# Present Status of Muonium HFS measurement in J-PARC

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on behalf of the MuSEUM Collaboration

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(Muonium Spectroscopy Experiment Using Microwave)

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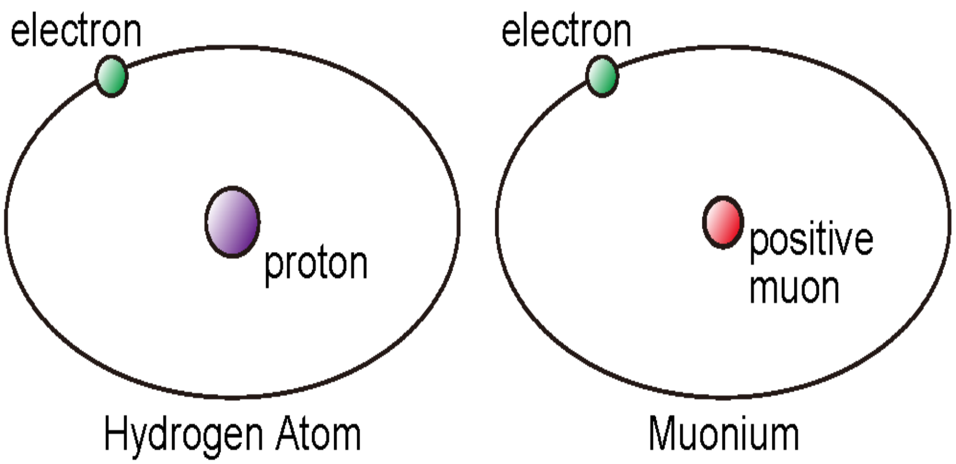
# What is Muonium ?

**Muon:**

- Elementary particle (lepton)
- 200 times heavier than an electron
- Lifetime of 2.2 microseconds.

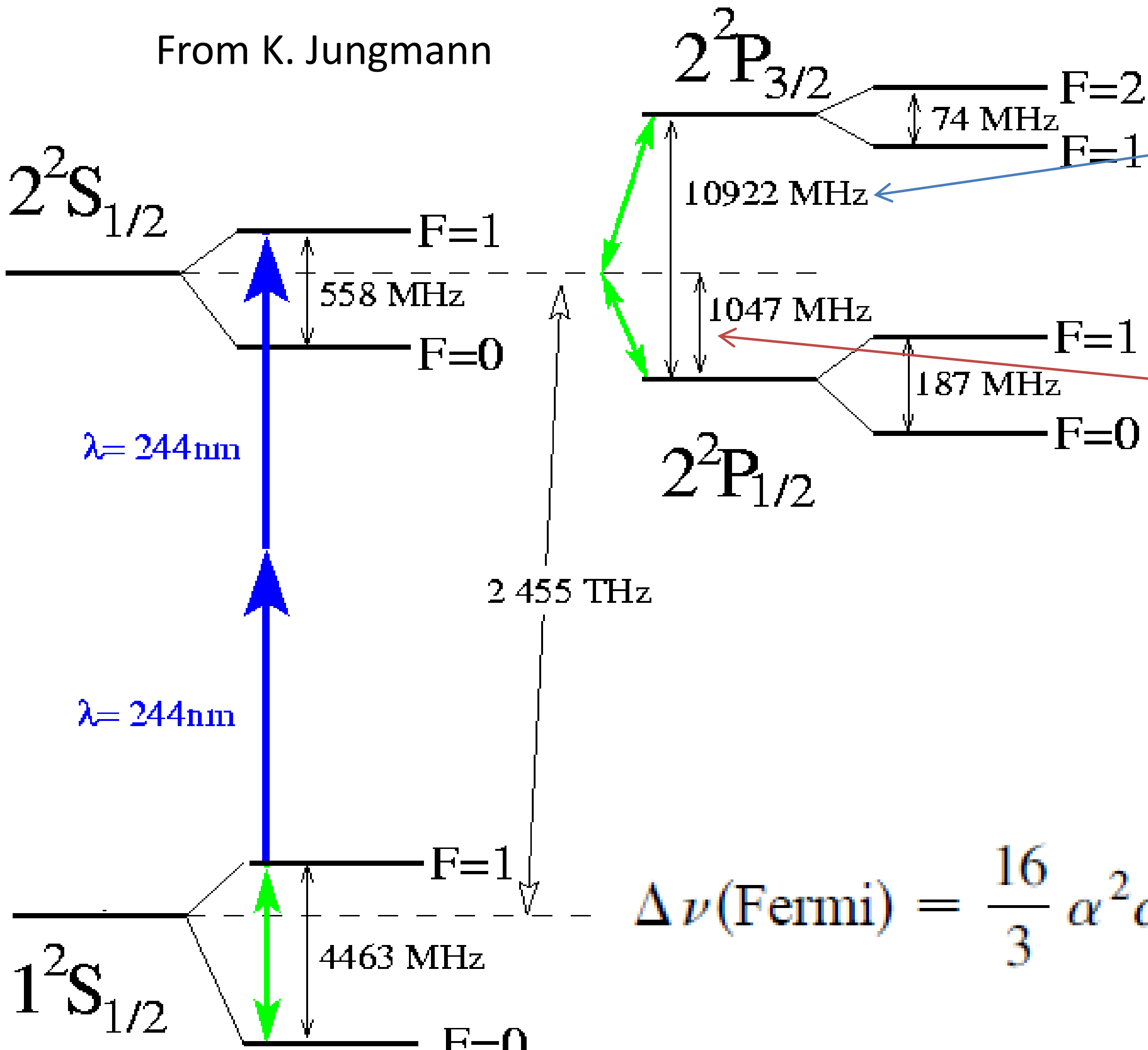



**Muonium:**

- Bound state of a positive muon and an electron.
- Hydrogen-like atom free from the finite size of the nucleon.
- Most suitable for validation of bound state quantum electrodynamics (QED).
- Theoretical and experimental precision of the hyperfine structure comparable.

# Mu Energy Diagram

From K. Jungmann




Fine Structure explained by Dirac

Classical Lamb Shift QED Tomonaga, Shwinger, Feynman

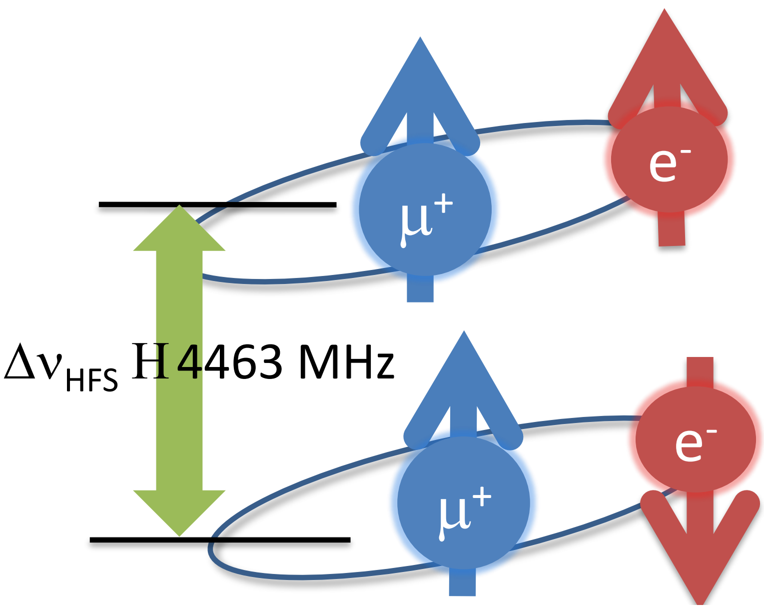
$$\Delta\nu(\mathrm{Fermi}) = \frac{16}{3}\alpha^2 c R_\infty \frac{m_e}{m_\mu}\left[1+\frac{m_e}{m_\mu}\right]^{-3}.$$

Not included QED weak hadronic correction

# Muonium Hyperfine Structure

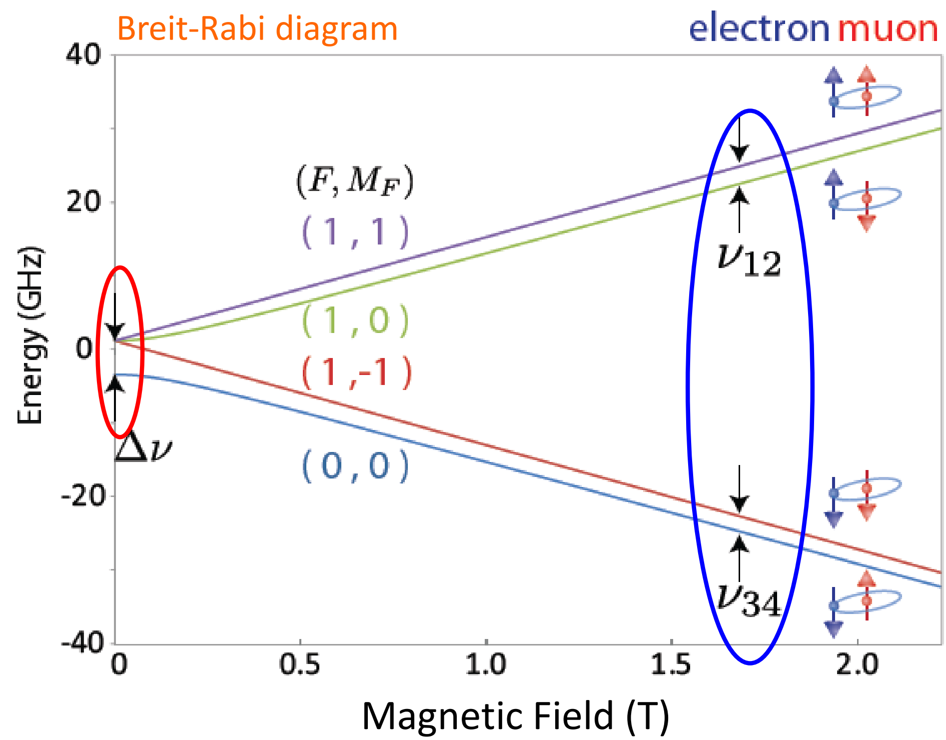
$$\mathcal{H} = h\Delta\nu \mathbf{I}_\mu \cdot \mathbf{J} - \mu_B^\mu g'_\mu \mathbf{I}_\mu \cdot \mathbf{H} + \mu_B^e g_J \mathbf{J} \cdot \mathbf{H}$$

$\Delta\nu_{HFS}$: Mu Hyperfine Structure




Pure lepton
= point particle

Zeeman Splitting




$\nu_{12}+\nu_{34} = \Delta\nu_{HFS}$ $\nu_{12}-\nu_{34} \propto \mu_\mu/\mu_p \propto m_\mu/m_p$

# Breit Rabi Diagram

$$\nu_{12} = -\frac{\mu_B^\mu g'_\mu H}{h} + \frac{\Delta\nu}{2}\left[(1 + x) - \sqrt{1 + x^2}\right],$$

$$\nu_{34} = +\frac{\mu_B^\mu g'_\mu H}{h} + \frac{\Delta\nu}{2}\left[(1 - x) + \sqrt{1 + x^2}\right],$$

$$x = (g_J \mu_B^e + g'_\mu \mu_B^\mu) H / (h \Delta\nu)$$

$$r'_e = \frac{g_J \mu_B^e}{\mu_p},$$

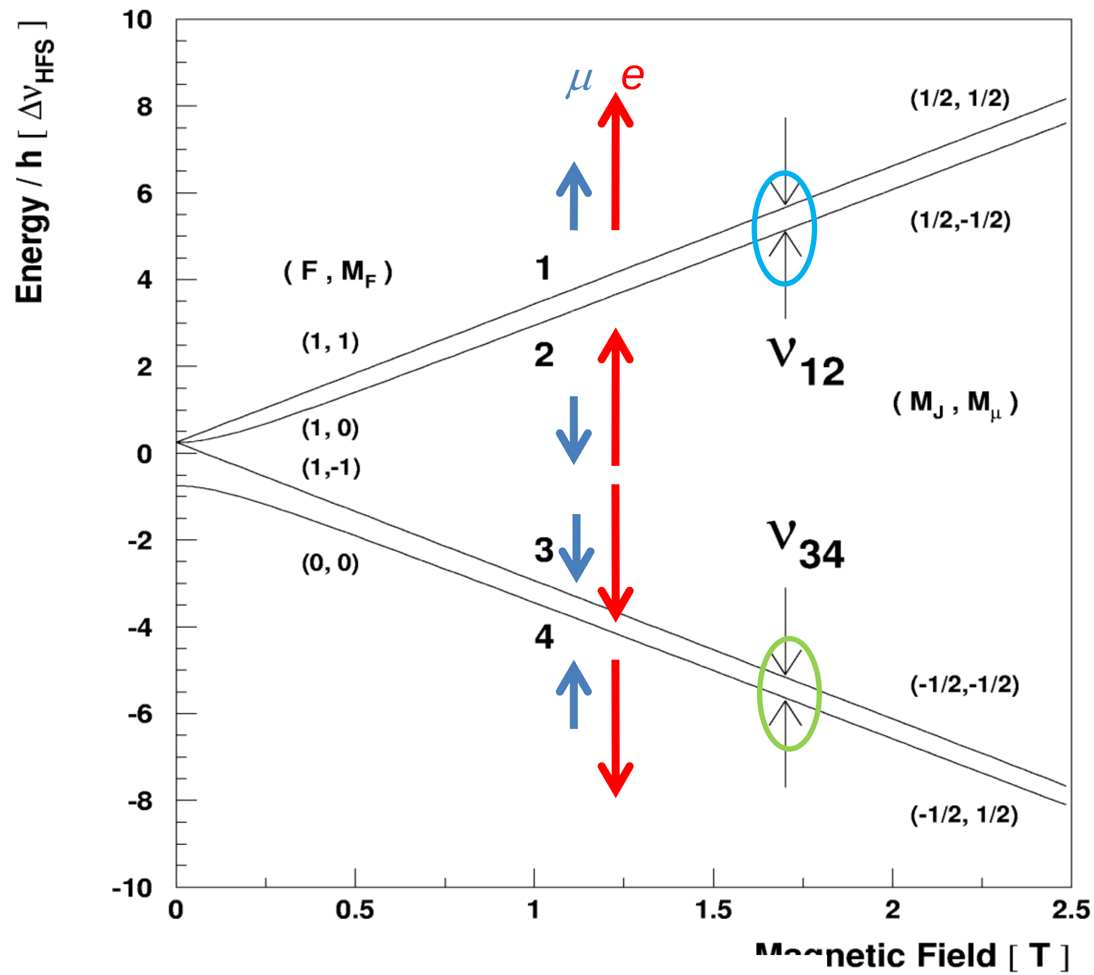
$$r'_\mu = \frac{g'_\mu \mu_B^\mu}{\mu_p},$$

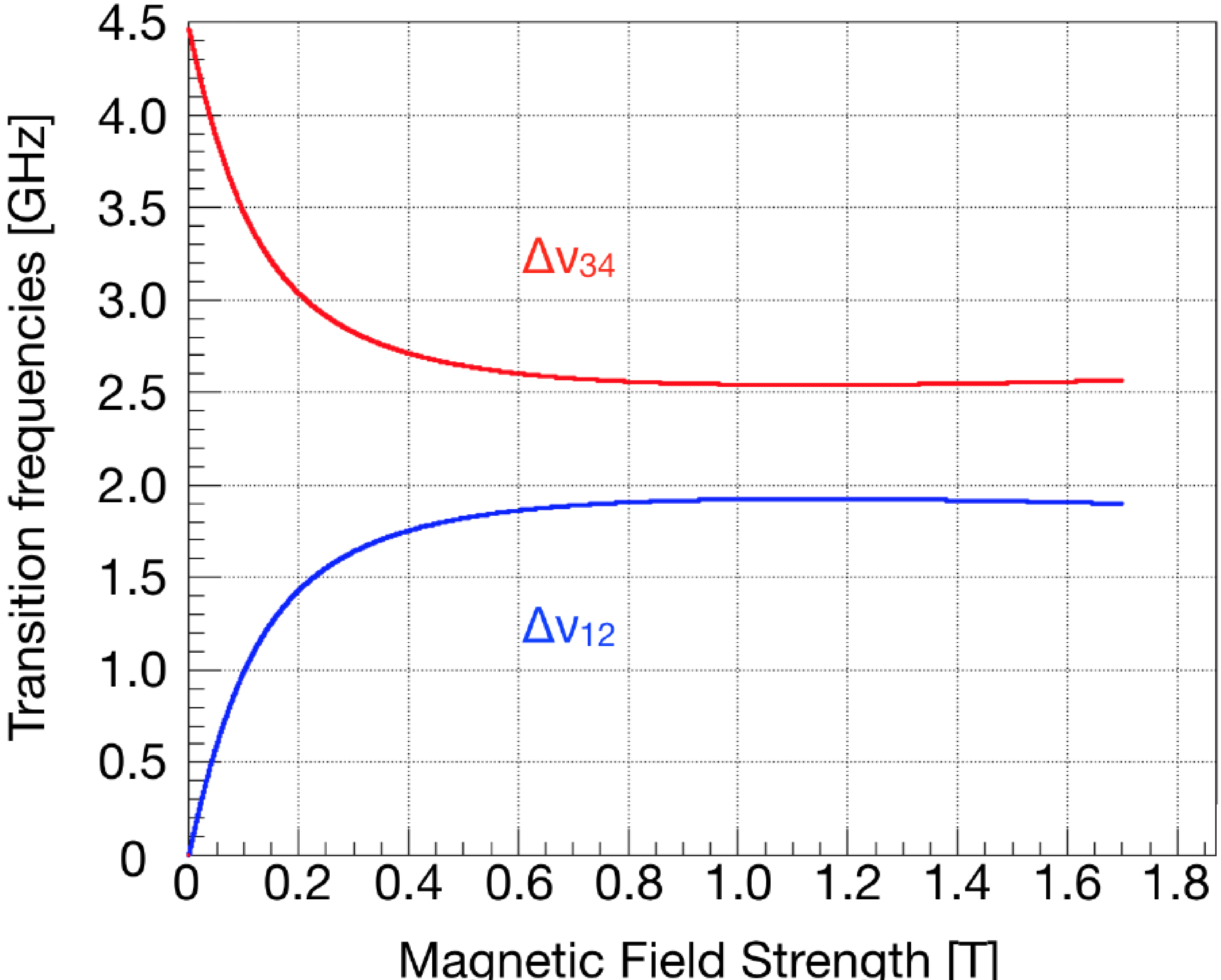
$$x = (r'_e + r'_\mu)\frac{\nu_p}{2\Delta\nu}.$$

$$\delta \equiv \nu_{34} - \nu_{12} = \frac{\mu_B^\mu g'_\mu \nu_p}{\mu_p} + \Delta\nu\left(\sqrt{1 + x^2} - x\right).$$

$$\frac{\mu_\mu}{\mu_p} = \frac{r'_\mu}{2}\frac{g_\mu}{g'_\mu}$$

$$= \frac{1}{4}\frac{1 - (\Delta\nu)^2 + \nu_p r'_e \delta + \delta^2}{\nu_p\left(\nu_p r'_e + \delta\right)}\left(1 - \frac{\alpha^2}{3}\left(1 - \frac{3}{2}\frac{m_e}{m_\mu}\right) - \left(\alpha^2\left(\frac{m_e}{m_\mu}\right)^2 - \frac{\alpha^3}{12\pi}\frac{m_e}{m_\mu} + \frac{97}{108}\alpha^4\right)\right)^{-1}$$





Transition frequencies [GHz]
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
Δν34
Δν12
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Magnetic Field Strength [T]

# History of Mu HFS measurement

| Time | Group | $\Delta\nu$ | ppm | B field (T) | Ref |
|---|---|---|---|---|---|
| 1961 | Yale-Nevis | $5500^{+2900}_{-1500}$ MHz | | 0.01-0.58 | [33, 34] |
| 1962 | Yale-Nevis | 4 461.3(2.0) MHz | 450 | 1.1353 | [35, 36] |
| 1964 | Yale-Nevis | 4 463.24(12) MHz | 27 | 0.5 | [37, 38] |
| 1966 | Yale-Nevis | 4 463.18(12) MHz | 27 | $2.7 \times 10^{-4}$ | [39] |
| 1969 | Yale-Nevis | 4 463.26(4) MHz | 9.0 | $3 \times 10^{-4}$ | [40] |
| 1969 | Chicago | 4 463.317(21) MHz | 4.7 | 1.1353 | [36, 41] |
| 1970 | Chicago | 4 463.302 2(89) MHz | 2.0 | 1.1353 | [42] |
| 1971 | Yales-Nevis | 4 463.308(11) MHz | 2.5 | $3 \times 10^{-4}$ and $1 \times 10^{-6}$ | [43] |
| 1973 | Chicago-SREL | 4 463 304.4(2.3) kHz | 0.5 | 0 | [44] |
| 1975 | LAMPF | 4 463 302.2(1.4) kHz | 0.3 | very weak | [45] |
| 1977 | LAMPF | 4 463 302.35(52) kHz | 0.12 | 1.36 | [46, 47] |
| 1982 | LAMPF | 4 463 302.88(16) kHz | 0.036 | 1.36 | [48] |
| 1999 | LAMPF | 4 463 302.765(53) kHz | 0.012 | 1.7 | [4] |

Table 2.1: Comparison of Mu HFS measurements.

