New Precision Measurement for Proton Zemach Radius with Laser Spectroscopy of Muonic Hydrogen

On behalf of Mup collaboration

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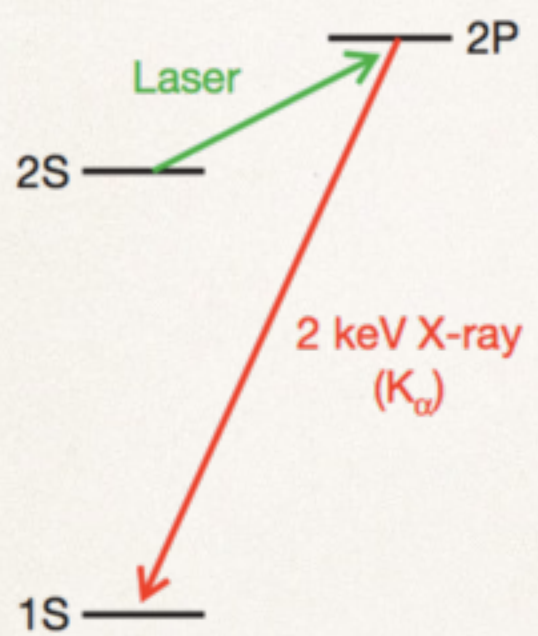
Oct. 21st, 2014

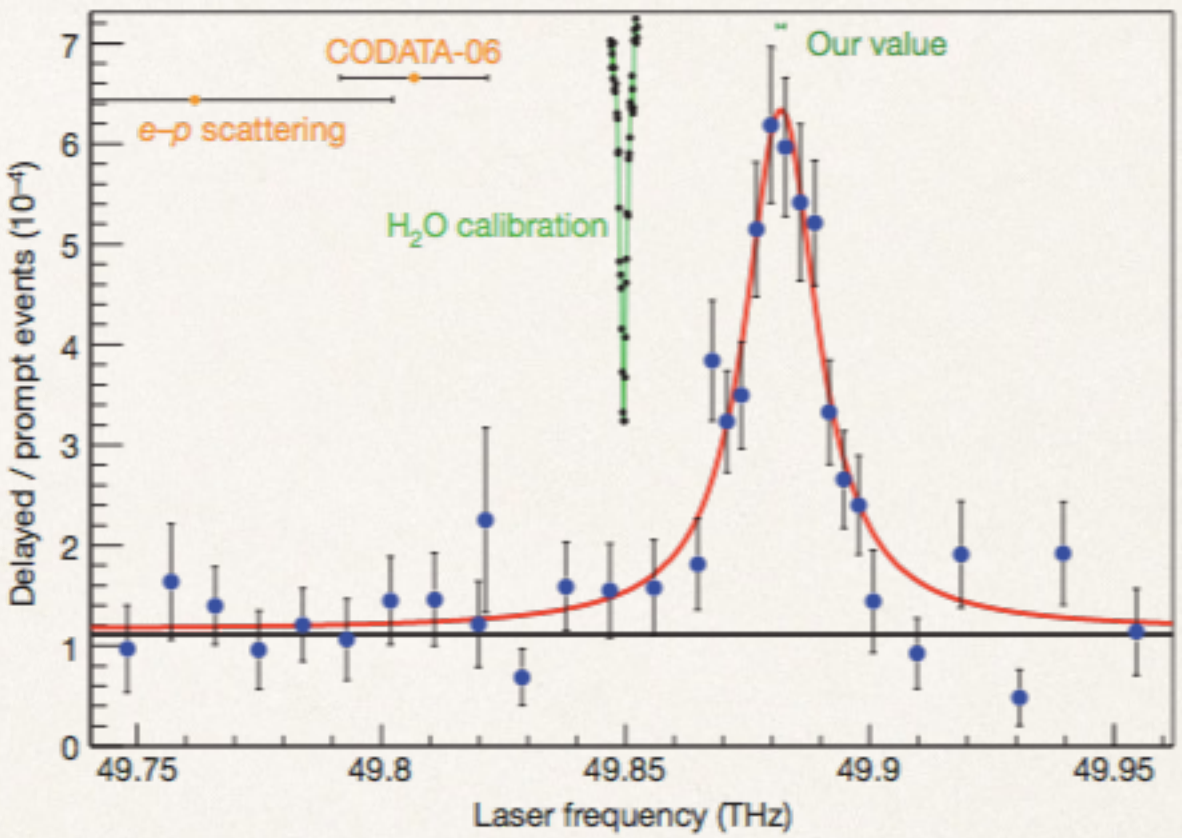
Outline

- Background & motivation
- Experimental setup
- Expected results
- Summary

Background & motivation

The beginning of proton size puzzle





PSI experiment operation principle:

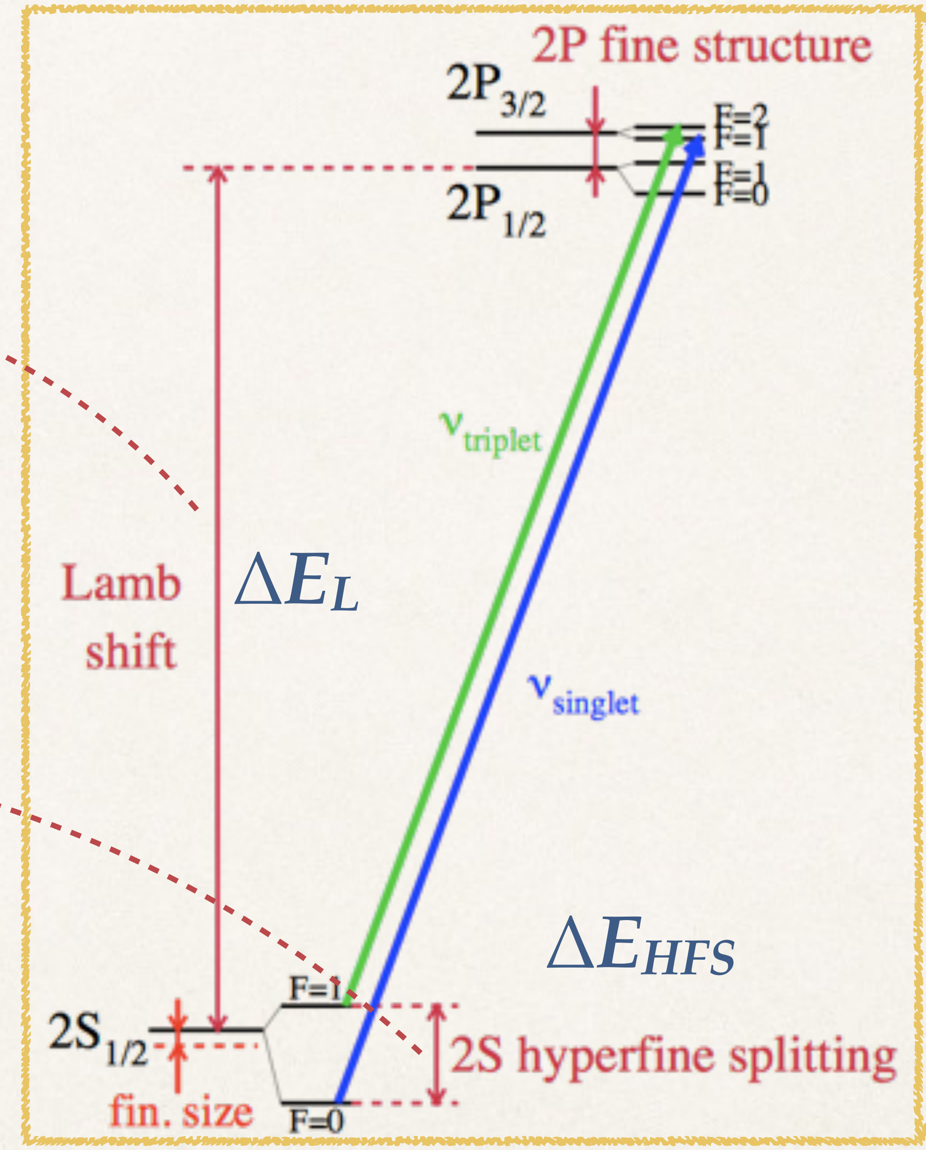
1. Search for 2S-2P level spacing by scanning laser wave length;
2. Coincidence with 2 keV x-ray(Kα) to identify resonance;
3. $r_E = 0.84087(39)$fm, 7-σ away from world data

