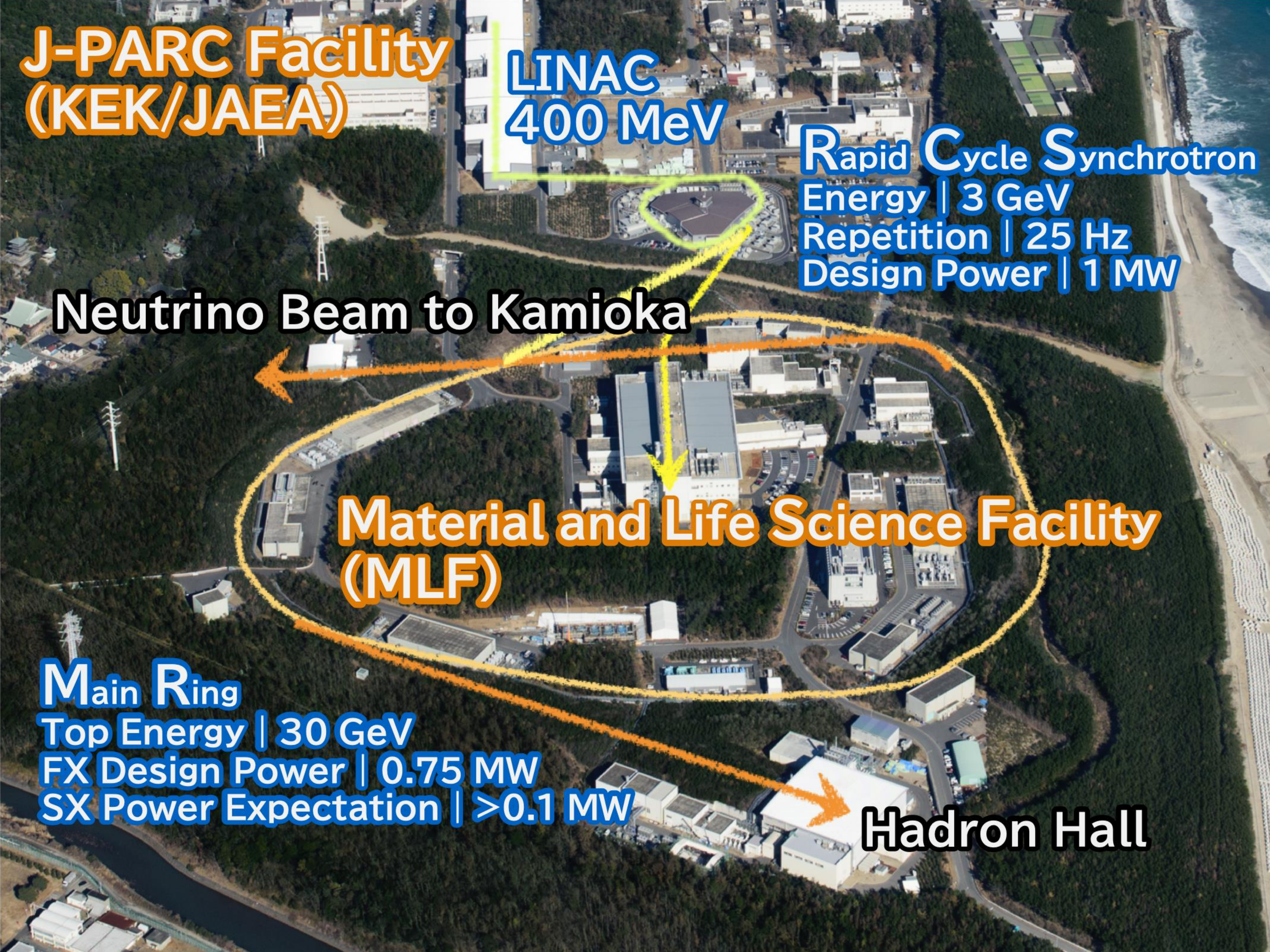
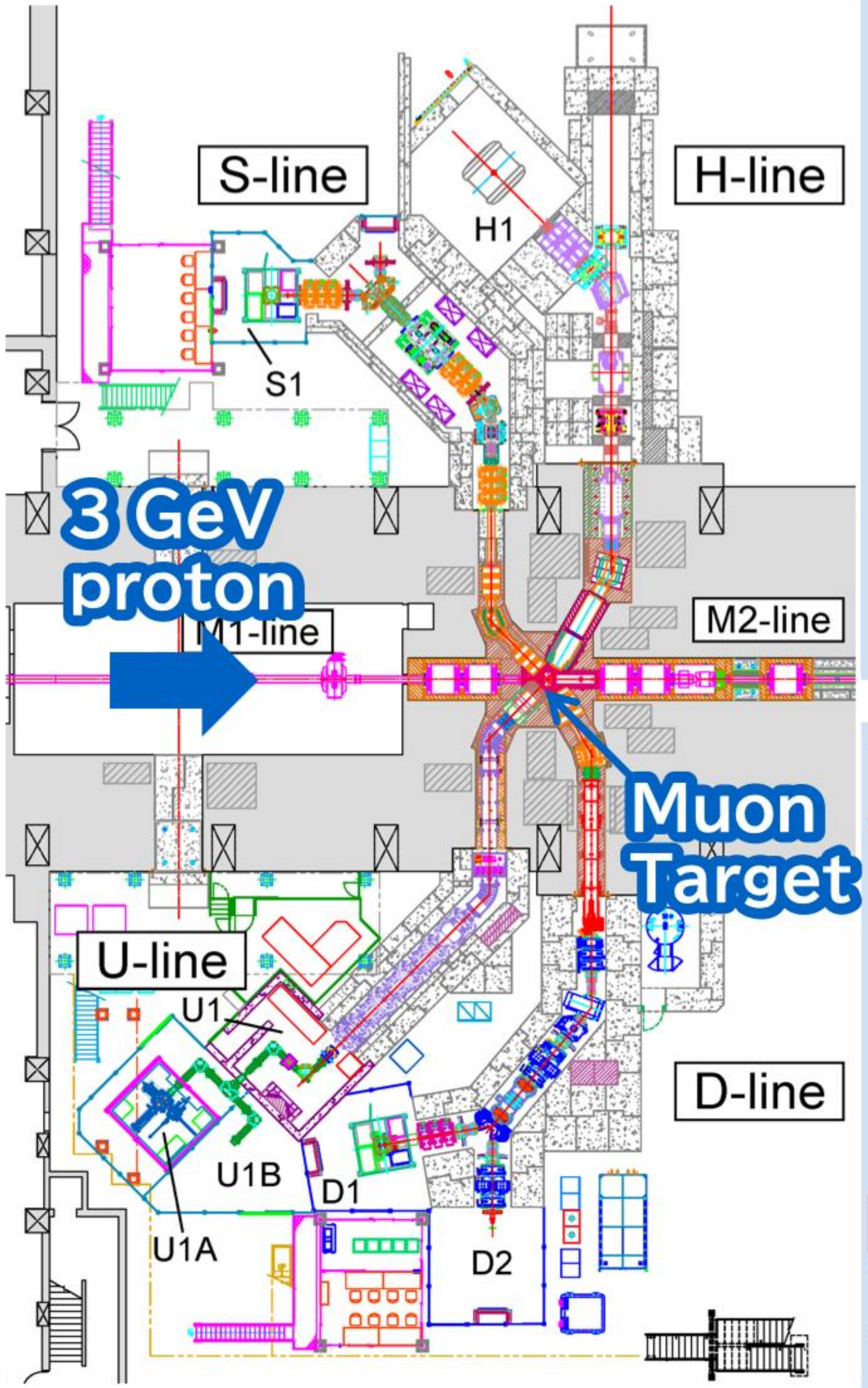
Muonium Spectroscopy in J-PARC

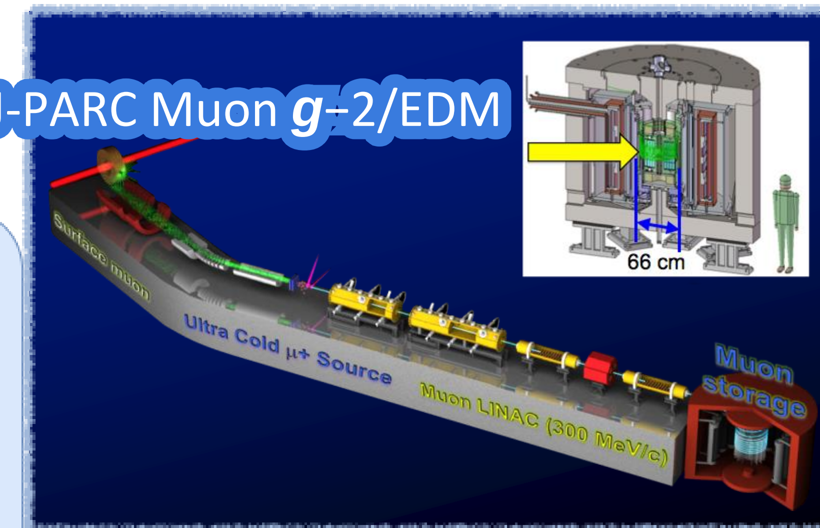
2022/08/18
Koichiro Shimomura (KEK IMSS)
For MuSEUM collaboration


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



Muon Precision Measurement in J-PARC MLF



Muon ***g***−2

New Physics beyond SM

QED

μ_μ, α, g_μ

QED

m_μ

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

Muonium (muonic He) HFS

Muon magnetic moment μ_μ

CPT for muon mass

QED

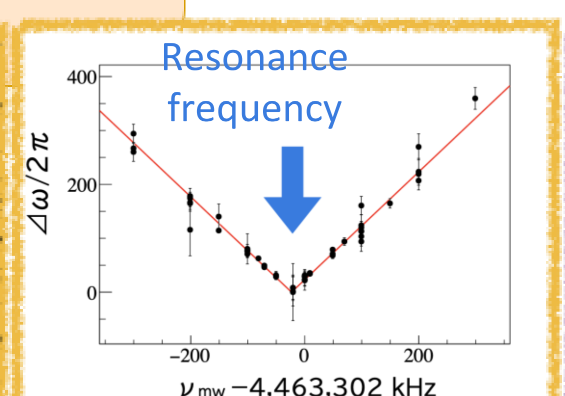
m_μ

Muonium 1s-2s

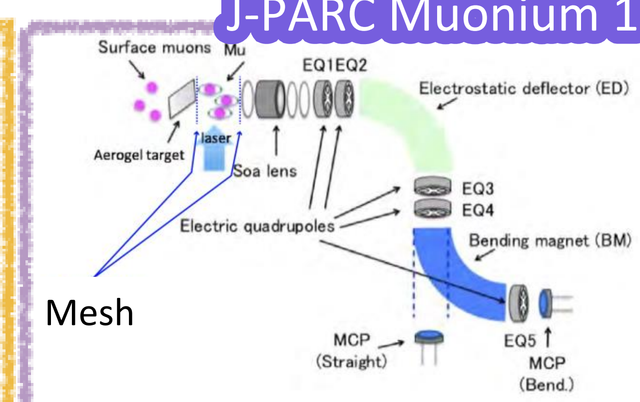
Muon mass m_μ

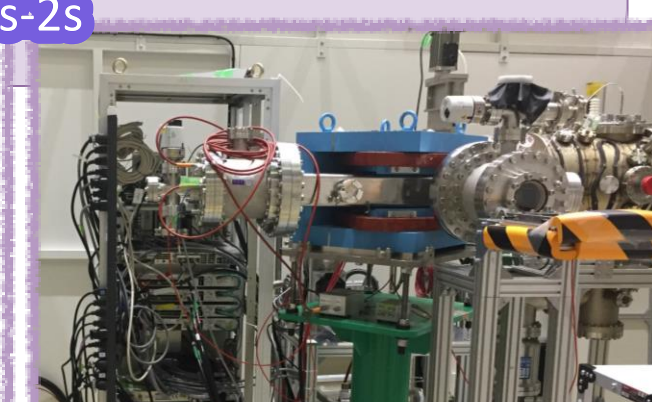
By K.Jungmann

MuSEUM

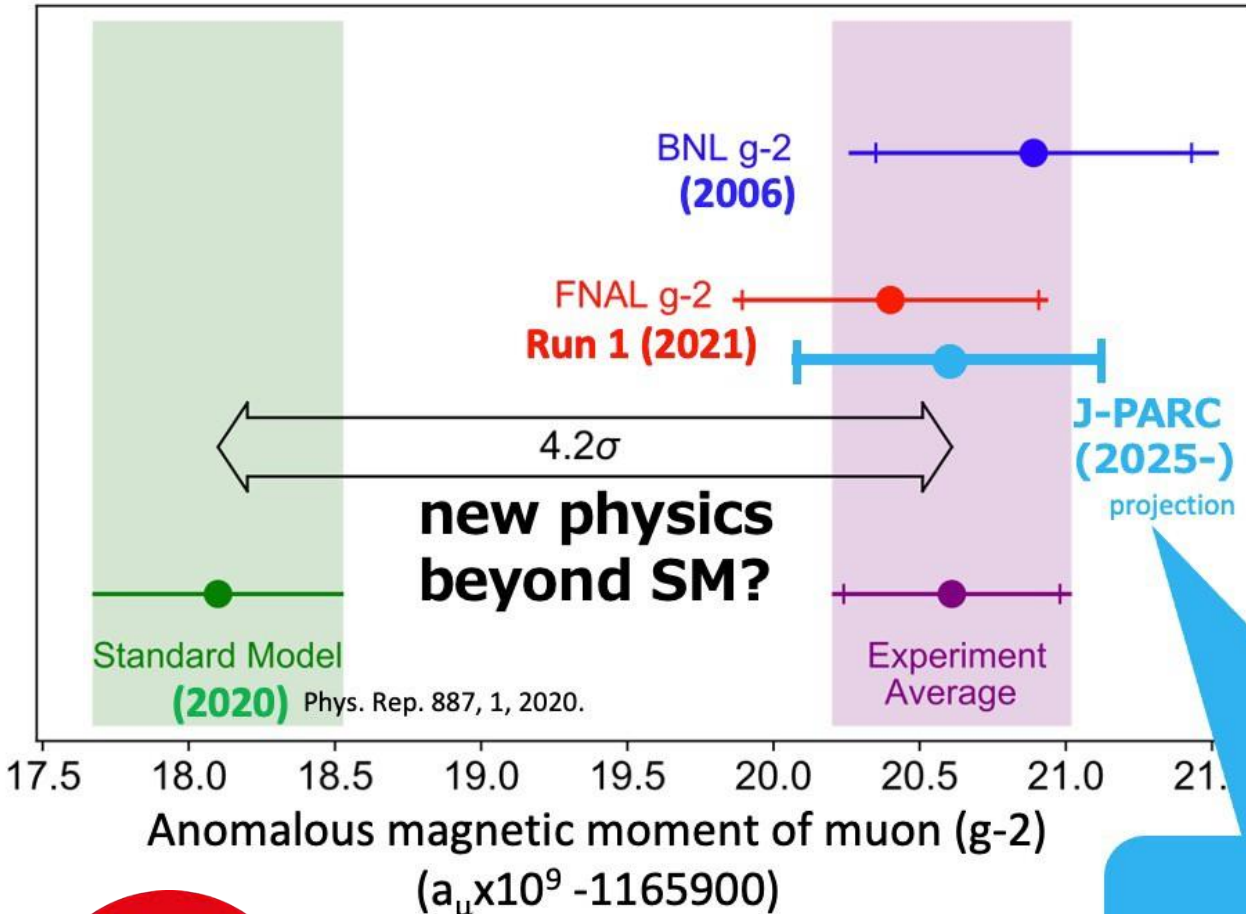


J-PARC Muonium 1s-2s





Muon g-2/EDM experiment



PRL 126, 141801 (2021)
Phys. Rev. D 103, 072002 (2021)
Phys. Rev. AB 24, 044002 (2021)
Phys. Rev. A 103, 042208 (2021)

