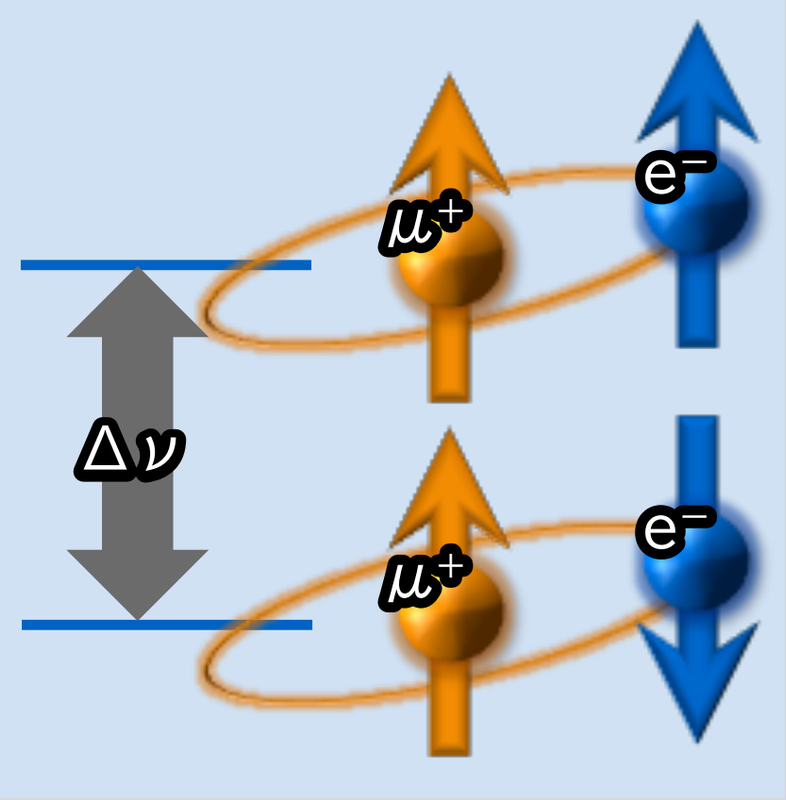
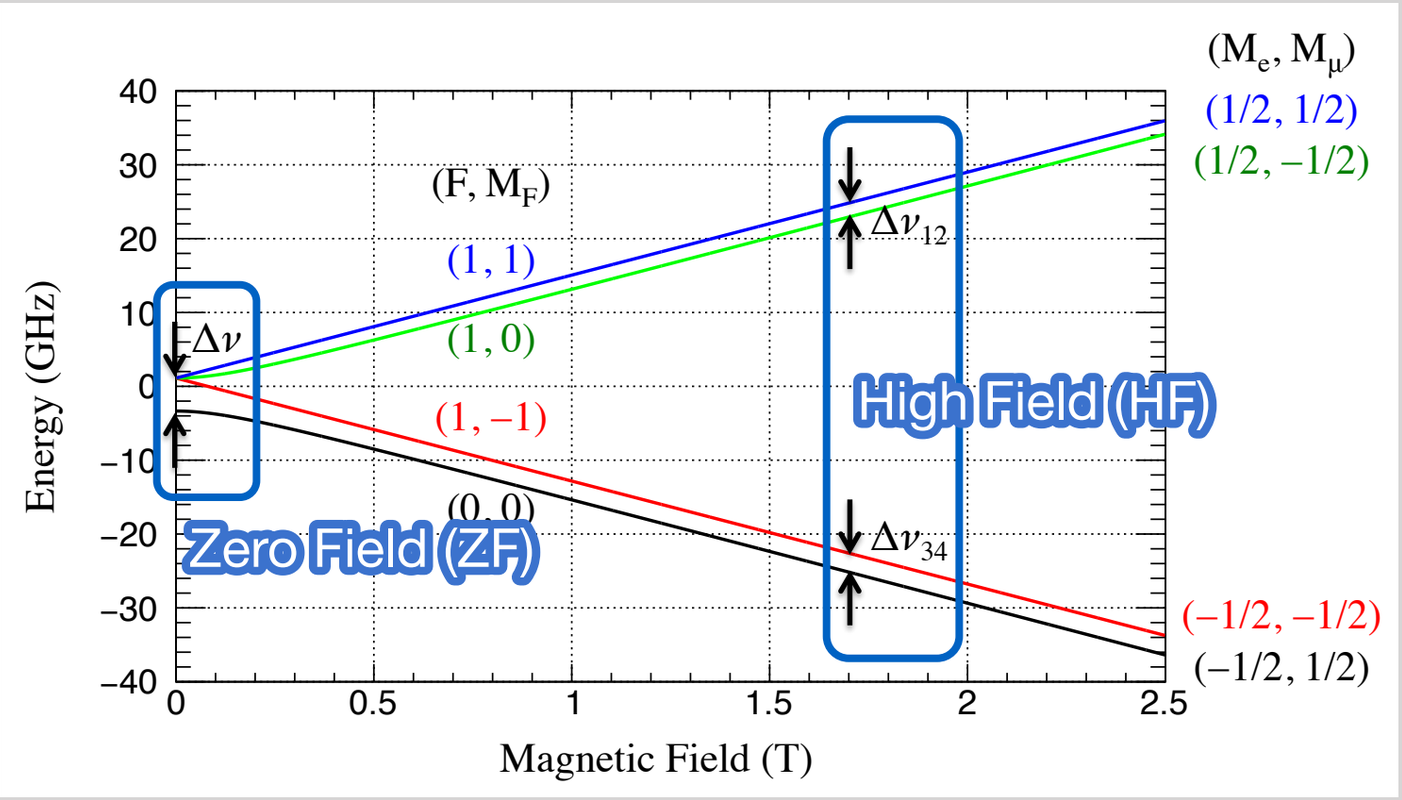
Zero-Field and High-Field Measurements of Muonium Hyperfine Structure with Rabi-Oscillation Spectroscopy

Shoichiro Nishimura / KEK IMSS
(MuSEUM Collaboration)

Muonium HFS

Muonium|Bound state of μ^+ and e^-





Experimental value $\Delta\nu$

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

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.)

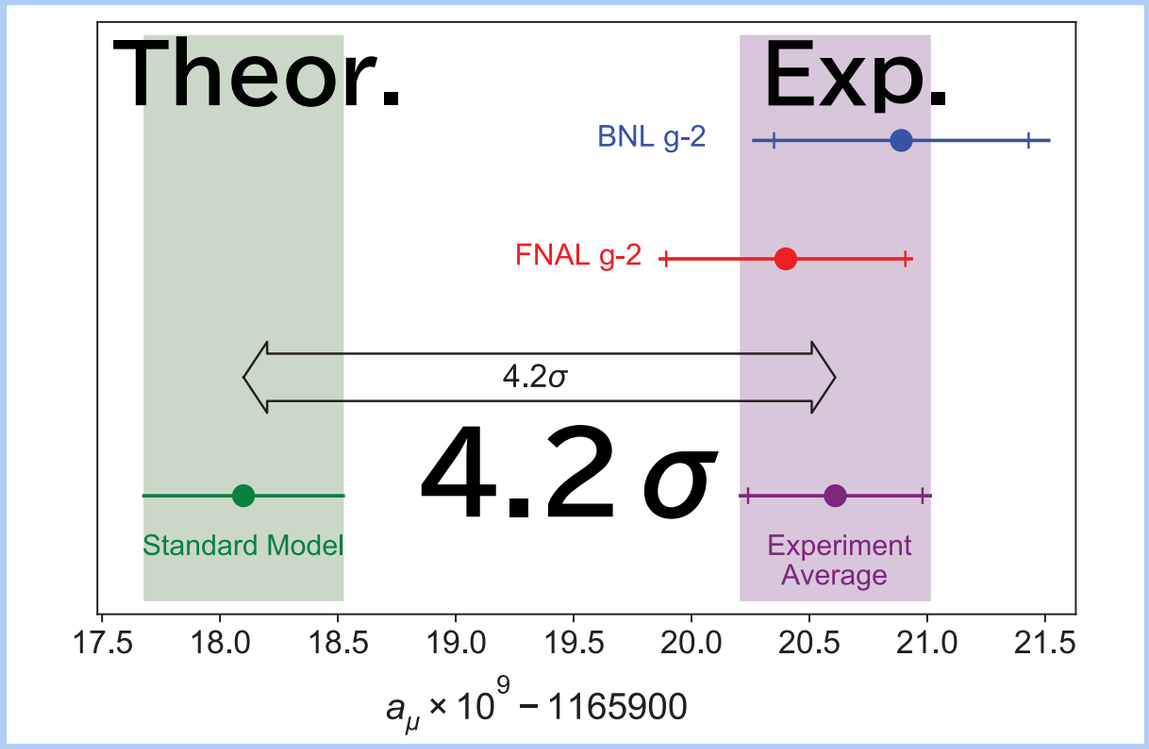
PRA 86 (2012) 024501, PRL 112 (2014) 173004, PRD 89 (2014) 014034

Relation between Muon $g-2$ and Mu HFS

Muon $g-2$

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

- $4.2\,\sigma$ 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)

