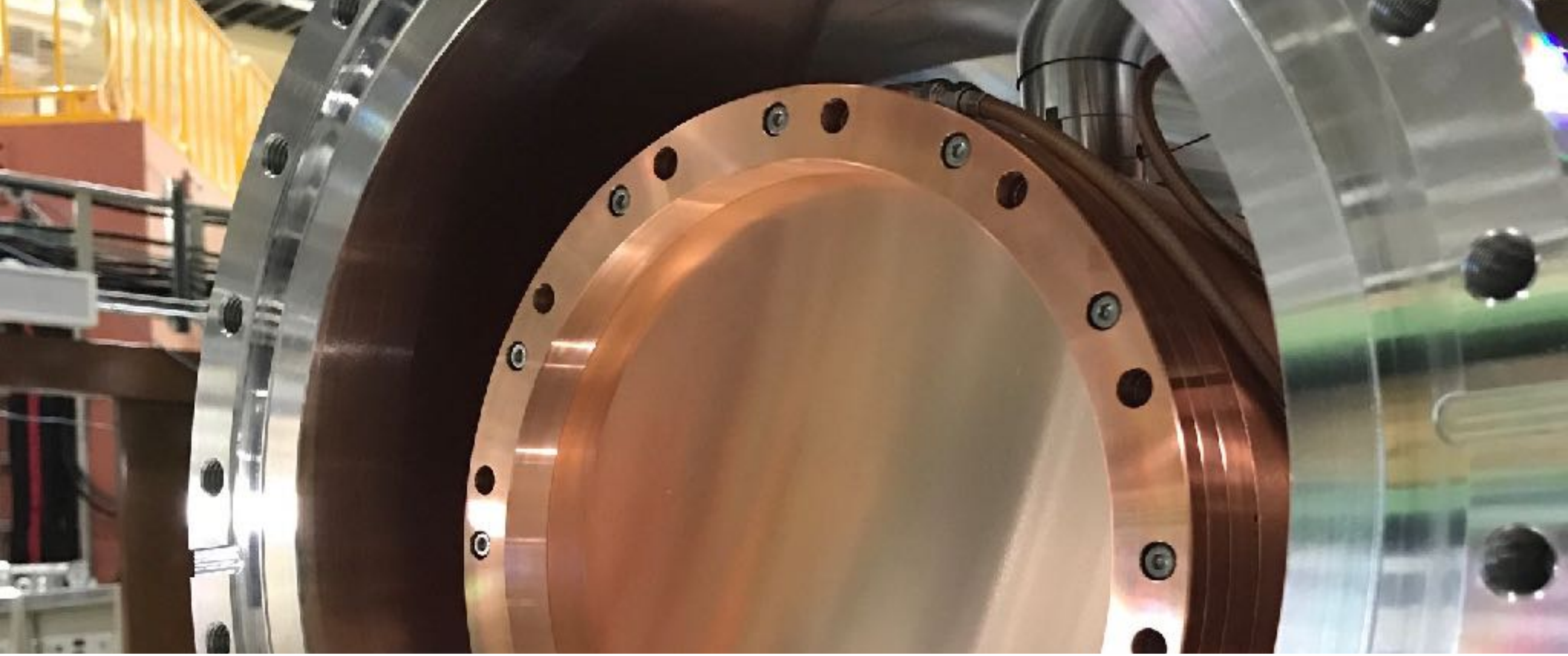


Spectroscopy of Muonium Hyperfine Structure at J-PARC

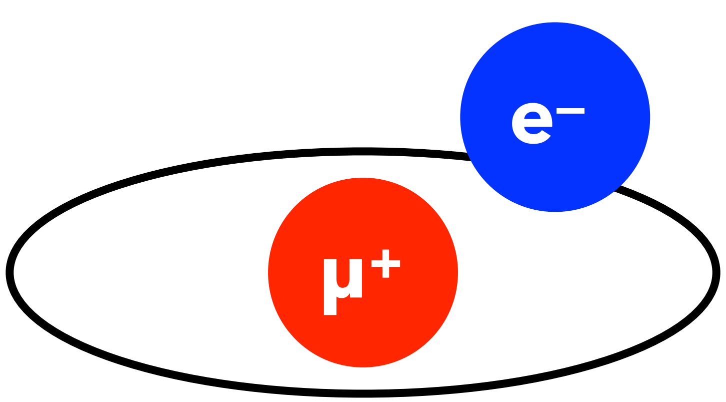
Yasuhiro UENO, from RIKEN, for MuSEUM collaboration

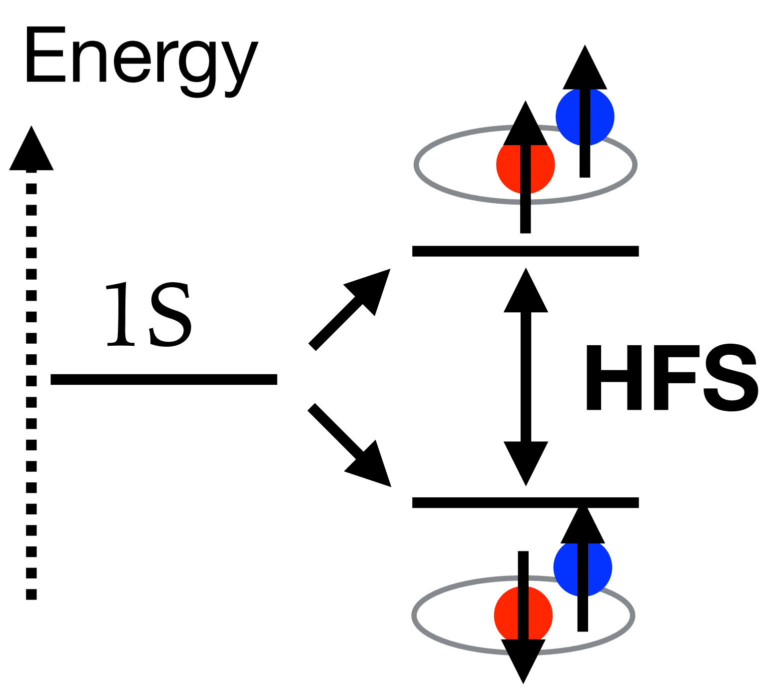
Agenda

- **Introduction**
  -Motivation
  -Procedure
  -Apparatus
- **Recent Measurements at low B field**
  -Result with lower gas pressure
- **R&D for future**
  -Mixture gas
  -magnet for high field measurement
  -Time differential method

Experiment: MuSEUM

- **<u>Mu</u>**onium **<u>S</u>**pectroscopy **<u>E</u>**xperiment **<u>U</u>**sing **<u>M</u>**icrowave
- Muonium: μ^+&e^-, no nuclear structure, calculation with high precision
- Two major motivations
  - **Test of the bound-state QED**
  - Most precise **determination of the muon magnetic moment** (synergy with the muon *g*-2 experiement)

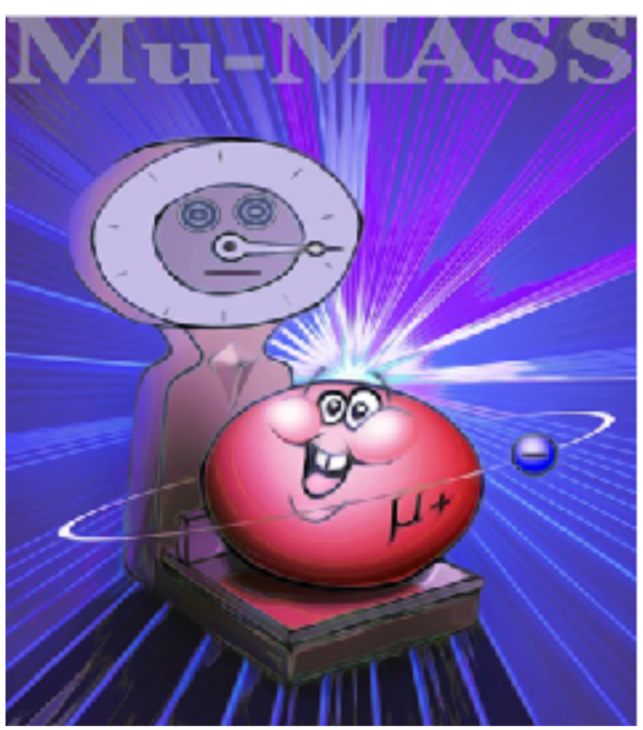




HFS	H	Mu
relative uncertainty of theory	560 ppb	115 ppb

Test of the Bound-State QED

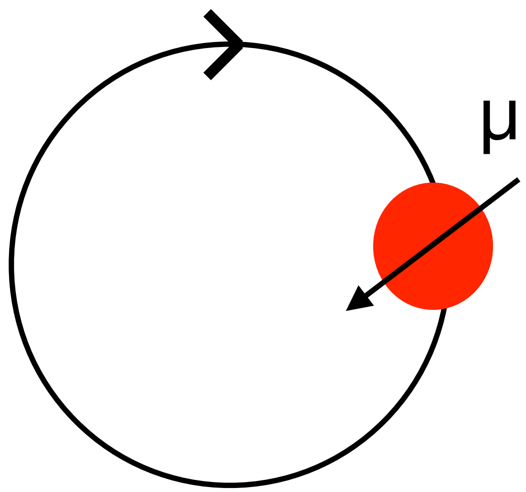
- ν_{exp} = 4 463 302 765 (53) Hz   Experiment at LAMPF (1999)
- ν_{th} = 4 463 302 891 (511)(70)(2) Hz (m_{μ}/m_e)(QED)(α)   By Eides
- Effort in QED calculation for <10 Hz precision is in progress by Eides et al.
- Combined with independent muon mass determination
  → test of the bound-state QED



- **M**uoiu**M** l**A**ser **S**pectro**S**copy
  planned at PSI (Paul Scherrer Institute)
- Improve Muonium 1s-2s by a factor of 1000
- Determine the muon mass with 1 ppb
  (more than a factor of 100 improvement)

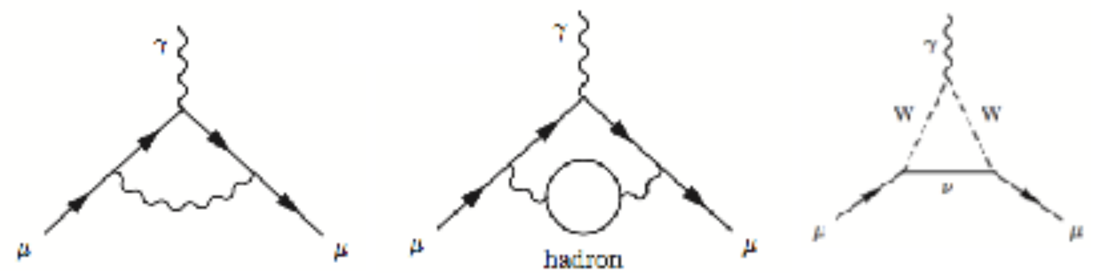
P. Crivelli, Hyperfine Interact., 239, 49 (2018)

Muon Magnetic Moment and Muon g-2



3.7σ discrepancy

A. Keshavarzi, *et al*., Phys. Rev. D. (2018)



Muon Ring **Experiment** at BNL

GW Bennett *et al*., PRD **73** 072003 (2006)

SM Theory including QED,

Weak, Hadronic contributions

Talk by D. Nomura

$$a_\mu = \frac{R}{\frac{\mu_\mu}{\mu_p} - R}$$

a_μ: muon *g*-2

(anomalous magentic moment)

R determined by muon ring Experiment:
Current: 540 ppb
Future: <140 ppb

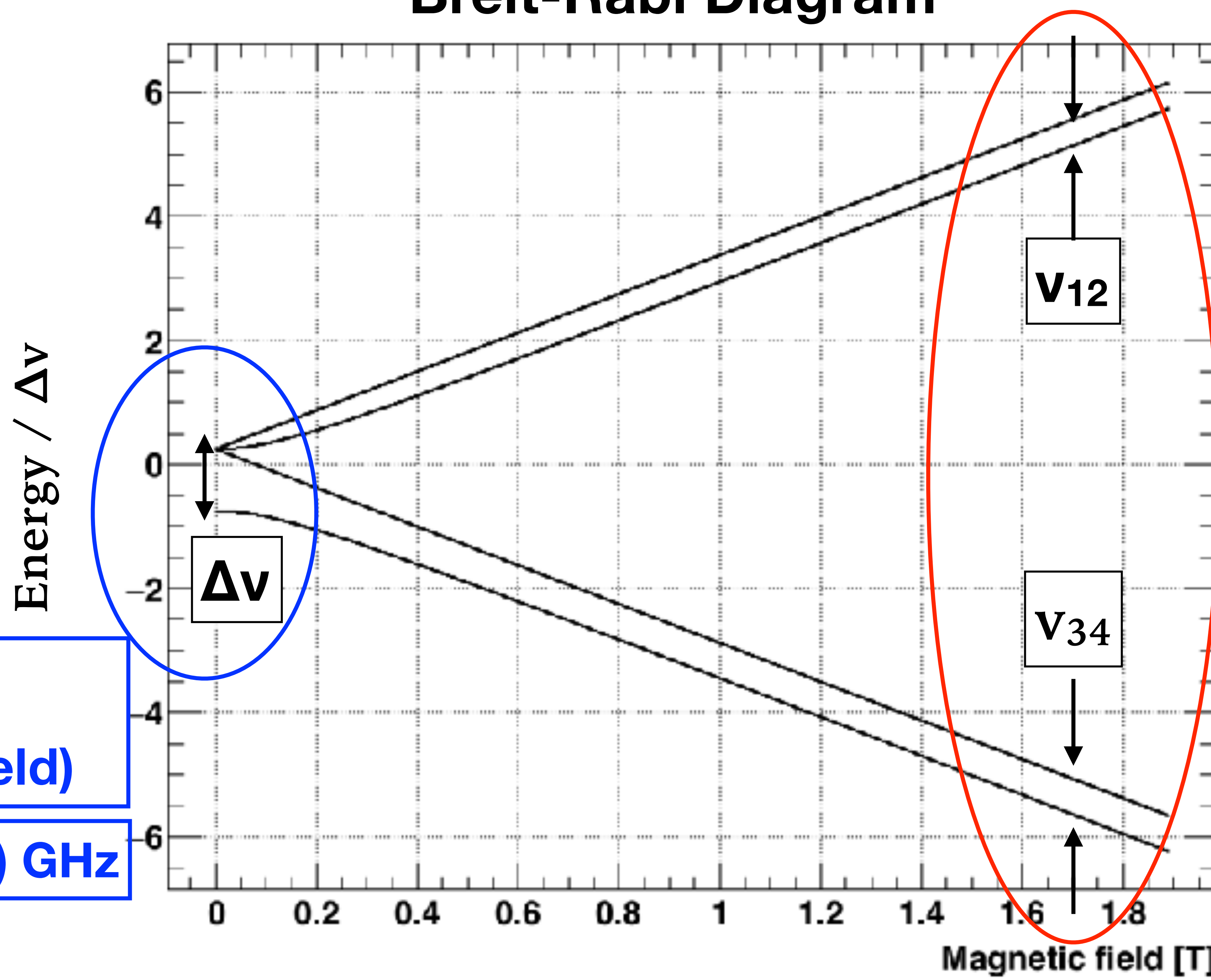
new experiments by Fermilab and J-PARC

Talks by S. Corrodi, and S. Lee

26 ppb (QED assumed) or
120 ppb (direct determination)
MuSEUM aim: 10 ppb (direct)

MuSEUM: Zeeman Splitting

Breit-Rabi Diagram



"Zero" Field

(very low B field)

4.463 3022 (14) GHz

High Field

(at 1.7 T)

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

$\nu_{12}-\nu_{34} \propto \mu_\mu/\mu_p$

4.463 302 765 (53) GHz

Both world records at **Los Alamos Meson Physics Facility (LAMPF)**

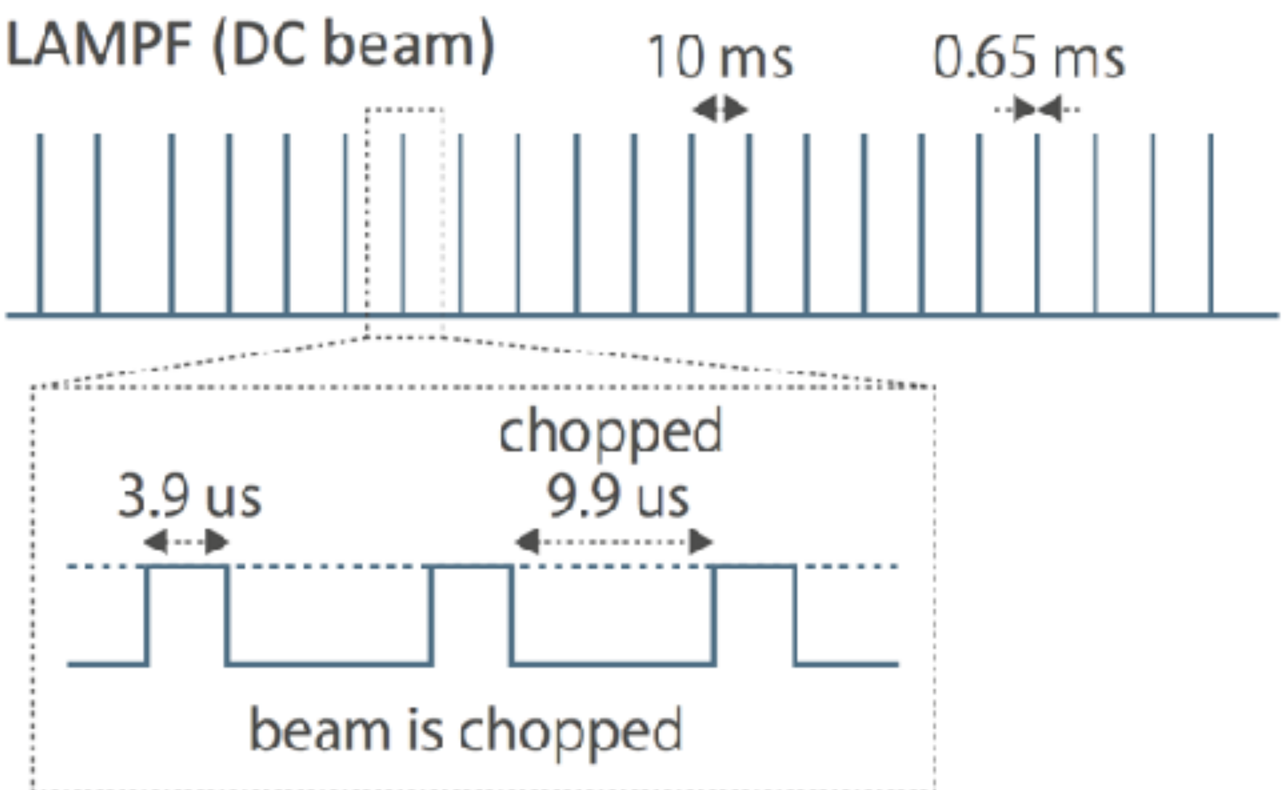
Their precision are **statistically limited, we need more muons!**

Intense Pulsed Muon Beam: J-PARC MLF

- ➤ The precision of the precursor experiments were limited by statistics
- ➤ We use the most intense pulsed muon beam at J-PARC MLF

