Precision measurement of muonium hyperfine structure at J-PARC

2017/09/28 NUFACT2017

Shun SEO (The University of Tokyo)
for MuSEUM collaboration

MuSEUM

東京大学
THE UNIVERSITY OF TOKYO

Outline

1. About MuSEUM

2. Apparatus

3. Results of resonance measurements

Outline

1. About MuSEUM

2. Apparatus

3. Results of resonance measurements

MuSEUM

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

MuSEUM

- **Collaborators**

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

JAEA

J-PARC

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

RIKEN

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

TOHOKU UNIVERSITY

K. S. Tanaka

M. Aoki,
D. Tomono

E. Torikai

UNIVERSITY OF MASSACHUSETTS AMHERST 1863

D. Kawall

K. Kubo

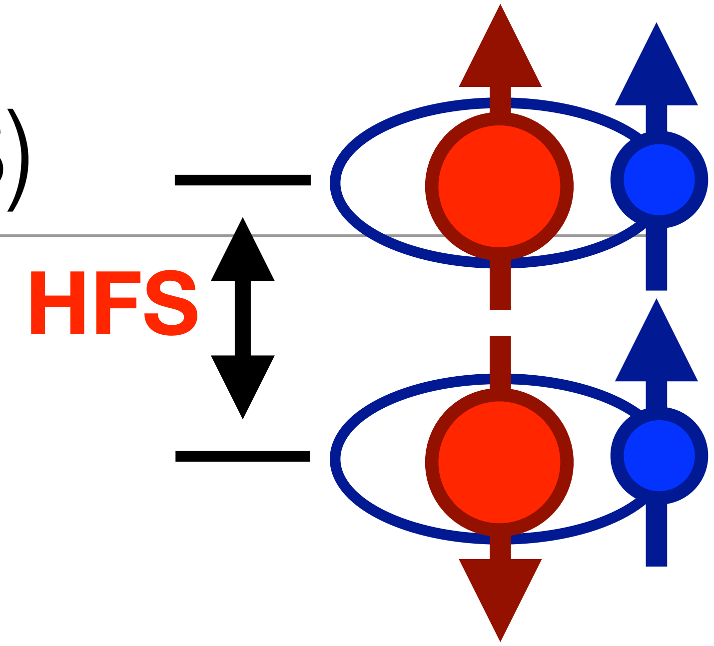
茨城大学 Ibaraki University

H. Iinuma

VERI LUX TAS MEA

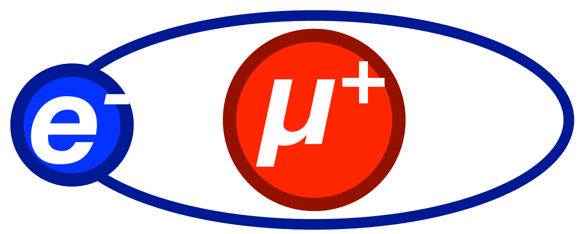
S. Choi

Muonium hyperfine structure (Mu HFS)



- What is Muonium?
  - Hydrogen-like atom: bound state of μ^+ and e^-
  - Theoretical calculation is highly precise

Muonium



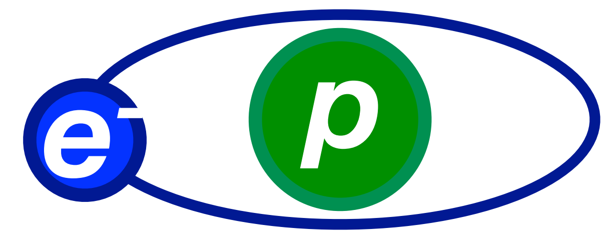
Consist only of leptons (purely-leptonic)

-> Theoretical value is calculated precisely

$\Delta\nu_{\mathrm{th}}$ = 4.463 302 891 (272) GHz (**63 ppb**)

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

Hydrogen



Proton consists of 3 quarks

-> Difficult to calculate theoretical value

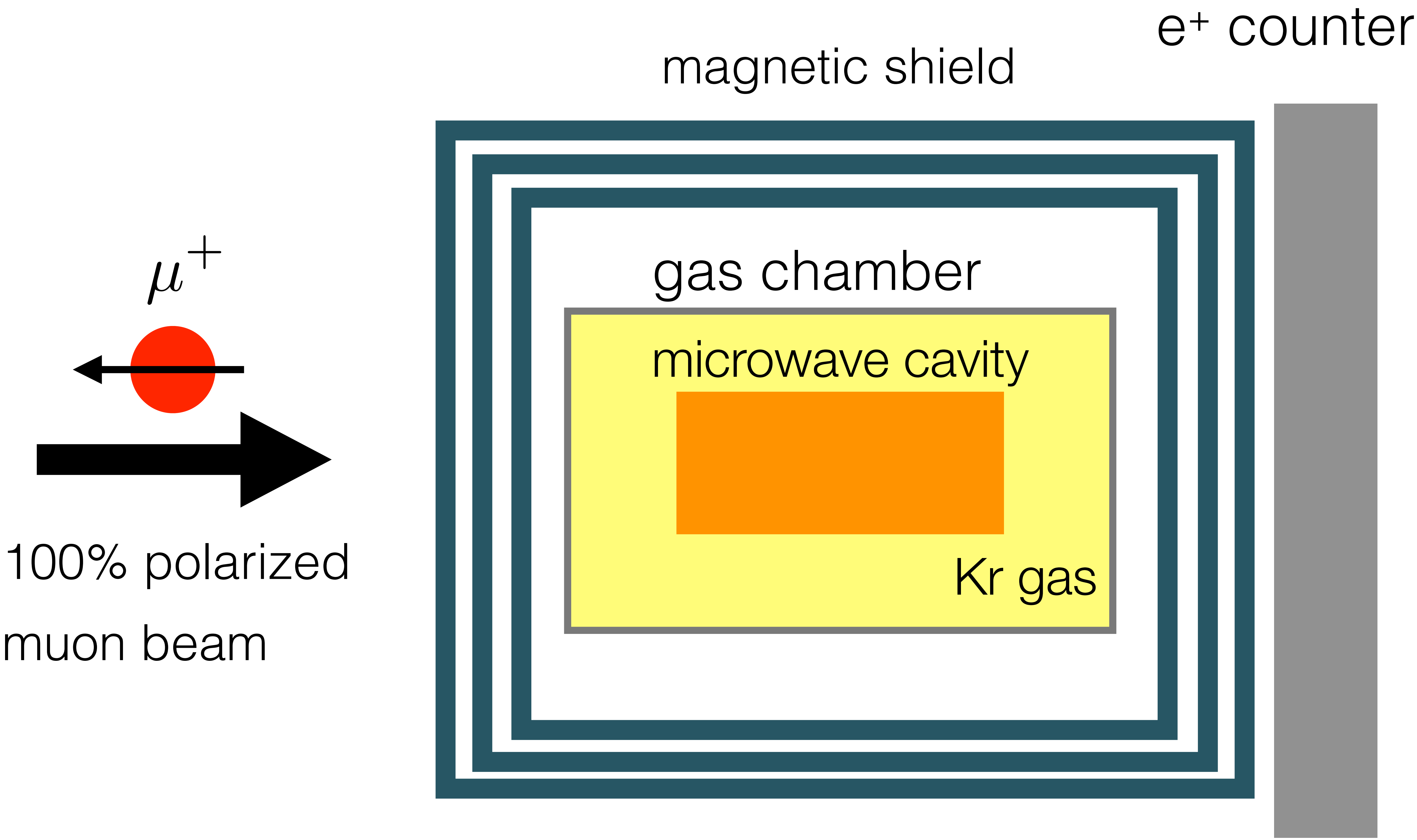
$\Delta\nu_{\mathrm{th}}$ = 1.420 403 1 (8) GHz (**560 ppb**)

M. I. Eides, *et al.*, "Theory of Light Hydrogenic Bound States" (2007)

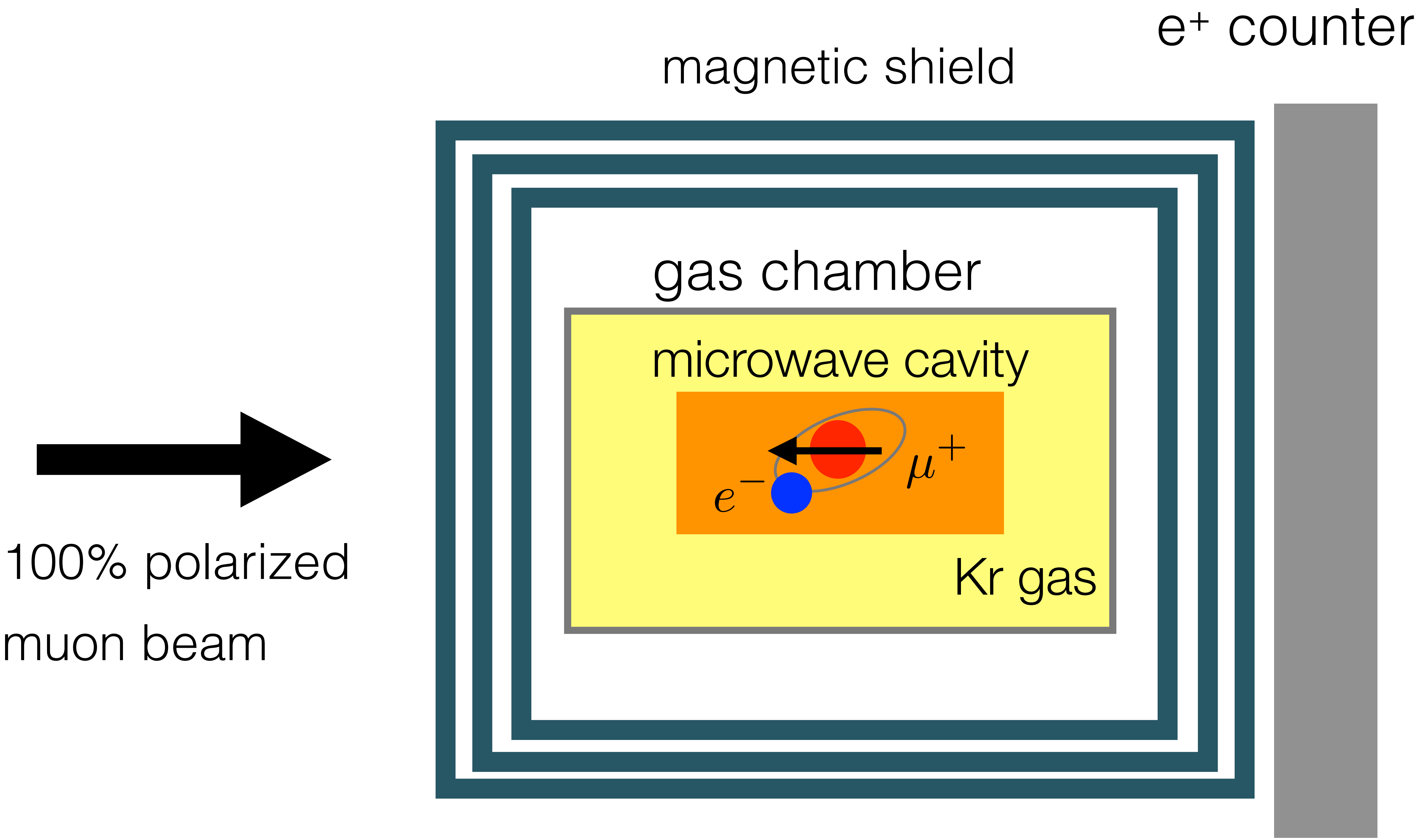
- **Motivation:**
  The most rigorous validation of the bound-state QED
- **Measurement of MuHFS in zero magnetic field is ongoing**
  - MuSEUM Goal: ten-fold improvement
    - Best record (Zero-field) : $\Delta\nu_{\mathrm{exp}}$ = 4.463 3022(14) GHz (300 ppb)

