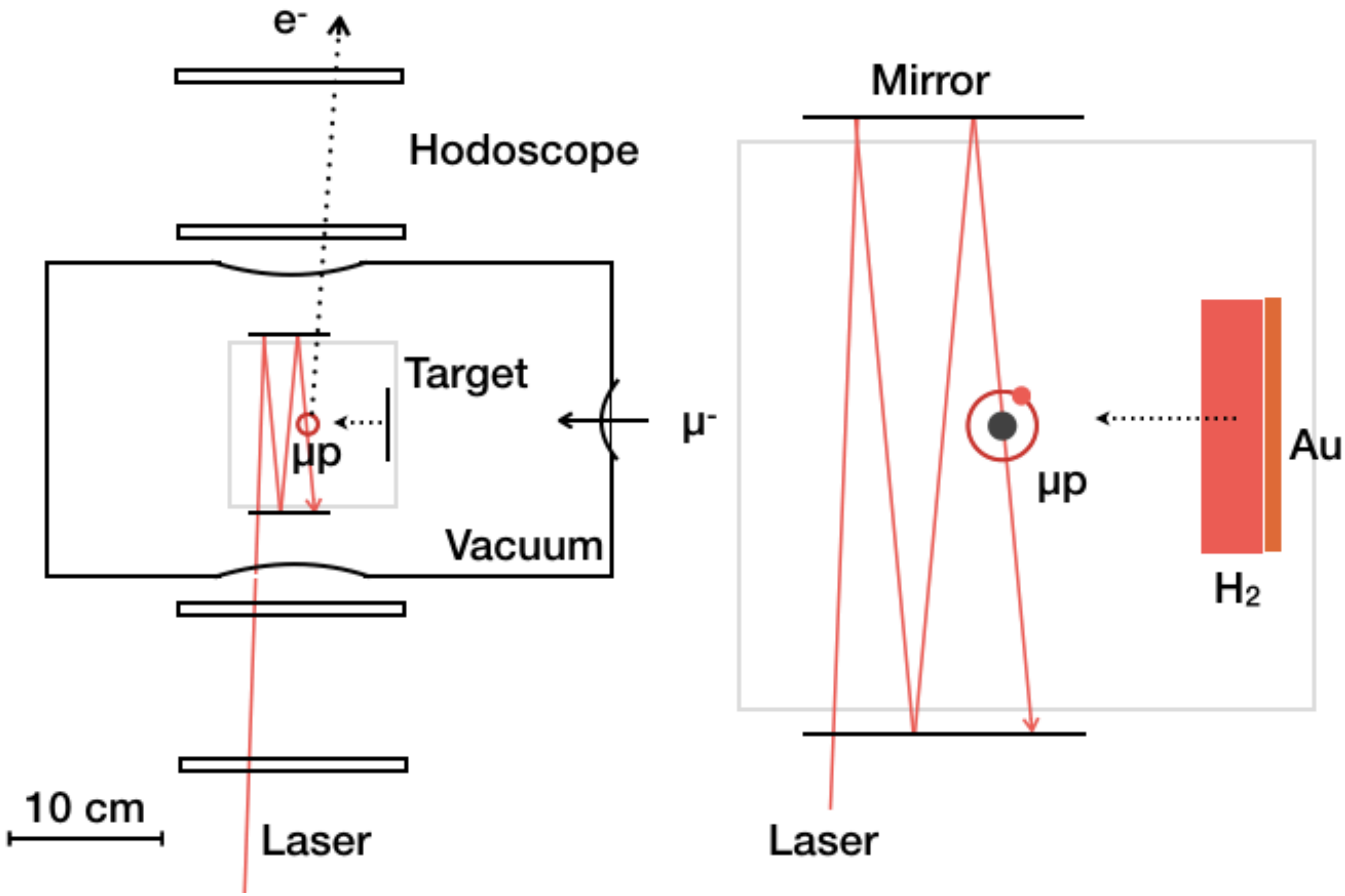
Emission energy has two components: 2 meV and 0.2 eV.

