High precision measurement of muonium hyperfine structure

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MuSEUM

東京大学
THE UNIVERSITY OF TOKYO

RIKEN

Outline

- Introduction
  - About muonium hyperfine structure
  - Related physics
  - Roadmap of MuSEUM experiment

- ZF Experiment
  - Experimental setup
  - Status of the ZF experiment

- Developments of HF experiment
  - R&D status of the superconducting magnet
  - R&D status of the NMR probe

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MuSEUM collaboration

Muonium **S**pectroscopy **E**xperiment **U**sing **M**icrowave

@ J-PARC MLF

Y. Fukao, Y. Ikedo, T.Ito, R. Kadono, N. Kawamura,
A.Koda, K. M. Kojima, T. Mibe, Y. Miyake,
K. Nagamine, T. Ogitsu, N. Saito,
K. Sasaki, Y. Sato K. Shimomura, P. Strasser,
A. Toyoda, K. Ueno, H. Yamaguchi,
T. Yamazaki, A. Yamamoto, M. Yoshida

K. Ishida,
M. Iwasaki,
O. Kamigaito,
S. Kanda

Y. Higashi, T. Higuchi, Y. Matsuda, T. Mizutani,
S. Nishimura, S. Seo, M. Tajima, T. Tanaka,
H. A. Torii, Y. Ueno, D. Yagi, H. Yasuda

H.M Shimizu
M. Kitaguchi

K. Kawagoe, J.Tojo, T. Yoshioka, T. Suehara
T. Yamanaka, M. Matama, T. Ito, Y. Tsutsumi

K. S. Tanaka

M. Aoki,
D. Tomono

E. Torikai

D. Kawall

K. Kubo

H. Iinuma

S. Choi

Goals of MuSEUM collaboration

- **High precision measurement of muonium hyperfine structure (MuHFS) in Zero field & High field**

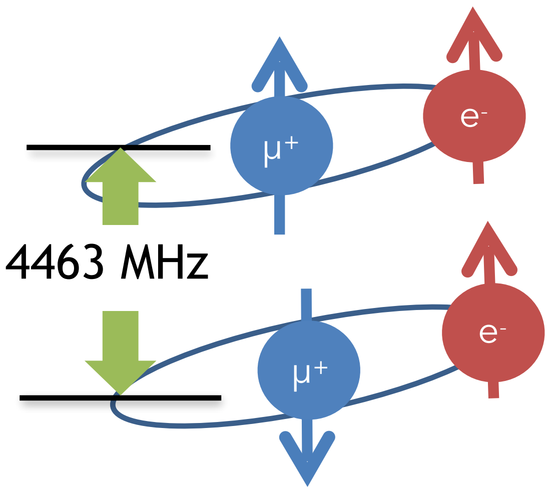
- Stringent test of bound state QED by comparing to the theoretical calculation

$$\Delta\nu_{\mathrm{HFS}}(theo) = 4\ 463\ 302\ 891(272)\mathrm{Hz}\ (63\mathrm{ppb})$$

D. Nomura and T. Teubner, Nucl. Phys. B **867**, 236 (2013).

$$\Delta\nu_{\mathrm{HFS}}(exp) = 4\ 463\ 302\ 765(53)\mathrm{Hz}\ (12\mathrm{ppb})$$

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



- Relative uncertainty of 1.7 T measurement at LAMPF
  MuHFS (ZF) : 300ppb
  MuHFS (HF) : 12ppb, μ_μ / μ_p and m_μ / m_e :120ppb

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

- MuSEUM's goal : Improve the precision by a factor of 10

MuHFS measurement with HF

- Hamiltonian describing energy splitting of the muonium $1^2S_{1/2}$ state

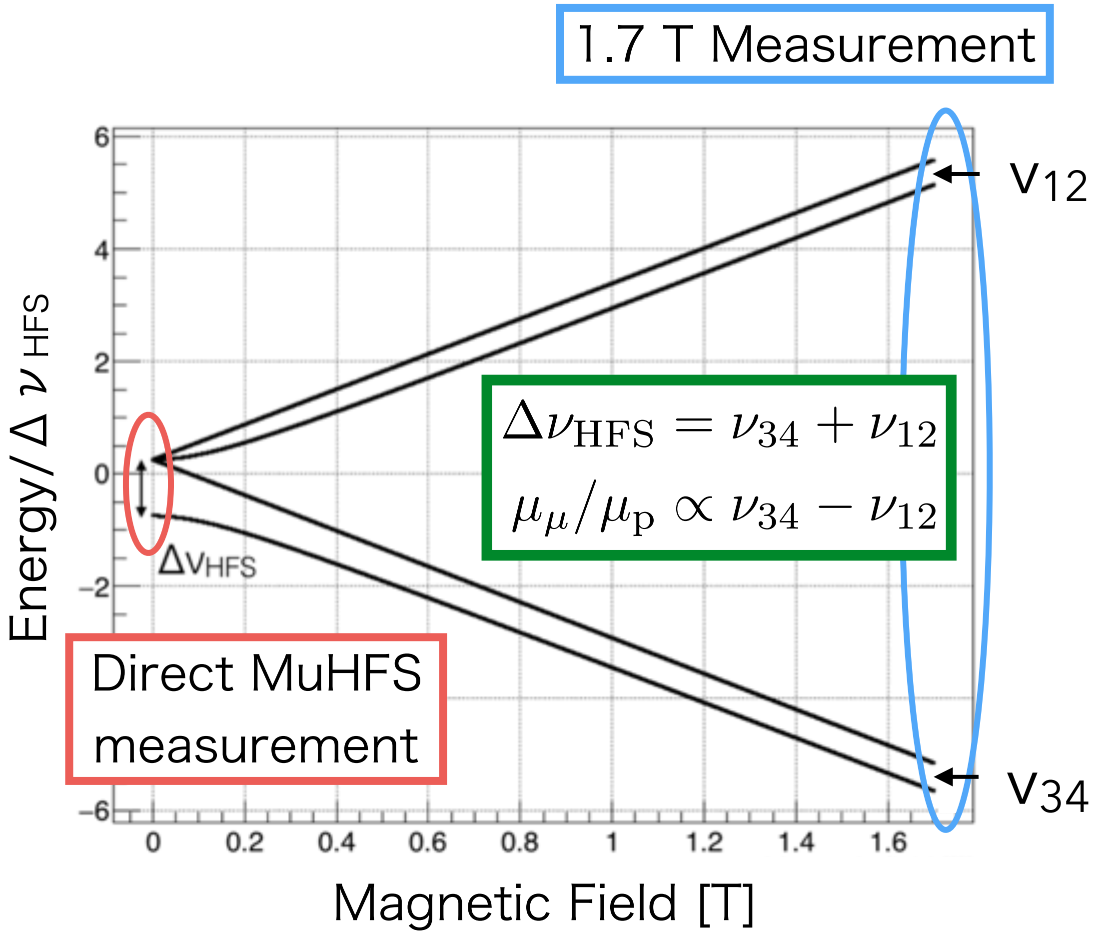
$$\mathcal{H} = \underbrace{h\Delta\nu_{\rm HFS}\vec{I}\cdot\vec{J}}_{\textbf{HFS}} + \underbrace{g_J\mu_B^e\vec{J}\cdot\vec{H} - g'_\mu\mu_B^\mu\vec{I}\cdot\vec{H}}_{\textbf{Zeeman splitting}}$$

- Spin states splits to substructure

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

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

$$(x \propto H)$$



1.7 T Measurement

$$\Delta\nu_{\rm HFS} = \nu_{34} + \nu_{12}$$
$$\mu_\mu/\mu_{\rm p} \propto \nu_{34} - \nu_{12}$$

Direct MuHFS measurement

- In the limit of a strong magnetic field (x>>1, x ~ 10.7 with 1.7 T)

$$\nu_{12} + \nu_{34} = \Delta\nu_{\rm HFS} \qquad \frac{\mu_\mu}{\mu_{\rm p}} = \frac{1}{2}\frac{(\nu_{34} - \nu_{12})}{\nu_{\rm p}}\frac{g_\mu}{g'_\mu} \qquad \frac{m_\mu}{m_e} = \frac{g_\mu}{2}\frac{\mu_{\rm p}}{\mu_\mu}\frac{\mu_B^e}{\mu_{\rm p}}$$

Related physics - muon magnetic moment

- ~3σ discrepancy between theory and experiment

$$a_\mu(exp) - a_\mu(th) = 250(89) \times 10^{-11}$$

(from CODATA 2014)

- μ_μ / μ_p : essential parameter for muon *g-2* measurement

$$a_\mu(exp) = \frac{(g-2)_\mu}{2} = \frac{R}{\lambda - R}$$

$$R = \omega_\mu / \omega_\mathrm{p} \ \ (540\mathrm{ppb})$$

G.W. Bennett et al., Phys. Rev. D **73** 072003 (2006).

$$\lambda = \mu_\mu / \mu_\mathrm{p} \ \ (30\mathrm{ppb})$$

W. Liu *et al.*, Phys. Rev. Lett. **82**, 711 (1999).
D. E. Groom *et al.,* Eur. Phys. J. C **15**, 1 (2000).

1. R : Planning 140ppb measurement at J-PARC and Fermilab

M. Otani, JPS Conf. Proc. **8**, 025008 (2015).
J. Grange Fermilab g-2 experiment technical design report (2015).

2. λ : 30ppb (HFS result + calculation) -> **direct** 10ppb measurement

Road map of Experiment

- Zero field measurement @MLF D2-line - ongoing
  - 2016 Jun. - 1st measurement
  - 2017 Feb. - 2nd measurement
  - 2017 Jun. - 3rd measurement
  - 2017 Dec. - Beam monitor test
  - 2018 Mar. - 4th measurement
  - 2018 Jun. - planning 5th measurement

- High field measurement @MLF H-line
  - Will be ready with H-line construction (2019~)