Precursor Measurement

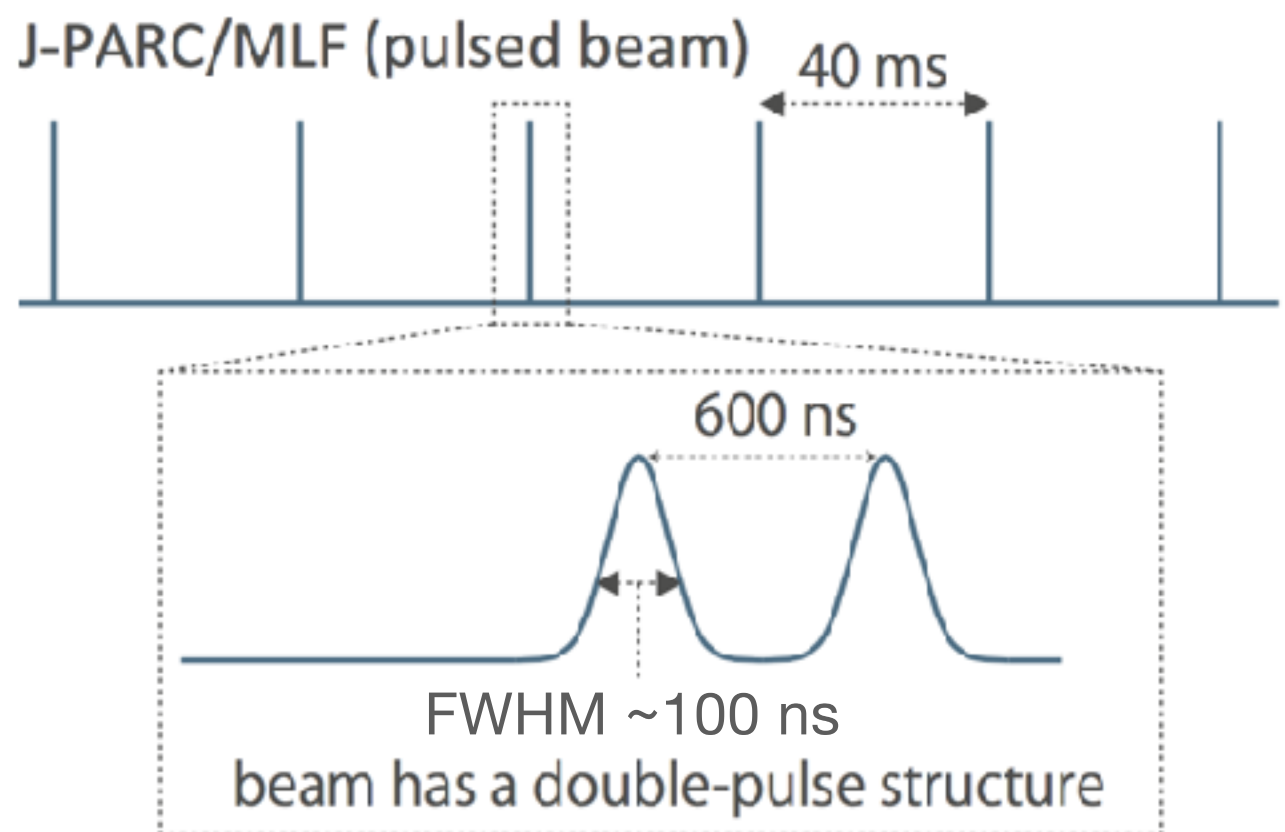
at LAMPF



after chop: 2×10^6 μ^+/sec

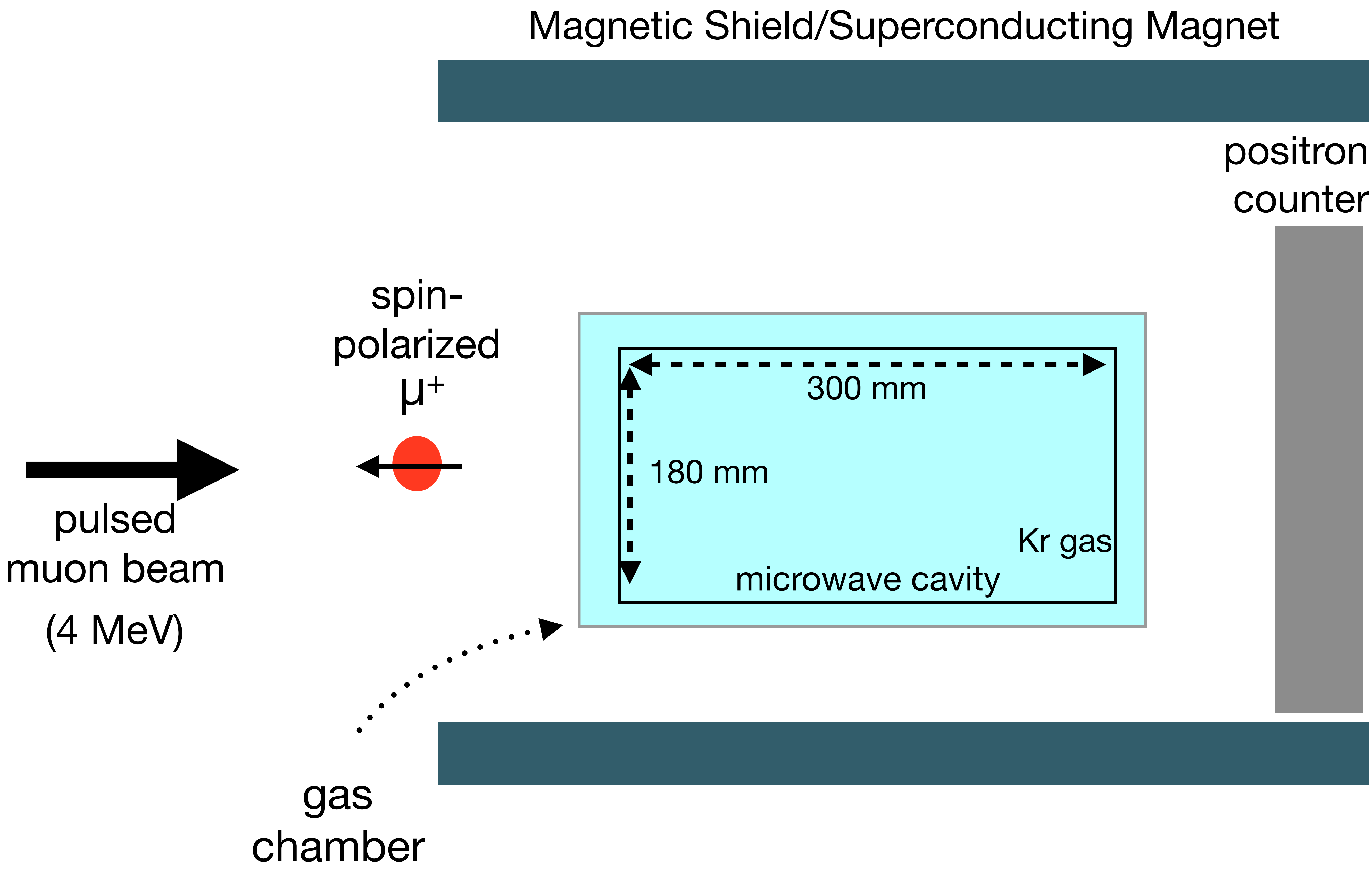
Our Measurement

at J-PARC MLF

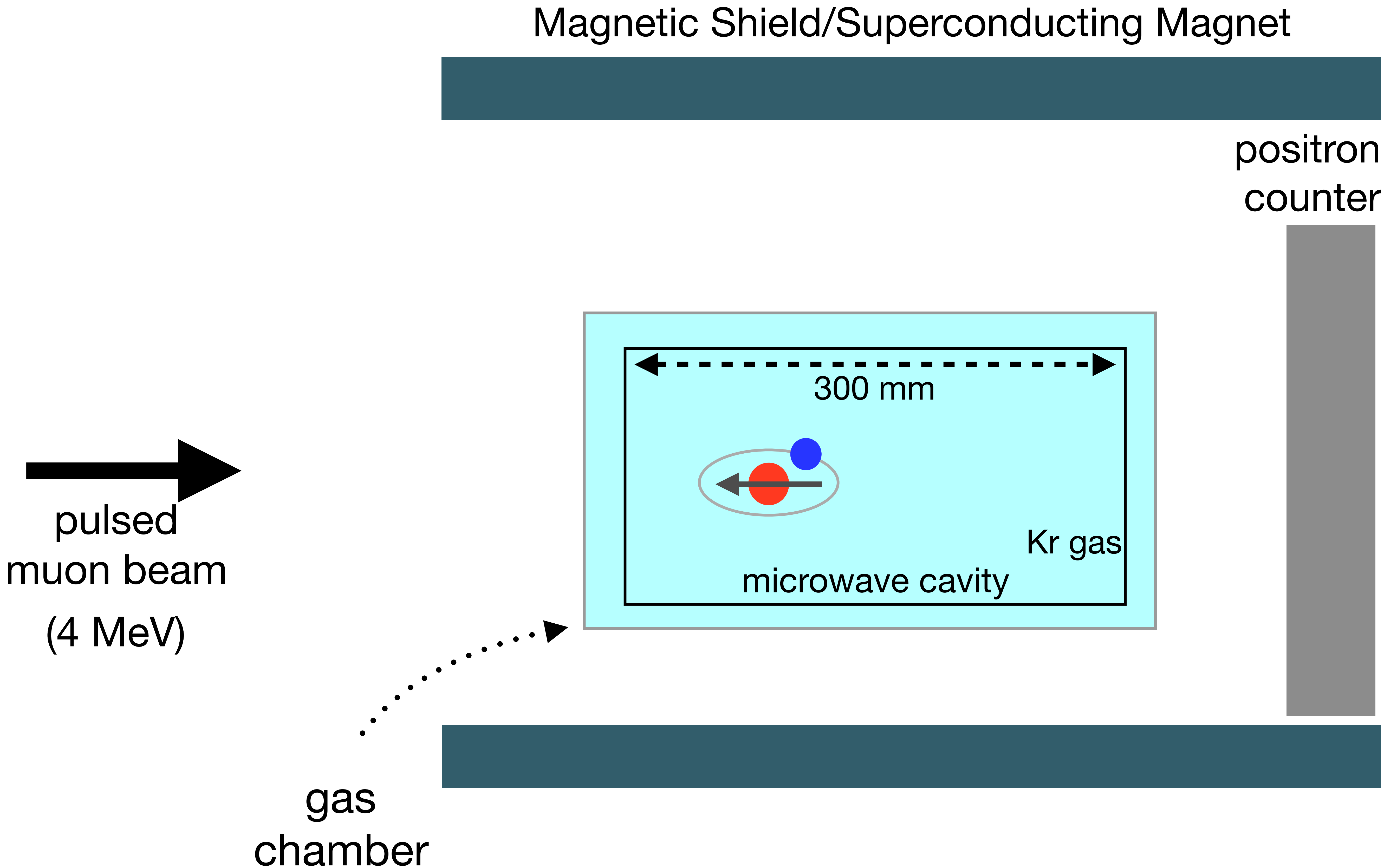


>10^8 μ^+/sec (H-Line 1 MW)