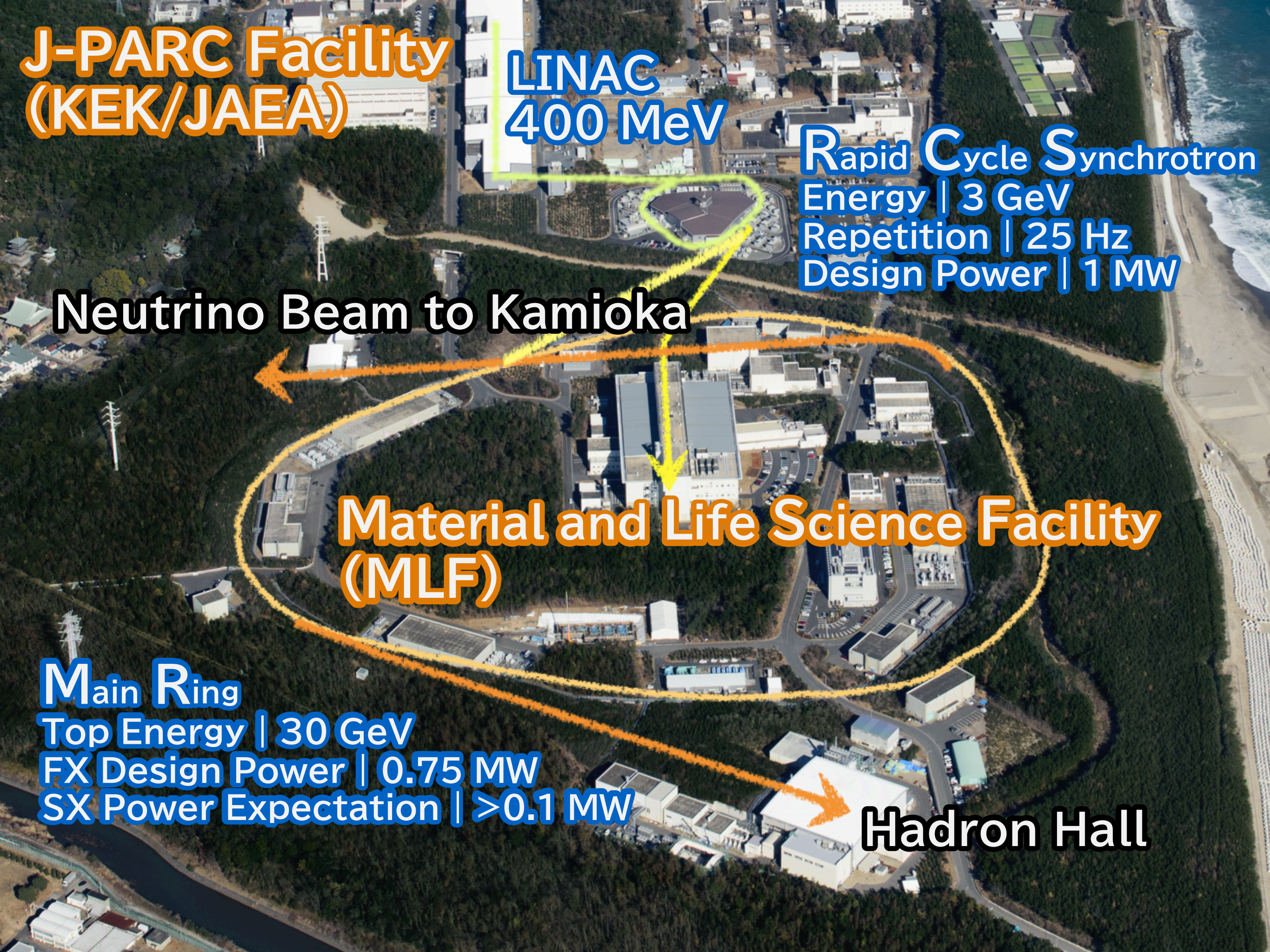
$$a_\mu = \frac{R}{\lambda - R}$$

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

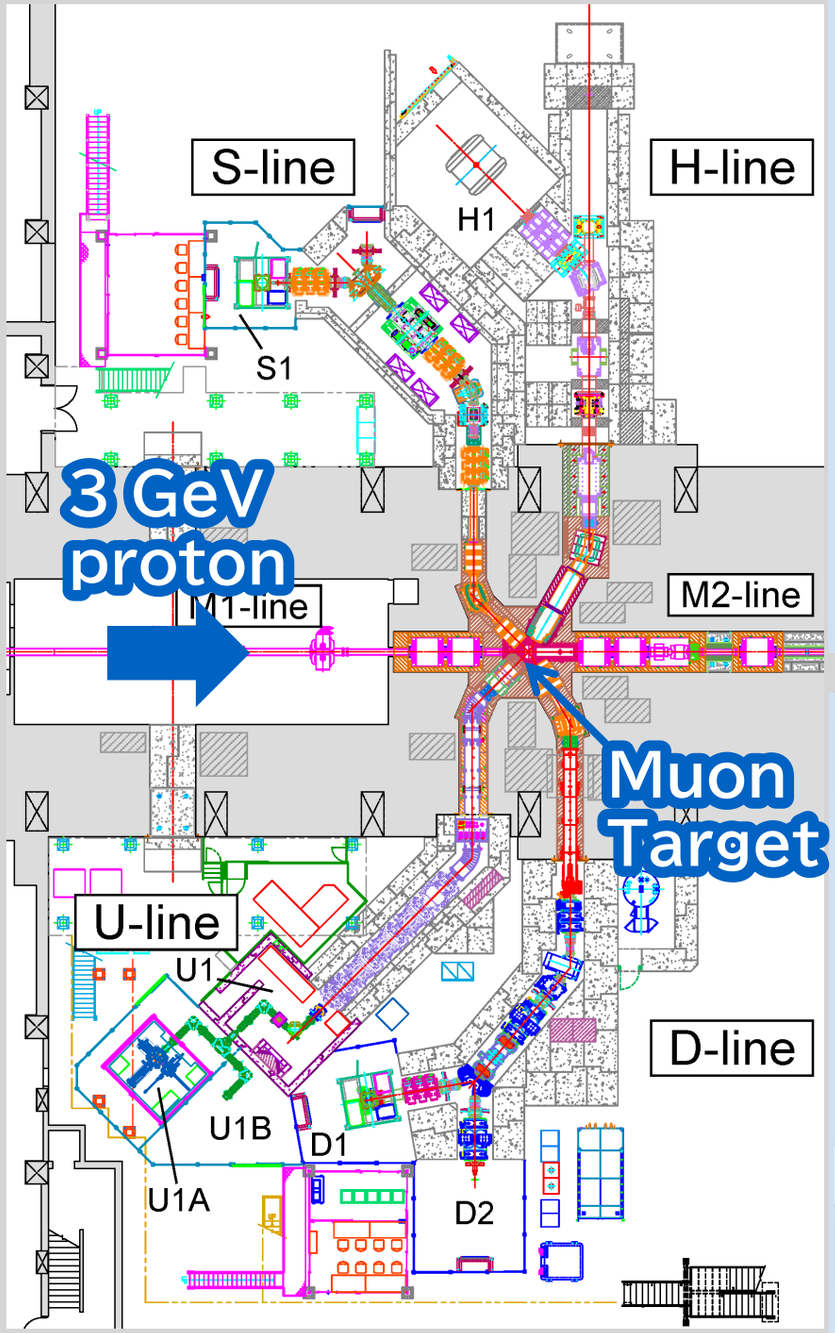
$g-2$ strage ring

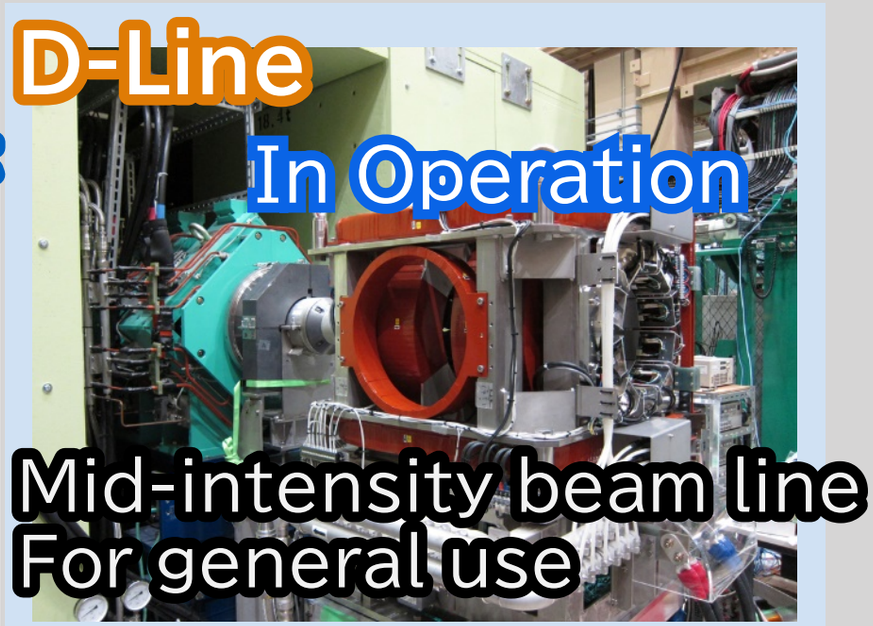
$$\lambda \equiv \frac{\mu_\mu}{\mu_p}$$

