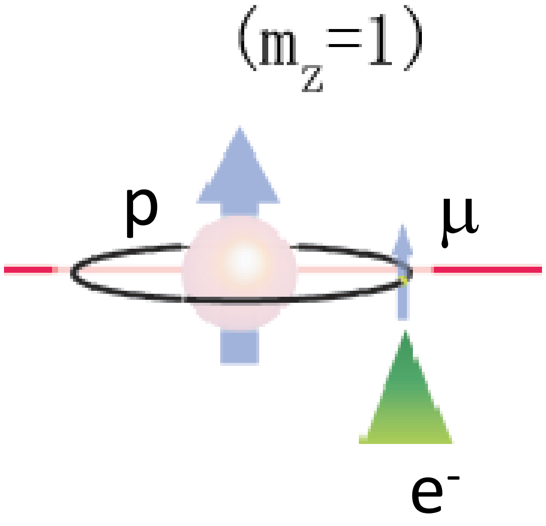
J-PARC Symposium 2019
Tsukuba, 25 Sep 2019

Laser spectroscopy of the 1s hyperfine splitting energy of muonic hydrogen for the determination of proton Zemach radius

K. Ishida

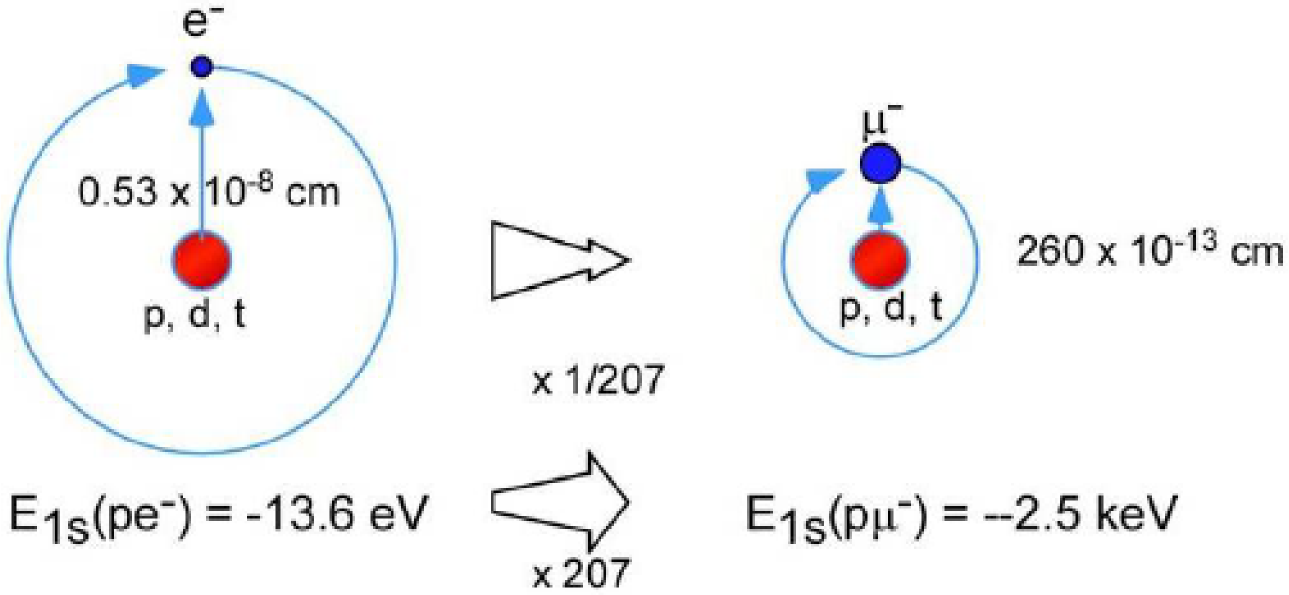
RIKEN

Proton Radius Puzzle
Zemach radius and hyperfine splitting
Plan of our measurement
Status



Hydrogen

Muonic hydrogen



Atomic binding energy ~ (m_μ/m_e)
Energy shift by proton size ~ $(m_\mu/m_e)^2$
Relative sensitivity ~ (m_μ/m_e) ~ 200

Proton radius puzzle?

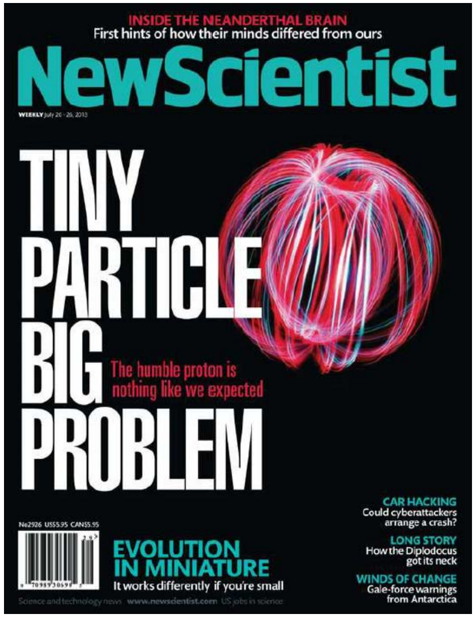
Proton - major constituent of matters
  charge, spin, mass - very well measured
Proton radius affects many precision measurements and should be known

Serious discrepancy was first found in 2010
  in new proton radius measurement using muonic hydrogen
The radius was smaller by 4% (7σ) from the CODATA value

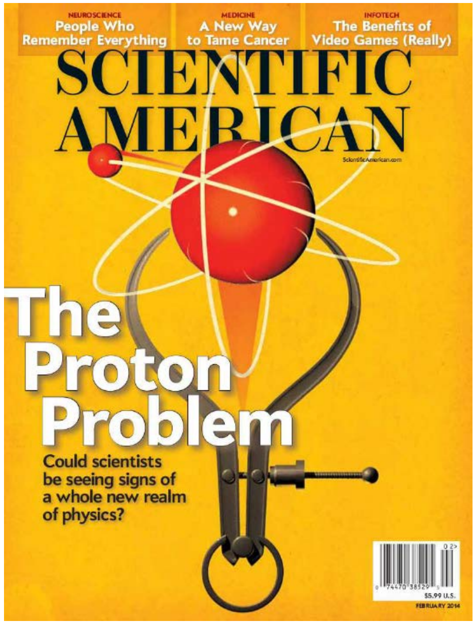
2010

2013

2013



2014



Proton Charge Radius Puzzle
PSI Measurement (μp 2s-2p by CREMA collaboration)

R. Pohl et al.,

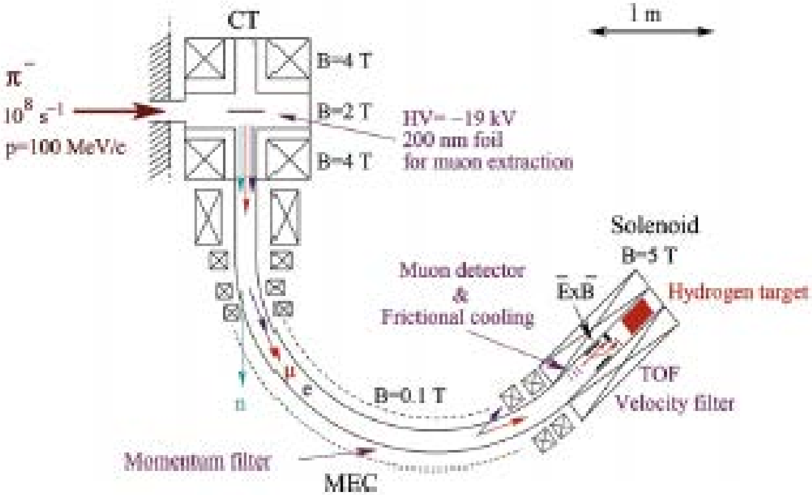
Can. J. Nucl. Phys. 89 , 37 (2011))

Measurement of 2s-2p energy difference

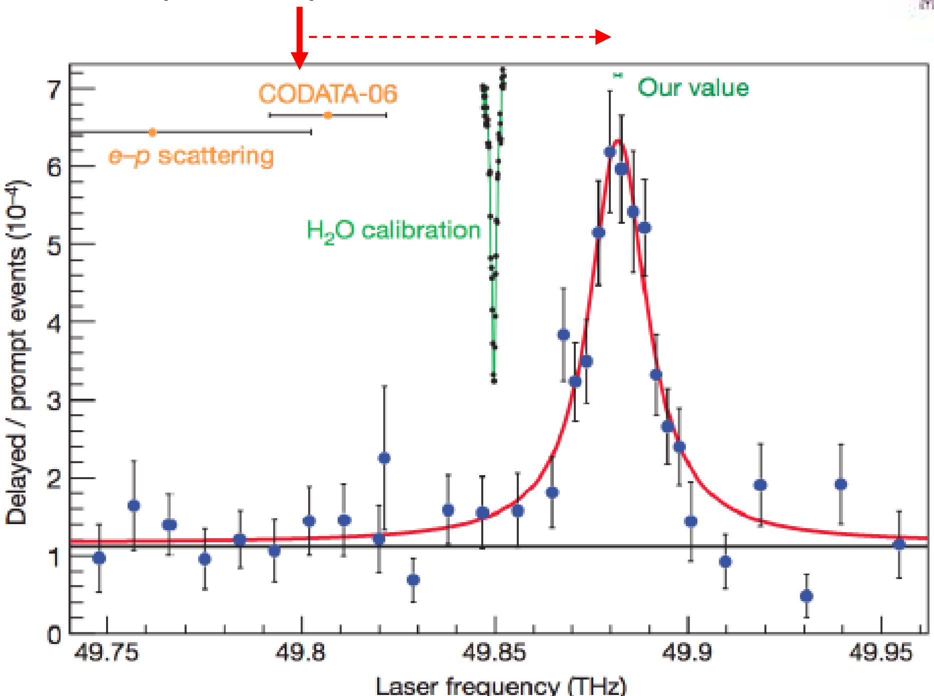
Formation of μp (1% feeds 2s)

