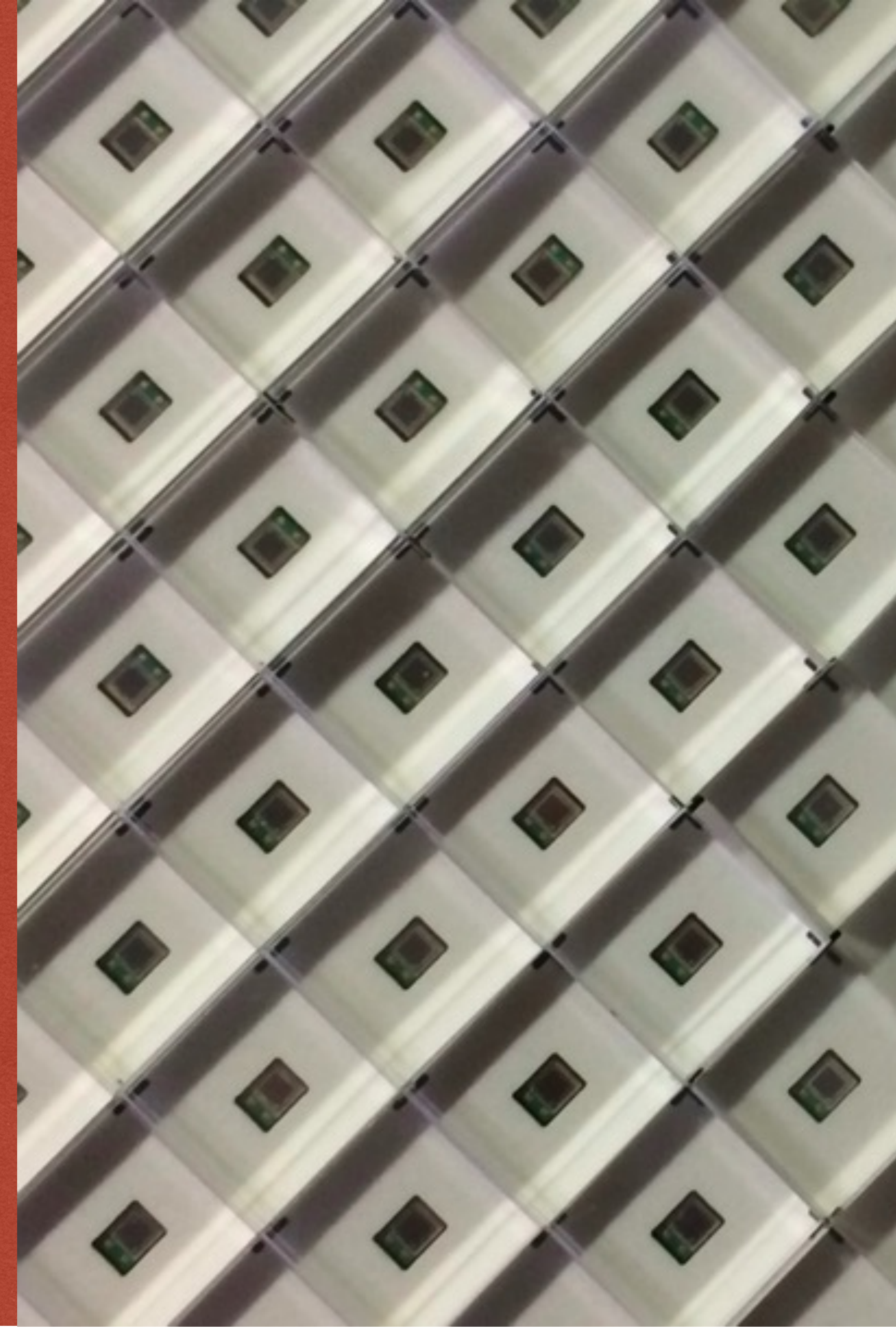
Precision Laser Spectroscopy of the Ground State Hyperfine Splitting in Muonic Hydrogen



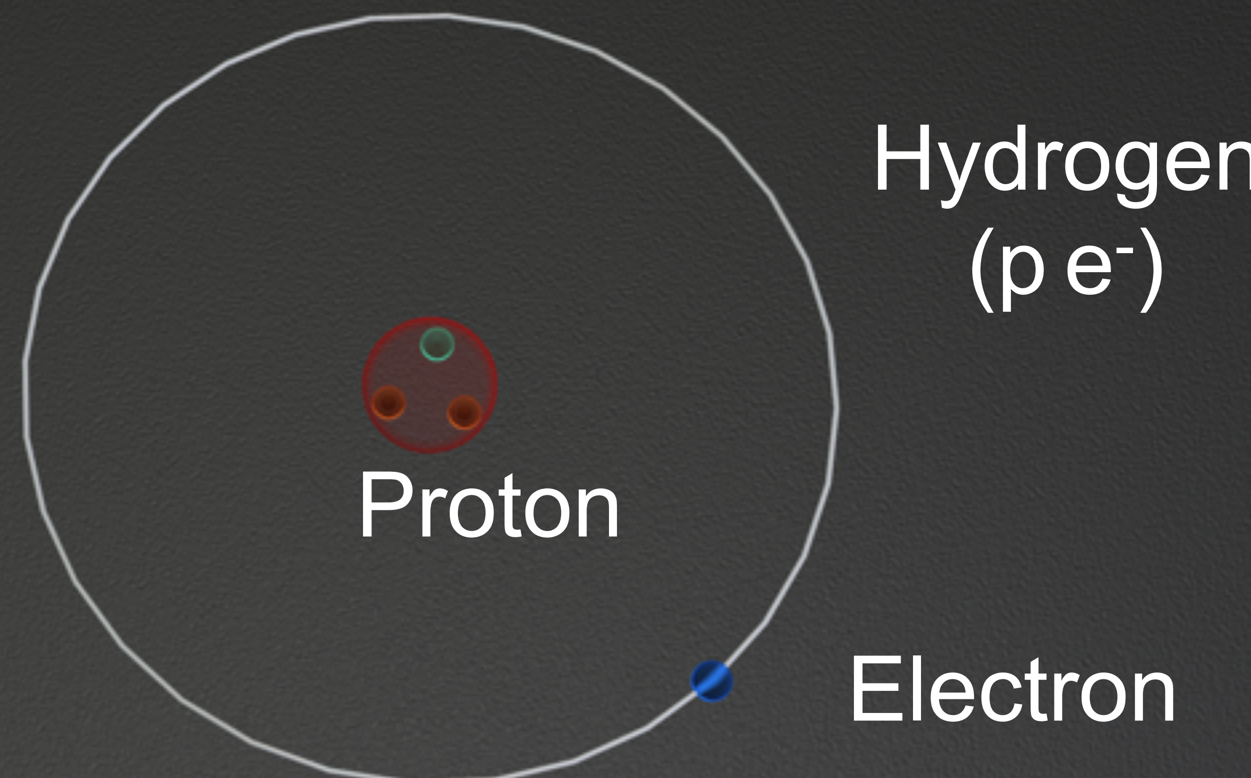
Sohtaro Kanda / RIKEN NISHINA CENTER

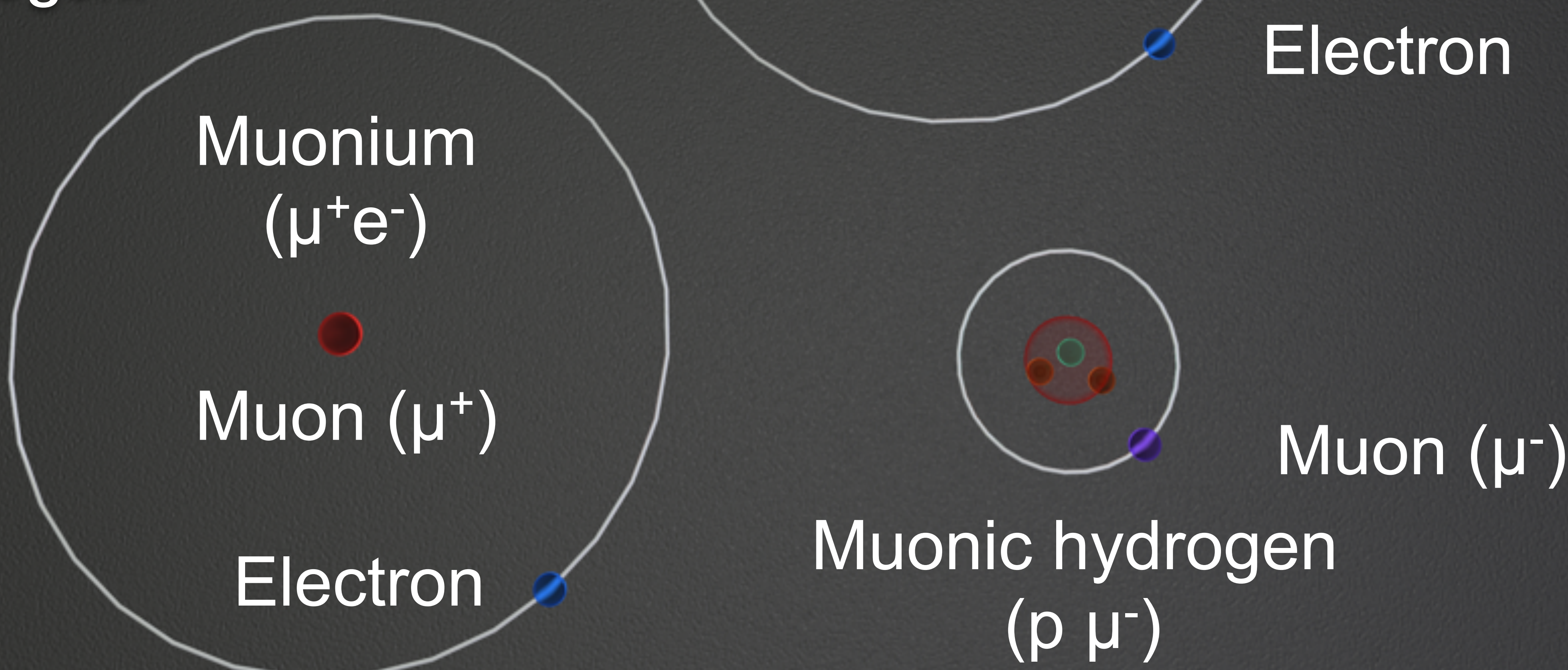
sohtaro.kanda@riken.jp

2017/09/27

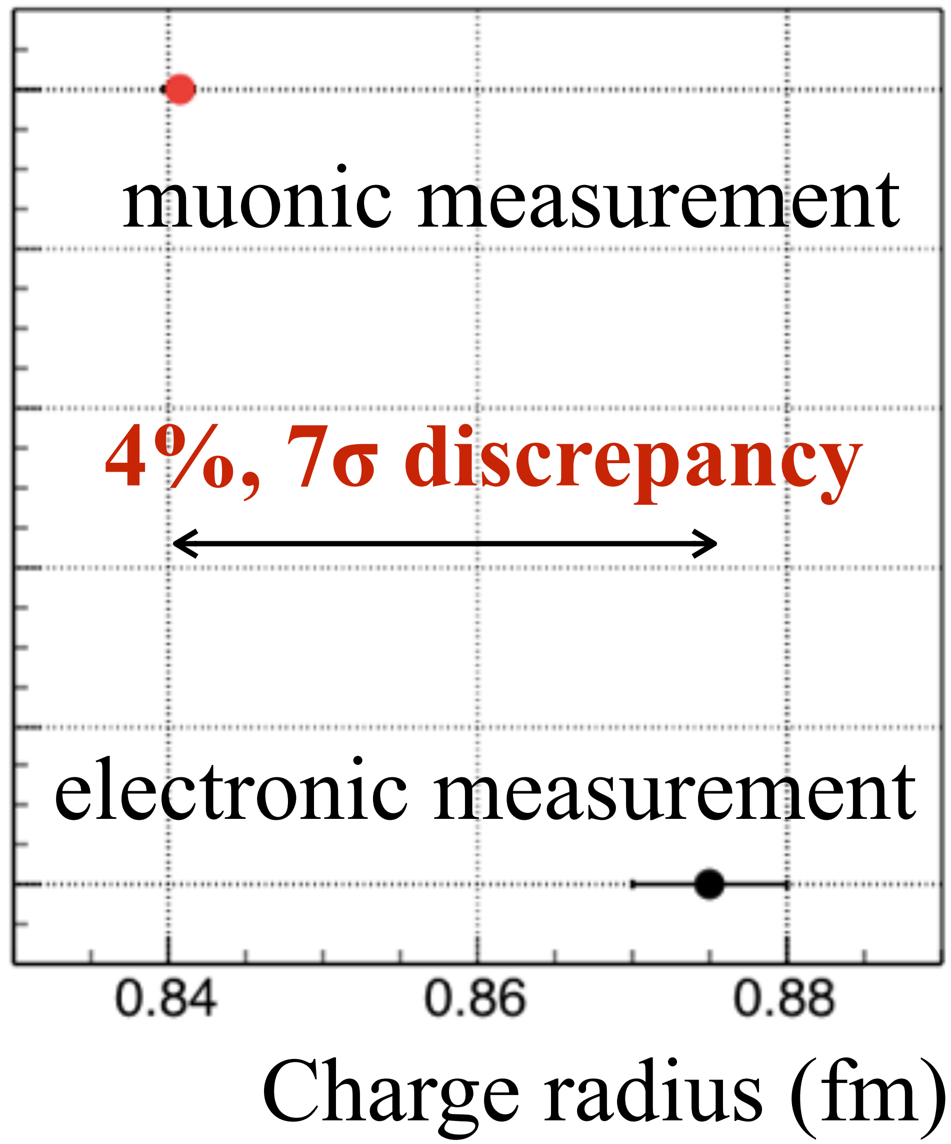
Exotic Atoms Involving Muon

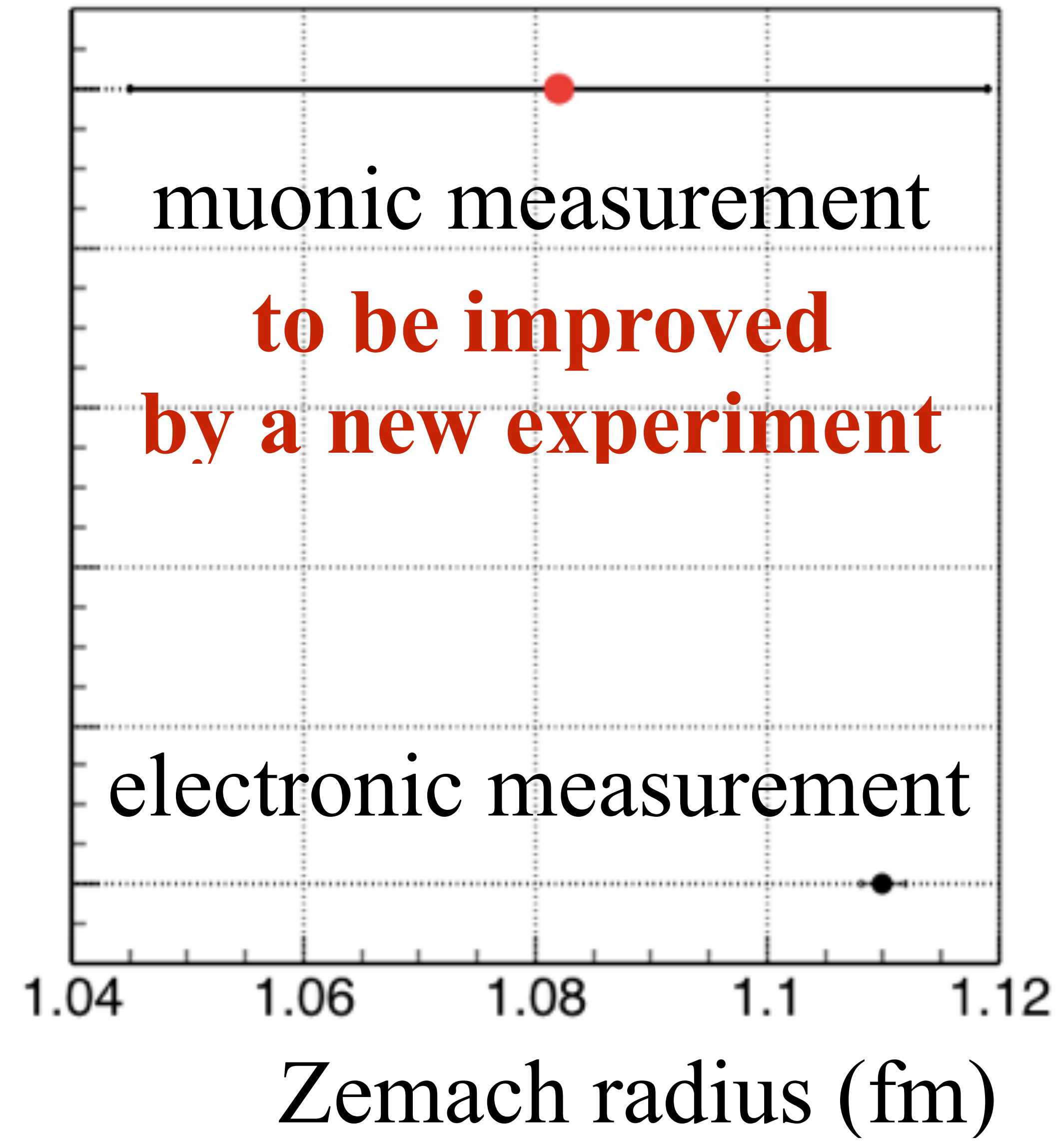
Muon is the 2nd generation particle of charged leptons. It is 200 times heavier than electron and decays in 2.2 μs of the mean lifetime. Muon forms a bound-state as well as hydrogen.