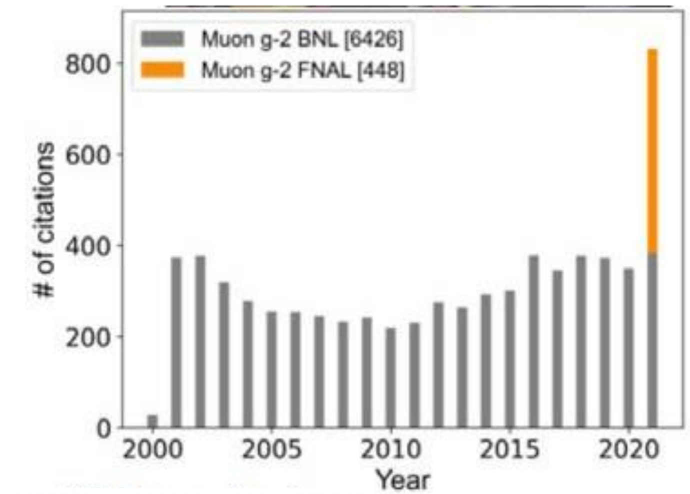
New result from FNAL on April 7, 2021

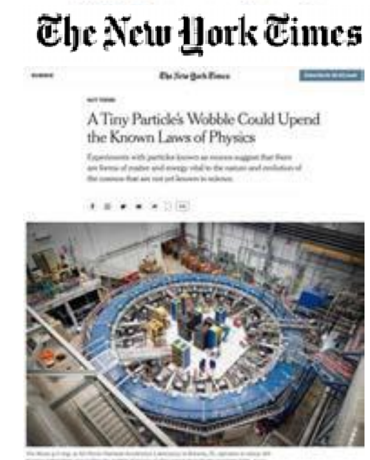
(1) Confirmed previous BNL result
(2) Deviation from the SM became 4.2σ (was 3.7σ)

- **More than 70 BSM preprints appeared in arXiv in a few days.**
- **450 citations as of today**

An independent measurement with entirely different systematics

Citation history of BNL & FNAL papers





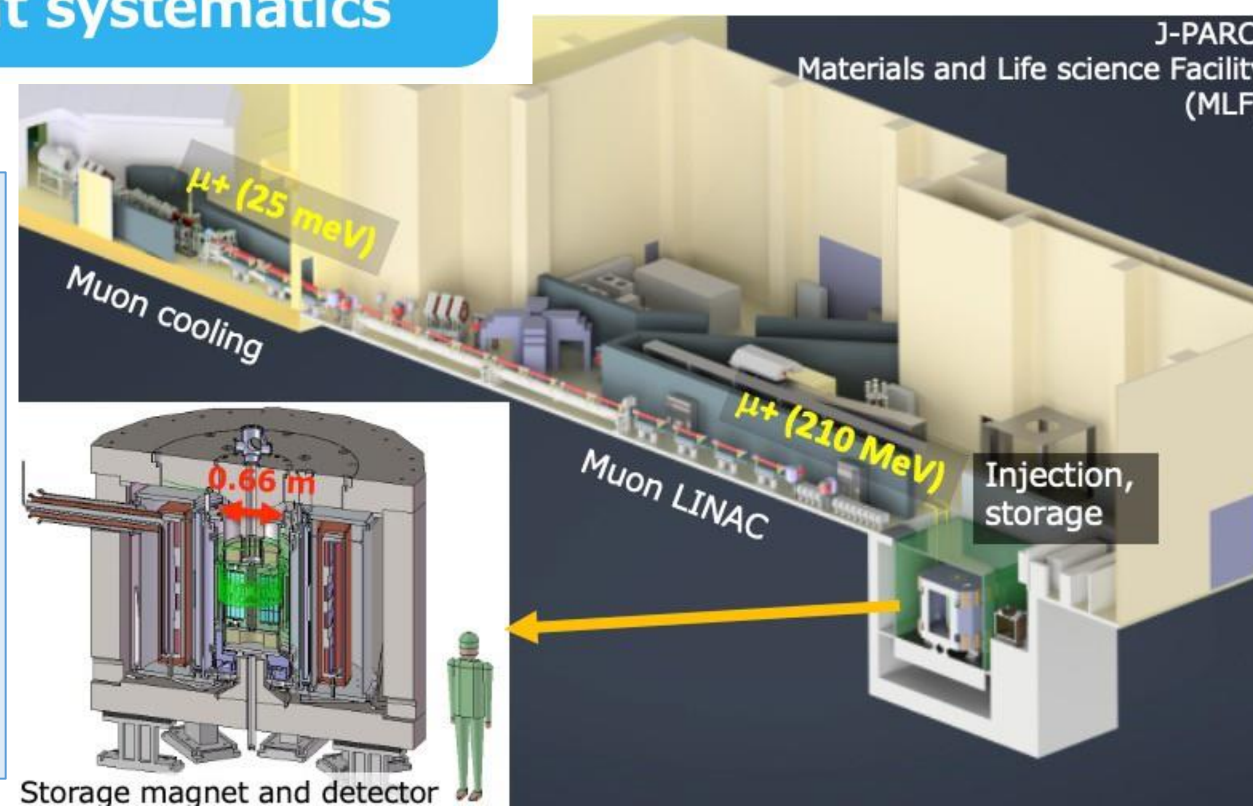
Other media articles in
Asahi shinbun, Yomiuri shinbunn,
Nikkei shinnbun, Tokyo-Chunichi shinbunn,
Jiji tushin, Nikkei Science, Newton

physicsworld TOP 10 BREAKTHROUGH 2021

https://physicsworld.com/a/physics-world-announces-its-finalists-for-the-2021-breakthrough-of-the-year/

Features of the J-PARC experiment

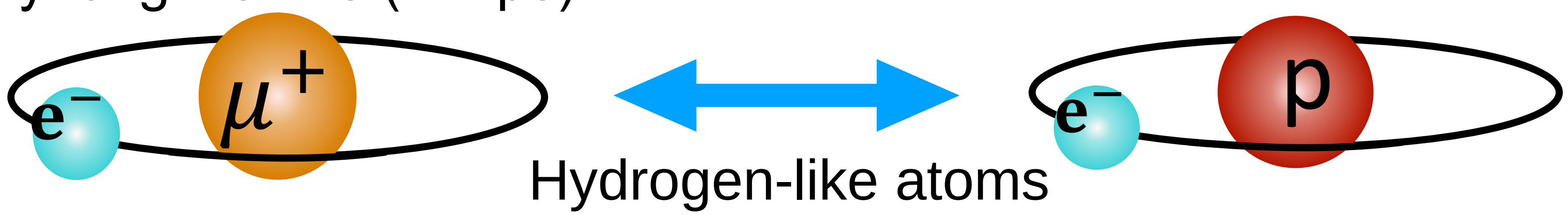
- **Low emittance beam** (1/1,000)
  - Improvements
    - High injection efficiency (x10)
    - Compact storage ring (1/20)
      - Better field uniformity (x10)
    - High granularity tracking detector (x10)
- Simultaneous measurement of EDM (x70 better)



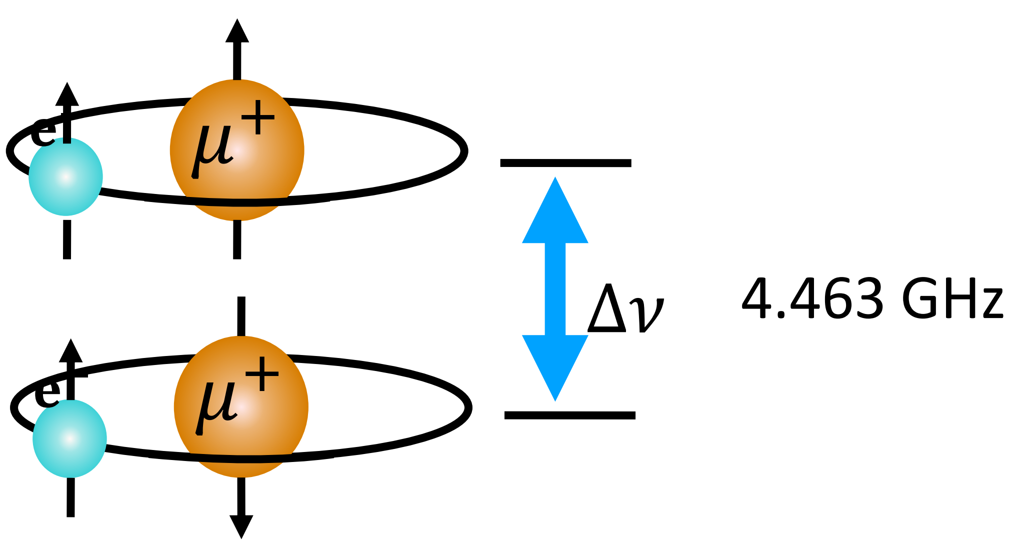
Muonium

Muonium

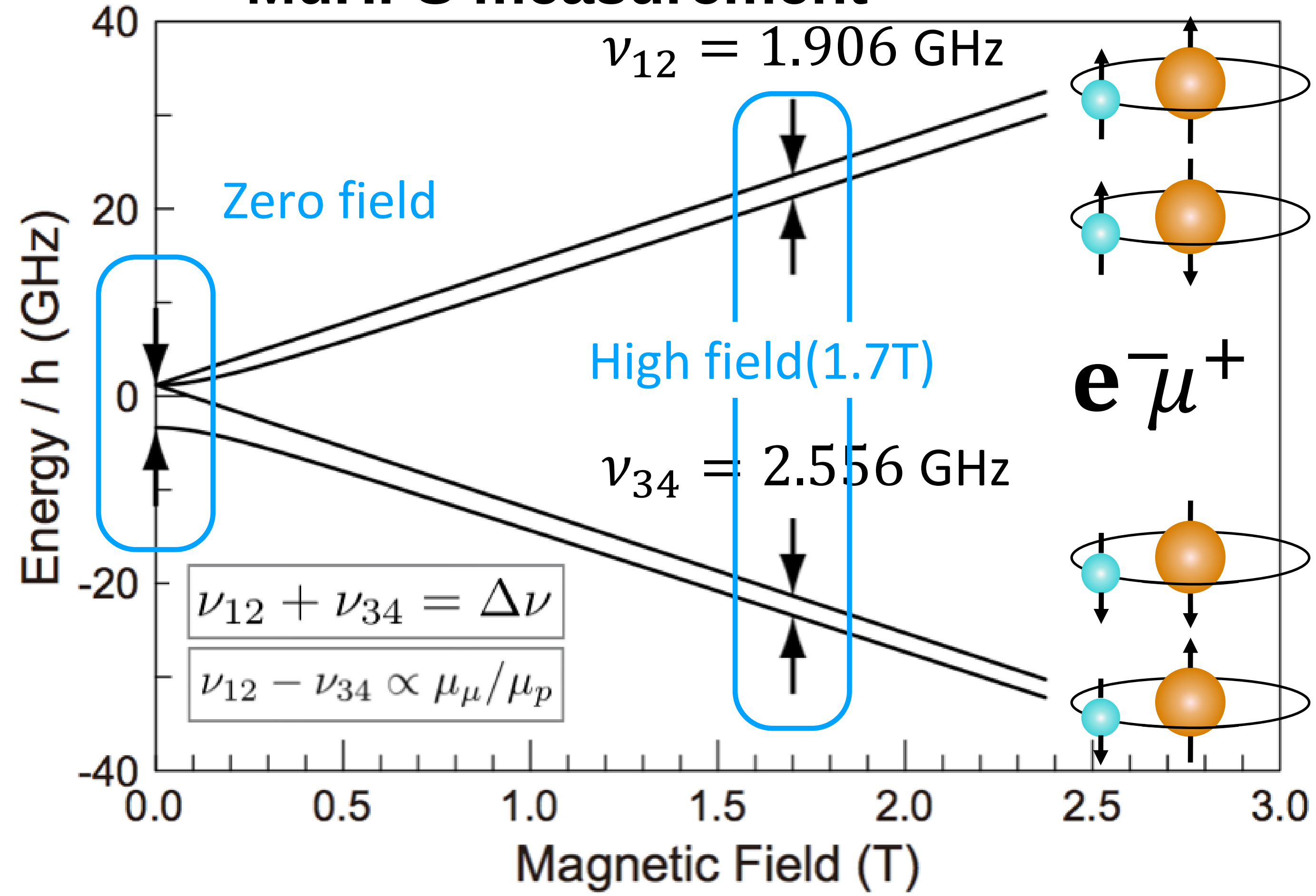
- The bound state of μ^+ and e^-
- No internal structure
- Relatively long lifetime (2.2 μs)