      D. E. Casperson, et al., Physics Lett. **59B** 397 (1975).

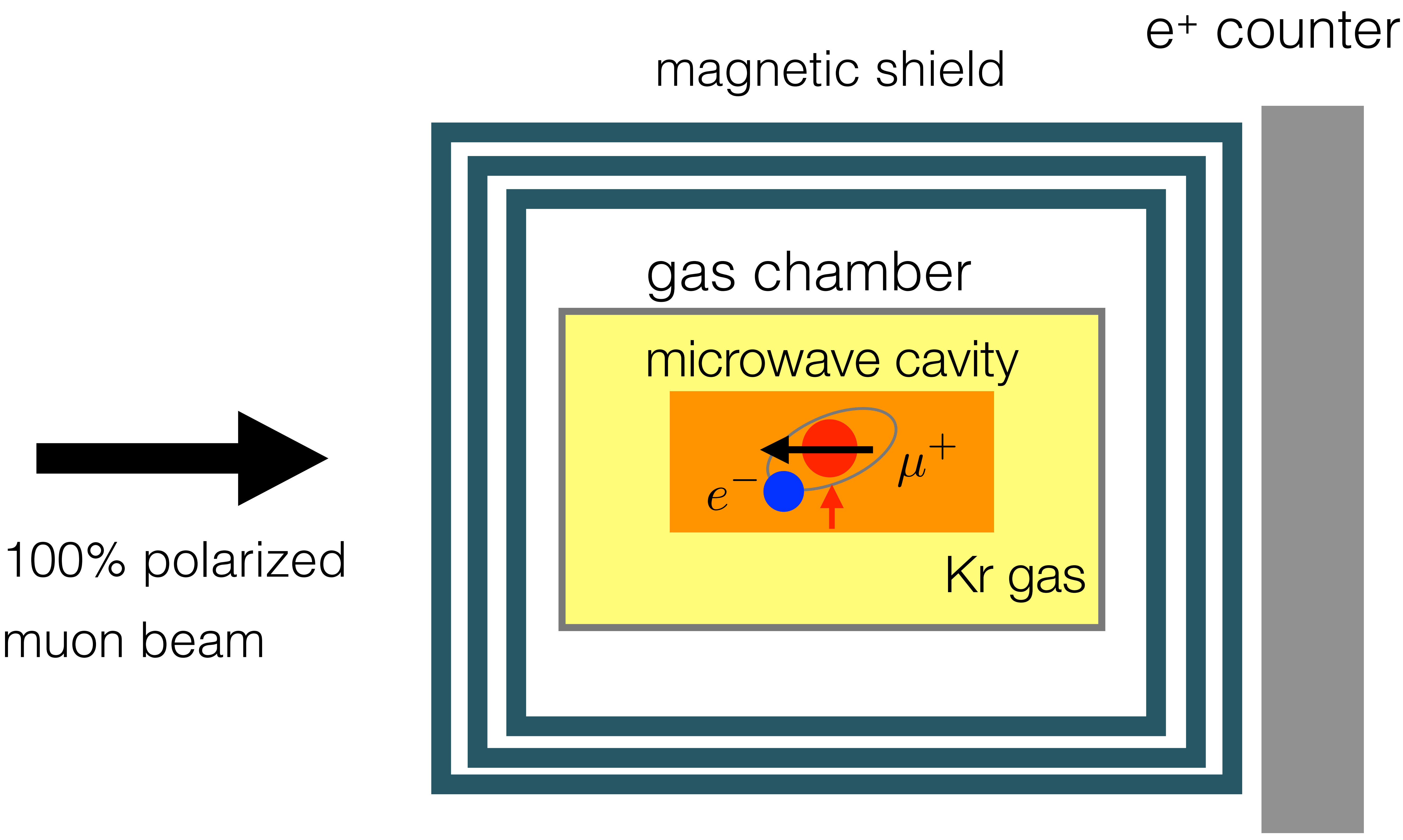
Experiment Procedure



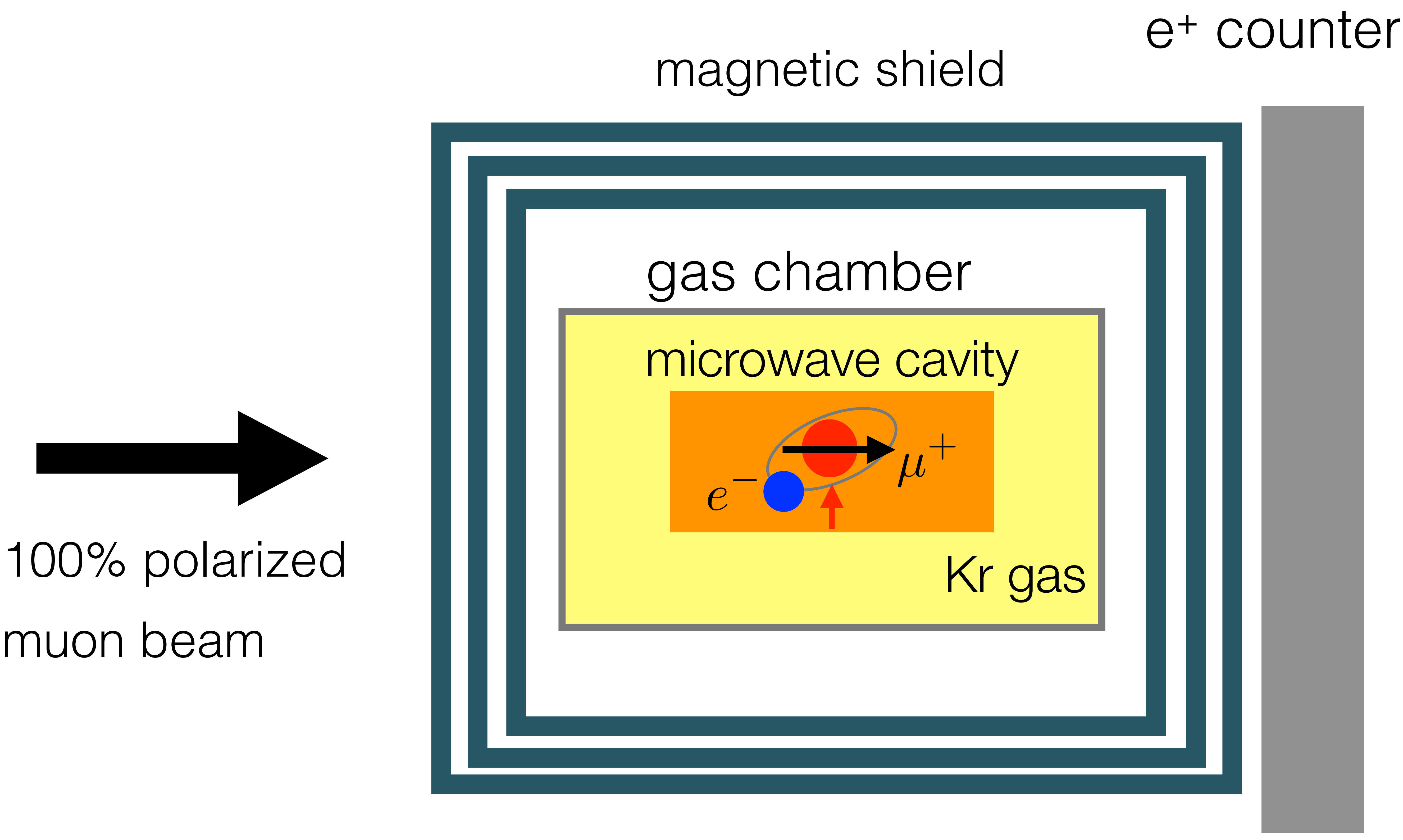
Experiment Procedure



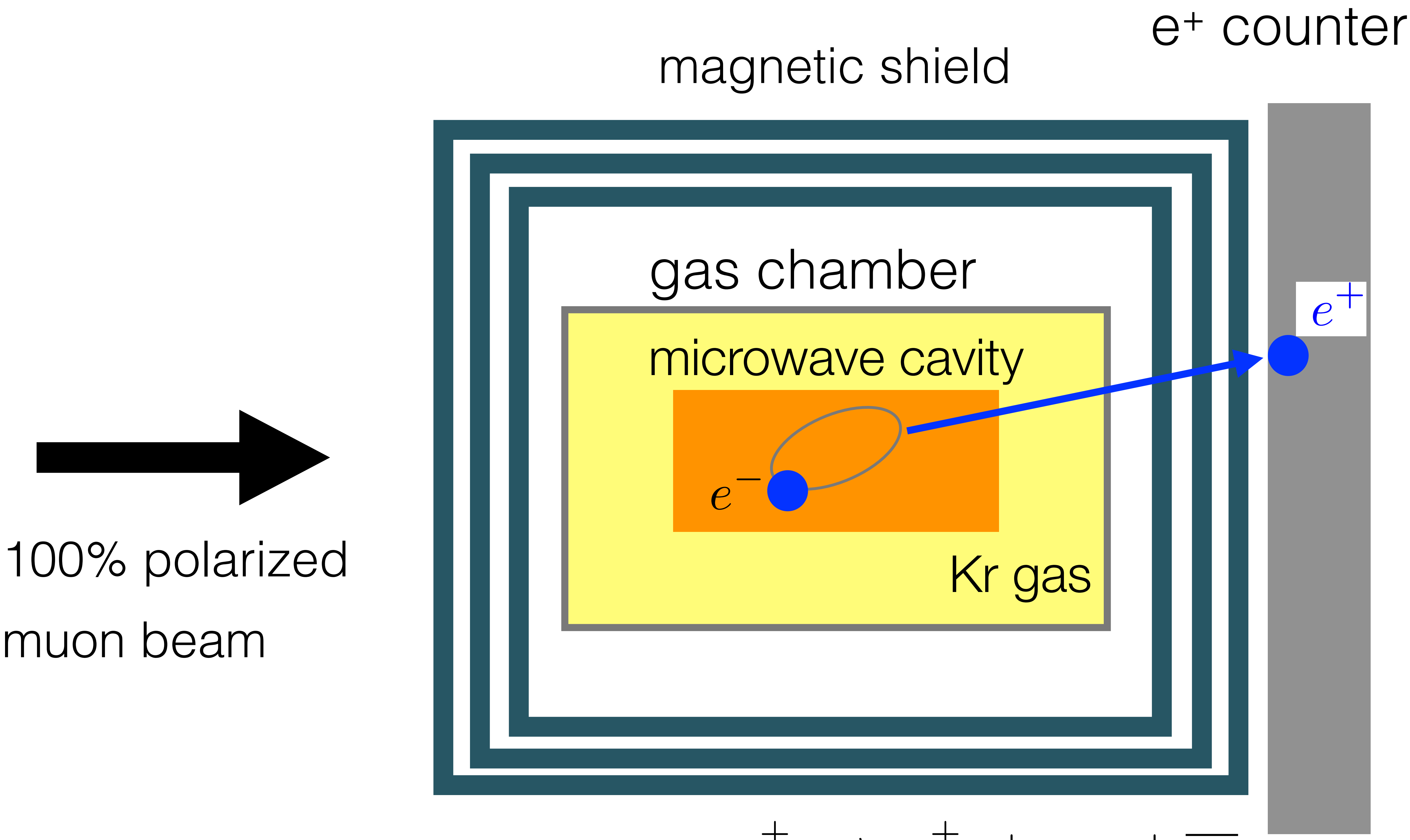
Experiment Procedure



Experiment Procedure



Experiment Procedure



$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu}$$

MuHFS experiment

- To conduct this experiment, we need to consider many points…

Magnetic field	large B-field rotate muon's spin
Gas pressure	shift resonance frequency (we want to measure the value in vacuum)
Gas impurity	other gases (especially O_2) can depolarize muon's spin
Microwave	stable frequency and power are required
Detector	high rate capability is required to prevent pileup (μ^+ beam has high intensity)

