Precision measurement of muonium hyperfine structure at J-PARC

2018/09/28

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for the MuSEUM collaboration

Outline

Introduction

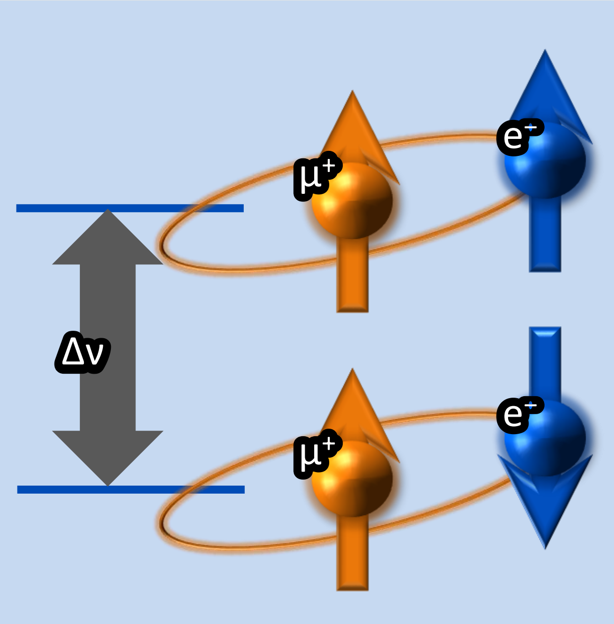
- Muonium Hyperfine Structure (HFS)
- Experimental procedure of MuSEUM
  (Muonium Spectroscopy Experiment Using Microwave)

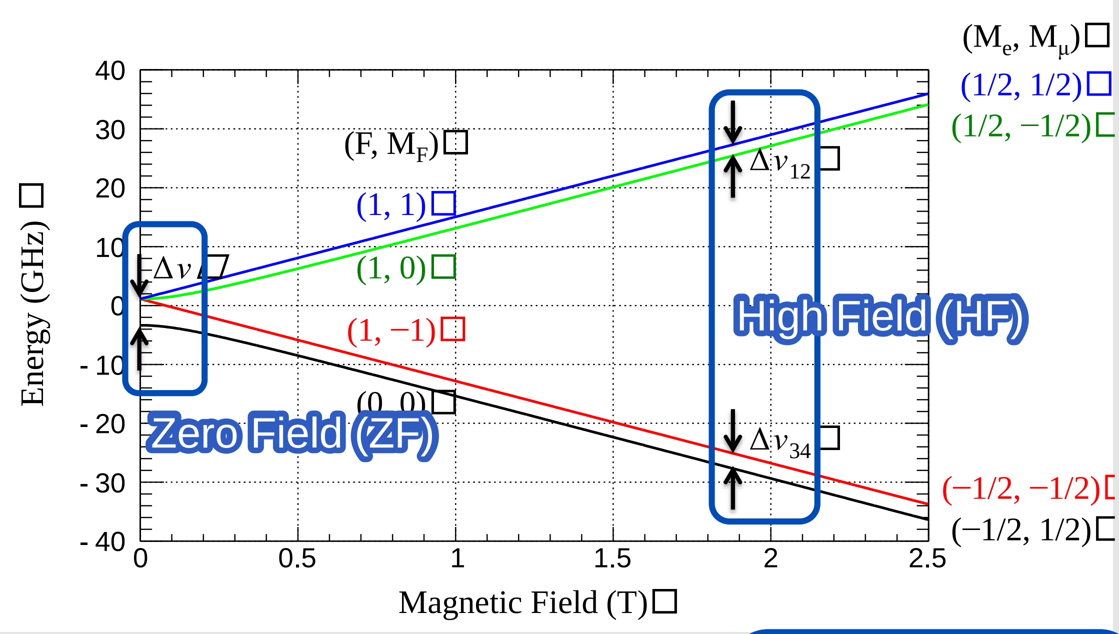
Status of MuSEUM

- New analysis method
  (Time differential method)
- Mu HFS measurement in 2017 & 2018

Muonium HFS

Muonium (Mu) | Bound state of μ^+ and e^-





Measurement value of Δν

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

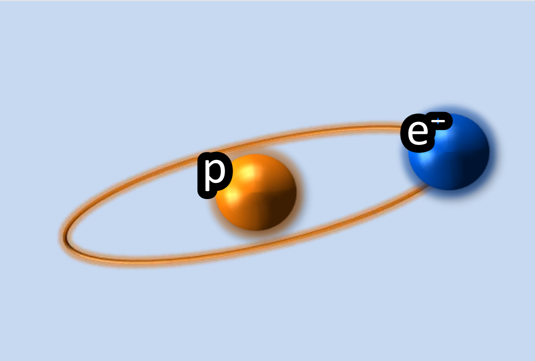
HF | 4 463 302.765(51)(17) kHz (12 ppb)

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

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

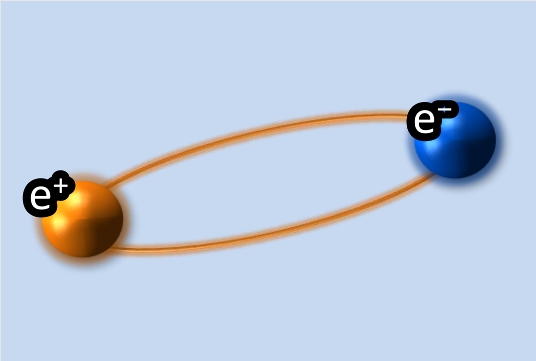
Phys. Lett. B59 (1975) 397-400， Phys. Rev. Lett. 82 (1999) 711-714

HFS Measurement of Hydrogen-like Atoms



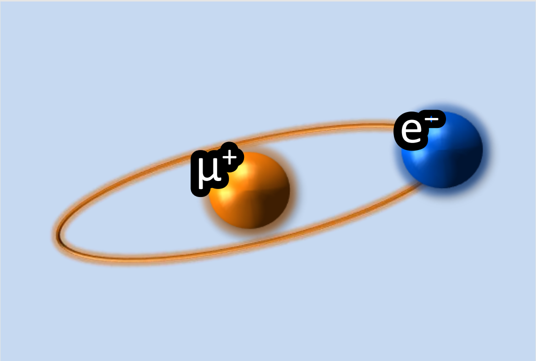
Hydrogen (H)

- Proton internal structure



Positronium （Ps)

- Large recoil effect
- Annihilation
- Short life time



Muonium （Mu）

- Purely-leptonic
- Long life time

	H	Ps	Mu
Experiment	0.2 ppt	3.1 ppm	310 ppb (ZF) | 12 ppb (HF)
Theory	1.2 ppm	1.1 ppm	61 ppb

Physics Motivation

Muonium HFS Measurement($\Delta\nu$)

↓

Verification of
Bound state QED

New physics beyond SM

↓

Determination of m_μ/m_e
(Muon mass)

Input parameter for SM

↓

$$\frac{m_\mu}{m_e} = \left(\frac{g_\mu}{g_e}\right)\left(\frac{\mu_p}{\mu_\mu}\right)\left(\frac{\mu_e}{\mu_p}\right)$$

Determination of μ_μ/μ_p
(Magnetic moment ratio)

↓

Experimental value
of $g-2$

Theory of Mu HFS

Theoretical value

- Uncertainty of physical constants are dominant
- Uncertainty of muon mass is largest

Table 1.3: Theoretical prediction of muonium HFS.

Term	Contribution (kHz)	Reference
Fermi energy and a_μ	4 459 031.819(253)	[11, 15]
a_e	5 170.926	[25]
Radiative correction of $\alpha^n\ (Z\alpha^m)$	−104.901(39)	[15, 25]
Recoil	−791.714(80)	[25]
Radiative-recoil	−3.427(70)	[25]
Electroweak	−0.065	[26]
Hadronic vacuum polarization	0.232 7(14)	[20, 21]
Hadronic higher order	0.005(2)	[22, 23]
Hadronic light by light	−0.000 0065(10)	[24]
Total	4 463 302.868(271)	[11]

Determination of muon mass

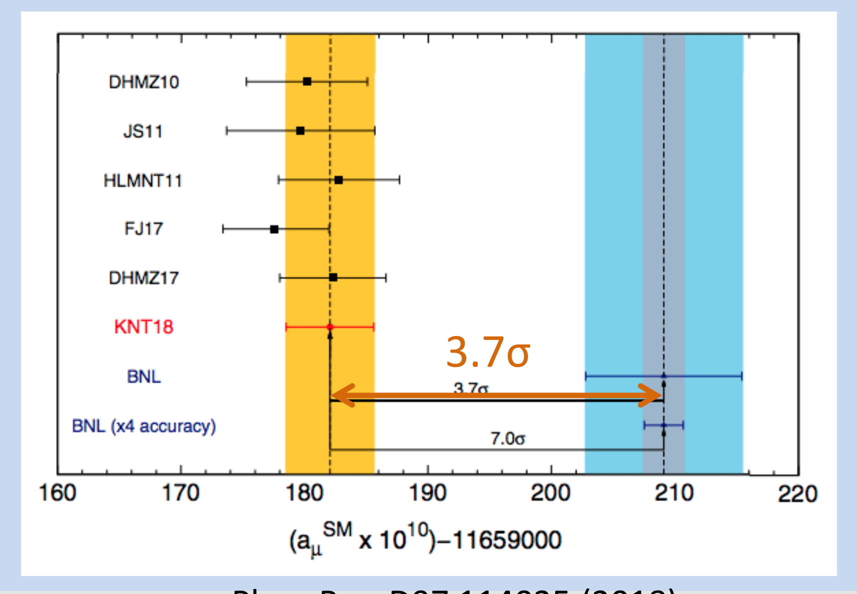
- Compare theoretical and experimental value of Mu HFS using muon-electron mass ratio as a parameter

m_μ/m_e=206.768 282 6(46) (22 ppb)

Relation between Muon *g*−2 and Mu HFS

Muon *g*−2 $a_\mu = \frac{g-2}{2}$

- 3.7σ discrepancy between theory and experiment
- Precision of experimental value | 0.54 ppm
- Goal of new experiment at J-PARC and FNAL | 0.14 ppm (Yamanaka-san's talk)
- Experimental value is obtained by using Mu HFS



Phys. Rev. D97 114025 (2018)

