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Measurement of the hyperfine splitting energy of the ground-state muonic hydrogen

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Outline

Proton Radius Puzzle

What is μp hyperfine state?
Sensitivity to Proton Zemach Radius

Proposed method
- Laser excitation
- Laser
- Target
- Estimation

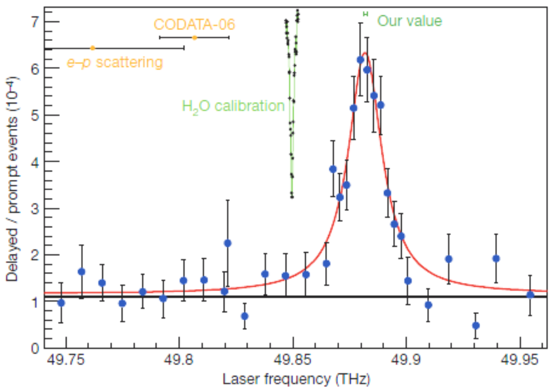
Summary

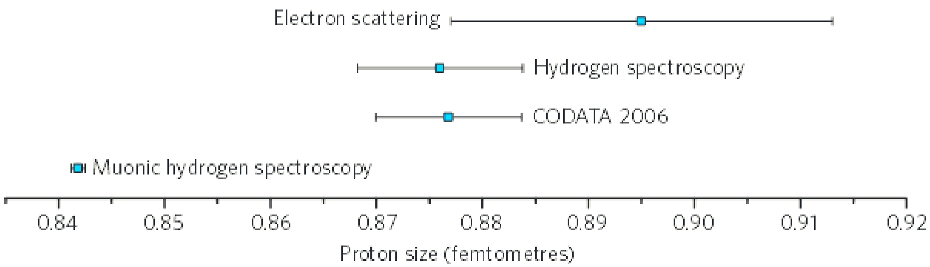
Proton Radius Puzzle

Muonic atom is a good probe of proton structure
because muon is 200 times closer to the nuclei than electron .

Precise measurement of Lamb shift lead to an unexpected "proton radius puzzle".

CODATA 0.8768(69)
PSI: 0.84184(67) *R. Pahl et al., Nature 466 (2010)*)



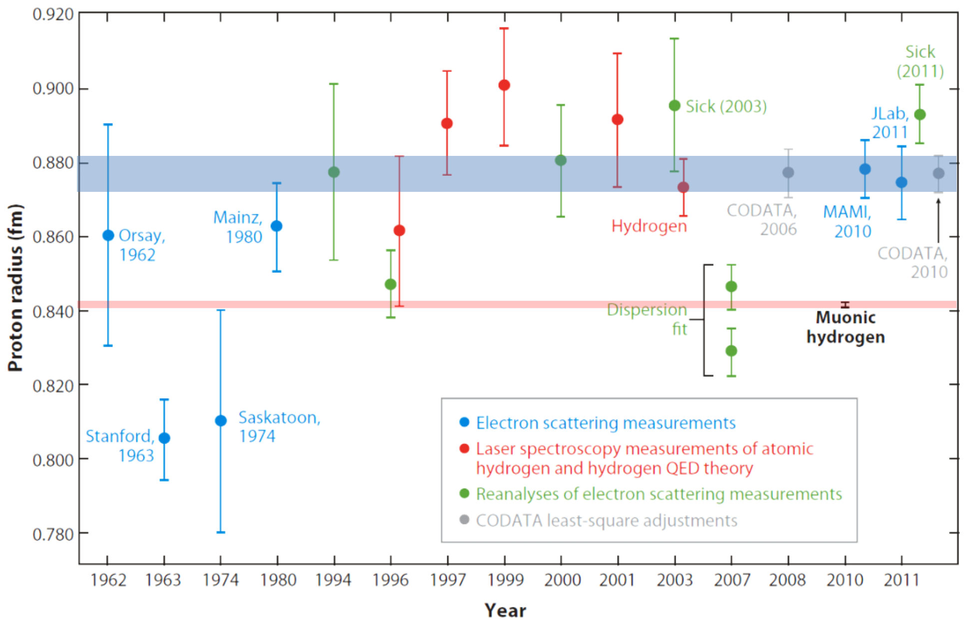


Proton radius from μp Lamb shift was 10 times more precise
and 5 times off from other measurements
(hydrogen atom and e-p scattering) allows.

Proton Radius Puzzle

Further measurement and analysis did not ease the discrepancy.

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



Errors in measurement?
Theoretical corrections wrong?
Broke lepton universality? new physics?

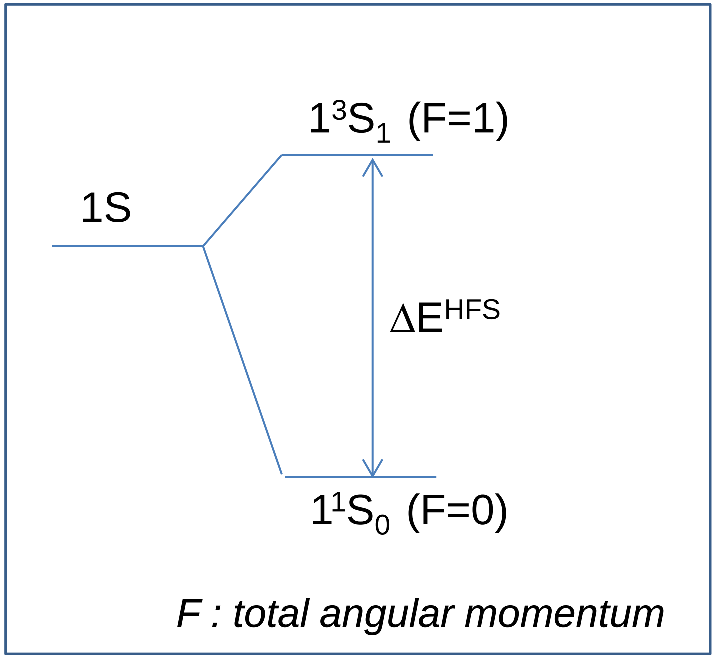
=> So far, no satisfactory explanation is given.

