The Proton Radius 2019 as XIX ESAC
Veli Losinj, 17 Sep 2019

Proton Radius Measurement with Muonic Atoms

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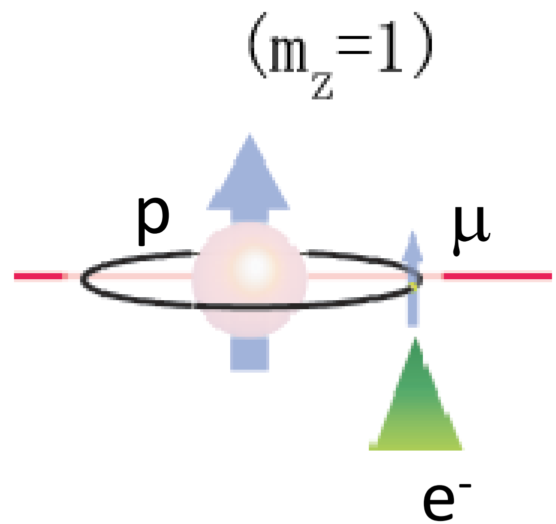
Proton Radius Puzzle
Muonic hydrogen atom (vs normal atom)
Zemach radius and hyperfine splitting
Plan of our measurement
Estimation

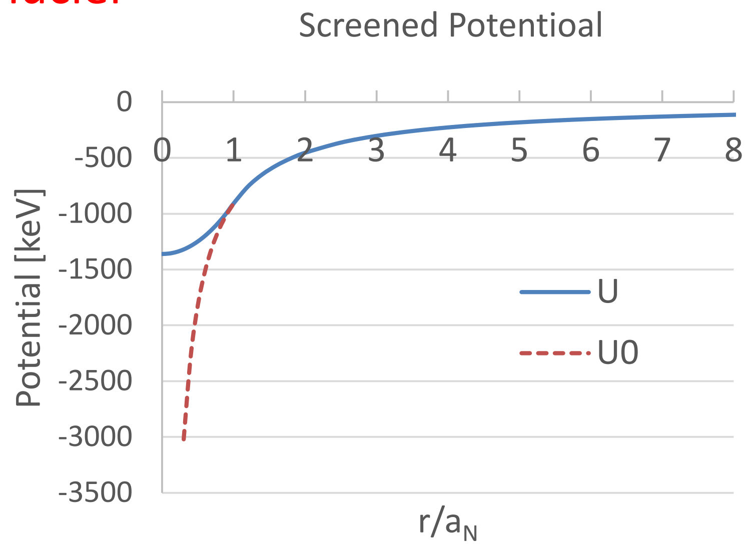
Progress and Status by S. Kanda



Proton size effect in atomic binding energy

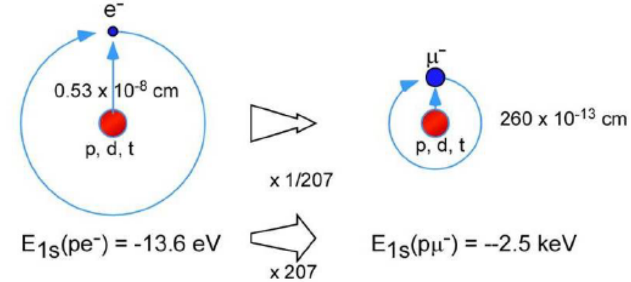
Principle of radius measurement from atomic spectroscopy :
Finite charge distribution affects binding energy due to reduced attraction while the electron/muon spends inside the nuclei

$\psi = 2\,(Z/a_B)^{3/2}\exp(-Zr/a_B)\,e^{i\phi}$
(Z: atomic number, a_B Bohr radius)
Energy shift by reduced charge inside nuclei
$\Delta E = \int_0^{a_N}[\psi H'\psi]d^3r$ (in 1st order)
$H' = 2Za_BR_y\,[(-1/a_N+1/r) + (r^2-a_N^2)/2a_N^3]$
(hard sphere model)
$\Delta E = 16\pi Z^4 R_y\,(a_N/a_B)^2$



R_E= 0.8768(69) fm CODATA

$$R_E = \int d^3r\, r^2 \rho_E(r)$$



While Bohr radius a_e = 53 pm => $R_E/a_e = 1.6 \times 10^{-5}$
200^2 times energy shift for muonic atom, while x200 in total energy scale
relatively 200 times more sensitivity for proton radius

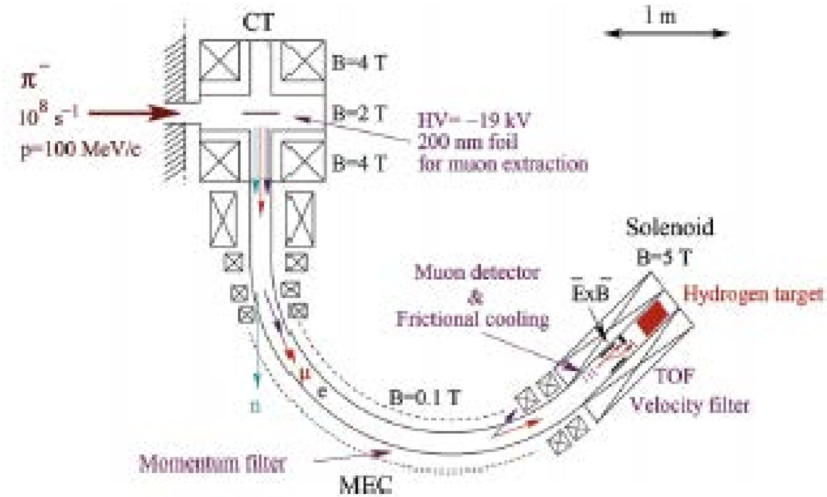
Proton Charge Radius Puzzle
PSI Measurement (μp 2s-2p by CREMA collaboration)

R. Pohl et al.,
Can. J. Nucl. Phys. 89 , 37 (2011)

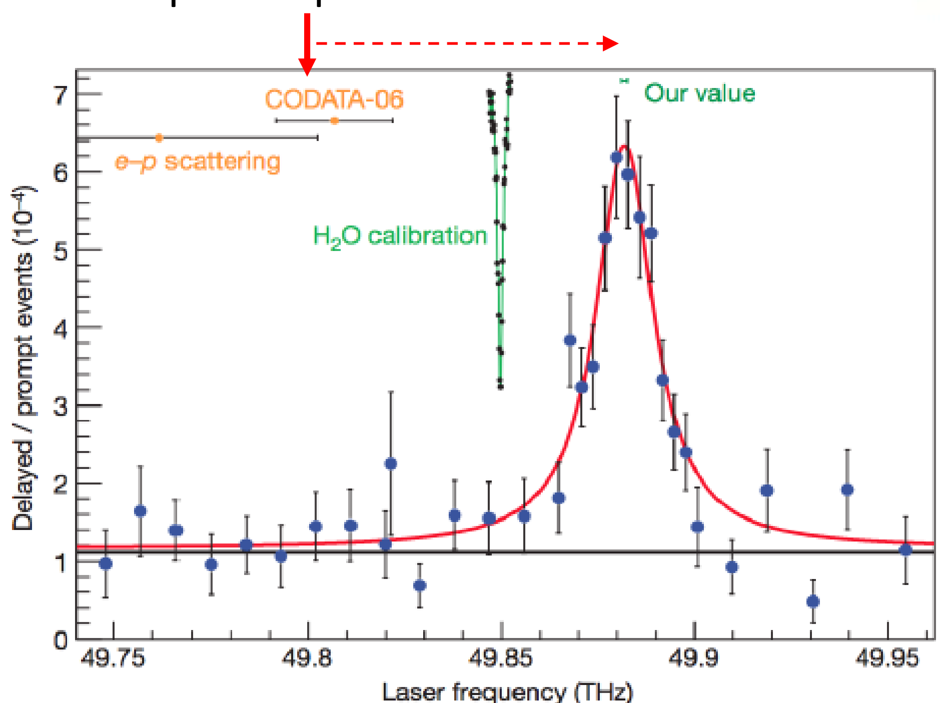
Measurement of 2s-2p energy difference

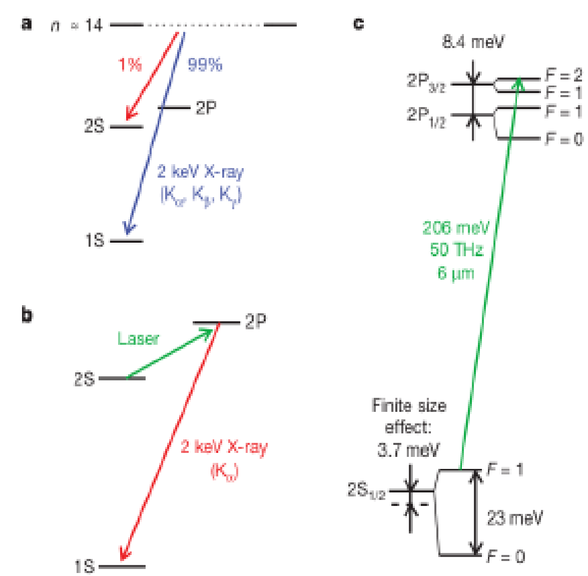
Formation of μp (1% feeds 2s)

- Laser resonant excitation of 2s-2p（Lamb Shift）
- Observation： 2s metastable state -> 2p->1s
- Frequency calibration relative H_2O absorption line



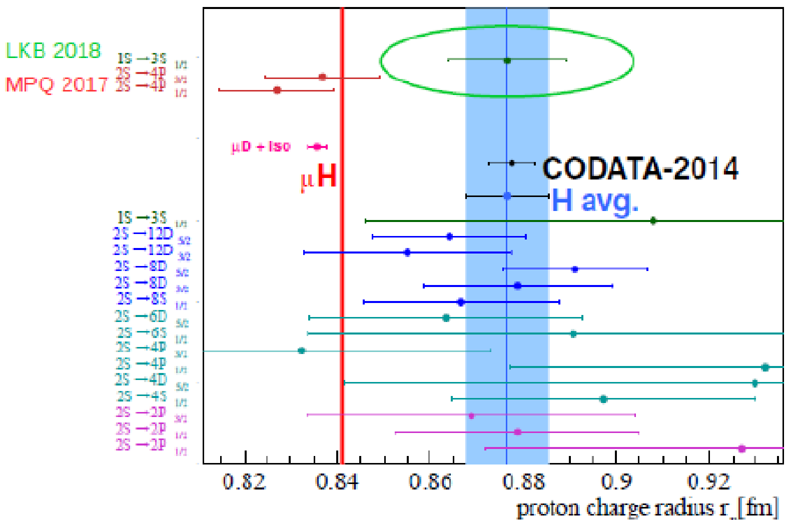
expected position





Where will we go?

