

# On the Possibility of Determining $\alpha$ from the Muon Sector at J-PARC

Shusei Kamioka

KEK, IPNS

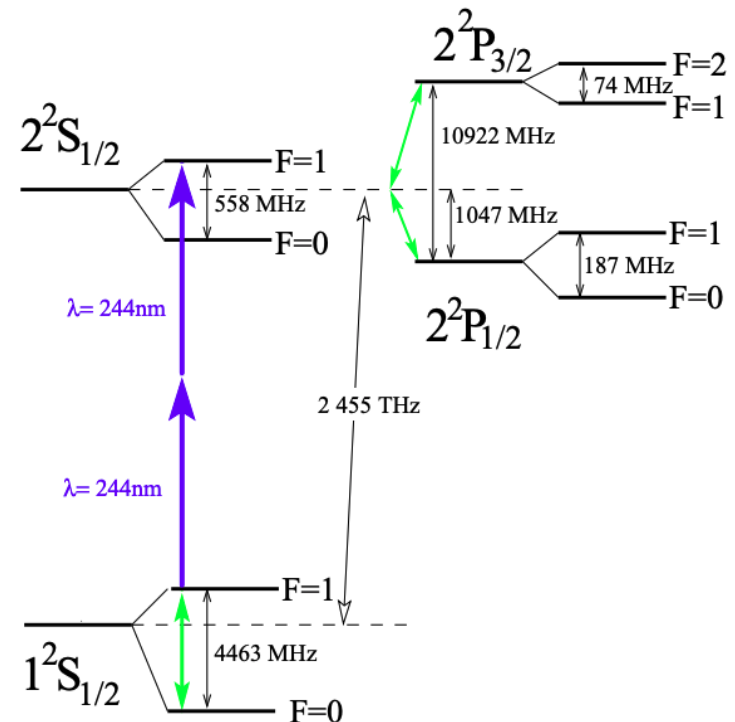
# Muon/Muonium

- **Muon:** 2<sup>nd</sup> generation of charged lepton,  $\tau=2.2\mu\text{s}$ ,  $m=106\text{MeV}$
- **Muonium:**  $\mu^+e^-$ ,  $\tau=2.2\mu\text{s}$ ,  $m=106\text{MeV}$ , pure leptonic system

✓ Various muon/muonium experiments are underway at J-PARC.

- MuSEUM -> talk by Patrick
- **AMuLET**
- **g-2/EDM experiment**

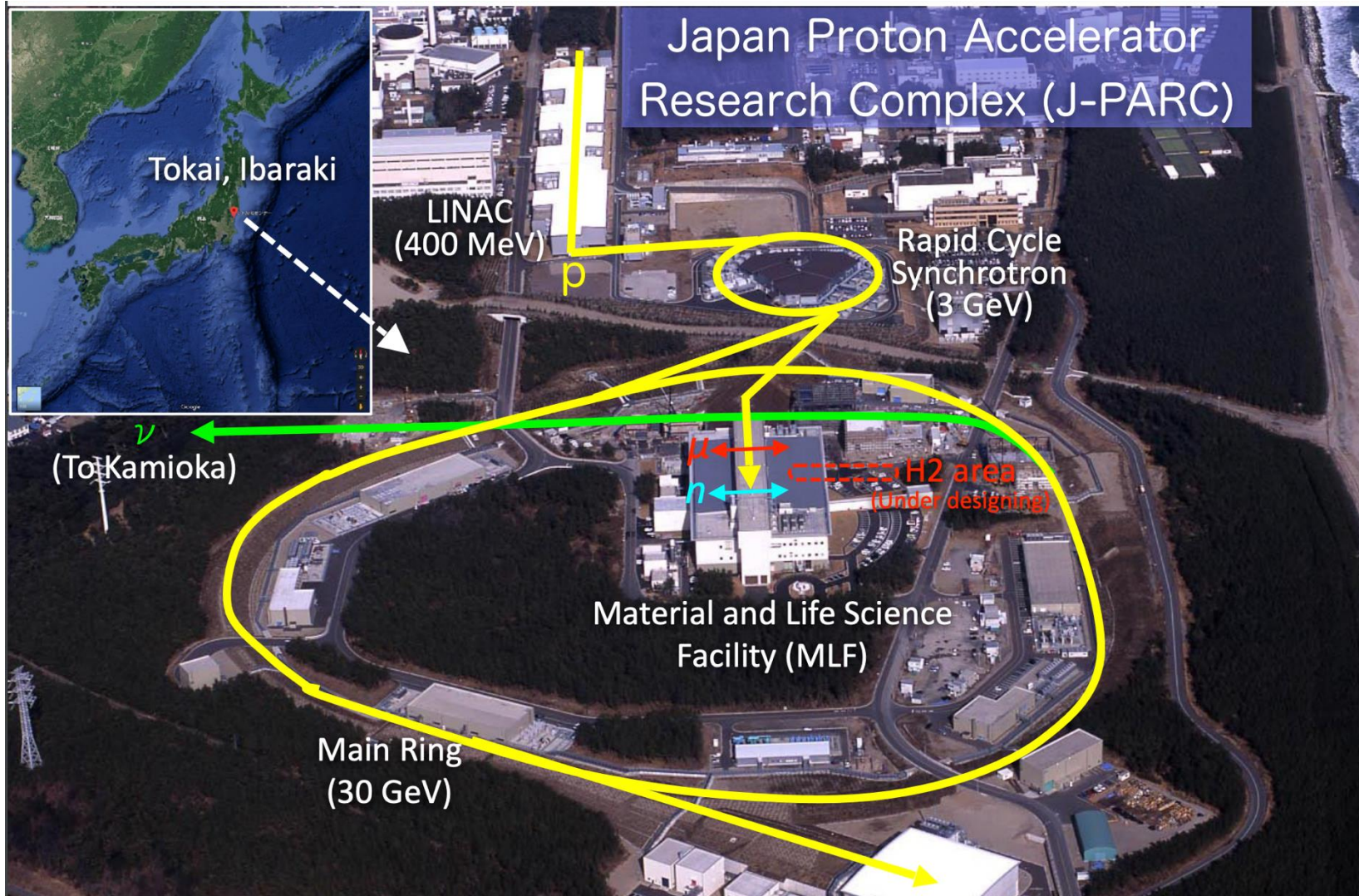
- I'd like to discuss the possibility of determination of  $\alpha$  at J-PARC, focusing on the remaining two experiments.



# J-PARC

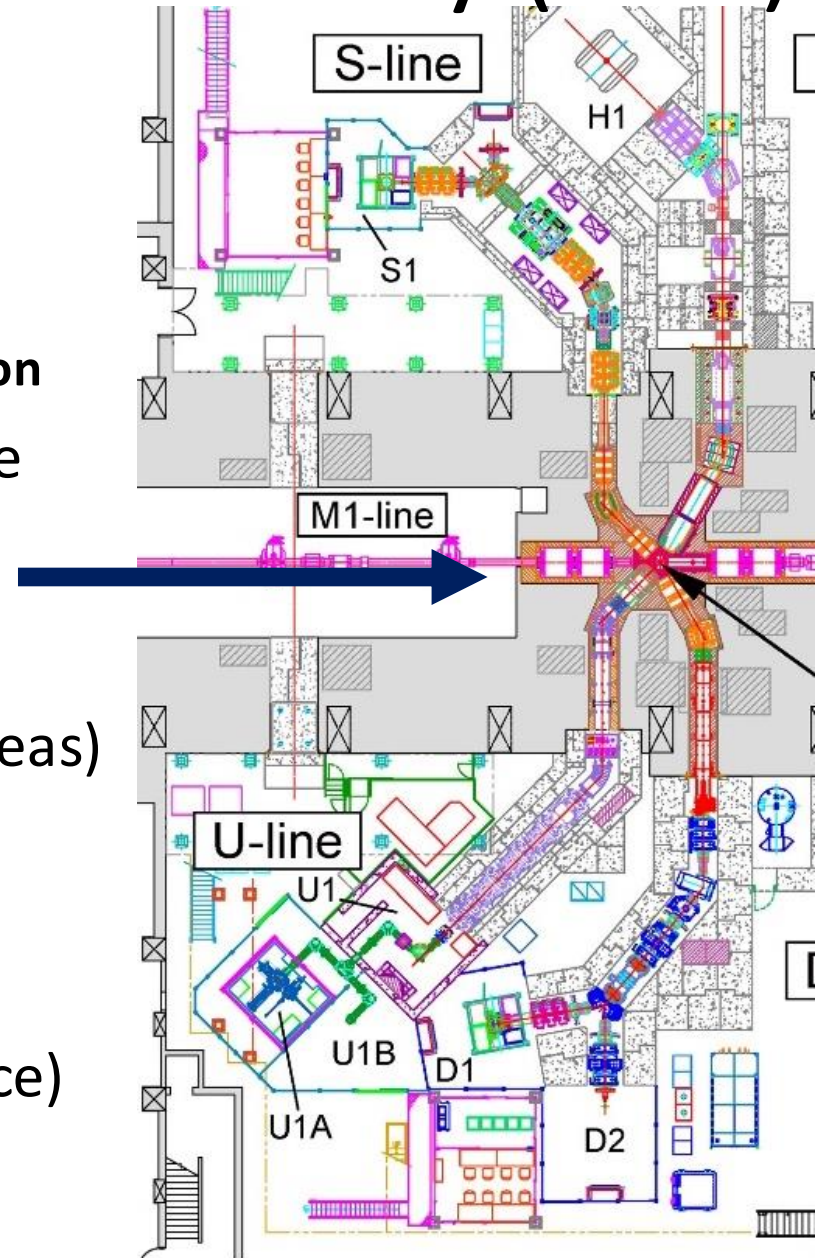
High intensity pulsed proton beam facility

- Particle physics experiment: **neutrino, hadron, neutron, muon**
- **Muon as a tertiary beam from proton ( $p \rightarrow \pi \rightarrow \text{muon}$ )**



# Material & life science facility (MLF)

- **1MW proton beam, 25Hz, 3GeV**
  - <10% of the beam is for muon production
- Pulsed, 100ns, double bunch structure
- $10^8 \mu^+/\text{s}$  (H-line, U-line)
  
- 4 muon beamlines (8 experimental areas)
  - **Muonium spectroscopy**
  - **$g-2/\text{EDM}$  experiment**
  - Muonic atom: strong-field QED
  - $\mu$  spin rotation (for material science)
  - Elemental analysis with  $\mu^-$  beam



# Muon/Muonium precision measurements at J-PARC

We use this triangle in the context of muon  $g-2$ ,  
but let us think about  $\alpha$  determination

J-PARC  $g-2$ /EDM (preparation)

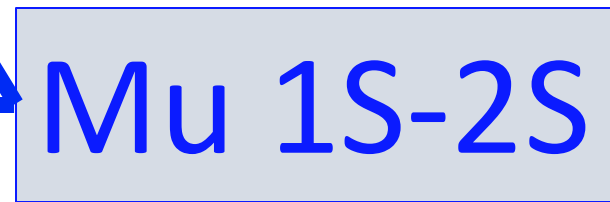


Inspired by Klaus Jungman

MuSEUM

Ongoing

AMuLE!



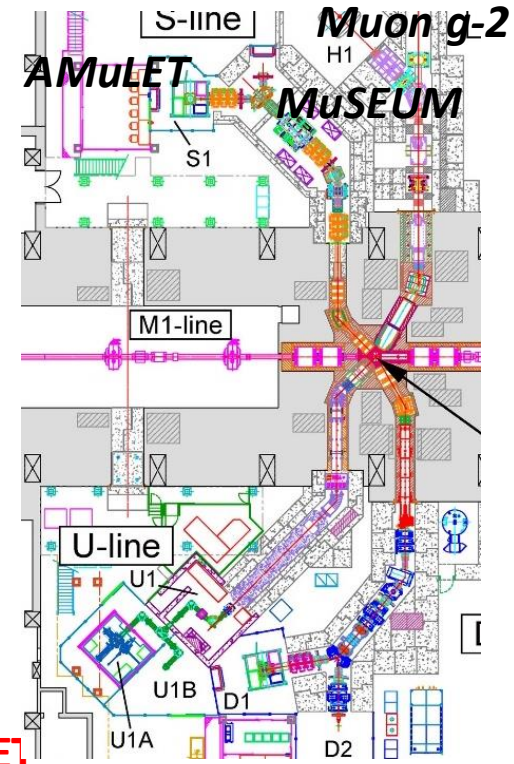
muonium

muonium

$\mu_\mu$

$m_\mu$

$m_\mu$



# Muon/Muonium

## precision measurements at J-PARC

We use this triangle in the ...  
but let us think about



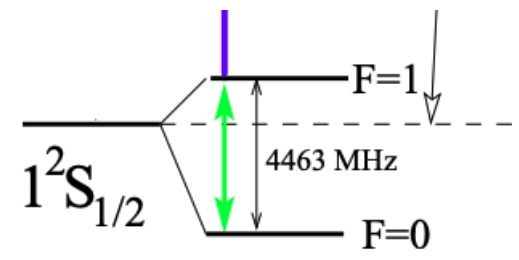
Detailed explanation by Patrick.