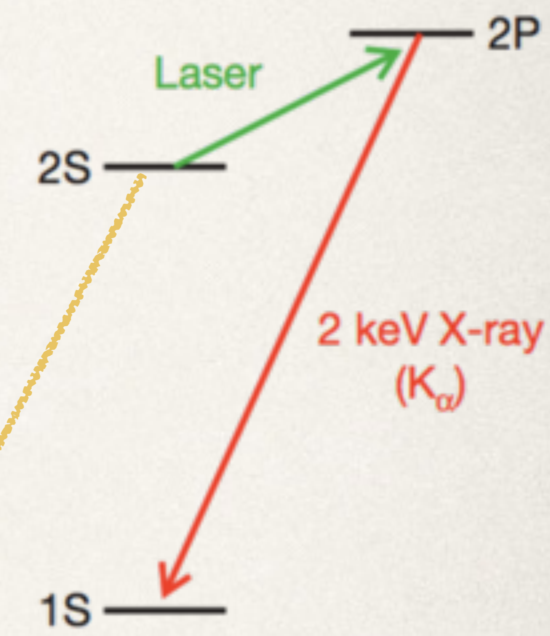
R. Pohl *et al.*, doi:10.1038/nature09250

Updated measurements @ PSI

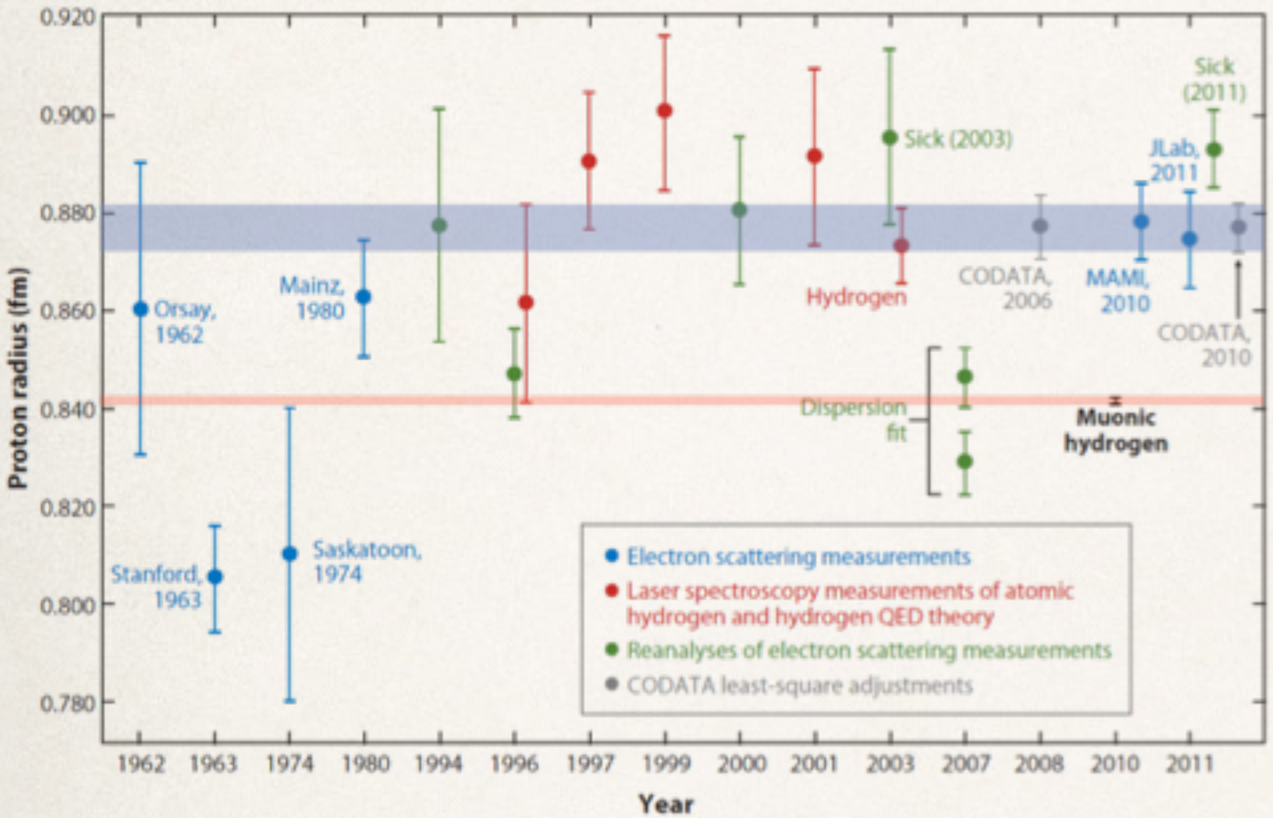
$$\Delta E_L = 0.25 h\nu_s + 0.75 h\nu_t$$
$$-8.8123(2)\text{meV}$$
$$\Rightarrow r_E = 0.84087(26^{exp})(29^{th})\text{fm}$$
$$\delta r_E / r_E \sim 0.046\%$$

$$\Delta E_{HFS} = h\nu_s - h\nu_t$$
$$+3.2480(2)\text{meV}$$
$$\Rightarrow r_Z = 1.082(31^{exp})(20^{th})\text{fm}$$
$$\delta r_Z / r_Z \sim 3.4\%$$





Proton radius data summary

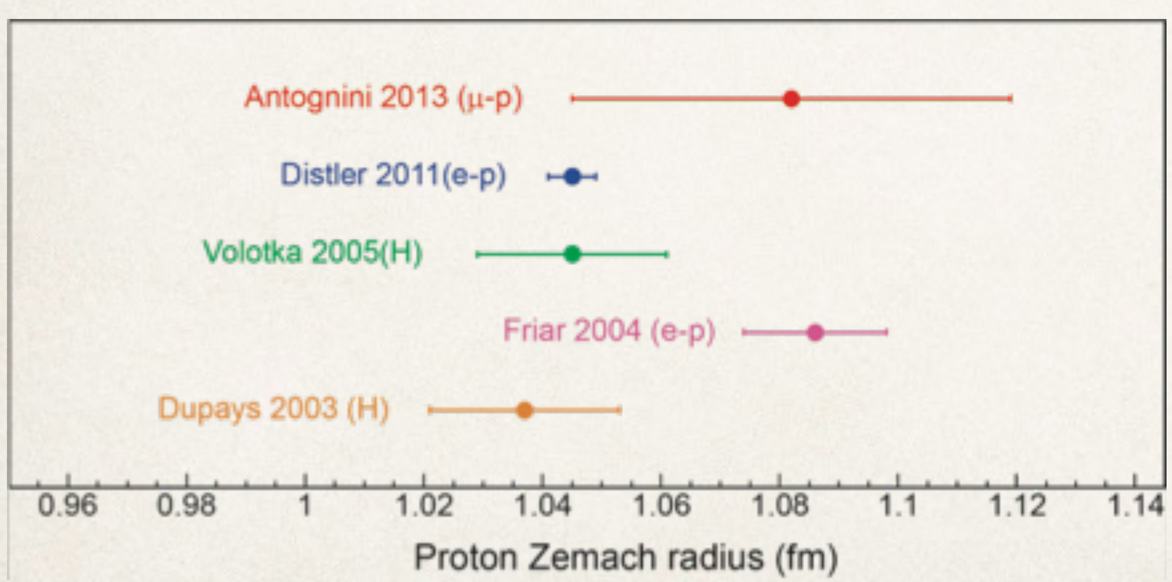


$$r_E^2 = \int d^3 r r^2 \rho_E(r)$$

7-σ deviation, $\delta r_E / r_E \sim 0.046\%$

Precision is the key:

1. with 1% accuracy, r_E will be "consistent";
2. what about r_Z with better accuracy?