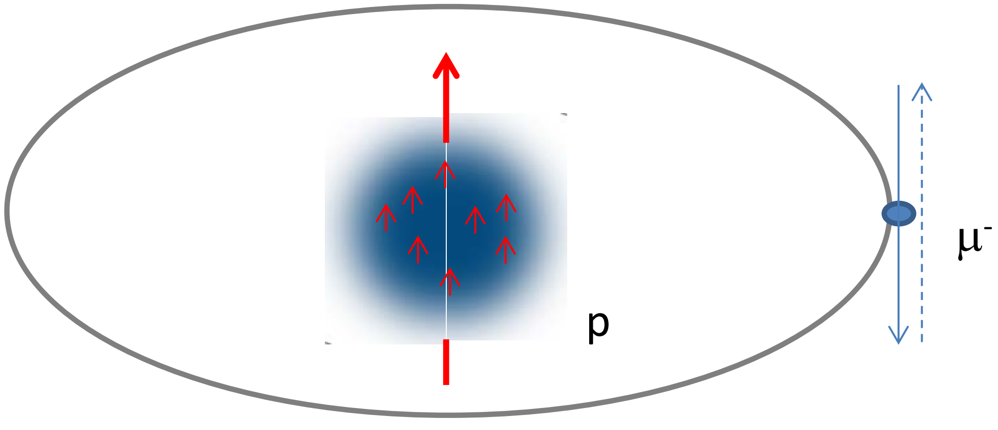
Zemach radius

What about other radius (magnetic)?
Zemach radius

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

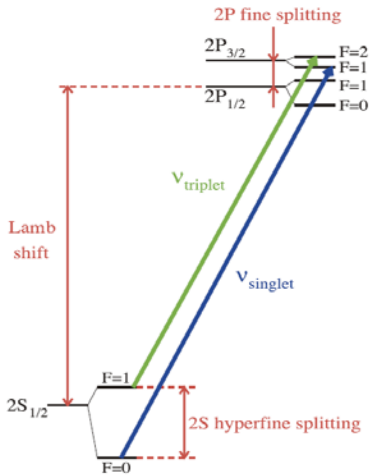
Another good quantity determined
from atomic hyper fine structure (HFS)
and e-p scattering
(spatial distribution of magnetic moment
smeared out by charge distribution
$\int d^3r \rho_M(r) |\varphi(r)|^2$)

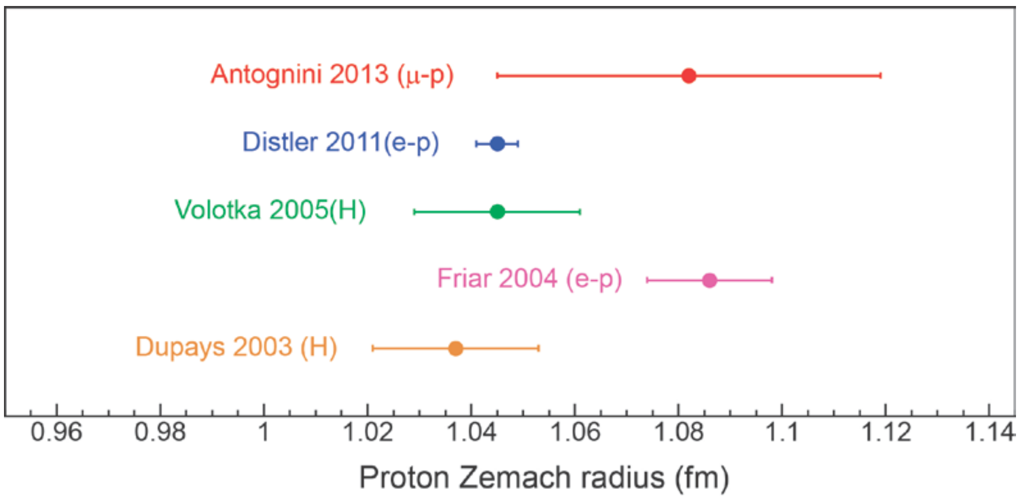




Zemach radius

μp result from 2s state HFS at PSI (from two lines).
was not contradictory, but the error was large.
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





Independent measurement is highly desirable.
We plan a direct measurement of 1s HFS energy.

HFS splitting energy
How a proton 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)

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

Expected Precision of Zemach Radius

$$R_Z = \{(E_F\ (1 + \delta_{QED} + \delta_{recoil}\ + \delta_{pol} + \delta_{hvp}) - \Delta E_{HFS}^{exp}\}/1.281(10?)$$

Dupays et al., Phys. Rev. A 68, 052503 2003

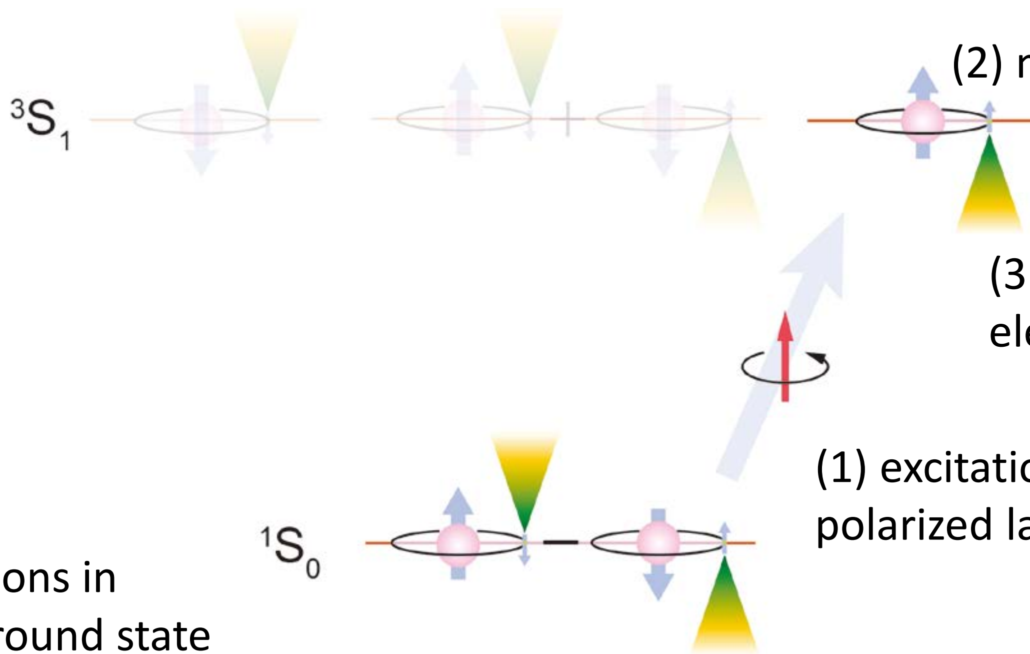
	Hydrogen		Muonic hydrogen	
	Magnitude	Uncertainty	Magnitude	Uncertainty
E^{F}	1418.84 MHz	0.01 ppm	182.443 meV	0.1 ppm
δ^{QED}	1.13×10^{-3}	$<0.001\times10^{-6}$	1.13×10^{-3}	10^{-6}
δ^{rigid}	39×10^{-6}	2×10^{-6}	7.5×10^{-3}	0.1×10^{-3}
δ^{recoil}	6×10^{-6}	10^{-8}	1.7×10^{-3}	10^{-6}
δ^{pol}	1.4×10^{-6}	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}