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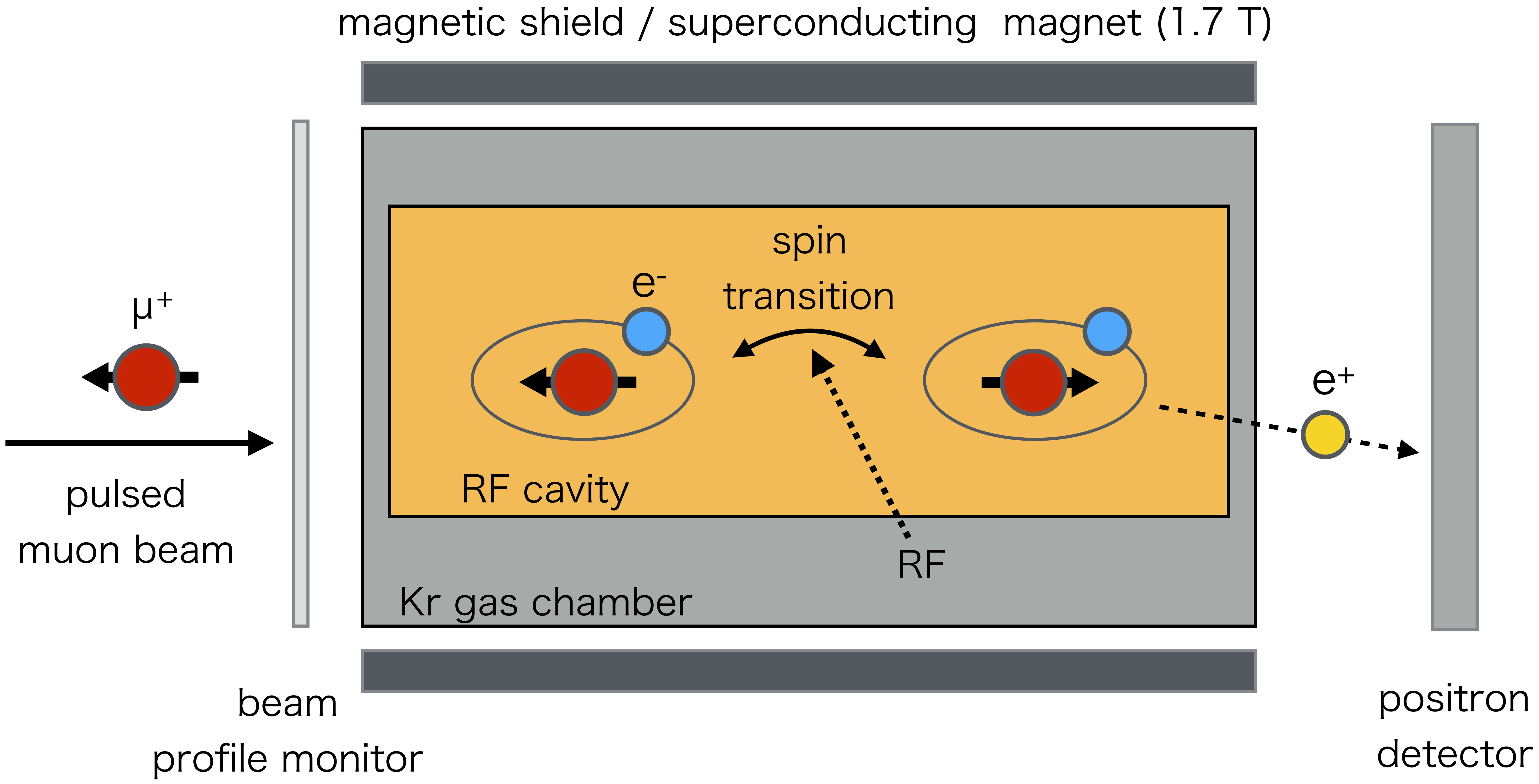
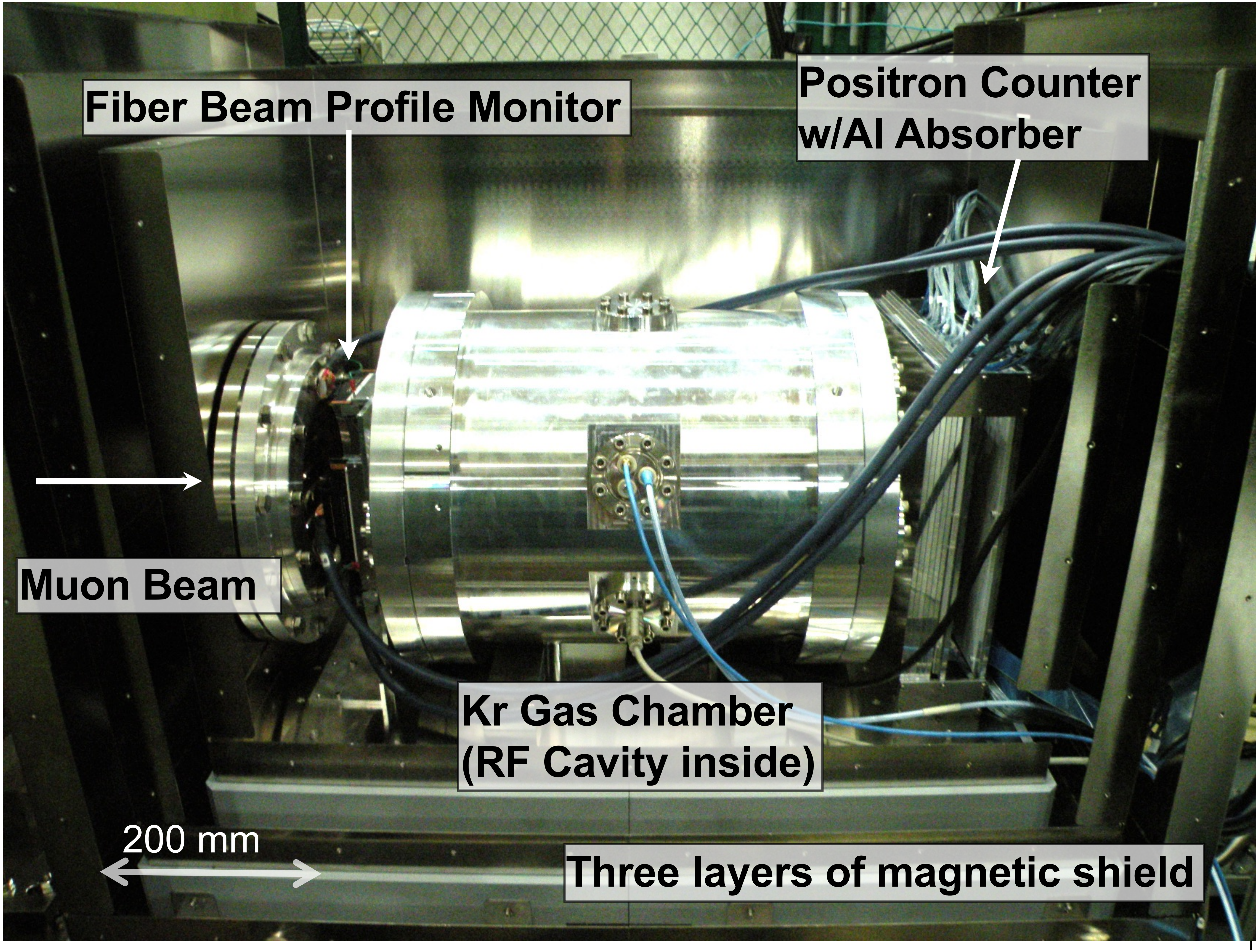
Setup of MuHFS measurement

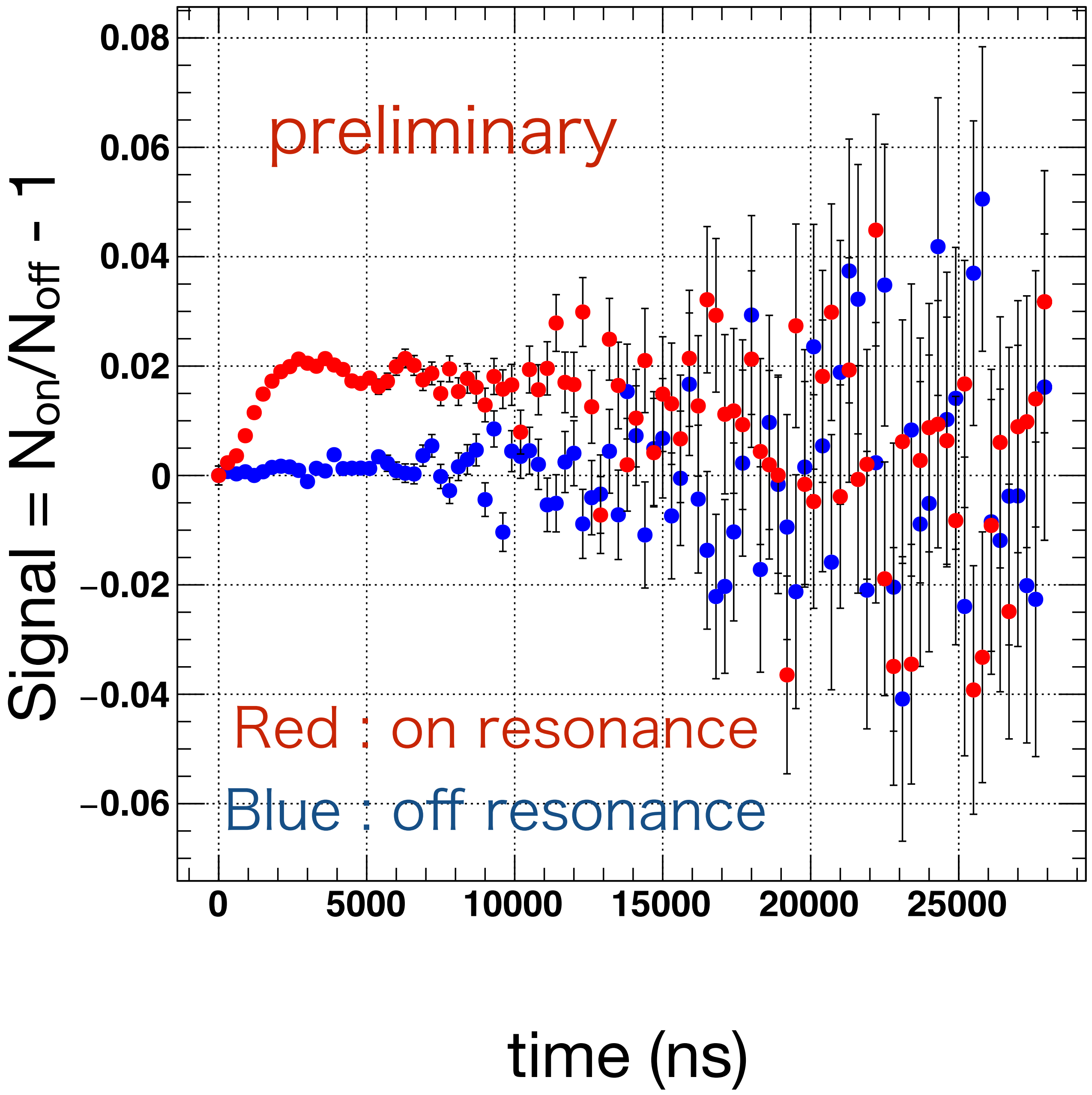


RF cavity resonant to ν_{12} with TM110 mode & ν_{34} with TM210 mode


Fiber Beam Profile Monitor
Positron Counter w/Al Absorber
Muon Beam
Kr Gas Chamber (RF Cavity inside)
200 mm
Three layers of magnetic shield