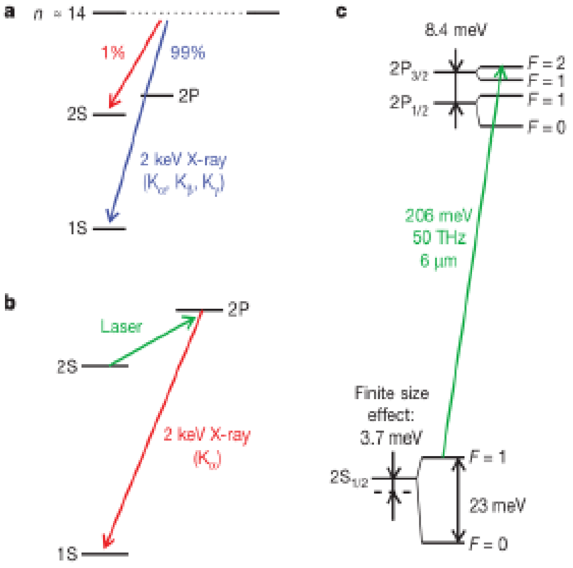
Laser resonant excitation of 2s-2p（Lamb Shift）

Observation： 2s metastable state -> 2p->1s



expected position

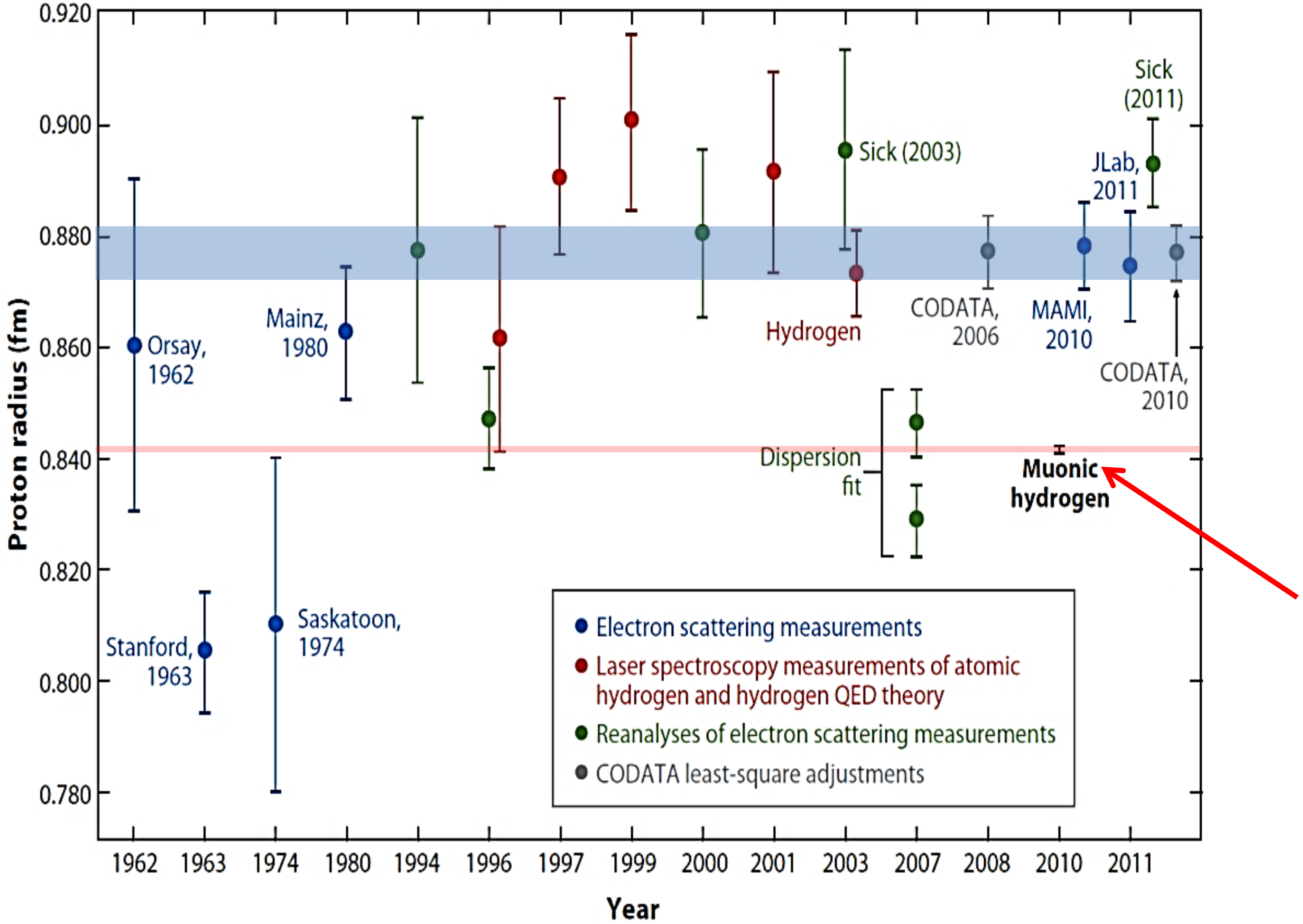




Proton Radius Puzzle

Further measurement and analysis did not ease the discrepancy.

R. Pohl et al., Ann. Rev. Nucl. Part. Sci. 63 (2013)242001

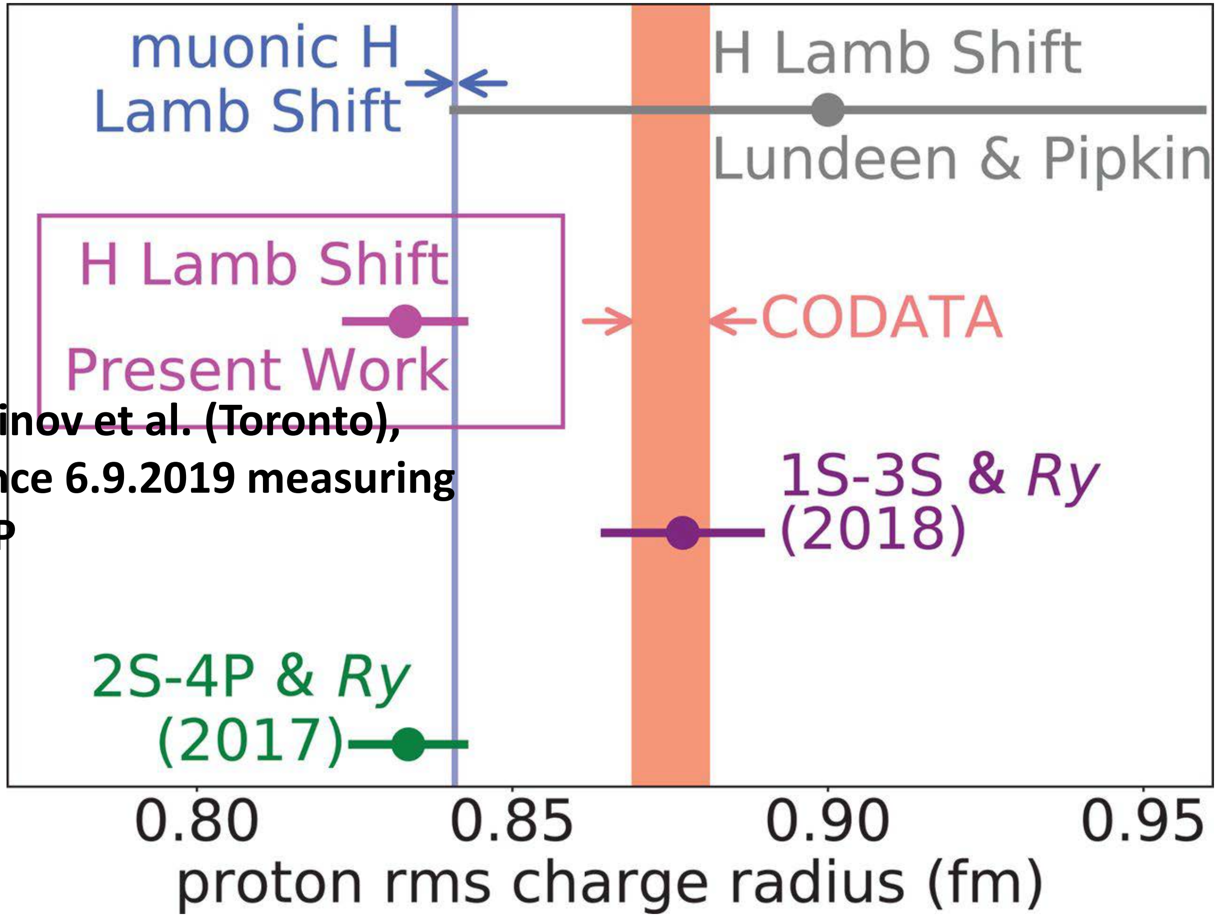


Proton Radius Puzzle: Recent Update

Hydrogen atom

three new results - some closer, some not ...

and existence of many older values ...