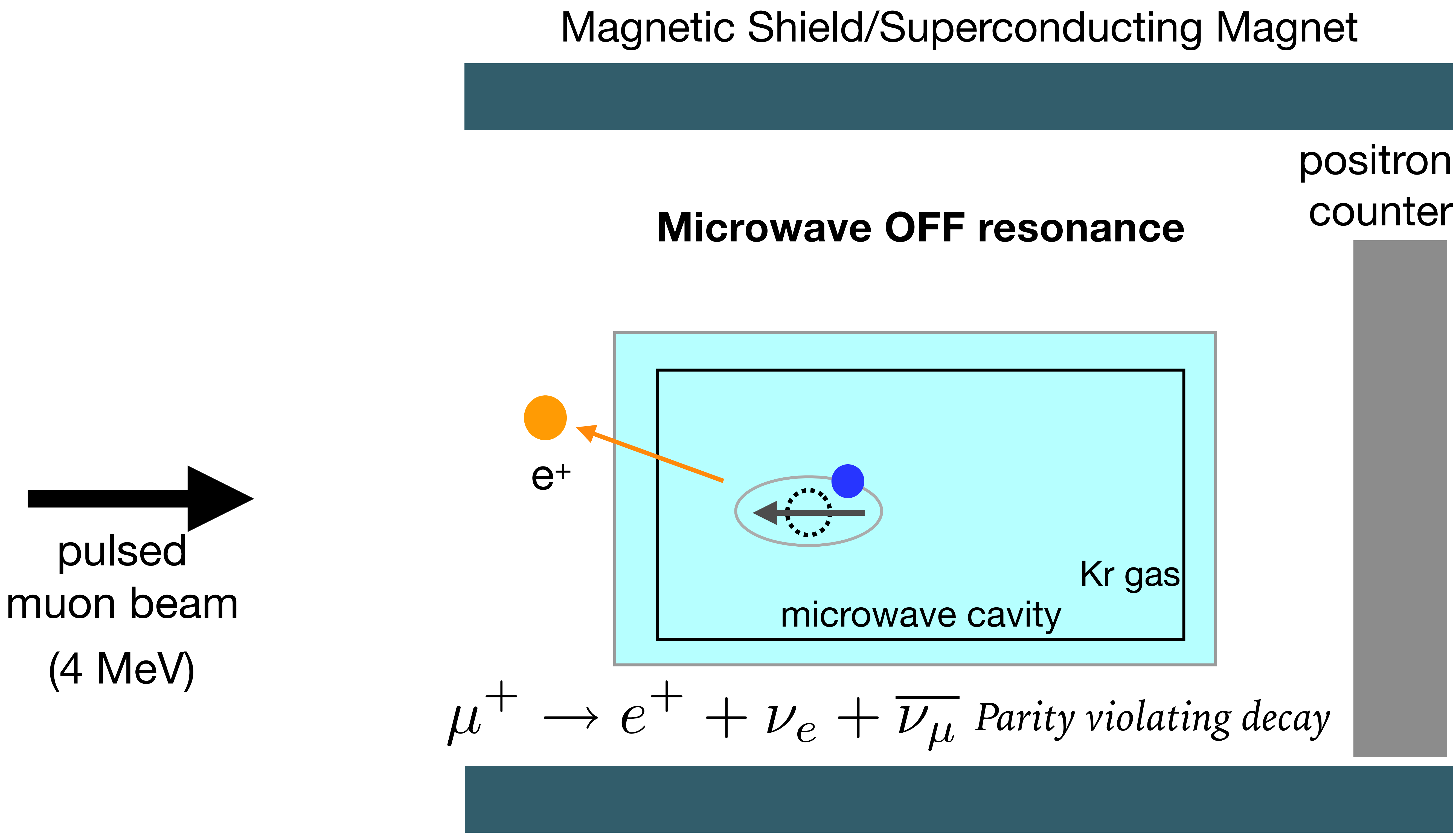
Procedure of Measurement



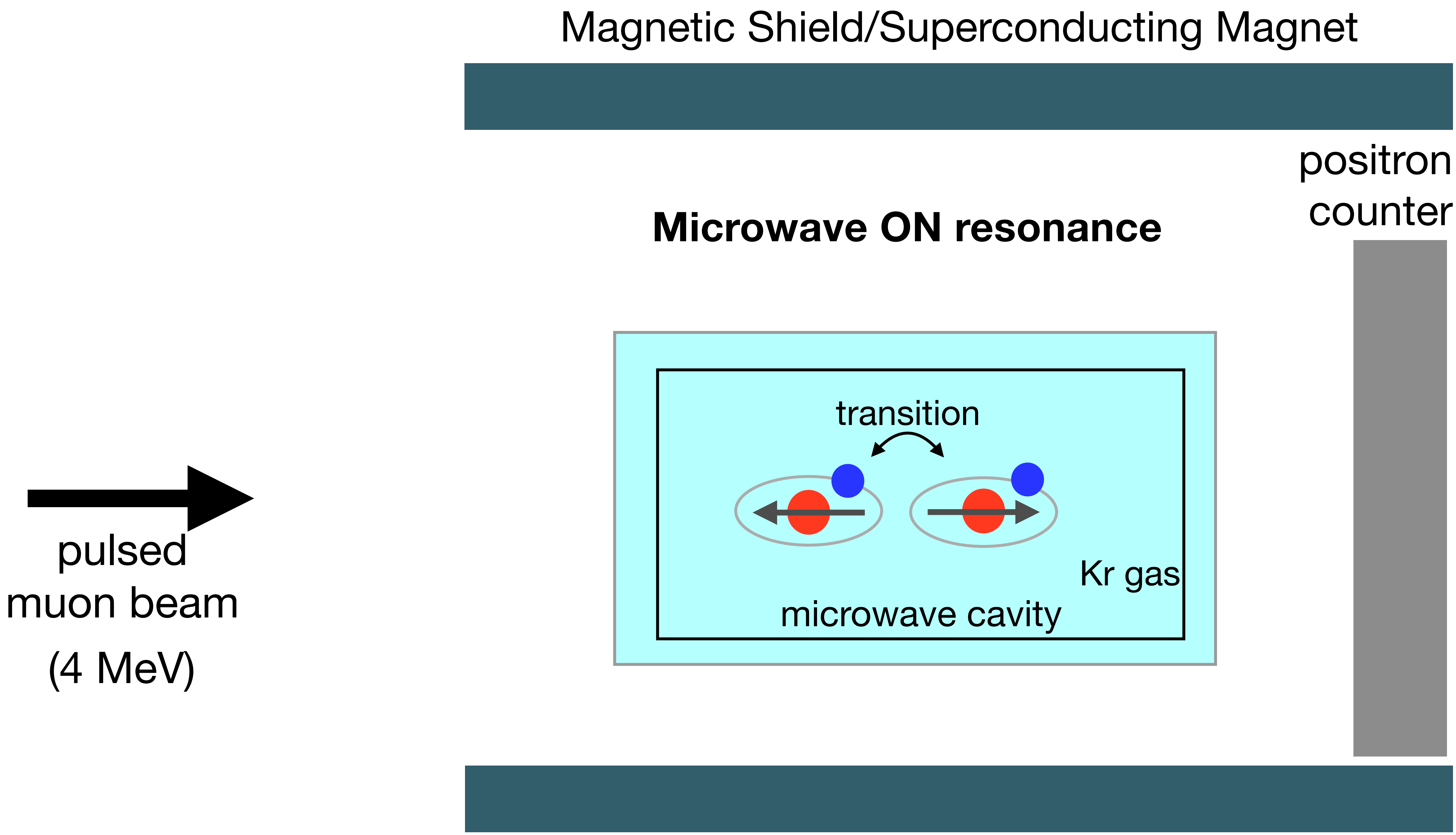
Procedure of Measurement



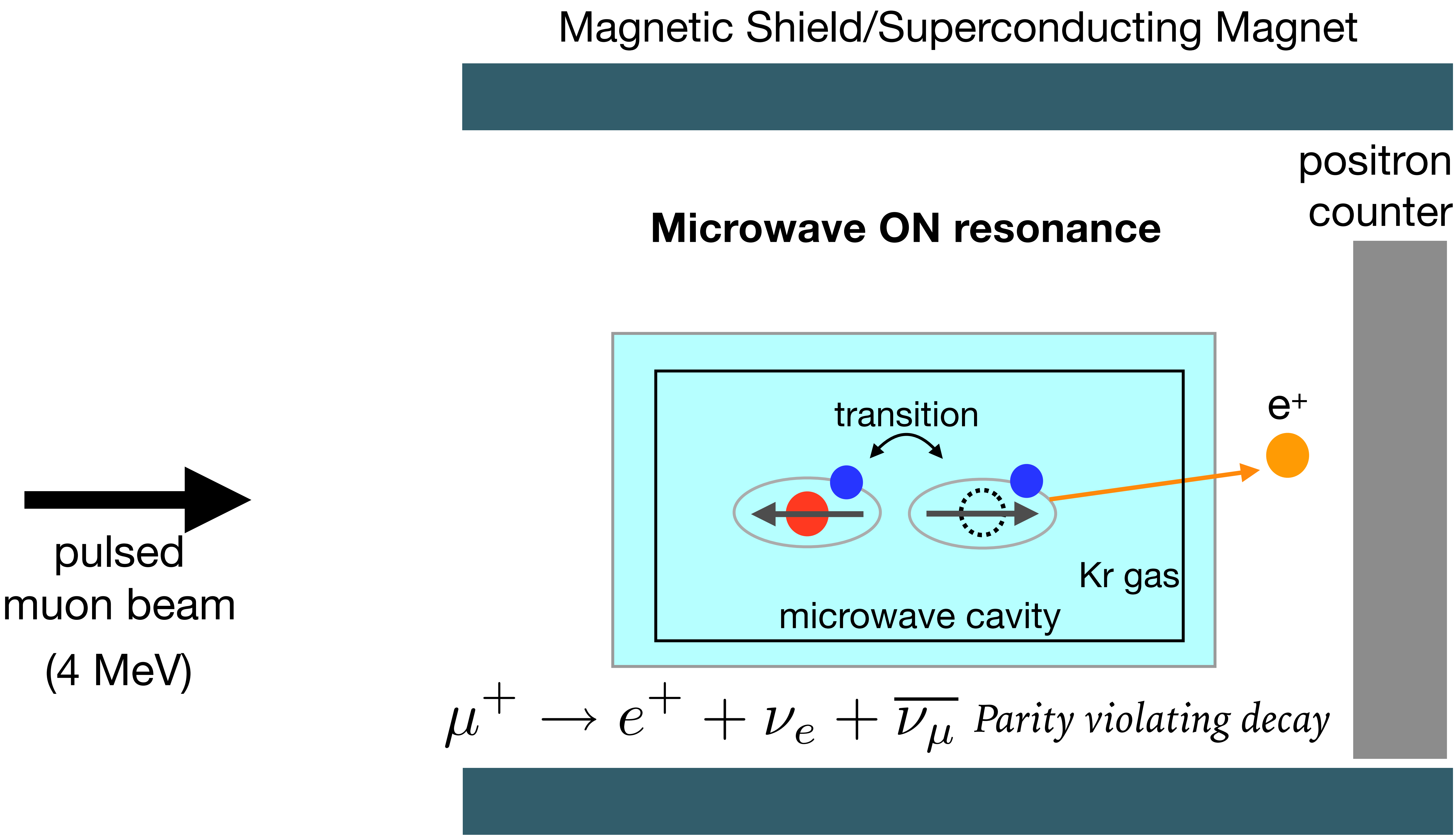
Procedure of Measurement



Procedure of Measurement

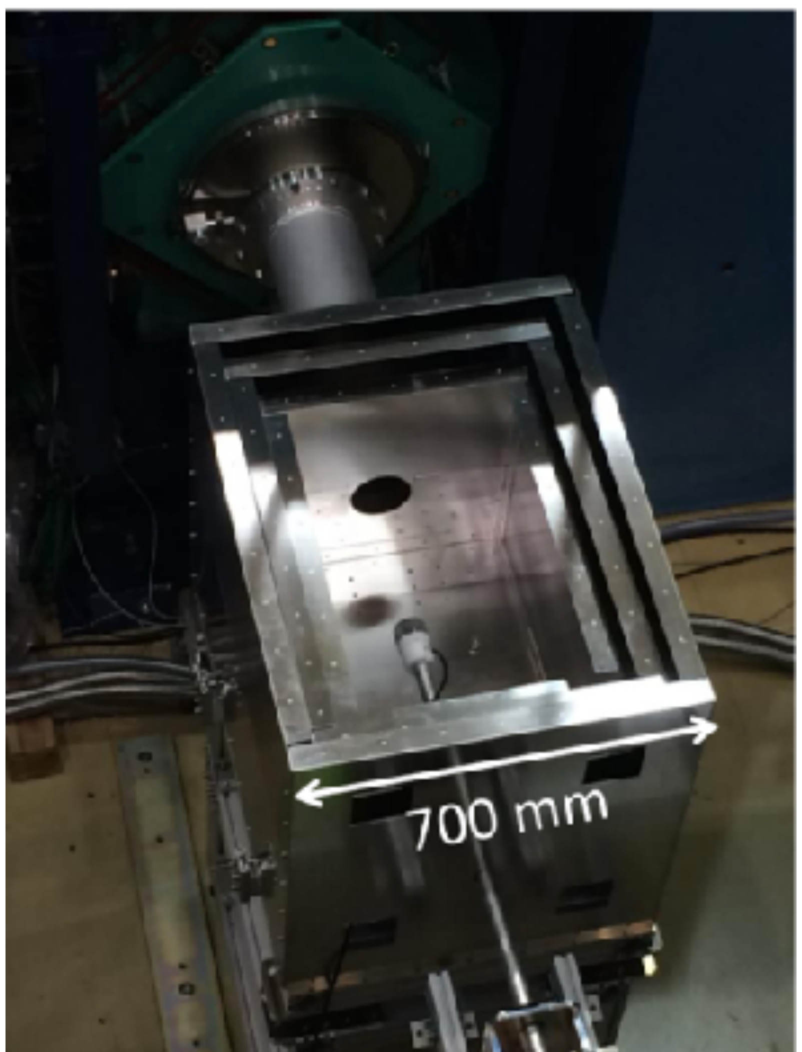


Procedure of Measurement

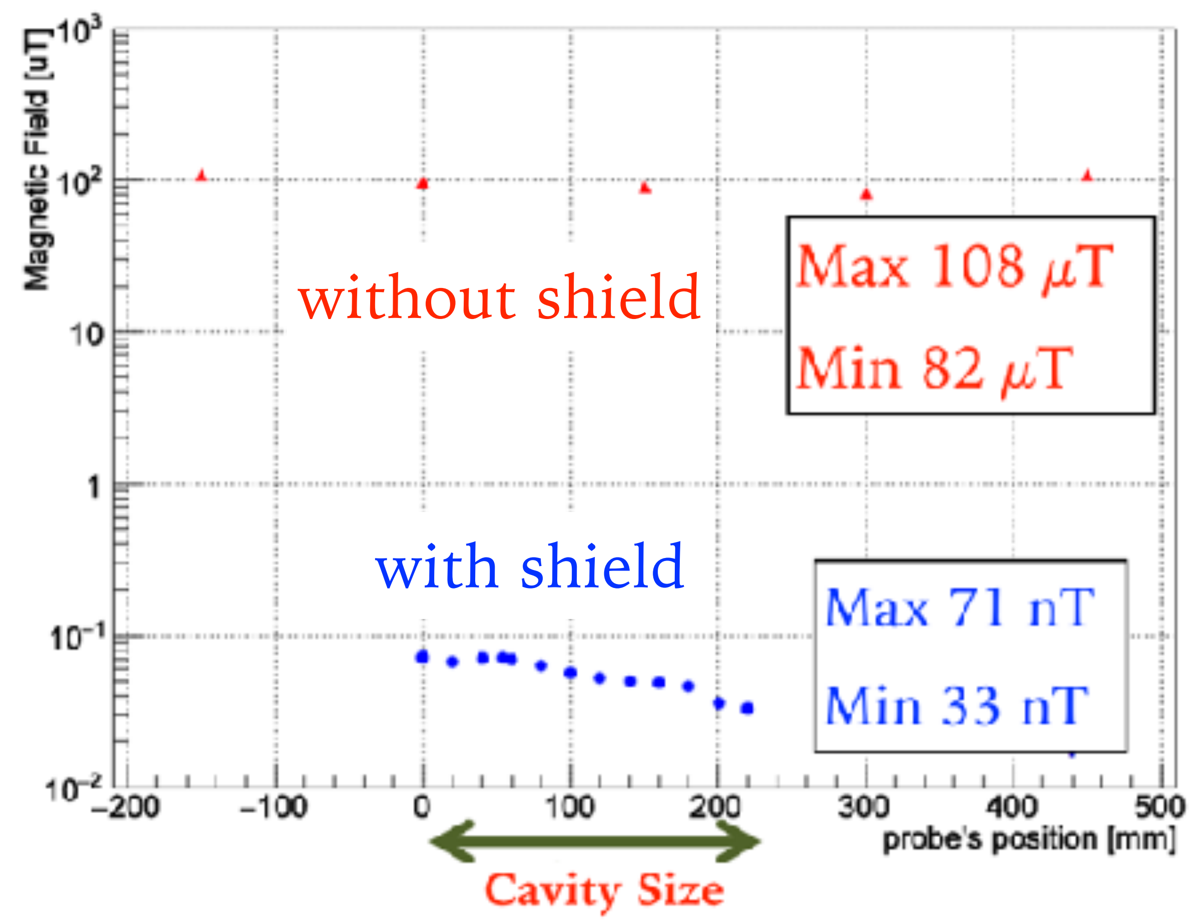


Shield for Magnetic Field

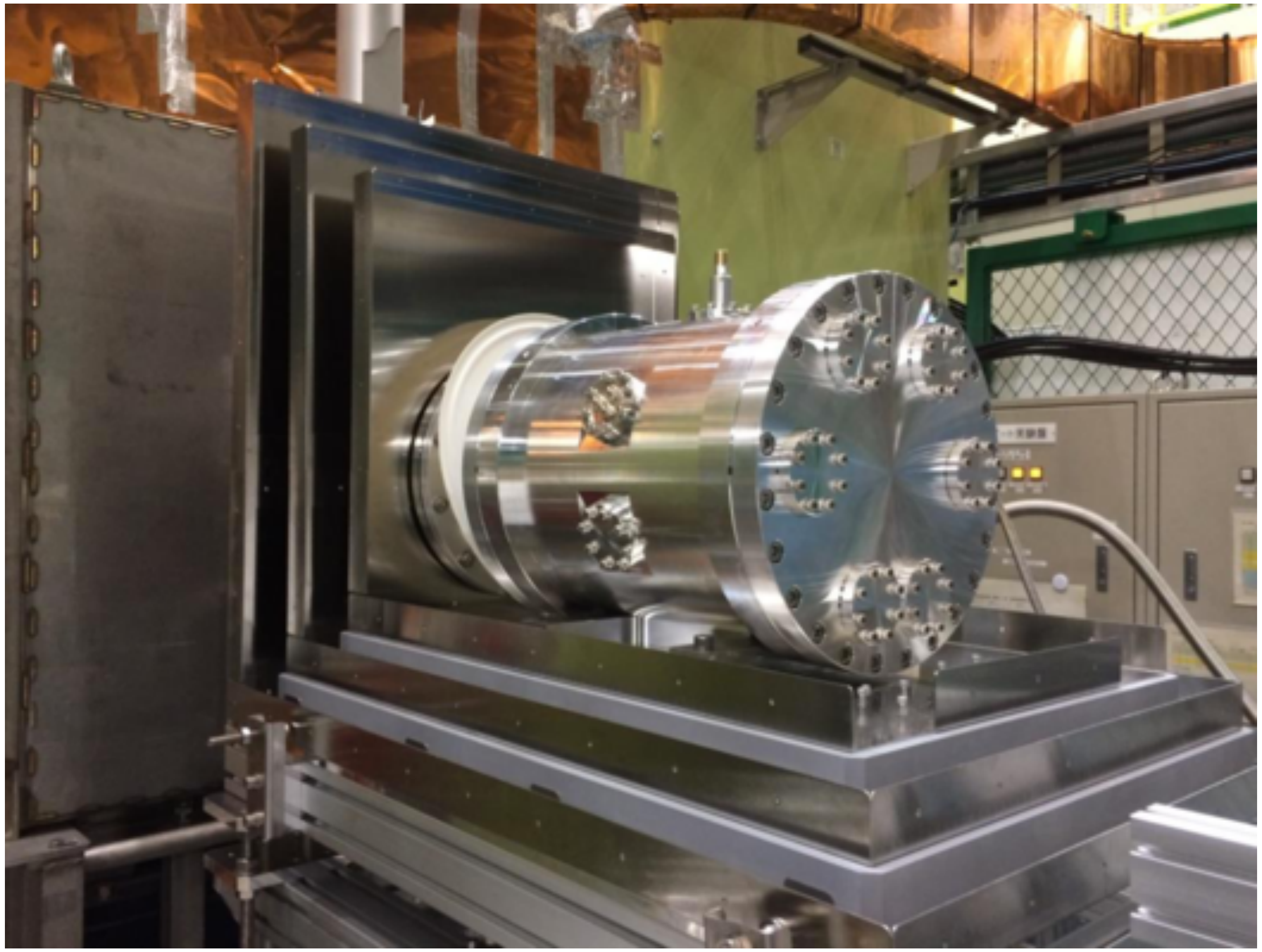
- Geomagnetic field and stray field from the beam line magnets
- **Three-layer permalloy shields** suppress the magnetic field (1/1000 supression)
- Field measurement by flux-gate probe