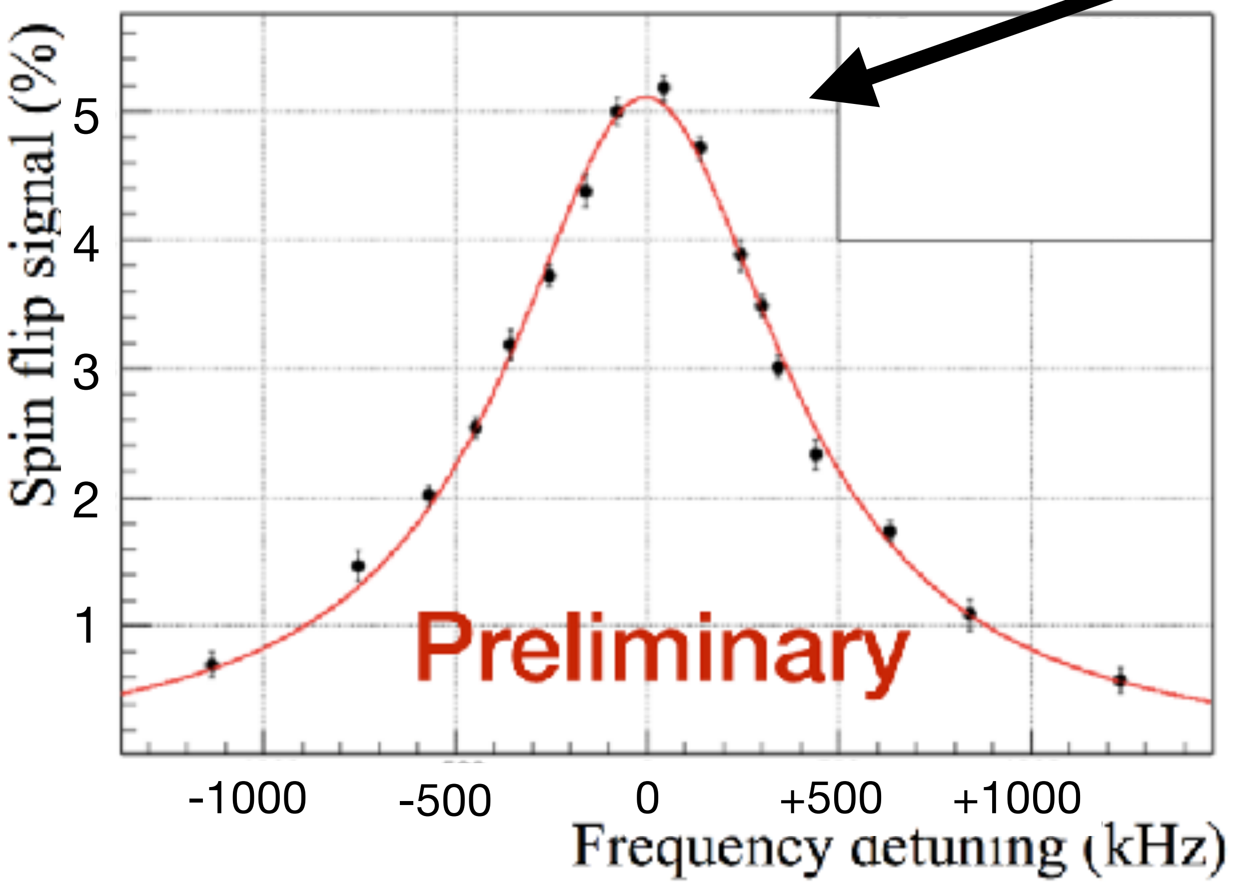
Time dependent spin flip signal

- Counting the numbers of the decay positron when RF ON/OFF
- Near at HFS resonance (~4.463 302GHz) -> red
- RF frequency far detuned ->blue

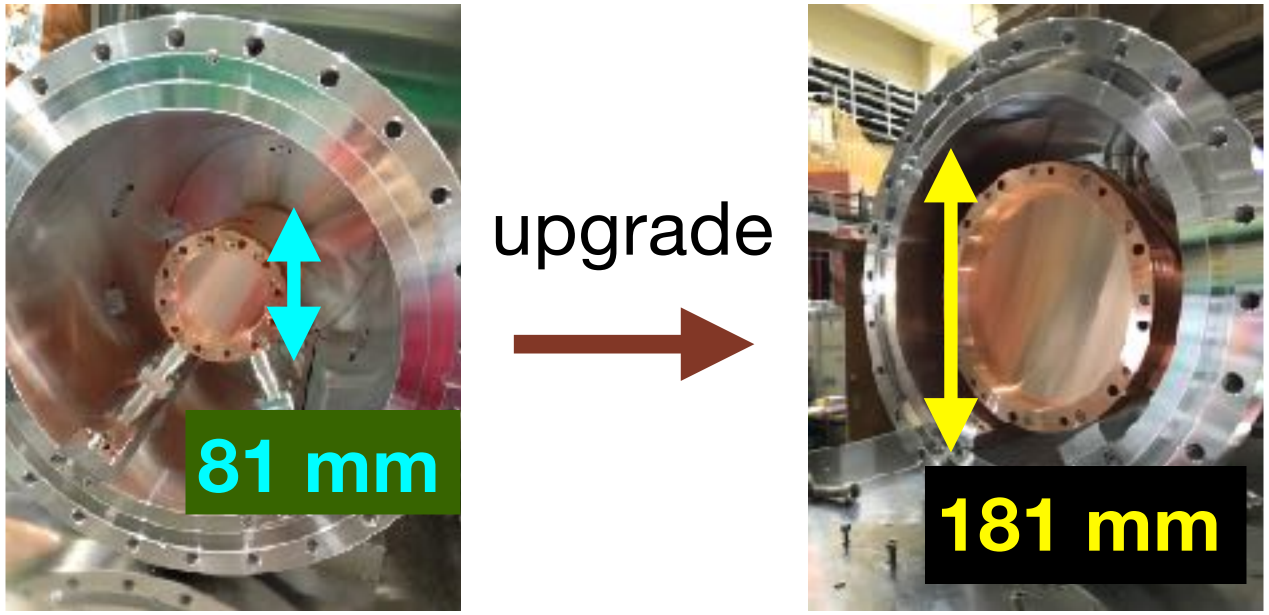


Previous ZF experiments

2016 June	2017 Feb	2017 June
1st observation **22 kHz precision**	**BG surpression** **RF optimization** **4 kHz precision**	**New Cavity** **(TM110 -> TM220 mode)**

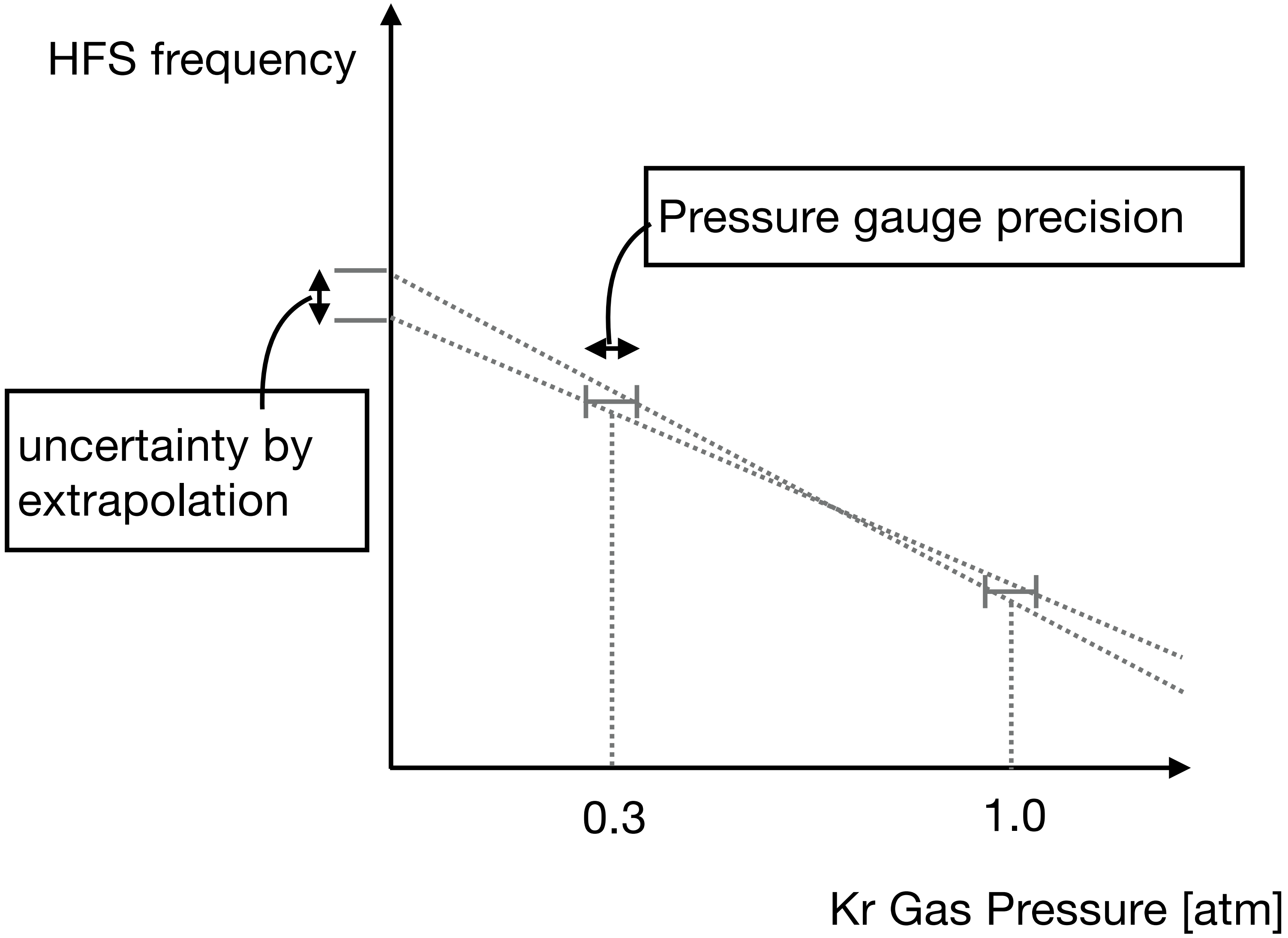


ZF’s world record 1.4kHz



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



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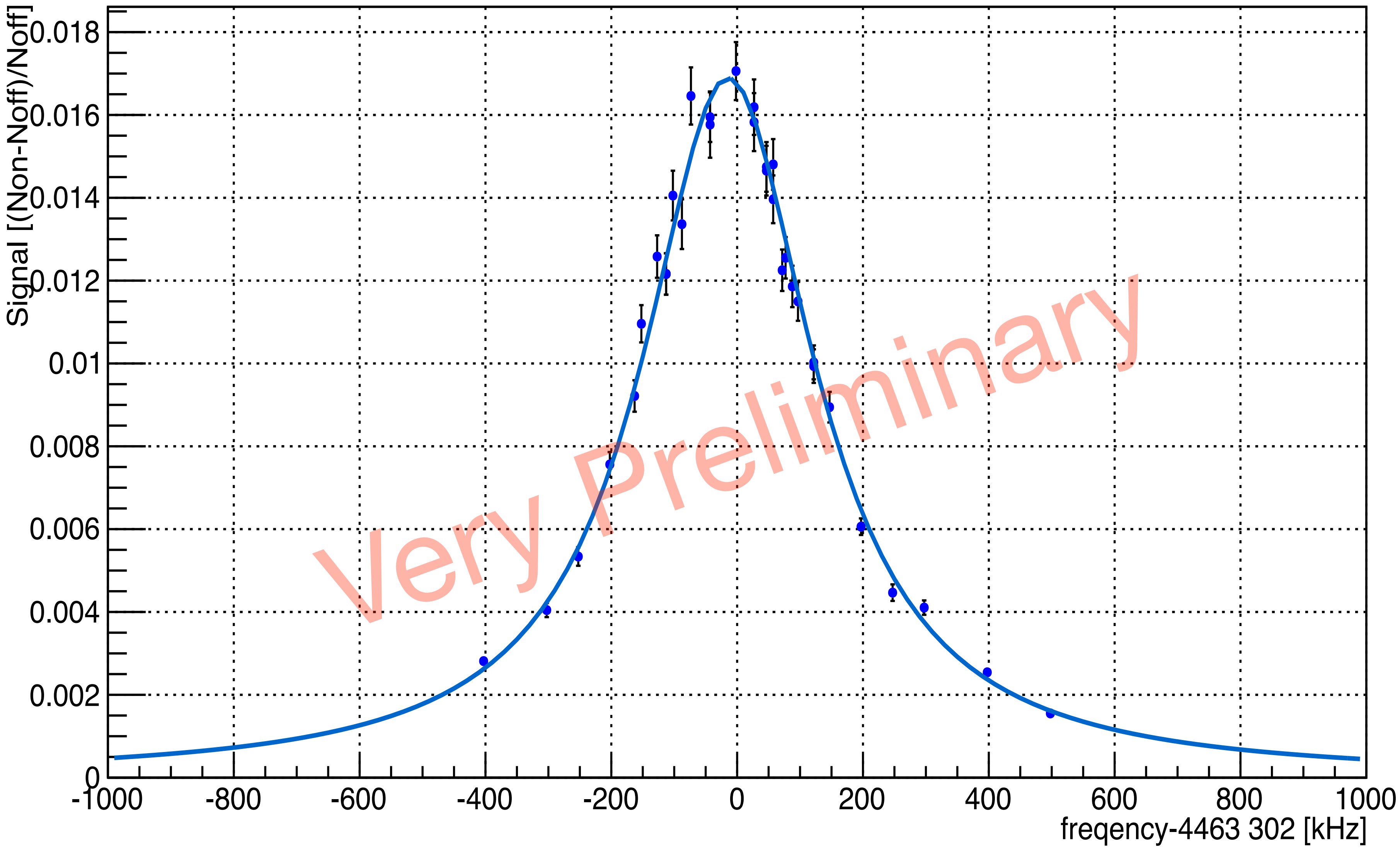