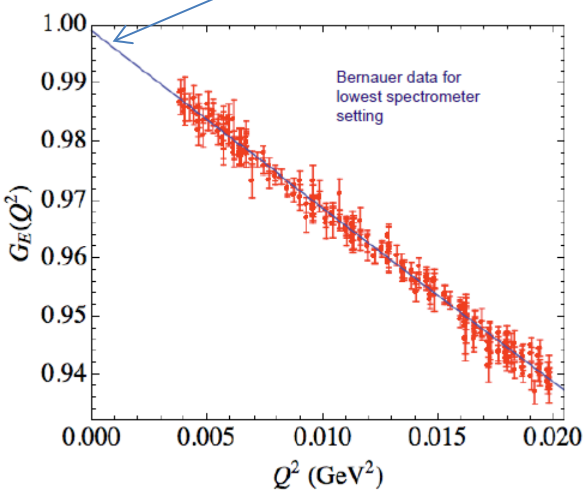


Bezginov et al. (Toronto), Science 6.9.2019 measuring 2S-2P

Proton Radius Puzzle: Recent Update

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \frac{\varepsilon G_E^2 + \tau G_M^2}{\varepsilon(1+\tau)}$$

from this slope



ep scattering

MAMI (Mainz) e-p high statistics data

consistent with previous values, detail analysis continuing

also, preparation of new better target, separation of G_M, ...

JRAD (Jefferson) e-p at high energy and low Q_2

new data indicates radius value consistent with μp Lamb shift

ULQ2 (Tohoku) low energy e-p preparing

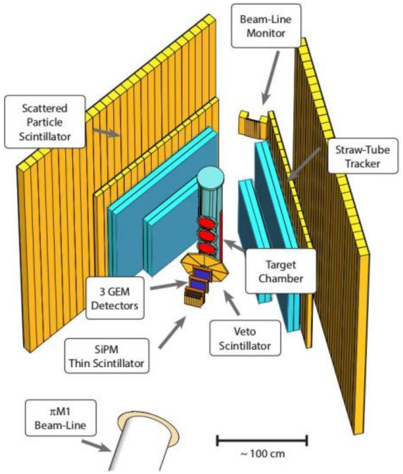
μp scattering

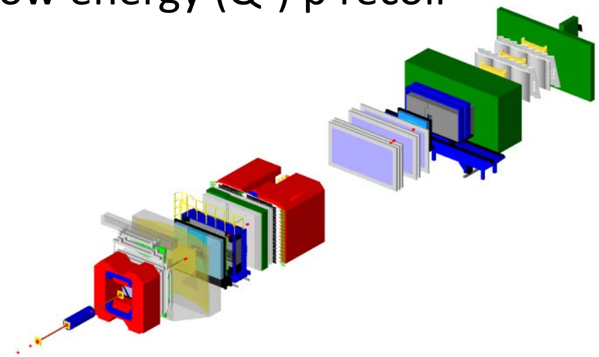
MUSE (PSI) μp/ep scattering direct comparison

- run nearly ready

COMPASS (CERN) 190GeV μ +low energy (Q^2) p recoil

- in a few years





Where will we go?

2018 CODATA lists "both" values
0.8751(61) fm 2014 CODATA value
0.8414(19) fm μp -atom Lamb shift

1. Need to be checked/confirmed

new measurements/data are arriving
still do not know how to understand new/old data ...

2. Checking theory/analysis

Many refined analysis of scattering data,...
Calculation of correction factors,...
Beyond SM, lepton universality breaking,...

3. Zemach radius r_Z

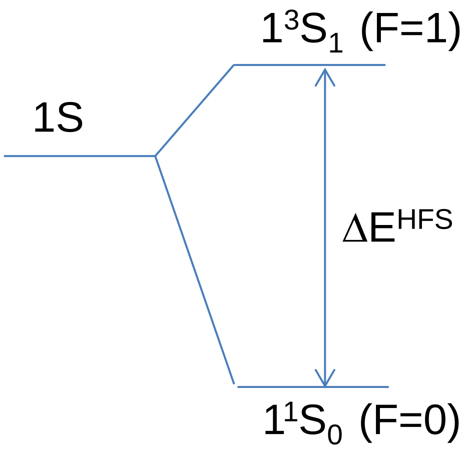
another proton radius accessible by spectroscopy
includes magnetic structure

Zemach radius

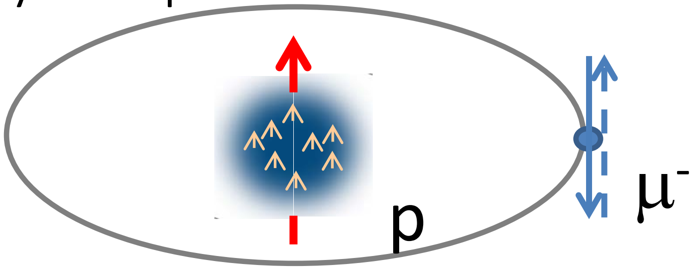
How about magnetic radius of proton?
=> Hyperfine splitting is related to the magnetic moment.
Zemach radius A.C. Zemach, Phs.Rev.C 104, 1771(1956).

$$R_Z = \int d^3r\, r \int d^3r' \rho_E(r')\rho_M(r-r')$$

convolution of charge and magnetic moment distribution



Why not only magnetic but also charge distribution?
=> Hyperfine coupling is affected with distributed magnetic moment
=> Charge distribution reduces muon attraction and modify overlap



Through R_Z measurement,
If the muon and electron determination are consistent
-> some problem in charge radius measurements?
If they are different
-> radius puzzle continues,
size of discrepancies may give us hint

Zemach radius so far

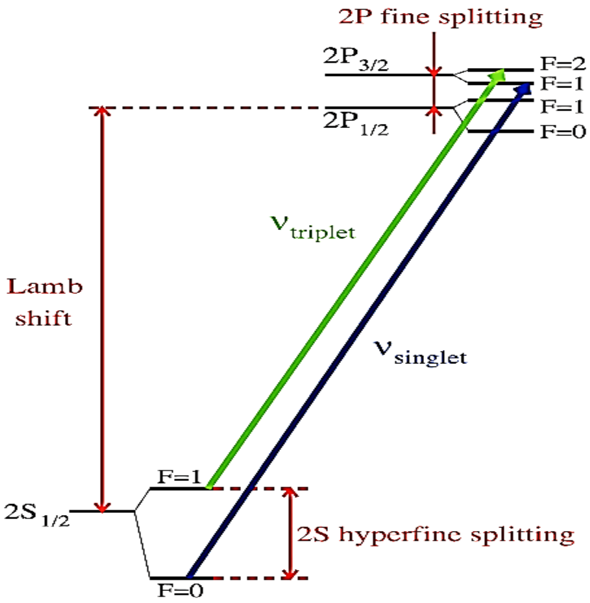
2s HFS was indirectly determined in the same CREMA experiment at PSI (from two lines)

R_Z = 1.082(37) fm [A. Antognini, et al., Science 339 (2013) 417]

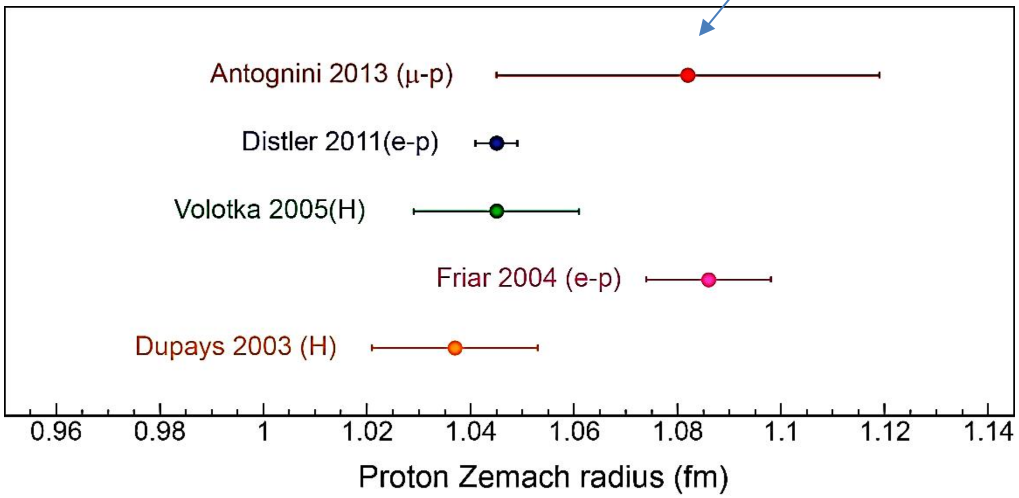
from e-p : 1.086(12), 1.045(4) fm

from H spectroscopy : 1.047(16) , 1.037(16) fm

No definitive interpretation with proton radius puzzle because of the large error bar