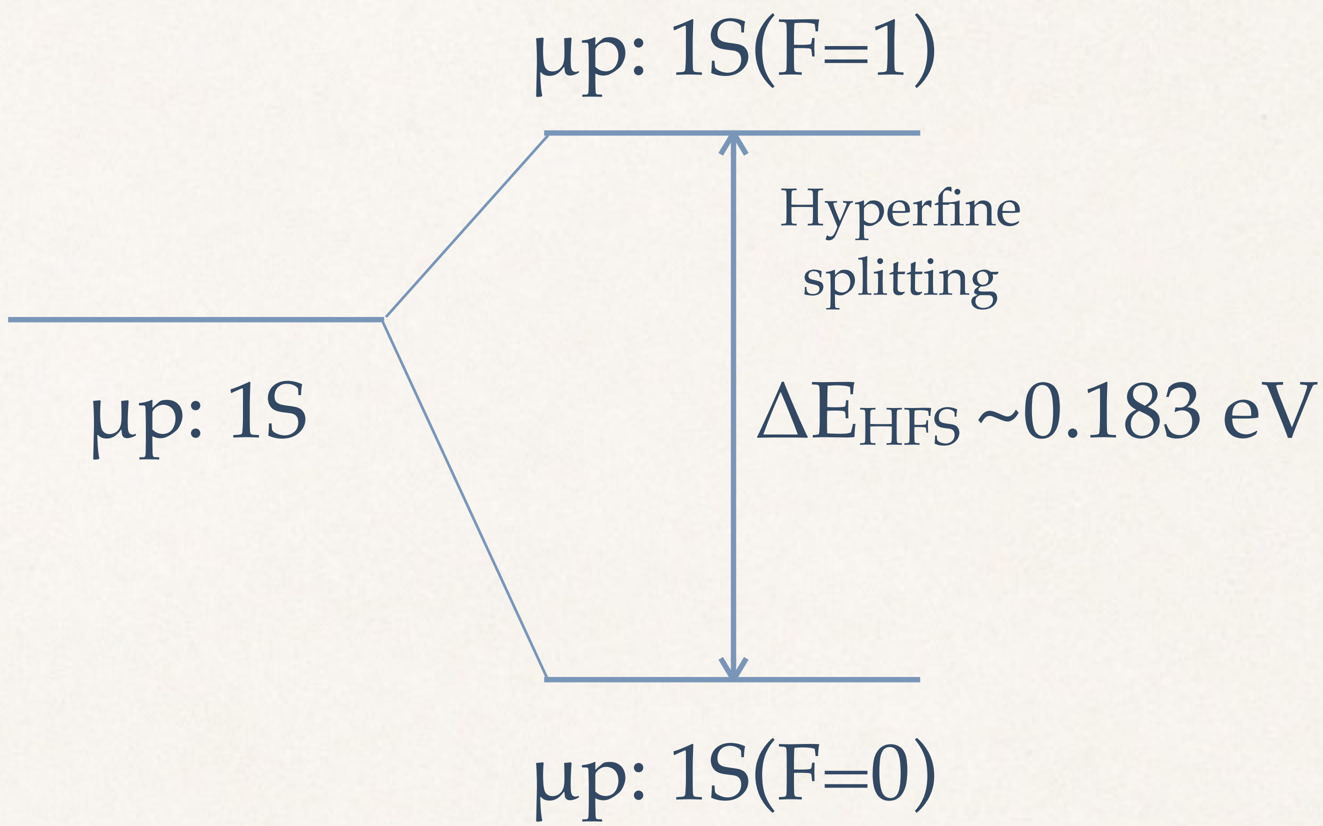


$$r_Z = \int d^3 r \int d^3 r' r' \rho_E(r) \rho_M(r - r')$$

compatible, $\delta r_Z / r_Z \sim 3.4\%$

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

Our proposed measurement



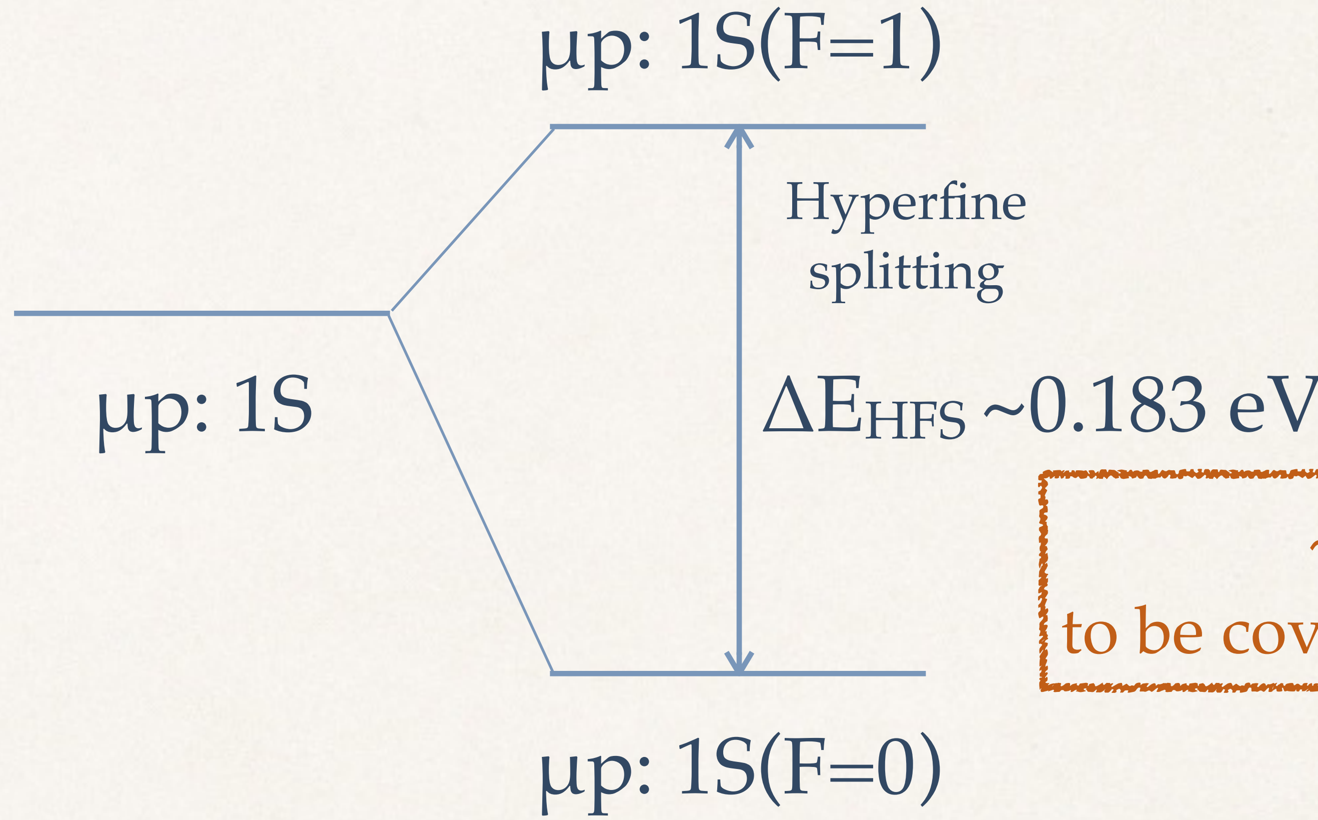
$$\Delta E^{th}_{HFS} = E_F(1 + \delta_{QED} + \delta_{str})$$
$$= E_F(1 + \delta_{QED} + \delta_{Zemach} + \delta_{recoil} + \delta_{pol} + \delta_{hvp})$$