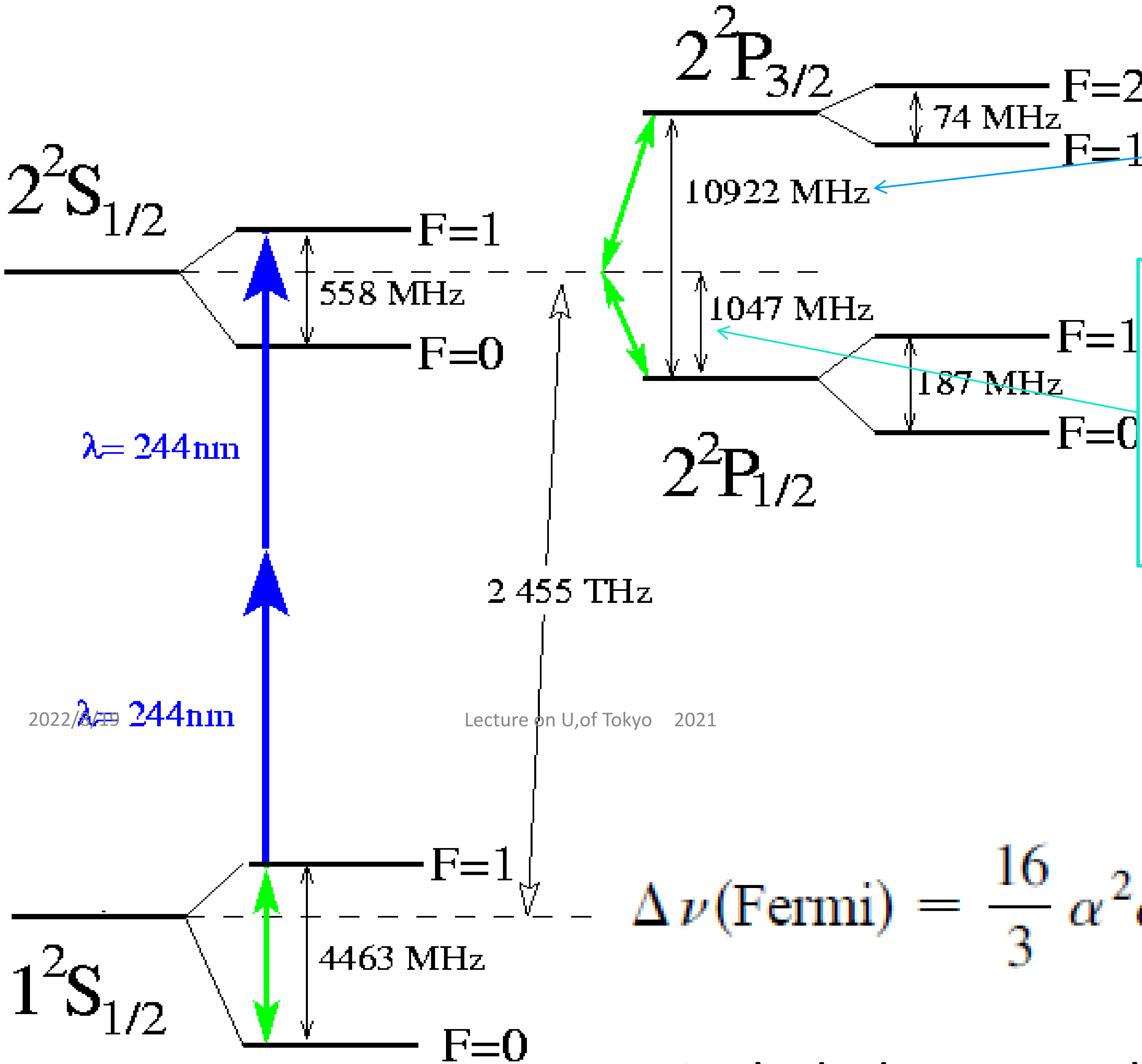
- **Muonium Hyperfine Structure (MuHFS:$\Delta\nu$)**



- **Two independent methods for the MuHFS measurement**



Mu Energy Diagram



Fine Structure explained by Dirac

Classical Lamb Shift
QED
Tomonaga, Shwinger, Feynman

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

Not included QED weak hadronic correction

Precise measurement of Mu HFS

- The most rigorous validation of the bound-state QED

ν_{HFS}(exp) 4463.302 765(53) MHz (12 ppb) LAMPF1999

μ_μ/μ_p =3.18334524(37) (120ppb)

m_μ/m_e=206.768277(24) (120ppb)

ν_{HFS}(theory) 4463.302 891 (514) MHz (121 ppb) D. Nomura (2013)

ν_{HFS}(QED) 4463.302 720 (512) (98) (3) MHz(m_μ/m_e) (QED) (α)

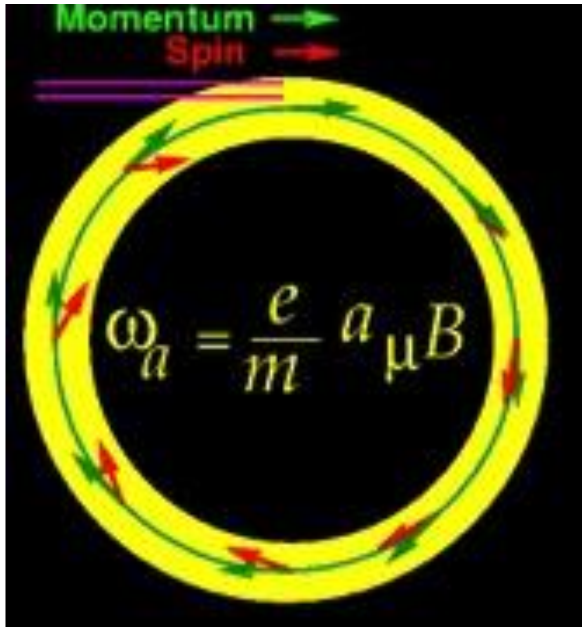
ν_{HFS}(weak) -65 Hz

ν_{HFS}(had v.p) 232(1) Hz

ν_{HFS}(had. h.o) 5 Hz

QED calculation →Effort for 10 Hz is in progress by Eides *et al*.
Phys. Rev. A **86**, 024501 (2012), PRL.. 112, 173004 (2014),
Phys. Rev. D **89**, 014034 (2014)

Precise measurement of Mu HFS



- Strong relationship with muon *g*−2
  - 4.2σ deviation btw. theory and experiment

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right] \qquad a_\mu = \frac{g-2}{2}$$

  - Angular frequency of spin precession ω

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

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

From *g*−2 storage ring

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

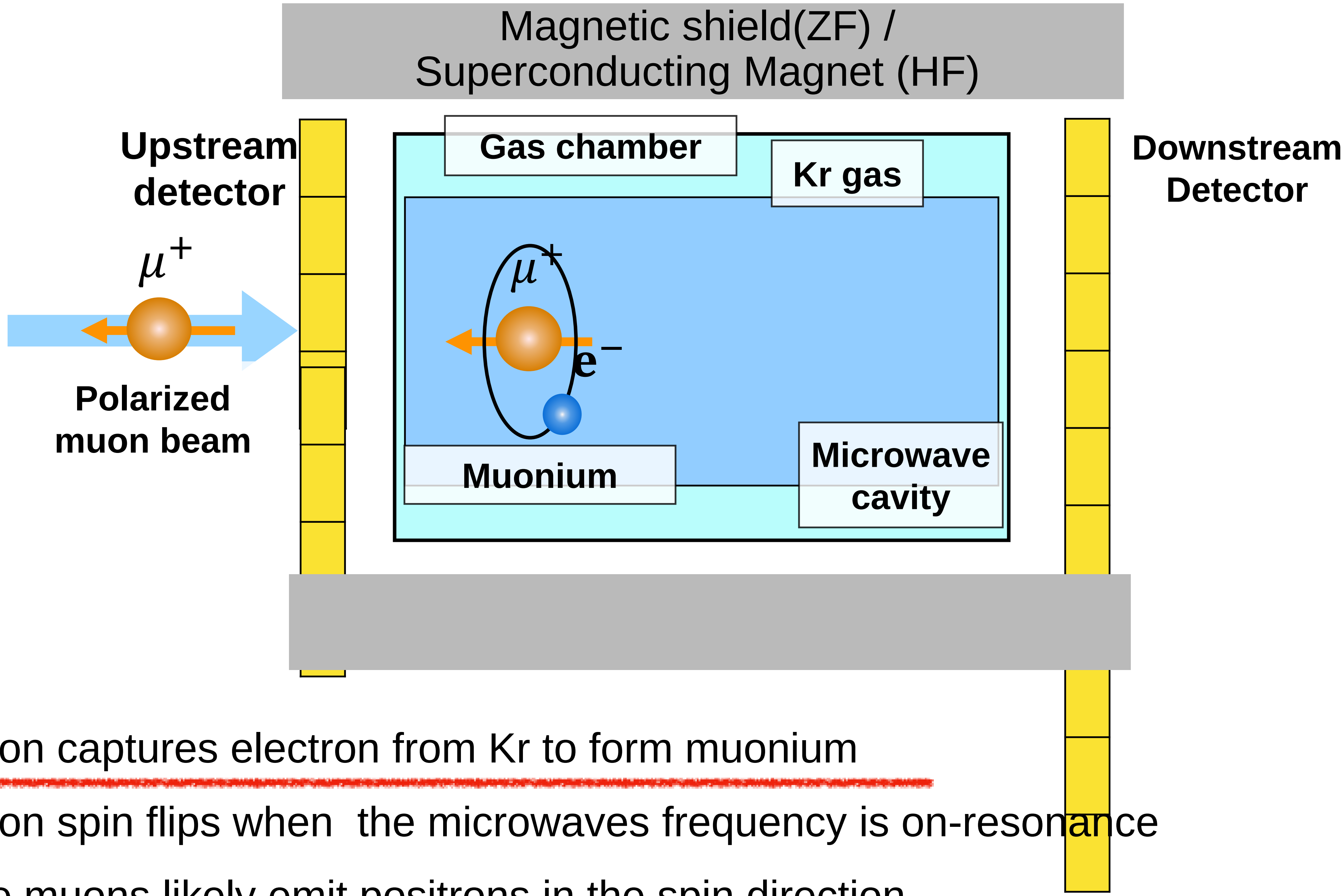
From muonium HFS

  - It is important to measure precise **muon mass** independently

 μ_μ/μ_p accuracy from direct measurement 120ppb

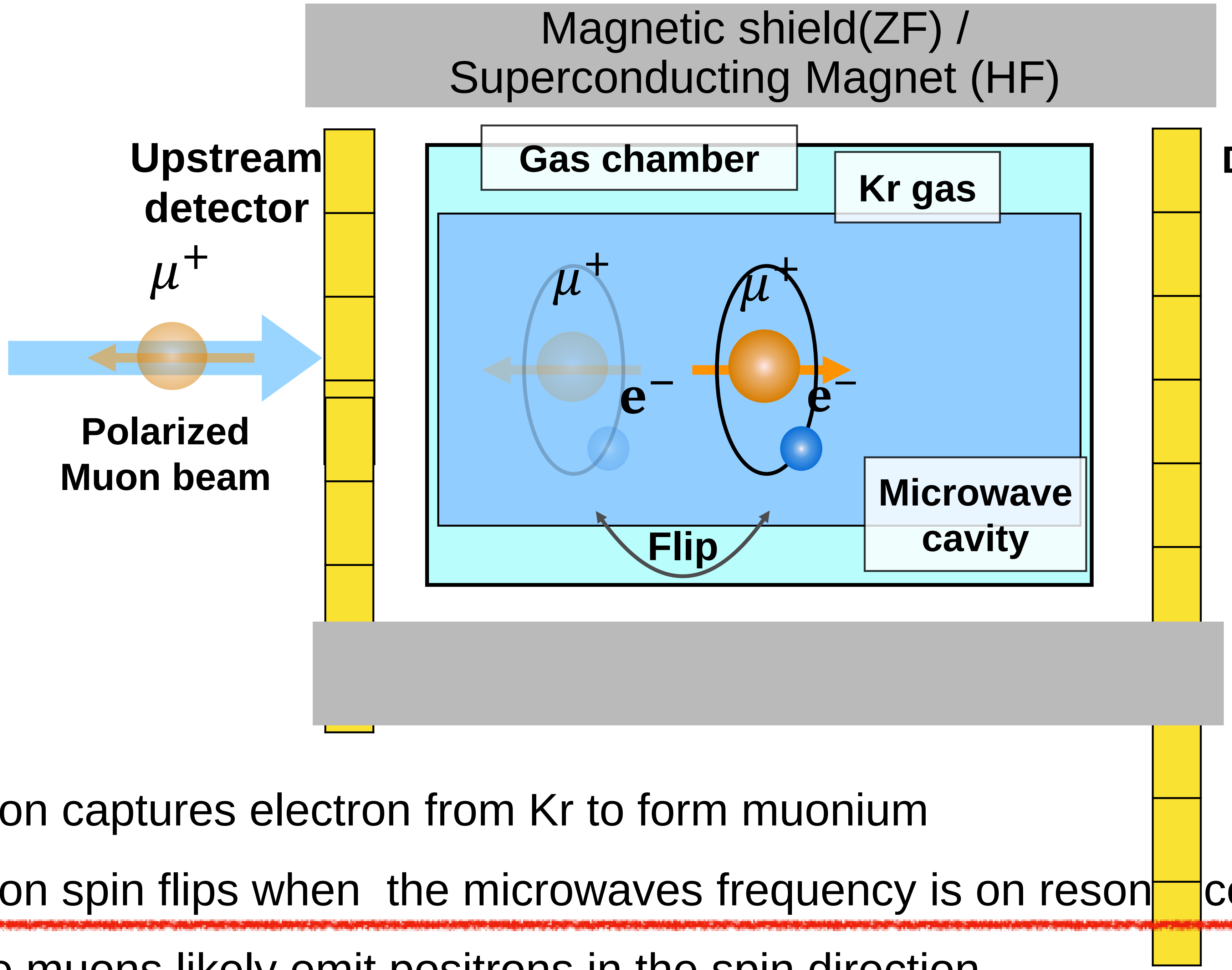
W. Liu *et al.* , *Phys. Rev. Lett.* ***82*** **,** ***711 (1999***

Experimental Procedure



- Muon captures electron from Kr to form muonium
- Muon spin flips when the microwaves frequency is on-resonance
- The muons likely emit positrons in the spin direction
- MuHFS is determined from the relationship between microwave frequency and asymmetry of the counts in the downstream/upstream detectors.