Muon 2S HFS



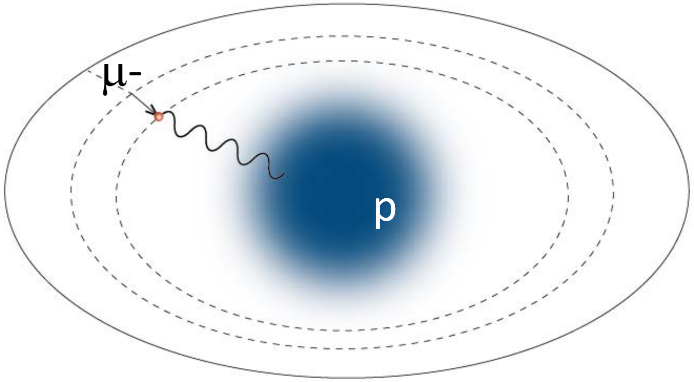
Need high precision values

Direct measurement of 1s HFS has chance to determine Rz to better than 1%

Formation of Muonic Hydrogen atom (μ^-p)

Muon stops in hydrogen

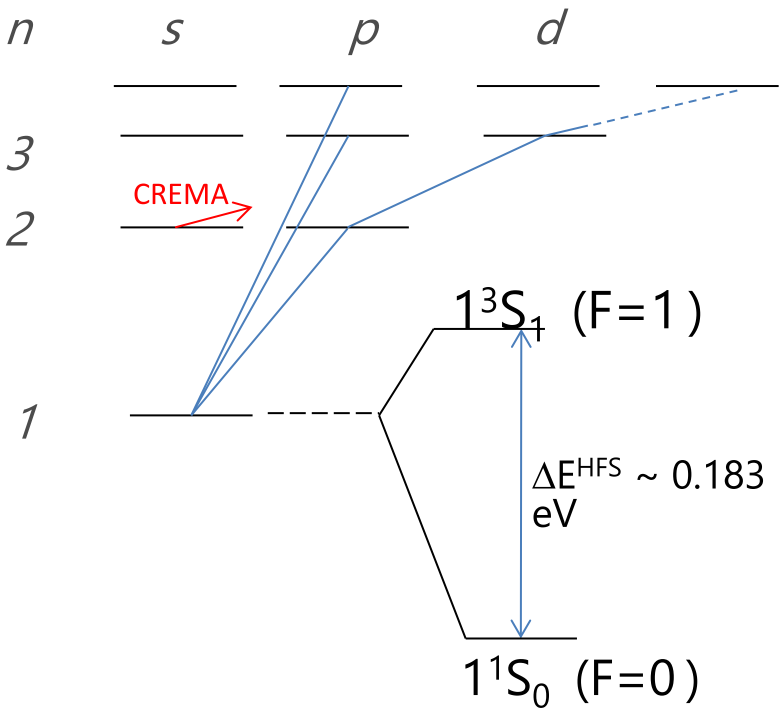
Muon capture at high orbit and cascade to ground state



Rapid conversion to lower hyperfine state
=> no muon polarization left

→ g.s. μ^--p atom

All muons reach 1s ground state
vs. 1% only to 2S in PSI Lam Shift measurement



HFS splitting energy
How is the Zemach radius determined?

In the first order, proportional to muon and proton magnetic moments ($1/m_\mu$ and μ_p) and to $1/R_{\mu p}{}^3$ but with correction terms, some are structure dependent

$$\Delta E_{HFS}^{exp} = E_F\left(1 + \delta_{QED} + \delta_{Zemach} + \delta_{recoil} + \delta_{pol} + \delta_{hvp}\right)$$

Fermi term: $$E_F = \frac{8}{3}\alpha^4 \frac{m_{\mu(e)}^2\, m_p^2}{\left(m_{\mu(e)} + m_p\right)^3}\,\mu_p$$

δ_{QED}: higher order QED correction (well known)

$\delta_{Zemach} = -2\alpha m_{\mu p} R_z + O(\alpha^2)$

δ_{recoil} : recoil (well known)

δ_{pol} : proton polarizability (internal dynamics of protons)

δ_{hvp} : hadron vacuum polarization (small)

$$R_Z = \left\{\left(E_F\,(1 + \delta_{QED} + \delta_{recoil}\ + \delta_{pol} + \delta_{hvp}\right) - \Delta E_{HFS}^{exp}\right\}/1.281$$ = 1.0XX(13) fm

1130(1) ppm 1700(1) ppm 20(2) ppm

460(80) ppm (2) ppm

proton polarizability

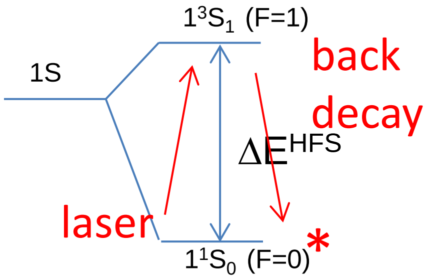
R_Z will be improved to 1 % (with present limitation by δ_{pol} precision).

or even better with improvement of δ_{pol} (dispersion relation, QCD, ...),

Zemach radius measurement with muons

There are three proposals

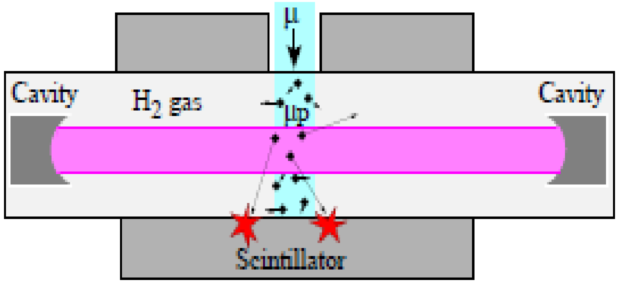
This will make independent measurements possible



Two groups use increased kinetic energy after back decay

1) CREMA-3 at PSI

Faster µp diffusion to wall



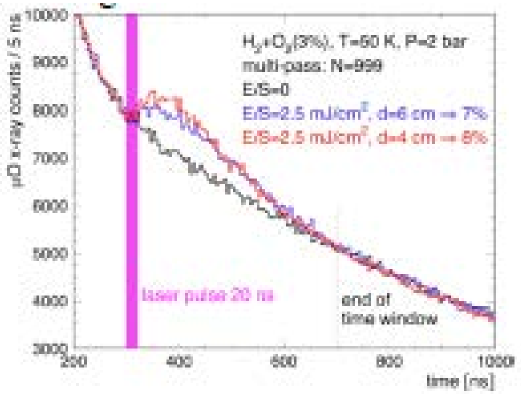
2) FAMU proposal to RIKEN-RAL

energy dependent muon transfer rate to admixture oxygen

Bakalov et al., Phys. Lett. A 172 (1993) 277

µp + O -> µO + p ↘ x-rays

transfer x-ray simulation

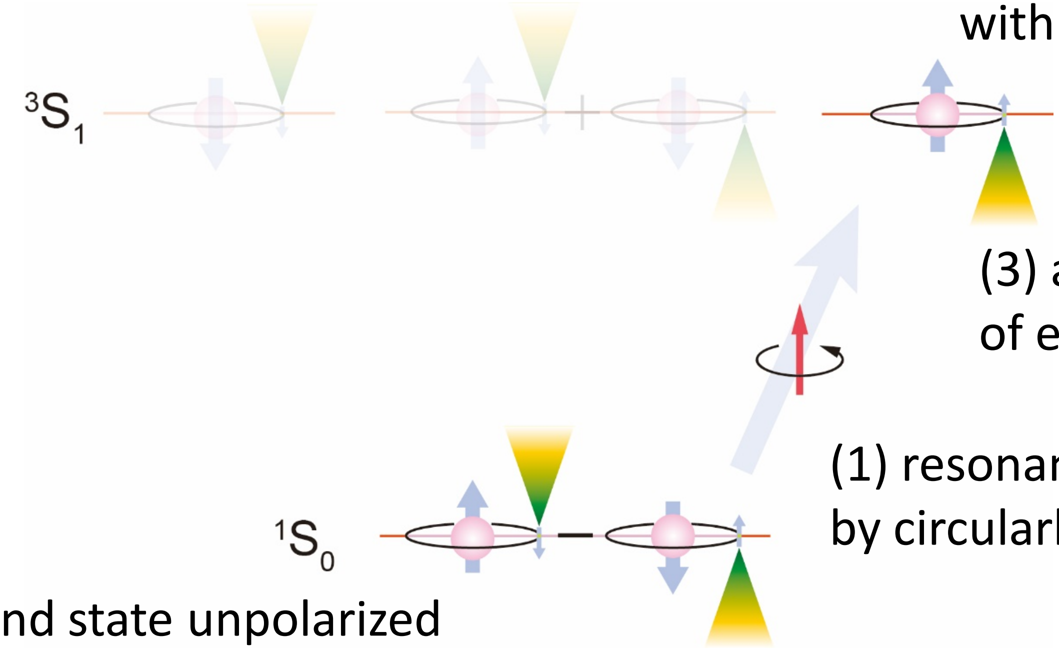


3) RIKEN group propose spin polarization measurement at RIKEN-RAL and J-PARC

simple & straightforward

Zemach radius measurement with muons

3) RIKEN group propose spin polarization measurement at RAL and J-PARC
(idea started in discussion in RIKEN including M. Iwasaki and Ishida in 2013)