$$E_F = \frac{8}{3}\alpha^4 \frac{m_\mu^2 m_p^2}{m_\mu + m_p}\mu_p$$

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

A. Dupays *et al.*, Phys. Rev. A 68 (2003) 052503

Our proposed measurement



~2 ppm
to be covered in this talk

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

1130(1) ppm | 1700(1) ppm | 460(80) ppm dominant factor! | 20(2) ppm

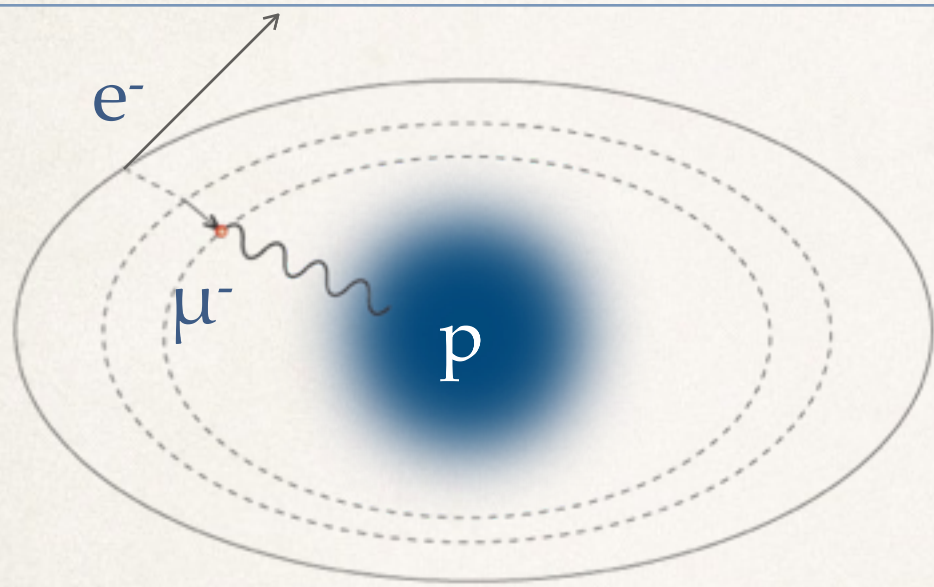
⇒ $\delta r_Z / r_Z \sim 1\%$ (3 times better than PSI results)

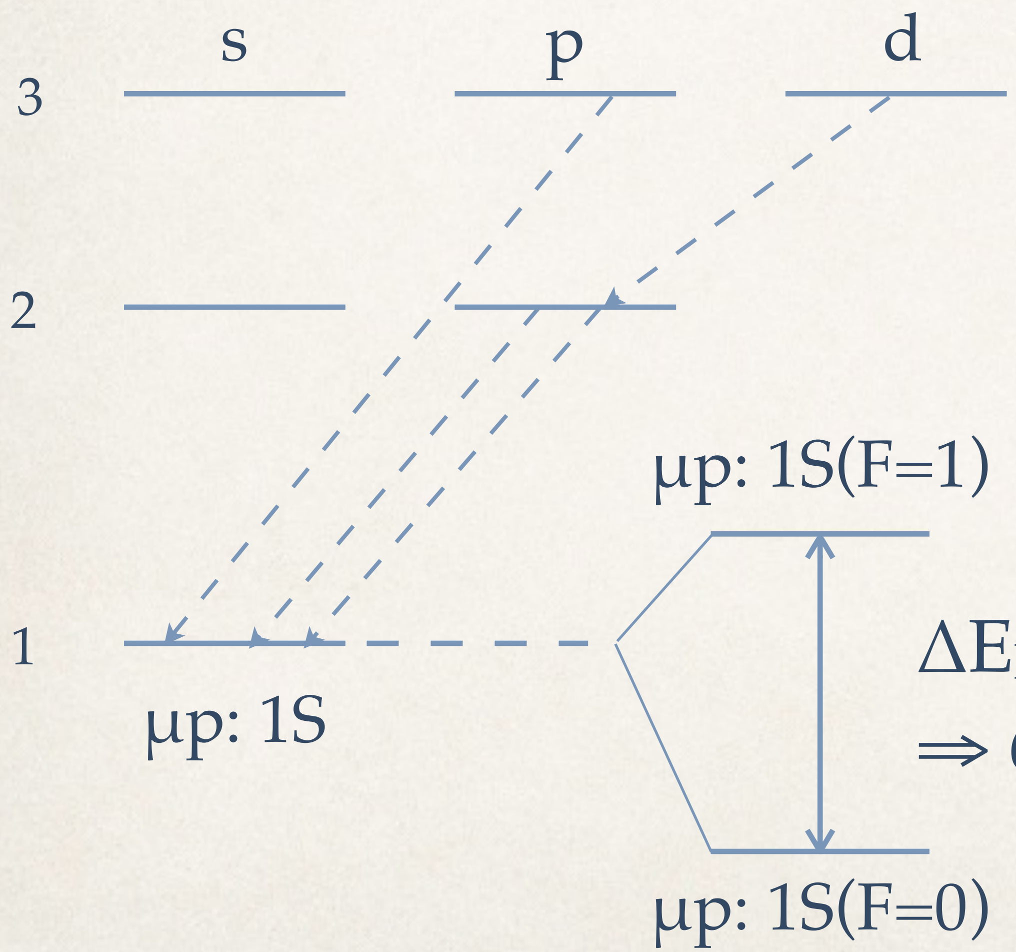
A. Dupays *et al.*, Phys. Rev. A 68 (2003) 052503

Experimental setup:

how to measure ΔE_{HFS} with 2ppm accuracy?