- Goal
  - ✓ **13ppb** determination of  $\mu_\mu/\mu_p \rightarrow$  Input for g-2 determination.
  - ✓ **2 ppb** measurement of  $\Delta\nu_{1S-HFS}$

J-PARC g-2/E

$$\nu_{34} - \nu_{12} \propto \frac{\mu_\mu}{\mu_p}$$

$$\Delta\nu_{1S-HFS} \approx \frac{16}{3} \alpha^2 R_\infty \frac{\mu_\mu}{\mu_B} \left(1 + \frac{m_e}{m_\mu}\right)^{-3}$$



MuSEUM

**Mu HFS**

muonium

$m_\mu$

**Mu 1S-2S**

muonium

# Muon/Muonium precision measurements at J-PARC

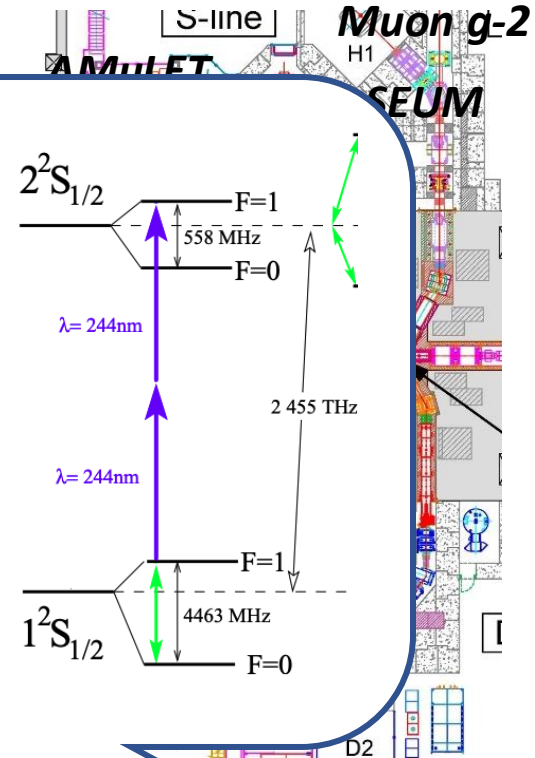
We use this triangle in the context of muon  $g-2$   
but

Laser spectroscopy of 1S-2S energy interval at J-PARC

- Goal
  - ✓ **100kHz** precision of the transition frequency
  - ✓ = **8ppb** determination of  $m_\mu/m_e$
- $m_\mu/m_e$  is input for muon-related theoretical calculation

Mu-MASS at PSI is also ongoing

$$\nu_{1S-2S} = \frac{3}{4} \frac{R_\infty c}{(1 + m_e/m_\mu)} [1 + \delta_{1S-2S}]$$



MuSEUM

Ongoing

Mu HFS

muonium

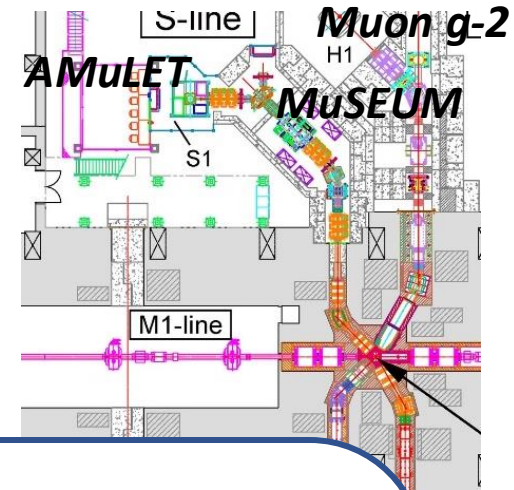
$m_\mu$

Mu 1S-2S

muonium

# Muon/Muonium precision measurements at J-PARC

We use this triangle in the context of muon g-2,  
but let us think about  $\alpha$  determination



J-PARC g-2/EDM (preparation)

g-2

Measurement of muon spin precession frq in magnetic field ( $\omega_a$ )

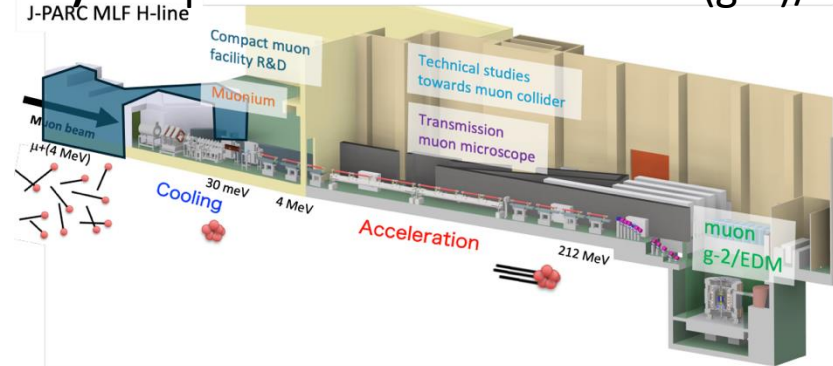
- + measurement of B-field by NMR probes ( $\omega_p$ )
- Goal
  - ✓ 460ppb ( $\rightarrow$ 100pb in the future) independent determination of  $(g-2)/2$

MuS

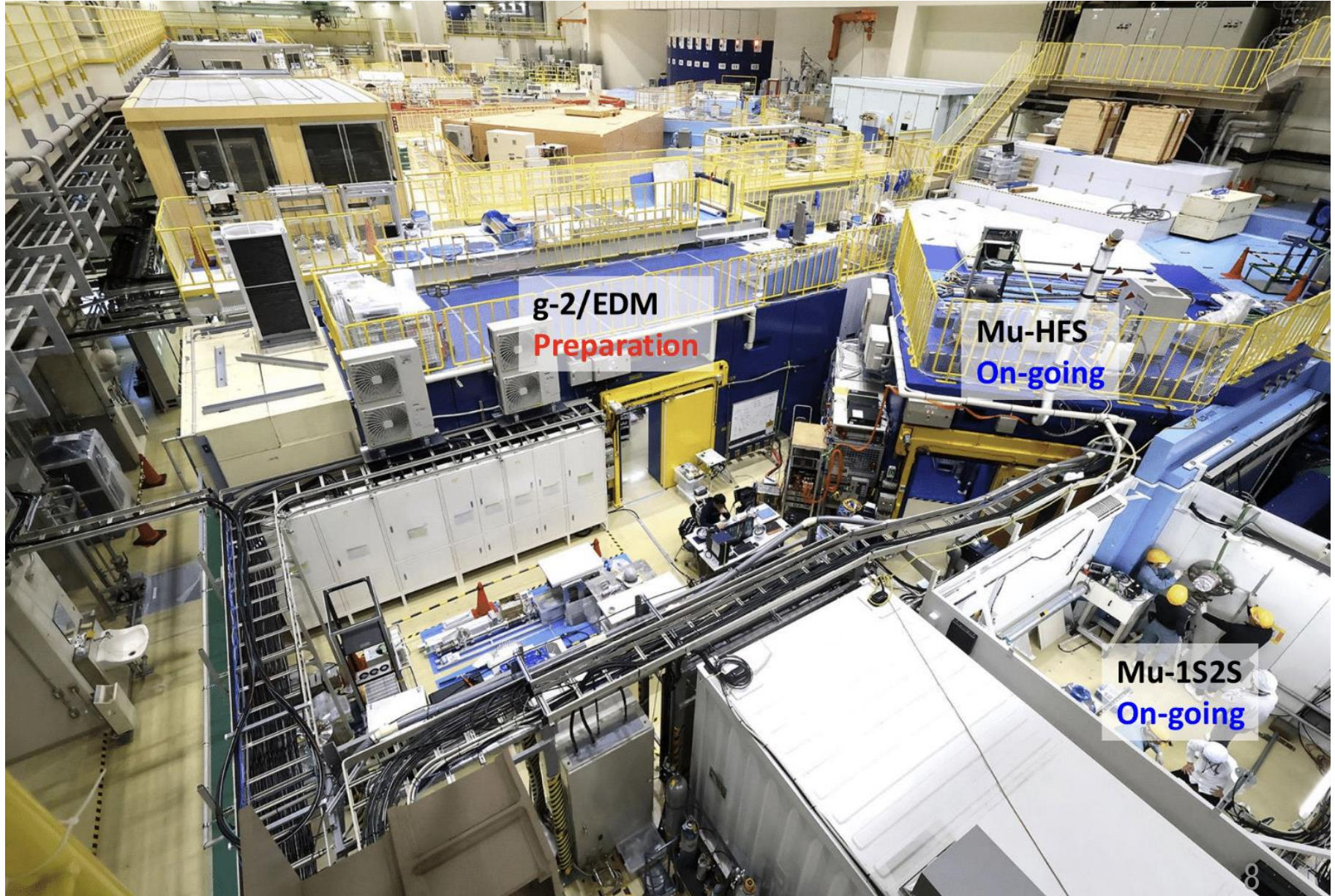


muon

$$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\frac{\omega_a}{\omega_p} - \frac{\mu_\mu}{\mu_p}}$$



# Experimental areas



**g-2/EDM  
Preparation**

**Mu-HFS  
On-going**


**Mu-1S2S  
On-going**



# Muon mass

- ✓ The uncertainty is dominated by uncertainty of  $m_\mu/m_e$ 
  - 120ppb, determined from Mu HFS  $\rightarrow \Delta \nu_{\text{HFS}}^{\text{th}} = 511 \text{ Hz}$
- The new input of  $m_\mu/m_e$  with better precision is necessary

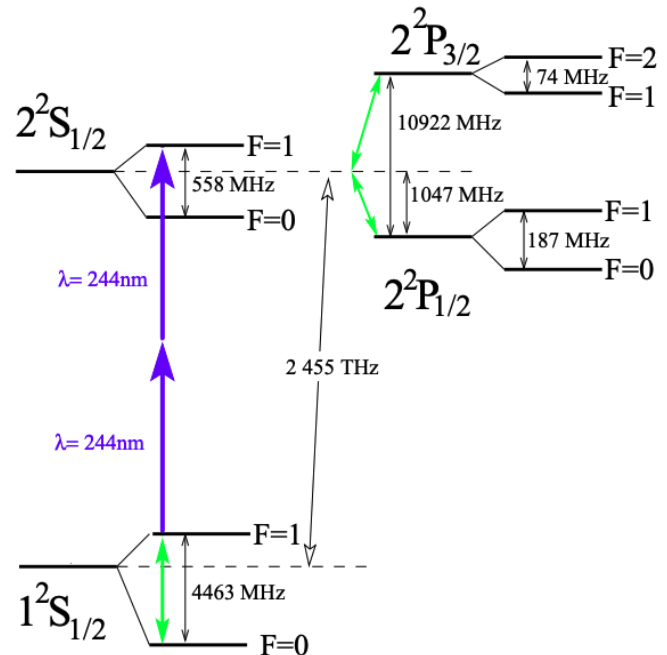
$$\checkmark \nu_{\text{HFS}}^{\text{th}} = 4463\,302\,868 \text{ (515) Hz} + 237\text{Hz} - 65 \text{ Hz}$$

  
 (511)(70)(2) Hz  
 $m_\mu/m_e$

HVP      Electroweak

- ✓ **Uncertainty of  $m_\mu/m_e$  should be < 1 ppb.**
- Mu 1S–2S experiments are underway towards the new determination of it.
- **1ppb precision ~ 10kHz precision of  $\nu_{1\text{S}-2\text{S}}$**

$$\nu_{1\text{S}-2\text{S}} = \frac{3}{4} \frac{R_\infty hc}{(1 + m_e/m_\mu)} [1 + \delta_{1\text{S}-2\text{S}}]:$$



# Muon g-2, HFS and HVP

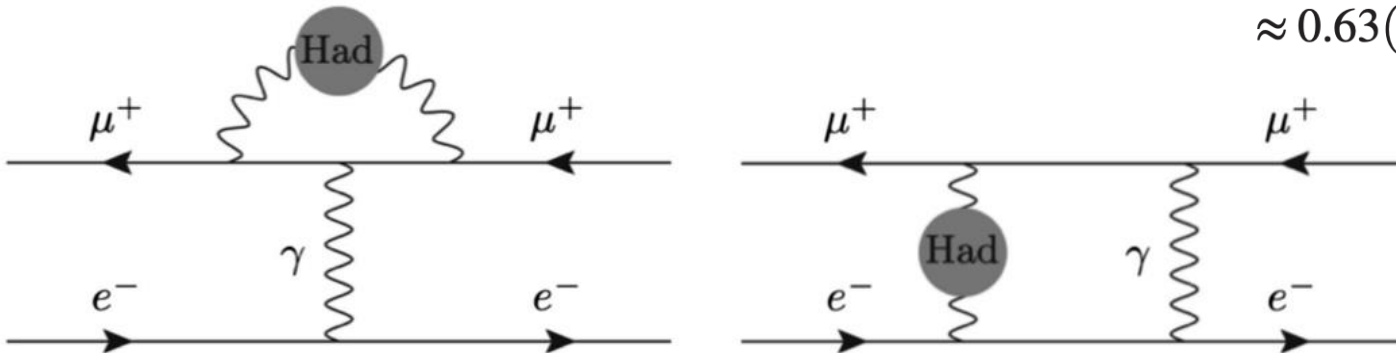
✓ Muonium HFS is also not free from **HVP contribution**