Mu HFS measurement


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



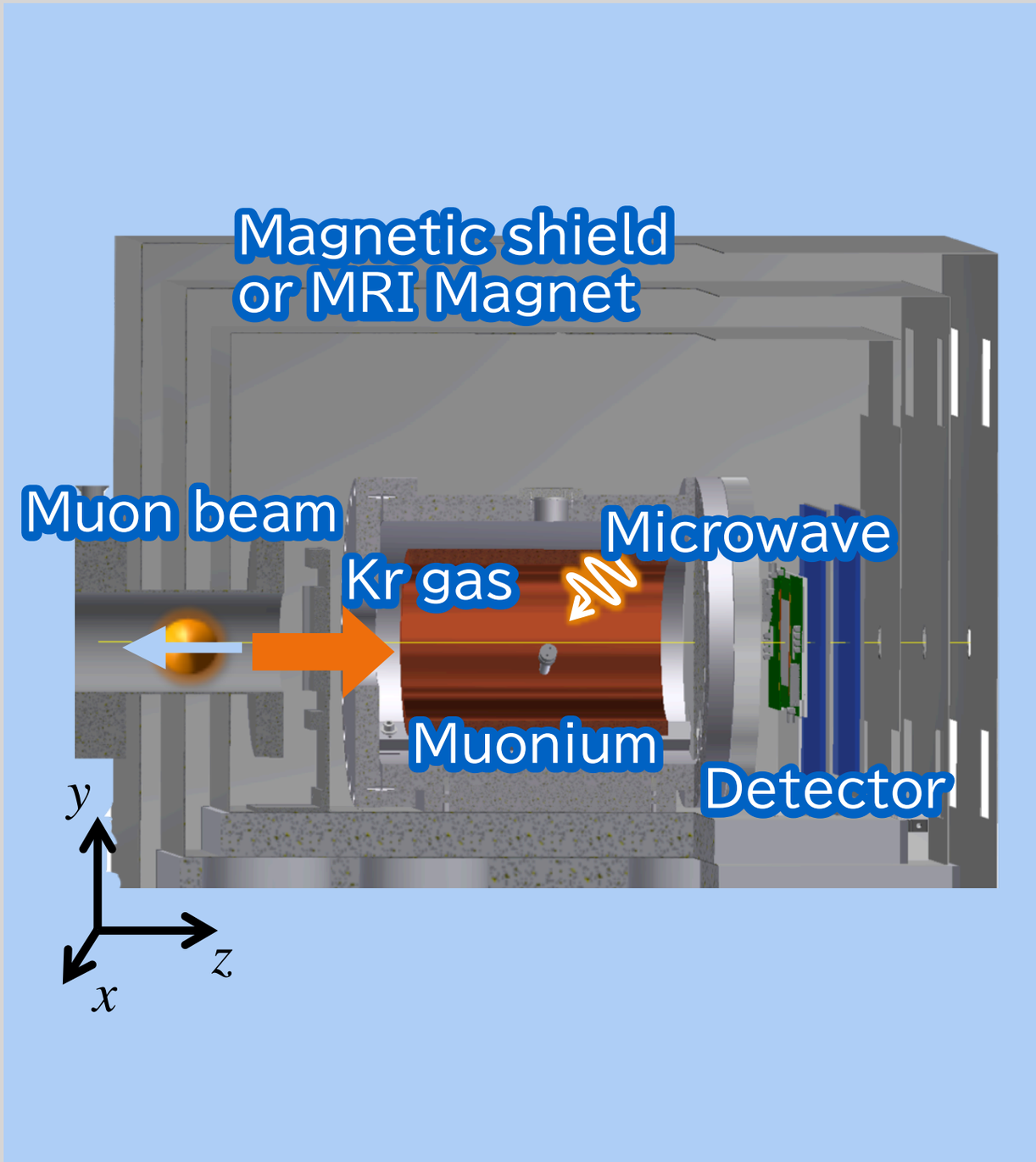


MuSEUM Setup

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

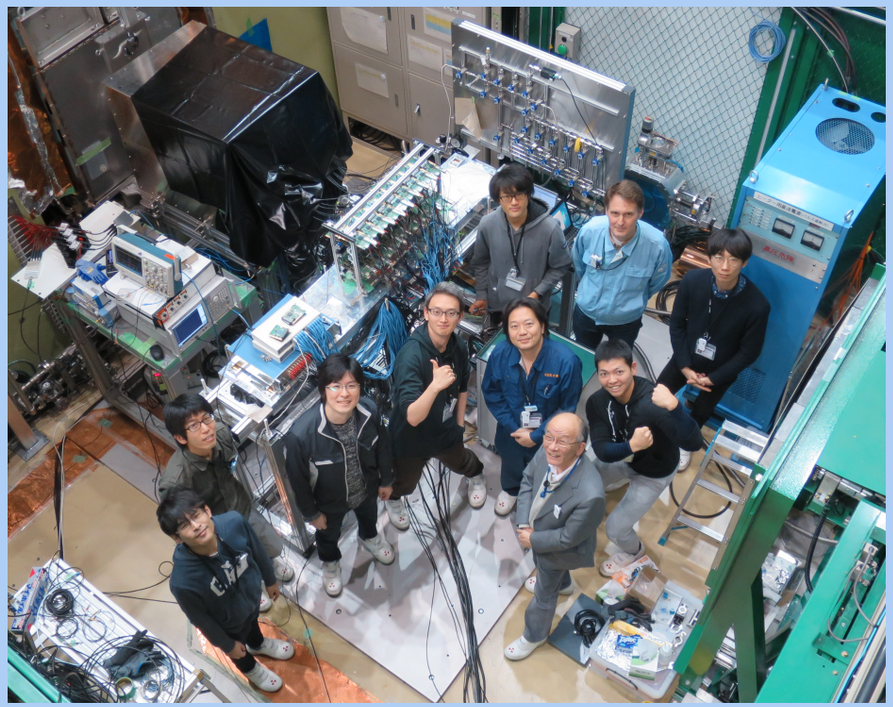
- Mu HFS resonance was measured at Kr 1 atm

2018

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

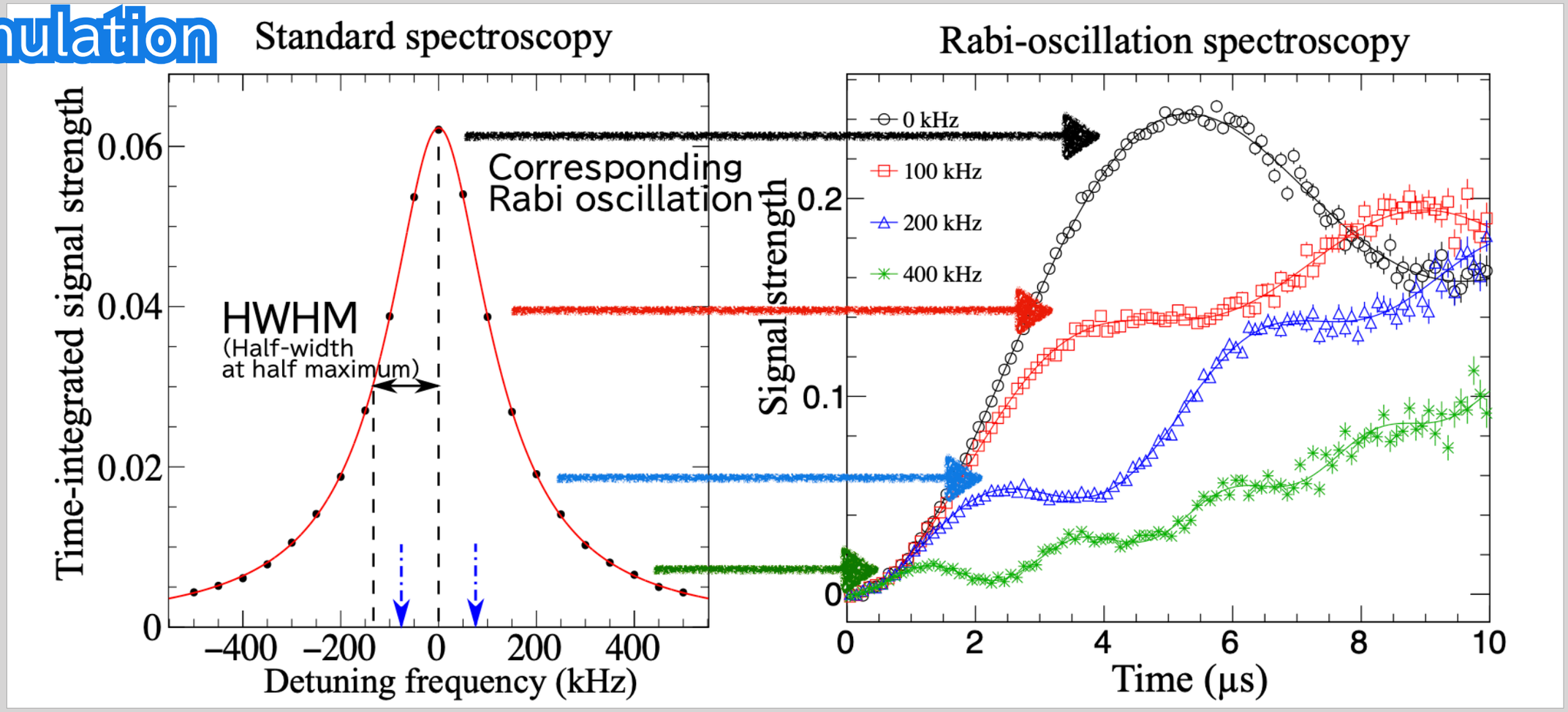
2019

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



Comparison of conventional and Rabi-oscillation spectroscopy

Simulation



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

Time dependence of signal

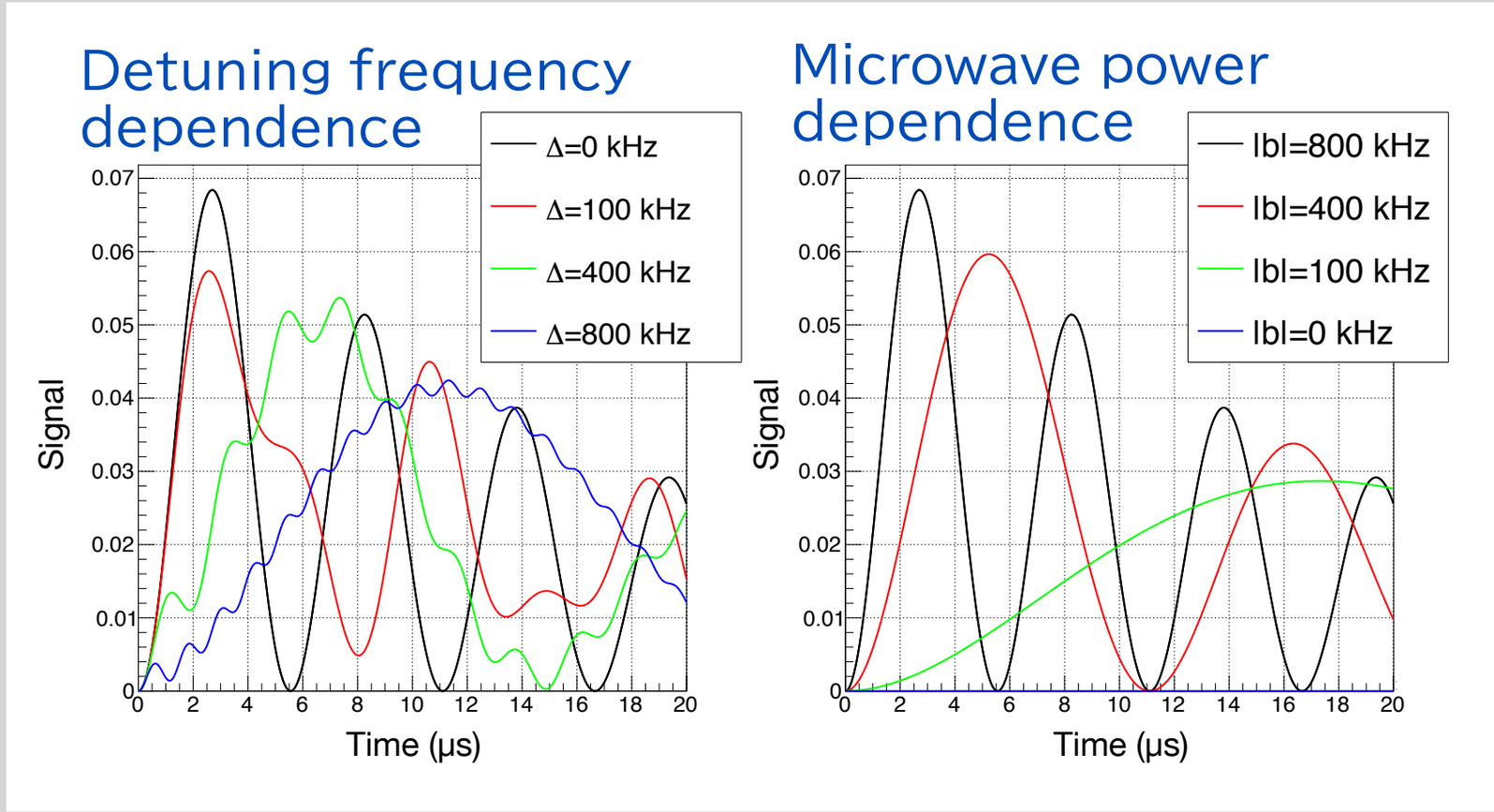
$$dS_{\mathrm{diff}} = \frac{aP}{2}\frac{\left(C(t)-1\right)\cos\theta_s \mathrm{e}^{-(\lambda+\gamma)t}}{\left(1+\frac{aP}{2}\mathrm{e}^{-\lambda t}\cos\theta_s\right)\mathrm{e}^{-\gamma t}}$$