Zemach

Uncertainty of the polarizability is dominant (~1 % of the Zemach term).
R_Z = 1.0??(xx) fm (xx <14)
Improvement by factor3 expected.

How can we measure it?

Muonic proton ground state HFS energy has never been measured before
(In contrast to precise muonium HFS - see Patrick's talk.)
Proposed method



(2) muon spin is polarized

(3) detect by muon decay electron emission direction

(1) excitation by circularly-polarized laser

(0) all muons in μp HFS ground state

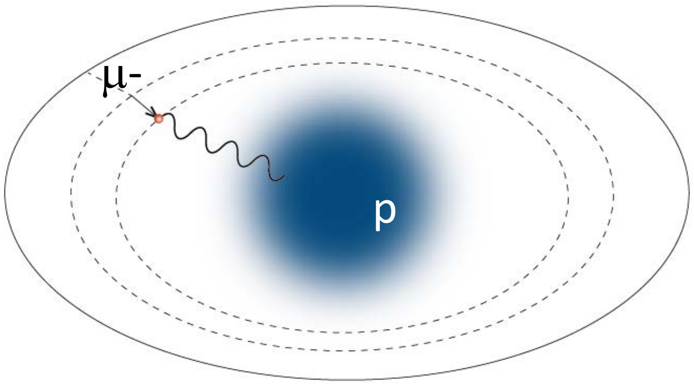
also,
Another approach using detection of epithermal muon transfer effect by INFN group
Bakalov et al., Phys. Lett. A 172 (1993) 277

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

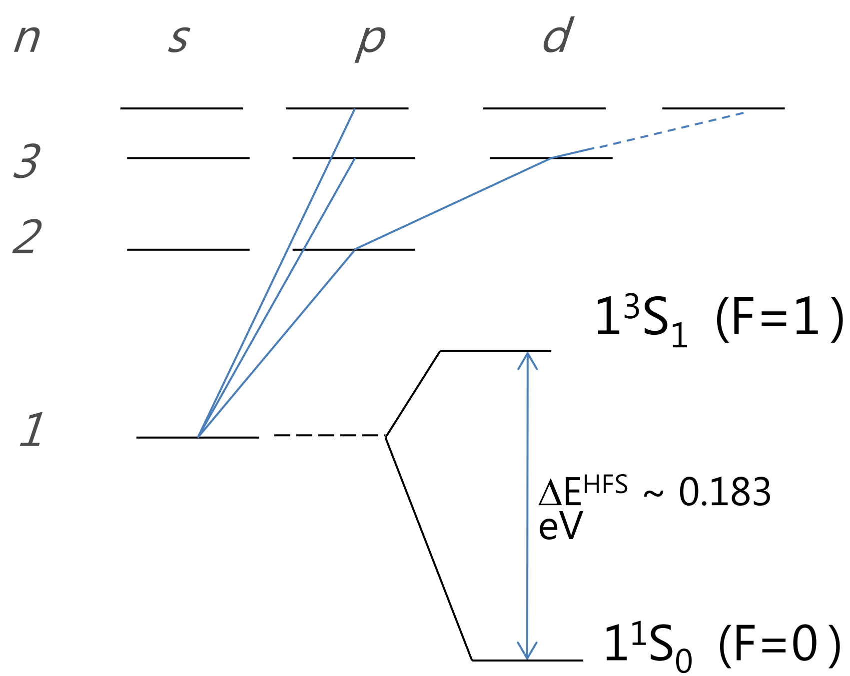
Muon stops in hydrogen

Muon capture at high orbit and cascade to ground state

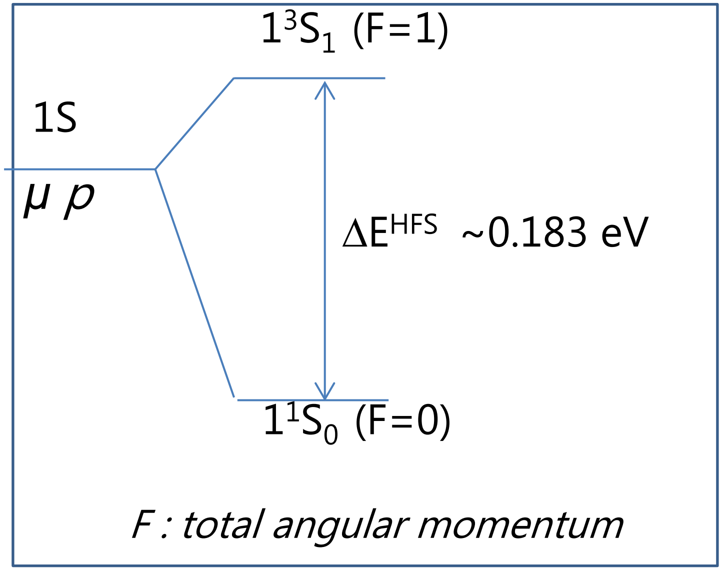
Rapid conversion to lower hyperfine state
=> no muon polarization left



→ g.s. μ^--*p* atom



Excitation by laser



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
- $\mathbf{B_+(t)} = (1/\sqrt{2}\, B_0 \cos\omega t,\ 1/\sqrt{2}\, B_0 \sin\omega t,\ 0)$
- $dP/dt = 2\pi/\hbar\,|(\mu_\mu+\mu_p)B_0|^2/4\ \ \delta(\nu-\nu_0)$