(0) ground state unpolarized

(1) resonant excitation
by circularly polarized laser

(2) formation of triplet state
with muon spin polarized

(3) asymmetric emission
of electron from muon decay

All based only on well known processes!
No need of phenomenological simulation

RIKEN MuP Collaboration

K. Ishida, S. Kanda, M. Iwasaki, M. Sato*, Y. Ma,
S. Okada, S. Aikawa, H. Ueno, A. Takamine,
K. Midorikawa, N. Saito, S. Wada, M. Yumoto
RIKEN
Y. Matsuda, K. Tanaka**
Graduate of School of Arts and Science, The University of Tokyo
Y. Oishi
KEK
* Present address: KEK
*** Present address: CYRIC, Tohoku Univ.*

New collaborators are welcome

Key for the measurement

1. Increase excitation rate (M1 transition) and polarization

Intense mid infrared laser developed at RIKEN +multi-pass cavity

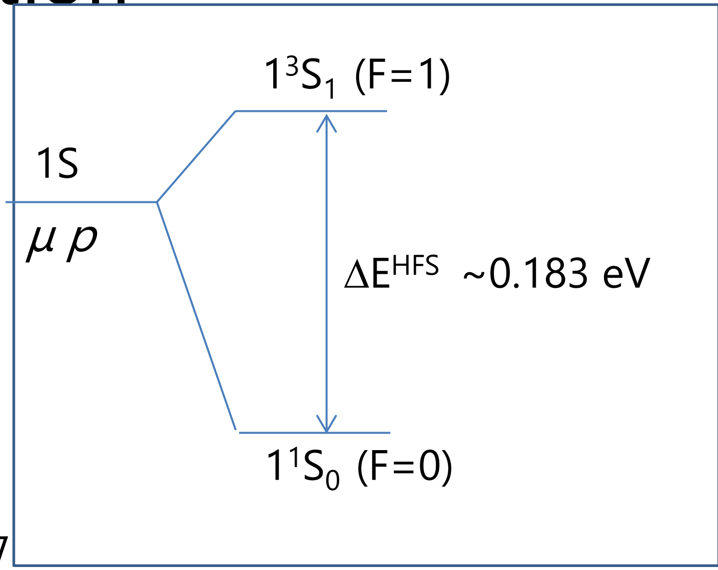
2. Many muonic hydrogen atoms

Intense pulsed muon beam at RIKEN-RAL and J-PARC
Optimum gas condition, gas container,
muon stopping simulation/measurement (test at RIKEN-RAL)

3. Optimization of polarization detection

Detectors, Filtering by lifetime, Background reduction

Plan: Laser excitation



F : total angular momentum

Laser requirement for μp 1S HFS
0.183 eV = 6.8 μm = 44 THz

Excitation rate

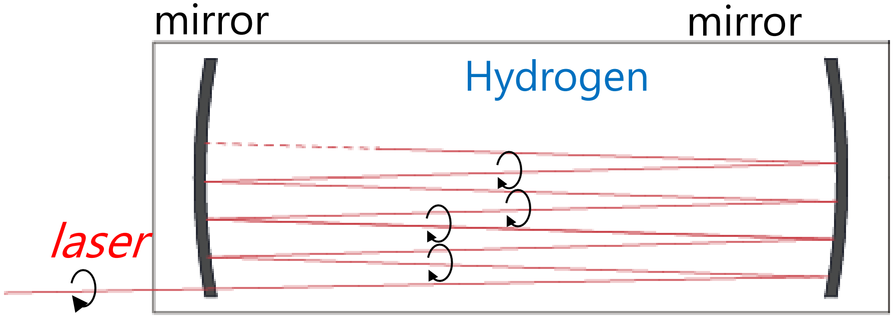
$$P = 2 \times 10^{-5} \frac{E}{S\sqrt{T}}$$

E/S : laser power density [J/m²], T : temperature [K]

Doppler broadening (cooling to ~20 K helps => 63 MHz)
(A. Adamczak et al., NIM B 281 (2012) 72,
with correction by 1/4 , private communication)

ex. E = 40 mJ, *S*= 4 cm², T= 20 K, then *P* = 4.5 x 10^{-4}

by using multi-pass cavity（like PSI）
high reflective mirror 99.95%
P=45% after 1000 pass
However, ...

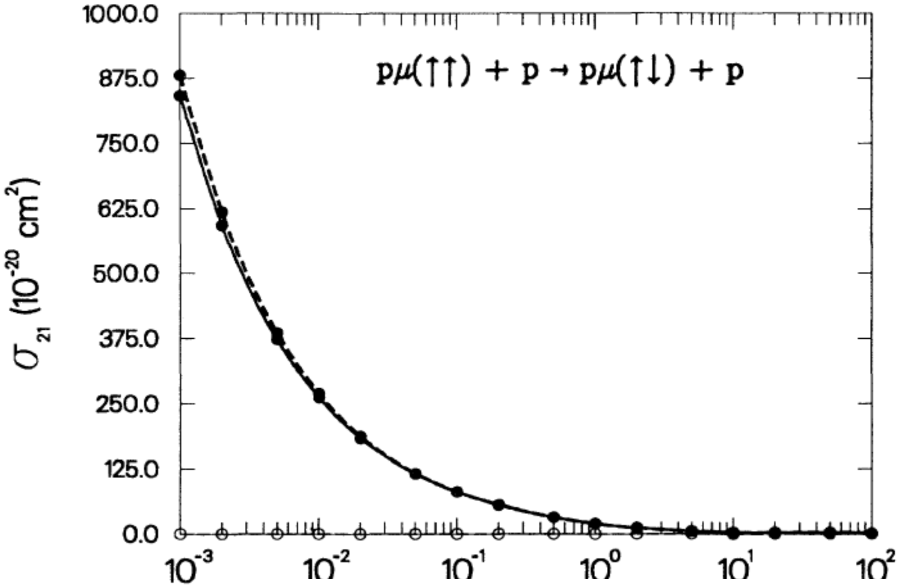


Experimental challenge : loss of polarization

Muon may lose polarization before decay
by external collision)

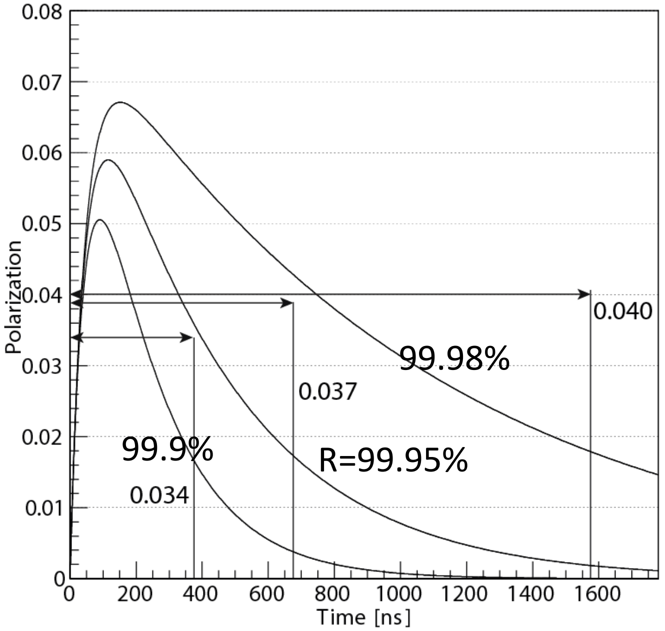
$$\mu p(\uparrow\uparrow) + p \rightarrow \mu p(\uparrow\downarrow) + p$$

Theoretical calculations (no measured rate)
J. Cohen, Phys. Rev. A 43 (1991) 466



Solution:
Use low density hydrogen to keep polarization
50 ns at 0.001 LHD (Liquid Hydrogen Density)
500 ns at 0.0001 LHD