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

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

Time spectrum sum. of cos

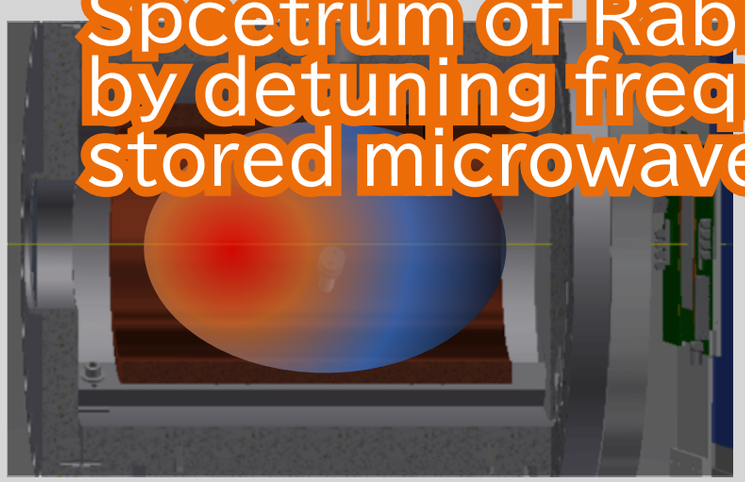
- It can extract much information
  - Mu HFS
  - Microwave power
  - Spin relaxation rate
- Mu HFS is extracted from only one detuning frequency data



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

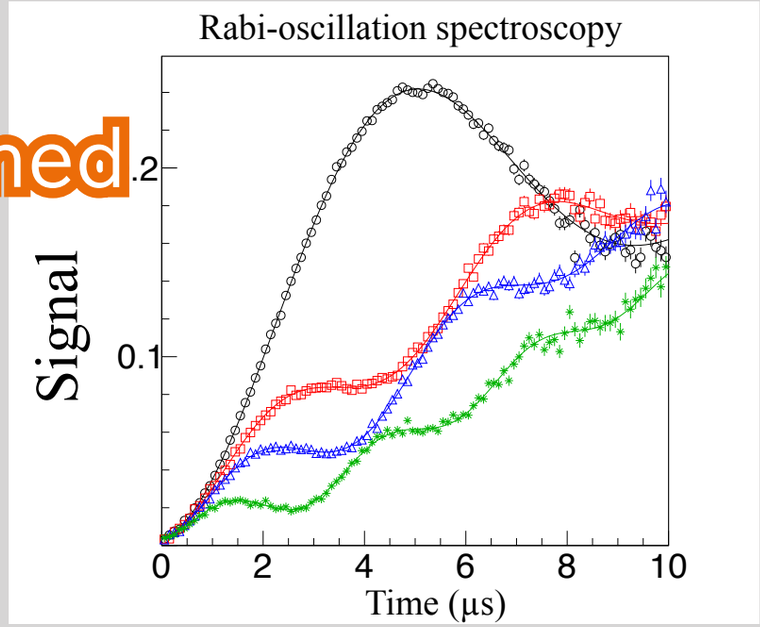


Muon stopping distribution

+

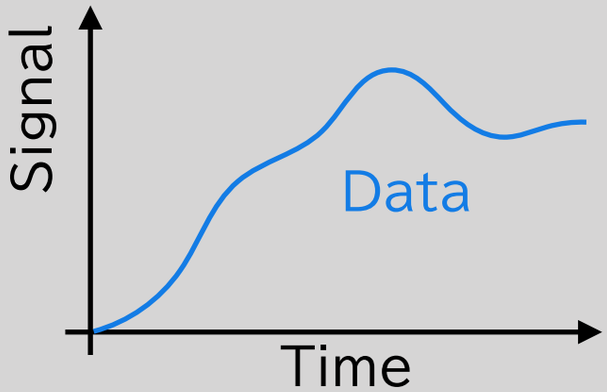
Microwave power distribution

=



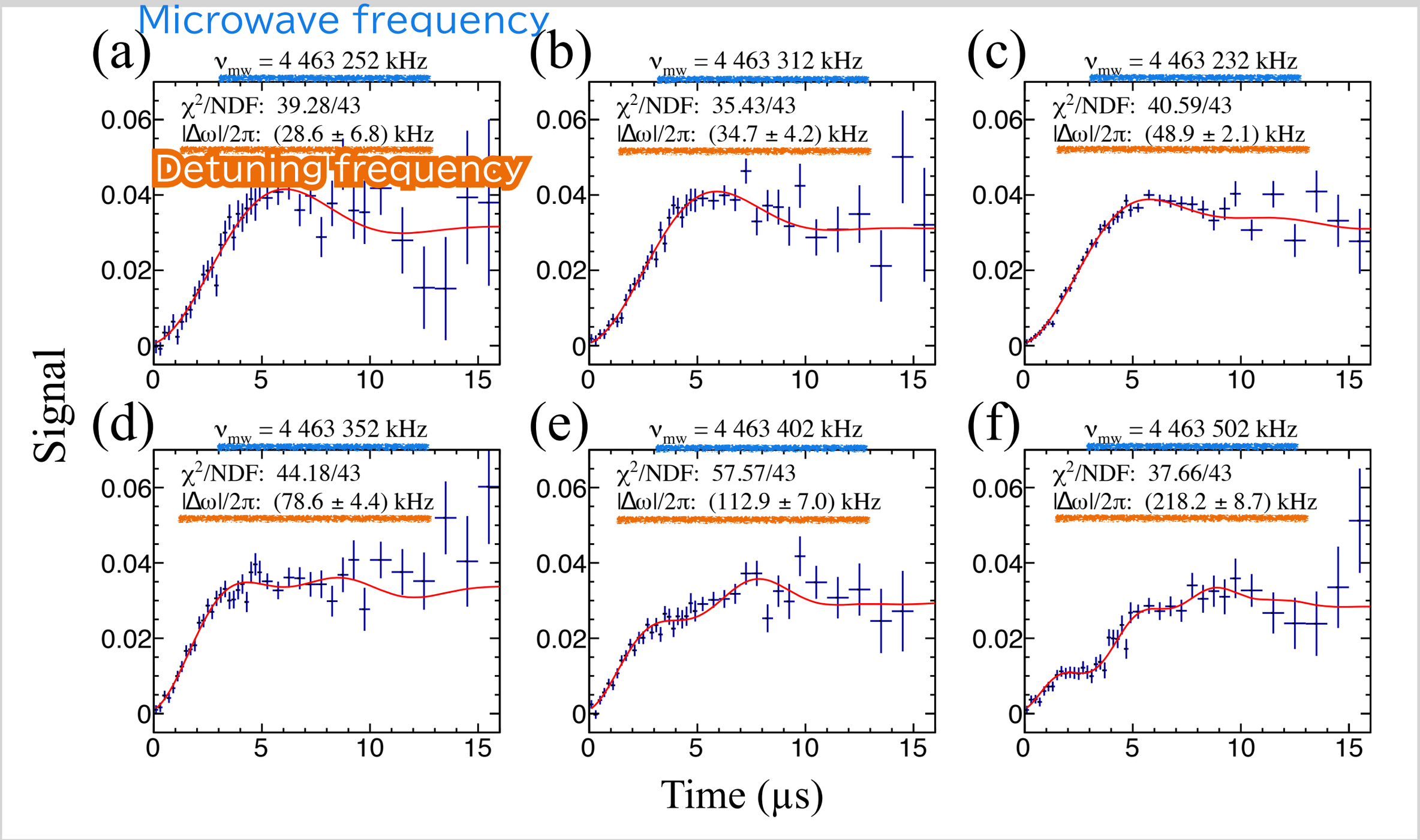
Rabi-oscillation signal from all muonium

Fit estimated signal to the obtained data

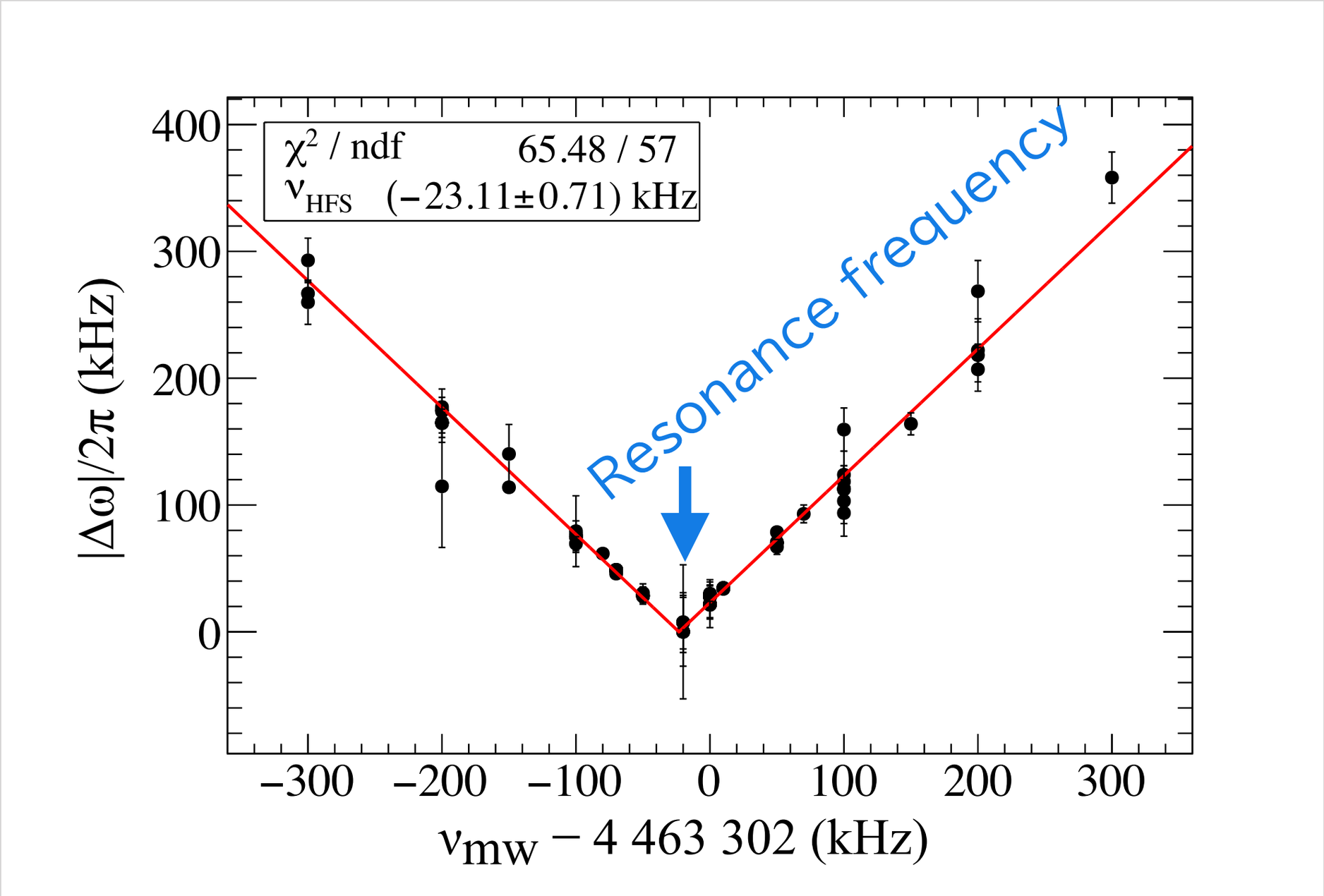


We can obtain the detuning frequency from the single microwave frequency data

Results of Rabi-oscillation spectroscopy



Results of Rabi-oscillation method (multiple microwave frequency)



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

Papers on our experiment

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. Se 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, H. Yasuda,[3] T. Yoshioka,[7] and K. Shimomura[1,2,4]
(MuSEUM Collaboration)

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As a method to determine the resonance frequency, Rabi-oscillation spectroscopy has been developed. In contrast to conventional spectroscopy which draws the resonance curve, Rabi-oscillation spectroscopy fits the time evolution of the Rabi oscillation. By selecting the optimized frequency, it is shown that the precision is twice as good as conventional spectroscopy with a frequency sweep. Furthermore, the data under different conditions can be treated in a unified manner, allowing more efficient measurements for systems consisting of a limited number of short-lived particles produced by accelerators such as muons. We have developed a fitting function that takes into account the spatial distribution of muonium and the spatial distribution of the microwave intensity to apply this method to ground-state muonium hyperfine structure measurements at zero field. It was applied to the actual measurement data, and the resonance frequencies were determined under various conditions. The result of our analysis gives $\nu_{\mathrm{HFS}} = 4\,463\,301.61 \pm 0.71$ kHz.