etc…

Outline

1. About MuSEUM

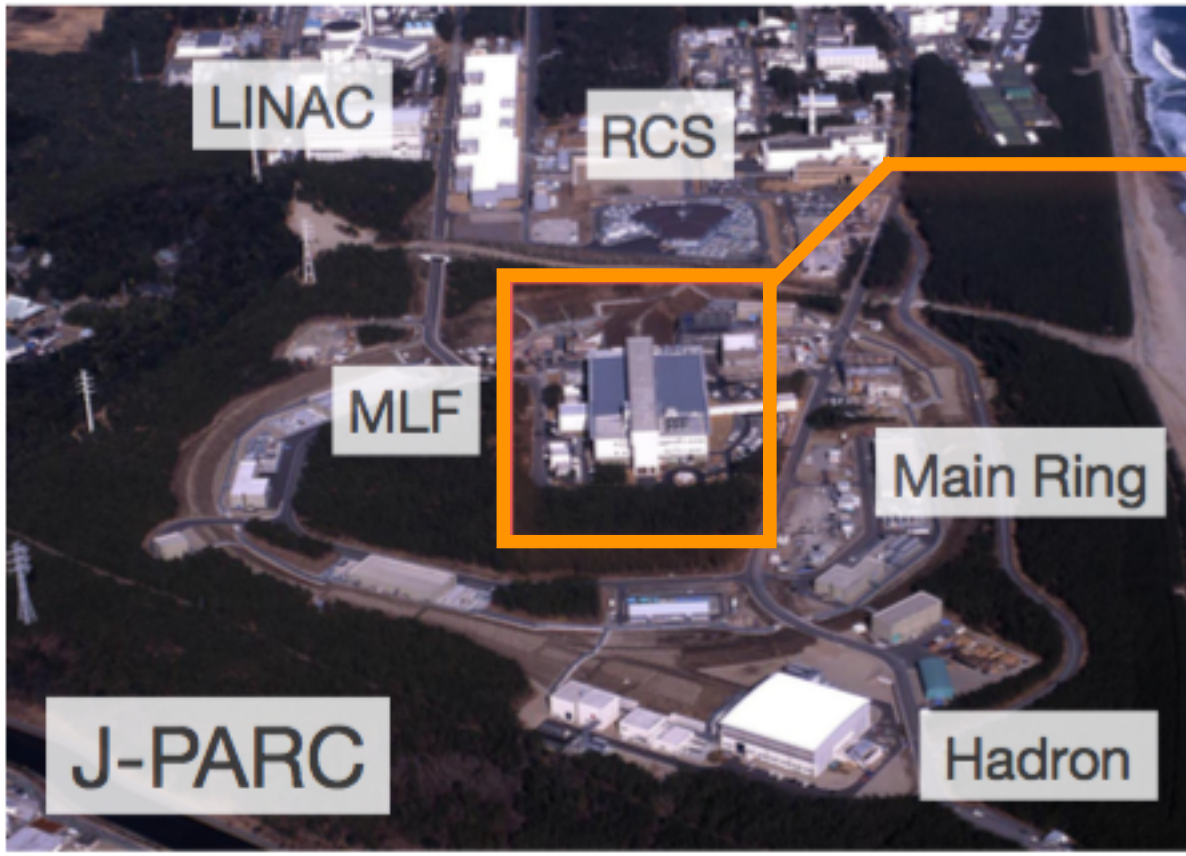
2. Apparatus

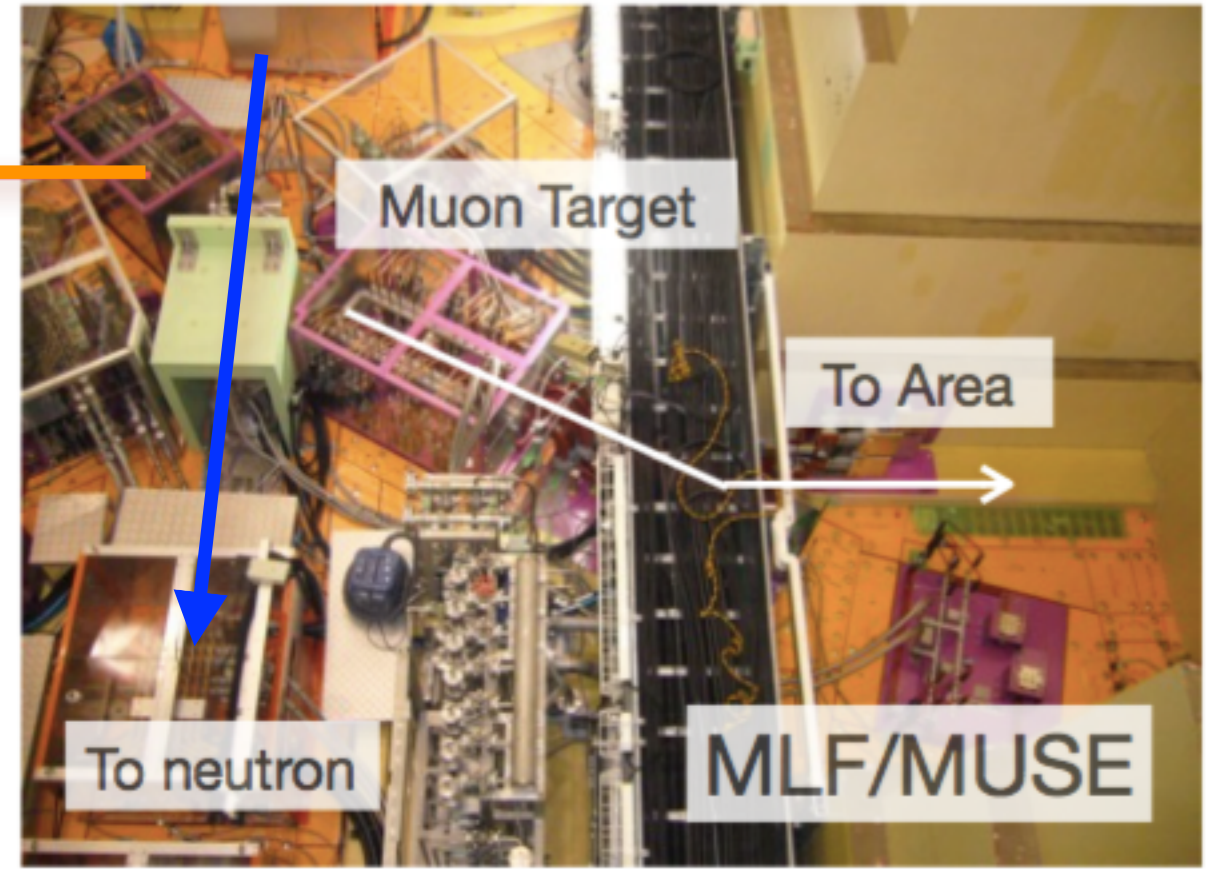
3. Results of resonance measurements

Apparatus list

- Beam line (J-PARC MLF)
- Magnetic shield and field probe
- Microwave Cavity and RF system
- Gas Handling system
- Positron detector

Beam line (J-PARC MLF)





- **The most intense pulsed muon beam**
- 100 % polarized muon is obtained from a parity violating decay of stopped pion

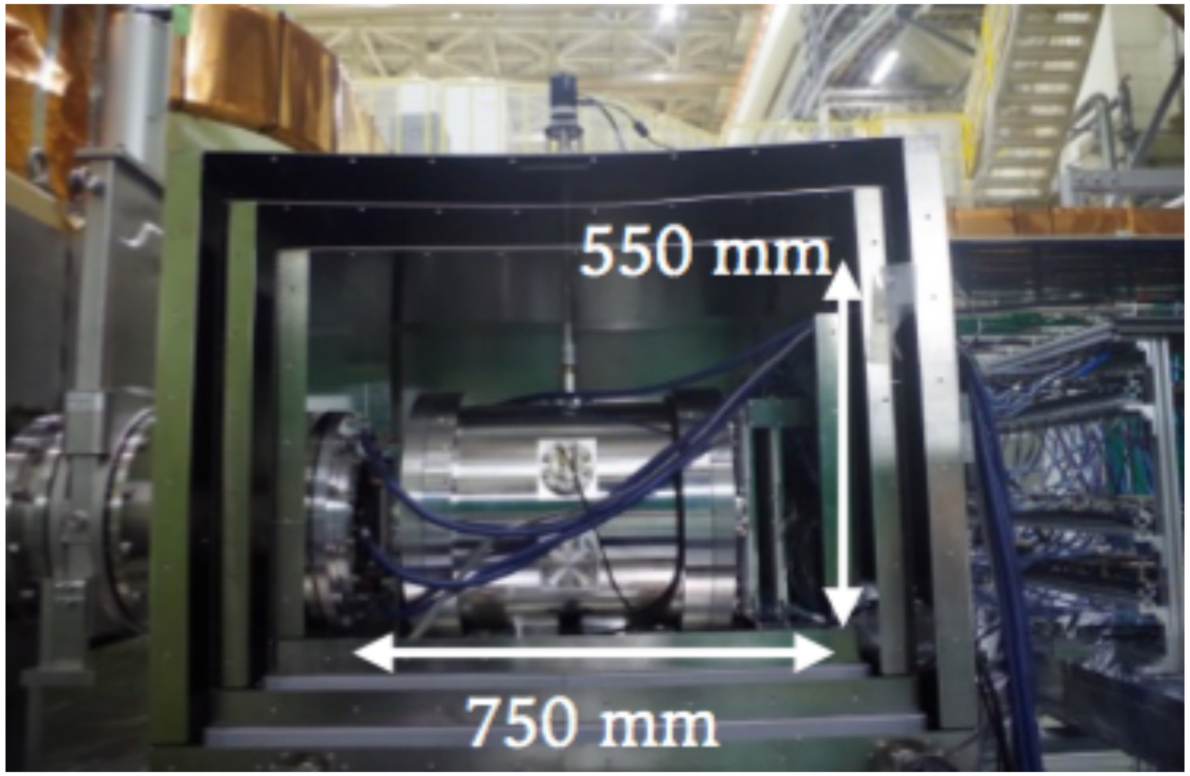
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

- D-Line: 1.0×10^7 muon/sec (in case of 1 MW operation)

Magnetic shield and field probe

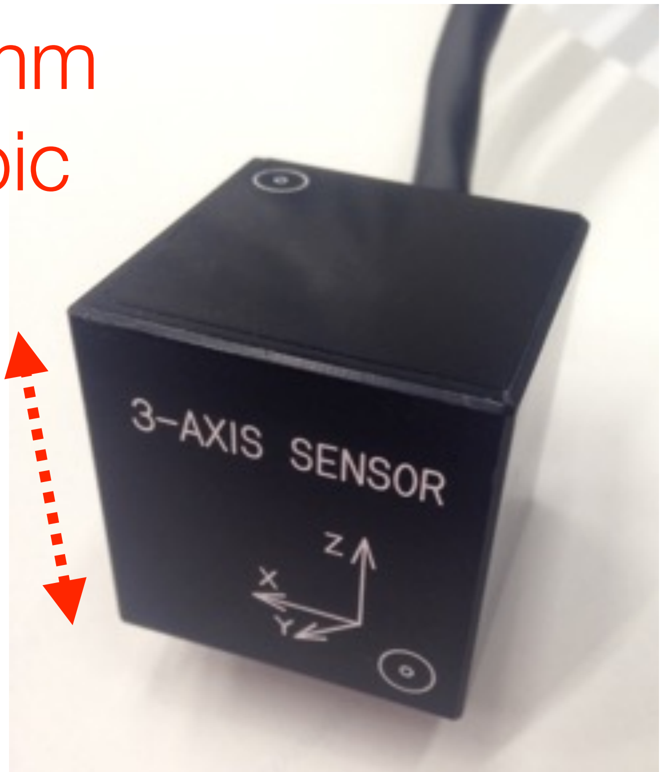
- Magnetic field rotates spin of muonium
  - B field ~100 μT in the beam area rotates the spin ~3 times in 2.2 μs

  -> Require to suppress B-field
- Three layers of permalloy forms magnetic shield.
- Measured B-field in the microwave cavity with a triaxial fluxgate magnetic probe (0.5 nT resolution for each axis, linearity 5 nT).



