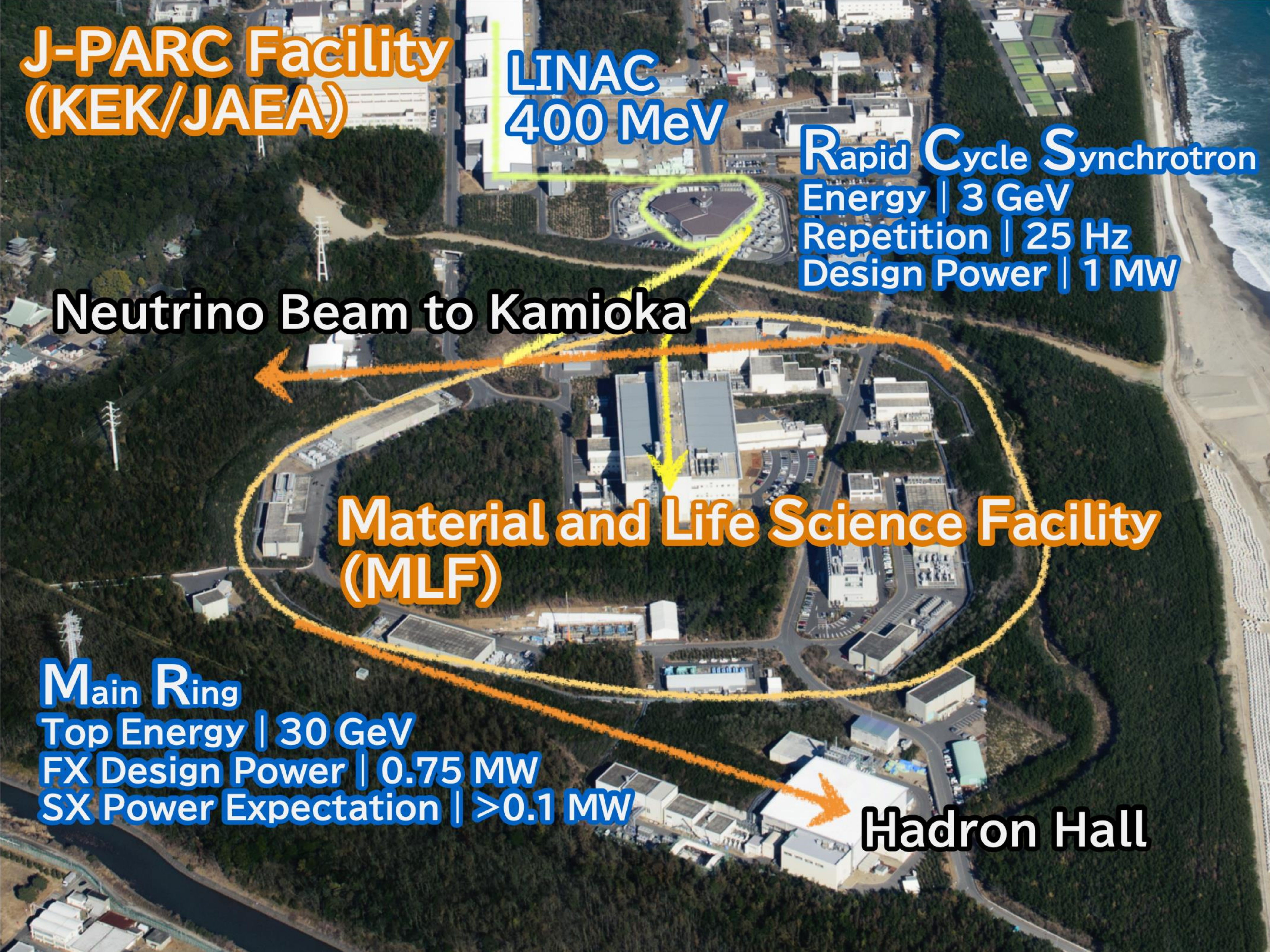
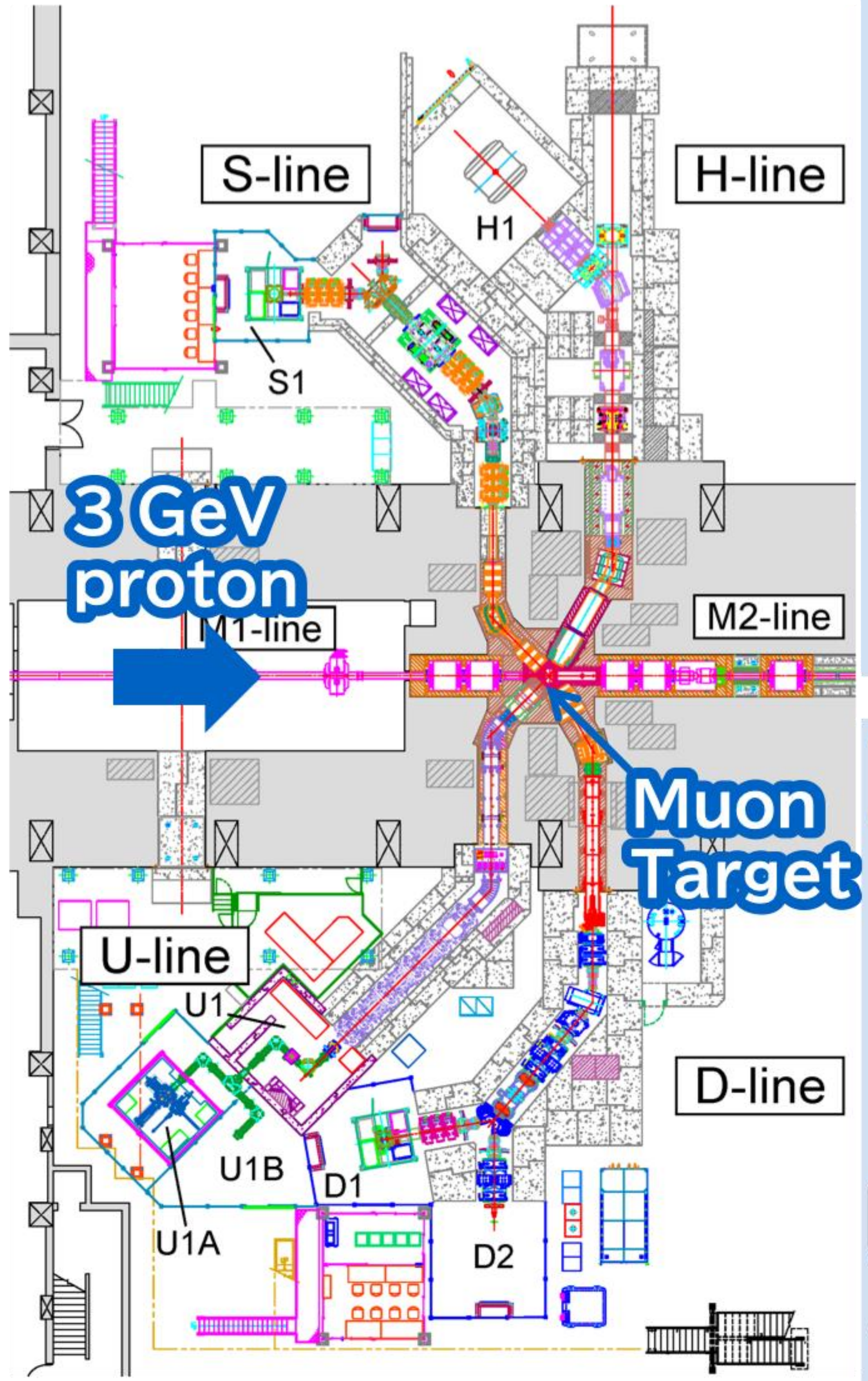
Muonium Spectroscopy in J-PARC

2022/08/18

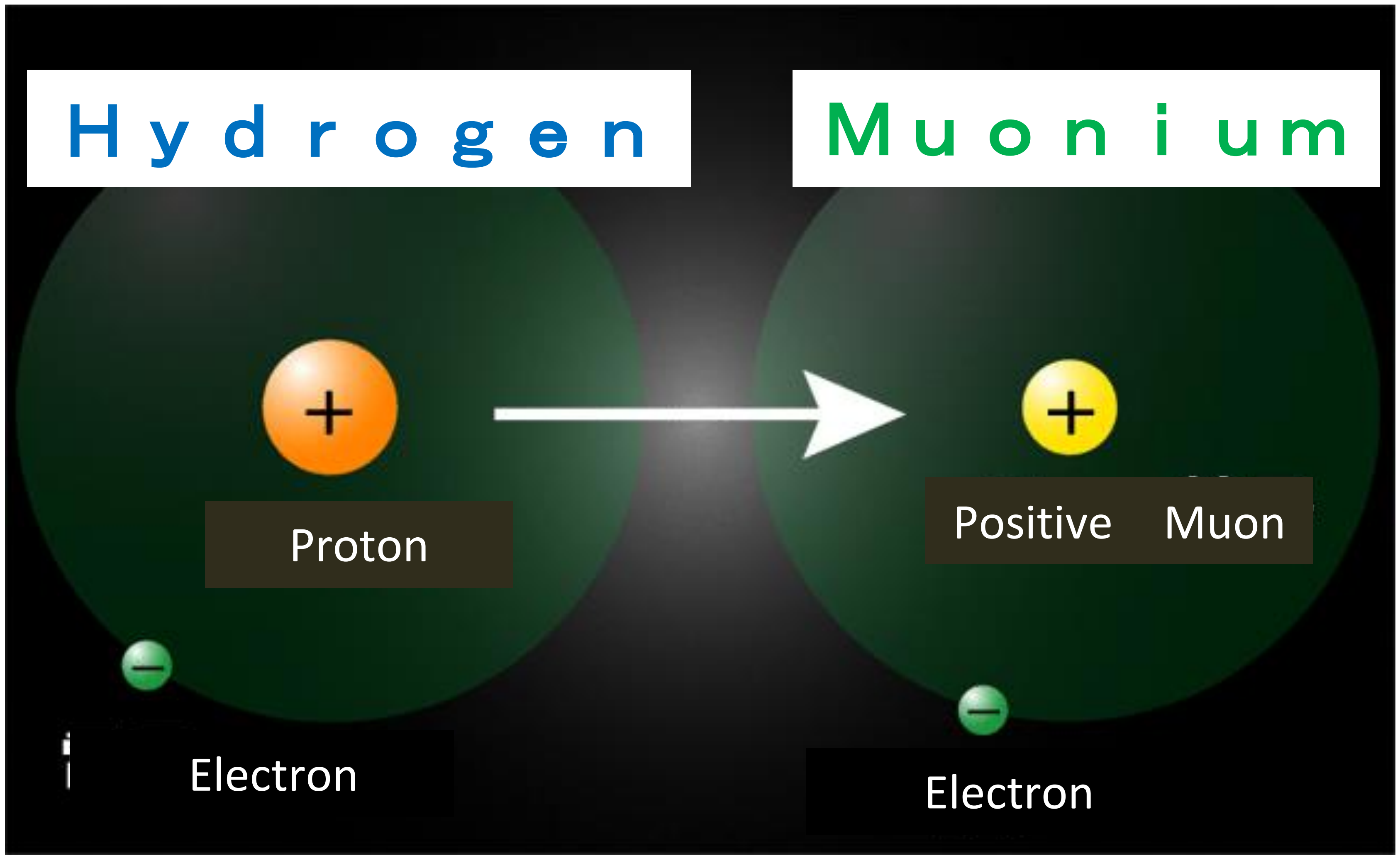
Koichiro Shimomura (KEK IMSS)
For MuSEUM collaboration


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

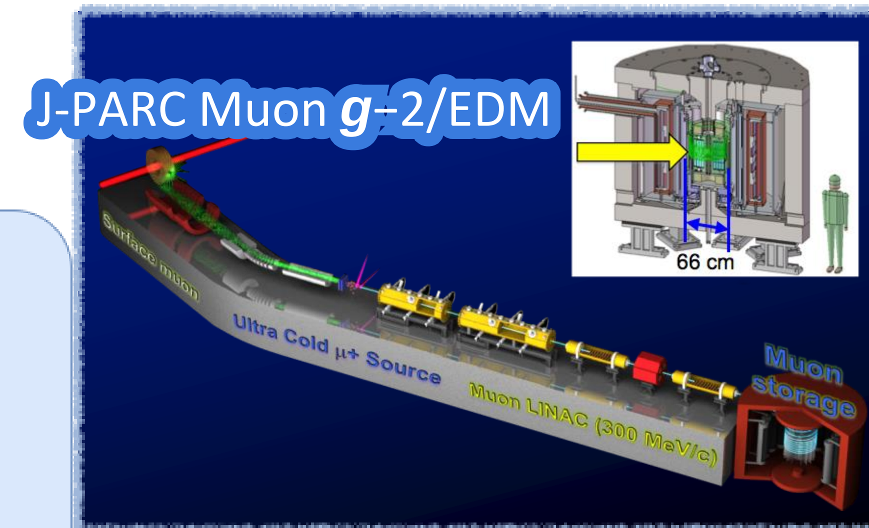


Muonium



- Pure leptonic bound system, free from finite size effect.
  - Good example for testing QED,
    - HFS,1s-2s, Lamb shift
- Muonium is also useful in condensed matter physics and chemistry
- Reduced mass of electron in hydrogen and muonium differ only 0.5%

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

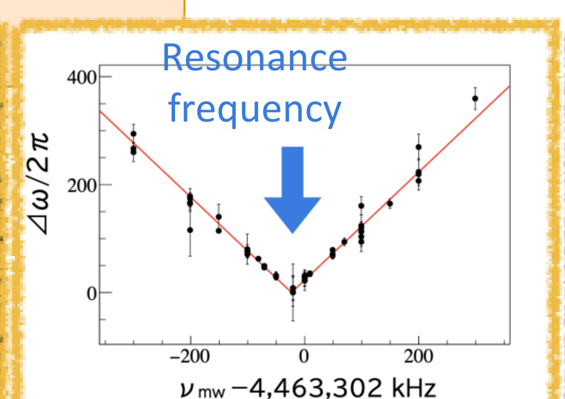
QED

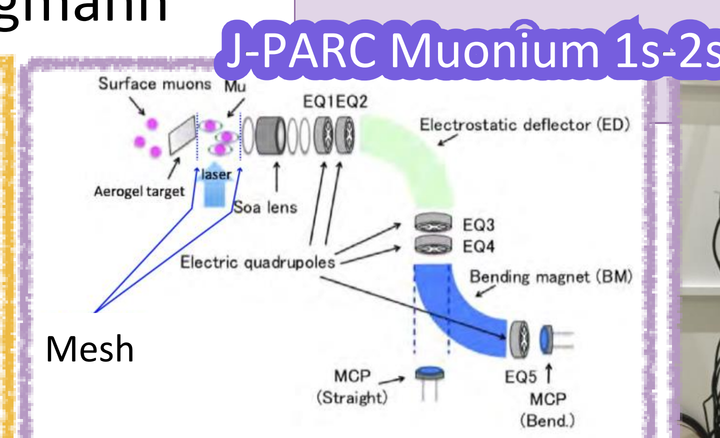
m_μ

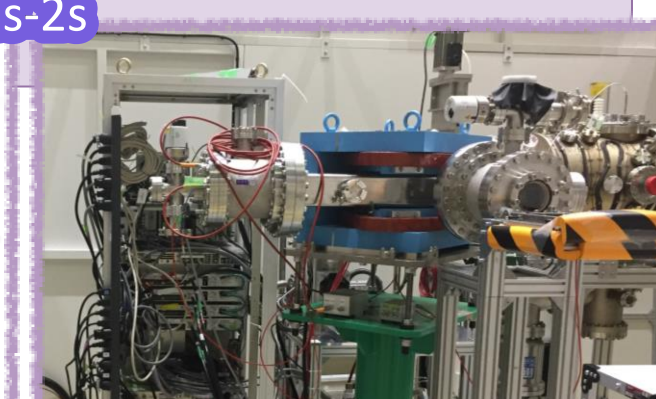
Muonium 1s-2s

Muon mass m_μ

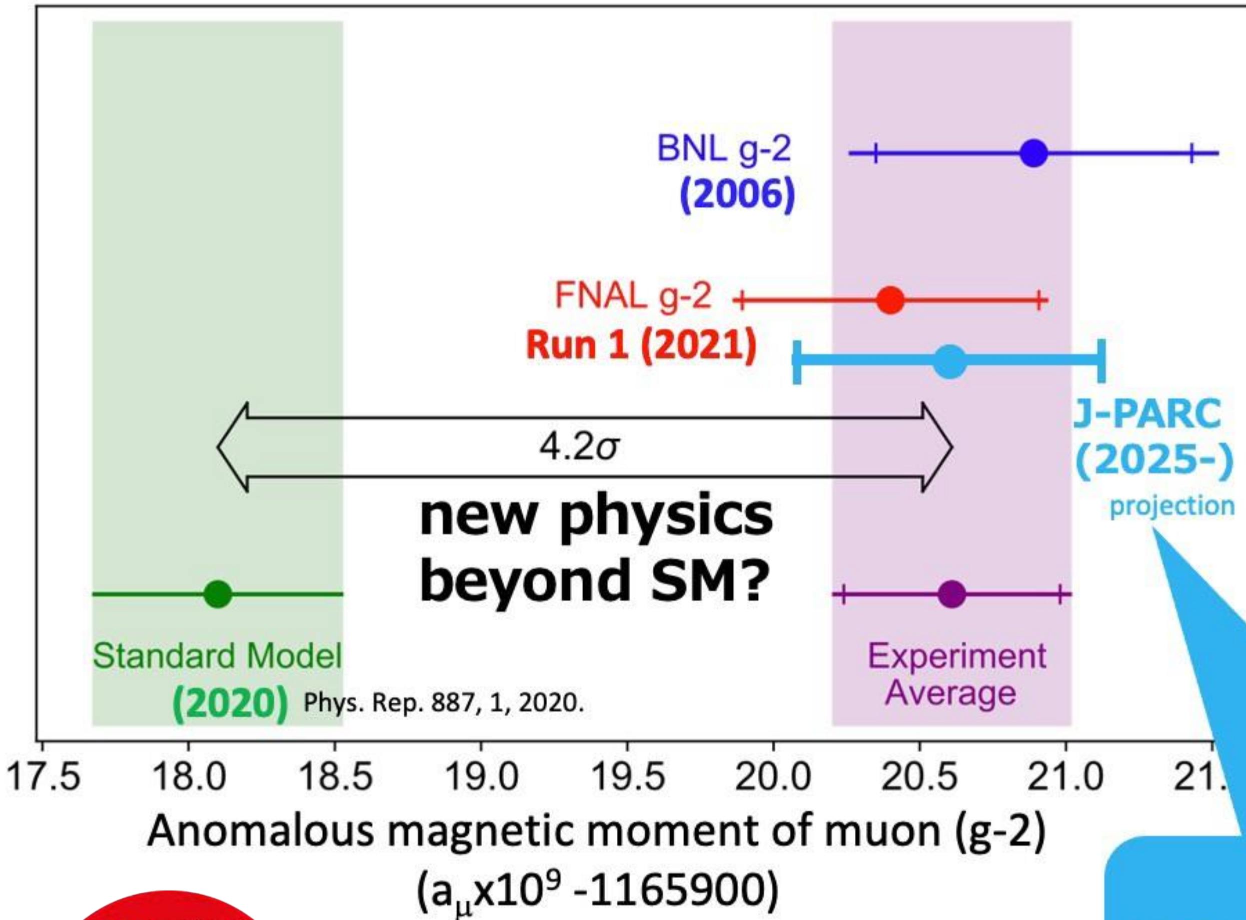
By K.Jungmann







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)

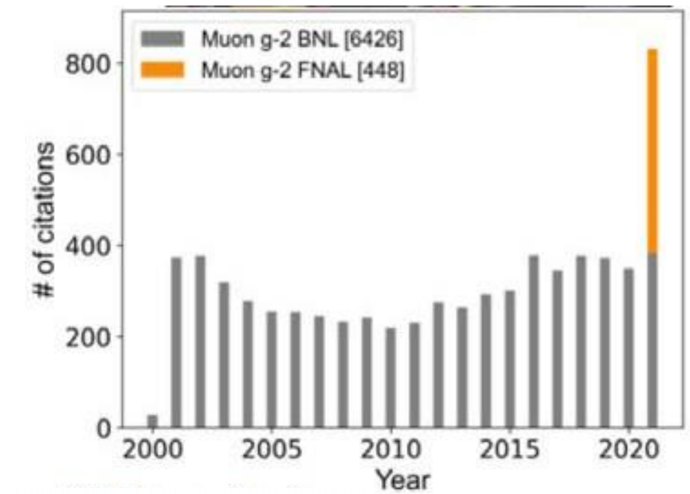
New result from FNAL on April 7, 2021

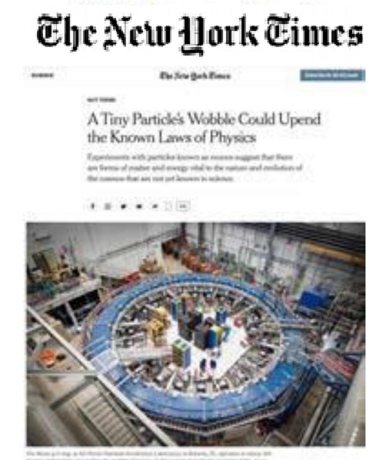
(1) Confirmed previous BNL result
(2) Deviation from the SM became 4.2σ (was 3.7σ)

