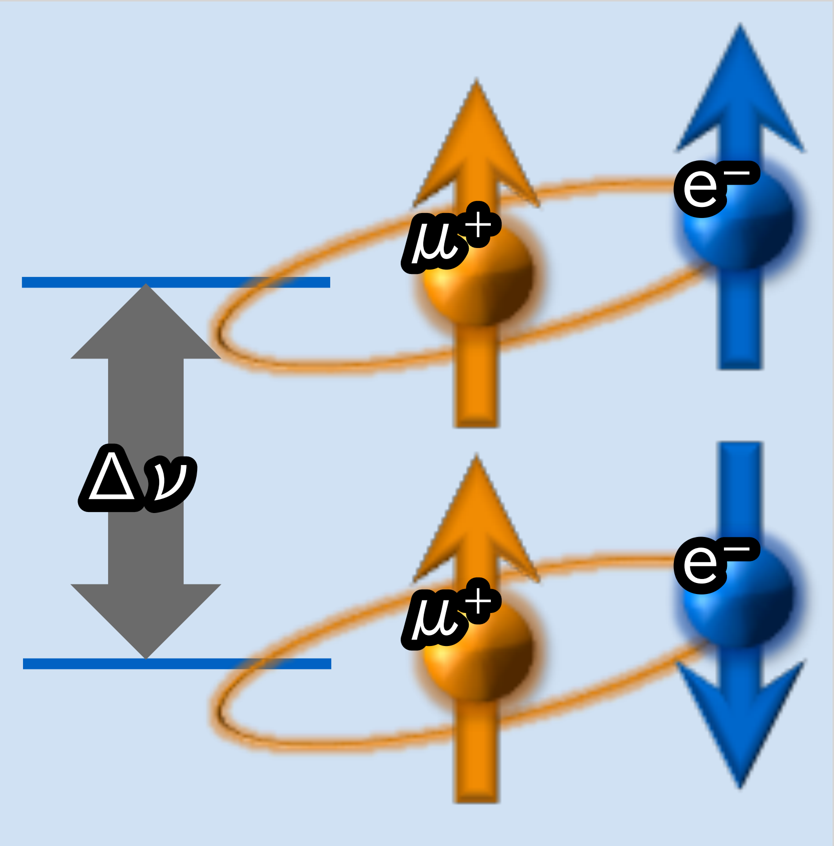
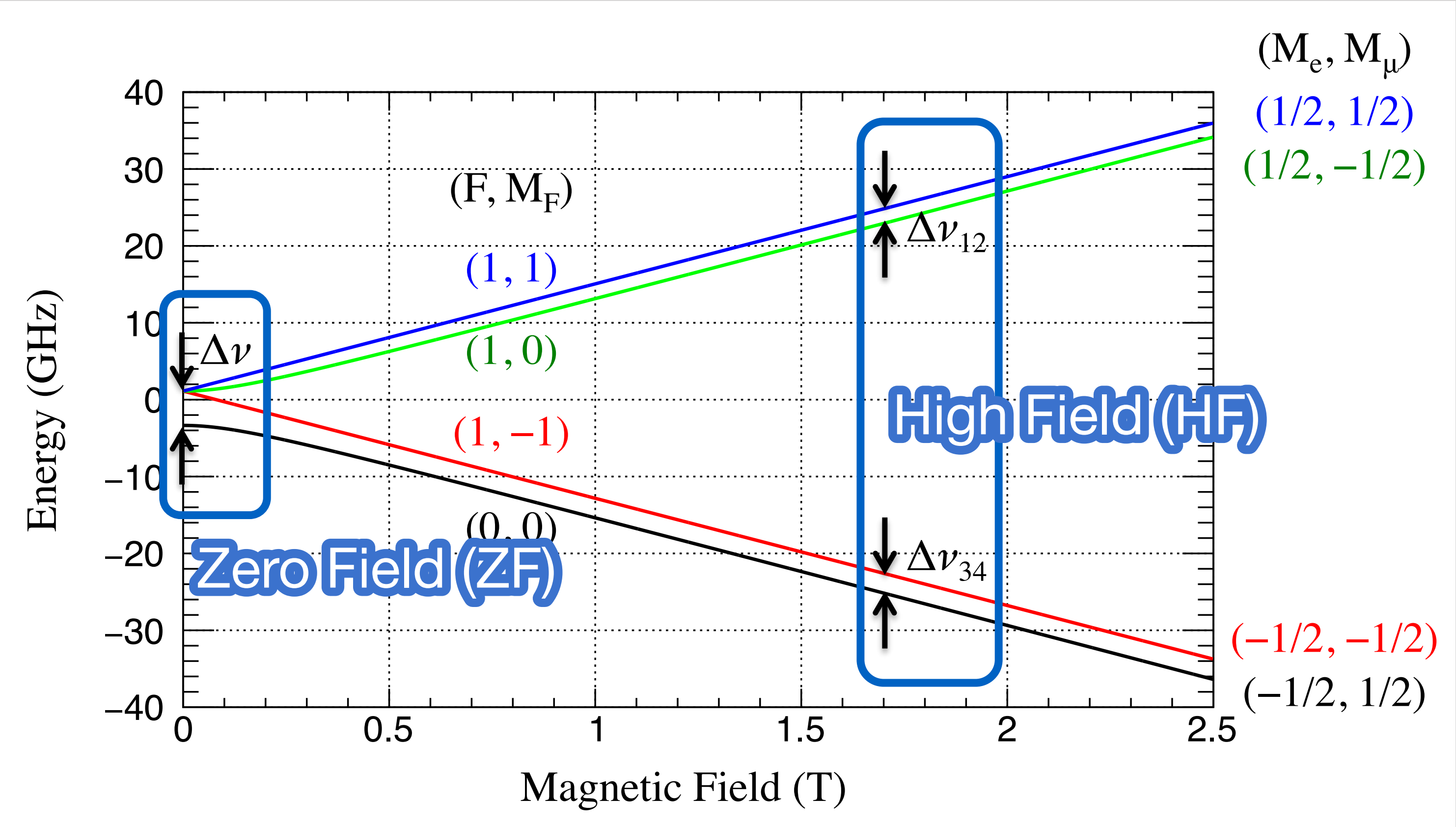
Precision Measurement of Muonium Hyperfine Structure at J-PARC

Shoichiro Nishimura
KEK IMSS / J-PARC
(MuSEUM Collaboration)

Muonium HFS

Muonium | Bound state of μ^+ and e$^-$





Experimental value Δ ν

ZF | 4 463 302.2(14) kHz (310 ppb)

HF | 4 463 302.765(51)(17) kHz (12 ppb)

Phys. Lett. B**59** (1975) 397-400 , Phys. Rev. Lett. **82** (1999) 711-714

$$\nu_{12} + \nu_{34} = \Delta\nu$$

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

Statistic uncertainty is dominant

Our goal | ~2ppb

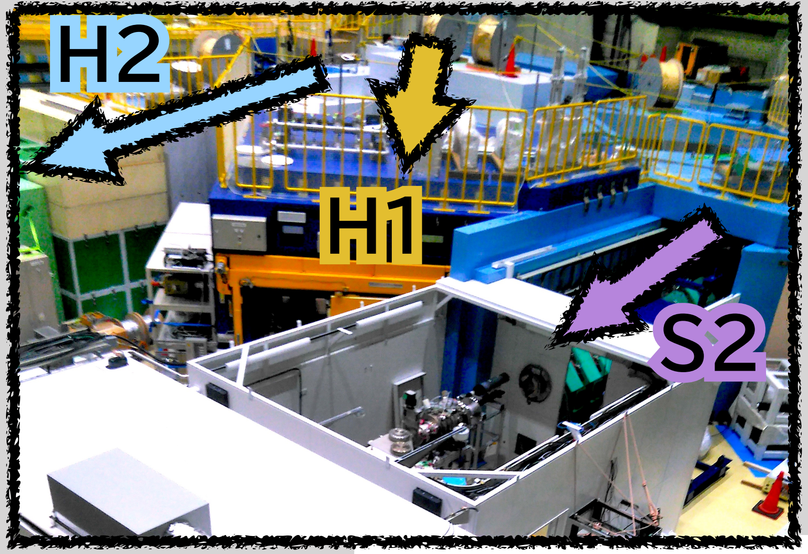
Most precise Test of Bound State QED

ν_{HFS}(theory)	4463.302 868 (515) MHz[120 ppb]
ν_{HFS}(QED)	4463.302 720 (511) (70) (2) MHz
	(m_μ/m_e) (QED) (α)
ν_{HFS}(weak)	-65 Hz
ν_{HFS}(had. v.p.)	232 (1) Hz
ν_{HFS}(had. h.o.)	5 (2) Hz

$$\nu\,(\mathrm{Fermi}) = \frac{16}{3}\alpha^2 c R_\infty \boxed{\frac{m_e}{m_\mu}\left(1+\frac{m_e}{m_\mu}\right)^{-3}}$$

QED calculation| Effort for 10 Hz accuracy in progress (by Eides et al.)

Muon Precision Measurement @ J-PARC MLF

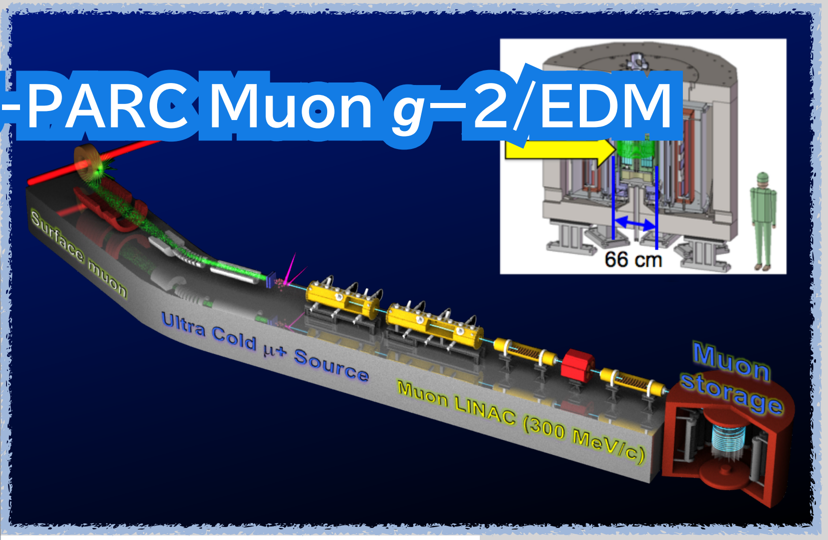


Jungmann's Triangle

Muon $g-2$

New Physics beyond SM

J-PARC Muon $g-2$/EDM



QED
μ_μ, α, g_μ

QED
m_μ

$$\vec{\mu}_\mu = g_\mu \frac{eh}{2m_\mu c}\vec{s}$$

Muonium HFS

Muon magnetic moment μ_μ

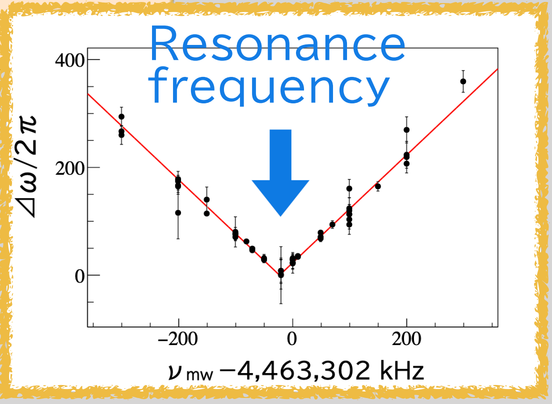
Fine-structure constant α

QED
m_μ

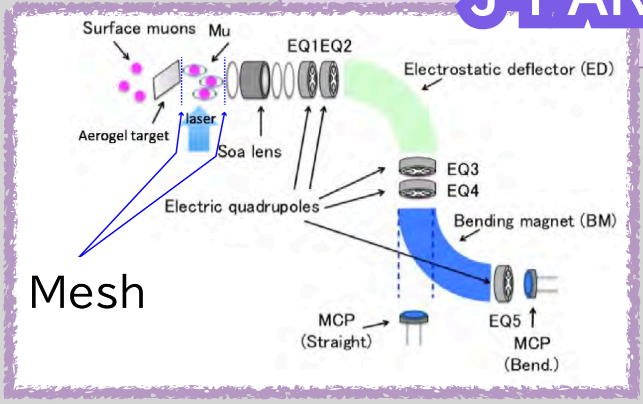
Muonium 1s-2s

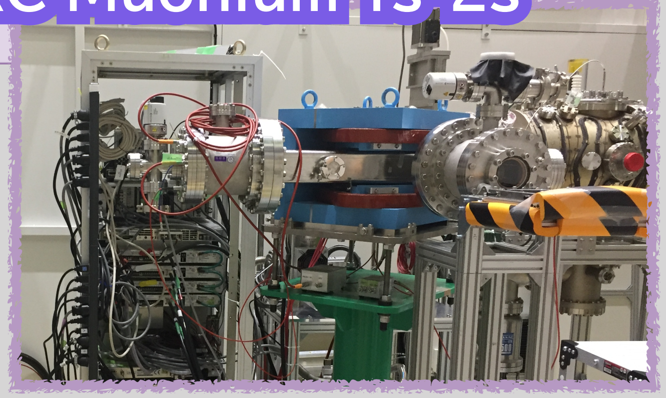
Muon mass m_μ

MuSEUM



J-PARC Muonium 1s-2s



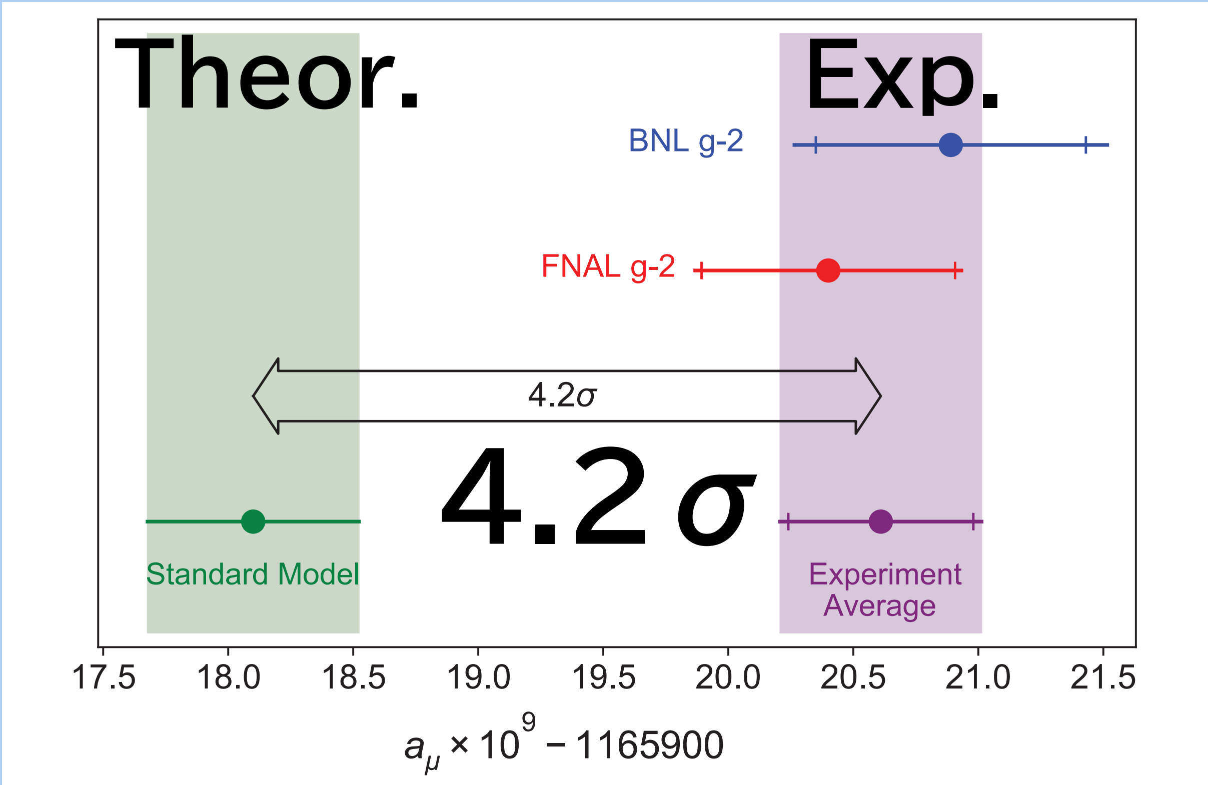


Relation between Muon *g*−2 and Mu HFS

Muon *g*−2

$$a_\mu = \frac{g-2}{2}$$

- 4.2 σ discrepancy between theory and experiment
- Precision of Exp. value | 0.35 ppm
- Goal of new Experiment at J-PARC and FNAL | 0.1 ppm
- Experimental value is obtained by using Mu HFS result



B Abi et al. (Muon g−2 Collaboration), PRL126 141801 (2021)

$$a_\mu = \frac{R}{\lambda - R}$$

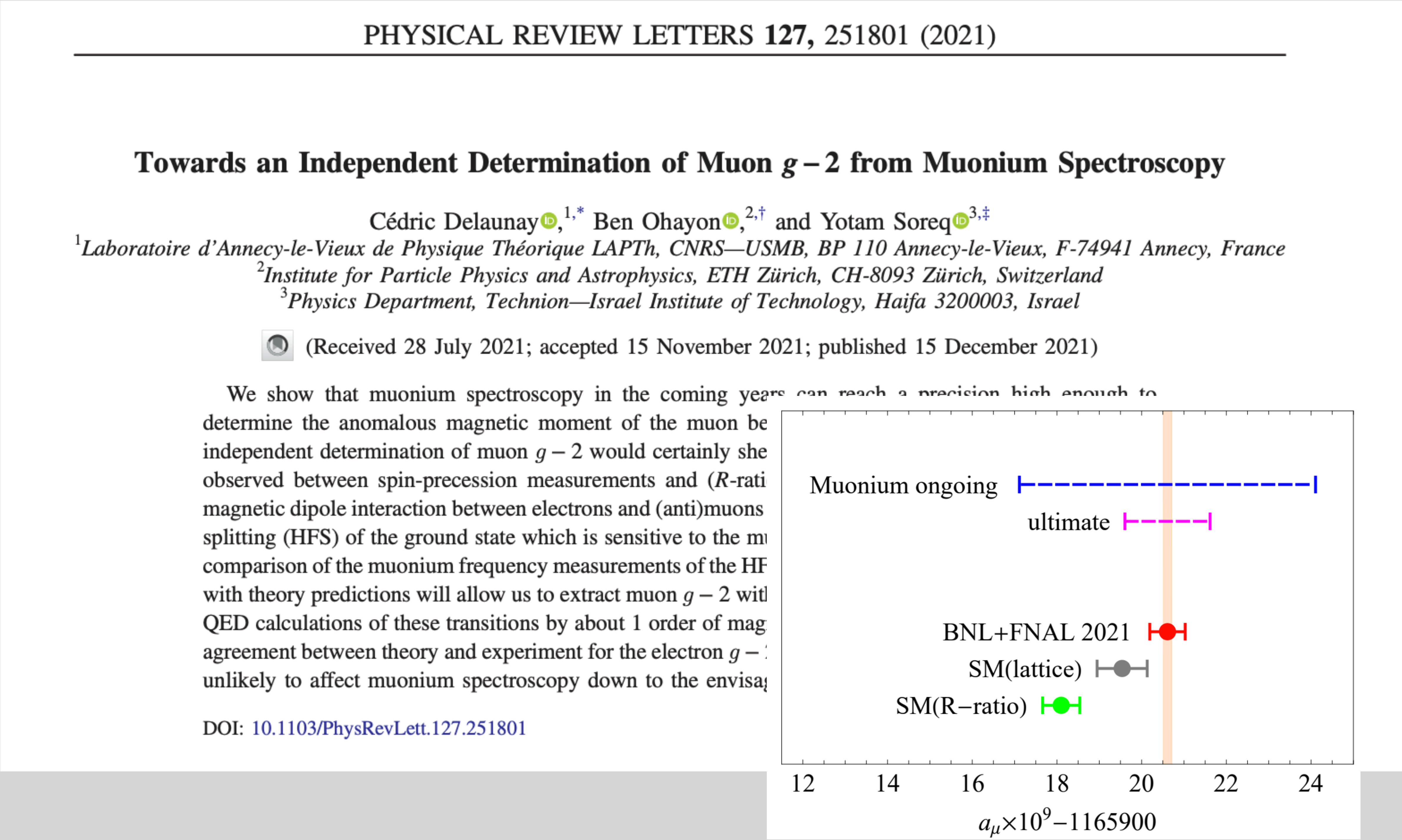
$$R \equiv \frac{\omega_a}{\omega_p}$$

g−2 strage ring

$$\lambda \equiv \frac{\mu_\mu}{\mu_p}$$

Mu HFS measurement

MuHFS + Mu 1s-2s = *g*−2



PHYSICAL REVIEW LETTERS **127,** 251801 (2021)