Measurement principle

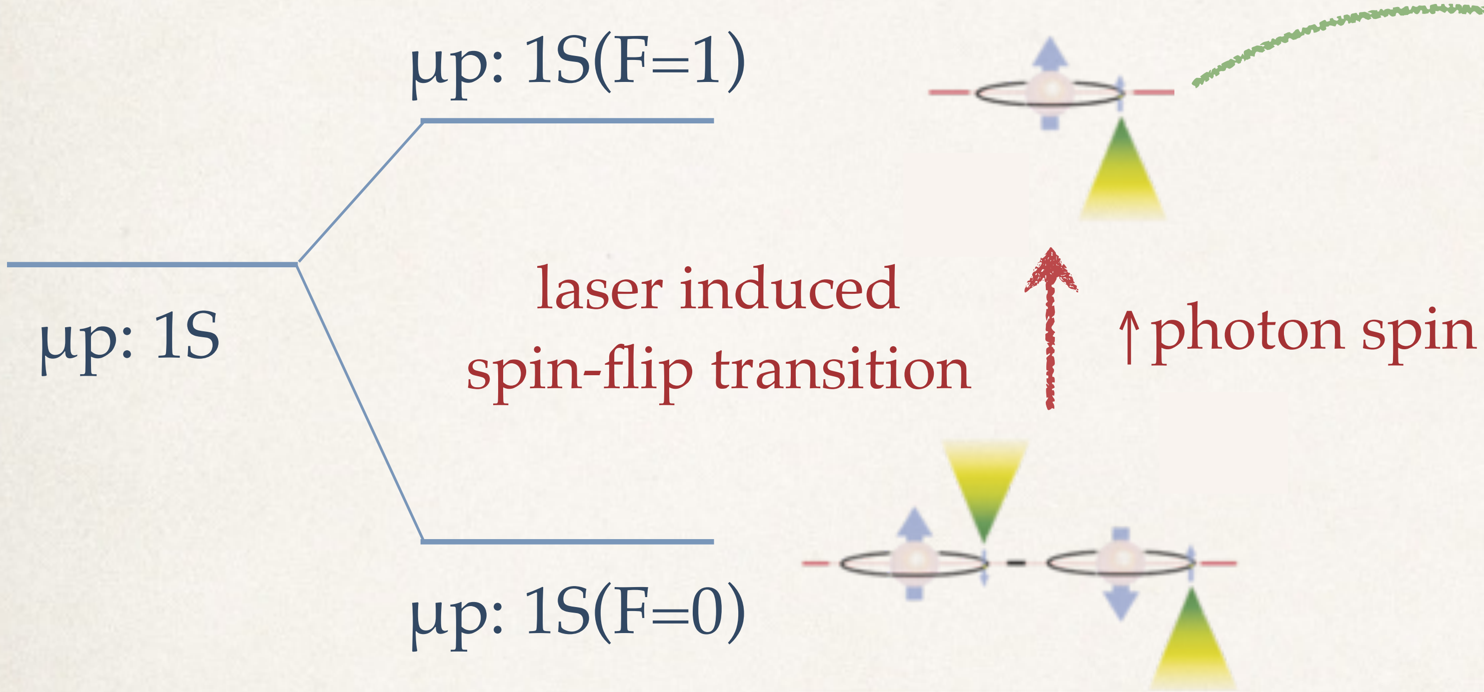


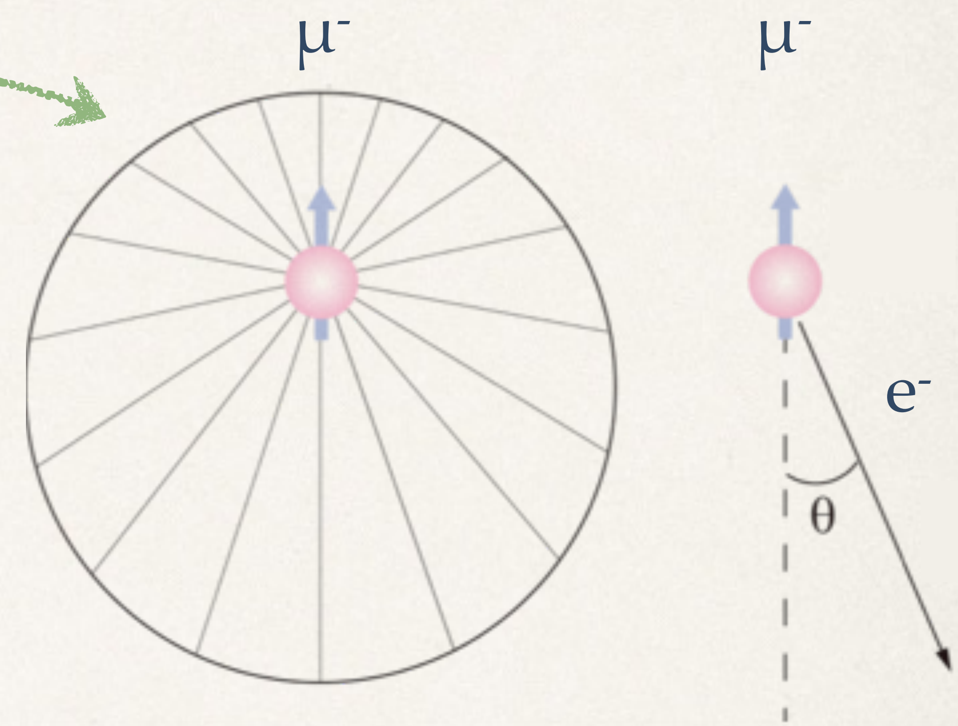


1. μ^- captured by Hydrogen gas (RAL or J-PARC);
2. formation of 1S ground state;
3. 1S(F=0)→1S(F=1) transition(M1) by laser;
4. measure decay asymmetry of polarised μ^- decay to identify resonance

ΔE_{HFS}(1S) ~ 0.183 eV (45 THz)
⇒ 6.8μm (mid-infrared laser)

Measurement principle





1. shoot μ^- beam on Hydrogen target & formation of muonic hydrogen(μp);
2. shed laser on muonic hydrogen & scanning over laser wave length to search for μp:1S(F=0)→1S(F=1) resonance frequency;
3. identify resonance frequency by detecting maximum $\mu^- \to e^- + \nu_e + \nu_\mu$ decay asymmetry

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

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

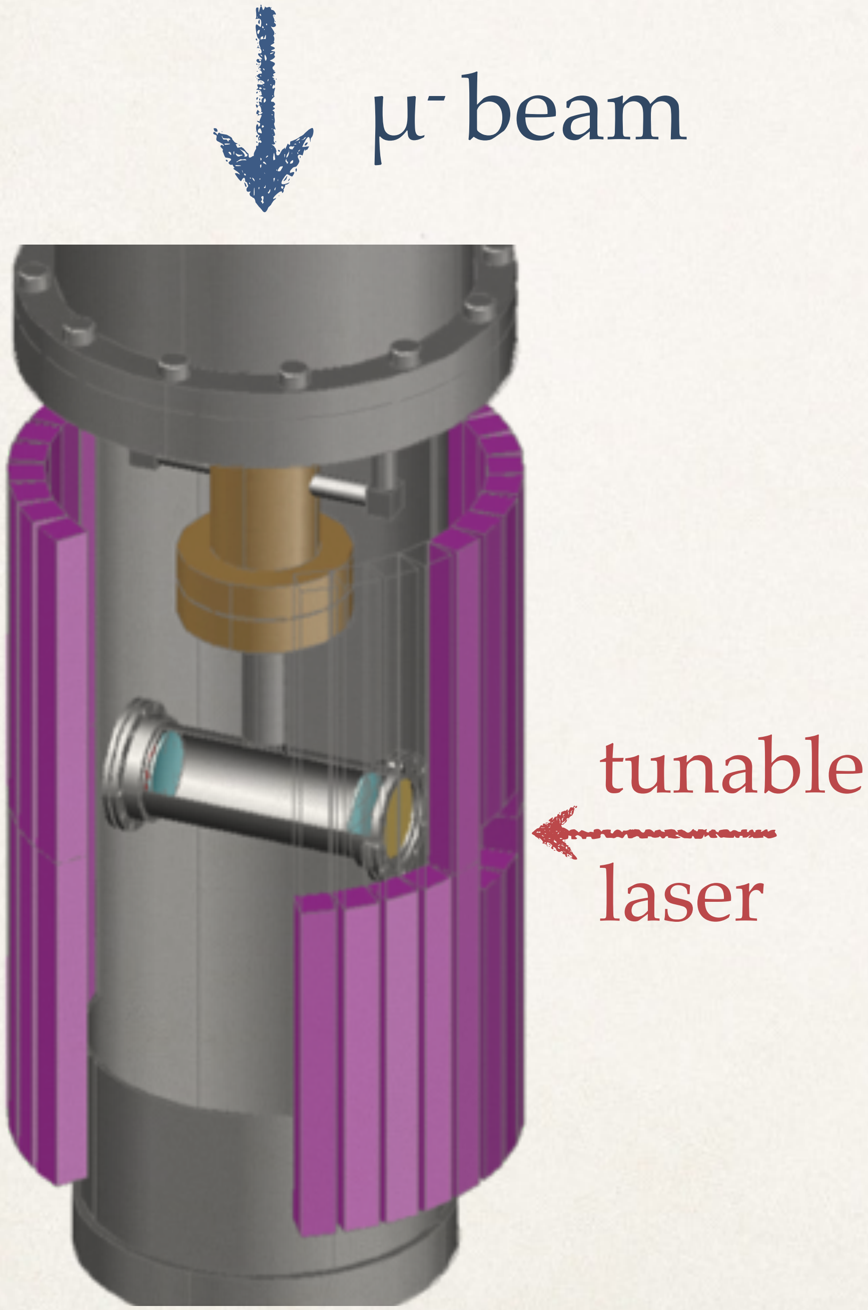
$$Asymmetry = \frac{N_F - N_B}{N_F + N_B}$$