Experimental Procedure



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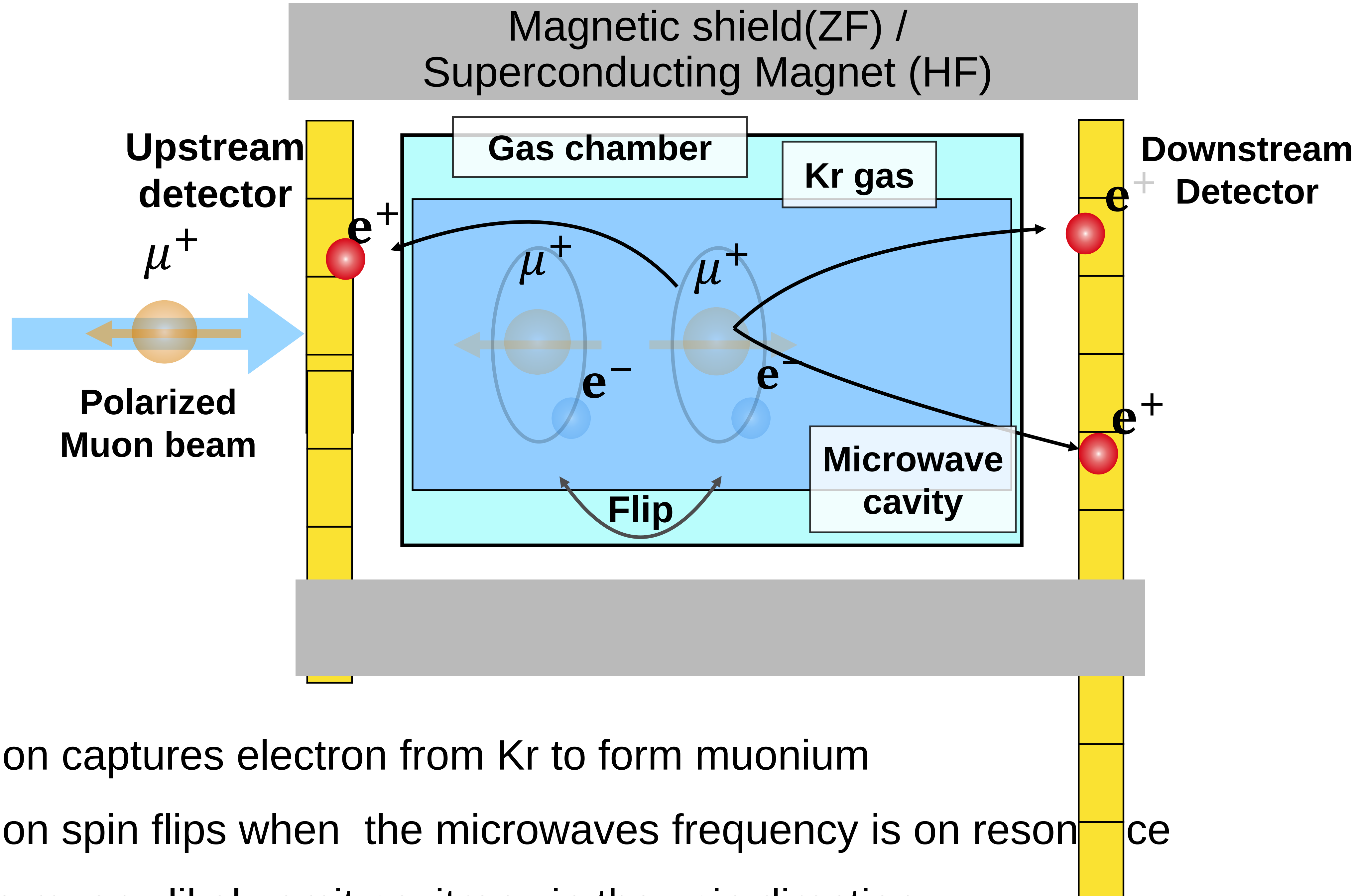

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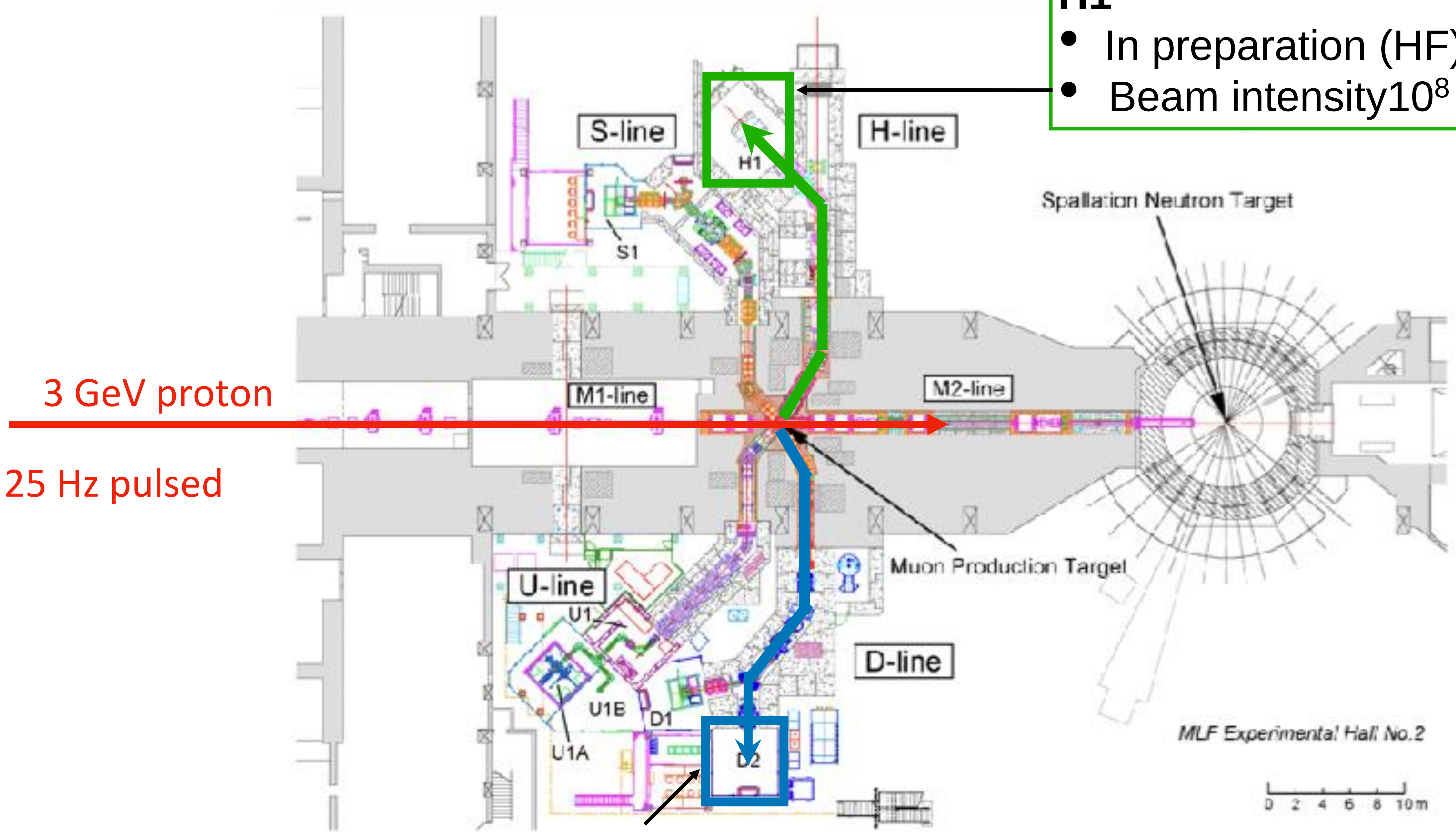
Beam Line @J-PARC MLF MUSE

H1
- In preparation (HF)
- Beam intensity10^8 μ^+/s

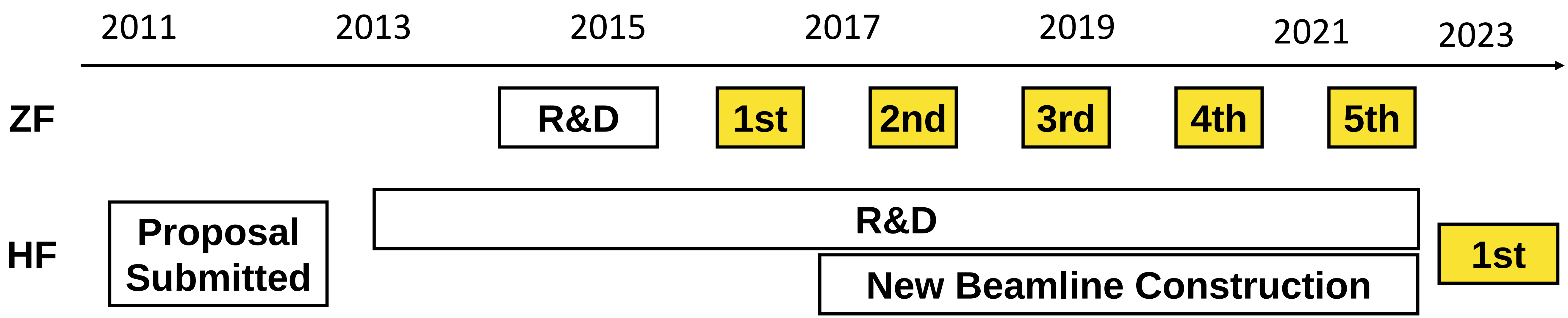


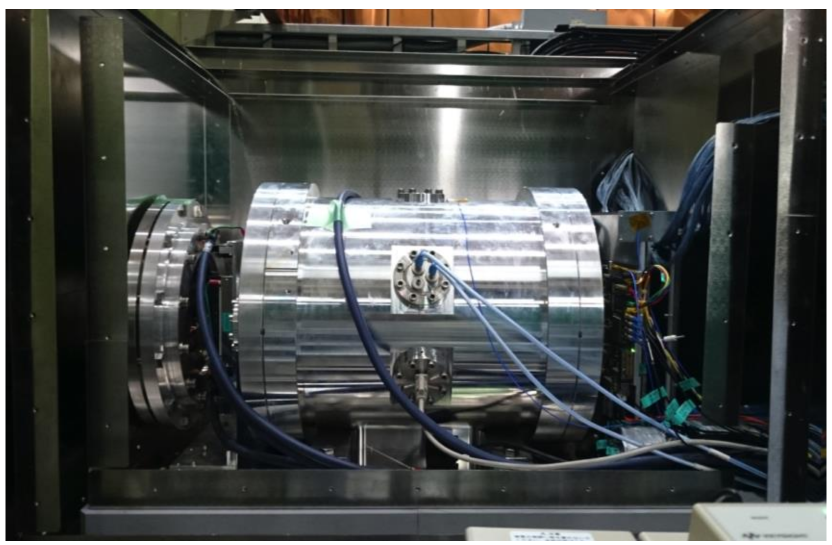
D2
- Completed (ZF)
- Beam intensity 6×10^6 μ^+/s (0.6 MW)

N. Kawamura et al., PTEP 2018 (2018). doi:10.1093/ptep/pty116, 113G01.

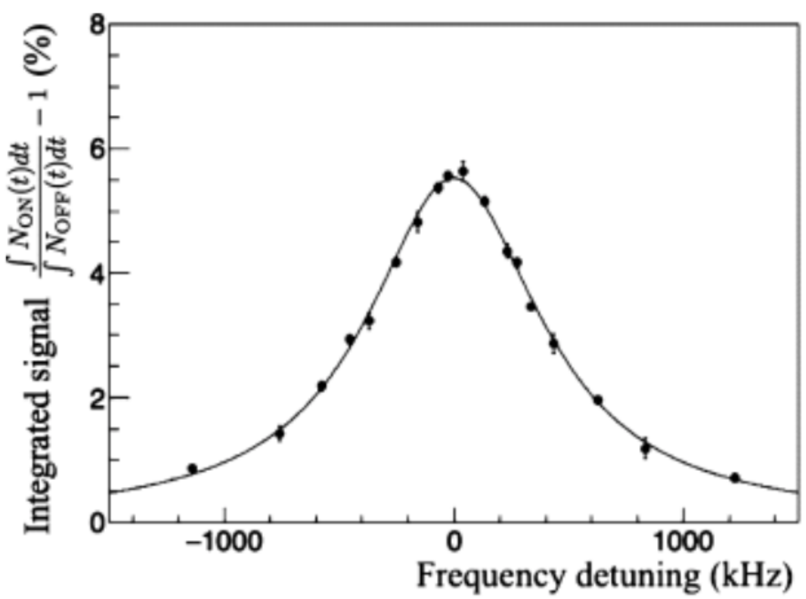
W. Higemoto, *Quantum Beam Sci*. **1** (2017) 11.

Status of MuSEUM (2014 - 22)



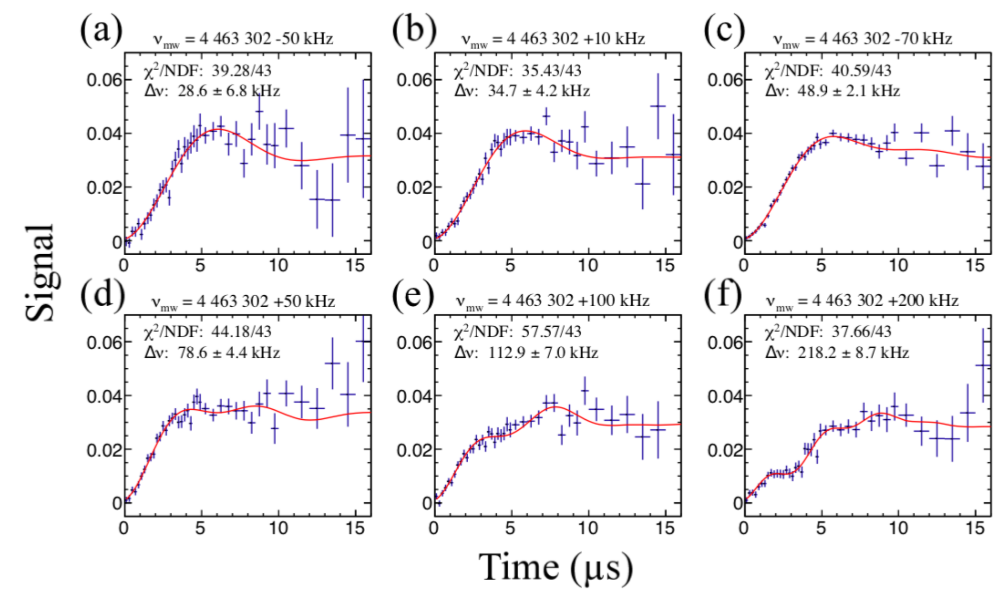


Experimental setup



resonance result(in 2016)