Rp from H spectroscopy



Beyer, Maisenbacher, RP et al, Science 358, 79 (2017)
Fleurbaey , PhD thesis (2017)

(by R. Pohl)

1. Need to be checked/confirmed
   more evidences, theories, ...

2. Other r_E measurements with muons
   Muonic deuterium (done)
   Muonic He3, He4 (nearly done)
   μp and ep scattering (MUSE) in progress

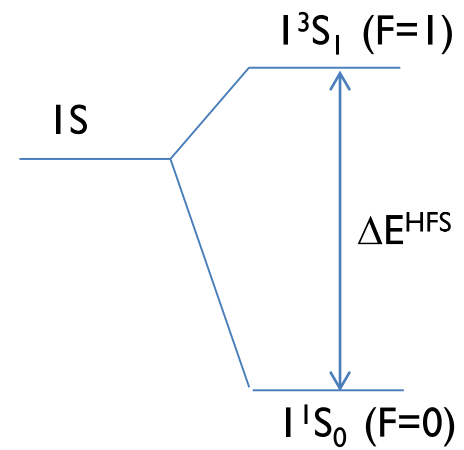
3. Zemach radius r_Z
   another proton radius accessible by spectroscopy
   includes magnetic structure

Zemach radius

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

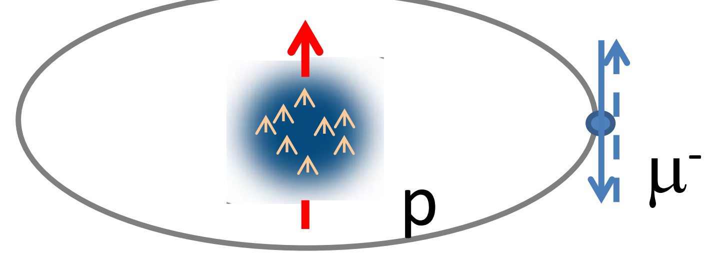
$$R_Z = \int d^3r\, r \int d^3r' \rho_E(r')\rho_M(r-r')$$

convolution of charge and magnetic moment distribution



F : total angular momentum

Why not only magnetic distribution?
In point charge limit
=> Hyperfine coupling with distributed magnetic moment
Coupling largest for moments at center, becomes weaker outside.
In point magnetic moment limit.
=> Charge distribution reduces muon attraction,
lower muon overlap with nuclear charge
In both cases, lead to smaller HFS energy



Zemach radius

Zemach radius A.C. Zemach, Phs.Rev.C 104, 1771(1956).

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

If the muon and electron determination of Zemach radius 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

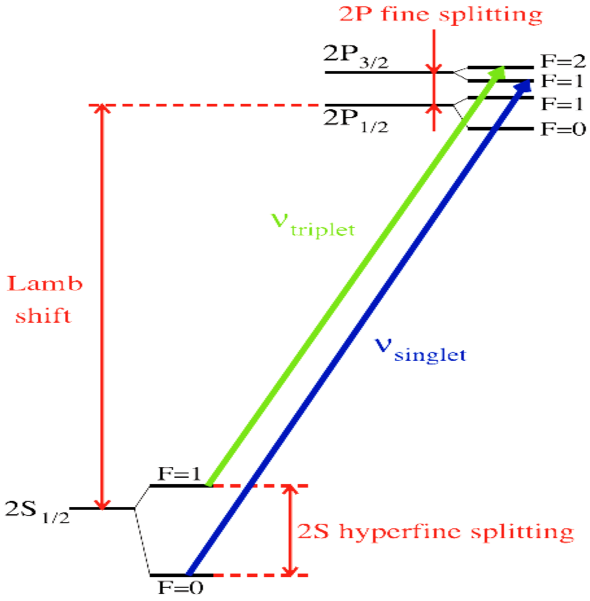
2s HFS was indirectly determined in the same CREMA experiment at PSI (from two lines)

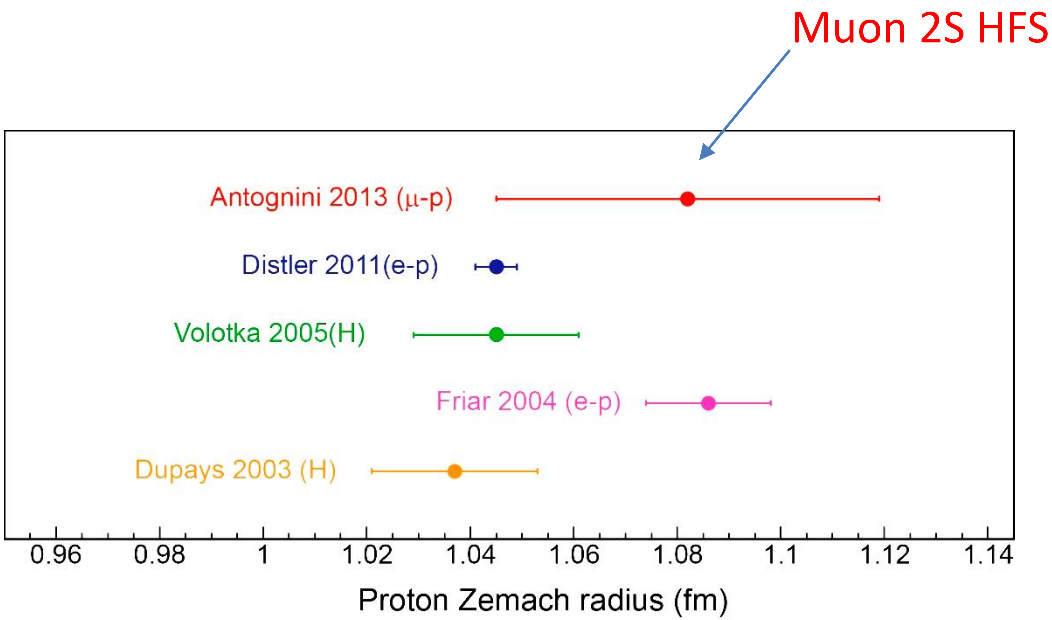
R_Z = 1.082(37) fm   [A. Antognini, et al., Science 339 (2013) 417]

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





Need high precision values

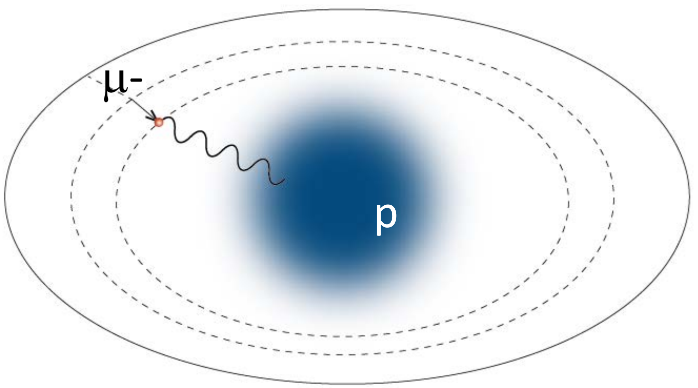
Direct measurement of 1s HFS has chance to determine Rz to better than 1%

Formation of Muonic Hydrogen atom ($\mu^- p$)

Muon stops in hydrogen

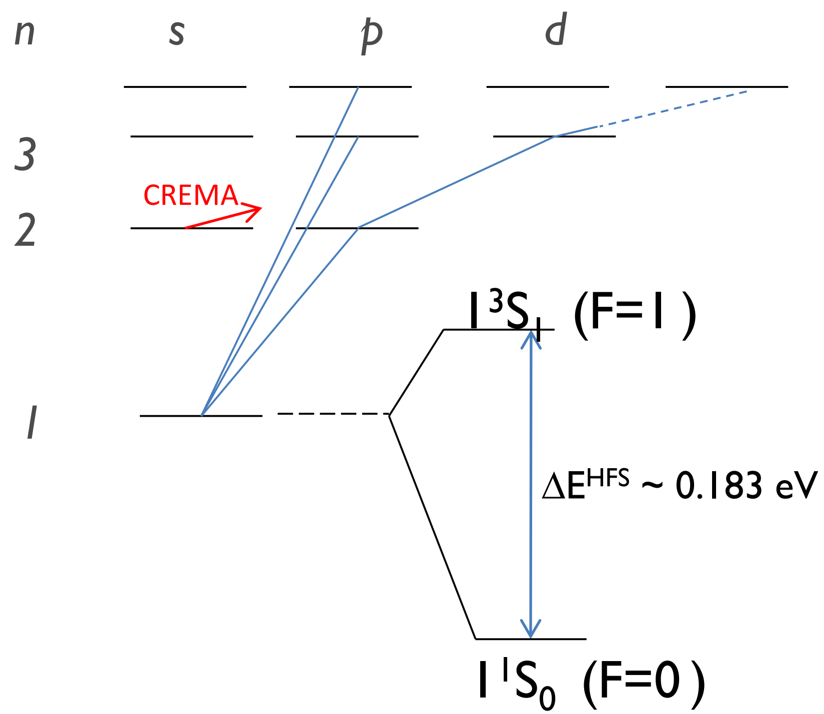
Muon capture at high orbit and cascade to ground state

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?