Magnetic shield and gas chamber

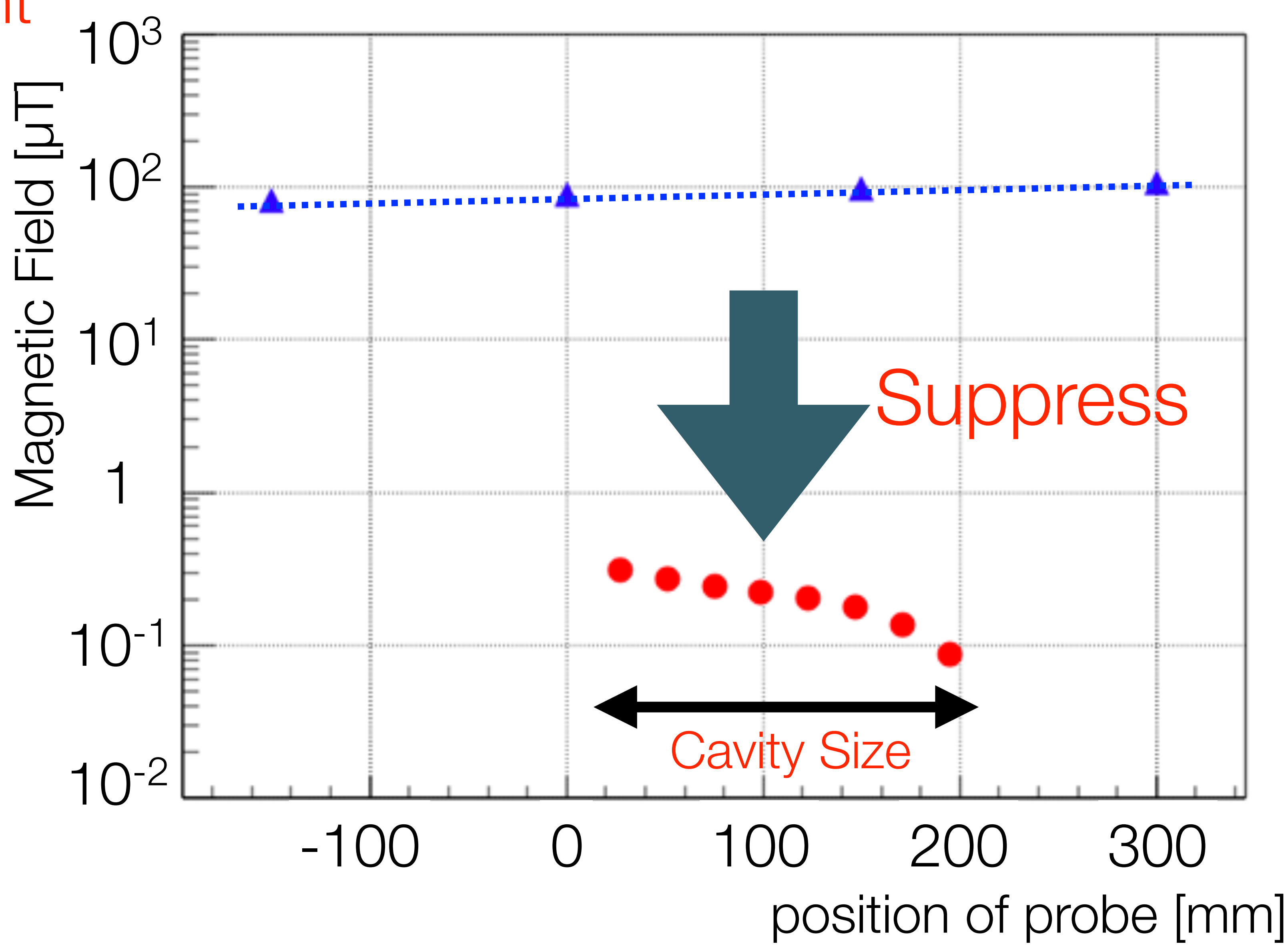
35 mm cubic



Flux gate probe

Magnetic shield and field probe

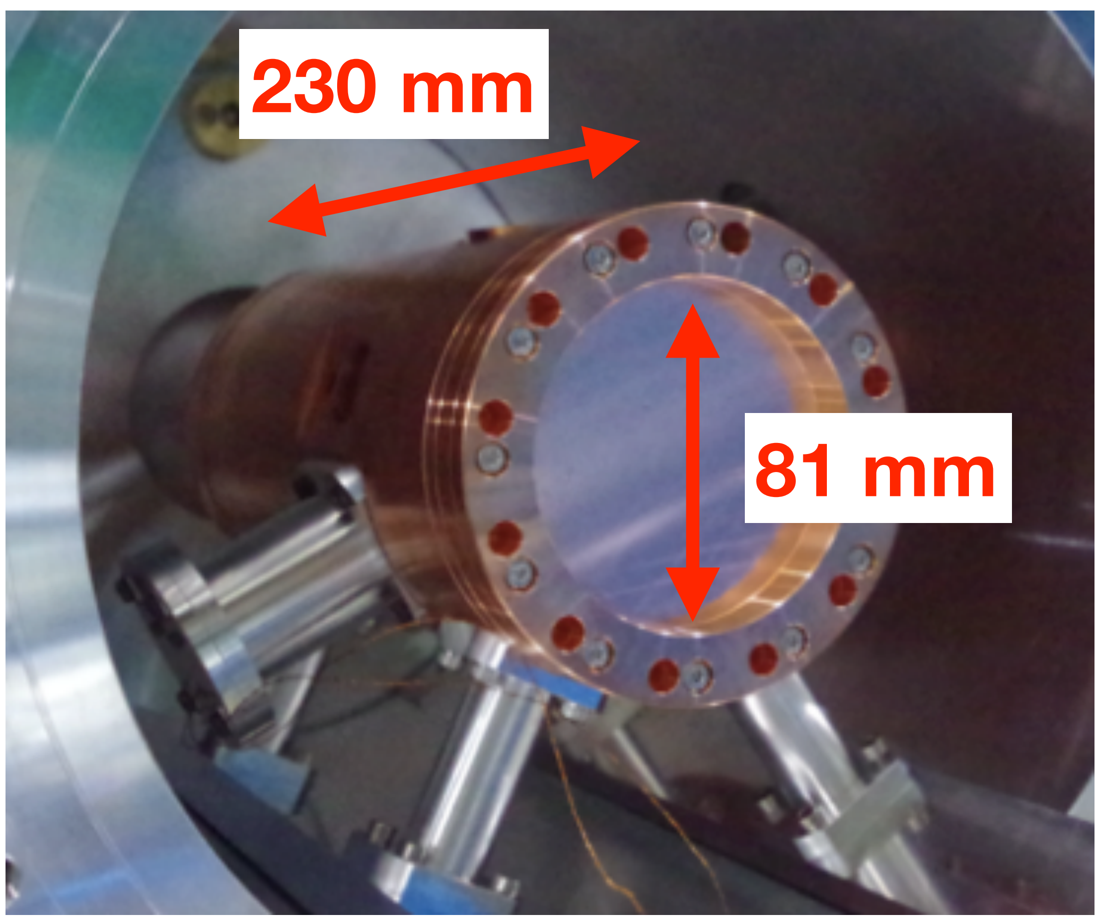
- Without the magnetic shield, B-field ~100 μT
- The shield suppresses the B-field to less than 350 nT,
- Mu spin rotation in 2.2 μs (muon's lifetime) is less than 3.3 ° -> This is sufficient

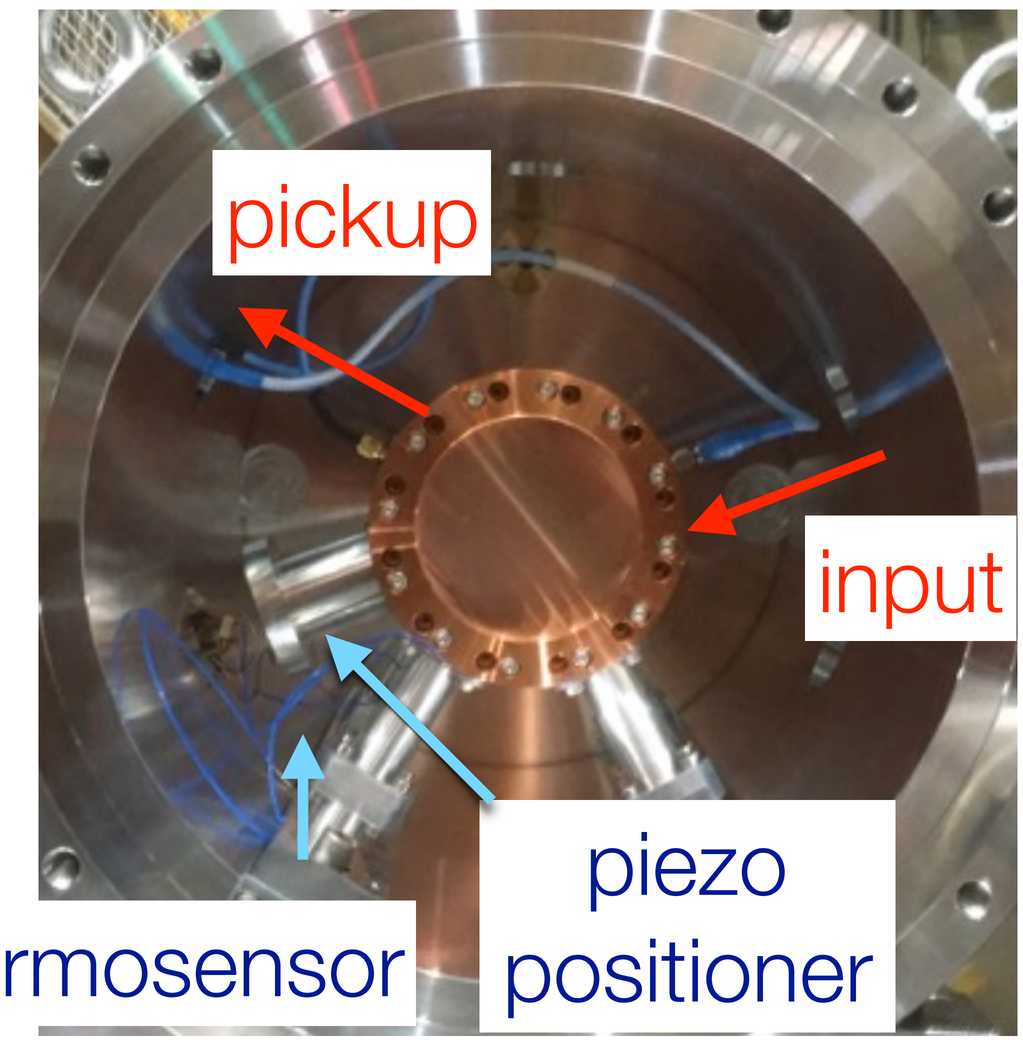


B-field with and without shield (Log Scale)
(▲ : without Shield, ● : with Shield)

Microwave Cavity and RF system

- Copper microwave cavity
- Power stability is monitored by a dedicated monitoring antenna during the measurement
- 4.463 GHz ± 1.5 MHz tuning with a piezo positioner
- Q factor is about 10,000, enough for storing energy in cavity.