Towards an Independent Determination of Muon $g-2$ from Muonium Spectroscopy

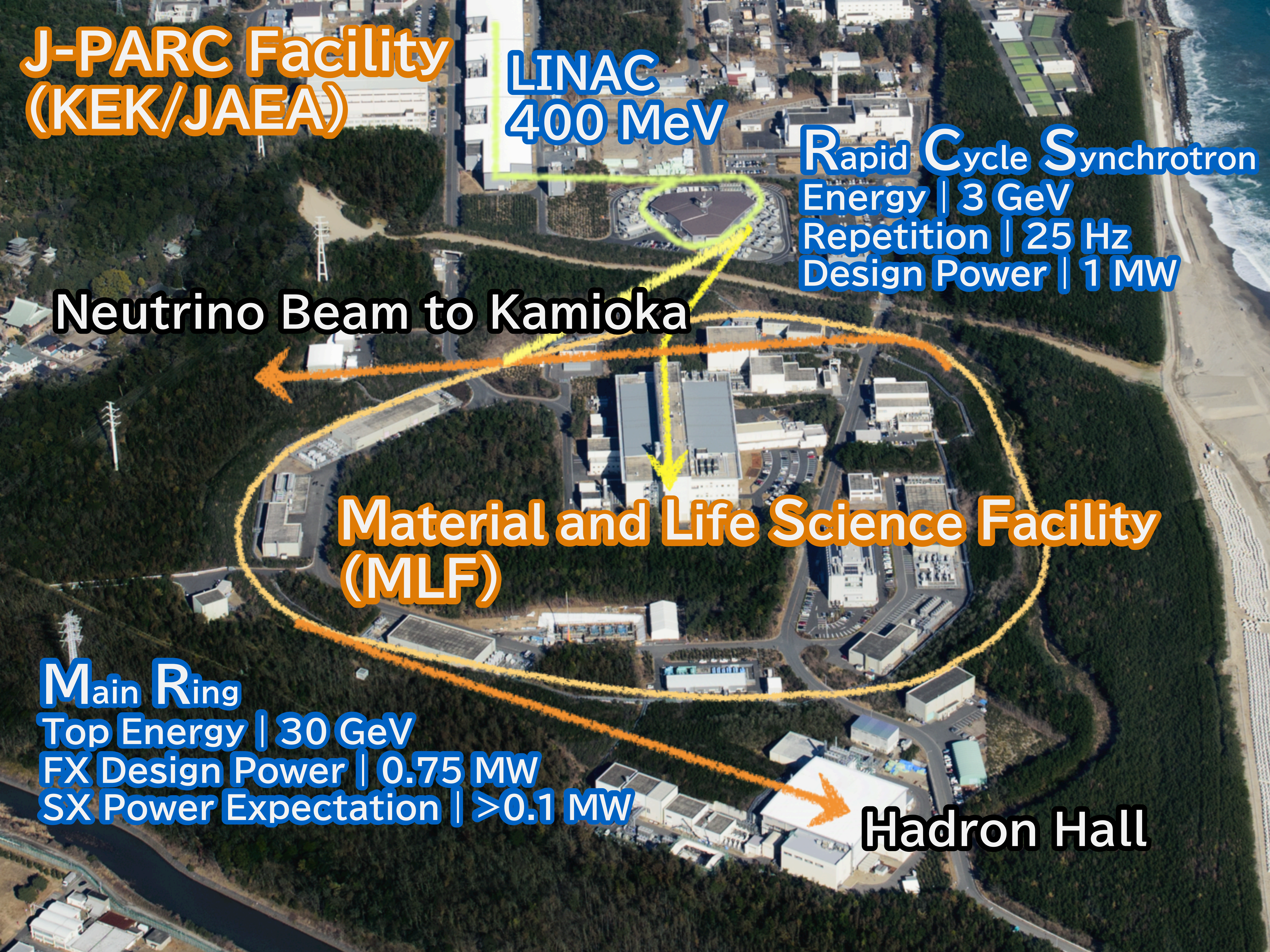
Cédric Delaunay,[1,*] Ben Ohayon,[2,†] and Yotam Soreq[3,‡]
[1]*Laboratoire d'Annecy-le-Vieux de Physique Théorique LAPTh, CNRS—USMB, BP 110 Annecy-le-Vieux, F-74941 Annecy, France*
[2]*Institute for Particle Physics and Astrophysics, ETH Zürich, CH-8093 Zürich, Switzerland*
[3]*Physics Department, Technion—Israel Institute of Technology, Haifa 3200003, Israel*

(Received 28 July 2021; accepted 15 November 2021; published 15 December 2021)

We show that muonium spectroscopy in the coming years can reach a precision high enough to
determine the anomalous magnetic moment of the muon be
independent determination of muon $g-2$ would certainly she
observed between spin-precession measurements and (R-rati
magnetic dipole interaction between electrons and (anti)muons
splitting (HFS) of the ground state which is sensitive to the m
comparison of the muonium frequency measurements of the HF
with theory predictions will allow us to extract muon $g-2$ wit
QED calculations of these transitions by about 1 order of mag
agreement between theory and experiment for the electron $g-$
unlikely to affect muonium spectroscopy down to the envisa

DOI: 10.1103/PhysRevLett.127.251801

J-PARC Facility (KEK/JAEA)



LINAC
400 MeV

Rapid Cycle Synchrotron
Energy | 3 GeV
Repetition | 25 Hz
Design Power | 1 MW

Neutrino Beam to Kamioka

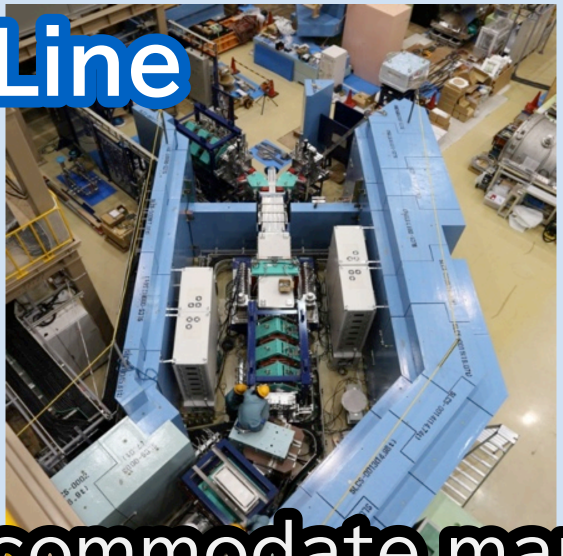
Material and Life Science Facility (MLF)

Main Ring
Top Energy | 30 GeV
FX Design Power | 0.75 MW
SX Power Expectation | >0.1 MW

Hadron Hall

Muon Facility MUSE @ MLF

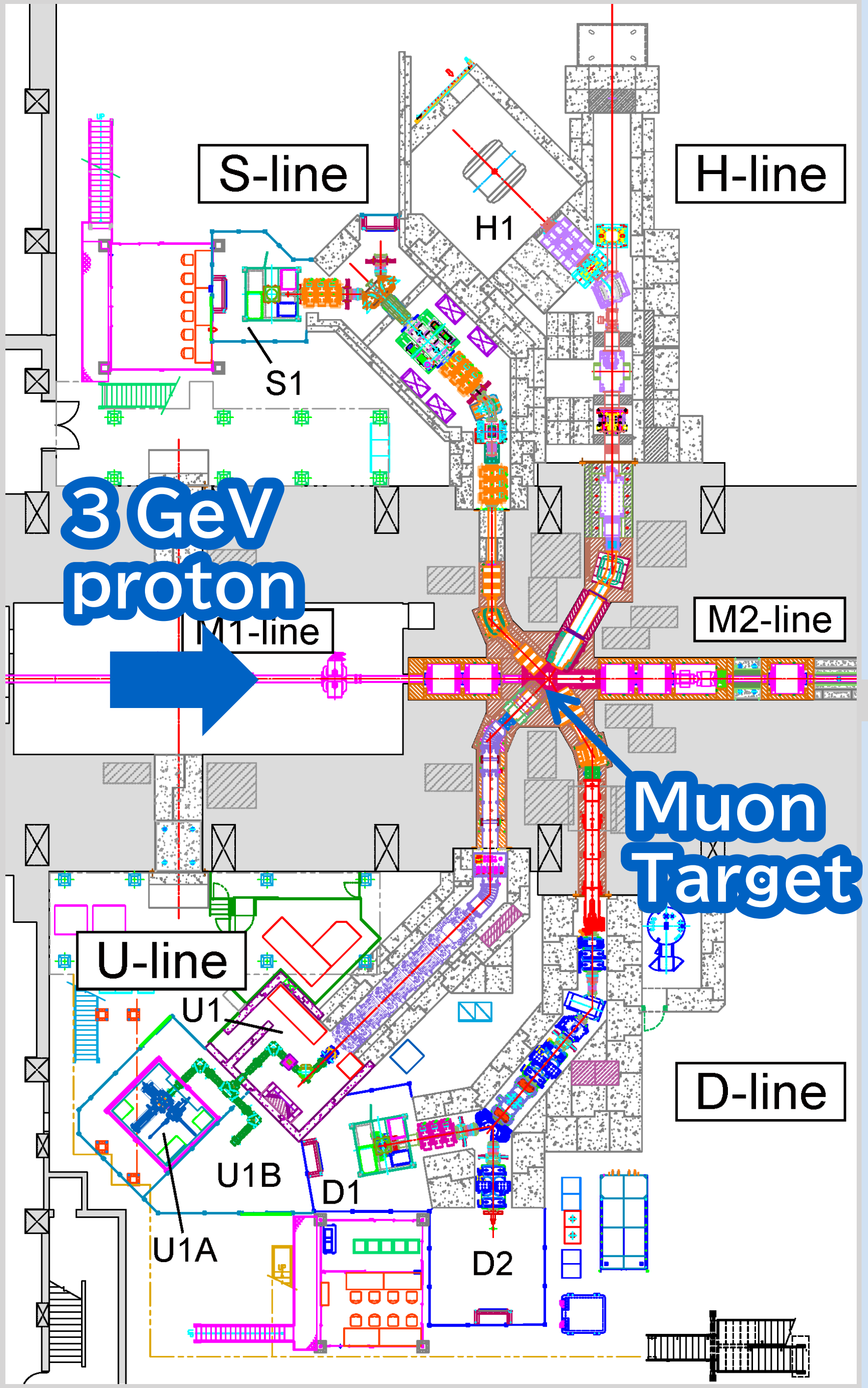
S-Line



Accommodate many μSR experiments

U-Line

Very unique Ultra-Slow Muon Beam



3 GeV proton

Muon Target

H-Line

H1-Area

D-Line

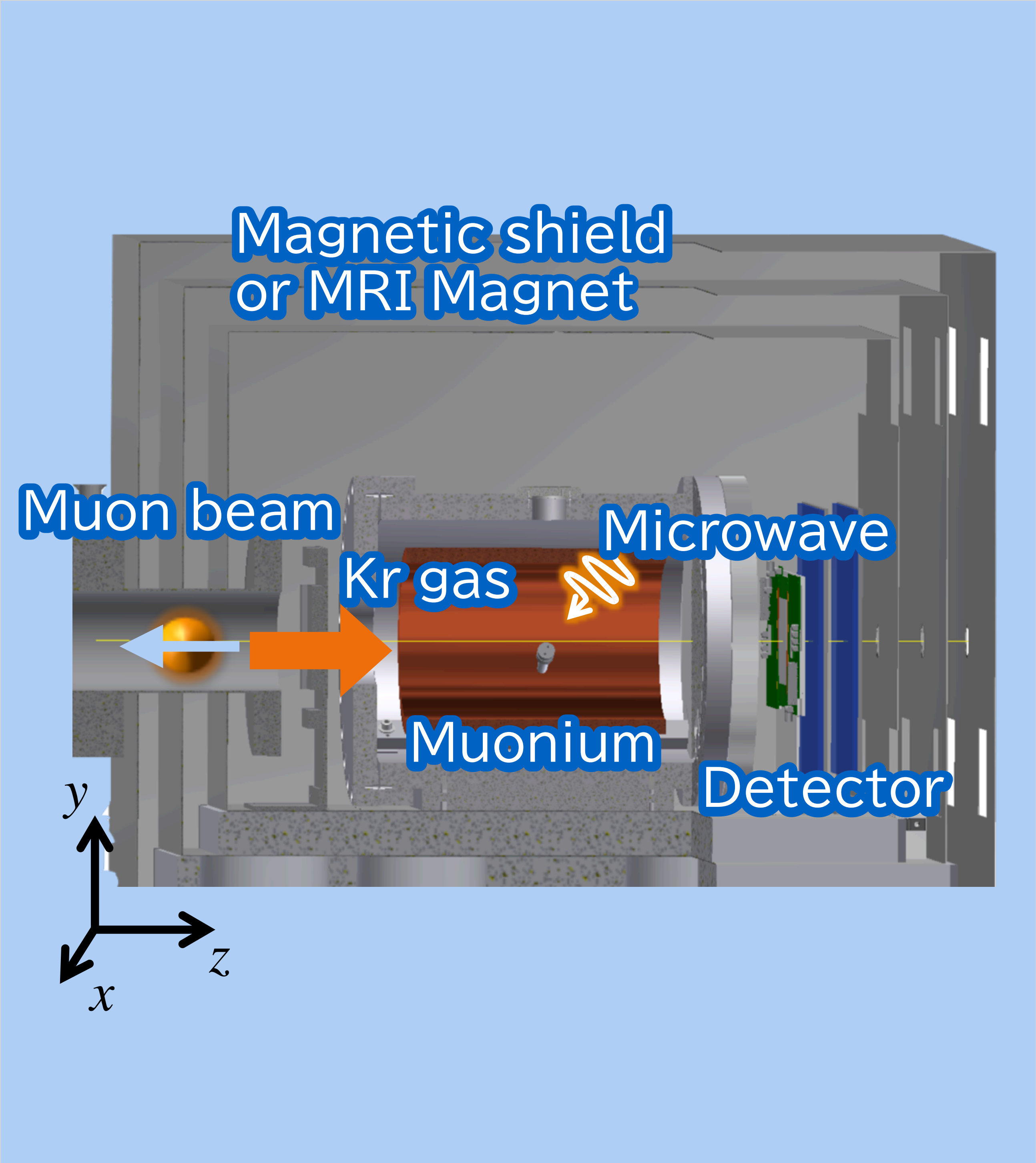
Mid-intensity beam line For general use

MuSEUM Setup

Measurement principal

- Polarized muon beam
- Kr gas target
- Muonium formation
- State transition by microwave and spin flip
- Measuring the number of positron

Signal | $(N_{on}-N_{off})/N_{off}$
N_{on} | # of positron when RF ON
N_{off} | “ RF OFF



MuSEUM Zero Field Experiment

2017

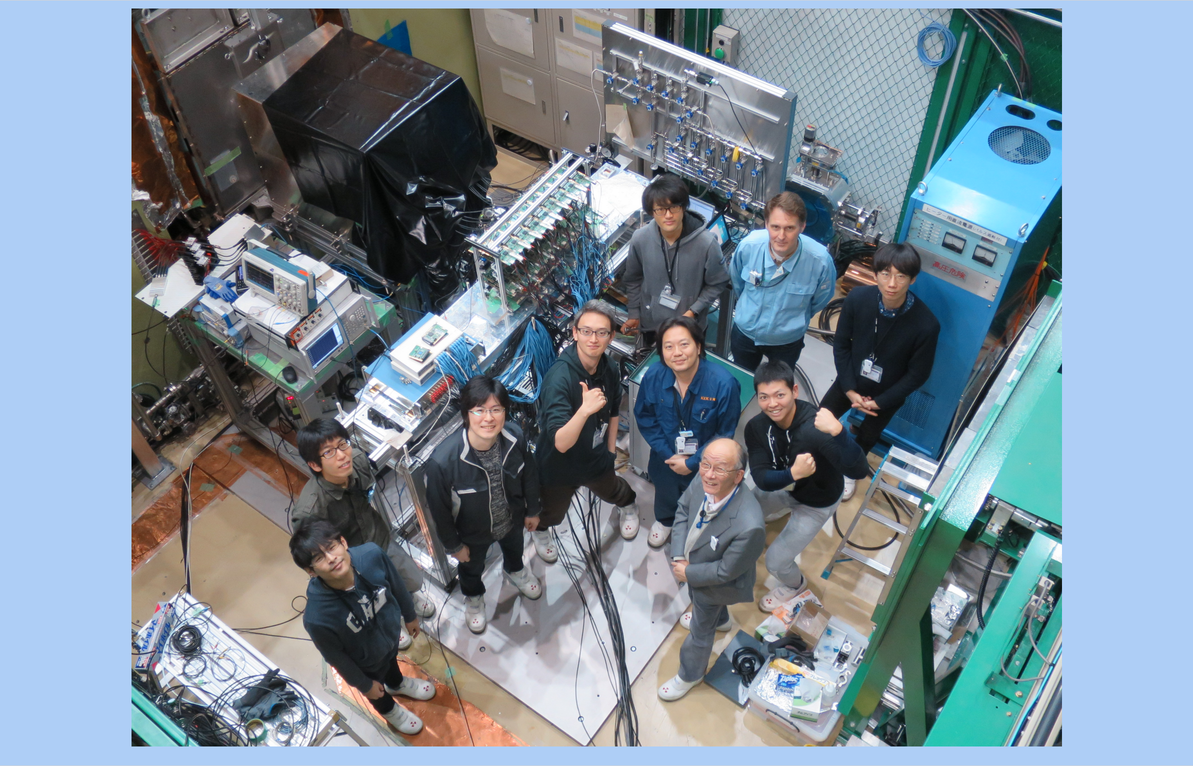
- Mu HFS resonance was measured at Kr 1 atm