It is, in 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)

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

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

460(80) ppm   (2) ppm

proton polarizability

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

We request improvement of δ_{pol} (by QCD?).

Expected precision of Zemach radius

$$R_Z = \{(E_F\,(1 + \delta_{QED} + \delta_{recoil} + \delta_{pol} + \delta_{hvp}) - \Delta E^{exp}_{HFS}\}/1.281$$

δ_{QED}: 1130(1) ppm; δ_{recoil}: 1700(1) ppm; δ_{pol}: 460(80) ppm; δ_{hvp}: 20(2) ppm; ΔE^{exp}_{HFS}: (2) ppm

Dupays et al., PRA 2003

	Hydrogen		Muonic hydrogen	
	Magnitude	Uncertainty	Magnitude	Uncertainty
E^F	1418.84 MHz	0.01 ppm	182.443 meV	0.1 ppm
δ^{QED}	1.13×10^{-3}	$<0.001\times10^{-6}$	1.13×10^{-3}	10^{-6}
δ^{rigid}	39×10^{-6}	2×10^{-6}	7.5×10^{-3}	0.1×10^{-3}
δ^{recoil}	6×10^{-6}	10^{-8}	$1,7\times10^{-3}$	10^{-6}
δ^{pol}	1.4×10^{-6}	0.6×10^{-6}	0.46×10^{-3}	0.08×10^{-3}
δ^{hvp}	10^{-8}	10^{-9}	0.02×10^{-3}	0.002×10^{-3}

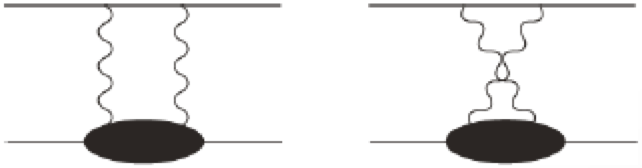
R_Z = 1.0XX(13) fm

is dominated in precisiton, but

oved factor ~3 from PSI results,

e need help of theorists to improve
ecision.

mprovement of proton polarizability correction (δ_{pol}) drastically reduces
uncertainty of Rz

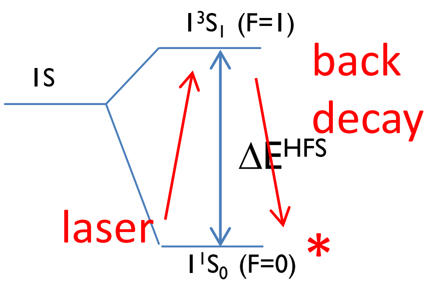


e-p	*1.4(6) ppm*
μ-p	*460(80) ppm*

check with R_Z determined by "electronic" and "muonic" measurement

Zemach radius measurement with muons

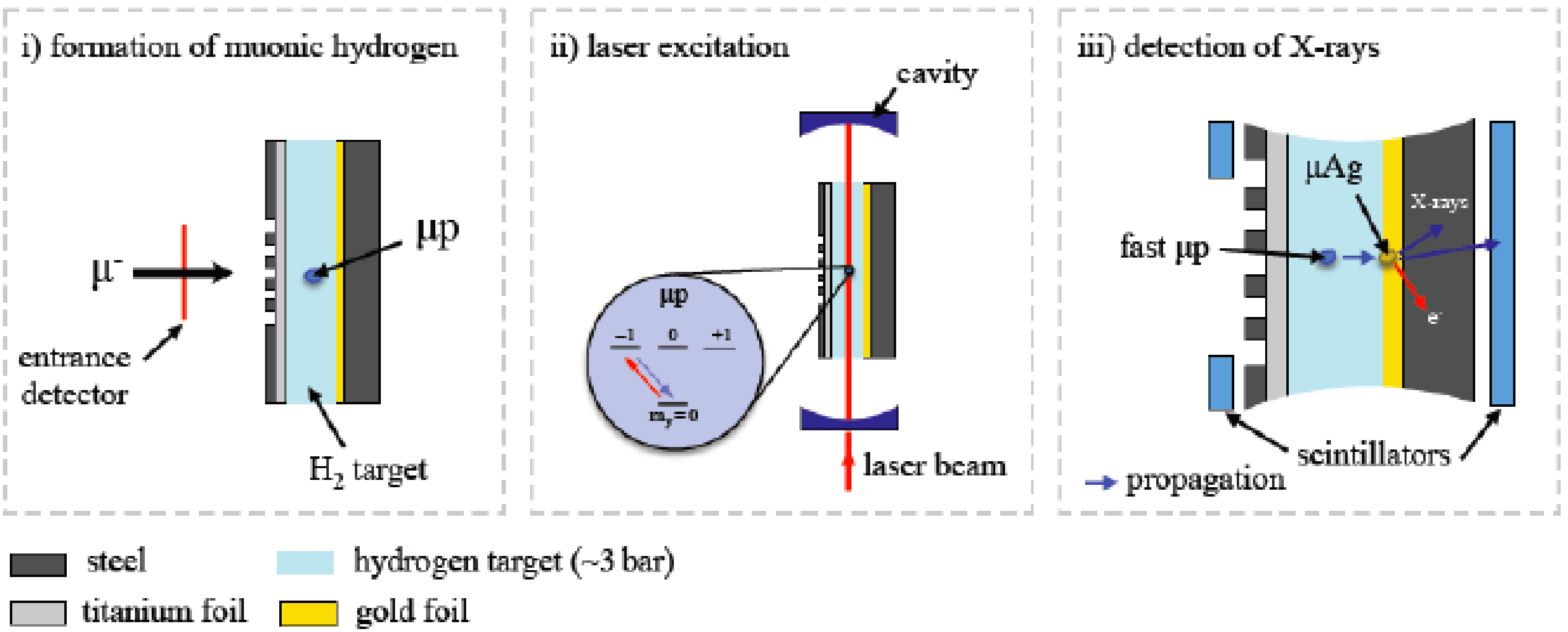
There are three proposals



Two groups use increased μp kinetic energy after back decay from laser excited states

1) CREMA-3 at PSI

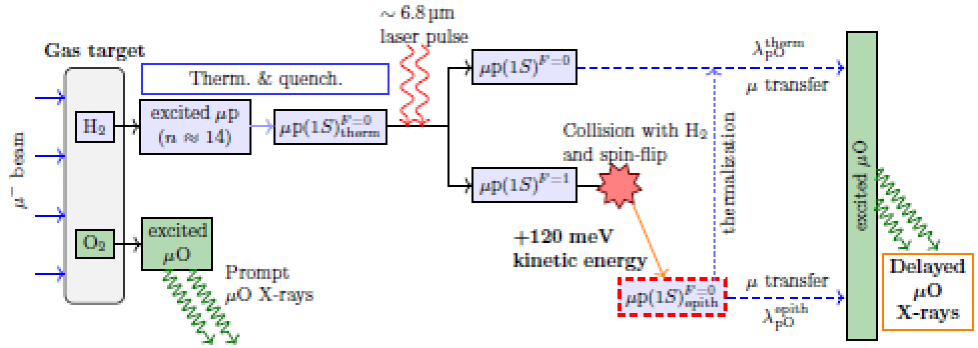
Faster μp diffusion to wall



Zemach radius measurement with muons

2) FAMU at RIKEN-RAL (Vachi's talk and others)
energy dependent muon transfer rate to admixture oxygen
Bakalov et al., Phys. Lett. A 172 (1993) 277

μp + O -> μO + p
x-rays



Several papers on kinetic energy depend transfer measurement published

Adamczak et al, JINST 11, 05007 (2016)
Mocchuuttiet al, JINST 13,12033 (2018)
Adamczak et al, JINST 13, 02019 (2018)