S. Kanda et al., Phys. Lett. B 815 (2021) 136154.

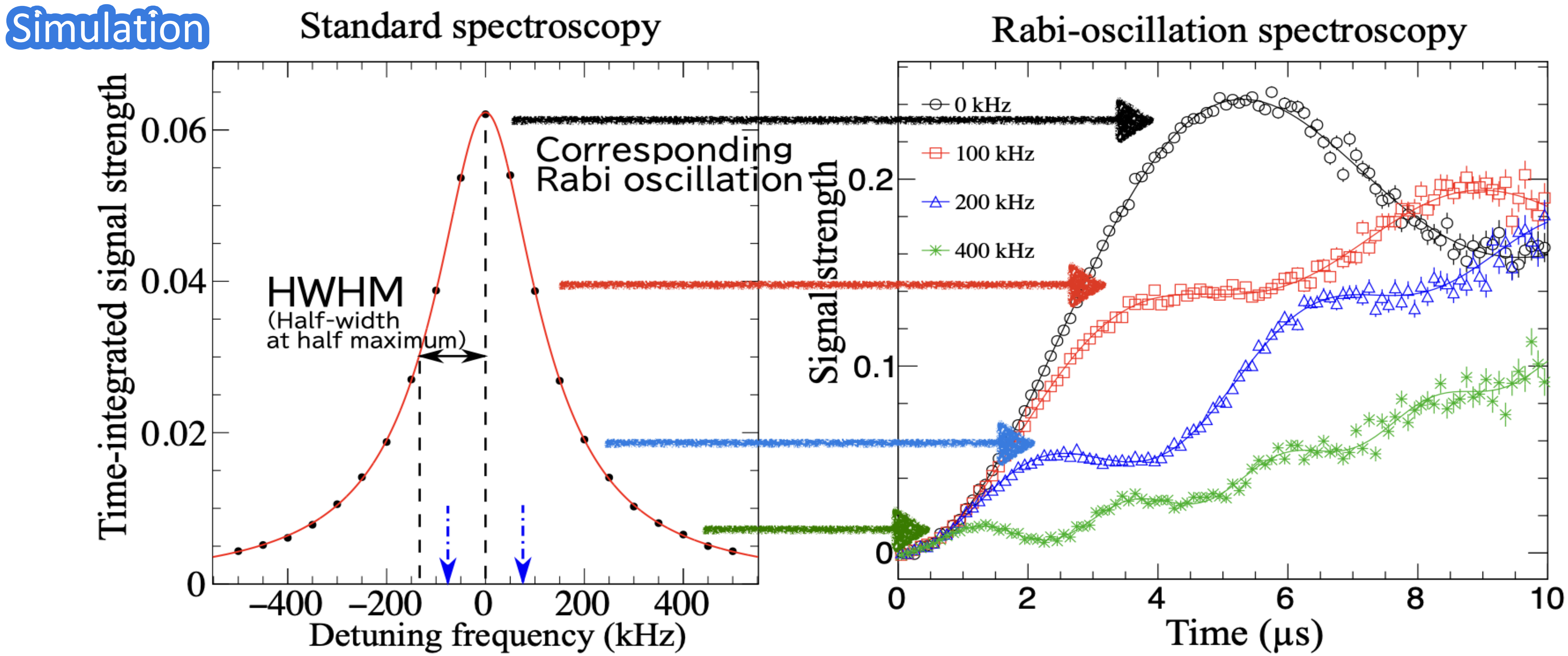


Rabi-oscillation spectroscopy

S. Nishimura et al., Phys. Rev. A 104 (2021) 020801

- Until the construction of the HF beamline, ZF experiments were conducted at the existing beamline to verify the principle.
- Developed Rabi-oscillation spectroscopy, reaching an accuracy of 160 ppb (a world record for the zero field experiment).
- We are preparing for the first HF experiment.

Comparison of conventional and Rabi-oscillation spectroscopy



Standard

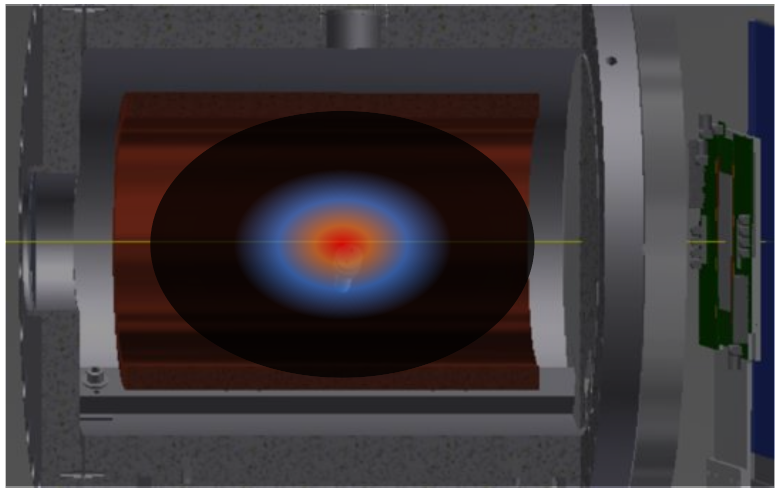
- Drawing the resonance curve with microwave frequency sweep
- Asymmetry in the microwave power across a resonance line would lead to difficulties in extracting the line center

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



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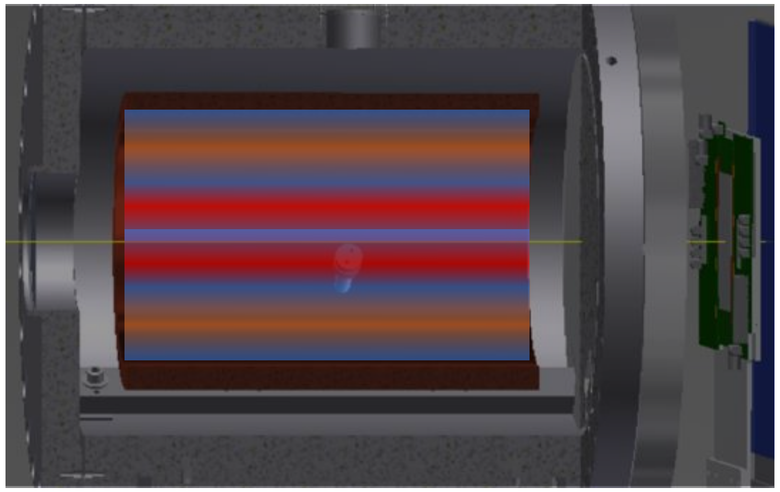

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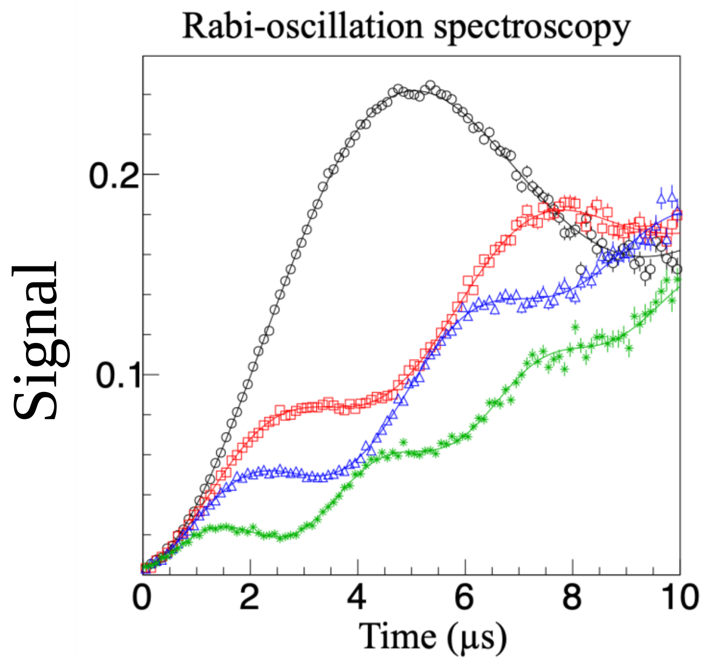
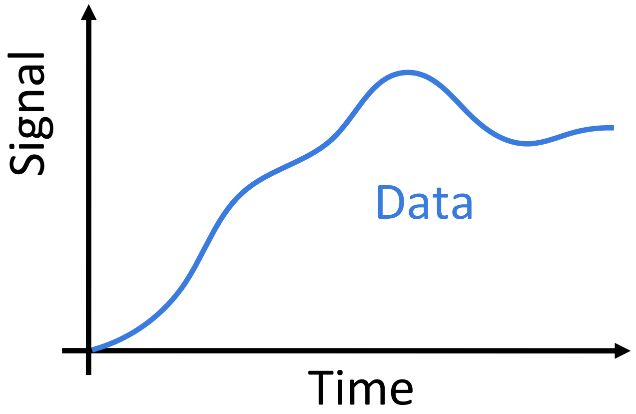


Muon stopping distribution

Microwave power distribution

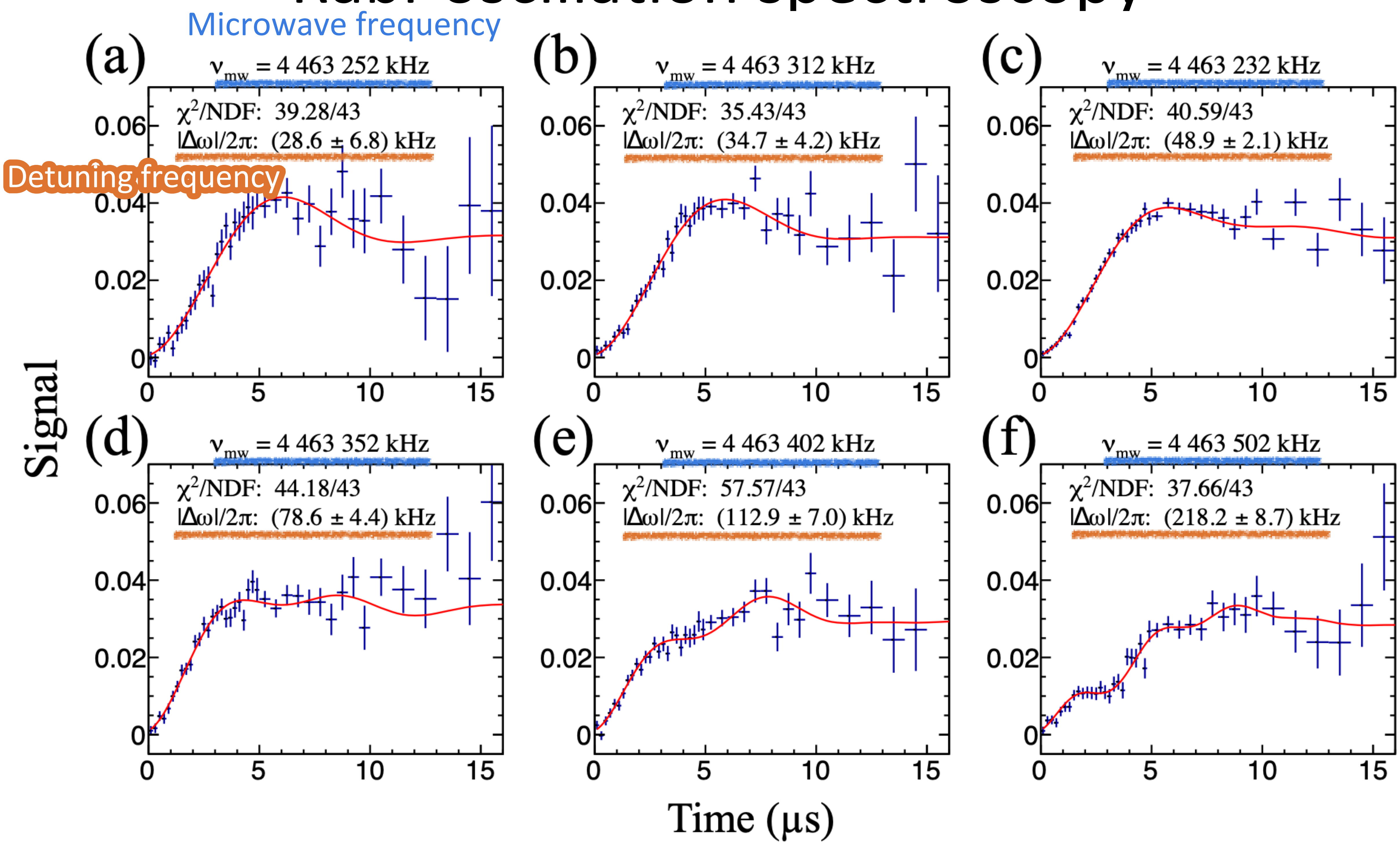
Rabi-oscillation signal from all muonium

Fit estimated signal to the obtained data

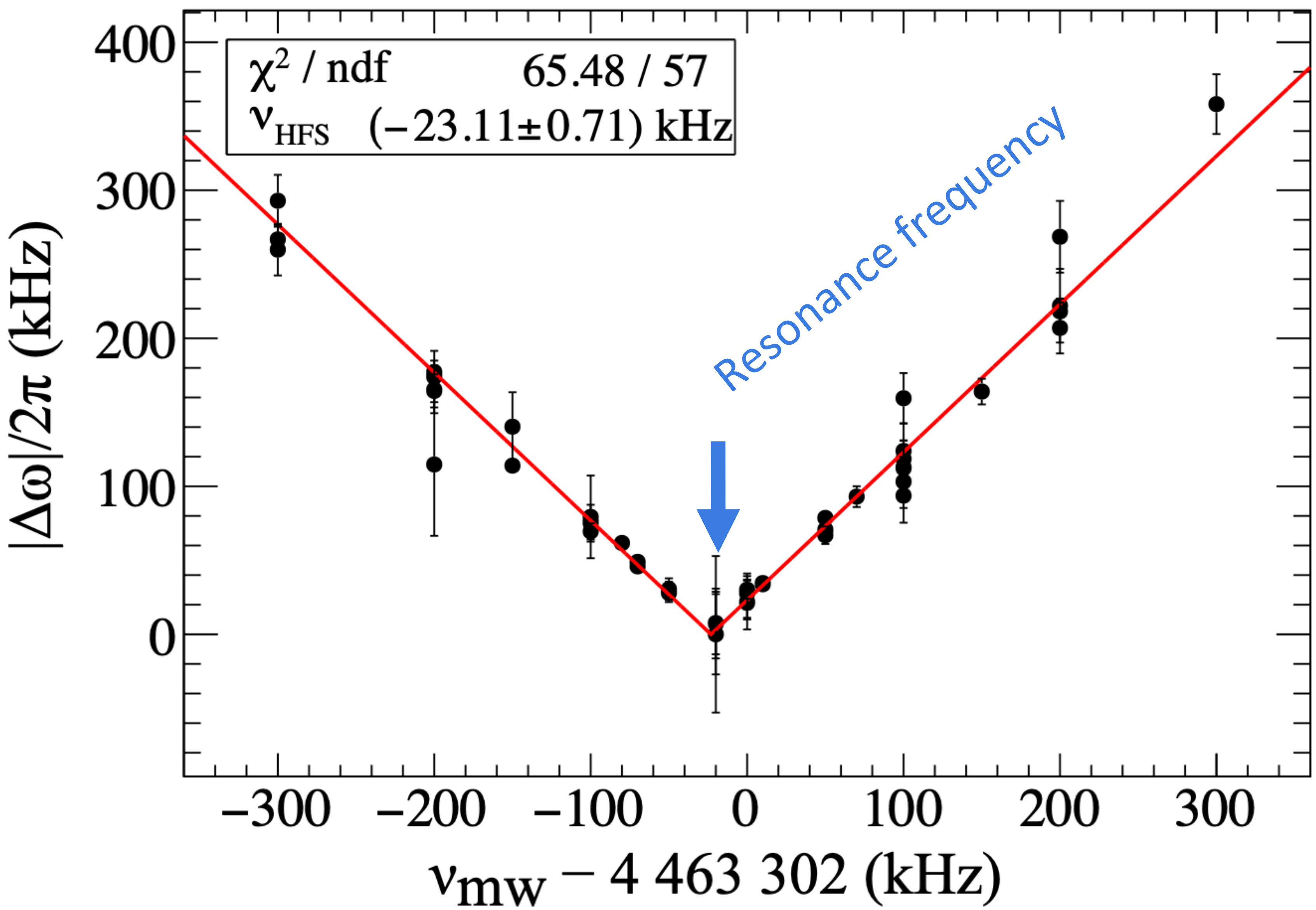


We can obtain the detuning frequency from the single microwave frequency data

Results of Rabi-oscillation spectroscopy



Results of Rabi-oscillation method (multiple microwave frequency)



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

New Muon Beamline

- T. Yamazaki, N. Kawamura, A. Toyoda (KEK).
- A. Toyoda et al., "J-PARC MUSE H-Line optimization for the g-2 and MuHFS experiments", J. Phys.: Conf. Ser. 408 012073 (2013).
- N. Kawamura, et al., "New concept for a large-acceptance general-purpose muon beamline", PTEP 113G01 (2018).