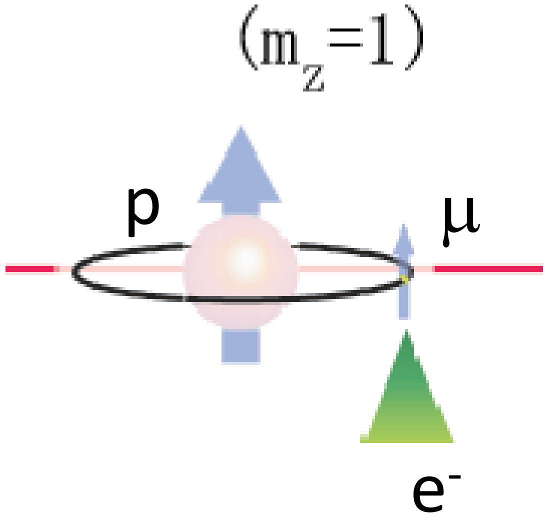
Laser=40 mJ, 0.001LHD

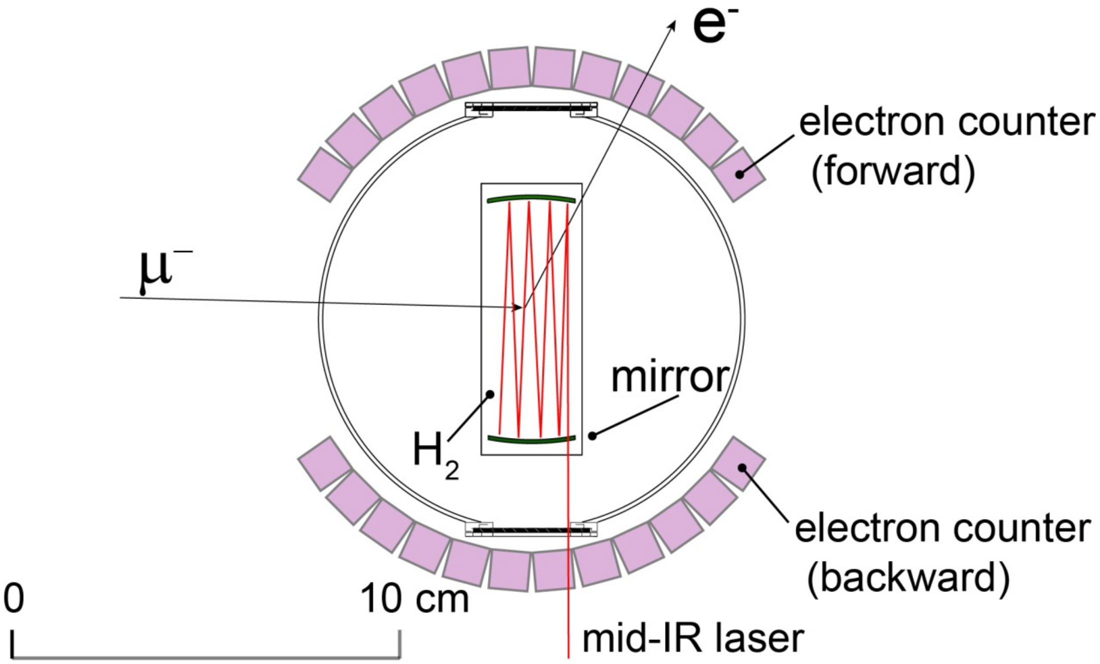


Muon Polarization Calculation: build up and decay
0.001 HD target
Excitation by 40 mJ
Multi-pass laser cavity
Polarization of 0.037 in a time gate 0.7 μs (0.001 LHD)

Detection of Polarization

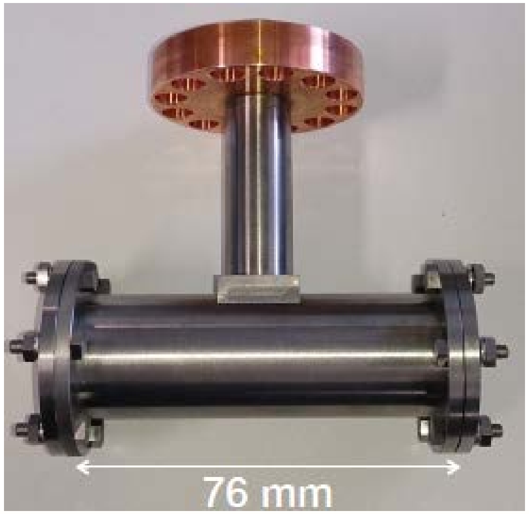
Circularly polarized laser select of one the excited sub-state
=> complete muon spin polarization
Muon decays with 2.2 μs lifetime and emits electrons asymmetrically to the spin.
$\mu^- \rightarrow e^- \nu \nu$





M. Sato, et al. "Laser Spectroscopy of Ground State Hyperfine Splitting Energy of Muonic Hydrogen"
JPS Conf. Proc. 8 , 025005 (2015)

Muon stopping simulation and background

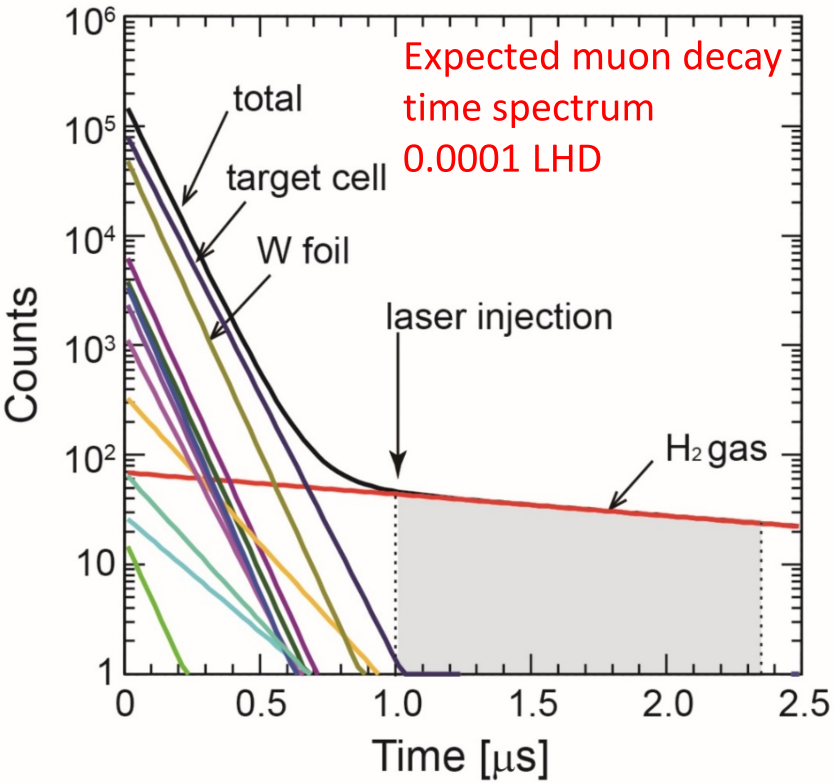


Condition:
H2 target cell 0.0001 LHD and 4 cm^2 x 6 cm 20 K
40 MeV/c pulsed muon beam at RIKEN-RAL

Geant Simulation Result:
0.1% of incoming mons stops in 0.0001 LHD hydrogen gas
(or 1% at 0.001 LHD)

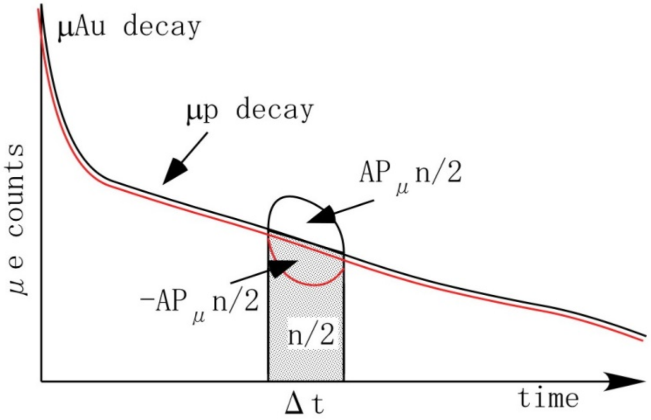
Using high-Z materials as the target cell, muons in those materials disappear quickly by nuclear capture (90ns in silver)

Laser injection after 1 μs
when backgrounds died away


Expected muon decay time spectrum 0.0001 LHD

Yield estimation (statistics)

Observe forward/backward ratio for the polarization effect
N_F, N_B in time gate
$(N_F-N_B)/(N_F+N_B) = A_0 P$



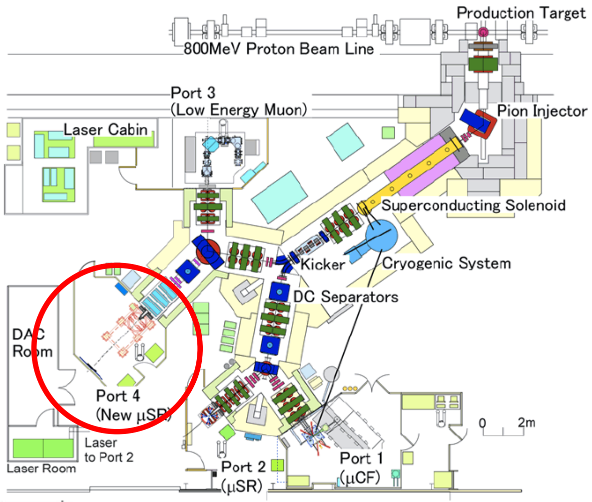
Beam condition
Intensity 2.2×10^4 /s @40 MeV/c (RIKEN-RAL)
Momentum width $\sigma_p/p_0 = 2\%$
Target condition
H2 gas 0.001 LHD, Volume $4\text{cm}^2 \times 6$ cm
Laser
40 mJ, 99.95% reflectivity, cavity length
Detector (solid angle 28% each, polarization sensitivity factor 0.23)

Time gate : laser at 1.0 μs after muon + 1.33 μs detection gate
statistics in 5 hours
=> signal N_F-N_B, ~240
fluctuation $\Delta N_F+\Delta N_B \sim \sqrt{(N_F+N_B)}$ ~80
significance = $(N_F-N_B)/\sqrt{(N_F+N_B)} \sim 3\sigma$
Time is doubled (~10 hour) for accumulating laser on and off
Scan of 100 laser wave length points = 1000 hours => 40~50 days
Fine scan near resonance takes another +30 days.