- **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





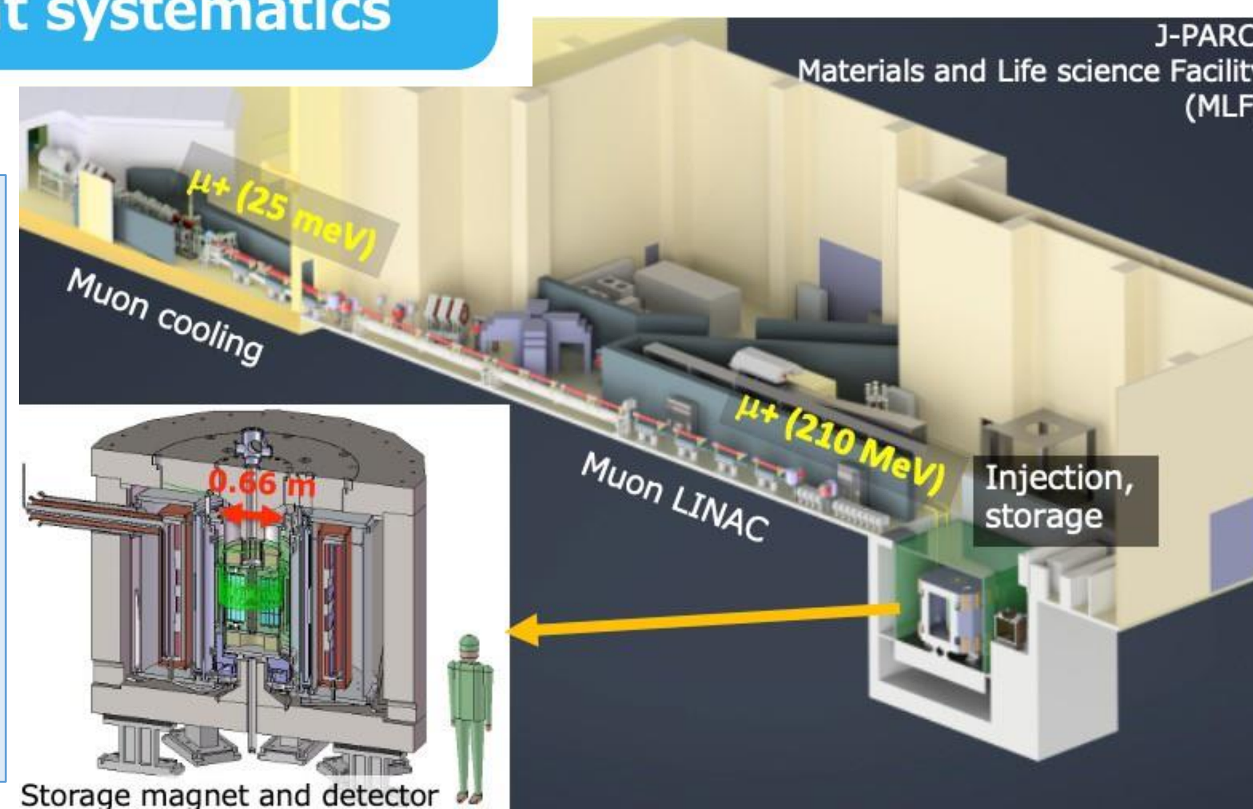
Other media articles in
Asahi shinbun, Yomiuri shinbun,
Nikkei shinbun, Tokyo-Chunichi shinbun,
Jiji tushin, Nikkei Science, Newton

physicsworld TOP 10 BREAKTHROUGH 2021

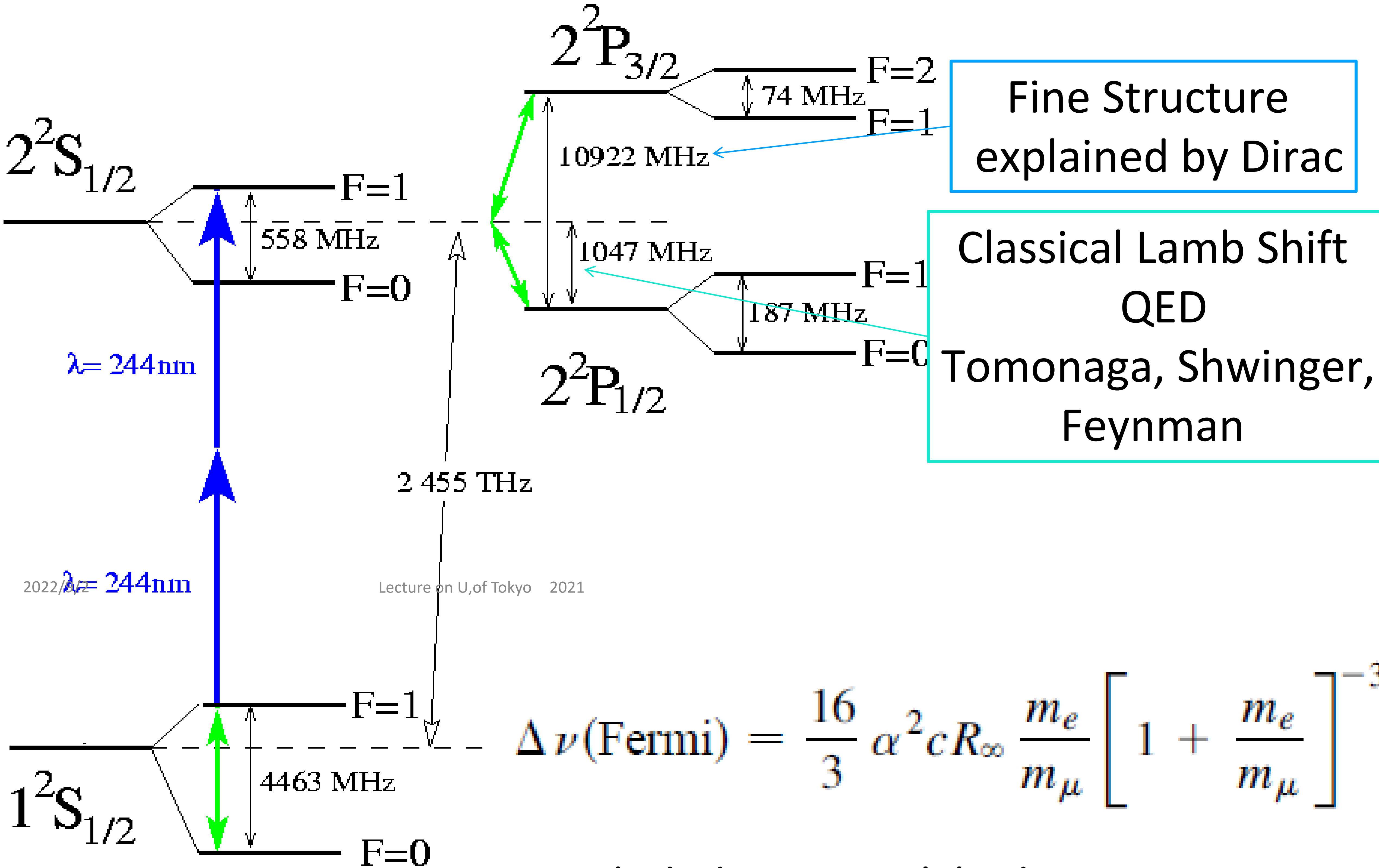
https://physicsworld.com/a/physics-world-announces-its-finalists-for-the-2021-breakthrough-of-the-year/

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)



Mu Energy Diagram



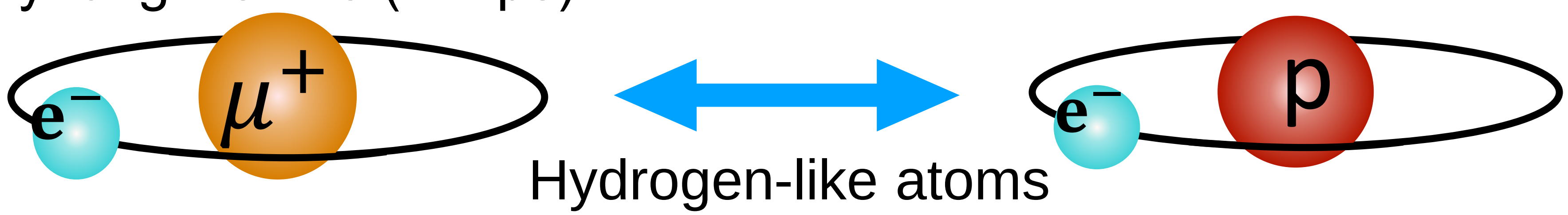
$$\Delta\nu(\text{Fermi}) = \frac{16}{3}\alpha^2 c R_\infty \frac{m_e}{m_\mu}\left[1 + \frac{m_e}{m_\mu}\right]^{-3}.$$

Not included QED weak hadronic correction

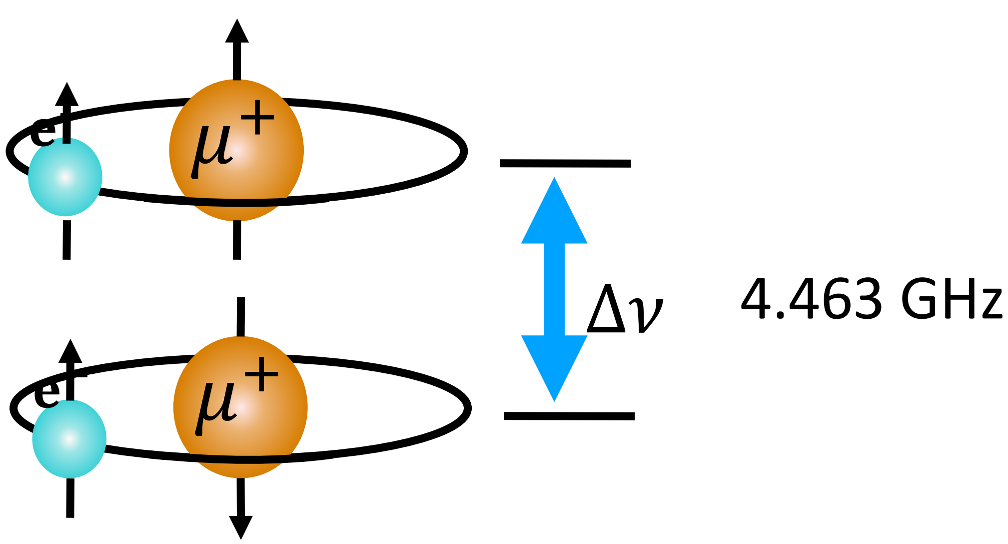
Muonium

Muonium

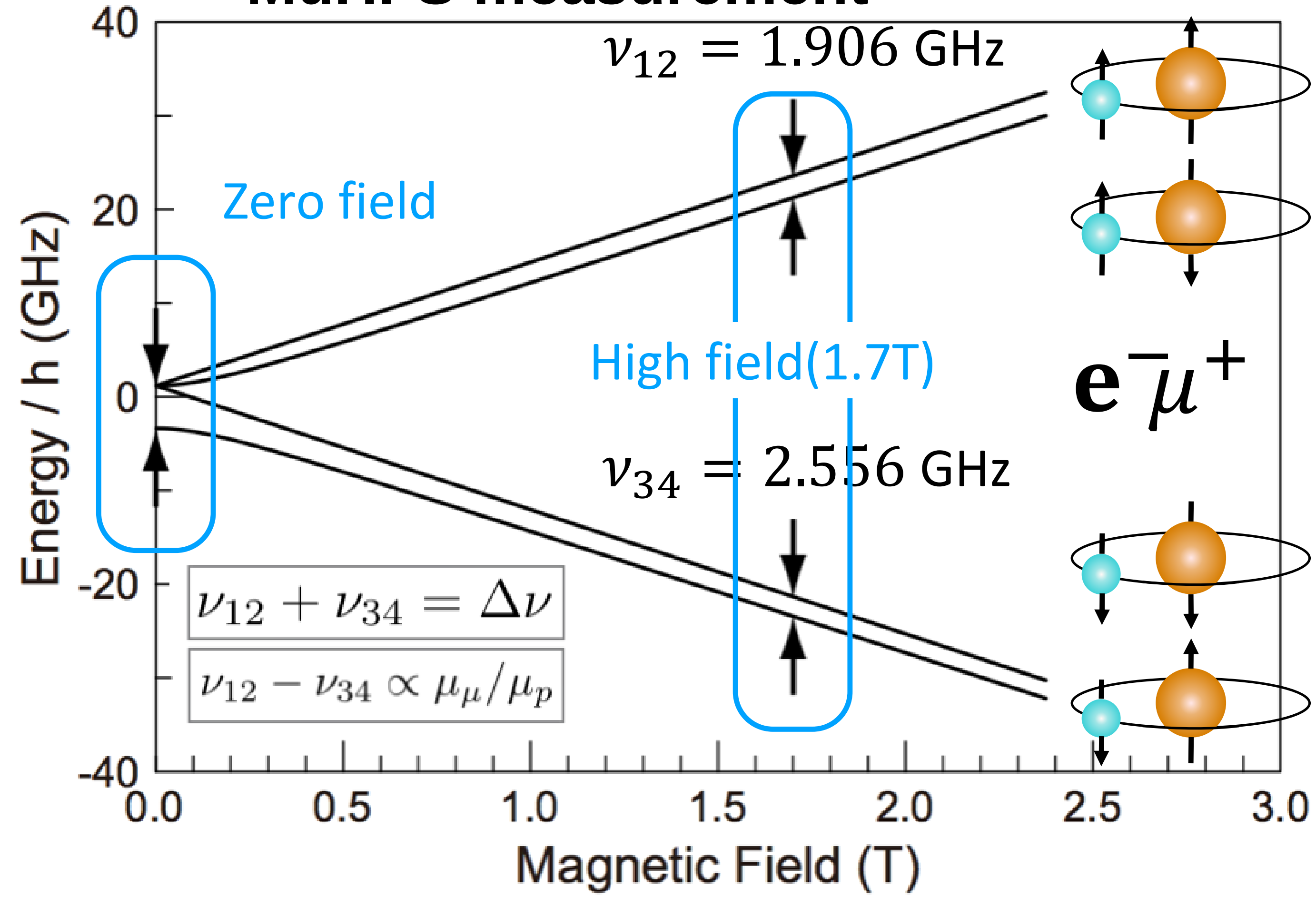
- The bound state of μ^+ and e^-
- No internal structure
- Relatively long lifetime (2.2 μs)



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



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



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)

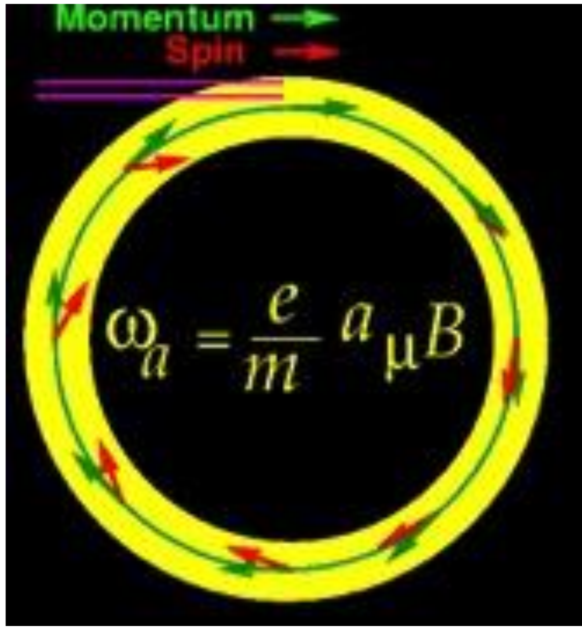
ν_{HFS}(weak) -65 Hz

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

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

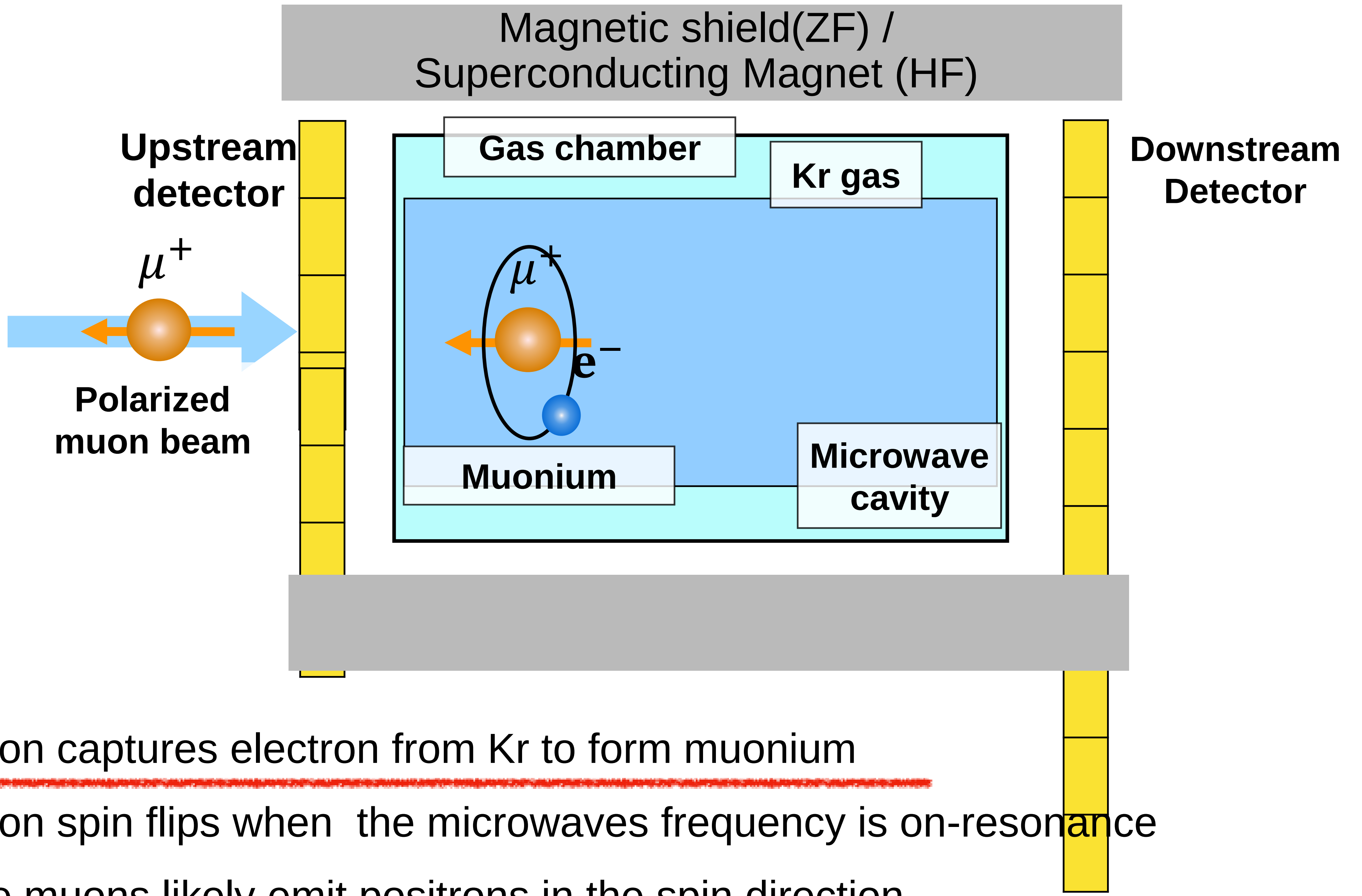
From *g*−2 storage ring — From muonium HFS

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

□ μ_μ/μ_p accuracy from direct measurement 120ppb

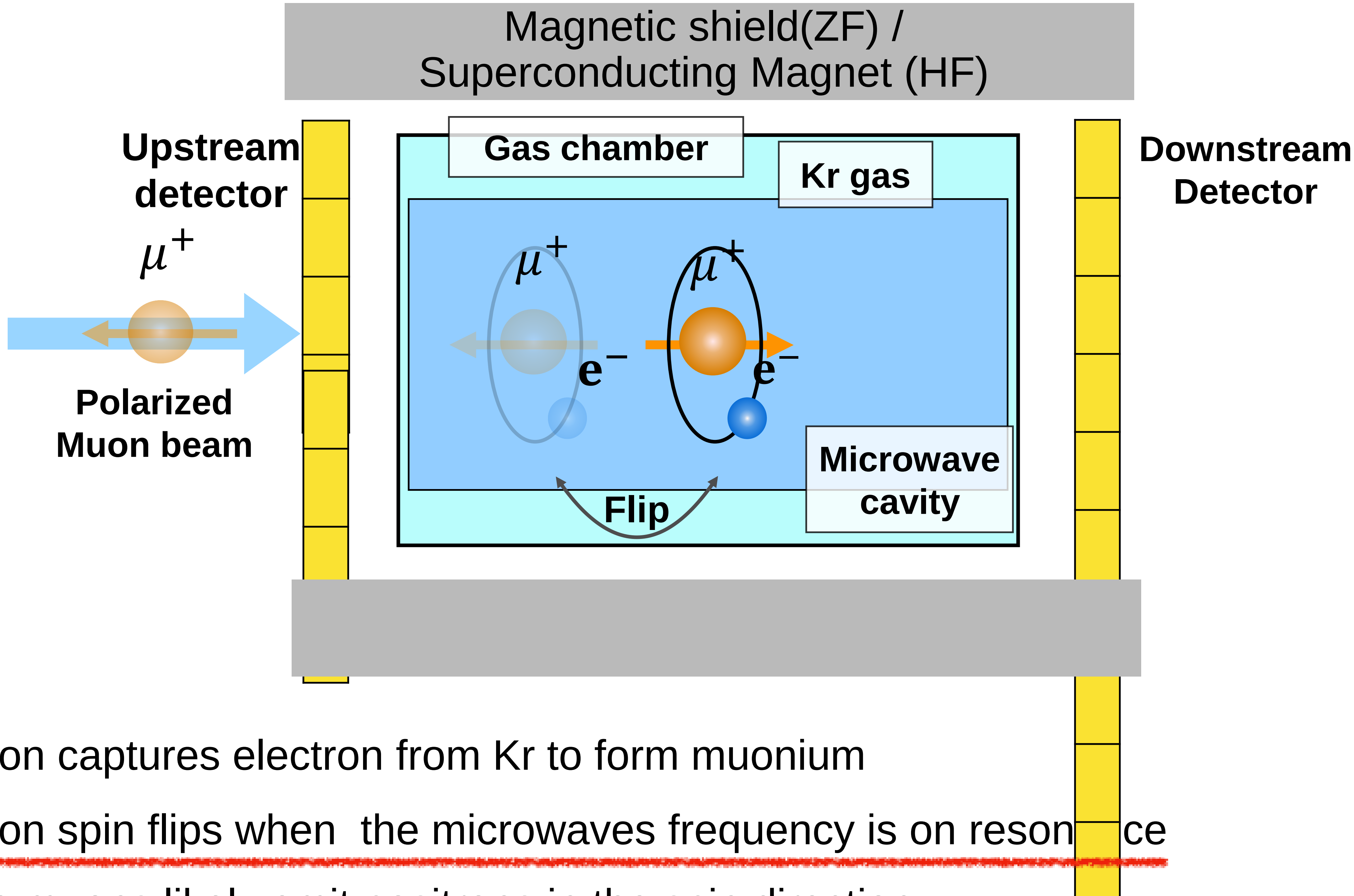
W. Liu *et al.* , *Phys. Rev. Lett.* ***82*** **,** ***711 (1999***

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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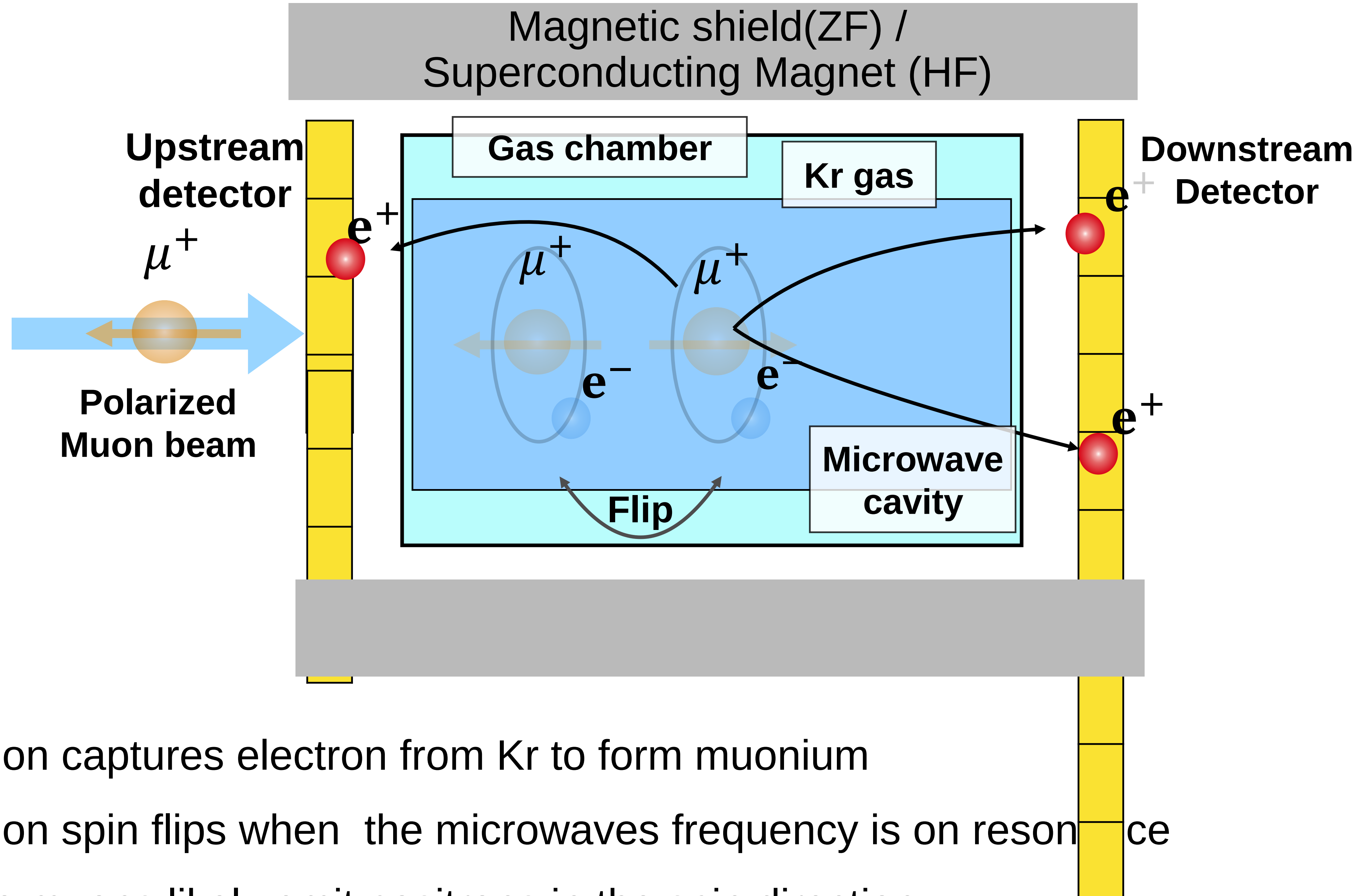

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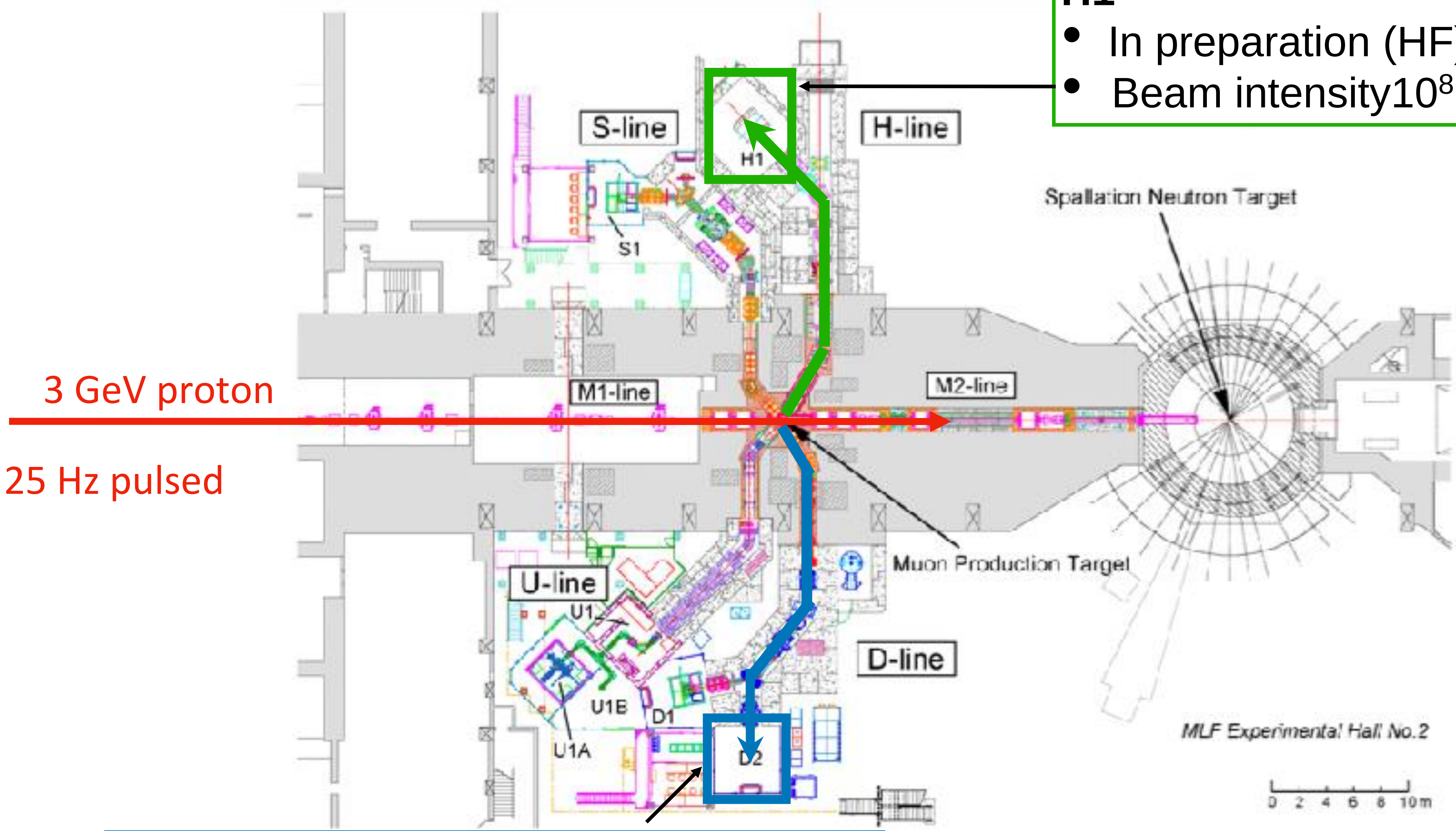
Beam Line @J-PARC MLF MUSE



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.