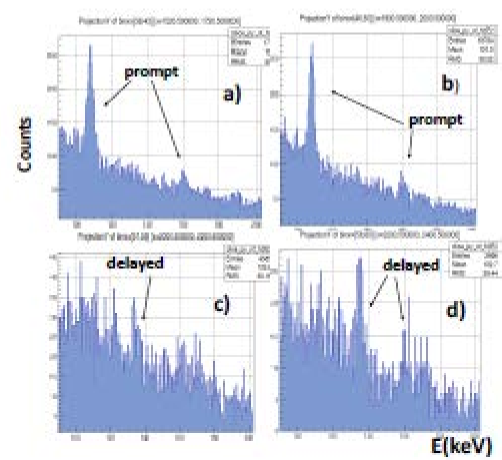
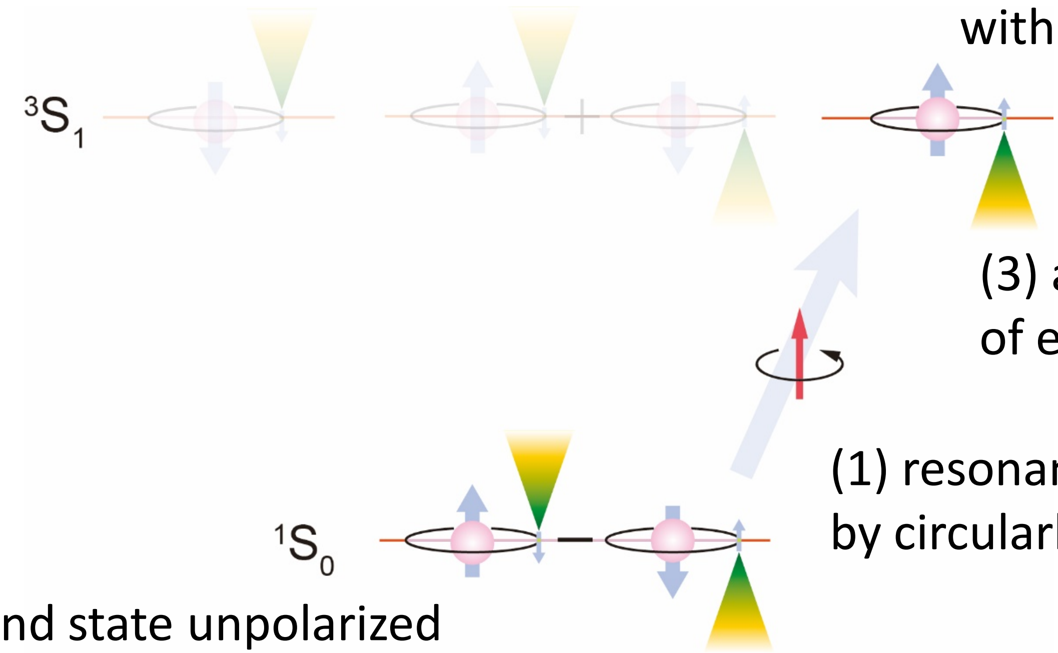


Figure 23. Time evolution of the $K_\alpha(2p \to 1s)$ line energy distribution, as reconstructed from the GEM-S HPGe detector, in four time slices. (a) 1520–1720 ns, (b) 1800–2000 ns, (c) 2000–2200 ns and (d) 2200–2400 ns.

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)

(2) formation of triplet state
with muon spin polarized



(3) asymmetric emission
of electron from muon decay

(1) resonant excitation
by circularly polarized laser

(0) ground state unpolarized

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,
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KEK
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** *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

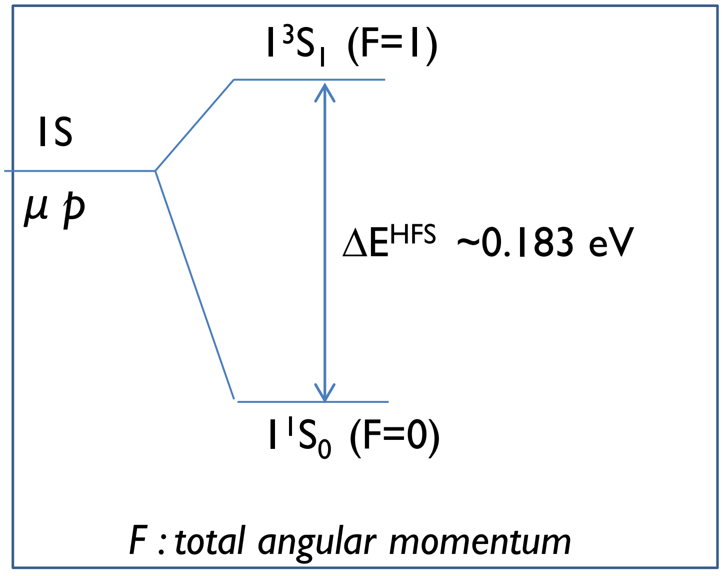
2. Many muonic hydrogen atoms

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

Laser excitation



Laser requirement for μp 1S HFS
 0.183 eV = 6.8 μm = 44 THz
 tunable by ~10^{-3} (40 GHz) - to cover uncertainty
 narrow band width 50 MHz (1 ppm)

Magnetic transition
 $\mathbf{B_+(t)}$ = (1/√2 B_0 cosωt, 1/√2 B_0 sinωt, 0)
 $dP/dt = 2\pi/\hbar |(\mu_\mu+\mu_p)B_0|^2 /4 \ \delta(\nu-\nu_0)$

with convolution of Doppler broadening by μp velocity distribution (~√T)
(A. Adamczak et al., NIM B 281 (2012) 72, with correction by 1/4 , private communication)

Single shot transition probability

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

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

Doppler broadening (cooling to ~20 K helps => 63 MHz)

Laser excitation

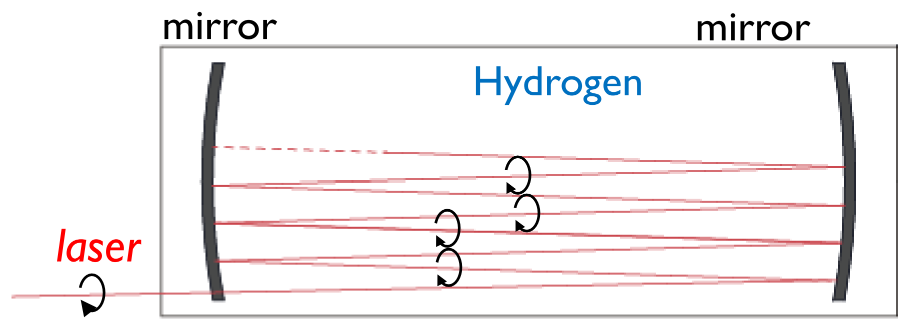
Small excitation rate because of M1 transition

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

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

ex. *E* = 40 mJ, *S*= 4 cm², T= 20 K, then *P* = 4.5 x 10⁻⁴

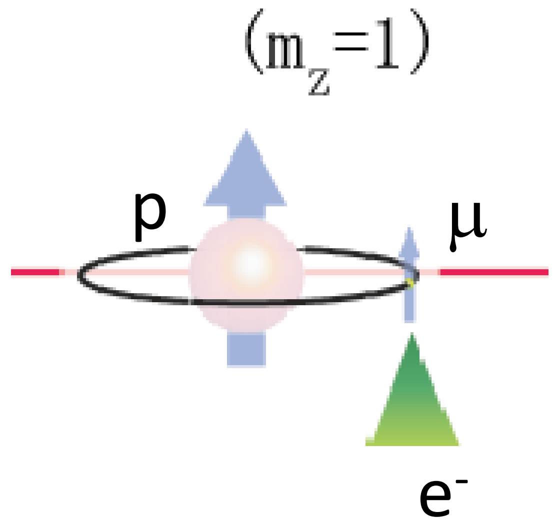
too low efficiency with one pass

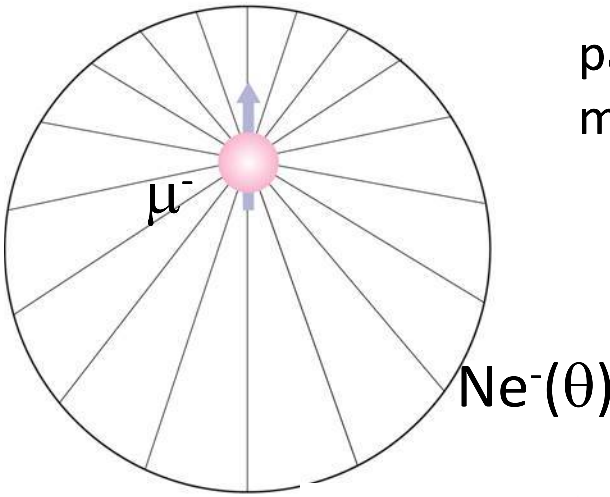


use of multi-pass cavity (like PSI)
 high reflective mirror 99.95%
 Cavity ray tracking calculation
P=45% with 1000 pass
(P reduced to ~7% expected if quench is included : see below)
40mJ per pulse and 50Hz laser is required

Detection of Polarization

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





parity-violating muon decay!

$$d\sigma_{e^-}(\theta)d\Omega \propto \left(1 - \frac{1}{3}P\cos\theta\right)d\Omega$$

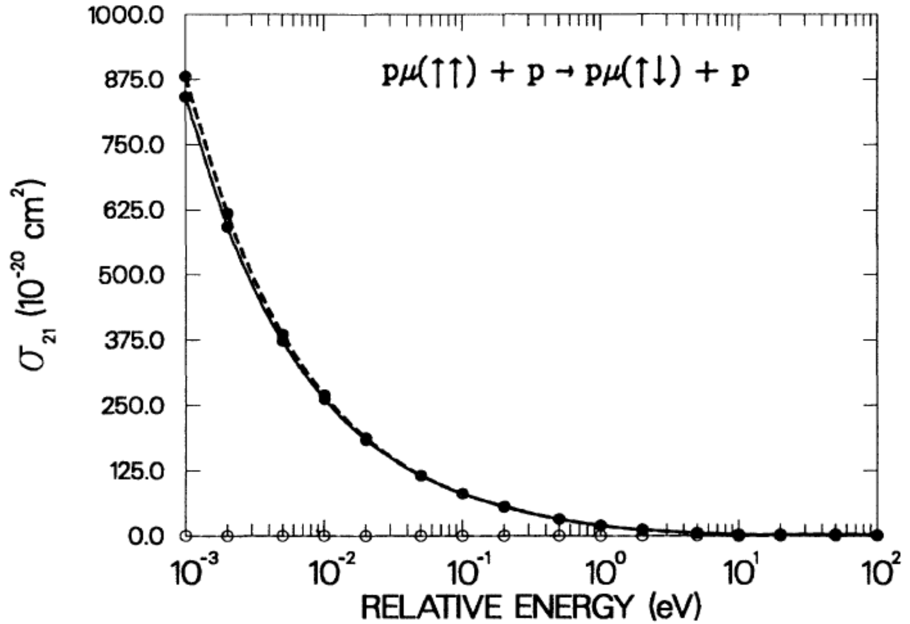
M. Sato, et al. "Laser Spectroscopy of Ground State Hyperfine Splitting Energy of Muonic Hydrogen"
JPS Conf. Proc. 8 , 025005 (2015)