Data analysis is ongoing

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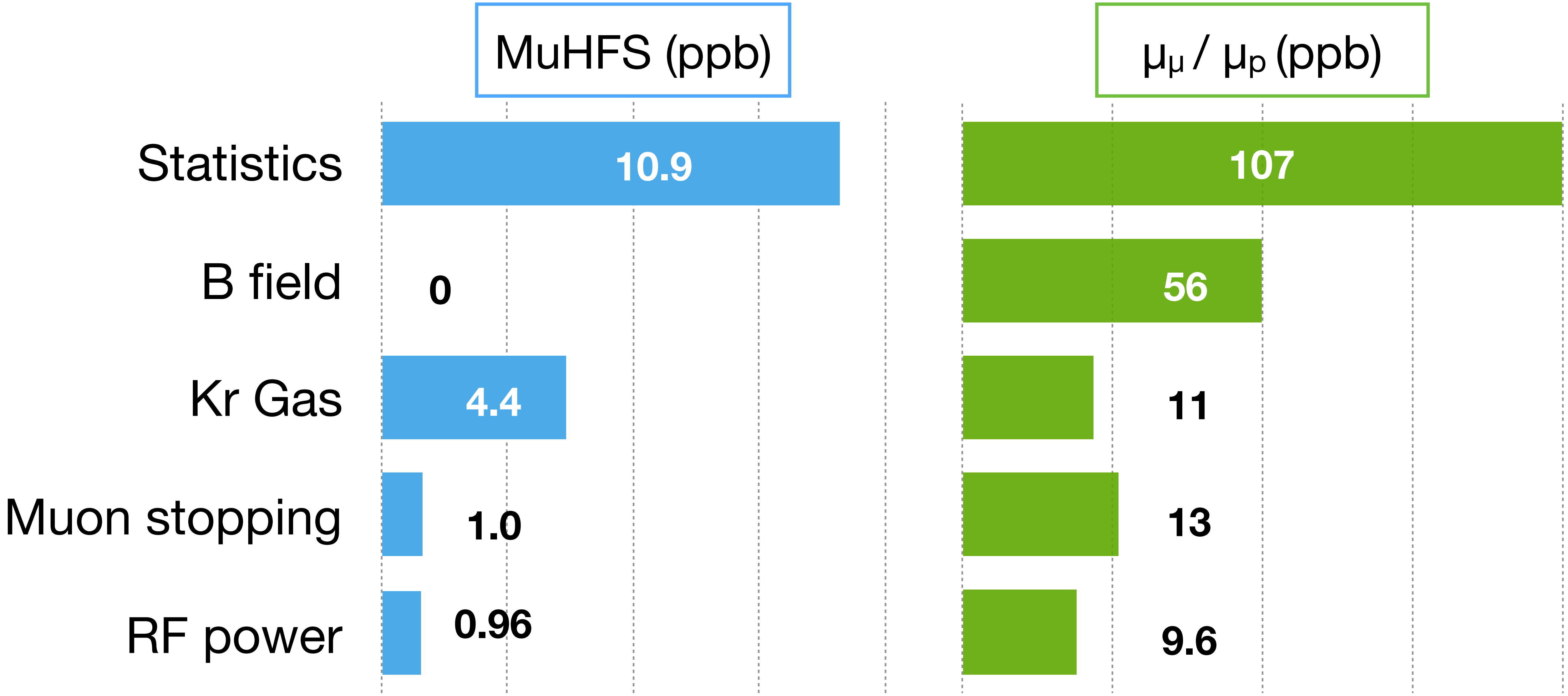
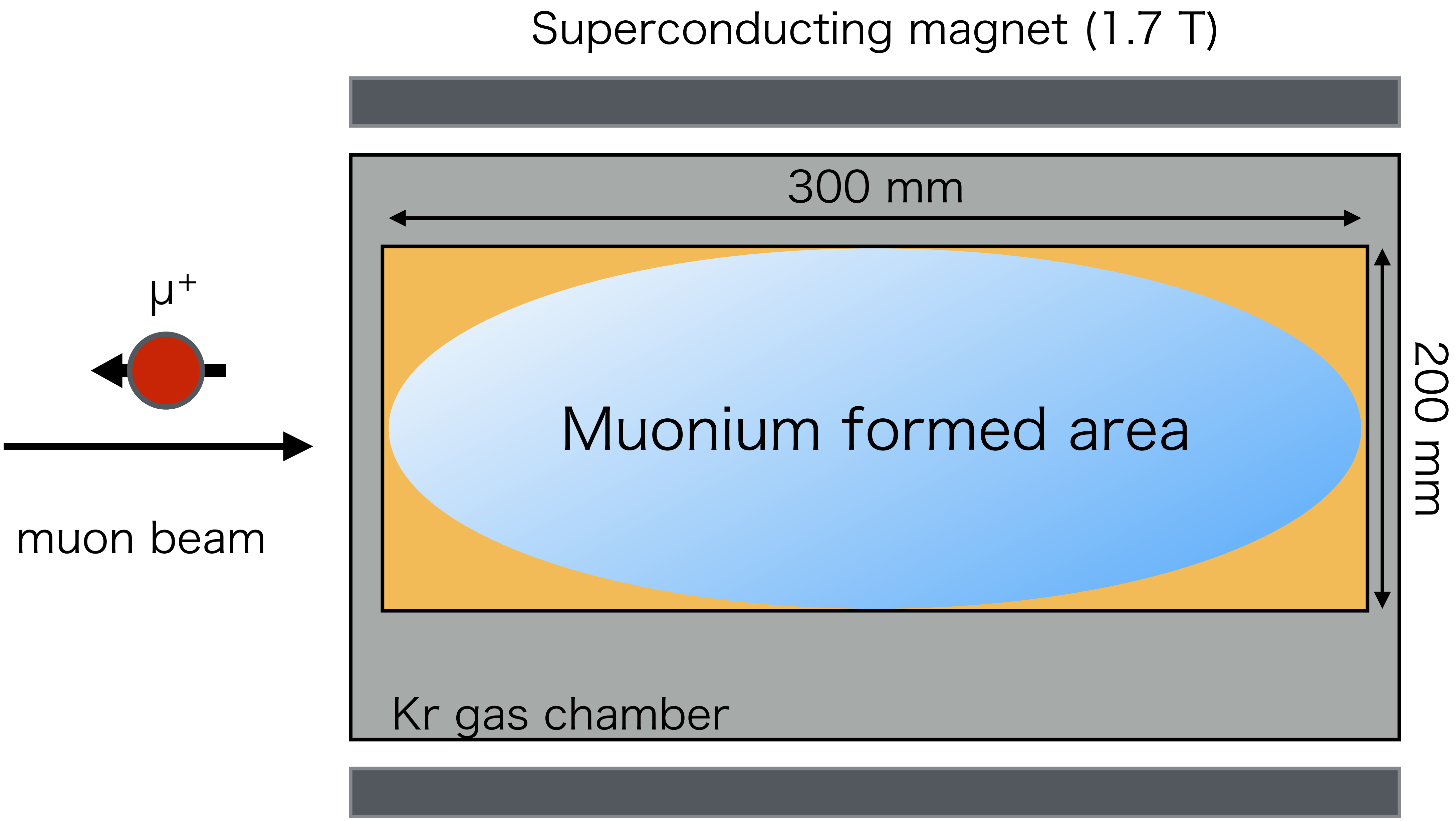
Uncertainties of LAMPF experiment



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

- Mainly limited by statistics - installation of H-Line @ J-PARC MLF
- Magnetic field inhomogeneity causes next

Required B-field at MuSEUM

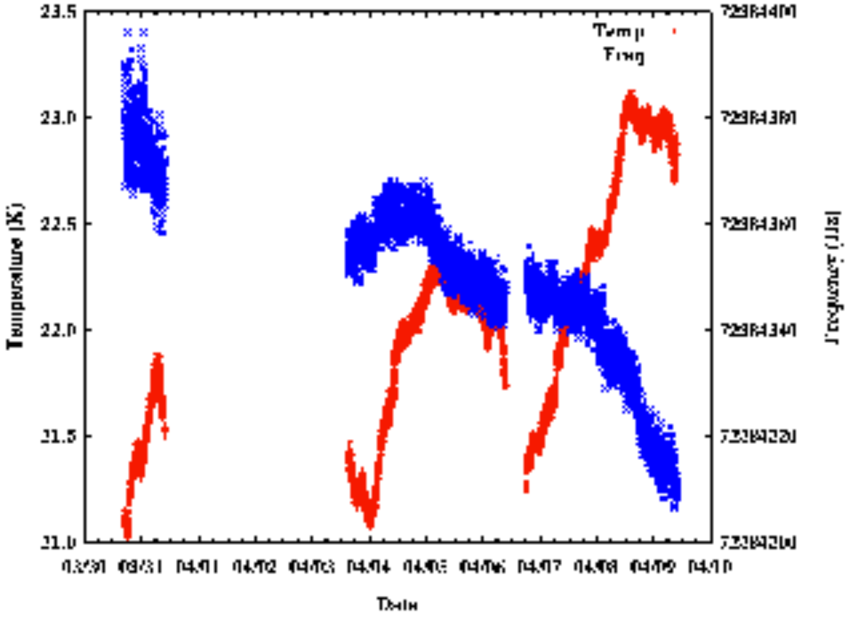


- Required ~0.1ppm homogeneity of 1.7 T in the spheroid muonium formed area (z= 300 mm, r=100 mm)