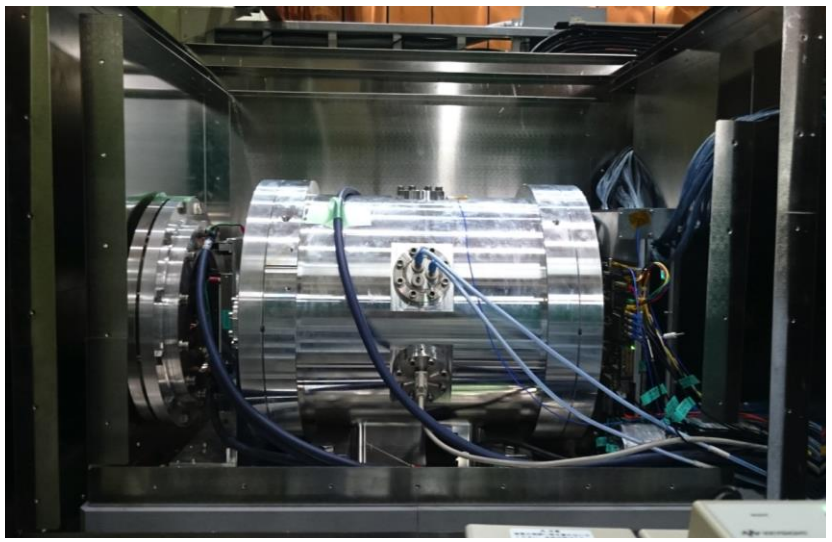
W. Higemoto, *Quantum Beam Sci*. **1** (2017) 11.

Status of MuSEUM (2014 - 22)

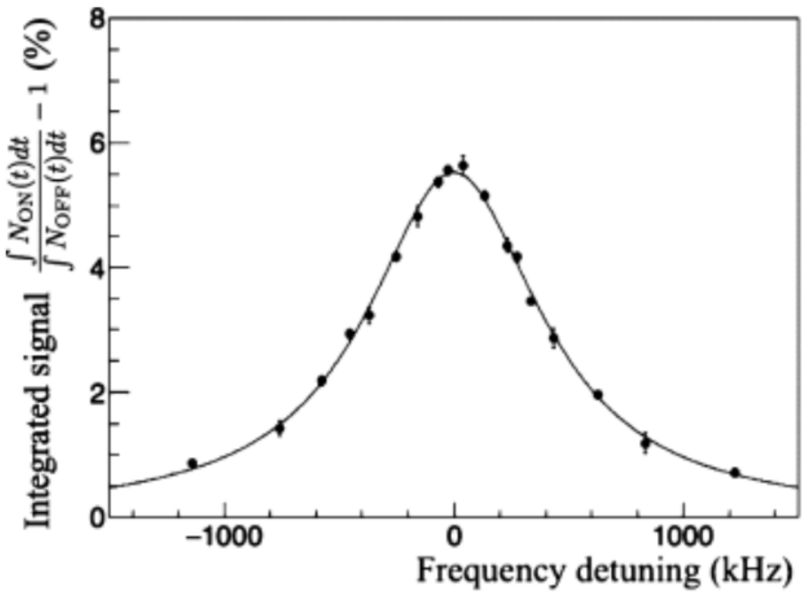
2011 | 2013 | 2015 | 2017 | 2019 | 2021 | 2023

ZF: **R&D** | **1st** | **2nd** | **3rd** | **4th** | **5th**

HF: **Proposal Submitted** | **R&D** | **New Beamline Construction** | **1st**

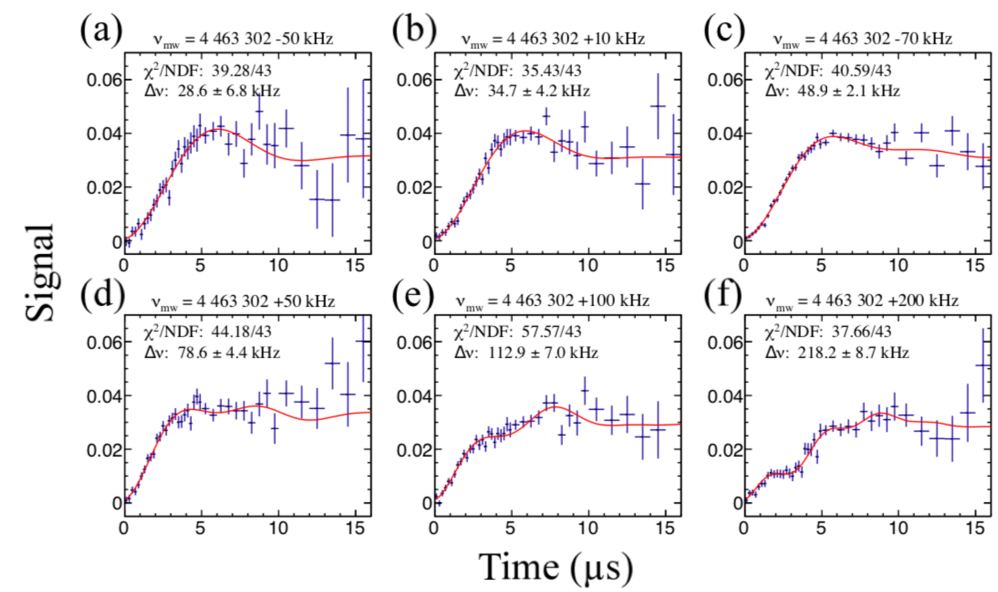


Experimental setup



resonance result(in 2016)

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

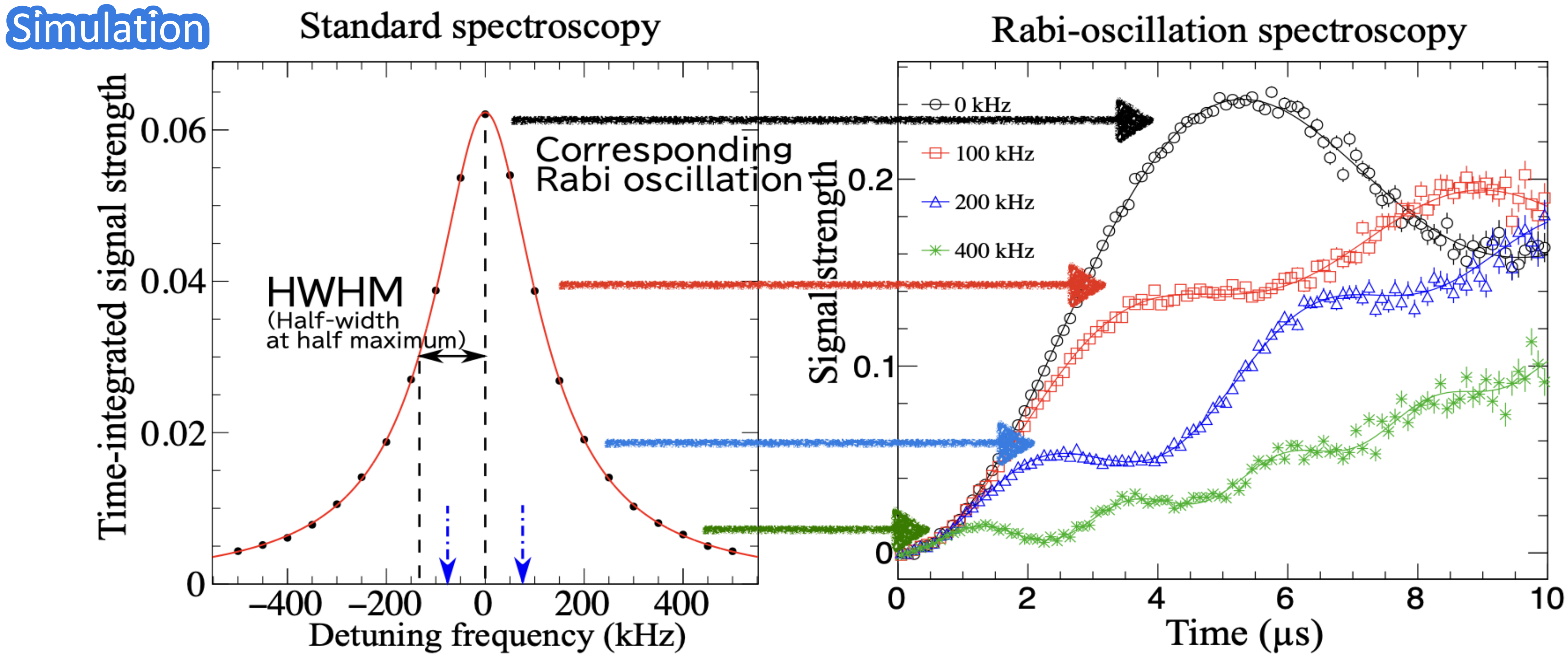


Rabi-oscillation spectroscopy

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

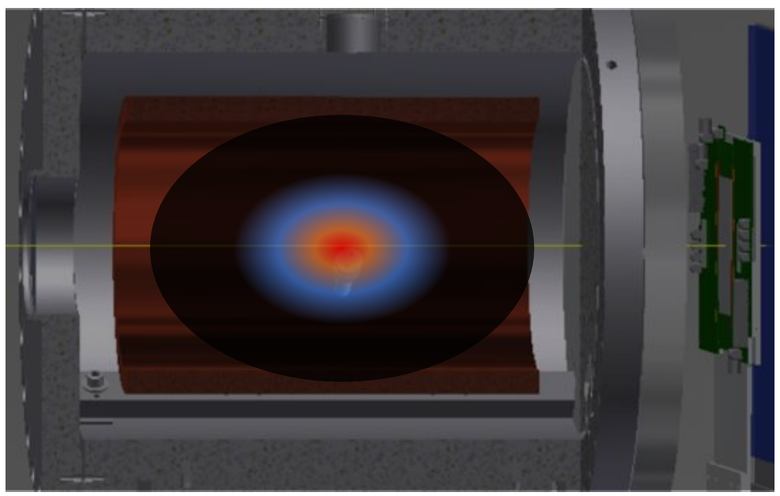
- Drawing the resonance curve with microwave frequency sweep
- Asymmetry in the microwave power across a resonance line would lead to difficulties in extracting the line center

Rabi-oscillation spectroscopy

- The detuning frequency is directly obtained from the Rabi oscillation
- No need to sweep microwave frequency

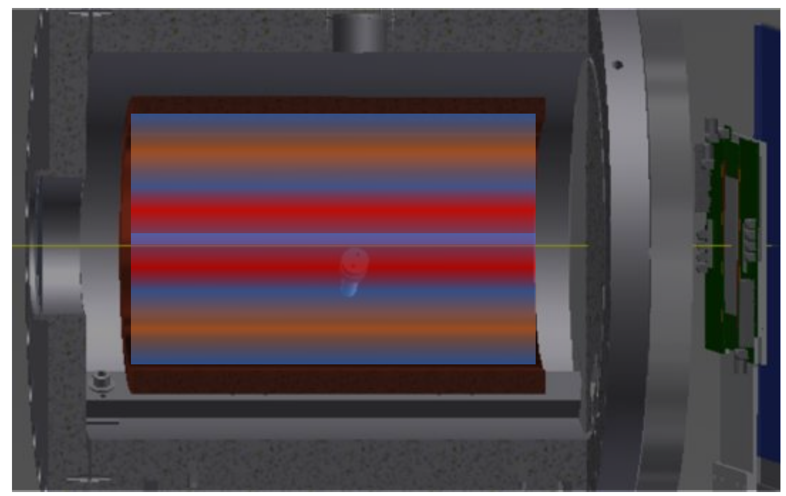
Rabi-oscillation spectroscopy analysis

- Estimation of the signal of Rabi-oscillation by the simulation



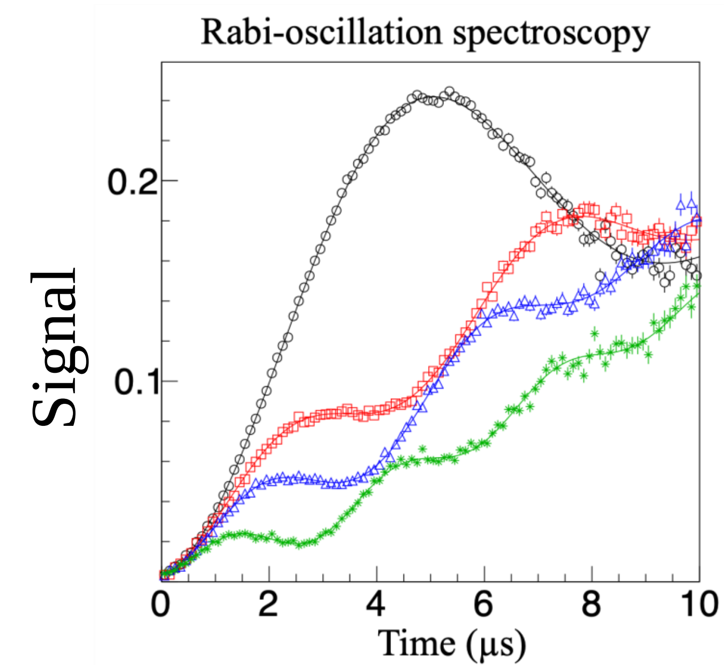
Muon stopping distribution

+



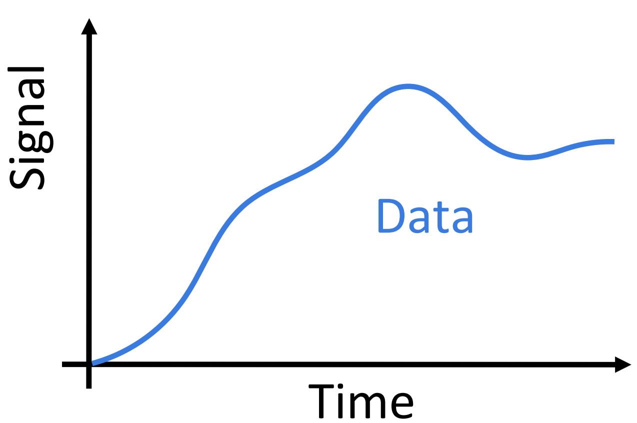
Microwave power distribution

=



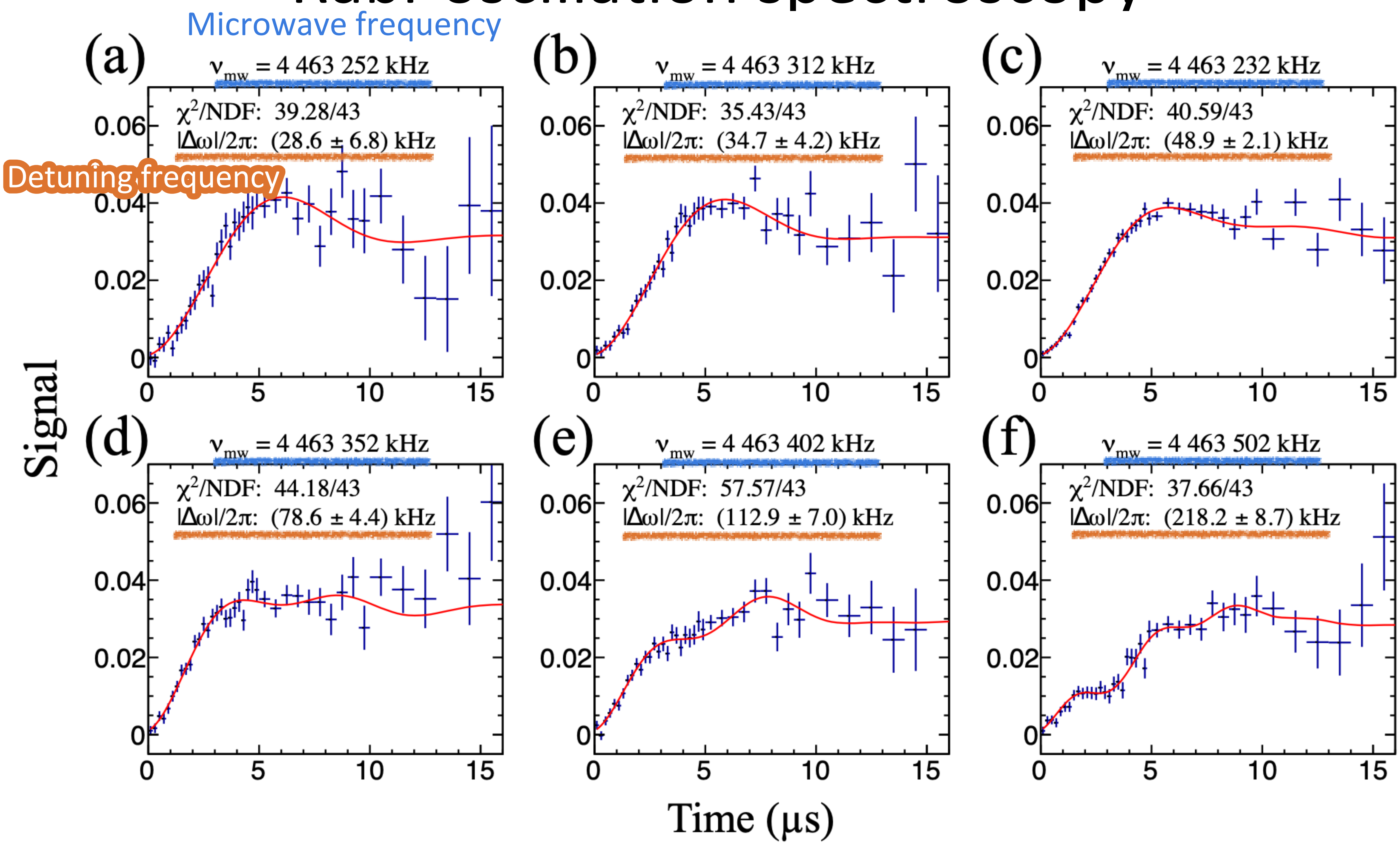
Rabi-oscillation signal from all muonium

Fit estimated signal to the obtained data

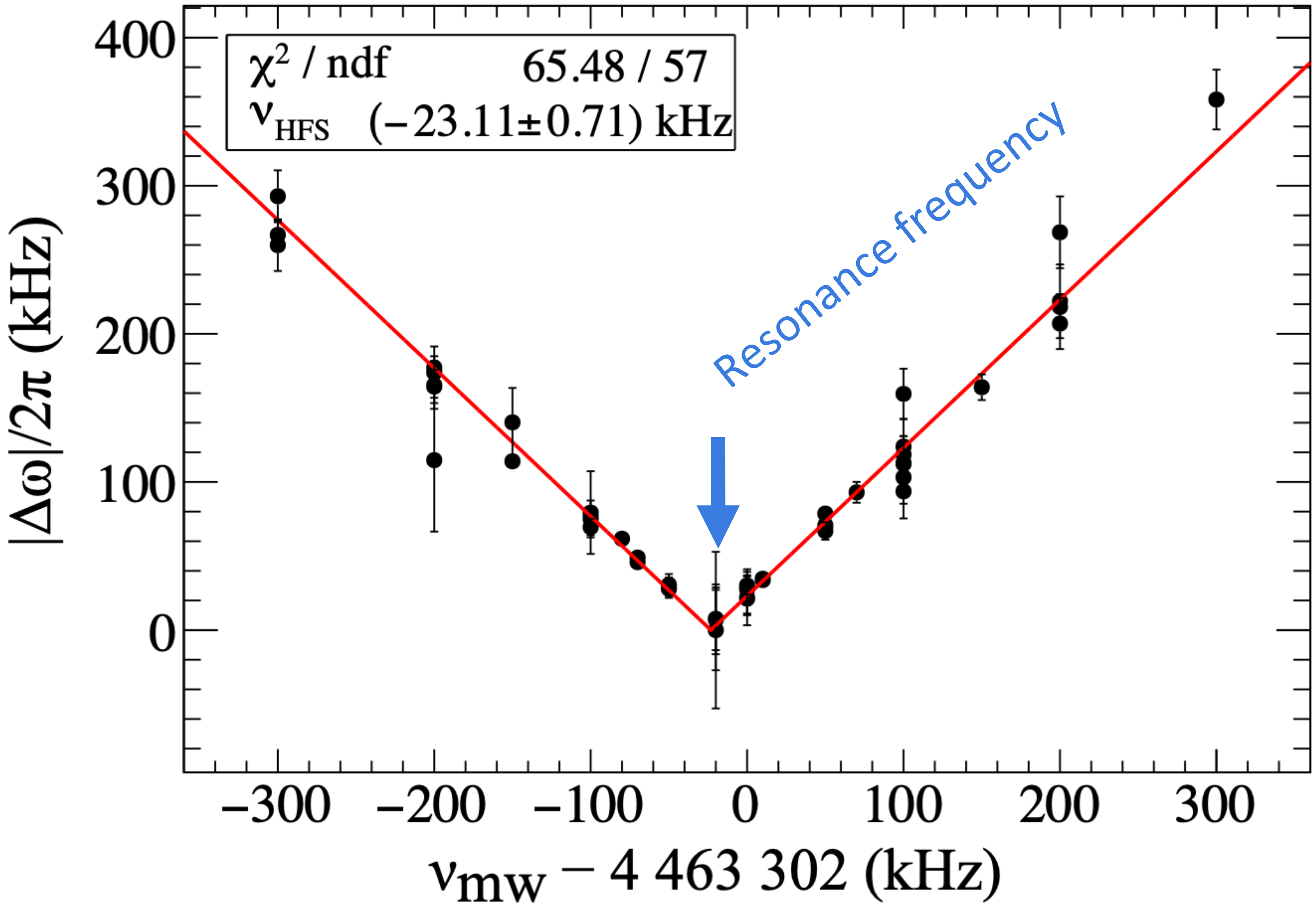


We can obtain the detuning frequency from the single microwave frequency data

Results of Rabi-oscillation spectroscopy



Results of Rabi-oscillation method (multiple microwave frequency)