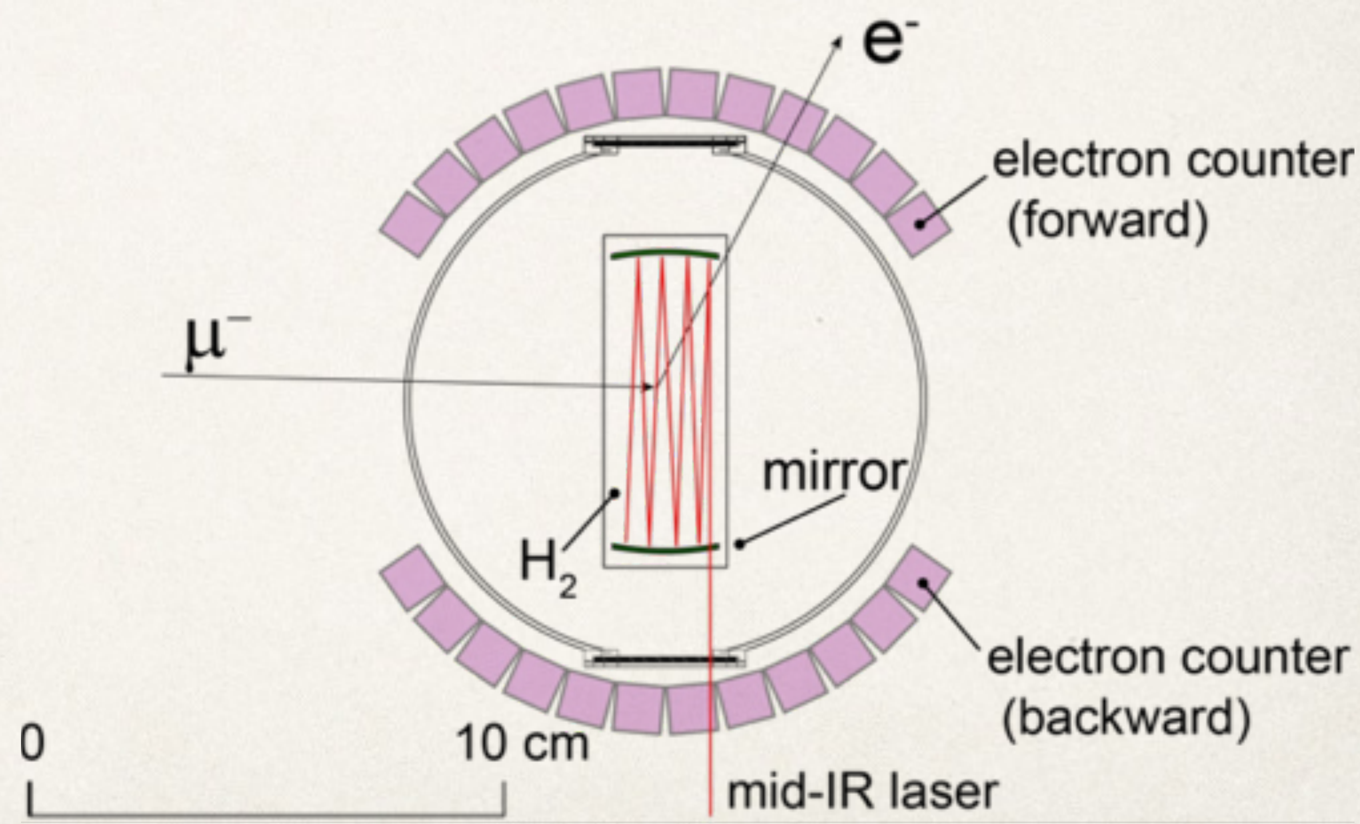
Experiment concept: target & counter

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

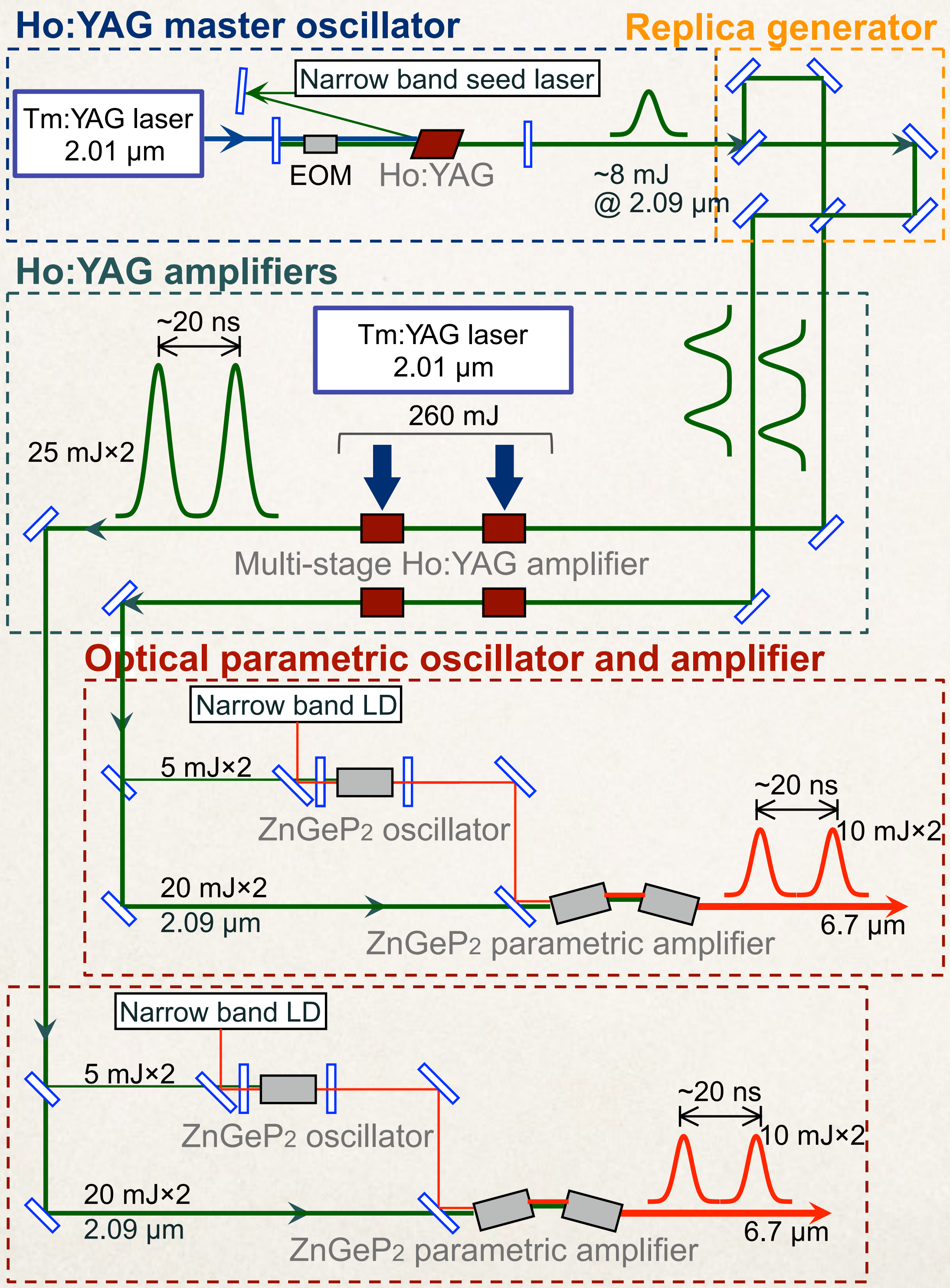
$$d\sigma_{e^-}(\theta)d\Omega \propto \left(1 - \frac{1}{3}Pcos\theta\right)$$