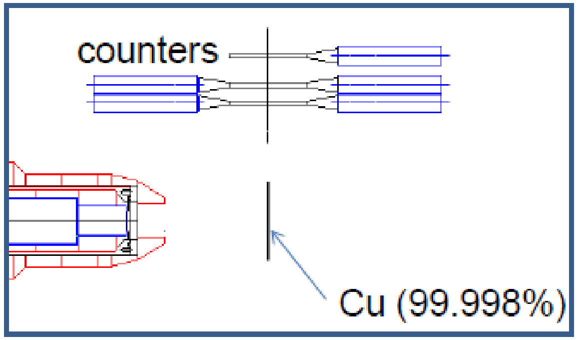
Beam test of background level

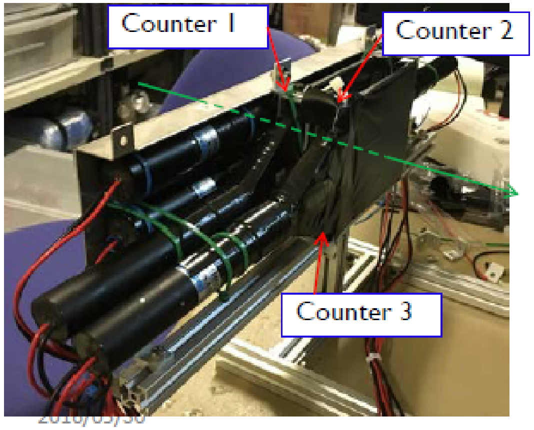
Beam test at RIKEN-RAL

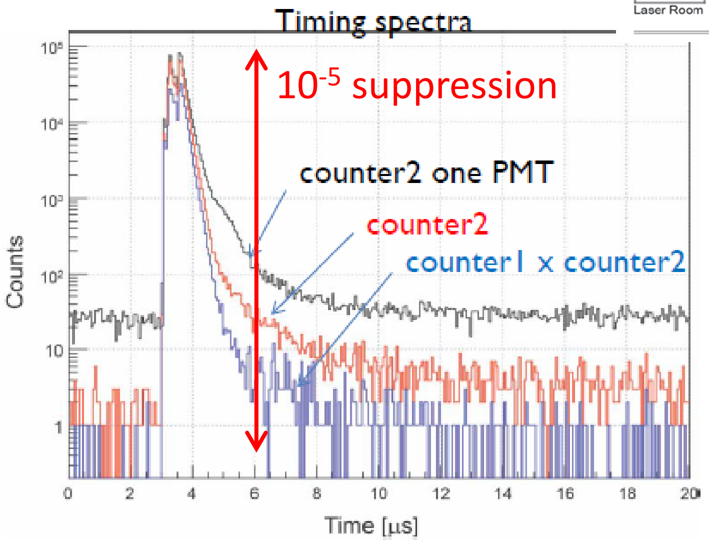
- Muons stopped in Cu target
- We confirmed
  - Fast decay out of muons in high-Z materials like Cu
  - Low background level (< 10^{-4}) at ~1 μs



Beam time in May (5/11-13) : CHRONUS → coincidence counters





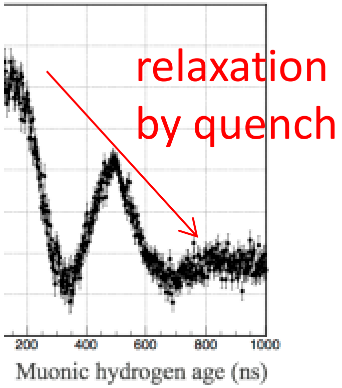


background can be suppressed with hit-timing coincidence

➡ design the prototype of electron counters
beam test with dilute gas

Also, studies on muon stopping in thin H2 target

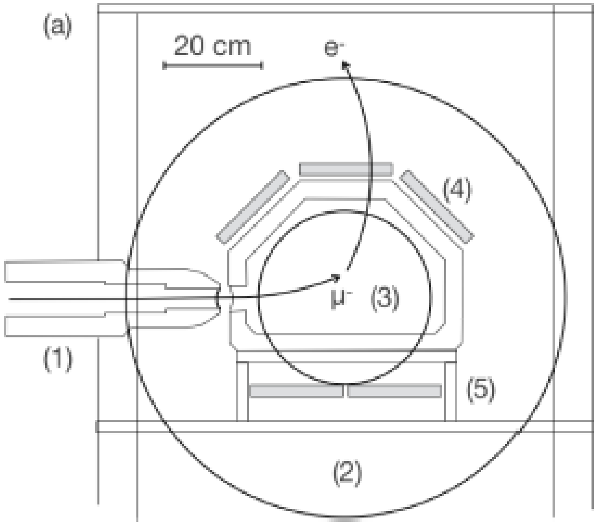
R&D study: Measurement of muon polarization in hydrogen and quench rate of triplet state



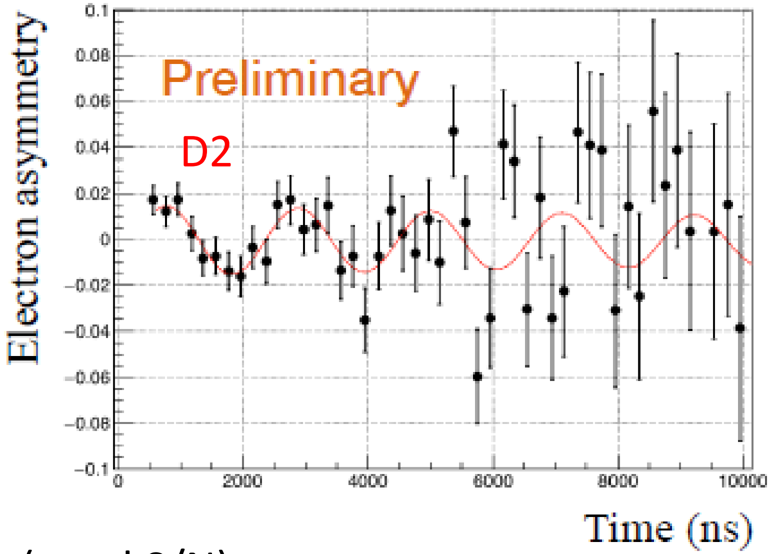
relaxation by quench

"Measurement" of triplet μp quench rate (S. Kanda)
by muon spin rotation method
μp(F=1) 3.1 MHz@0.067T, μd(F=3/2) 3.1 MHz @0.057T

Challenge: Stopping S/N of muons in thin H2 gas (0.1~1 atm) and rejection of wall stop muons



Measurement done at RIKEN-RAL with D2 in September 2018,

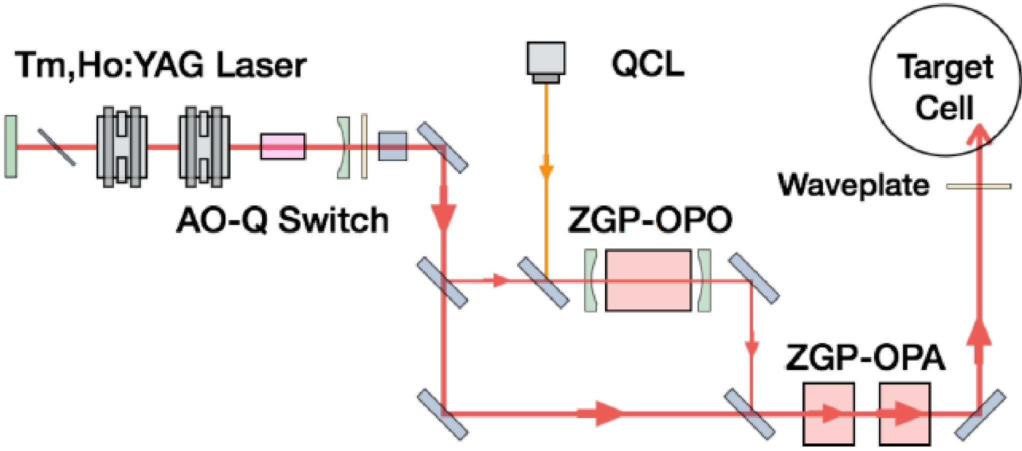


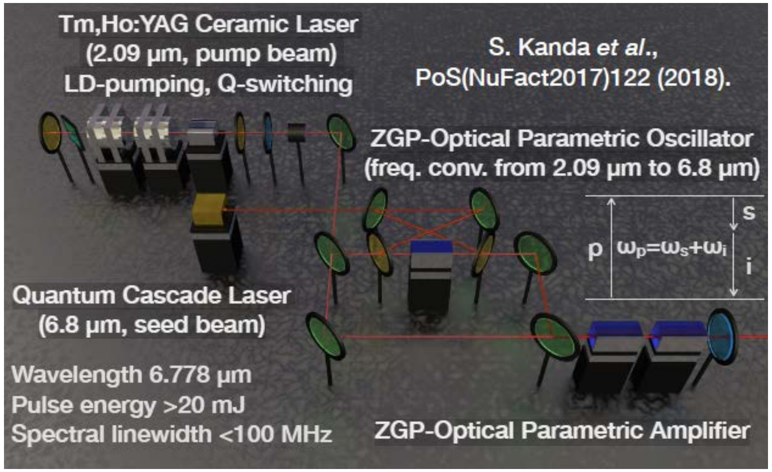
Preliminary

D2

H2 planned in Nov
use of 20 MeV/c muons (good S/N)