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

Papers on MuSEUM

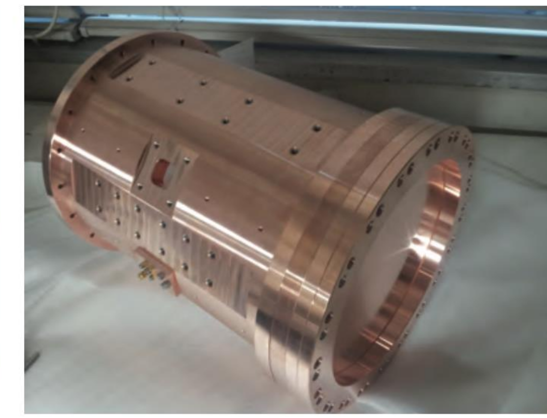
ZF and HF cavity

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

ELSEVIER

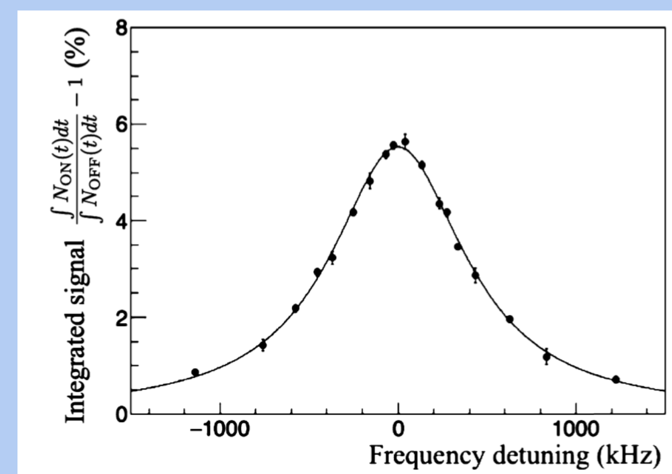
Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

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]



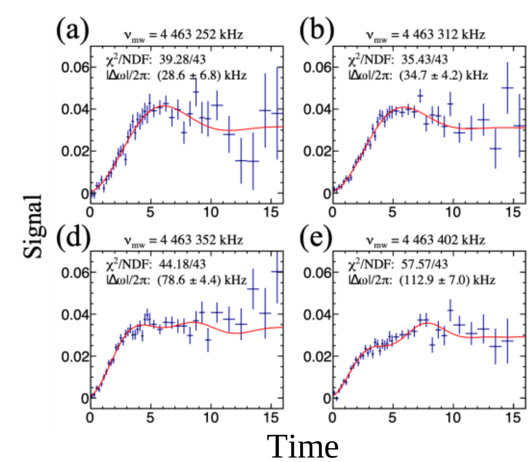
Rabi-oscillation spectroscopy

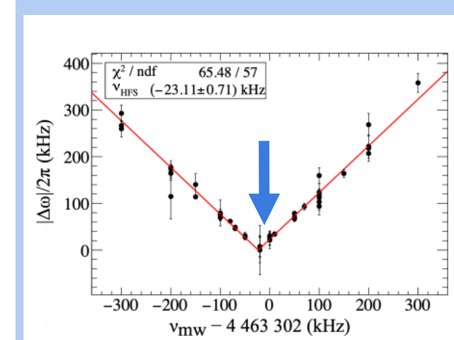
PHYSICAL REVIEW A **104**, L020801 (2021)

Letter

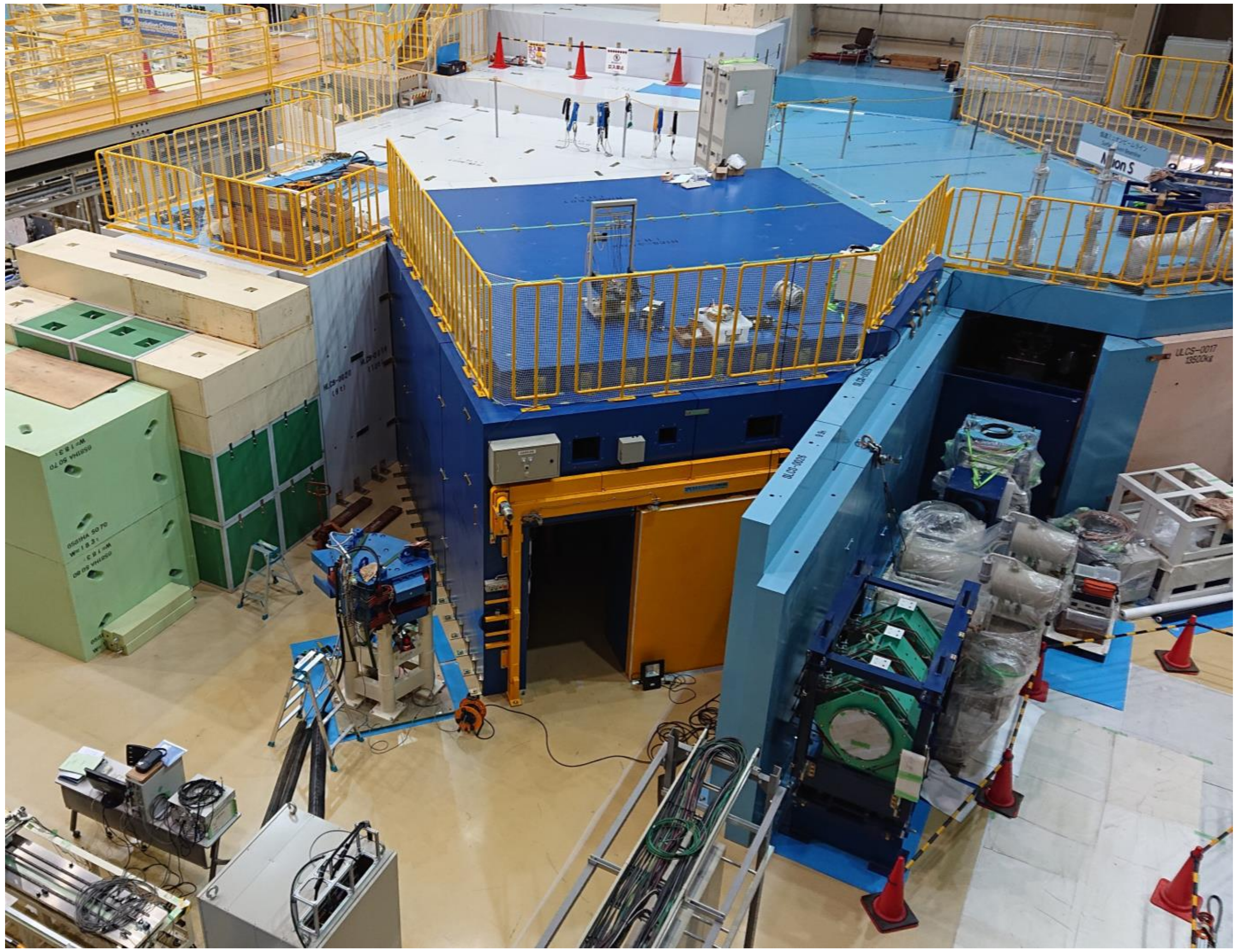
Rabi-oscillation spectroscopy of the hyperfine structure of muonium atoms

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)





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.**

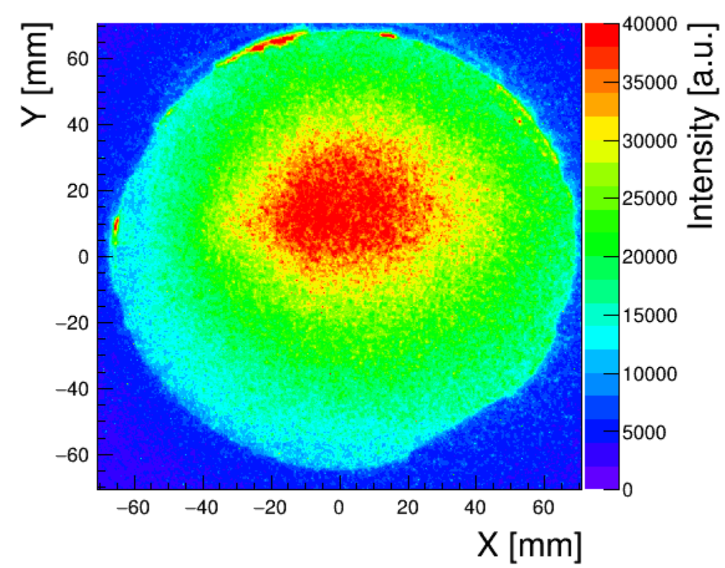
New muon H-line starts operation!

First beam on Jan. 15th, 2022!

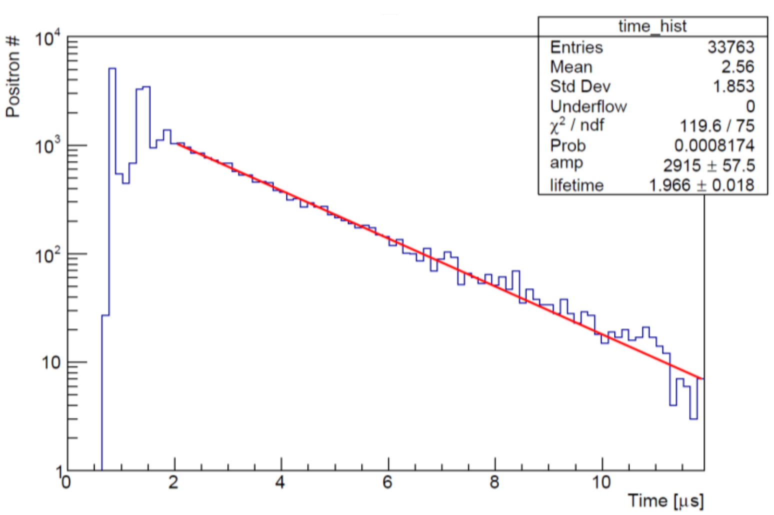
Beam commissioning is on-going with many members and groups

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

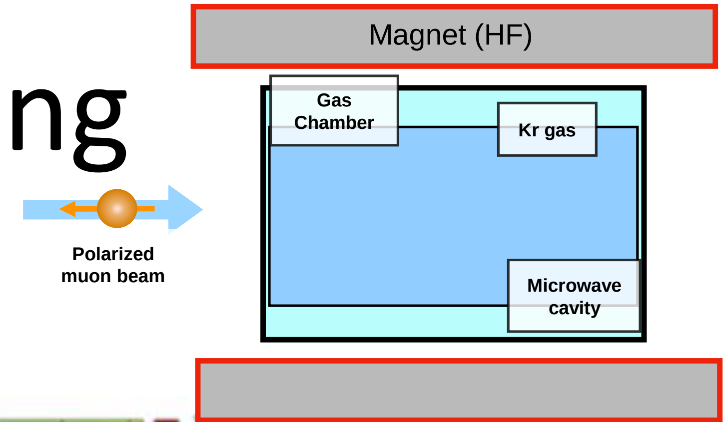


Time spectrum of muon decays



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

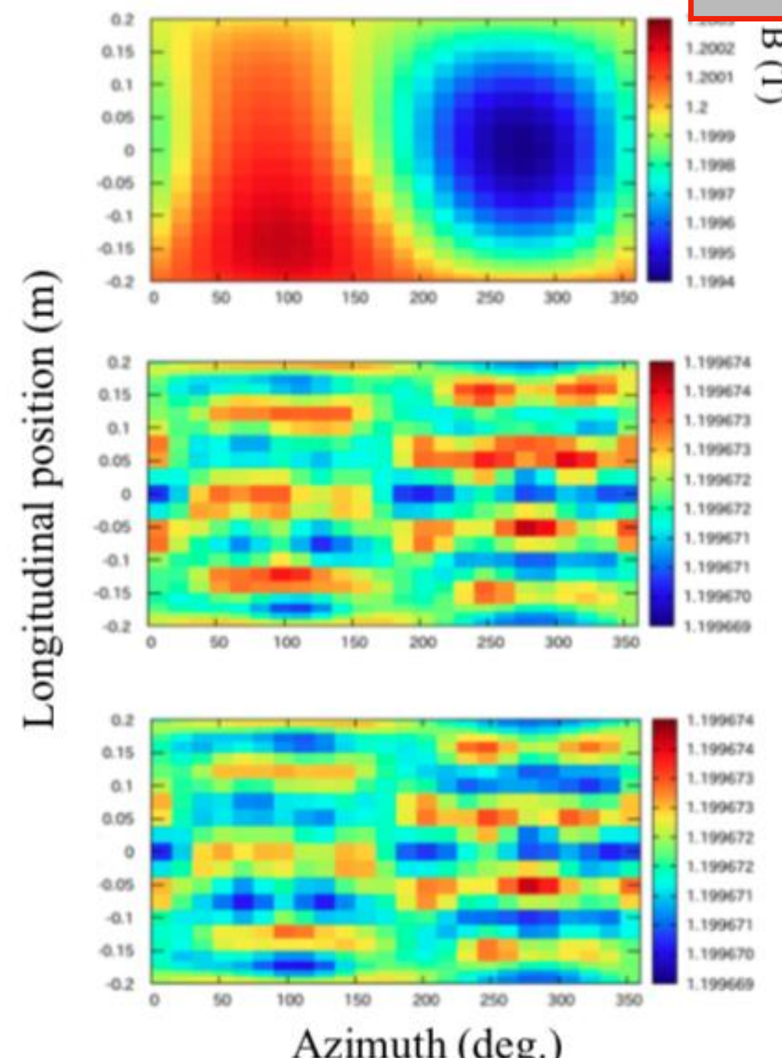
Magnet & Passive Shimming



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)

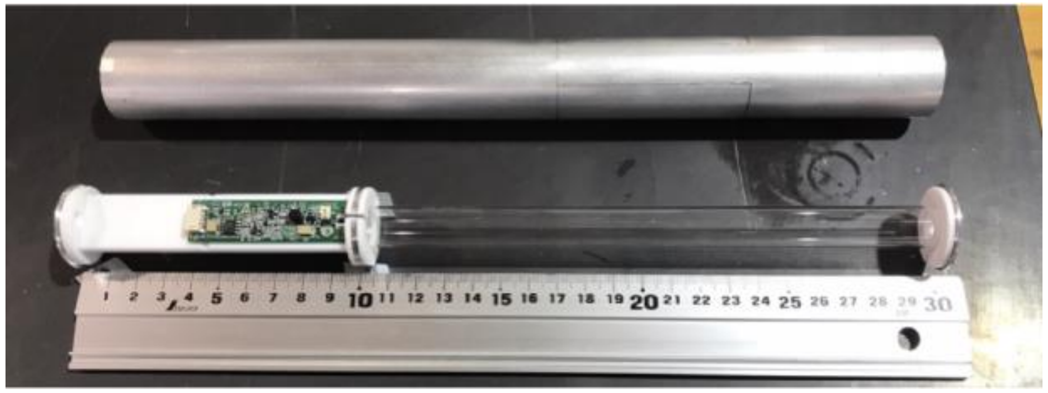
Magnetic putty.
0.17 ppm (p-p)

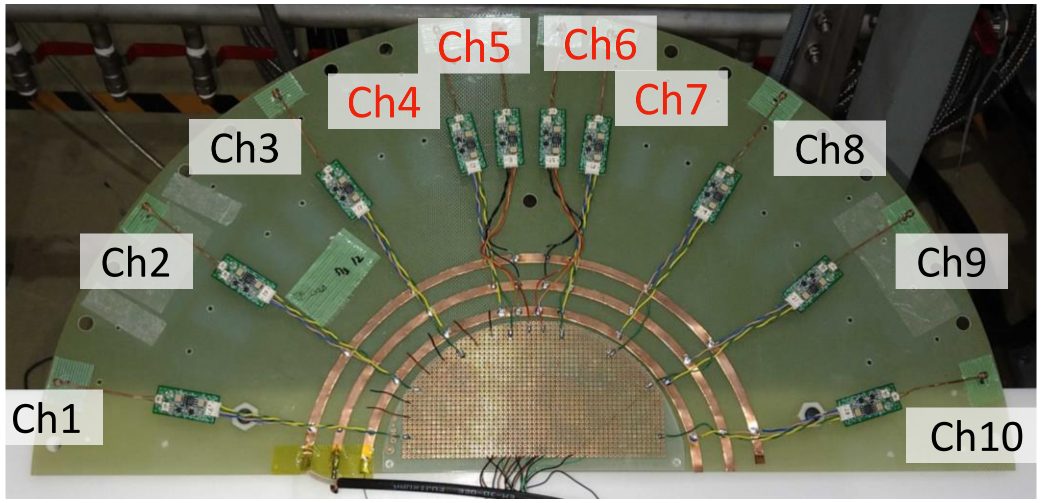
Shimming process by passive shimming method (1.2 T)

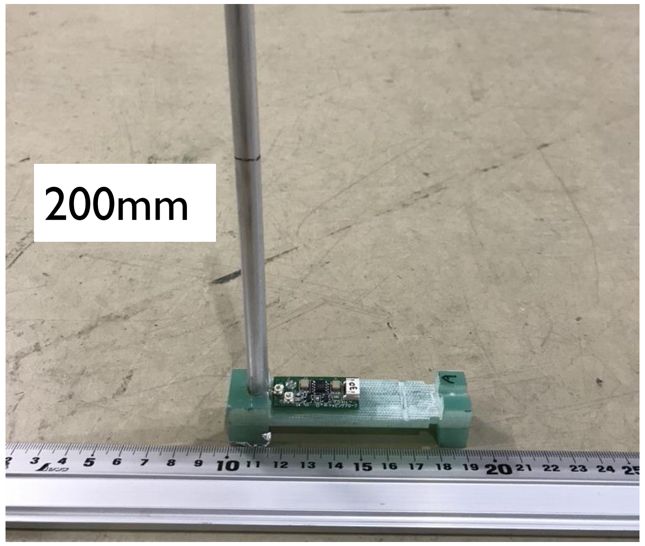
The accuracy of the magnetic field is an important point for high field experiments.

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)

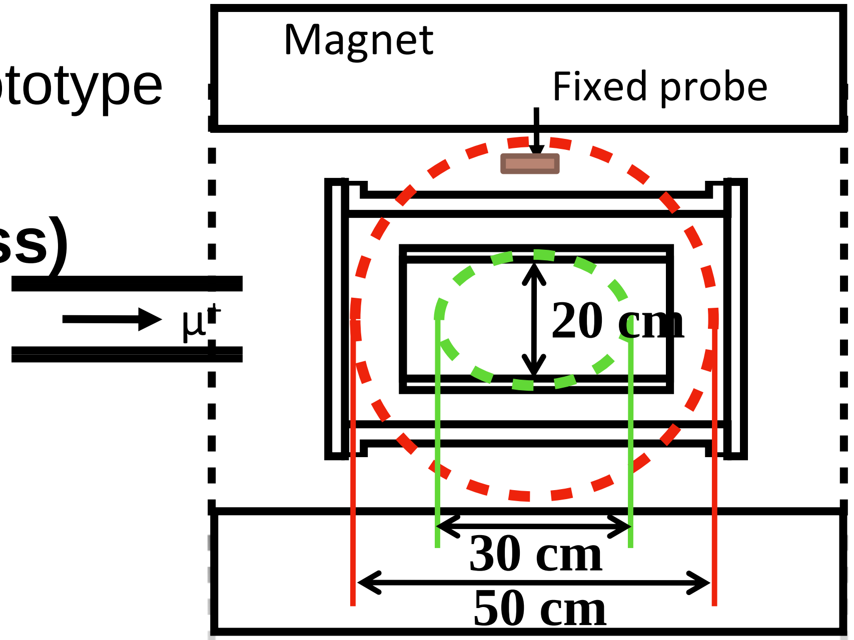
- A high-precision NMR probe to calibrate others.
- An accuracy of 15 ppb has been achieved.
- Cross-calibration is underway in a joint research project between Japan and the US.

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

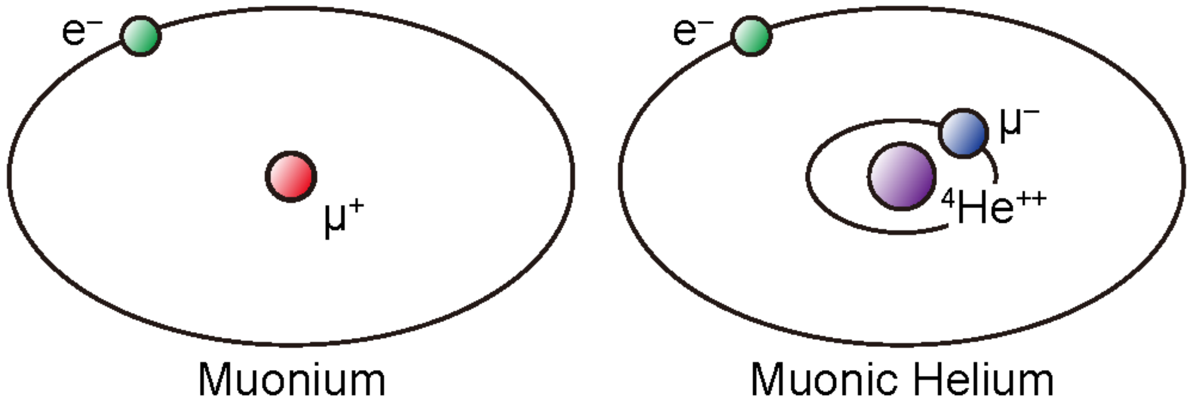
HFS uncertainty for high field experiments

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.

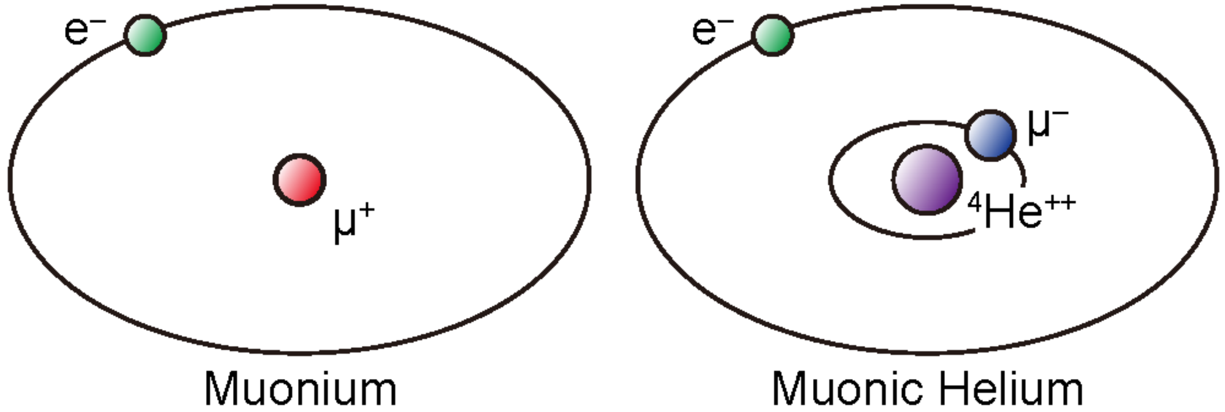
We are aiming for a precision of 5 Hz, a ten-fold improvement from the 53 Hz of the previous experiment.

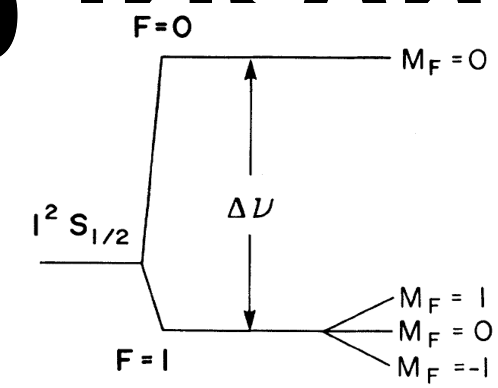
Muonic Helium Atom



- System composed of a helium atom in which one of the two electrons is replaced by a negative muon (μ^-) (bound muon Bohr radius: **$r_\mu \cong 1/400\ a_o$**).
- Hydrogen-like atom very similar to muonium (Mu).
- Ground state hyperfine structure (HFS) results from the interaction of the remaining electron and the negative muon magnetic moment (almost equal to that of muonium but inverted).
- Same technique as with muonium used to measure muonic helium HFS.
- Sensitive tool to test **3-body atomic system** and **bound-state QED** theory, and determine fundamental constants of the **negative muon magnetic moment** and **mass** to test **CPT invariance** with **2^{nd} generation lepton**.