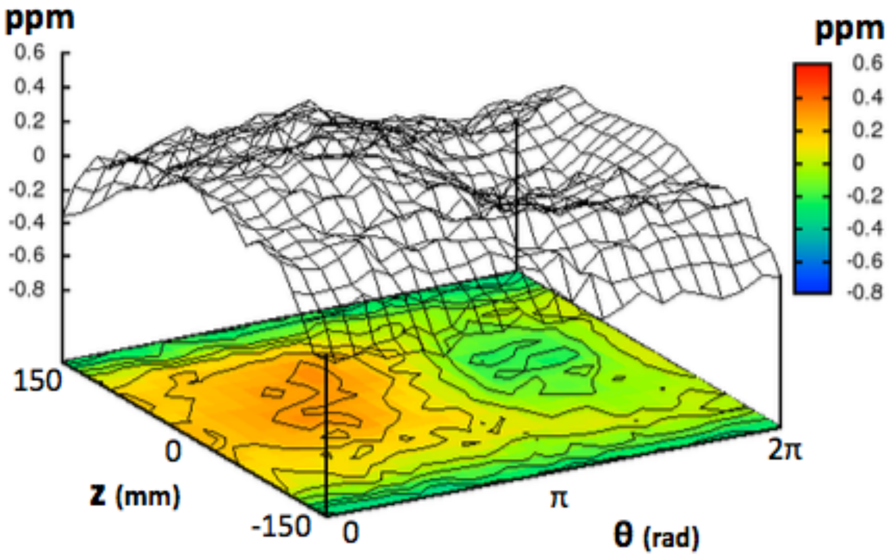
MRI magnet status

- Solenoid MRI magnet for MuSEUM
  @ J-PARC (max 2.9 T, used in 1.7 T)

- B-field drifted 64Hz per 9 days
  (2015/3/30 - 2015/4/9)
  - 3ppb/h stability

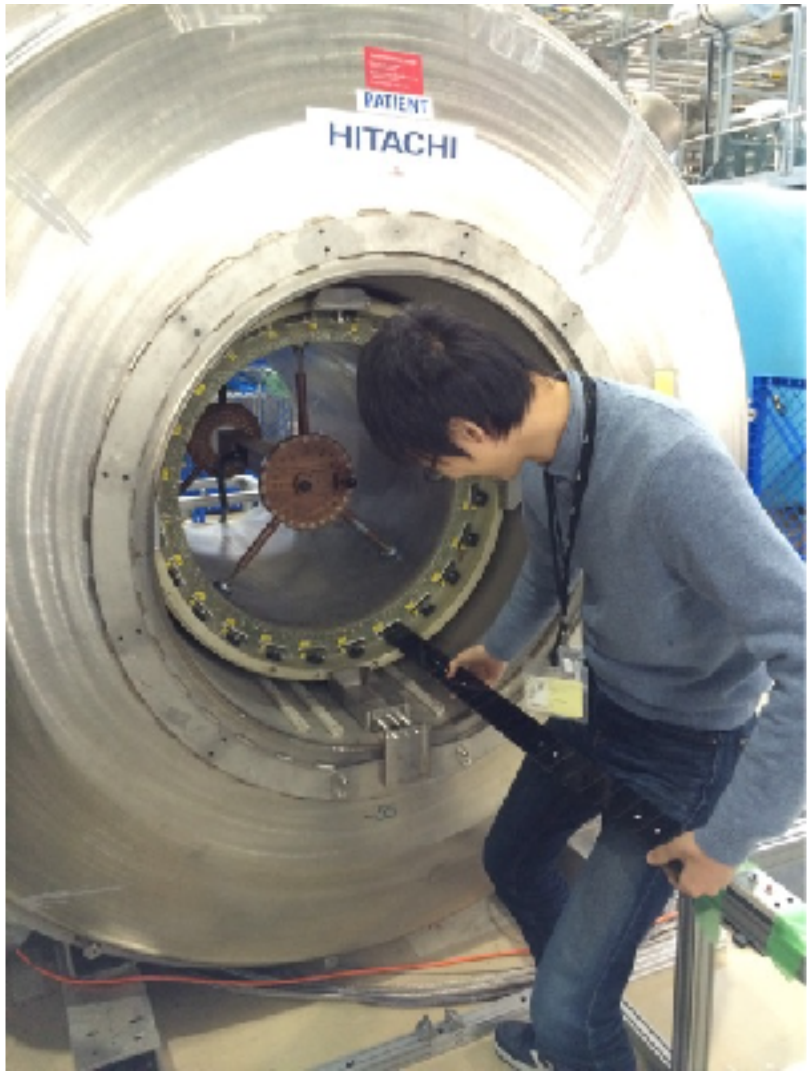


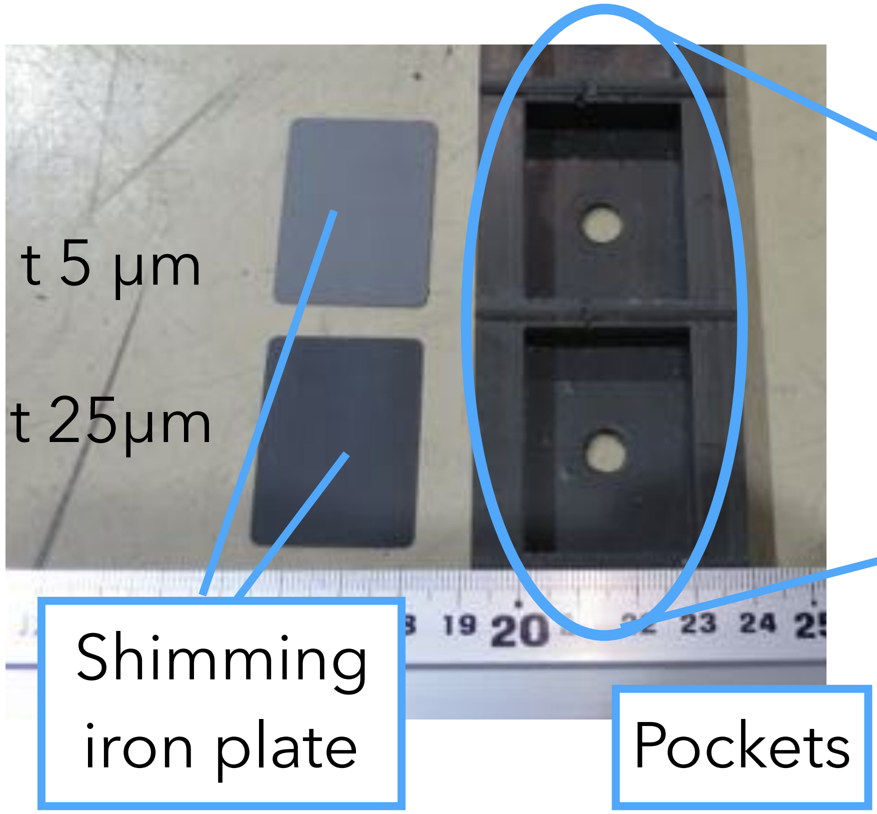
- B-field homogeneity suppressed to 0.8ppm by shimming the MRI magnet with shim trays
- 576 points measured by single NMR probe (including B-field drift, alignment error etc.)



B-field improvement - shimming

- Shimming by placing iron plates (5 & 25um thickness) in 24 pockets* 24 trays = 576 pockets inside the magnet
- Optimized homogeneity to 0.80ppm of 1.7 T in target area (mapped by single NMR probe)





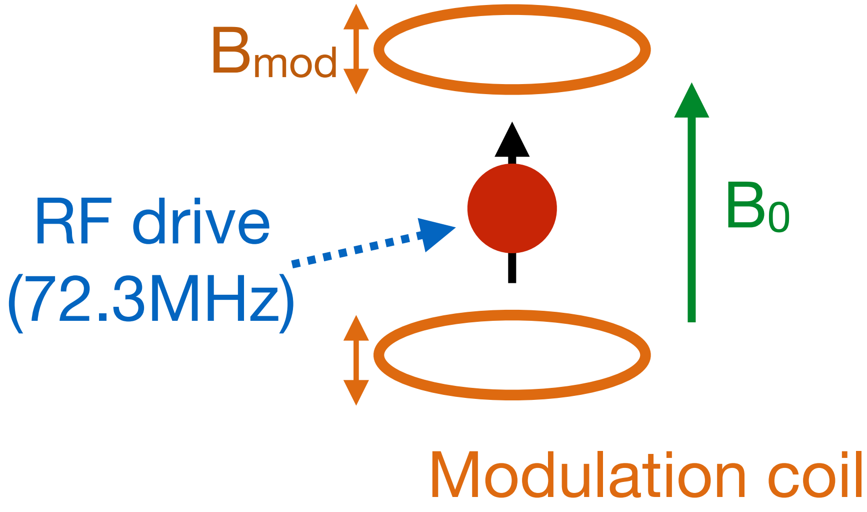
Thin and thick iron plates for shimming
(W 40 mm, D 30 mm, t 5 or 25µm)

Shim tray

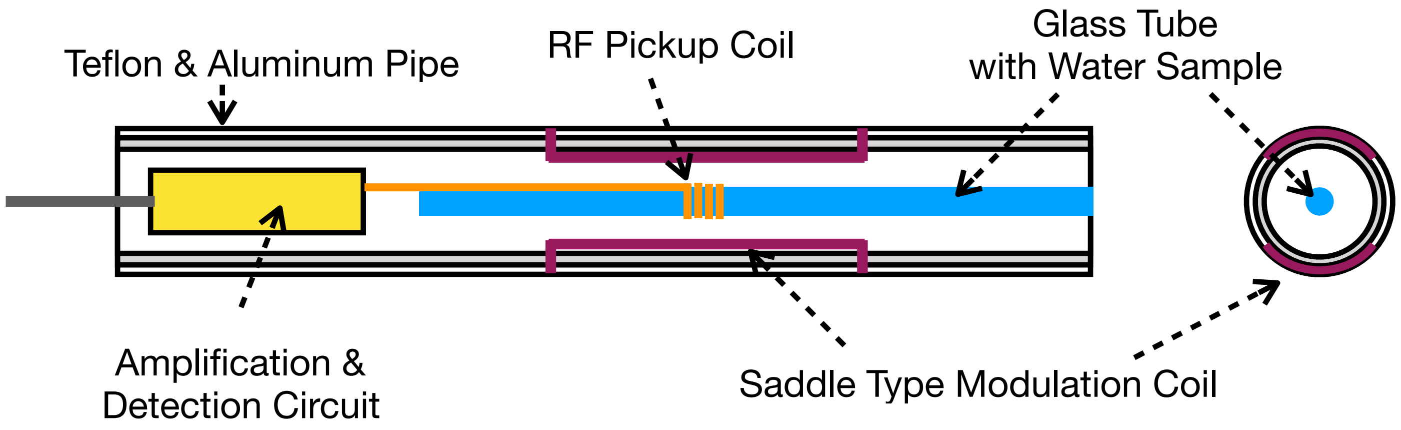
CW-NMR probe

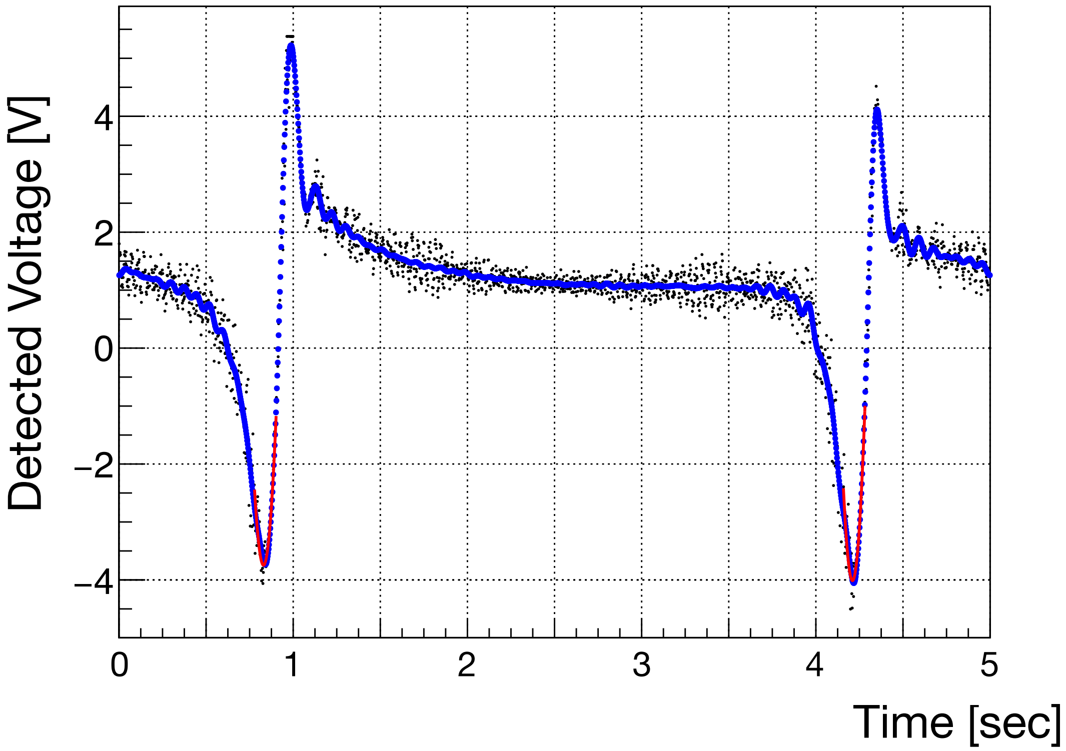
- NMR(Nuclear Magnetic Resonance)

