

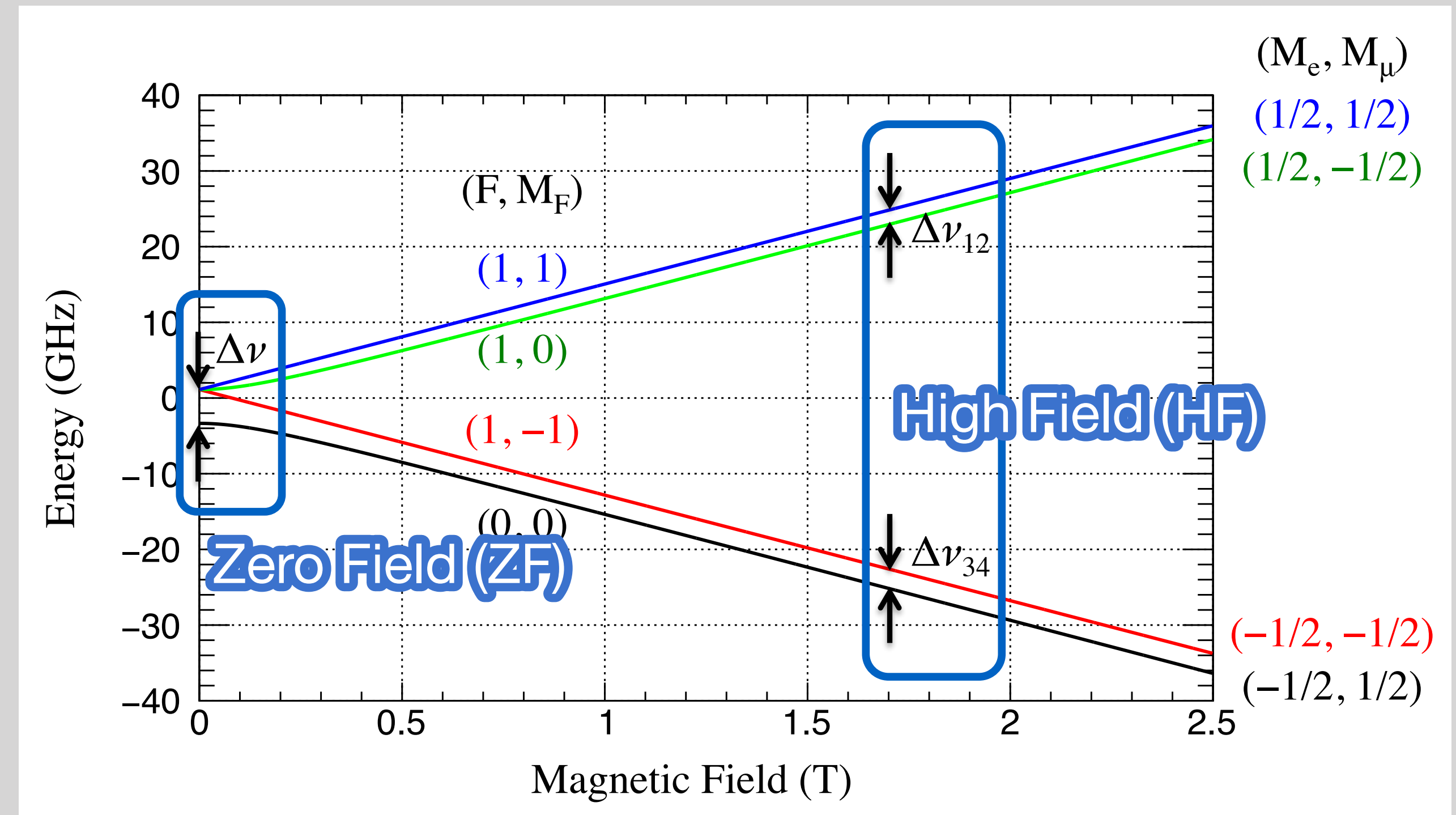
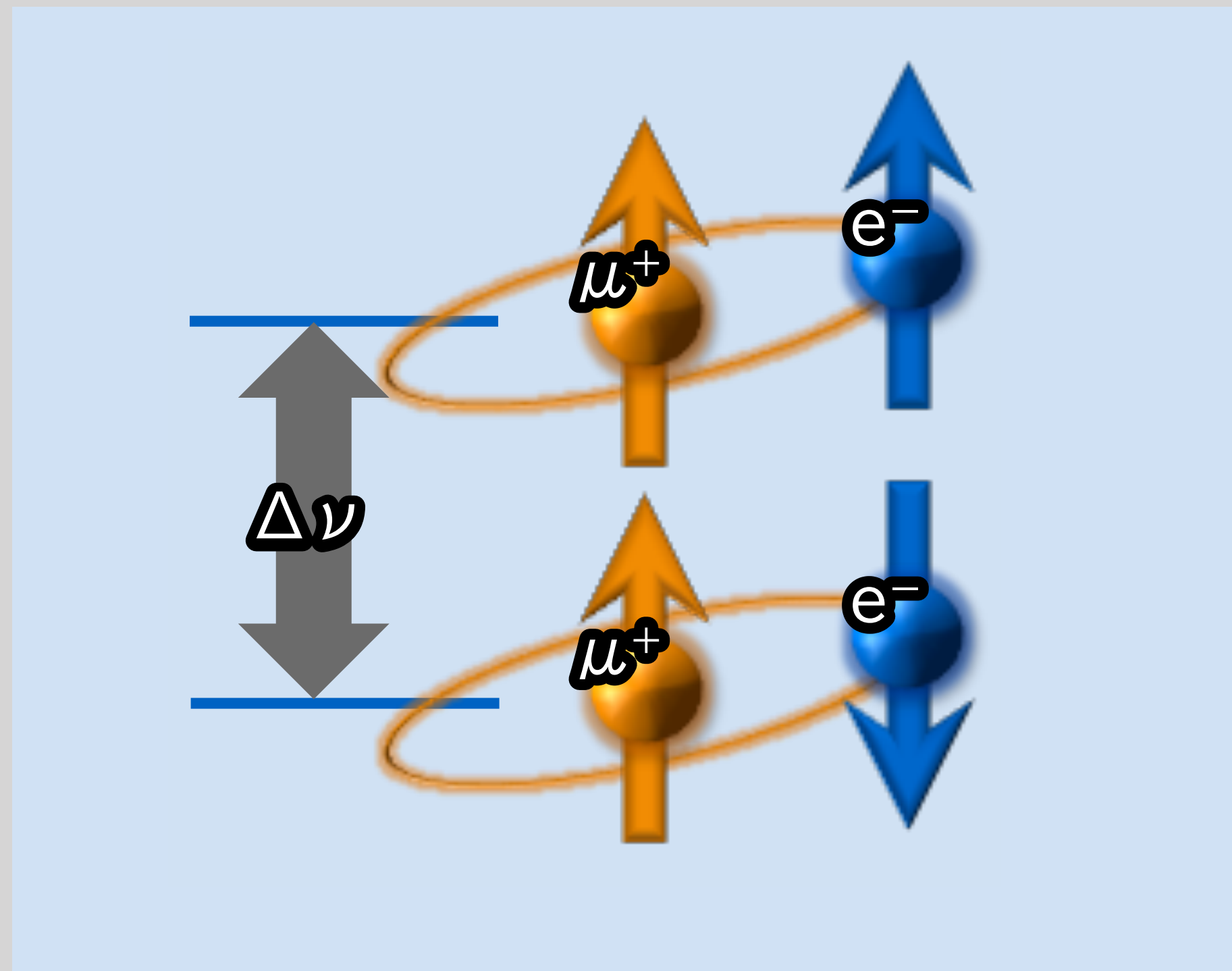
Precise Spectroscopy of Muonium Hyperfine Structure in High Magnetic Field