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)

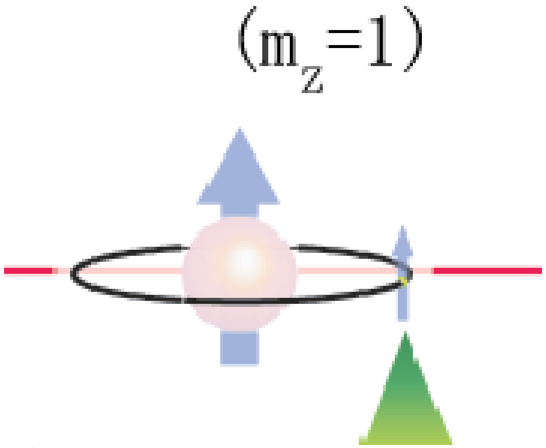
$$P = 2 \times 10^{-5} \frac{E}{S\sqrt{T}}$$

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

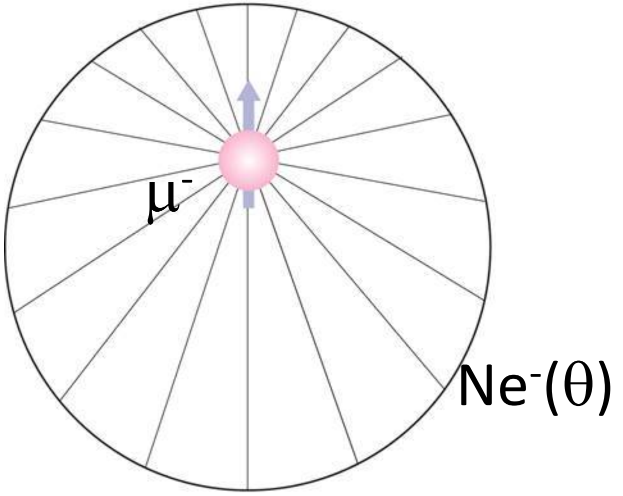
High intensity laser is required => pulsed laser and pulsed muon
Doppler broadening (cooling to ~20 K helps => 63 MHz)

Detection of Polarization

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



However, ...

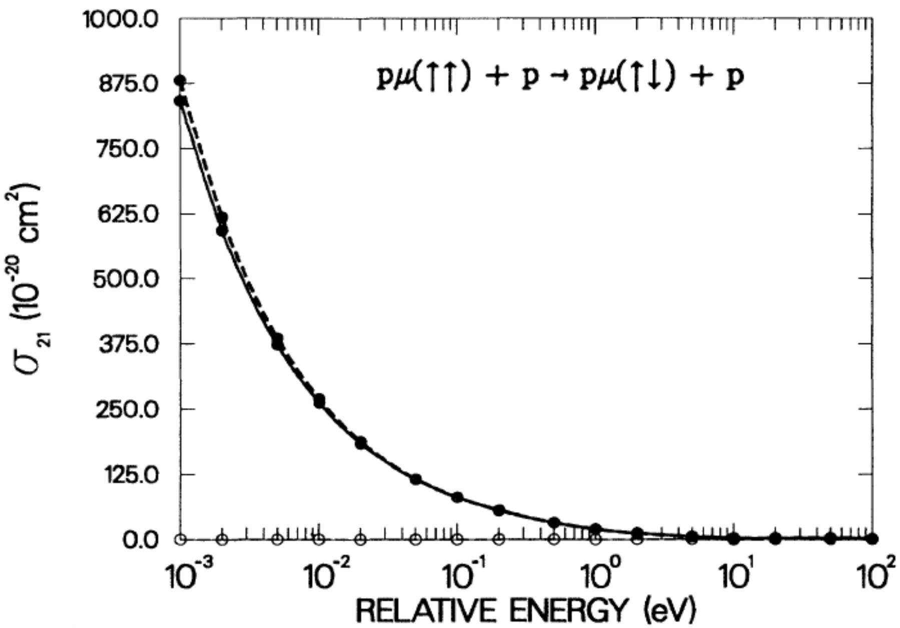


Quench of triplet state

Triplet state may convert back to singlet state before muon decay by external collision (no directly measured rate)

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

J. Cohen, Phys. Rev. A 43 (1991) 466



50 ps at liquid hydrogen density (LHD)
50 ns at 0.001 LHD,
500 ns at 0.0001 LHD
The hydrogen density has to be small.