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ZF experimental apparatus

Physics Letters B 815 (2021) 136154

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Physics Letters B

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

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]

ZF and HF cavity

PTEP

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

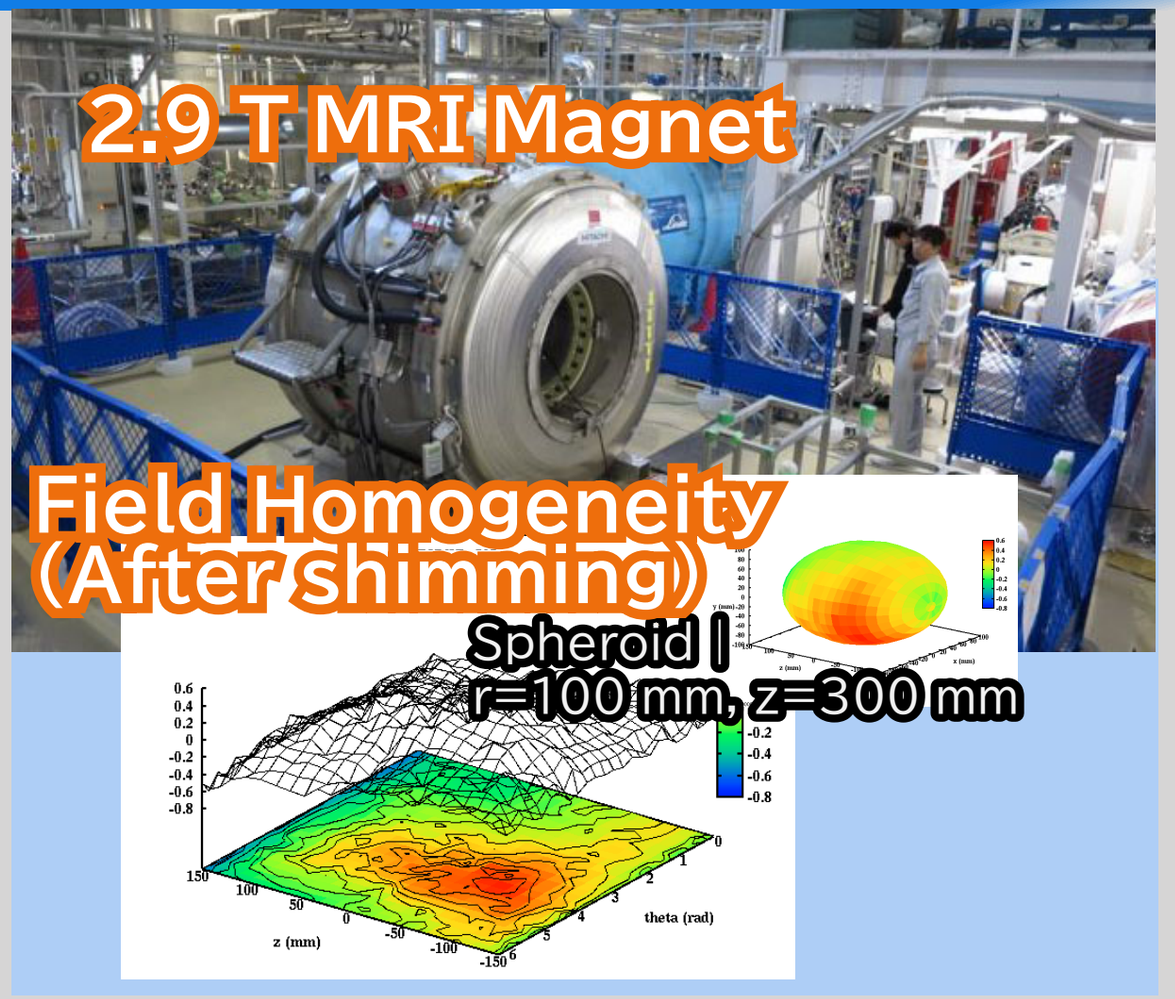
Development of microwave cavities for measurement of muonium hyperfine structure at J-PARC

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]

Development for High Field Exp.

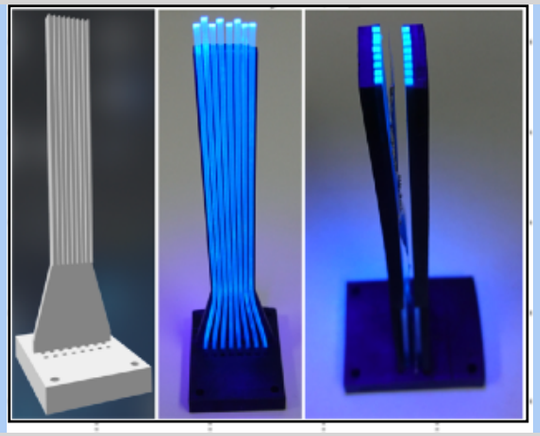
Magnetic Field

- CW-NMR prove
- Shimming
  - r=100mm/z=300mm Spheroid Volume
  - Field uniformity | 0.27 ppm was achieved