Magic Field

Spin Echo

Zero Field
World Record

Old Mu Method

High Field
World Record

K.S.Tanaka thesis

# Most Precise Test of Bound State QED

**Experiment:**

LAMPF Experiment (1999)

$\nu_{HFS}$(exp) 4463.302 765 (53) MHz [12 ppb]

$\mu_\mu/\mu_p$ = 3.18334524(37) [120ppb]

$m_\mu/m_e$ = 206.768277(24) [120ppb]

**Theory:**

$\nu_{HFS}$(theory) 4463.302 868 (271) MHz [61 ppb]

$\nu_{HFS}$(QED) 4463.302 720 (518) (70) (2) MHz

($m_\mu/m_e$) (QED) ($\alpha$) By Eides

$\nu_{HFS}$(weak) -65 Hz

$\nu_{HFS}$(had. v.p.) 232 (1) Hz

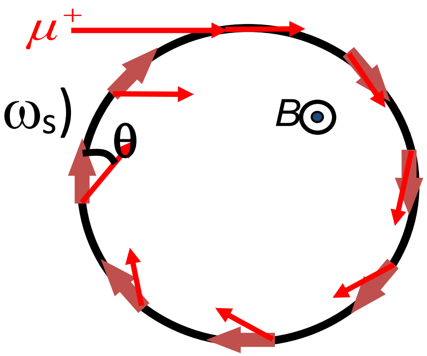
$\nu_{HFS}$(had. h.o.) 5 (2) Hz

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

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

# Why Mu HFS measurement is so important?

## *g*-2 E821(BNL) 0.5ppm 3.6σ deviation




- Measurement of the deviation of muon spin direction ($\omega_s$) and muon momentum direction ($\omega_c$) $\omega_a \propto (g-2)/2 = a_\mu$

$$\Rightarrow \vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E}\right]$$

$a_\mu$ *an independent precise muon mass measurement is required!*

- The ratio to the proton NMR frequency is important!

$$\Rightarrow \boxed{a_\mu = \frac{R}{\lambda - R}} \qquad R \equiv \frac{\omega_a}{\omega_p} \qquad \lambda \equiv \frac{\mu_\mu}{\mu_p}$$

From g-2 storage ring From Muonium HFS

$$\frac{\omega_a}{\omega_L(\mu)} = \frac{a_\mu\left(\frac{eB}{mc}\right)}{g_\mu\left(\frac{eB}{2mc}\right)} = \frac{a_\mu}{\left(\frac{g_\mu}{2}\right)} = \frac{a_\mu}{1+a_\mu}$$

$$= \frac{\omega_a}{\omega_L(p)}\frac{\omega_L(p)}{\omega_L(\mu)} = \frac{\omega_a}{\omega_p}\frac{\mu_p}{\mu_\mu} = R/\lambda$$

$\mu_\mu/\mu_p$ accuracy from direct measurement of 120 ppb.

*W. Liu et al., Phys. Rev. Lett. 82 (1999) 711*

# *How to improve the accuracy of $m_\mu/m_e$?*

Comparison between theoretical and experimental value of $\Delta\nu$

$$\Delta\nu(\text{Fermi}) = \frac{16}{3}\alpha^2 c R_\infty \frac{m_e}{m_\mu}\left[1+\frac{m_e}{m_\mu}\right]^{-3} \quad + \text{higher order}$$

where recoil term 800kHz (120ppm) and so on are included.

$R_\infty$ = 10973731.568639(91)m$^{-1}$(0.09ppt)

（Cs atomic beam interferometory）

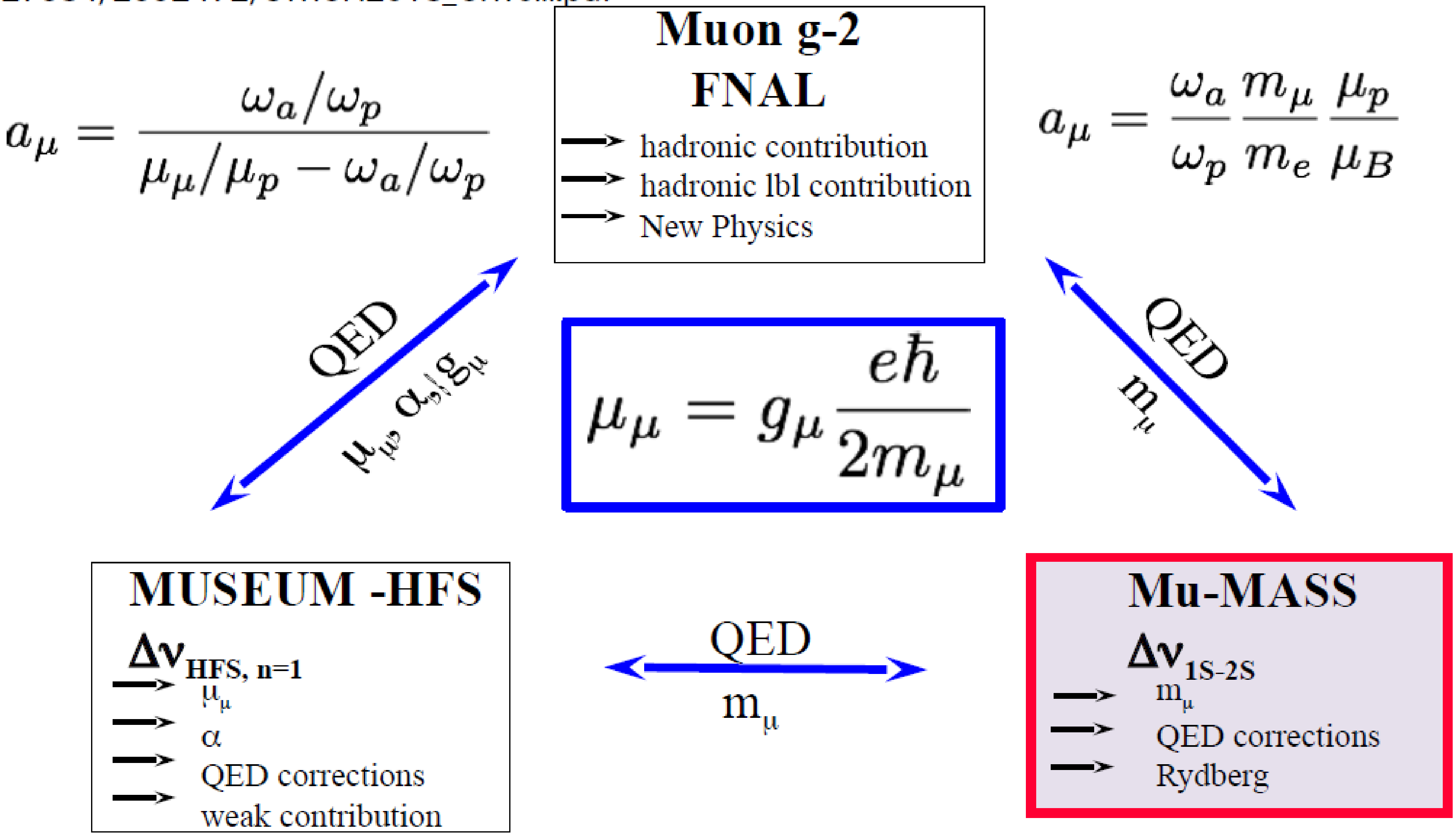
$\alpha^{-1}$=137.03599958(52) (3.8ppb)

（from electron *g-2*）

$m_\mu/m_e$=206.7682826(46) (22ppb), $\mu_\mu/\mu_p$=3.183345396(94) (24ppb)

This value is used for the determination of *g-2*.

https://indico.cern.ch/event/687183/contributions/2928847/attachments/1627584/2592472/SWICH2018_Crivelli.pdf




From K. Jungmann

# Exiotic particle search

a pseudo vector boson

$$-\frac{\alpha}{r} \longrightarrow -\frac{\alpha + \alpha''(\mathbf{s}_1 \cdot \mathbf{s}_2) e^{-\lambda r}}{r},$$

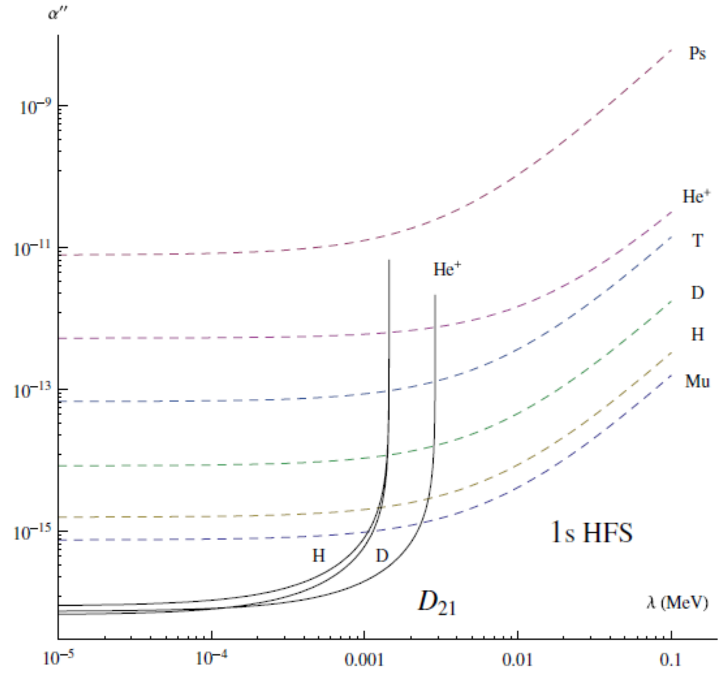



Fig. 2 on PRL 104, 220406 (2010)

a massive vector boson

$$\frac{\Delta E_{\rm hfs}}{E_{\rm hfs}} = \frac{8\alpha' m_e}{m_V} = \frac{8\alpha\kappa(\kappa + g_V/e) m_e}{m_V}.$$

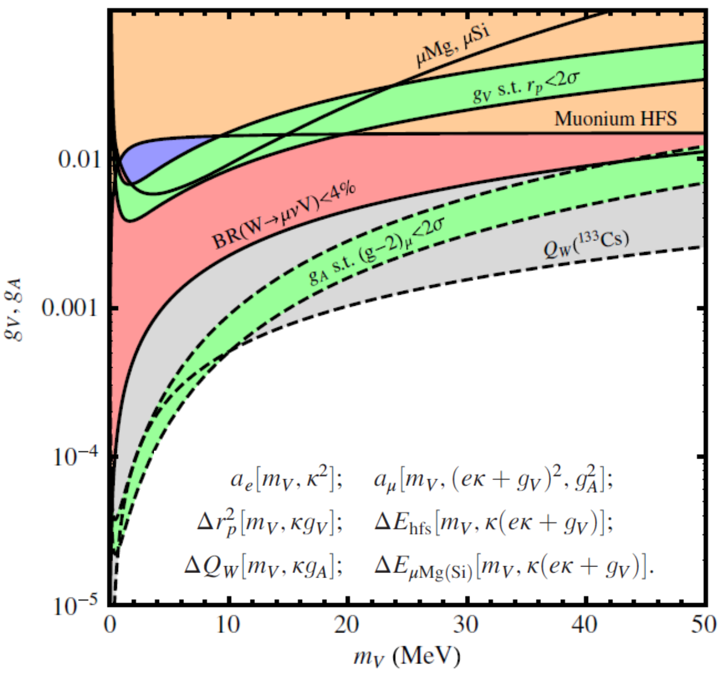



Fig. 6 on PRD90, 073004(2014).

S. G. Karshenboim *et al*., PRL 104, 220406 (2010), PRD82, 113013(2010). PRA 84, 064502(2011) , PRD90, 073004(2014).

# Test of CPT and Lorentz Invariance

CPT broken Theory ⇒ Lorentz symmetry is broken

*O.W. Greenberg, PRL 89 (2002) 231602*
*R. Blihm, V.A. Kosteleky, C.D. Lane, PRL 84 (2000) 1098*
*V.W. Hughs et al., PRL 87(2002) 111804*

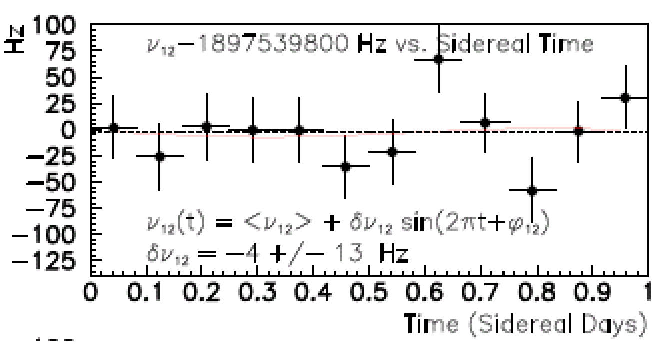
CPT violation search

Ex: Muon difference $g_{\mu+}/\ g_{\mu-}$ $10^{-8}$

$g_{\mu}$-2/MuHFS precise measurement

Lorentz symmetry violating term in STE Lagrangian b
Corresponding MuHFS $\Delta\nu_{12/34}$
These value might change in sidereal time (23h56m)

$\tilde{b}_3^{\mu}/\pi = -\delta\Delta\nu_{12} = \delta\Delta\nu_{34}$




LAMPF Exp. Figure of Merit

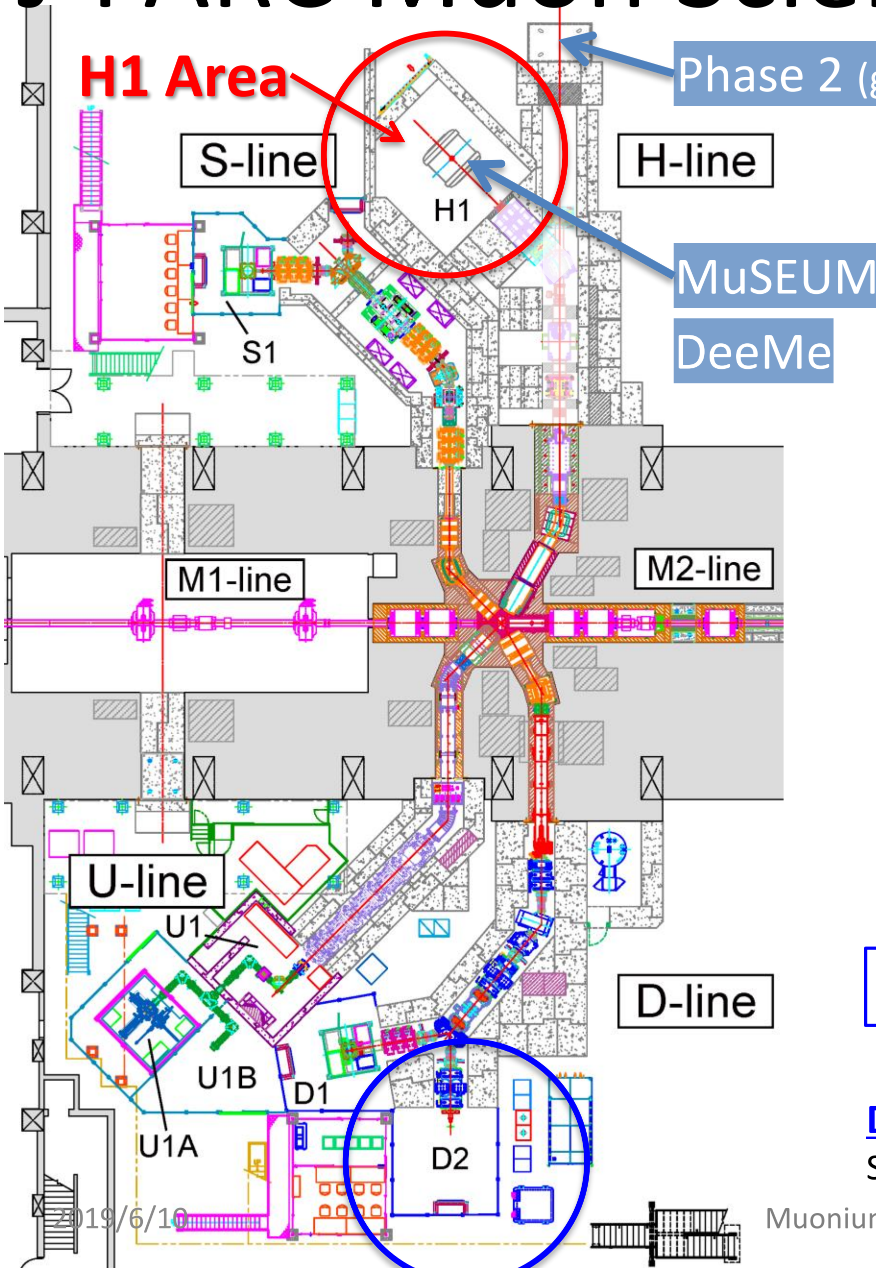
$$2\sqrt{(b^{\mu+}{}_X)^2 + (b^{\mu+}{}_Y)^2}\,/\,m_\mu < 5\times10^{-22}$$

Plank scale sensitivity

$m_\mu/M_P \sim 10^{-20}$

*V.A. Kostelecky, A.J. Vargas, PRD 92 (2015) 056002*

# J-PARC Muon Science Facility (MUSE)




**Under construction**

**H-Line: for particle and atomic physics large scale experiments, "precison frontier".**

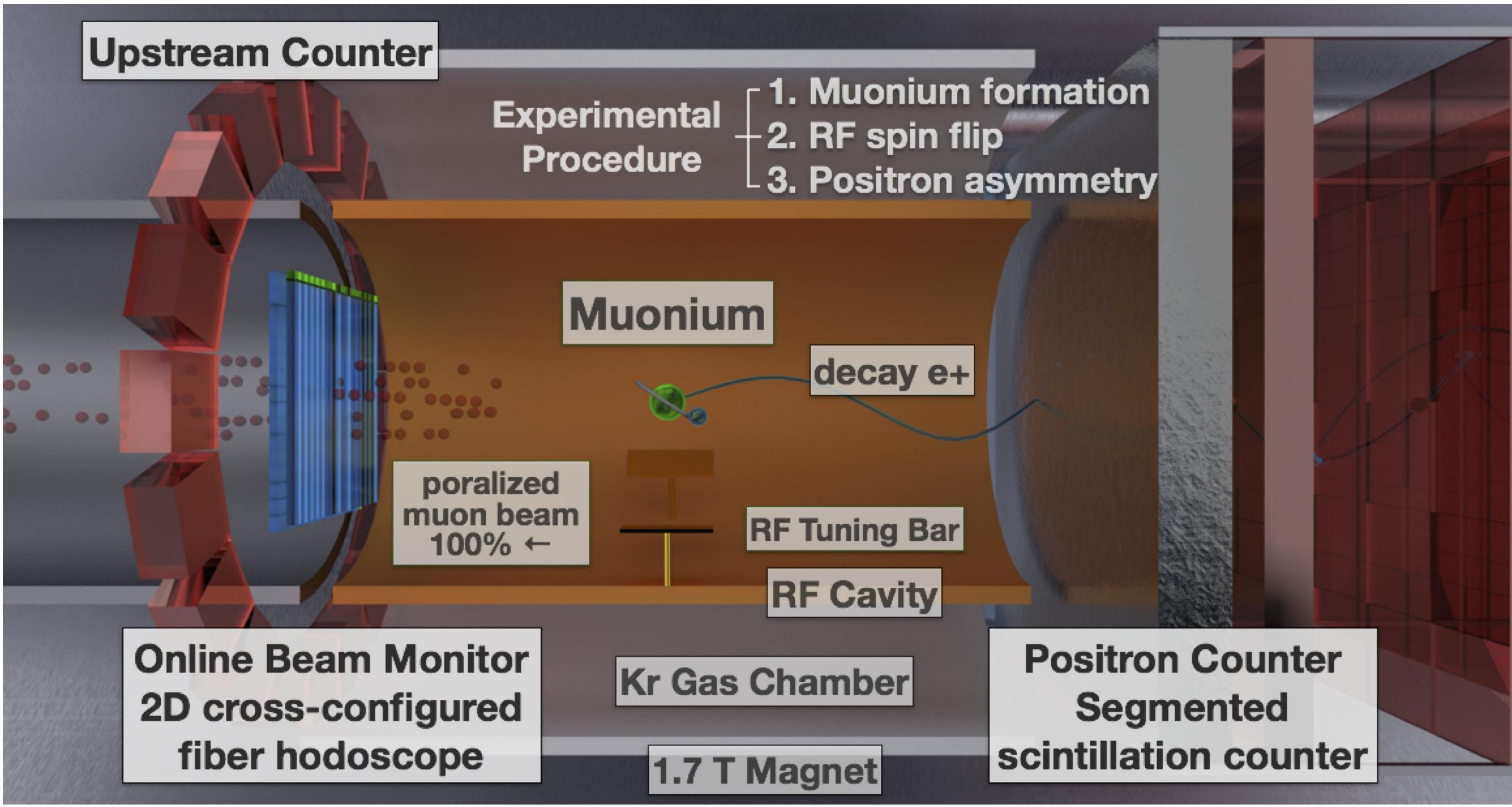
Higher intensity tunable (4 – 50 MeV) $\mu^+$ & $\mu^-$ beam.
(Exp.: MuSEUM, Deeme, g-2, …)


**MLF Experimental Hall No. 1 (2018)**

**Beamline in Operation**

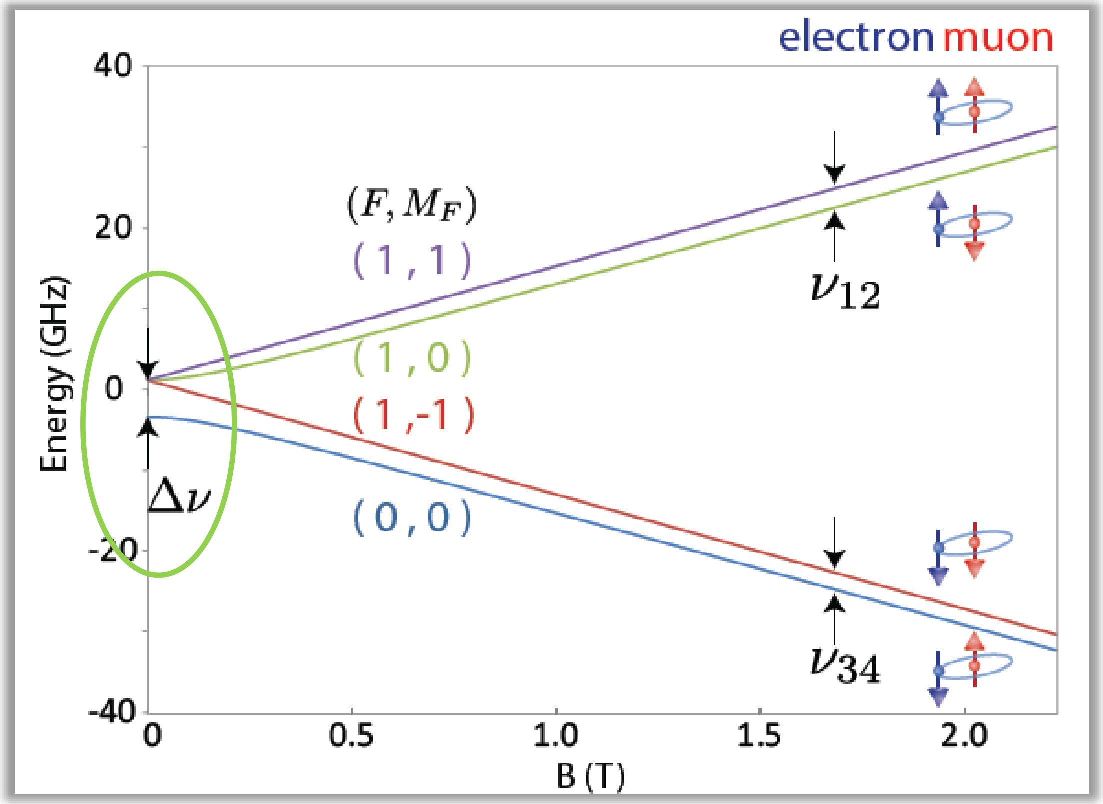
**D-Line: Decay and Surface muon** ($\mu^+$ & $\mu^-$)
Slow (50 keV) – fast (50 MeV) beam, general purpose.