Experimental feasibility

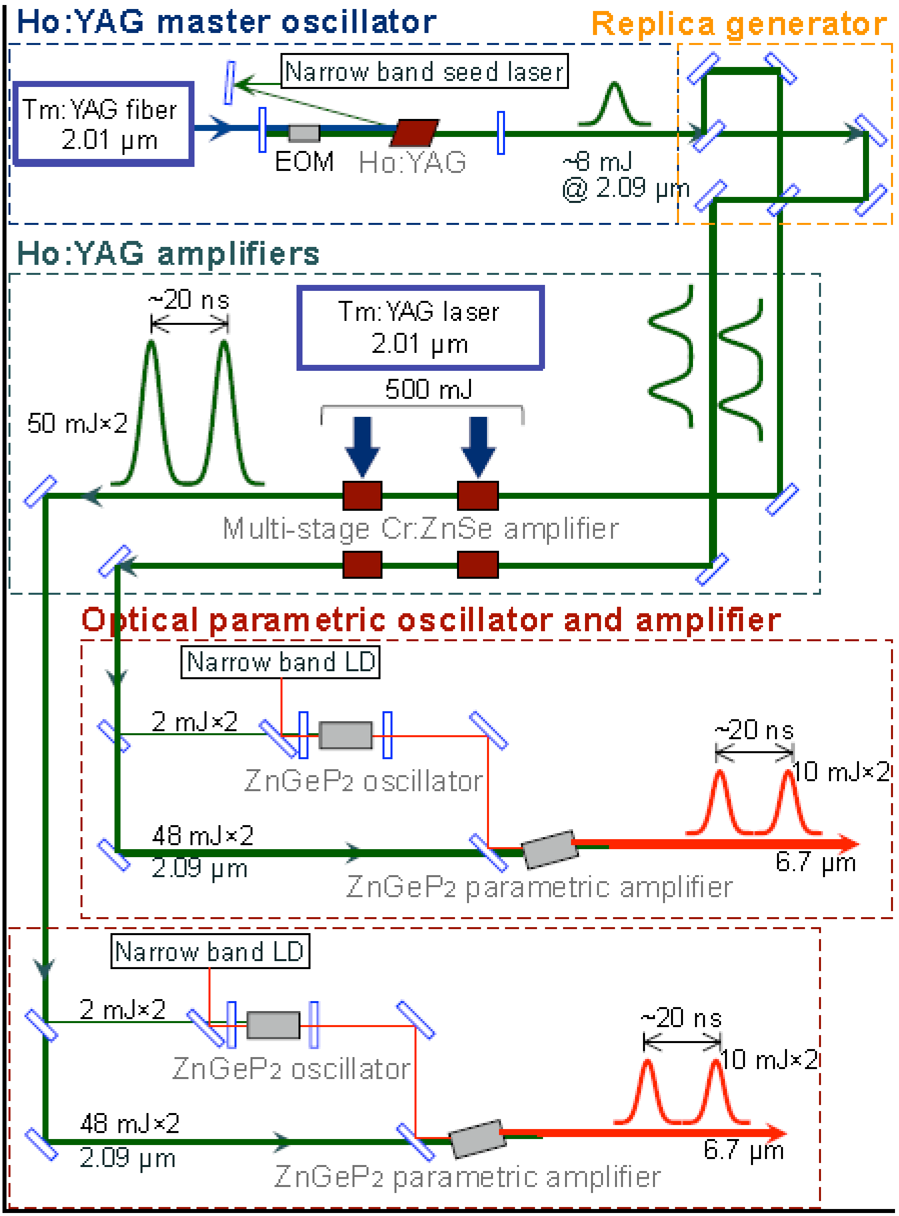
Excitation fast enough (laser power requirement) ?

Detection efficiency (detection before quench)?

Muon rate and event rate?

Background?

Laser



Tunable infra-red laser (5 mJ) was developed by RIKEN laser group

A new laser is feasible
10 mJ x double pulse
and 2 sets
will give 40 mJ

Excitation Rate

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

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

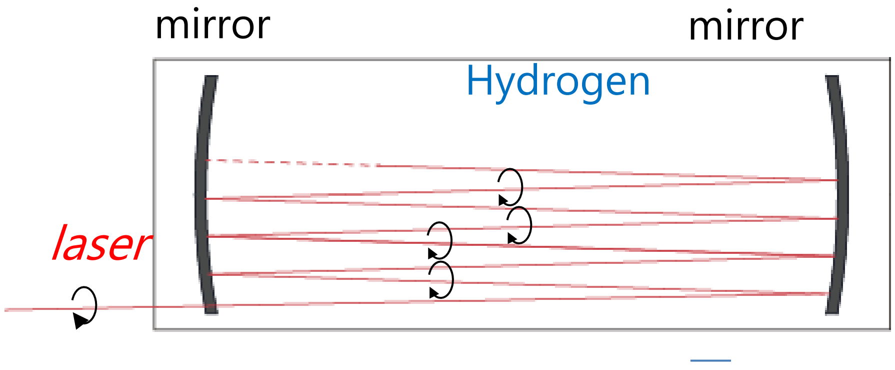
ex. E = 40 mJ, *S*= 4 cm², T= 20 K, then *P* = 4.5×10^{-4}

This is too small.

We need multi-pass cavity

High-reflectivity mirror 99.95%

Cavity design by beam ray tracing program



Target & Detector

Target Requirement

Large muon stopping -> high density, large volume

Small μp quenching -> low density

High laser density -> small volume

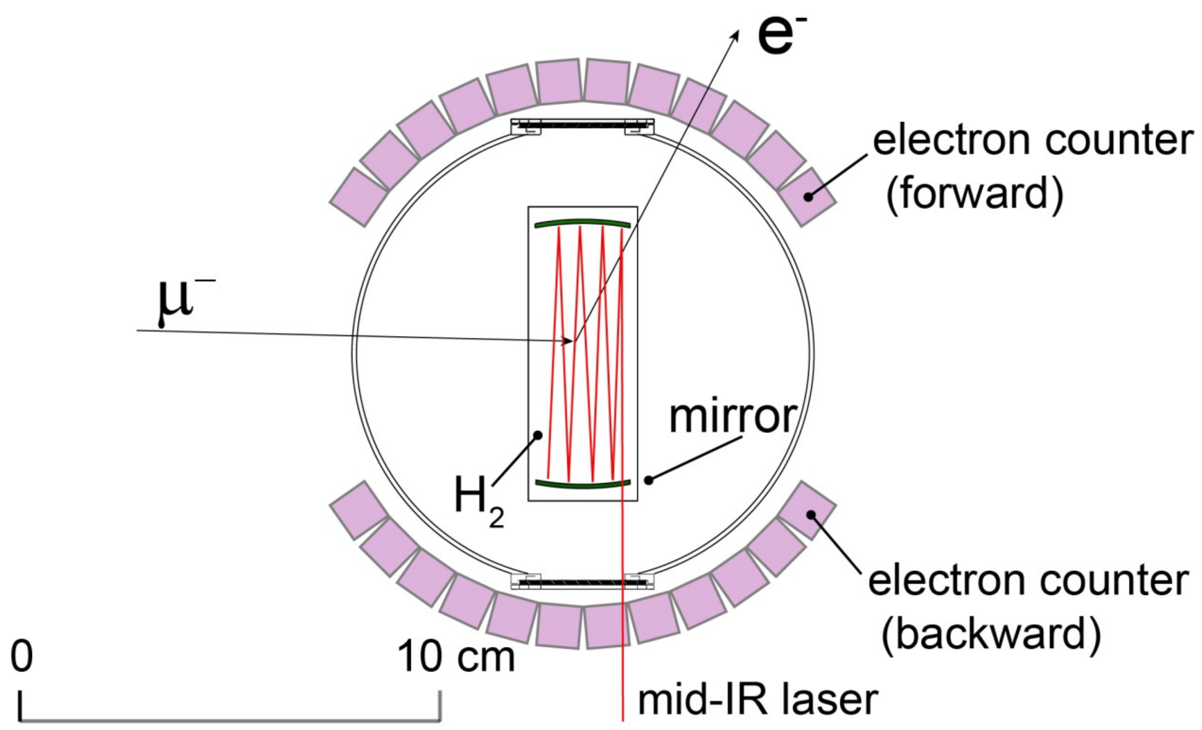
=> Let's take 0.0001 LHD and 4 cm^2 x 6 cm