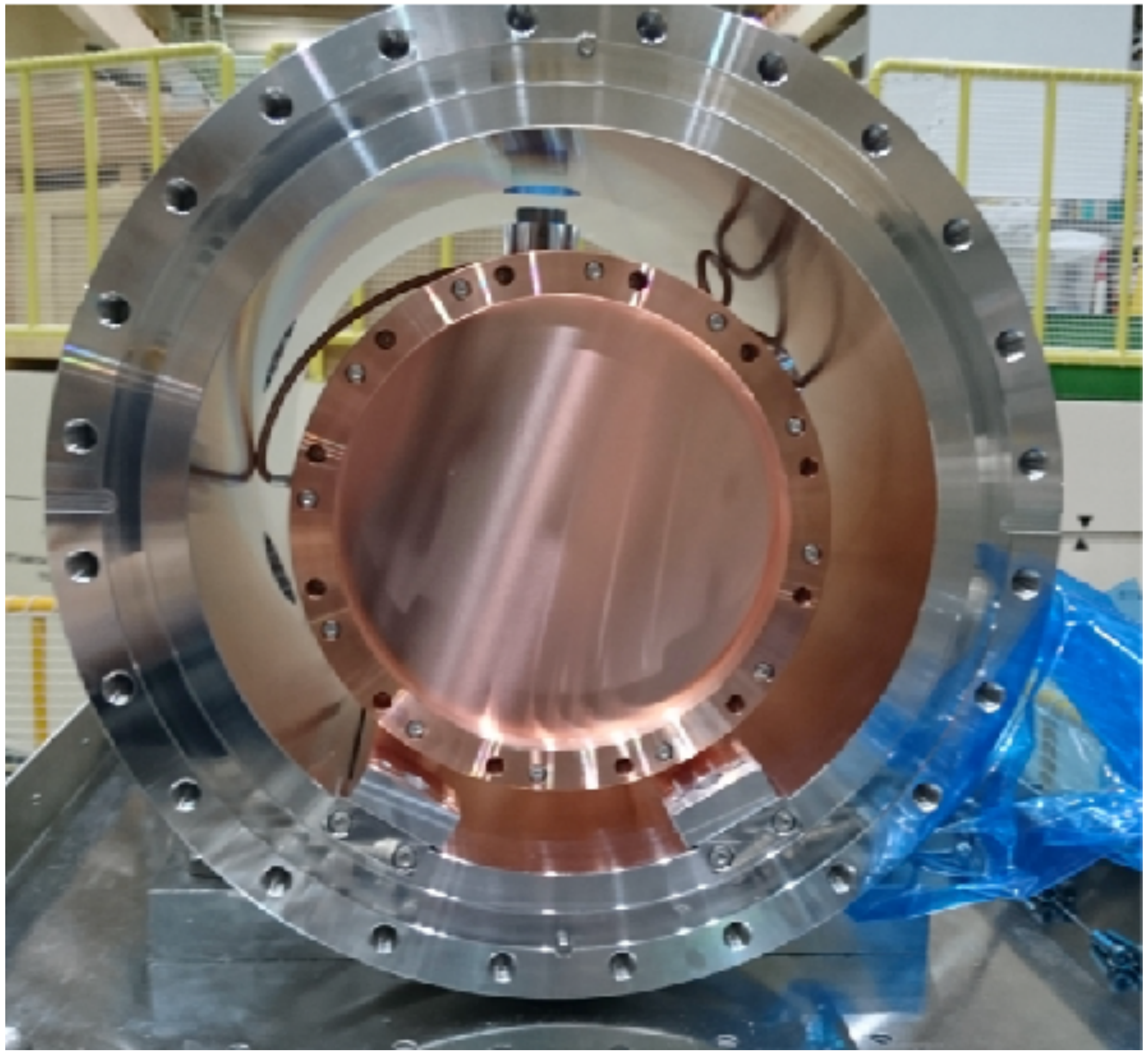


Comparison of field with and without the shield



Gas Chamber and Microwave Cavity

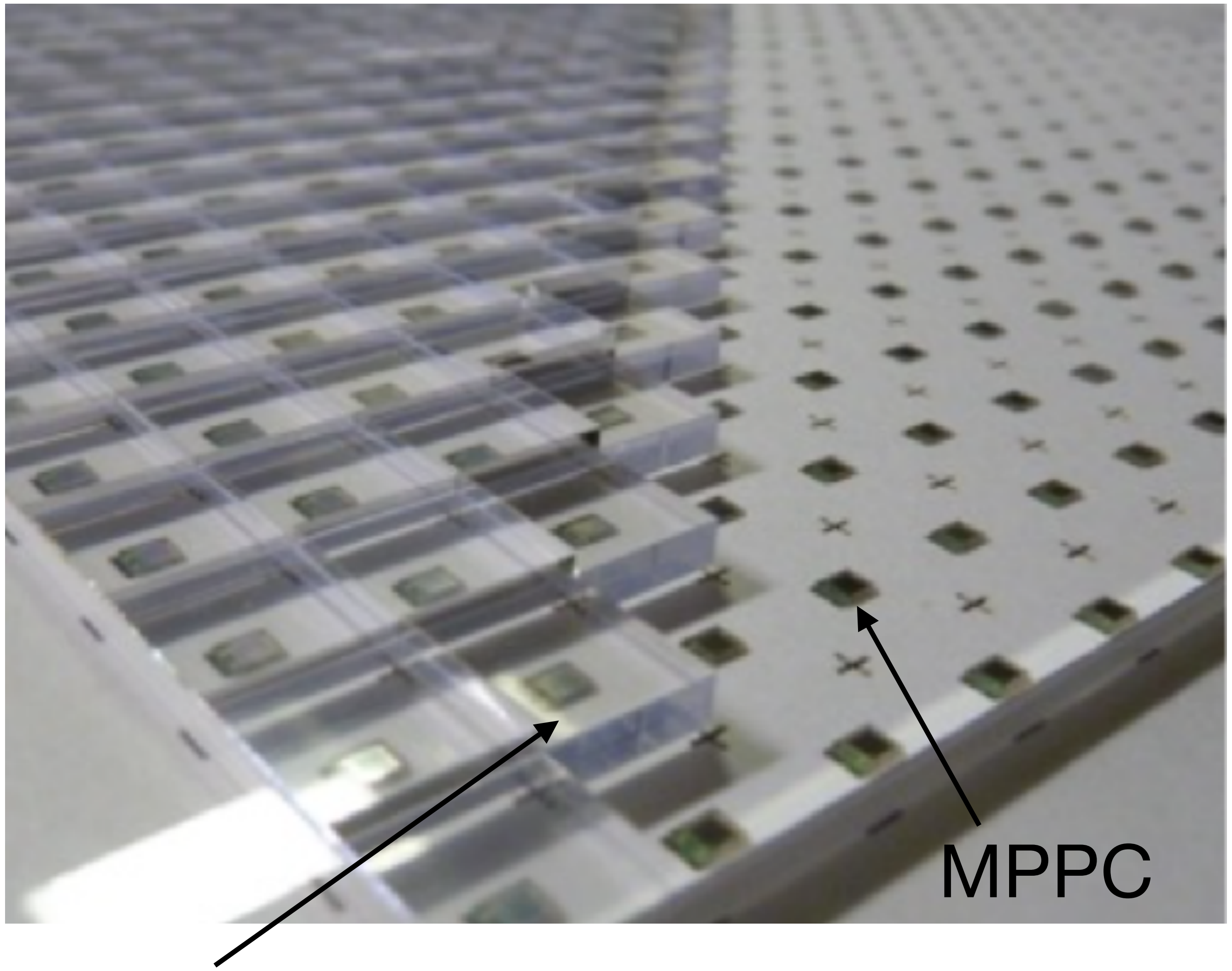


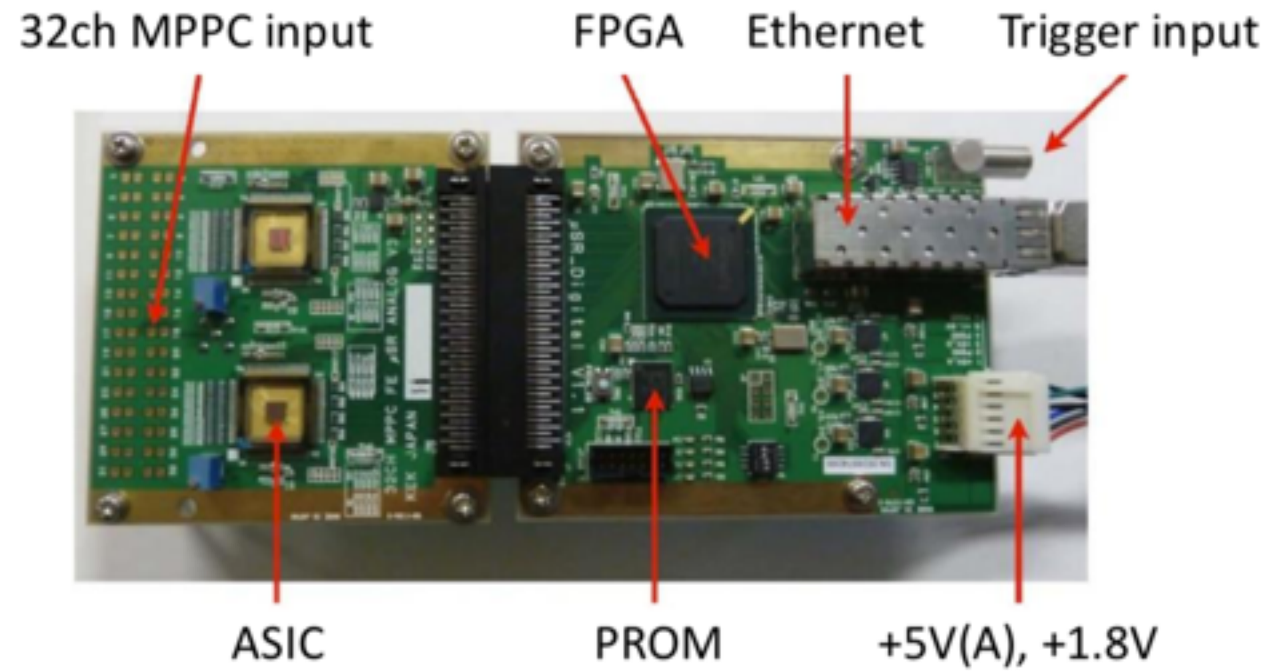


- Gas pressure monitored by a capacitance gauge
  Impurity measured by Q-MASS spectrometer
- Cavity Q factor ~10000, Input power ~1 W
  Cavity resonance frequency is tunable: 4463 ± 1 MHz

Positron Detector

Plastic Scintillator + MPPC(SiPM) + Kalliope read out board





Plastic Scintillator

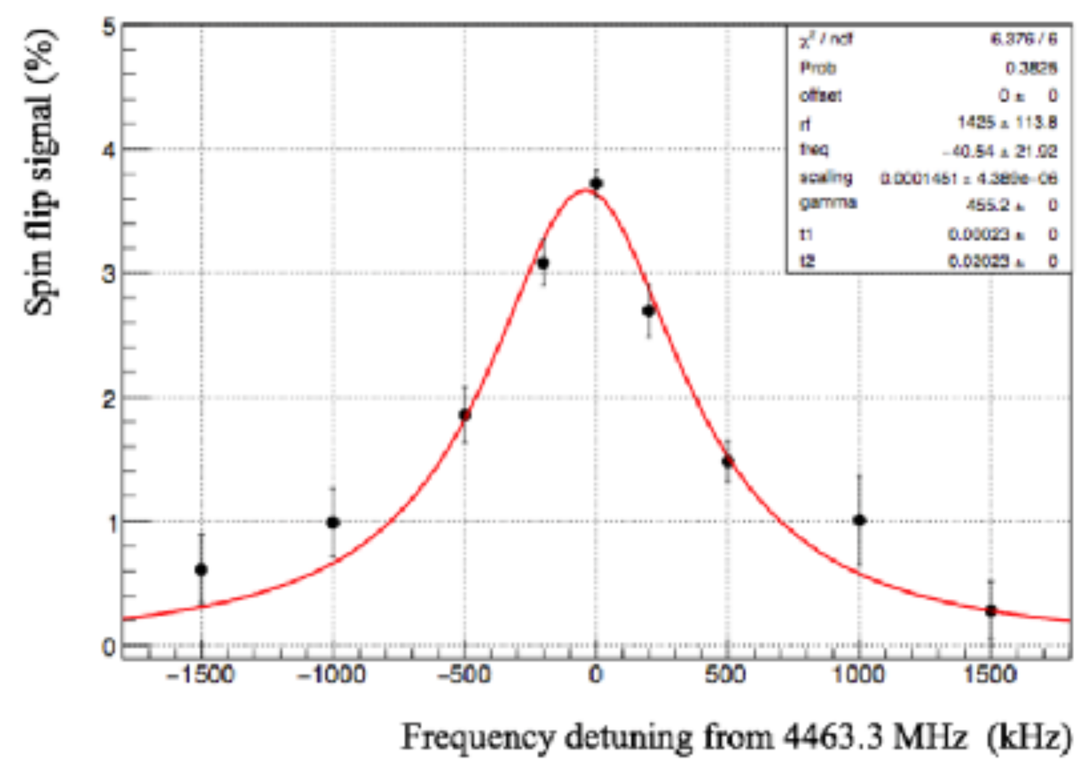
- ➤ Unit cell: 10 mm × 10 mm
- ➤ Covers 240 mm × 240 mm
- ➤ Two layers, 1152 ch in total

Agenda

- **Introduction**
  - -Motivation
  - -Procedure
  - -Apparatus
- **Recent Measurements at low B field**
  - -Result with lower gas pressure
- **R&D for future**
  - -Mixture gas
  - -magnet for high field measurement
  - -Time differential method

First Result in 2016

- Measurement in 2016 at zero field at D-Line (Beam Power 200 kW) at Kr pressure = 1.0 atm
- First result: 4.463 292(22) GHz
  precision: 22 kHz, statistically limited (world record: 1.4 kHz)
- First measurement of MuHFS using a pulsed muon beam

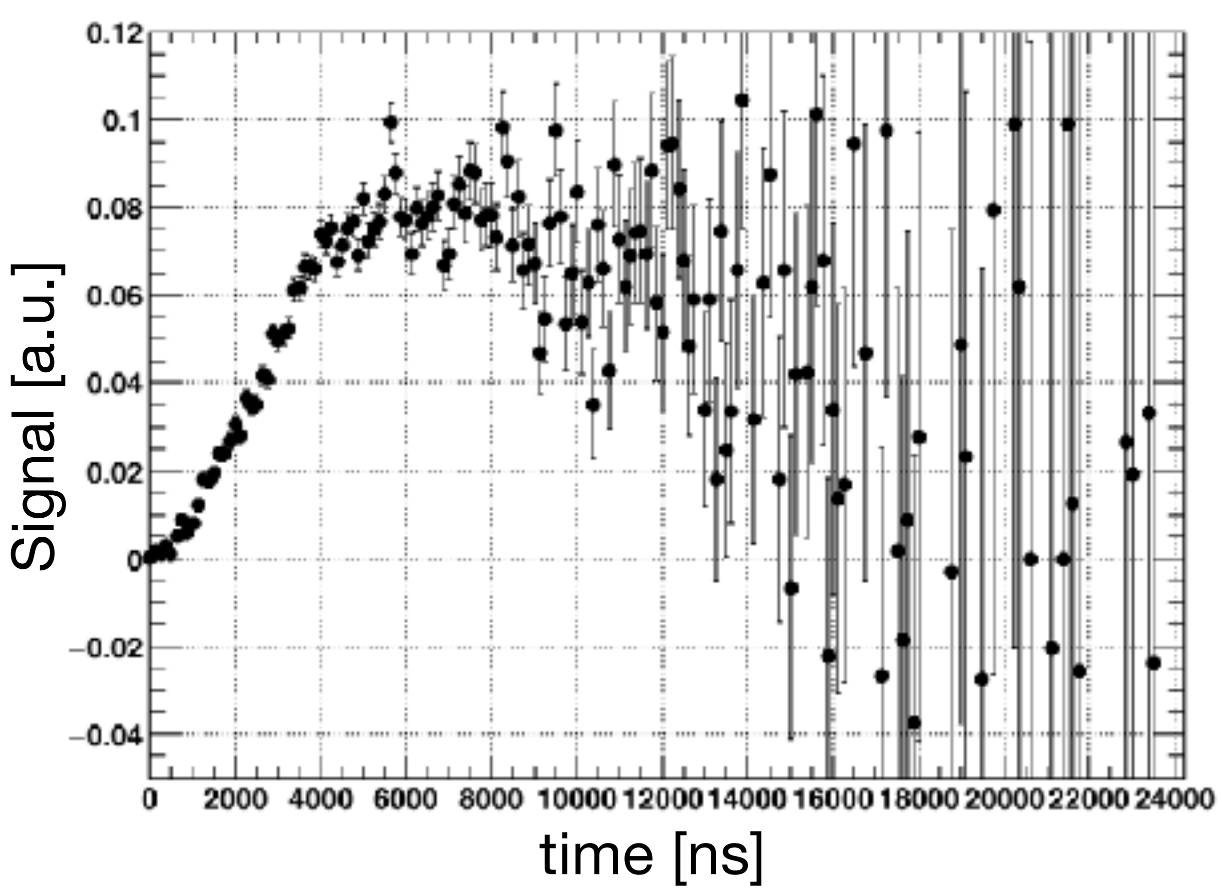


S. Kanda, PoS (INPC2016) 170 (2017)

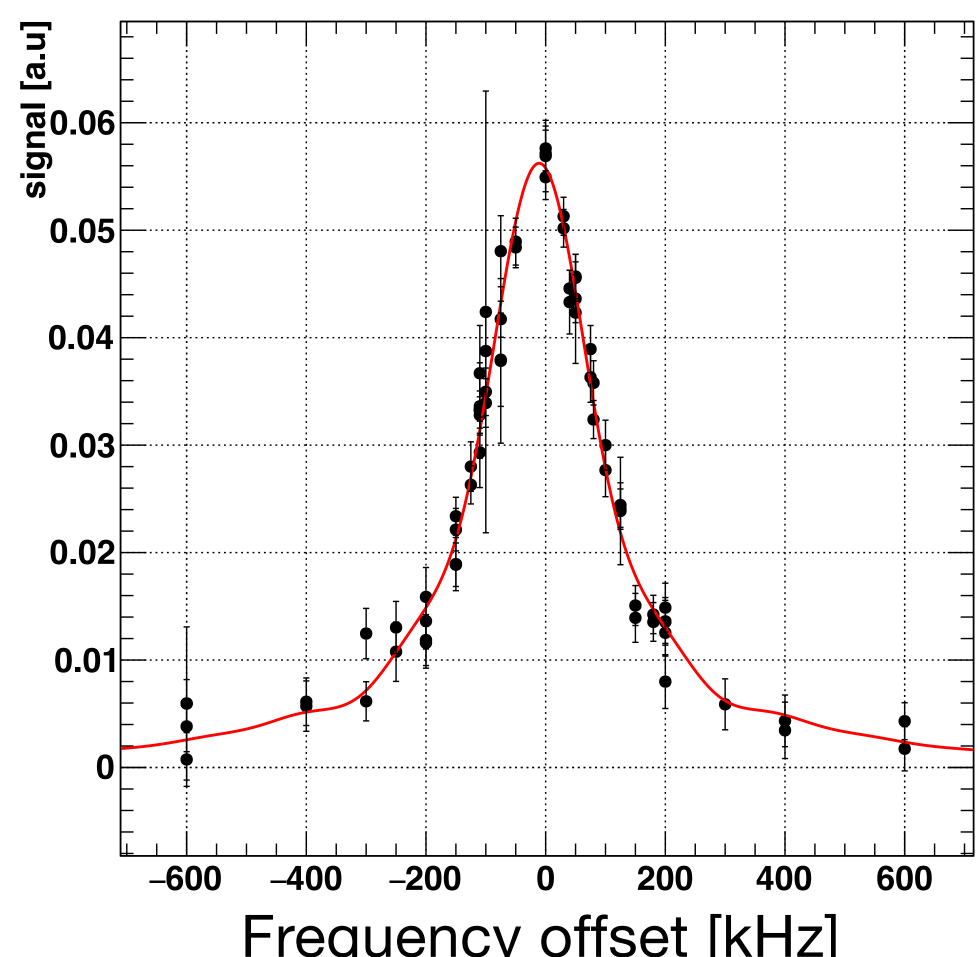
Measurement at Lower Kr Pressure

- MuHFS shifts in Kr, we need a value in vacuo to compare with theory
- Measurement at lower Kr pressure points (0.3-1.0 atm) in 2018,2019 (D-Line, with improved beam power ~500 kW)
- (Measurement at less than 0.8 atm has not been done before)

Kr = 0.7 atm, on resoance

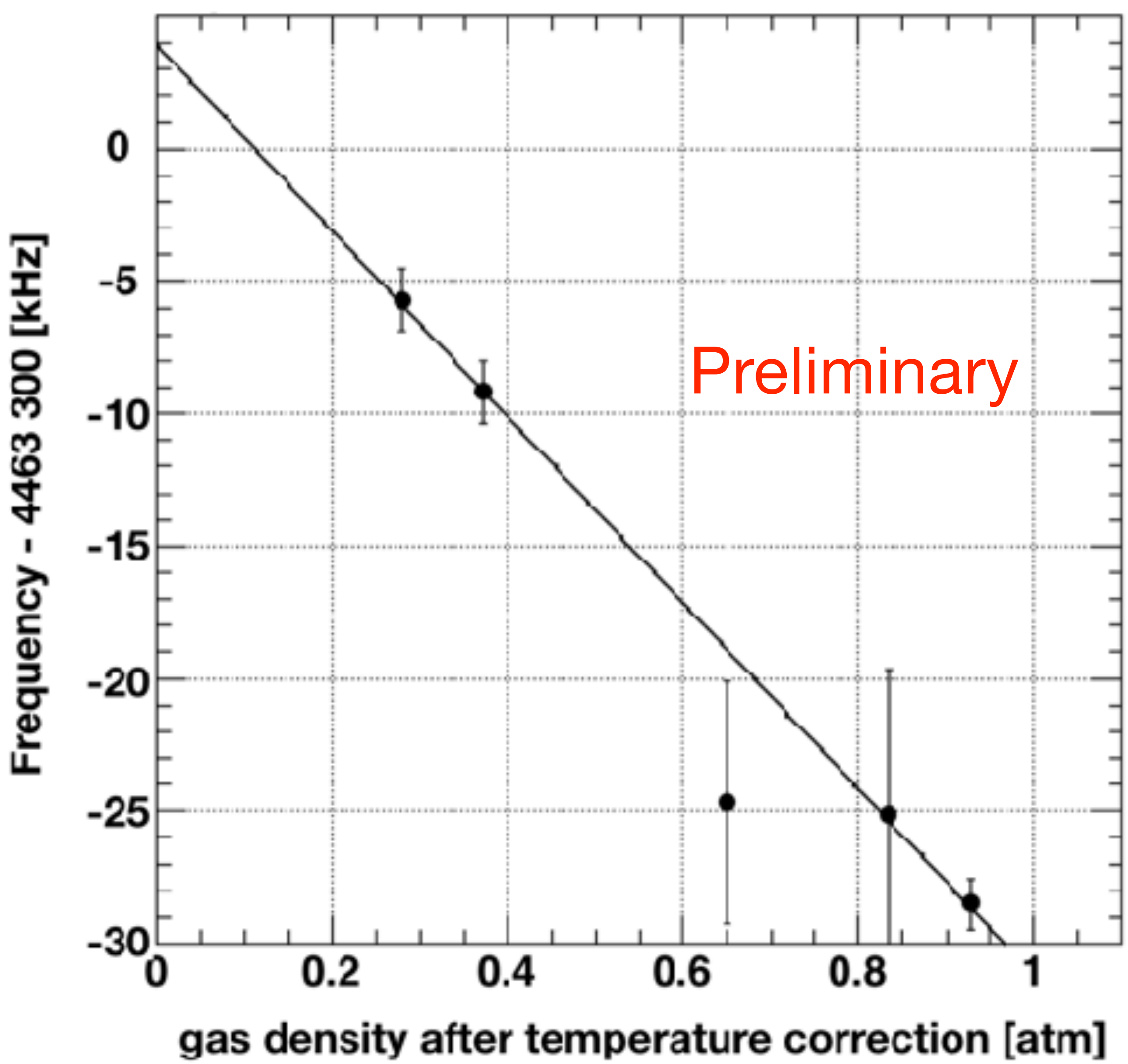


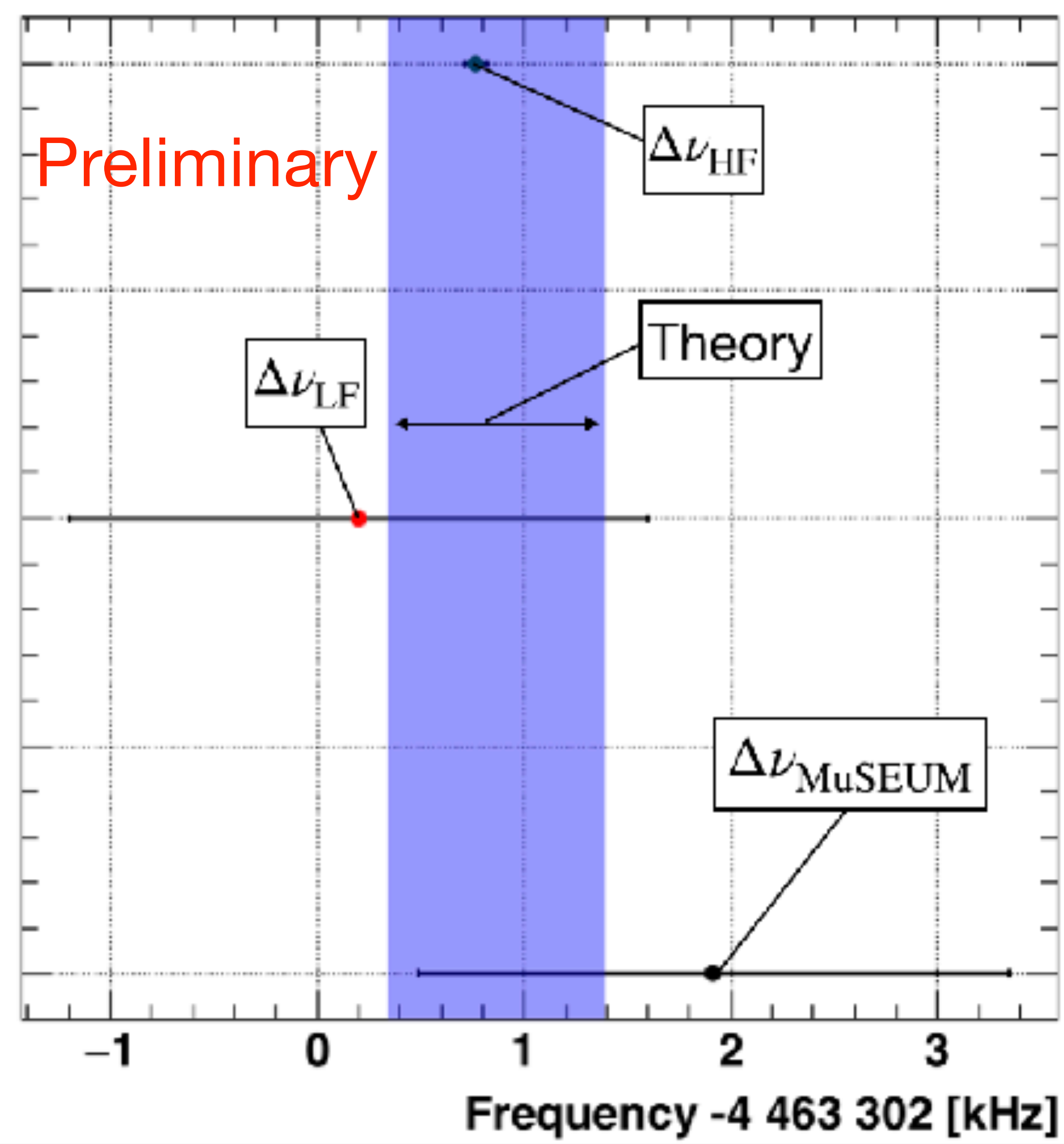
Kr = 0.4 atm



Measurement at Lower Kr Pressure

- Extrapolated the results to obtain the MuHFS in vacuo
- The uncertainty is comparable to the world record (1.4 kHz)
- Our result is consistent with the theory and the precursor experiment