Proton Radius Puzzle



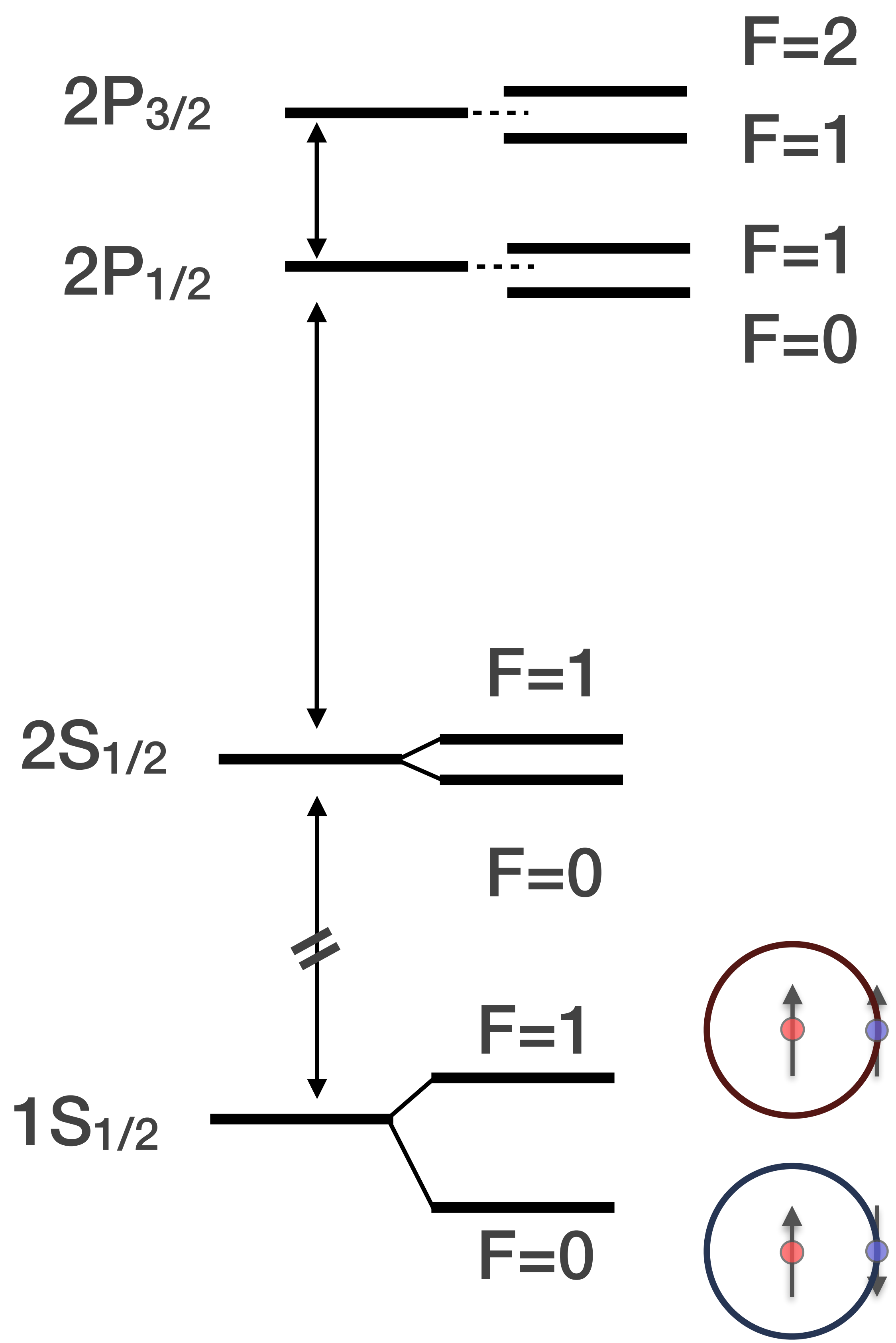


There is no definitive interpretation of the puzzle and new, independent experiment is needed.

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).

Muonic Hydrogen Spectroscopy



Fine Structure : 8.4 meV

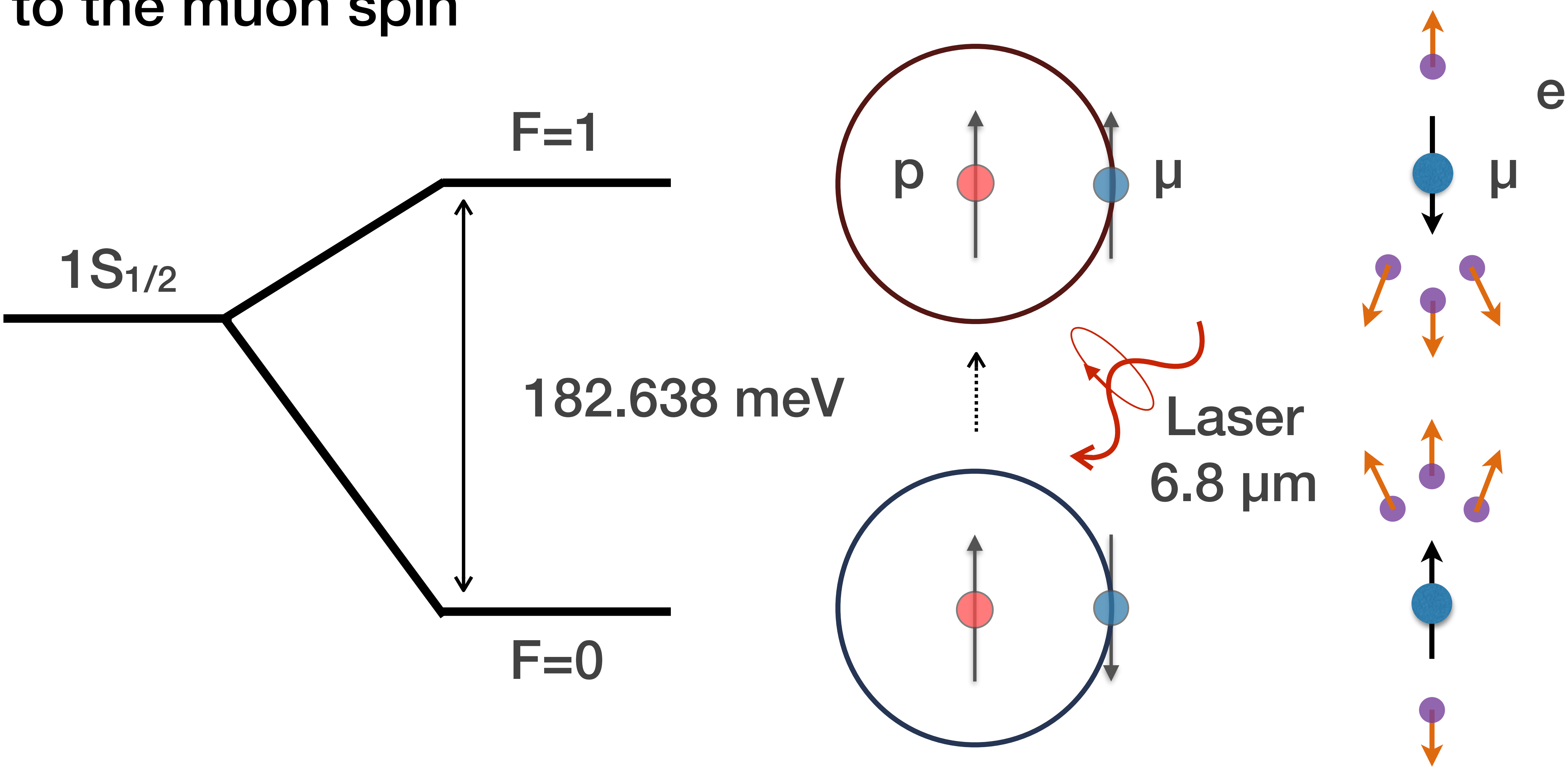
Lamb Shift : 206 meV=6 μm
Finite size effect 3.7 meV
-> Charge Radius
(Experiment at PSI)

2S-HFS : 23 meV=54 μm

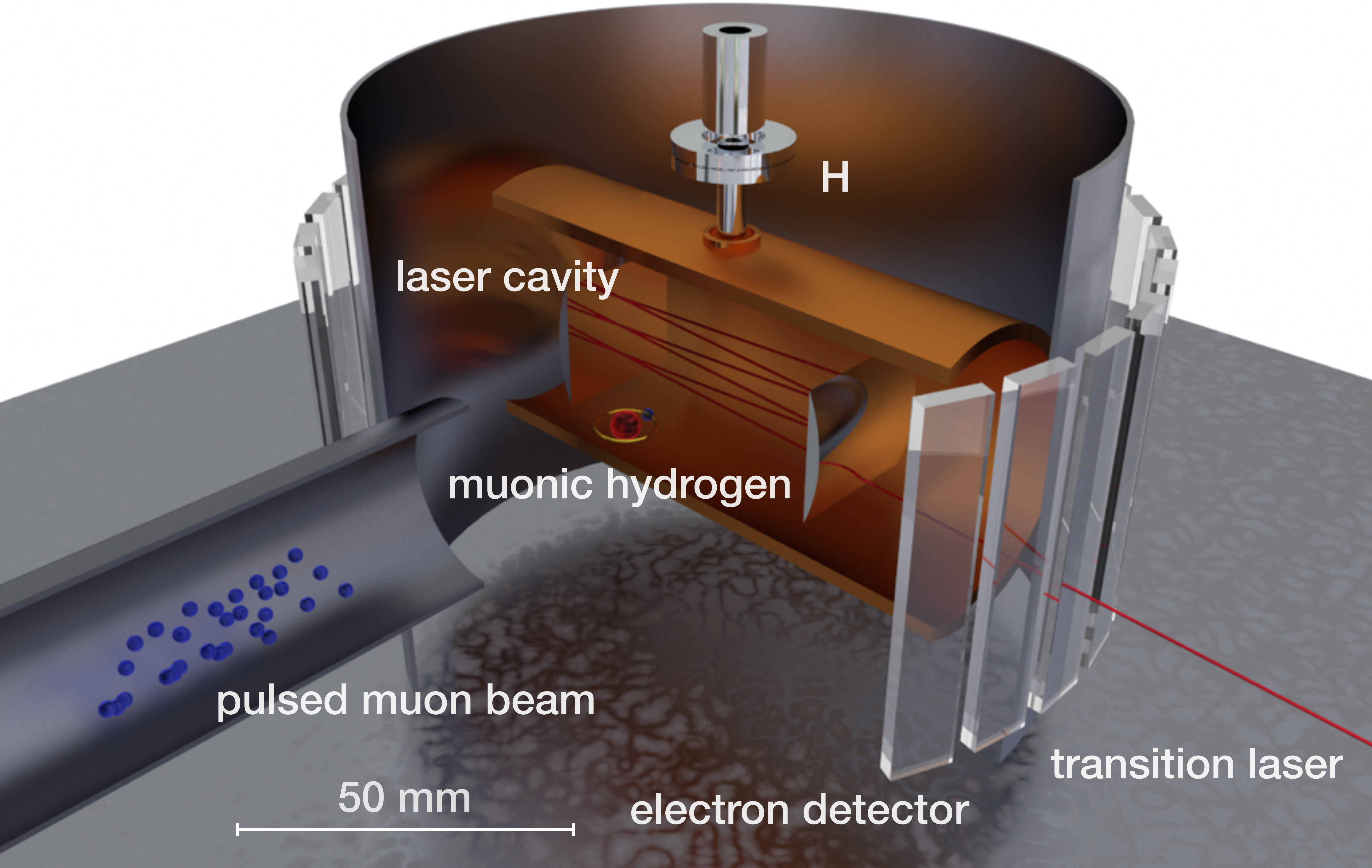
1S-HFS : 183 meV=6.8 μm
Finite size effect 1.3 meV
->Zemach Radius
(Our experiment)

Muonic Hydrogen HFS

- MuP HFS transition is induced by a circular polarized laser light
- The emission angle of decay electron is correlated to the muon spin