Obstacle to the experiment - quench rate

Triplet to singlet quenching before muon decay by external collision

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

will lose muon polarization.
Theoretical calculations
J. Cohen, Phys. Rev. A 43 (1991) 466
No experimental data on μp yet
(rate for μd is slower and
well know by μCF)



Cross section proportional to 1/v
So, quench rate is almost energy (or temperature) independent.
Triplet state lifetime ~50 ps at liquid hydrogen density (LHD)

How we manage the difficulty - quench rate

Triplet state lifetime 50 ps at liquid hydrogen density (LHD)

For polarization measurement by muon decay (2.2 μs),
we need longer keeping time.
Will use low density hydrogen
  50 ns at 0.001 LHD,
  500 ns at 0.0001 LHD

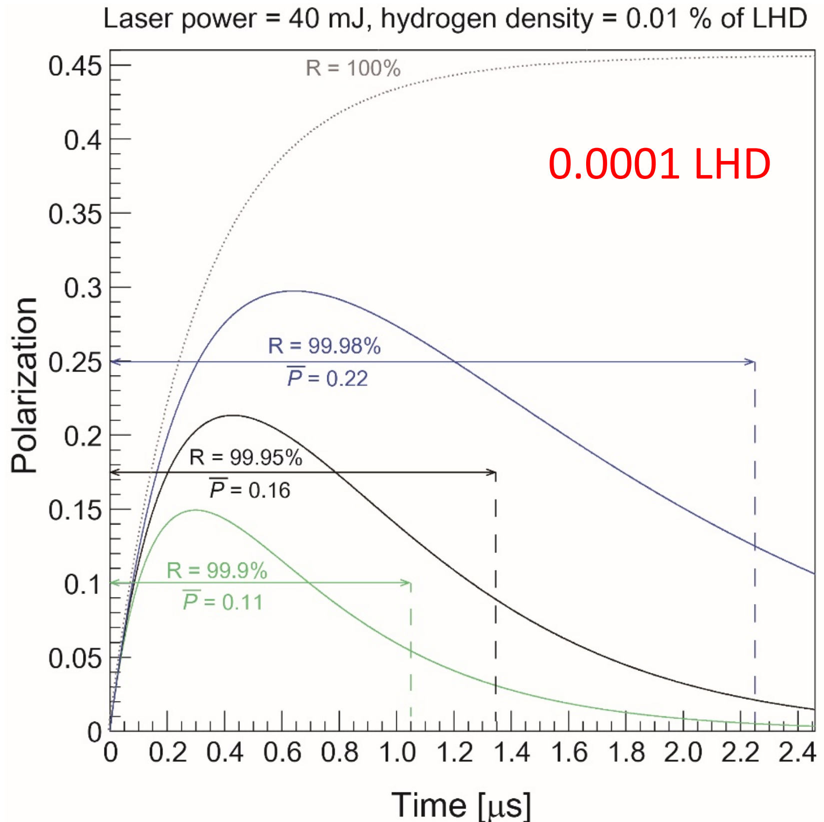
⇒ Target Requirement
  Large muon stopping -> high density, large volume
  Small μp quenching -> low density
  High laser density -> small volume
We need to optimize the target volume and the gas density

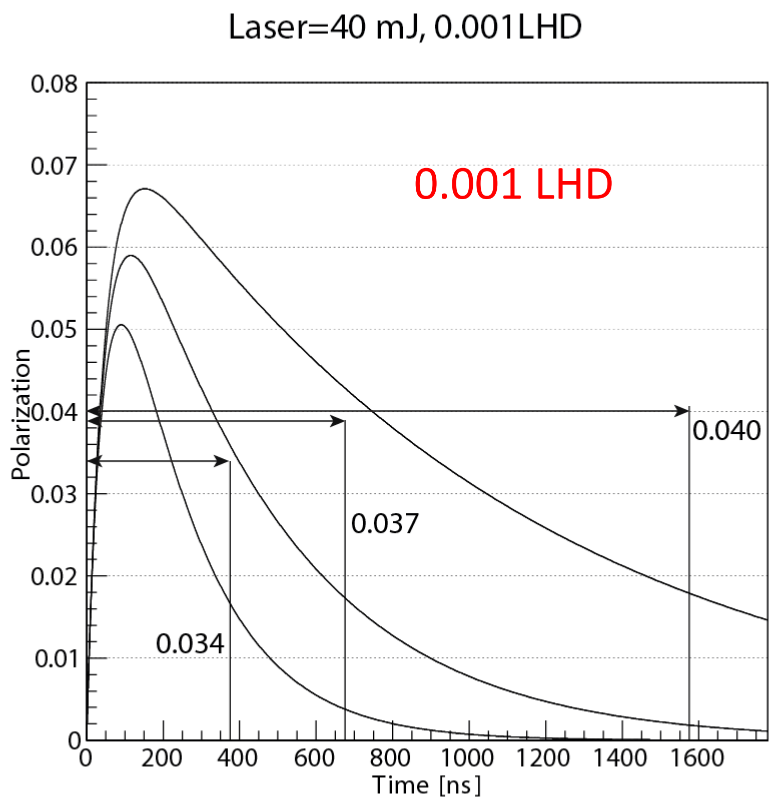
We have other option to avoid this quench
with novel target => Kanda's talk

Polarization vs time

Calculation of muon polarization build up with
- Excitation per single pass (4.5×10^{-4})
- Multi-pass laser cavity with loss by reflectivity
- and μp HFS quenching (500 ns for 0.0001 LHD, 50 ns for 0.001 LHD)

Average polarization
- 0.16 in a time gate 1.33 μs (0.0001 LHD)
- 0.037 in 0.67 μs for 0.001 LHD)





Target & Detector

Target Requirement

Optimization of gas density

Number of stop muons or polarization

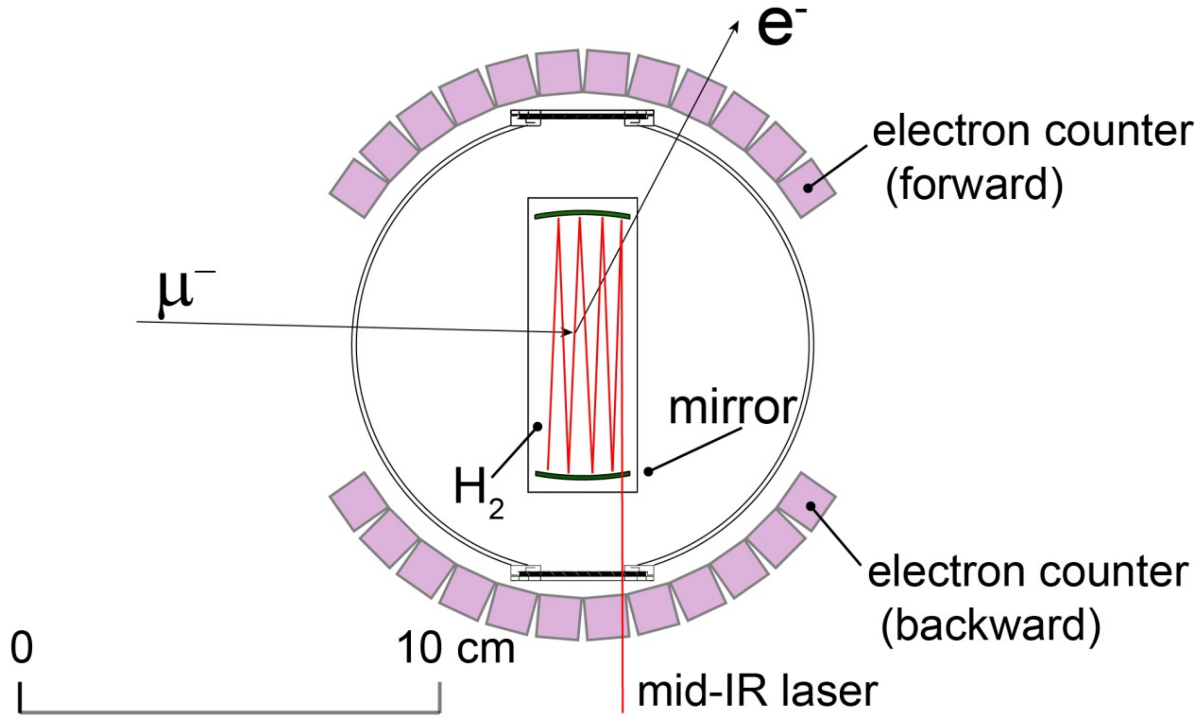
=> Let's take 0.0001 LHD and 4 cm^2 x 6 cm