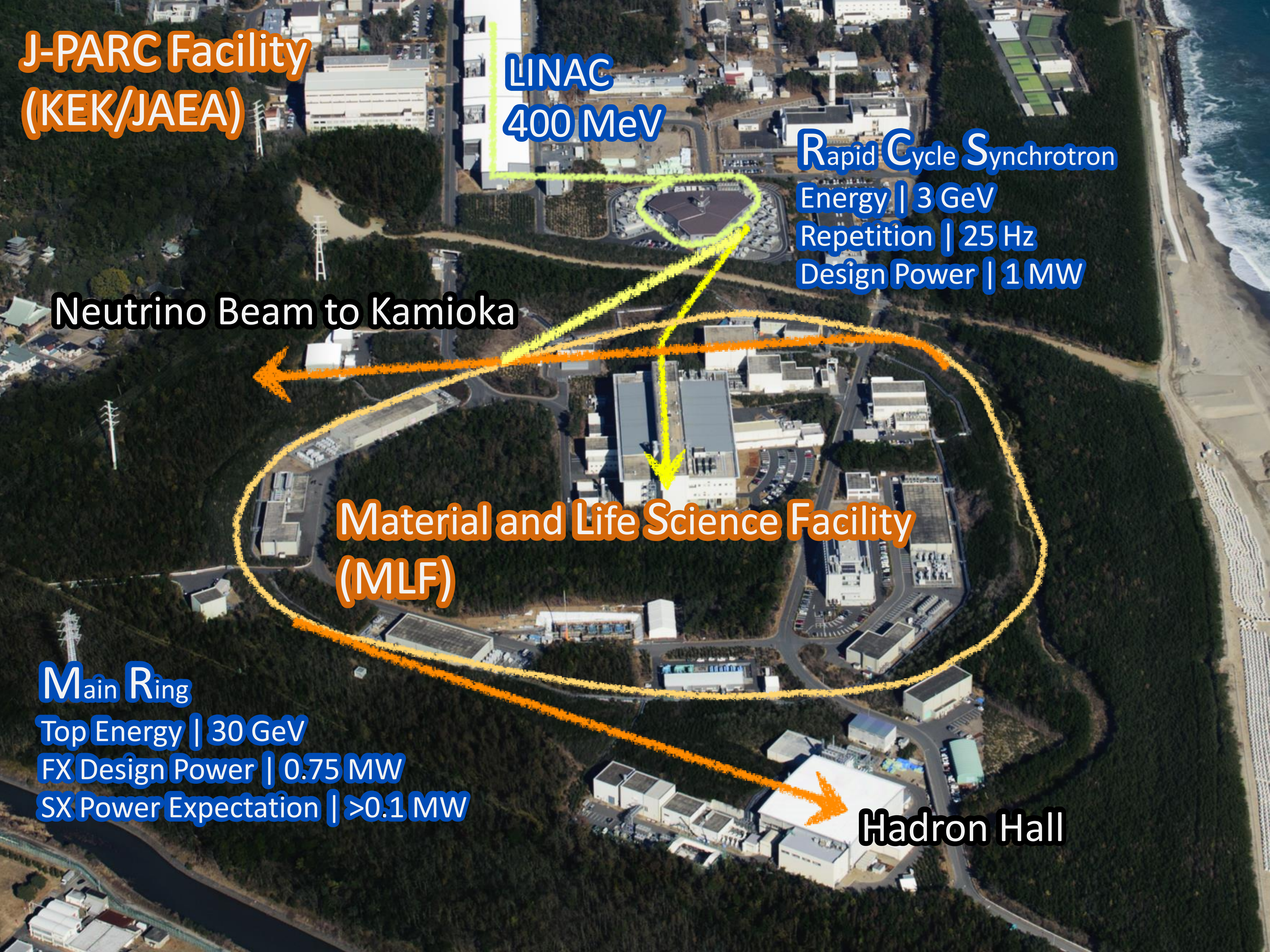
$$a_\mu = \frac{R}{\lambda - R}$$

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

g−2 storage ring

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

Mu HFS

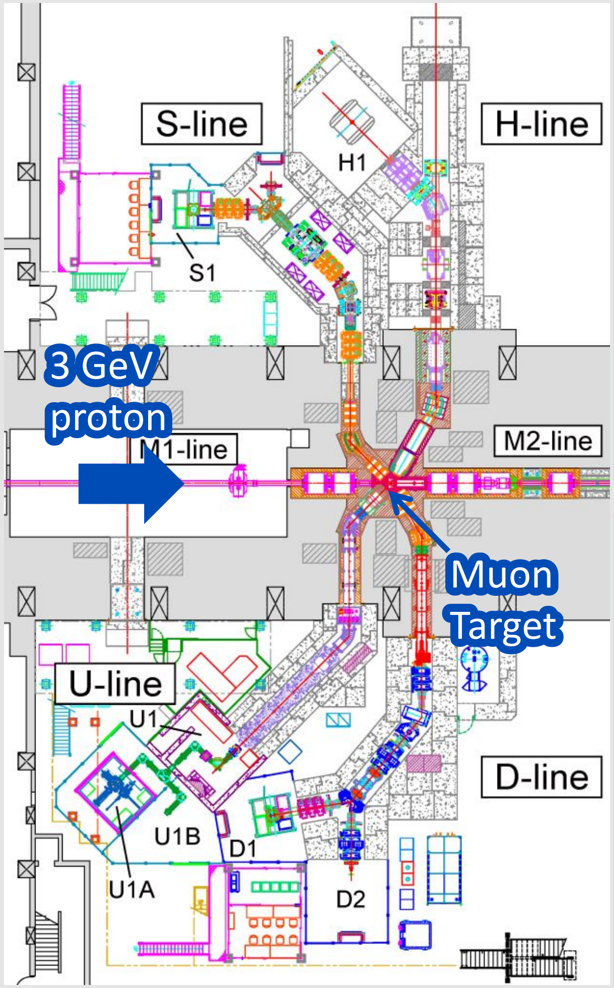


J-PARC Facility
(KEK/JAEA)
LINAC
400 MeV
Rapid Cycle Synchrotron
Energy | 3 GeV
Repetition | 25 Hz
Design Power | 1 MW
Neutrino Beam to Kamioka
Material and Life Science Facility
(MLF)
Main Ring
Top Energy | 30 GeV
FX Design Power | 0.75 MW
SX Power Expectation | >0.1 MW
Hadron Hall

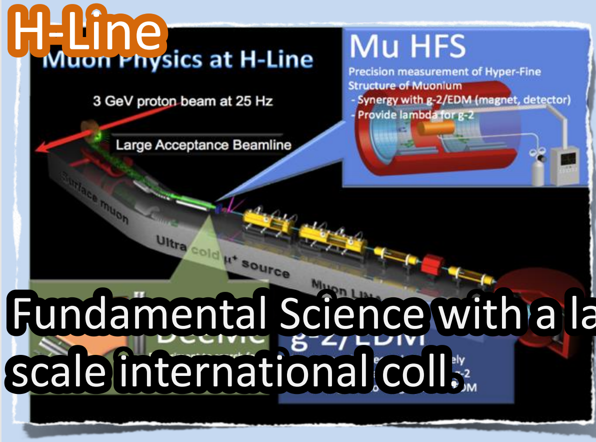
Muon facility MUSE @ MLF

S-Line

Accommodate many μSR experiments



H-Line

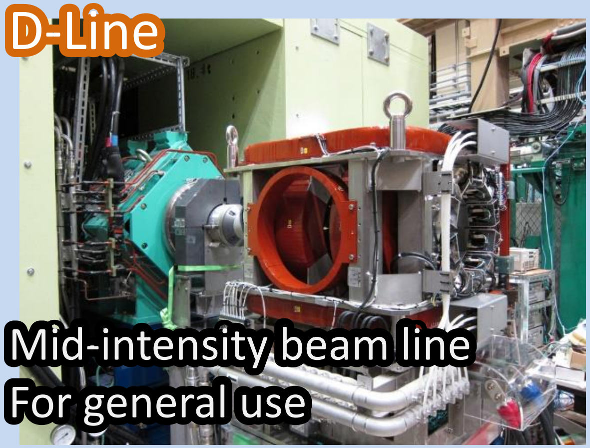


Fundamental Science with a large scale international coll.

U-Line

Very unique Ultra-Slow Muon Beam

D-Line

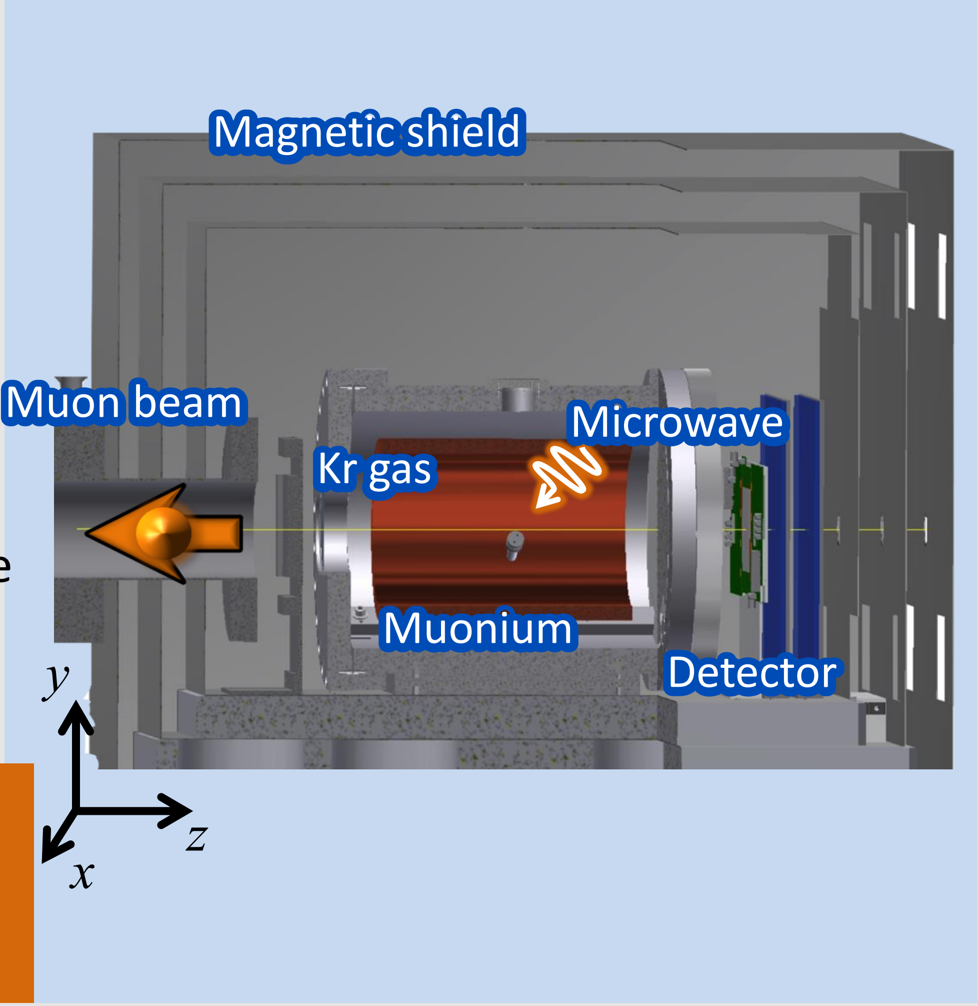


Mid-intensity beam line
For general use

MuSEUM setup

Measurement principal

- Polarized muon beam
- Kr gas target
  Muonium formation
- State transition
  by microwave
- Downstream detectors measure
  the number of positron and time



Signal | $(N_{on} - N_{off})/N_{off}$

N_{on} |# of positron when RF on

N_{off} | " RF off

Time Integral Method

Signal of all positrons

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

$\Delta\omega$ / Detuning angular frequency

$|b|$ / Microwave magnetic field intensity

λ / Spin relaxation rate

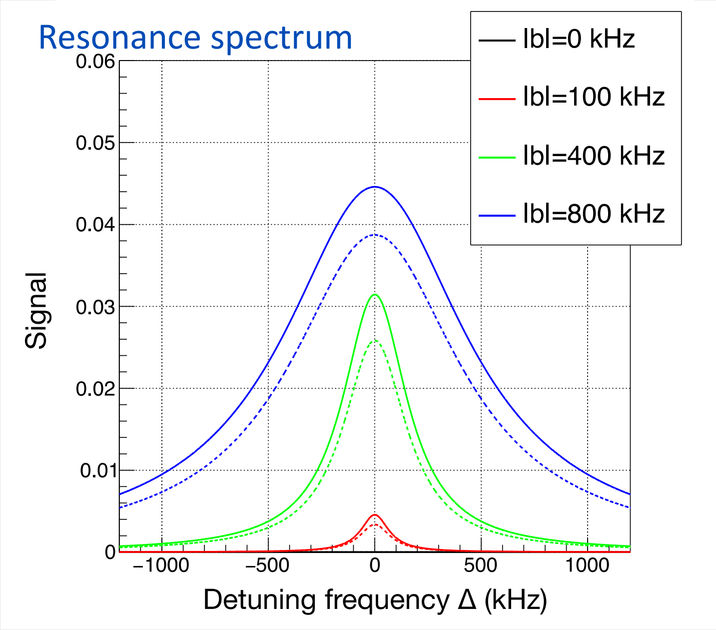
γ / Muon decay rate

P / Muon spin polarization

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

Resonance spectrum | Lorentzian function

- Peak of Lorentzian is equal to Mu HFS frequency
- Mu HFS is determined by multiple frequency data
- Width and height of spectrum is changed by microwave power



Time Differential Method

Time dependence of signal

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

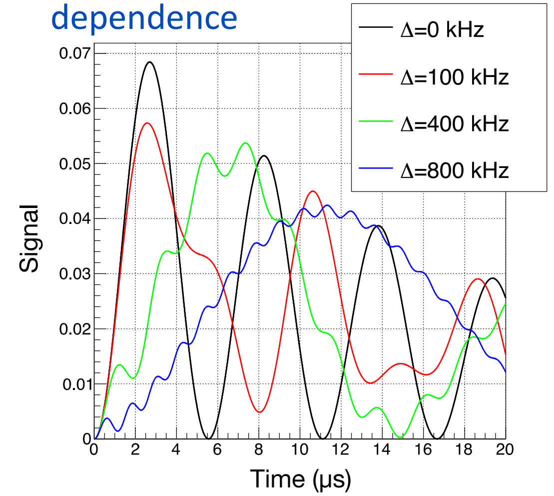
$$C\left(t\right) = \frac{G_+}{\Gamma}\cos G_- t + \frac{G_-}{\Gamma}\cos G_+ t$$