$$Asymmetry = \frac{N_F - N_B}{N_F + N_B}$$





Experiment concept: laser system



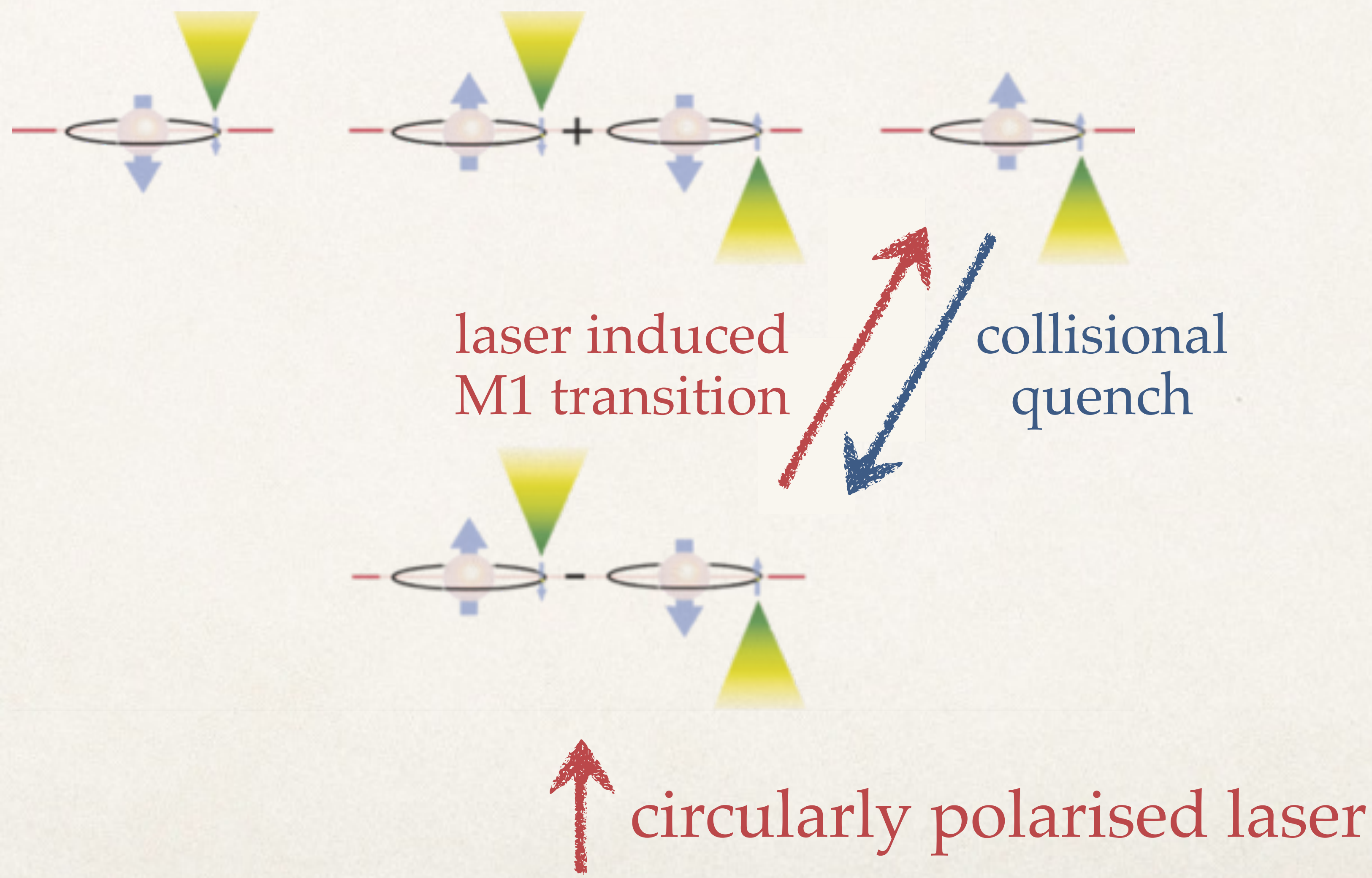
Laser system parameters:

1. Tunable mid-infrared laser (R&D by Wada group@RIKEN);
2. 6.8 µm (> 6 GHz tunability);
3. repetition ~ 50 Hz;
4. band width ~ 50 MHz;
5. double pulse 10 mJ×2 sets = 40 mJ;
6. OPO controlled seed;

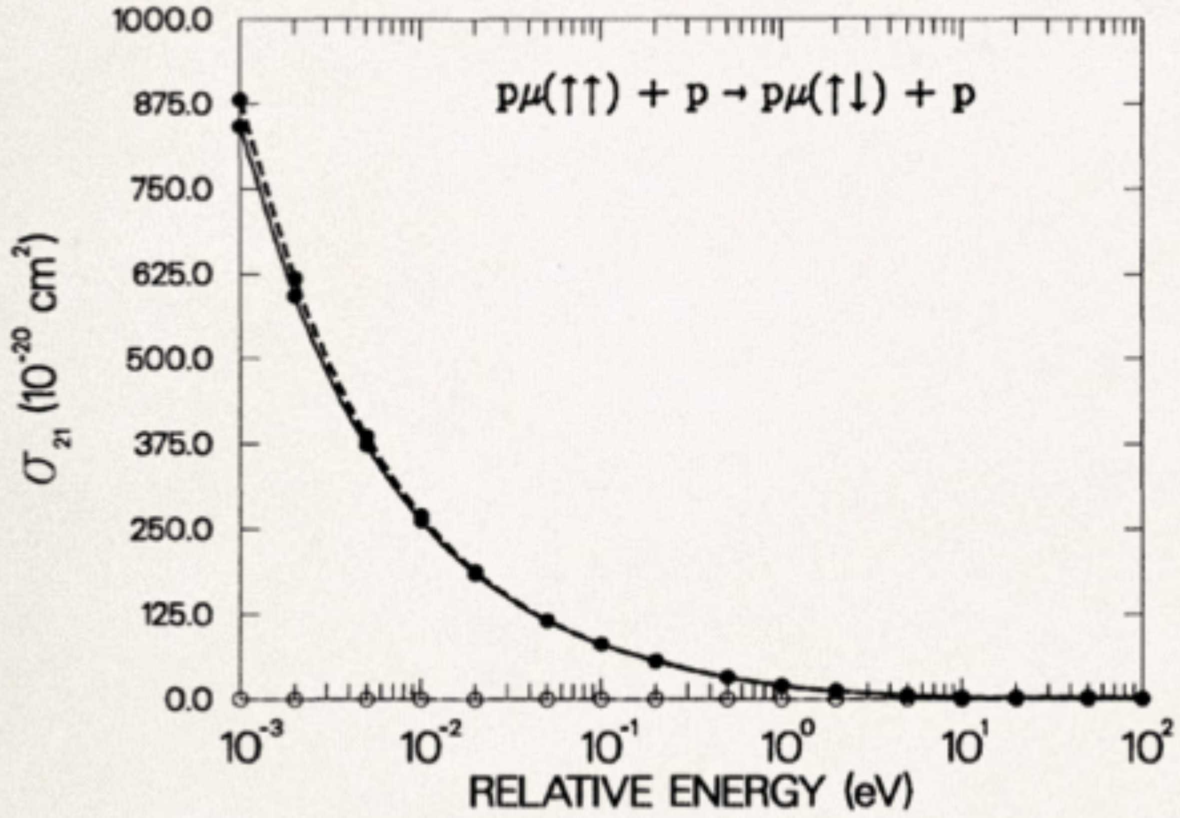
Expected results

Yield estimation

Competition between laser induced transition
and collisional quench.