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

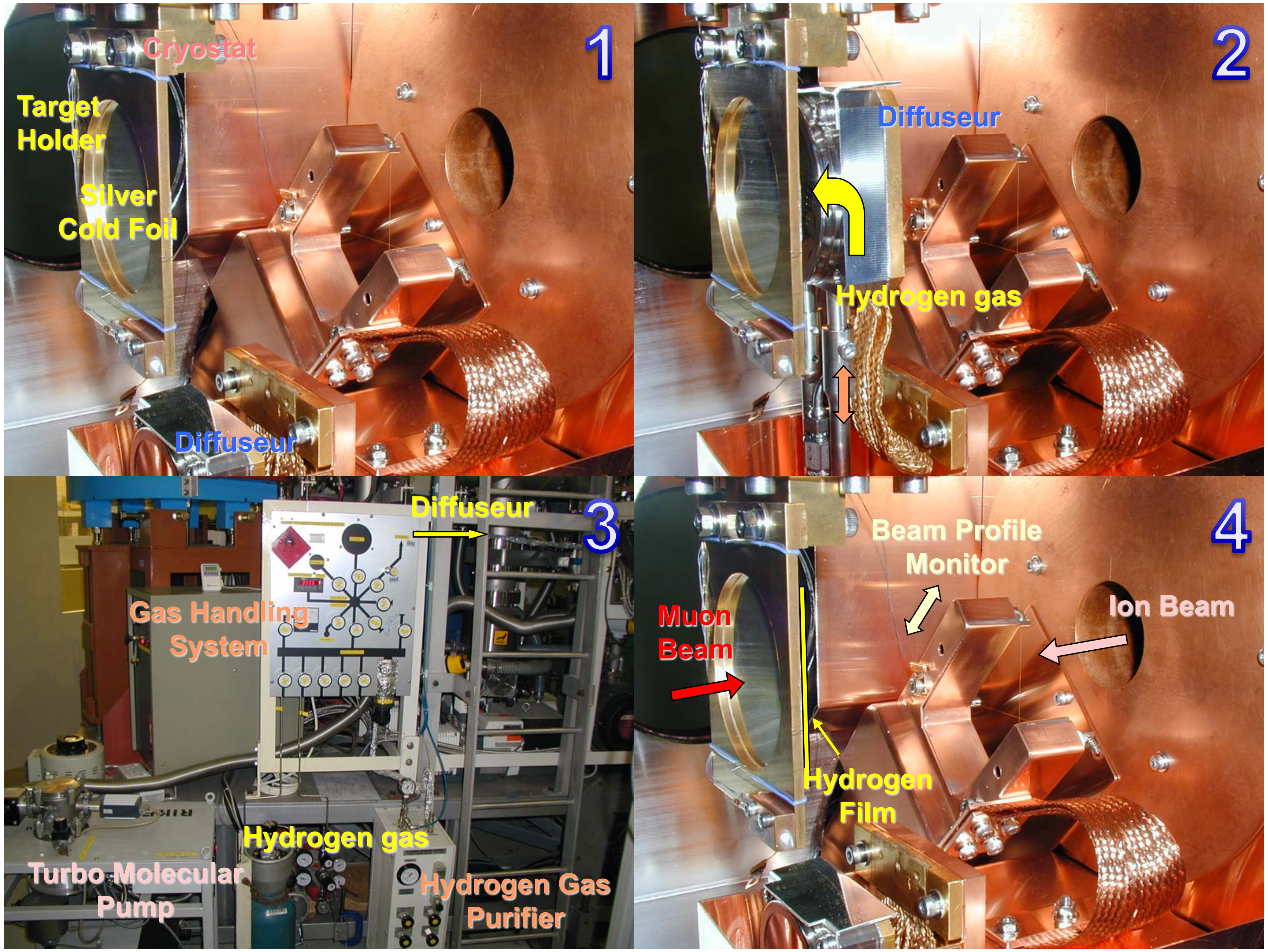


In-flight spectroscopy is free from the collisional quenching.

Systematics is dominated by the Doppler effect (500 MHz at 0.2 eV).

An experimental proposal was submitted to J-PARC.