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

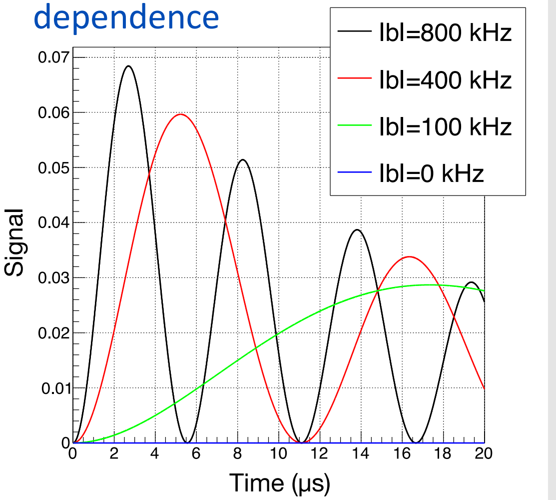
Time spectrum | Summation of cos

- contains more information
  - Mu HFS frequency
  - Microwave power
  - Spin relaxation time
- can determine Mu HFS by only one detuning frequency data

Detuning frequency dependence



Microwave power dependence



Previous Experiment / MuSEUM

Previous(@LAMPF)

- Continuous muon beam
- Statistical uncertainty is dominant
- Time integral method (Conventional method)

MuSEUM

- J-PARC high-intensity pulsed muon beam
- High-rate capable detector
- New analysis method

1. Improve statistics by high-intensity beam
2. Development of the silicon strip detector
3. Time differential method

Status of MuSEUM

Zero field	High field

Development of basic components
（Magnetic shield, Gas system, Cavity, Detectors）

2016 — Mu HFS measurement by the conventional method

Production of the super conducting magnet

2017 — Development of the new method (time differential)

Development of the magnetic prove

2018 — Measurement of Kr gas pressure dependence

Static magnetic field measurement

2019 — Achieve the best precision

High field experiment

Time Integral Signal (Simulation)

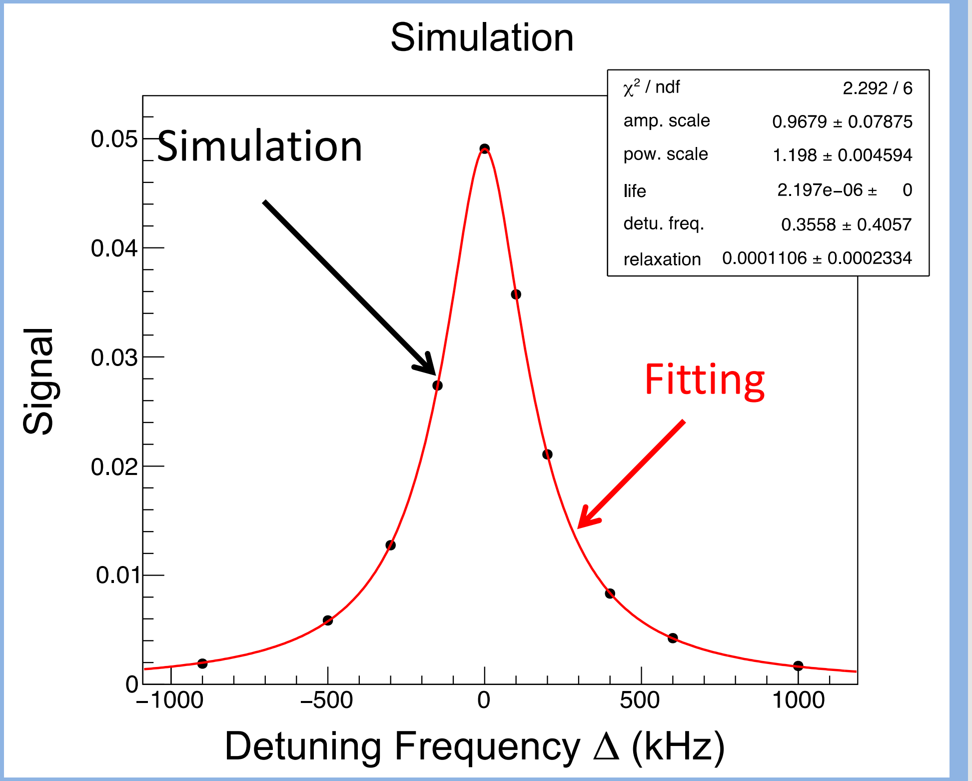
Time integral signal

- Measurement point | 10 points
- 7.8×10^{10} muon/point

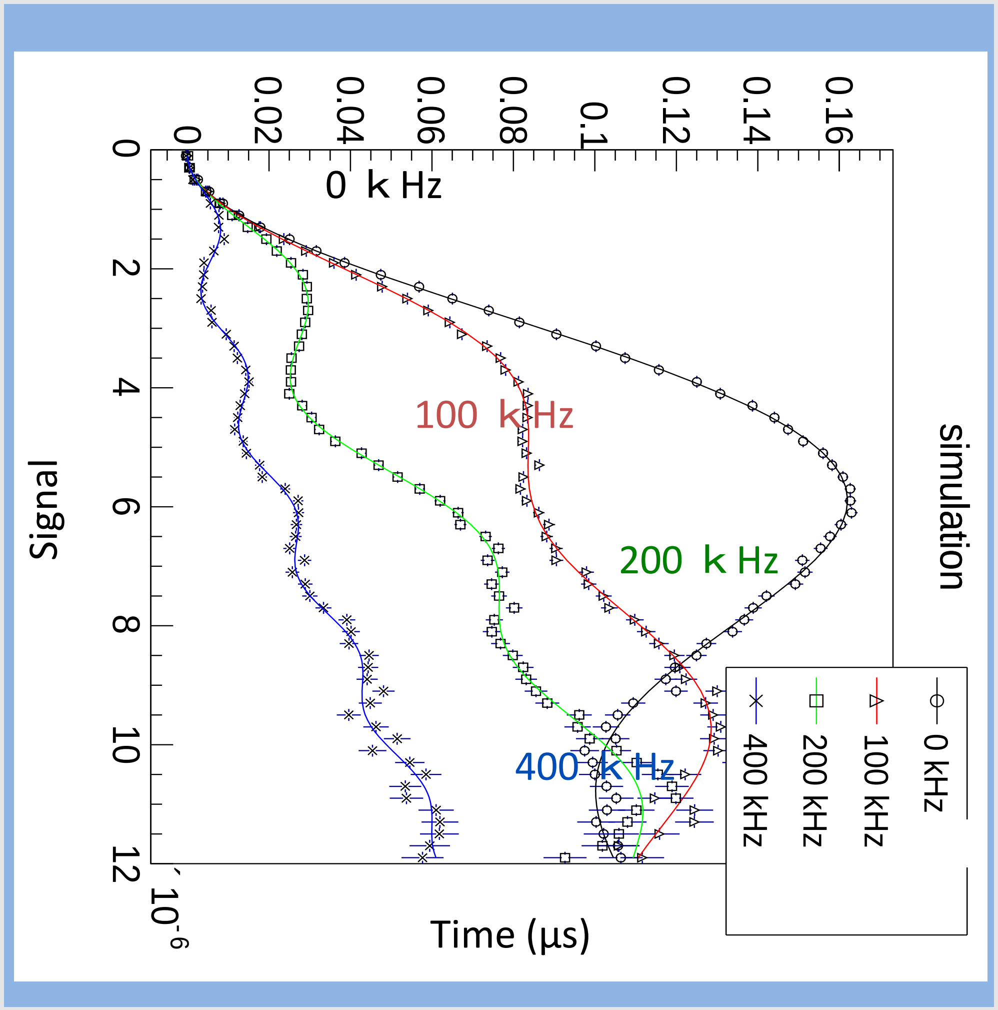
Fitting function

- Summation of Lorentzian function considering microwave power distribution felt by muonium

HFS precision | 0.41 kHz



Time Differential Signal （Simulation）

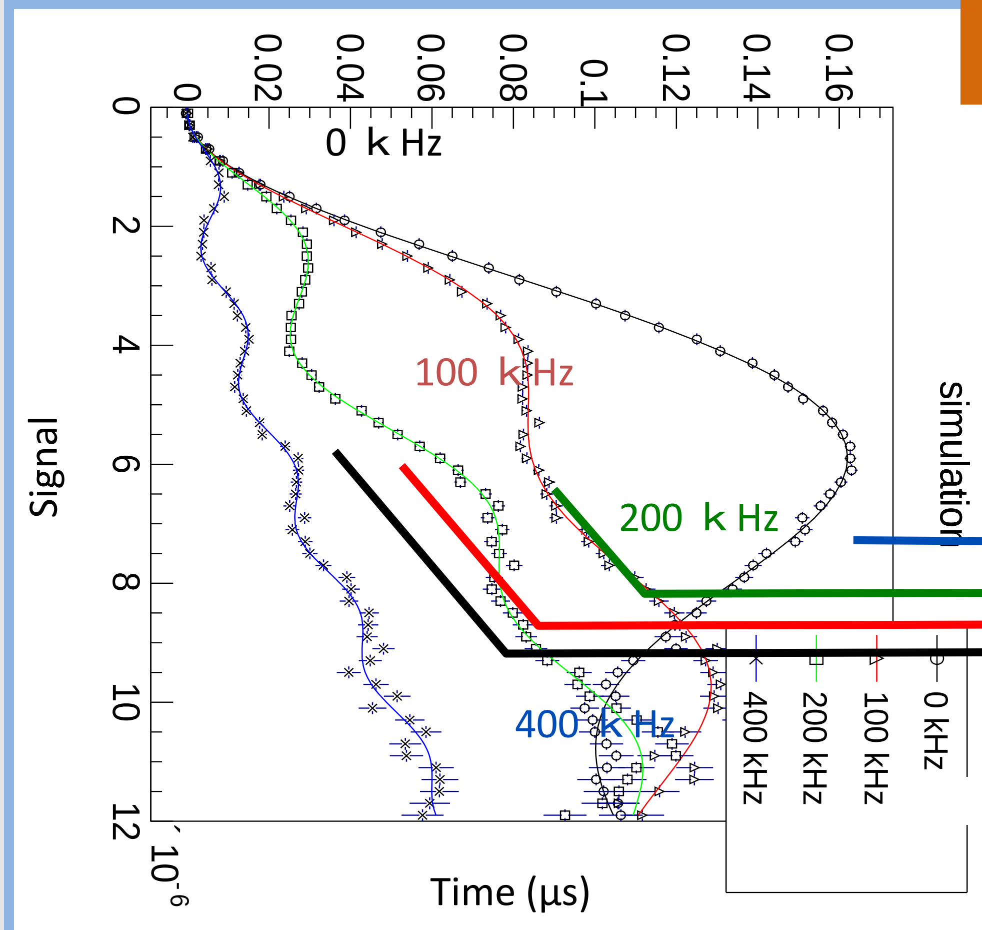


- Time differential signal | Same statistics as time integral method
- Time spectrum are changed by the detuning frequency