# MuSEUM Experimental Layout



# Zero field measurement at D Line

## Important milestone for HF measurement-

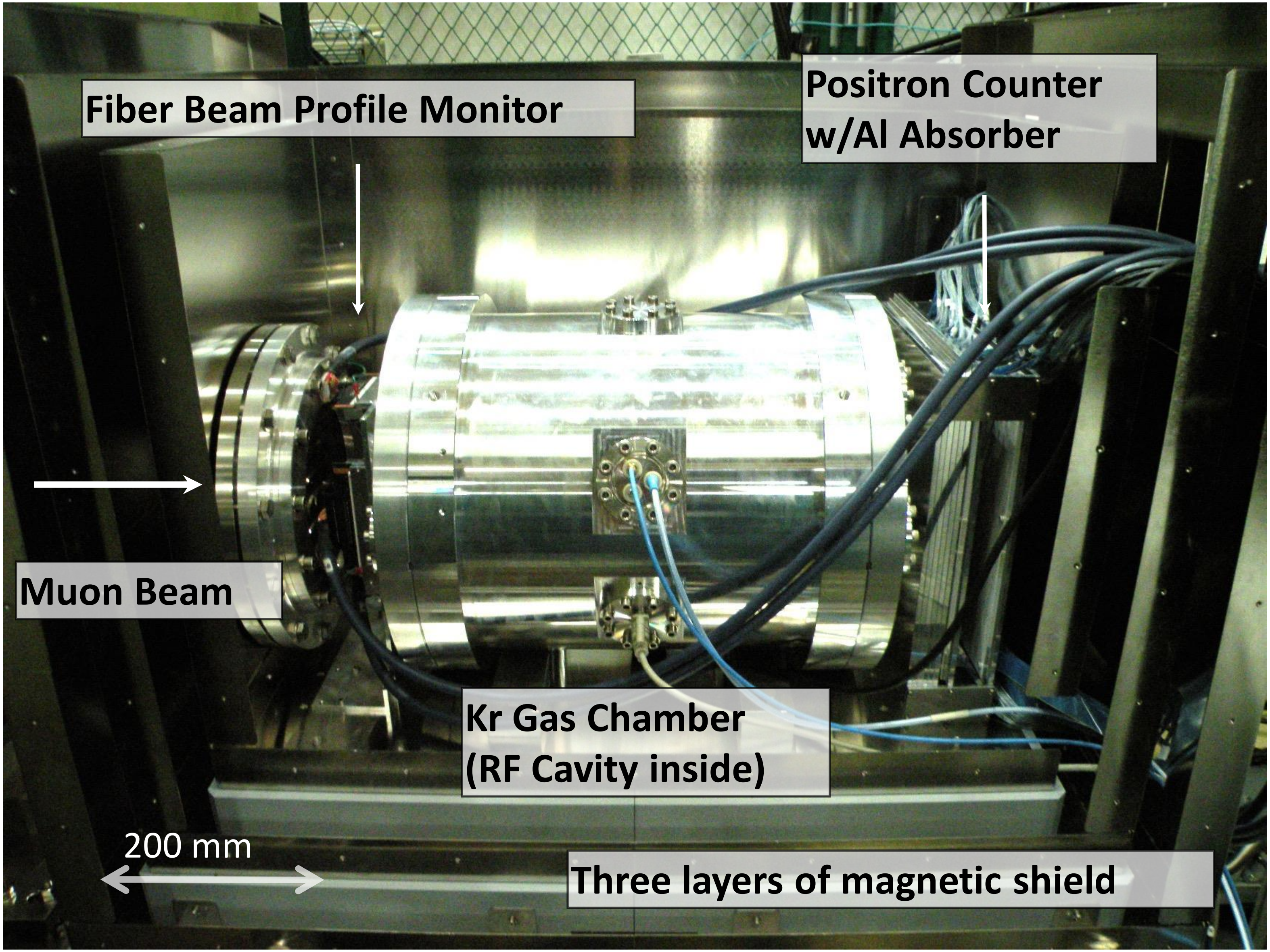



Two additional components are required.

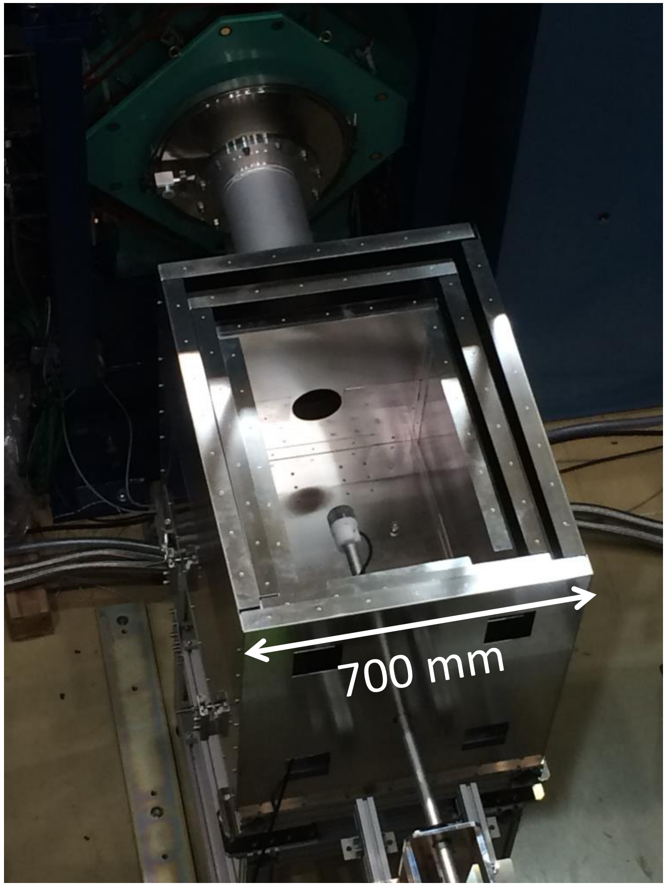
・Permalloy magnetic shield

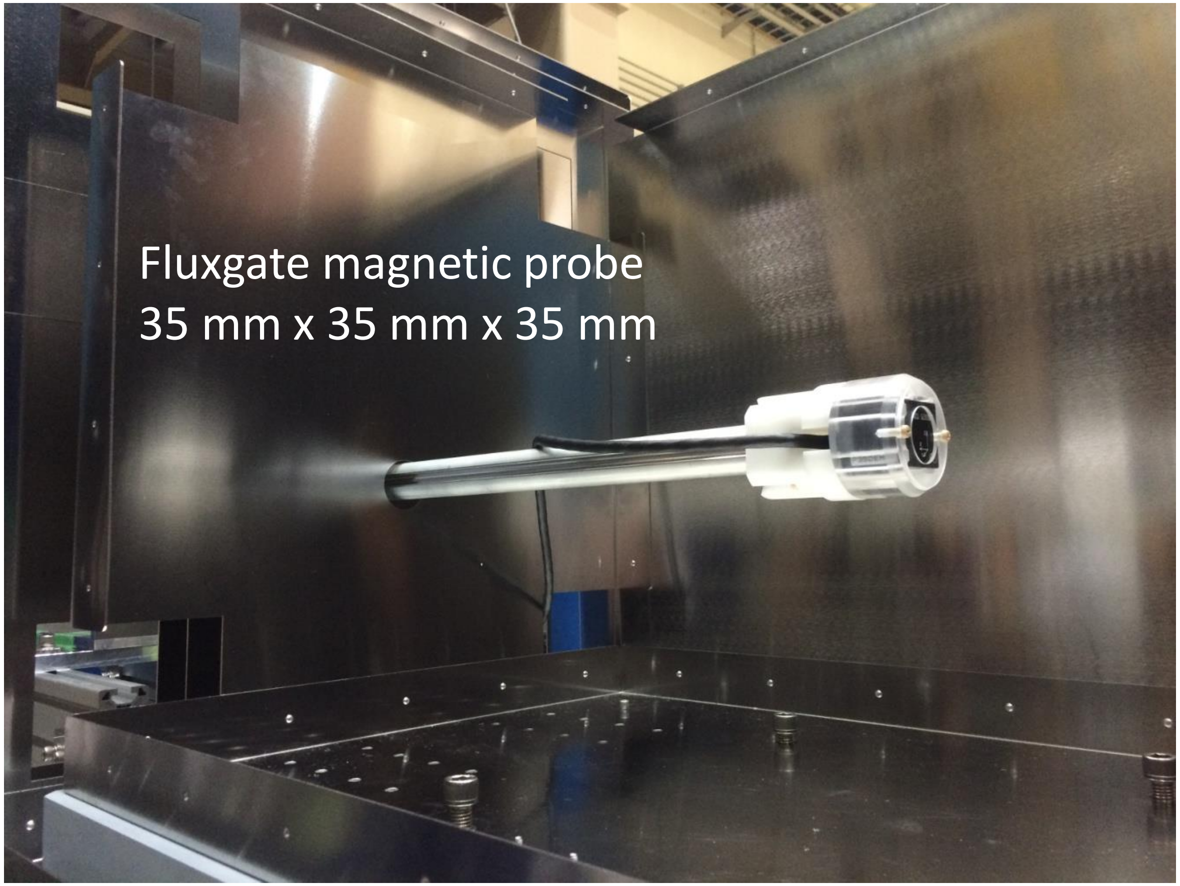
・RF cavity for ZF

# Resonance Measurement Setup



# Magnetic Shield and Field Probe

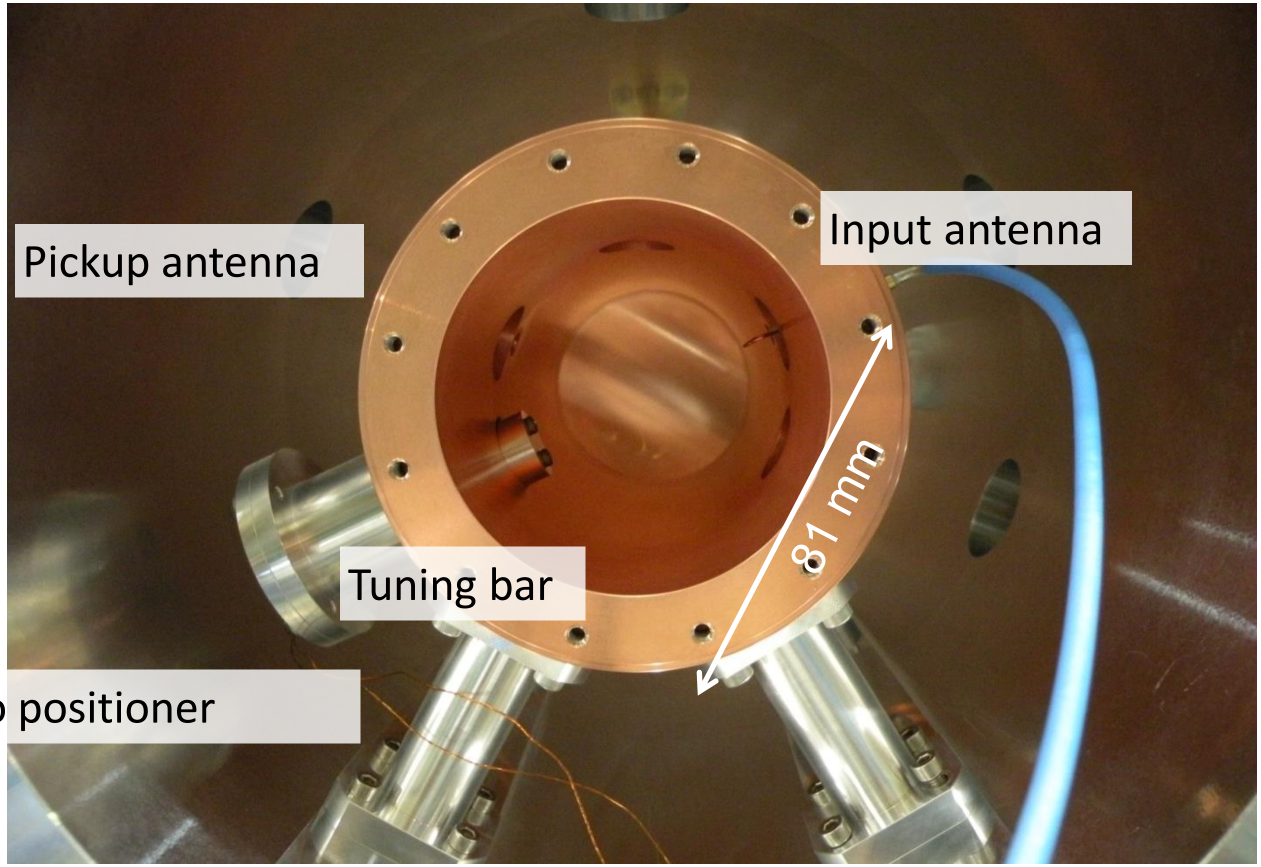



Assembled magnetic shield without top boards

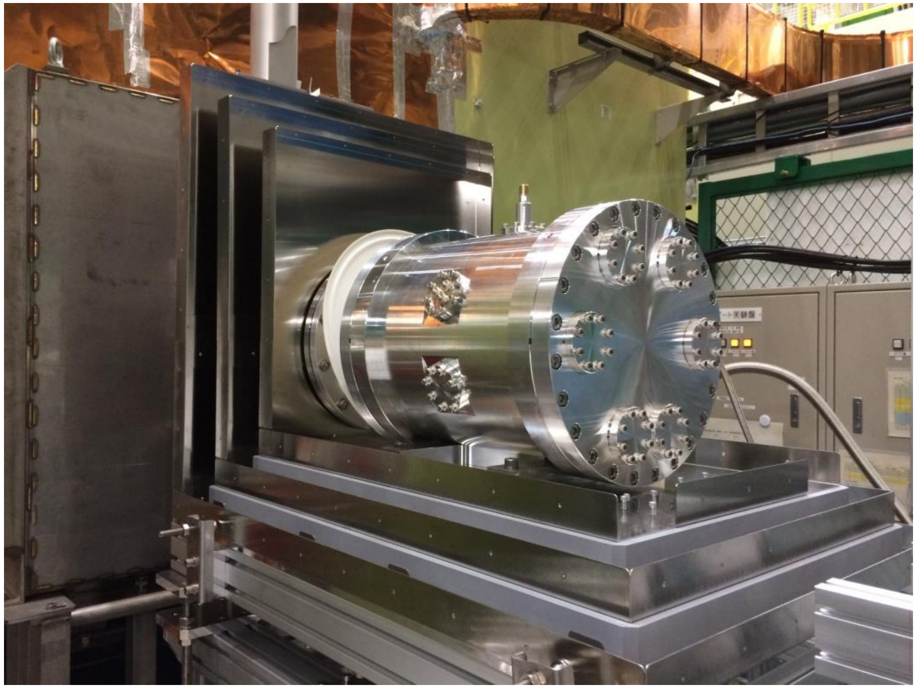
Magnetic field probe holder and its moving system

# Inside of the Gas Chamber




- Expected Q-value is 10000, microwave power is up to 3 W
- TM110 mode at 4.463 GHz, +-1 MHz tuning by a piezo positioner

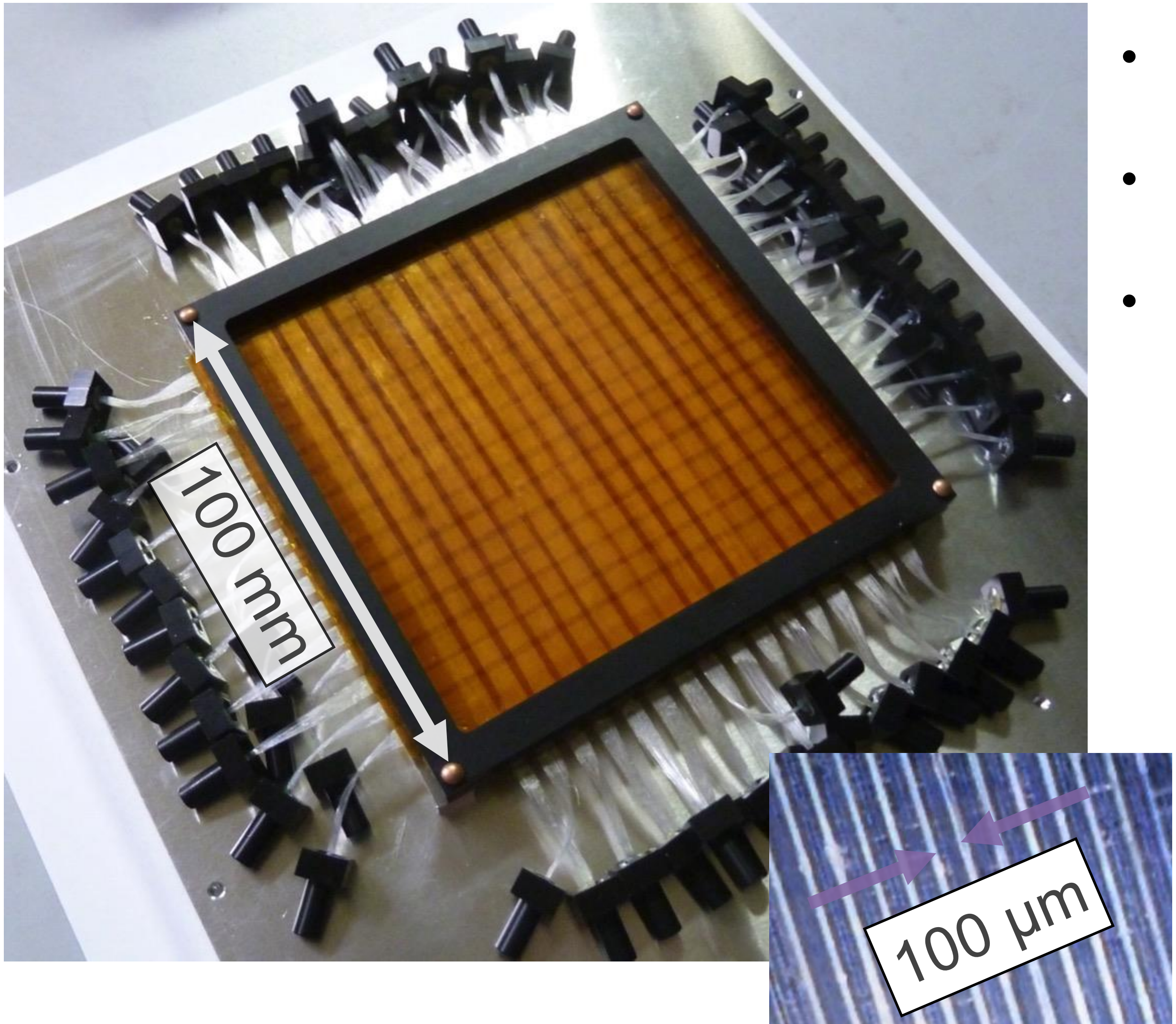
# Gas Chamber and Gas Handling



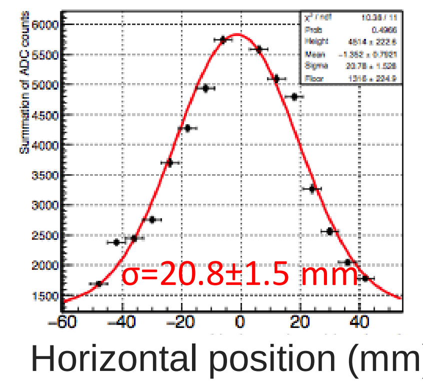
- 425 mm length, 280 mm diameter, 100 μm Al beam window
- Gas pressure is monitored by a capacitance gauge
- Gas purity is measured by Q-Mass spectrometer