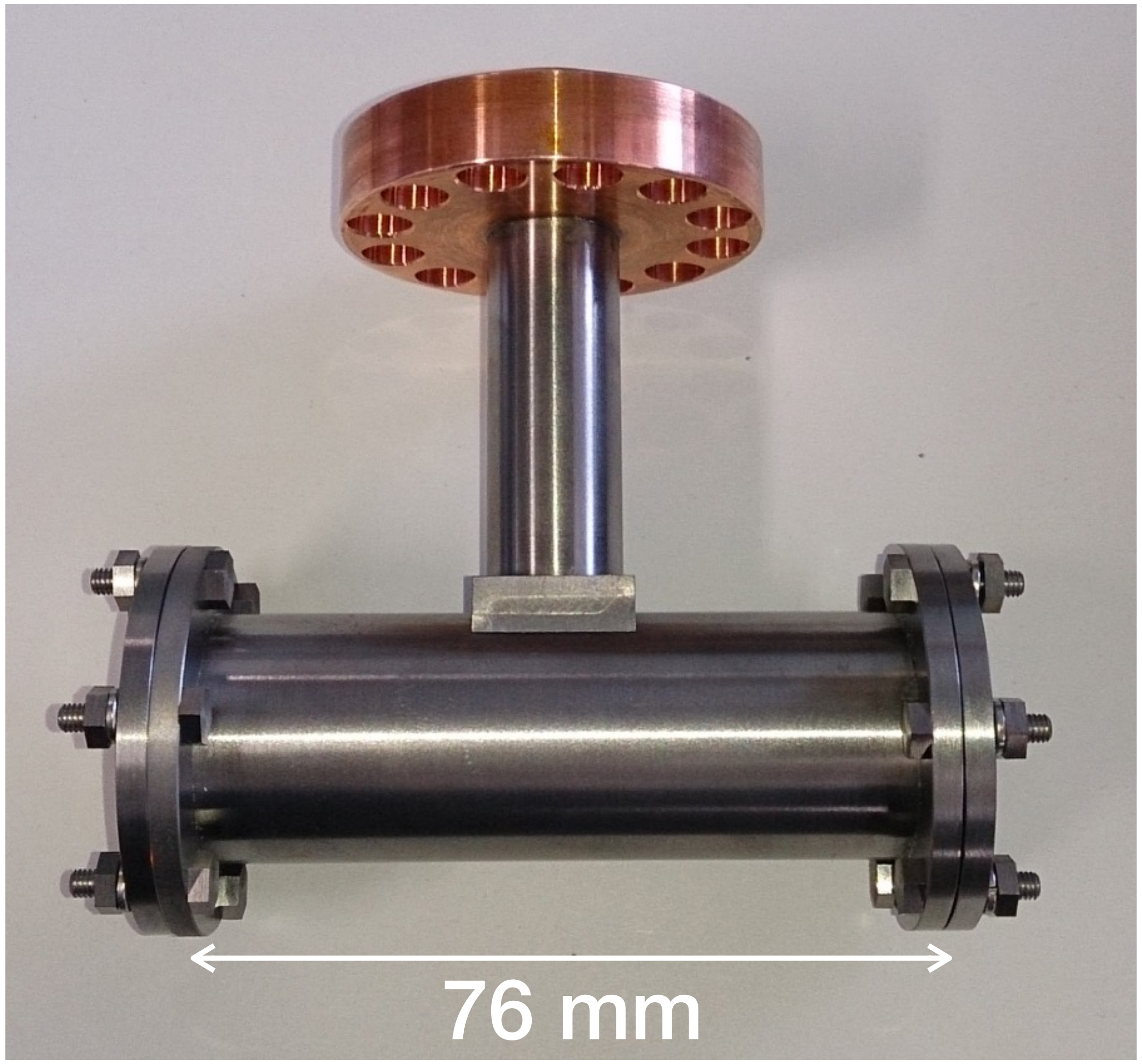
Solid Hydrogen Target



- Hydrogen solid target was established for μA* experiment at RIKEN RAL. Hydrogen gas is sprayed on a gold (silver) foil at 3 K.