Detector

Solid angle ~28% each

Asymmetry factor

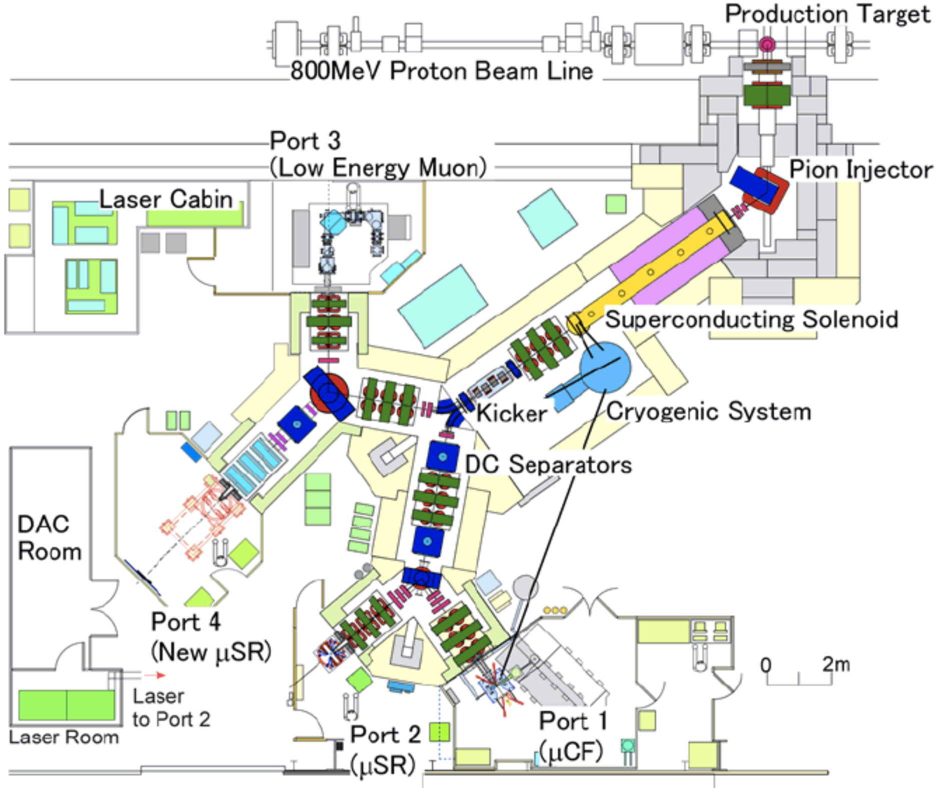
(polarization sensitivity)~0.23



Muon beam

We need a pulsed muon beam
<= One laser shot covers as many muons as possible.

We plan a first measurement at RIKEN-RAL Muon Facility.
A dedicated experimental area will be arranged.