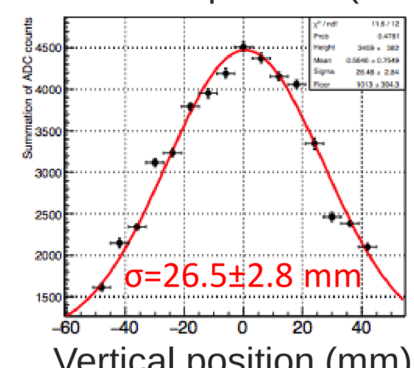
# Muon Beam Profile Monitor

Kanda, Ueno, Toyoda



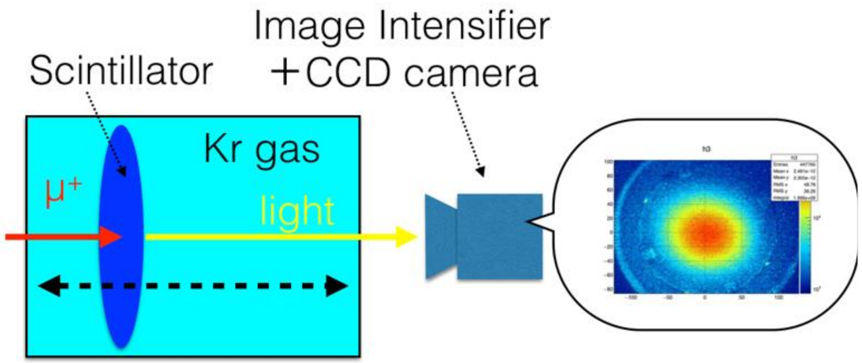

- Two layers of 100-μm fiber hodoscope (2x16ch).
- 3 x 3mm$^2$ active area MPPC with 15-μm pixel pitch.
- EASIROC readout

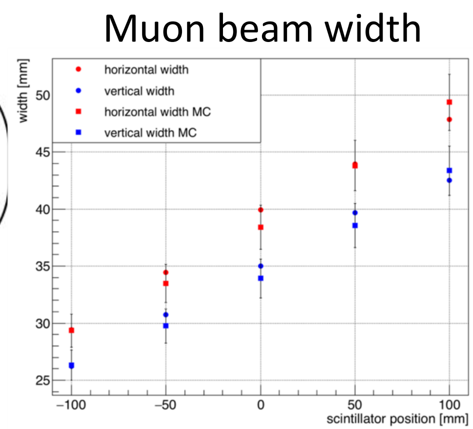


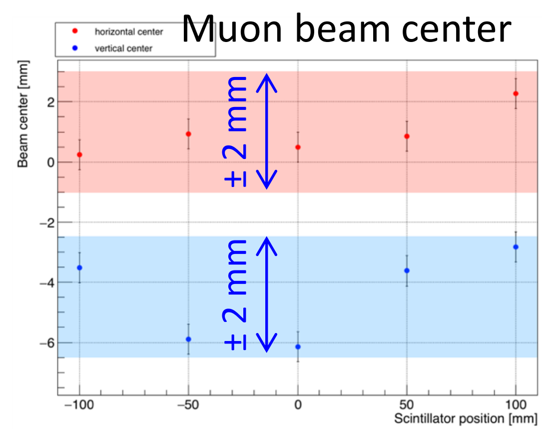



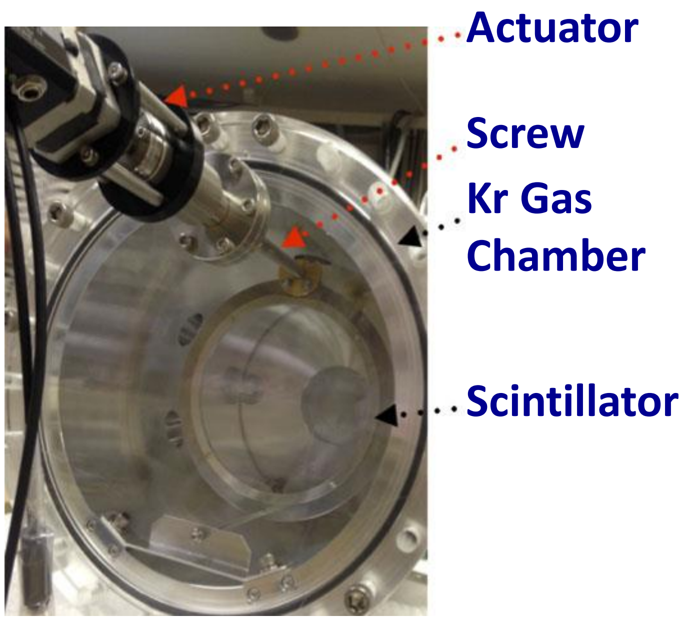
# Offline 3D Beam Profile Monitor

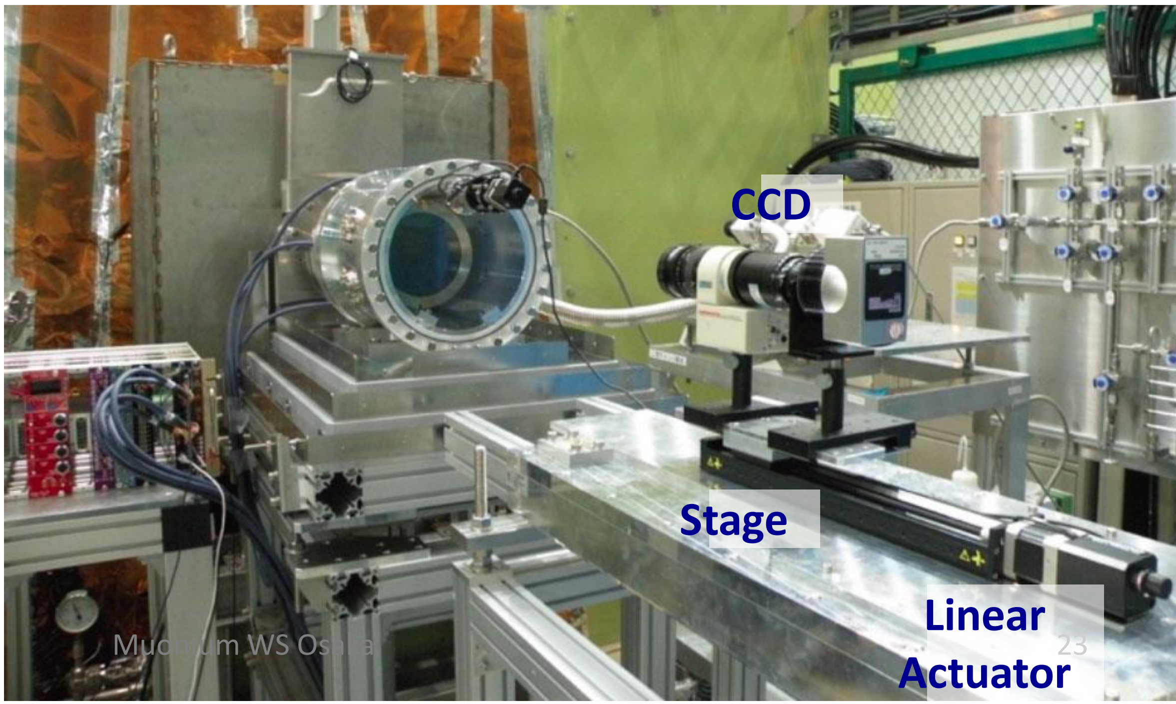
Ueno, Kanda, Toyoda, Ito



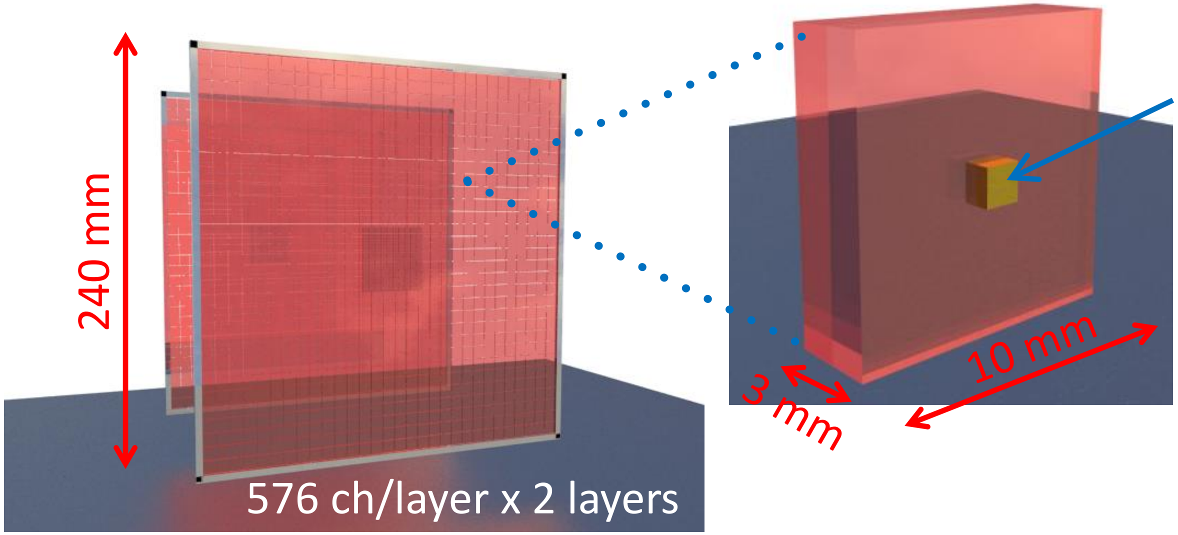



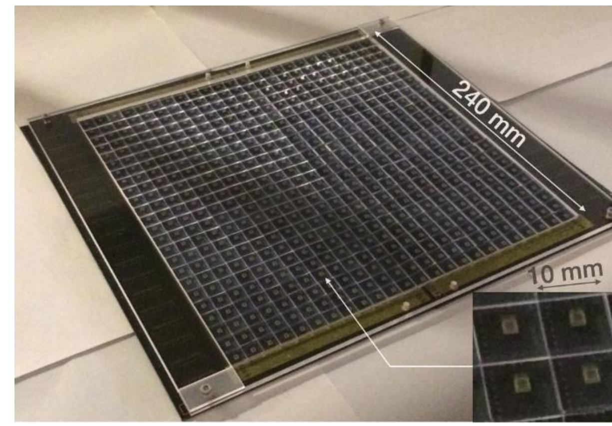



# Positron Counter (1): Scintillation Position Detector

Kanda, Kojima

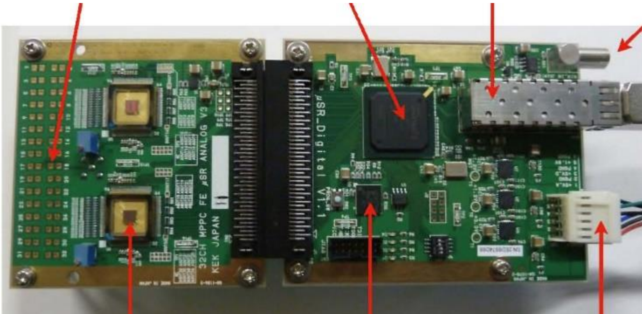



MPPC (Multi-Pixel Photon Counter)
1.3 mm x 1.3 mm active area
(Hamamatsu)




## Plastic scintillator + MPPC + Kaliope readout circuit

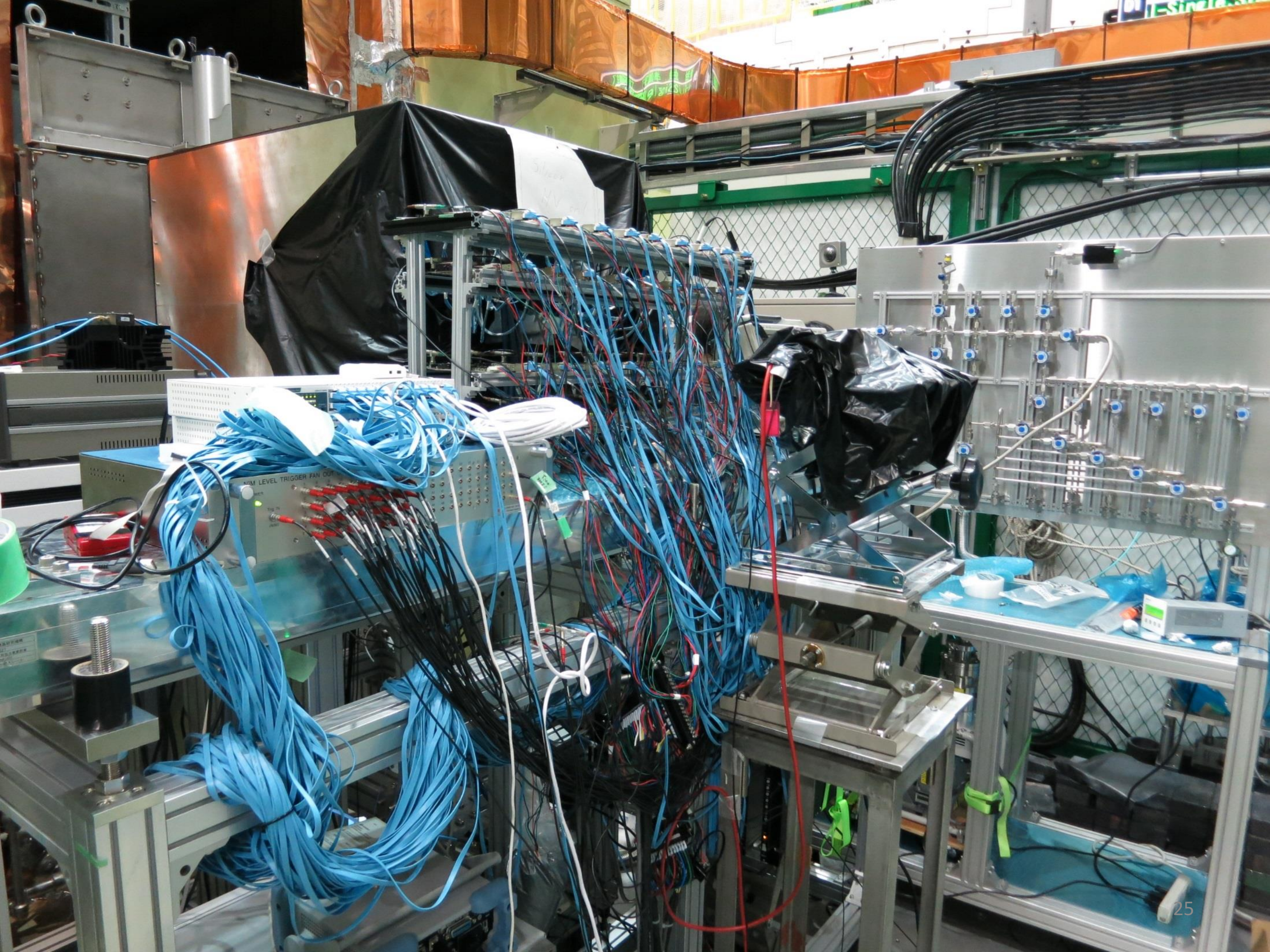
32ch MPPC input    FPGA    Ethernet    Trigger input



ASIC    PROM    +5V(A), +1.8V

**Segmented scintillation detector**

- Scintillation counter with SiPM readout
- Unit cell: 10 mm × 10 mm × 3 mm$^t$
- Area: 240 mm × 240 mm
- 24x24 segments x 2 layers = 1152 ch
- High-rate capability required
- Pileup loss at 3 MHz/ch ~ 2%


NIM LEVEL TRIGGER FAN OUT

# First Resonance Search

2016. June. 3(24h)
Beam profile measurement

2016. June. 12-14(60h)
Muonium Resonance Search

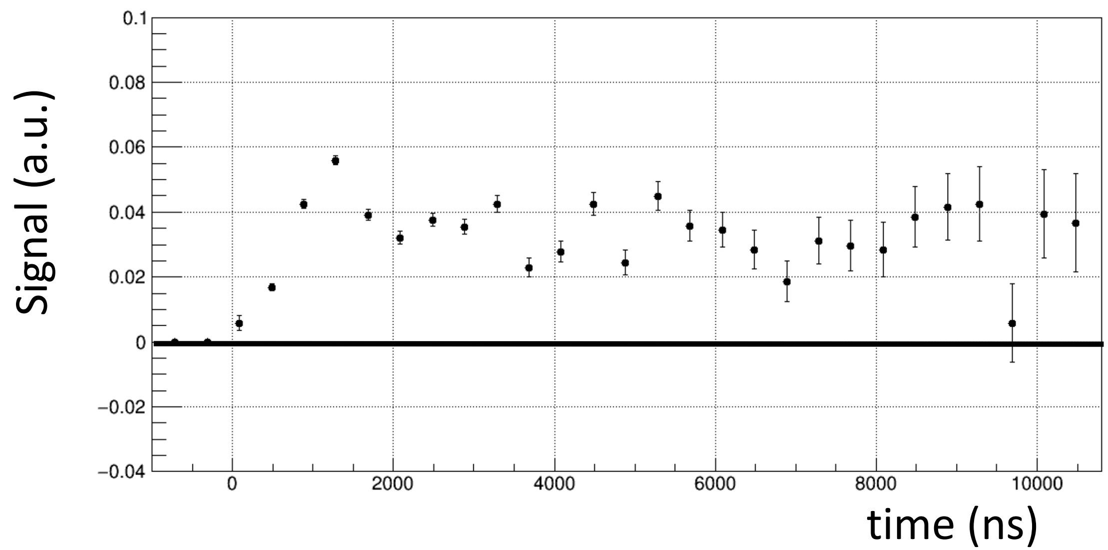
Results

1 Good zero field condition (~100nT) was obtained.
2 Beam profile was successfully measured.
3 Enough RF power and cavity Q value were obtained
4 All detectors were working properly.
5 After several trial, Muonium HFS resonances was obtained!