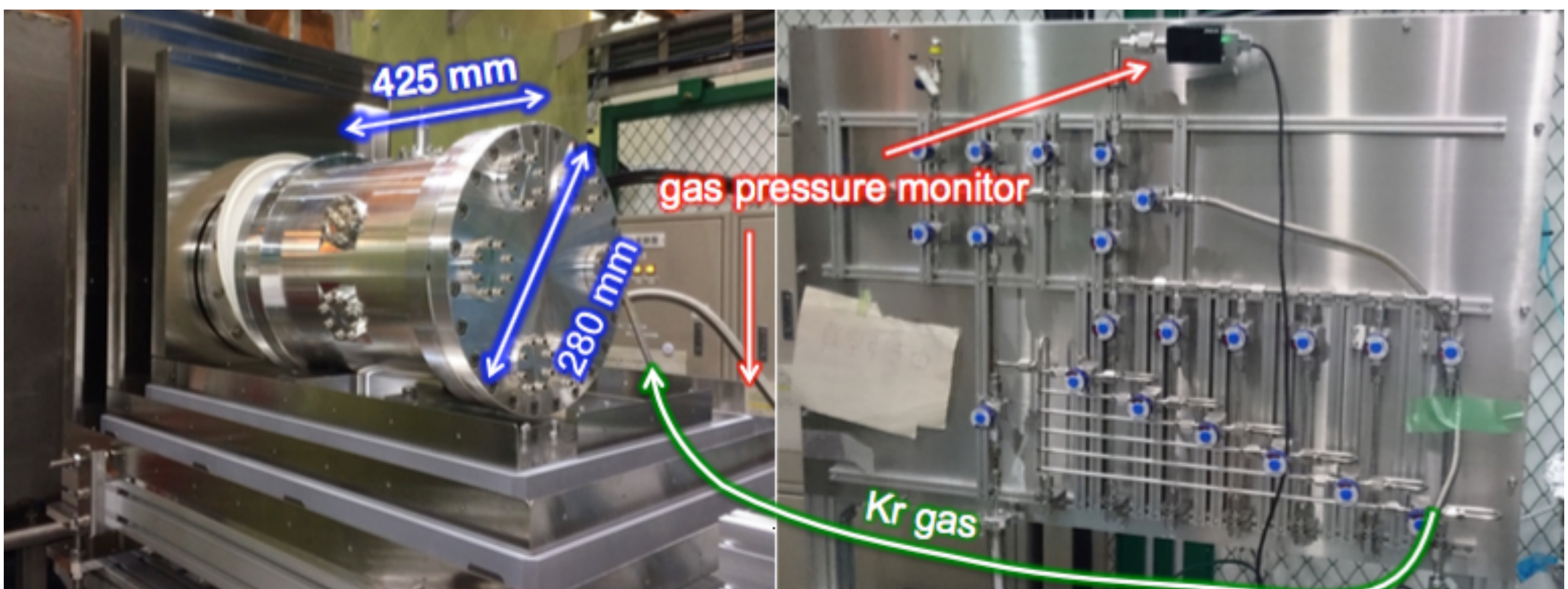




TM110 Cavity

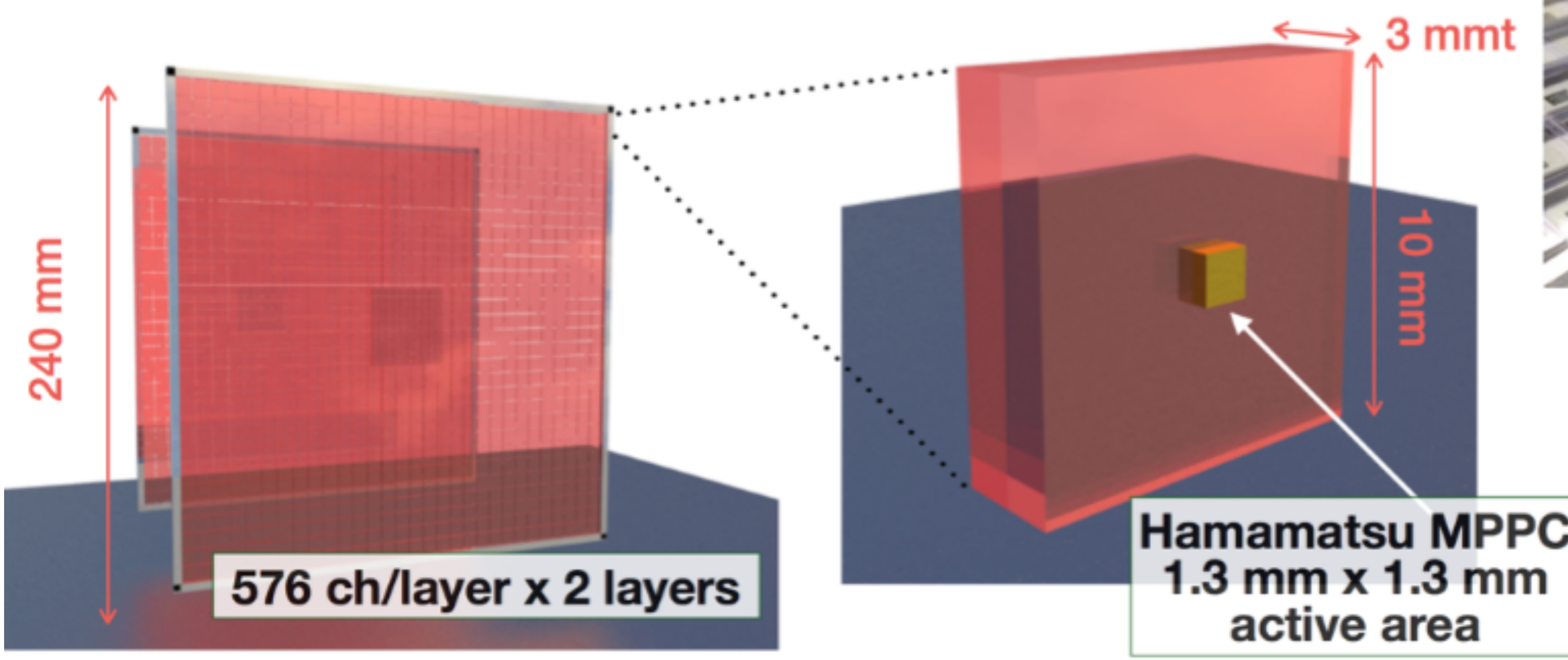
Gas Handling system

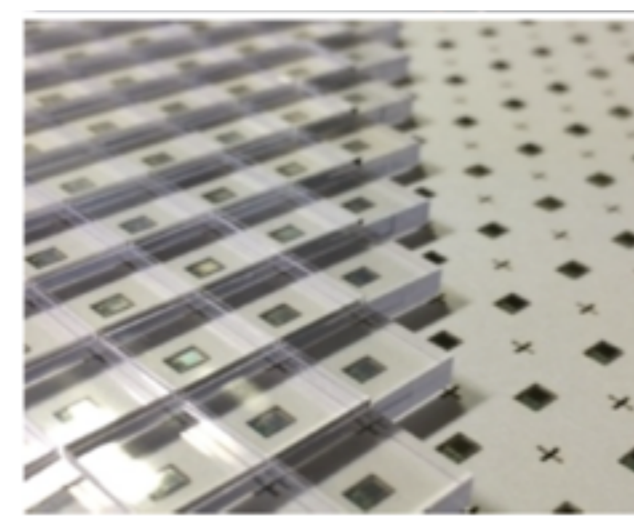
- Collisions of the muonium with Kr shift the resonance frequency
  - Gas pressure is monitored by a capacitance gauge
    - fluctuation ~0.002 Pa/min (at 1.0 atm)
- Gas impurity causes muon spin depolarization
  - Gas purity is measured by a Q-Mass spectrometer
    - O_2 ~0.4 ppm



Positron detector

- High rate capability is required
- Detector property:
  - Segmented (10 mm×10 mm×3mmt) Scintillator
  - Readout: Hamamatsu MPPC (Si photomultiplier)
  - Unit cell is 10 mm×10 mm× 3 mmt
  - 240 mm× 240 mm area, 1152 ch in total





S. Kanda, PoS (PhotoDet2015) 039 (2016)

Outline

1. About MuSEUM

2. Apparatus

3. Results of resonance measurements

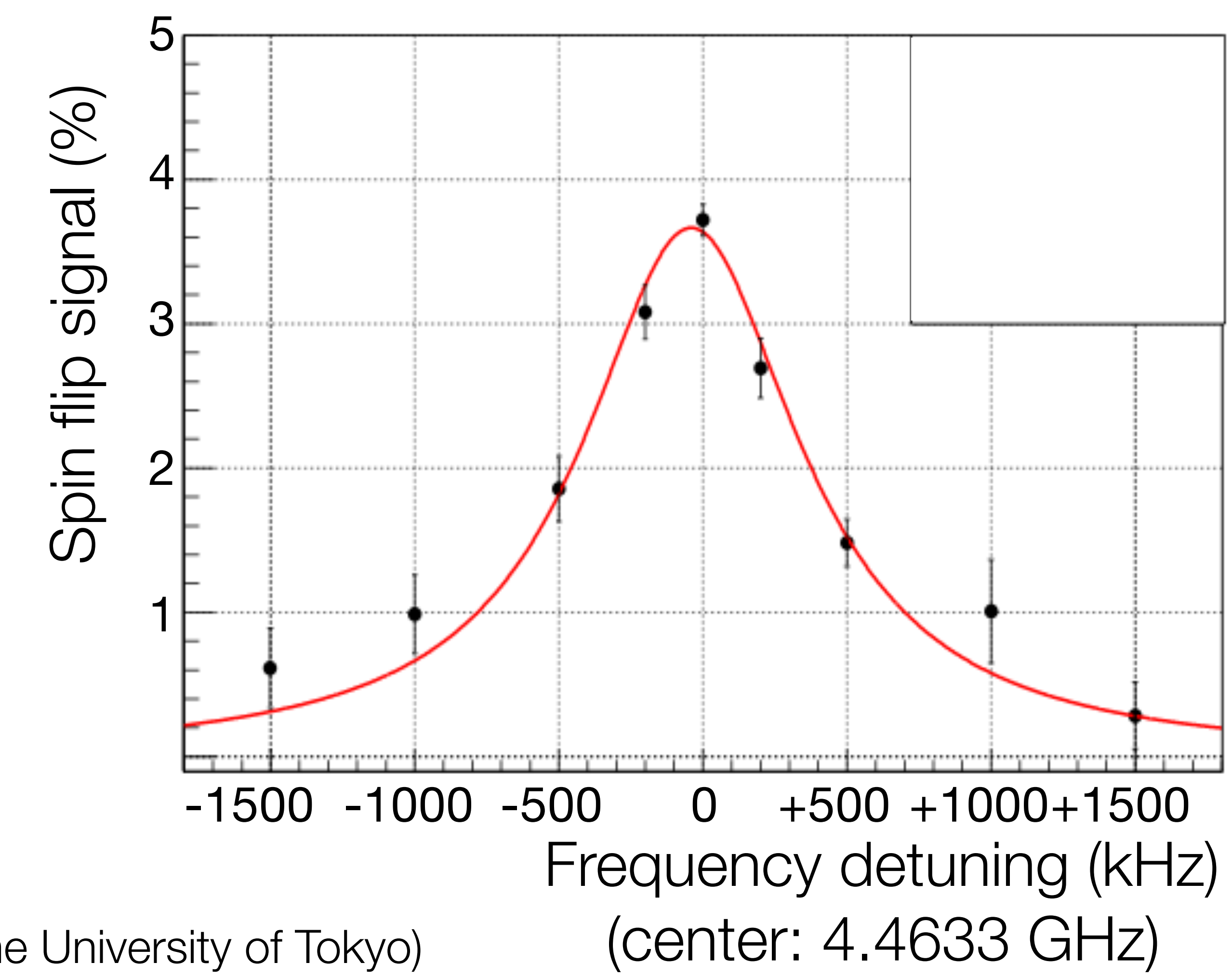
1st Beam Time: 2016 June

- Microwave/gas system and e^+ counters worked properly
- The first muonium hyperfine resonance using pulsed beam was observed
- Result of measurement in 8 hours:

  4.463 292 (22) GHz (4.9 ppm)

  c.f.) Precursor exp. 4.463 3022(14) GHz (300 ppb)

D. E. Casperson, et al., Physics Lett. **59B** 397 (1975).



1st Beam Time: 2016 June

- Statistical uncertainty: 22 kHz (data taken for 8 hours)
- Systematic uncertainty:

Source	Contribution (Hz)
Gas pressure extrapolation	**119**
Gas pressure fluctuation	6
Microwave power drift	26
Gas impurity	12
Magnetic field	0
Detector pileup	2
others	9.8
Total	**123**