Uncertainty in Weak Field Measurement

- Current statistical uncertainty: 1400 Hz in 3 days
  With new beamline and 100-days run: **40 Hz** is expected
  Further improvement is achievable
- Systematic uncertainty: currently 112 Hz, <10 Hz in future

Systematic uncertainty table

Contribution	Uncertainty [Hz]
Pressure Gauge	79
Pressure Fluctuation	24
Quadratic Term	(2)
Frequency Reference	45
Power Drift	60
Muon Beam	6
Others	< 1
Total	112

Agenda

- **Introduction**
  - -Motivation
  - -Procedure
  - -Apparatus
- **Recent Measurements at low B field**
  - -Result with lower gas pressure
- **R&D for future**
  - -Mixture gas
  - -magnet for high field measurement
  - -Time differential method

Systematic Uncertainties for High Field

	specification	$\Delta\nu$	μ_μ/μ_p
B field		0	26 ppb
RF stability	0.02%	0.8 ppb	8 ppb
Collision with Kr		1.0 ppb	5 ppb
Kr Temperature	0.2 K	0.4 ppb	4 ppb
Detector pile up		< 0.5 ppb	3 ppb
Others		< 0.8 ppb	7 ppb
Overall		**< 1.6 ppb (8 Hz)**	**29 ppb**

Collisional Shift and Gas Species

- Systematic uncertainty from the collisional shift is dominant
- There are two major effect from the collision
  - Pauli exclusion effect (Short-range)
    -> positive shift
  - Van der Waals interaction effect (Long-range)
    -> negative shift
    dominant for large Z atom

J. Chem. Phys. 32, 972 (1960)

H-HFS pressure dependence in noble gas

B. K. Rao *et al.*, Phys. Rev. A 2(4) 1411(1970).

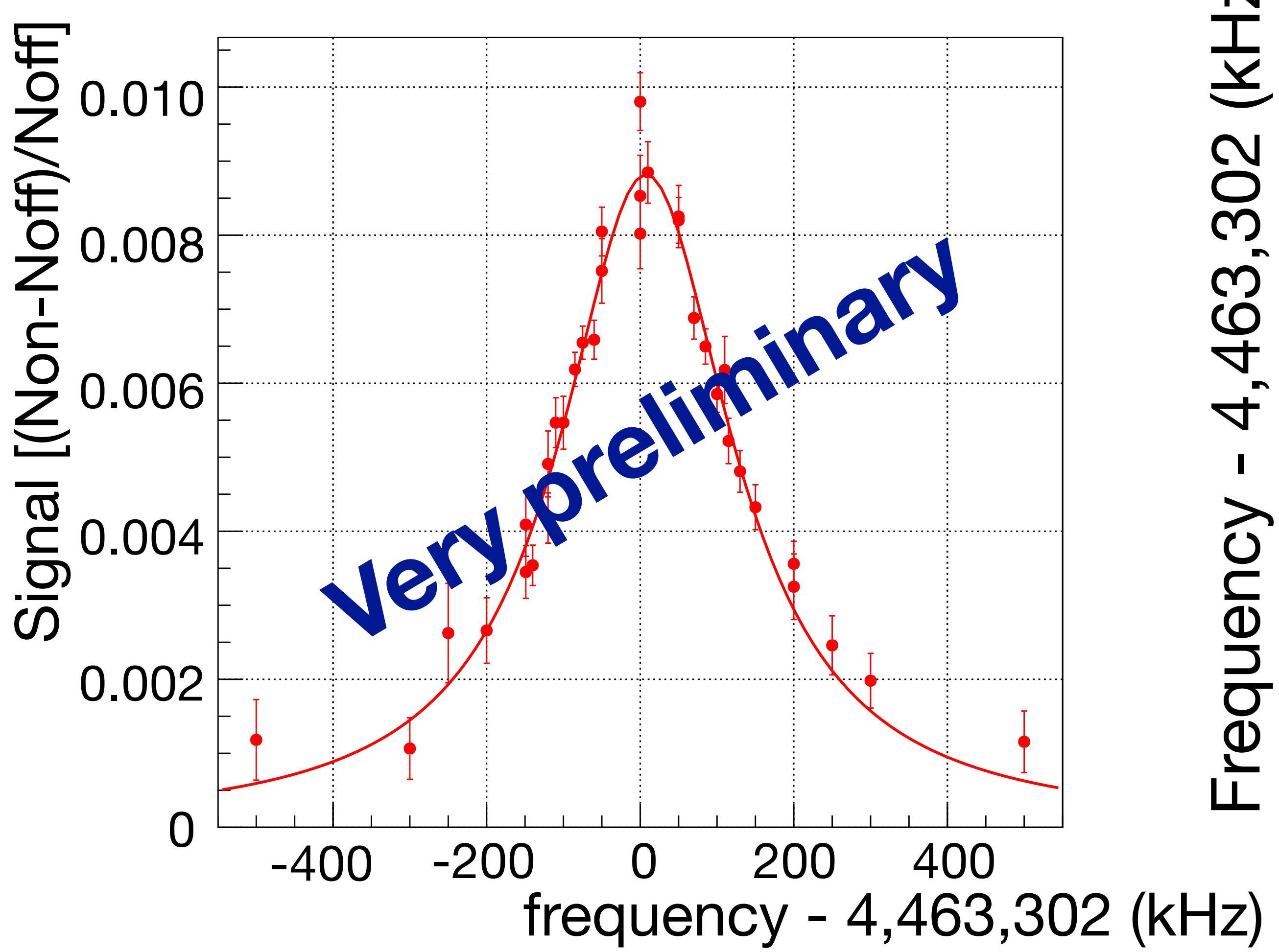
TABLE V. Values of the fractional pressure shift f_p for all five systems at 273 °K.

System	f_p (in 10^{-9}/ Torr) Short-range	Long-range	Total	Experiment
H-He[a]	2.130	− 0.952	1.178	4.80
H-He[b]	2.679	− 0.950	1.729	4.80
H-Ne	2.059	− 1.952	0.107	2.88
H-Ar	4.556	− 7.827	−3.081	−4.77
H-Kr	7.525	−11.842	−4.317	−10.40
H-Xe	10.922	−17.560	−6.638	−20.00

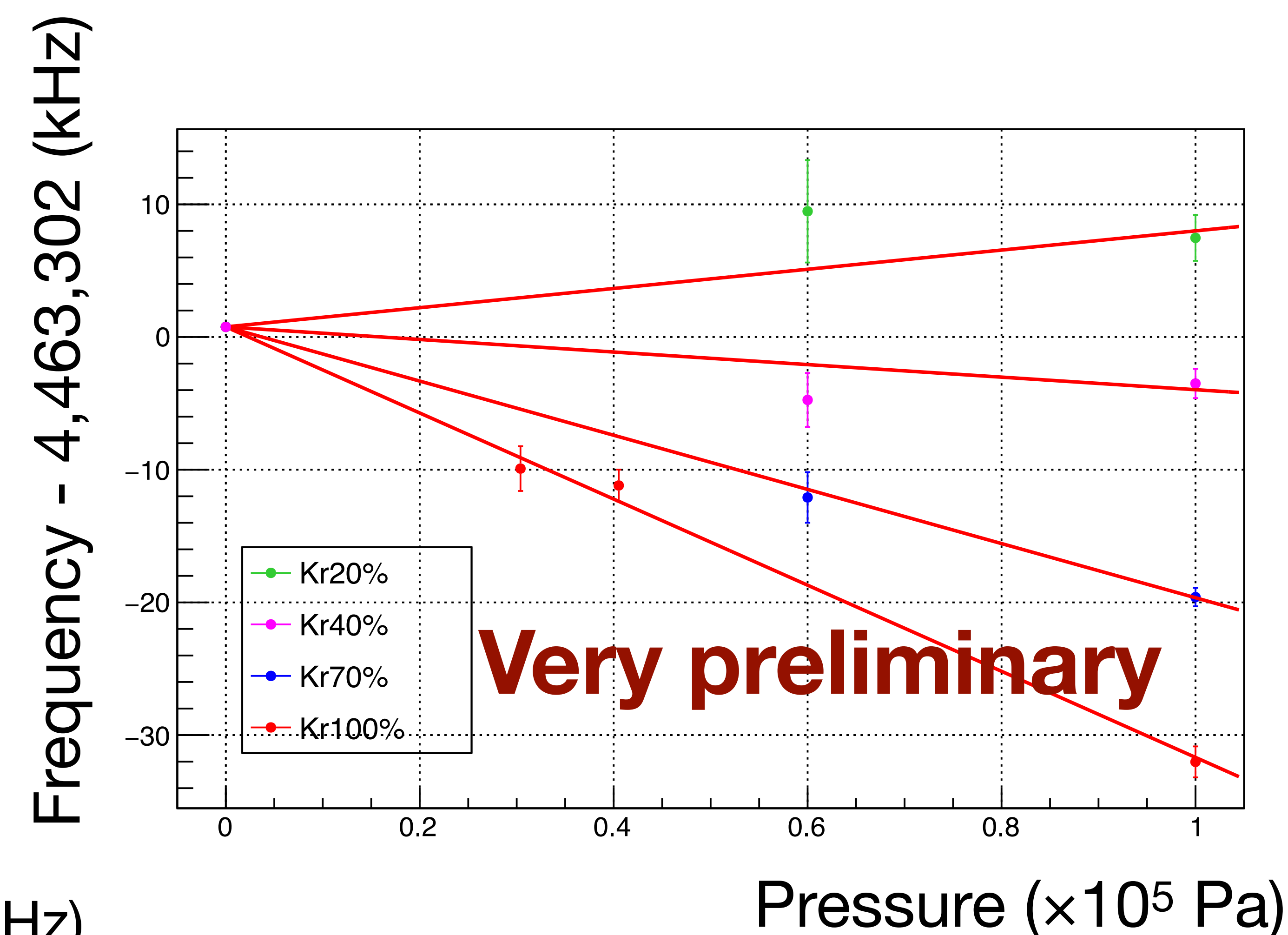
- **He-Kr mixture gas can reduce the collisional shift**
- From Hydrogen HFS, Kr:He=4.8:10.4=Kr32% is ideal

Beam time in Mar & June 2019

- Used mixture gas Kr-He to suppress the extrapolation uncertainty
- Confirmed Mu formation in Kr-He gas, and observed MuHFS resonance



resonance with Kr 20% gas at 1.0 atm



Work by S. Seo (Univ. of Tokyo)

Systematic Uncertainties for High Field

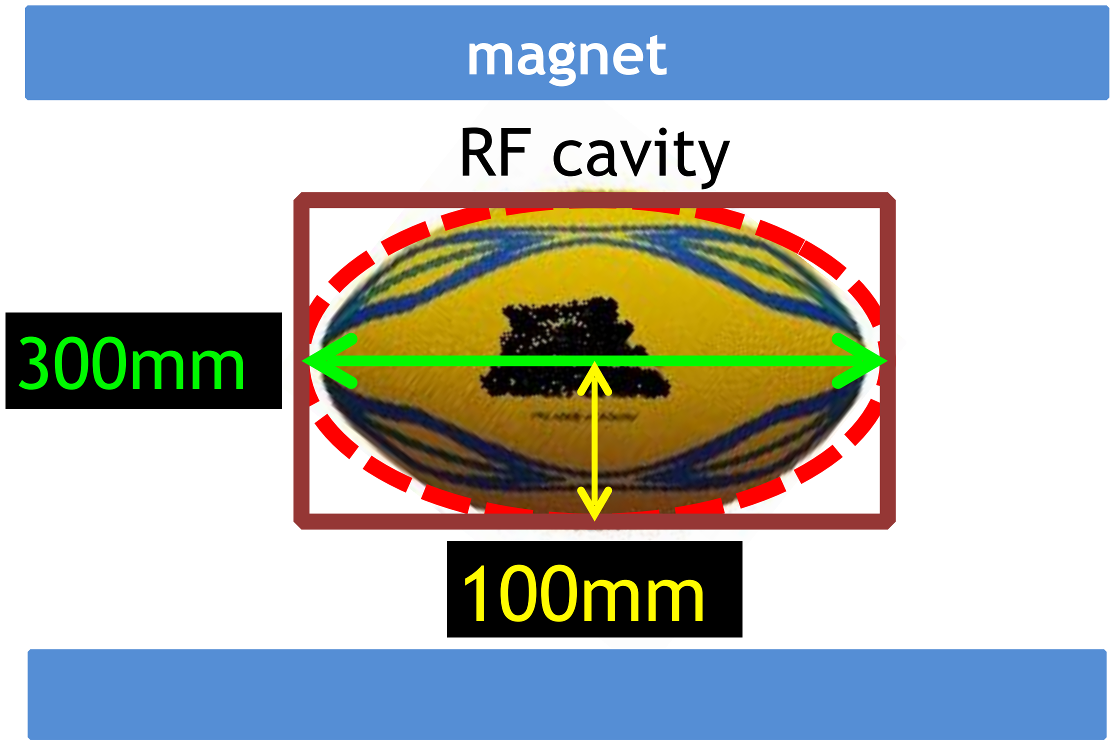
	specification	Δν	μ_μ/μ_p
B field		0	26 ppb
RF stability	0.02%	0.8 ppb	8 ppb
Collision with Kr		1.0 ppb	5 ppb
Kr Temperature	0.2 K	0.4 ppb	4 ppb
Detector pile up		< 0.5 ppb	3 ppb
Others		< 0.8 ppb	7 ppb
Overall		**< 1.6 ppb (8 Hz)**	**29 ppb**

Superconducting Magnet for 1.7 T Field

- Time stability: **3 ppb/hour** over 10 days period (required stability 100 ppb/h)

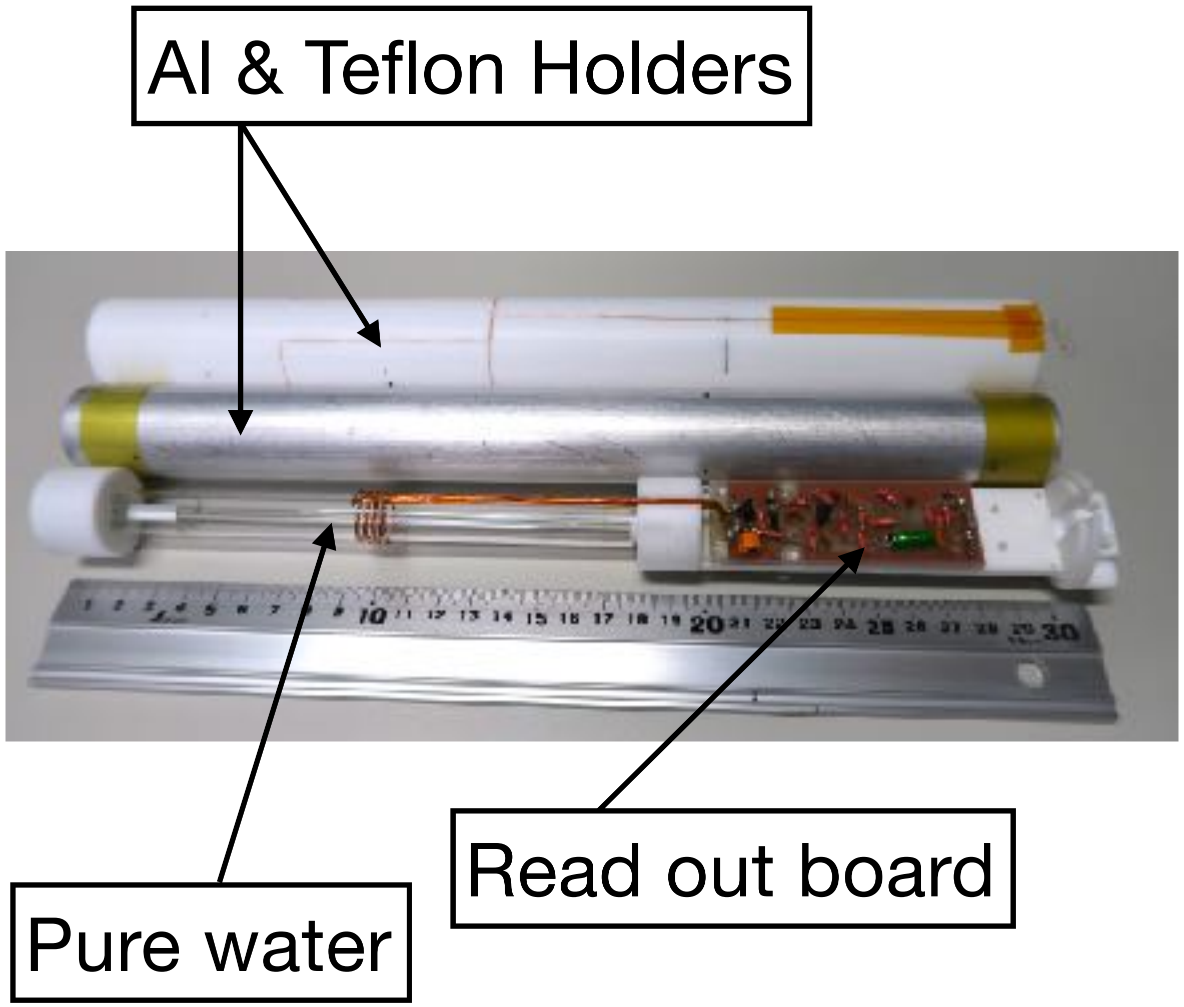
By K. Sasaki and M. Abe (KEK)