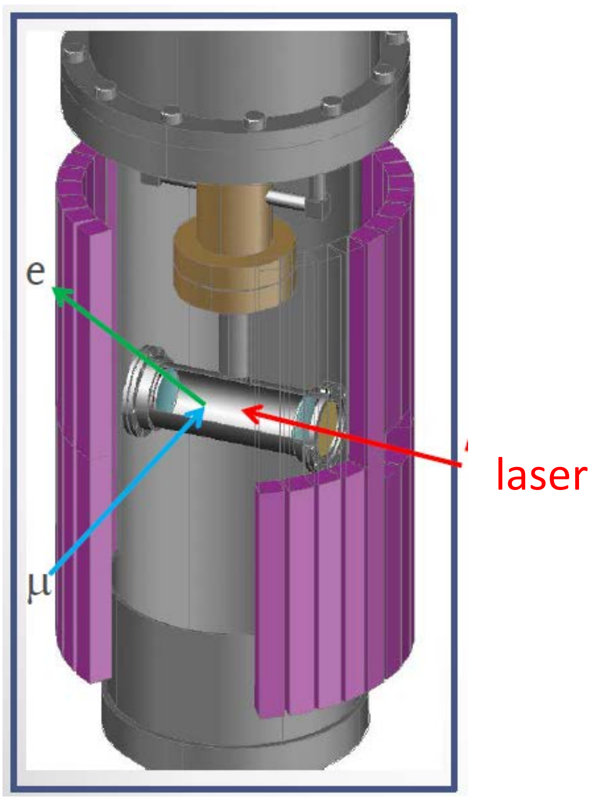
Detector

Solid angle ~28% each

Asymmetry factor

(polarization sensitivity)~0.23





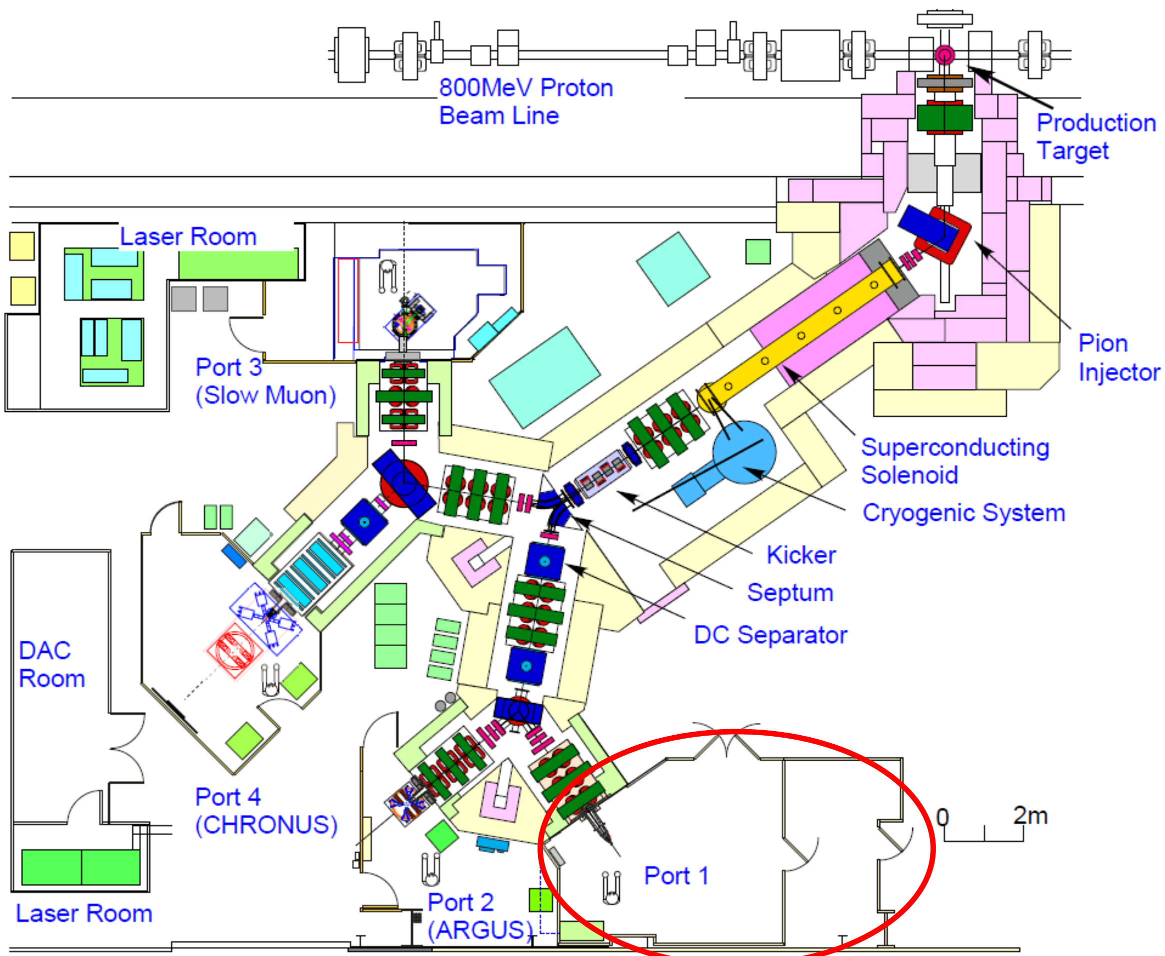
Muon beam at RIKEN-RAL Muon Facility

RIKEN-RAL Muon Facility in ISIS, UK

Pulsed muon is a good match to high intensity laser

Port 4 has been used for test measurements.

Port 1 is being converted to laser compatible room (Vachi's talk).



Typical muon intensity

2.2×10^4 [s^{-1}]

at p = 40 MeV/c

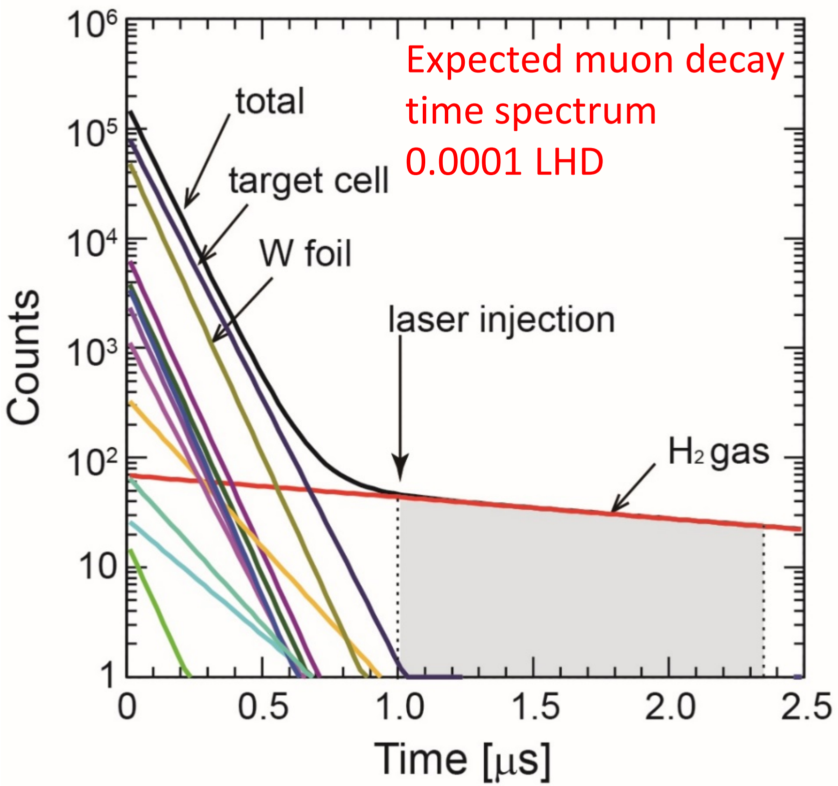
Muon stopping simulation and background

Condition:
Hydrogen target cell cooled to 20 K by GM-type refrigerator
40 MeV/c pulsed muon beam at RIKEN-RAL Muon Facility

Geant 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



Beam test of background level

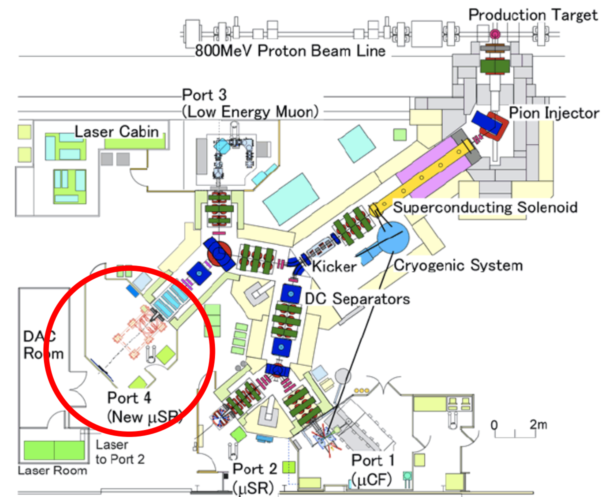
Beam test at RIKEN-RAL

Muons stopped in Cu target

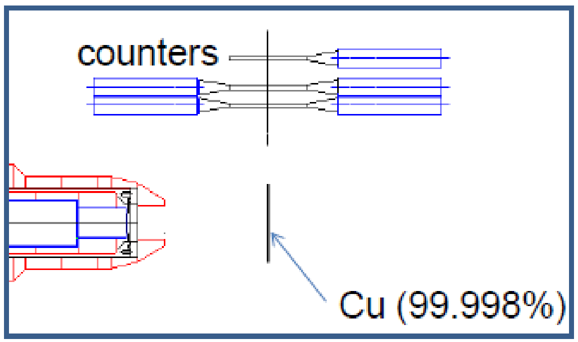
We confirmed

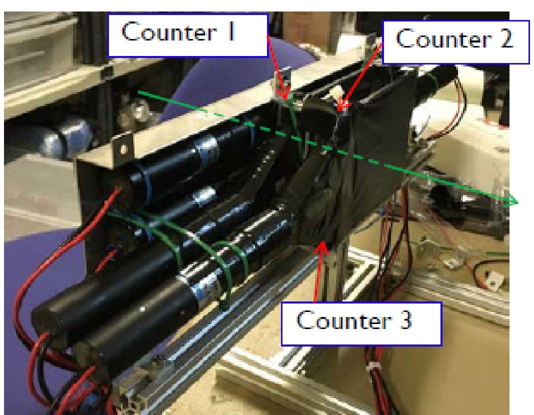
Fast decay out of muons in high-Z materials like Cu