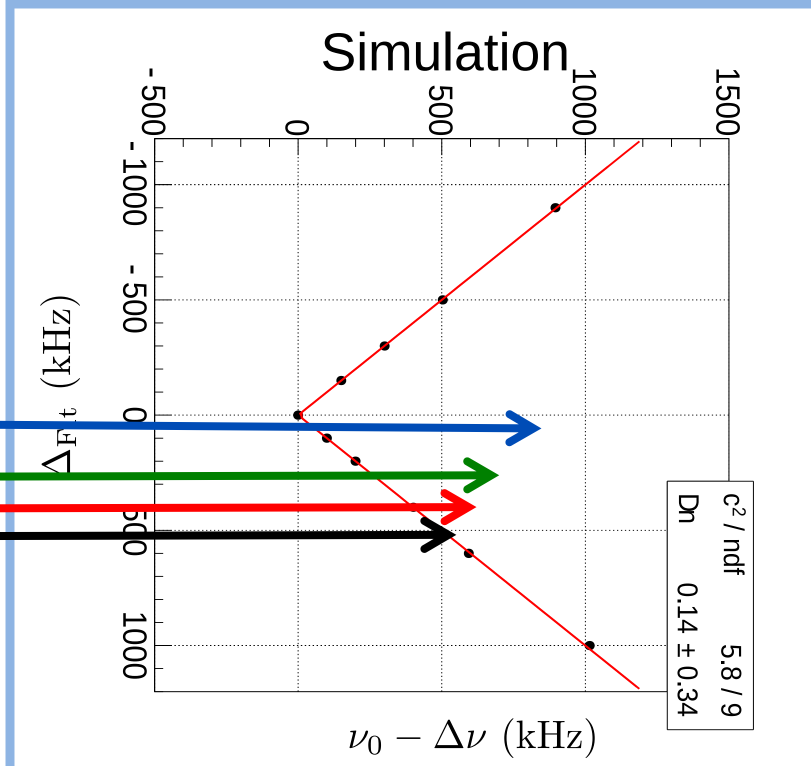
Fitting function

- Summation of cosine considering microwave power distribution felt by muonium

Time Differential Signal (Simulation)

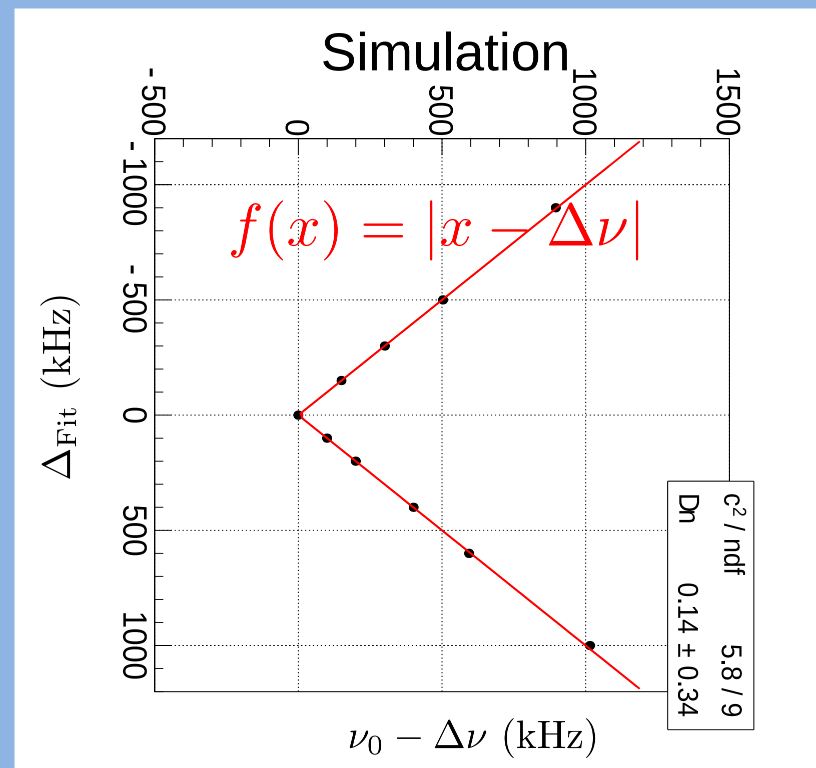


Mu HFS is obtained by only one detuning frequency data



Multiple Time Differential Data

Mu HFS is determined by multiple results of time differential method



Time Integral Method
| 0.41 kHz

Time Differential Method
| 0.34 kHz

15% improvement

More Efficient Measurement

Concentrating one frequency is the most efficient method

Time Integral Method
| 0.41 kHz

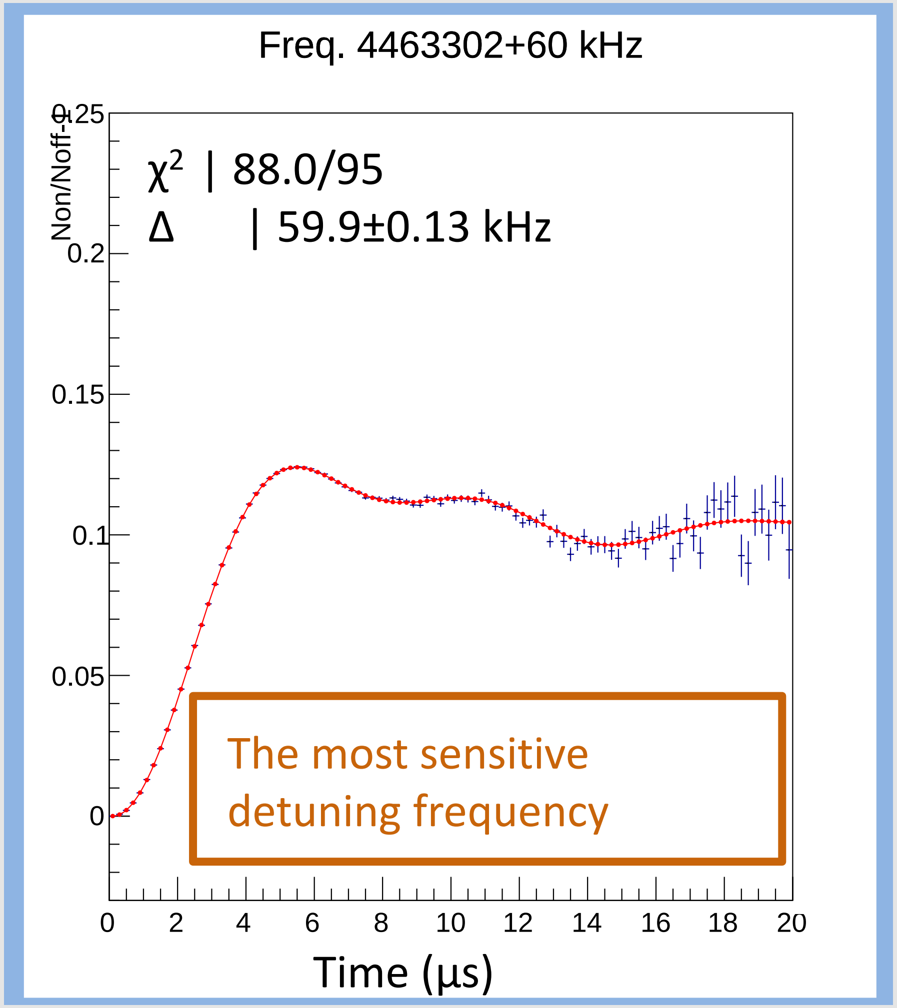
↓

Time Differential Method
| 0.34 kHz

↓

Time differential Method
(Concentrate on Δ=60 kHz)
| 0.13 kHz

3.2 times improvement compared to the time integral method



Mu HFS Measurement in 2017

Experimental site

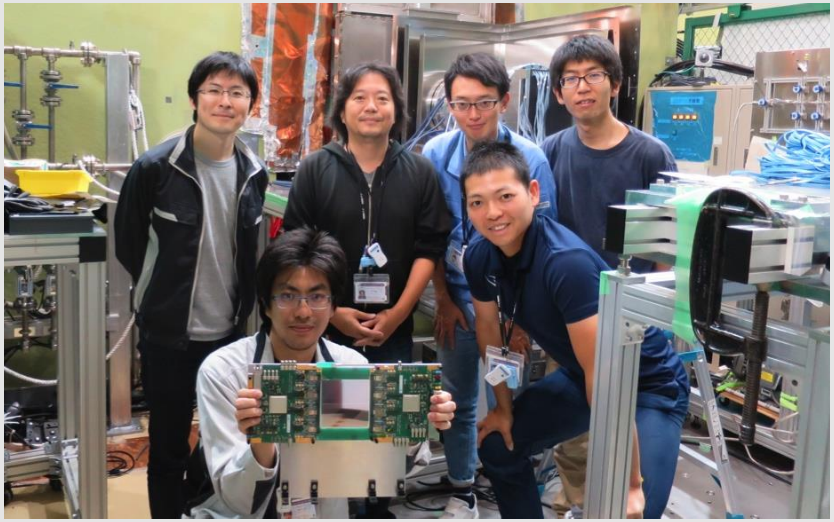
- J-PARC MLF D-line (D2)

Period

- 13-19 June 2017

Condition

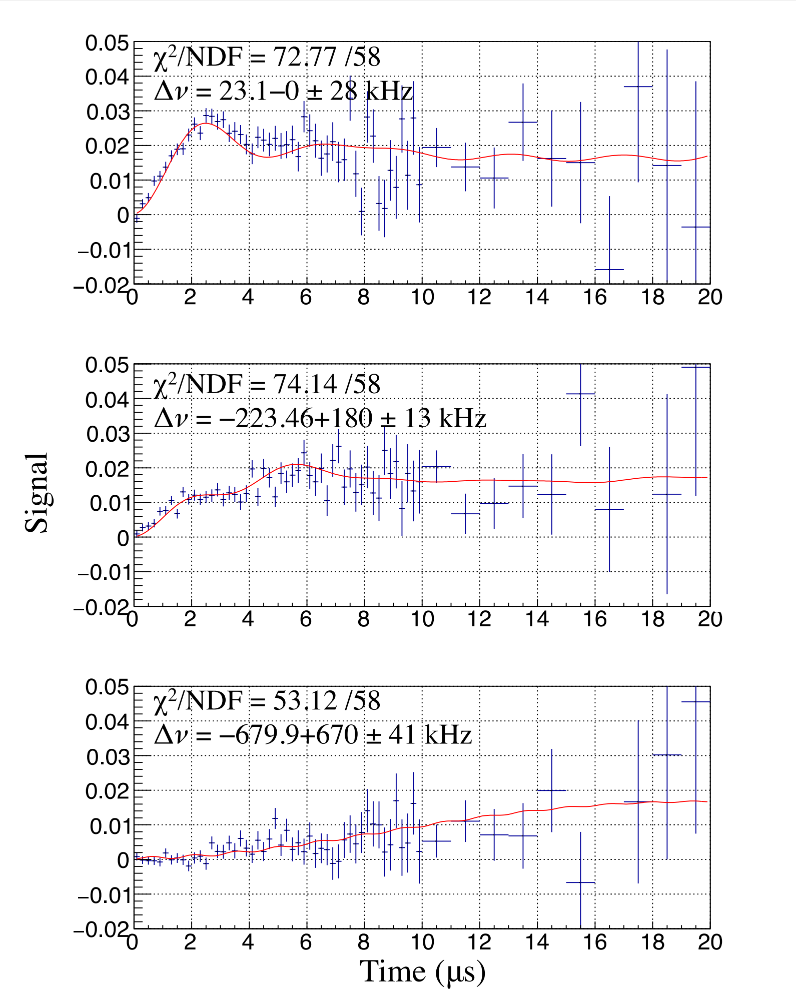
- Proton beam intensity | 150 kW
- Single pulse
- 1 atm Kr gas pressure
- Measurement sequence | Turning microwave On/Off every 15 minutes



Analysis by the Time Differential Method

Time differential muon spin resonance signal was observed

- Detuning frequency dependence is similar to the simulation results
- Same fitting function as the simulation
- Mu HFS was obtained from each detuning frequency data