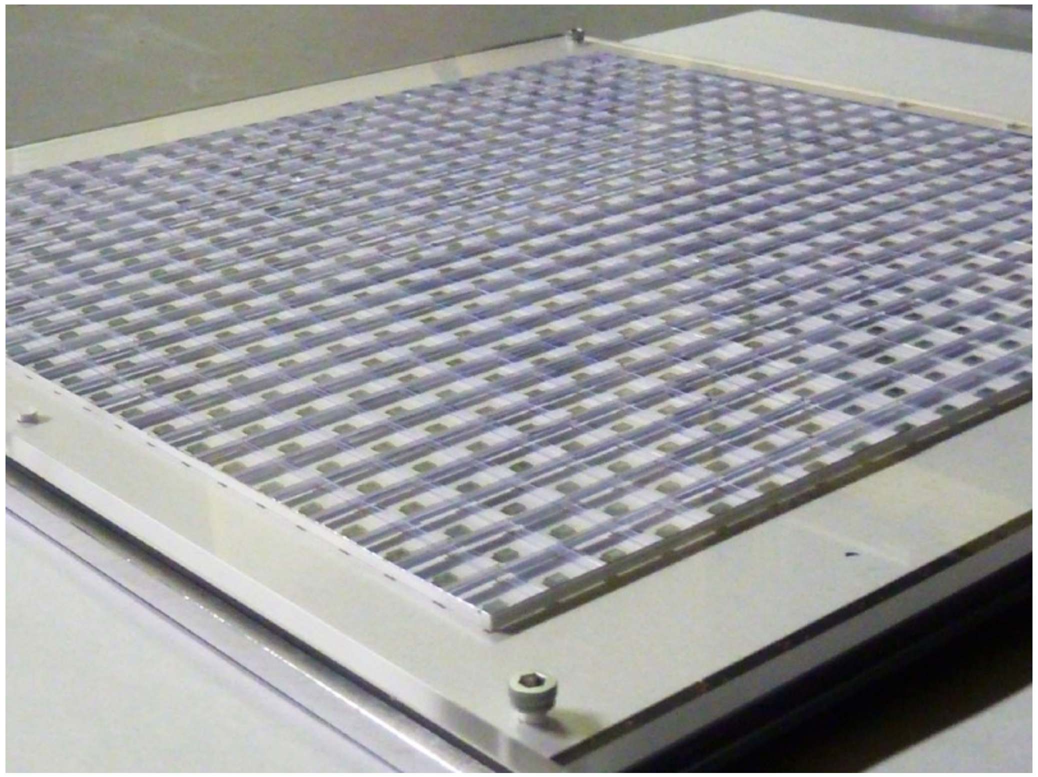
P. Strasser *et al.*, Nucl. Instrum. Methods, A 460, 451 (2001).

Gas Hydrogen Target

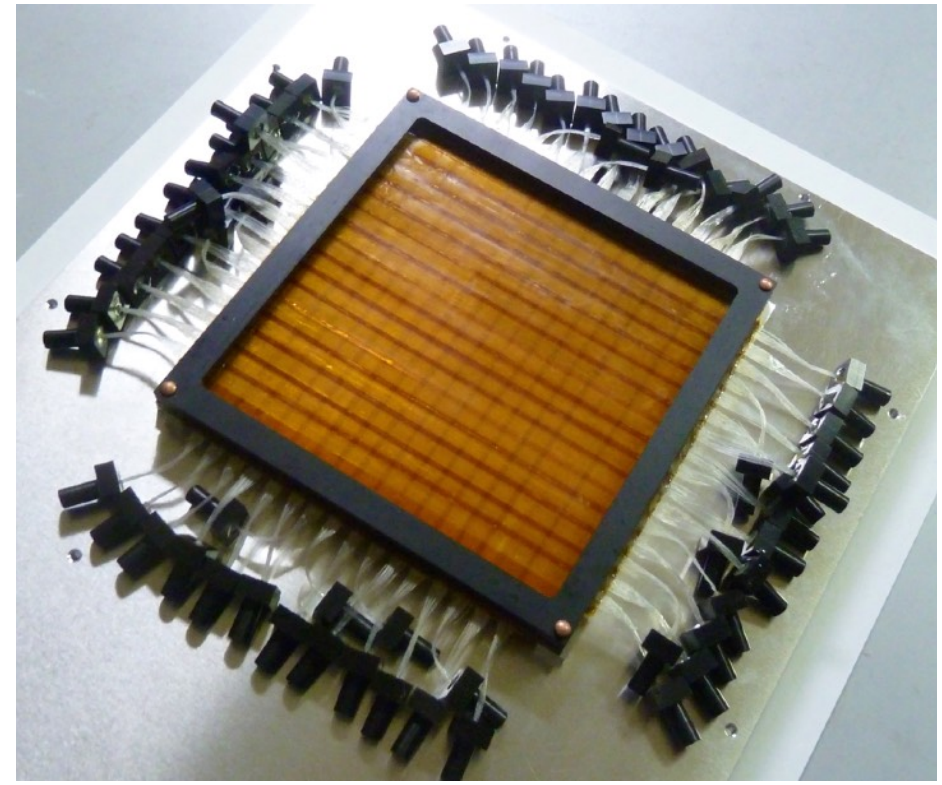


- Temperature is controlled by using a GM cryostat.
- Gas temperature ranges from RT to 20 K.
- Gas density is monitored by a baratron pressure gauge.
- Target cell is made of tungsten for background suppression.