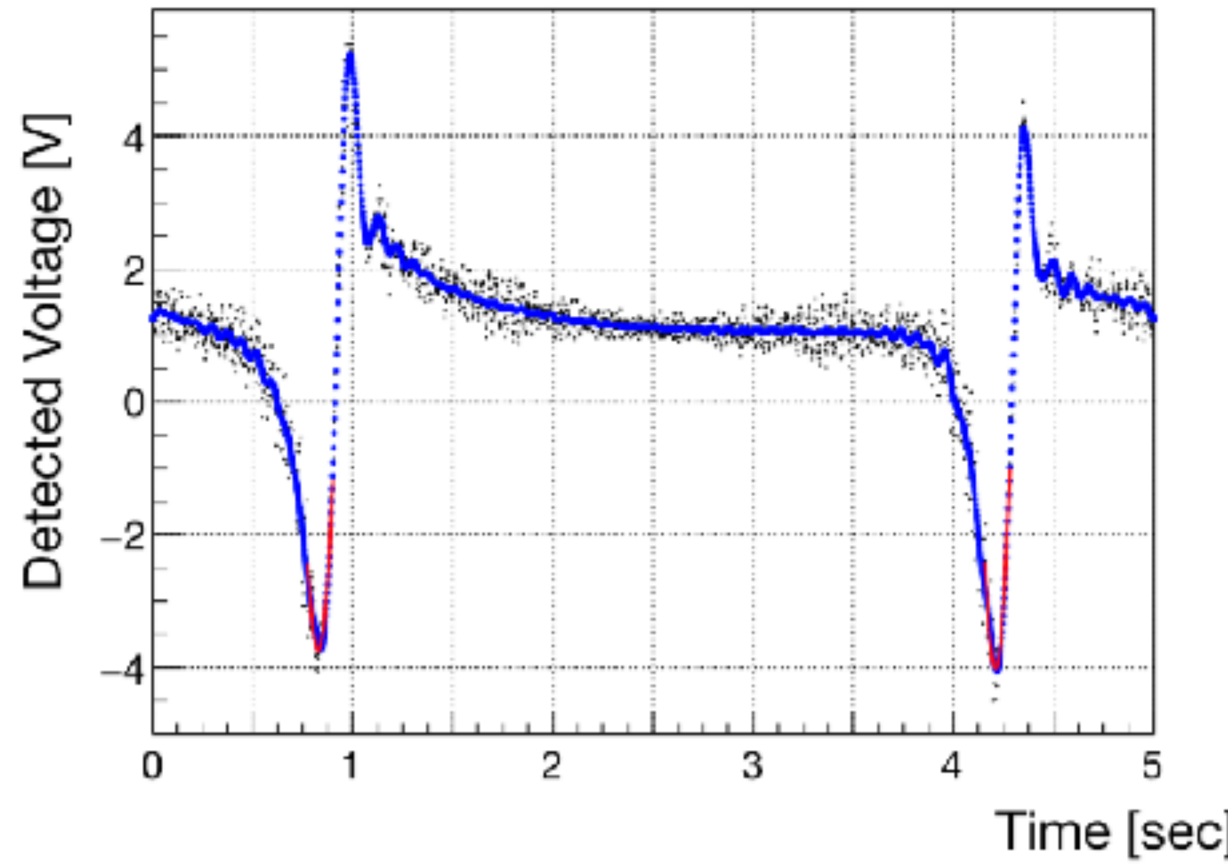
- Required uniformity is 1 ppm in a rugby-ball sized volume by shimming we achieved **0.3 ppm**



NMR Magnetometer

Work by K. Sasaki, H. Yamaguchi (KEK) and T. Tanaka (Univ. of Tokyo)

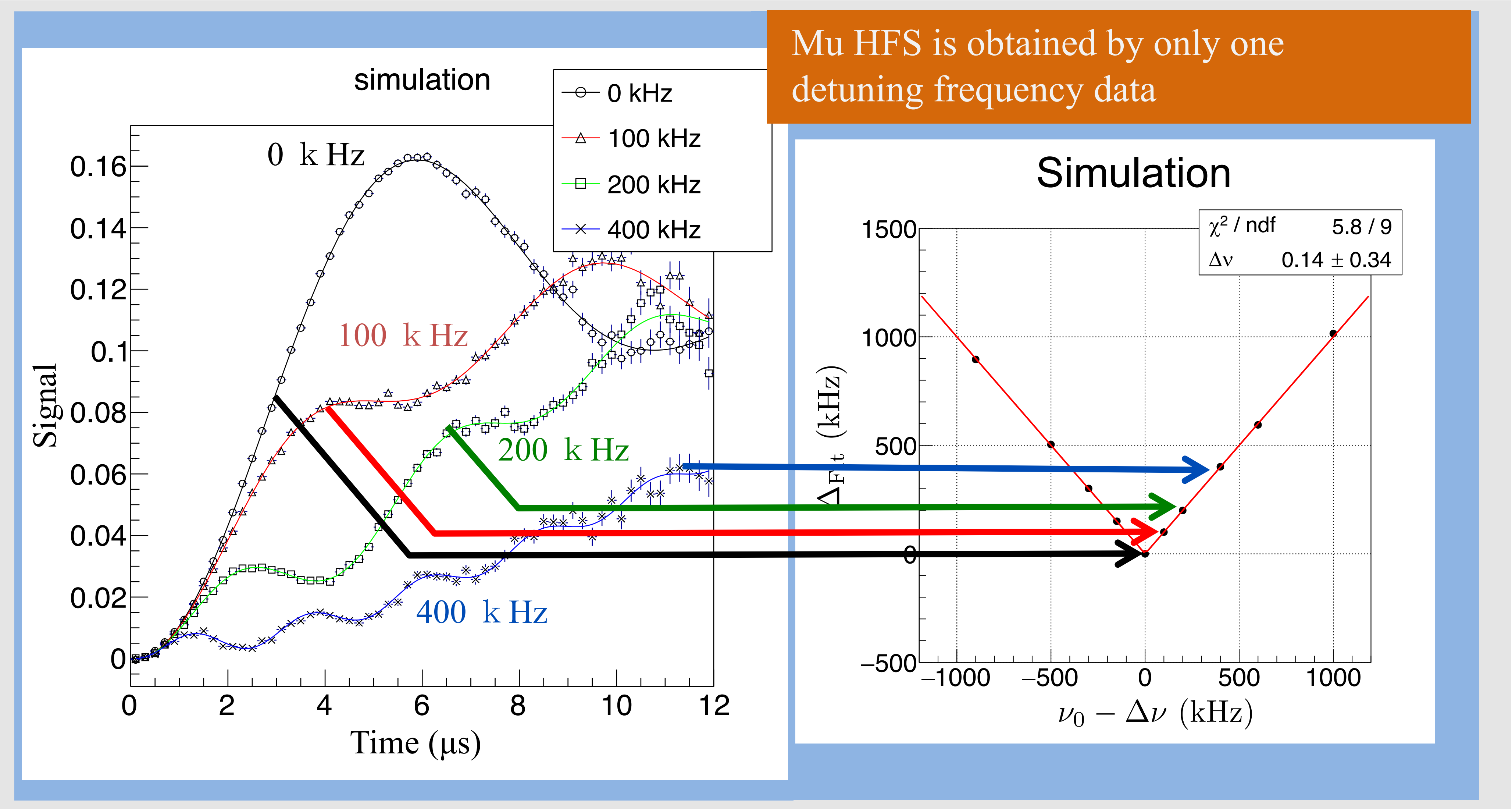




- Proton NMR (Nuclear Magnetic Resonance) in pure water
- Cross-check measurement at 1.45 and 1.7 T with NMR probes used in Fermilab muon *g*-2 experiment
- Progress in the precision: 18 ppb (2017) → **12 ppb** (2019)

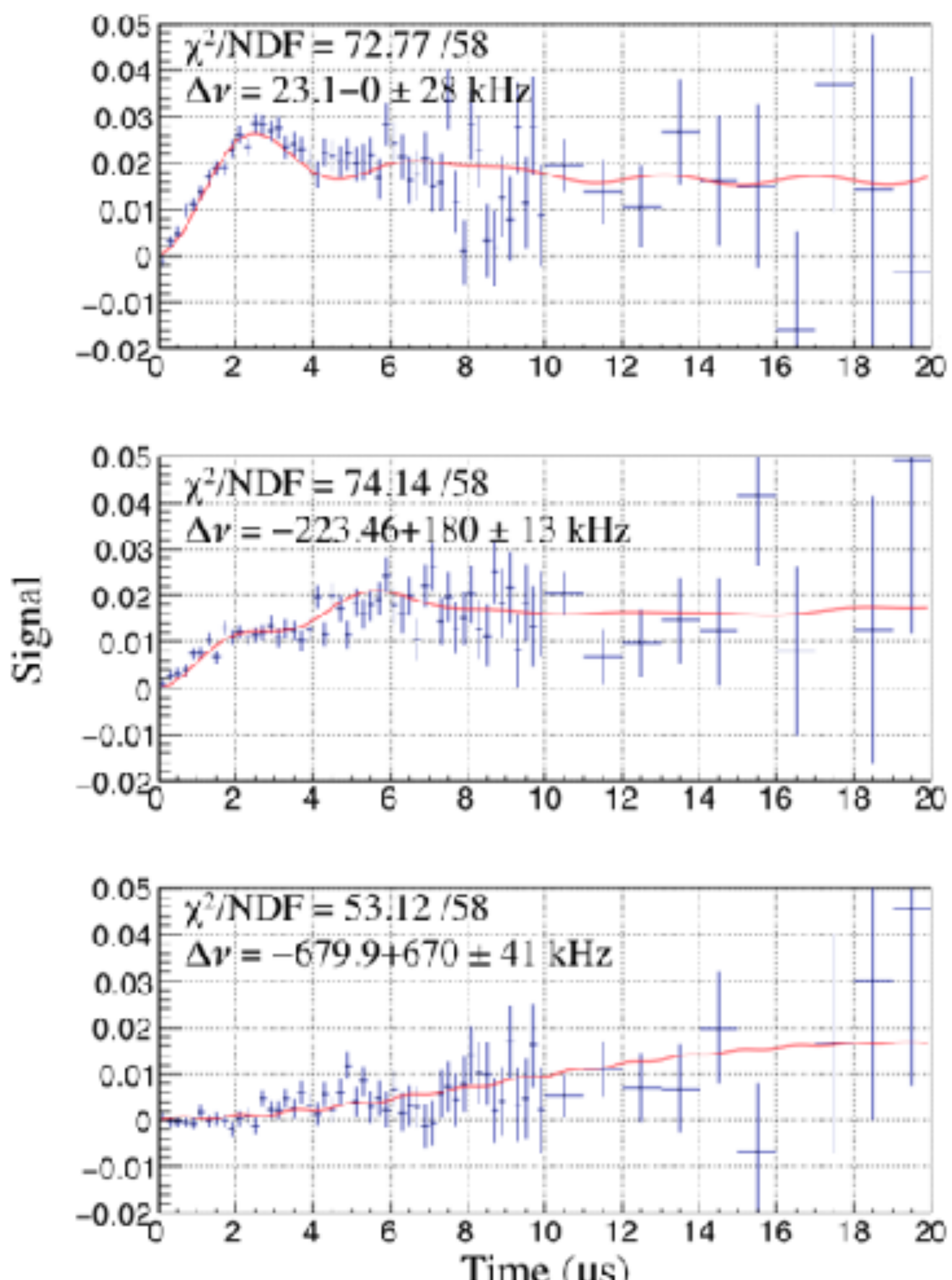
Time Differential Method: Simulation

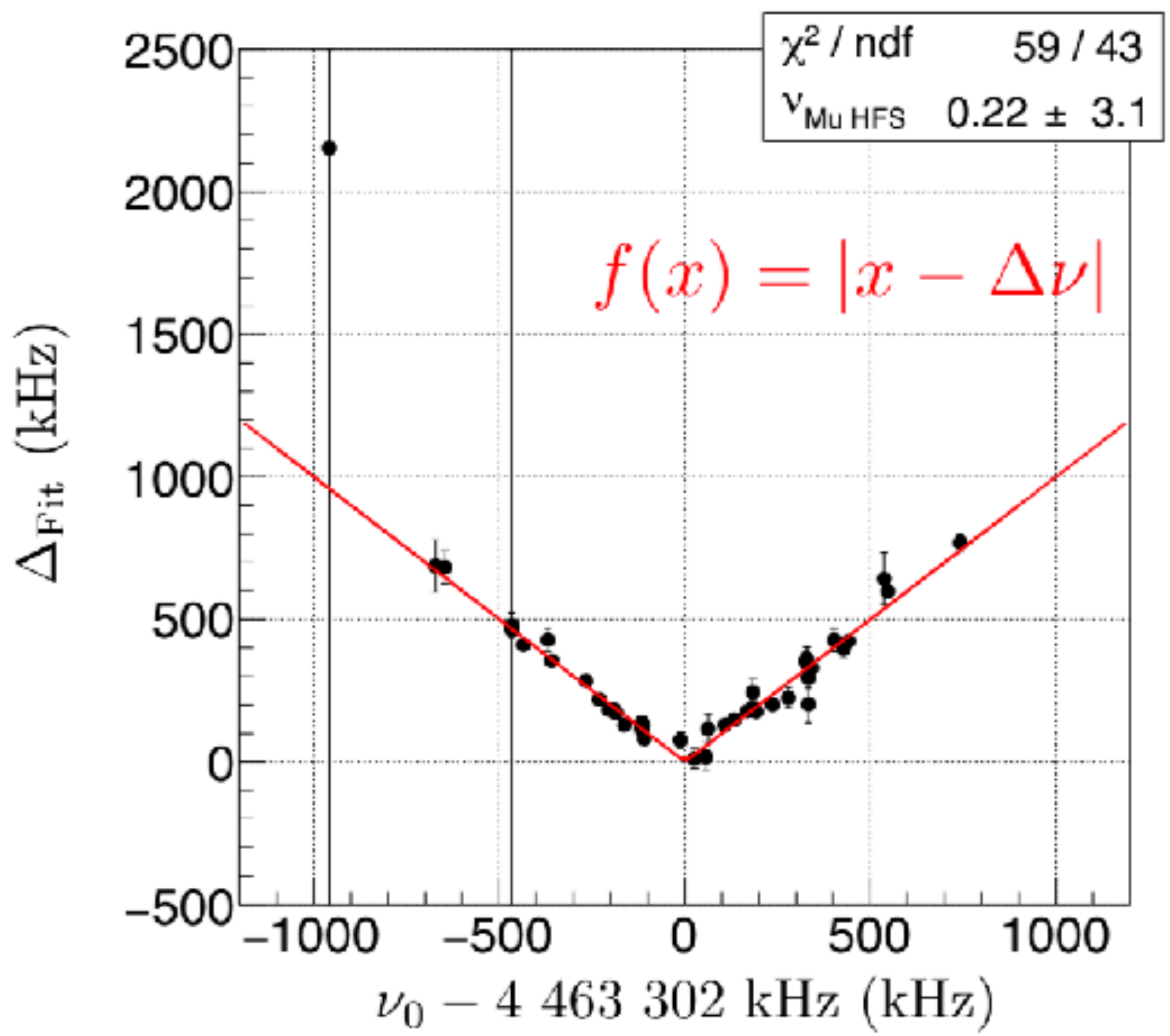
- MuHFS determined by fitting the time-dependent signal of muon spin flip (Rabi oscillation)
- No need to take data at many microwave frequency points
  a method immune to the systematic uncertainty from the microwave power dependence on frequency



Time Differential Method: data in 2017

- First result obtained by time differential method *By S. Nishimura (KEK)*
- Promising method to improve the precision

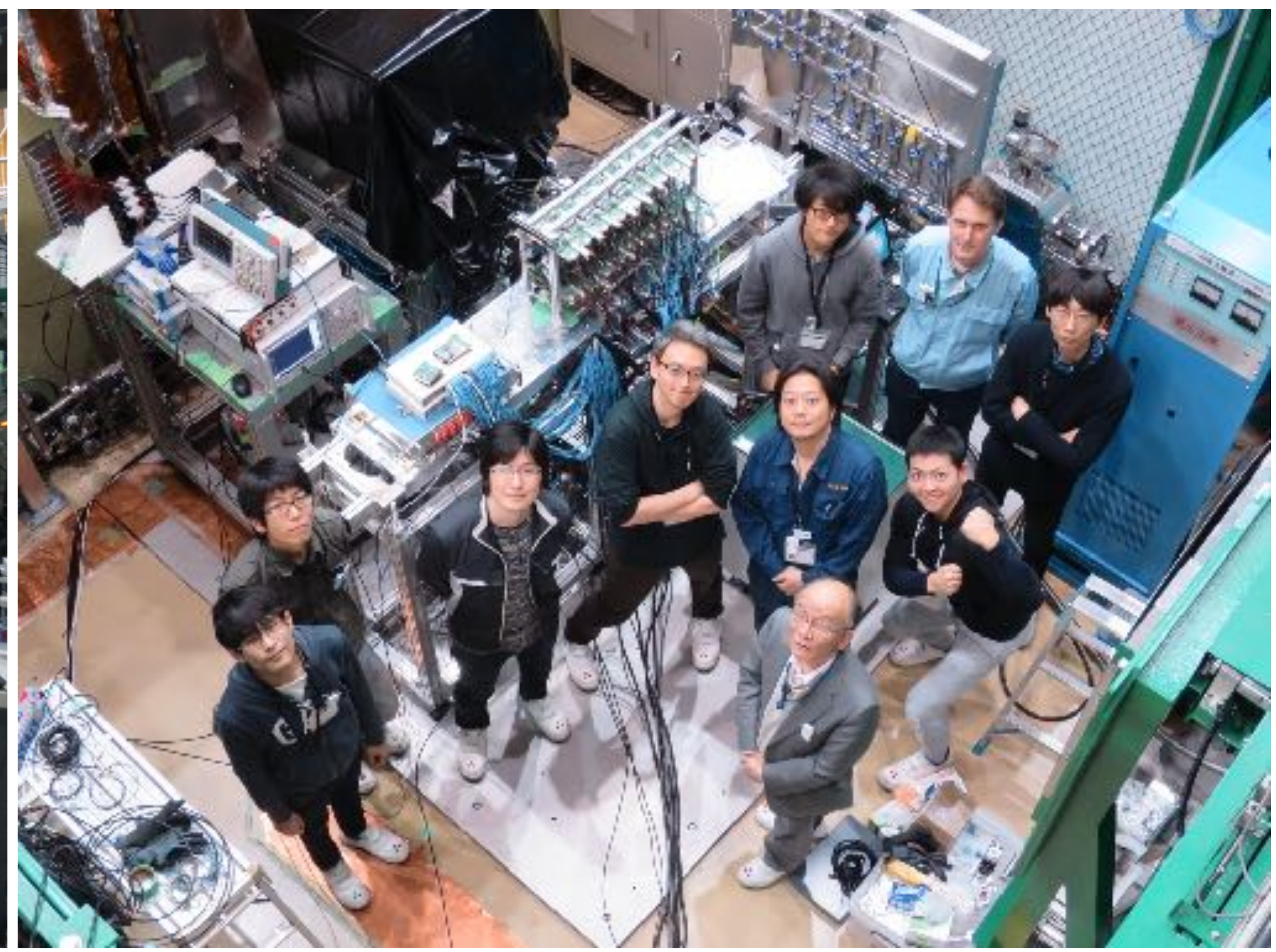




Summary and Prospect

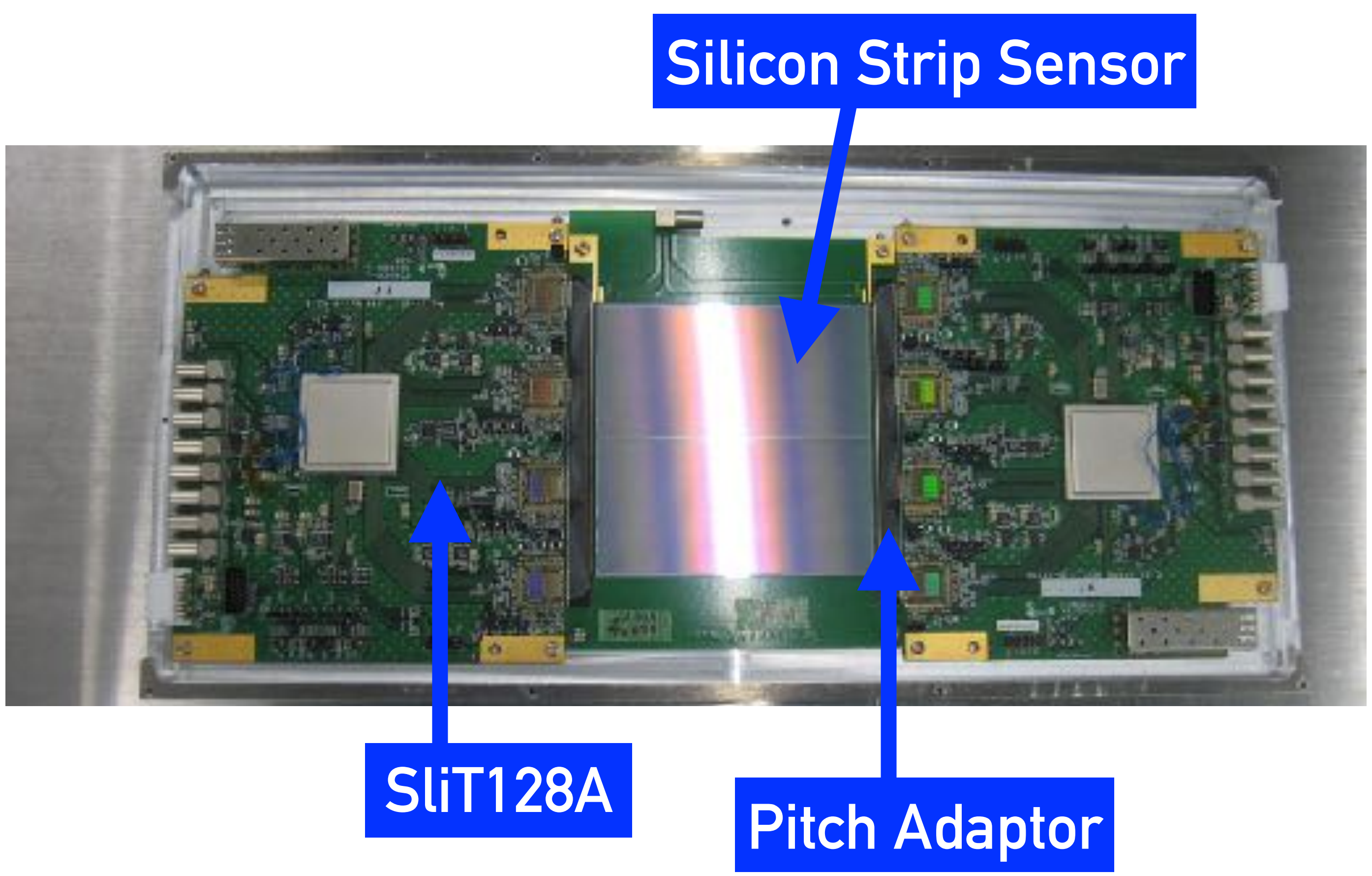
- MuSEUM
  Test of the bound-state QED
  Determination of muon magnetic moment
  -synergy with muon g-2
- Recent measurement with lower Kr gas pressures at low B field consistent with theory and the precursor experiment
- R&D for future experiment
  First measurement using Kr-He mixture gas
  Magnet and magnetometer development for high field measurement
  First analysis using time differential method
- MuHFS 2 ppb, μ_μ/μ_p 30 ppb is achievable
  (a factor of 10 improvements from the precursor experiment)
  Further improvement is in progress