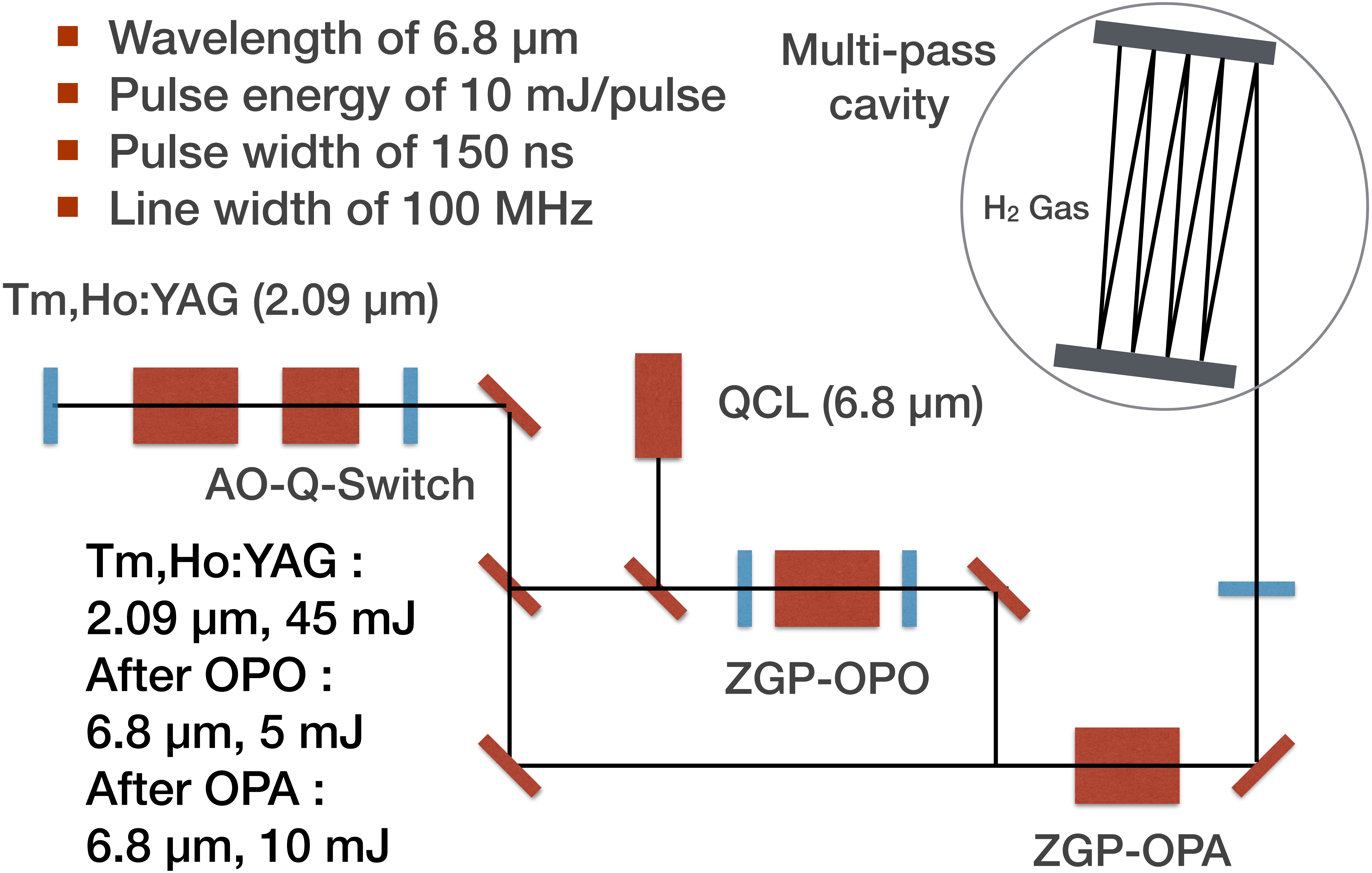


New μp 1S-HFS Measurement



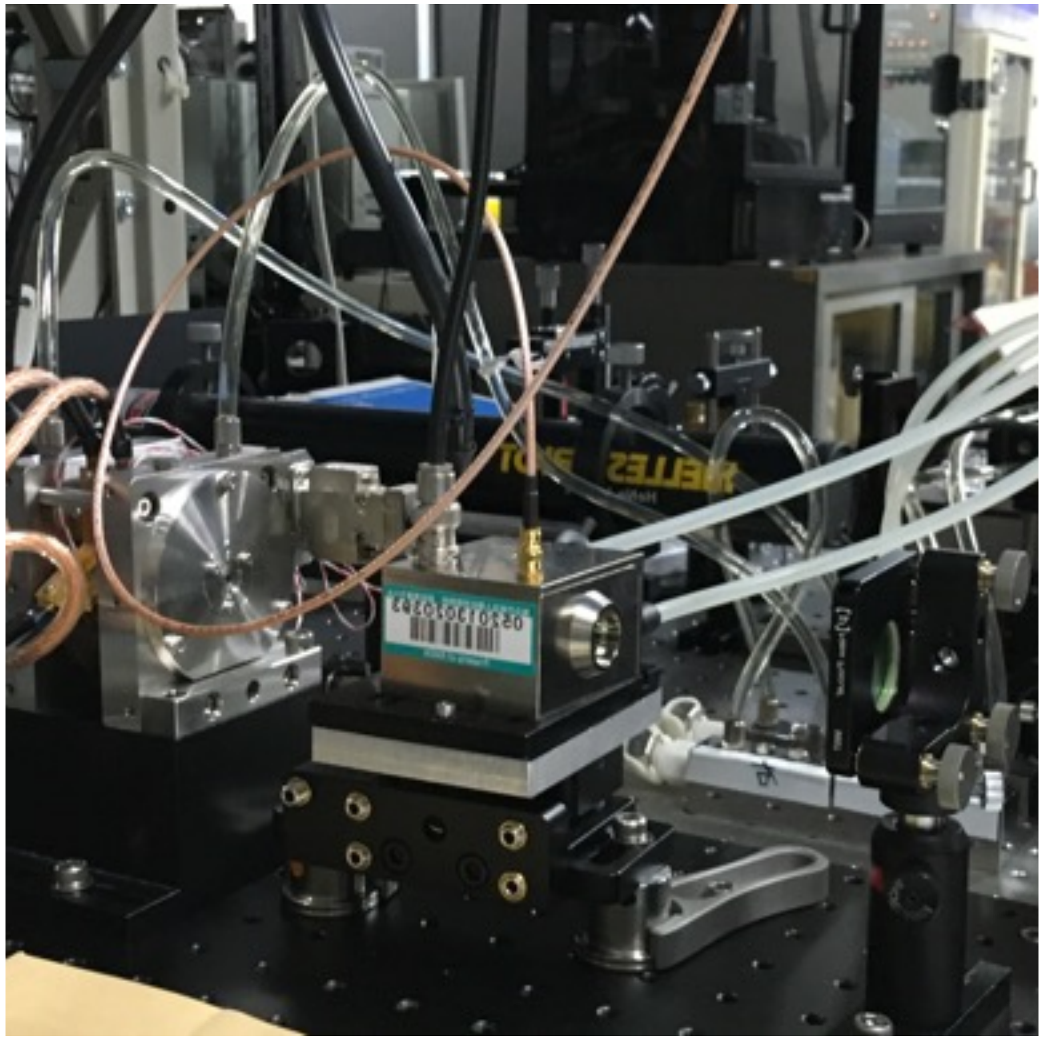
High-intensity pulsed mid-IR laser

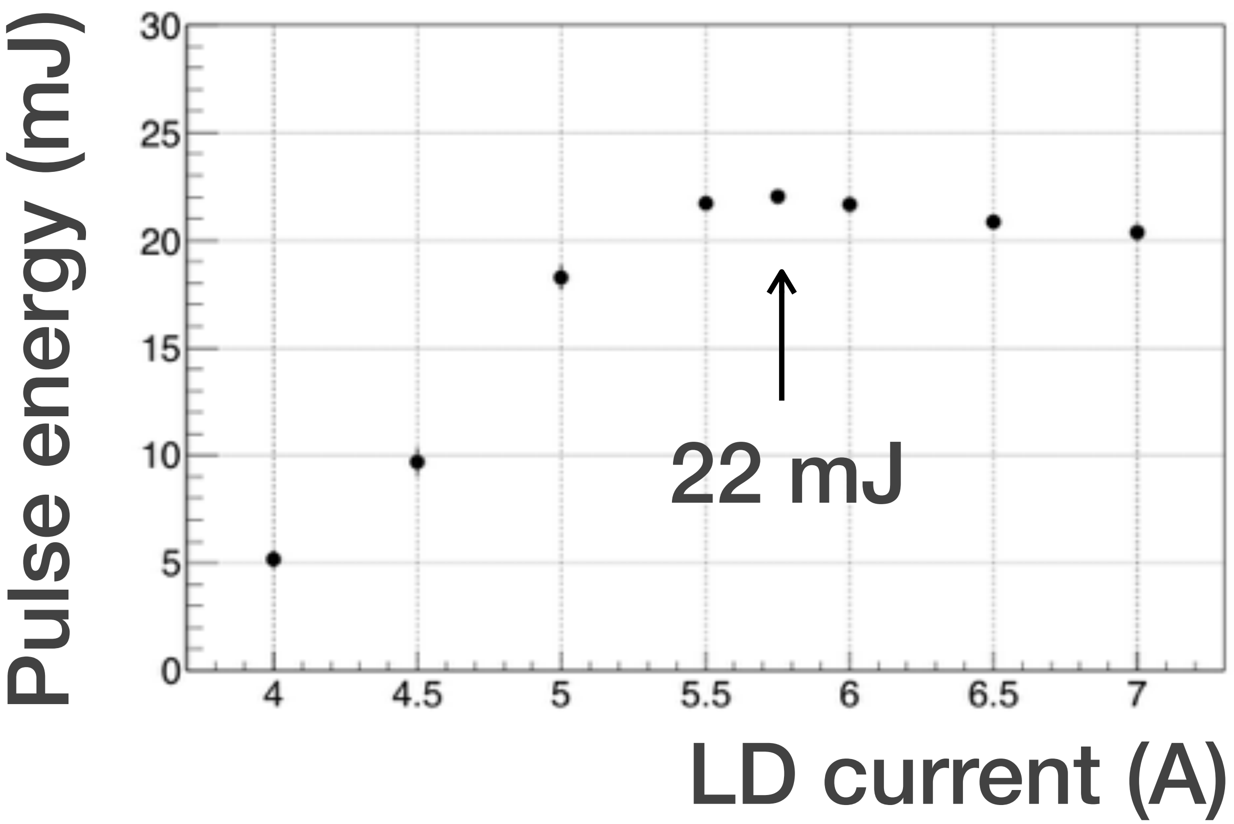
- Wavelength of 6.8 µm
- Pulse energy of 10 mJ/pulse
- Pulse width of 150 ns
- Line width of 100 MHz

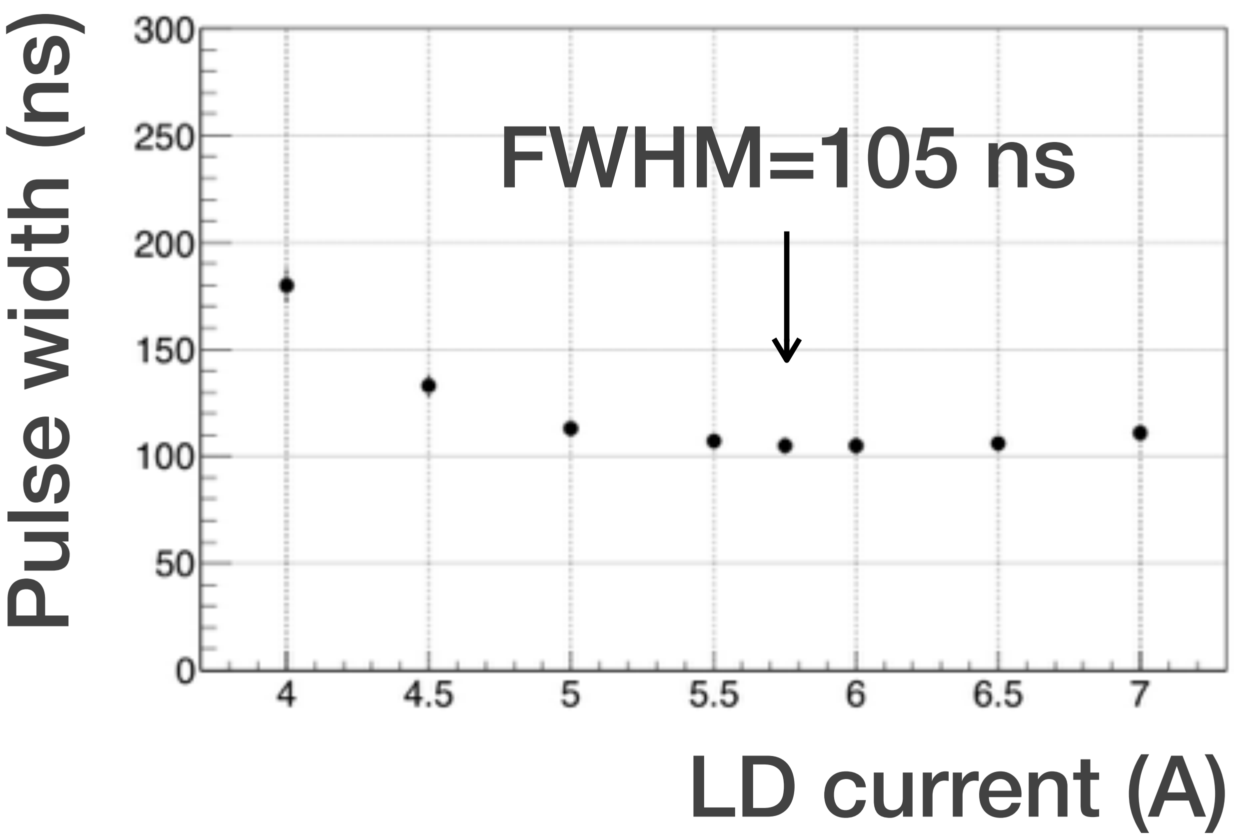


Tm,Ho:YAG :
2.09 µm, 45 mJ
After OPO :
6.8 µm, 5 mJ
After OPA :
6.8 µm, 10 mJ

Tm,Ho: YAG Laser

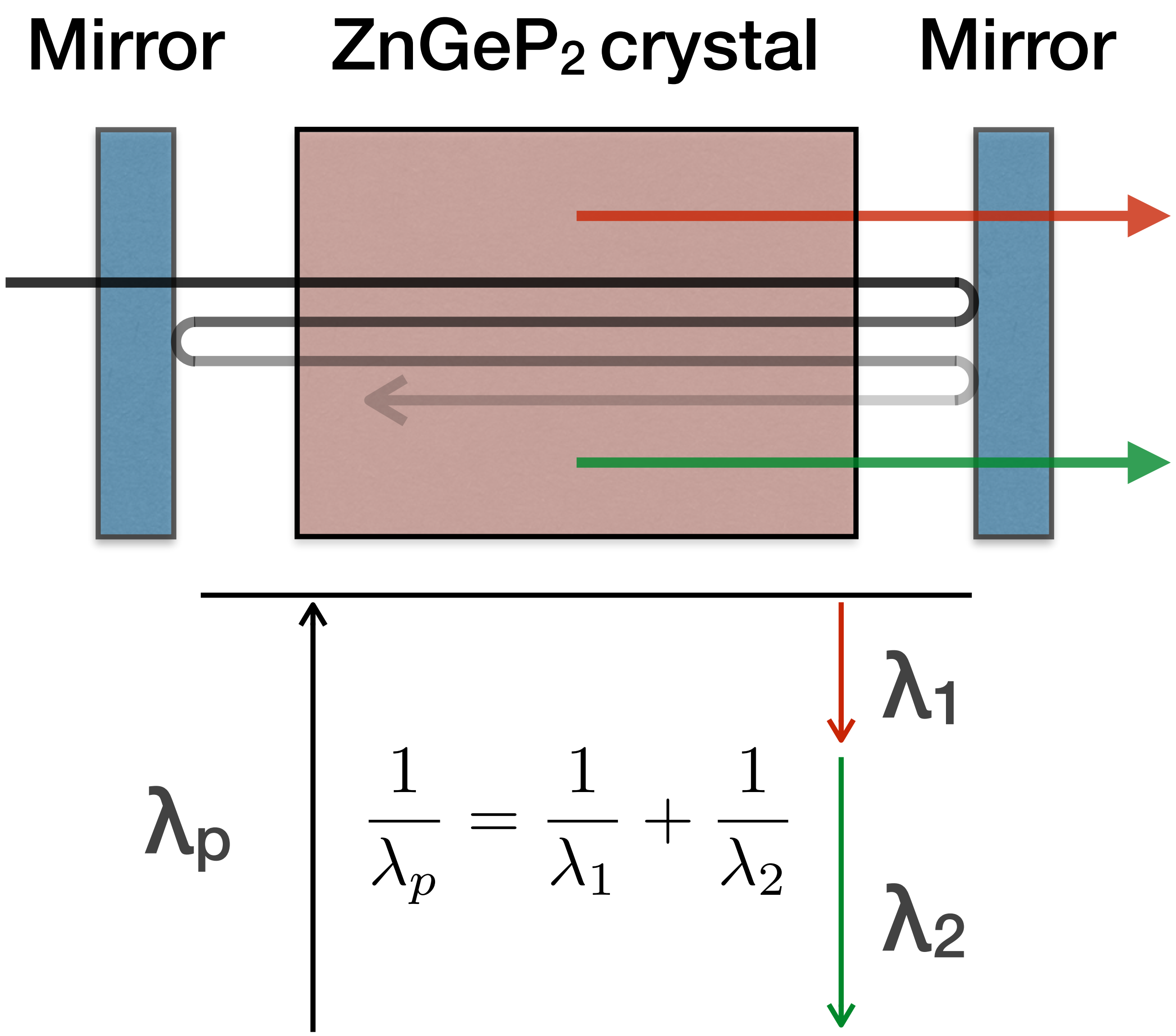


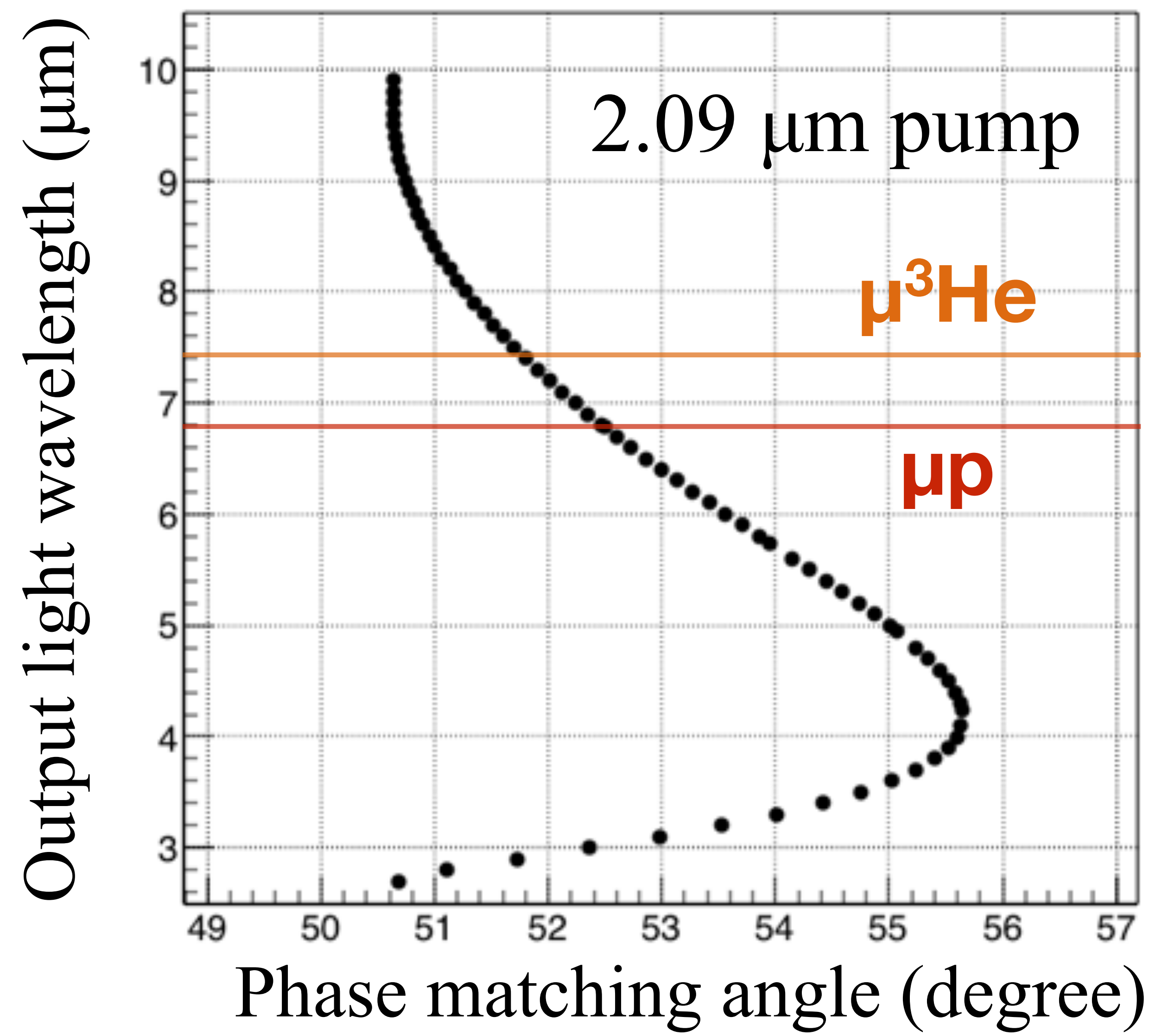




- Tm, Ho: YAG laser
- LD pumping and Q-switching
- Development is in progress with supports from Advanced Photonics group in RIKEN