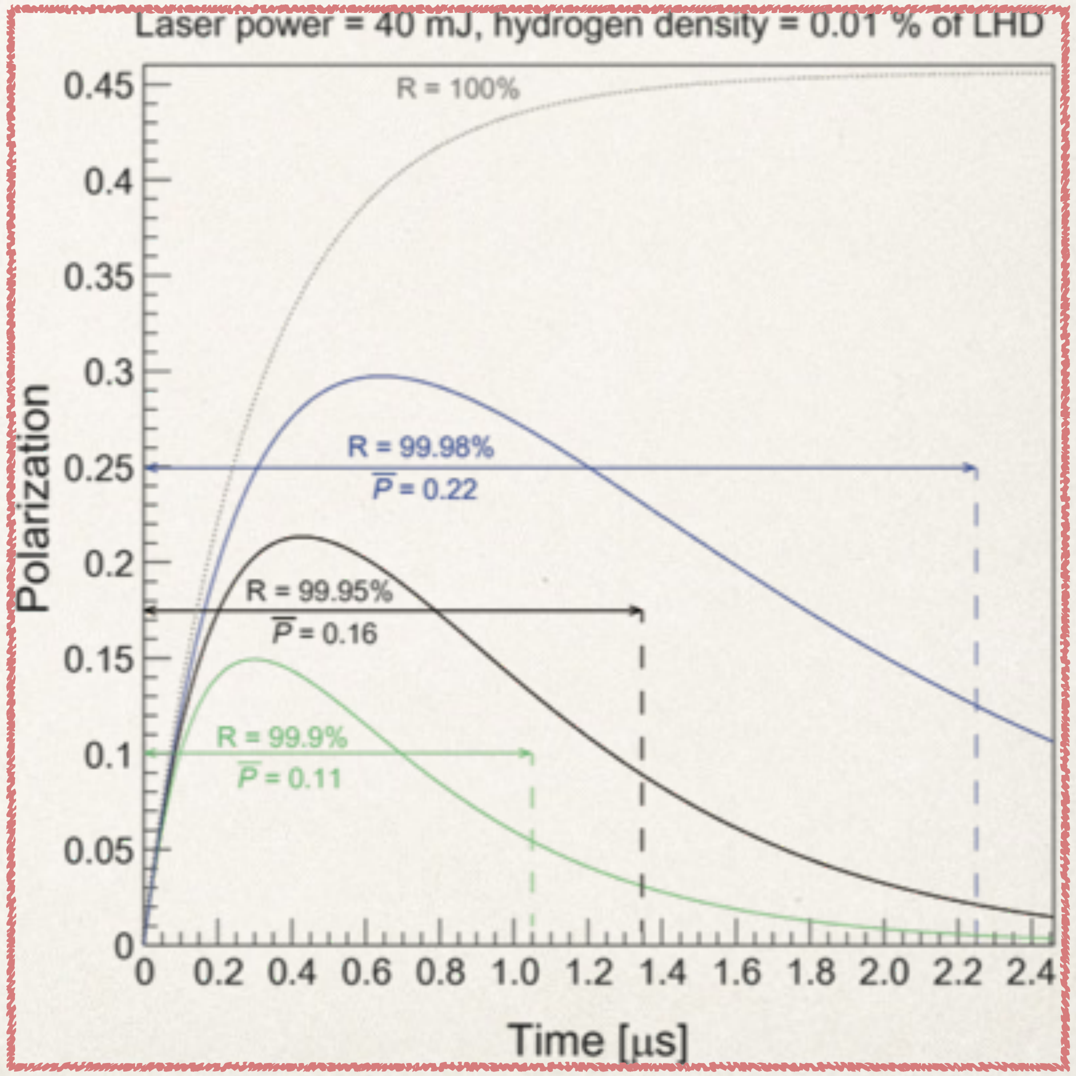
Yield estimation



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

Collisional quench rate proportional to target density:
τ = 500 ns with ρ = 0.01%LHD

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



J. Cohen, Phys. Rev. A 43 (1991) 9

Beam time estimation

$$Significance(\sigma) = \frac{signal}{fluctuation} = \frac{N_F - N_B}{\sqrt{N_F + N_B}}$$

RAL pulsed muon source:

- intensity: 2.4×104 (50 Hz);
- momentum: 40 MeV/c (±4%);

Laser system:

- power: 40 mJ;
- band width: 50 MHz;
- mirror: 99.95%;

H_2 target:

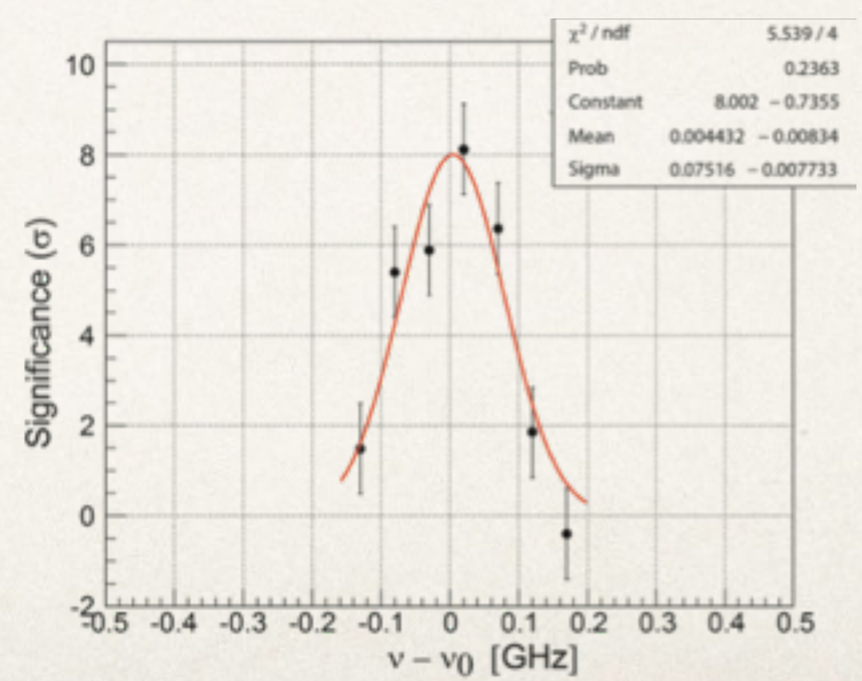
- 0.0001 LHD

Three scanning-stage approach:

- 3σ (wide range): 25 days;
- 5σ (interested region): 11 days;
- 7σ (precise): 8 days;

44 days beam time!

scan interval: 100 MHz (2ppm accuracy);
scan region: ±5.7 GHz ($\delta_{Zemach}+\delta_{pol}$);



Summary

- New proposal for precision Zemach radius measurement with laser spectroscopy
- Detector & laser system R&D are ready
- Beam time request has been proposed to RAL & J-PARC facility