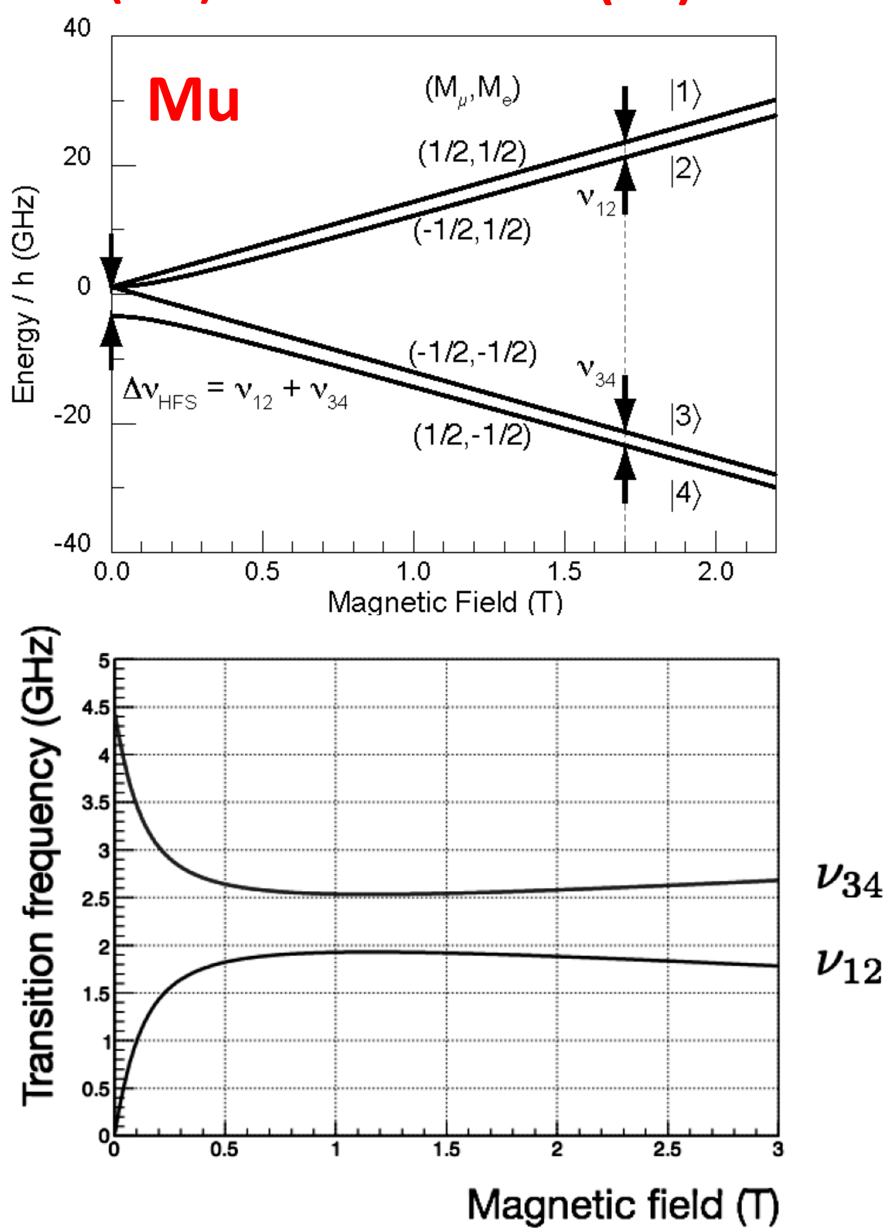
Mu & μHe HFS Comparison



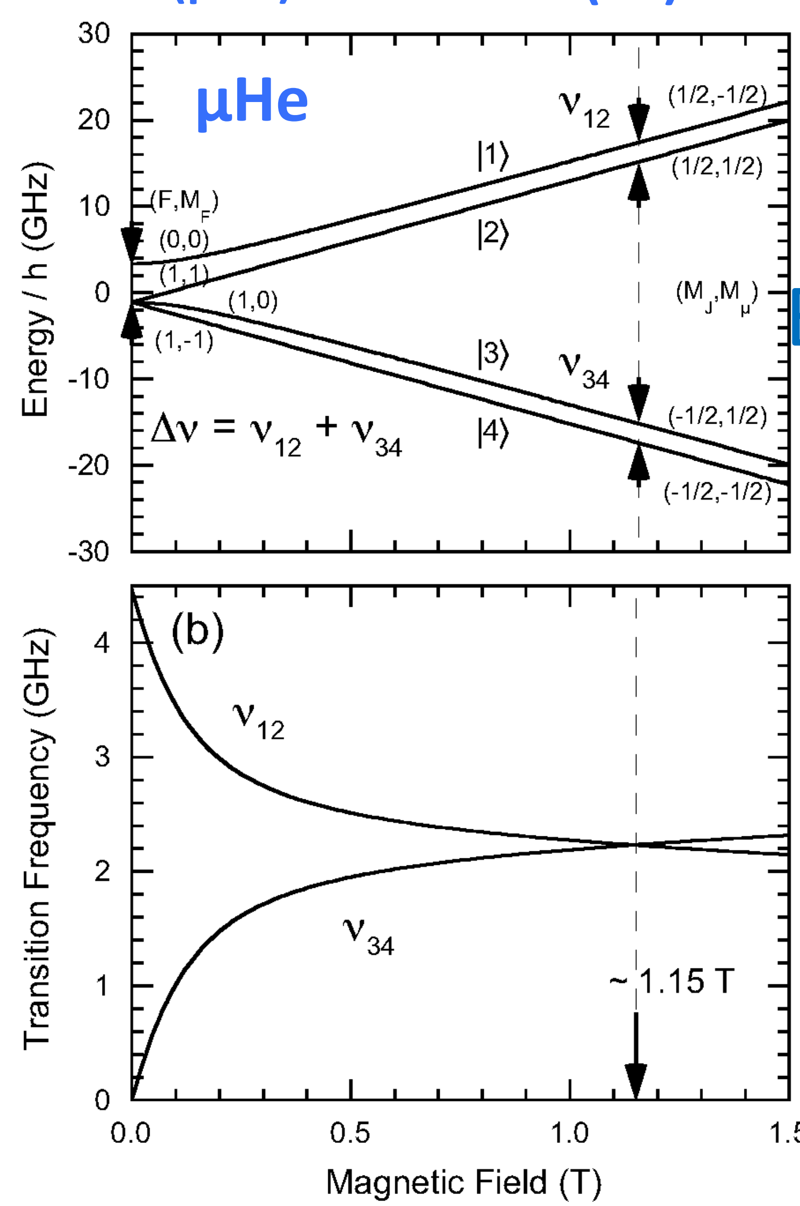


Ground state muonic helium HFS structure and low field Zeeman splitting

$\Delta\nu(\text{Mu}) = 4463.302765(53)$ MHz



$\Delta\nu(\mu\text{He}) = 4465.004(29)$ MHz



Breit-Rabi energy level diagrams

Muonic Helium Atom HFS

The **$^4He\mu^-e^-$** ground state energy levels in an static magnetic field $\vec{H}$ are given by the Hamiltonian

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

where g_J and g'_μ are the g-factors of the electron and muon bound in $^4He\mu^-e^-$, respectively.

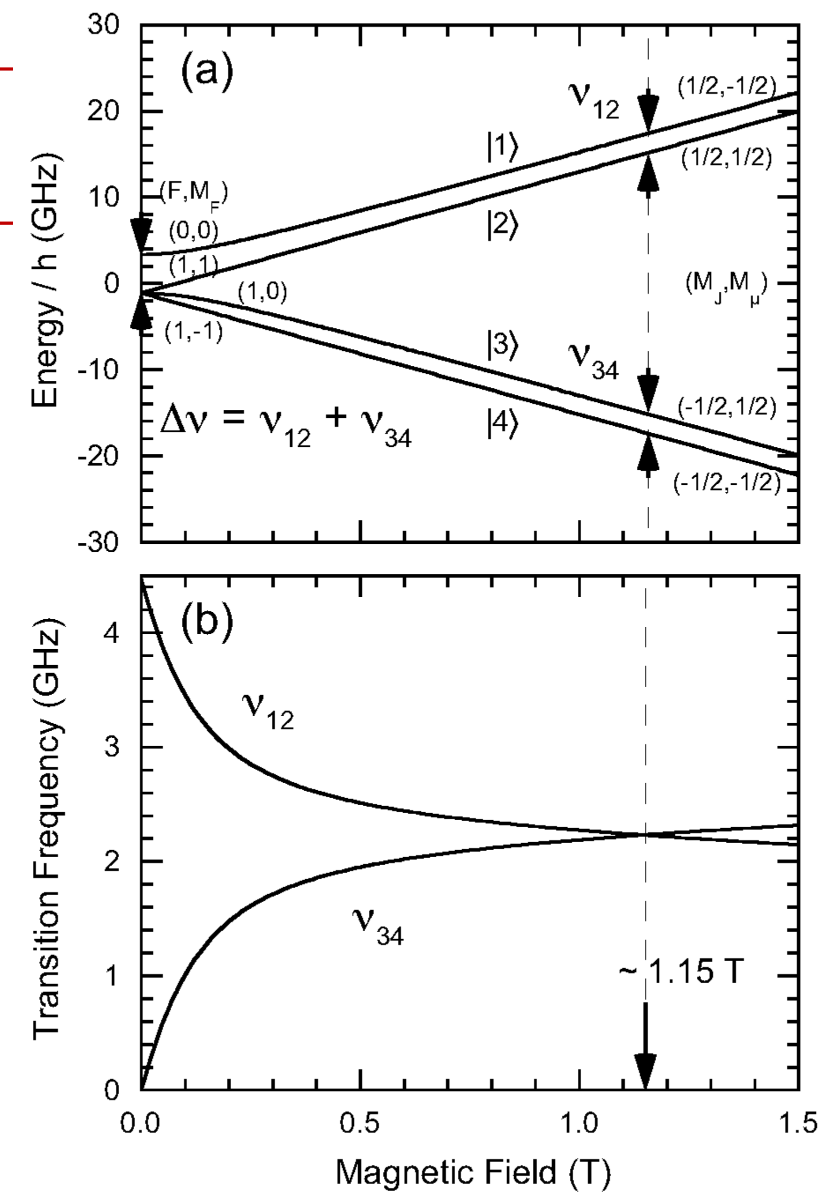
The transitions frequencies ν_{12} and ν_{34} are given by the Breit-Rabi formula. And, same as with muonium,

- The sum of ν_{12} and ν_{34} is constant, and equal to the ground state hyperfine splitting $\Delta\nu$ at zero field:

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

- The difference is directly related to the ratio of the negative muon and proton magnetic moments μ_{μ^-}/μ_p:

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



(a) Breit-Rabi energy level diagram
(b) HFS transition frequencies for muonic helium (□□ □ 4.465 GHz).

C. J. Gardner *et al.*, Phys. Rev. Lett. **48**,1168 (1982); PhD Thesis, Yale University, 1983 (unpublished)

Previous μHe HFS Experiments

Zero Field (SIN)

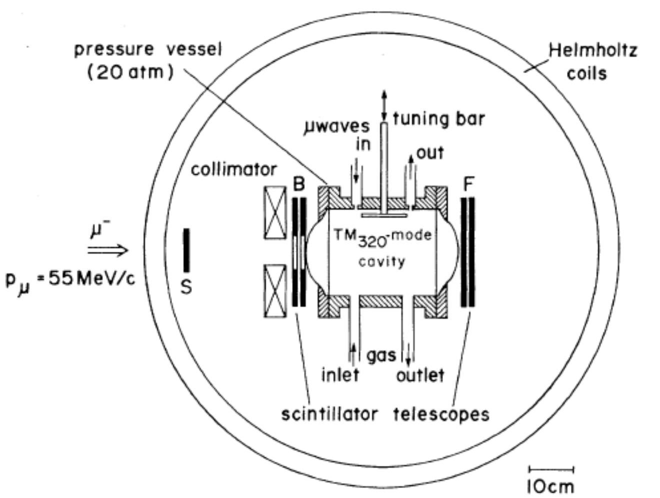


FIG. 2. Schematic view of the apparatus. The Helmholtz coils are used for muon-spin rotation. A cylindrical high-permeability metal shield (diameter 50 cm, length 100 cm) was installed (not shown in the figure) during the microwave magnetic-resonance experiment to reduce the stray magnetic fields.

$\Delta\nu$ = 4464.95(6) MHz
[13 ppm]

pressure: 20 atm

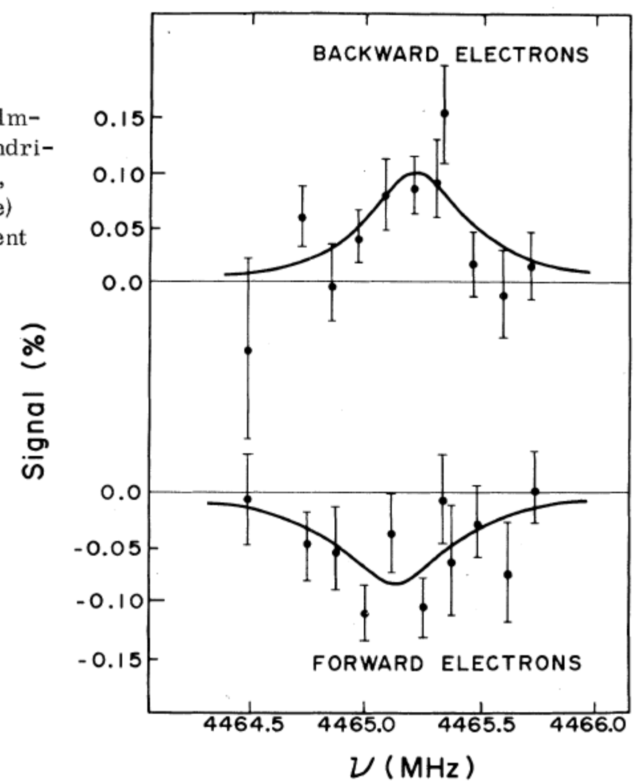


FIG. 3. Resonance curves for the $\Delta F = \pm 1$, $\Delta M_F = \pm 1$ hfs transitions in $({}^4He^{++}\mu^- e^-)^0$, simultaneously observed in the backward (upper graph) and forward (lower graph) electron telescopes as a function of the microwave resonance frequency.

High Field (LAMPF)

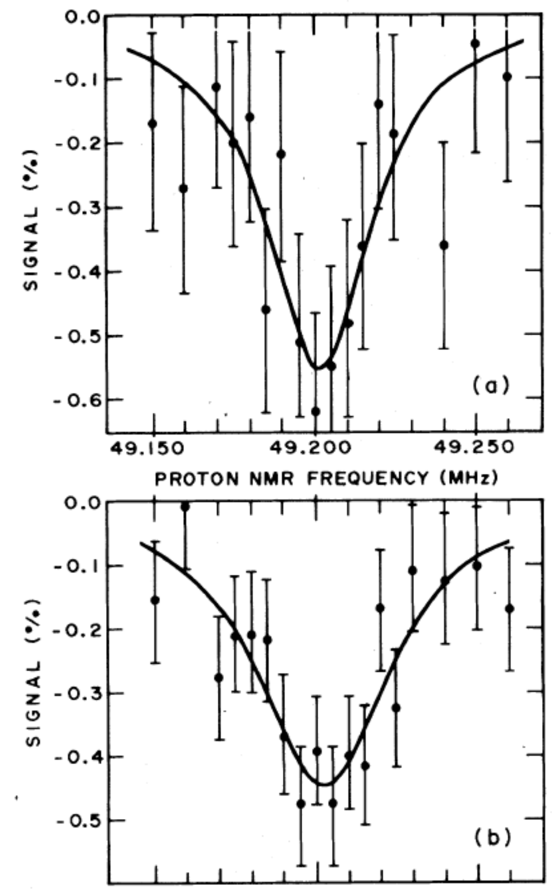


FIG. 1. Typical resonance curves for the ν_{12} transition obtained with the forward telescope at (a) 15 atm and (b) 5 atm. The data for these curves were obtained in (a) 24 h and (b) 100 h. For each curve obtained with the forward telescope there is a corresponding curve for the backward telescope.

pressure: 5 & 15 atm

$\Delta\nu$ = 4465.004(29) MHz
[6.5 ppm]

μ_{μ^-}/μ_p = 3.18328(15)
[47 ppm]

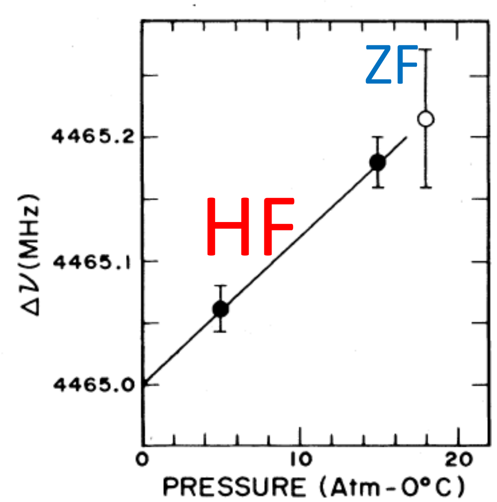


FIG. 2. $\Delta\nu$ as a function of He + Xe(1.5%) gas pressure. Closed circles show the results of this experiment; the open circle is the result of Ref. 3. The straight line shows the linear extrapolation used to extract $\Delta\nu(0)$.

ZF: H. Orth, et al., Phys. Rev. Lett. 45 (1980) 1483
HF: C. J. Gardner, et al., Phys. Rev. Lett. 48 (1982) 1168

CPT with 2nd Generation Lepton

- The "**positive muon mass**" is experimentally determined by muonium ground state HFS measurement through μ_{μ^+}/μ_p to **120 ppb** [5].
- The direct experimental value of the "**negative muon mass**" is only determined to **3.1 ppm** from muonic X-ray studies using bent-crystal spectrometer [7]. μ_{μ^-} obtained within the same accuracy.
  - The ratio μ_{μ^+}/μ_{μ^-} gives a **CPT invariance test** at a level of **3 ppm** [8].
- μ_{μ^-}/μ_p also needed to determine a_{μ^-} and its g factor g_{μ^-} in the existing BNL muon g–2 experiment [9] (maybe soon at Fermilab).

[5] W. Liu, *et al.*, Phys. Rev. Lett. **82** (1999) 711.
[6] P. Crivelli, Hyperfine Interact. **239** (2018) 49
[7] I. Beltrami, *et al.*, Nucl. Phys. A **451** (1986) 679.
[8] X. Fei, Phys. Rev. A **49** (1994) 1470.
[9] G. W. Bennett *et al.*, Phys. Rev. A **92** (2004) 161802.

More precise measurement of the negative muon magnetic moment highly desirable !

Why so difficult compared to Mu?

Muonic helium atom residual polarization

- Depolarization during muon cascade → ~6% expected for most I = 0 atoms.
- Helium capturing a muon forms **($(^4He\mu^-)^+$)** ion → need an **electron donor !!!**
- Previously 1–2% **xenon** (IP = **12.1 eV**) was used. But, **Xe** (**Z=54**) prevents efficient μ^- capture by **He** (**Z=2**), due to the Z-law.
- Recently **methane** (**CH_4**) found more efficient because of its reduced total charge (**Z=10**) and similar IP of **12.5 eV**. Polarization of **5%** reported.

D. J. Arseneau, *et al.*, J. Phys. Chem. B **120** (2016) 1641.

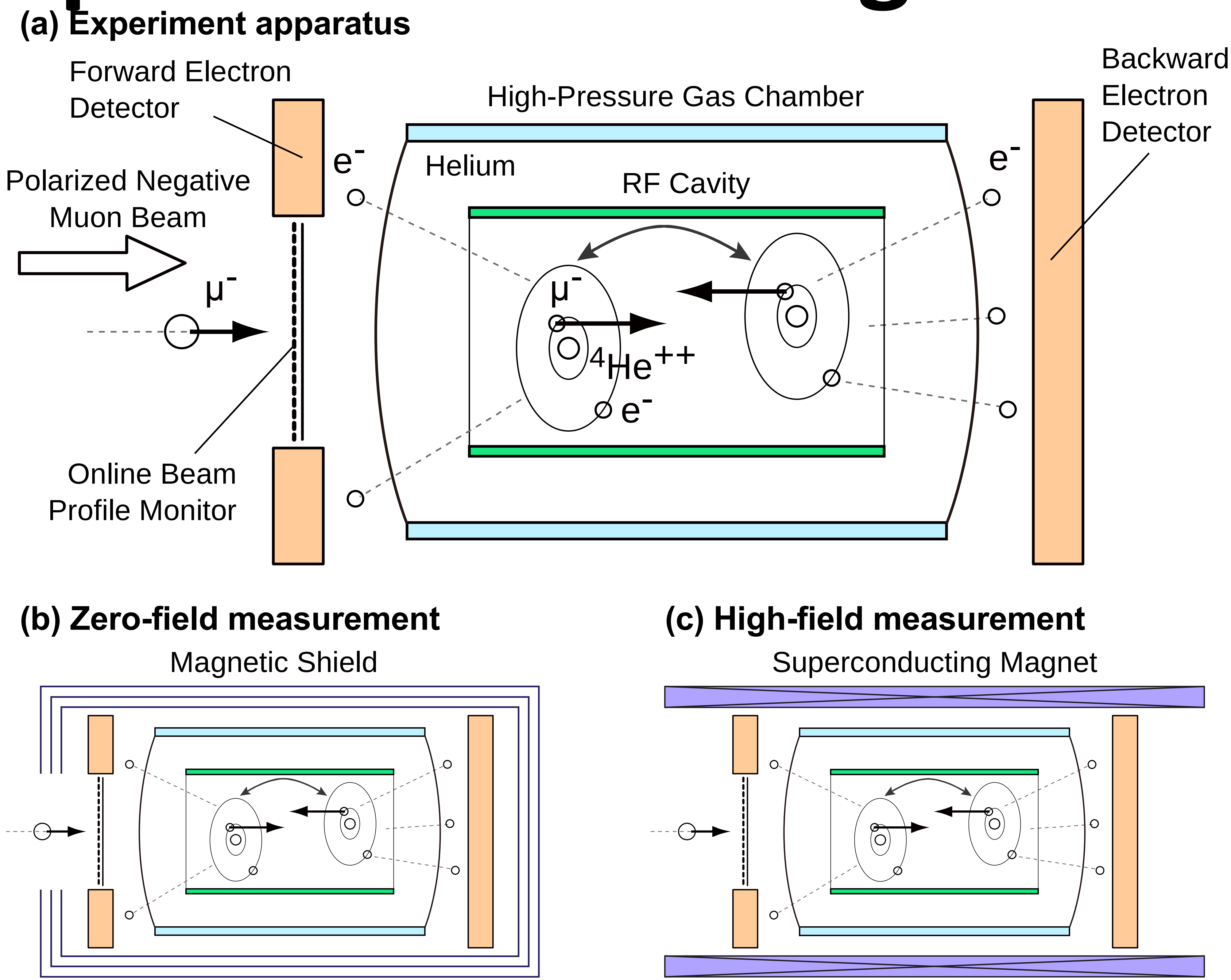
Negative Muon Beam Intensity

- Negative muon beam are generally 10 – 100 times less intense than surface (positive) muon beam.

Theoretical calculation of muonic helium ground state HFS ($\Delta\nu$)

- Very similar to Mu, but in reality complicated because of interaction and QED effects in three-body systems, thus theoretical approach has been limited.
- 1980s experimental values by far still outweigh any theoretical calculations.

Experimental Arrangement



Expected Improvements

Previous experiments: ($\Delta\nu$: 6.5 ppm, μ_{μ^-}/μ_p: 47 ppm)

- 5 ´ 10^4 μ^-/s at 55 MeV/c (low field), 4 ´ 10^4 μ^-/s at 35 MeV/c (high field)

H-line:

- ~10^7 μ^-/s at 30 MeV/c (at 1-MW proton beam power)

$\rightarrow$ ~10^4 times more statistics (intensity ´ ~10^3 & runtime of 100 days)

Statistical Improvement	$\Delta\nu$	μ_{μ^-}/μ_p
10^4 statistics (´100)	100 ppb	1000 ppb
Rabi Spectroscopy (´3)	30 ppb	350 ppb
Highly-Polarized μ^-He (´7)	4 ppb	50 ppb

Very Very Preliminary !!!

Systematic uncertainties:

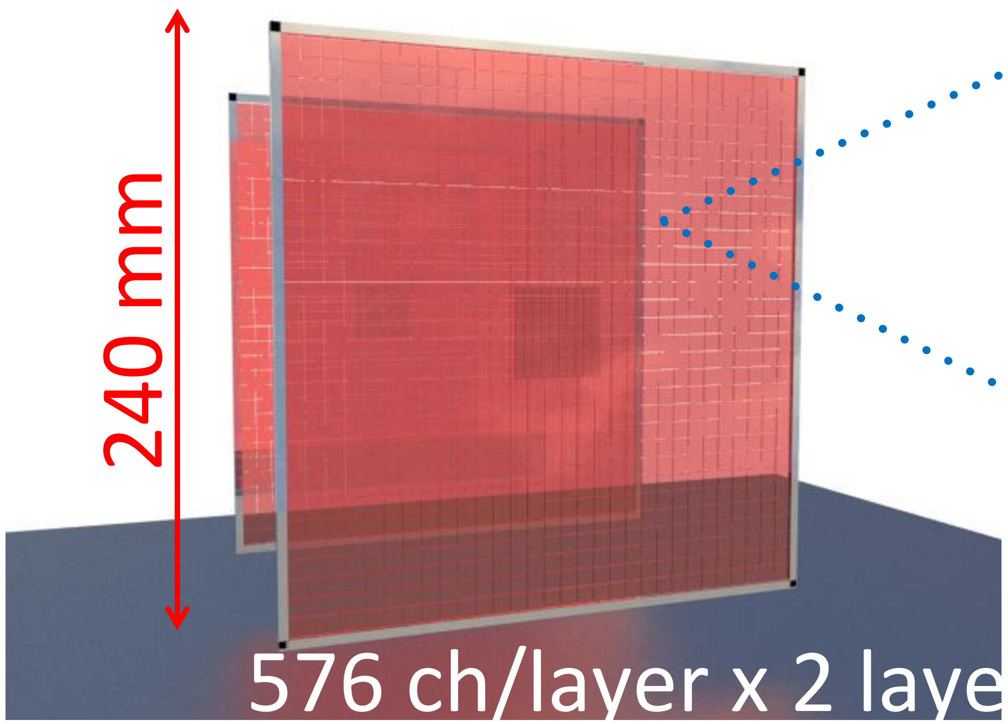
- MuSEUM experiment has similar systematical errors.
- Present estimation: ~2 ppb for $\Delta\nu$ and ~20 ppb for μ_{μ^-}/μ_p.