Particle Detectors



Electron detector (24 cm x 24 cm)
Segmented scintillation counter with SiPM readout



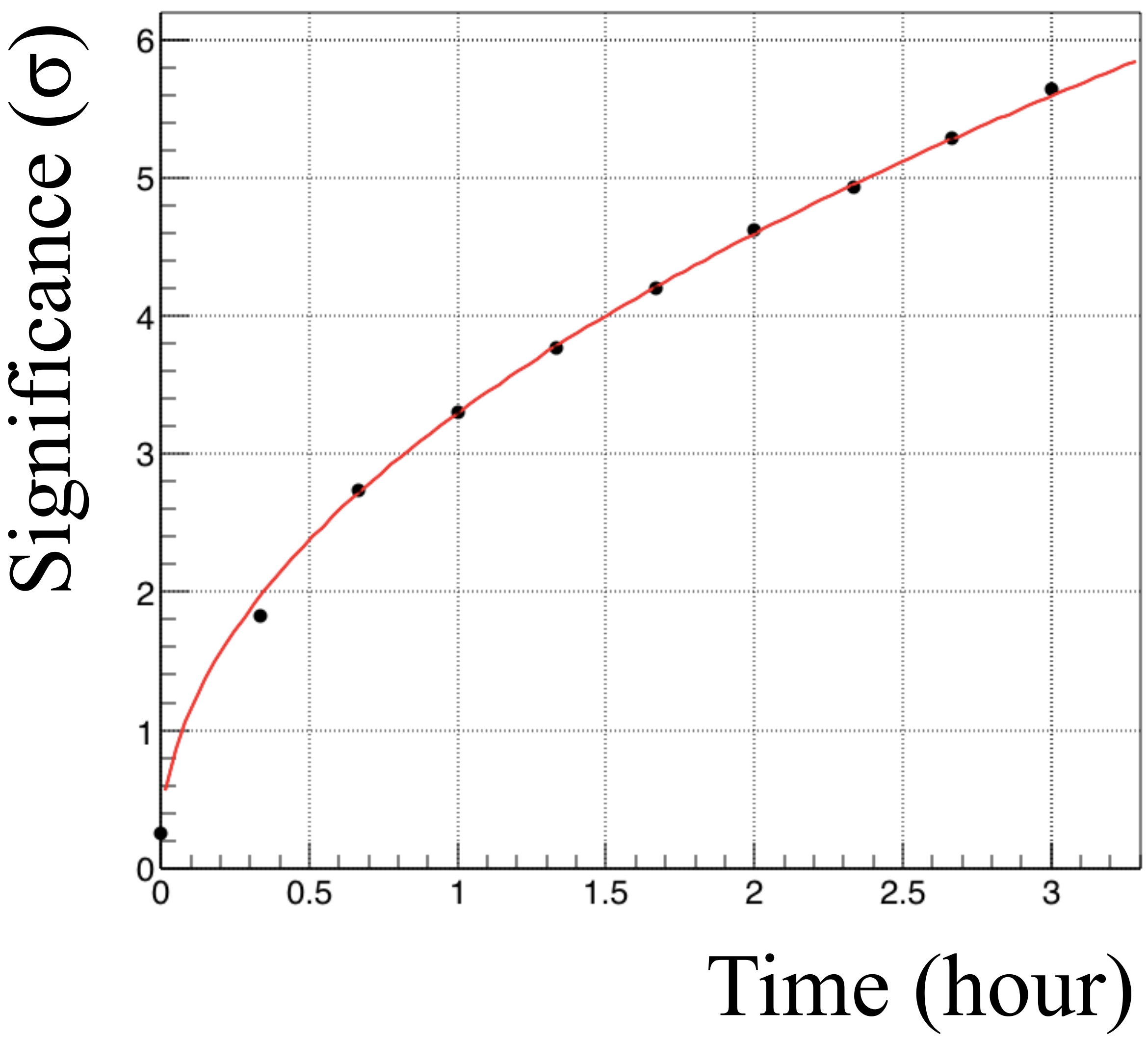
Muon detector (10 cm x 10 cm)
Thin scintillating fiber hodoscope