Mu HFS Frequency Measurement

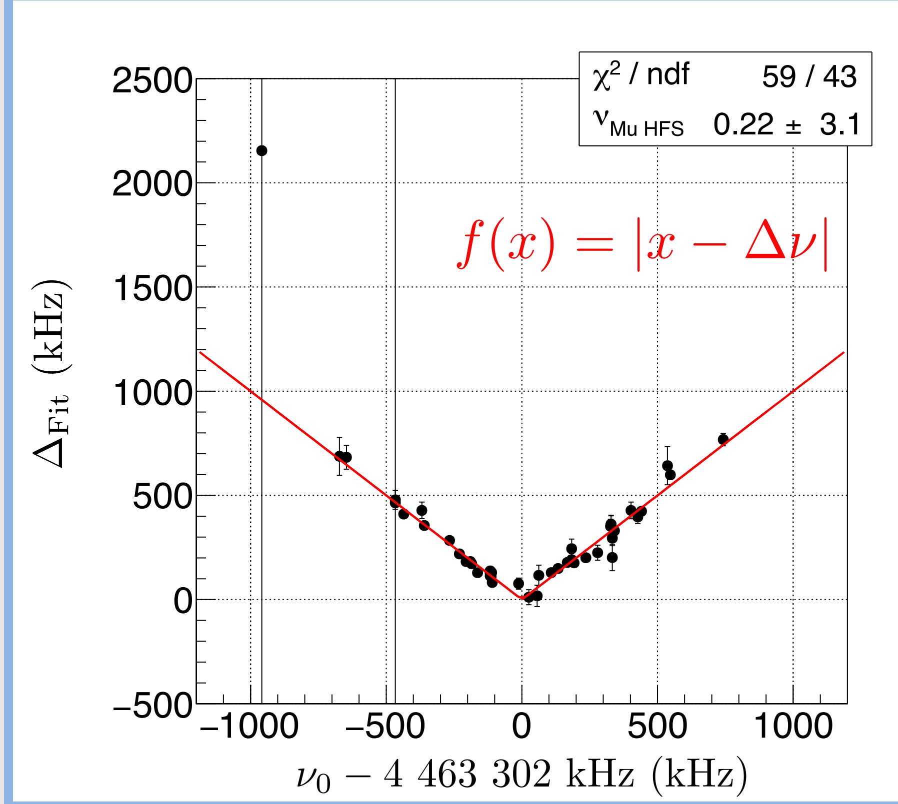
Mu HFS was obtained from multiple data

- Obtained $\Delta\nu_{Mu}$

4 463 302.2 ± 3.1 kHz

experiments

Previous experiment
ZF | 4 463 302.2(14) kHz
HF | 4 463 302.765(50)(17) kHz



Phys. Lett. B59 (1975) 397-400 , Phys. Rev. Lett. 82 (1999) 711-714

Statistical Uncertainty

Item	June 2016	June 2017	Prospects
Analysis method	Time integral	Time differential	Time differential
Beam line	D line	D line	H line (D line×10)
Beam power	200 kW	150 kW	1 MW
Measurement period	8 hours	31 hours	80 days
Microwave cavity	TM110	TM220	TM220
Detector area	240×240 mm^2	98.77×98.77 mm^2	98.77×98.77 mm^2 ×4
Statistic Uncertainty	22,000 Hz	3,100 Hz | 690 ppb	24 Hz | 5 ppb

2016→2017

- Seven times improvement

Prospects

- will achieve 5 ppb, which is the best precision

Systematic Uncertainty

Item	June 2017	Prospects
Gas pressure fluctuation	7 Hz	7 Hz
Gas pressure extrapolation	66 Hz	7 Hz
Gas impurity	0 Hz	0 Hz
Static magnetic field	0 Hz	0 Hz
Microwave power drift （including muon beam profile）	200 Hz	1 Hz
Pileup event loss	10 Hz	1 Hz
Time Calibration	1 Hz	1 Hz
Total	200 Hz	10 Hz

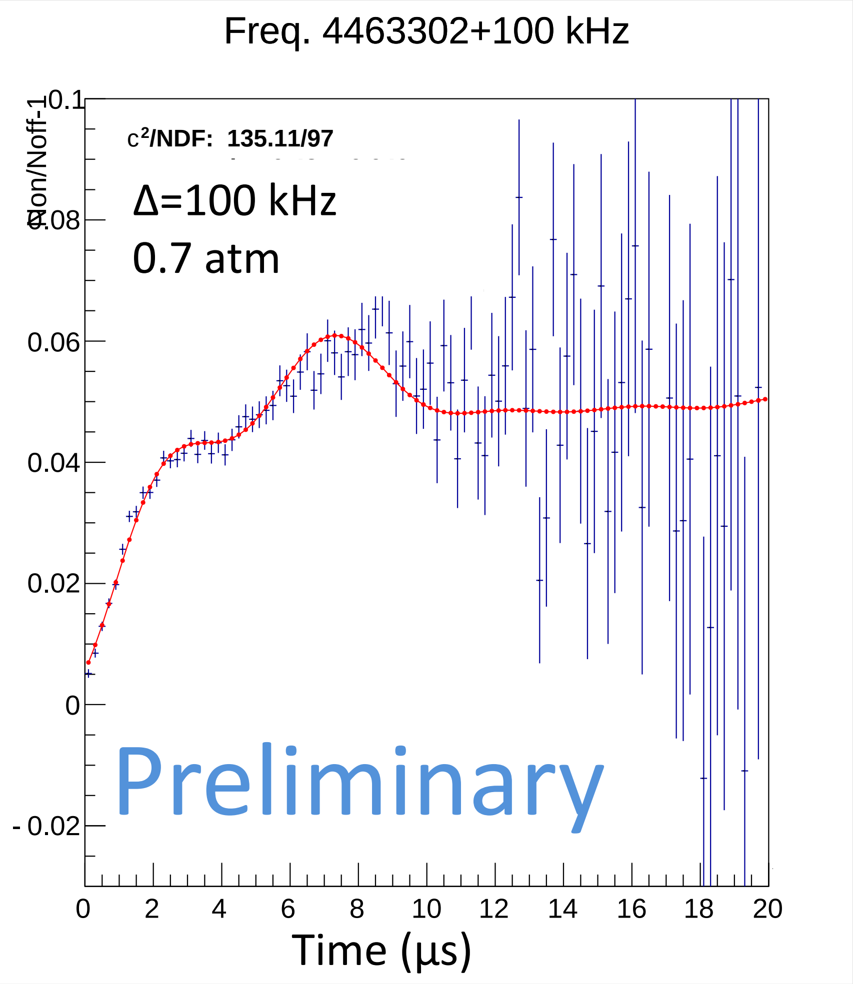
- Systematic uncertainty was much smaller than statistical uncertainty in June 2017
- Systematic can be as small as the previous experiment

Mu HFS Measurement in 2018

Kr gas pressure shift

- Resonance frequency is shifted due to collision of muonium & the Kr atom
- Gas pressure
  in the experiment in 2018
  | 0.3 atm, 0.7 atm
- Spin flip resonance signal was obtained for each gas pressure

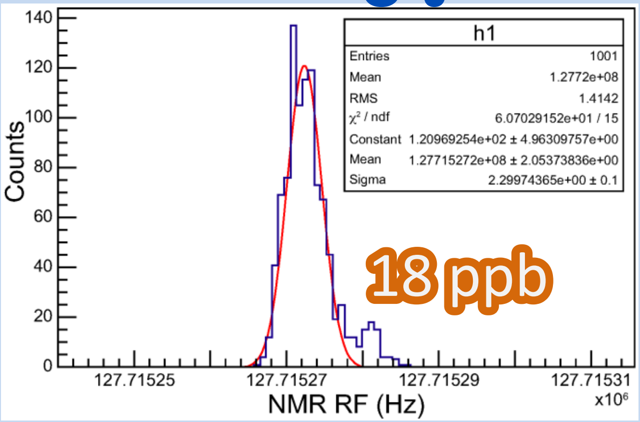
Analysis is ongoing



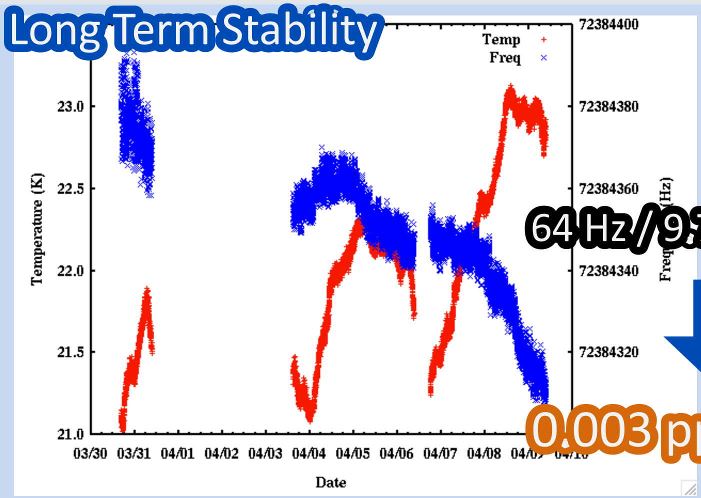
MRI Magnet for High-Field Experiment

Second-hand 2.9 T MRI magnet

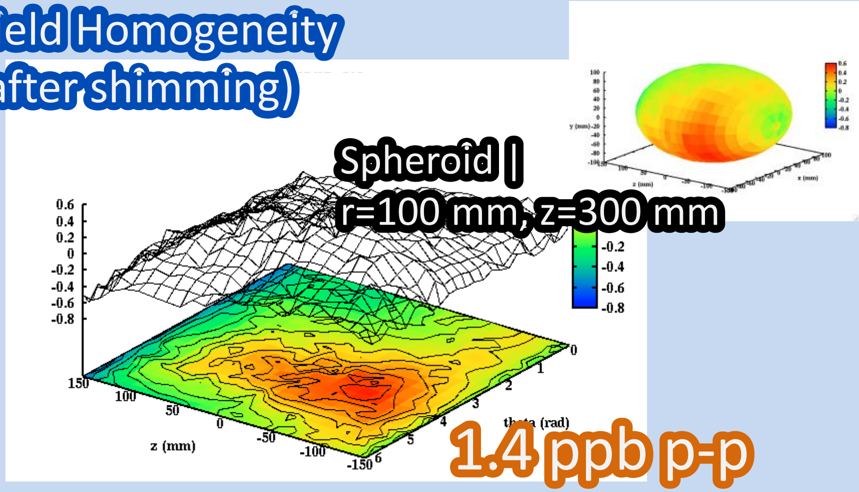
CW-NMR Field Monitoring System



Long Term Stability



Field Homogeneity (after shimming)



Summary and Prospects

Summary

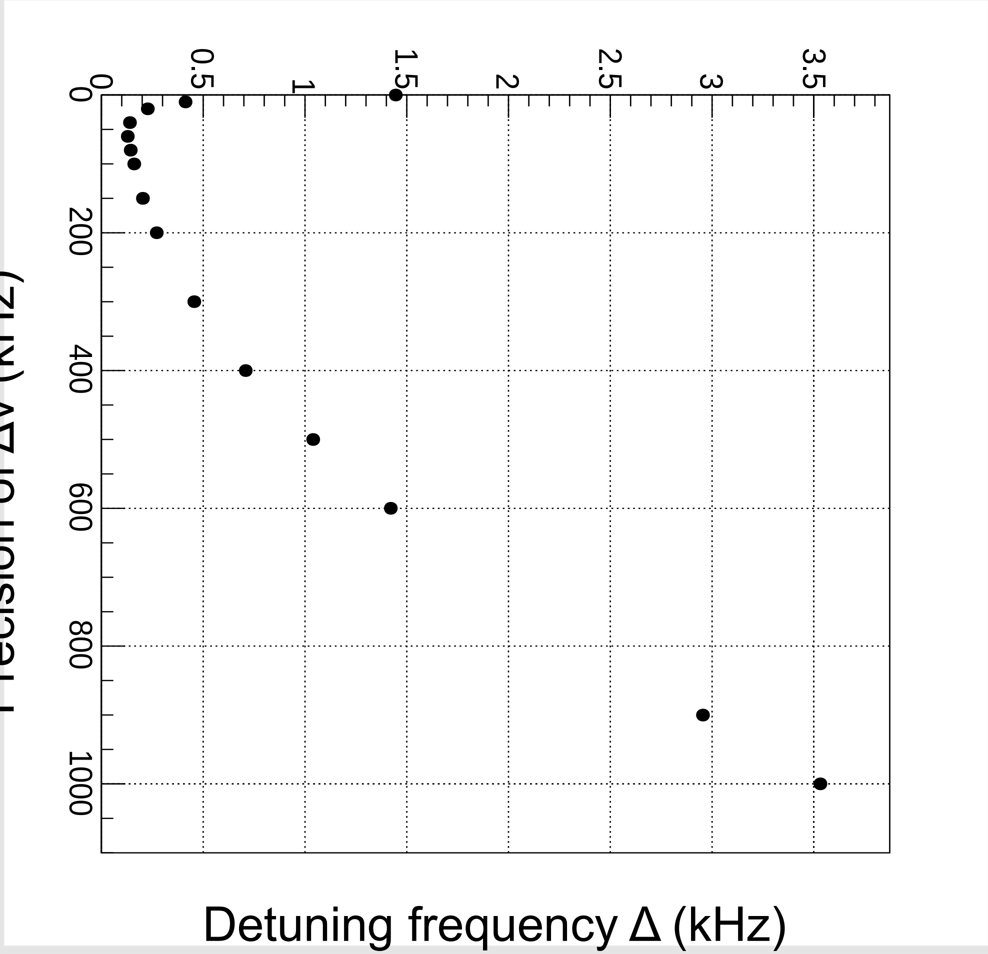
- Mu HFS measurement
  - Verification of Bound state QED, muon $g-2$, muon mass and magnetic moment ratio
- Time differential method
  - Improving statistic uncertainty by 3.2 times compared to the time integral method
  - Measurement in June 2017
    $\Delta\nu = 4\,463\,302.2 \pm 3.1 \pm 0.2$ kHz
- Measurement in June 2018
  - Pressure dependence was measured
  - Analysis is ongoing