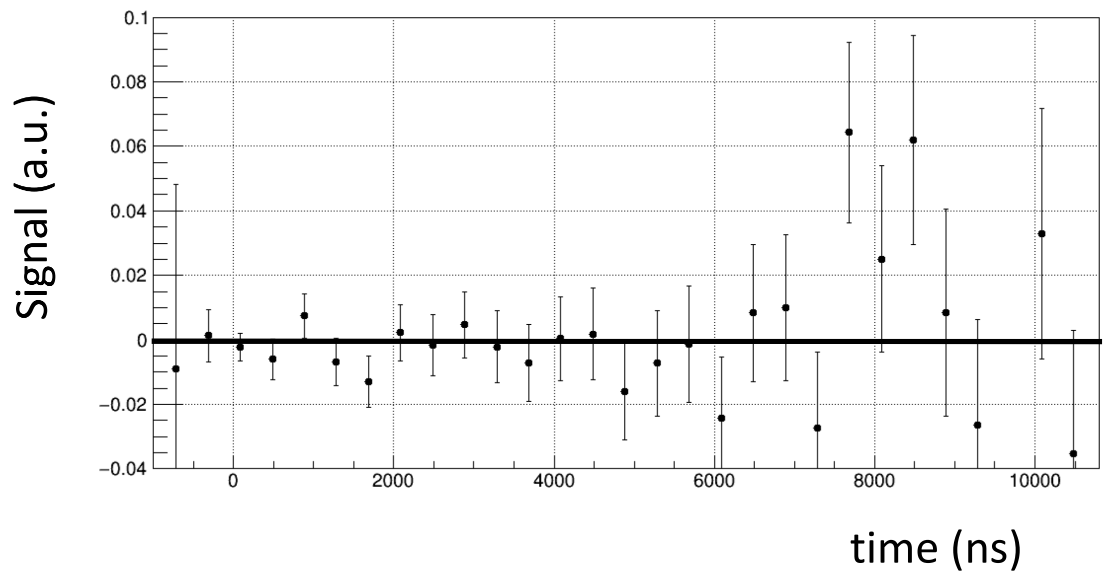
# Time Dependent Spin Flip Signal

Kanda thesis

Near at Resonance
4463.1 MHz
RF frequency
1.0 Kr atm
27.4 MeV/c muon



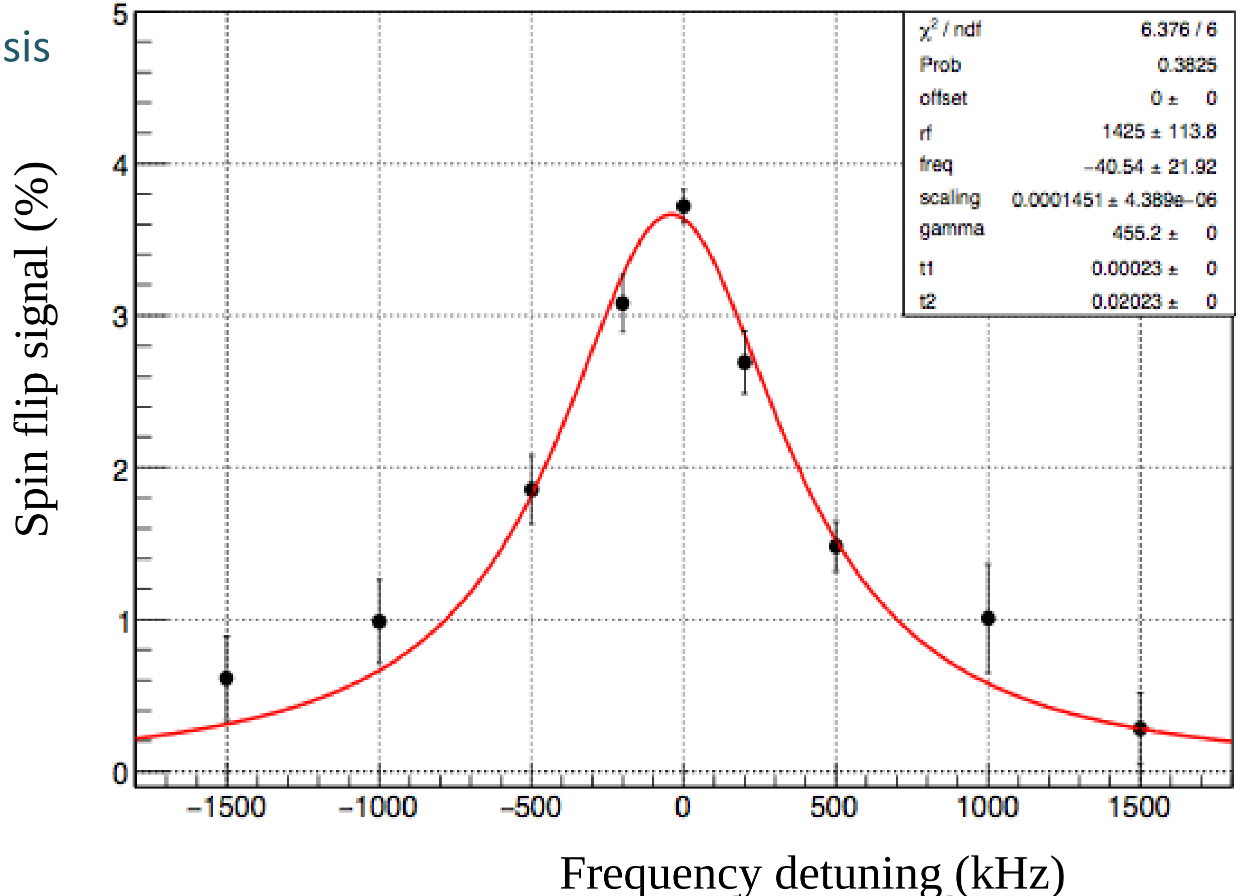

Off-Resonance
RF frequency was far detuned
1.0 Kr atm
27.4 MeV/c muon




Signal = ON/OFF-1

# Resonance Lineshape

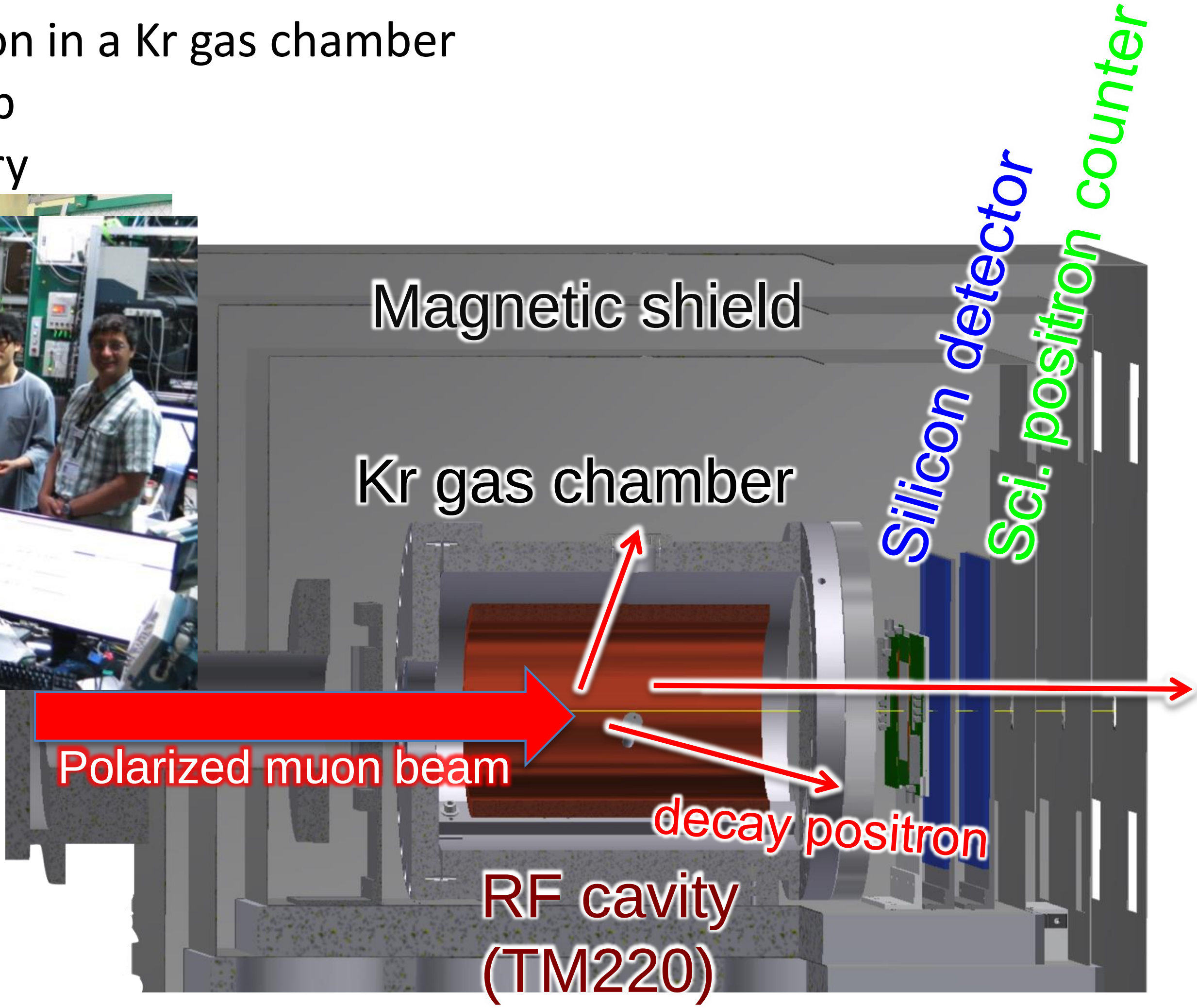
Kanda thesis




- Muonium HFS resonance was observed
- Fitted by Lorenzian and freq. center was 4463.1+-0.02 MHz
- Expectation from precursor experiments is 4463.1 MHz

# MuSEUM Zero Field Experiment

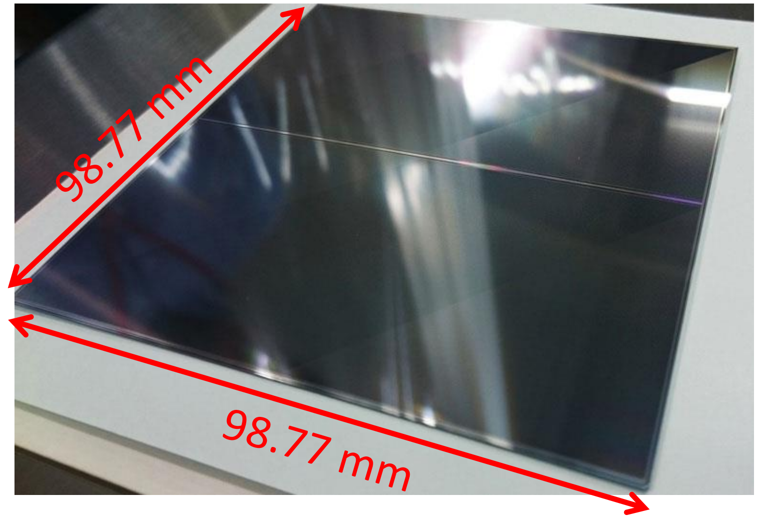
- Experimental Procedure
  - Muonium formation in a Kr gas chamber
  - Microwave spin flip
  - Positron asymmetry

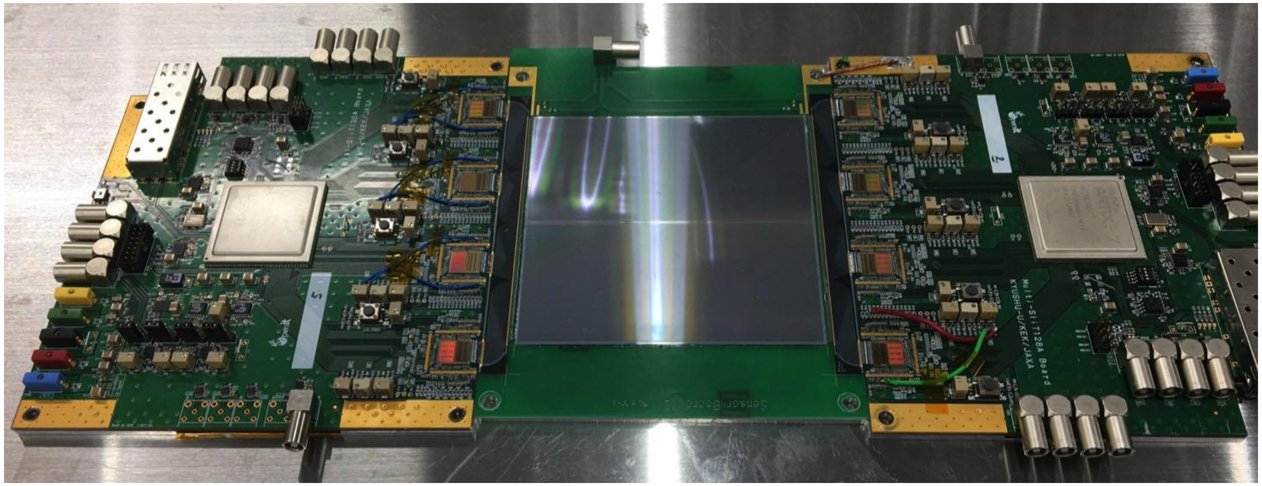


# Positron Counter (2): Silicon Strip Detector

Nishimura

| Item | Specification |
|---|---|
| Sensor type | single-sided, p+ on n |
| Size | 98.77 mm × 98.77 mm |
| Active Area | 97.28 mm × 97.28 mm |
| Strip pitch | 0.19 mm |
| Strip length | 48.575 mm |
| No. of strips | 512 x 2 blocks |
| Thickness | 0.32 mm |



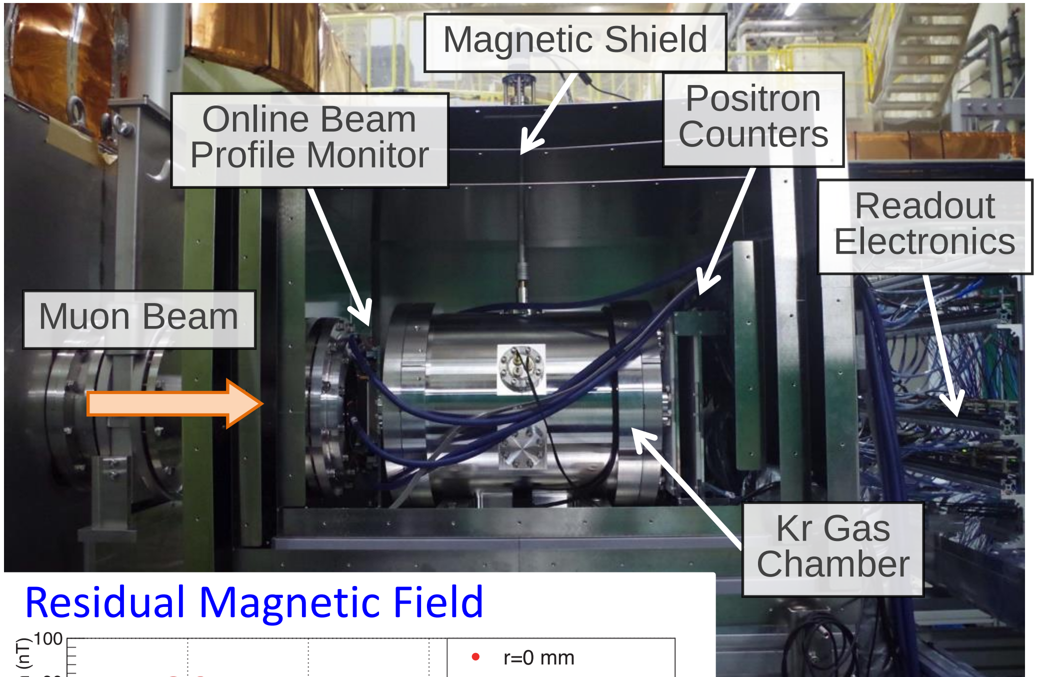



**Silicon strip detector**

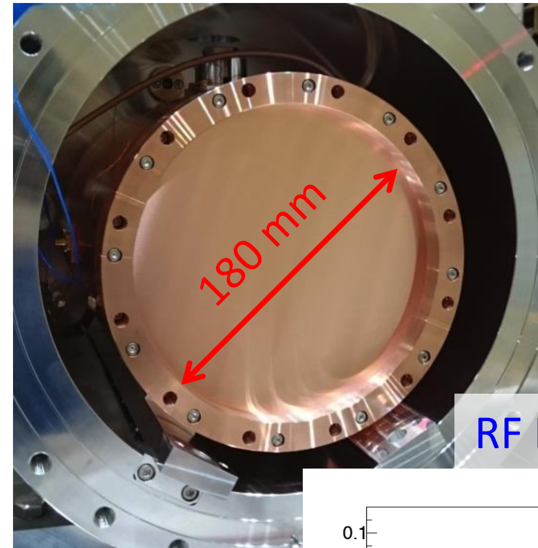
- Readout chips (SliT128A, 128 ch/chip)
- Developed for J-PARC g−2/EDM experiment
- Highly-segmented
- High-rate capability
- S/N ~ 21

# Zero Field Measurements at D-Line

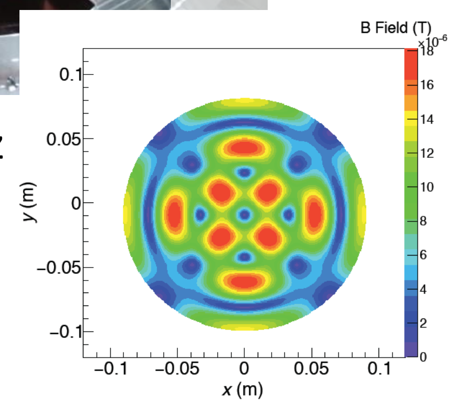
## Experimental Setup




## New RF Cavity for Zero Field



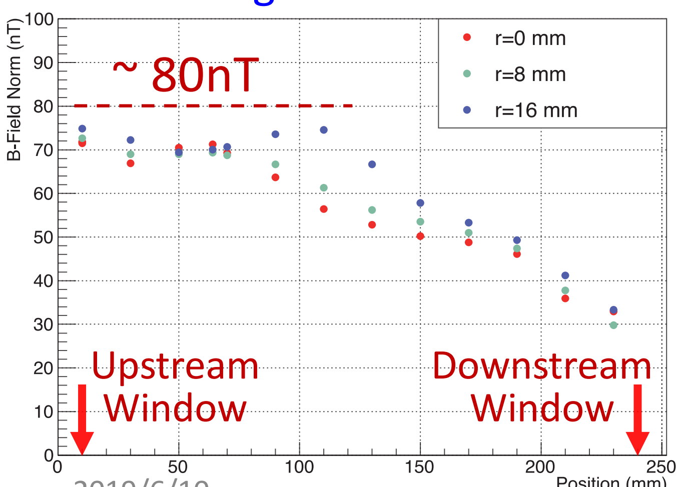

## RF Intensity

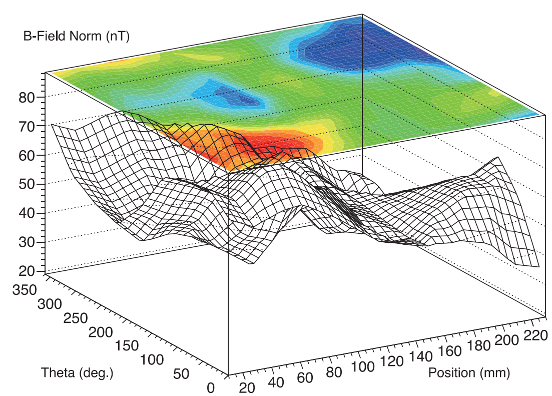



$\Delta\nu$ = 4.463 GHz

TM220 mode
Larger cavity
More muon stop
Q-Value: 20,000 (calc.)

## Residual Magnetic Field

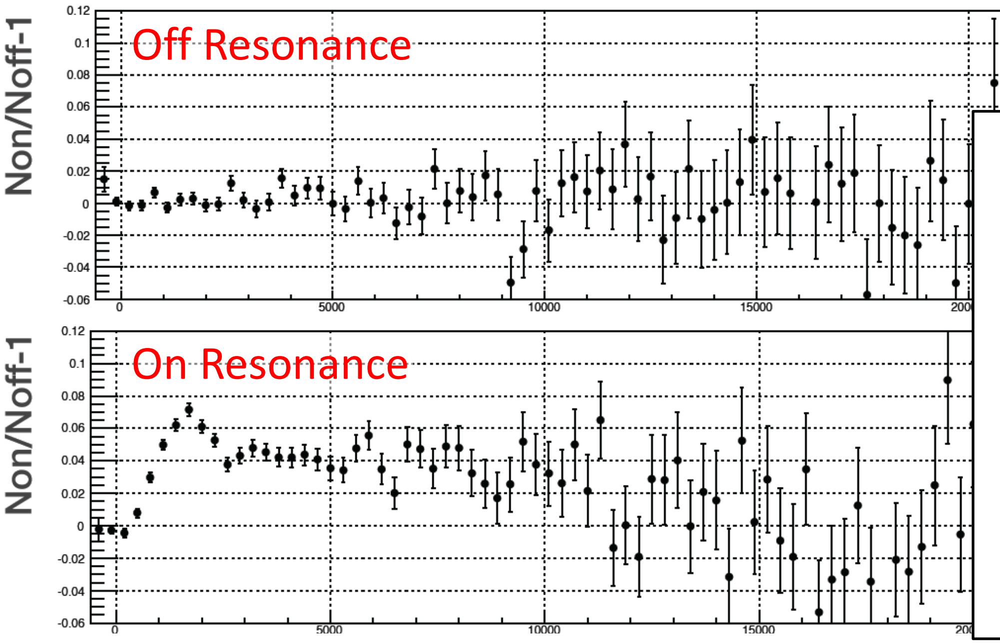


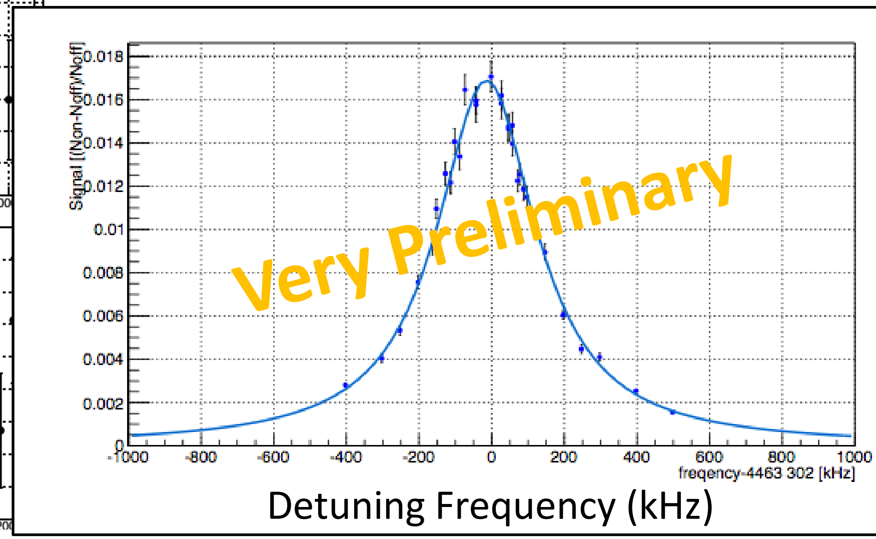
# Results (1): Time Integral Method

Conventional Method

– Scintillation Position Detector Data –




Resonance Line Shape (2018 March)




**Statistical uncertainty:**

2016 Feb. ~ 20 kHz (5ppm)

2017 Feb. ~ 4 kHz (1ppm)

2017 June ~ 2 kHz (0.5ppm)

2018 March ~ 1kHz, measured at 0.4, 0.55, 0.7 atm.

2018 June ~ 1kHz, measured at 0.3 atm Kr gas pressure.

} New world record at ZF ??? Data analysis on going

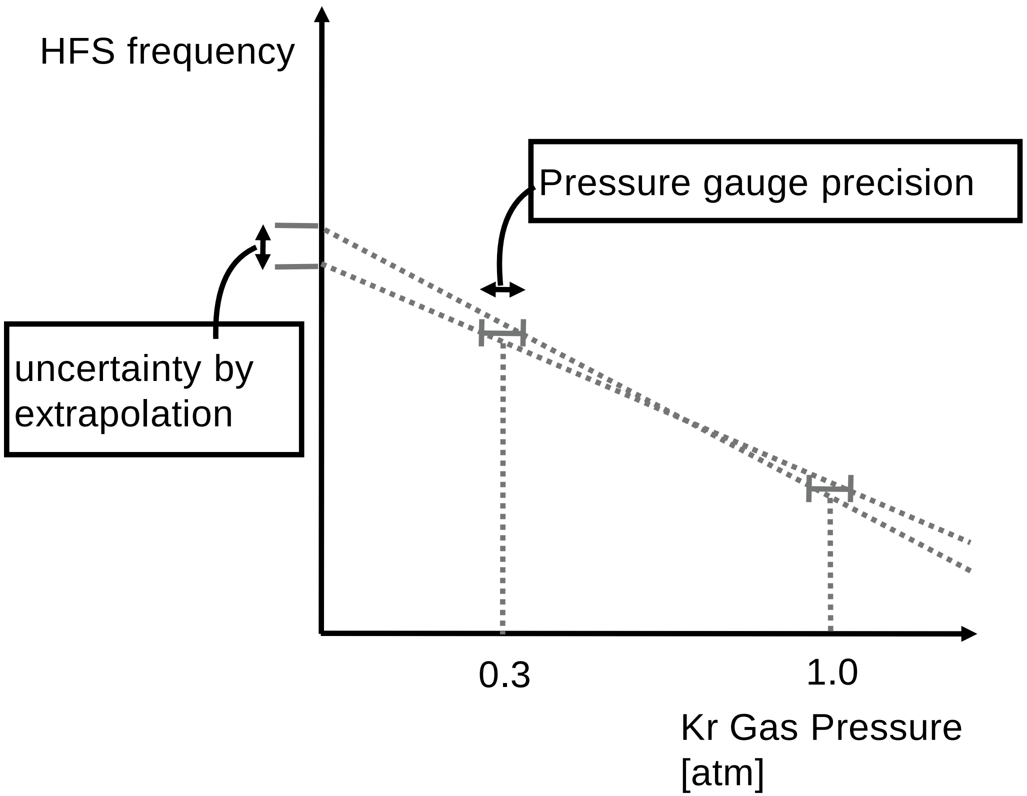
Previous ZF Experiment at LAMPF:

$\Delta\nu_{HFS} = 4\,463\,302.2 \pm 1.4$ kHz (0.3 ppm)

**Systematic uncertainty:** Estimation in progress

# Latest Experiment

- 2018 Mar 9th - 16th @ J-PARC D2-Line
- Purpose : Measure the HFS value in vacuum by extrapolation
- Measured with 0.4, 0.55 and 0.7 atm Kr gas pressure

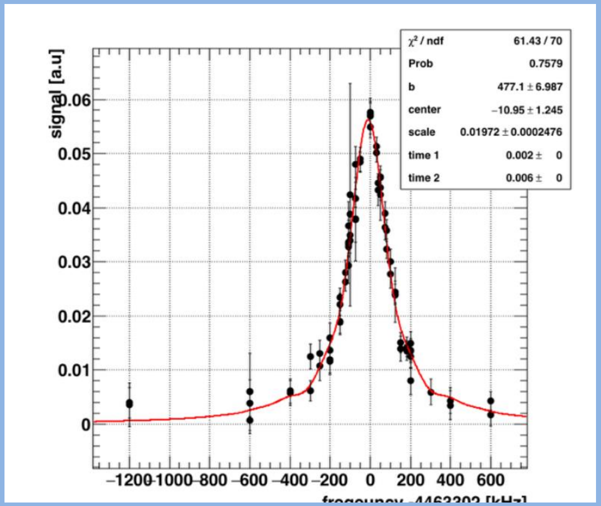



# Mu HFS Measurement in 2018

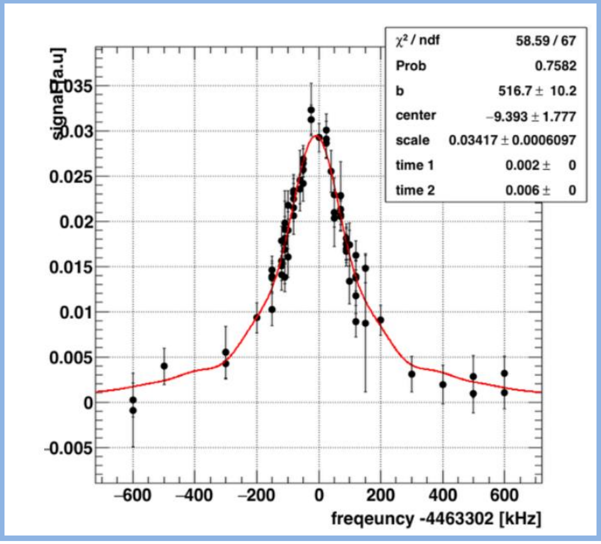
Ueno thesis

- 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, 0.4, 1.0 atm
  - Spin flip resonance signal was obtained for each gas pressure

0.4 atm



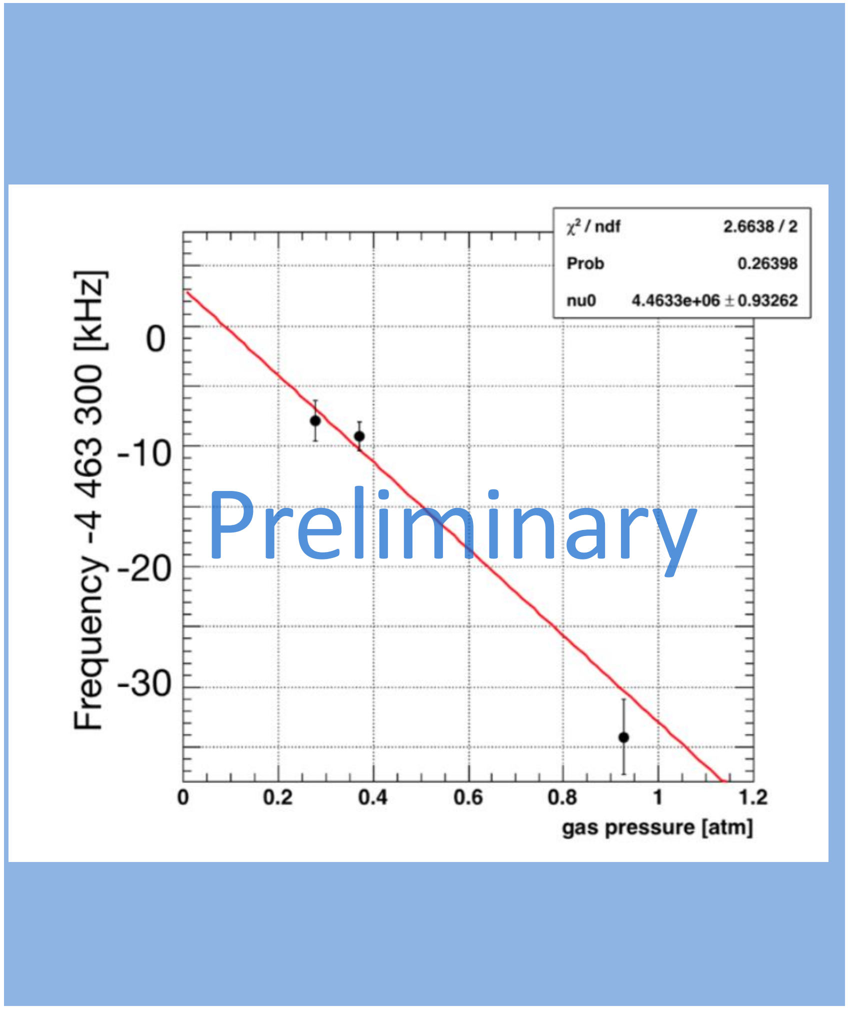

0.3 atm



# Mu HFS Measurement in 2018

Ueno thesis

- 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, 0.4,1.0 atm
  - Spin flip resonance signal was obtained for each gas pressure
- Recent analysis achieved 0.9kHz ! (Assume previous pressure )

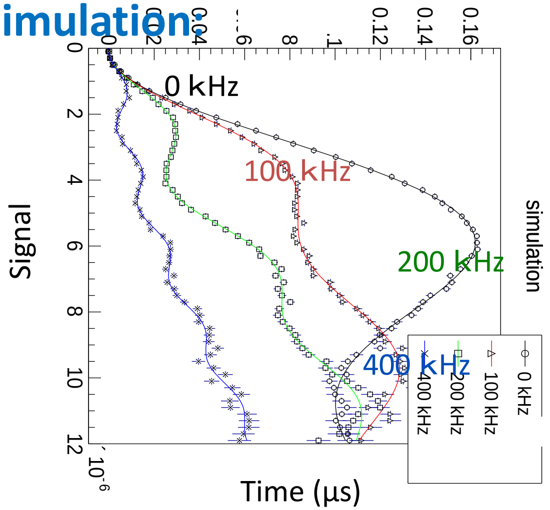


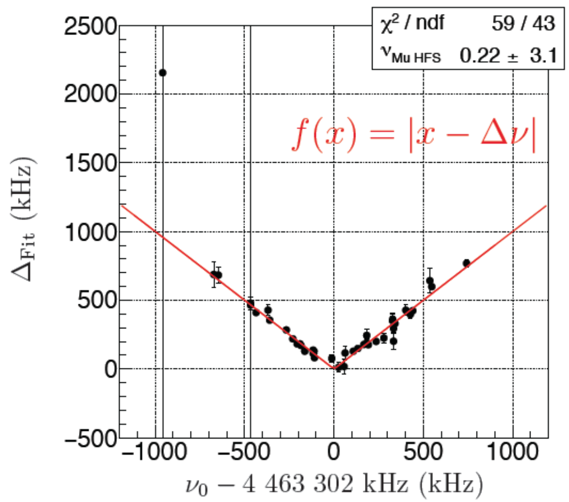
# Results (2): Time Differential Method

## – Silicon Strip Detector Data –

Nishimura thesis

**Simulation:**




**Preliminary**

$\Delta\nu_{\mathrm{HFS}} = 4\ 463\ 302.2$ kHz $\pm\ 3.1 \pm 0.2$ kHz

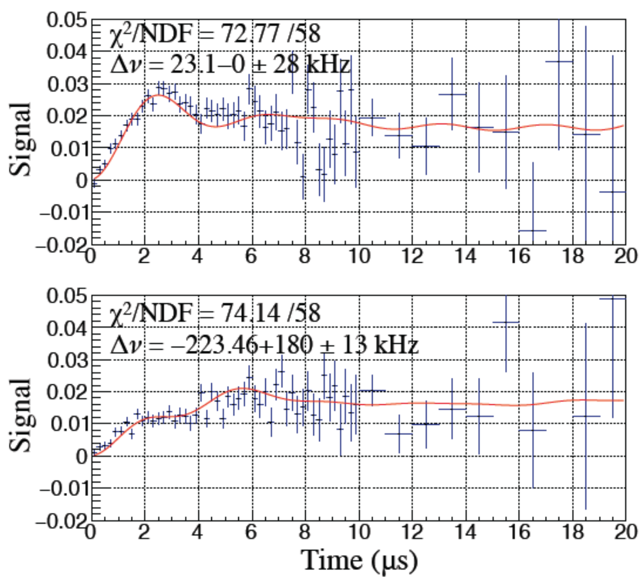
**Statistics:**

- less data (smaller detector area)

**Systematics (main):**

- RF power drift (200 Hz)
- gas pressure extrapolation (66 Hz) (only one pressure data !)

**Experiment (2017 June):**




**Possible advantages of this method:**

- Each detuning frequency data fitted individually.
- Can determine $\Delta\nu_{\mathrm{HFS}}$ 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 systematics of RF power variation (free fitting parameter).
- Need high-statistics data.

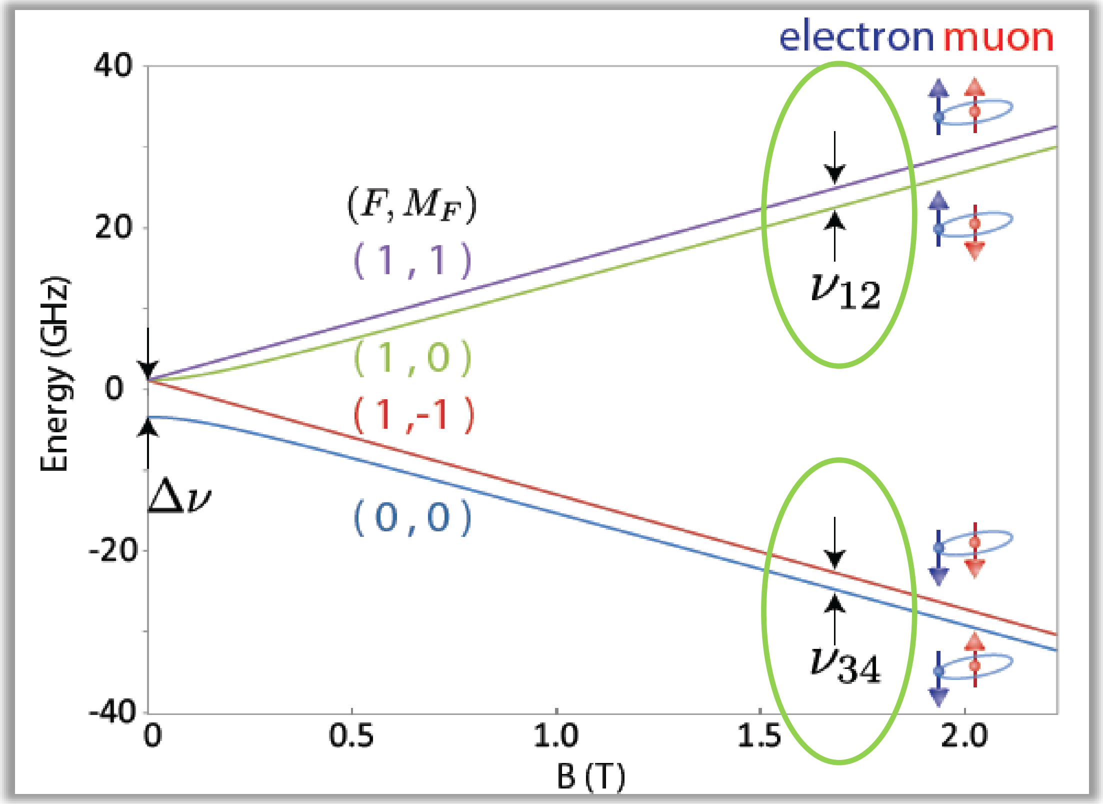
# Systematic Uncertainty

Nishimura

| 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 | 1 Hz | 1 Hz |
| Time Calibration | 1 Hz | 1 Hz |
| Total | 200 Hz | 10 Hz |

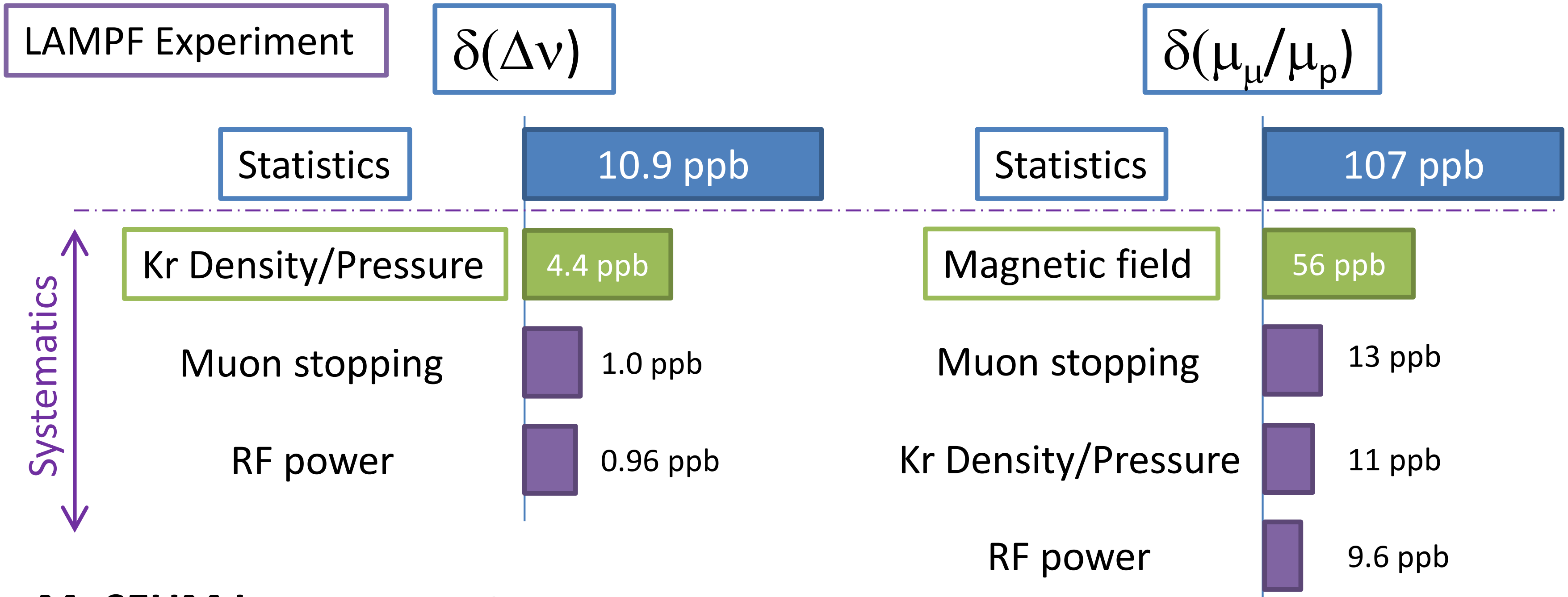
– Systematic uncertainty was much smaller than statistical uncertainty in June 2017
– Systematic can be as small as the previous experiment

# High field measurement at H Line




Two additional components are required.
・Permalloy magnetic shield
・RF cavity for ZF

# Improvement of statistics




**MuSEUM Improvements:**

Statistics:

LAMPF: DC $10^7$/s total $10^{13}$ → x200 → J-PARC/MUSE: **Pulsed 1x10⁸**/s H-Line total $2\times10^{15}$

Systematics:
- magnetic field accuracy & uniformity
- pressure dependence (longer cavity lower pressure)
- muon stopping distribution measurement
- RF power stability

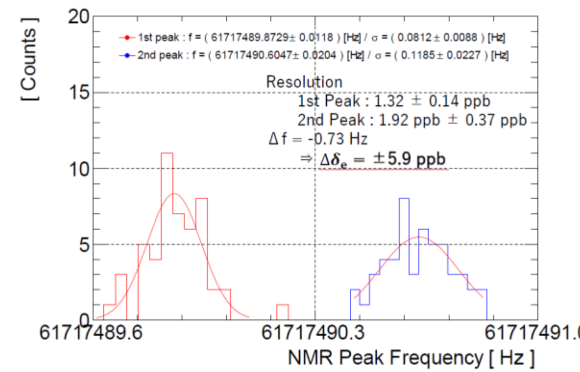
# MRI Magnet for High-Field Experiment

Sasaki, Yamaguchi , T. Tanaka

## Second-hand 2.9 T MRI magnet

## CW-NMR Field Monitoring System

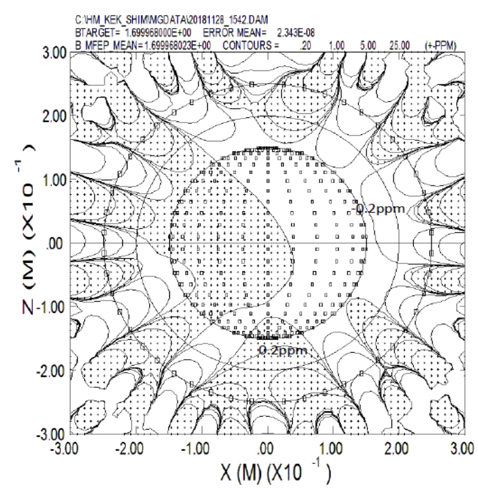
18 ppb→5.9 ppb (2017→2018)



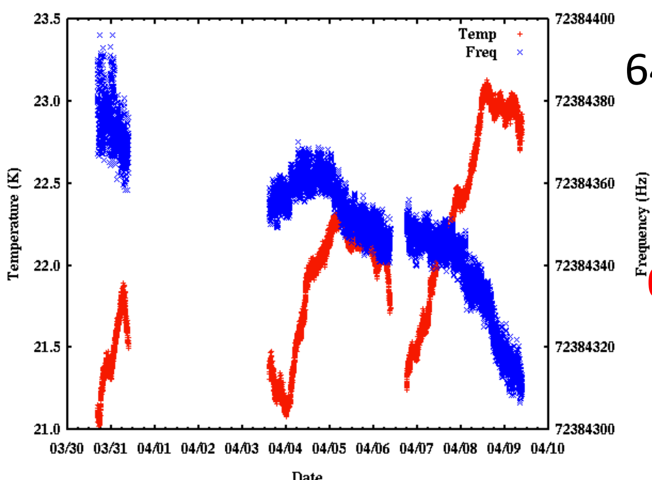

## Field Homogeneity (after shimming)

Spheroid : r=100 mm, z=300 mm

1.4 ppm p-p→0.27 ppm p-p (2017→2018)