ZGP Optical Parametric Oscillator

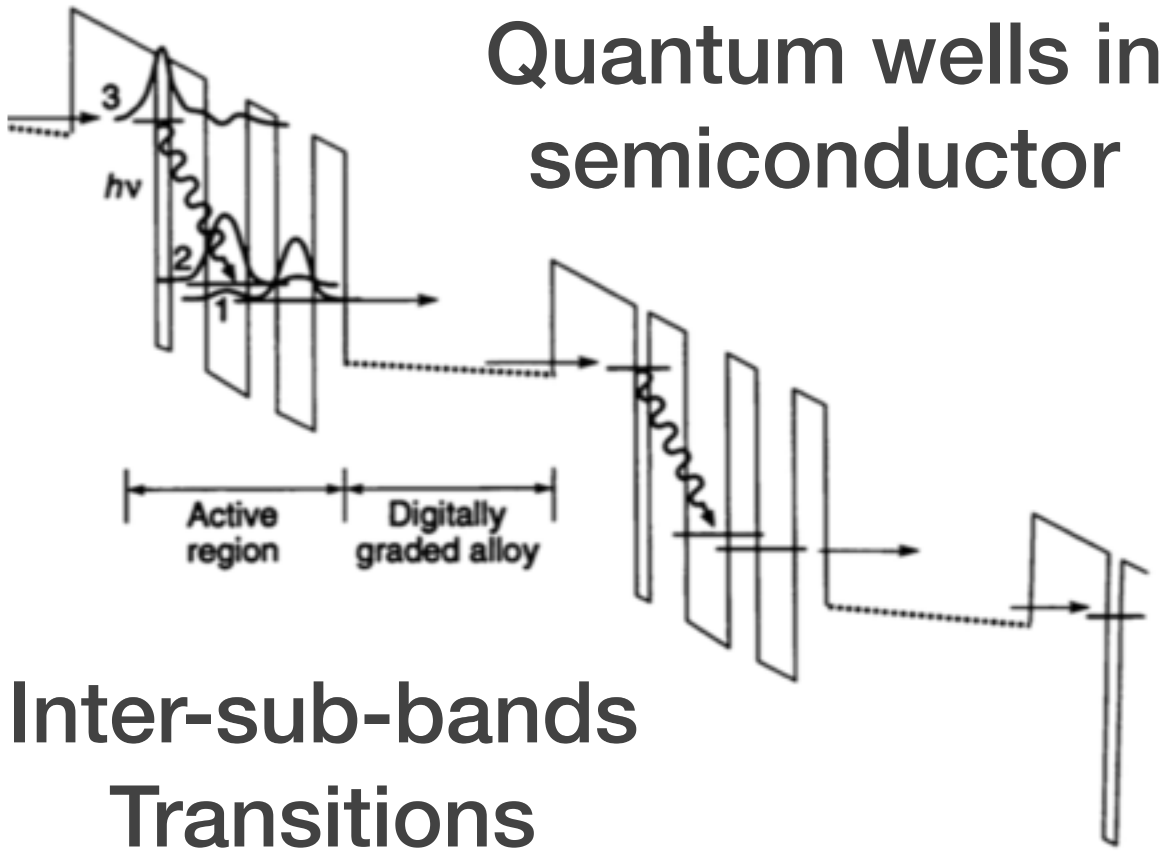




- **Optical parametric oscillator provides two lower frequency lights from a pumping light via non-linear optical effect.**
- **ZGP is an optimum from viewpoints of the damage threshold and non-linear optical coefficient.**
- **All-solid mid-infrared light source covers both μp 1S-HFS and μHe 2S-HFS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

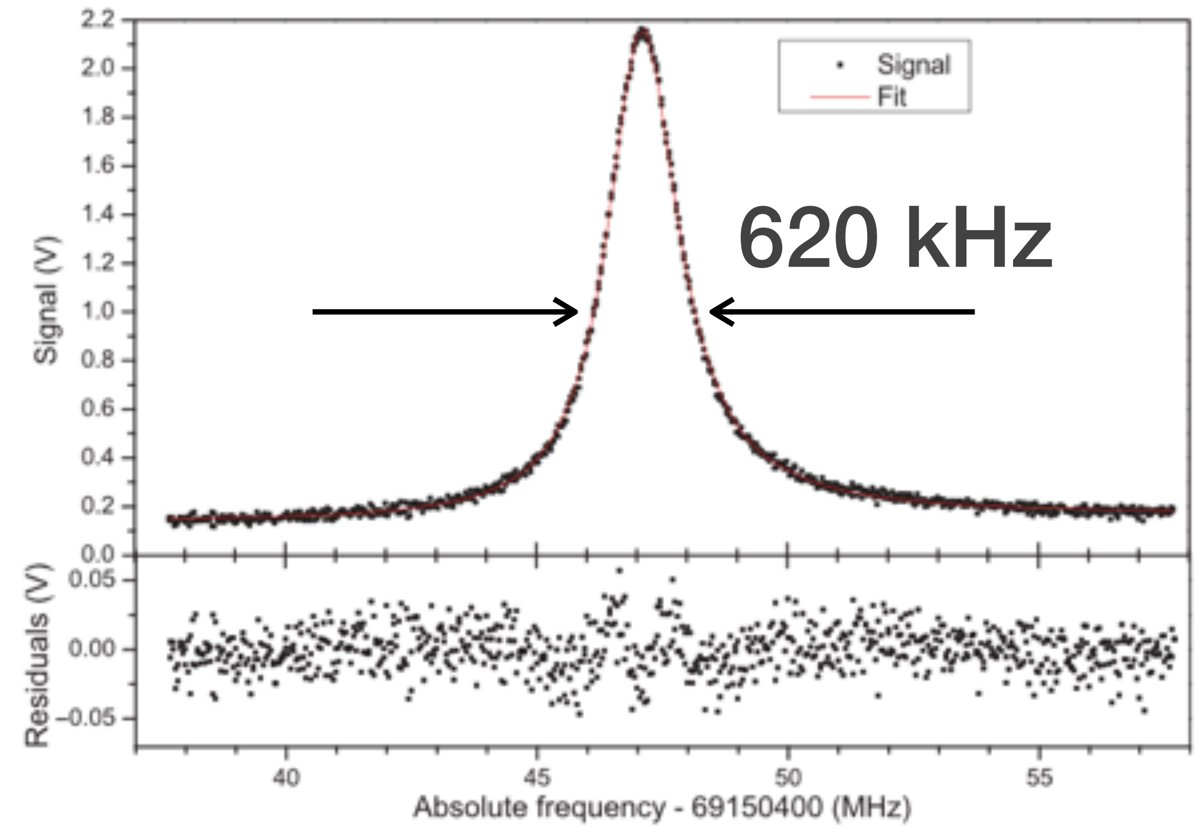
Quantum Cascade Laser

Quantum wells in semiconductor



Inter-sub-bands Transitions

Structure of QCL

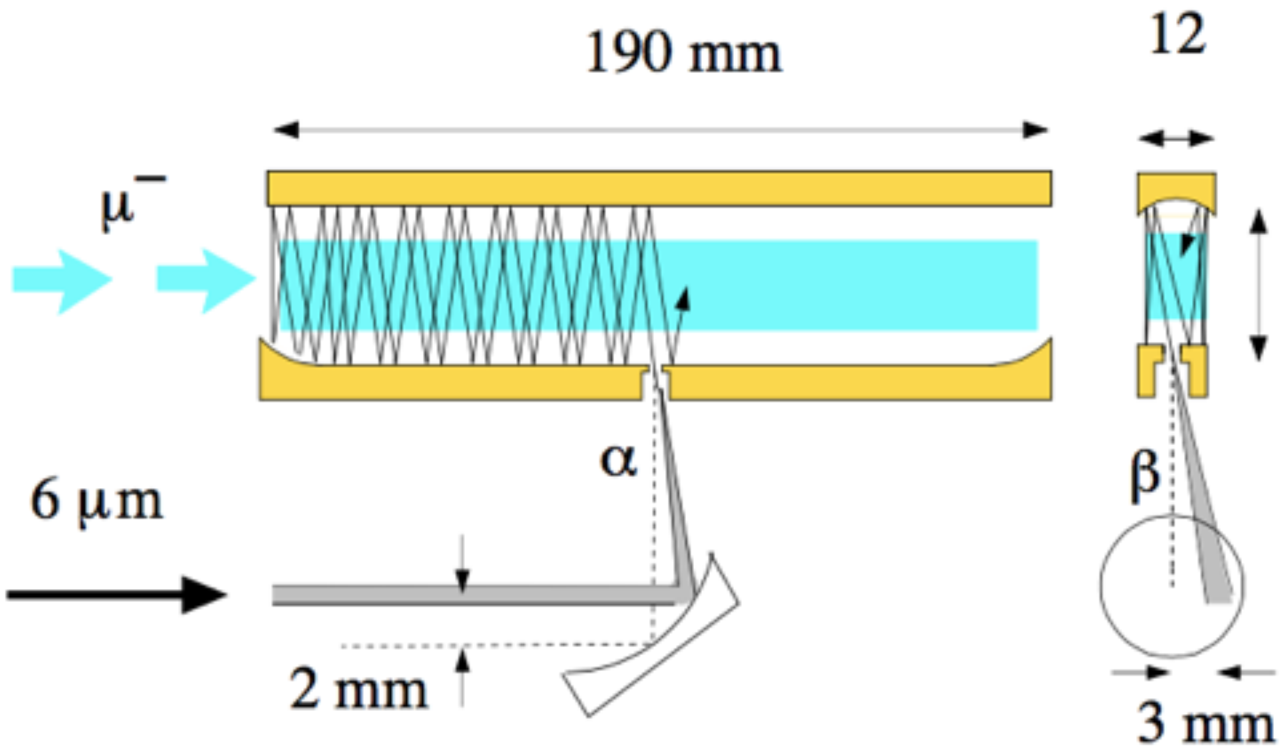


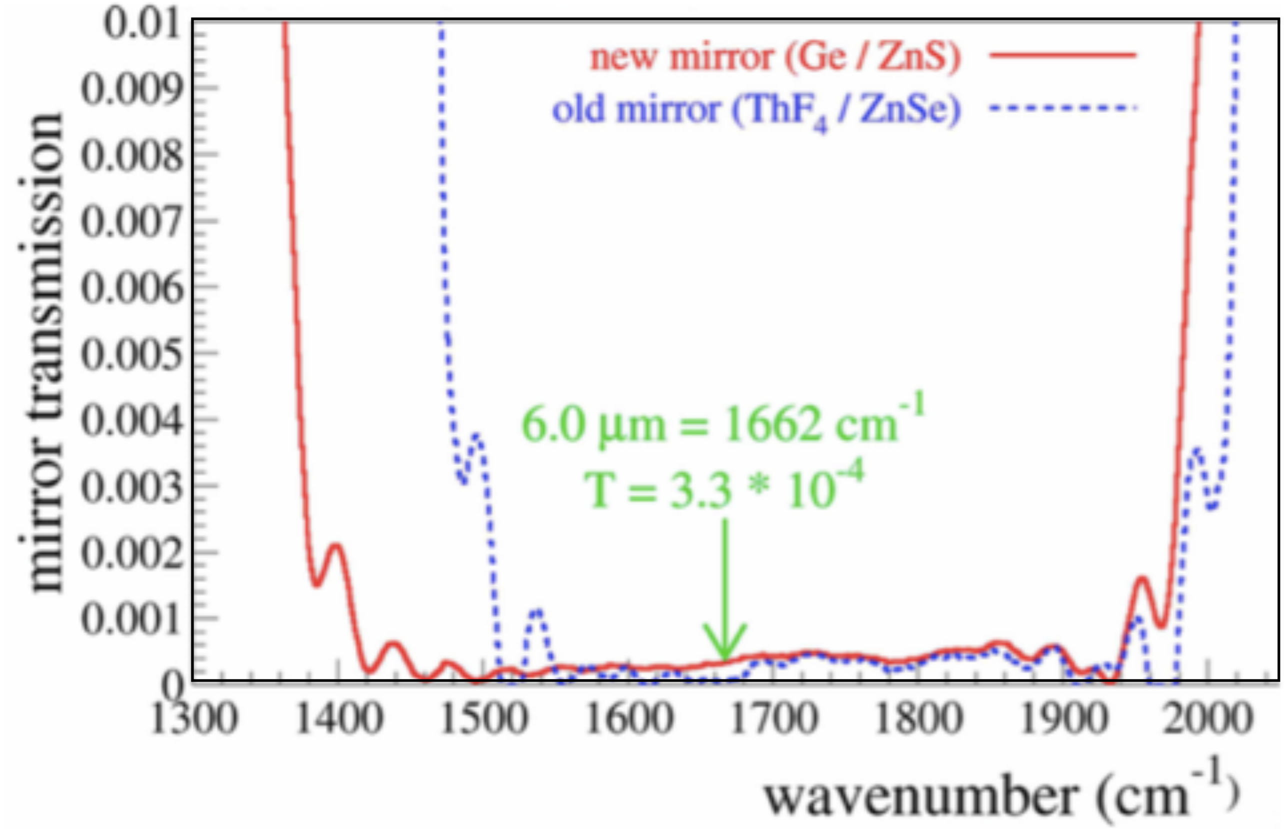
CO_2 absorption spectrum

- **Quantum cascade laser has extremely narrow intrinsic line width**
- **QCL provides a seeding light for ZGP-OPO (a few GHz -> 100 MHz)**
- **CW, 6.8 μm, 20 mW, mode-hop-free**
- **Manufacturing is in progress.**

J. Faist *et al*., Science 22 (1994).
I. Galli *et al*., Molecular Physics 111 (2010) 2041-2045.

Non Resonant Multipass Cavity



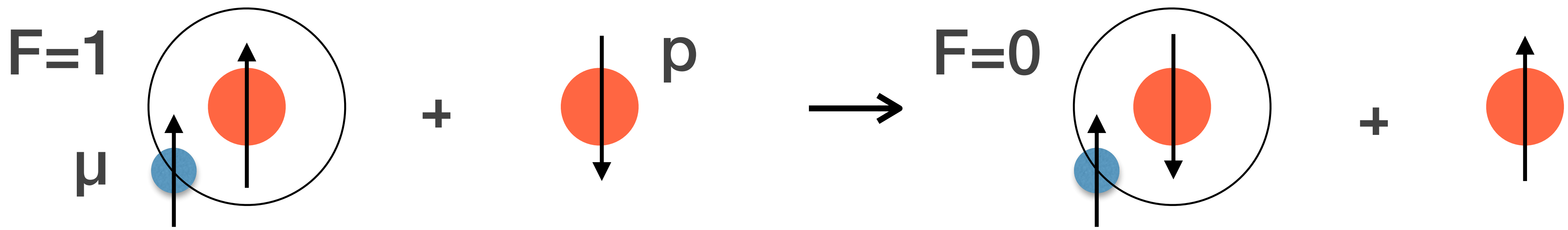


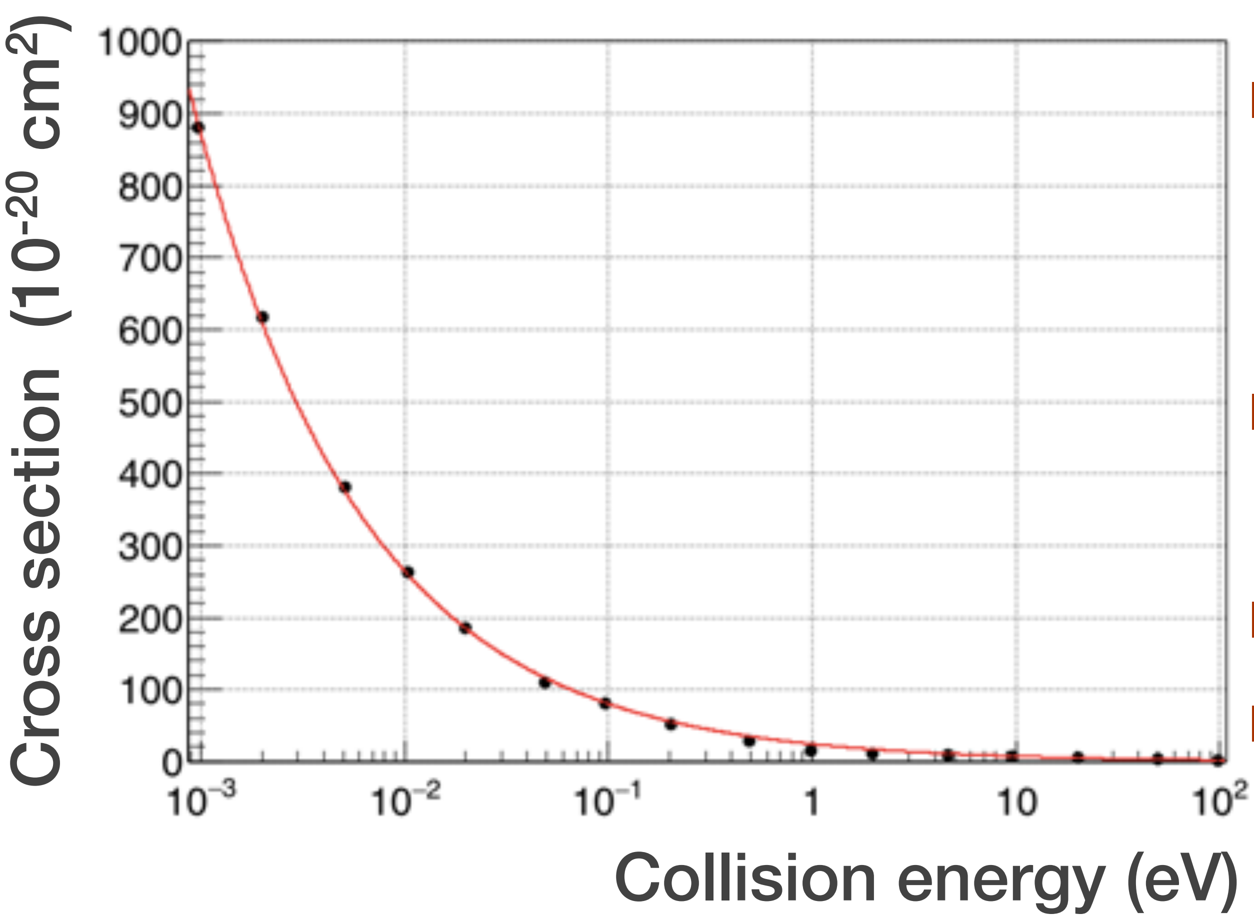
Nebel Tobias, Ph. D Thesis, Ludwig-Maximilians-Universität, München (2010).