- A high-intensity beamline is under construction that can provides beams of $1 \times 10^8 \mu^+/s$ or more.

LAMPF : $2 \times 10^6 \mu^+/s$

J-PARC D Line : $5 \times 10^6 \mu^+/s$
(MuSEUM ZF)

- **First beam was provided from 2022.Jan. !**

- **In high field experiments, the statistical accuracy reaches 5 Hz (1.2 ppb) after 40 days of the measurement.**

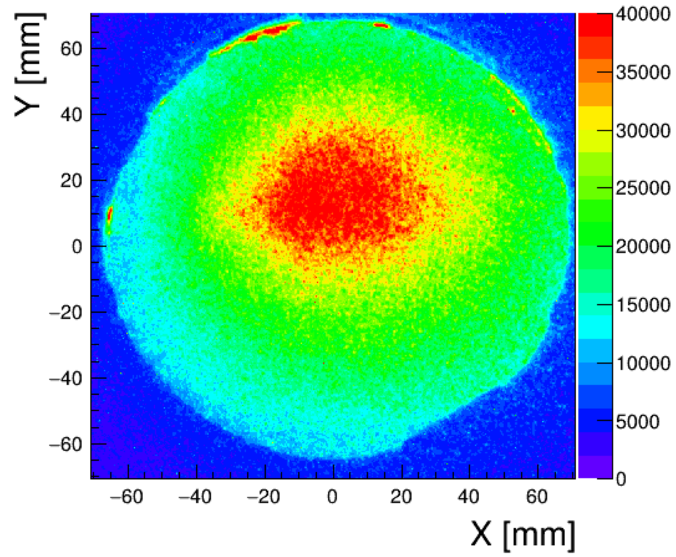
New muon H-line starts operation!

First beam on Jan. 15th, 2022!

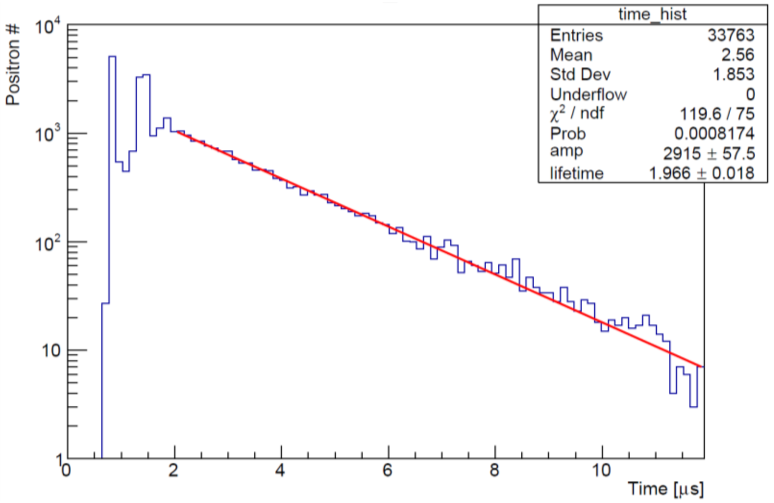
Beam commissioning is on-going with many members and groups

KEK, SOKENDAI, Osaka city university, Osaka university, Nagoya University, Niigata university, Ibaraki university, and Kyushu university

Muon beam profile
σ_x=44mm, σ_y=24mm

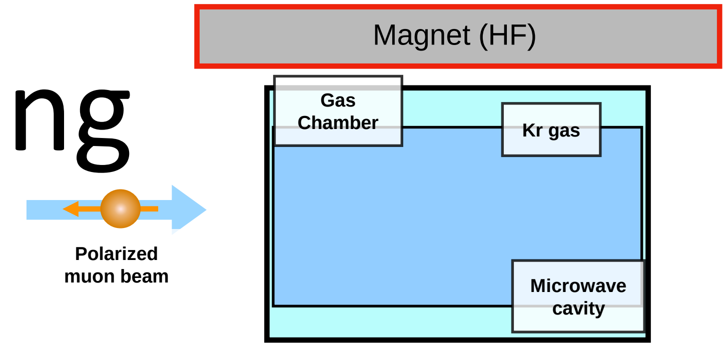


Time spectrum of muon decays



Muon intensity is roughly consistent with our expectation (>10^8 /s with1MW).

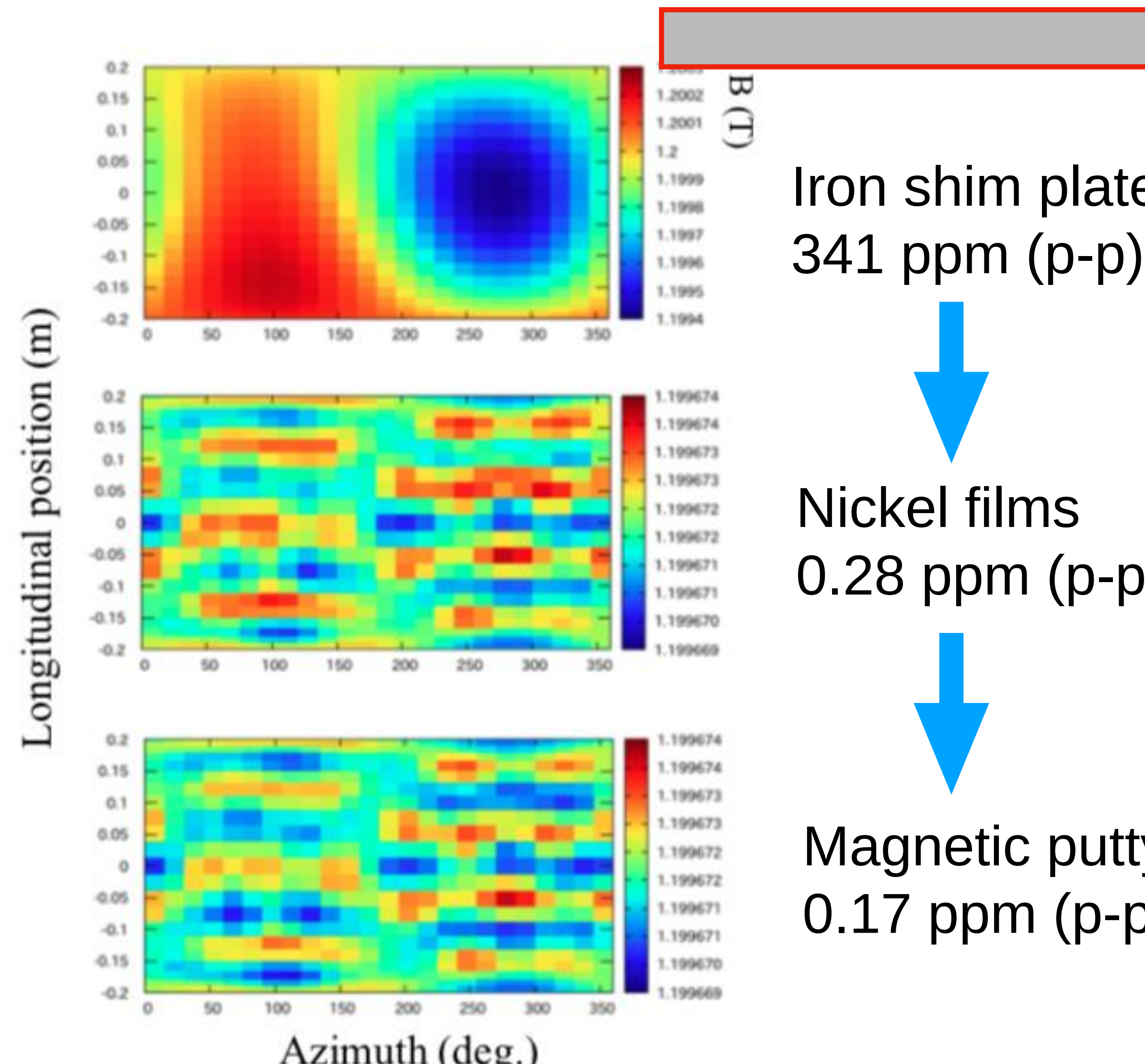
Magnet & Passive Shimming



Superconducting Magnetic field : 1.7T

Requirements for the field are

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



Iron shim plates
341 ppm (p-p)

Nickel films
0.28 ppm (p-p)

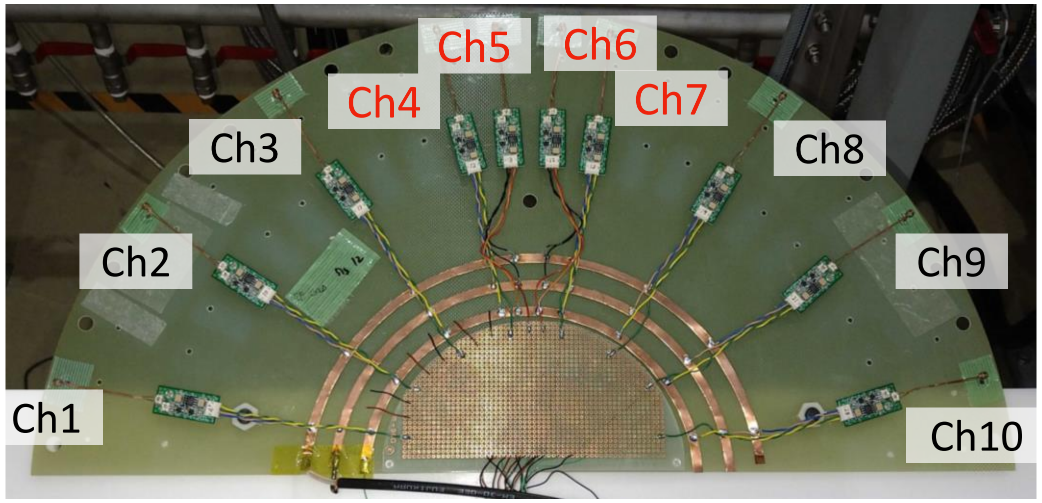
Magnetic putty.
0.17 ppm (p-p)

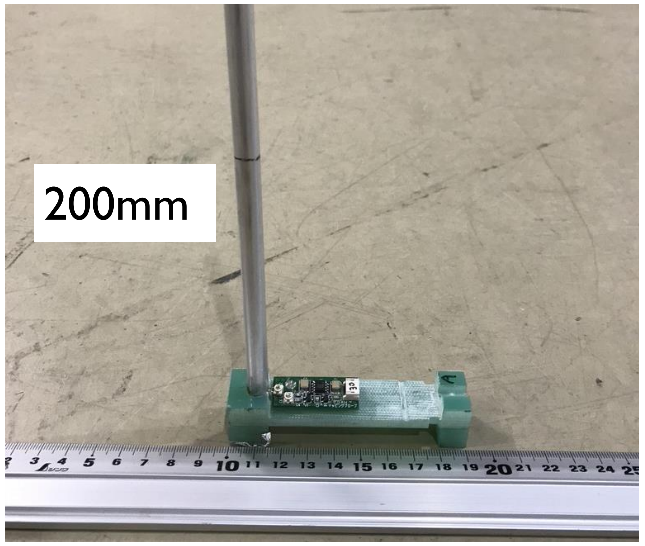
Shimming process by passive shimming method (1.2 T)

The accuracy of the magnetic field is an important point for high field experiments.

M. Abe, magn. reson. med. sci., vol. 16, no.4, Oct. Pp. 284-296,2017.
K. Sasaki, et al., IEEE Trans. Appl. Supercond.,10.1109/TASC.2022.3190803 (2022).