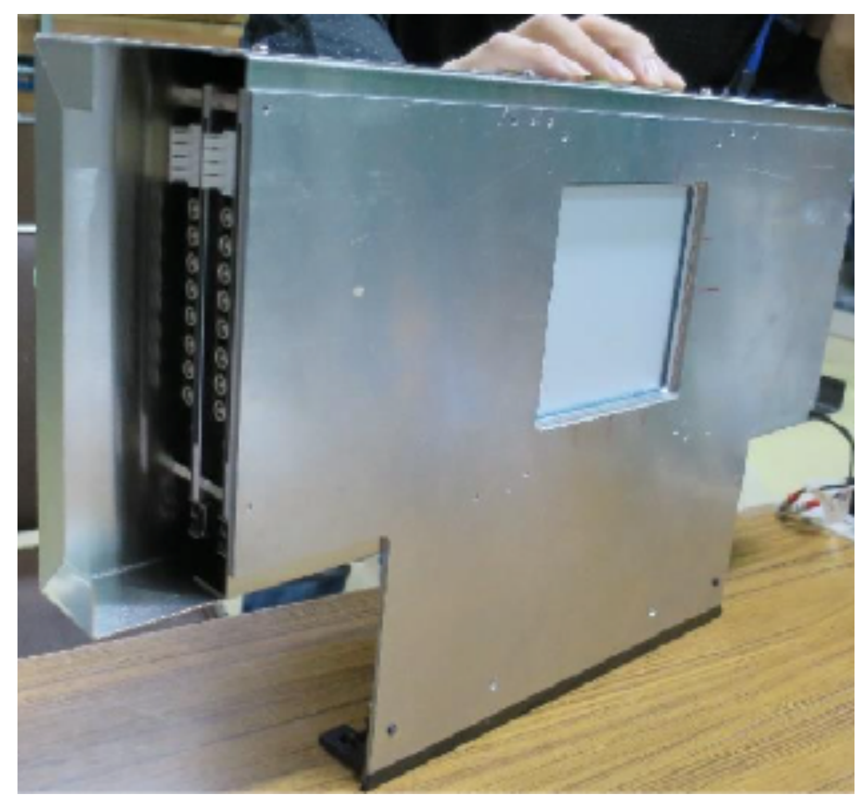
Thank you!



Silicon Strip Sensor

- Developped for muon *g*-2 J-PARC experiment
- Capable of high-rate counting; R&D for H-Line measurement in future
- There was stray magnetic field from the detector board; made a permalloy shiled for the detector
- Performed satisfactory in beam time on June 2019





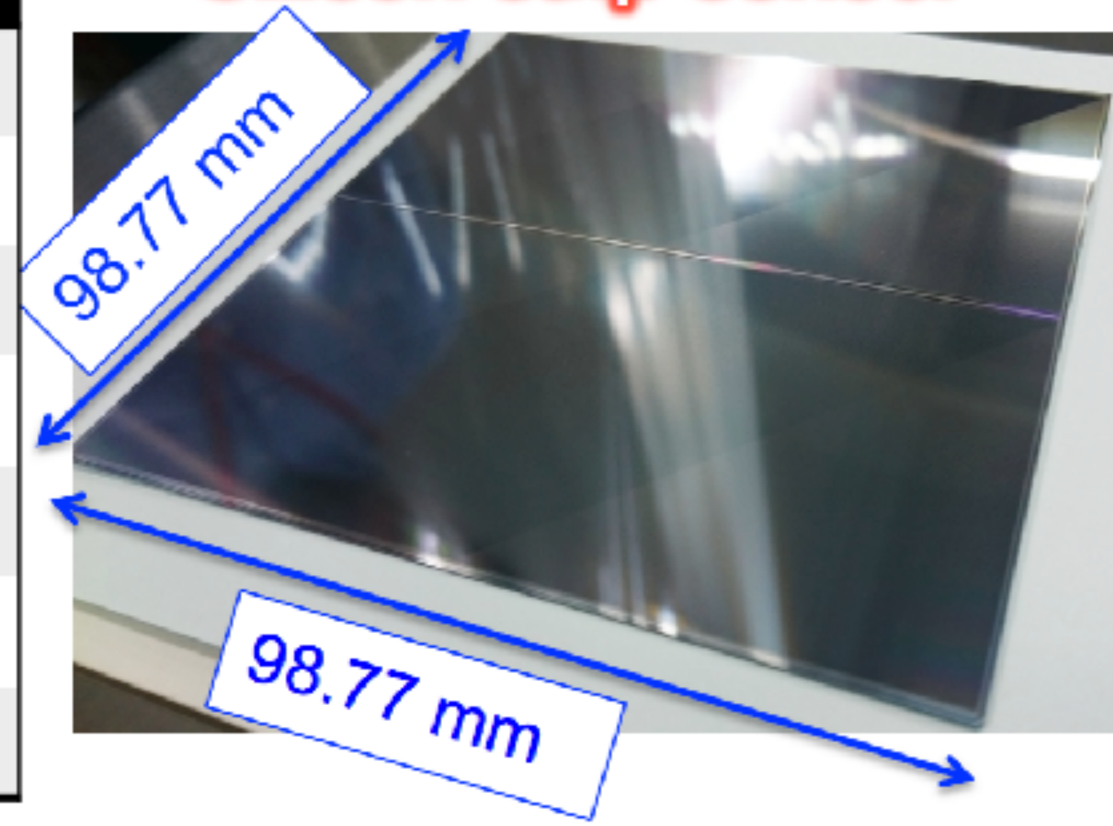
Uncertainty in Weak Field Measurement

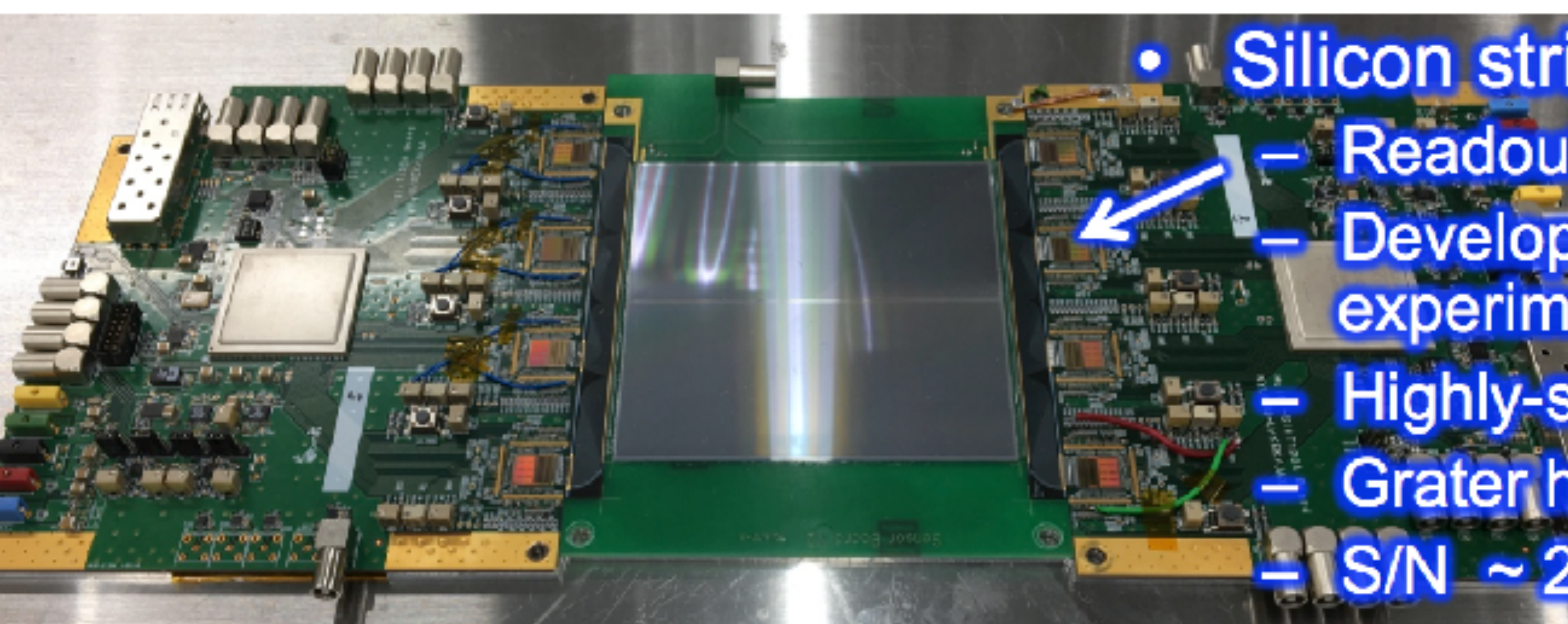
Contribution	Uncertainty [Hz]	in future [Hz]
Pressure Gauge	79	8
Pressure Fluctuation	24	2
Quadratic Term	(2)	0
Frequency Reference	45	<1
Power Drift	60	1
Muon Beam	6	6
Others	< 1	<1
Total	112	10

Silicon Strip Detector

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
# of strips	512 × 2 blocks
Thickness	0.32 mm

Silicon strip sensor





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

Microwave Cavity and System

Signal Generator

↓

Amplifier

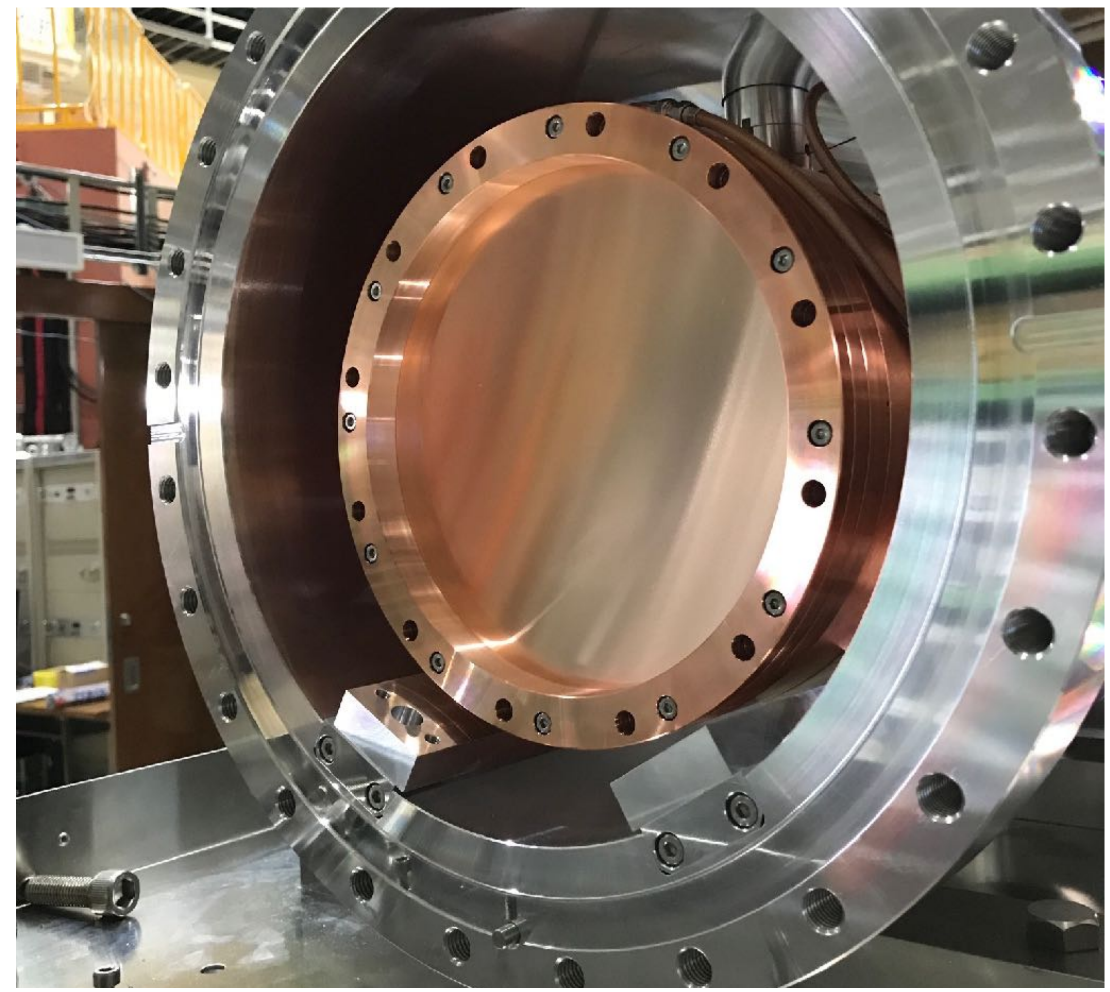
↓

cables & feedthrough → input

↓ -30 dB

Power monitor 1

Cavity



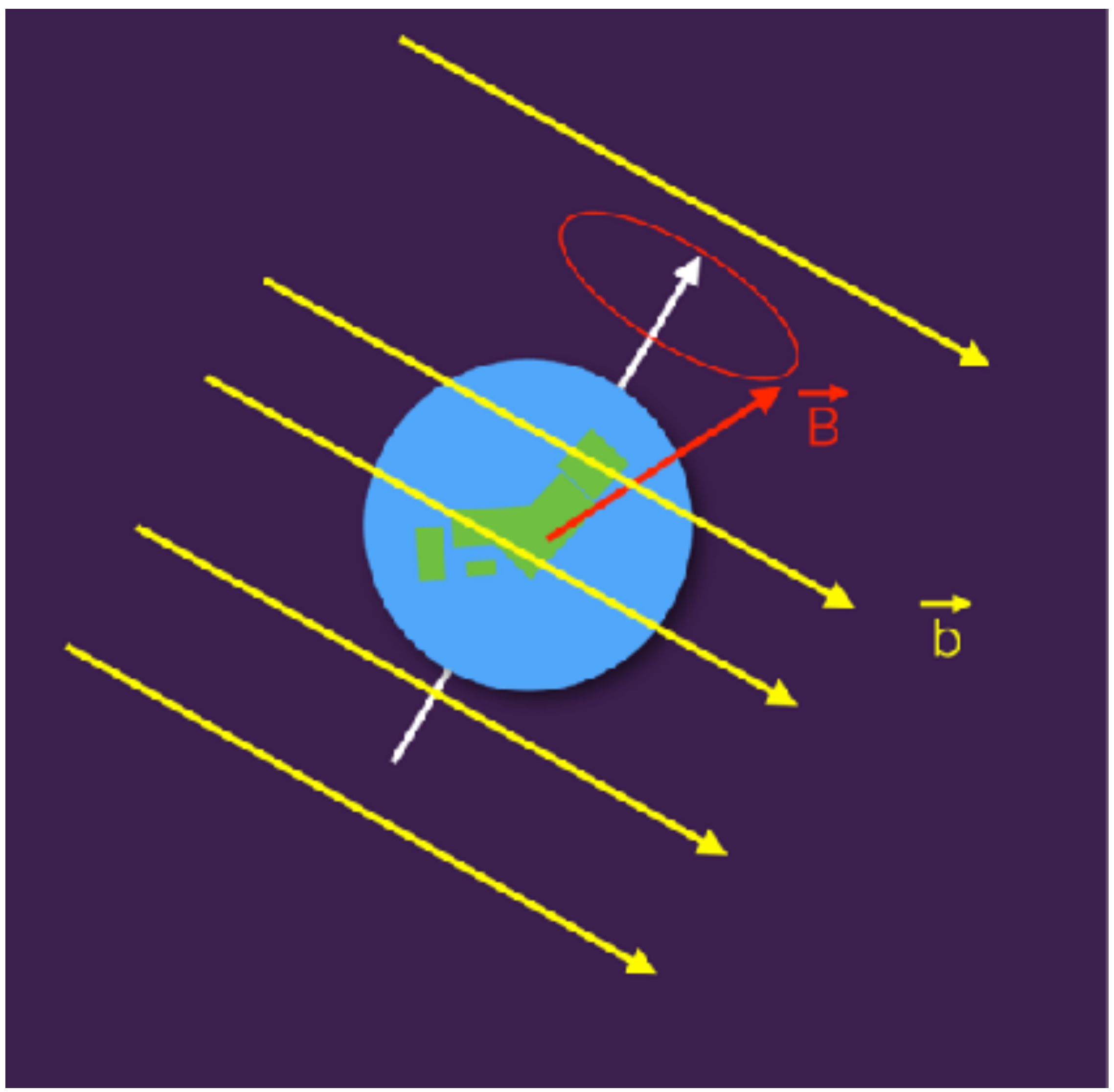
↓ pick up

Power monitor 2

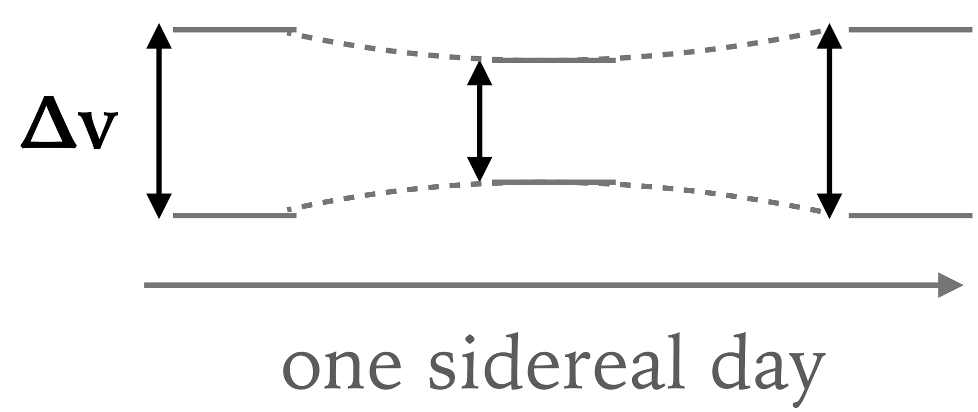
- TM220 mode cavity, Q =10000
- Typical input power: 1 W
- Power stability is monitored