- **Dielectric coated mirrors are placed facing each other for increase of light pass-length in target gas volume.**
- **Reflectivity of 99.95% is expected and it provides 2000 times of laser light reflection in the cavity.**
- **Prototype mirrors are on the drawing board.**
- **A method to evaluate laser energy density in the cavity is under study.**

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

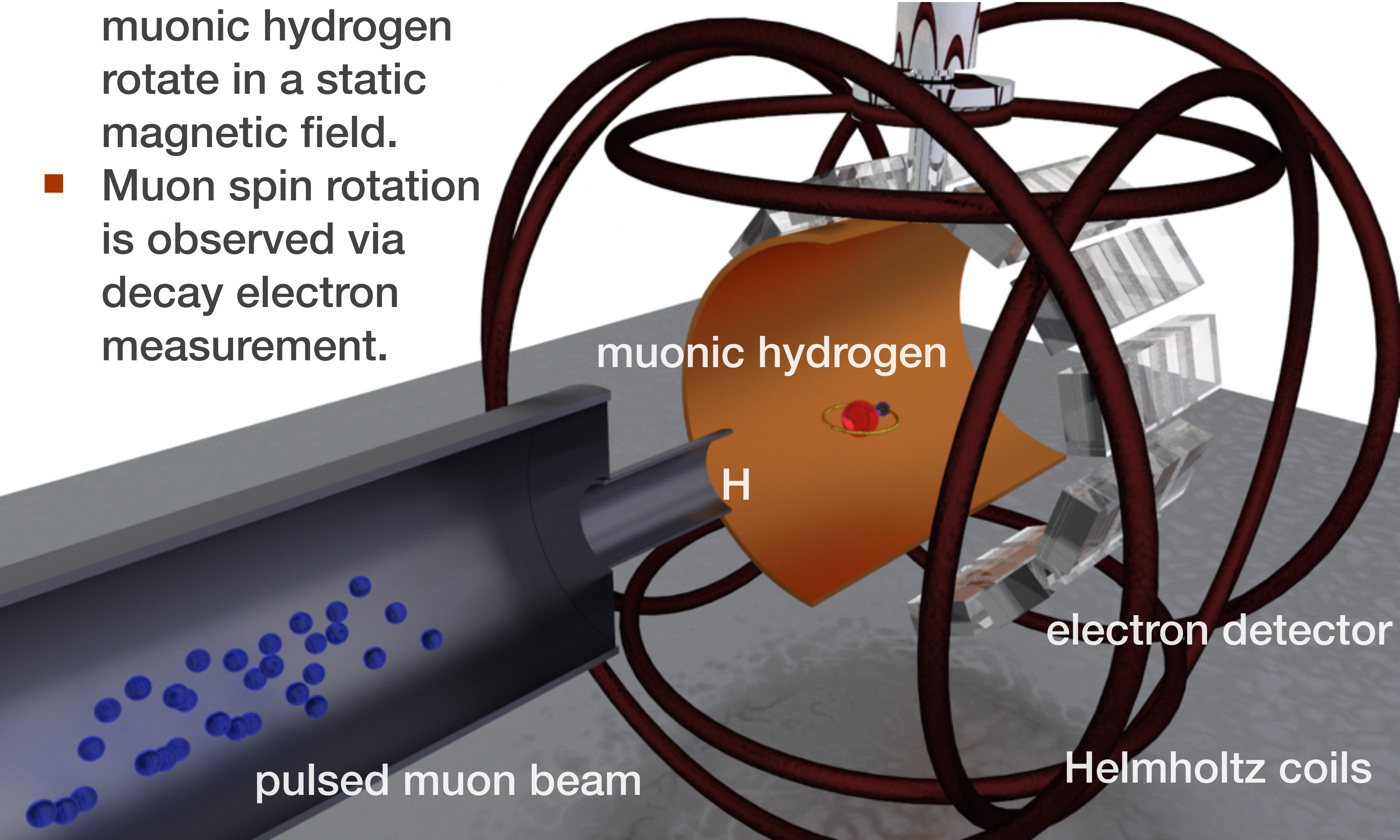




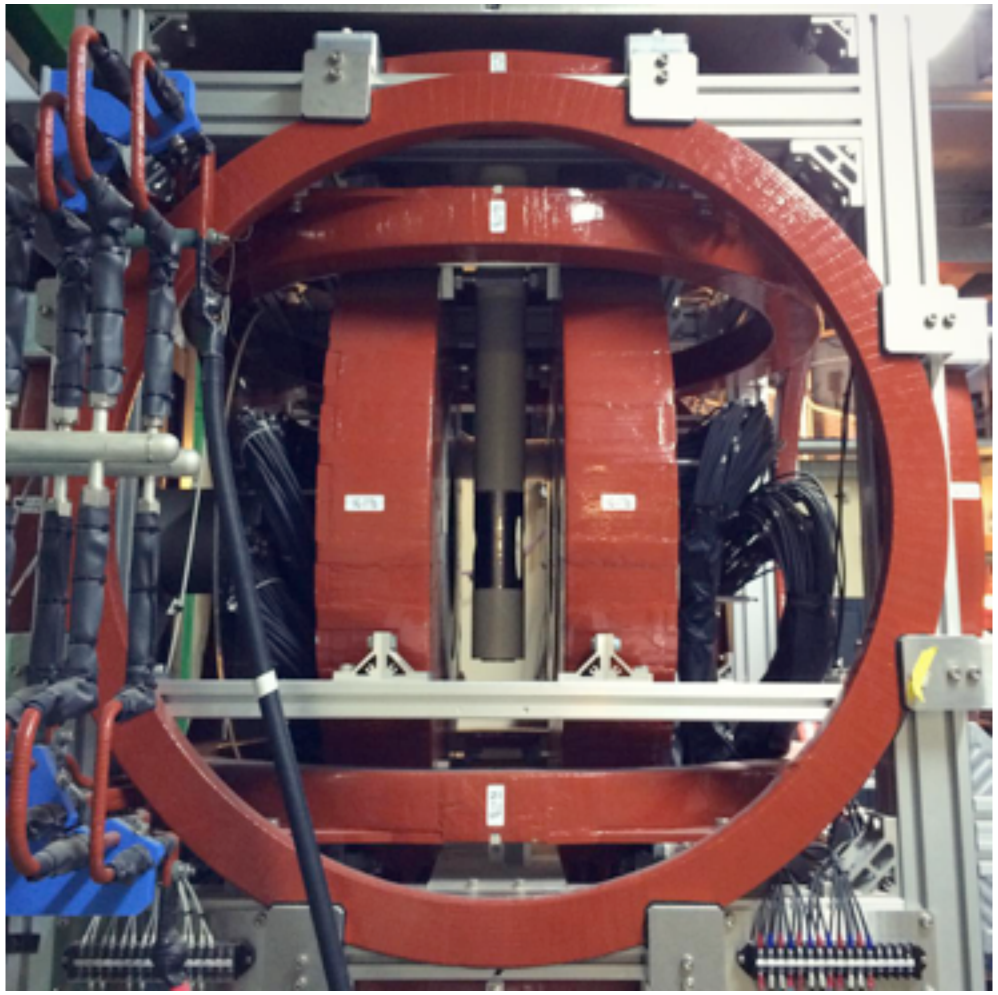
- Quenching rate depends on collision energy (gas temperature) and gas pressure
- Expected lifetime at 20 K, 0.06 atm is 50 ns
- J.S. Cohen, PRA 43, 3460 (1991)
- A new measurement was proposed

Quenching Rate Measurement

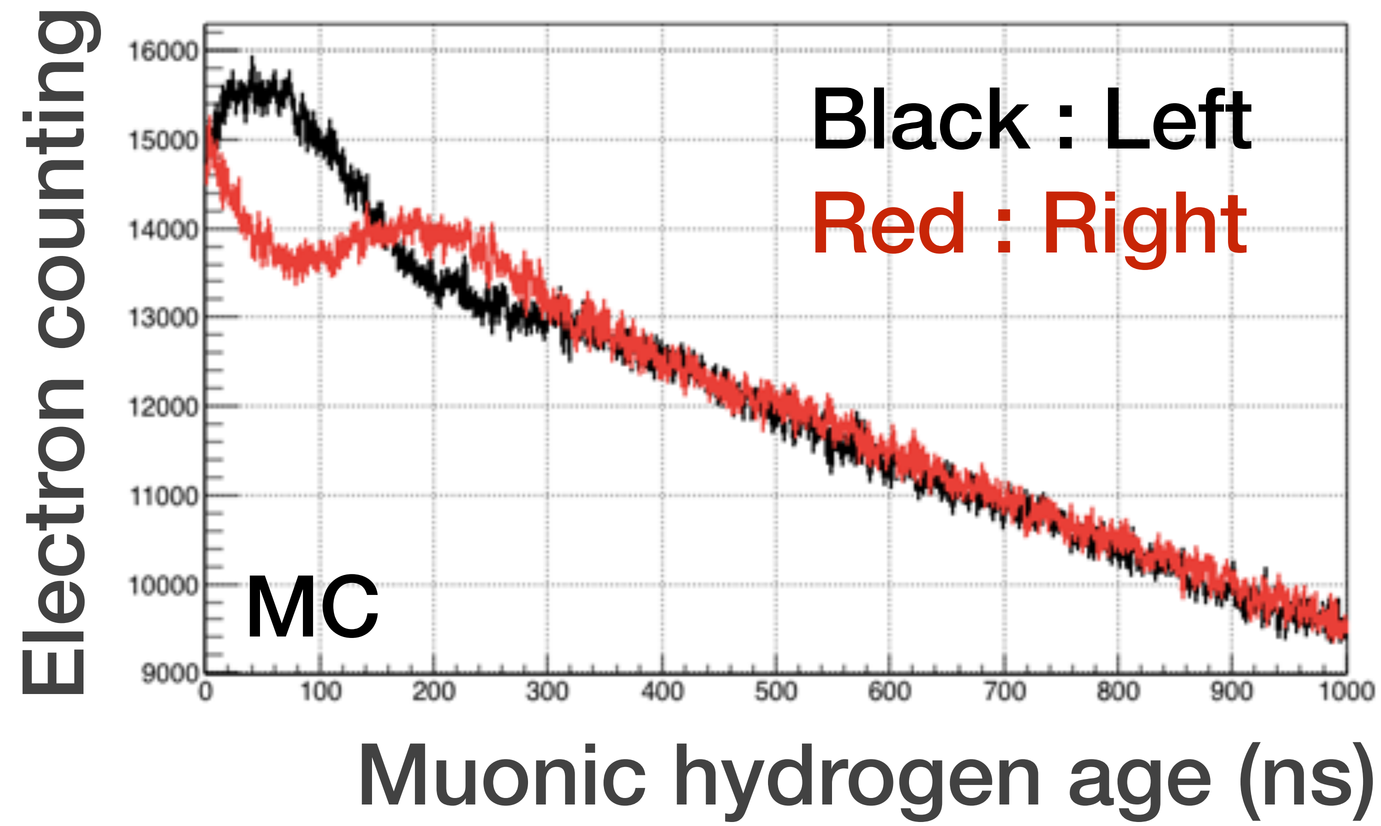
- Only munos in F=1 muonic hydrogen rotate in a static magnetic field.
- Muon spin rotation is observed via decay electron measurement.

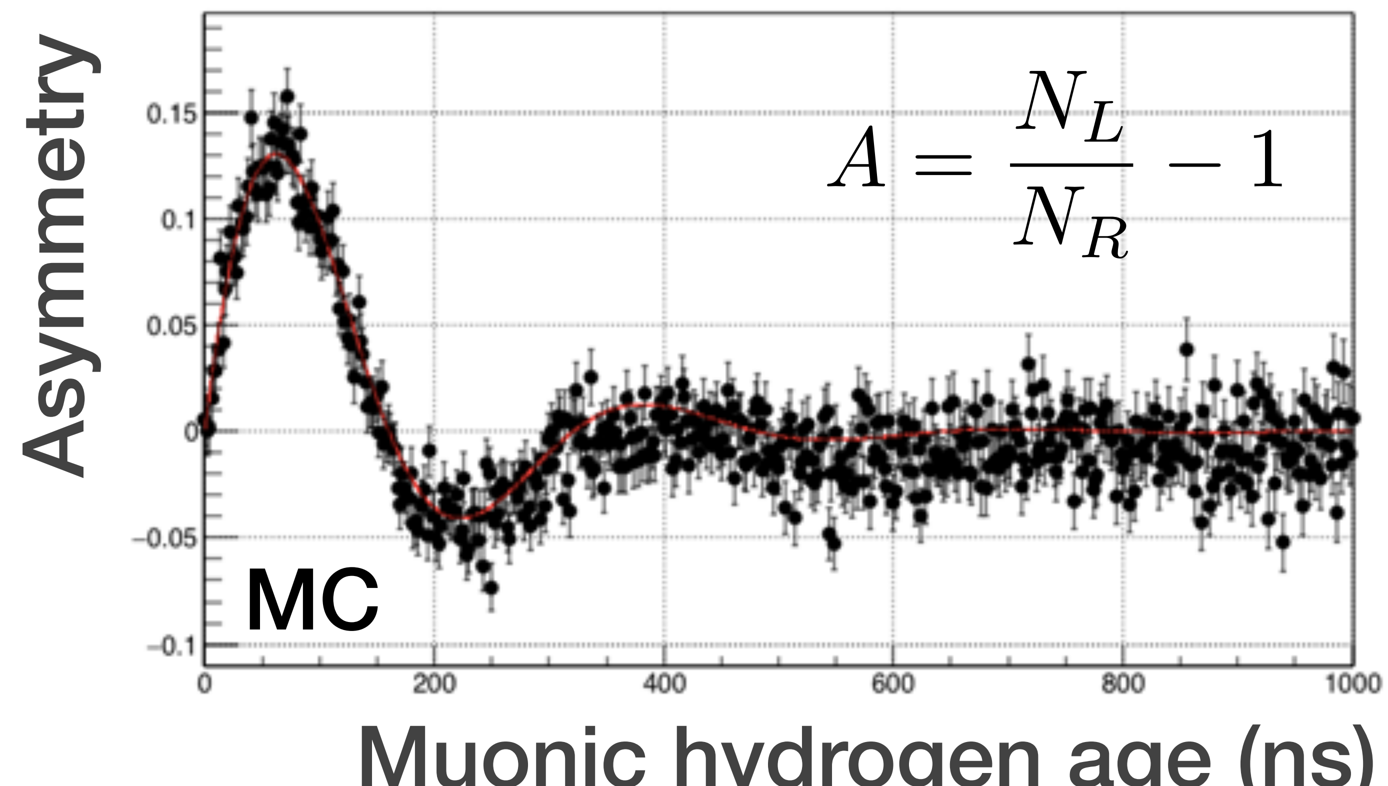


Quenching Rate Measurement

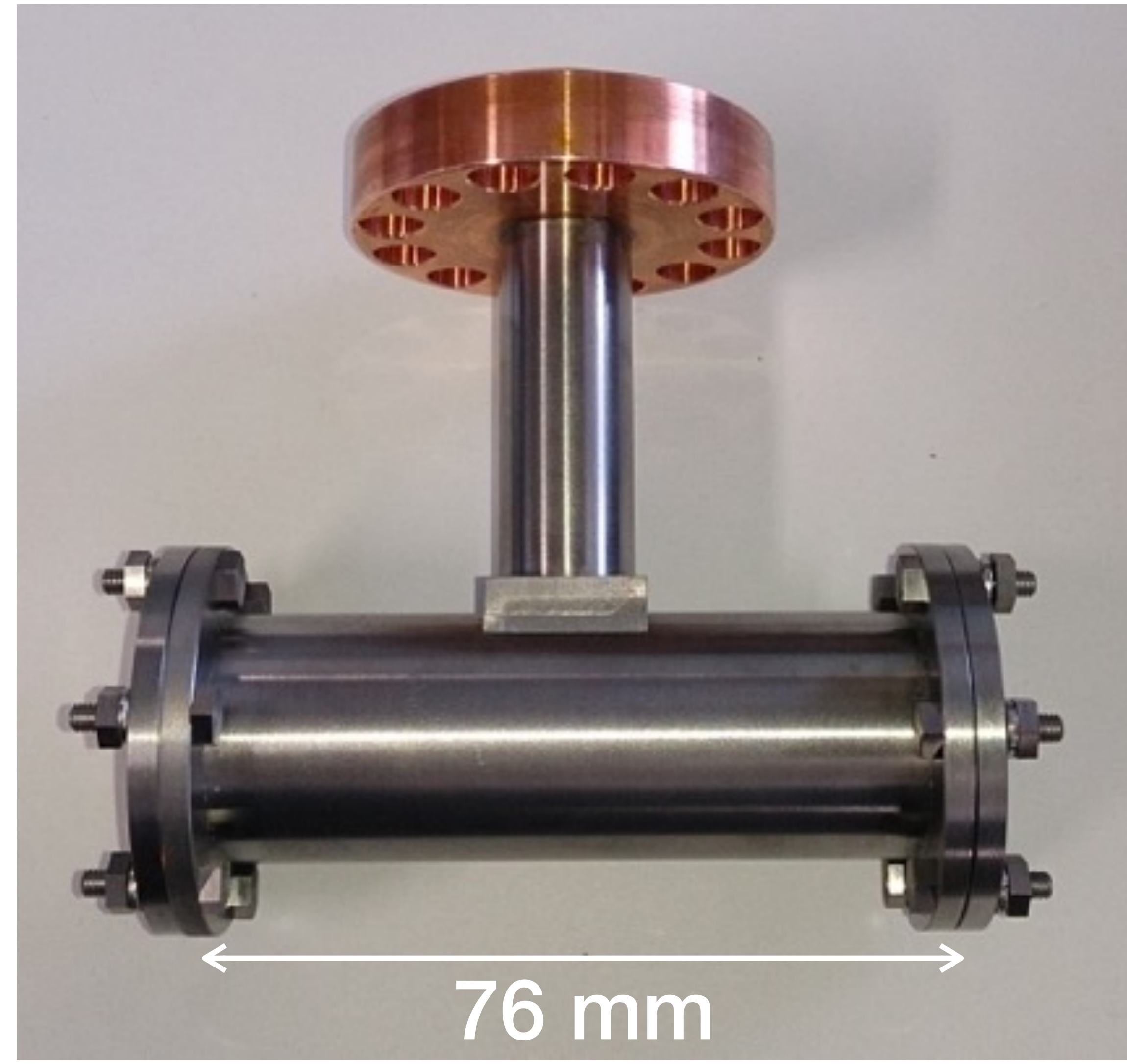


- CRONUS spectrometer at RIKEN-RAL muon facility.
- A transverse field of 600 Gauss is applied in the exp.
- Left/Right electron angular asymmetry is measured.