- This paper<sup>[1]</sup> discusses that prediction would be **shifted by 16Hz (~4ppb)** depending on the choice of HVP scenario, together with HVP contribution to  $a_\mu$  in  $\nu_{\text{HFS}}$ .
  - The paper originally discusses the best way to test the HVP (CMD3 or KNT19) from different observables.

$$\frac{\nu_{\text{HFS}}}{\nu_F} = 1 + a_\mu + \Delta_{\text{HFS}}^{\text{QED}} + \Delta_{\text{HFS}}^{\text{weak}} + \Delta_{\text{HFS}}^{\text{HVP}}$$

$$\nu_{\text{HFS}}^{\text{HVP}} = (a_\mu^{\text{HVP}} + \Delta_{\text{HFS}}^{\text{HVP}})\nu_F \approx 1.63\nu_F a_\mu^{\text{HVP}} \quad \Delta_{\text{HFS}}^{\text{HVP}} \approx 6 \frac{m_\rho^2}{m_\mu^2} K_{\text{Mu}}(m_\rho^2)(a_\mu^{\text{HVP}})_{e^+e^-}$$

$$\approx 0.63(a_\mu^{\text{HVP}})_{e^+e^-}.$$



# Intermission recap

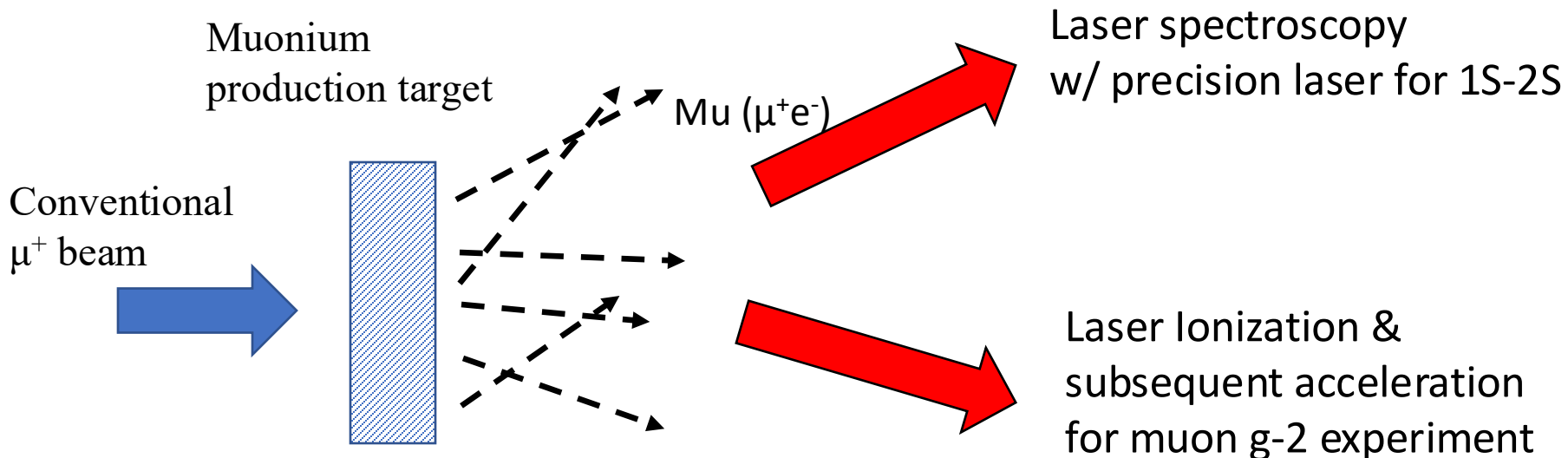
- Various muon/muonium experiments at J-PARC
  - MuSEUM → Talk by Patrick.
  - **Muon g-2 ← my main work**
  - **Muonium 1S-2S**
- **I will review the two experiment above.**
  - In addition, possibility towards better precision

	Current precision	Ultimate goal to determine $\alpha$	Ongoing at J-PARC
$\nu_{\text{HFS}}$ (exp)	<b>12 ppb</b>	<1ppb	<b>2ppb (MuSEUM)</b>
$m_{\mu}/m_e$	<b>120 ppb</b>	<1ppb ( $\Delta\nu_{1S-2S} \sim 10\text{kHz}$ )	<b>8 ppb (AMuLET)</b> ✳
QED calculation of $\nu_{\text{HFS}}^{\text{th}}$	<b>70Hz</b> (or <b>16ppb of <math>\nu_{\text{HFS}}^{\text{th}}</math> )</b>	5Hz ?? (~1ppb)	-

+ HVP scenario ~ 4ppb  
→ g-2 experiment

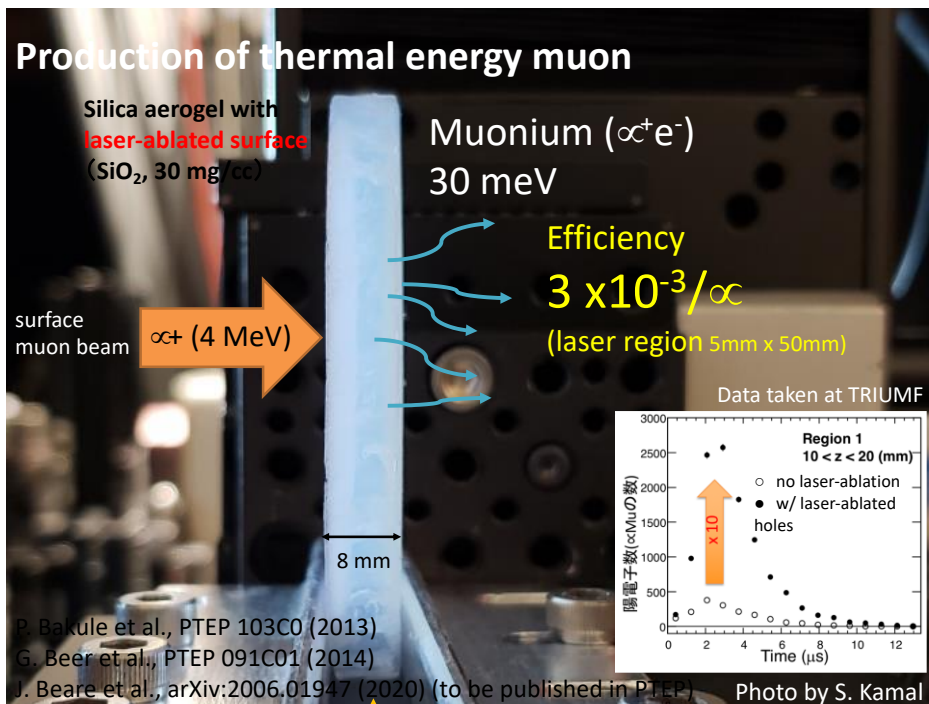
# Core technology for both experiment: muonium production target

- ✓ **Production of slow muonium** in vacuum is important.
  - Muon g-2: a tool for “cooling” of muon beam
  - 1S-2S: Obviously, it is necessary.
- Mu-target determines the statistical precision of both experiments. It also related to the systematic uncertainty.
- We need **more Muonium with slower velocity**.

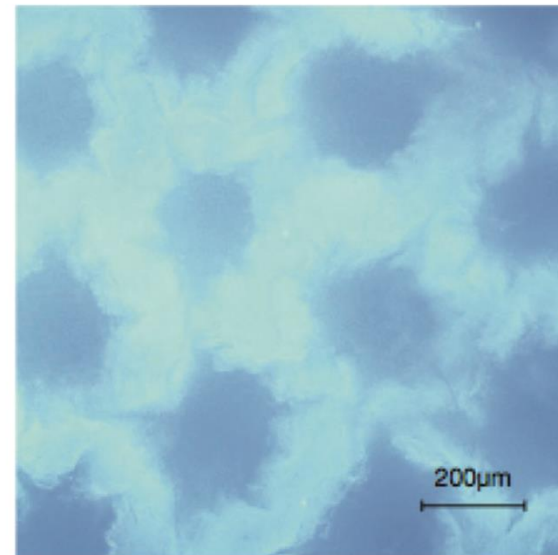


# Vacuum muonium source at J-PARC

- We invented a **laser ablated aerogel target for Mu production**
  - Conventional target
    - Tungsten target: 2000K → Lower temperature is better
    - Silica aerogel: low emission efficiency
    - Silica powder: good efficiency but less stable
- Emission efficiency is 10 times more than conventional SiO<sub>2</sub> target



Drilled by using a fs laser



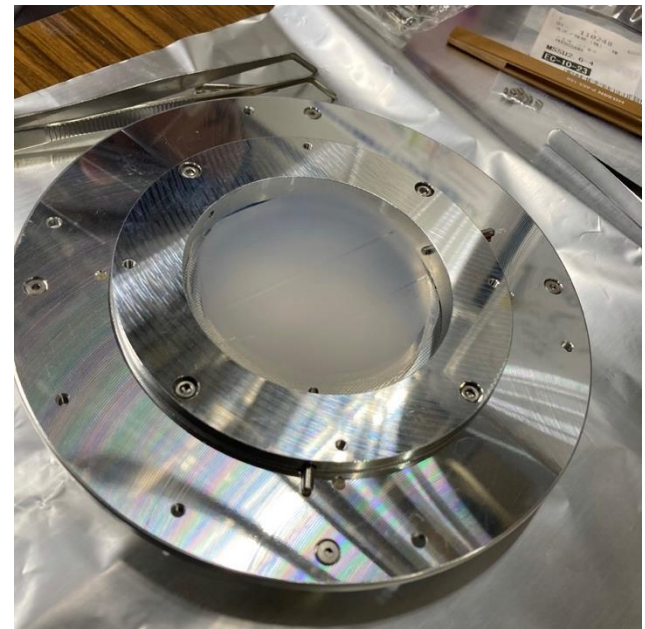
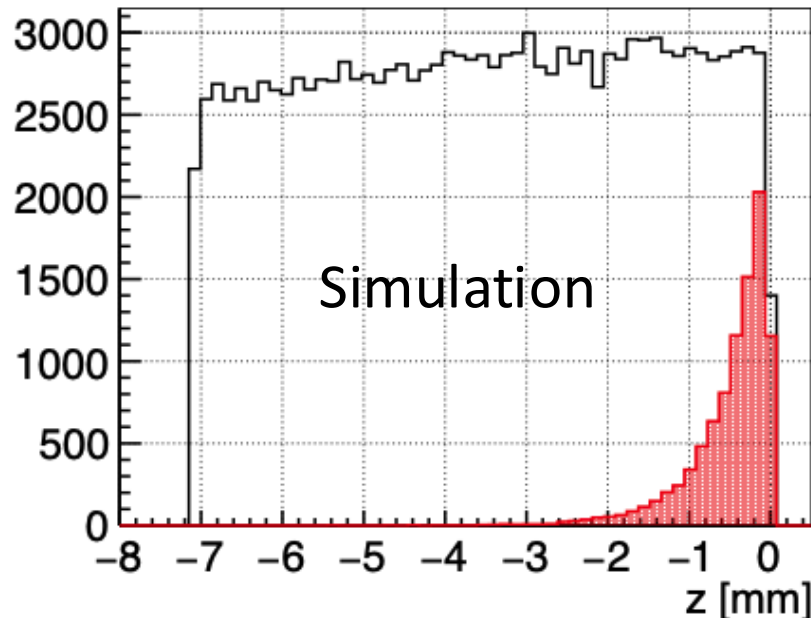
# Expected performance

- The Mu diffusion inside the target is modeled as a random walk inside it, based on the experimental data
  - ✓ Only muon stopping near the surface can be emitted into vacuum
  - ✓ Laser ablation = increase of effective surface
  - ✓ Mu is thermalized to the target temperature
- ✓ **~1 % total emission efficiency is expected. 300K = mean velocity is 8 km/s**