2018

- Measurement at 0.3, 0.4, 0.7 atm
  - Lower pressure than previous experiment
- Development of Rabi-oscillation spectroscopy

2019

- Measurement with Kr-He mixture gas
- Upgrade of silicon strip detector



Rabi-oscillation spectroscopy

Time dependence of signal

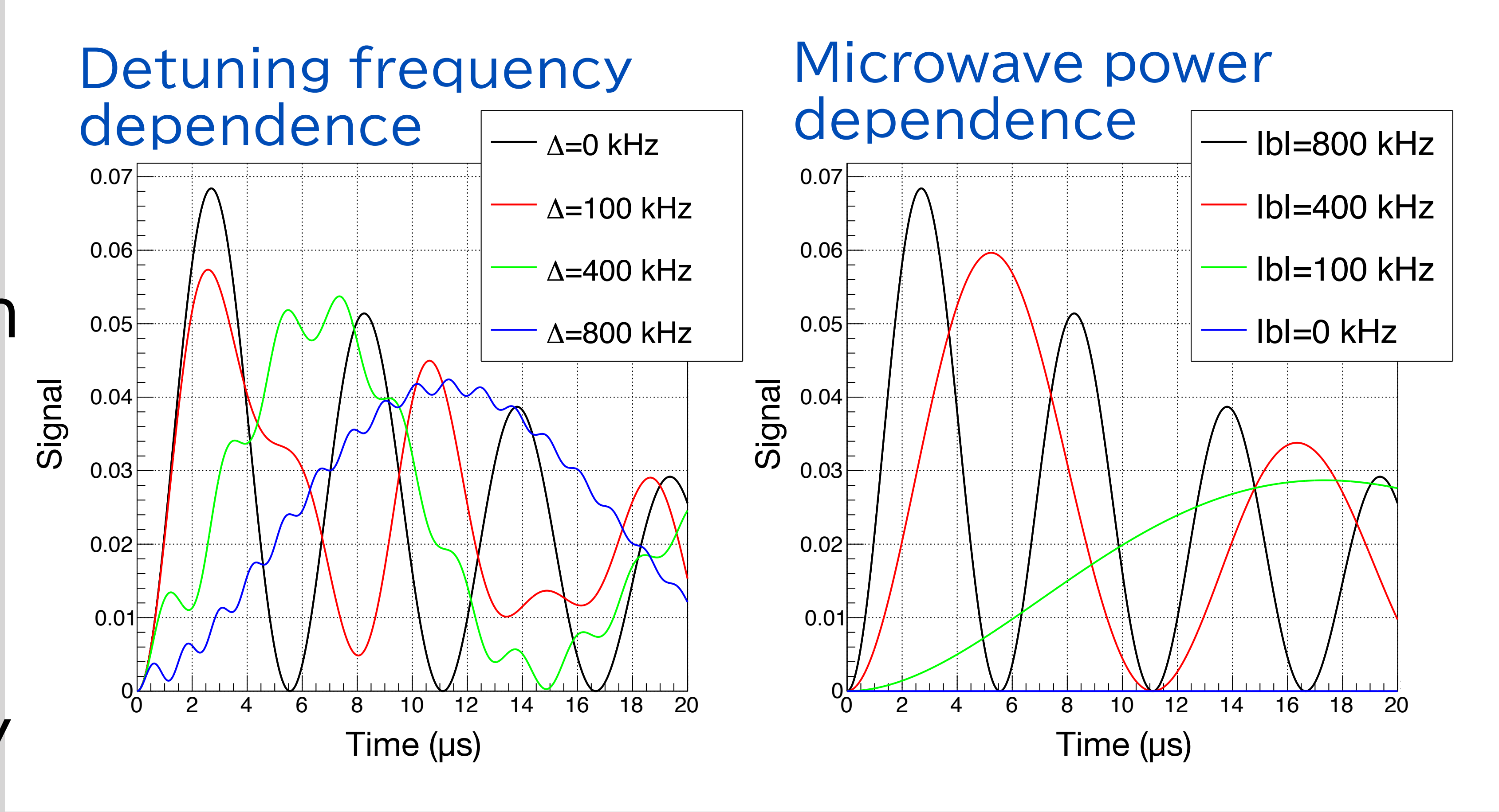
$$dS_{\mathrm{diff}} = \frac{aP}{2}\frac{\left(\boxed{C\left(t\right)-1}\right)\cos\theta_s \mathrm{e}^{-(\lambda+\gamma)t}}{\left(1+\frac{aP}{2}\mathrm{e}^{-\lambda t}\cos\theta_s\right)\mathrm{e}^{-\gamma t}}$$

$$C\left(t\right) = \frac{G_+}{\Gamma}\cos G_- t + \frac{G_-}{\Gamma}\cos G_+ t$$

$$G_\pm = \frac{\Gamma \pm \Delta\omega}{2} \qquad \Gamma = \sqrt{\Delta\omega^2 + 8\left|b\right|^2}$$

Time spectrum sum. of cos

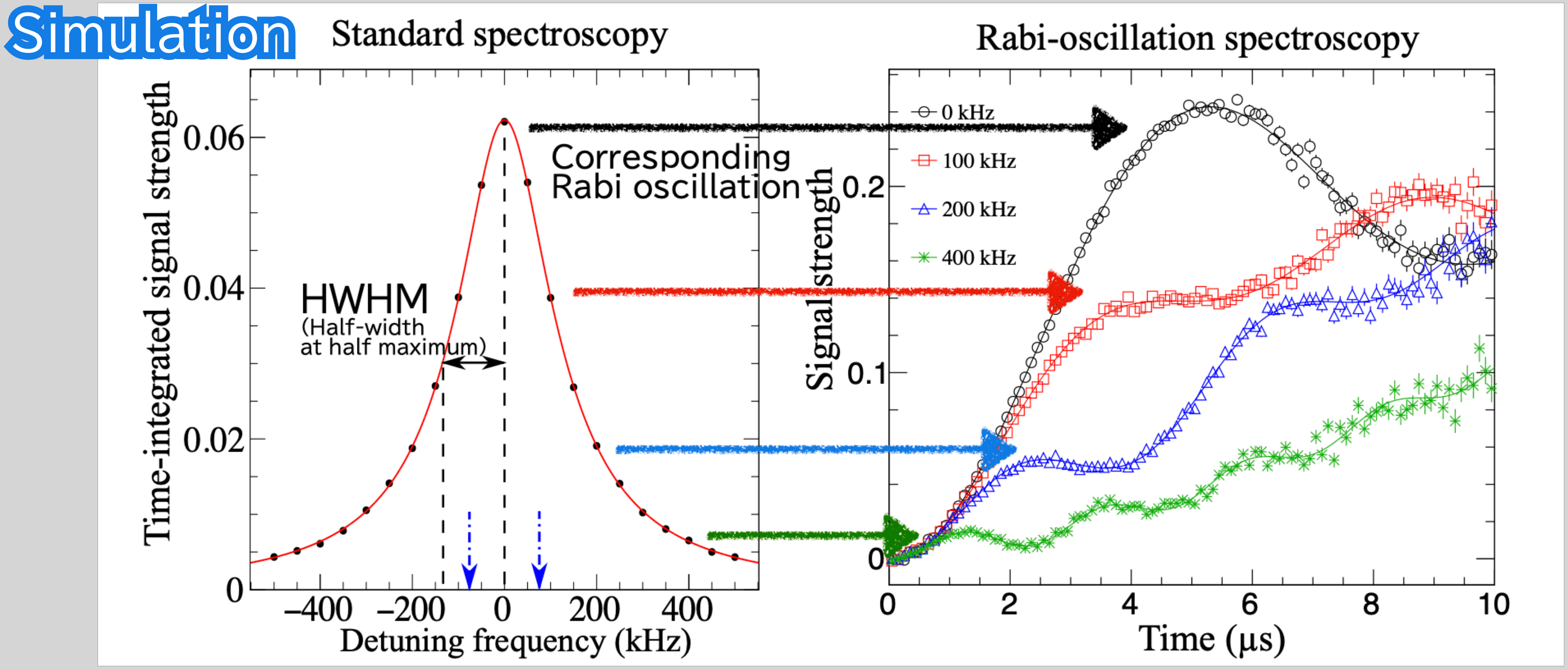
- It can extract much information
  - Mu HFS
  - Microwave power
  - Spin relaxation rate
- No need to sweep frequency



Detuning frequency dependence

Microwave power dependence

Comparison of conventional and Rabi-oscillation spectroscopy



Standard

- Drawing the resonance curve with microwave frequency sweep
- Asymmetry in the microwave power across a resonance line would lead to difficulties in extracting the line center

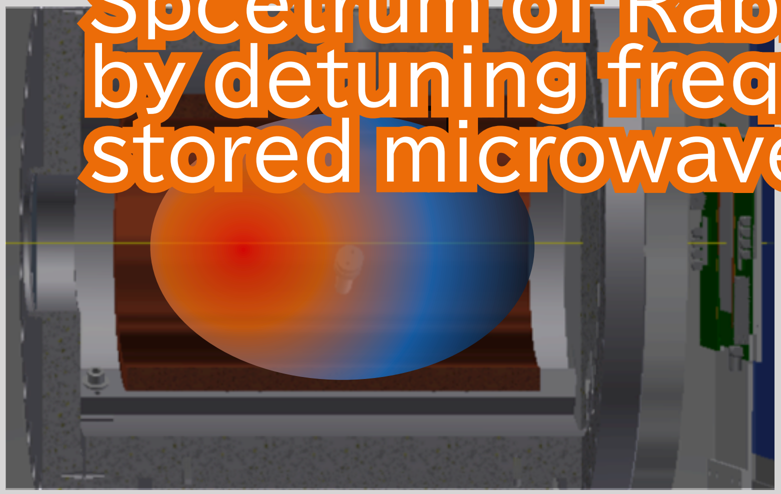
Rabi-oscillation spectroscopy

- The detuning frequency is directly obtained from the Rabi oscillation
- No need to sweep microwave frequency

Rabi-oscillation spectroscopy analysis

Estimation of the singal of Rabi-oscillation by the simulation

Spcetrum of Rabi-oscillation is determined by detuning frequency and stored microwave energy

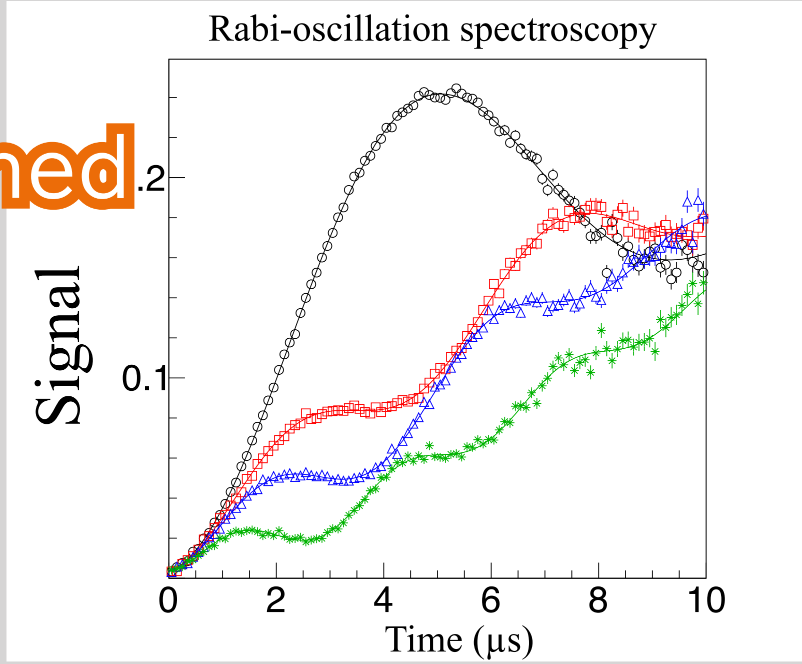


Muon stopping distribution

+

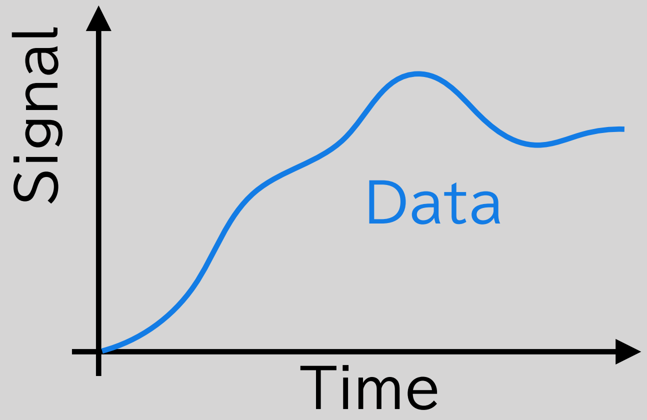
Microwave power distribution

=



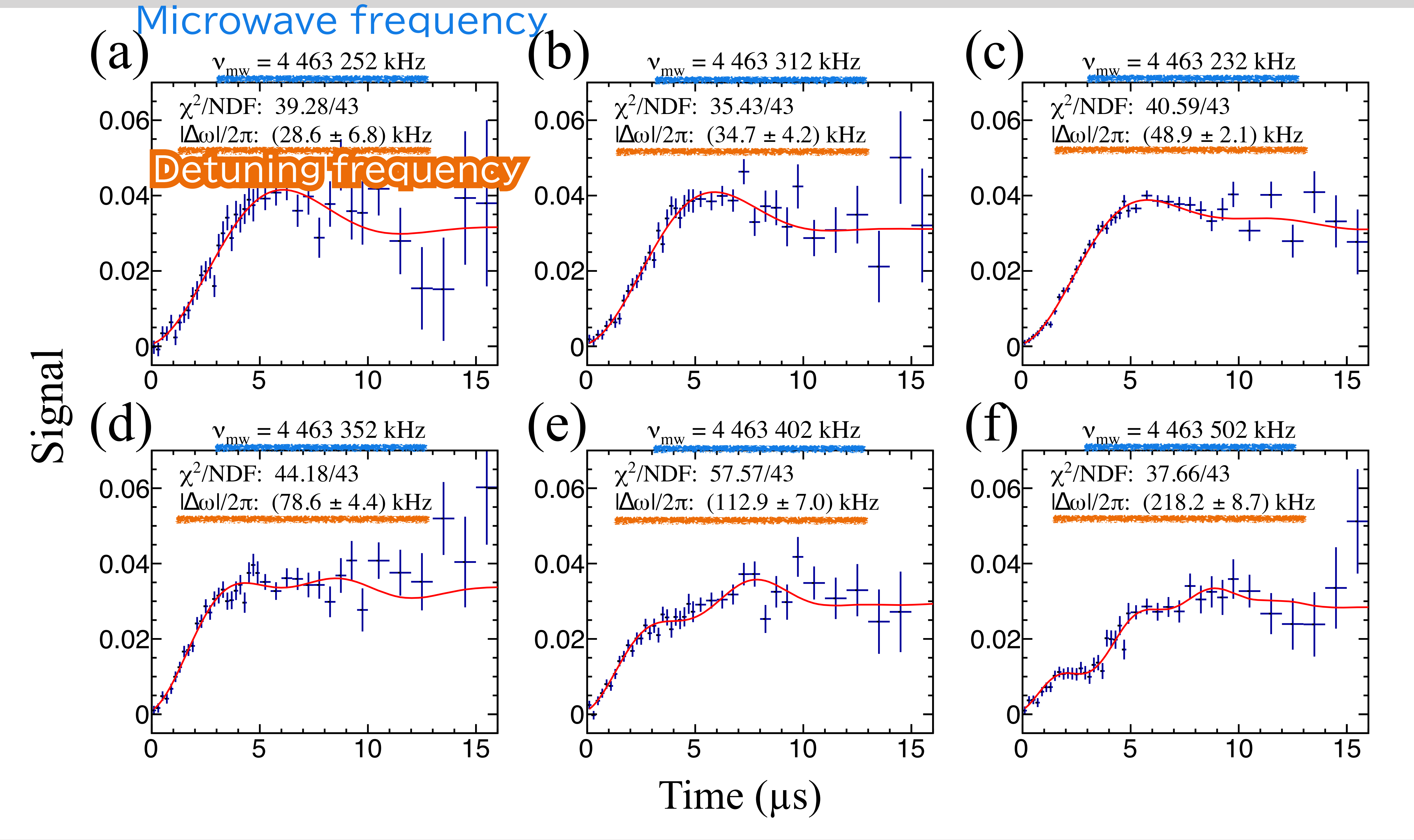
Rabi-oscillation signal from all muonium

Fit estimated signal to the obtained data

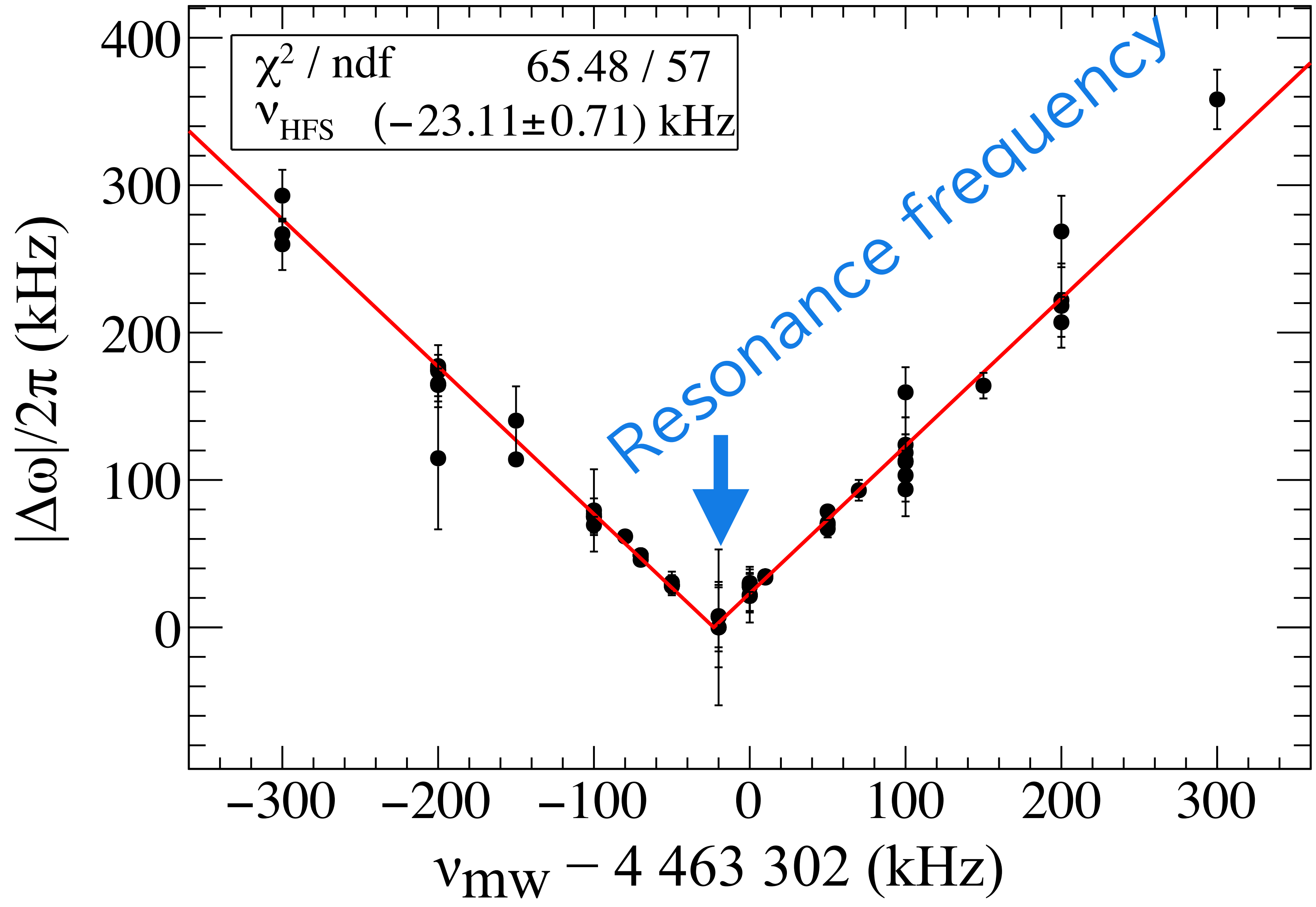


We can obtain the detuning frequency from the single microwave frequency data

Results of Rabi-oscillation spectroscopy



Results of Rabi-oscillation method (multiple microwave frequency)