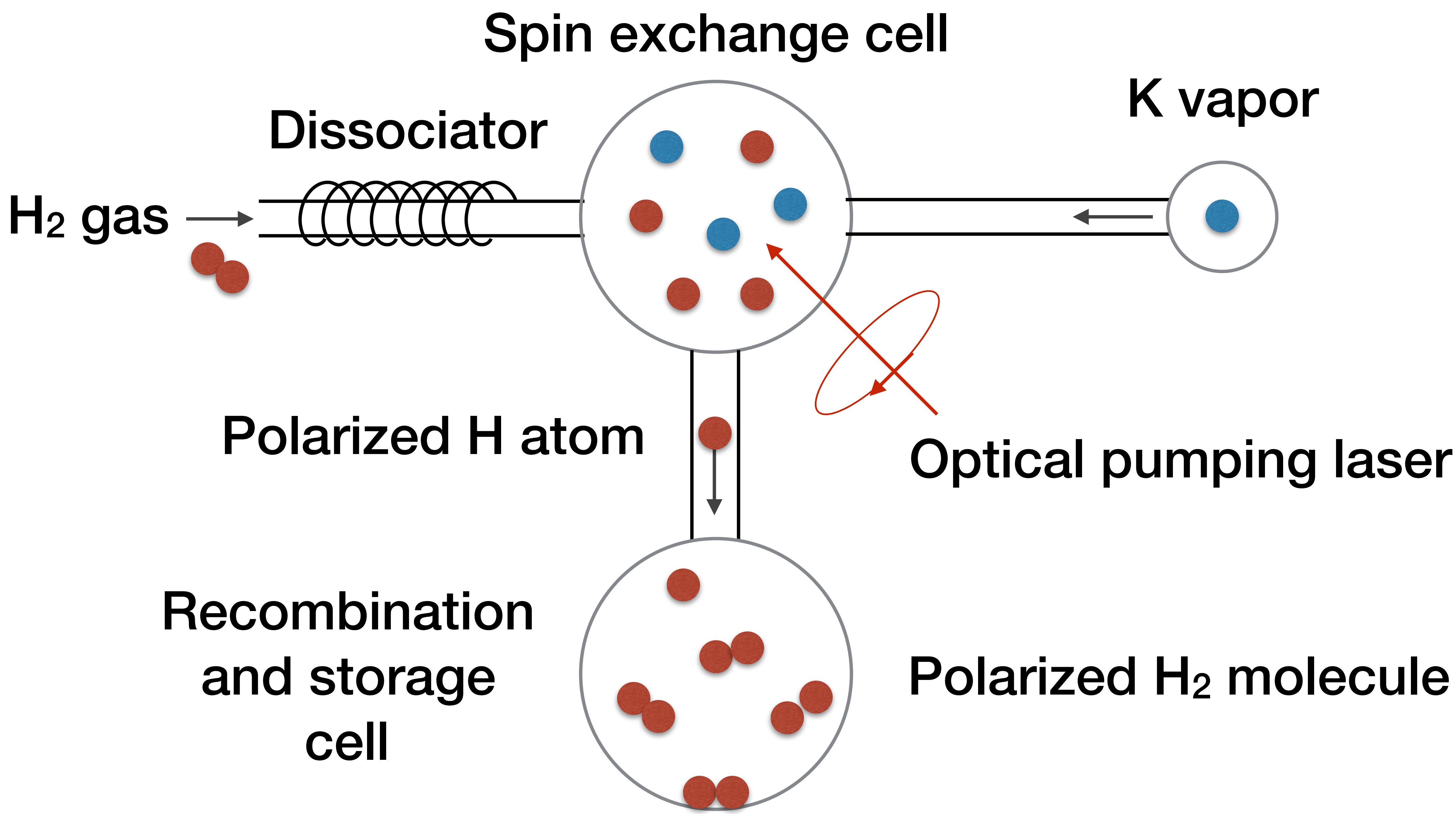


Hydrogen Gas Target System



- 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.

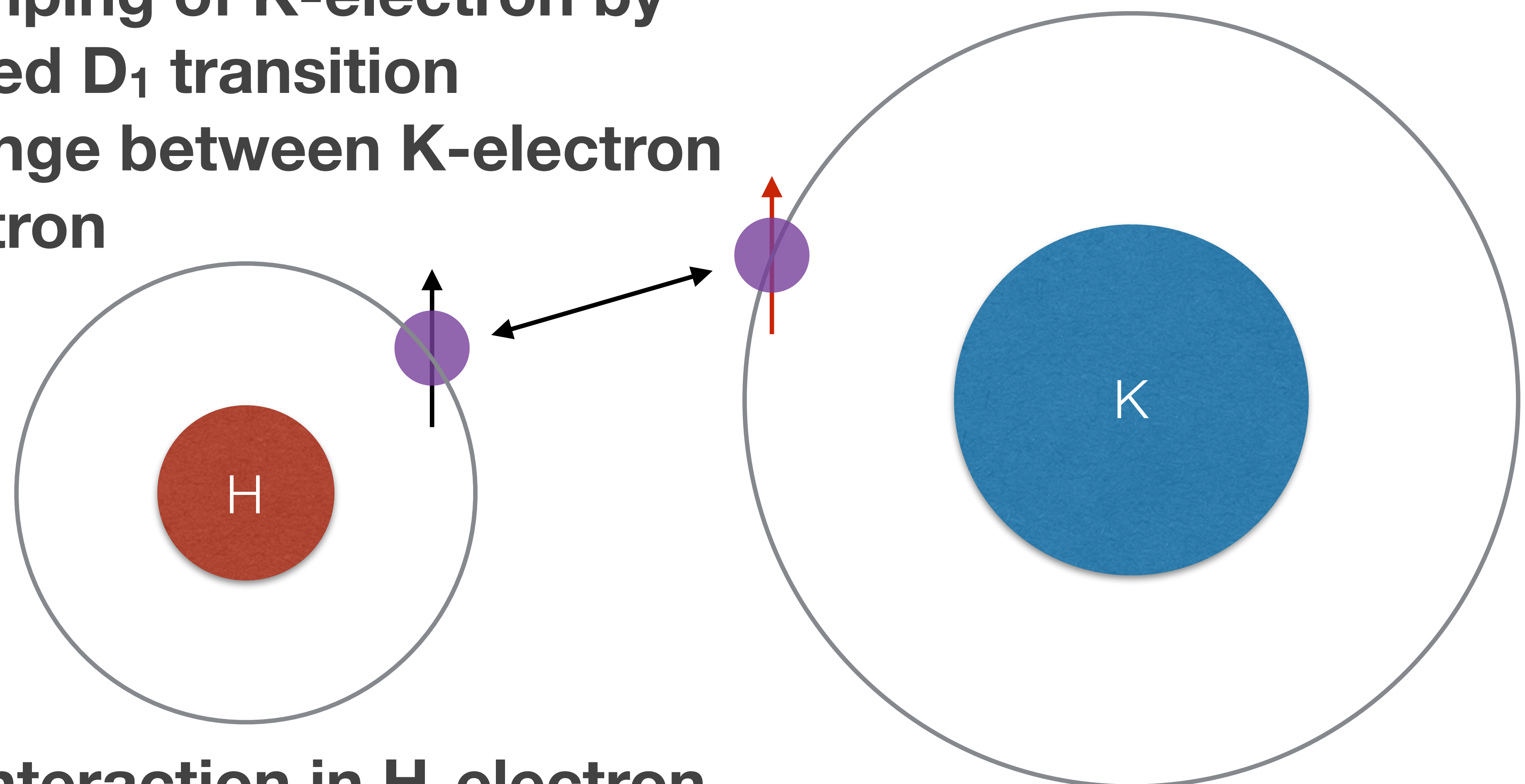
Nuclear Spin Polarized Target



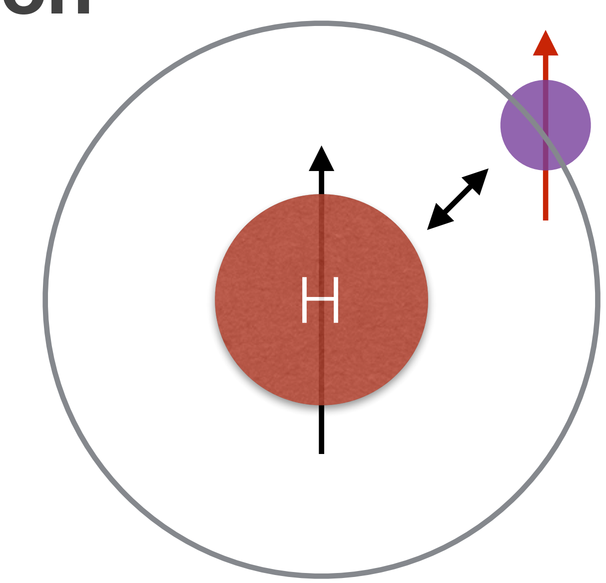
- If the hydrogen target is nuclear spin polarized, collisional hyperfine quenching is highly suppressed.
- Typical flux of atomic beam is 1×10^{16}.
- Our goal is 1×10^{19} atoms with the polarization of 80%.

Spin Exchange Optical Pumping

- **Optical pumping of K-electron by laser induced D_1 transition**
- **Spin exchange between K-electron and H-electron**

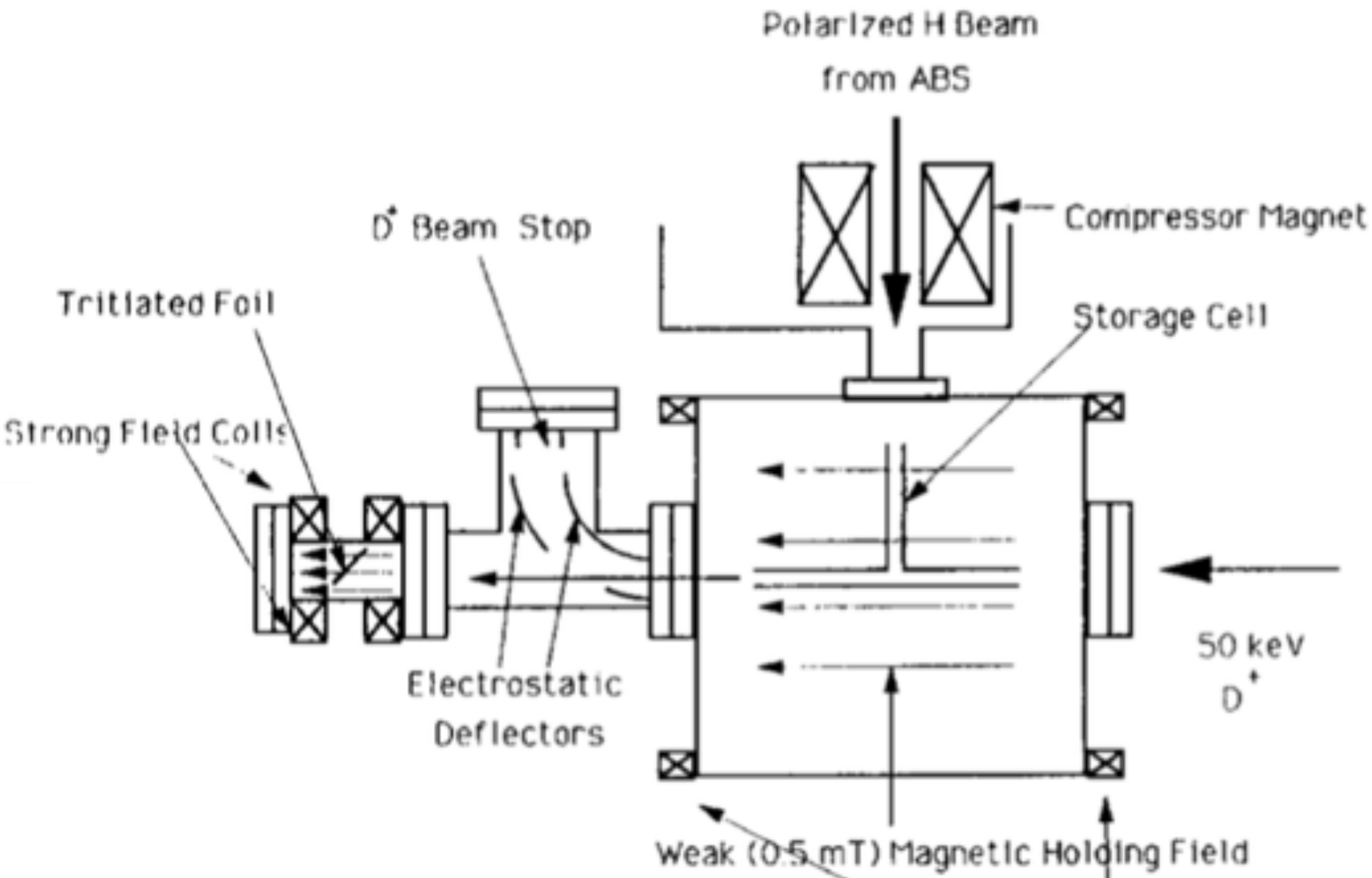


- **Hyperfine interaction in H-electron and H-proton**

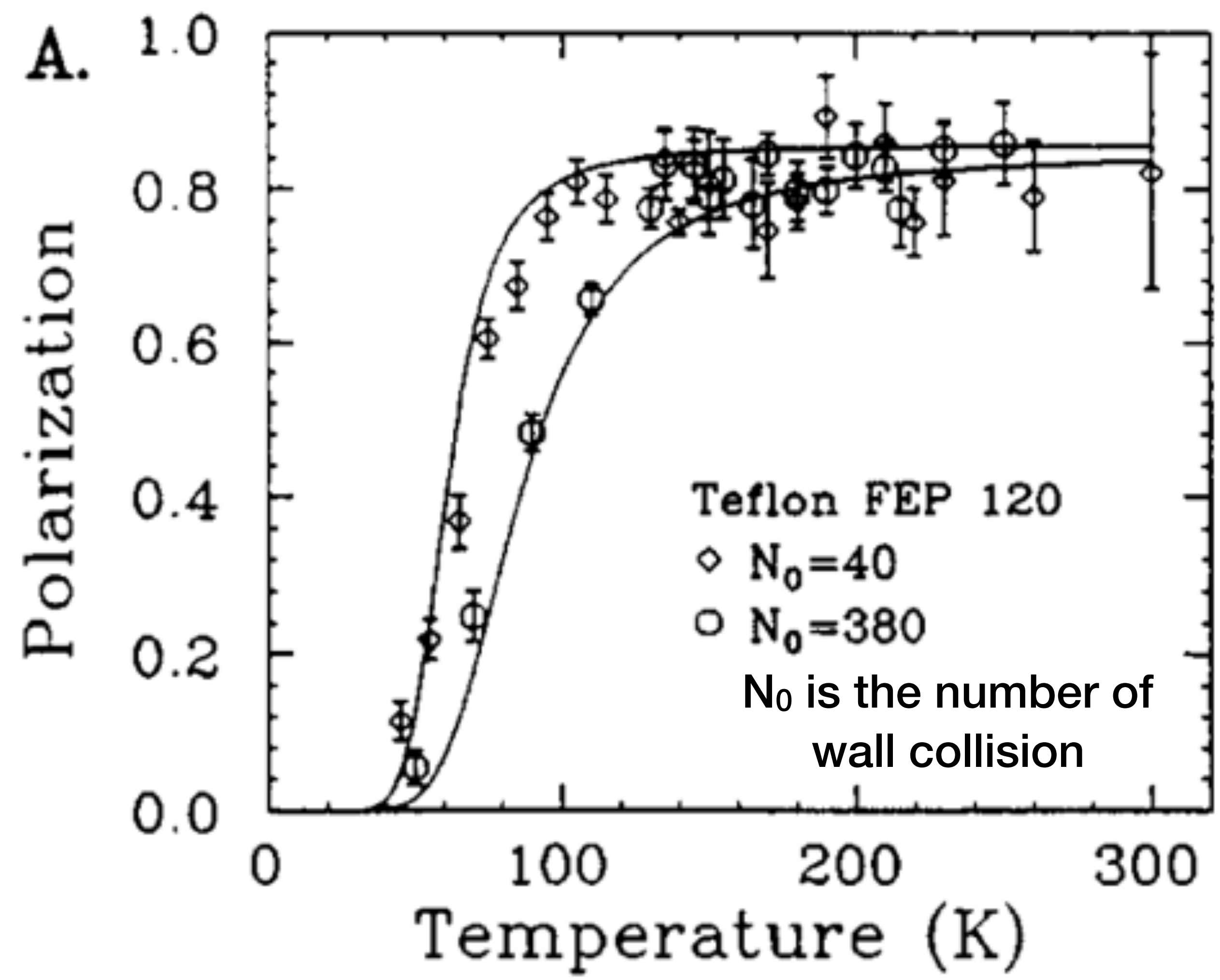


- ^{3}He is also polarized by this method.
- What happen in the case of molecular hydrogen?
- Feasibility study is in preparation.