Prospects

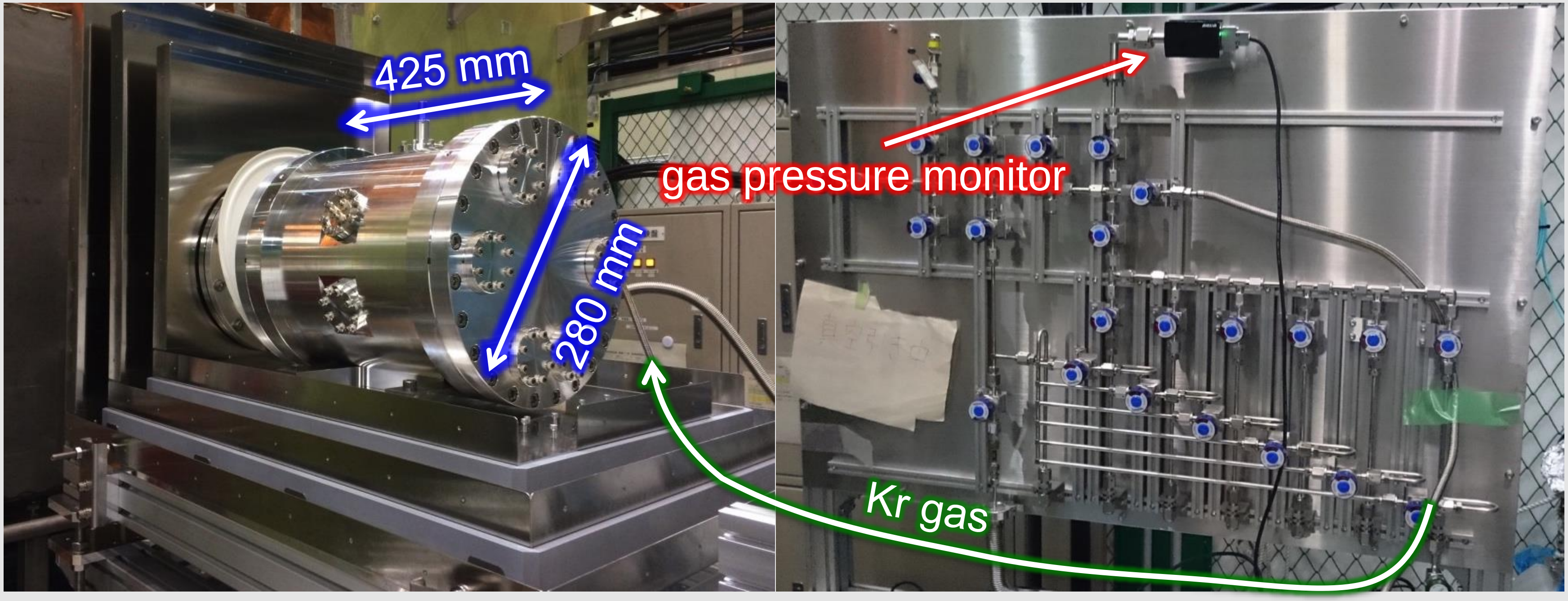
- Zero field experiment at the new beam line (H
- High field experiment

Back up

Detuning frequency dependence of Mu HFS precision



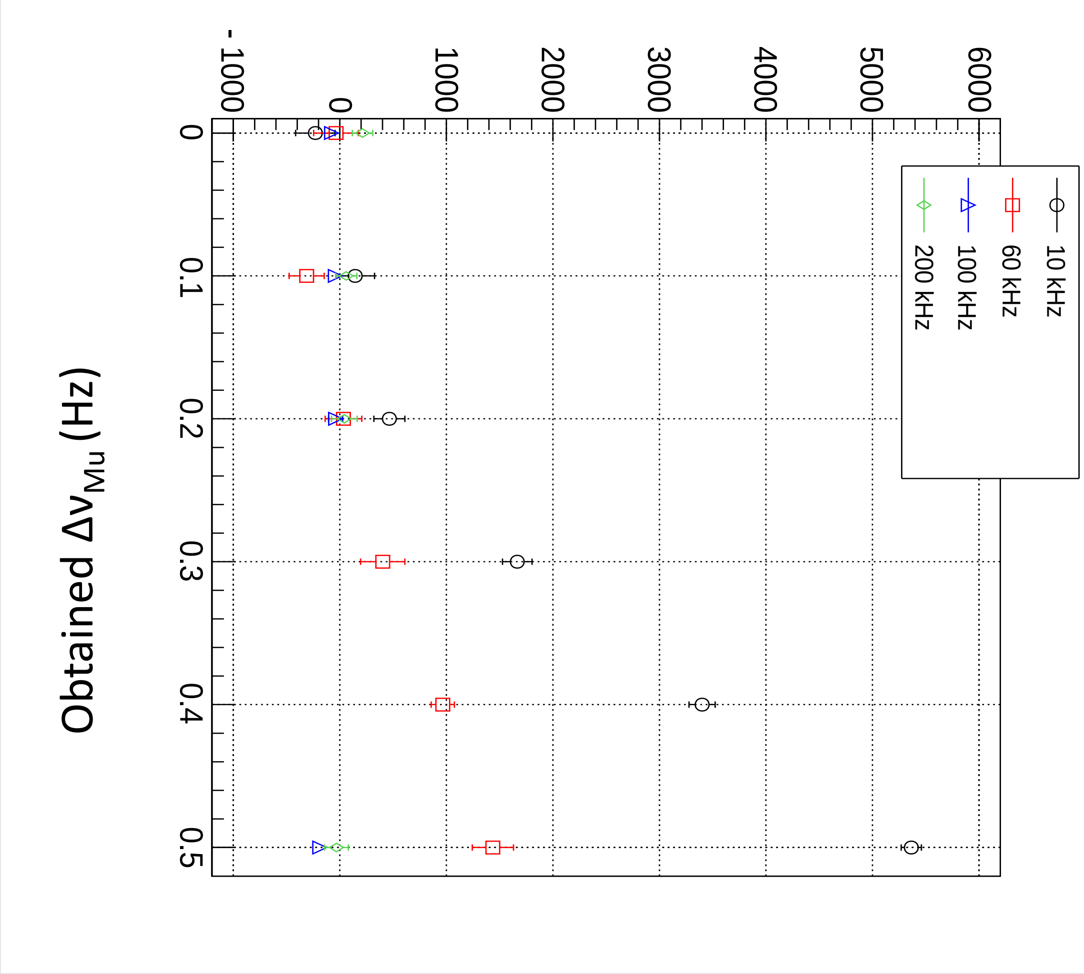
Kr Gas Control System



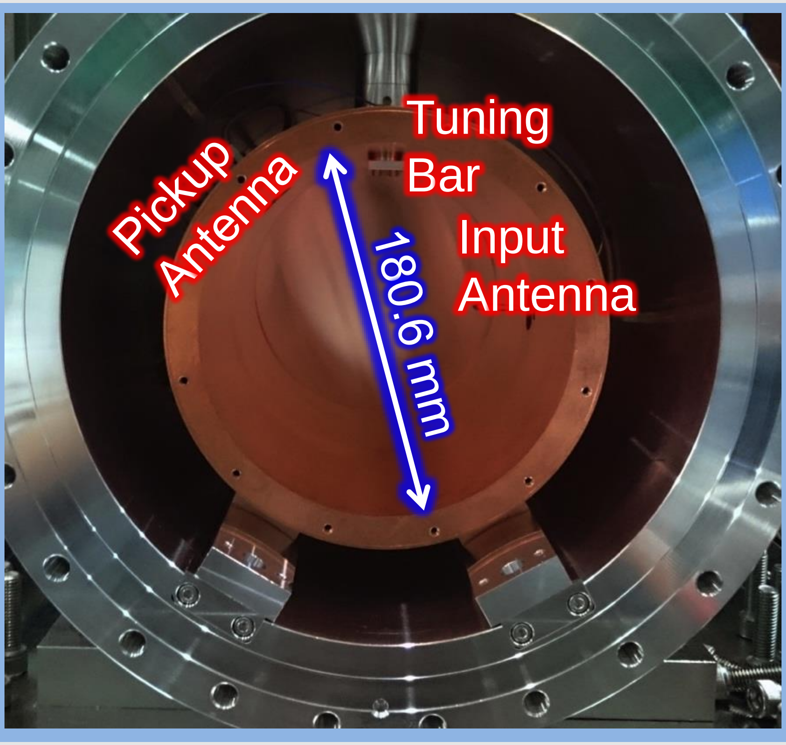
- Kr gas ／ High impurity（99.999%）
- Gas purity ／ Monitored by Q-mass
- Gas pressure ／ Monitored by pressure gauge

Uncertainty due to Power Drift

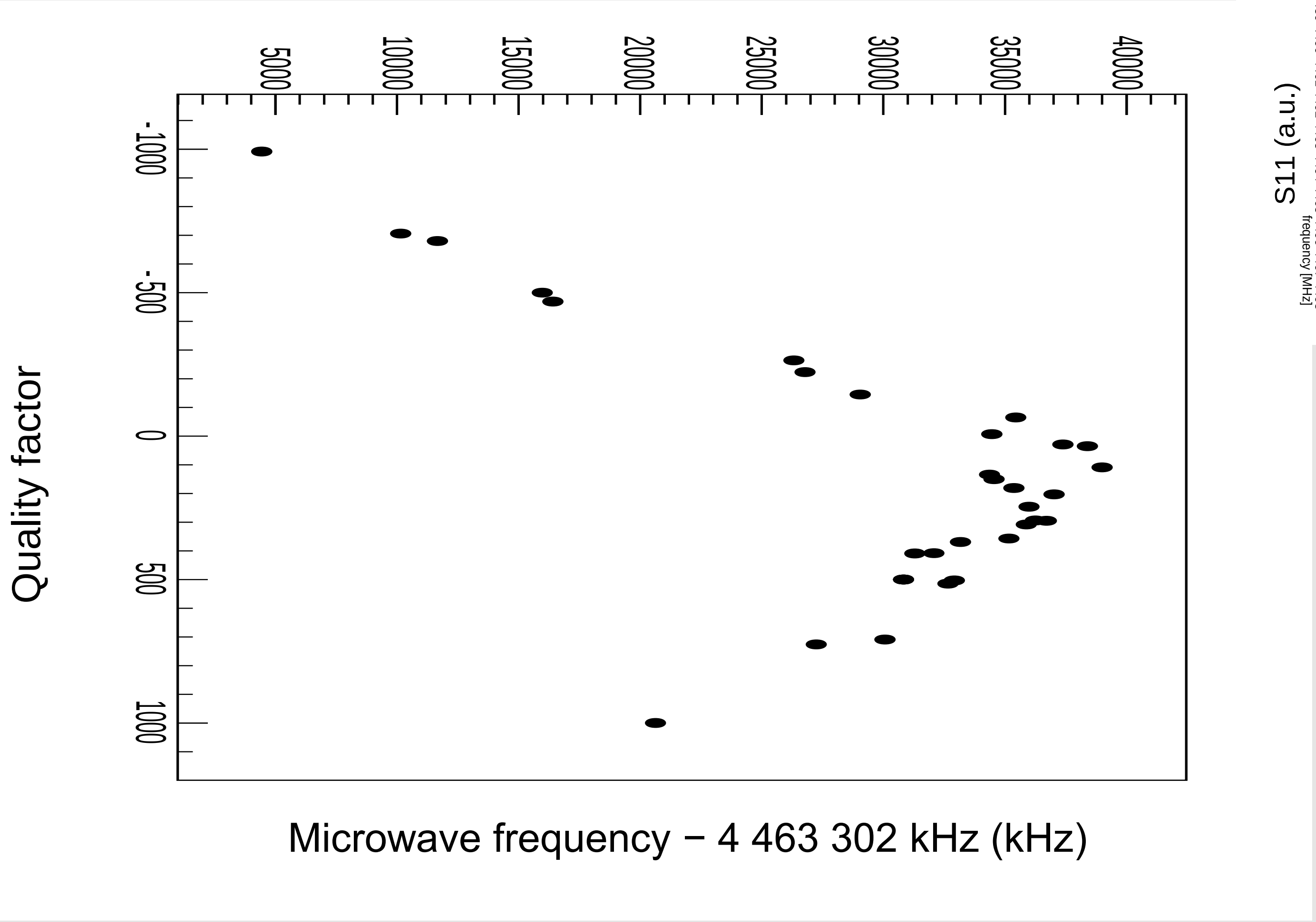
Uncertainty is estimated to be less than 200 Hz