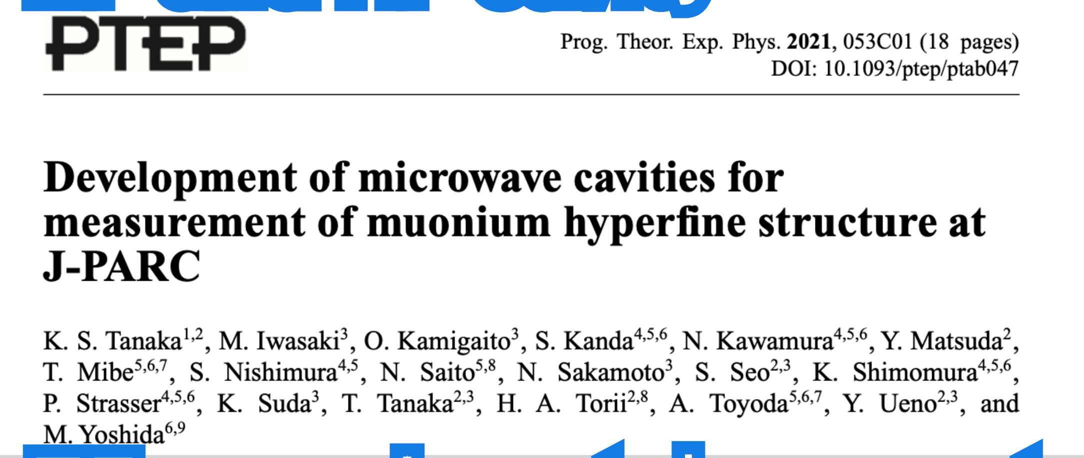
Result | **4,463,301.61 ± 0.71 kHz** (**160 ppb**)

Statistical Uncertainty

Item	June 2017	June 2018 (Kr 0.7 atm only)	Prospects
Analysis method	Time differential	Time differential	Time differential
Beam line	D line	D line	H line (D line×10)
Beam power	150 kW	525 kW	1 MW
Measurement period	31 hours	42.5 hours	30 days
Microwave cavity	TM220 (not stable)	TM220	TM220
Detector area	98.77×98.77 mm^2	98.77×98.77 mm^2	98.77×98.77 mm^2 ×4
Statistic Uncertainty	**3,100 Hz | 690 ppb**	**710 Hz | 160 ppb**	**19 Hz | 4 ppb**

Papers on MuSEUM

ZF and HF cavity

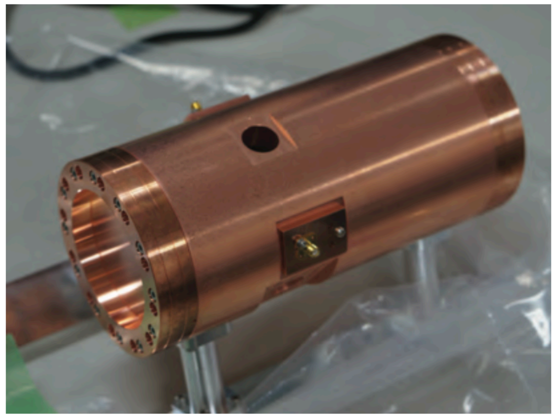


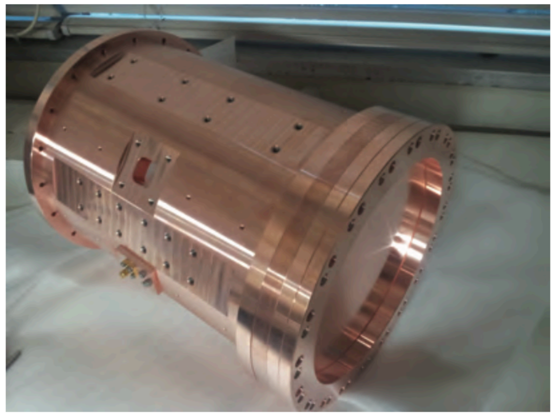
PTEP

Prog. Theor. Exp. Phys. **2021**, 053C01 (18 pages)
DOI: 10.1093/ptep/ptab047

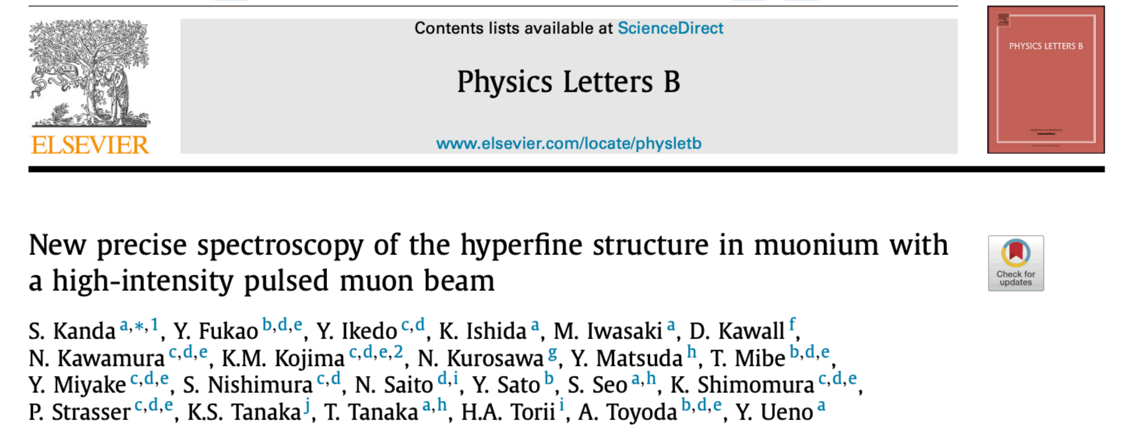
Development of microwave cavities for measurement of muonium hyperfine structure at J-PARC

K. S. Tanaka[1,2], M. Iwasaki[3], O. Kamigaito[3], S. Kanda[4,5,6], N. Kawamura[4,5,6], Y. Matsuda[2], T. Mibe[5,6,7], S. Nishimura[4,5], N. Saito[5,8], N. Sakamoto[3], S. Seo[2,3], K. Shimomura[4,5,6], P. Strasser[4,5,6], K. Suda[3], T. Tanaka[2,3], H. A. Torii[2,8], A. Toyoda[5,6,7], Y. Ueno[2,3], and M. Yoshida[6,9]





ZF experimental apparatus & first result



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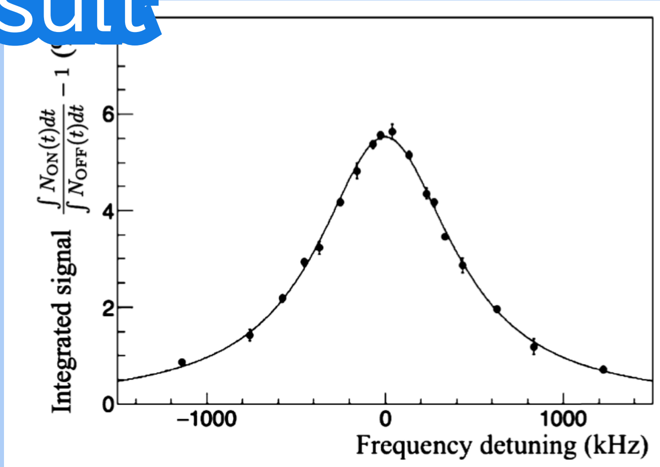
ELSEVIER

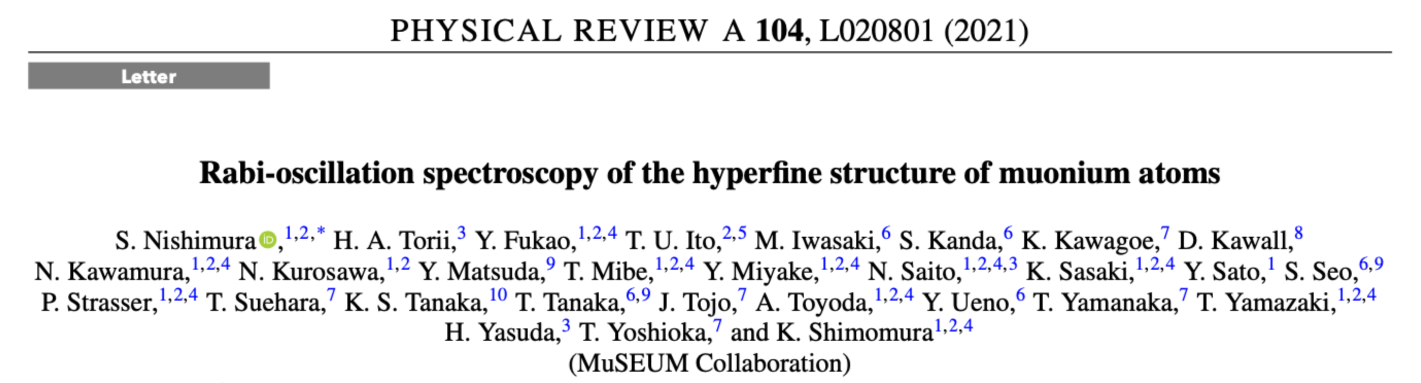
New precise spectroscopy of the hyperfine structure in muonium with a high-intensity pulsed muon beam

Check for updates

S. Kanda[a,*,1], Y. Fukao[b,d,e], Y. Ikedo[c,d], K. Ishida[a], M. Iwasaki[a], D. Kawall[f], N. Kawamura[c,d,e], K.M. Kojima[c,d,e,2], N. Kurosawa[g], Y. Matsuda[h], T. Mibe[b,d,e], Y. Miyake[c,d,e], S. Nishimura[c,d], N. Saito[d,i], Y. Sato[b], S. Seo[a,h], K. Shimomura[c,d,e], P. Strasser[c,d,e], K.S. Tanaka[j], T. Tanaka[a,h], H.A. Torii[i], A. Toyoda[b,d,e], Y. Ueno[a]



Rabi-oscillation spectroscopy

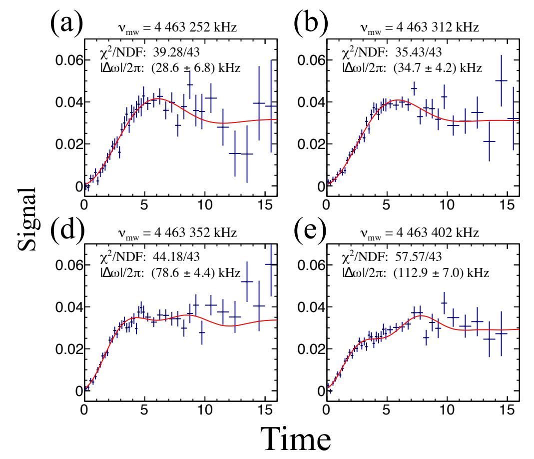


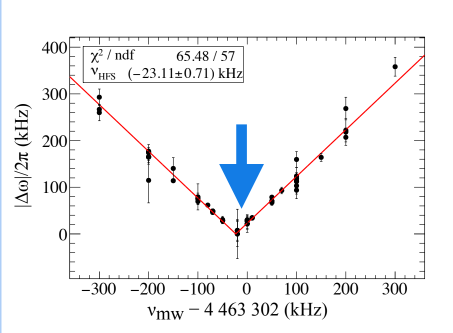
PHYSICAL REVIEW A **104**, L020801 (2021)

Letter

Rabi-oscillation spectroscopy of the hyperfine structure of muonium atoms

S. Nishimura,[1,2,*] H. A. Torii,[3] Y. Fukao,[1,2,4] T. U. Ito,[2,5] M. Iwasaki,[6] S. Kanda,[6] K. Kawagoe,[7] D. Kawall,[8] N. Kawamura,[1,2,4] N. Kurosawa,[1,2] Y. Matsuda,[9] T. Mibe,[1,2,4] Y. Miyake,[1,2,4] N. Saito,[1,2,4,3] K. Sasaki,[1,2,4] Y. Sato,[1] S. Seo,[6,9] P. Strasser,[1,2,4] T. Suehara,[7] K. S. Tanaka,[10] T. Tanaka,[6,9] J. Tojo,[7] A. Toyoda,[1,2,4] Y. Ueno,[6] T. Yamanaka,[7] T. Yamazaki,[1,2,4] H. Yasuda,[3] T. Yoshioka,[7] and K. Shimomura[1,2,4]
(MuSEUM Collaboration)