NMR Probes (by Tada *et al.*)





Three types of probes

A) Standard probe (Almost prepared)

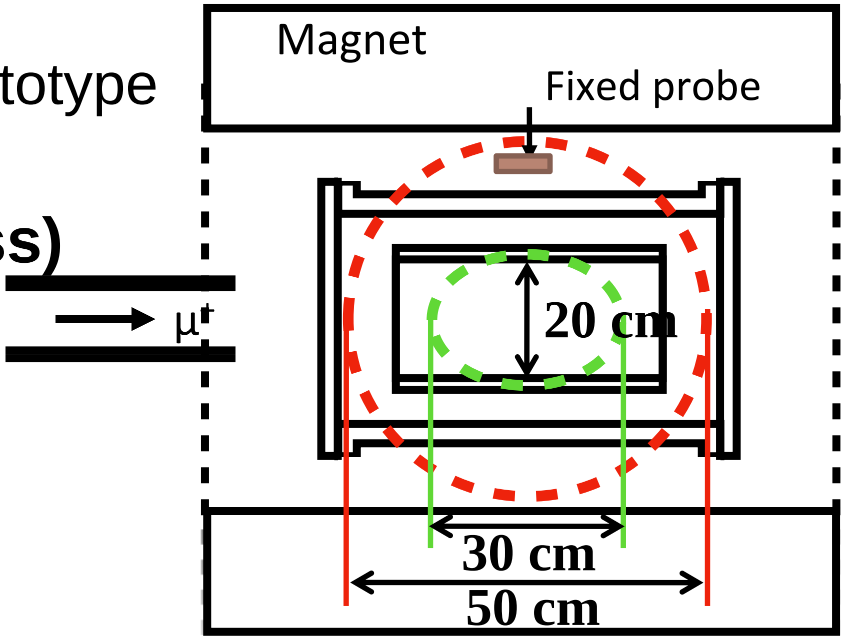
- A high-precision NMR probe to calibrate others.
- An accuracy of 15 ppb has been achieved.
- Cross-calibration is underway in a joint research project between Japan and the US.

B) Field camera (in progress)

- A 24-channels rotating NMR probe that maps magnetic fields.
- Developed two types : large and small
- Used for shimming
- Developed 10-channels prototype

C) Fixed probe (in progress)

- A compact probe to monitor magnetic field stability during experiment.



H. Yamaguchi, IEEE Trans. Appl. Supercond. Vol. 29, no. 5, Aug. 2019, Art. no. 9000904
H. Tada et al., IEEE Trans. Appl. Supercond.,10.1109/TASC.2022.3190264 (2022).

Expected Precision

HFS uncertainty for high field experiments

Contents	Uncertainty (Hz)	
B-Field and NMR probe	0	The NMR probe under development and passive shimming method
Gas	3	the new high-precision silicon gauge
Power drift	Less than 1	the temperature control
Pileup	2	the segmentation and front-end electronics
Impurity	Less than 1	the Q-Mass monitoring

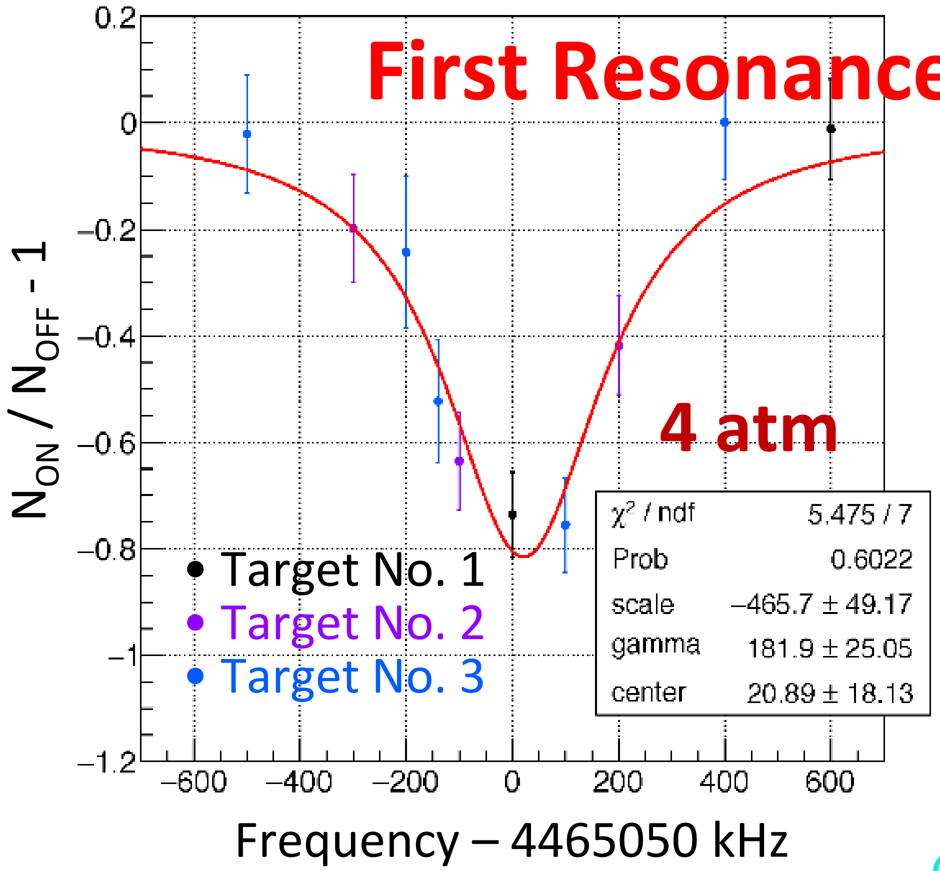
- B-Field and NMR probe accuracies will give an uncertainty of 8 ppb in the magnetic moment ratio μ_μ/μ_p.

We are aiming for a precision of 5 Hz, a ten-fold improvement from the 53 Hz of the previous experiment.

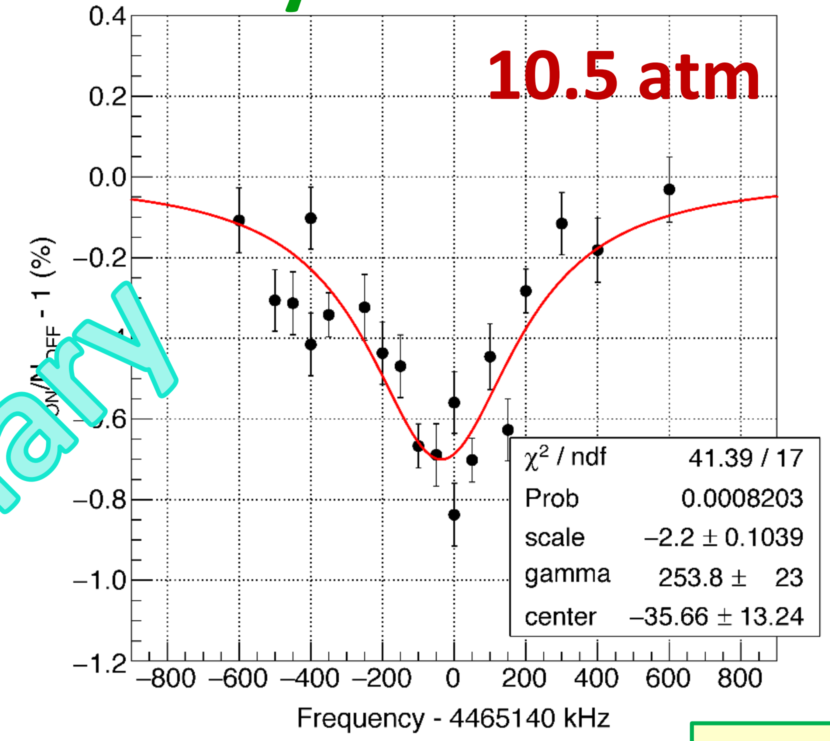
MuHe HFS Resonance Curve

March 11–17, 2021 Beamtime

First Resonance Observed



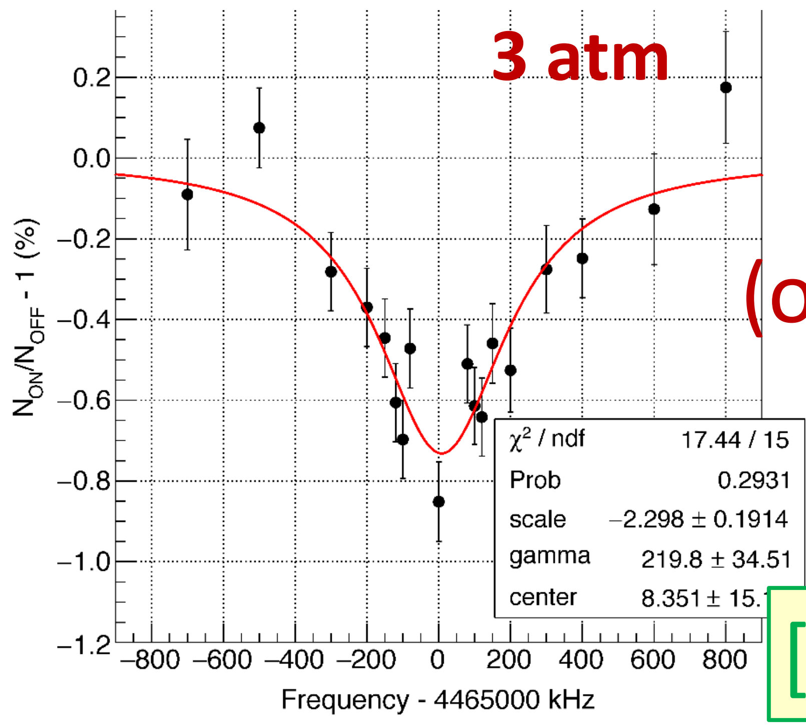
February 2022 Beamtime



Very Preliminary

[2021B0169]

May 2022 Beamtime



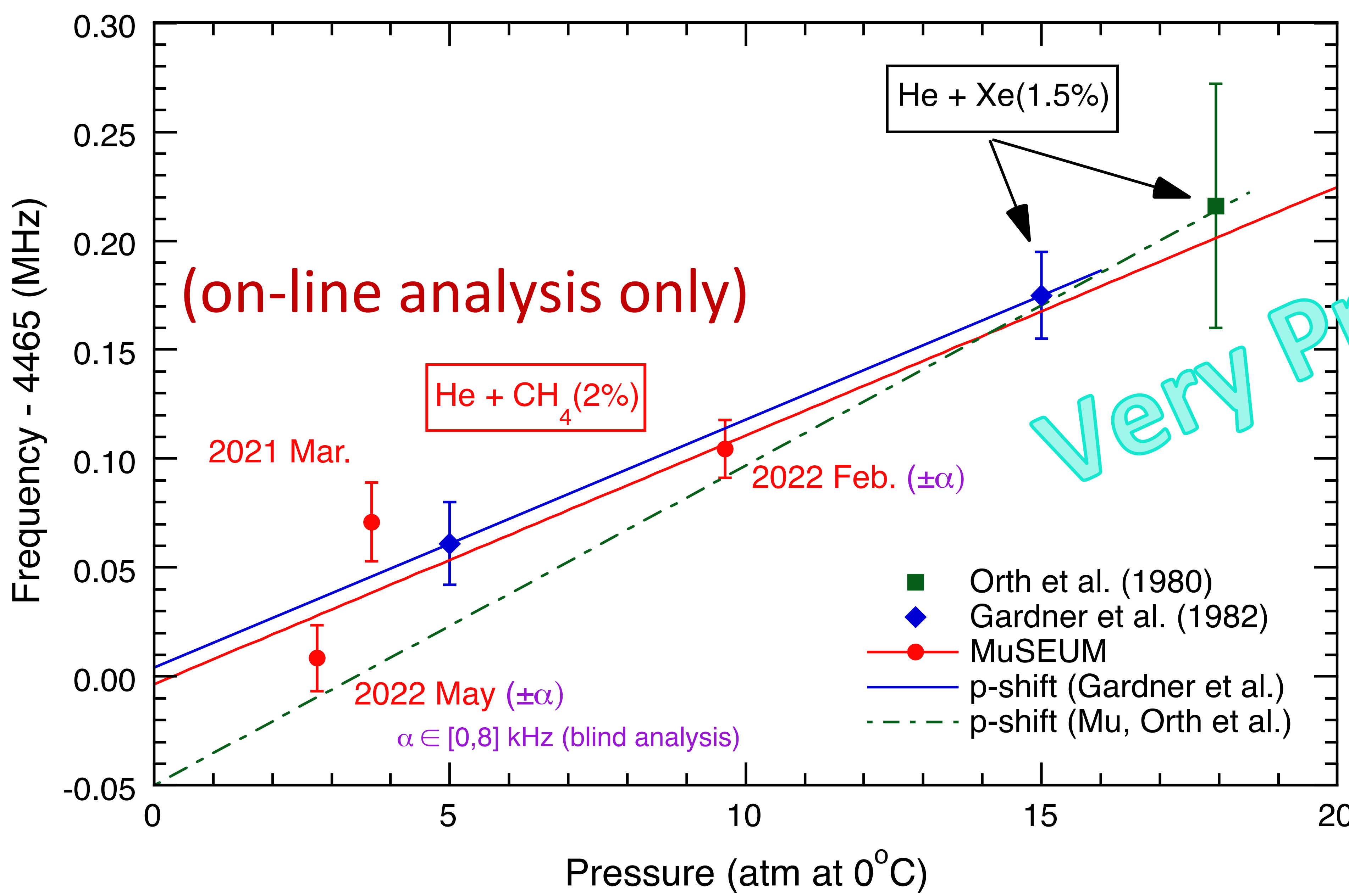
(on-line analysis onl

[2020B0333]

[2022A0159]

Time cut: electron data from 2 μs after second μ^- pulse !

Extrapolation to Zero Pressure



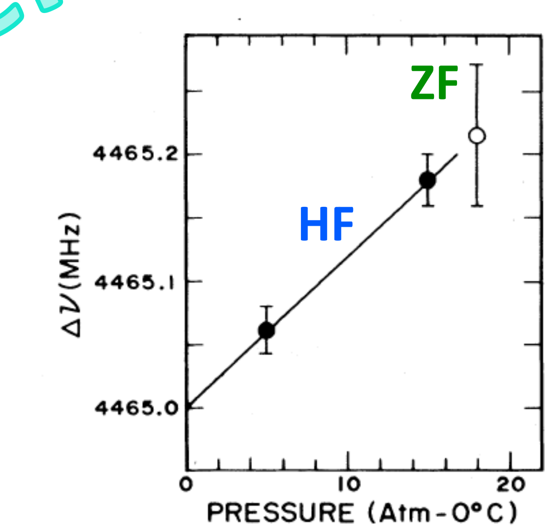


FIG. 2. Δν as a function of He+Xe(1.5%) gas pressure. Closed circles show the results of this experiment; the open circle is the result of Ref. 3. The straight line shows the linear extrapolation used to extract Δν(0).

$\Delta\nu$ = 4464.95(6) MHz (Orth et al.) [13 ppm] zero field (ZF)

$\Delta\nu$ = 4464.004(29) MHz (Gardner et al.) [6.5 ppm] high field (HF)

$\Delta\nu$ = 4464.997(18) MHz (MuSEUM) [4ppm] zero field

Tentative Result !!
"Blind" Analysis in progress

- **Probably a New World Record**

ZF: H. Orth et al., PRL 45 (1980) 1483
HF: C. J. Gardner et al., PRL48 (1982) 1168

Repolarization of Muonic He Atom

By spin exchange optical pumping (SEOP) with Rb vapors:

$(\mu^{-}He)^{+}$ ion will form molecular ion in few ns in high-pressure He gas (~10 atm).