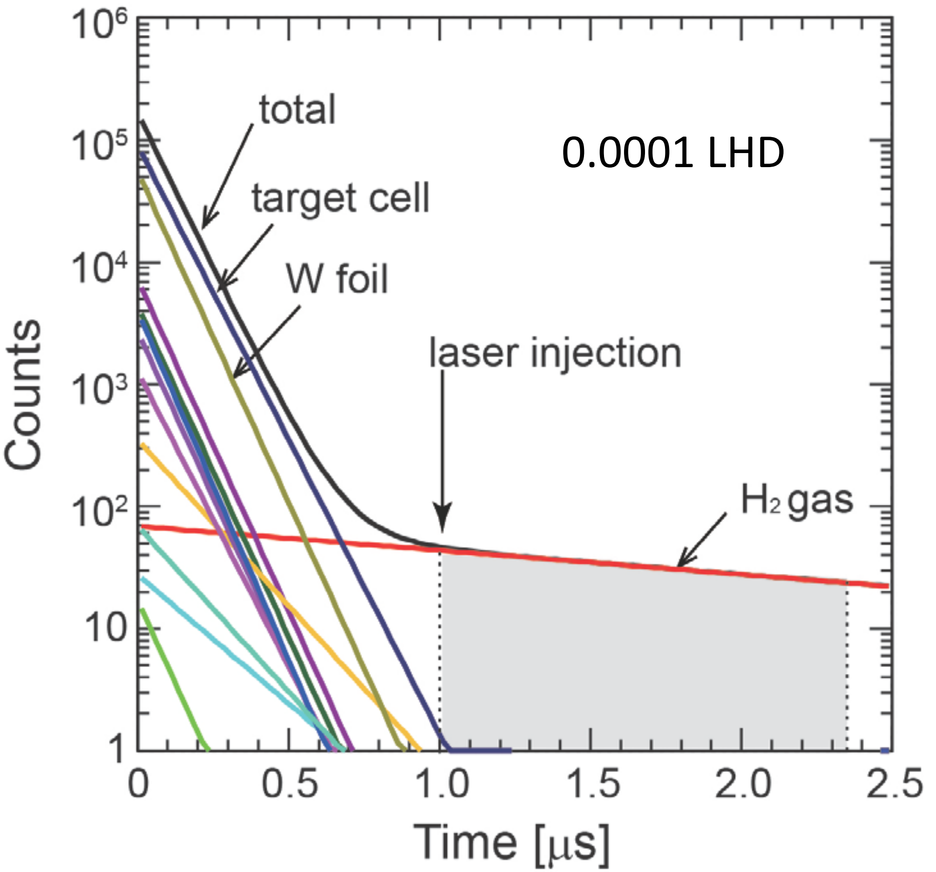


Typical muon intensity
2.2×10^4 [s^{-1}]
at p = 40 MeV/c

Muon stopping and background

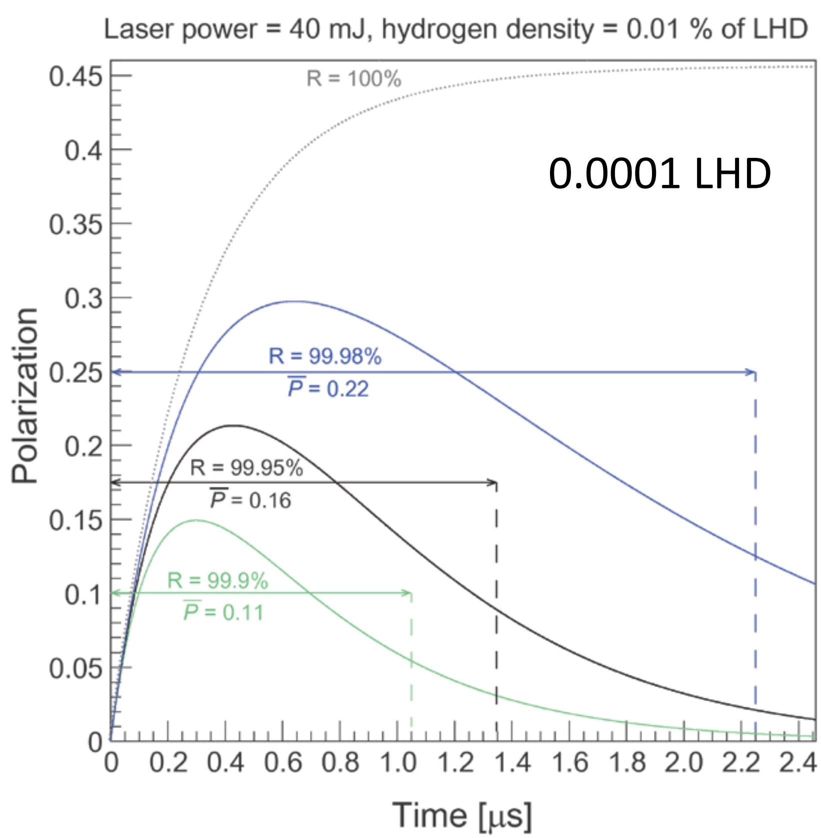
Hydrogen target cell cooled to 20 K by GM-type refrigerator
40 MeV/c muon

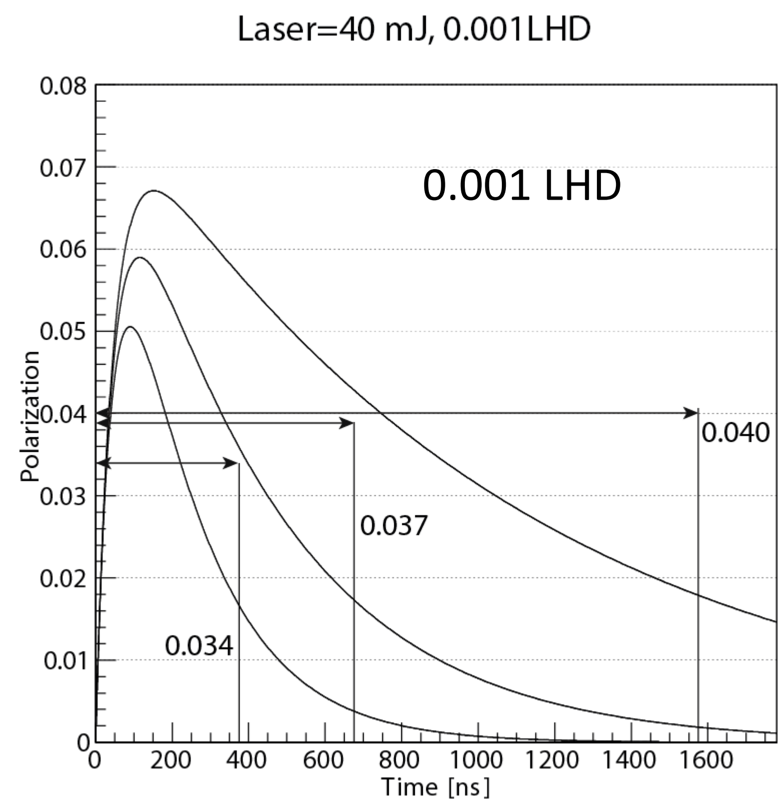
Only 0.01% of incoming mons stops in hydrogen.
Other muons stop in target vessel and surrounding materials.
=> We use only high-Z materials so those muons disappear
by nuclear capture (90ns in silver)
before laser injection.



Polarization vs time

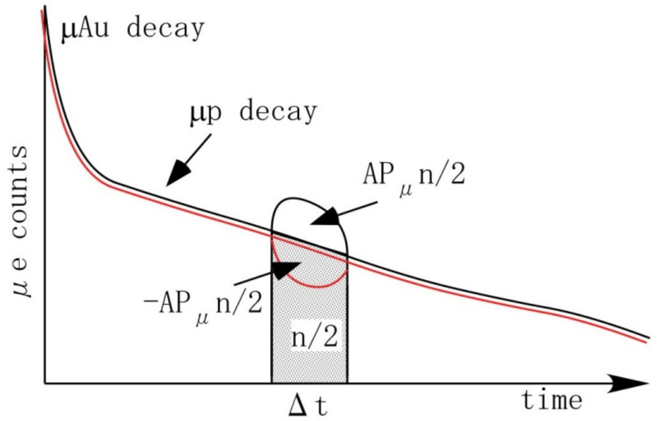
Calculation includes
  Excitation per single pass (4.5×10^{-4})
  Multi-pass laser cavity with loss by reflectivity
  and μp HFS quenching (500 ns for 0.0001 LHD, 50 ns for 0.001 LHD)
We get average polarization of 0.16 in a time gate 1.33 μs (0.0001 LHD)
(0.037 in 0.67 μs for 0.001 LHD)





Yield estimation (statistics)