Upstream Detector

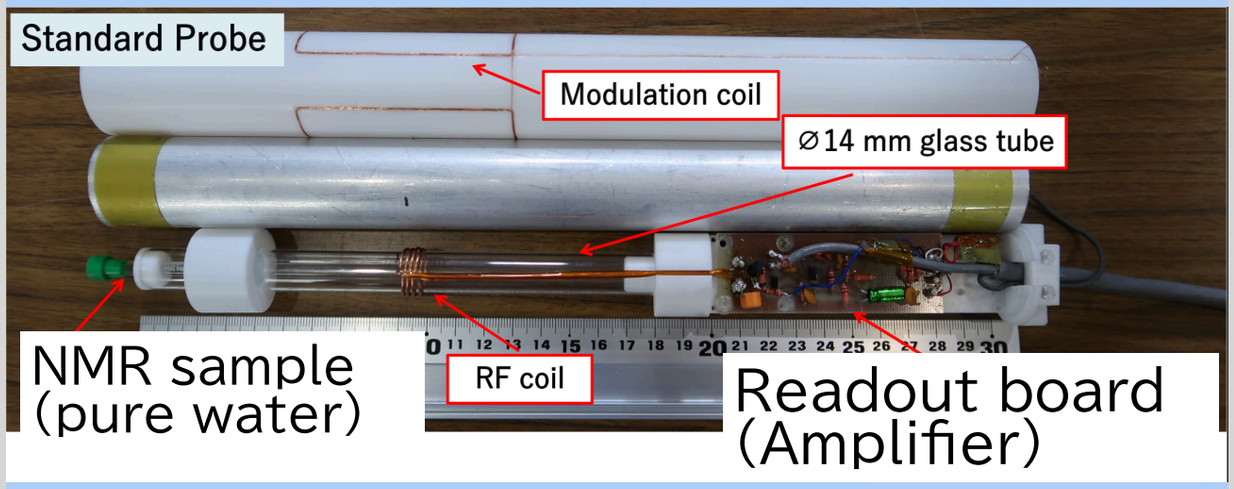
- Beam test of detector was completed



Development of CW-NMR

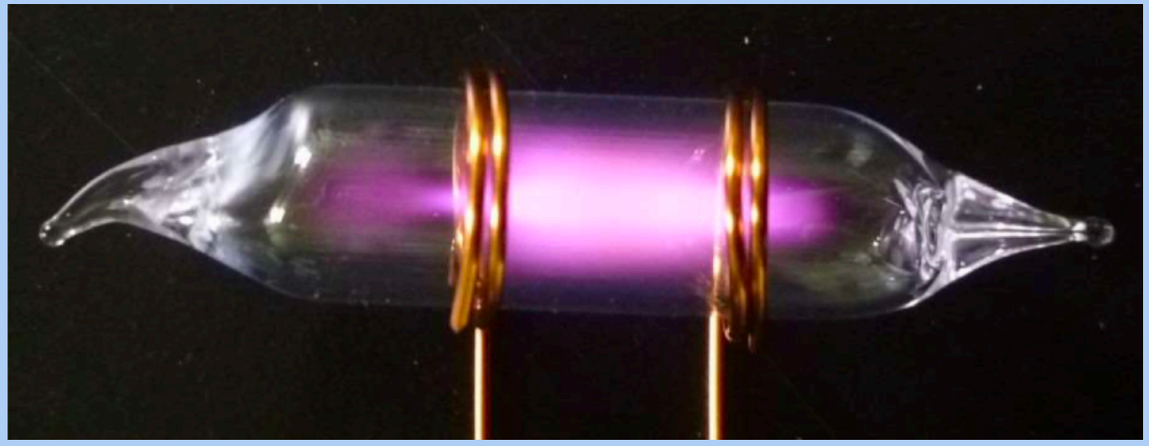
Pure water NMR probe

- Cross calibration
  - precision of 15 ppb has been achieved



^{3}He NMR probe

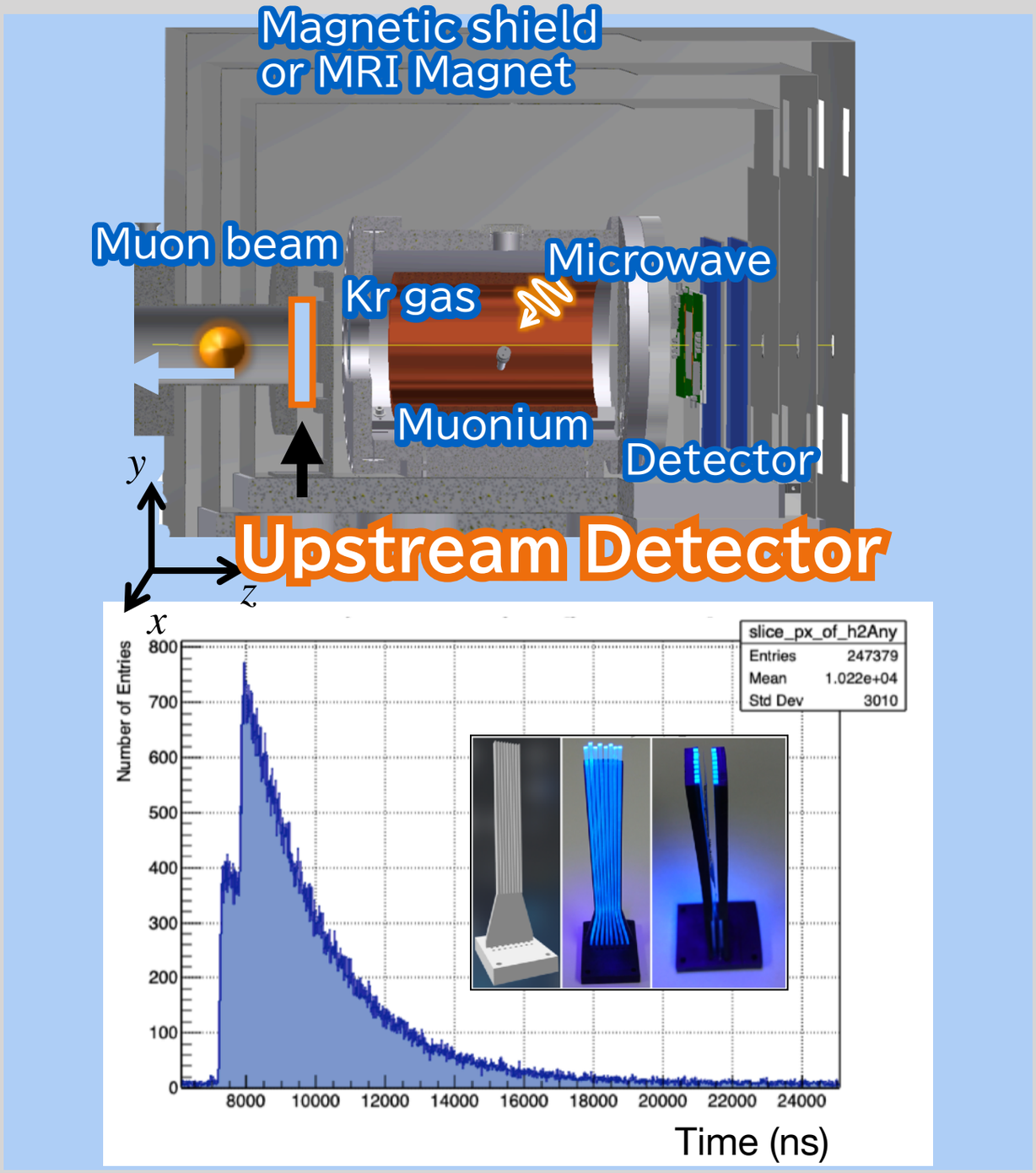
- Shielding effect can be improved
- Higher precision can be obtained (0.1 ppb)



Upstream Detector

Fiber scinillation detector

- The detector consists of Fiber scintillators and SiPMs
- To improve statistics
- Improving systematic uncertainty due to muon beam fluctuation (stopping distribution etc.)
- Signal of muon decay positron was observed
- Under construction



Summary

Mu HFS precision measurement

- Precise bound-state QED test
- Muon g-2

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
  - Higher precision can be achieved by using ^{3}He probe
- Development of the upstream detector

Back up

Time Integral Method

Signal of all positrons

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

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

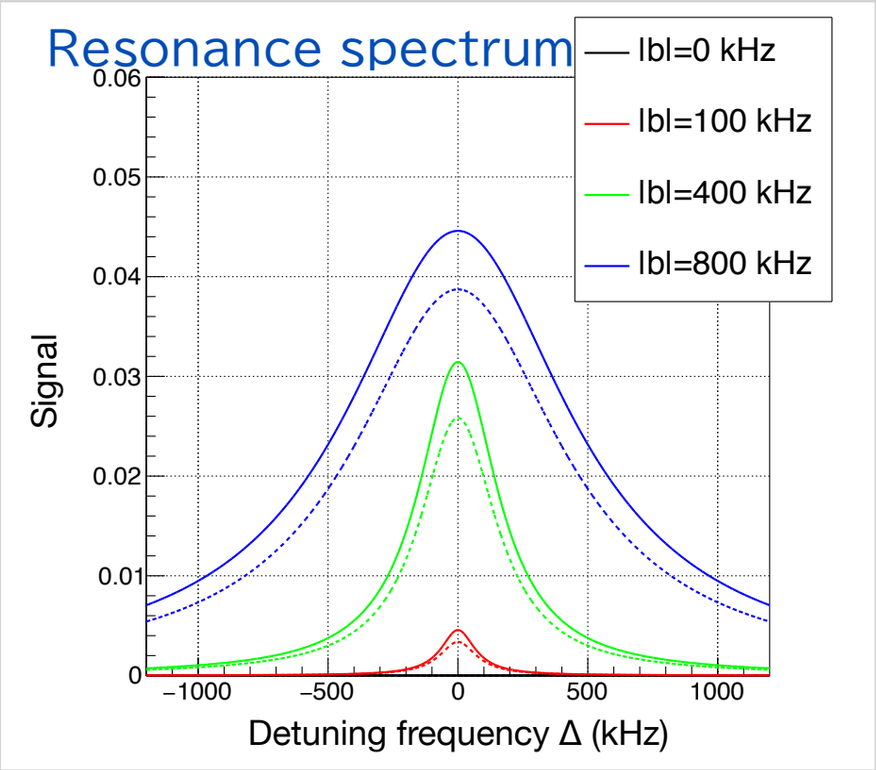
$|b|$ / Microwave magnetic field intensity