Lorentz (CPT) Invariance

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

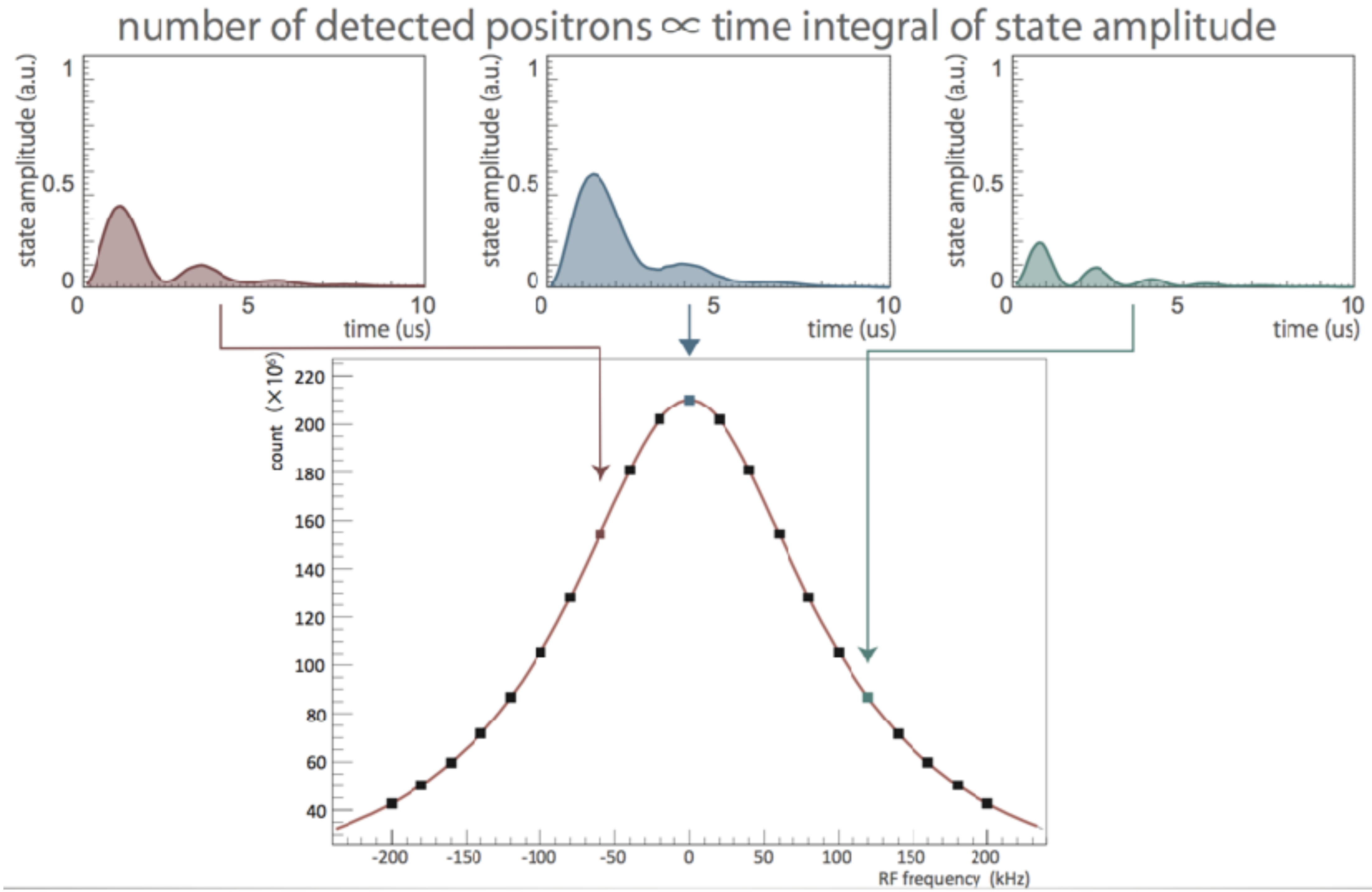


A. H. Gomes, V. A. Kostelecky and A. J. Vargas, PRD **90** 076009 (2014)



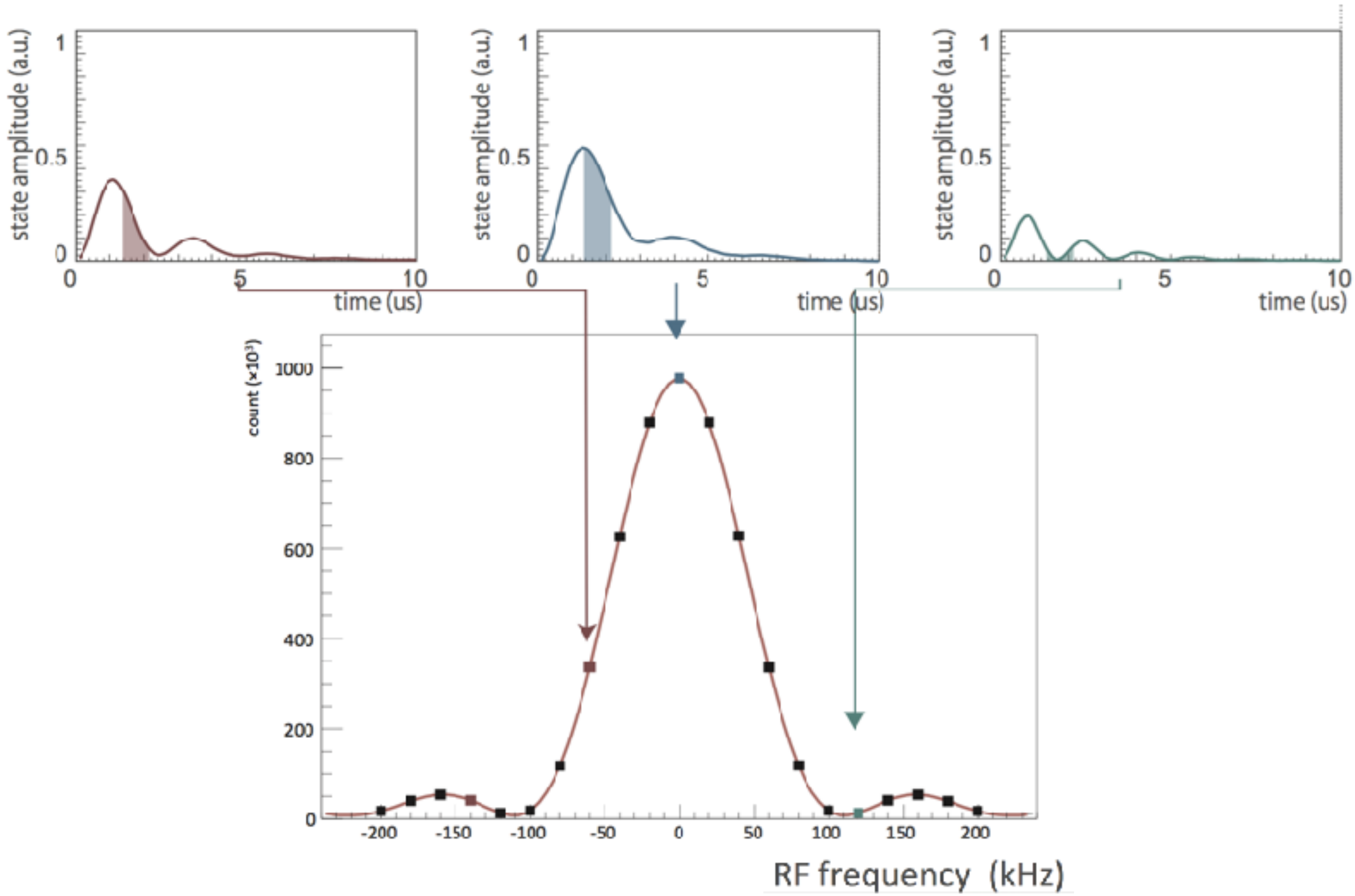
Conventional Method

- Integrate all the signal



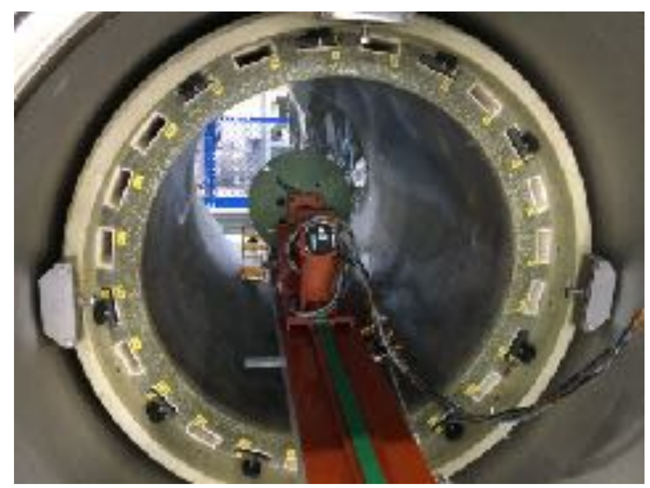
Old Muonium Method

➤ Line narrowing technique by the analysis using signals from a delayed time window; Long life time hence narrow natural width.



Passive Shimming Technique

- Required field uniformity: 1 ppm
- In addition to shiming coil, shimming by small iron plates is important
- The positions of the iron plates can be caluculated by the Singular Value Decomposition Method



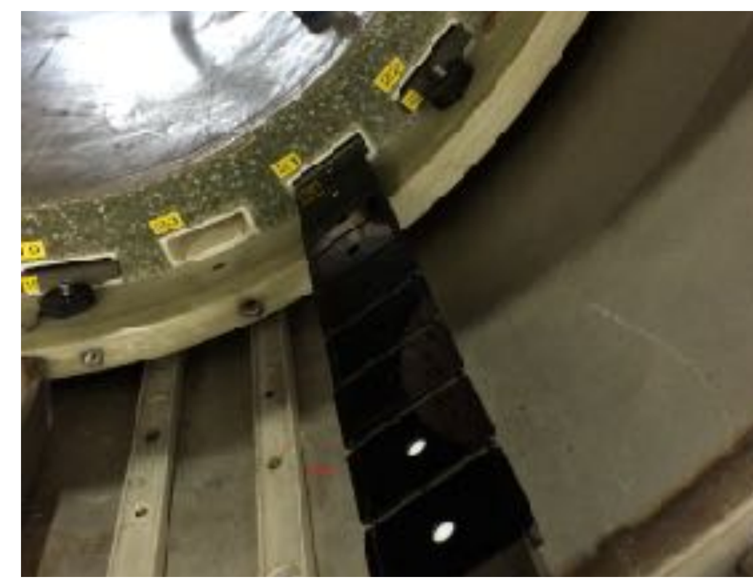
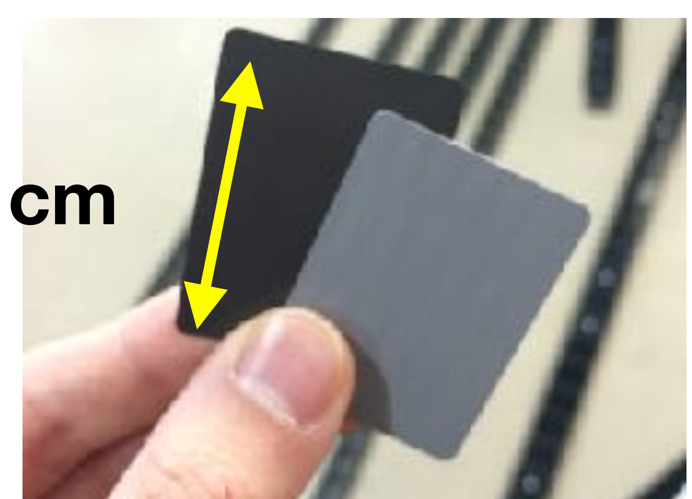


Plate Volume:

Thick: 0.325 cc

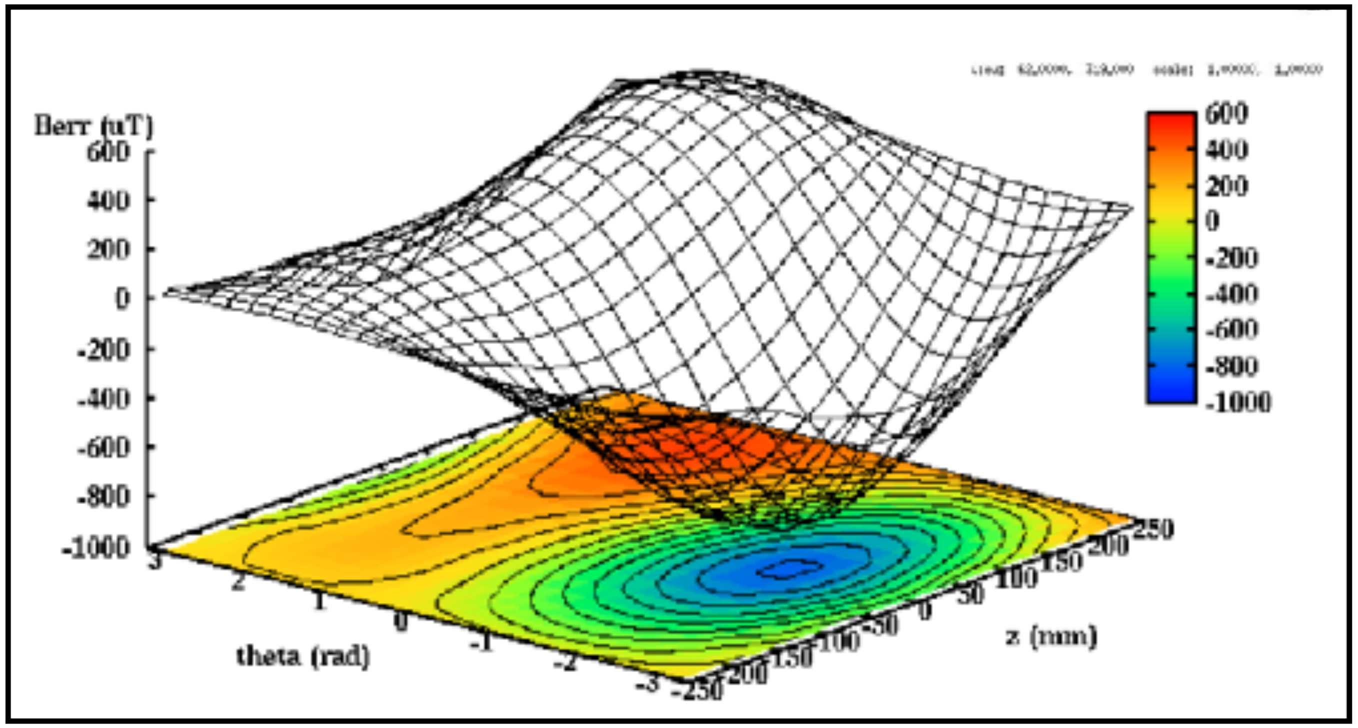
Thin: 0.065 cc



3 cm

Shimming

Peak-to-peak: 1000 ppm

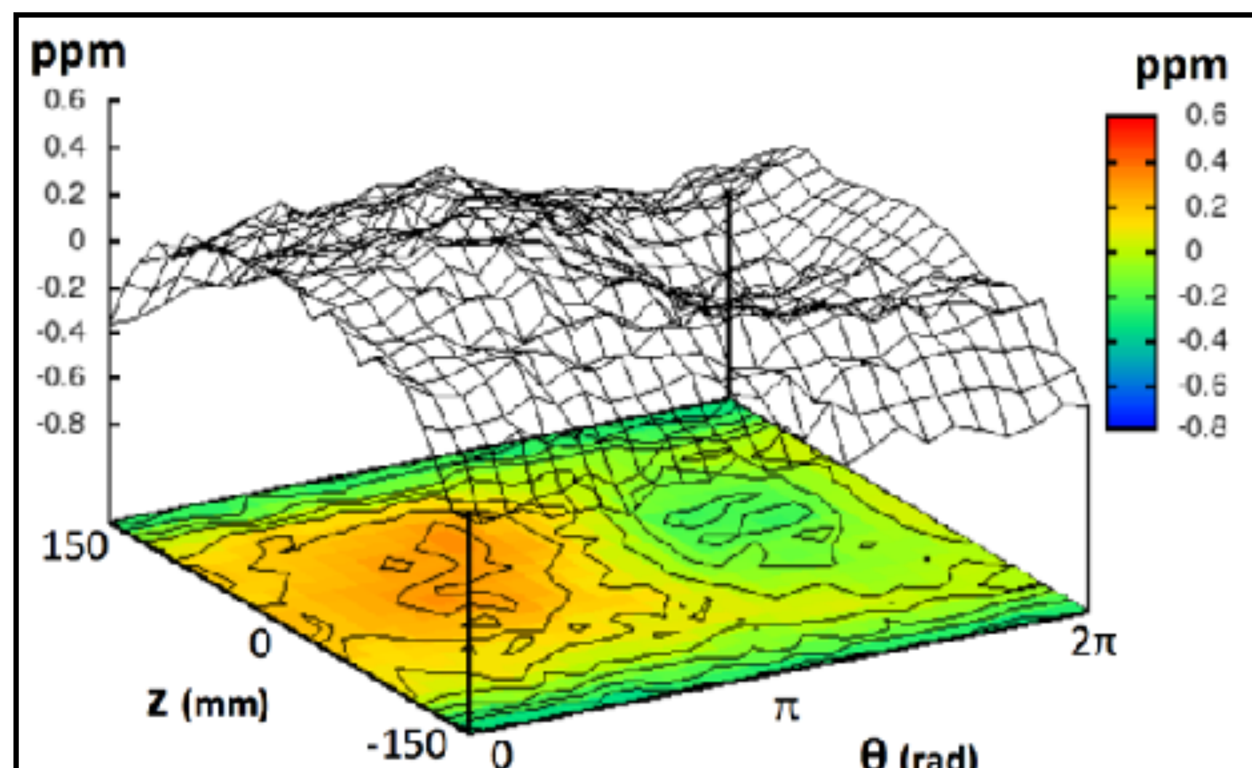


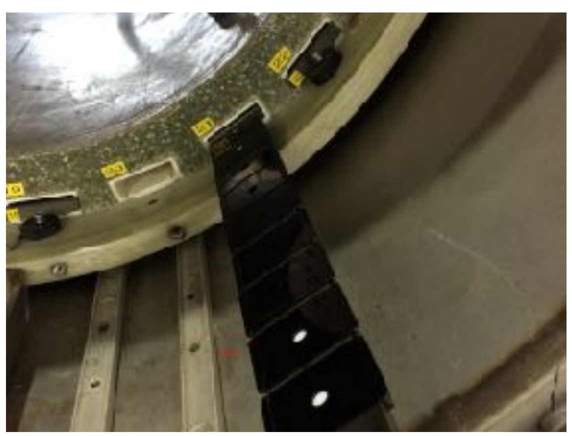
Field uniformity is improved by shimming using iron-plate

We have succeeded in obtaining required uniforimity

< 1 ppm

Peak-to-peak: 0.80 ppm





3 cm

Shimming

- By iron-plate shimming, uniformity 1000 ppm → 0.8 ppm

(required uniformity: 1 ppm)