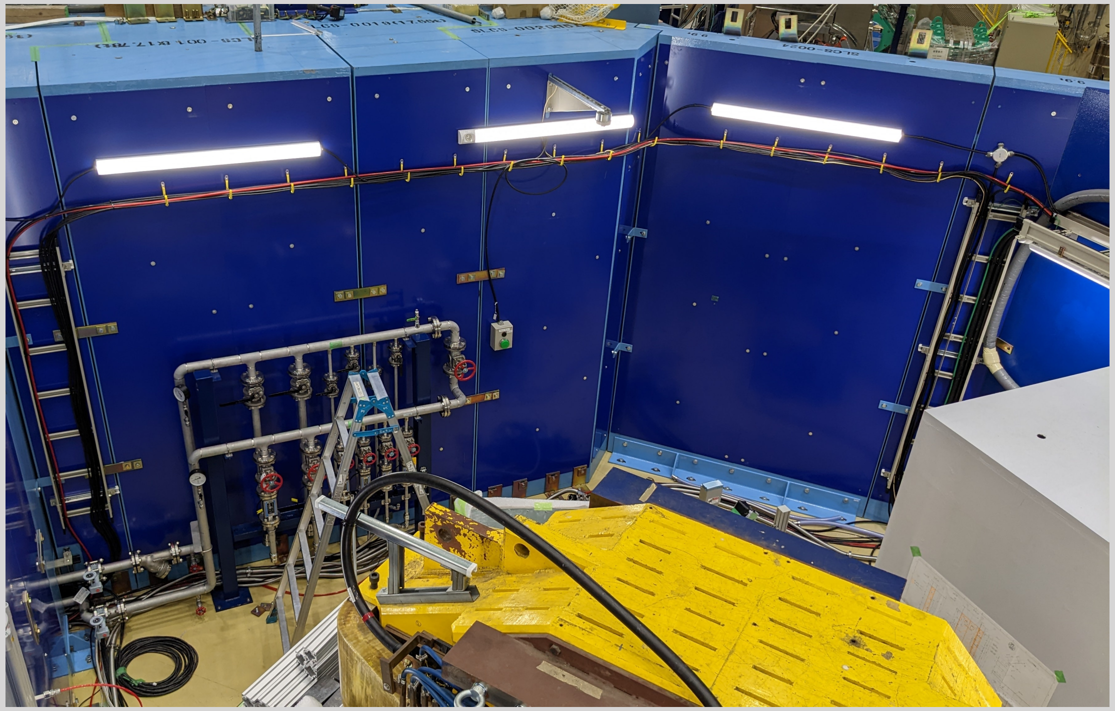


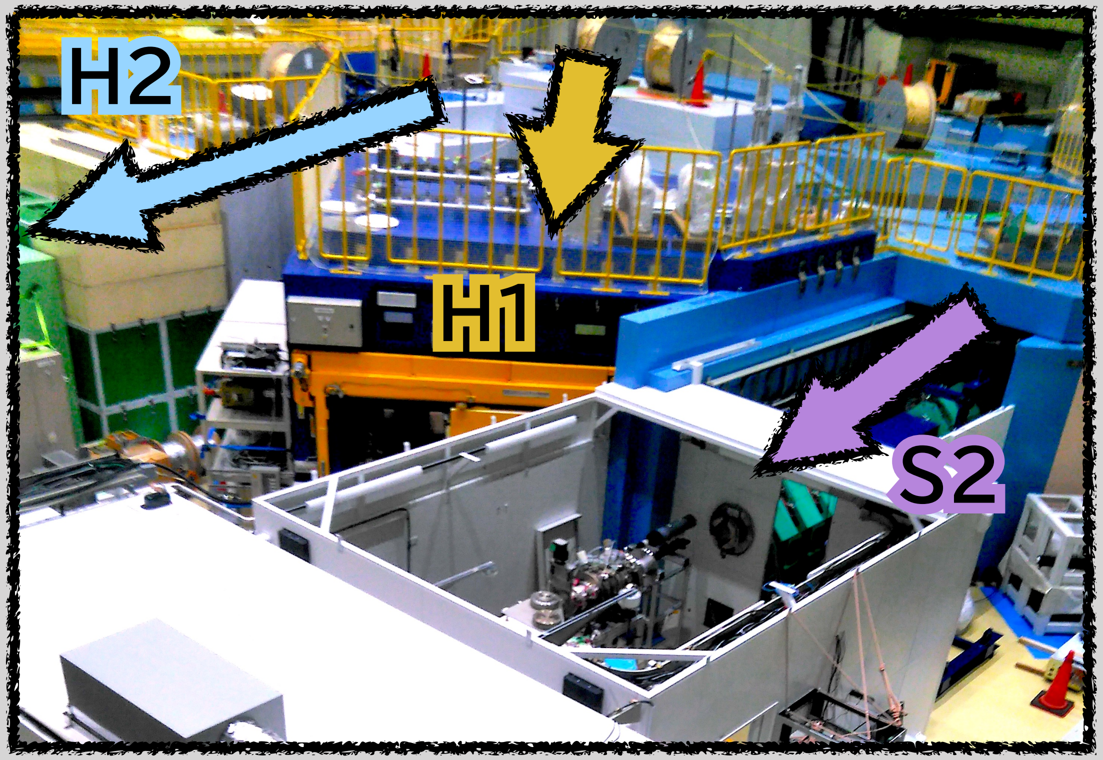


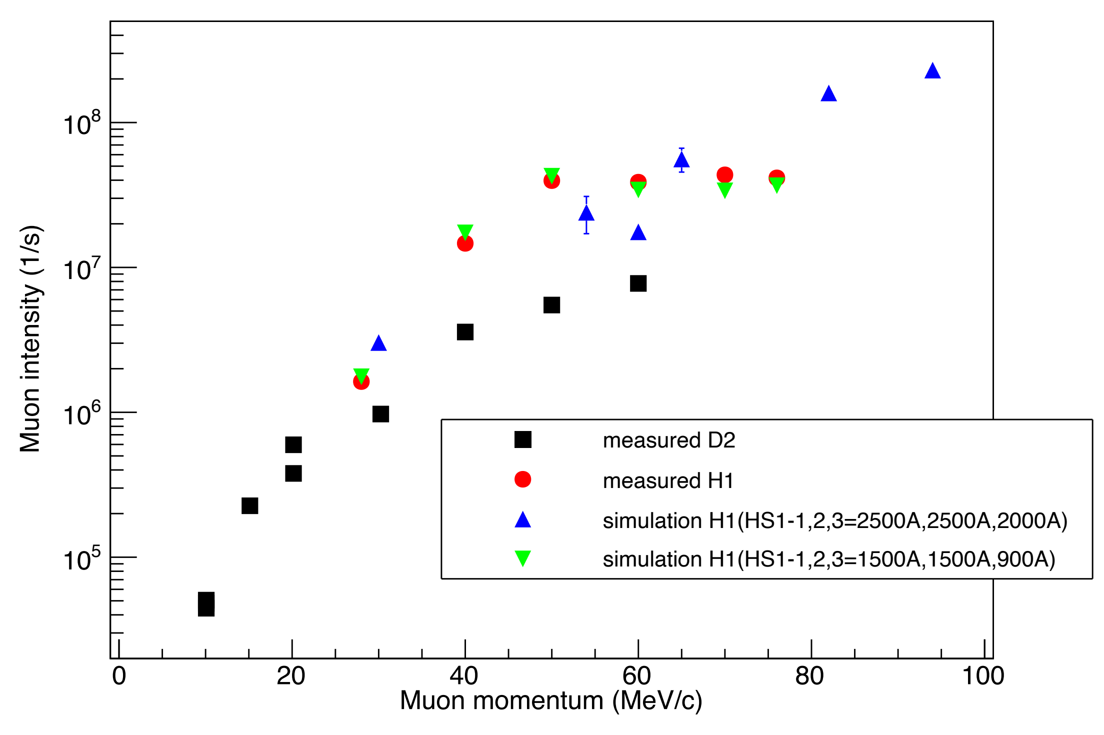
Development for HF Measurement

H Line (H1 Area)

- Beam commissioning has been done
- Steel plates for field uniformity were installed
- DC separator will be installed in this summer







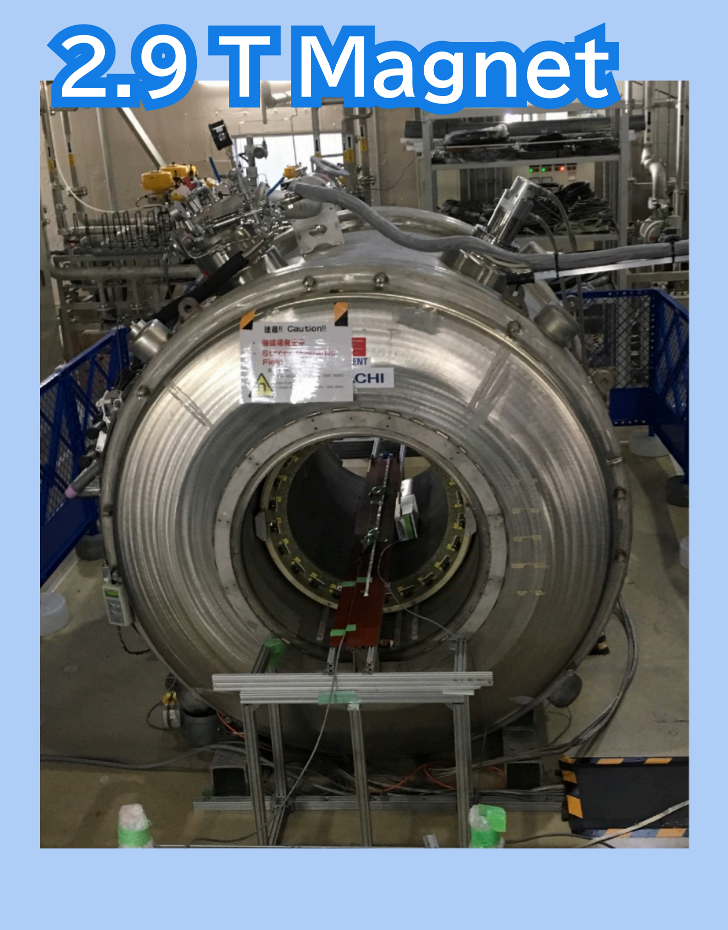
Magnet & Passive Shimming

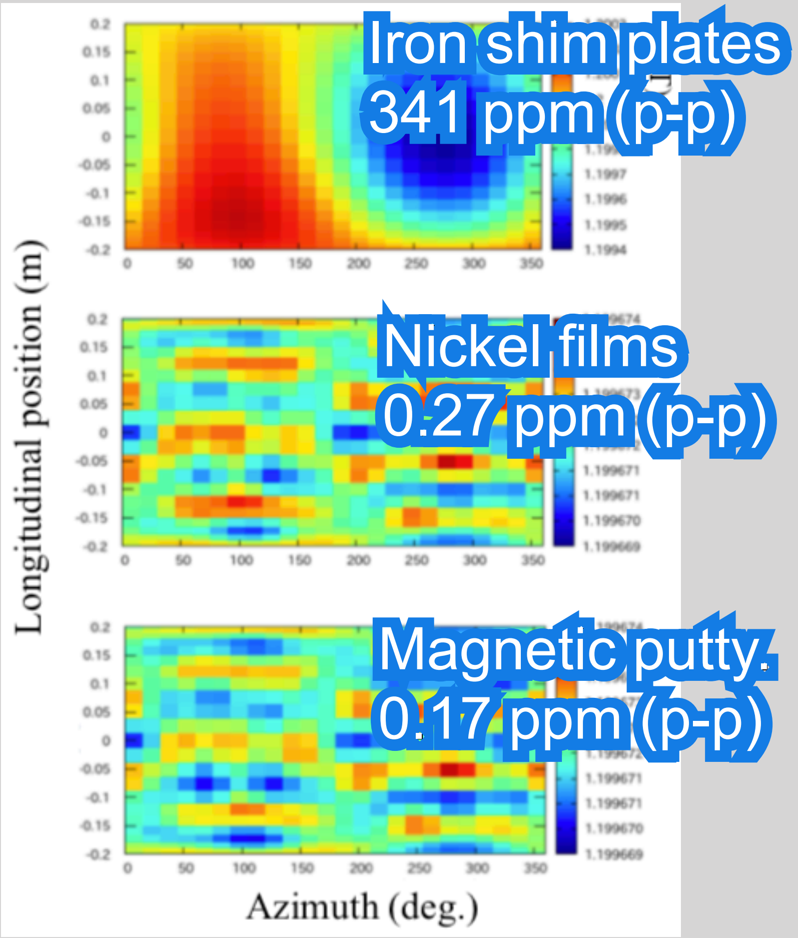
Requirements for magnetic field

- 0.2 ppm (peak-to-peak) uniformity in a spheroidal volume ($z = 30$ cm, $r = 10$ cm)
- ±0.1 ppm stability during measurement

Shimming

- Field uniformity 0.27 ppm has been achieved
- We can reach 0.17 ppm (Simulation)


2.9 T Magnet


Iron shim plates 341 ppm (p-p)

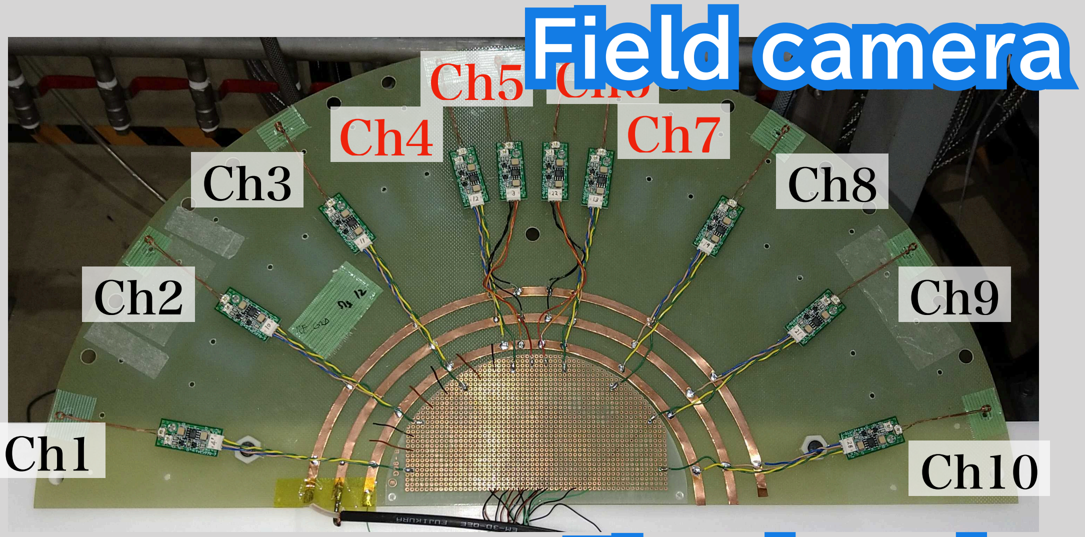
Nickel films 0.27 ppm (p-p)

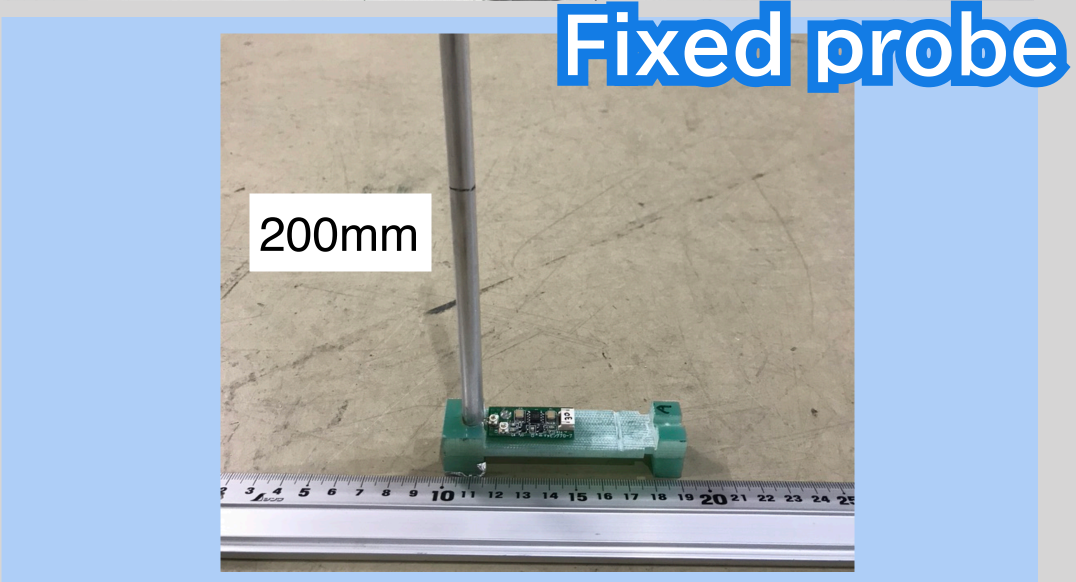
Magnetic putty 0.17 ppm (p-p)

Field Probe

Three type of probes

- Standard probe
  - ✦ Precision of 15 ppb has been achieved
- Field camera
  - ✦ A 24-channels rotating NMR probe that maps magnetic fields
  - ✦ Used for shimming
  - ✦ 10-channels prototype has been developed
- Fixed probe
  - ✦ Compact probe to monitor magnetic field stability during experiment



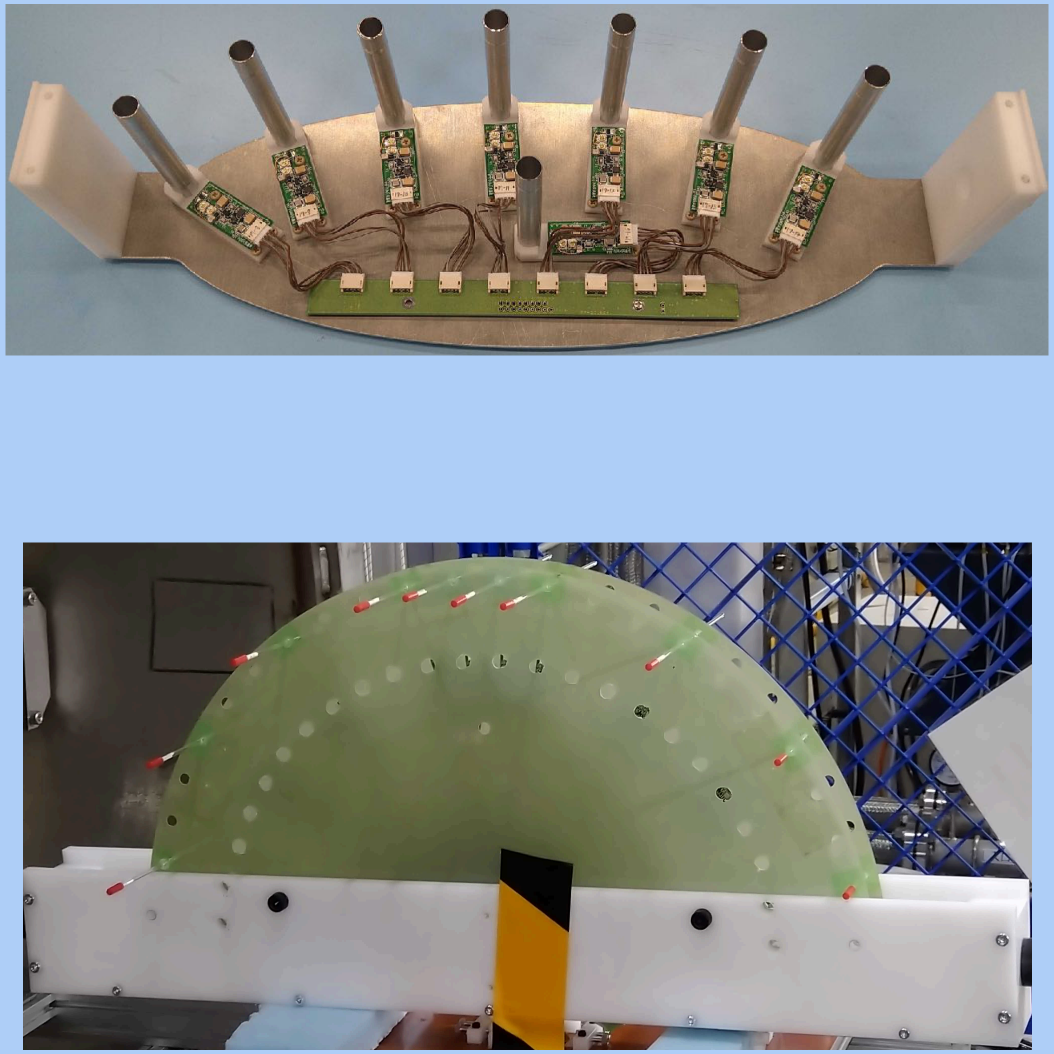


Field Camera

Study by Hiroki Tada (Nagoya Univ.)

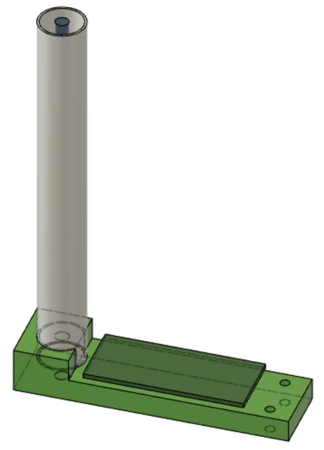
Scanning a sphere of 25 cm radius

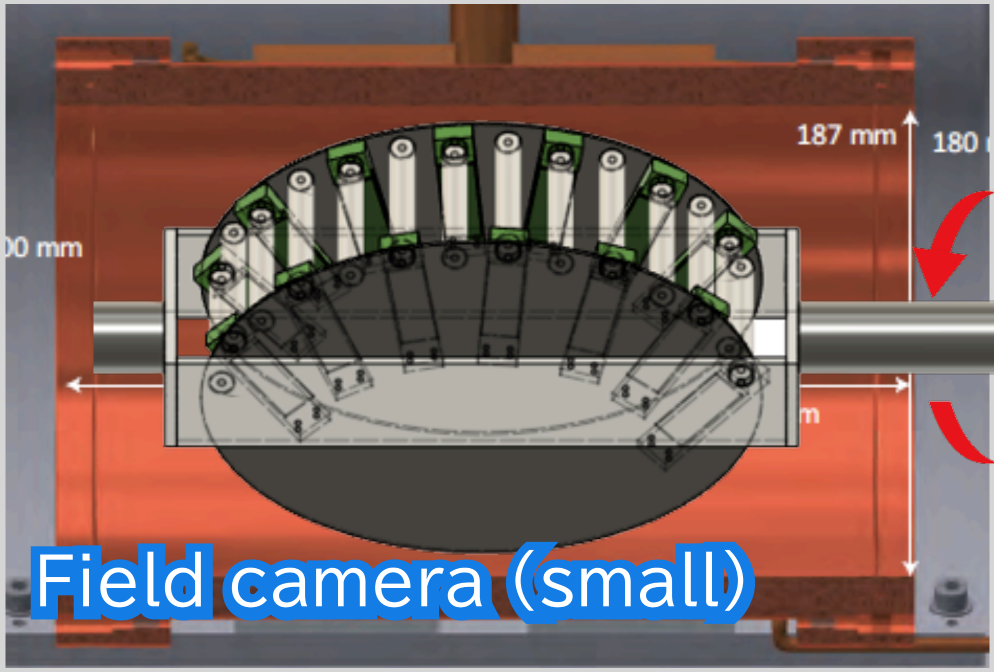
- 24-channels half-circle multi-channel system
- Scanning time | 3 hours (single probe) → 20 minutes (multi-channel system)