$$2\pi\nu_0 = \gamma_\mathrm{p} B \ (\gamma_\mathrm{p} = 267.52219 \times 10^6 \ [\mathrm{rad\ s^{-1}t^{-1}}])$$

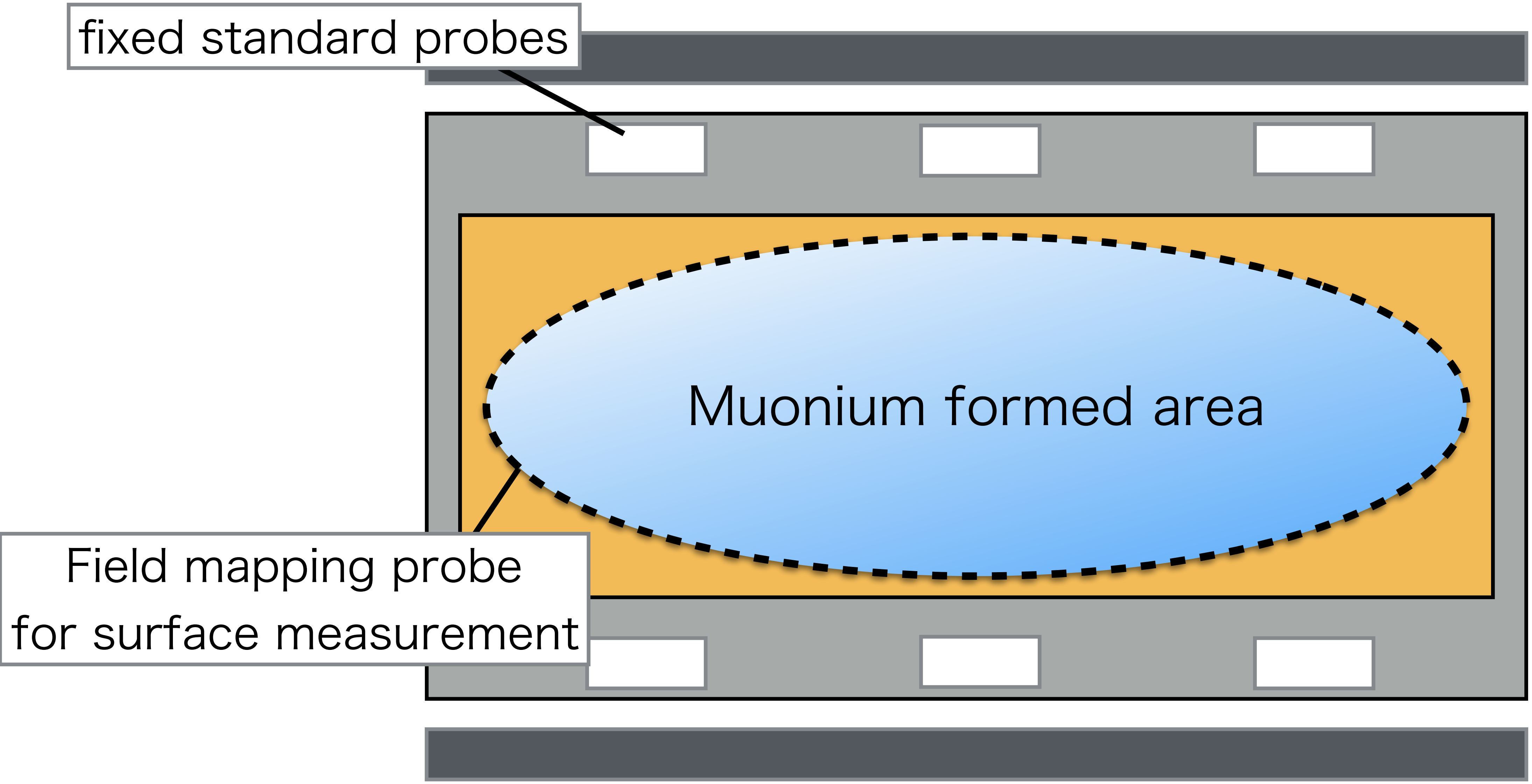


- Continuous wave NMR probe (CW-NMR)
  - Sweep the B-field mandatory by the modulation coil
  - Detect the envelope signal of proton NMR





NMR probes for MuSEUM experiment



- Stability per time - Online monitoring by fixed standard probes
- Homogeneity in Muonium formed area
  - Measurement by the multi channel field mapping probe

Probes used for the experiment

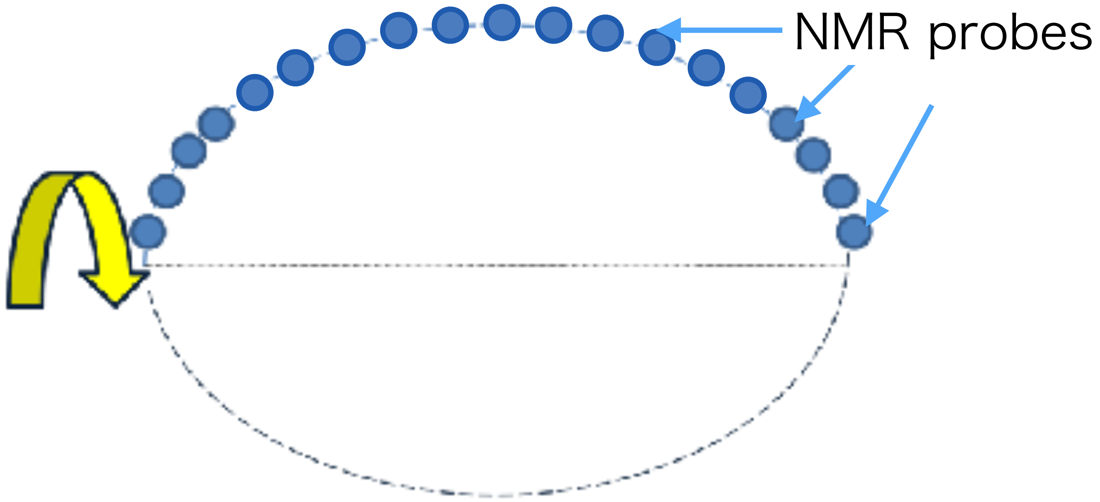
- Fixed standard probe : placing single-ch NMR probes for monitoring the stability of the B-field drift
- Motivation : Decrease the systematic shift caused by the material of the NMR probe

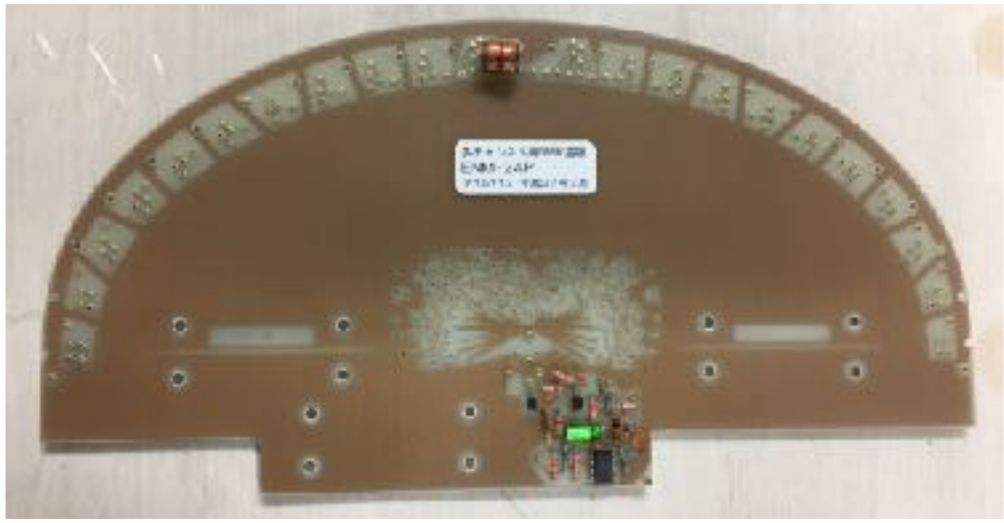
$$\nu_p = (1 - (\sigma(\mathrm{H_2O}) + \delta_b + \delta_\mathrm{p} + \delta_s))\nu_0$$

Measured B-field

External B-field

- Field mapping probe : Fast field mapping enables B-field measurement with low drift
- Design : 24ch NMR probes on half-oval plate to scan the surface