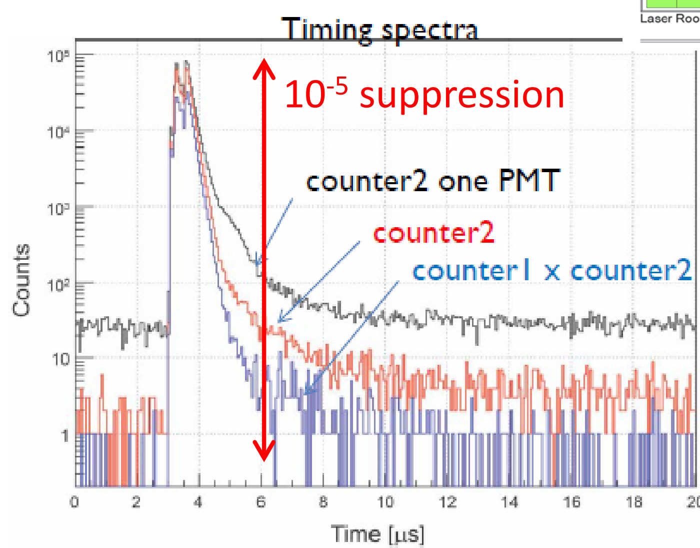
Low background level (< 10^{-4}) at ~1 μs



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







background can be suppressed with hit-timing coincidence

➡ design the prototype of electron counters

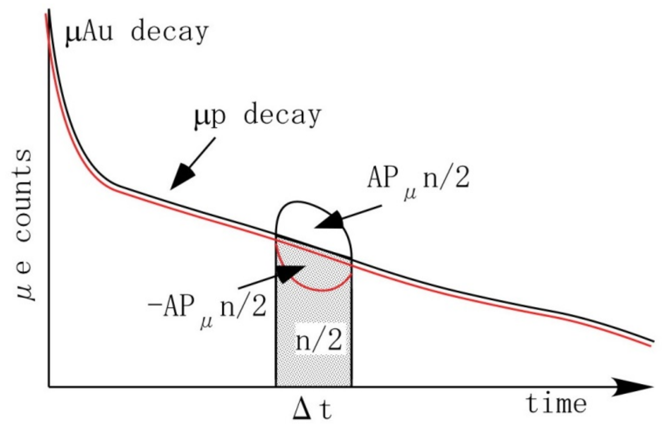
beam test with dilute gas

Further studies with H2 target

=> Kanda's talk

Yield estimation (statistics)

Take the 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 x 10^4 /s @40 MeV/c (J-PARC)
Momentum width $\sigma_p/p_0 = 2\%$
Target condition
H2 gas 0.001 LHD, Volume 4cm^2 x 6 cm

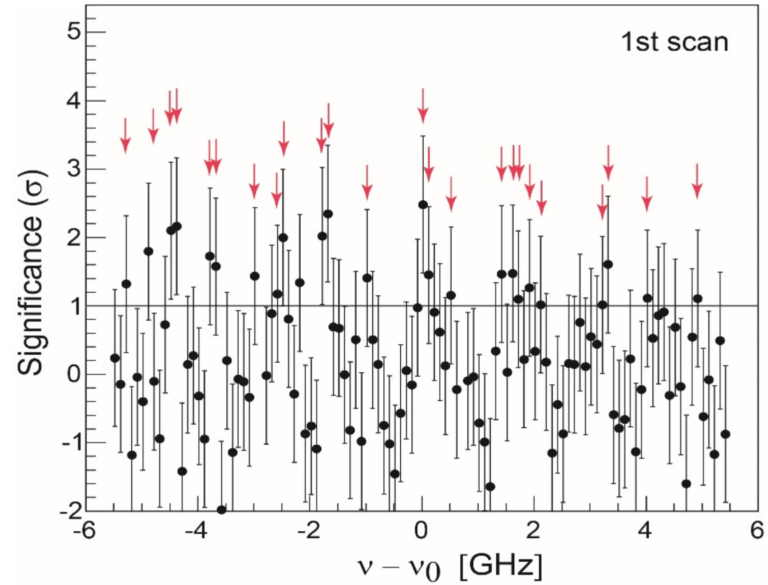
Laser
40 mJ, 99.95% reflectivity, cavity length

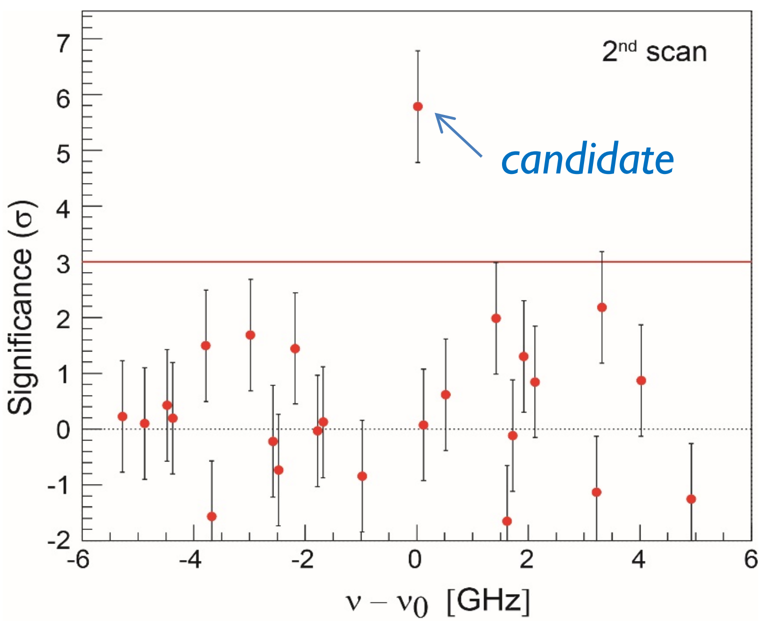
Detector (solid angle 28% each, polarization sensitivity factor 0.23)

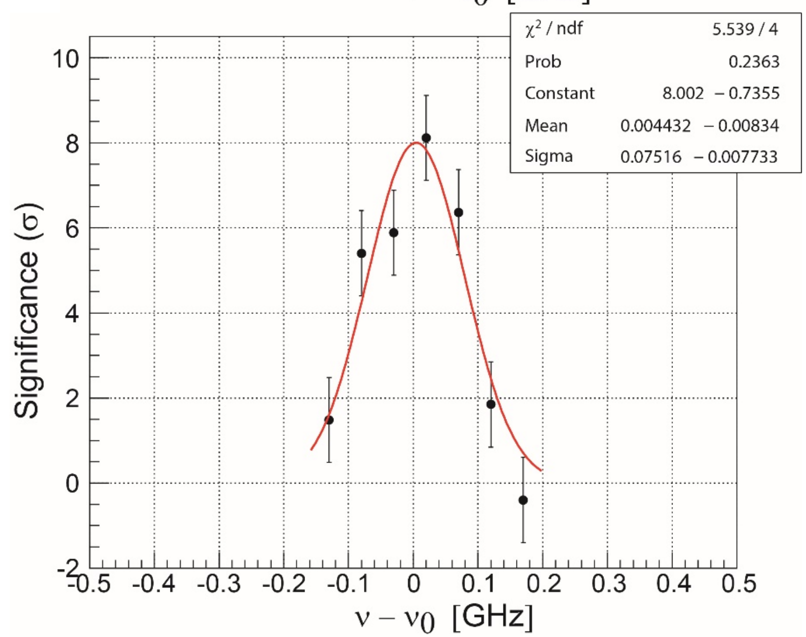
Time gate : laser at 1.0 μs after muon + 1.33 μs detection gate
statistics in 5 hours
=> signal N_F-N_B, ~240
fluctuation $\Delta N_F+\Delta N_B \sim \surd(N_F+N_B)$ ~80
significance = $(N_F-N_B)/ \surd(N_F+N_B) \sim 3\sigma$
Time is doubled (~10 hour) for accumulating laser on and off
Scan of 100 laser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

Resonance hunting & beam time estimate

We plan three steps hunting of resonance
over region +-5.7 GHz (theoretical ambiguityx3)
100MHz step (matching the resonance width)
1) 3σ scan ~50 days (100 points)
2) 5σ scan ~24 days
3) resonance curve ~16 days
=> 3 months beam time