$\Phi$  80mm & t=7mm

Black: Mu initial distribution in target

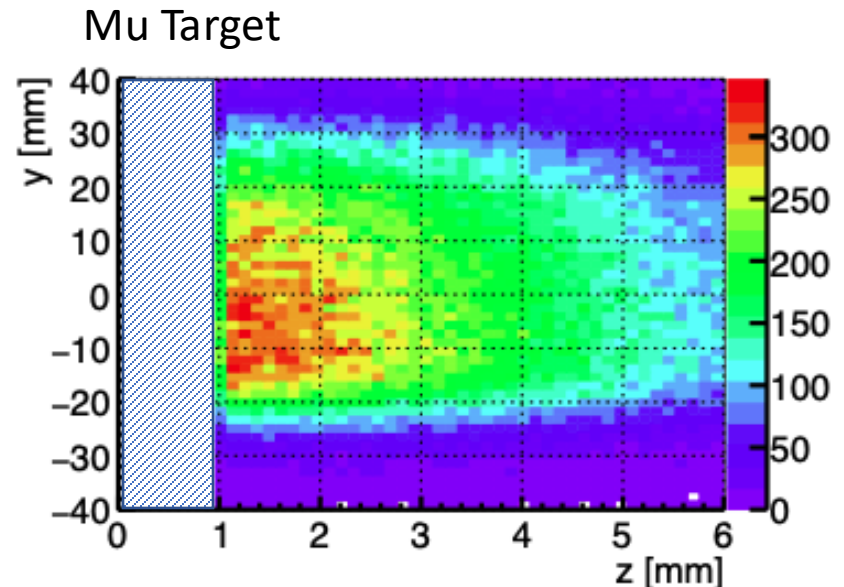
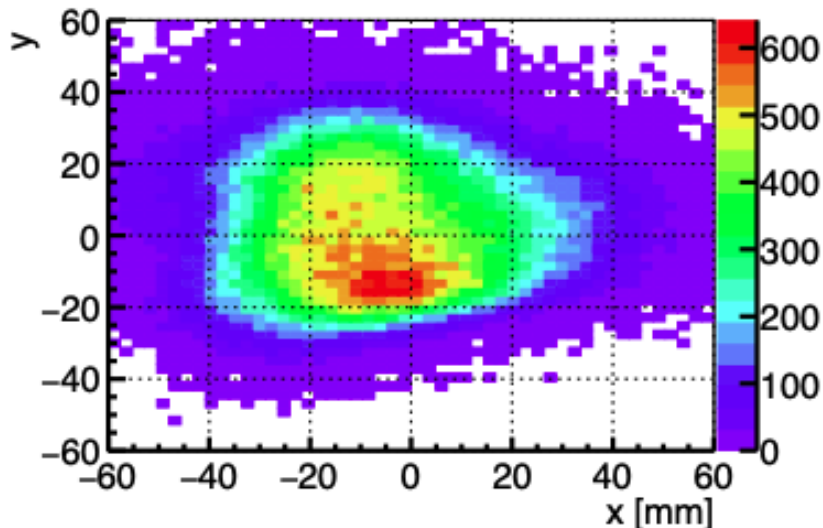
Red: Mu emitted to vacuum before decay



# Spatial distribution

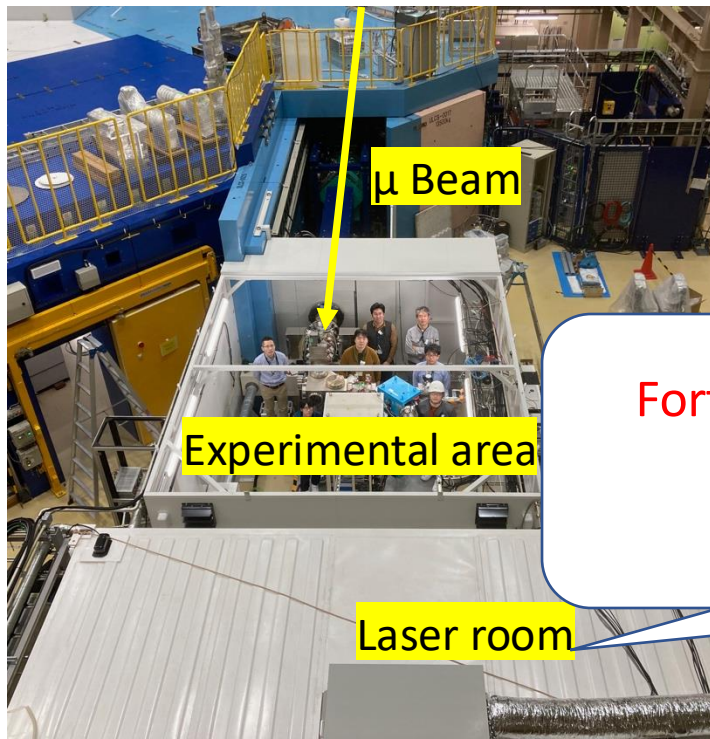
- Because the incident muon beam has a large spot size, the muonium cloud is broadly distributed
- For laser-related experiments, we either **need a very high-power laser** to cover the entire Mu cloud, or we can address **only a small fraction of it**.
  - Gradually emitted during a few  $\mu\text{s}$ .
  - Quickly escape from the laser spot ( $v \sim 8\text{mm}/\mu\text{s}$ )

Snapshot of muonium distribution after  $1.3\mu\text{s}$  of muon beam irradiation (simulation)



# Muonium 1S-2S laser spectroscopy experiment at J-PARC

- ✓ The AMuLET collaboration since 2019
  - PI: S. Uetake (Okayama university)
  - See his talk in SSP2025: [link](#)
  - Precise laser (Okayama univ) & Intense Pulsed  $\mu^+$  beam (J-PARC) & the laser ablated aerogel target
- Goal: 100kHz determination of  $\nu_{1S-2S} \rightarrow \Delta m_{\mu}/m_e = 8\text{ppb}$



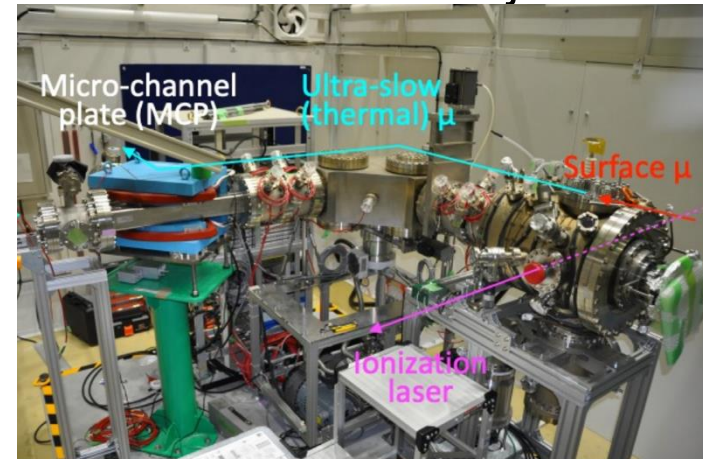
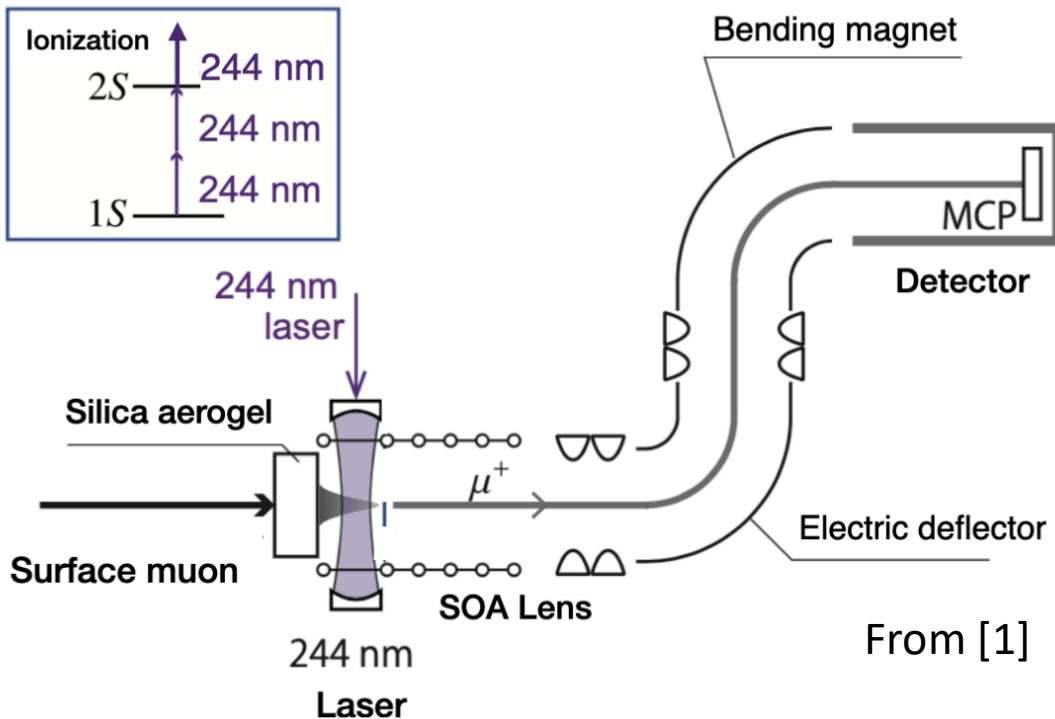
Currently, being performed at S2 area of S-line



Fortunately, there is a laser room for this experiment in the MLF.  
The laser is always here!

# Experimental setup

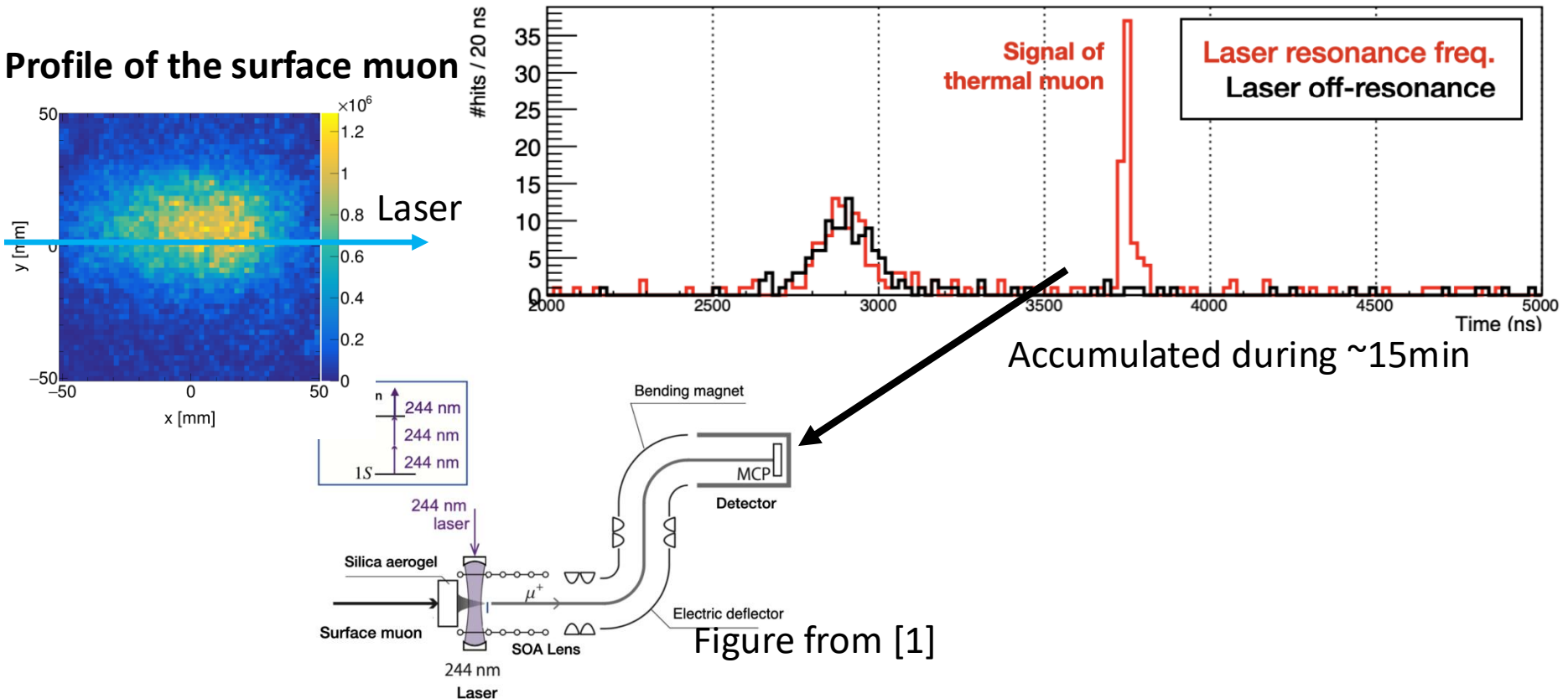
- Muon beam:  $1 \times 10^6 \mu/s$ , 25Hz  $\rightarrow$  # of Mu in vacuum  $\sim 10^3$  muonium/pulse
- Pulsed 244nm light source: 4HG of injection seeded Ti:S laser. (1mJ, 60ns, 25Hz)
  - Two photon excitation & ionization.
- Electrostatic lens & slow muon beamline: transport ionized muonium & rejection of background.
- MCP for signal detection (=ionized muon)



From [1]

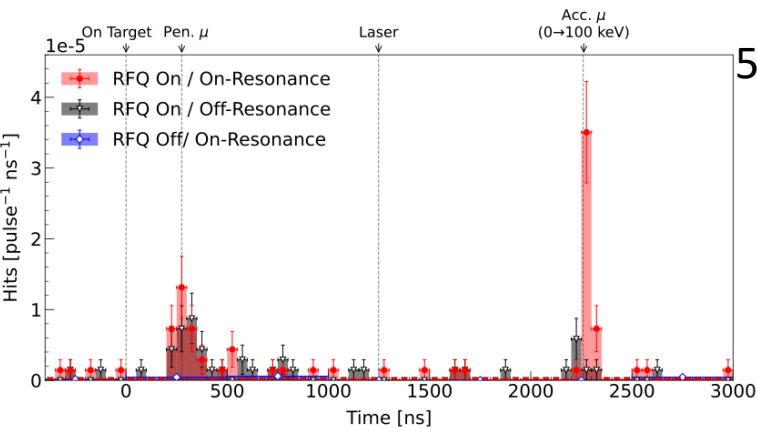
# Current status

- Pulsed muon & a pulse laser → **Clear signal can be observed at the MPC**
- **O(0.1)Hz of signal rate = ~100 times more than that of the previous experiment**
- ✓ **First signal in 2022.** Working on evaluation/reduction of systematic uncertainties.