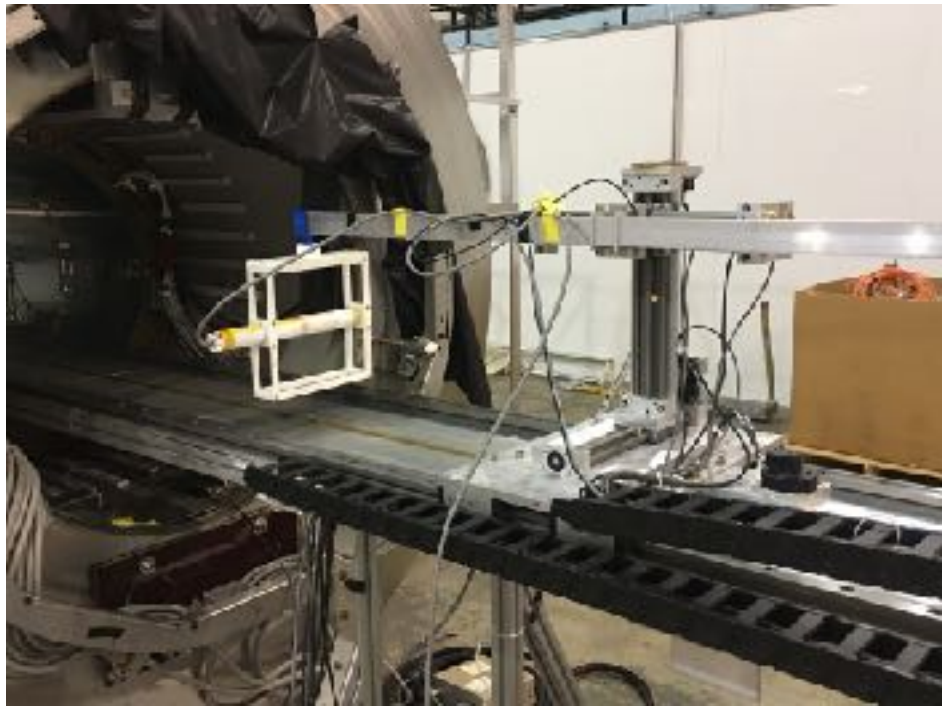


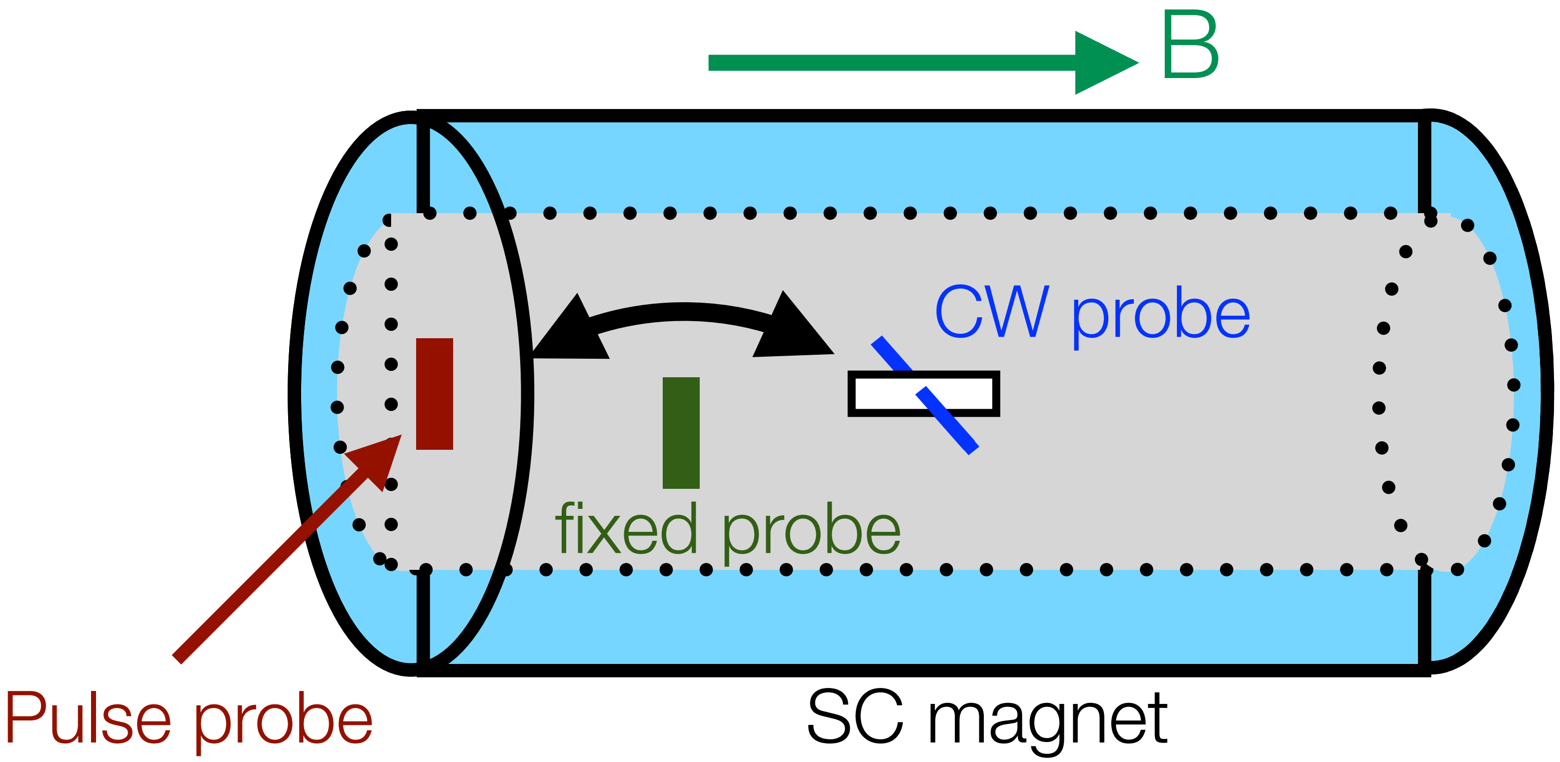


Prototype of field mapping probe

NMR probe cross calibration

- Mar 2017 : cross calibration with FermiLab g-2 group @ANL, B=1.45 T
- 20ppb agreement at blind analysis with CW and pulse NMR probe (preliminary)





- Found uncertainties caused by the material of the NMR probe itself, especially the circuit board - replace with non-magnetic materials
- Mar 2018 : 2nd cross calibration of the new NMR probe @ANL, B=1.45 T

Summary

- MuHFS measurement is a good probe to test the bound state QED and also μ_μ / μ_p and m_μ / m_e can be measured. For improvement, more statistics and high homogeneity of magnetic field are required.

- MuHFS measurements with extremely low magnetic field is in progress and we are close to the world record.

- The spec of the magnet fulfills the requirement of the MuSEUM experiment. We are now doing the R&D of the NMR probes.

Appendix

lambda used at g-2 measurement

Magnetic moment ratio values used at BNL(Brookhaven national laboratory) result was derived from Δν$_{\mathrm{HFS}}$ results by LAMPF (12ppb) applying to

$$\Delta\nu_{\mathrm{HFS}} = \frac{16}{3}\alpha^2 c R_\infty \frac{m_{\mathrm{e}}}{m_\mu}[1+\frac{m_{\mathrm{e}}}{m_\mu}]^{-3} + \mathrm{corrections}$$

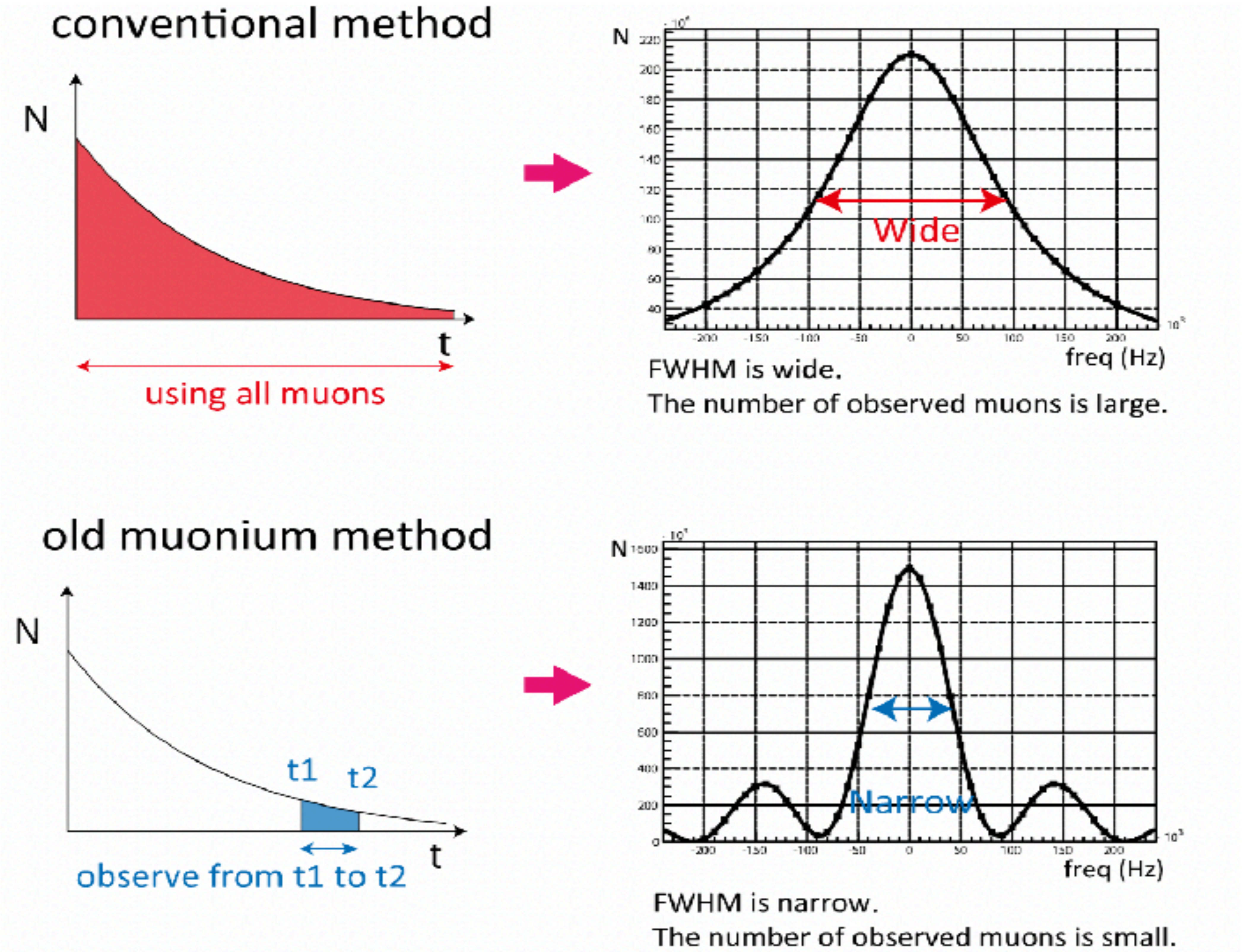
and the magnetic moment was calculated by the mass ratio as

$$\frac{\mu_\mu}{\mu_{\mathrm{p}}} = \frac{g_\mu}{2}\frac{m_{\mathrm{e}}}{m_\mu}\frac{\mu_B^{\mathrm{e}}}{\mu_{\mathrm{p}}}$$

which is called the **indirect** determination. This calculation assumes the SM of the correction terms.

(partially taken from D. Nomura's slide)

old muonium method



conventional method

using all muons

FWHM is wide.
The number of observed muons is large.

old muonium method

observe from t1 to t2

FWHM is narrow.
The number of observed muons is small.