(1) Polarization through dissociation of molecular ion $He(\mu^{-}He)^{+}$ via:

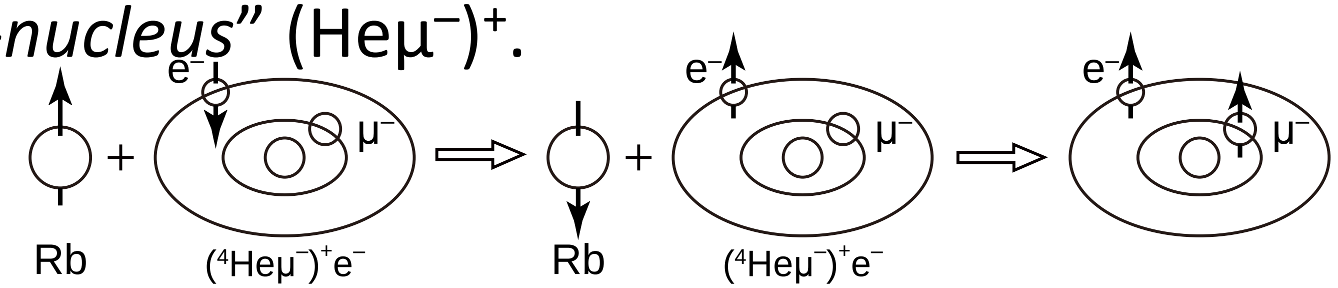
$$Rb\uparrow + He(\mu^{-}He)^{+} \rightarrow Rb^{+} + He + (\mu^{-}He)^{+}\, e^{-}\uparrow$$

After the charge exchange, the "*pseudo-nucleus*" $(He\mu^{-})^{+}$ and the polarized e^{-} are coupled through the HFS interaction, thus polarizing the muon.

(2) After neutral muonic atom formation, further polarization via:

$$Rb\uparrow + (\mu^{-}He)^{+} e^{-}\downarrow \rightarrow Rb\downarrow + (\mu^{-}He)^{+}\, e^{-}\uparrow$$

After short-lived collisions the polarization of the transferred e^{-} is shared with the "*pseudo-nucleus*" $(He\mu^{-})^{+}$.



for $\mu^{4}He$: 6% → 44%

Improvement by a factor 7 possible !

Muon Polarization in Muonic He

Glass cell target: (T ≈ 200°C)

- Sphere: ~Ø2.5 cm x 100-μm^t
- He: 8 atm
- Rb: 4.4 x 10^{14} atoms/cm^3
- N_2 : 75 Torr
- CH_4 : up to 250 Torr

$$A(t) = \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}}$$

Rb polarization reversed every 2 min.

$$P_\mu(t) = \frac{A(t)}{f(t)a_e}$$

$f(t)$: fraction from He, a_e: analyzing power

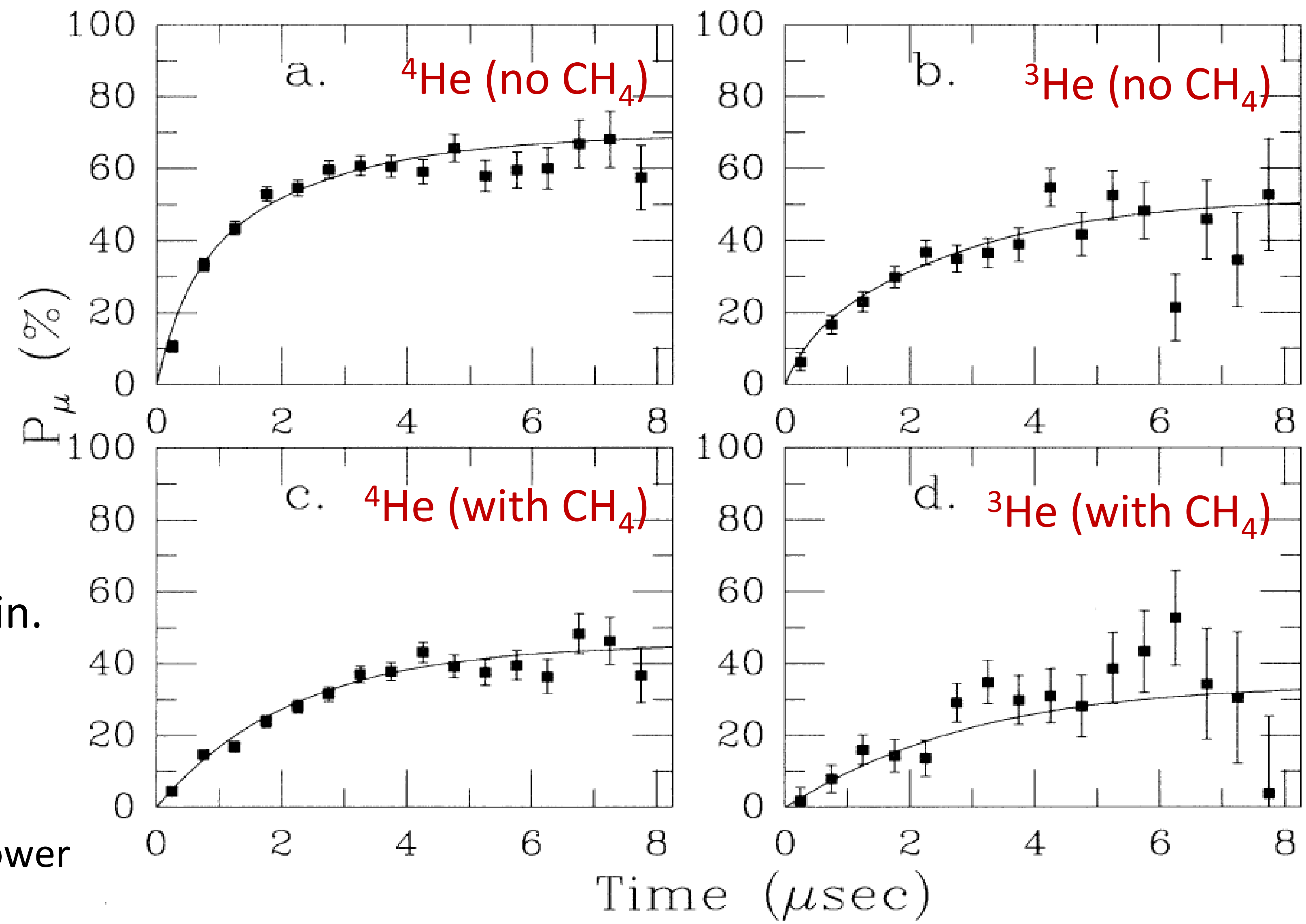


FIG. 1. Muon polarization as a function of time in muonic He. The four graphs correspond to four target cells: (a) ^{4}He without CH_4, (b) ^{3}He without CH_4, (c) ^{4}He with CH_4, and (d) ^{3}He with CH_4. The solid lines are given by (6) for (a) and (b), and by (5) for (c) and (d), where the numerical values of the parameters resulted from a global fit to all of the data (including the muonium data of Fig. 2).

A. S. Barton et al., Phys. Rev. Lett. **70**, 758 (1993)

SEOP for μHe HFS Measurements

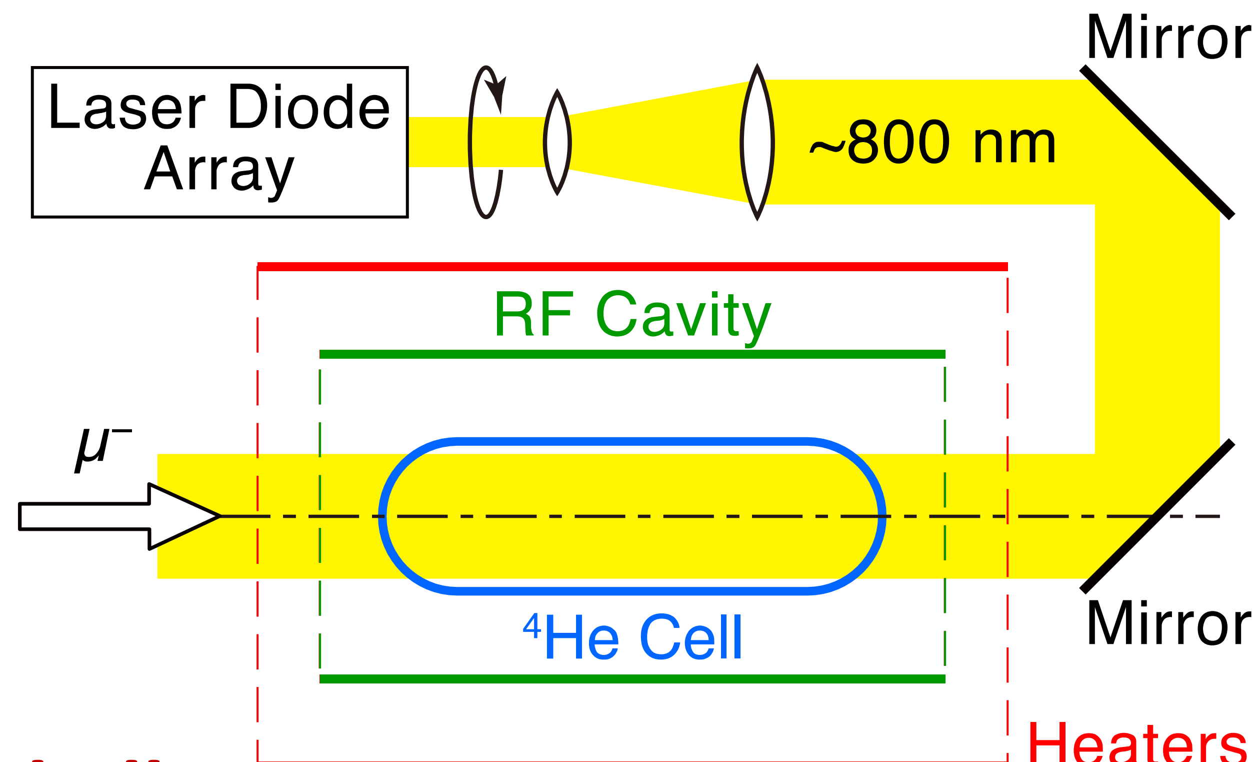
New MuSEUM-SEOP collaboration just started !

KEK: T. Ino, S. Kanda, S. Nishimura K. Shimomura
Nagoya Univ.: S. Fukumura, T. Okudaira, M. Kitaguchi, H. M. Shimizu
Tohoku Univ.: M. Fujita, Y. Ikeda (glass cell)
JAEA: T. Oku

Prototype Gas Cell

Ø74 mm x 152 mm
(picture from Ino San)

Schematic layout



Experimental Challenges:

- RF field inside glass cell (mesh windows, glass cell shape)
- SEOP in high magnetic field
- Magnetic field uniformity inside glass cell
- Gas pressure and temperature stability
- New systematics …

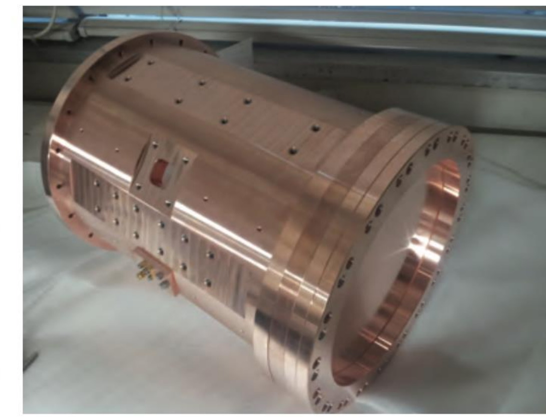
Papers on MuSEUM

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]

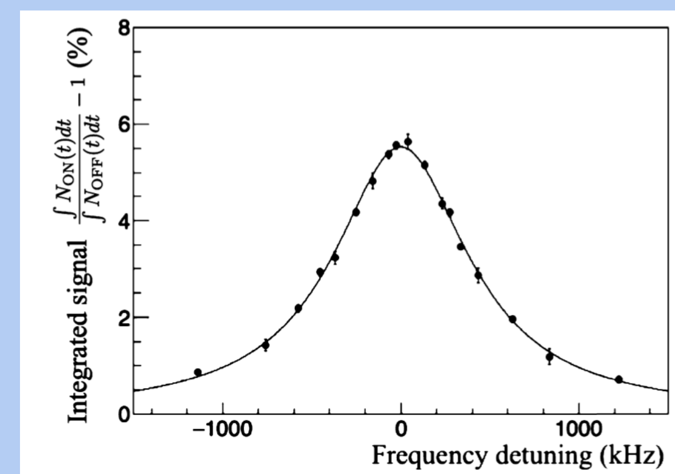


ZF experimental apparatus & first result

Contents lists available at ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb
ELSEVIER

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]

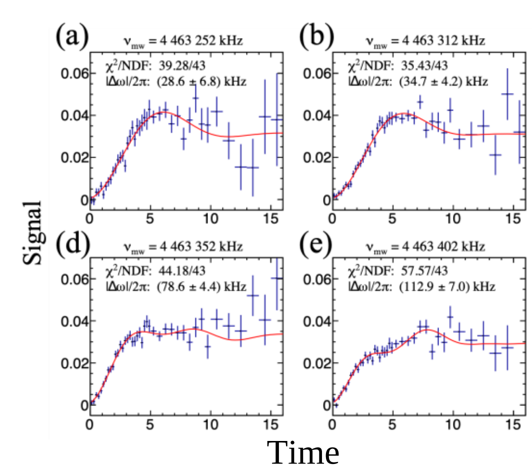


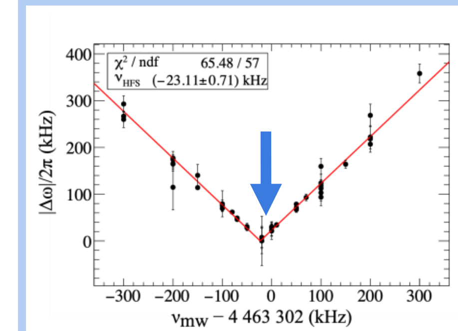
Rabi-oscillation spectroscopy

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)





Summary

- Muonium spectroscopy improves understanding of the Standard Model
- MuSEUM collaboration preparing for MuHFS measurements
- Proof of principle successfully completed with experiments at zero magnetic field
- High-field experiments are being prepared to achieve the highest accuracy
  →Development of the last component, the magnetic field measurement device, is underway
- High-field experiments are aimed for 2023 Jan.