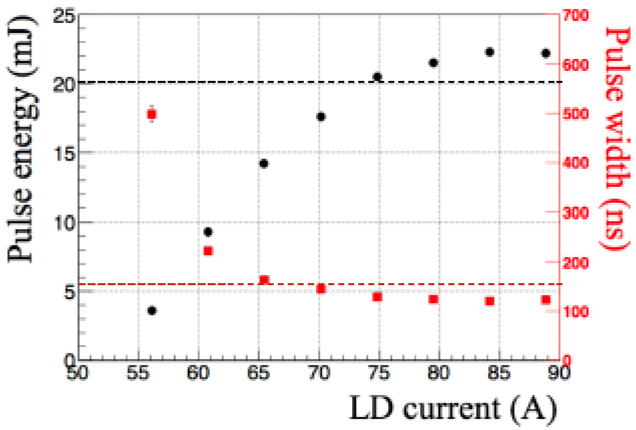
R&D Study : Laser



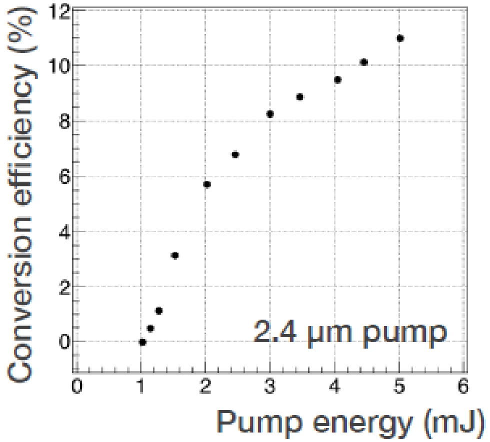


RIKEN laser group's experience on 6 µm laser
+ frequency stabilization with QCL
Achieve10mJ+10mJ with best matching component and multi-source injection
Optimizations of laser components are in progress.

2.09 µm output

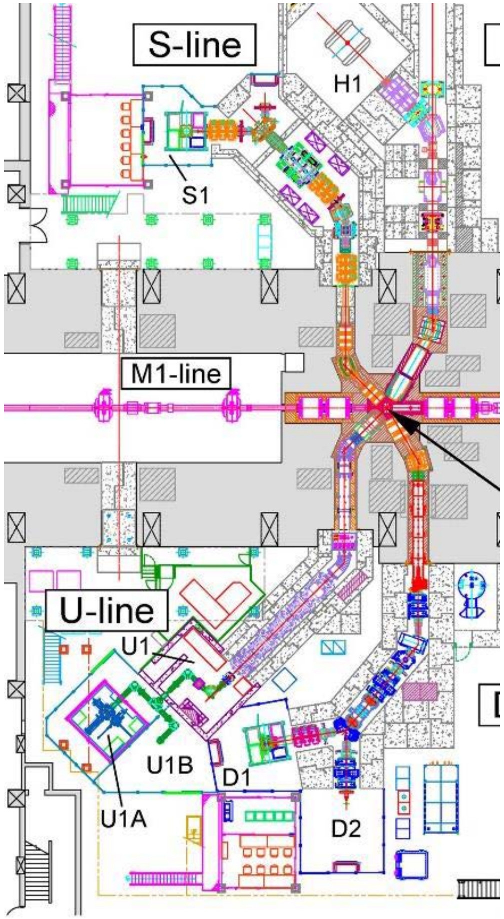


6 µm output



Beam time estimate: at J-PARC

If the laser power is half (~20 mJ), measurement at RIKEN-RAL is not practical (>1 year).
At J-PARC, with quicker data accumulation (x20?)
Same statistics could be obtained in ~20 days.



Alternative idea (S. Kanda)

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

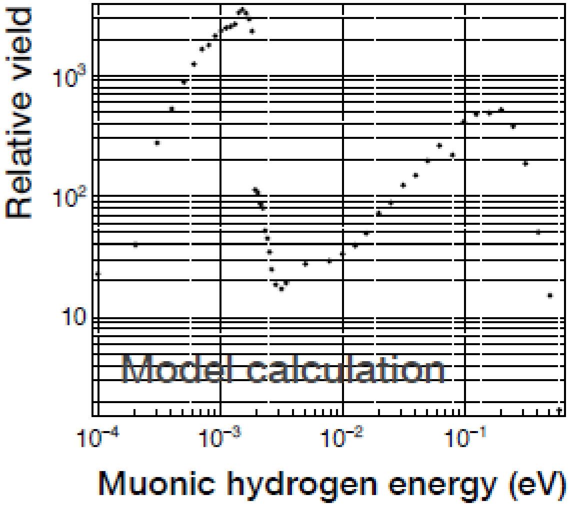
μp atomic beam from H2 film

No collisional quench! - much higher polarization

Emission efficiency ~0.5% at 0.2 eV (calc.)

Velocity ~6 mm/μs

Separation from decay in target by electron tracking



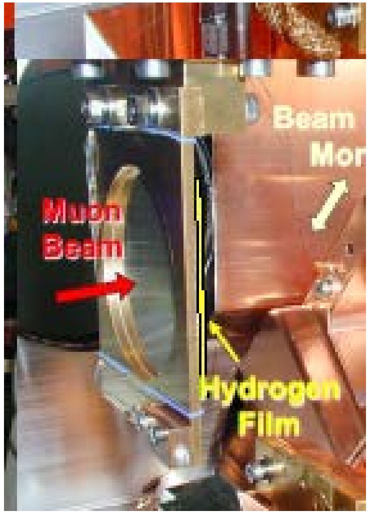
Using our expertise

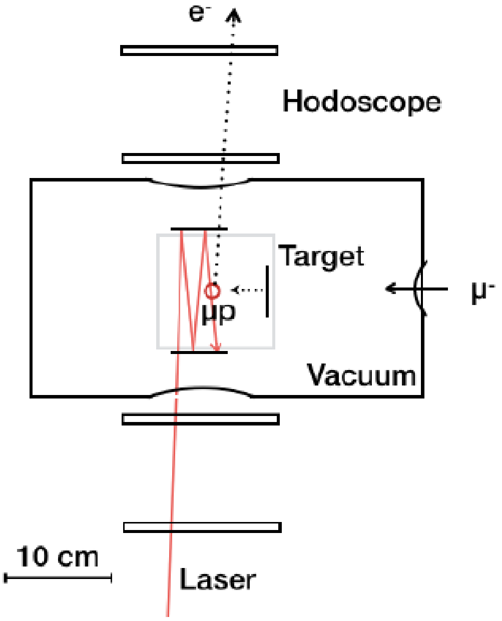
1) Solid hydrogen film target

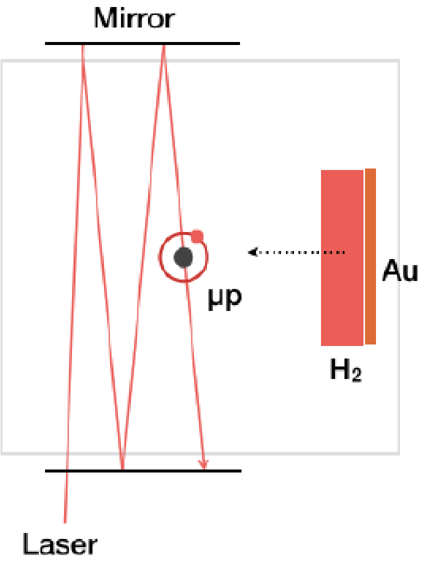
μA* by P. Strasser

2) Detection of muon decay in vacu

thermal Mu for g-2







Summary

Large discrepancy in proton radius values between measurements
"Proton radius puzzle"
New measurements and more data are arriving
but the puzzle has not been solved yet.

How about Zemach radius from μp HFS?
Preparing laser excitation and
detection with muon spin polarization

Status for the measurement
Instruments design, simulation for RIKEN-RAL/J-PARC
Test of mid-infrared laser components at RIKEN
Beam and μp polarization studies have started at RIKEN-RAL