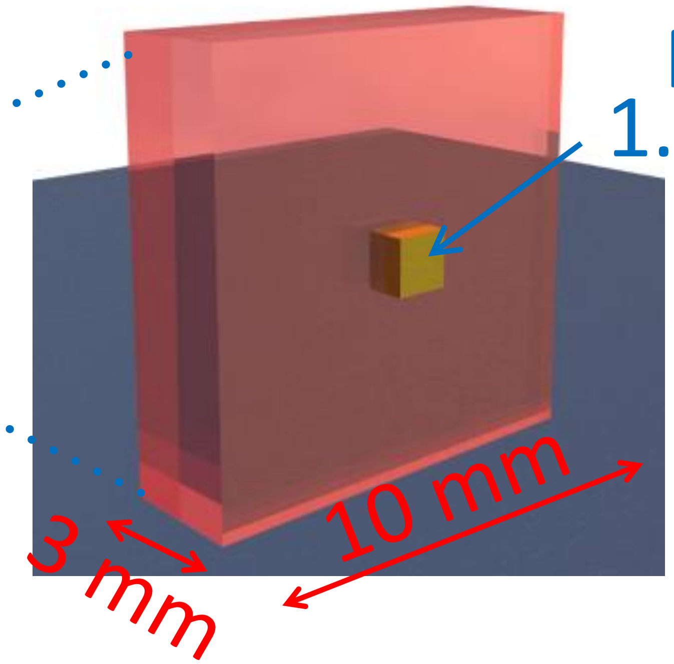
D-line: (zero field)

$\rightarrow$ 10^2–10^3 times more statistics (depending on beamtime allocation)

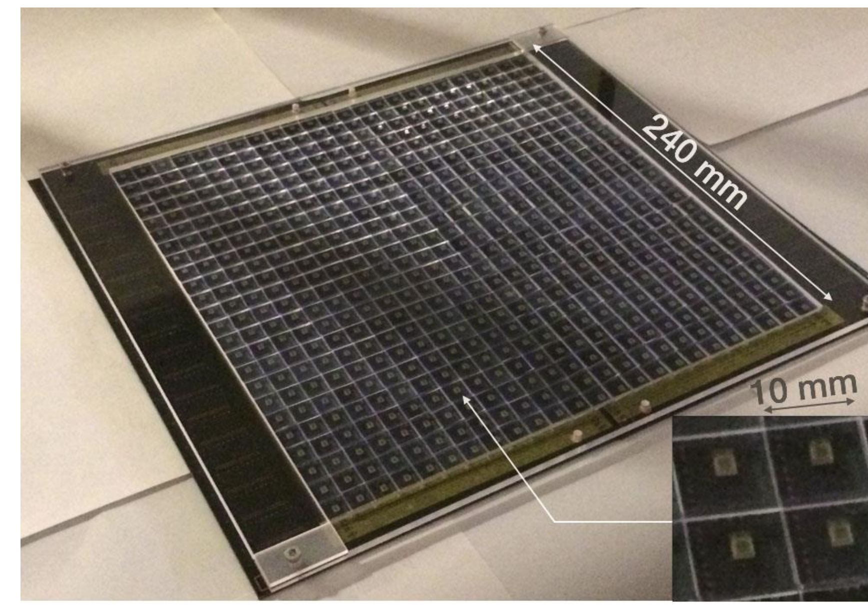
Positron Counter (1): Scintillation Position Detector

Kanda, Kojima

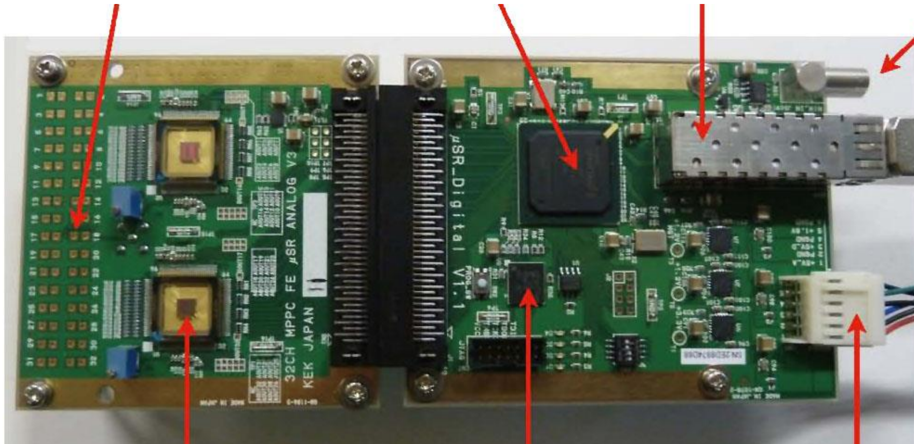




MPPC (Multi-Pixel Photon Counter)
1.3 mm x 1.3 mm active area
(Hamamatsu)



Plastic scintillator + MPPC + Kaliope readout circuit



Segmented scintillation detector

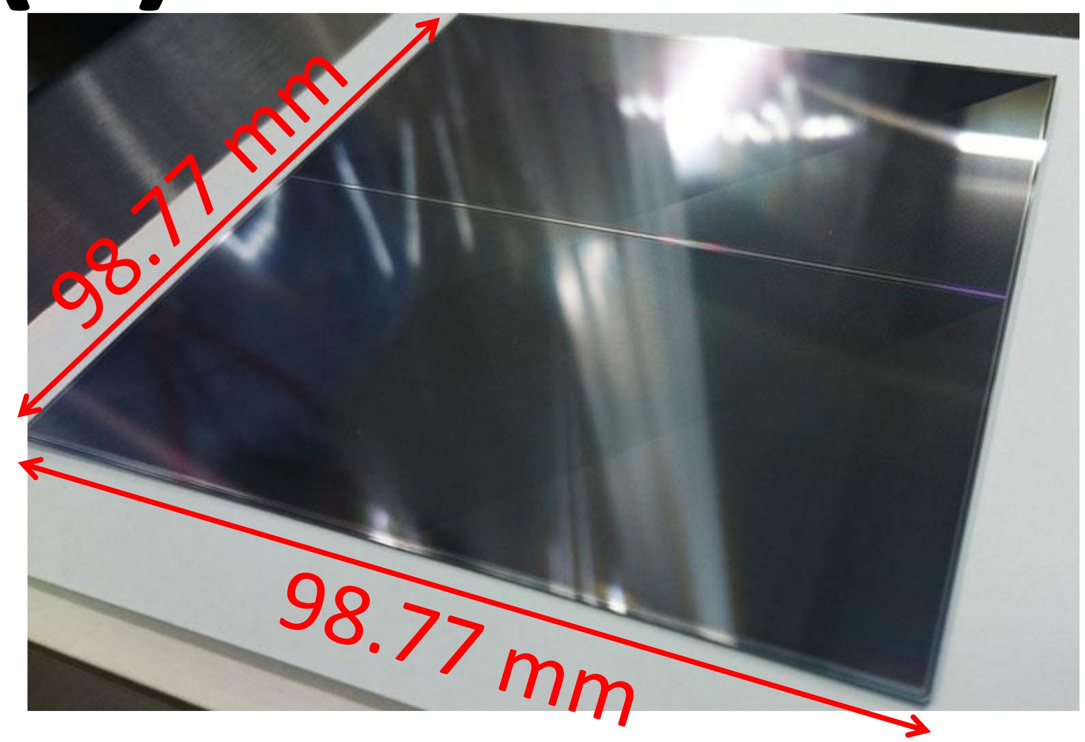
- Scintillation counter with SiPM readout
  - Unit cell: 10 mm × 10 mm × 3 mm^t
    - Area: 240 mm × 240 mm
  - 24x24 segments x 2 layers = 1152 ch
    - High-rate capability required
    - Pile-up loss at 3 MHz/ch ~ 2%

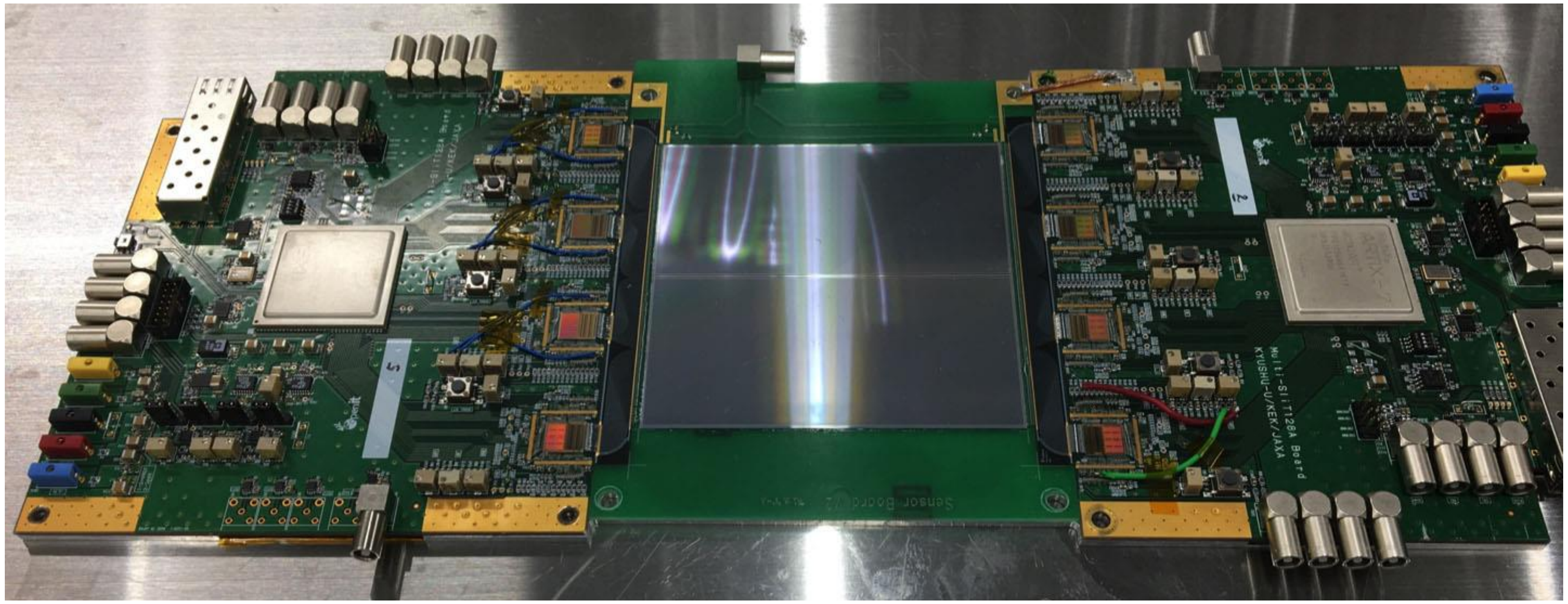
Slide from MuSEUM experiment

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

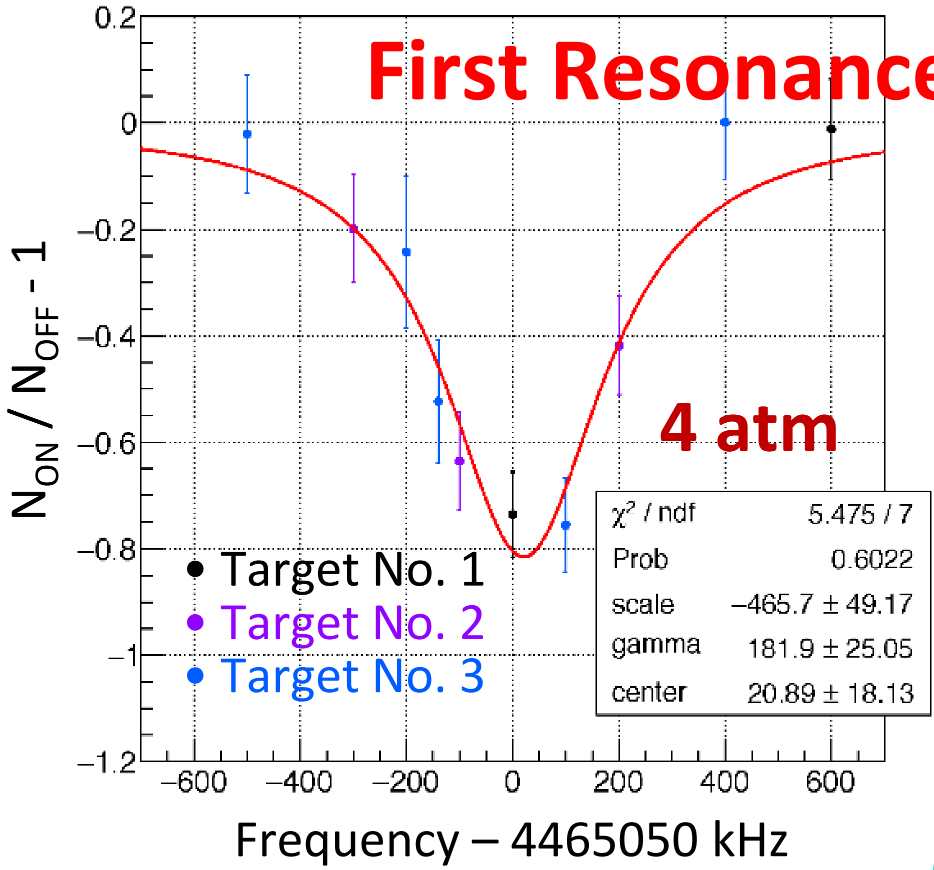
- Readout chips (SliT128A, 128 ch/chip)
- Developed for J-PARC g−2/EDM experiment
- Highly-segmented
- High-rate capability
- S/N ~ 21

Slide from MuSEUM experiment

MuHe HFS Resonance Curve

March 11–17, 2021 Beamtime

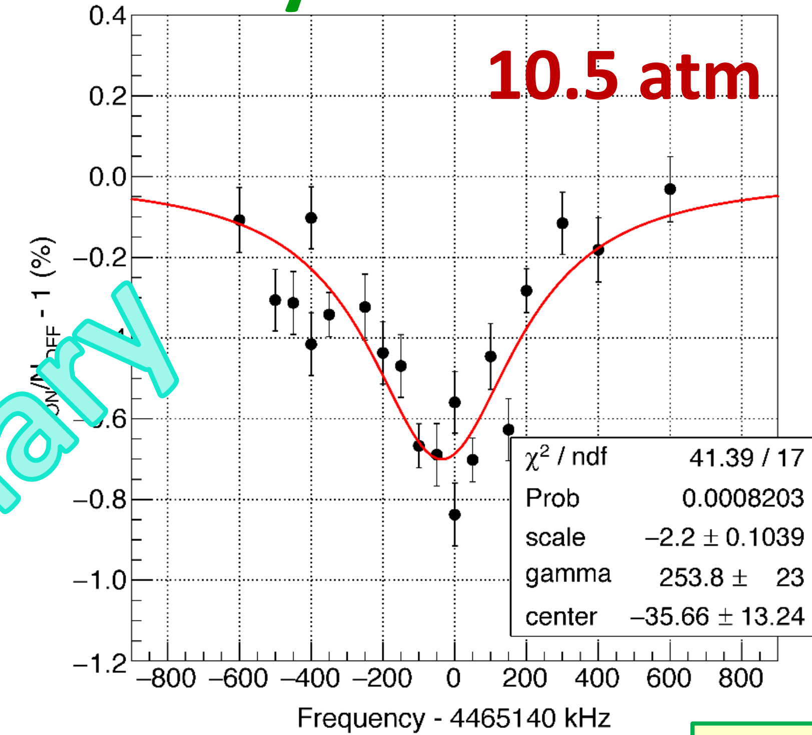
First Resonance Observed



[2020B0333]

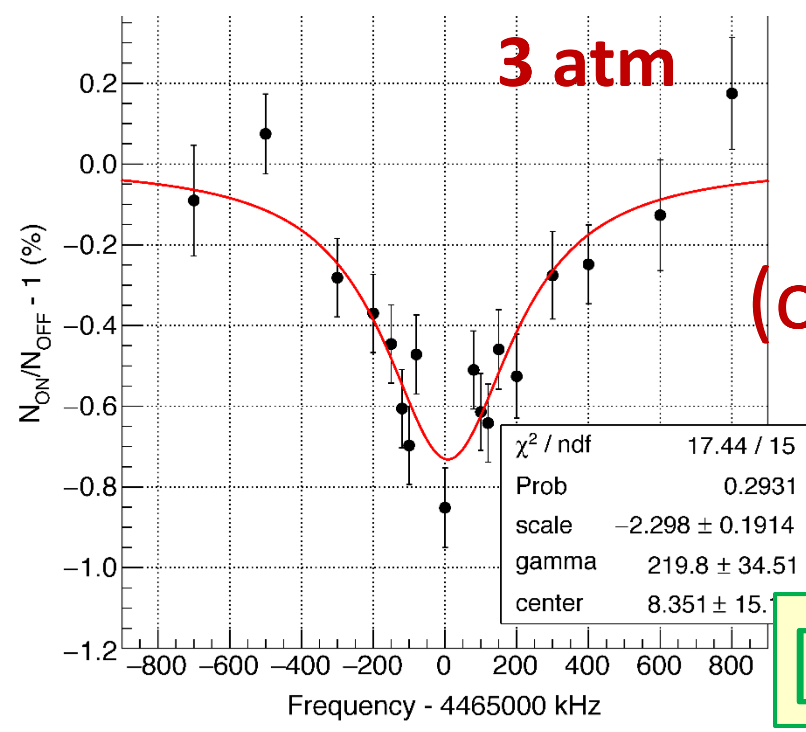
Very Preliminary

February 2022 Beamtime



[2021B0169]

May 2022 Beamtime

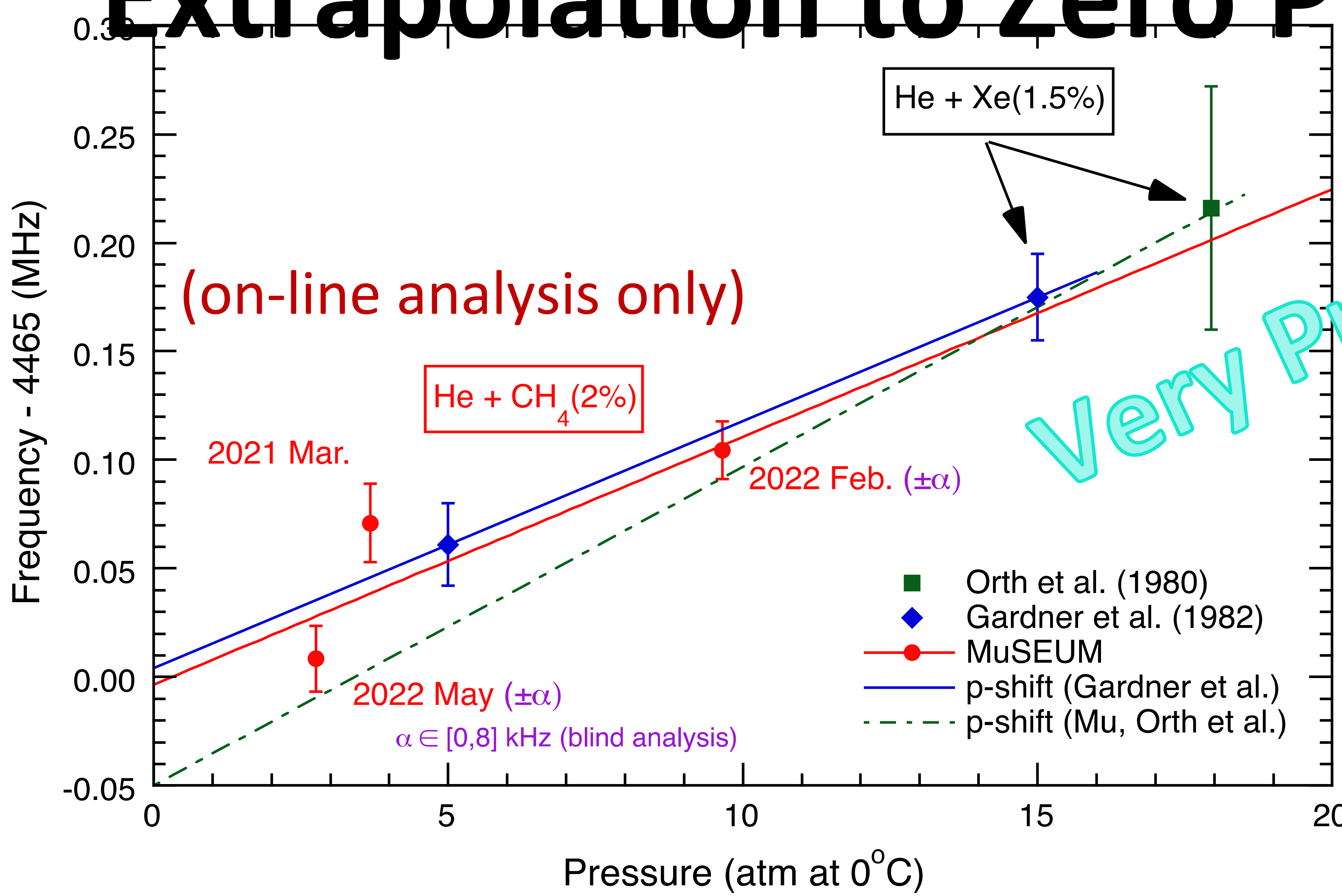


(on-line analysis onl

[2022A0159]

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

Extrapolation to Zero Pressure



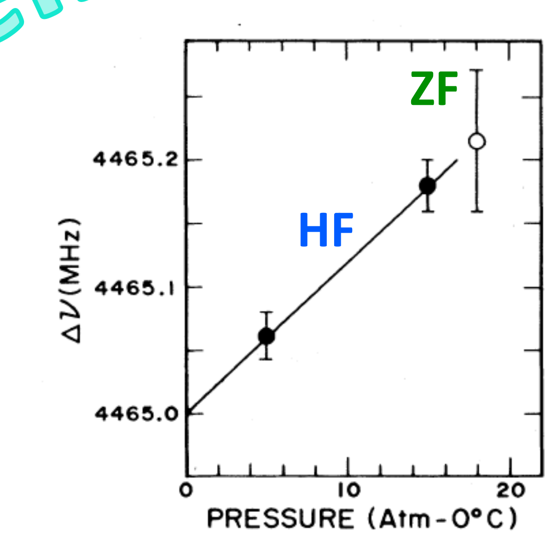


FIG. 2. Δν as a function of He+Xe(1.5%) gas pressure. Closed circles show the results of this experiment; the open circle is the result of Ref. 3. The straight line shows the linear extrapolation used to extract Δν(0).