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

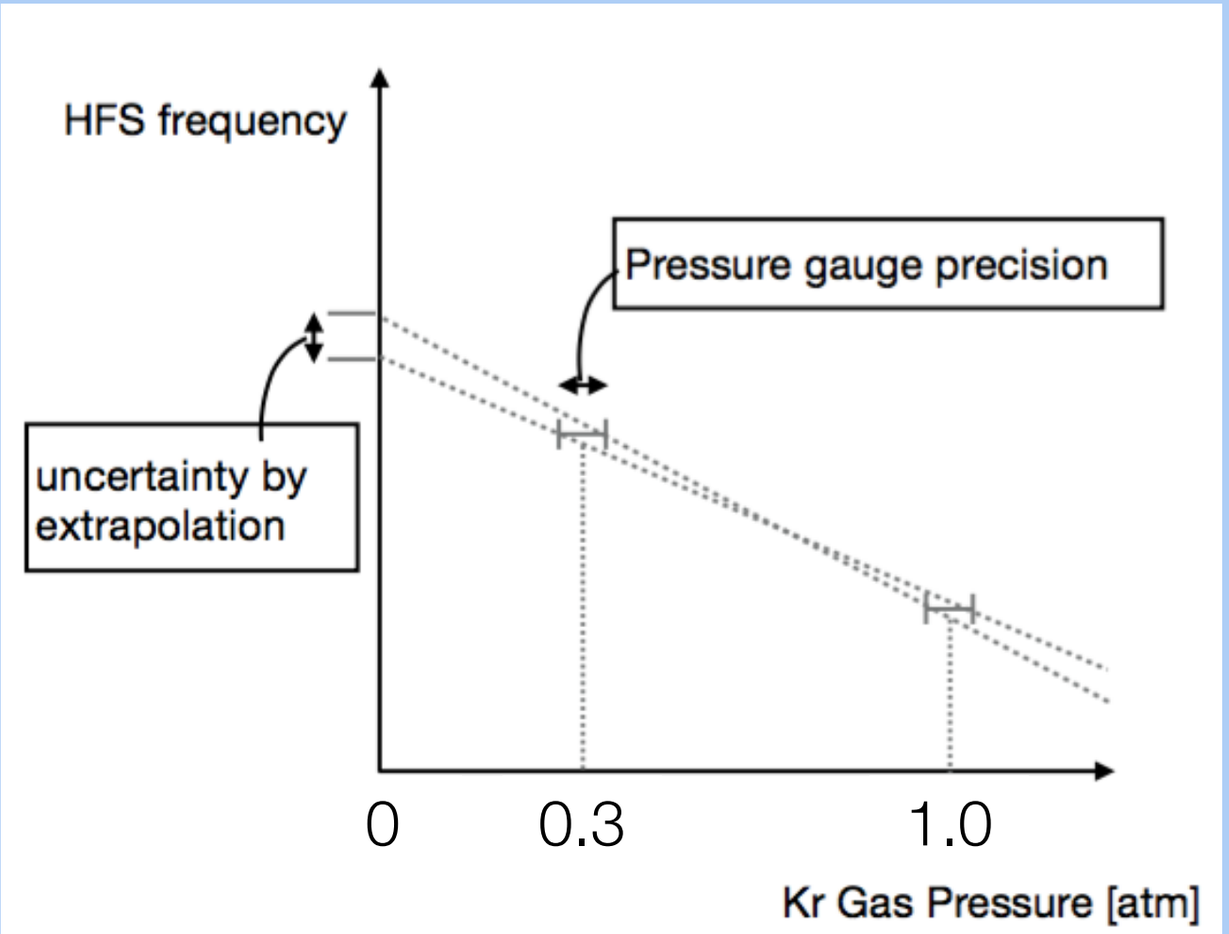
Various gas pressure measurement

↓

Extrapolation to 0 atm

↓

Mu HFS in vacuum

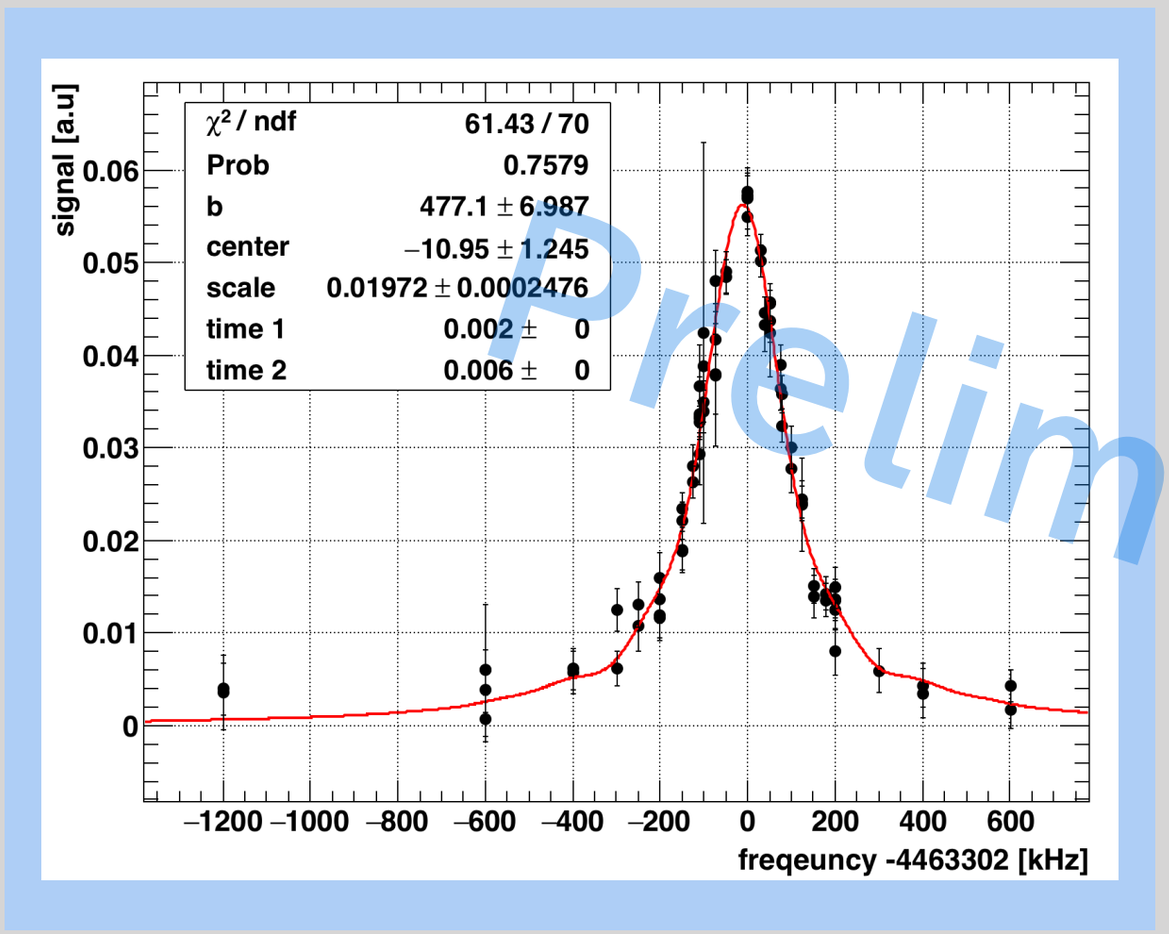


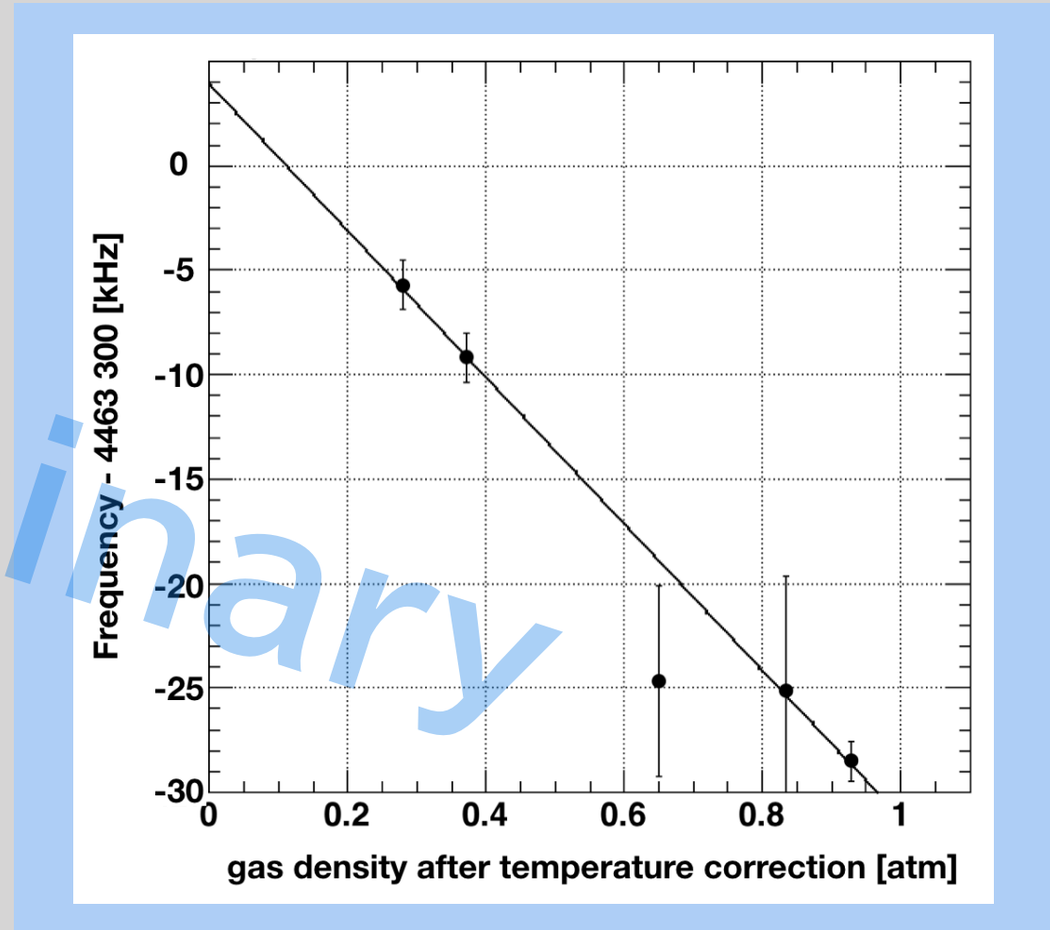
Gas Pressure Dependence of Mu HFS Transition Frequency

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)

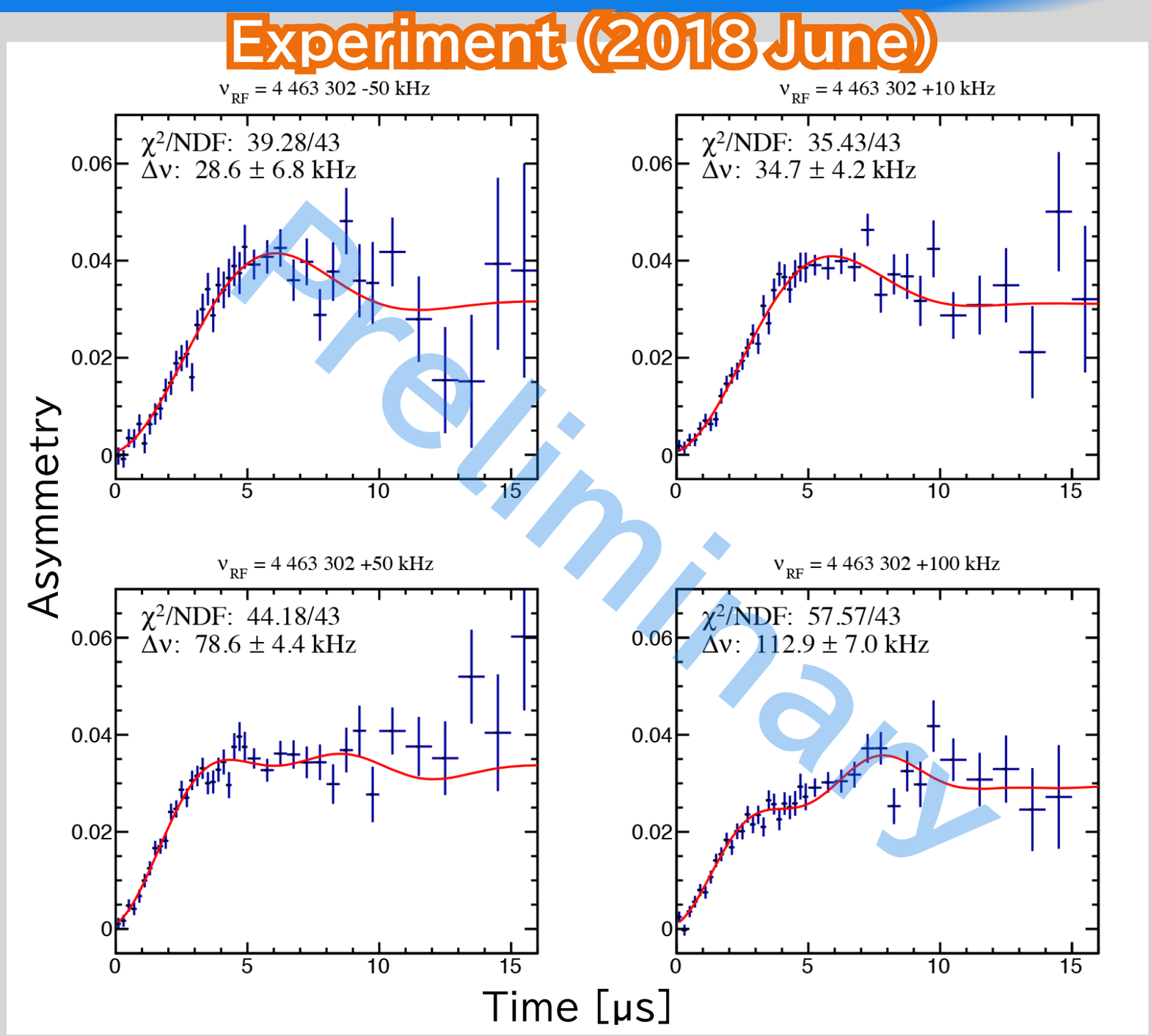




Development of New Analysis Method (Time Differential Method)

Possible advantage of this method

- Each detuning frequency data fitted individually
- Can determine Δ ν HFS with only one frequency data
- Most sensitive detuning frequency is ~60 kHz
- Can improve statistical uncertainty by 3.2 times compared to the conventional method
- Can reduce systematic of RF power variation (free fitting parameter)
- Need high statistics