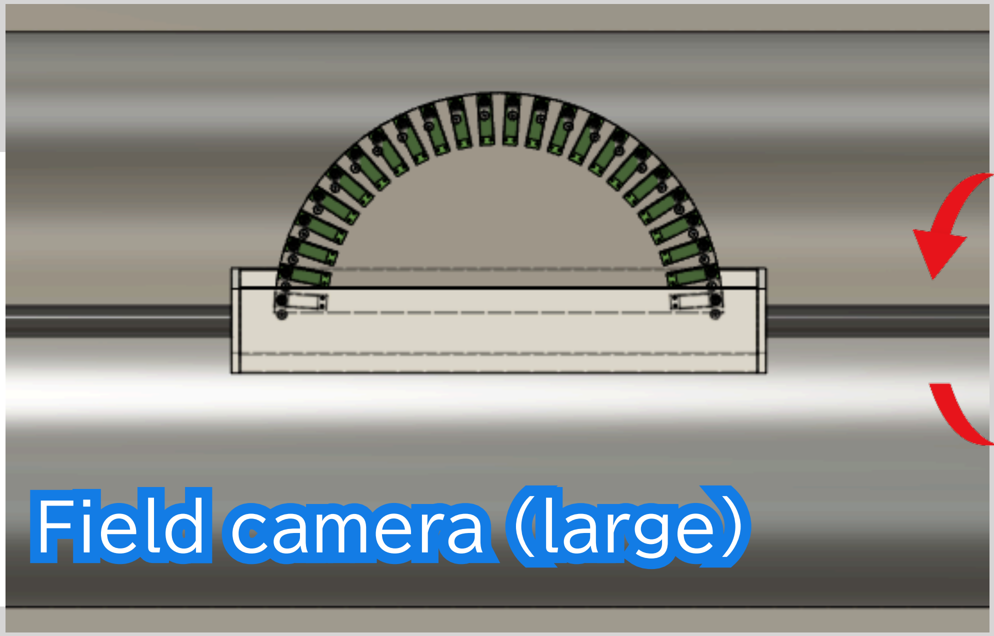
Prototype

Support structure





Field camera (small)



Field camera (large)

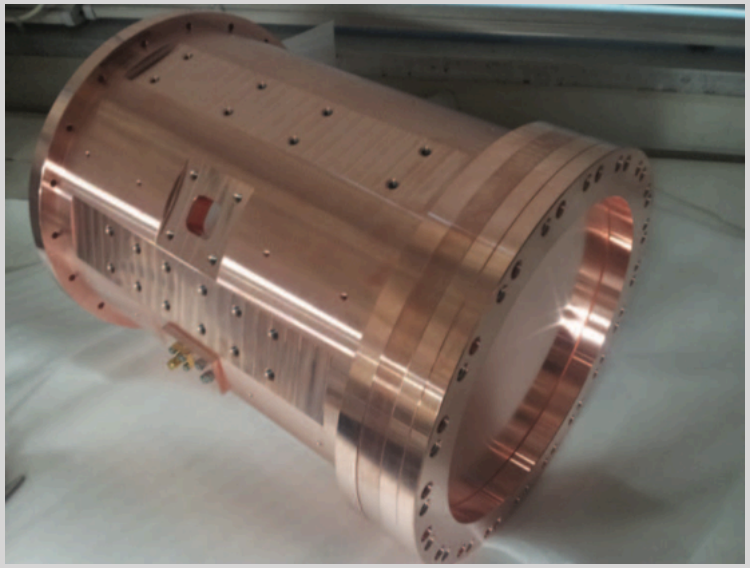
Microwave Cavity

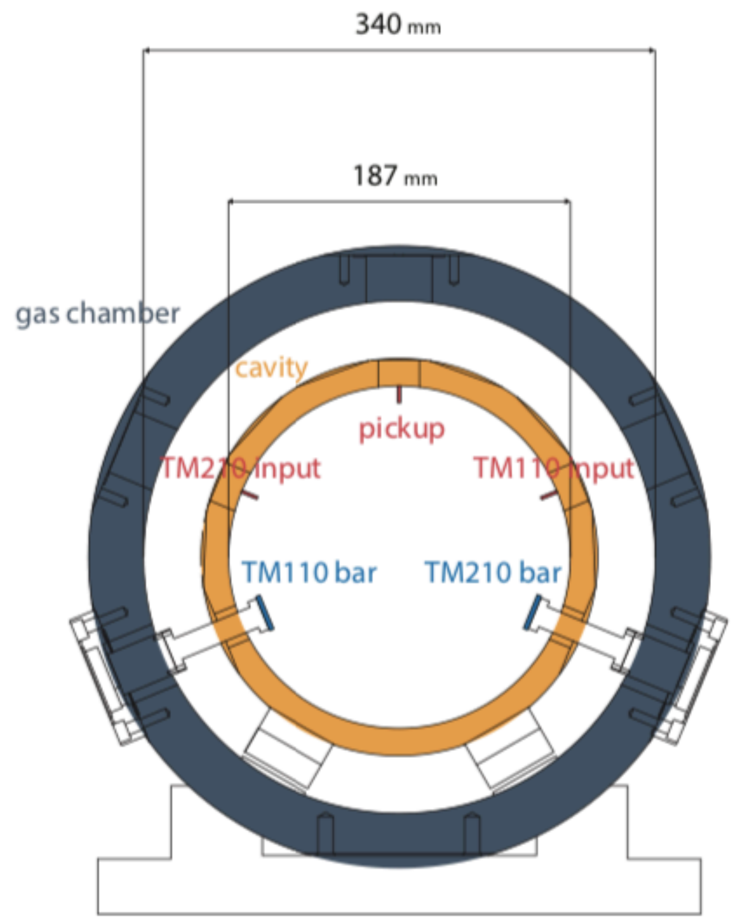
Cylindrical microwave cavity for HF

Resonance frequency

- TM110 | 1.95 GHz
- TM210 | 2.65 GHz
- Two tuning bars

Re-tuning in progress





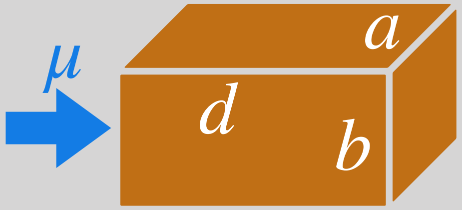
Rectangular Cavity for 2.9 T Measurement

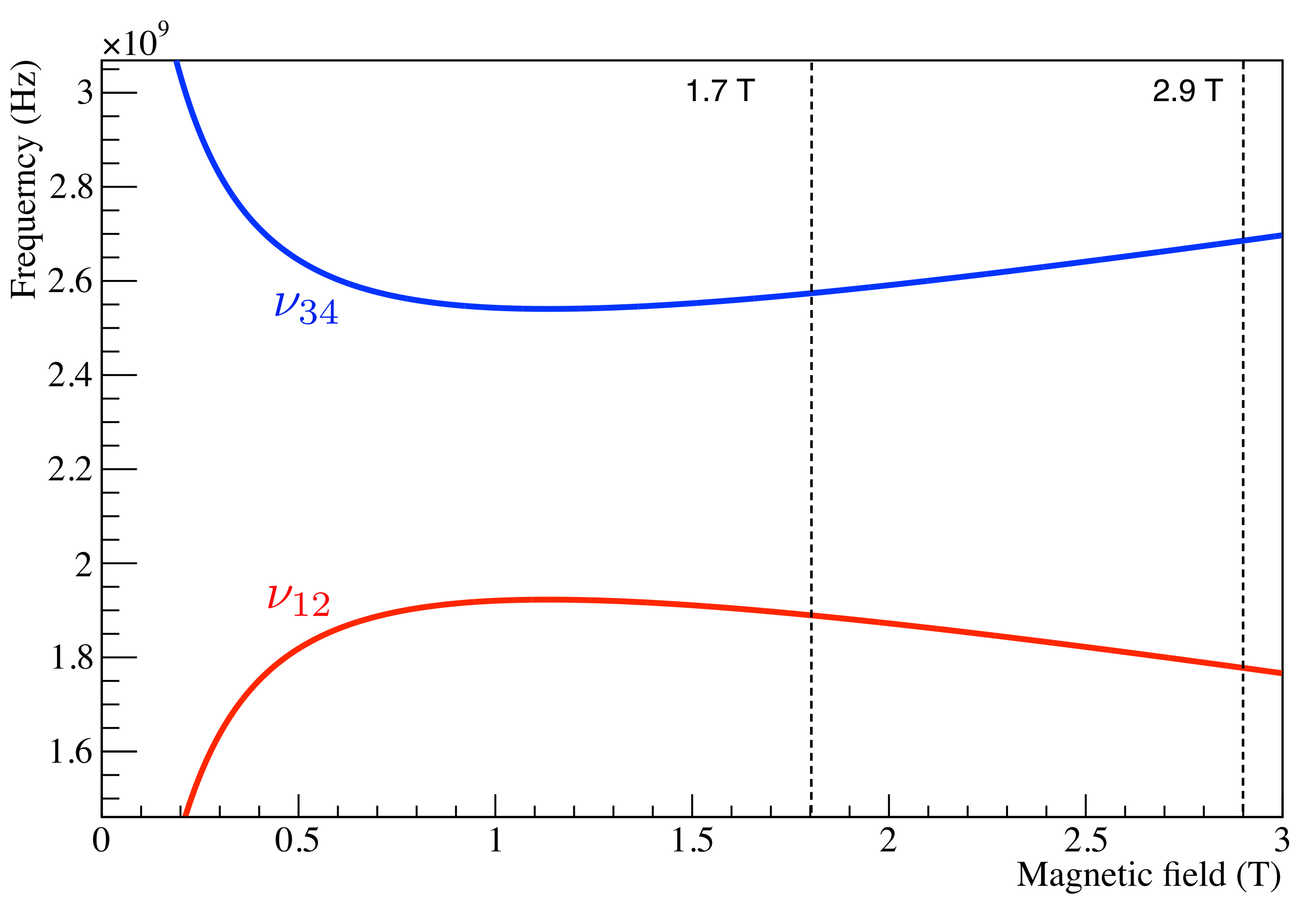
Study by Ryoto Iwai (KEK)

- Frequencies | $\nu_{12} = 1.778$ GHz, $\nu_{12} = 2.686$ GHz
- Cavity size | $a = 249.19$ mm, $b = 114.54$ mm

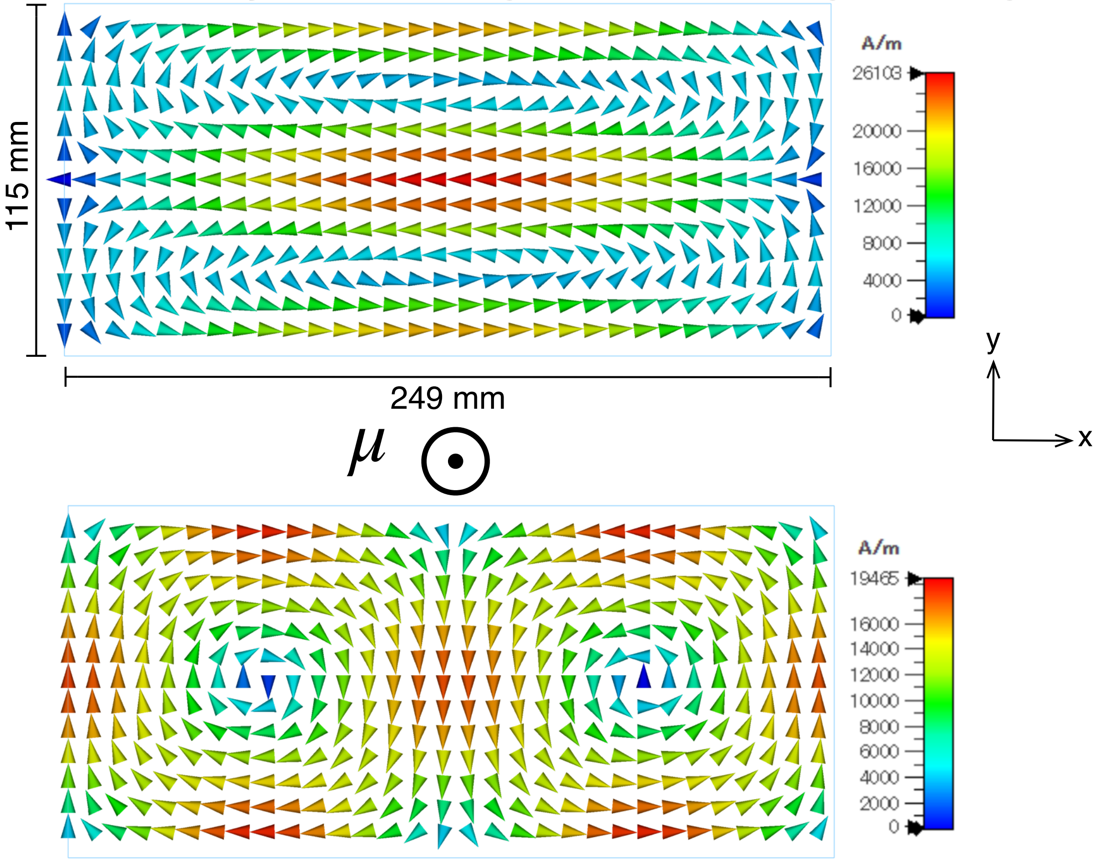
$$F_{mnl} = \frac{c}{2\sqrt{\mu_r \epsilon_r}} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{l}{d}\right)^2}$$

c : Speed of light
μ_r and ϵ_r : Relative permeabillity and permittivity
m, n, l : Mode numbers
a, b, d : Cavity dimensions





Cavity design is ongoing



Blind Analysis for MuSEUM

Hidden answer method

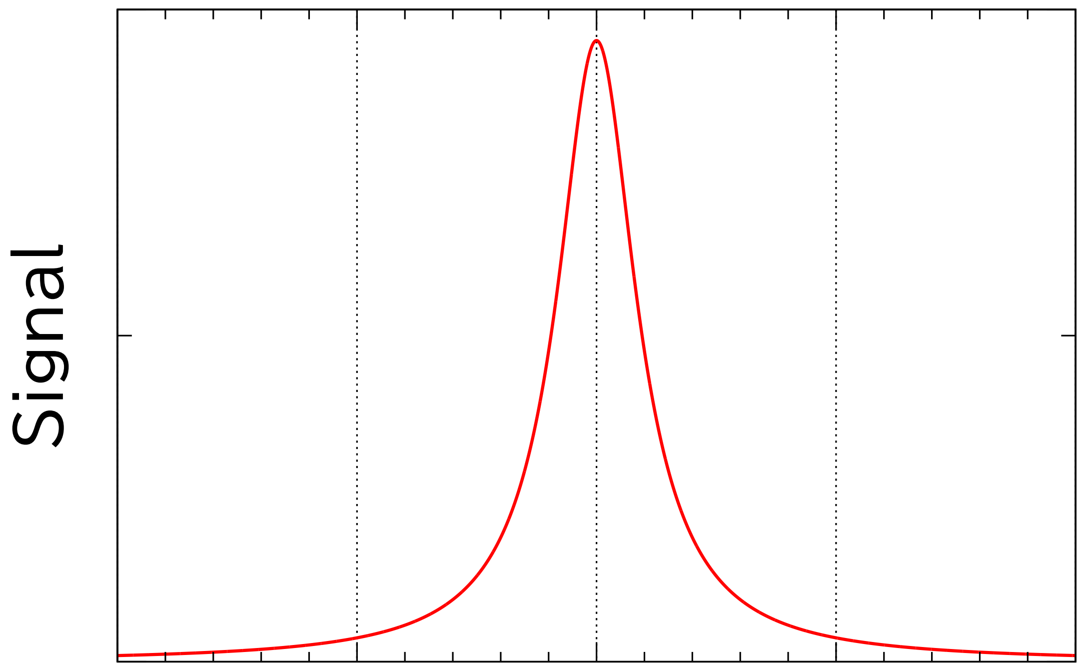
Value to be blinded | Injecting microwave frequency

- Microwave frequency input by user | ν_{set}
- Blinded offset | δ
- True microwave frequency | ν_{mw}

$$\nu_{\mathrm{mw}} = \nu_{\mathrm{set}} + \delta$$

- δ must be constant for all ν_{set} in order to draw a resonance curve
- If $|\delta| < 8$ kHz,
  - ✦ the blind value is sufficient for the target precision
  - ✦ the rate of change in stored microwave energy < 0.07%

Before opening the blind



$\nu_{\mathrm{mw}} - 4{,}463{,}302$ kHz $- \delta$

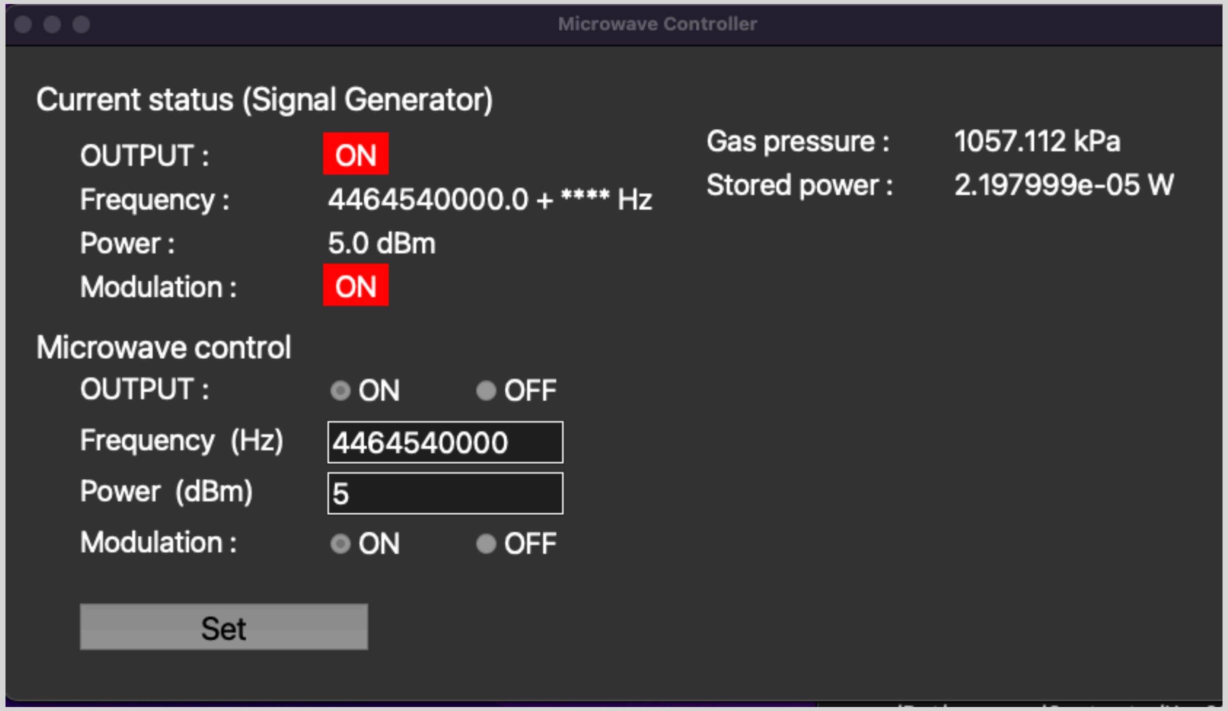
$= \nu_{\mathrm{set}} - 4{,}463{,}302$ kHz