ν = 4464.95(6) MHz (Orth et al.) [13 ppm] zero field (ZF)

4465.004(29) MHz (Gardner et al.) [6.5 ppm] high field (HF)

Δν = 4464.997(18) MHz (MuSEUM) [4ppm] zero field

Tentative Result !!
"Blind" Analysis in progress

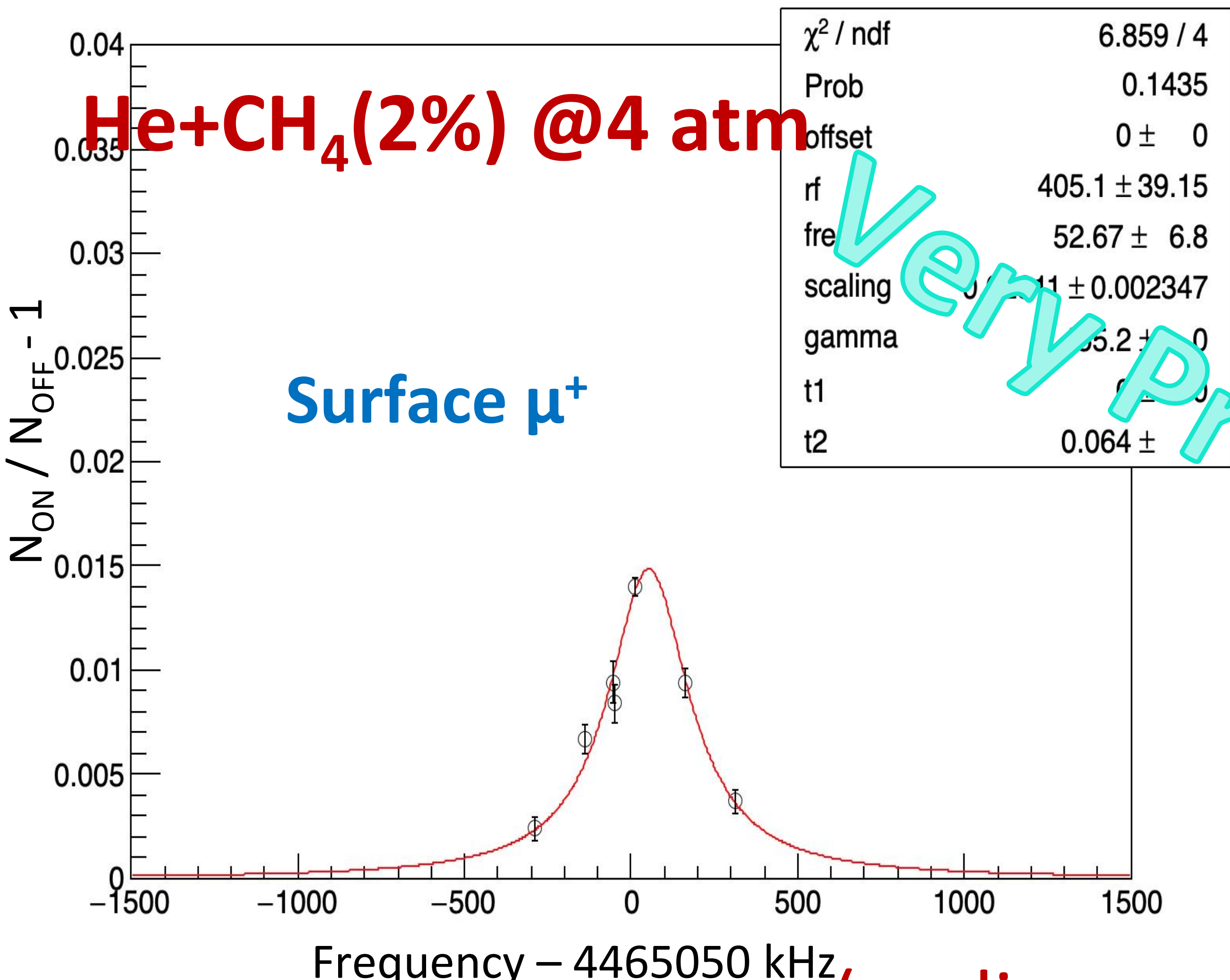
- **Probably a New World Record**

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

Muonium HFS Resonance Curve

MuSEUM Beamtime
(May 2021)

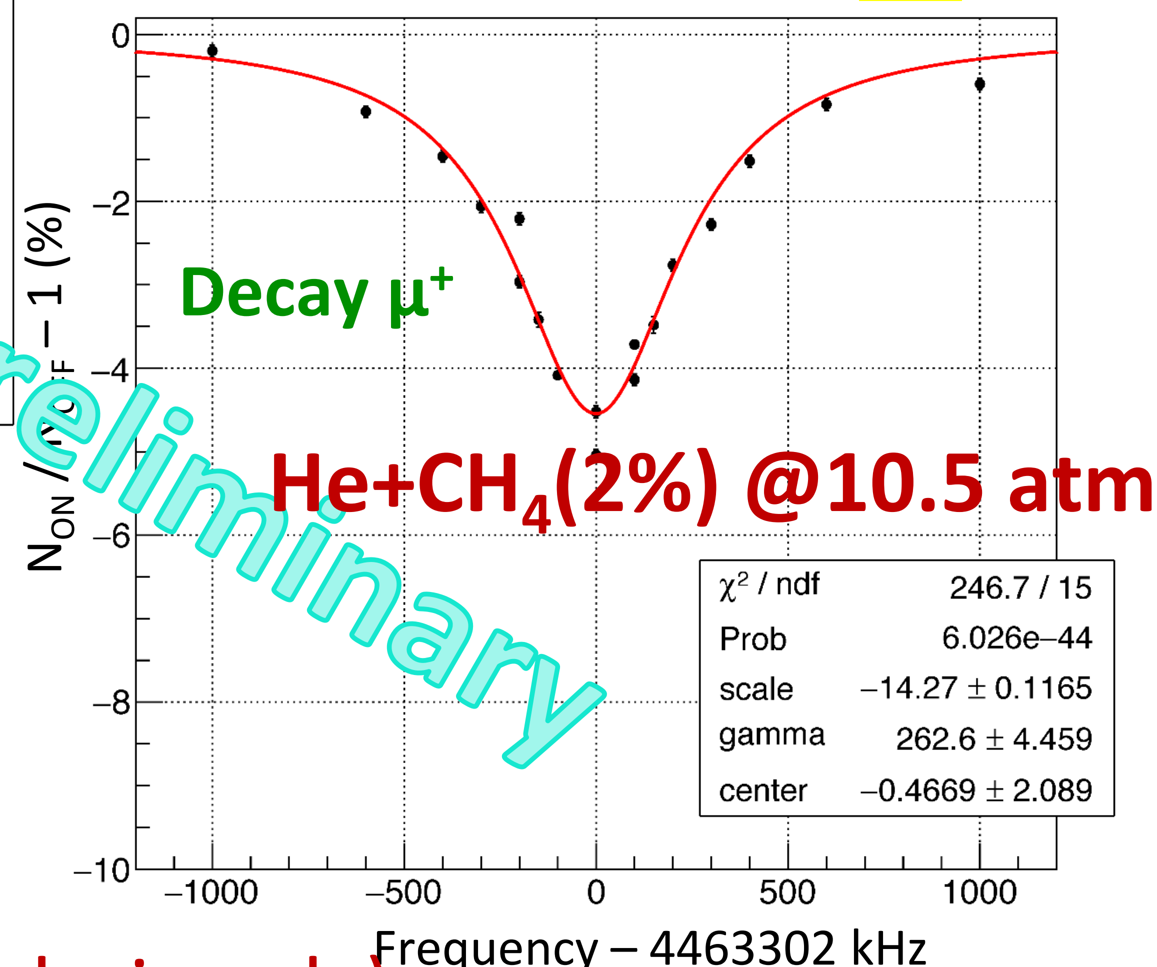
$\Delta\nu_{Mu}$(4 atm, RT)- $\Delta\nu_{Mu}$(0) = 52.7±6.8 kHz



MuHe Beamtime
(February - March 2022)

Blind analysis: α

$\Delta\nu_{Mu}$(10.5 atm, RT)- $\Delta\nu_{Mu}$(0)
= 139.5±2.1 kHz + α

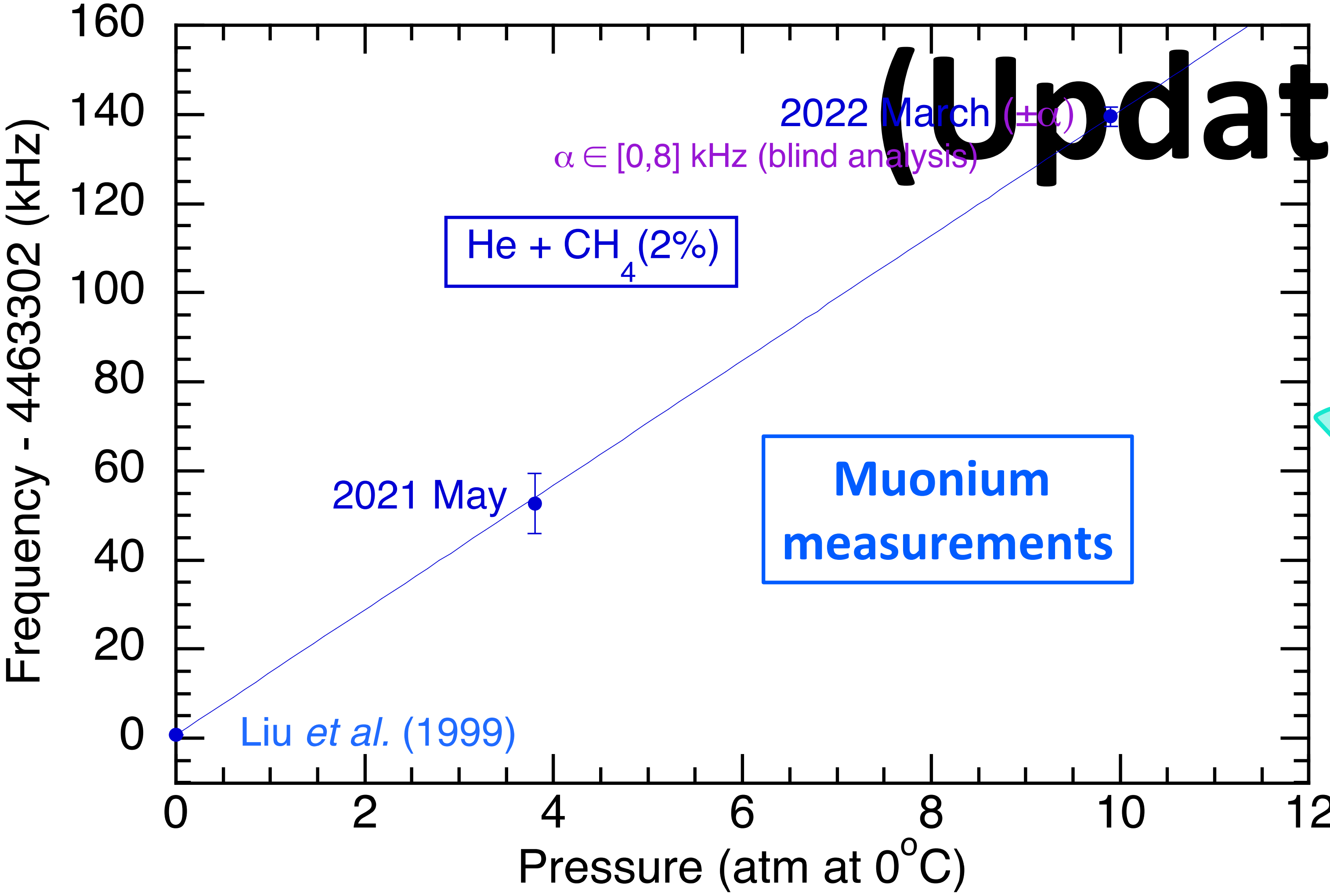


(on-line analysis only)

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

- **Determination of Mu pressure shift in He+CH_4(2**
  - **Comparision with μHe pressure shift**

Pressure Shift Comparison (Update)



Very Preliminary

[1] H. Orth et al., PRL 45 (1980) 1483
[2] C. J. Gardner et al., PRL48 (1982) 1168
[3] F. M. Pipkin et al., Phys. Rev. 127 (1962) 787
[4] E. S. Ensberg et al., Phys. Lett. 28A (1968) 106
[5] D. E. Casperson et al., Phys. Lett. 59B (1975) 397

(blind analysis)

	He + Xe(1.5%)	He + CH_4(2%)	Pure He
Mu	14.7 ± 0.9 kHz/atm [1]	**14.0 ± 0.2 kHz/atm (b.a.)**	n/a
^{4}He	11.4 ± 2.7 kHz/atm [2]	**11.4 ± 2.7 kHz/atm (b.a.)**	n/a
H	15.0 ± 0.3 kHz/atm [3,4]	–	16.3 ± 0.3 kHz/atm [3]

Pressure shift in noble gases: on isotopic effect observed for H, D, T

Highly-Polarized Muonic He Atom

Production of highly-polarized muonic helium atom by spin exchange optical pumping (SEOP)

VOLUME 70, NUMBER 6 PHYSICAL REVIEW LETTERS 8 FEBRUARY 1993

Highly Polarized Muonic He Produced by Collisions with Laser Optically Pumped Rb

A. S. Barton, P. Bogorad, G. D. Cates, H. Mabuchi, H. Middleton, and N. R. Newbury
Department of Physics, Princeton University, Princeton, New Jersey 08544

R. Holmes, J. McCracken, P. A. Souder, and J. Xu
Department of Physics, Syracuse University, Syracuse, New York 13244

D. Tupa
Los Alamos National Laboratory, Los Alamos, New Mexico 87545
(Received 24 September 1992)

We have formed highly polarized muonic helium by stopping unpolarized negative muons in a mixture of unpolarized gaseous He and laser polarized Rb vapor. The stopped muons form muonic He ions which are neutralized and polarized by collisions with Rb. Average polarizations for ^{3}He and ^{4}He of (26.8±2.3)% and (44.2±3.5)% were achieved, representing a tenfold increase over previous methods. Relevant cross sections were determined from the time evolution of the polarization. Highly polarized muonic He is valuable for measurements of the induced pseudoscalar coupling g_p in nuclear muon capture.

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

for μ^4He: 6% → 44%

Improvement by a factor 7 achieved !

Maximum theoretical polarization: ^{4}He = 100%, ^{3}He 75%

Polarization 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:

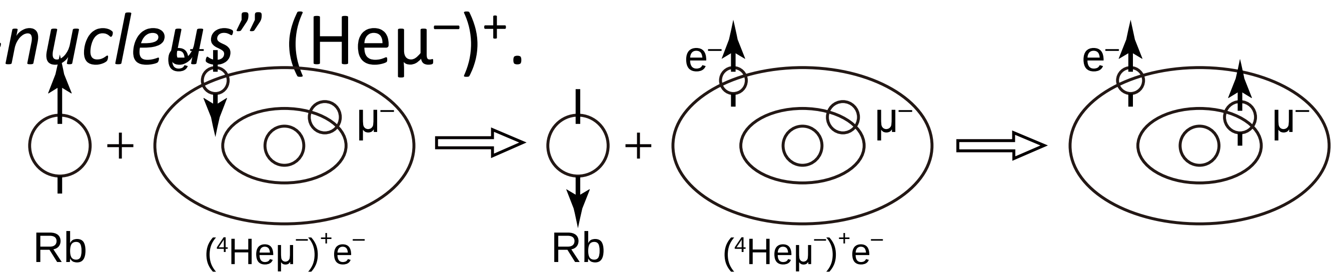
$$Rb\uparrow + He(\mu^{-}He)^{+} \rightarrow Rb^{+} + He + (\mu^{-}He)^{+}\, e^{-}\uparrow$$

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 helium atom is formed, 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*" $(He\mu^{-})^{+}$.



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

SEOP for μHe HFS Measurements

New MuSEUM-SEOP collaboration just started !

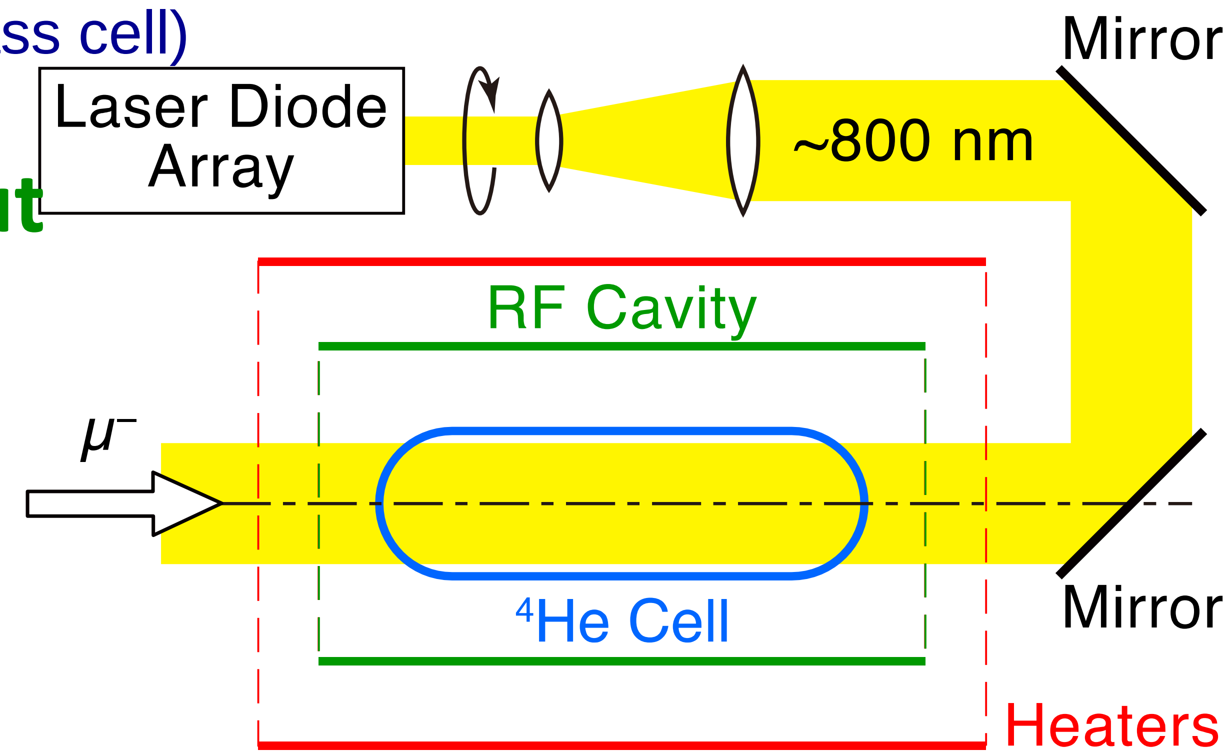
KEK: T. Ino, S. Kanda, S. Nishimura K. Shimomura

Nagoya Univ.: S. Fukumura, T. Okudaira, M. Kitaguchi, H. M. Shimizu

Tohoku Univ.: M. Fujita, Y. Ikeda (glass cell)

JAEA: T. Oku

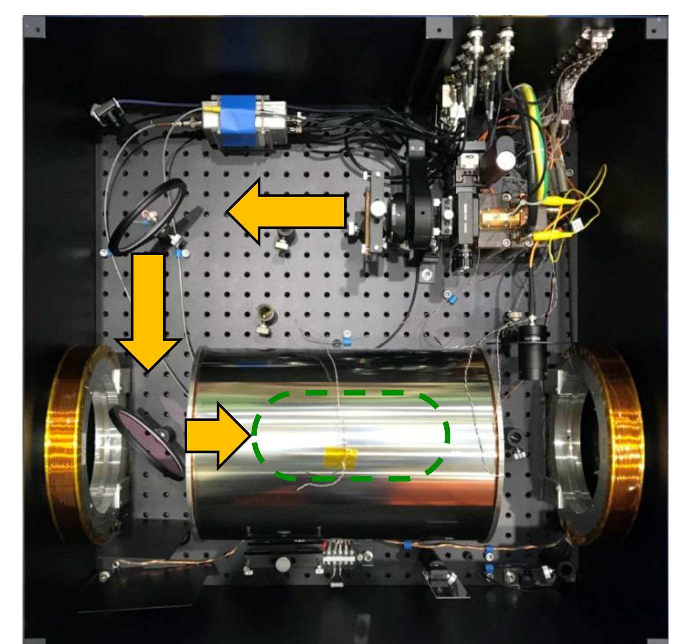
Schematic layout



Prototype Gas Cell
Ø74 mm x 152 mm
(picture from T. Ino)

Experimental Challenges:

- RF field inside glass cell
- SEOP in high magnetic field
- Magnetic field uniformity
- Gas pressure and temperature stability
- New systematics …



Example:
^{3}He gas spin filter of POLANO (MLF BL23) by T. Ino et al. (KEK)

New Laser System for µHe SEOP

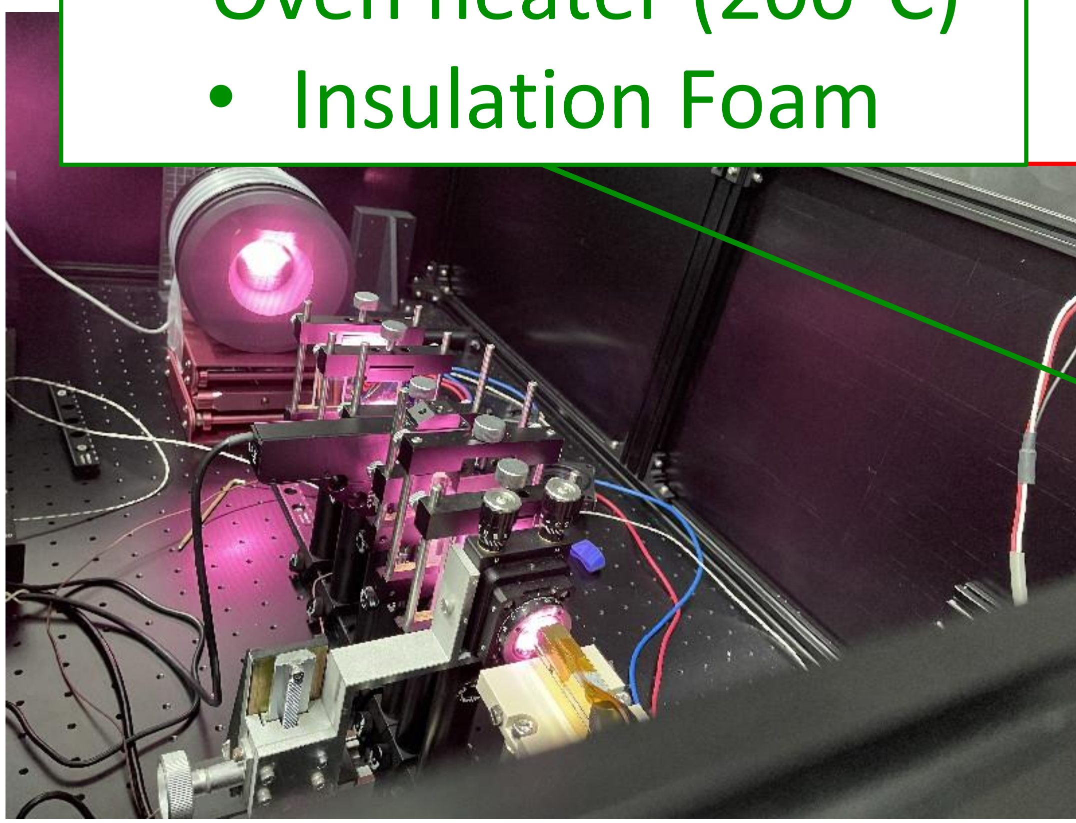
S. Fukumura
T. Okudaira

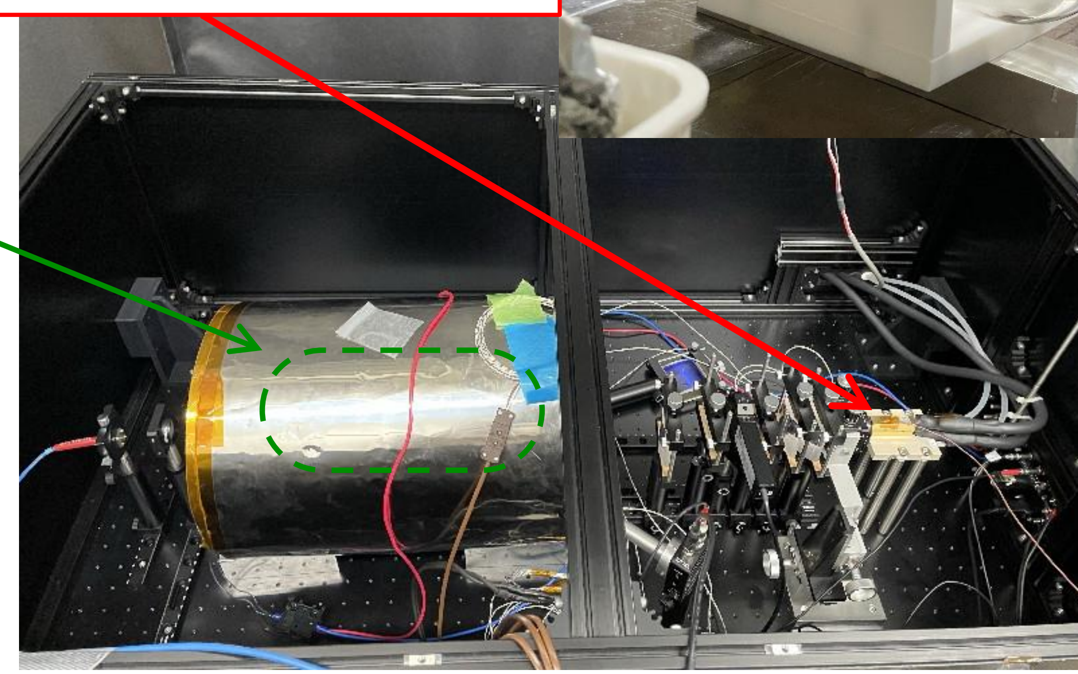
A laser system for muonic helium SEOP has been constructed:

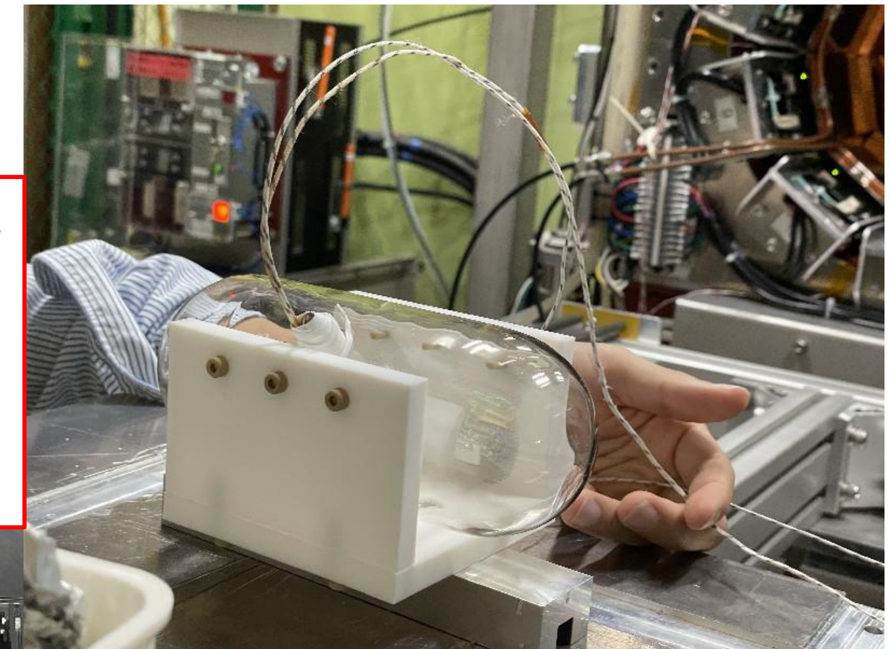
To confirm that SEOP is possible with the new laser, EPR signal was measured using a

SEOP Cell surrounded by
- Oven heater (200°C)
- Insulation Foam

aser Diode Array
- Power: ~60 W
- Wavelength: 795 nm
- Operating mode: CW





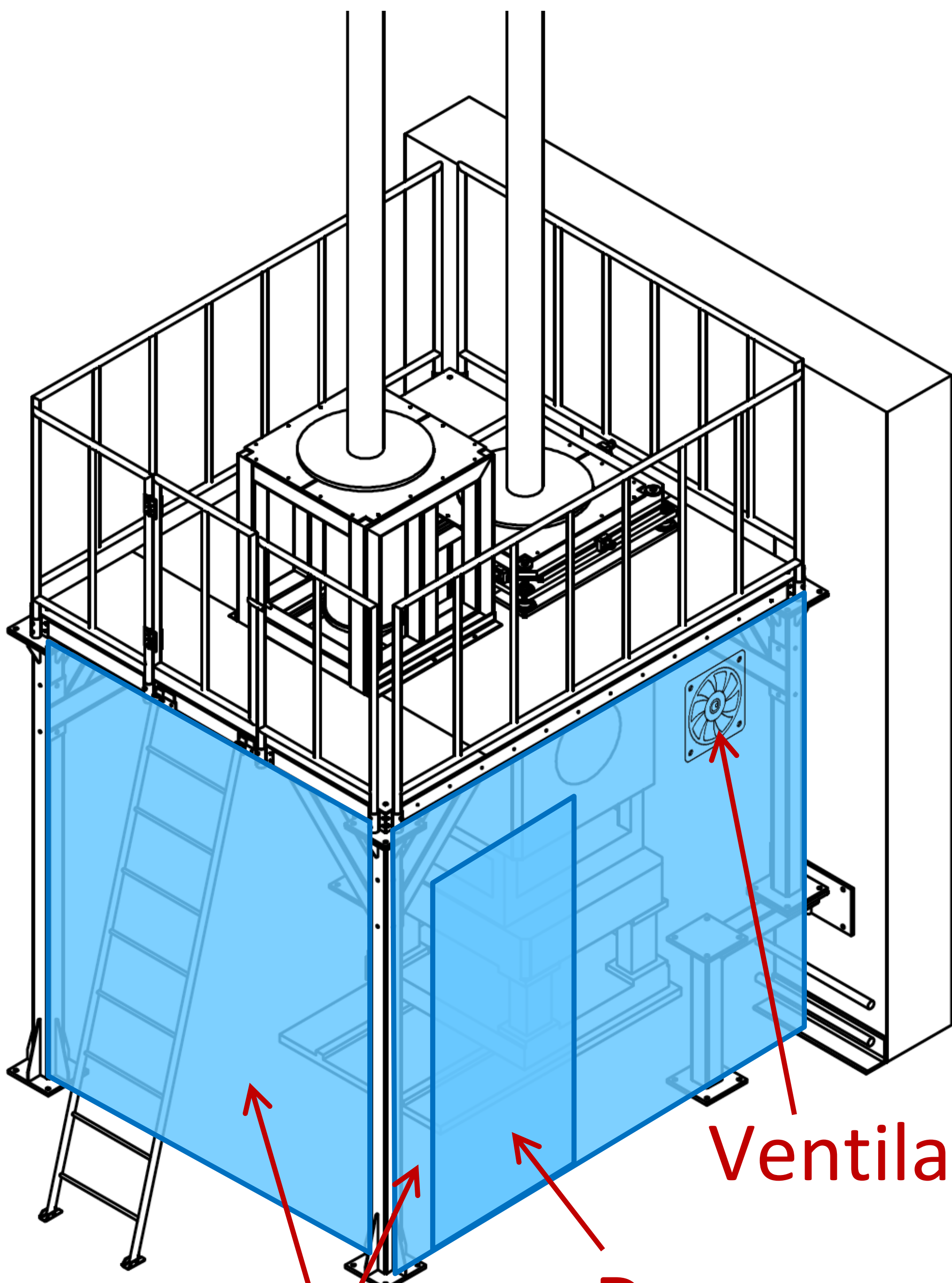


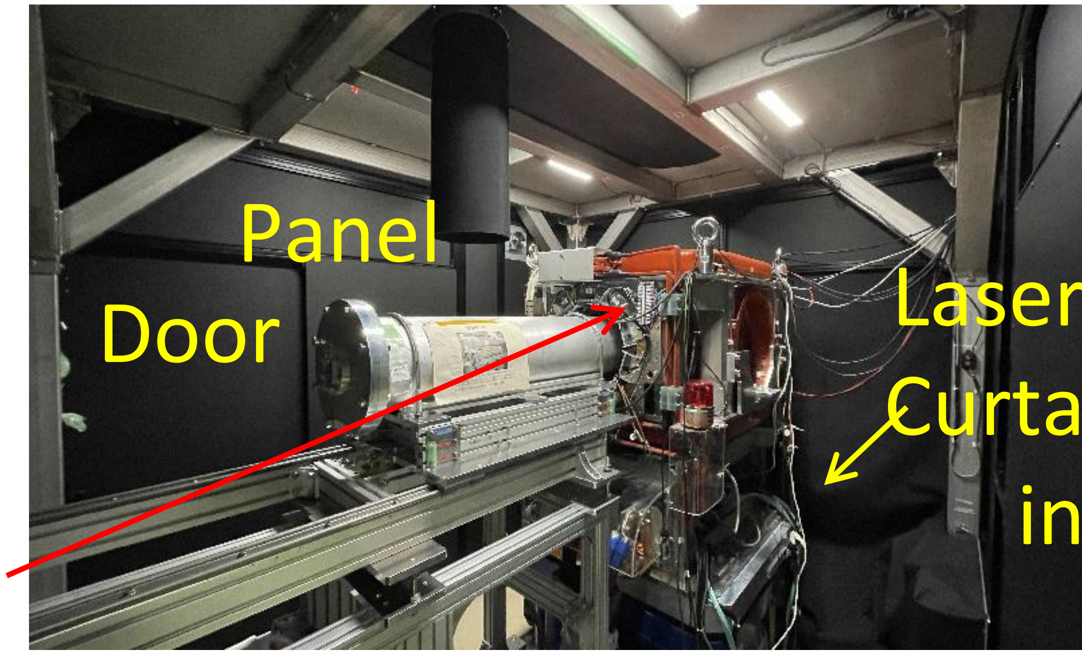
Prototype Gas Cell

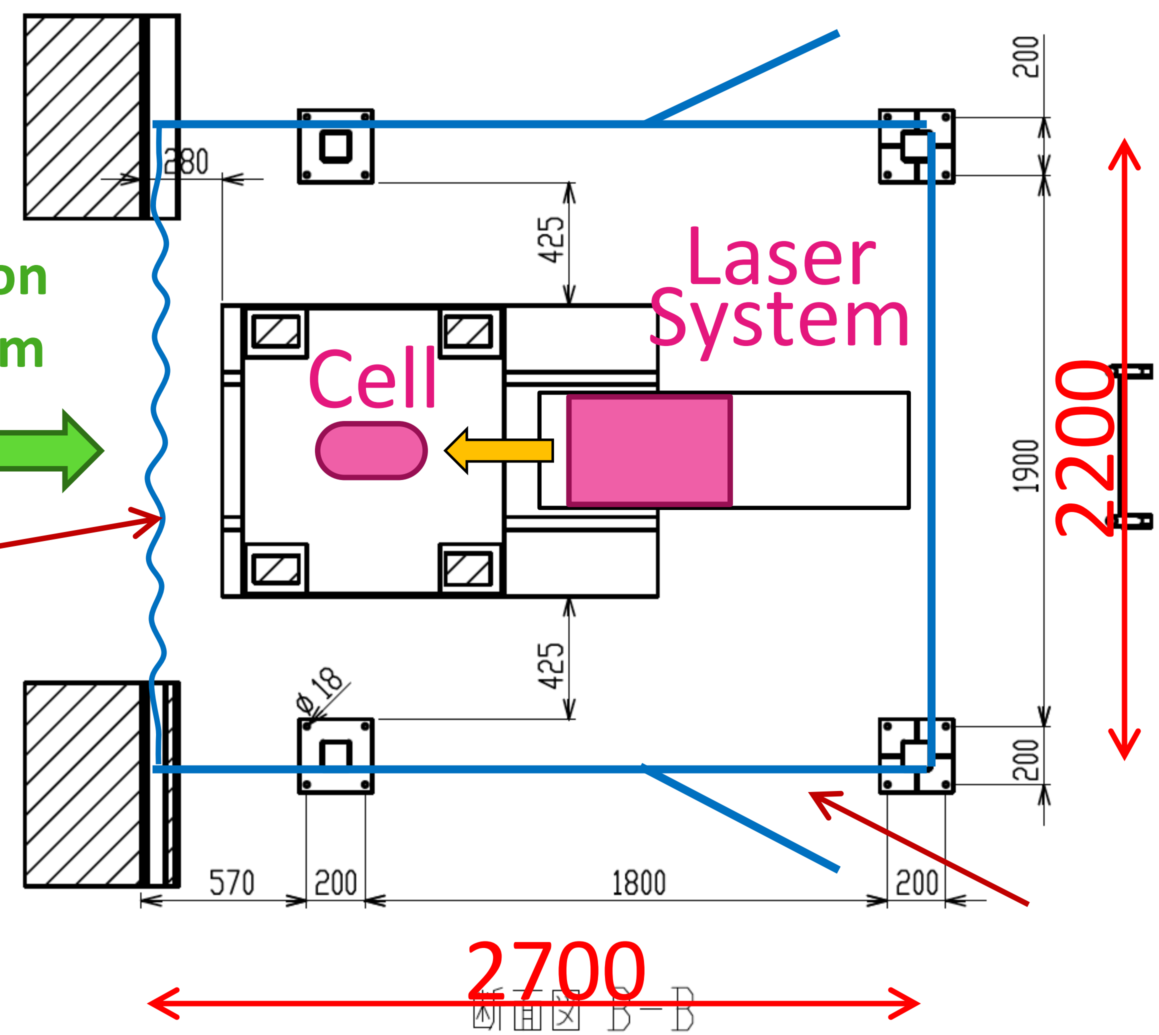
EPR: Electron Paramagnetic Resonance
- Excite Rb and K with RF and measure the de-excitation light intensity.
- The population of each sub-level can be estimated from the de-

Laser Enclosure at D1 Area

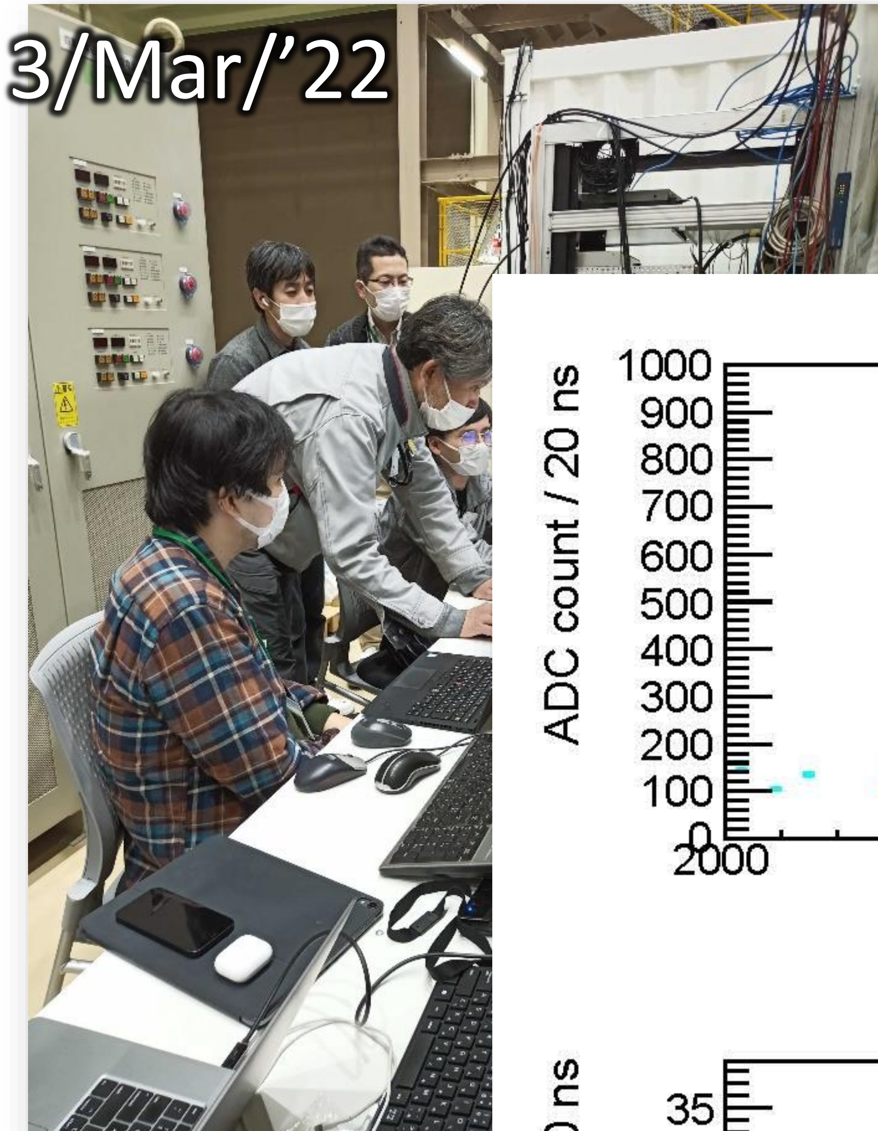
A removable laser enclosure for SEOP experiment at D1 area was constructed !





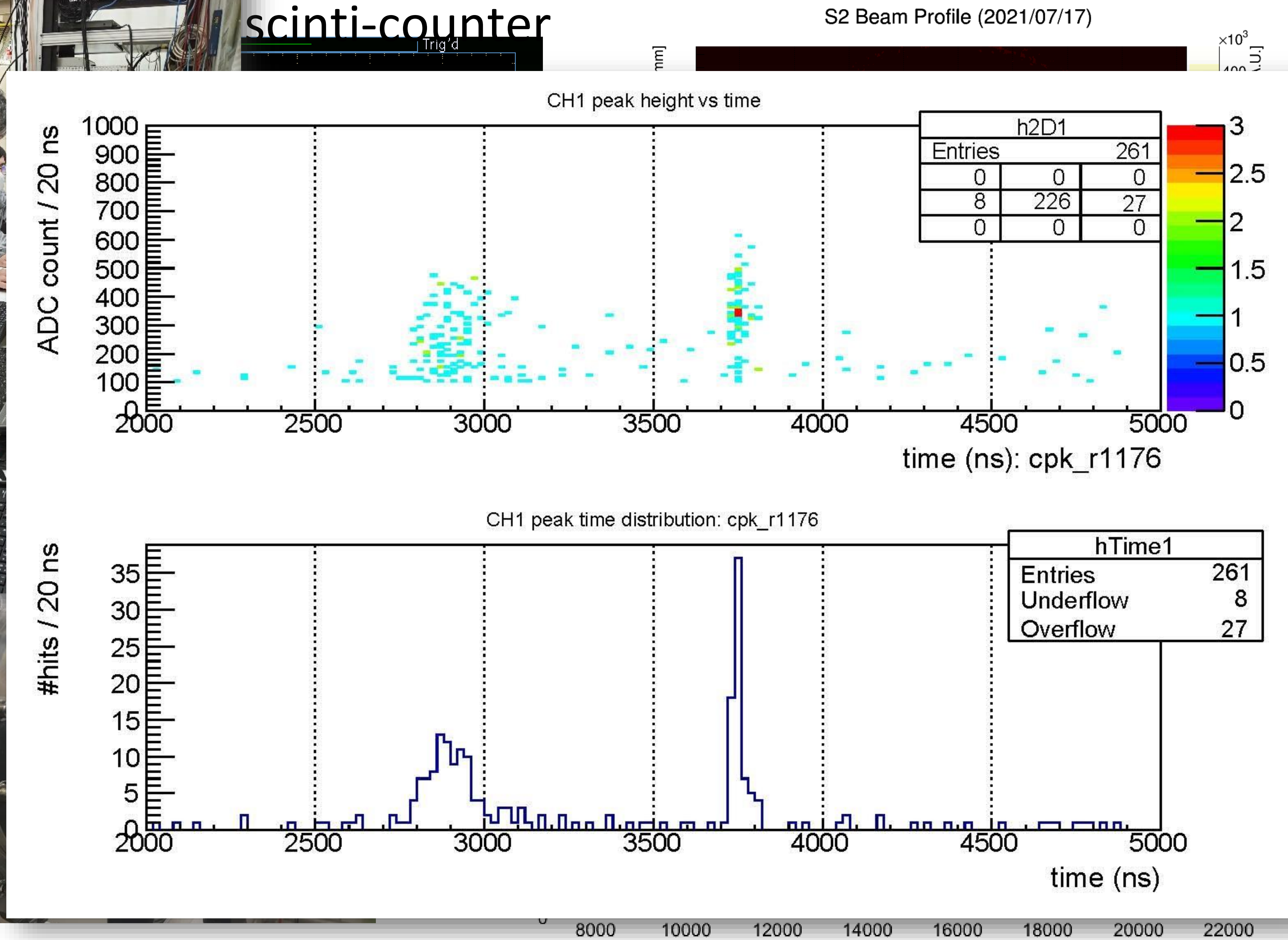


Mu 1s-2s



...st beam delivery to S2 area was achieved (17/Jul/'21).

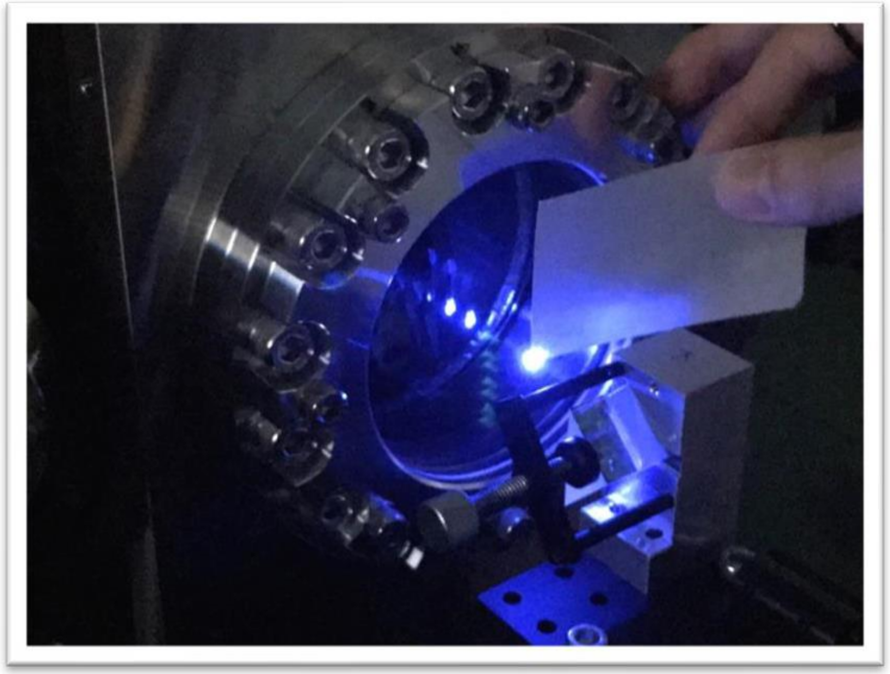
...scinti-counter

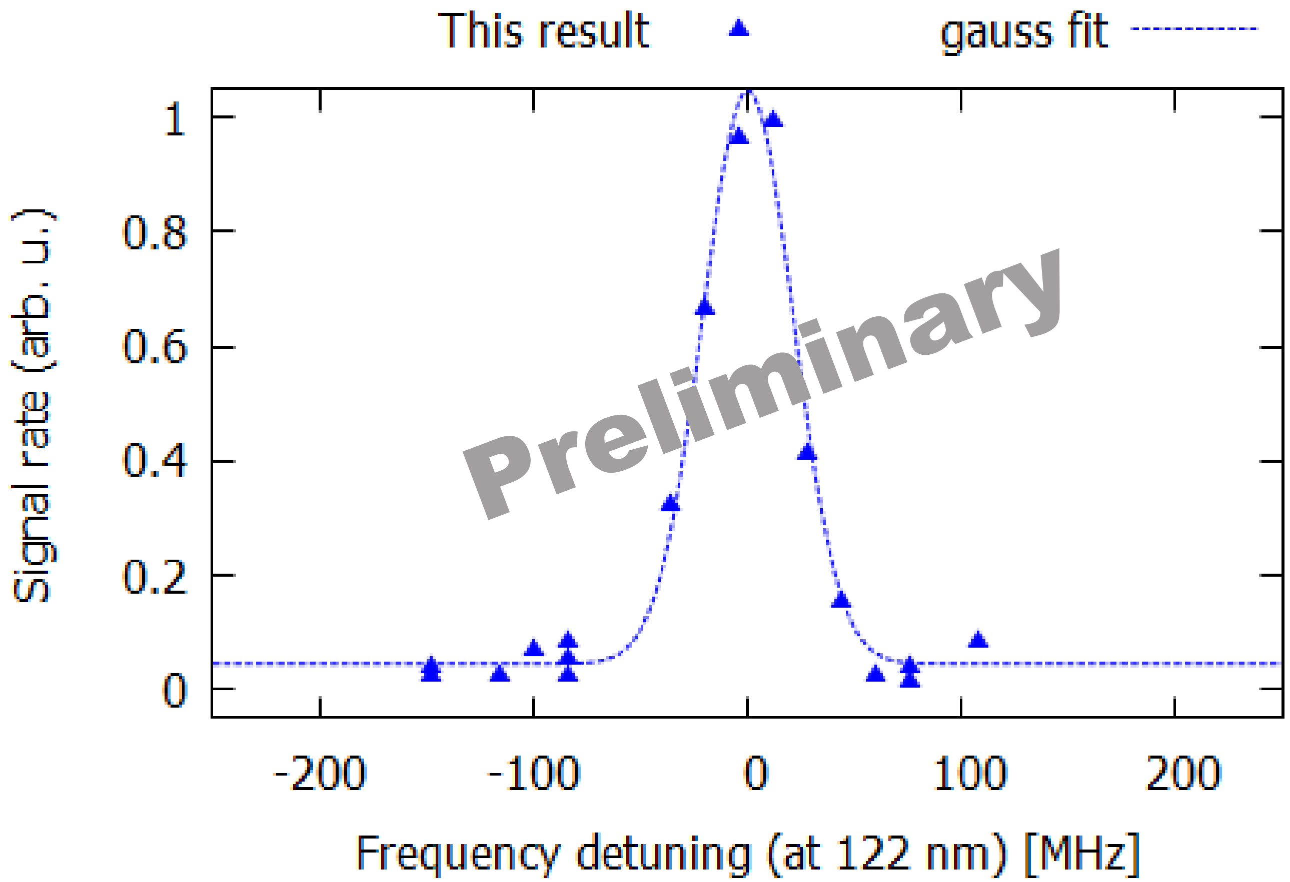


Scinti-counter at the S2 beam exit

Laser Spectroscopy of Mu 1S-2S Transition

244 nm Laser Light





Summary

- Muonium spectroscopy improves understanding of the Standard Model
- MuSEUM collaboration preparing for MuHFS measurements
- Experiments at zero magnetic field were successfully completed
- 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.
- Another MuSEUM (muonic He HFS measurement) is in good progress.
- Mu 1s-2s measurement started!