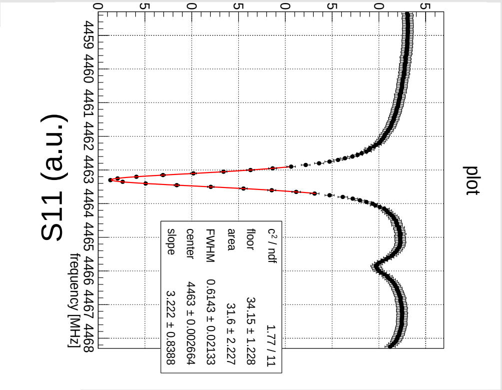


Microwave cavity

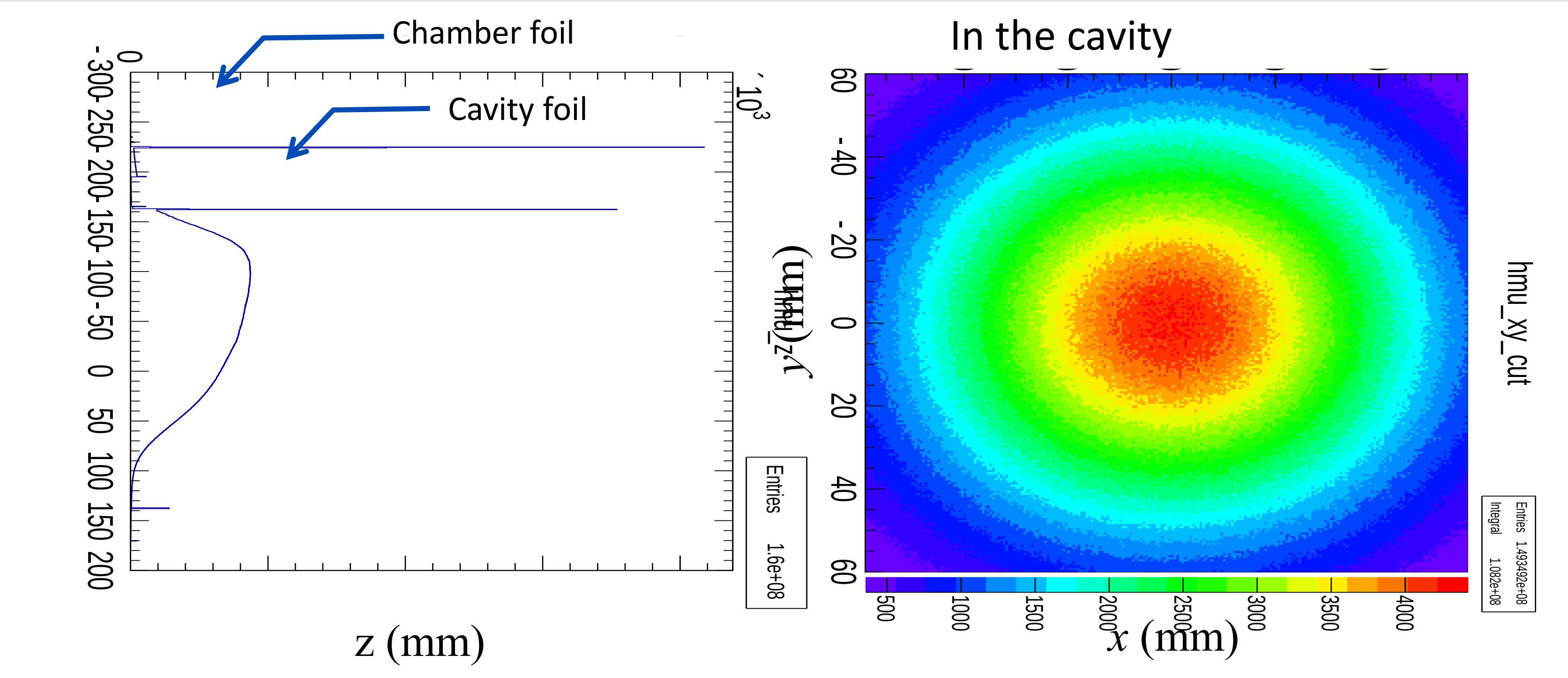


Frequency Dependence of Q-value





Muon Stopping Distribution



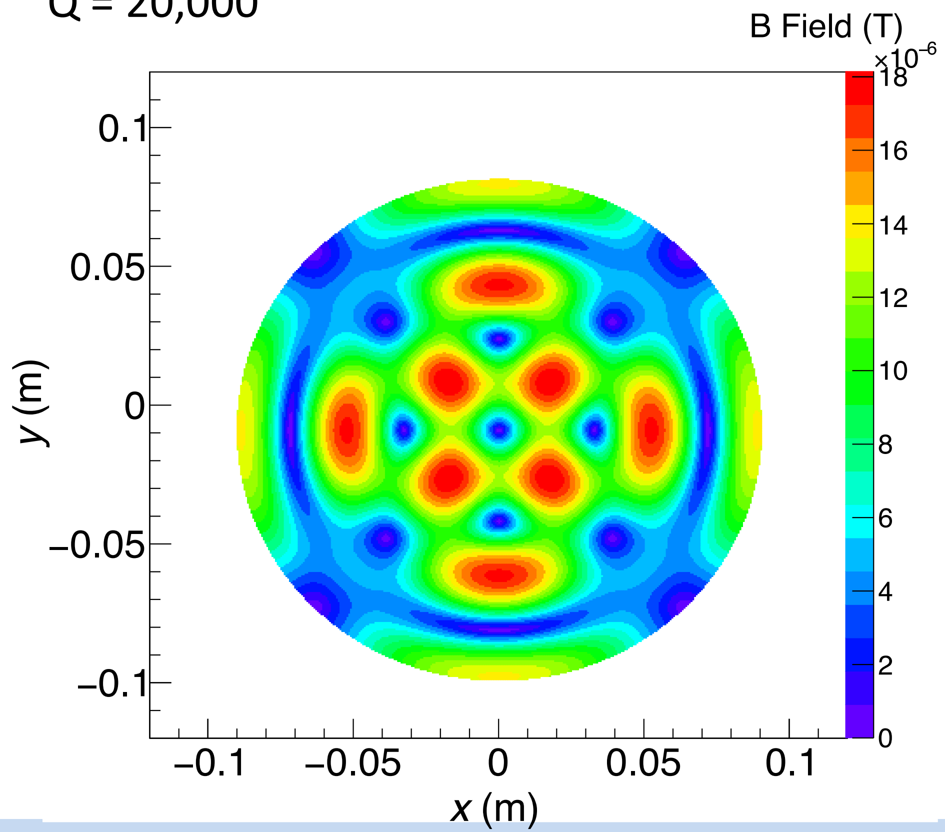
Geant4 Simulation results

Microwave field

TM220

Input power = 0.8 W

Q = 20,000



Silicon Strip Sensor

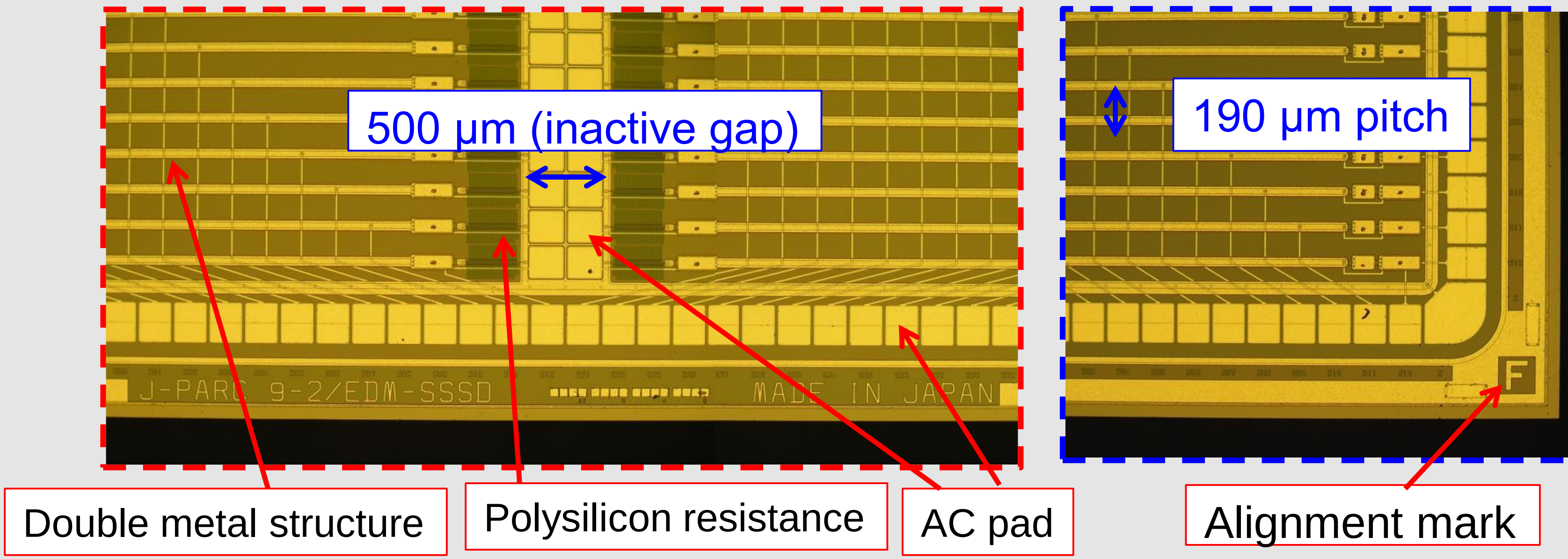
J-PARC *g*−2/EDM SSSD

Item	Specification
Sensor type	single-sided, p on n
Size	98.77 × 98.77 mm^2
Active area	97.28 × 97.28 mm^2
Strip pitch	190 µm
Strip length	48.575 mm
# of strips	512 × 2 blocks
Thickness	320 µm

Silicon Strip Sensor

J-PARC *g*−2/EDM SSSD

- Strip divided at the center of the sensor
- Double metal structure



Relation btw. *g*–2 & μ_μ/μ_p

Definition

$$\omega_a = a_\mu \frac{eB}{m_\mu c}$$

$$\mu_\mu = (1+a_\mu)\frac{e\hbar}{2m_\mu c}$$

$$B = \frac{\hbar}{2}\frac{\omega_p}{\mu_p}$$

$$\frac{R}{\lambda - R} = \frac{\frac{\omega_a}{\omega_p}}{\frac{\mu_\mu}{\mu_p} - \frac{\omega_a}{\omega_p}} = \frac{a_\mu \frac{e}{m_\mu c}\frac{\hbar}{2}\frac{\omega_p}{\mu_p}\frac{1}{\omega_p}}{(1+a_\mu)\frac{e\hbar}{2m_\mu c}\frac{1}{\mu_p} - a_\mu \frac{e}{m_\mu c}\frac{\hbar}{2}\frac{\omega_p}{\mu_p}\frac{1}{\omega_p}}$$