2026/05/18

**S. Nishimura | KEK IMSS
(MuSEUM Collaboration)**

Muonium Hyperfine Structure (Mu HFS)

Muonium | Bound state of muon & electron



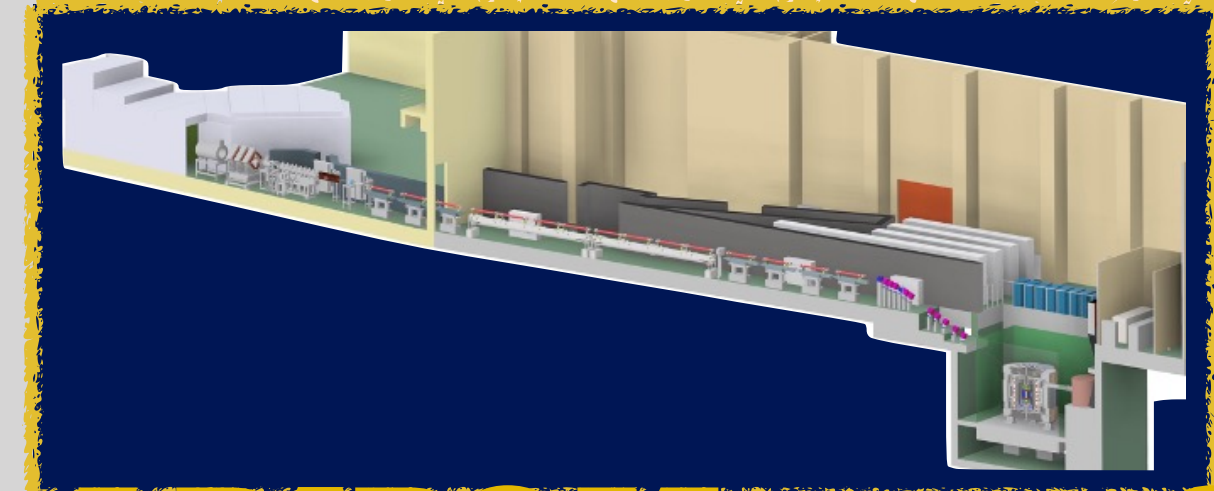