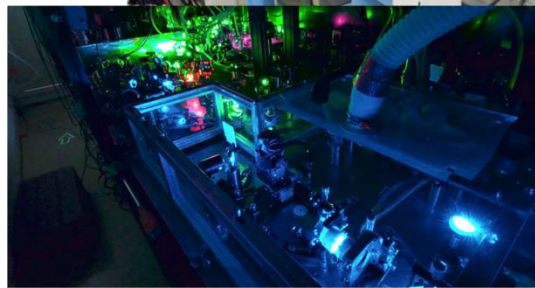
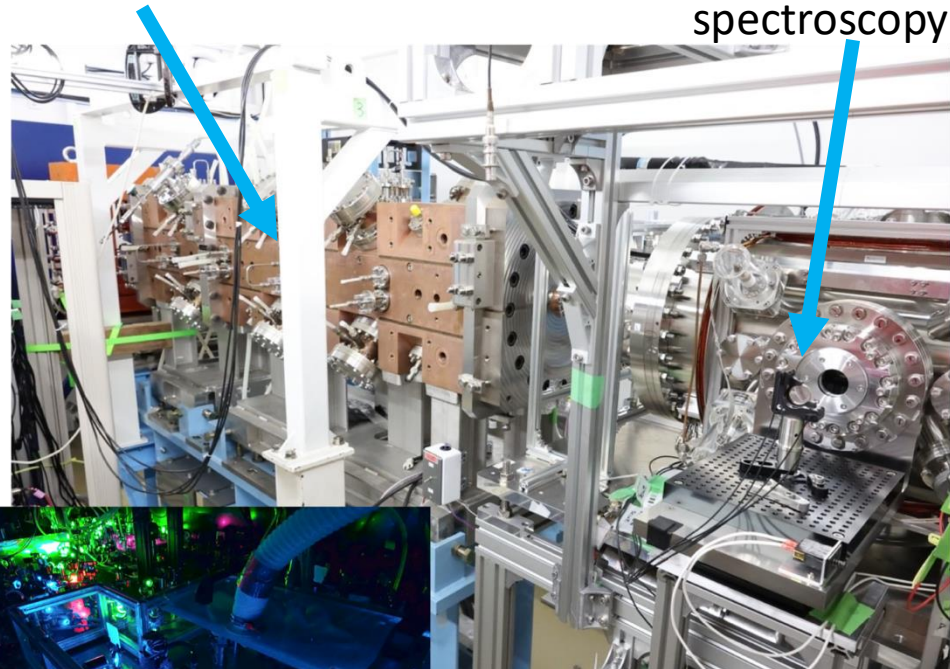
# Collaboration with muon g-2

- The world first demonstration of the RF-acceleration of muon.
- Ionized muon by 244nm laser was guided to the RF cavity (RFQ).
  - Phys. Rev. Lett. **134**, 245001 (editors' suggestion & cover image)



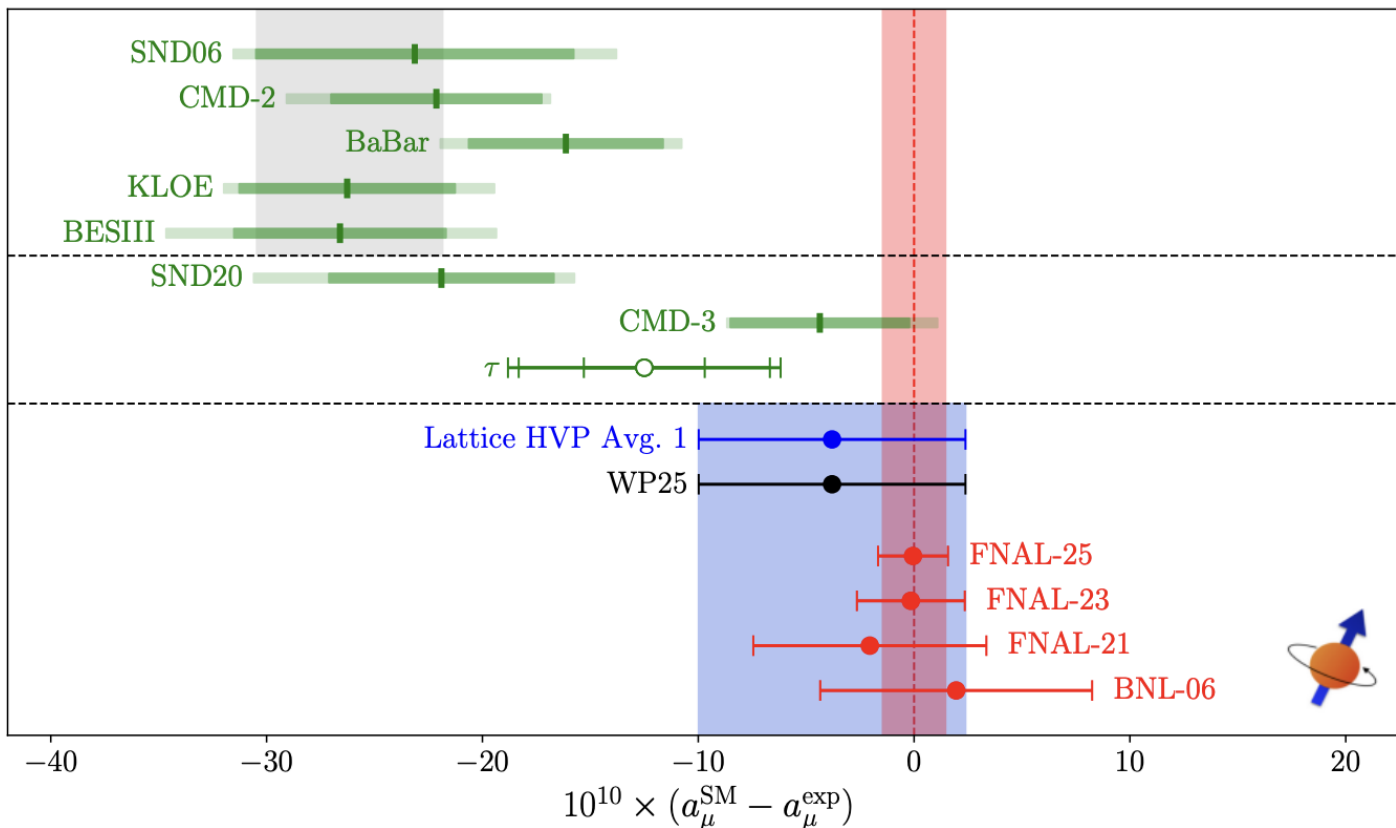
5.7keV→100keV acceleration cavity

Muonium production chamber & 244nm spectroscopy laser



# Muon g-2 experiment @ J-PARC

- Muon g-2: anomalous magnetic moment of muon
- Complicated situation: HVP contribution
- ✓ One important point: **an independent measurement of muon g-2 is lacking**
  - BNL, FNAL → the same approach using the same magnet



# Concept

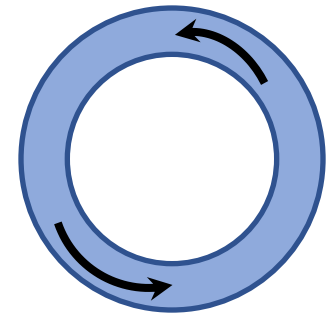
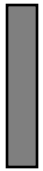
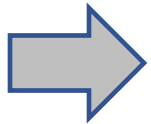
- Muon g-2 measurement is a storage ring experiment. Spin precession inside B-field
- The difficulty comes from **the quality of conventional muon beams. The storage of the muon beam is not so much simple.**
- Different from FNAL/BNL experiment, our idea is development of a good quality muon beam → **Cooling of positive muon + acceleration**

## *FNAL/BNL scheme*

Proton beam

Pion/muon beam

Momentum selection (3GeV)



Production target

$3\text{GeV}/c$

$1.45\text{T}$

*Storage ring: 14m*

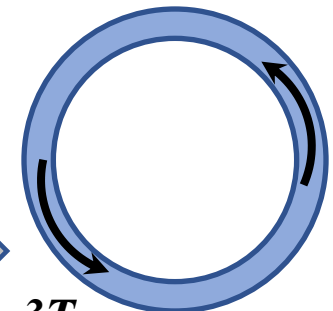
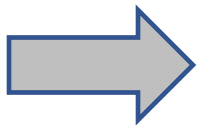
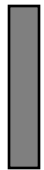
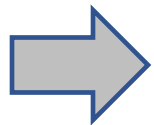
## *Our idea*

Proton beam

Pion/muon beam

**Muon cooling**

Muon accelerator



Production target

Momentum selection

$300\text{MeV}/c$

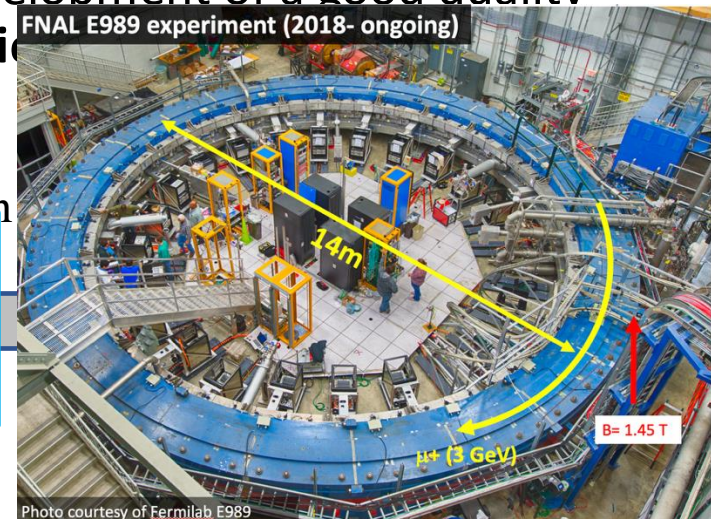
$3\text{T}$

*Storage ring: 66cm*

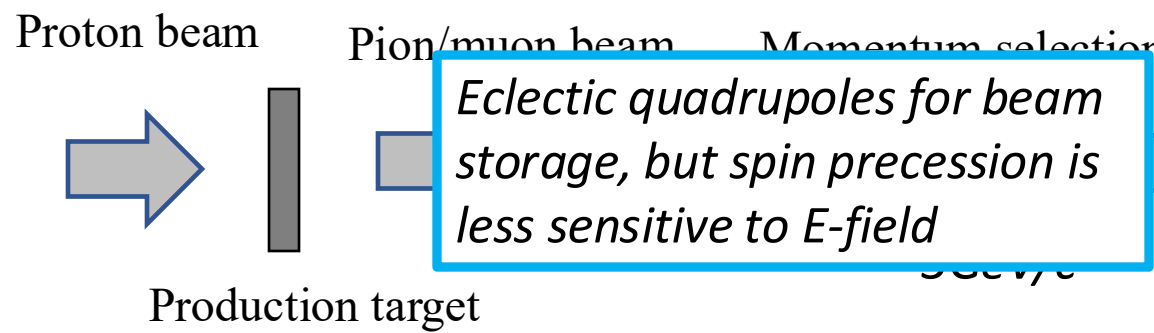
# Concept

- Muon g-2 measurement is a storage ring experiment. Spin precession inside B-field
- The difficulty comes from **the quality of conventional muon beams. The storage of the beam is not so much simple.**
- Different from FNAL/BNL experiment, our idea is development of a good quality muon beam → **Cooling of positive muon + acceleration**