(from K.S. Tanaka-san’s slide)

Related physics : Exotic particle search

a pseudo vector boson

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

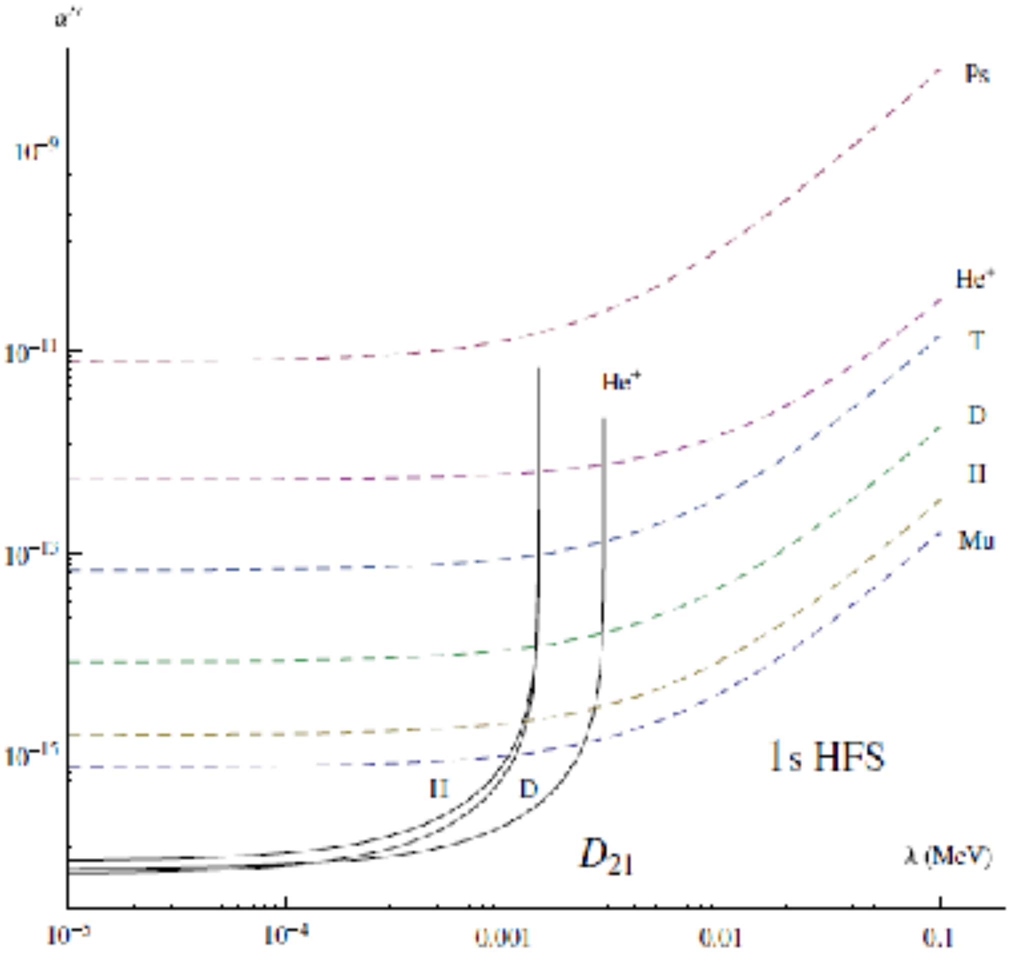


Fig. 2 on PRL 104, 220406 (2010)

a massive vector boson

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

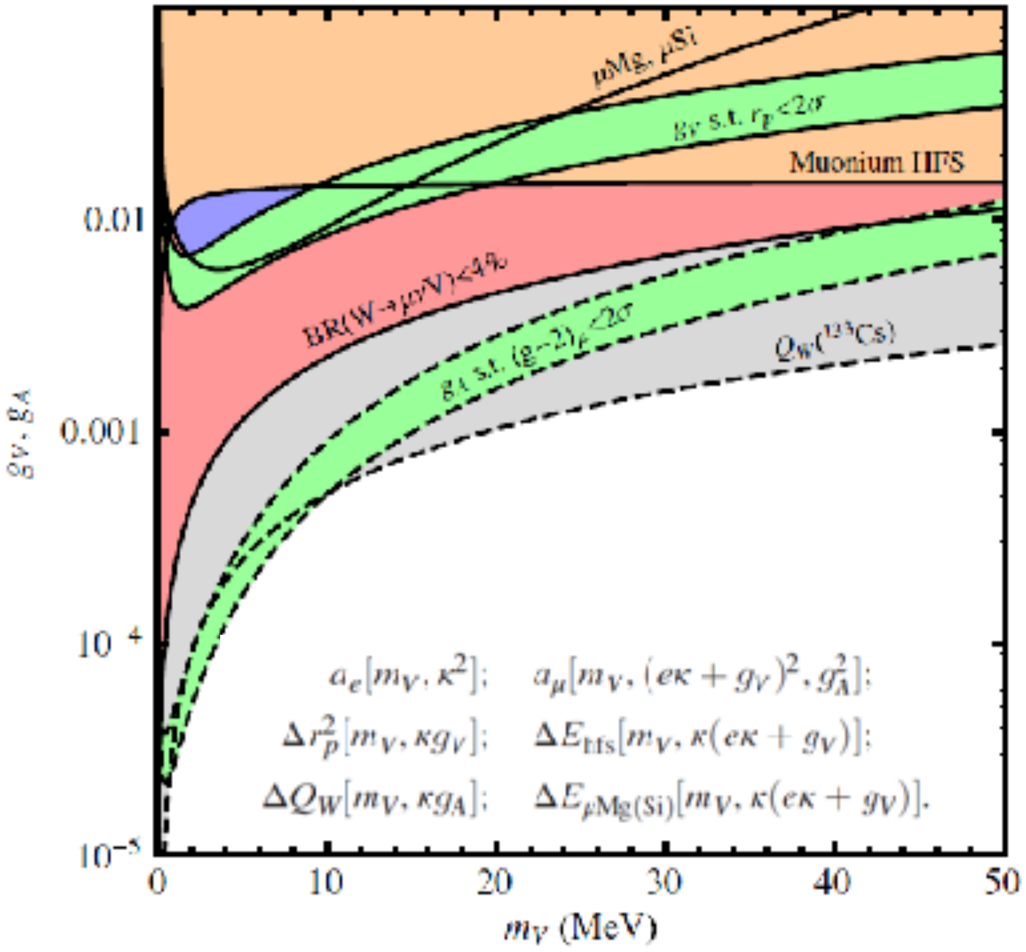


Fig. 6 on PRD90, 073004(2014).

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

(from K. Simomura-san's slide)

Related physics : Test of Loentz symmetry

CPT broken Theory⇒Lorentz symmetry is broken

R.Blihm, V.A. Kosteleky and C.D. Lane PRL84,1098(2000)
V.W. Hughs et al. PRL87,111804(2000

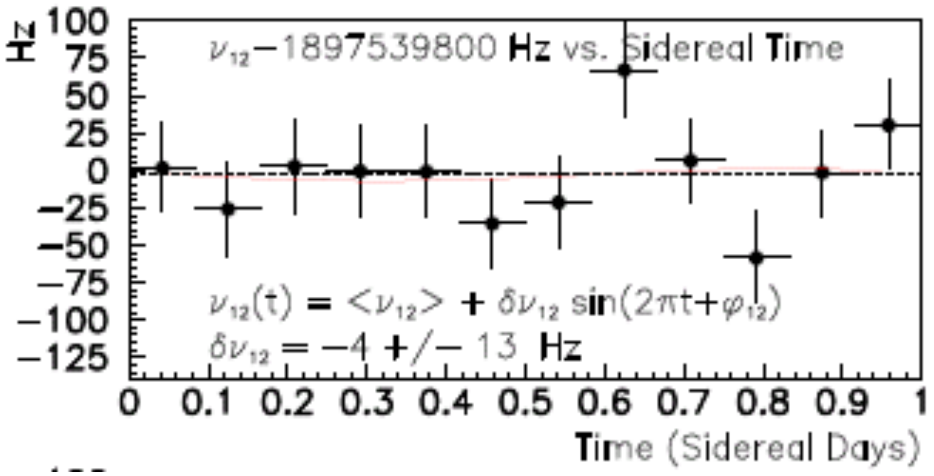
CPT violation search

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

g_μ-2/MuHFS precise measurement

Lorentz symmetry violating term in SME 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

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

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

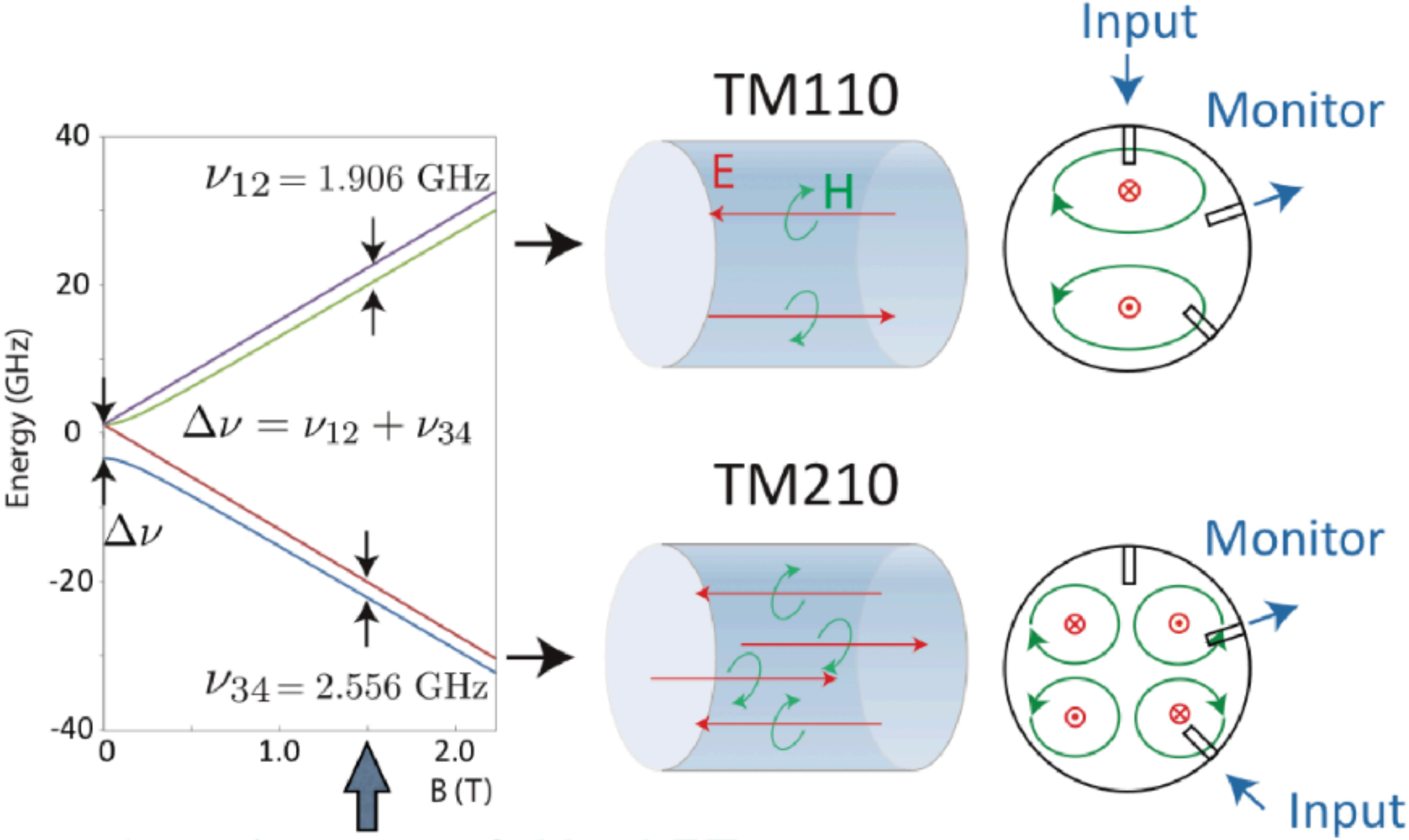
Plank scale sensitivity

Laboratory tests of Lorentz and CPT symmetry w/ muons
A.H. Gomes et. al., Phys.Rev.D90:076009,2014

(from K. Simomura-san's slide)

cavity design for HF measurement

two transitions two resonance modes



'magic' magnetic field = 1.7 T

(from K.S. Tanaka-san's slide)