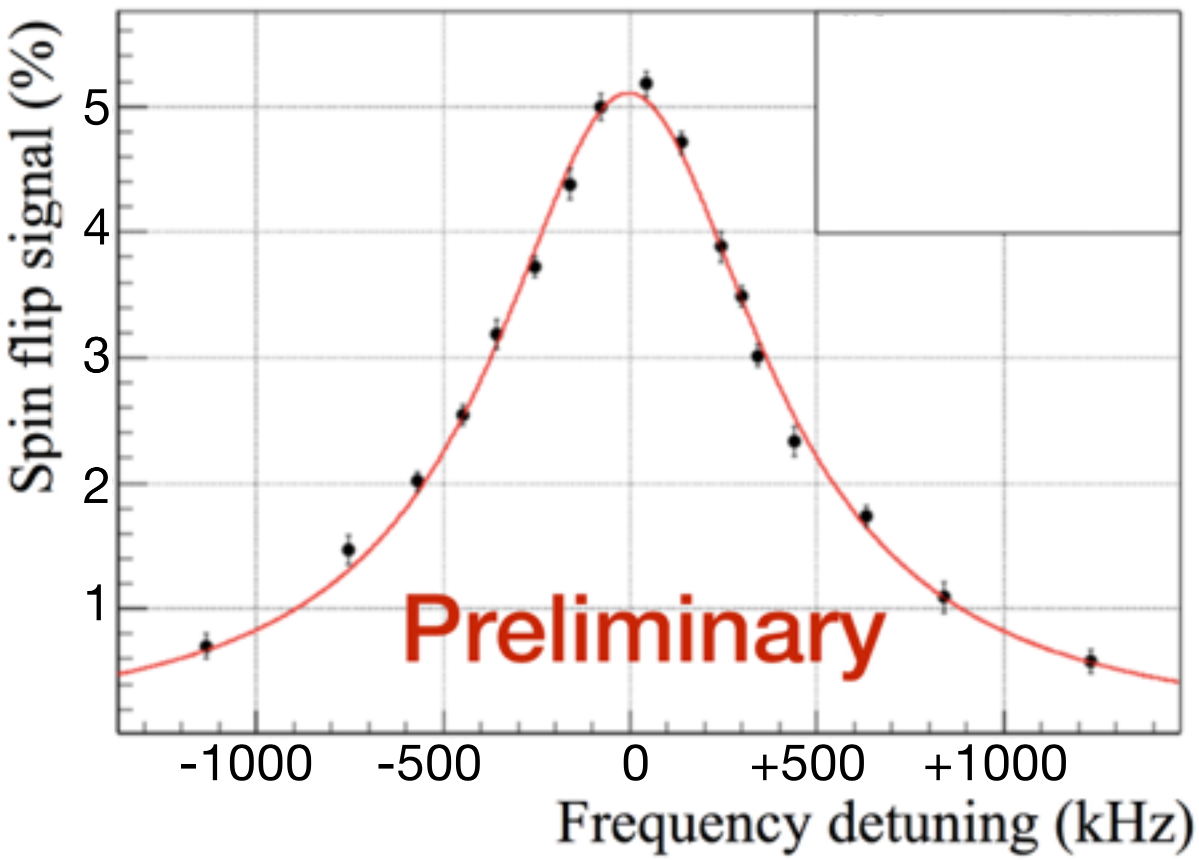
2nd Beam Time: 2017 February

- Improvement
  - The microwave power is optimized
  - Background reduction using Al moderator
- Result of measurement in 12 hours
  - Statistical uncertainty is 4.3 kHz.

c.f.) 1st result: 4.463 292 GHz ± 22 kHz (4.9 ppm)

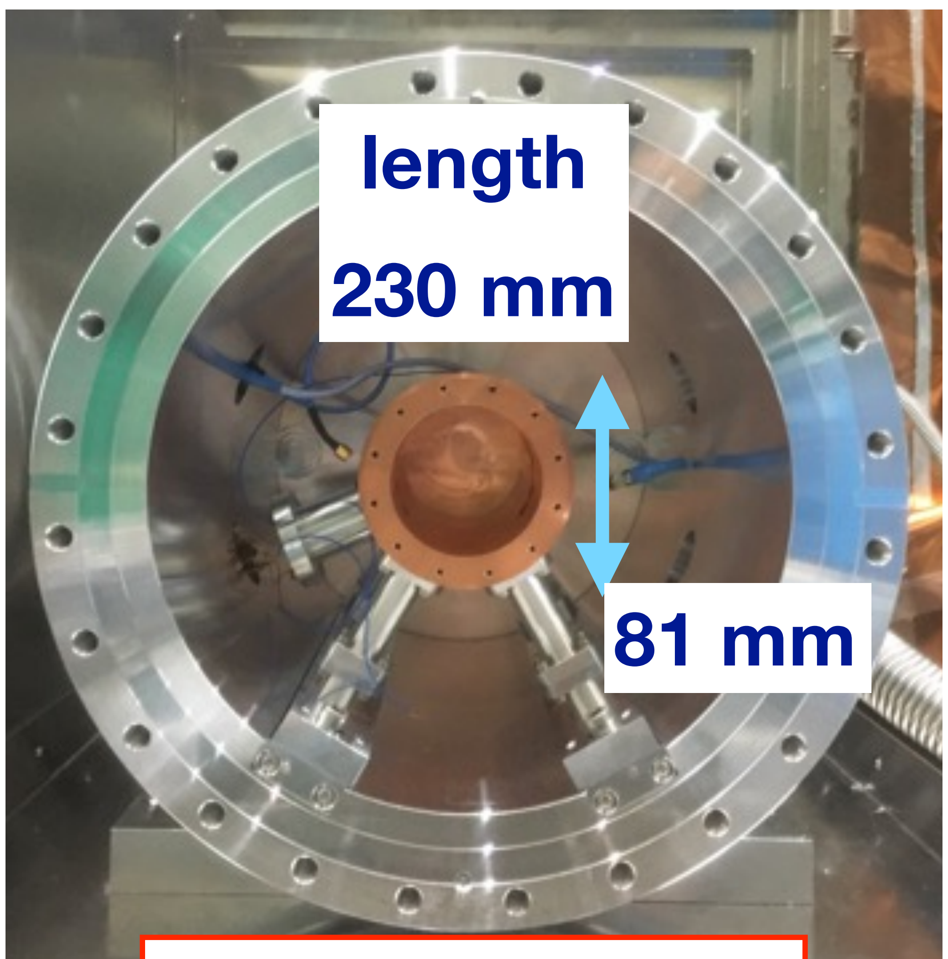
Precursor exp.: 4.463 3022 GHz ± 1.4 kHz (300 ppb)

D. E. Casperson, et al., Physics Lett. **59B** 397 (1975).



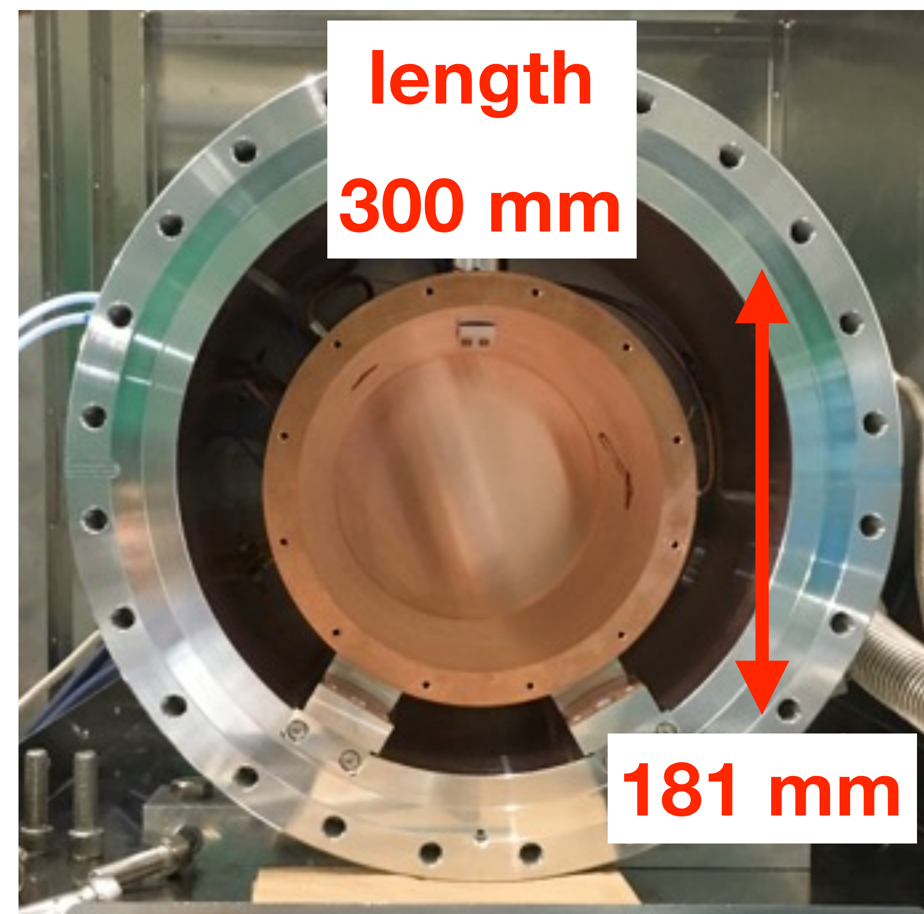
3rd Beam Time: 2017 June

- 3rd resonance measurement
- New TM220 mode cavity was installed
- Resonance observed
- Analysis is in progress



TM110 Cavity

Upgraded in June 2017



TM220 Cavity

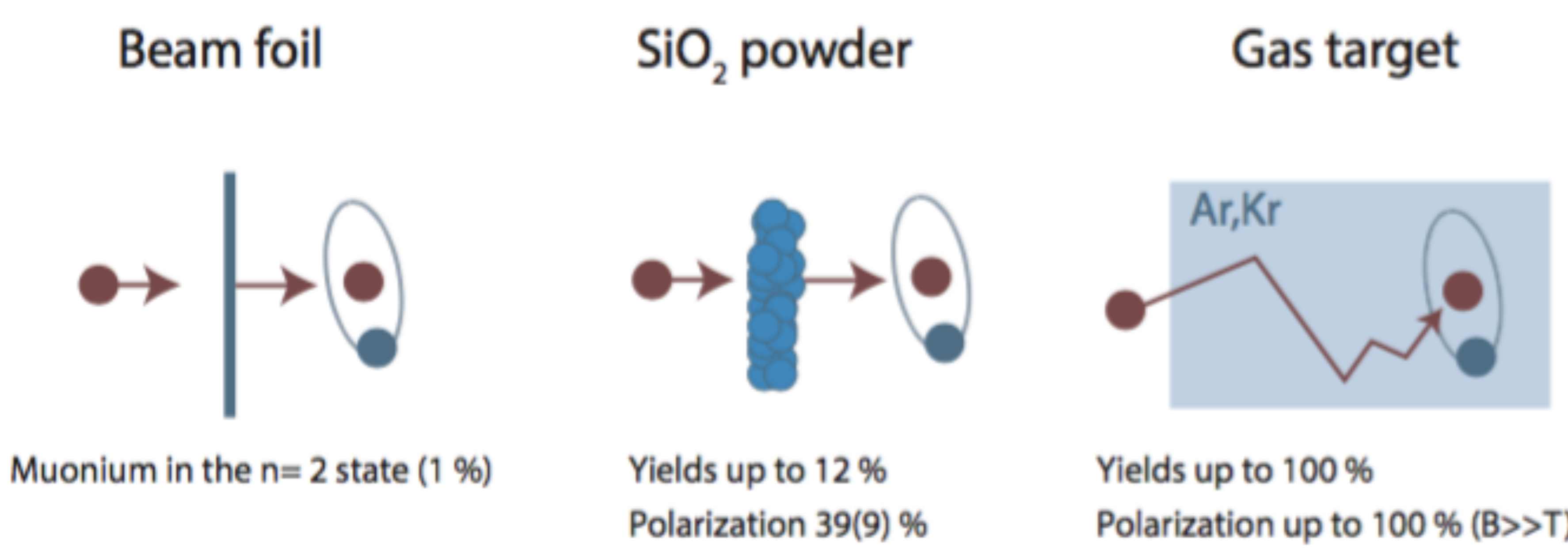
Summary and future prospect

- **Summary**
  - Precise measurement for muonium is the most rigorous validation of the bound-state QED.
  - MuSEUM group measured the hyperfine splitting in groud state of muonium by the spectroscopy at zero magnetic field.
  - Resonance was sucessfully observed at zero magnetic field in each measurement.
  - For the 1st measurement, we evaluated the value of MuHFS and its uncertainty. 4.463 292 (22) GHz (4.9 ppm)
- **Future prospect**
  - Data analysis of the 2nd and 3rd zero field experiment is in progress.
  - Next measurement will be done in early 2018.
  - R&D for high field experiment is also ongoing. -> Next T. Tanaka's talk

Appendix

Methods of Mu production for MuHFS experiment

- Beam foil
  - cannot apply to ours
  - appliable to the measurement of lamb shift transition ($2S_{1/2} - 2P_{1/2}$)
- SiO_2 powder
  - formed in vacuum (unlike gas target)
  - both the production rate and the polarization are insufficient
  - cannot distinguish between signals of muon decay in vacuum and in a powder target.