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

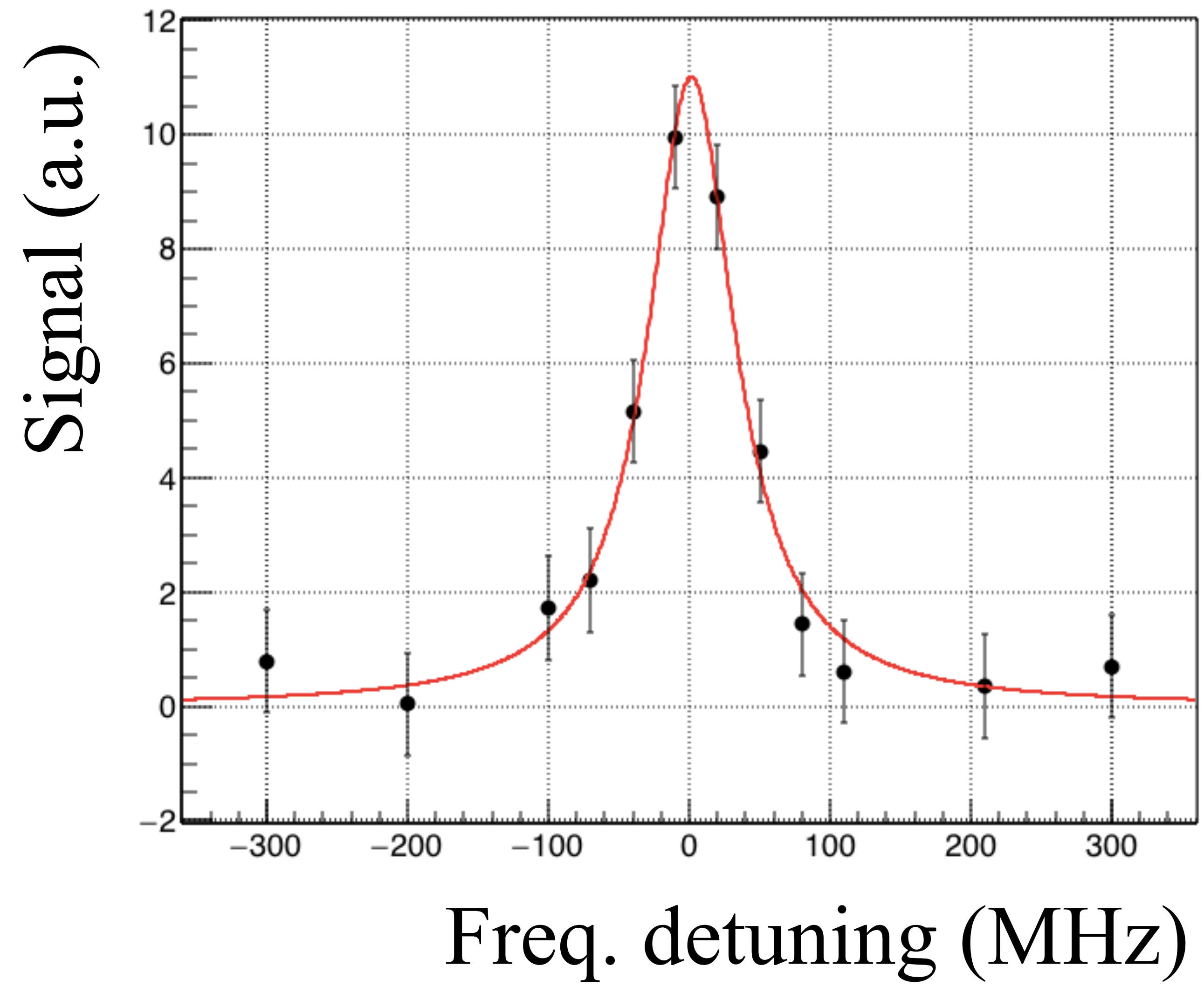
S. Kanda for the MuSEUM Collaboration, Proceedings of Science, PoS(INPC2016)170 (2017).
S. Kanda for the MuSEUM Collaboration, Proceedings of Science, PoS(PhotoDet2015)036 (2016).
S. Kanda for the MuSEUM Collaboration, RIKEN APR Vol. 48 (2016).

Expected Result

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 ground-state muonic hydrogen atom.
- Problem 1 : Necessity of a novel laser system
  - Tm,Ho:YAG ceramic laser was developed and sufficient performance was achieved.
- Problem 2: Collisional hyperfine quenching
  - New measurement of the quench rate was proposed and approved.
  - Alternative idea of in-flight spectroscopy was proposed.
- Two years for development, a year for spectroscopy.