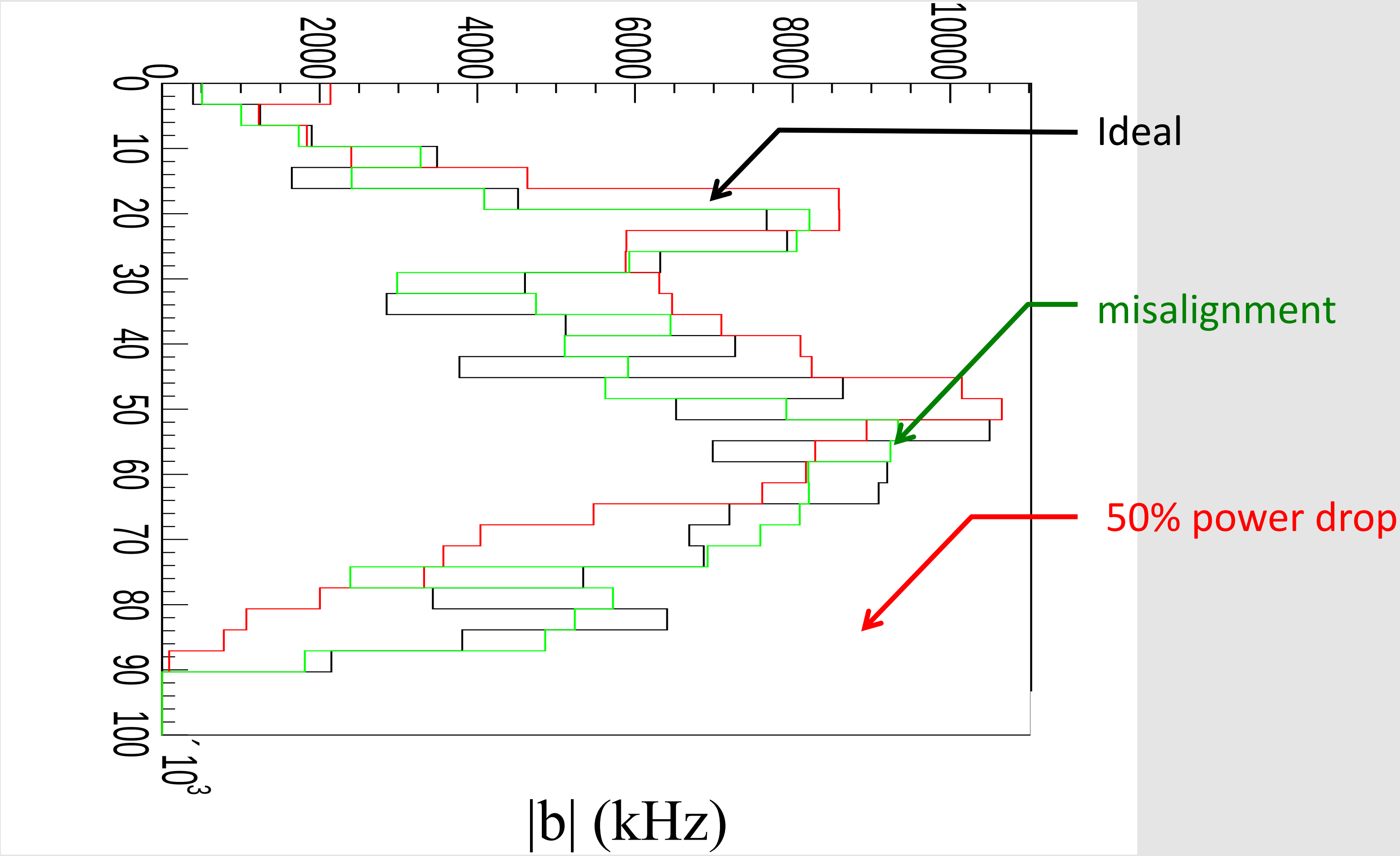
$$= \frac{a_\mu}{1 + a_\mu - a_\mu} = a_\mu$$

$$a_\mu = \frac{g_e}{2}\frac{\omega_a}{\omega_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e} \leftarrow \frac{m_\mu}{m_e} = \left(\frac{g_\mu}{g_e}\right)\left(\frac{\mu_p}{\mu_\mu}\right)\left(\frac{\mu_e}{\mu_p}\right)$$

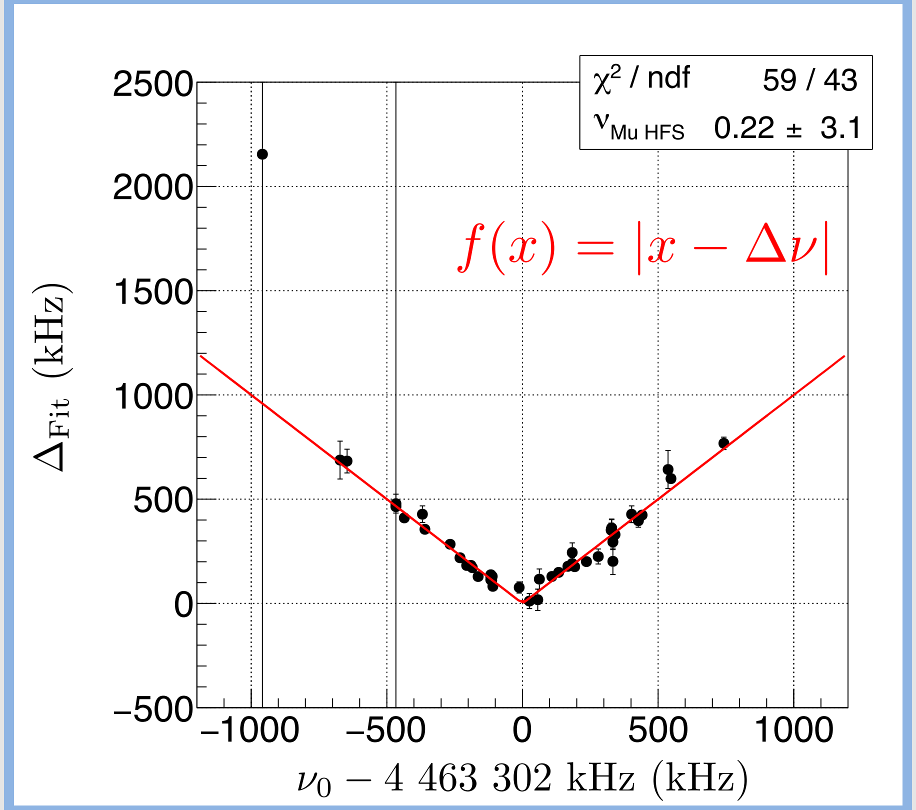
Sensor Quality Assurance

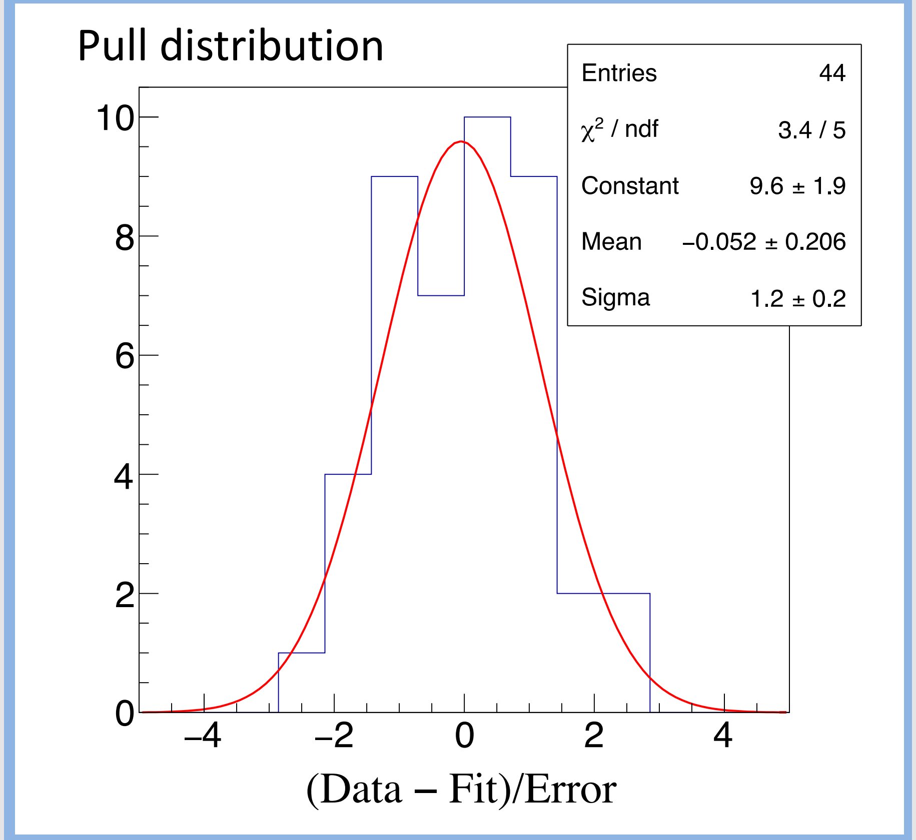
Item	Result	Expected
I-V	plateau were observed	-
C total	3050 pF	3100 pF
Full depletion voltage	～80 V	～80 V
C interstrip	7.1 pF	3.0 pF + α
Detector Capacitance	17 pF	9 pF + α
C coupling	167 pF	164 pF
R Polysilicon	～12 MΩ	5～15 MΩ

Microwave Power Distribution Felt by Muonium



Fitting Results





Fitting Function for Time Differential Method

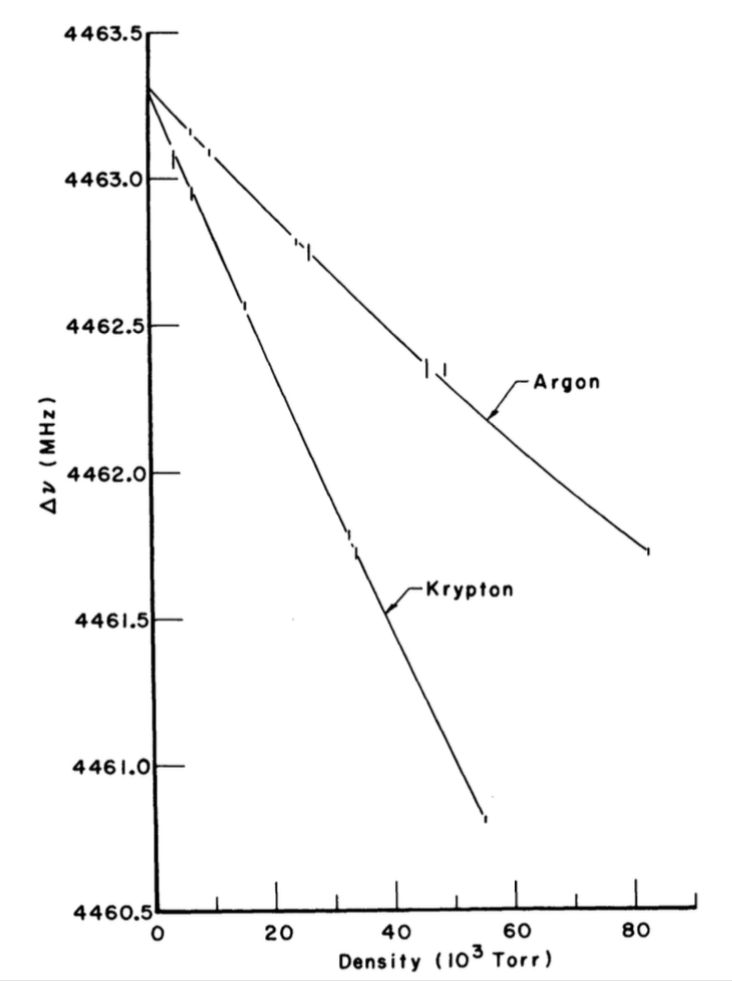
Fit parameters

$$f_{\rm diff}\left(t,\ p_1,\ p_2,\ \Delta,\ \lambda,\ t_0\right) = p_1 \frac{\frac{aP}{2}\sum_i N_i\left(\frac{G_+}{\Gamma}\cos G_-\left(t-t_0\right)+\frac{G_-}{\Gamma}\cos G_+\left(t-t_0\right)-1\right)S_i}{\sum_i N_i\left(1+\frac{aP}{2}S_i\right)},$$

Kr gas pressure shift

$$\Delta\nu_{\mathrm{HFS}}(0)\left(1 + aD + bD^2\right) = \nu_0 - \Delta,$$

Shift (@ 22℃、1 atm) | −33 kHz



Gas impurity