Why Kr gas?

- noble gases are suitable to to avoid chemical reactions and depolarizing collisions

$\mu^+ + e^- + \mathrm{Kr}^+$

Ionization E of Kr = 14.00 eV

I.E. of Mu = 13.54 eV

$\mu^+ + \mathrm{Kr} \rightarrow \mu^+ e^- + \mathrm{Kr}^+.$

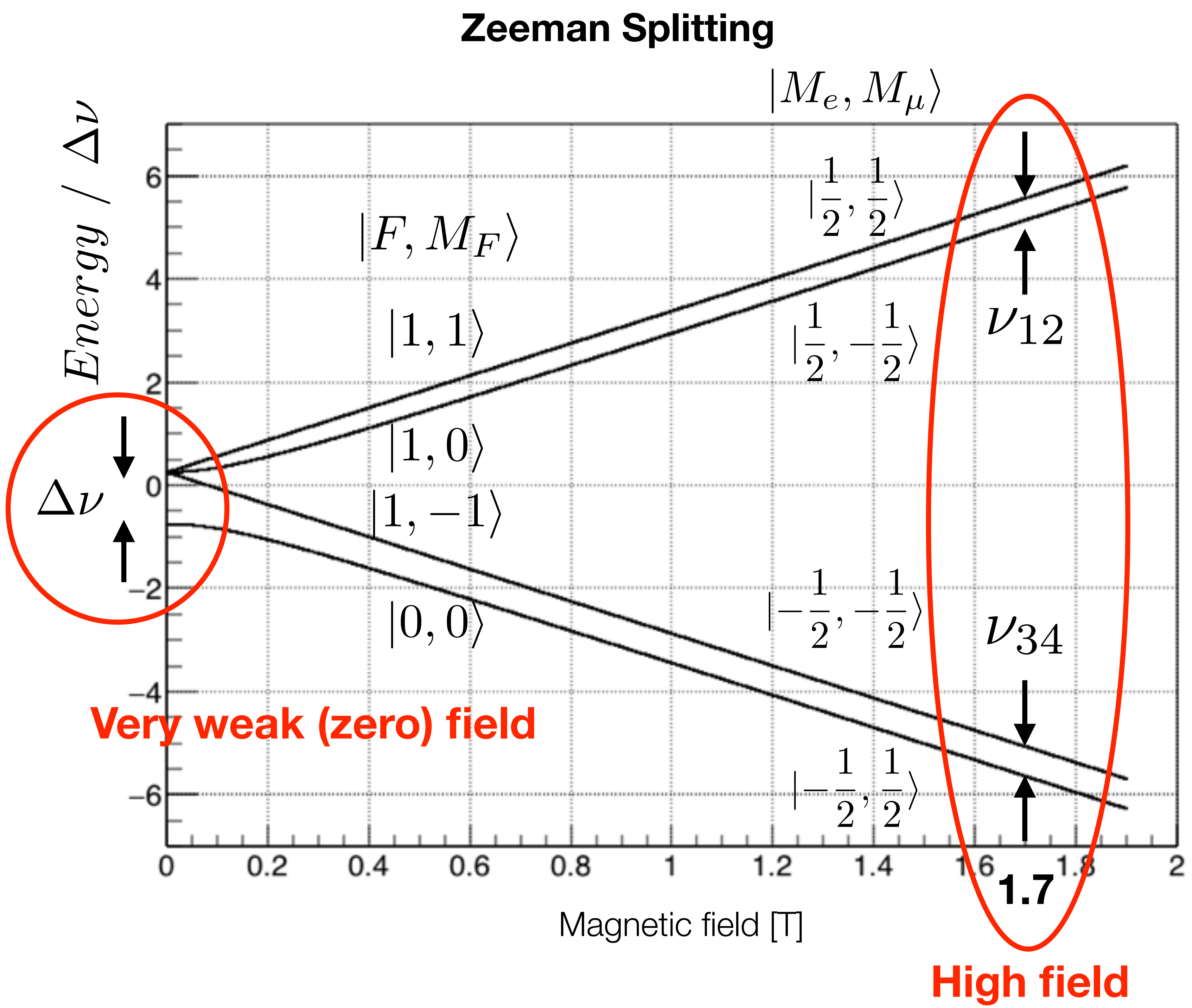
Threshold energy = 0.46 eV

low energy Mu

- Kr -> Mu fraction f_Mu ~ 100 % -> ideal

atom or molecule	threshold energy (eV)	pressure (atm)	f_{Mu}
He	+11.04	1.2–3.1	0(1)
Ne	+8.02	1.2	7(5)
Ar	+2.22	1.0–2.8	74(4)
Kr	+0.46	0.4–0.95	100(5)
Xe	-1.41	0.4–0.65	100(4)
N_2	+2.0	1.0–2.4	84(4)
CH_4	-0.6	1.2–3.0	87(4)

Table 3.1: Threshold energies for muonium formation [9] and the pressure-independent muonium fractions f_{Mu} [10].



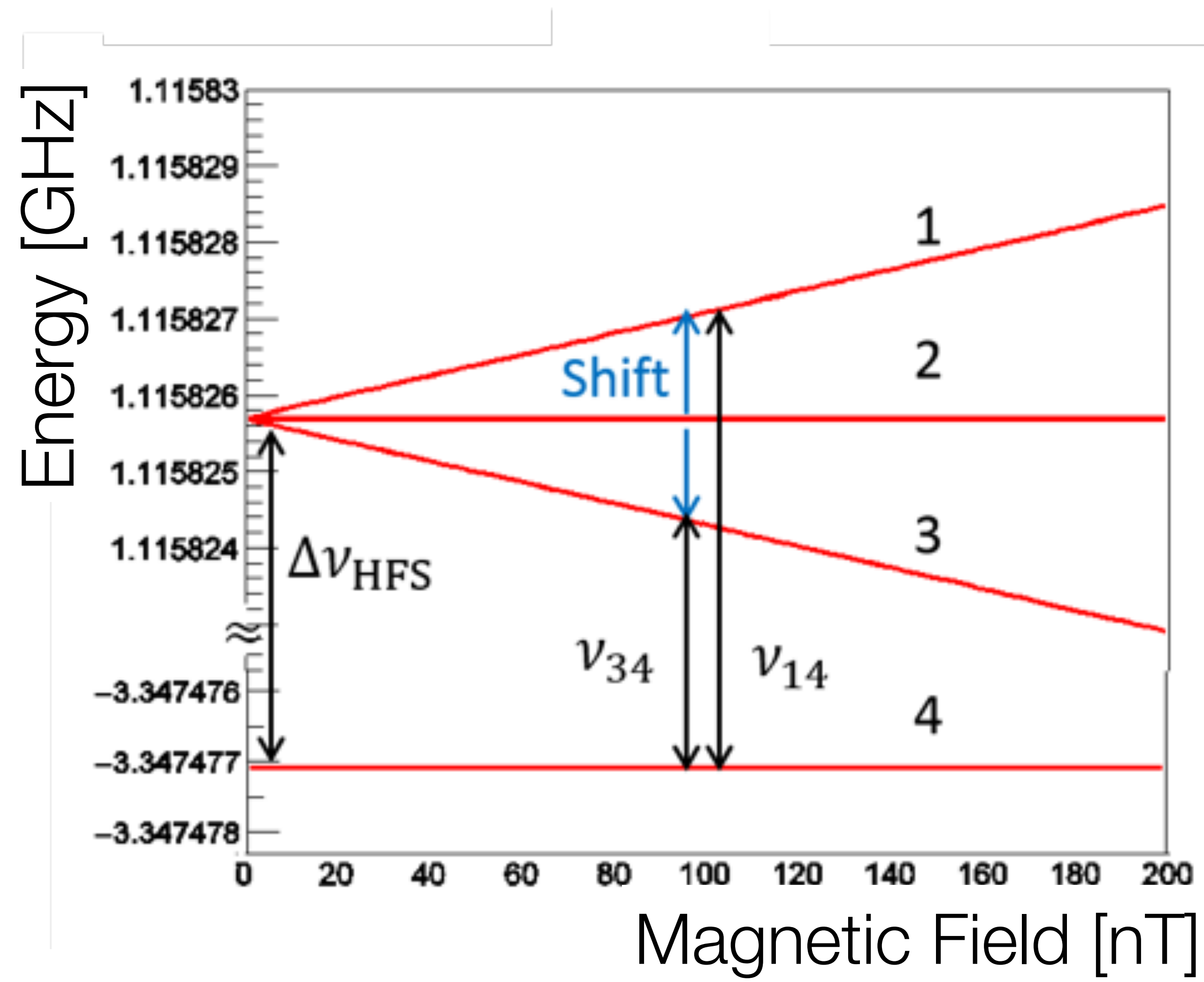
Zeeman Splitting
$|M_e, M_\mu\rangle$
$|F, M_F\rangle$
$|\frac{1}{2}, \frac{1}{2}\rangle$
$|\frac{1}{2}, -\frac{1}{2}\rangle$
$|-\frac{1}{2}, -\frac{1}{2}\rangle$
$|-\frac{1}{2}, \frac{1}{2}\rangle$
$|1, 1\rangle$
$|1, 0\rangle$
$|1, -1\rangle$
$|0, 0\rangle$
ν_{12}
ν_{34}
$\Delta\nu$
$Energy\ /\ \Delta\nu$
Magnetic field [T]
1.7
Very weak (zero) field
High field

Other B-field effect

- Only the transitions between 1- 4 and 3-4 contribute to the signal
- Those two frequencies (ν_{14}, ν_{34}) shift by 14 Hz/nT in opposite directions

$\Rightarrow$ Broadening effect on the signal

In B-field ~ a few Tesla, this effect is negligible.



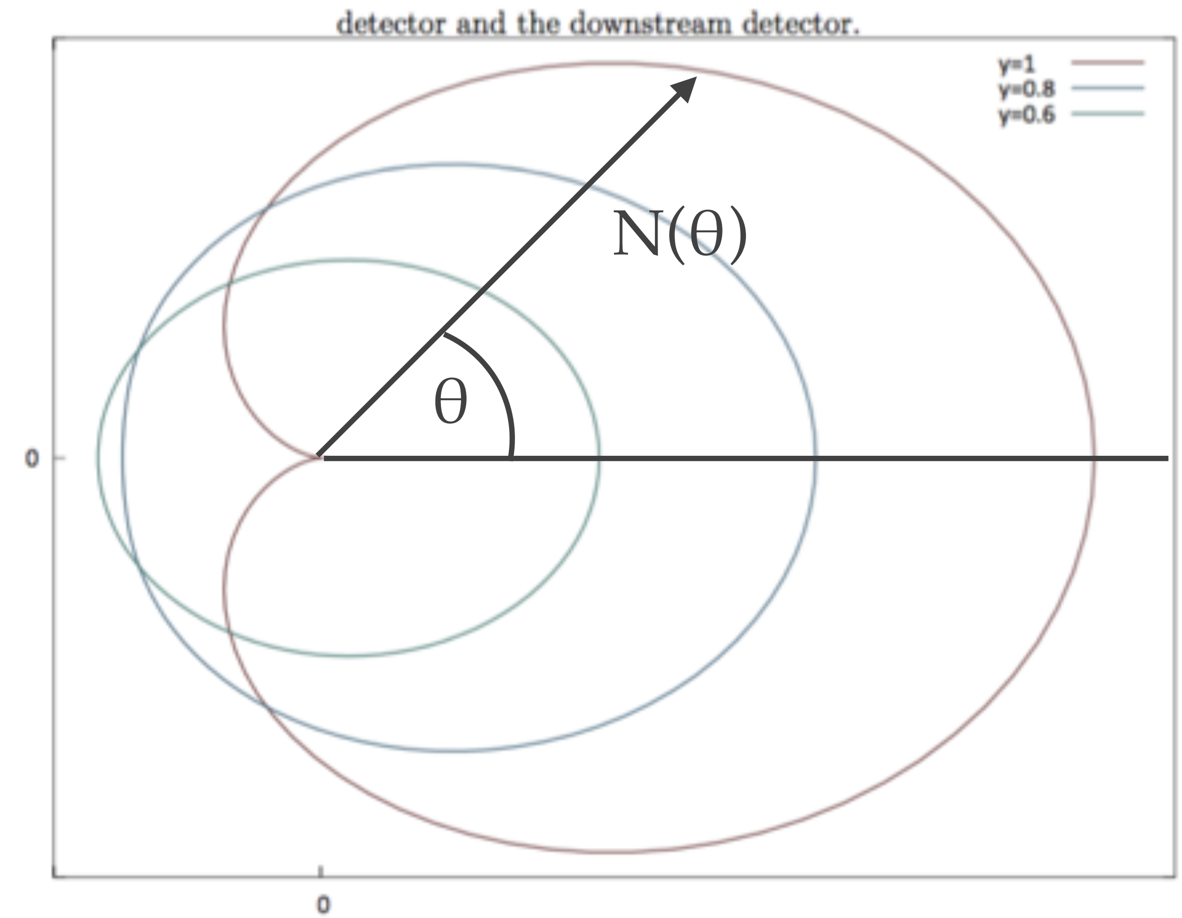
Energy-diagram of muonium in ground state