Spin Polarized Hydrogen Molecule



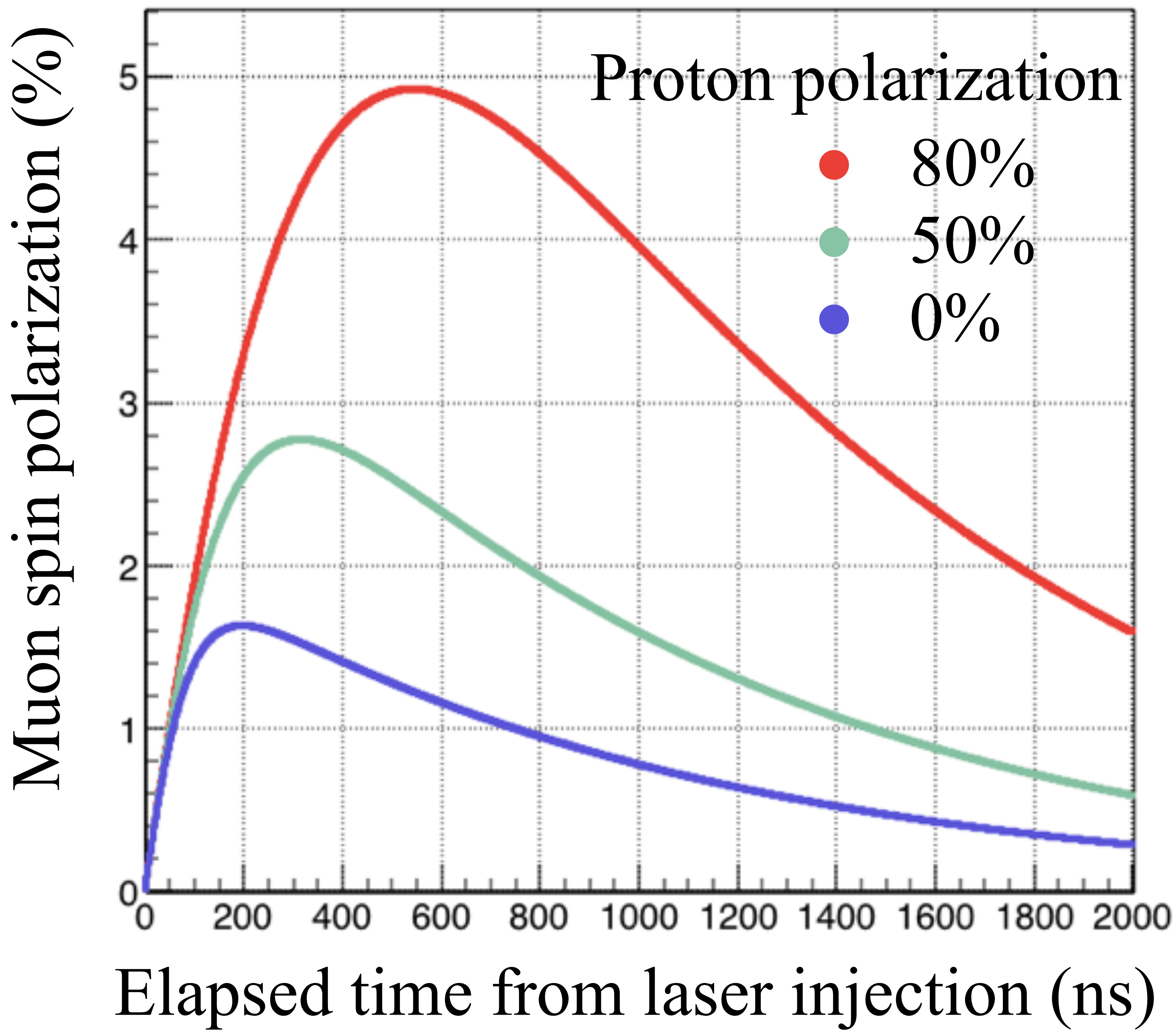
Atomic Beam Source
at HERA



- **After hydrogen atoms recombination on the wall, nuclear spin polarization remains.**
- **Polarization depends on the number of wall collision and wall temperature (sticking duration on the wall).**

J. S. Price and W. Haeberli, NIM A, 349, 2 (1994).

Proton Polarization Effect

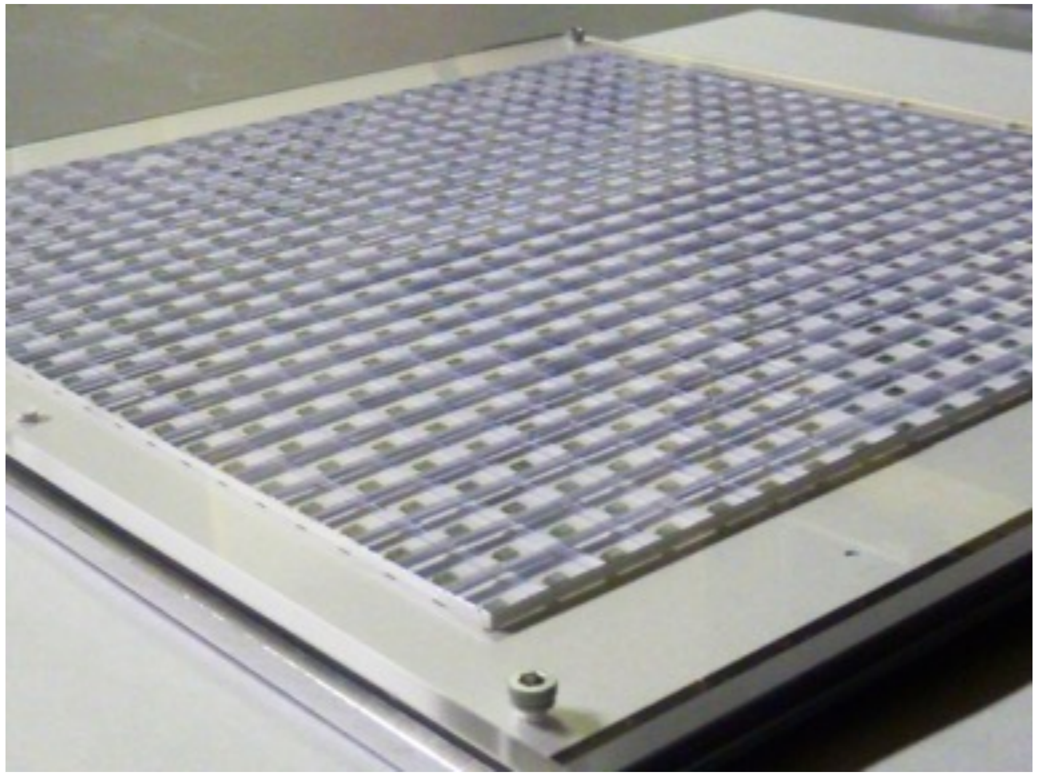


- Calculated muon spin polarization as a function of time.
- Nuclear spin polarized target is highly effective to suppress the collisional quenching of the triplet state.

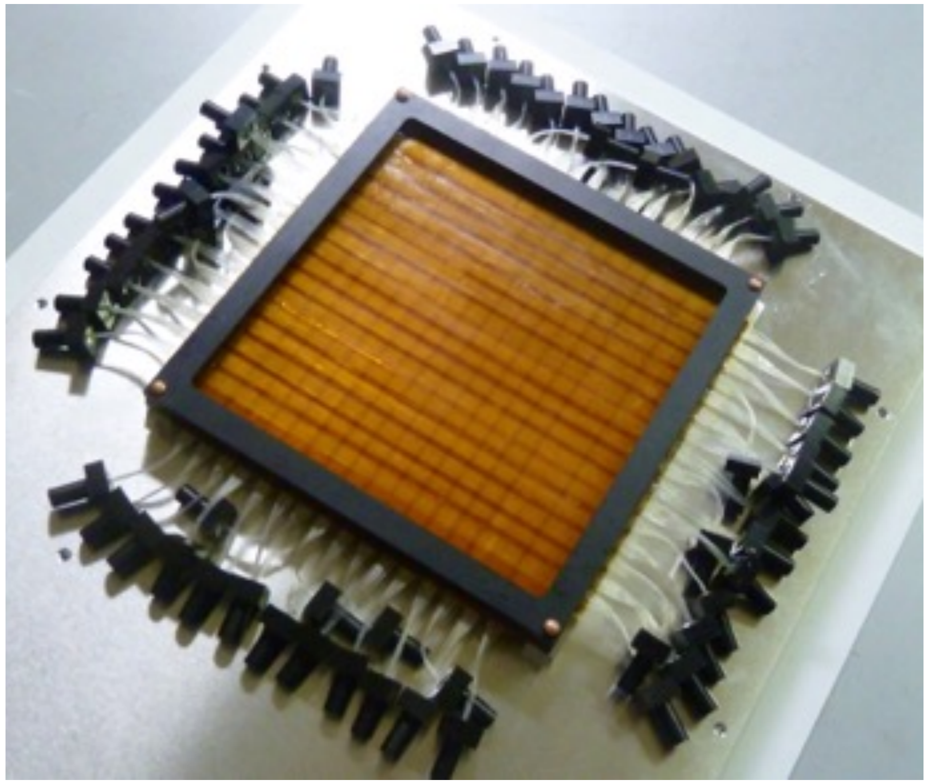
Pulsed Muon Beam

Property	RAL	J-PARC
Cycle	50 Hz	25 Hz
Intensity	22,000 muon/s at 40 MeV/*c*	350,000 muon/s at 40 MeV/*c*
Spacial Spread	σ = 17 mm	σ = 20 mm
Momentum Spread	Δp = +- 4%	Δp = +-5%

Particle Detectors



Electron detector
Segmented scintillation counter with SiPM readout



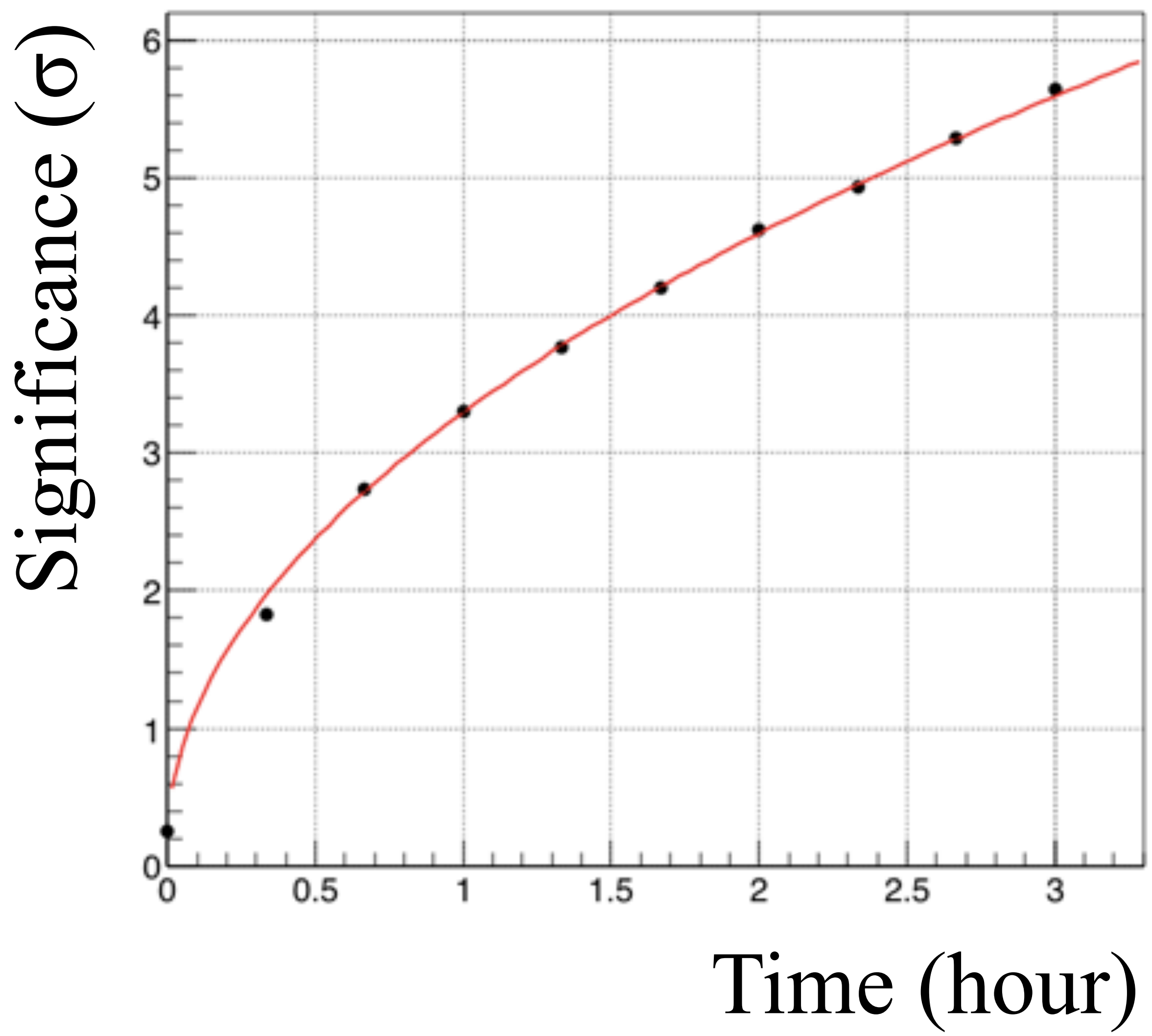
Muon detector
Thin scintillation fiber hodoscope

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

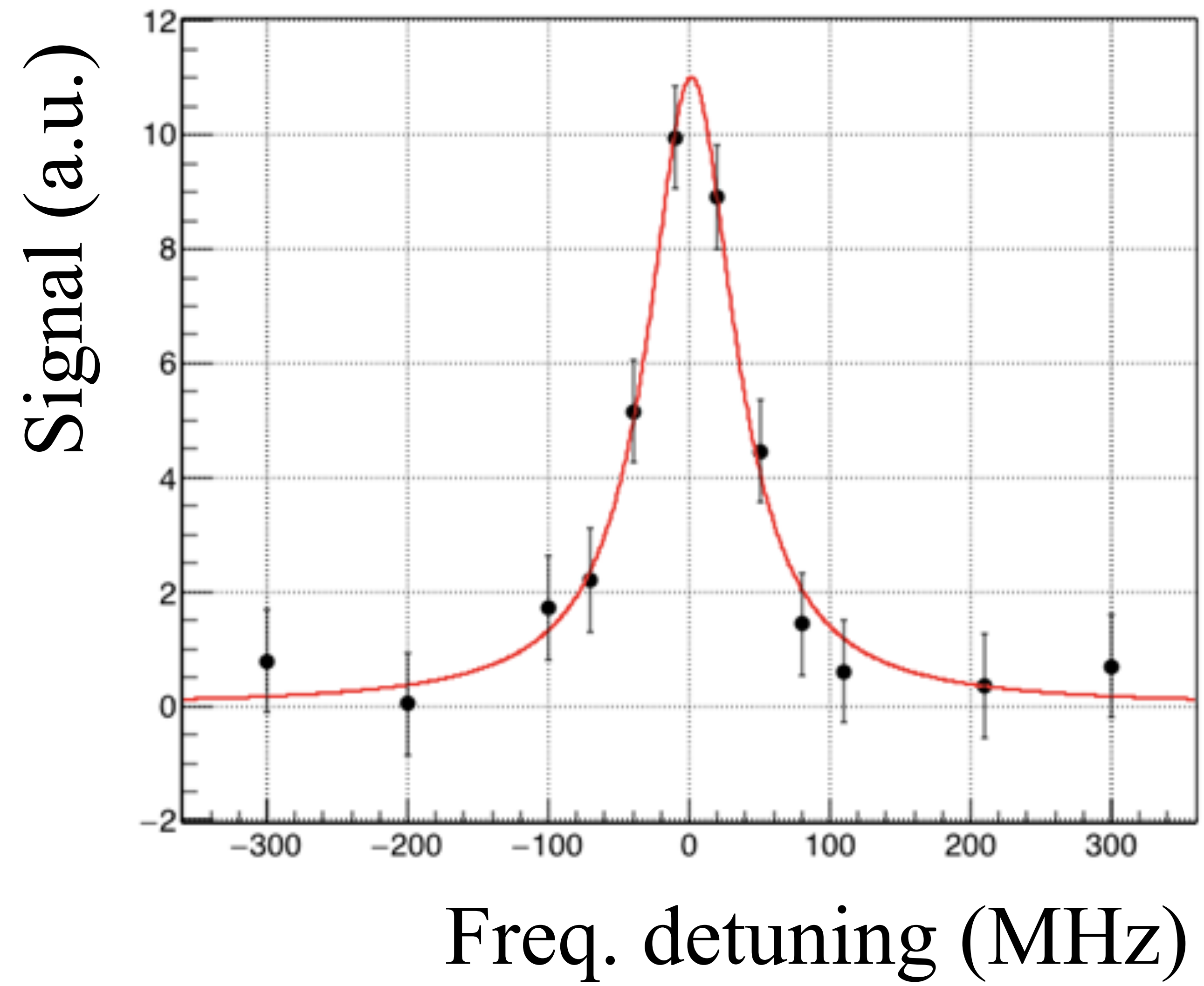
S. Kanda for the MuSEUM Collaboration, Proceedings of Science, PoS(INPC2016)170, in press.
S. Kanda for the MuSEUM Collaboration, Proceedings of Science, PoS(PhotoDet2015)036 (2016).
S. Kanda for the MuSEUM Collaboration, RIKEN APR Vol. 48 (2016).