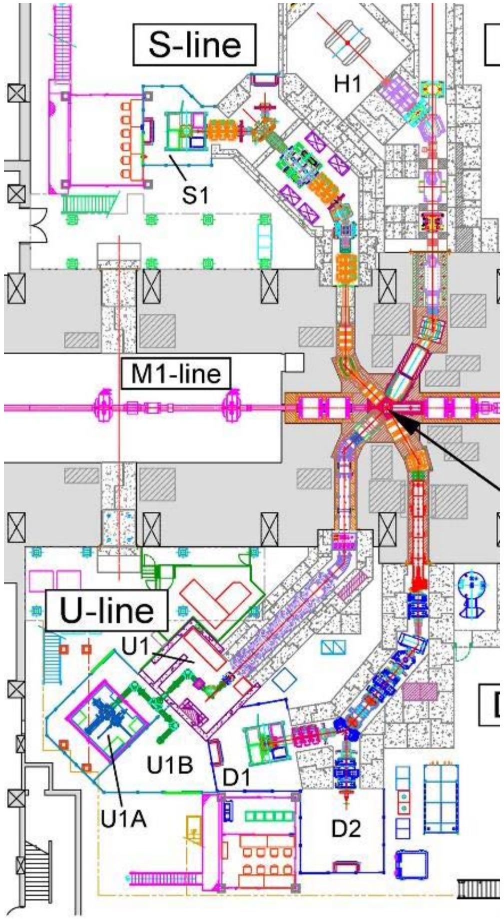




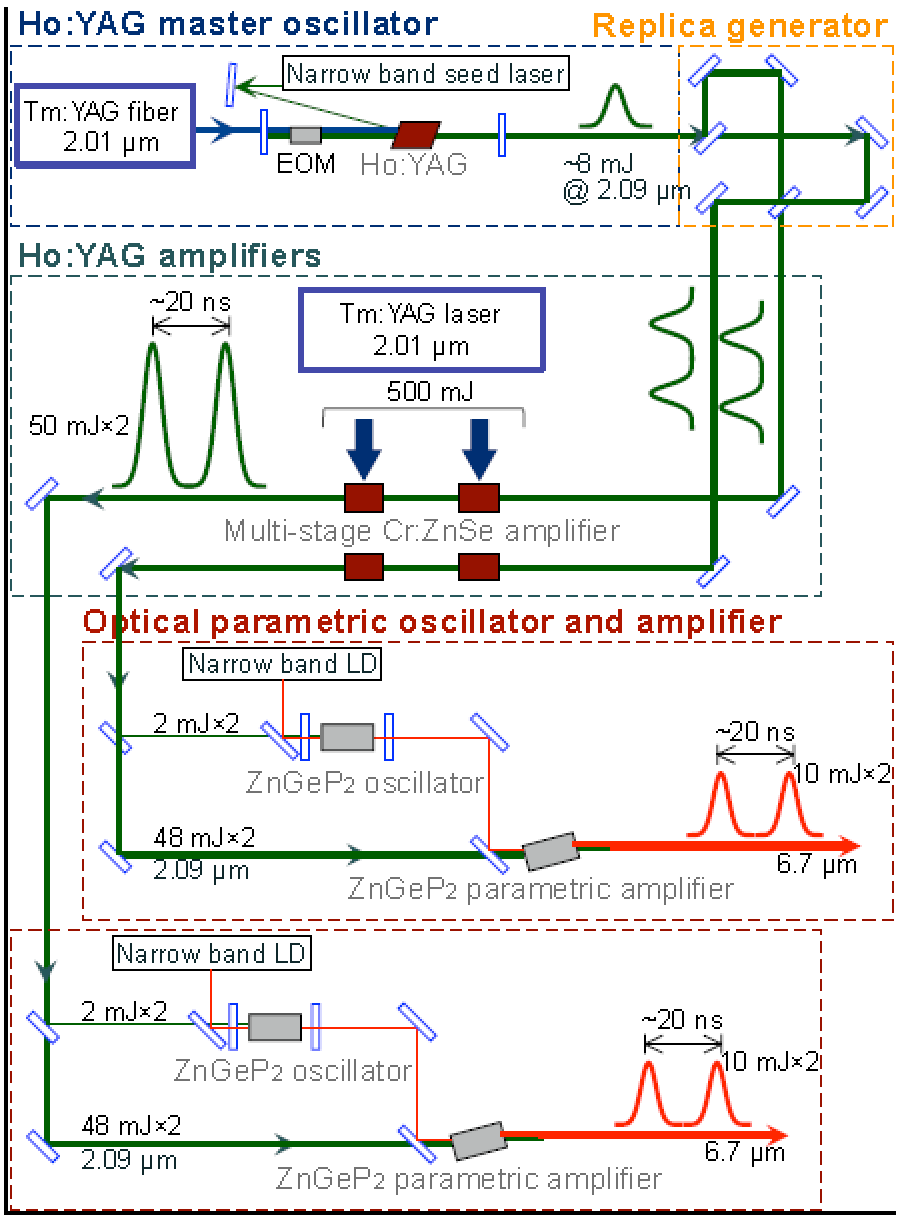
Beam time estimate: at J-PARC

At J-PARC MUSE D-line, we can earn statistics quicker (x8?)
based on 40 MeV/c μ^- intensity and beam characteristics scaling.
Same statistics could be obtained in ~12 days.

Laser installation & long term occupation
of the area for preparation
are issues to be discussed



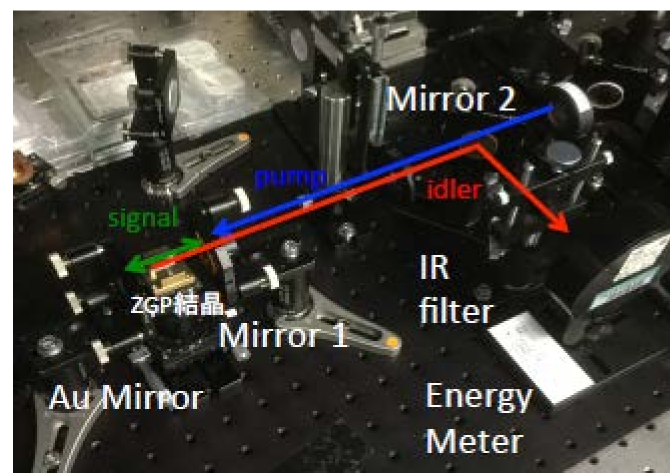
Keys: Laser



RIKEN laser group had experience of developing intense 6 μm laser（5mJ）
We apply frequency stabilization and increasing intensity based on this

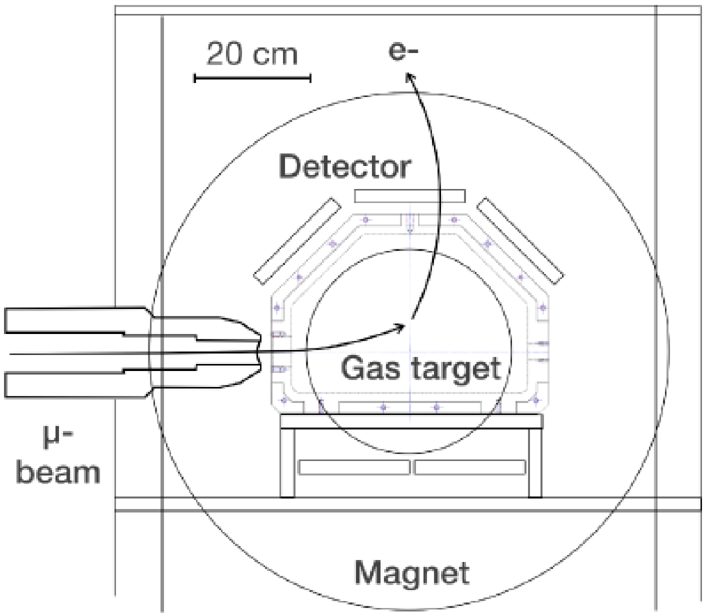
Achieve 40 mJ with best matching component and multi-source injection

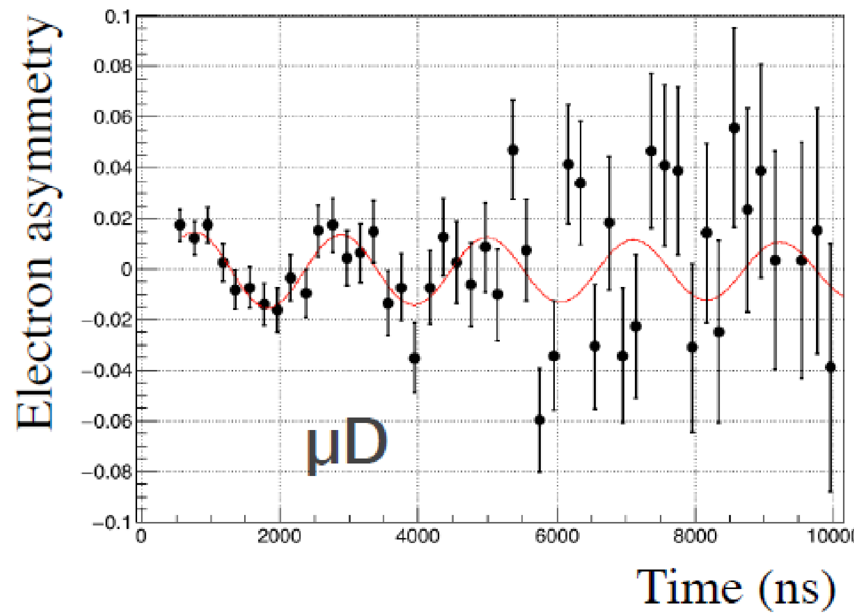
Components studies are in progress
Cr:ZnSe oscillation, Cr:ZnSe amplification.
ZGP OPO (=> more in Kanda's talk)



Keys: triplet-single quench rate

HF quench rate is the key factor
will be measured and compared with theoretical estimates
quartet μd spin precession(~10μs lifetime in gas) done Sep 2018





triplet μp quench rate (<1μs lifetime) planned in 2019
more challenging because of predicted short decay time
need of low density gas (~0. 1 bar)
=> more detail in Kanda's talk

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?
We propose measurement of HFS energy
by laser excitation and detection with muon spin polarization

Preparation status to be presented by Sohtaro Kanda