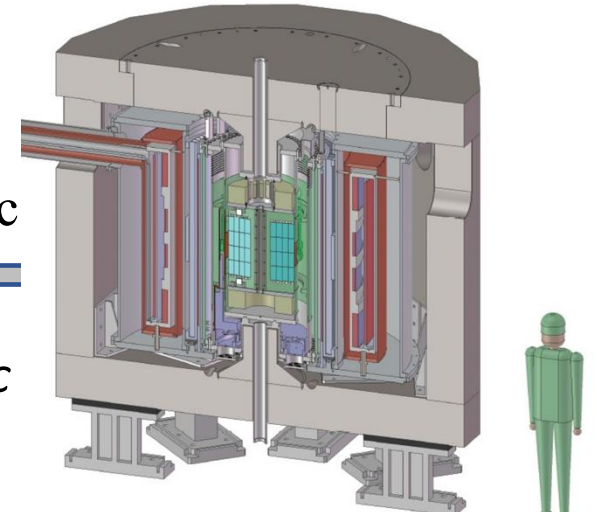
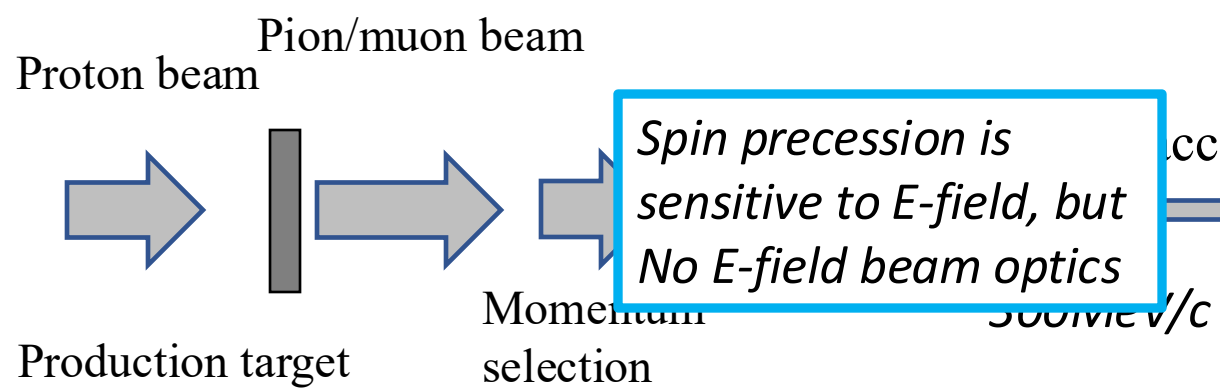
FNAL E989 experiment (2018- ongoing)



FNAL/BNL scheme

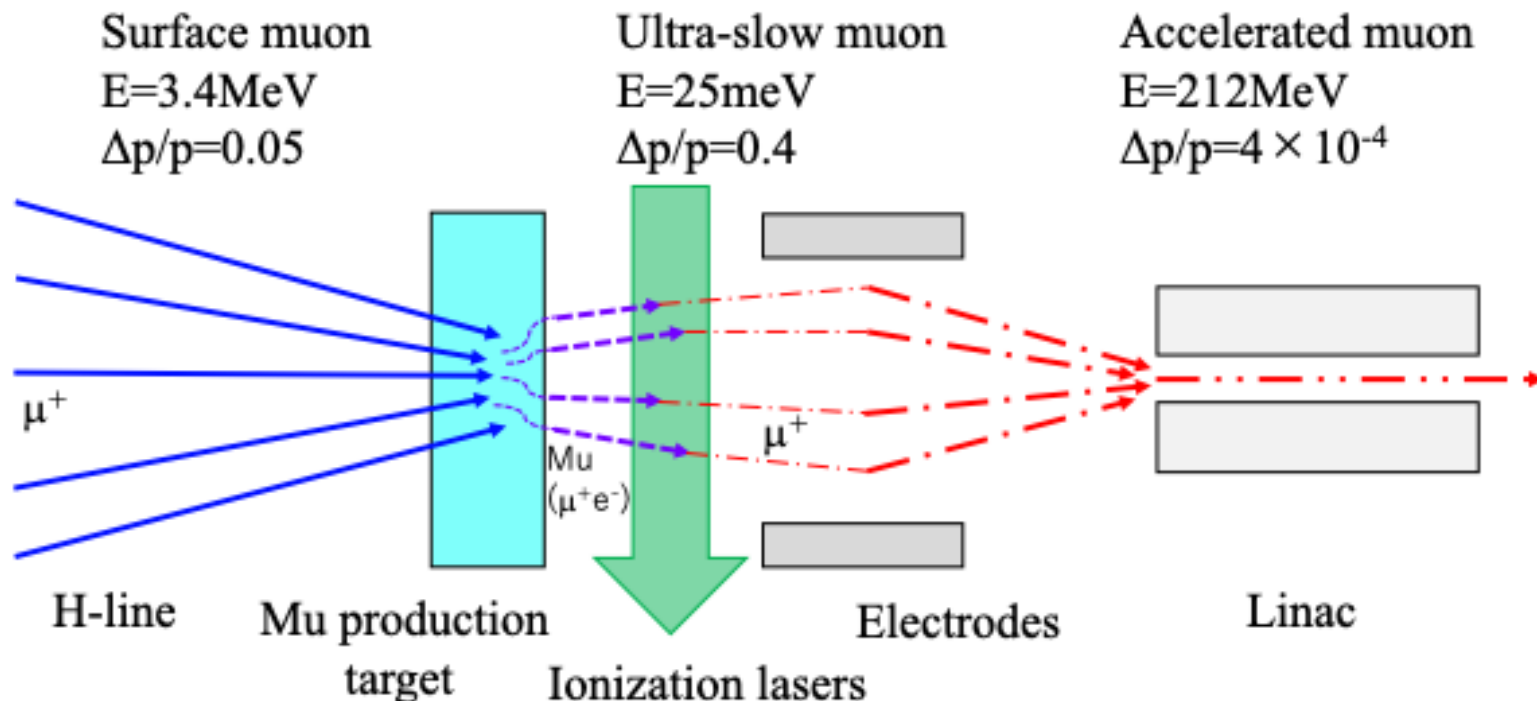


Our idea



# Muon cooling for the g-2 experiment

- **Muon cooling**: production of thermal muonium and laser ionization of it
  - The protocol is similar to the 1S-2S experiment, but we need a light source dedicated to **the efficient ionization of muonium**.
  - REMPI via 2P state using 122nm & 355nm light source
- ✓  $10^8$ -fold reduction of energy. (Normalized) Emittance is reduced from 1000 mm mrad to  $1 \pi$  mm mrad. About  $10^5$  muon/s @ storage ring is necessary .

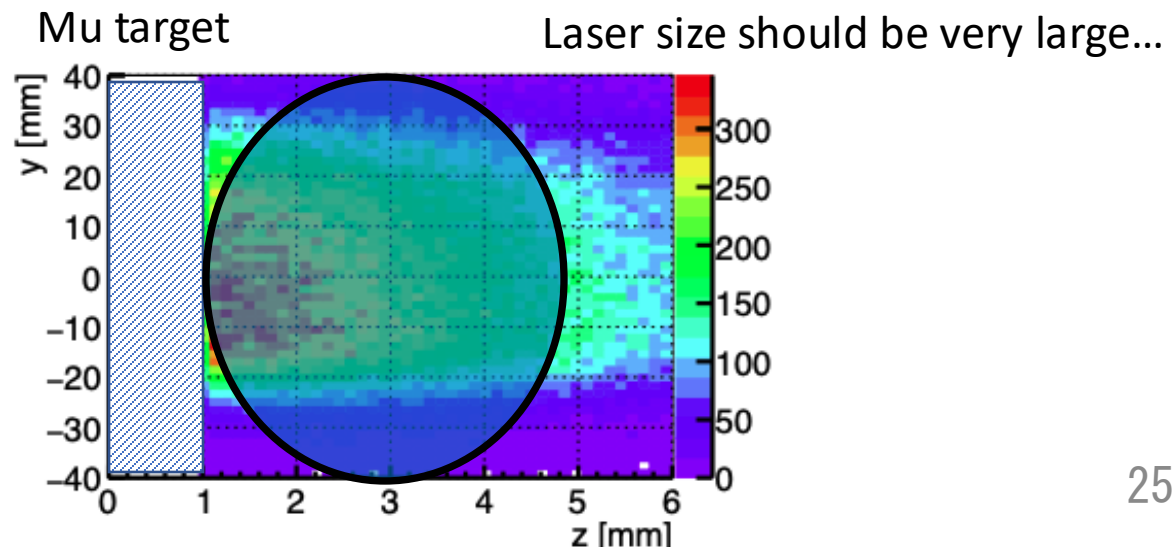
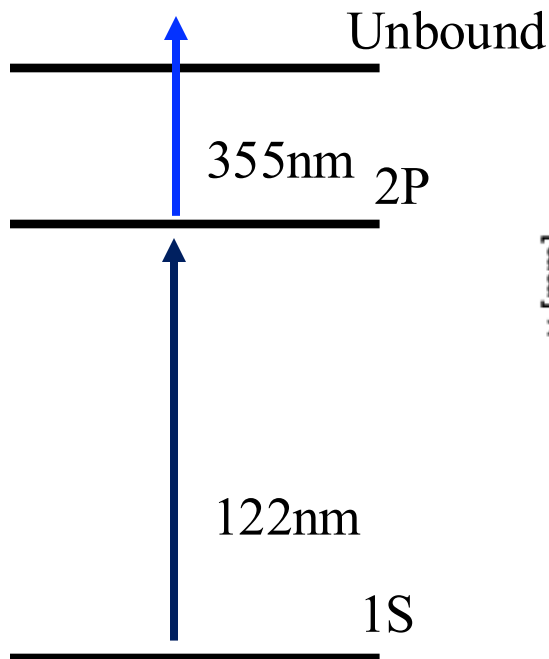


# Another core technology @ J-PARC: Intense 122nm light source

- Light source for Mu  $1S \rightarrow 2P$  excitation is challenging because of its short wavelength.
- Long history of intense 122nm pulsed light source development at J-PARC.
- Together with intense 355nm pulsed laser,  **$\sim 10\%$  ionization of Mu** is required.

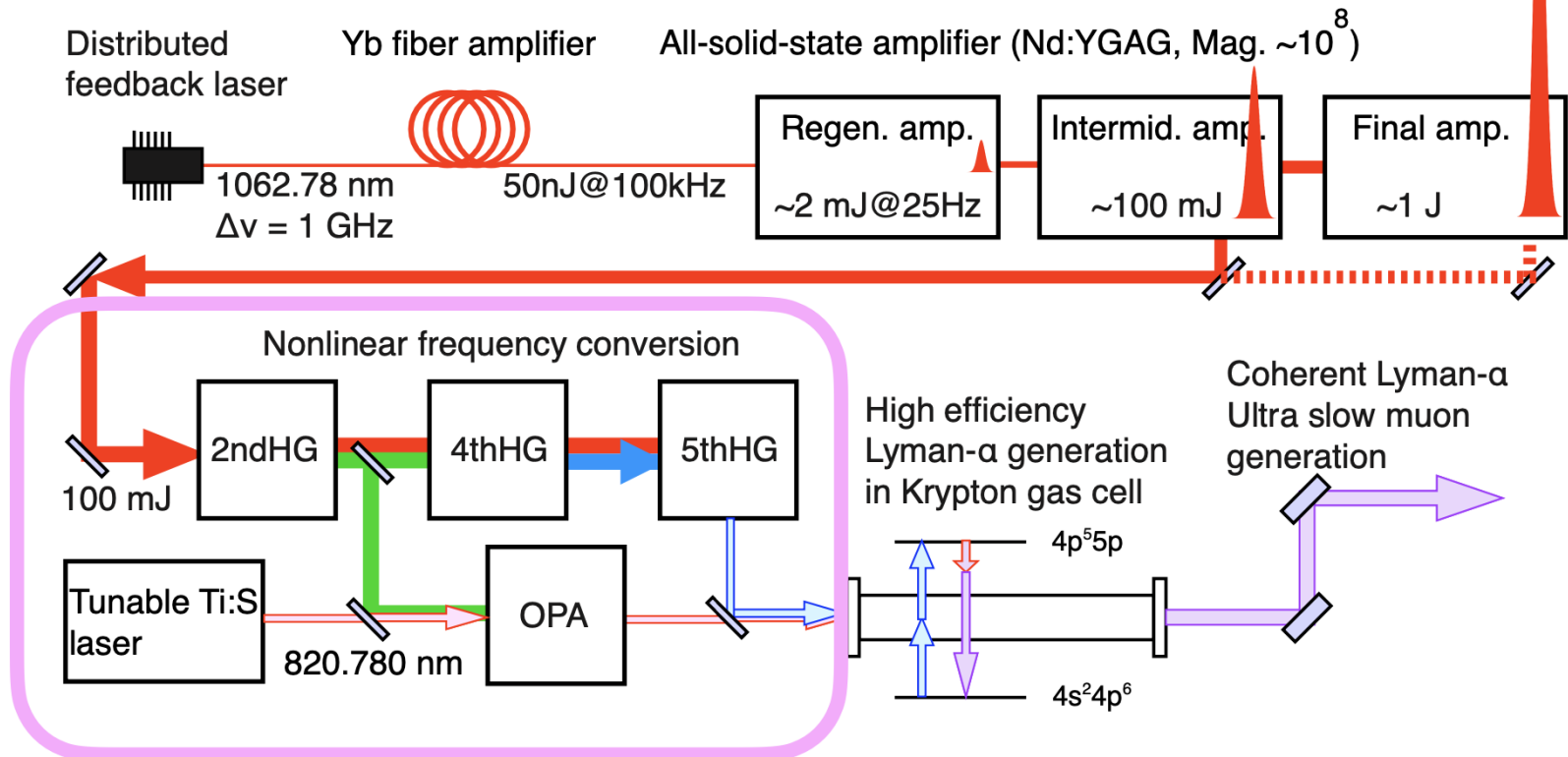
## Requirements

- **$100\mu\text{J}$**  to fully cover the muonium cloud
- **$25\text{Hz}$**  repetition rate
- **$80\text{GHz}$**  linewidth to match the doppler broadening
- **$2\text{ns}$**  pulse duration for pulse duration compression