Statistical Significance

Statistics on resonance



Laser frequency scan



- **The laser pulse energy of 20 mJ, the hydrogen polarisation of 80%, and the beam intensity of 3.5×10^5 muon/s gives 3σ in an hour**
- **At J-PARC, two weeks of measurement is enough for HFS resonance spectroscopy.**

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

Supplements

New Experiment

- Experiments at PSI measured Lamb shifts in 2S states
  - Lamb shifts -> Charge radius
  - Lamb shifts -> 2S-HFS -> Zemach radius
- Charge radius : Significant discrepancy was observed
- Zemach radius : Still large uncertainty to discuss
- Direct measurement of the μp HFS

Transition	Energy meV	Wavelength μm
μp 1S-HFS	182.6	6.778
μp 2S-HFS	22.8	54.3
μd 1S-HFS	50.3	24.6
μd 2S-HFS	6.27	197
μ3He 1S-HFS	1371	0.9
μ3He 2S-HFS	167	7.4
μp Lamb Shift	206	6.0

Pulsed Muon Beam

Property	RAL	J-PARC
Cycle	50 Hz	25 Hz
Intensity	22,000 muon/s at 40 MeV/*c*	350,000 muon/s at 40 MeV/*c*
Spacial Spread	σ = 17 mm	σ = 20 mm
Momentum Spread	Δp = +- 4%	Δp = +-5%

Muon Polarization

On the depolarization of negative muons in hydrogen

A. P. Bukhvostov and N. P. Popov

B. P. Konstantinov Leningrad Institute of Nuclear Physics, Academy of Sciences of the USSR
(Submitted 22 July 1981)
Zh. Eksp. Teor. Fiz. **82**, 23–33 (January 1982)

The magnitude of the residual polarization of μ^- mesons stopping in hydrogen (protium or deuterium) is computed. The rate of Auger collisions between the excited mesic atoms and the target atoms is computed in the eikonal approximation; it turns out be significantly lower than the rate computed earlier in the Born approximation. The dependence of the Auger-collision rate on the target density leads to the result that the residual polarization of muons varies somewhat as the gas pressure is varied. The available experimental data on the depolarization of muons in hydrogen are discussed.

PACS numbers: 36.10.Dr, 51.90. + r, 34.90. + q

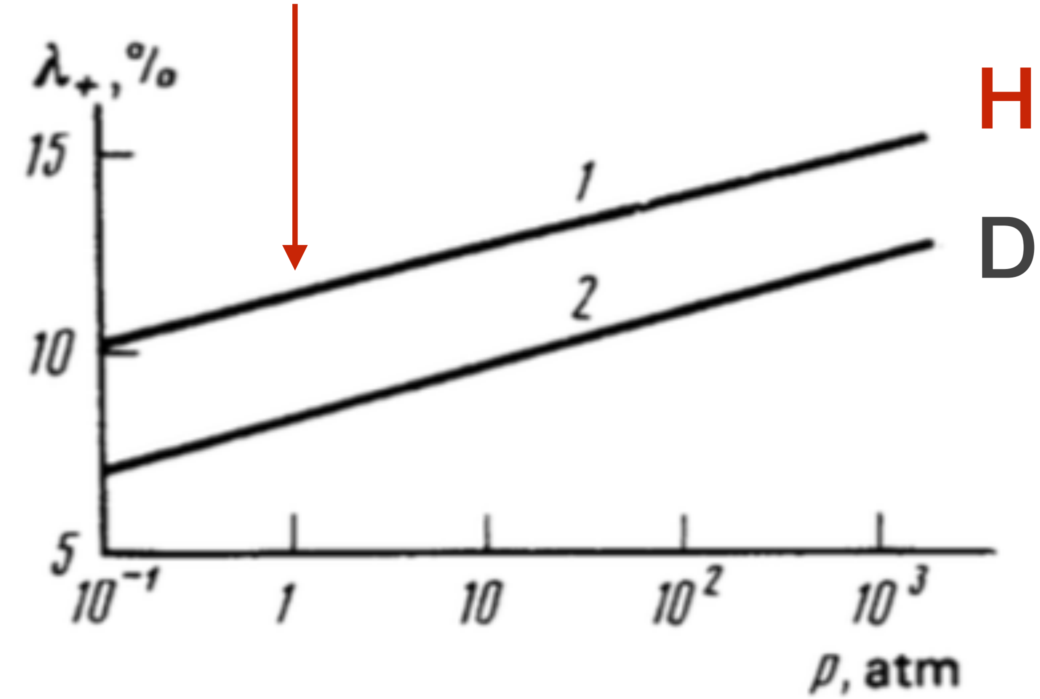
This residual polarization was taken account in muon spin precession simulation.

TABLE I. Values of the residual polarization of the muons in mesic protium ($\lambda_- = 0$) and deuterium atoms as a function of the principal quantum number n_1 starting from which the depolarizing cascade is switched on.

n_1	λ_+		λ_-
	Protium	Deuterium	
2	0.1596	0.1337	0.0100
3	0.1534	0.1251	0.0064
4	0.1392	0.1116	0.0028
5	0.1272	0.1006	0.0001
6	0.1177	0.0920	−0.0020
7	0.1103	0.0854	−0.0037
8	0.1044	0.0802	−0.0050
9	0.0996	0.0758	−0.0060
10	0.0956	0.0723	−0.0068

H D

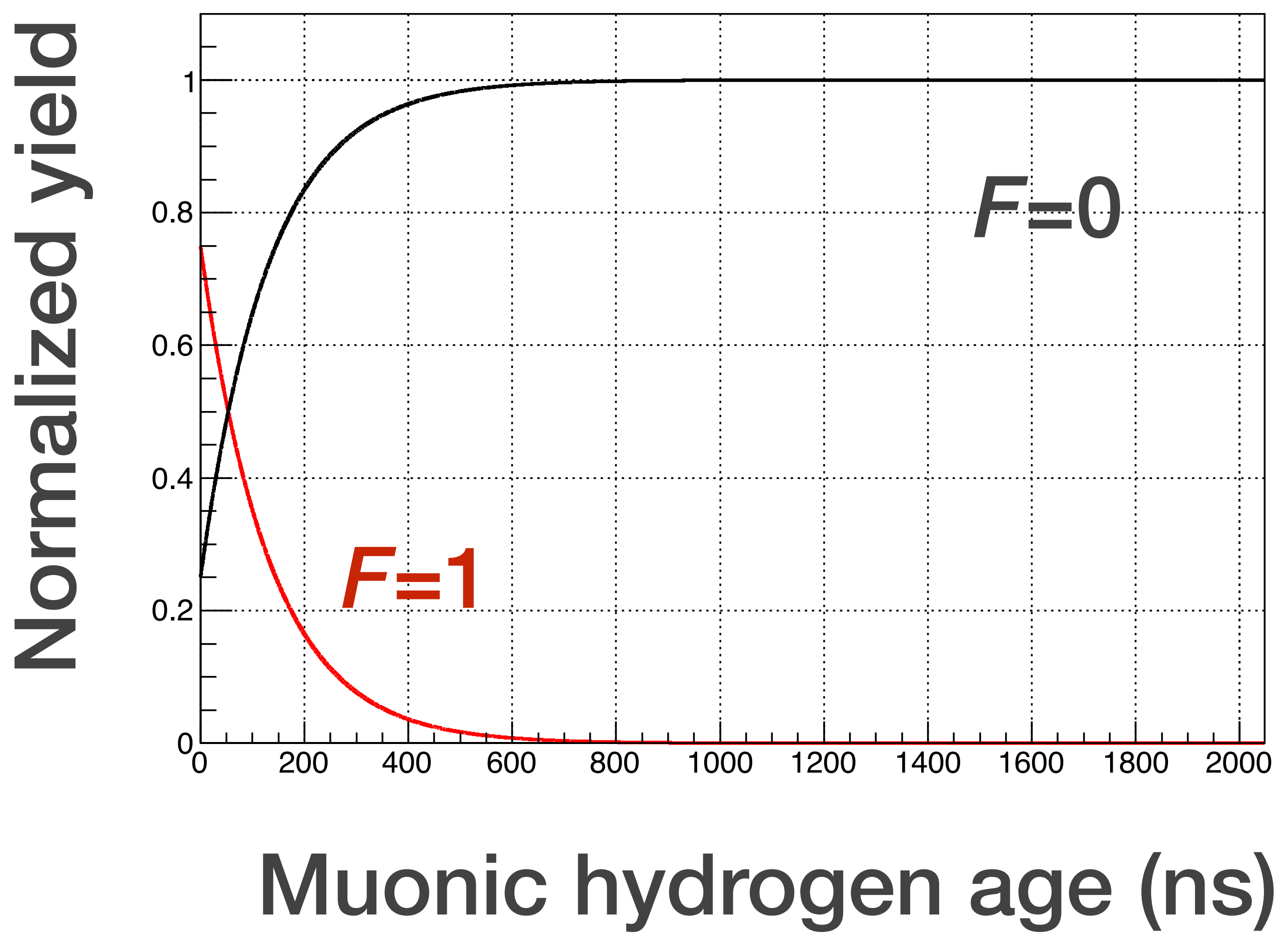
12% at 1 atm



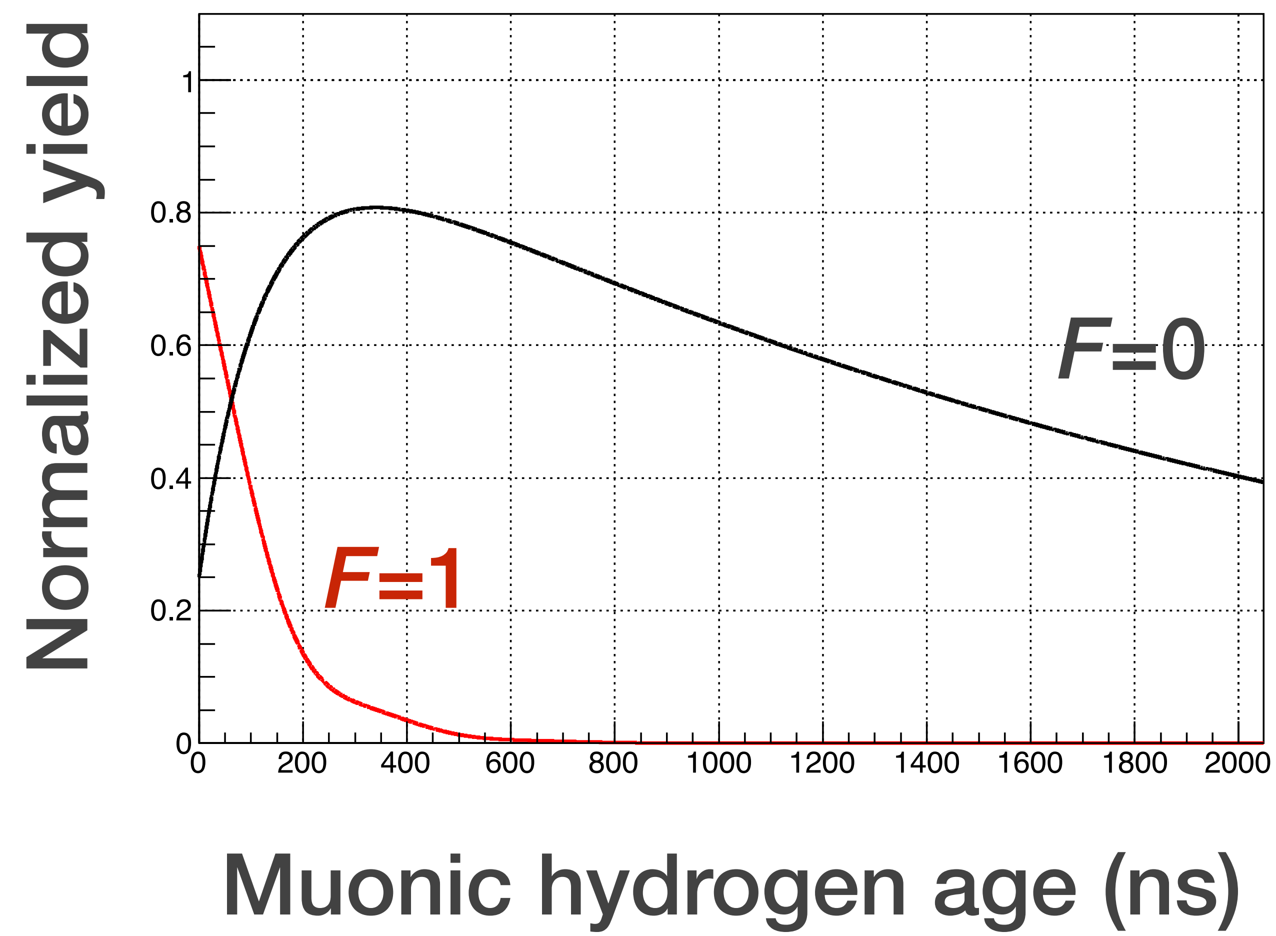
Zh.Eksp.Teor.Fiz. 82, 23 (1982).

State Population

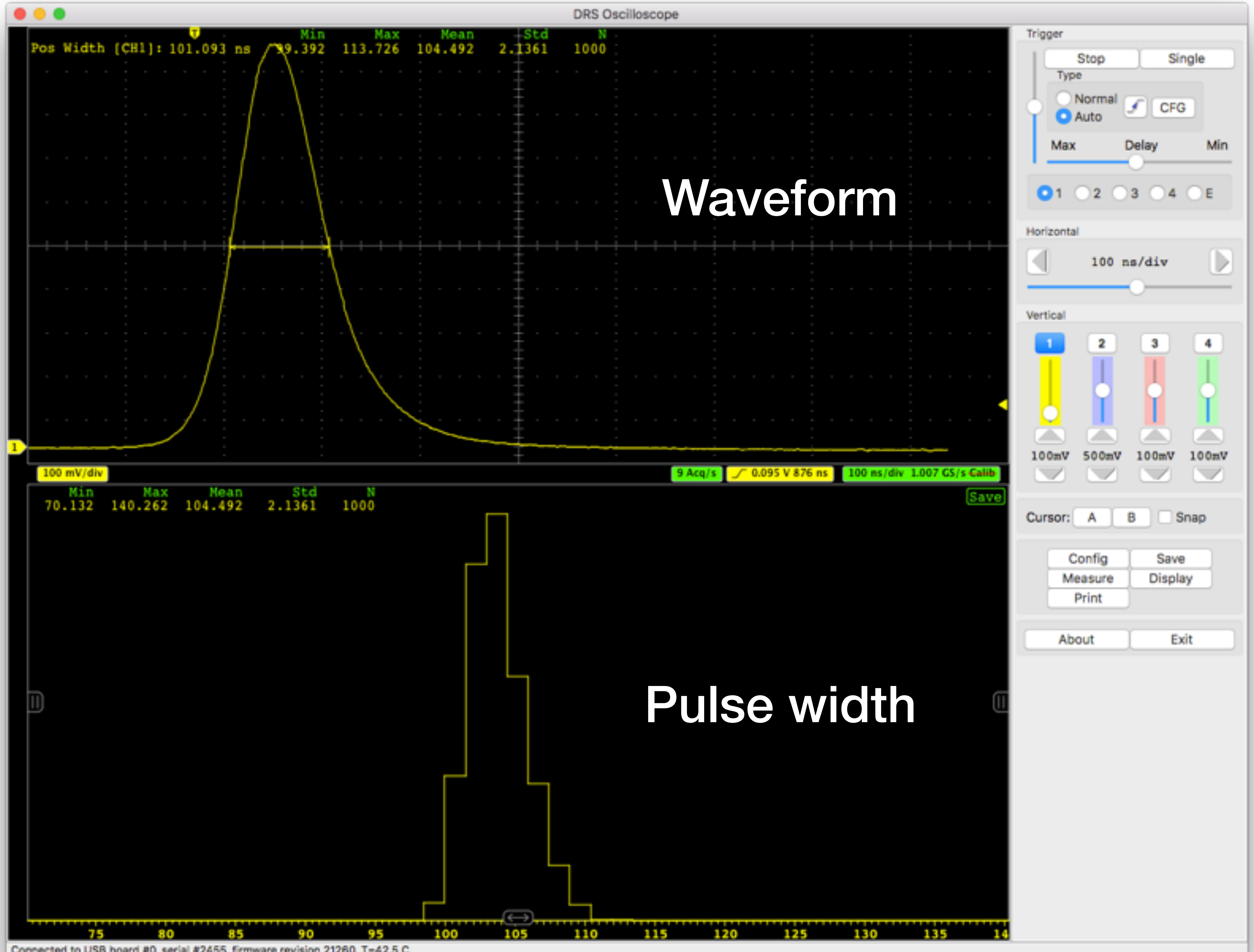
State population



Electron spectrum



PD Waveform


DRS Oscilloscope
Pos Width [CH1]: 101.093 ns
Min Max Mean Std N
99.392 113.726 104.492 2.1361 1000
Waveform
100 mV/div
9 Acq/s
0.095 V 876 ns
100 ns/div 1.007 GS/s Calib
Min Max Mean Std N
70.132 140.262 104.492 2.1361 1000
Save
Pulse width
75 80 85 90 95 100 105 110 115 120 125 130 135
Trigger
Stop
Single
Type
Normal
Auto
CFG
Max
Delay
Min
Horizontal
100 ns/div
Vertical
100mV 500mV 100mV 100mV
Cursor: A B Snap
Config
Save
Measure
Display
Print
About
Exit
Connected to USB board #0, serial #2455, firmware revision 21260, T=42.5 C