S.G. Controller & Slow Monitor

Implemented in Python3

Function

- Password is required to execute
- Displayed value on the signal generator is blinded
- There are some safety/ protection features to prevent mis-operation
- Microwave power and gas pressure are also monitored and recorded


Microwave Controller

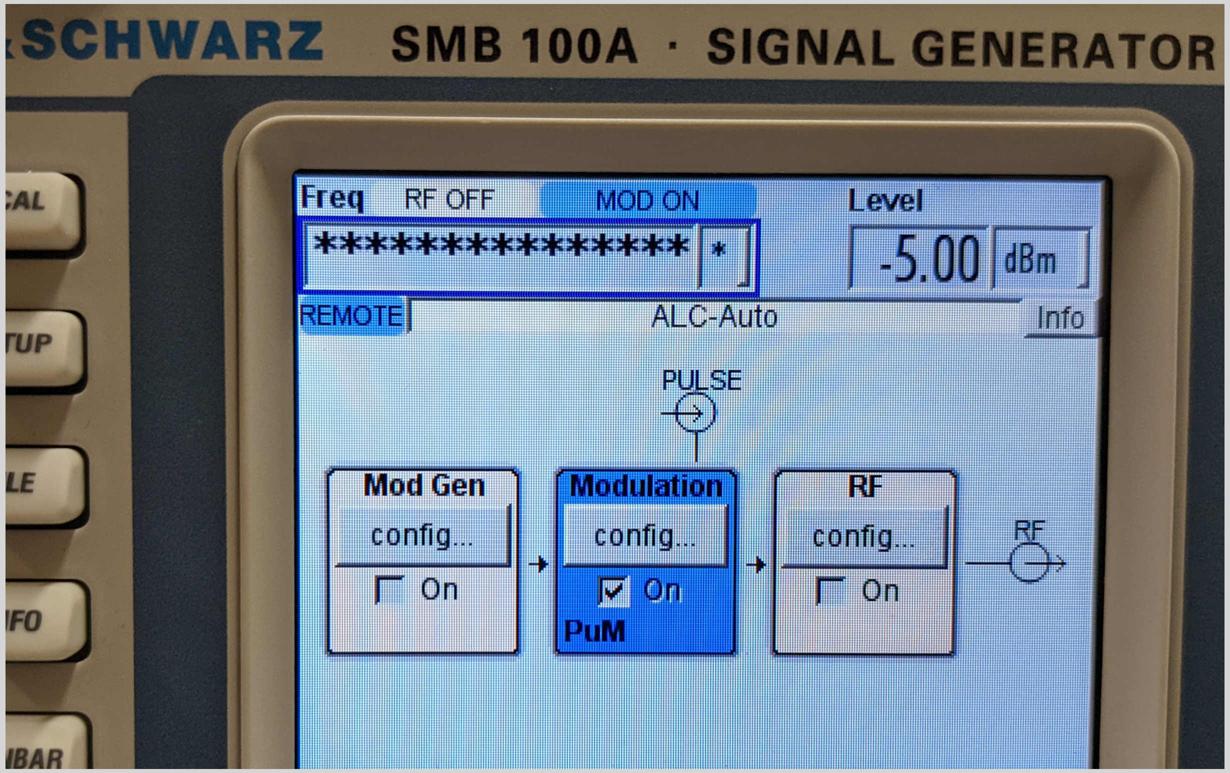
Current status (Signal Generator)

OUTPUT : ON
Frequency : 4464540000.0 + **** Hz
Power : 5.0 dBm
Modulation : ON

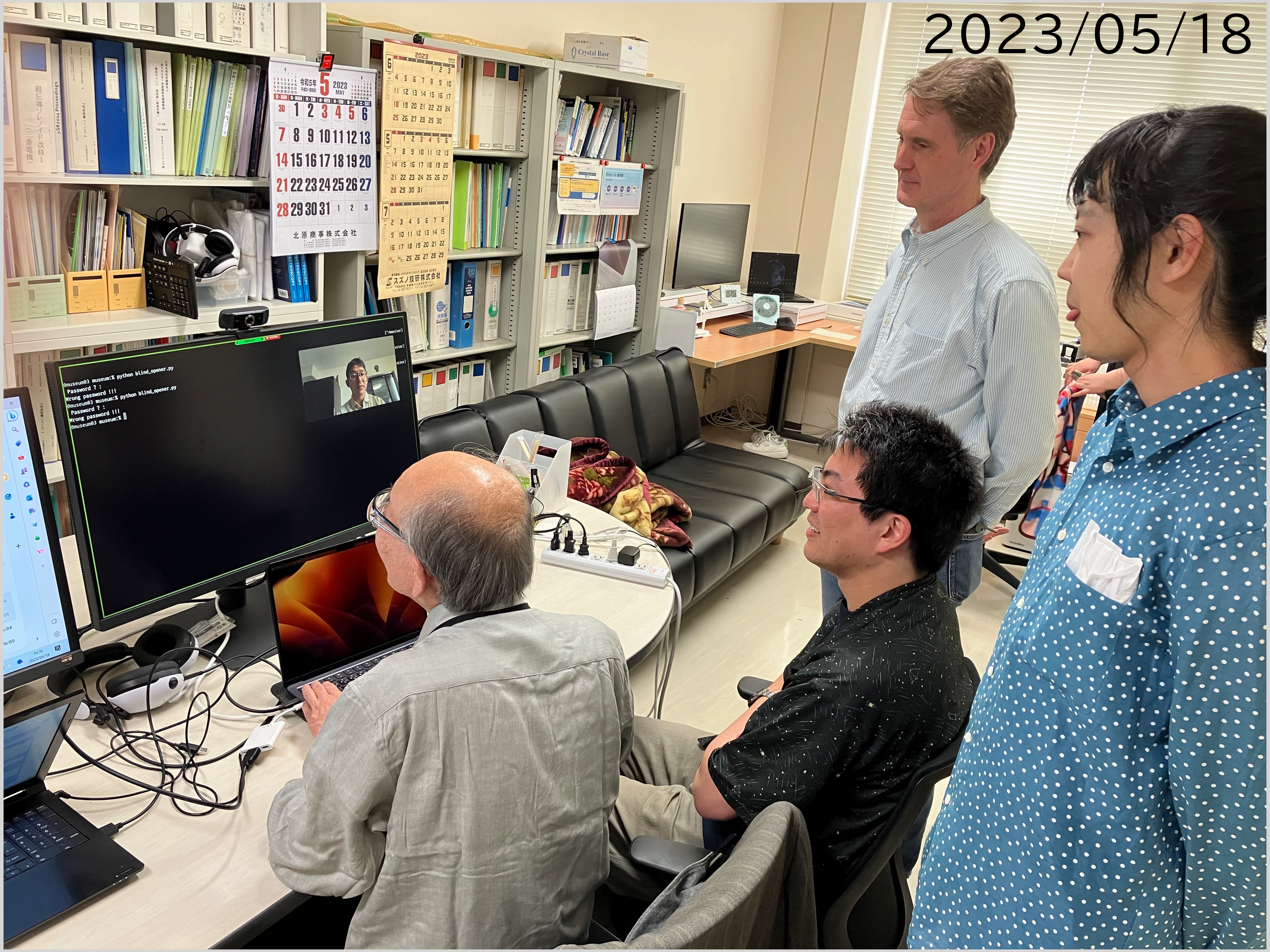
Gas pressure : 1057.112 kPa
Stored power : 2.197999e-05 W

Microwave control

OUTPUT : ○ ON ○ OFF
Frequency (Hz) 4464540000
Power (dBm) 5
Modulation : ○ ON ○ OFF



Blind Test (for μHe)



2023/05/18

```
@museum03 museum:% python blind_opener.py
 Password ? :
Wrong password !!!
@museum03 museum:% python blind_opener.py
 Password ? :
Wrong password !!!
@museum03 museum:% ▌
```

Summary

Mu HFS precision measurement

- Precise bound-state QED test
- Muon g-2 & Muonium 1s-2s

Zero Field Experiment

- Rabi-oscillation spectroscopy
  - ✦ 160 ppb (world highest precision in ZF measurement)

High Field Experiment

- Field uniformity | 0.27 ppm was achieved
- Development of CW-NMR | 15 ppb was achieved
- Ready to start measurement in this FY

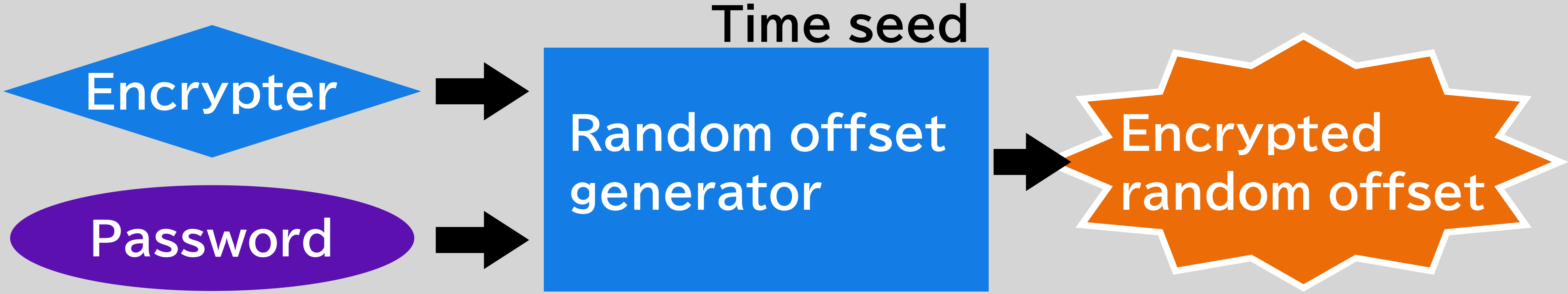
Back up

Systematic Uncertainty

Item	June 2017	June 2018	Prospects
Gas pressure fluctuation	7 Hz	25 Hz	3 Hz
Gas pressure extrapolation	66 Hz	24 Hz	3 Hz
Gas impurity	0 Hz	0 Hz	0 Hz
Static magnetic field	0 Hz	0 Hz	0 Hz
Microwave power drift (including muon beam profile)	200 Hz	10 Hz	< 1 Hz
Pileup event loss	10 Hz	10 Hz	< 1 Hz
Time accuracy of detector	1 Hz	1 Hz	1 Hz
Total	**200 Hz**	**37 Hz**	**4.6 Hz**

Blind Generation & Setting

Blind generation


Time seed

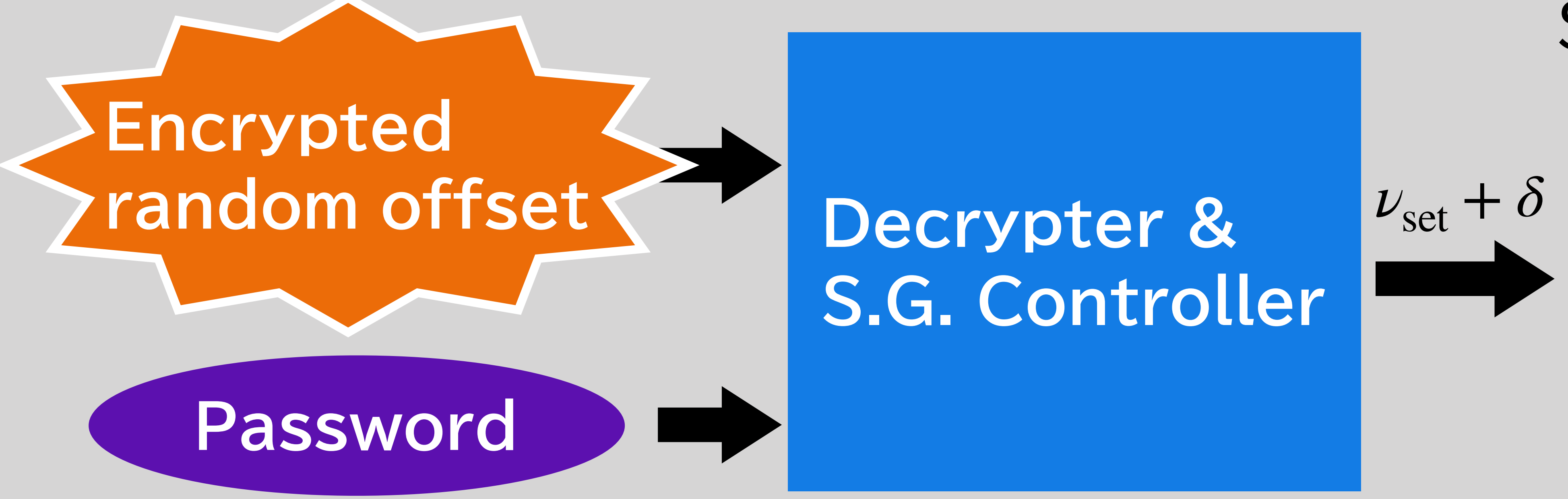
Encrypter

Password

Random offset generator

Encrypted random offset

Blind setting

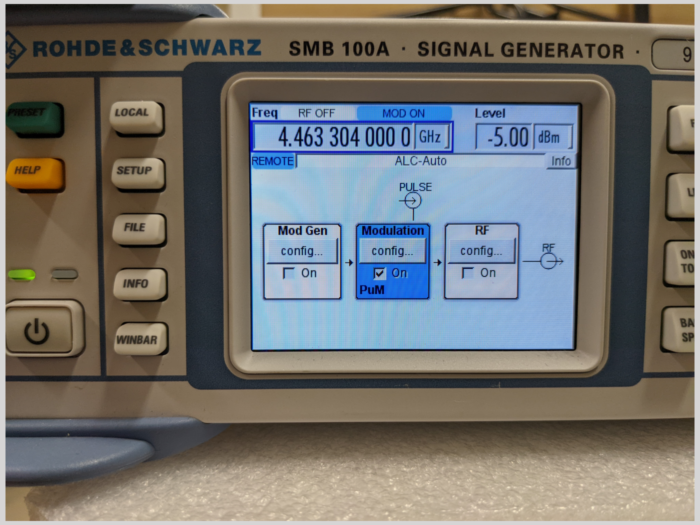

Encrypted random offset

Password

Decrypter & S.G. Controller

$\nu_{\mathrm{set}} + \delta$

Signal Generator



●★■ separated after measurement

Standard Spectroscopy

Signal of all positrons

$$S_{\mathrm{int}} = \frac{\frac{aP}{2}\cos\theta}{1+\frac{\lambda}{\gamma}+\frac{aP}{2}\cos\theta}\boxed{\frac{-2\,|b|^2\left(\gamma'^2+2\,|b|^2\right)}{\left(\gamma'^2+2\,|b|^2\right)^2+\gamma'^2\Delta\omega^2}}$$

Resonance spectrum| Lorentzian

- Sweeping the microwave frequency (or magnetic field)
- Mu HFS is obtained from the center of Lorentzian
- Width and height of spectrum depend on the microwave power

$\Delta\omega$ / Detuning angular frequency

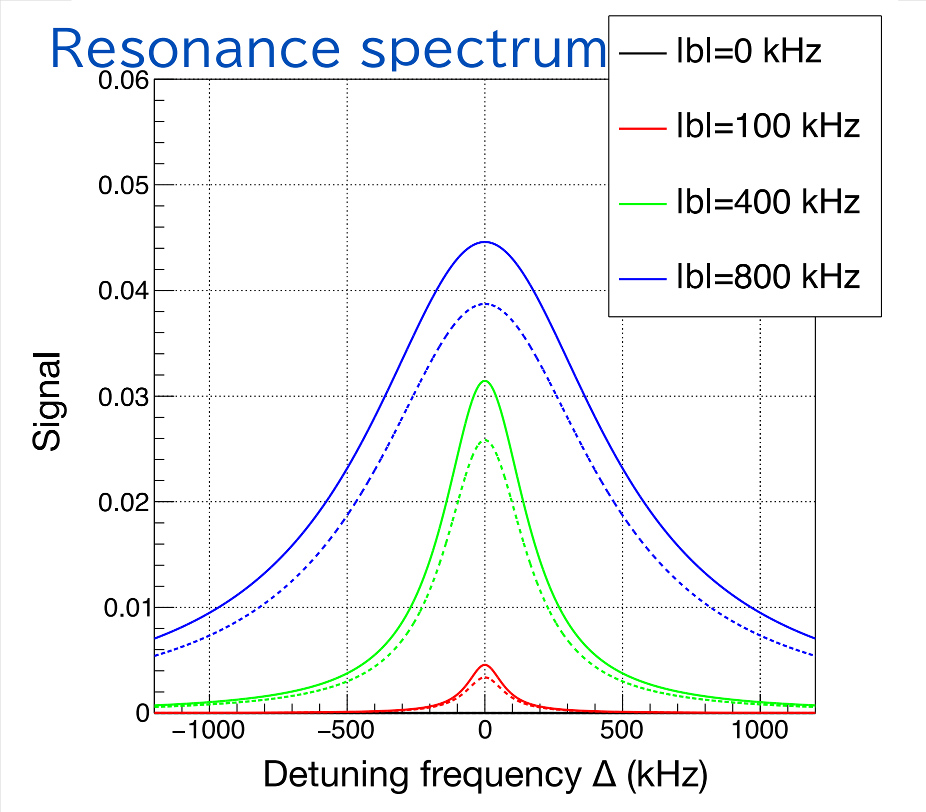
$|b|$ / Microwave magnetic field intensity