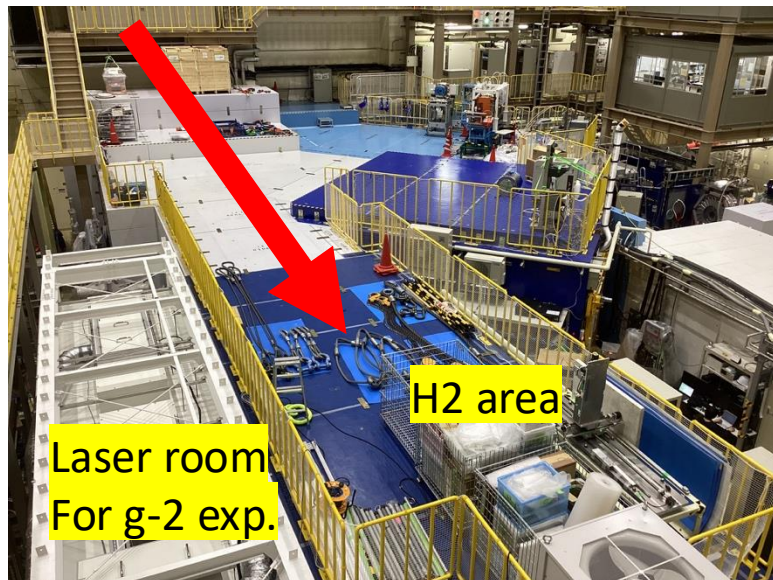
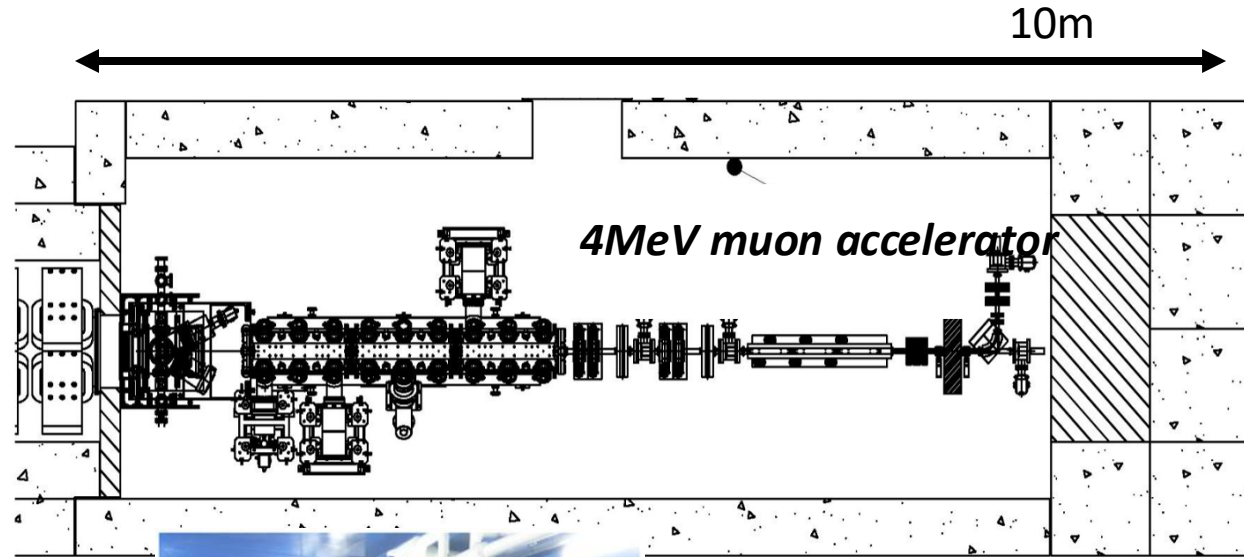
# Design of the light source

- Originally developed at different muon beamline at MLF
  - $\sim 25\mu\text{J}$  has been achieved  $\rightarrow$  Aiming  $100\mu\text{J}$  with the upgraded design
- VUV production: Four wave Mixing in a few meter-long Kr/Ar gas
  - 212nm coherent light** : 5thHG of 1063nm pulse
  - Frequency broadened 820nm pulse** from a Ti:S cavity



# Current status of the experiment

- Experimental area for muon cooling and 4MeV accelerator is ready
- Primary muon beam was successfully delivered in this April.
- Beamline for cooled muon transport is being installed.



Low energy muon transport

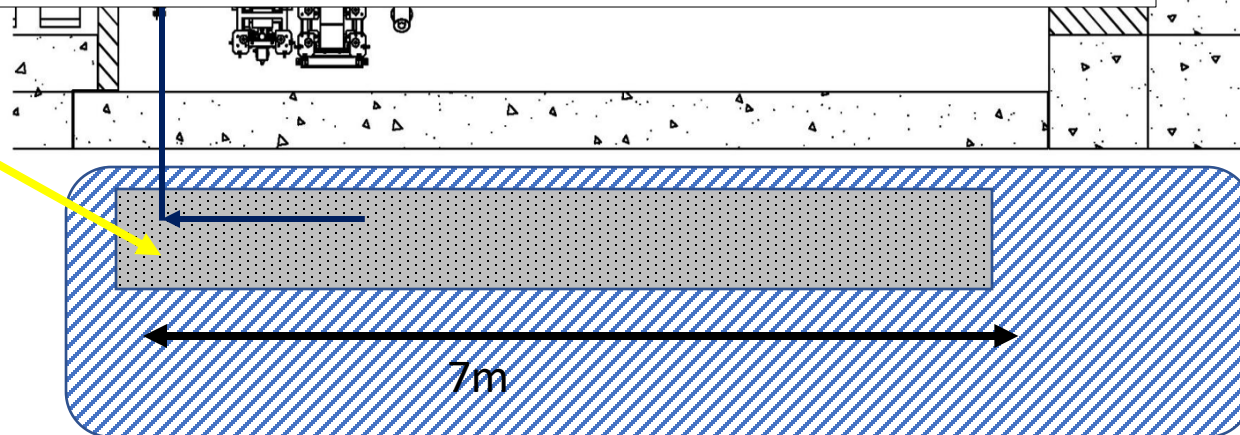
Under commissioning just now using 244nm laser for 1S-2S experiment

# Current status of laser

- A new laser room adjacent to the experimental area is also ready
- Construction of the light source is underway.
  - 3m-long gas cell for VUV production
  - VUV light transport chambers
  - Low energy operation from this winter → 0.5% ionization
  - All amplifiers & new 355nm laser by 2028 → 10% ionization.

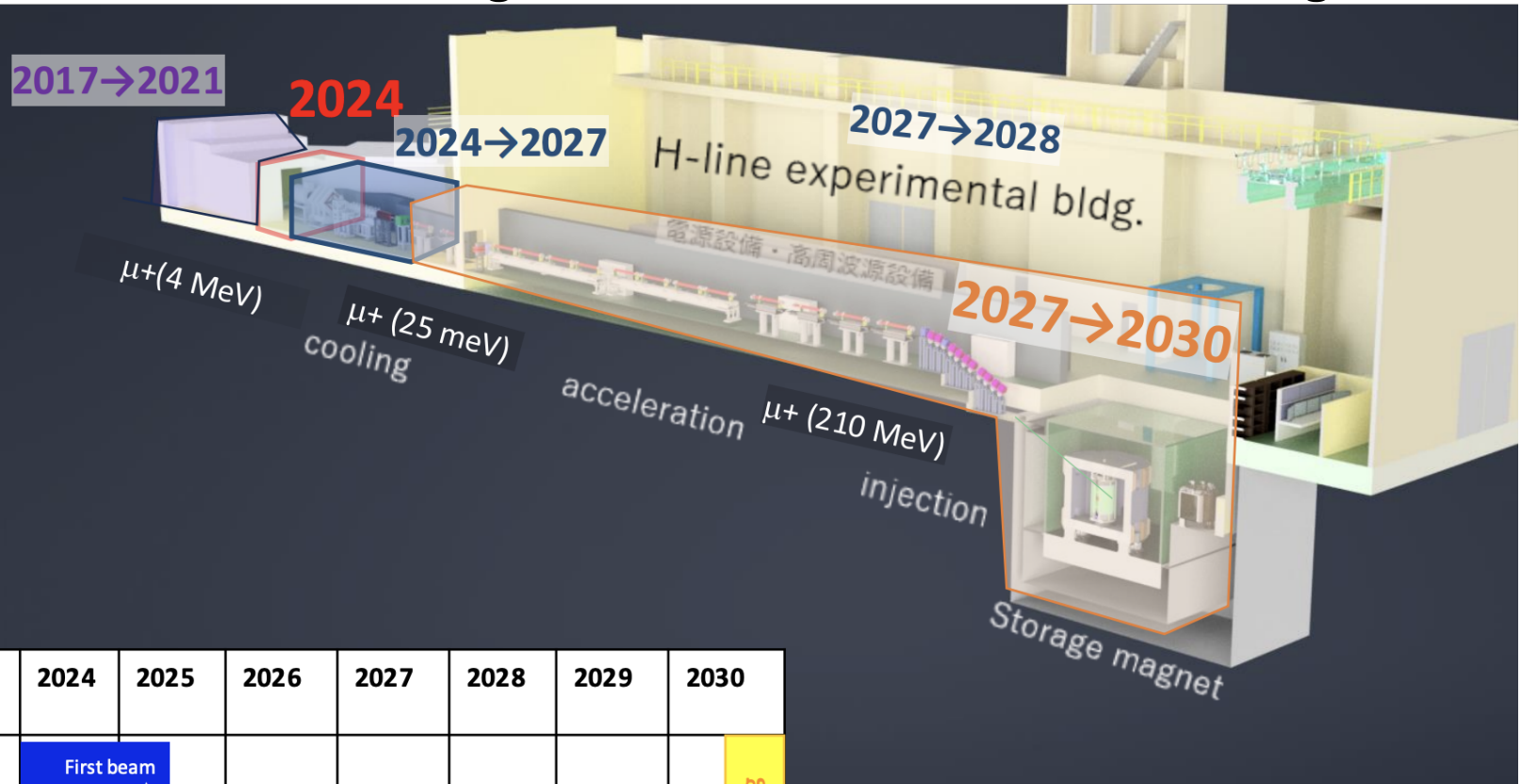


The first operation of this system is scheduled for his Dec.  
(beam time has been allocated, but the laser is not ready yet..)