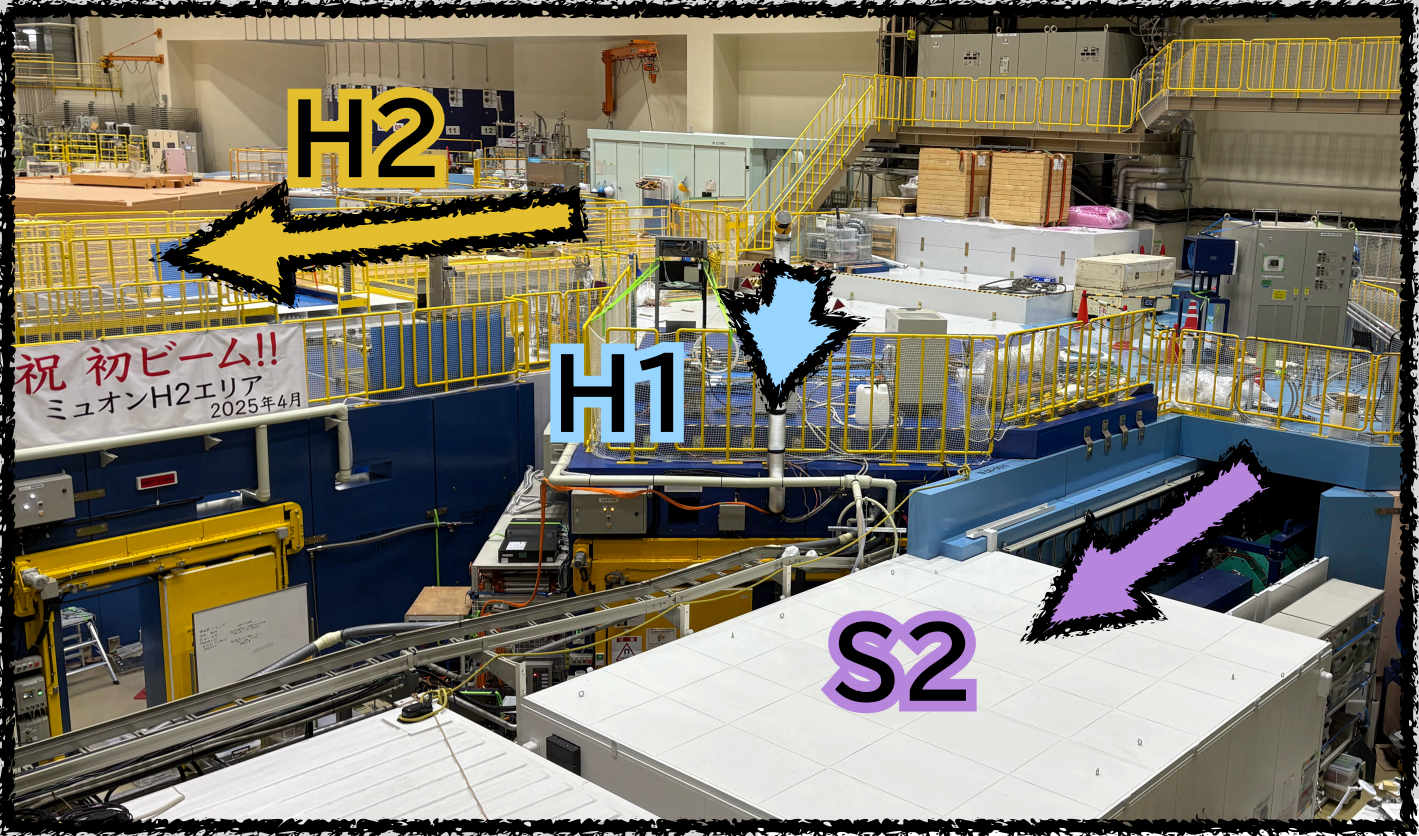
$\Delta \nu$ in previous experiment
 4 463 302.765(51)(17) kHz (12 ppb)
 Statistical uncertainty is dominant
 Phys. Rev. Lett. **82** (1999) 711-714