## Long Term Stability



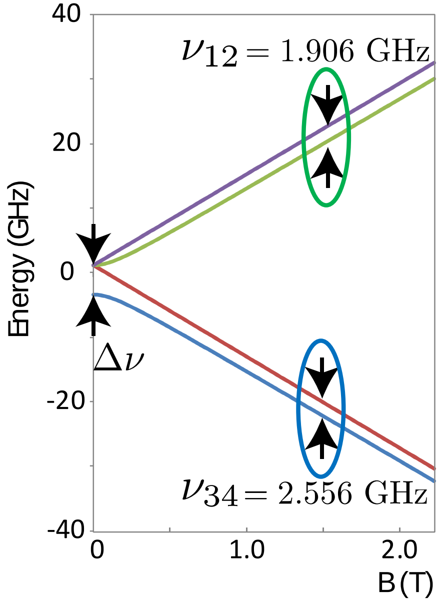

64 Hz / 9.7 days

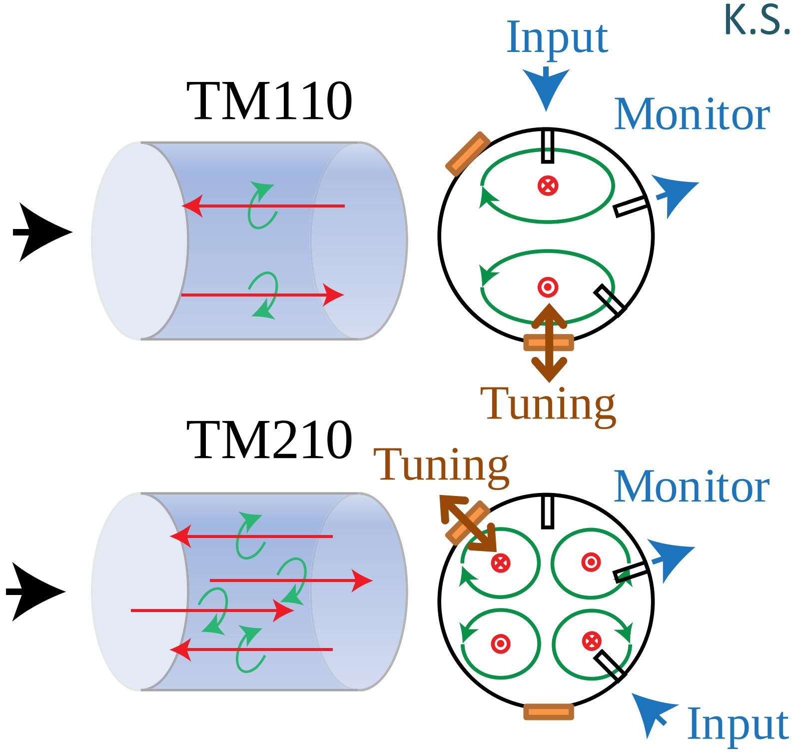
↓

0.003 ppm /h

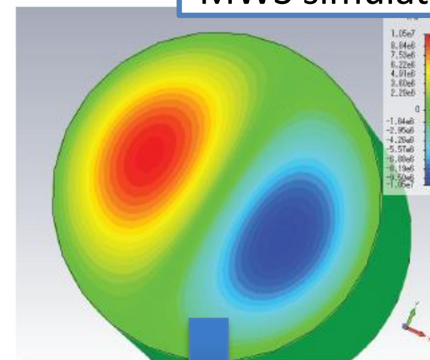
# RF Cavity for High Field Experiment

K.S. Tanaka, Seo

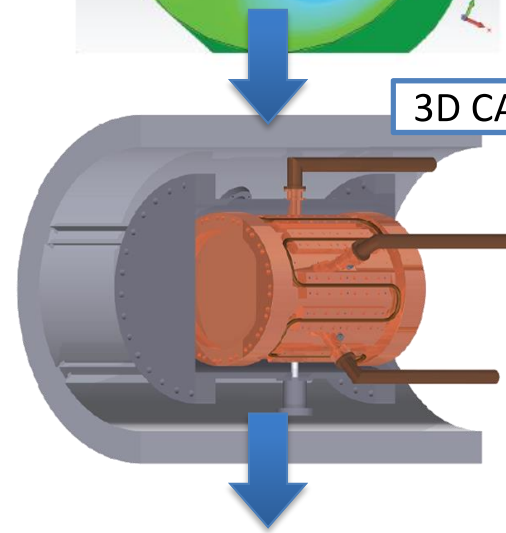


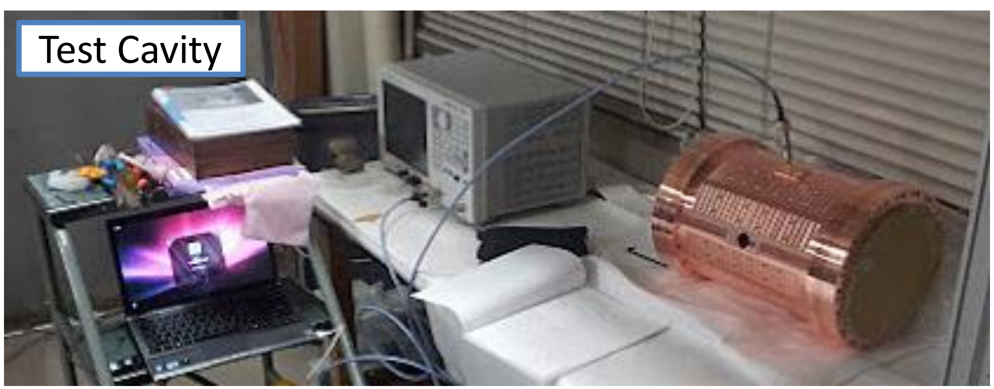

MWS simulation



3D CAD



Test Cavity



Q Value

| Modes | Q (measured) | Q (simulation) |
|---|---|---|
| TM110 | 11,300 | 29,700 |
| TM210 | 8,050 | 28,900 |

# Preliminary Systematic Error (HF)

| | Accuracy | $\nu_{12}$ and $\nu_{34}$ | $\delta(\Delta\nu_{HFS})$ | $\delta(\mu_\mu/\mu_p)$ |
|---|---|---|---|---|
| Magnetic Field* | 30 ppb | | 0.0 ppb | 15 ppb |
| RF power* | 0.2 % | 4 Hz | 0.8 ppb | 8 ppb |
| Kr gas temperature | 0.2 deg. | < 2 Hz | 0.4 ppb | 4 ppb |
| Kr gas pressure | 1 Pa | 1 Hz | 0.2 ppb | 0 ppb |
| H impurity | <50 ppm | 1 Hz | 0.5 ppb | 0 ppb |
| Quadratic dependence | | 5 Hz | 1.0 ppb | 5 ppb |
| Muonium position (x,y) | 1 mm | 3 Hz | 0.6 ppb | 6 ppb |
| Muonium position (z) | 1 mm | < 1 Hz | 0.2 ppb | 2 ppb |
| Beamline | 10(e-4) | < 1 Hz | 0.2 ppb | 2 ppb |
| Detector pile-up | w/ absorber | 0.3 Hz | < 0.1 ppb | < 1 ppb |

*should be re-estimated by latest progress and further MC simulation.

*should be re-estimated by latest progress of Time differential method.

Total systematic error of $\Delta\nu_{HFS}$~2 ppb, and $\mu_\mu/\mu_p$ ~ 20 ppb

# Plan for Measurement

FY2020 Zero Field Measurement H line
50 days？ Less than 12ppb uncertainty

FY2021 High Field Measurement at H line (1.7T)
50 days 50 times statics

FY2022 High Field Measurement at H line (1.13T)
50 days 50 times statics
（magic field, rectangular cavity）

FY2023 High Field Measurement at H line (3T)
50 days 50 times statics
（Better condition for $\mu_\mu$ determination, rectangular cavity）

# Summary and Next Step

- Zero-field measurements at existing beamline (D-Line) in progress for engineering run of the apparatus.
  - ➢ Muonium HFS resonance clearly observed !
  - ➢ Soon new world record at zero field ! (data analysis in progress)
  - ➢ Several Analysis Methods are in progress (Old Muonium, Time differential)
  - ➢ Time-Differential Method promising to improve statistics and reduce RF power fluctuation systematics.
  - ➢ Need improvement of the RF power stability (systematics) !!!
  - ➢ 4 Doctor thesis 5 Master thesis
- New Precise muonium HFS measurements at high magnetic field will be carried out in a few years (H-Line).

- Present expected systematic error estimated as

| | | |
|---|---|---|
| HFS | ~ 2 ppb (~8Hz) | *preliminary* |
| Magnetic moment ($\mu_\mu/\mu_p$) | ~ 20 ppb | |

**Stay tuned !**

# Backup Slides

# Time Integral Method

- Signal of all positrons

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

Δω / Detuning angular frequency

|b| / Microwave magnetic field intensity

λ / Spin relaxation rate

γ / Muon decay rate

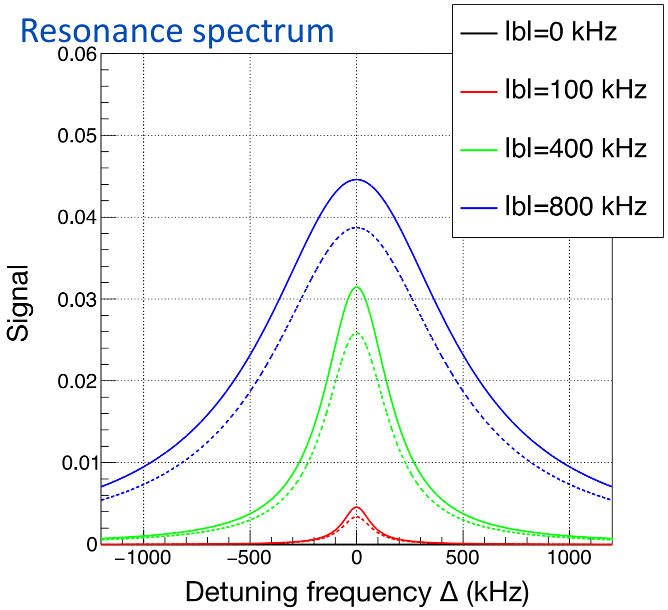
P / Muon spin polarization

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

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

Resonance spectrum



# Time Differential Method

## Time dependence of signal

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

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

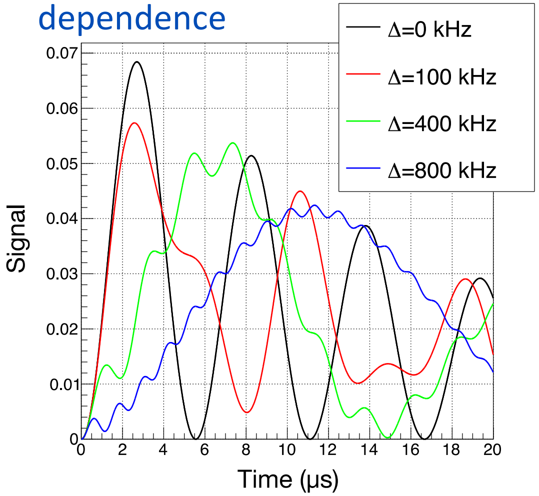
$$G_\pm = \frac{\Gamma \pm \Delta\omega}{2} \qquad \Gamma = \sqrt{\Delta\omega^2 + 8\left|b\right|^2}$$

Time spectrum |

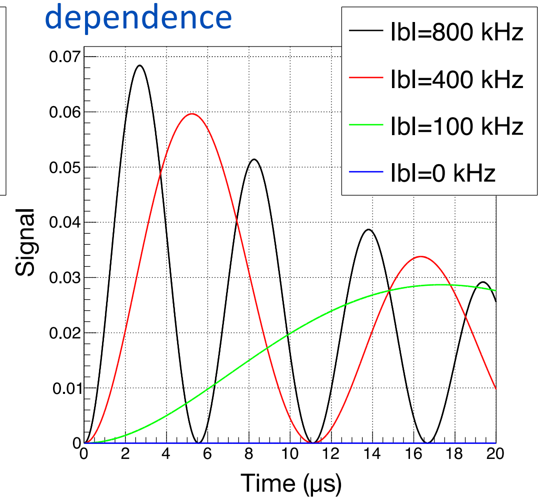
Summation of cos

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

Detuning frequency dependence

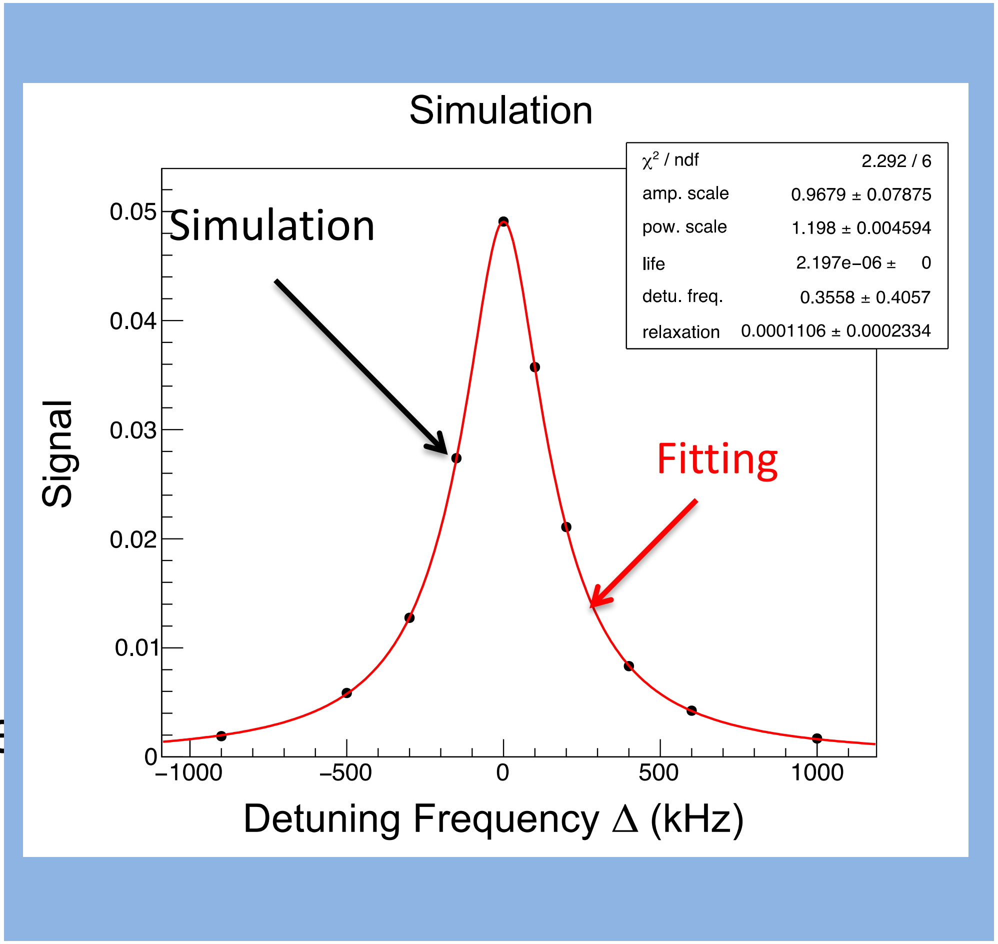



Microwave power dependence

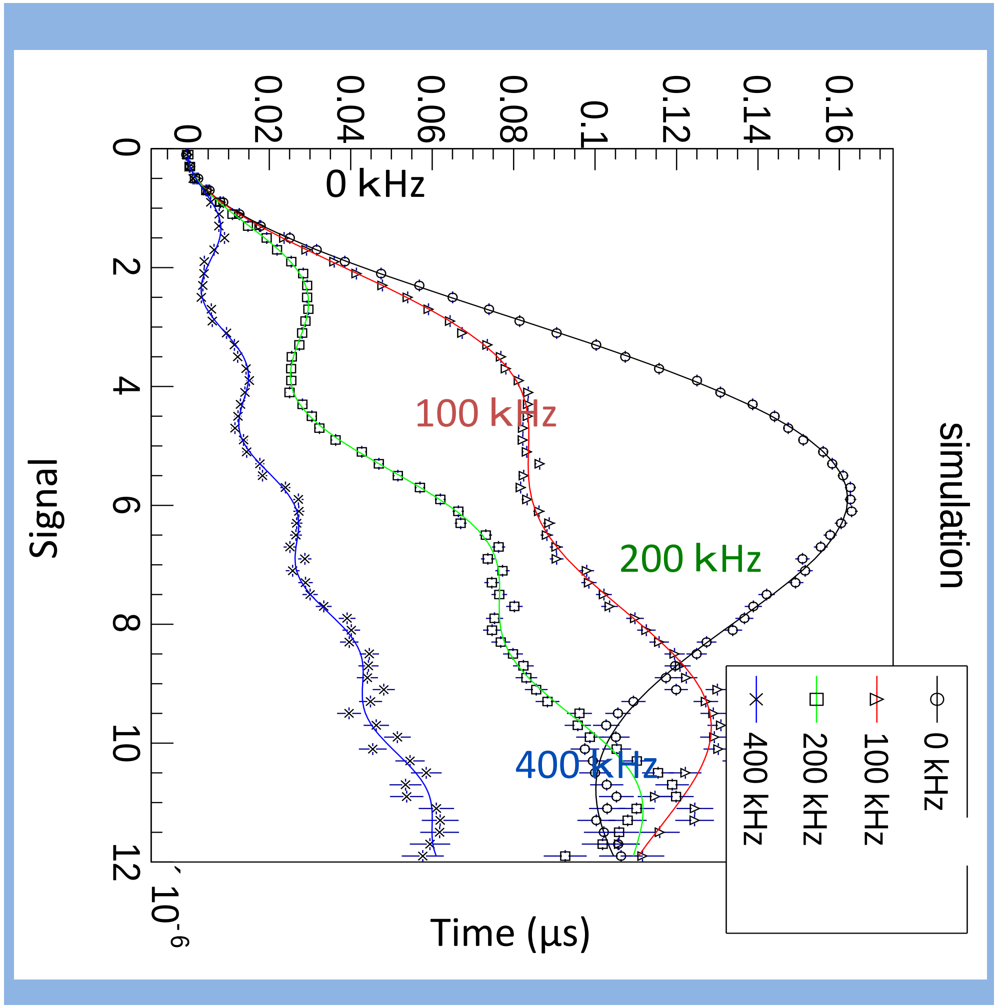


# Time Integral Signal (Simulation)

- Simulation setup
  - Measurement point | 10 points
  - $7.8 \times 10^{10}$ muon/point
- Fitting function for Time integral method
  - Summation of Lorentzian function considering microwave power distribution felt by muonium



# Time Differential Signal (Simulation)

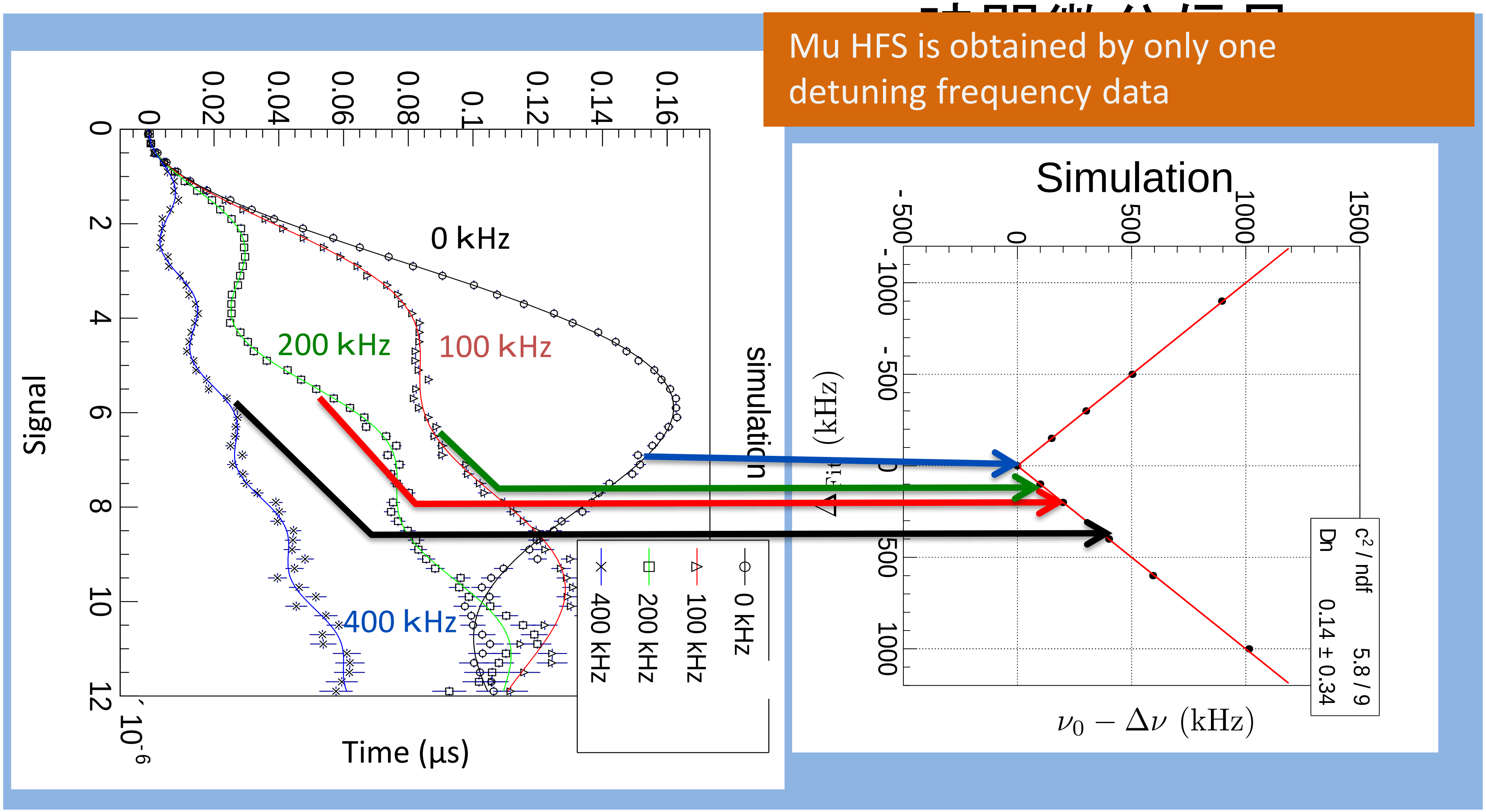



- Time differential signal | Same statistics as time integral method
- Time spectrum are changed by the detuning frequency