Muon decay

- Angular distribution of decay e^+ is

$$N(y,\theta) = \frac{\gamma}{2\pi} y^2[(3-2y) + (2y-1)\cos\theta]$$

- y : e^+ momentum in units of $\frac{1}{2} m_\mu c$
- θ : angle between μ spin direction and e^+ momentum



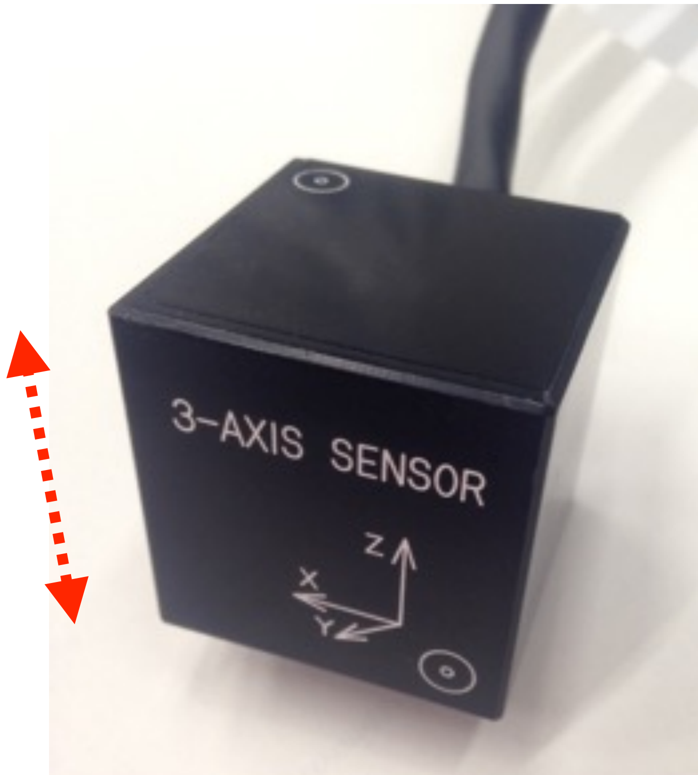
- maximum momentum of decay e^+ is

$$P_{\max} = \frac{m_\mu^2 - m_e^2}{2m_\mu} c \approx \frac{1}{2} m_\mu c = 52.83 \text{ MeV/c}$$

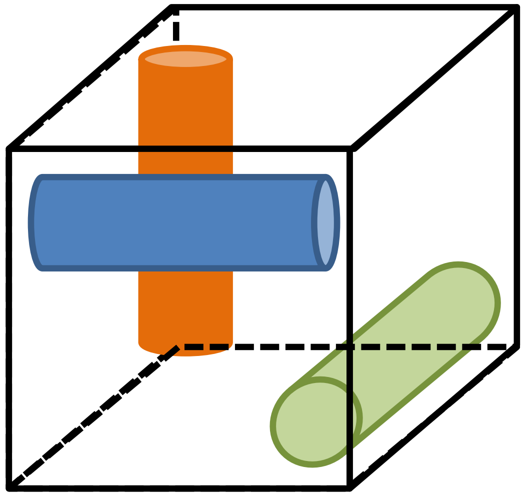
Flux Gate Probe

- Triaxial fluxgate magnetic probe (made by MTI Corp., FM-3500)
- 0.5 nT resolution for each axis, linearity 5 nT

35 mm
cubic



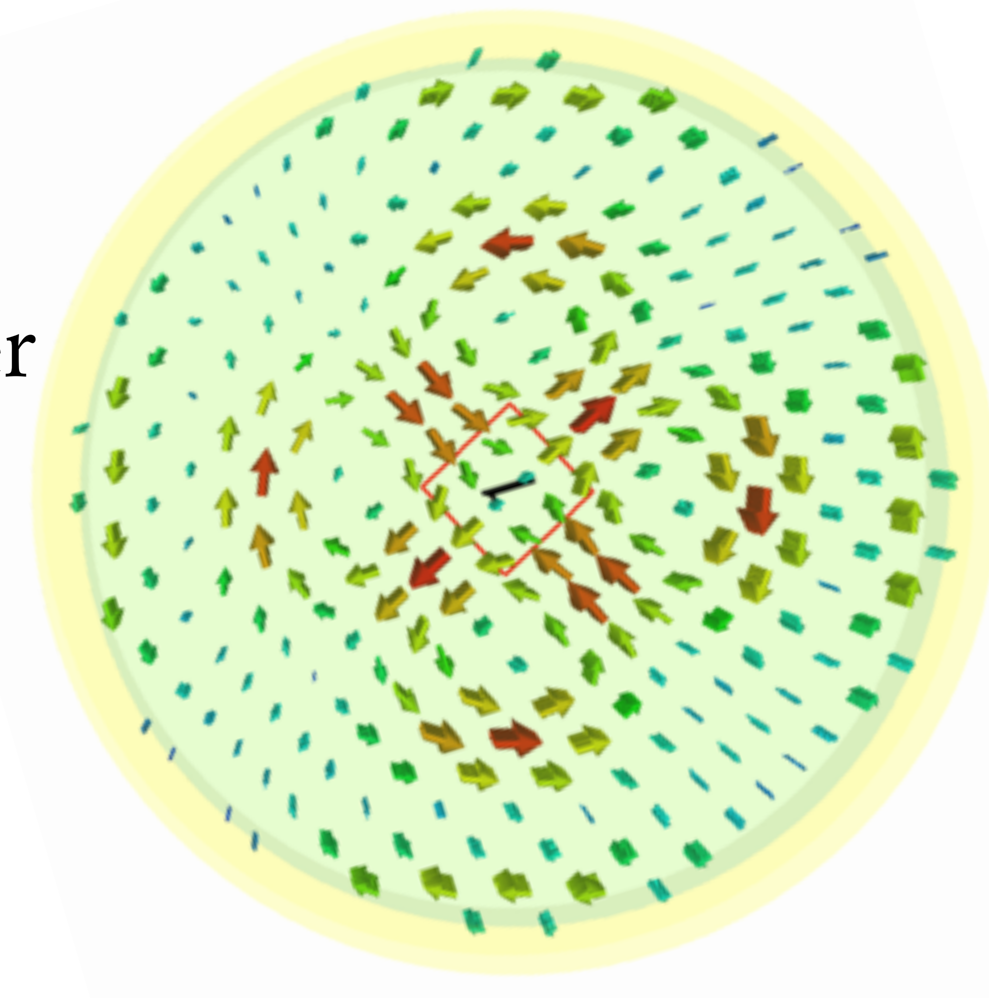
Flux gate probe



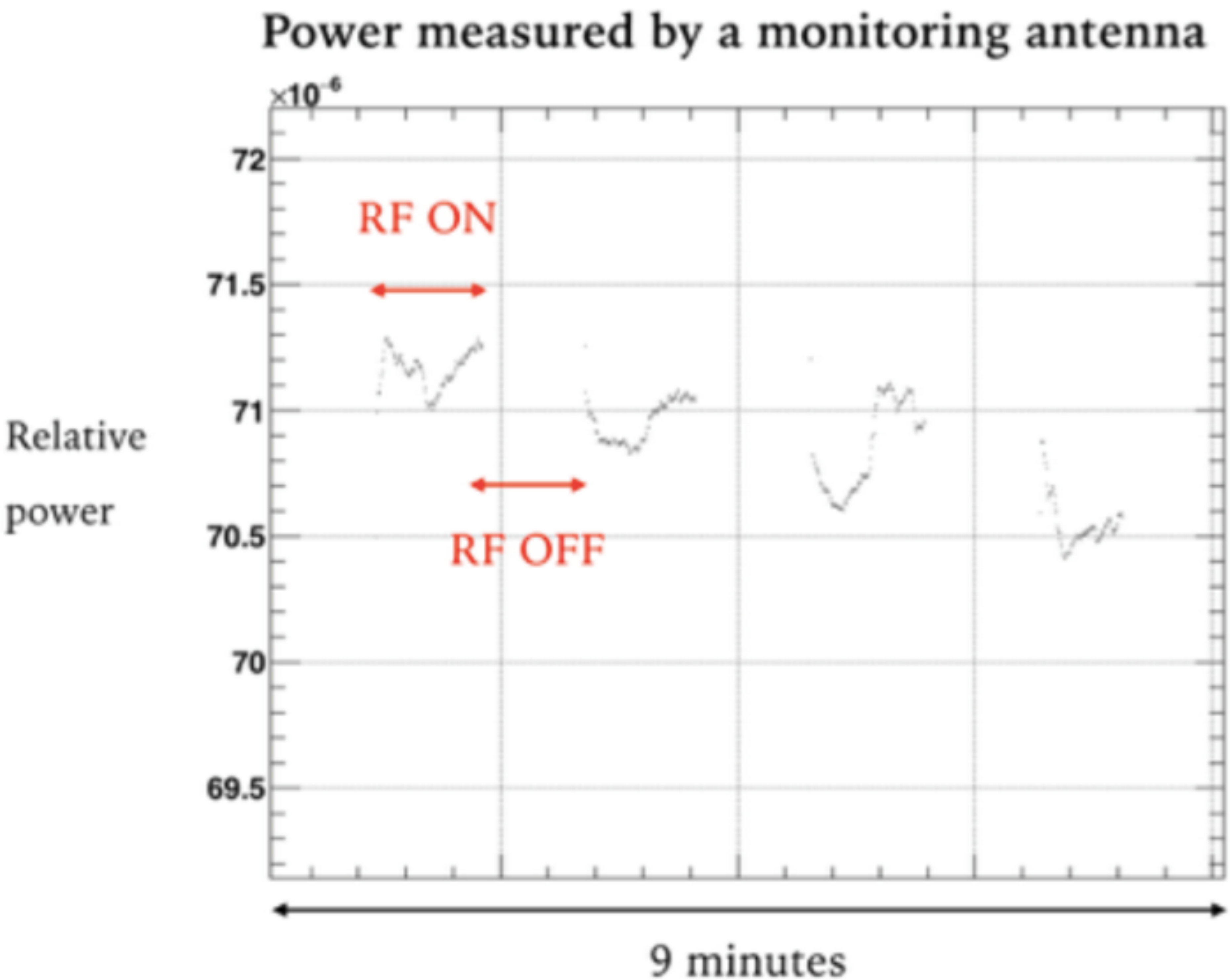
positons of 3 coils in the probe

Recent Development: New Cavity

- **Using higher mode, the cavity diameter can be enlarged**
- Less muons stop in the cavity wall, more muoniums available: **reducing the background and enhancing the signa**l
- We designed TM220 mode cavity (φ 180 mm) by the numerical computation using CST studio for the validation of mode isolation, frequency tunablilty
- cf. Gaussian beam width (1σ) is 30 mm
- Cavity is longer (300 mm) than any other old cavities: enables the measurements at lower gas pressure, reducing the systematic uncertainty due to the collision of Mu with Kr



Power measured by a monitoring antenna



MuSEUM: CPT and Lorentz Invariance 14

- CPT (Lorentz) violating background field can be detected as **sidereal** (or annual) **oscillation of the hyperfine frequency**
- Constraint on Standard Model Extension (SME) parameters

A. H. Gomes, V. A. Kostelecky and A. J. Vargas,
PRD **90** 076009 (2014)