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

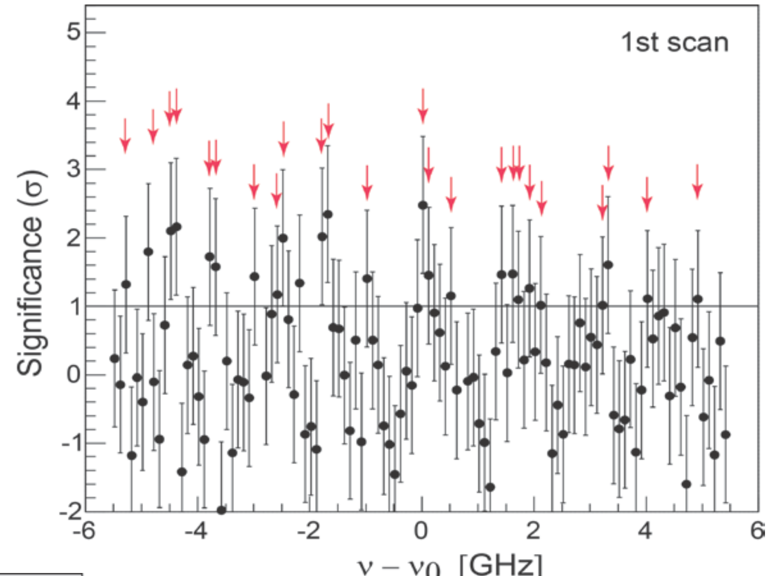


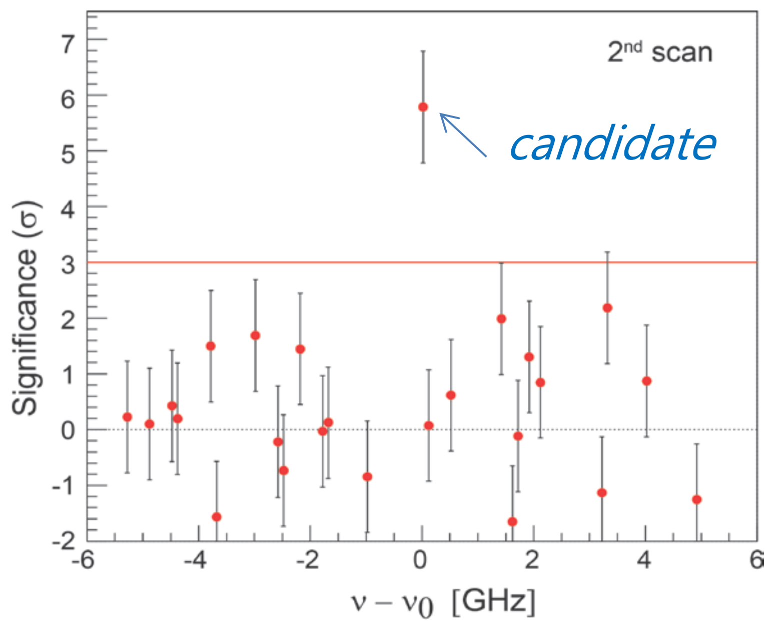
Beam condition
Intensity 2.2×10^4 /s @40 MeV/c
Momentum width $\sigma_p/p_0 = 4\%$
Target condition
H2 gas 0.0001 LHD, Volume $4\text{cm}^2 \times 6$ cm
Laser
40 mJ, 99.95% reflectivity, cavity length
Detector (solid angle 28% each, polarization sensitivity factor 0.23)

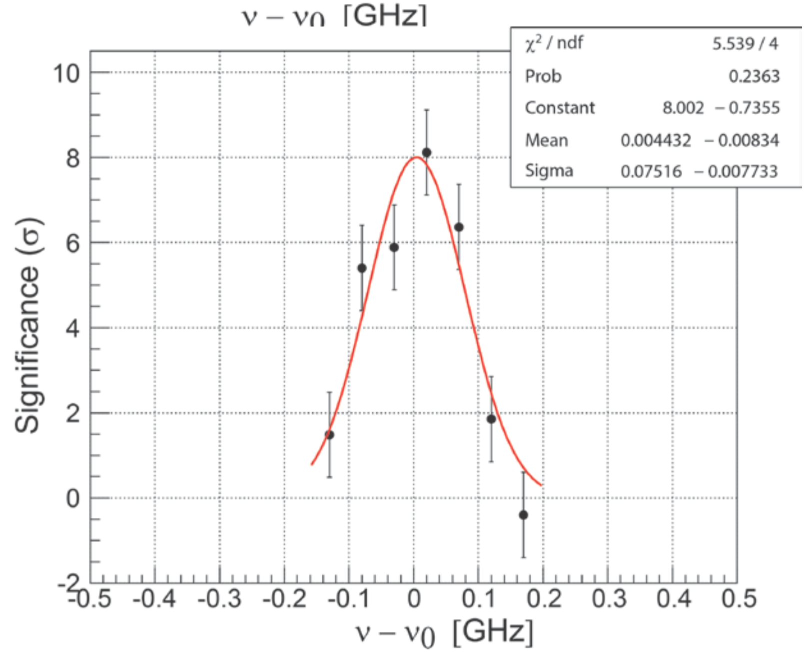
Time gate : laser at 1.0 μs after muon + 1.33 μs detection gate
statistics in 5 hours
=> signal $N_F - N_B$, ~240
fluctuation $\Delta N_F + \Delta N_B \sim \sqrt{(N_F + N_B)}$ ~80
significance = $(N_F - N_B)/\sqrt{(N_F + N_B)} \sim 3\sigma$

Resonance hunting & beam time estimate

We plan three steps hunting
of resonance
over region +-5.7 GHz, step 100 MHz
1) 3σ peak ~25 days
2) 5σ peak ~11 days
3) resonance curve ~8 days
=> 1.5 months beam time







Beam time estimate (2)

At J-PARC MUSE, we can earn statistics much quicker (x8?).
Same statistics could be obtained in 5 days.
For the moment, long time occupation of the experimental area is "very" difficult.

	RIKEN-RAL	J-PARC
Beam power [kW]	160	300 (=>1000)
Repetition [Hz]	50	25
Proton energy [GeV]	0.8	3
Prod. target thickness [mm]	?	?x2
Momentum bite [%]	4	10?
Double pulse interval [ns]	320	600
Muon rate at 40 MeV/c	2.2×10^4 [/s]	5×10^5 [/s]

Collaboration

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New collaborators are welcome

Summary

We are planning the first measurement
of the ground state hyperfine splitting energy
in muonic hydrogen using mid-infrared laser

The expected HFS energy accuracy is 2 ppm.
The Zemach radius determination is 1%
(limited by calculation of repolarization term).

Experiment is feasible at RIKEN-RAL Muon Facility
with pulsed muon source.
(J-PARC MUSE is another candidate)