- 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



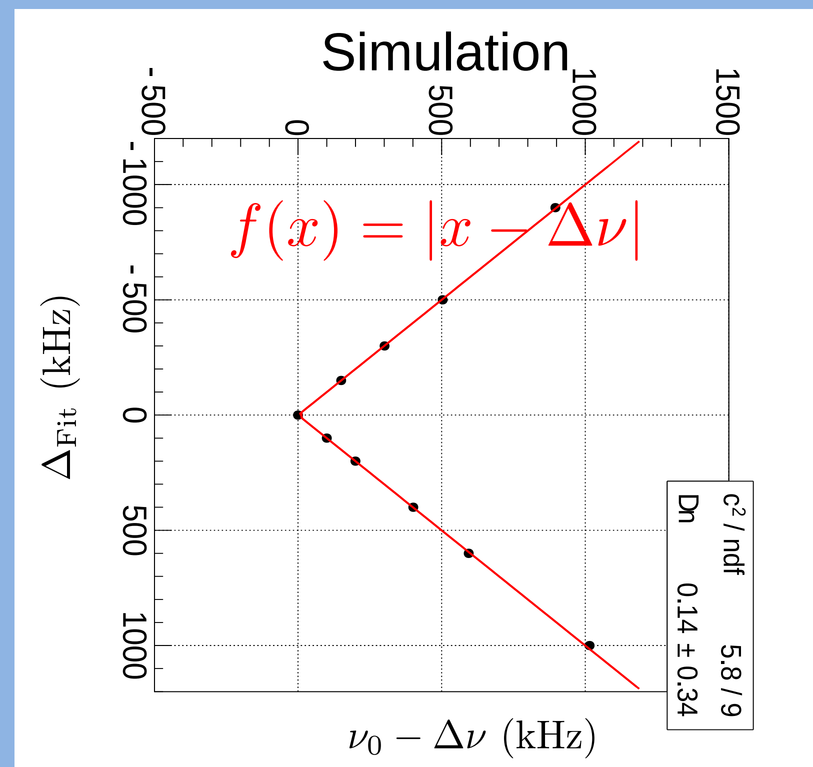
# Multiple Time Differential Data

- 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

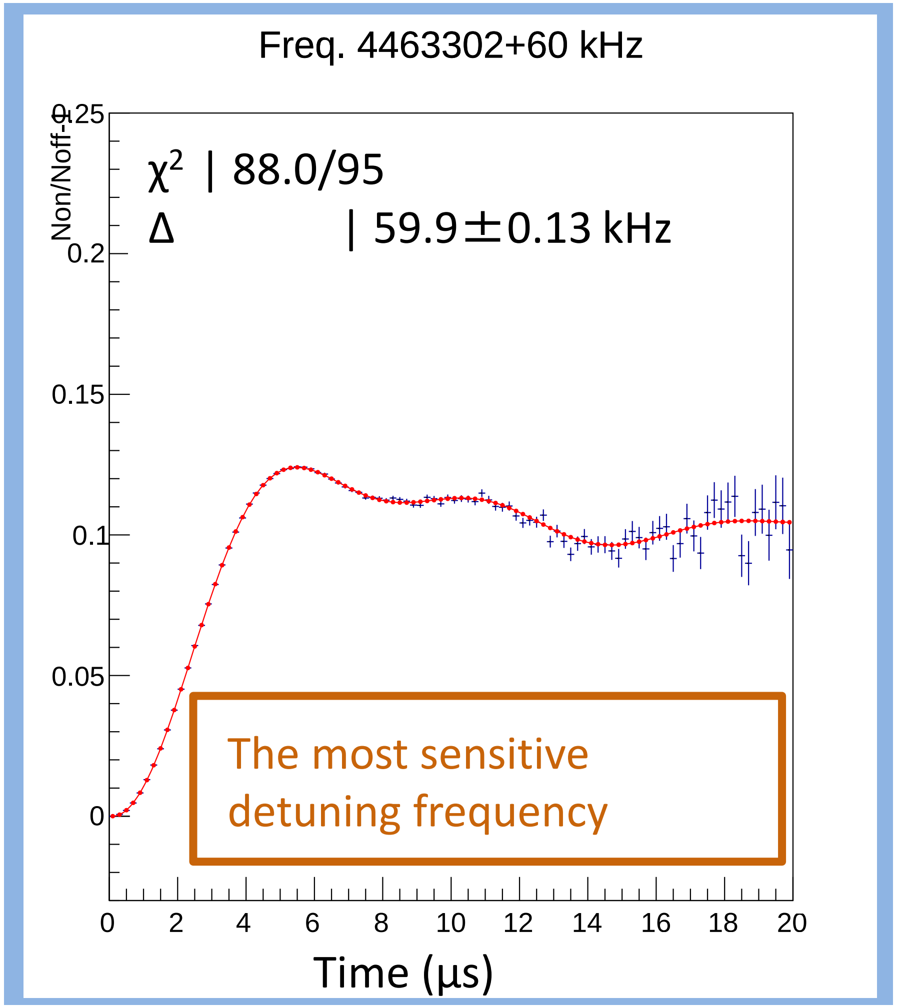
↓

Time Differential Method
| 0.34 kHz

↓

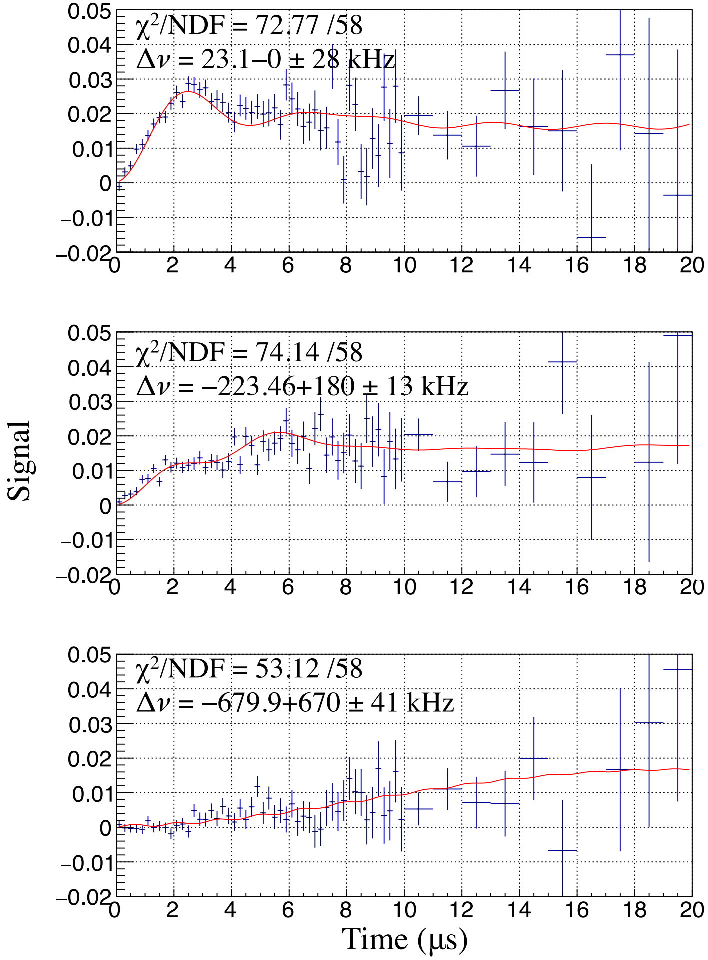
Time differential Method
(Concentrate on Δ=60 kHz)
| 0.13 kHz

3.2 times improvement compared to the time integral method



# Analysis by the Time Differential Method (2017)

- 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



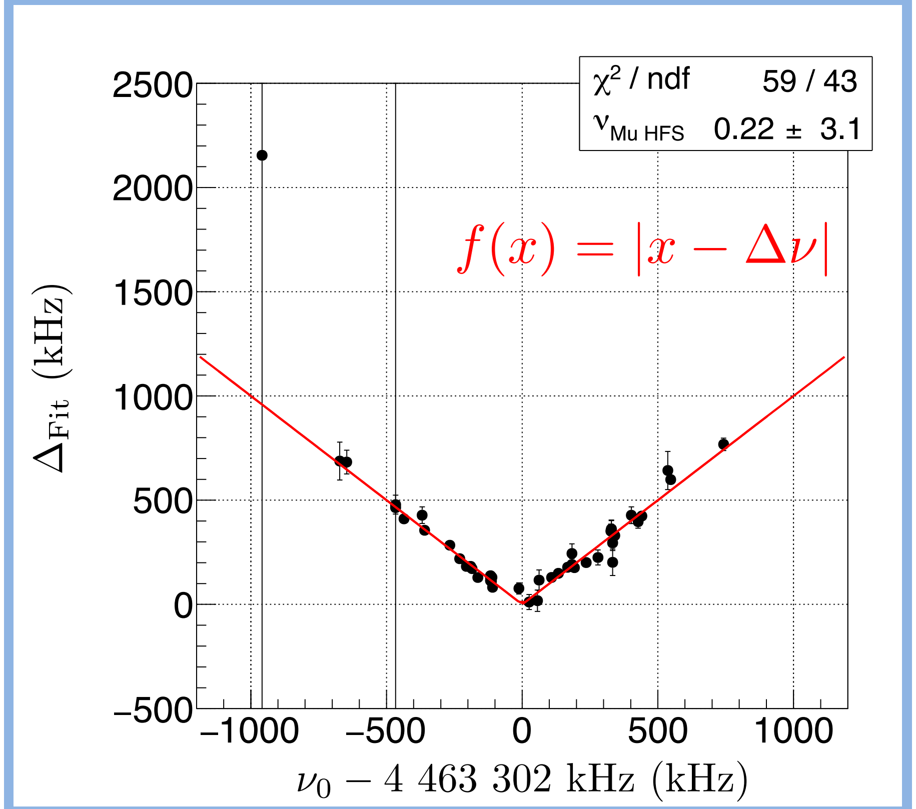
# Mu HFS Measurement (2017)

- Mu HFS was obtained from multiple data
  - Obtained $\Delta\nu_{Mu}$

4 463 302.2 ± 3.1 kHz

  - It is consistent to the previous experiments

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

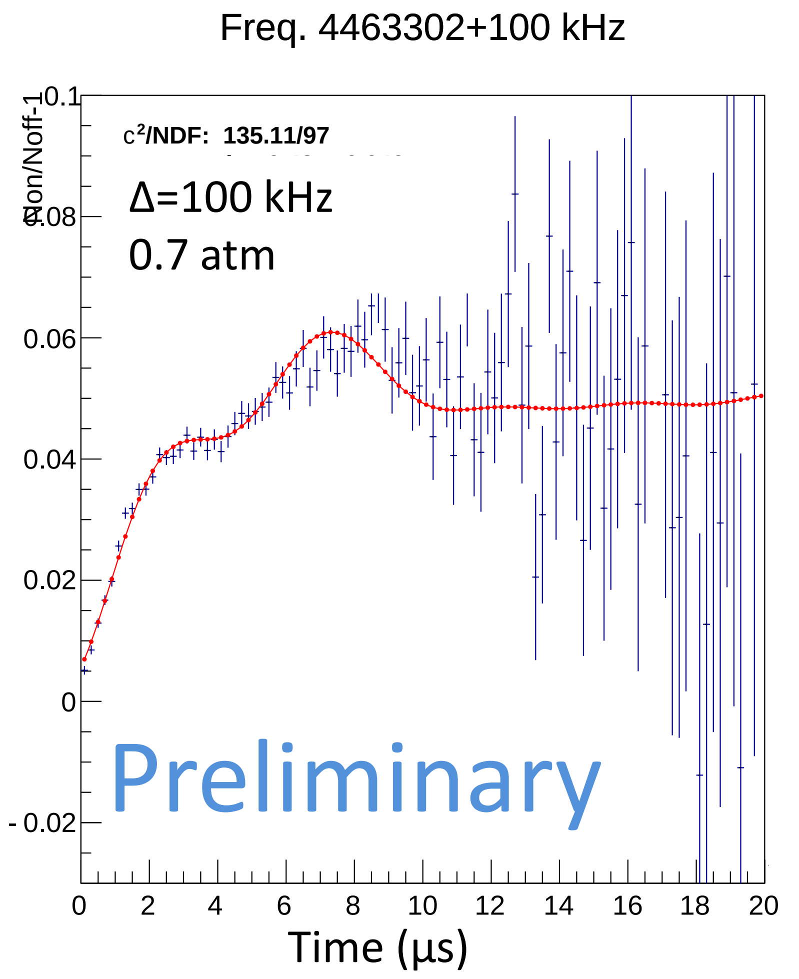



Phys. Lett. B59 (1975) 397-400， Phys. Rev. Lett. 82 (1999) 711-714

# Mu HFS Measurement in 2018

Nishimura

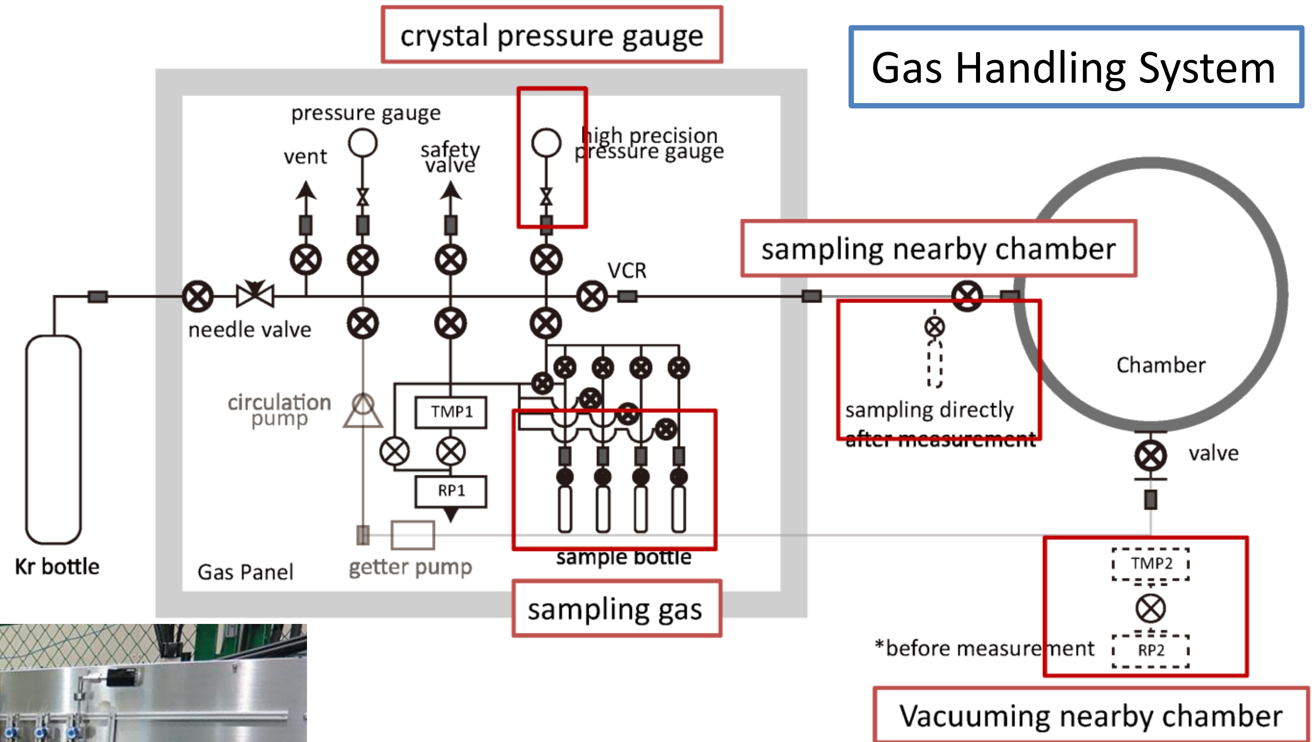
- Kr gas pressure shift
  - Resonance frequency is shifted due to collision of muonium & the Kr atom
  - Gas pressure in the experiment in 2018 | 0.3, 0.4, 0.7 atm
  - Spin flip resonance signal was obtained for each gas pressure
- Analysis is ongoing

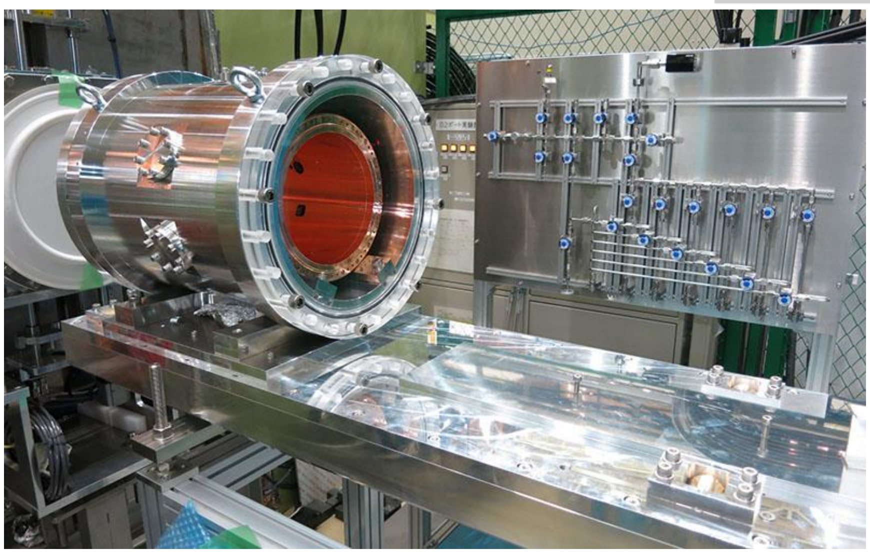


## Precision of the hyperfine structure (HFS, $\Delta\nu$):

| Hydrogen-like atom | Experiment | Theory | $(\Delta\nu_{theo} - \Delta\nu_{exp})/\Delta\nu_{exp}$ |
|---|---|---|---|
| Hydrogen | 0.2 ppt | 1.2 ppm | (-0.45 ± 1.2) ppm |
| Positronium | 3.3 ppm | 2.0 ppm | (15 ± 4) ppm |
| Muonium (Zero-Field) | 310 ppb | 61 ppb | (150 ± 320) ppb |
| Muonium (High-Field) | 12 ppb | 61 ppb | (23 ± 62) ppb |

# RF Cavity & Gas Chamber

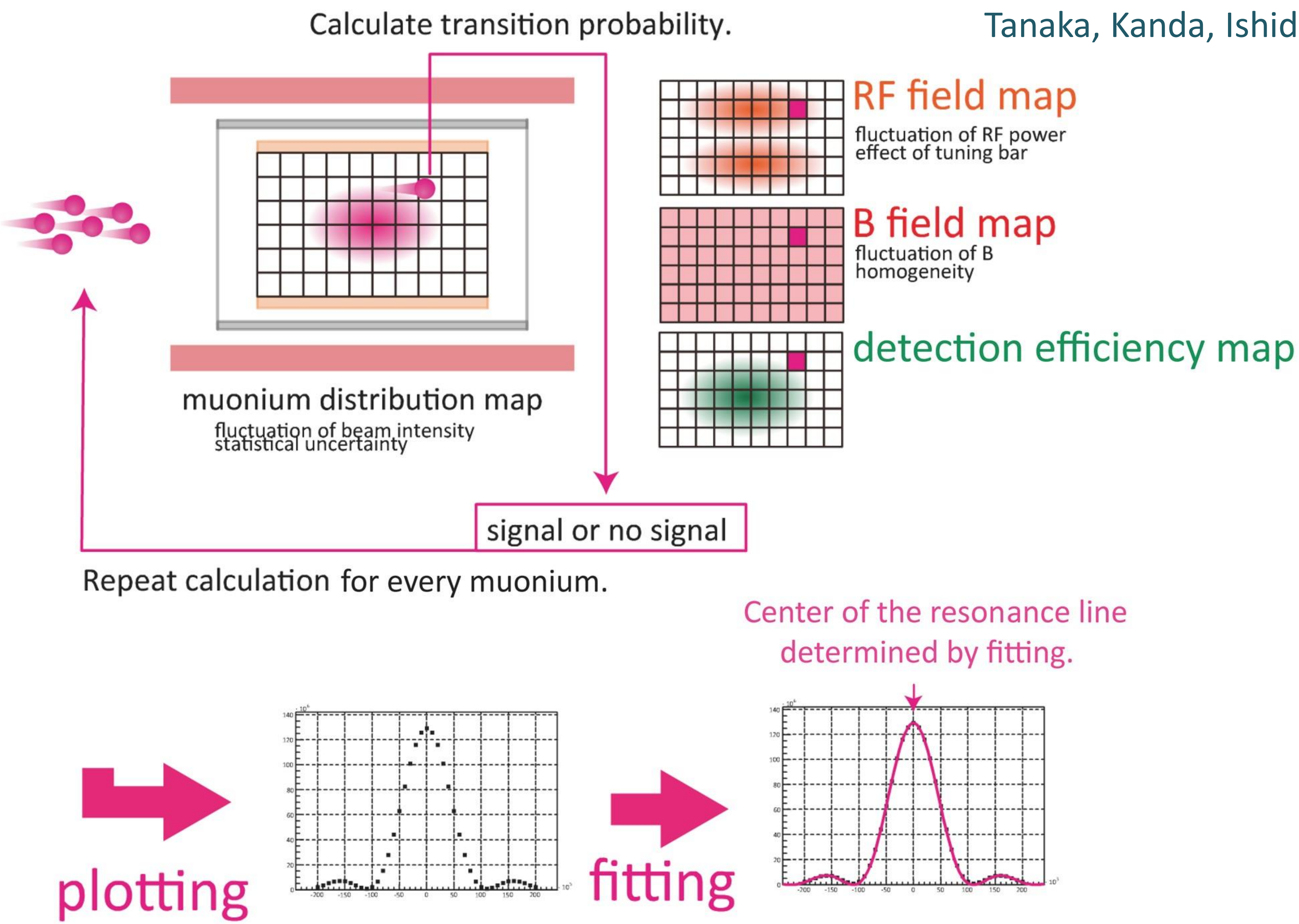


- Pressure: 0.5 – 1.5 atm
- Readout precision: several ppm (crystal gauge: 0.008% of full range)
- Contamination: below 1ppm.
- gas sampling before, during and after the experiment (several weeks).

# Systematic Error

Tanaka, Kanda, Ishida



# Old Muonium in ZF field