λ / Spin relaxation rate

γ / Muon decay rate

P / Muon spin polarization

$$\gamma' = \gamma + \lambda$$



Gas Pressure Dependence of Mu HFS Transition Frequency

Gas pressure shift

- Transition frequency is shift due to collision between Mu and target gas atom

$$\Delta\nu(P) = (1 + aP + bP^2)\Delta\nu(P=0)$$

P : gas pressure, a, b : parameters

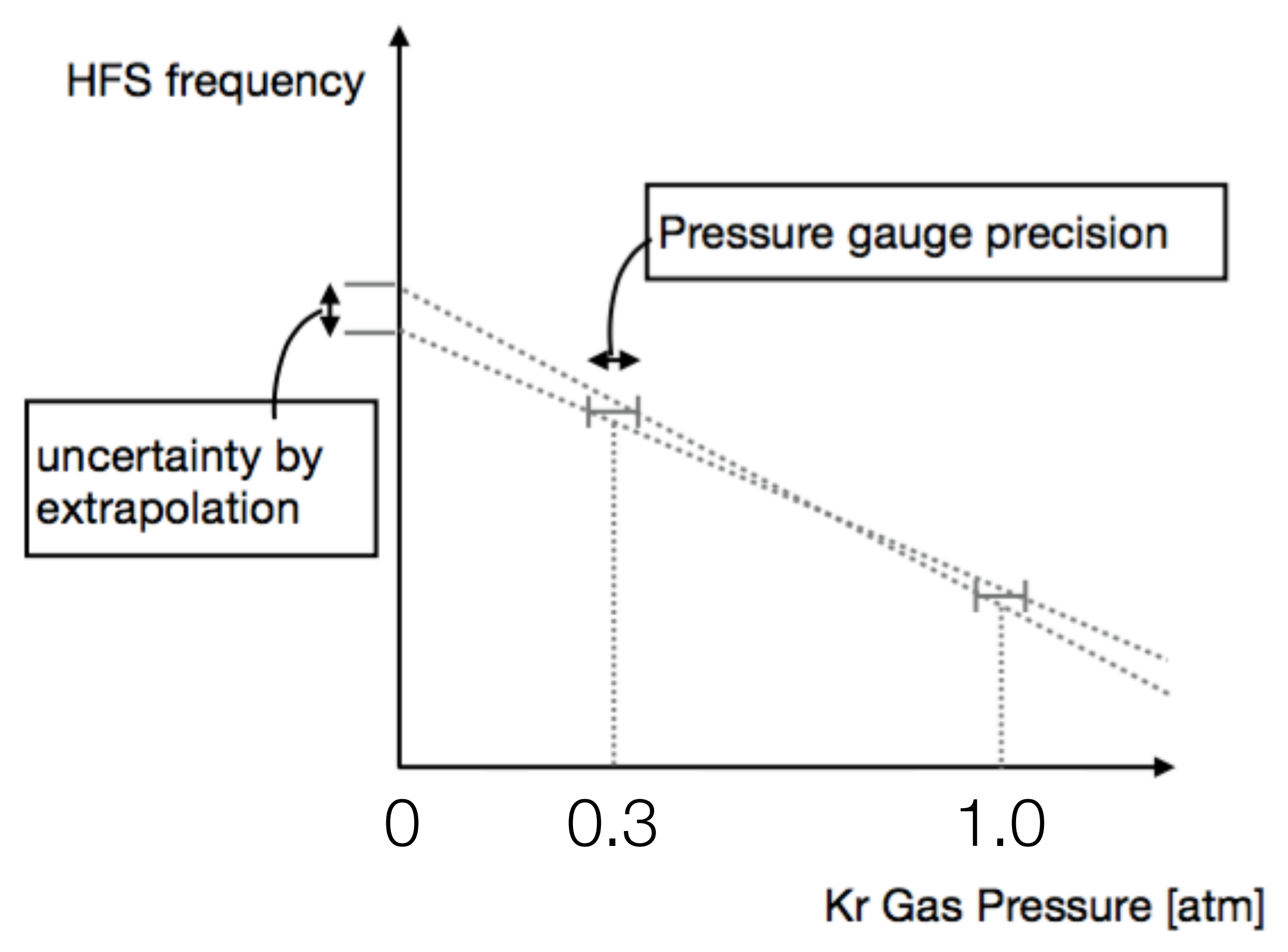
Various gas pressure measurement

↓

Extrapolation to 0 atm

↓

Mu HFS in vacuum

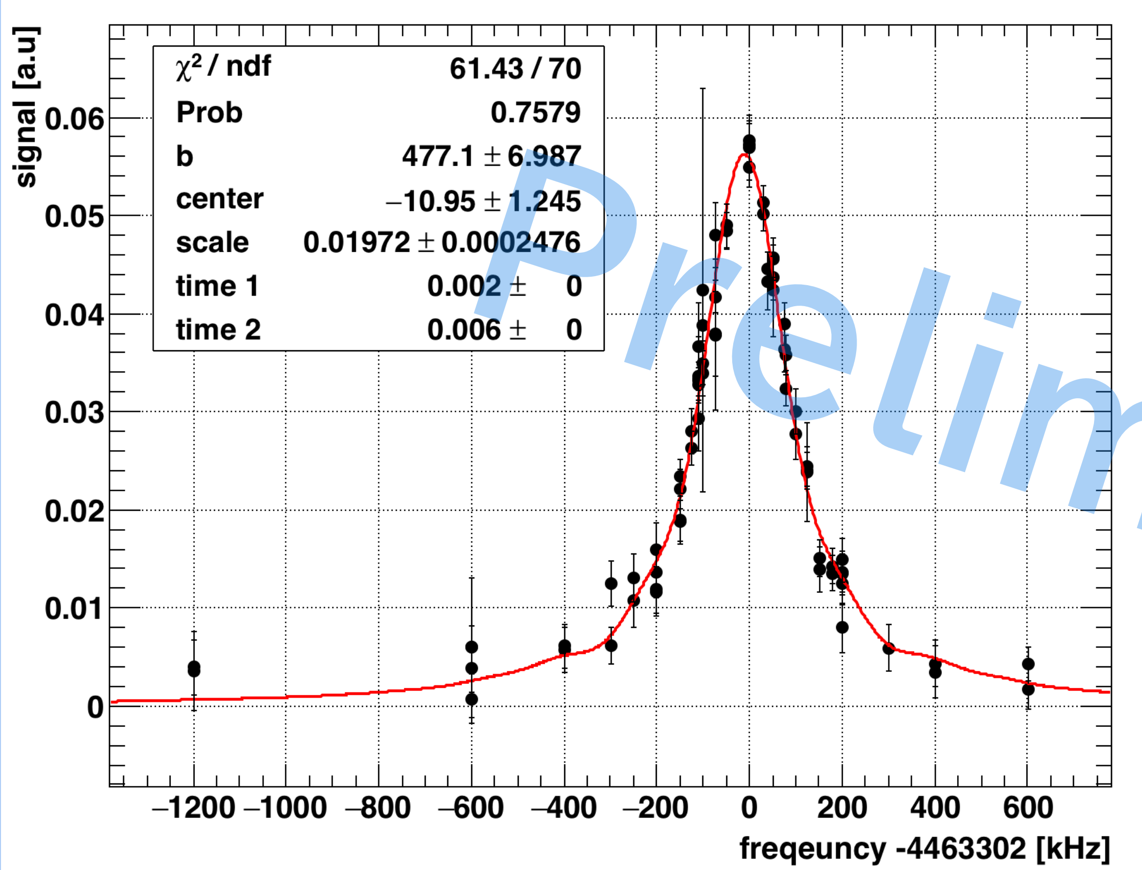


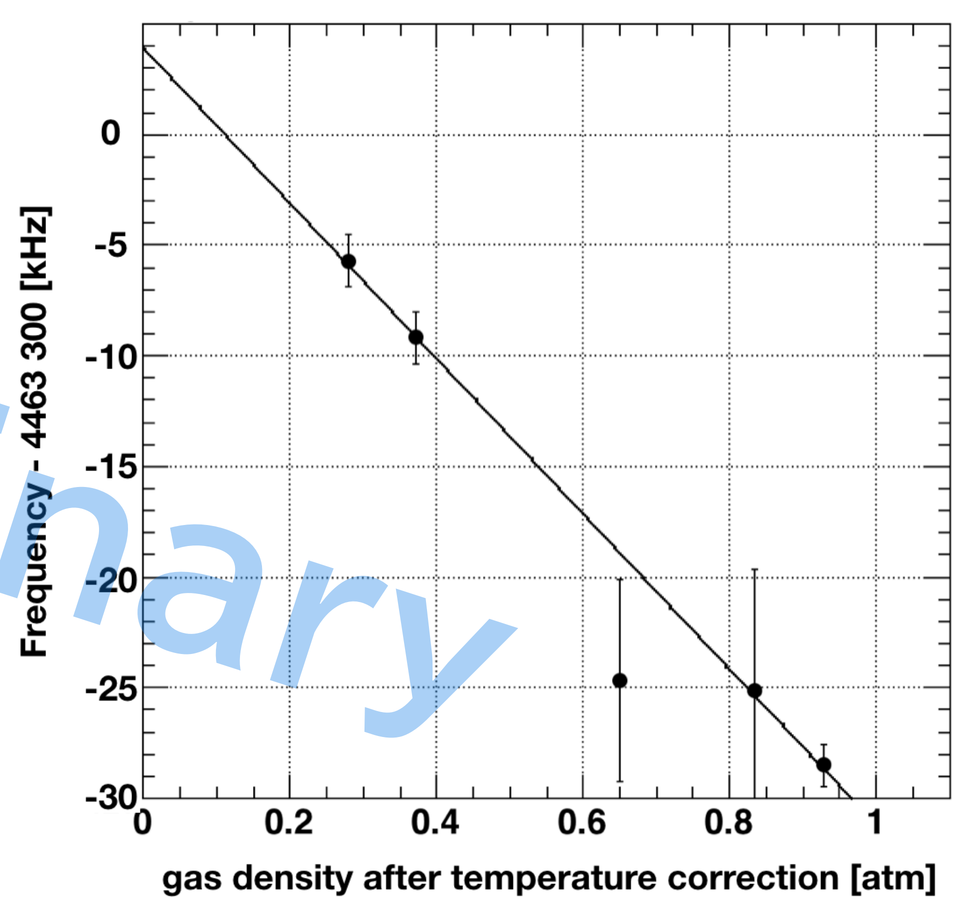
Gas Pressure Dependence of Mu HFS Transition Frequency

Experiment in 2018 June

- Spin flip resonance signal was observed for several gas pressure
- Recent analysis achieved 0.9 kHz (Assume previous pressure)

Y. Ueno (Riken)



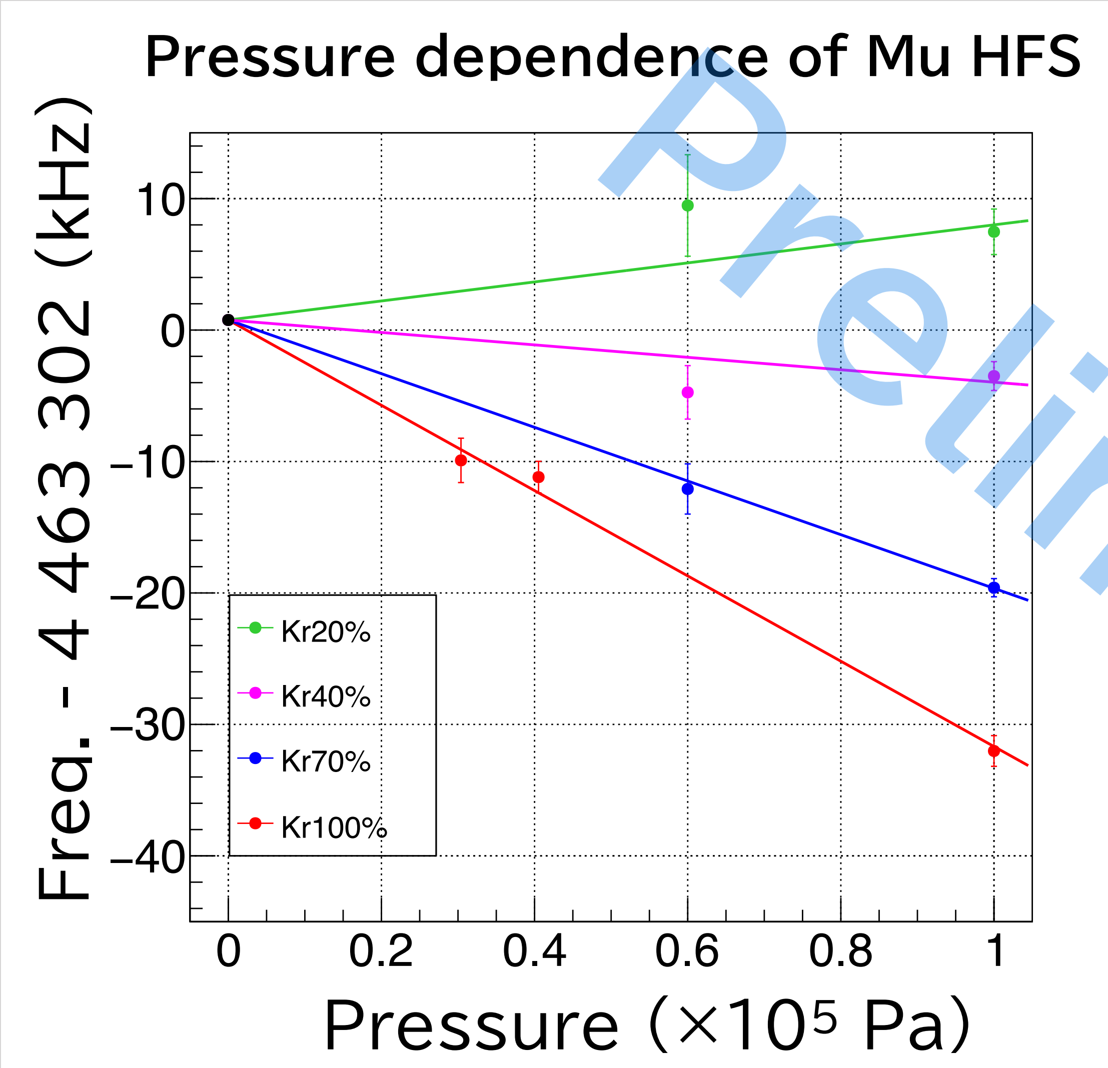


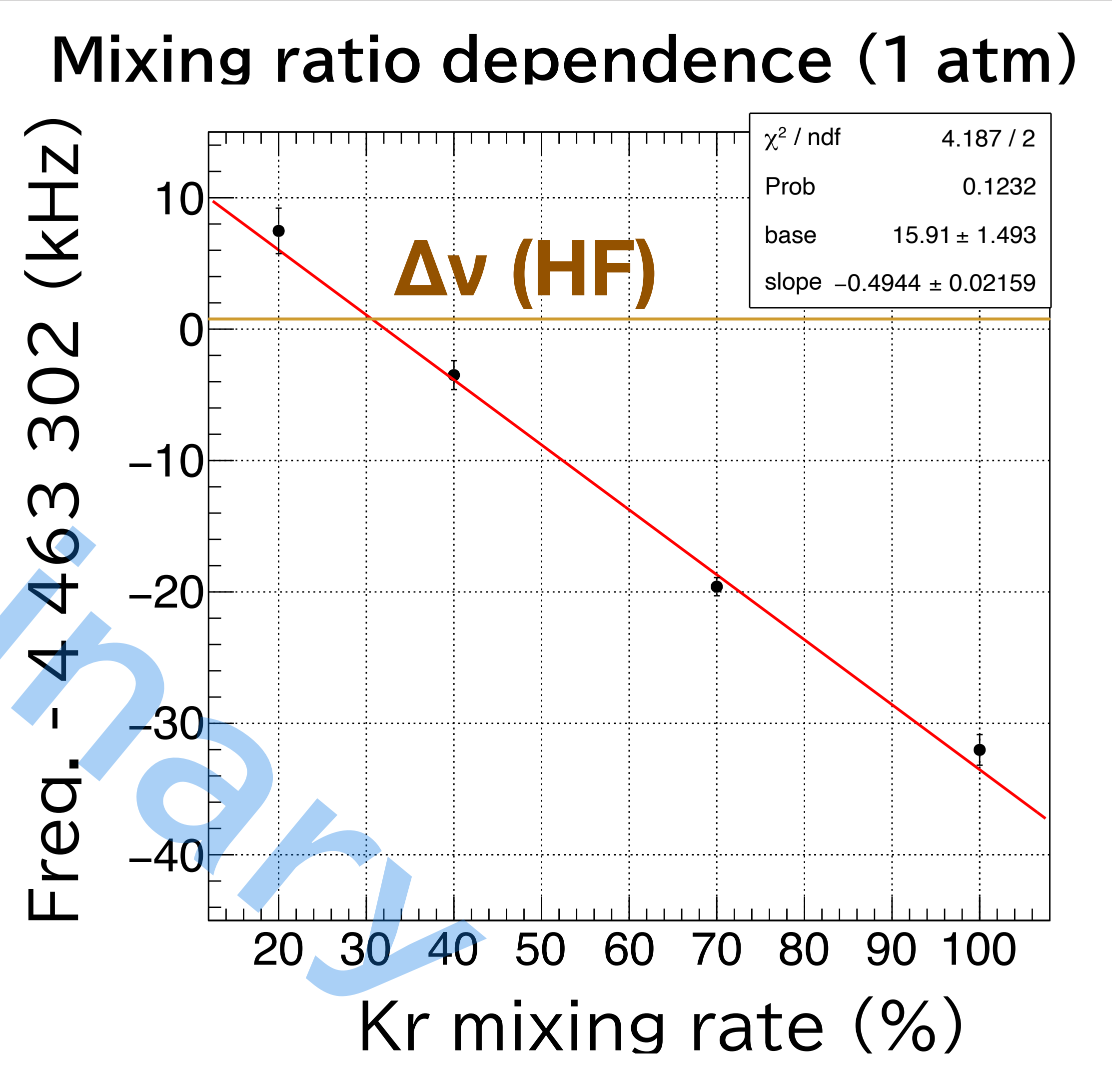
Kr-He Mixture Gas

Dependence of transition frequency shift is reverse between Kr and He

- Pressure dependence is cancelled at Kr/He mixing ratio = 30%

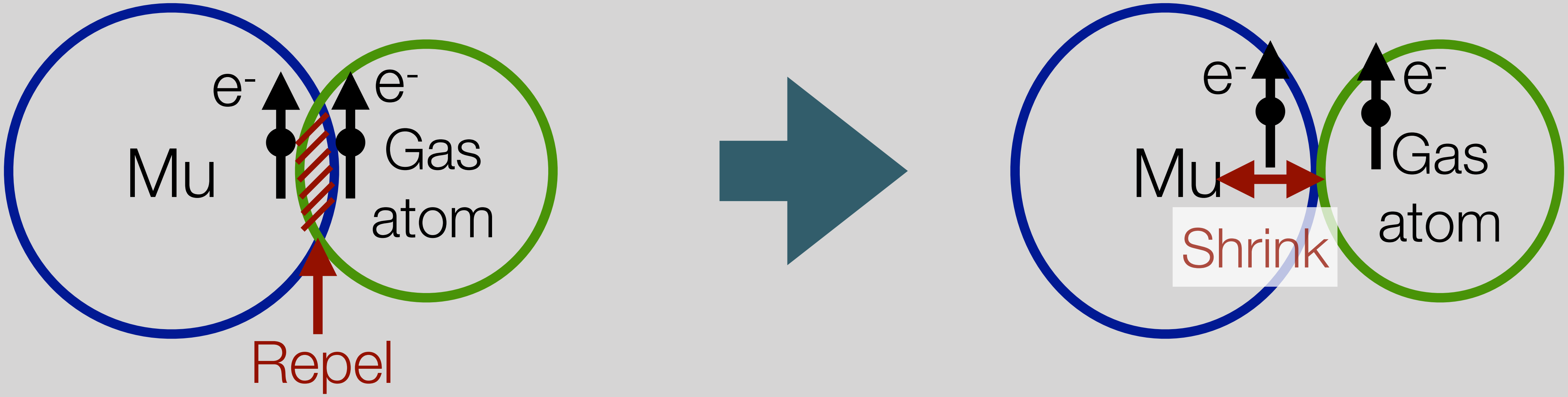
S. Seo (The Univ. of Tokyo)


Pressure dependence of Mu HFS


Mixing ratio dependence (1 atm)

Transition Frequency Shift due to collision

- Pauli exclusion principle -> Increasing transition frequency



- van der Waals force -> Decreasing frequency