# Towards the measurement

- We need a new building for muon accelerator & a 3T magnet



	2024	2025	2026	2027	2028	2029	2030
Beamline	First beam ★						
Bldg. & facility	design refinement				Construction		
Source, LINAC, storage	source	★ Ionization test at H2 area					
	LINAC	★ 4.3 Me@H2				210 MeV ★	
	Storage			procurement	Installation ★		
Detector	positron tracker magnetic field monitors					Installation ★	

Commissioning, data taking

## History

- 2009 proposal
- 2015 TDR
- 2016 IPNS focused review
- 2016 SAC (priority #3)
- 2019 KEK-IPNS stage-2, KEK-IMSS stage-2
- 2024 MEXT funding (partial construction)
- 2025 MEXT funding (partial construction)

# Comparison with other experiments

This table is old (compiled before FNAL result)

	BNL-E821	Fermilab-E989	Our experiment
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz $\gamma$	29.3		3
Polarization	100%		50%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric quadrupole		Very weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.37 $\mu$ s		2.11 $\mu$ s
Number of detected $e^+$	$5.0 \times 10^9$	$1.6 \times 10^{11}$	$5.7 \times 10^{11}$
Number of detected $e^-$	$3.6 \times 10^9$	–	–
$a_\mu$ precision (stat.)	460 ppb	100 ppb	450 ppb
(syst.)	280 ppb	100 ppb	<70 ppb
EDM precision (stat.)	$0.2 \times 10^{-19}$ e · cm	–	$1.5 \times 10^{-21}$ e · cm
(syst.)	$0.9 \times 10^{-19}$ e · cm	–	$0.36 \times 10^{-21}$ e · cm

$$\frac{\sigma_{\omega_a}^{\text{exp}}}{\omega_a} = \frac{\sqrt{2}}{\gamma \tau A \sqrt{N_0}} \frac{1}{\omega_a} ; \quad \begin{array}{l} \text{Pros: smaller syst. \& no correction on } \omega_a \\ \text{Cons: shorter lifetime } (\gamma) \end{array}$$

# Comparison with other experiments

This table is old (compiled before FNAL result)

	BNL-E821	Fermilab-E989	Our experiment
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz $\gamma$	29.3		3
Polarization	100%		50%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric quadrupole		Very weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.37 $\mu$ s		2.11 $\mu$ s
Number of detected $e^+$	$5.0 \times 10^9$	$1.6 \times 10^{11}$	$5.7 \times 10^{11}$
Number of detected $e^-$	$3.6 \times 10^9$	–	–
$a_\mu$ precision (stat.)	460 ppb	100 ppb	450 ppb
(syst.)	2%		<70 ppb
EDM precision (stat.)	$0.2 \times 10^{-21}$ e · cm		$6 \times 10^{-21}$ e · cm
(syst.)	$0.9 \times 10^{-21}$ e · cm		

Timing shift due to the pile up of decay positron (36ppb) and Position accuracy of the field mapping NMR probe (45ppb) would be the dominant source

$$\frac{\sigma_{\omega_a}^{\text{exp}}}{\omega_a} = \frac{\sqrt{2}}{\gamma \tau A \sqrt{N_0}} \frac{1}{\omega_a}$$

tion on  $\omega_a$

# Towards better sensitivity

We may want

- $\sim$  ppb precision of  $\mu\text{HFS}$
- $\sim$  pbb precision of  $\mu$   $1S-2S$  ( $<10\text{kHz}$ )
- Understanding of HVP contribution
- (reduction of bound state QED calculation uncertainty)

# Improvement of g-2 sensitivity

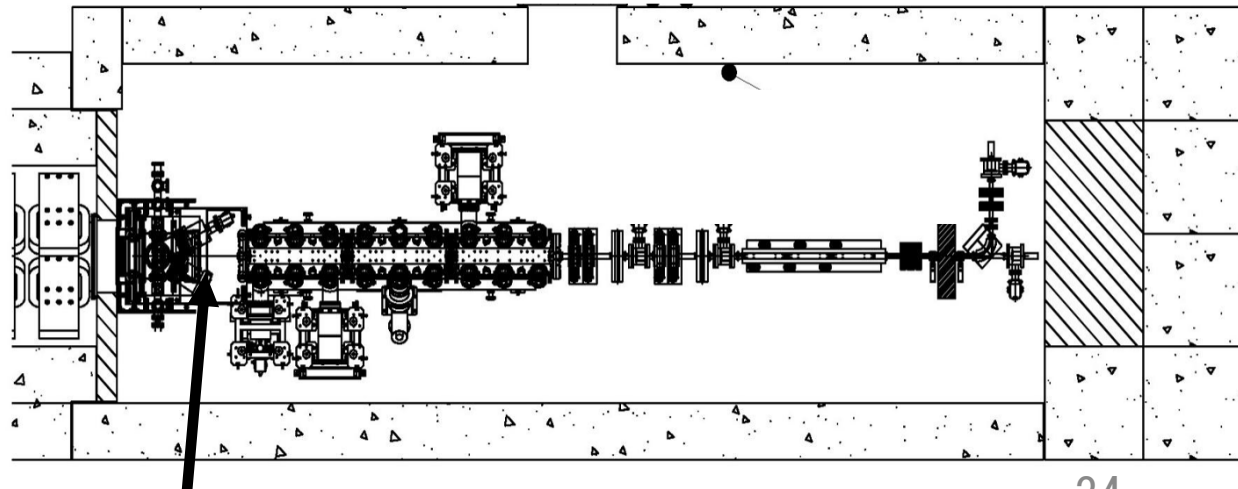
- Our target sensitivity is 460ppb → **another factor 4 improvement** is required to be comparable to the FNAL g-2 result.
- We are discussing the upgrade strategy
  - **Higher energy : 200MeV → ??**
  - **Stronger magnetic field: 3T → ??**
  - **Optical pumping of Mu: 50% of spin polarization → < 100%**
  - **More Mu target + more laser energy: another × 5 more cooled muon??**

$$\frac{\Delta\omega_a}{\omega_a} = \frac{1}{\omega_a \gamma \tau P} \sqrt{\frac{2}{NA^2}} \quad \omega_a = a_\mu \frac{eB}{m}$$

An internal team has been newly formed in this year to discuss the higher sensitivity upgrade more seriously

# Synergy between g-2 & Mu laser spectroscopy exp.??

- ✓ Though the **experimental area for the g-2 experiment was designed for the g-2 experiment**, the environment is rather suitable for the Mu laser spectroscopy.
  - Intense muon beam: **× 100** compared to the beam for 1S–2S spectroscopy
  - **Muonium production target**: permanently installed in the area
  - **Clean room**: w/ vacuum chamber to the experimental area
  - **Ionized muon detection system**: permanently installed in the area
- **Mu laser spectroscopy w/ better precision would be possible ?**
- **Any other interesting laser spectroscopy???** 1S–X ?

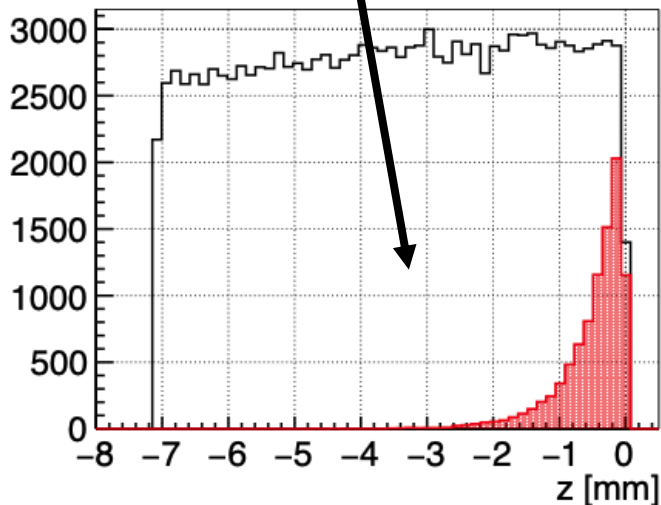


There is a compact beamline to study the ionized muon

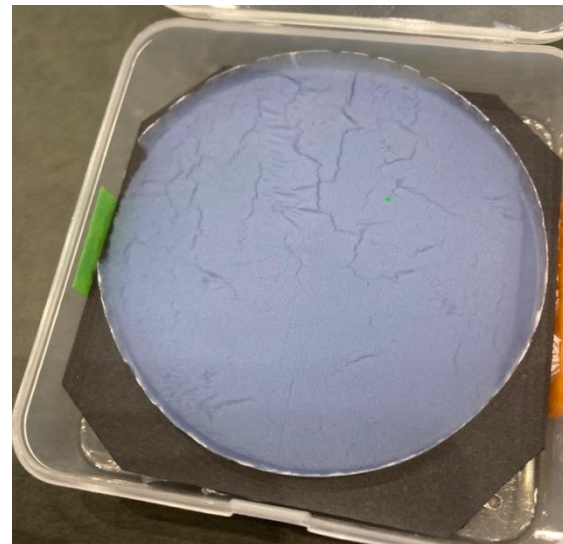
# Lower temperature Mu target

- Velocity of thermal muonium is fast:  $v \sim 8\text{mm}/\mu\text{s}$ 
  - Transit time broadening ( $d \sim 1\text{mm}$ ):  $\sim 3\text{MHz}$  & 2<sup>nd</sup> order doppler:  $\sim 1\text{MHz}$
  - **Natural width: 150kHz** ← ultimate goal.
- ✓ We may need a cold target. Current target is too bulky to be cooled.
  - In addition: Low temperature → slower Mu diffusion → More Mu decay.
  - Smaller & thin target → Less muon stopping inside the target.

Even under the 300K condition,  
these Mu decay before emission

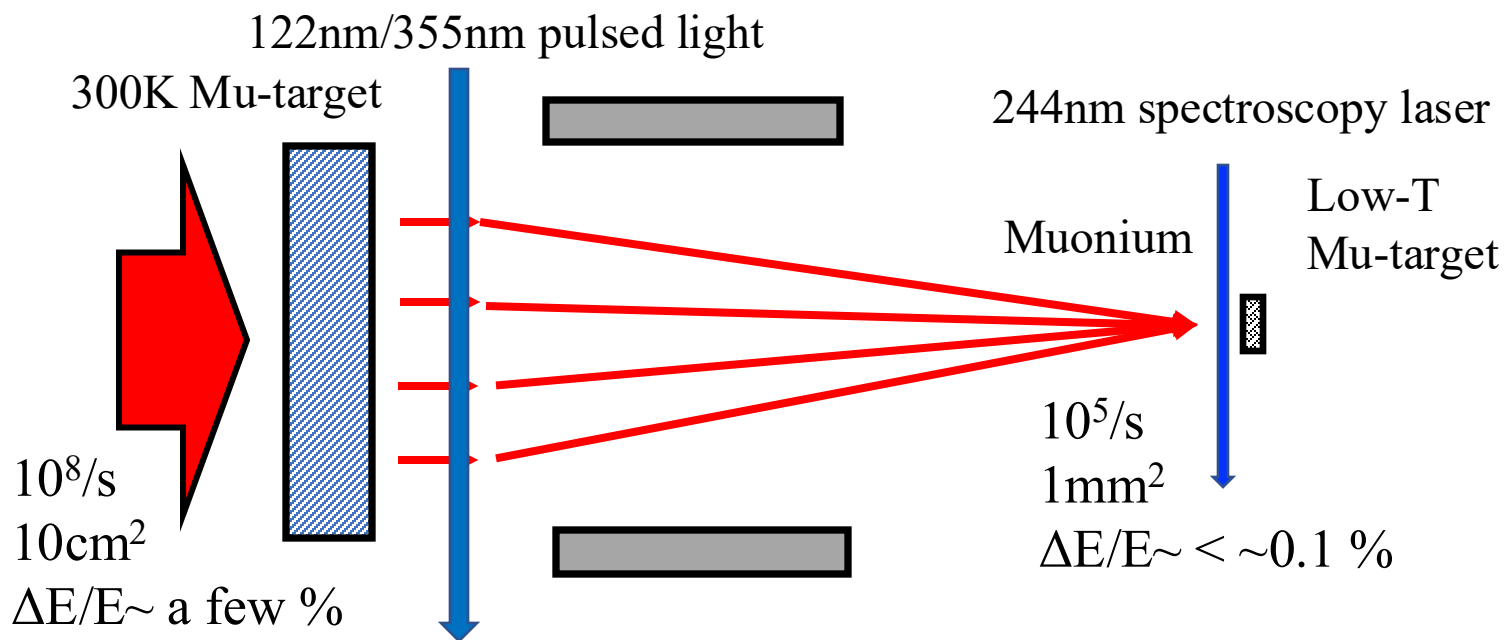


$\Phi 80\text{mm}$  &  $t=7\text{mm}$



# Reproduction of muonium from the cooled muon beam ??

- Cooled muon beam for g-2 exp. is as intense as  $10^5 \mu/s$ ,  $\sim 10\text{keV}$  and can be focused to 1mm size.
  - This is huge improvement compared to the conventional beam !!
- Multiple step of  $\mu$  cooling has been proposed for  $\mu$  microscope and under R&D.
- We may have a chance to install a thin & compact Mu target with low temperature.



# Towards determination of alpha at J-PARC...

- Various programs are ongoing. Near future milestones are...
  - ✓ Competition of MuHFS: 2ppb determination of  $\Delta v_{\text{HFS}}$
  - ✓ Determination of muon mass: 100kHz (AMuLET)
  - ✓ HVP,  $a_{\mu}$   $\rightarrow$  g-2 experiment with independent method: 460ppb
- In the future, we need
  - ✓ MuHFS: another factors of improvement is necessary. How ??
  - ✓ Muon mass  $\rightarrow$  H-line & cold Mu source ?
  - ✓ HVP,  $a_{\mu}$   $\rightarrow$  higher spin polarization, higher energy, higher magnetic field ???

# Summary

- J-PARC is one of the most intense muon facility in the world
- ✓ Various muon/muonium experiments are underway
  - MuSEUM
  - AMuLET
  - Muon  $g-2$ /EDM
- ✓ Combination of them (together with further improvement of the sensitivity) would make the independent determination of  $\alpha$  possible
  - ✓ In addition, we need the improvement of bound state QED