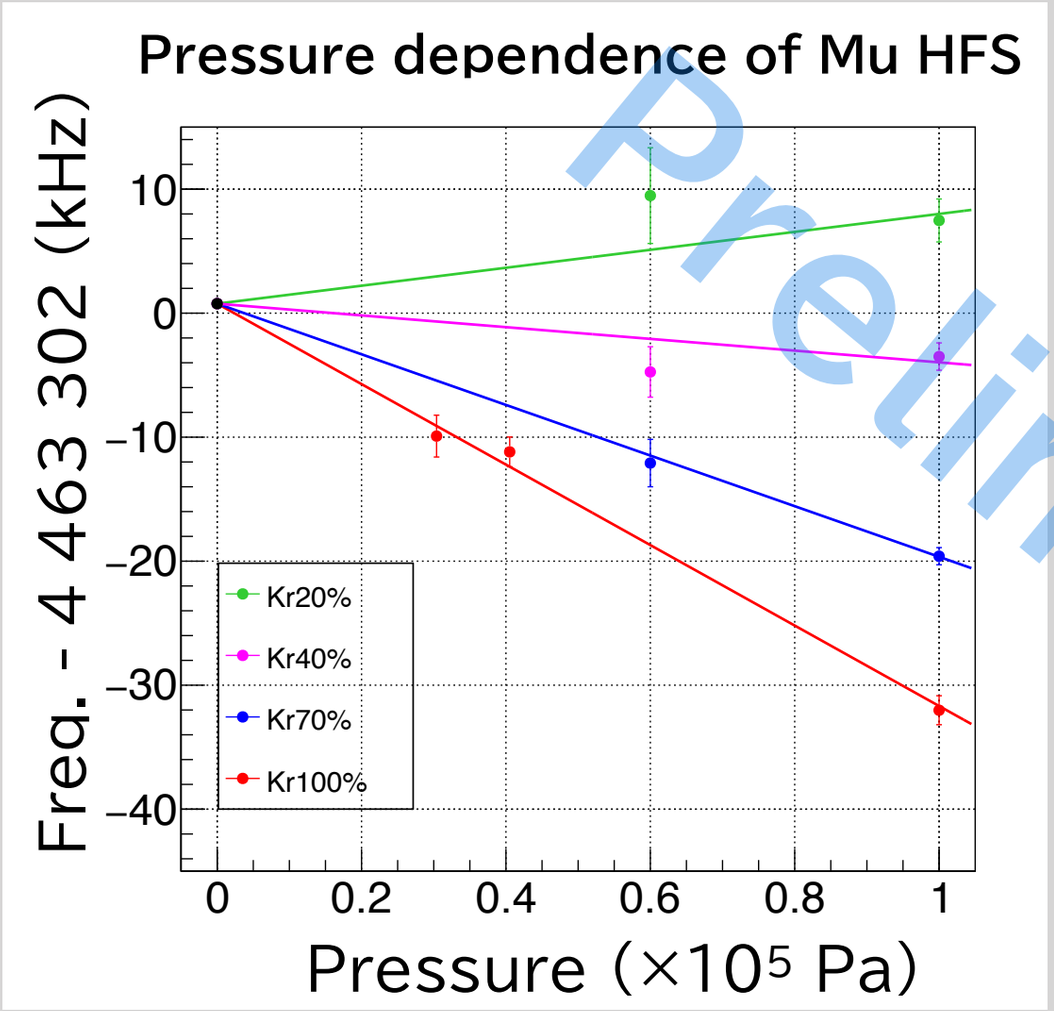


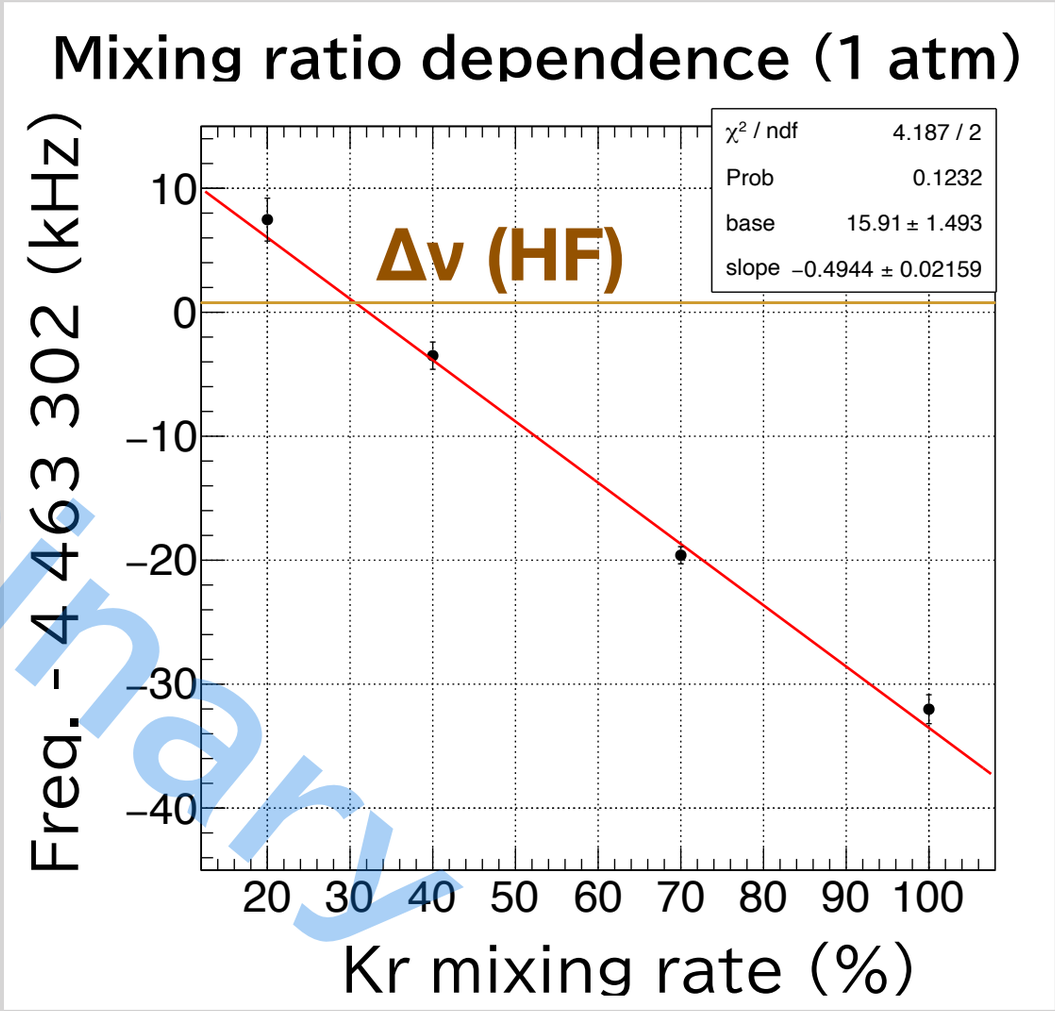
Kr-He Mixture Gas

Dependence of transition frequency shift is reverse between Kr and He

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

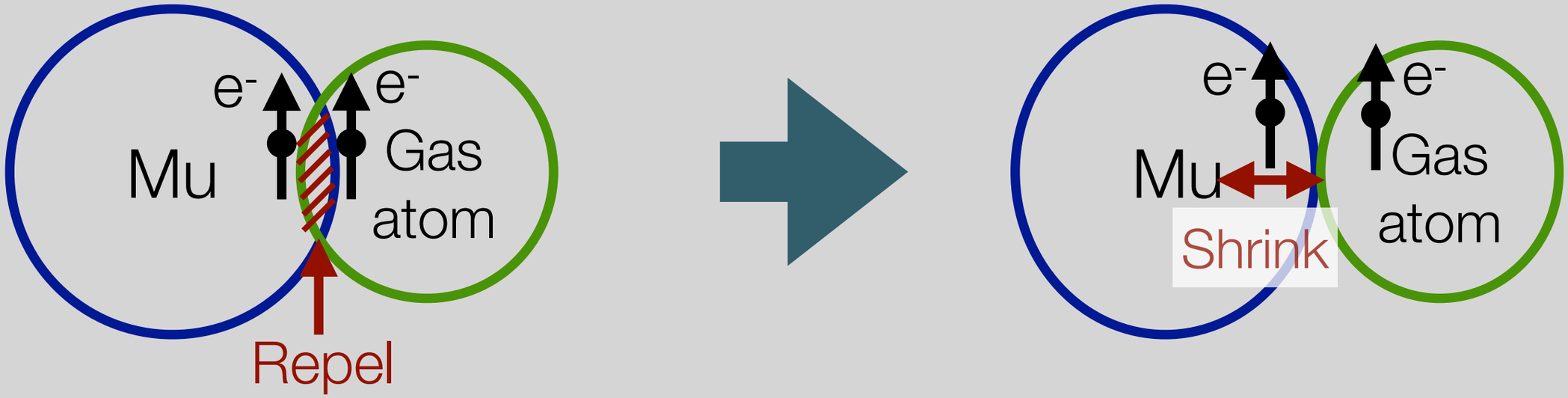
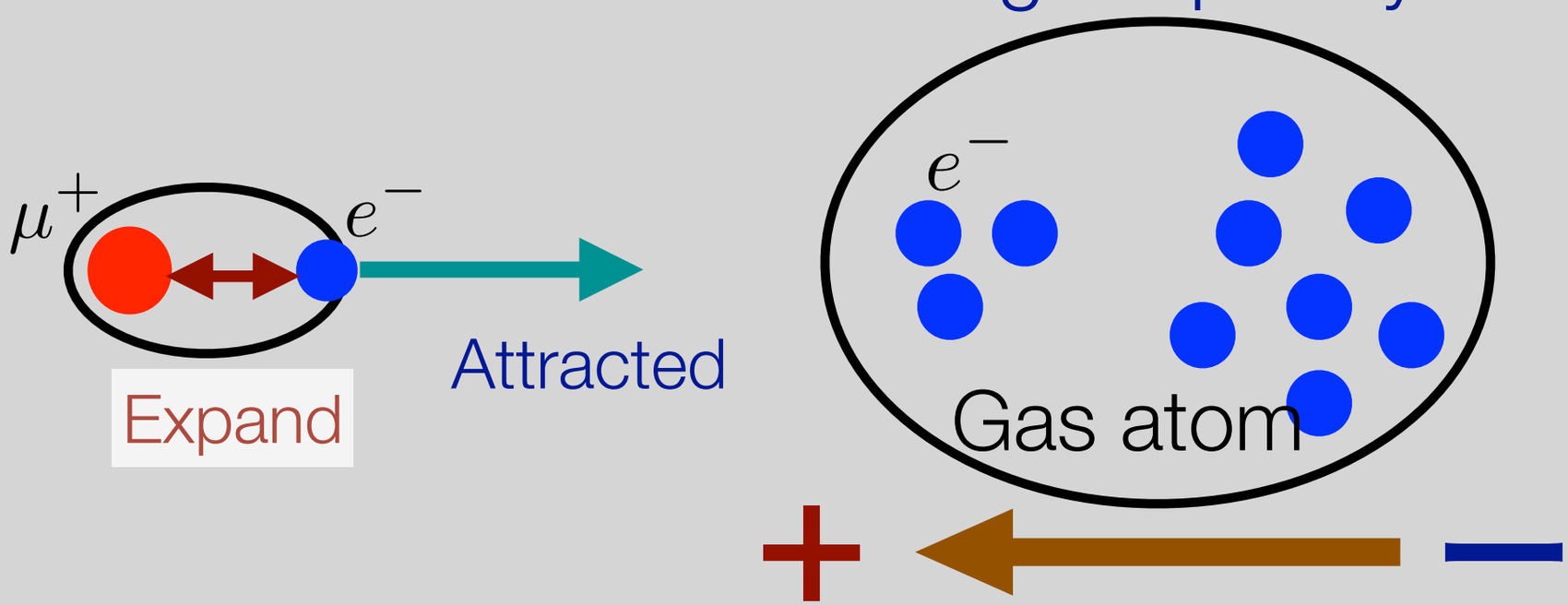
S. Seo (The Univ. of Tokyo)





Transition Frequency Shift due to collision

- Pauli exclusion principle -> Increasing transition frequency



- van der Waals force -> Decreasing frequency