Target precision | ~1 ppb

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

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

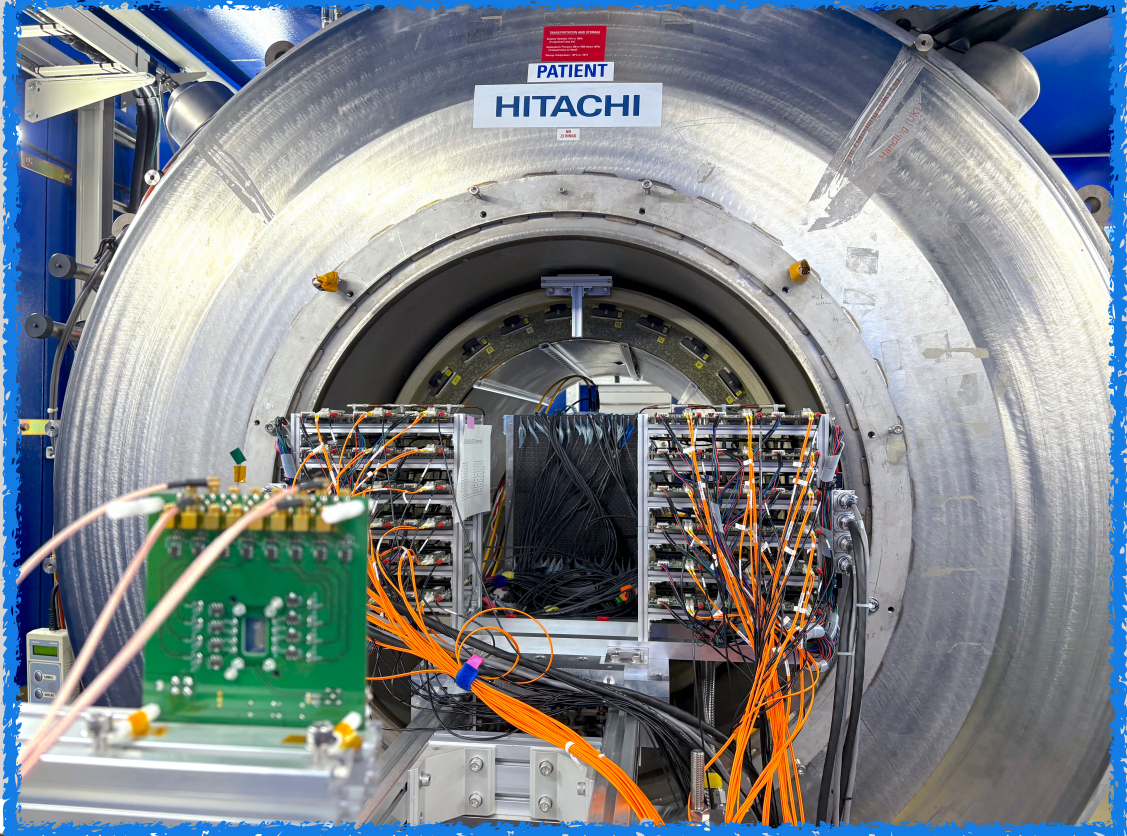
Jungmann's Triangle



J-PARC Muon g-2/EDM

Muonium HFS
 Muon magnetic moment μ_μ
 Fine-structure constant α

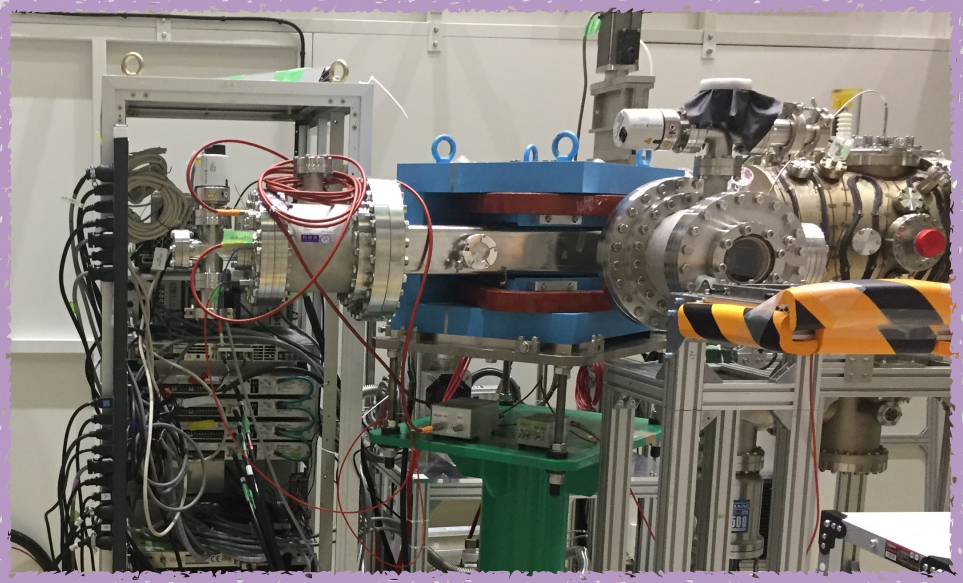
MuSEUM



Muon g-2
 New Physics beyond SM

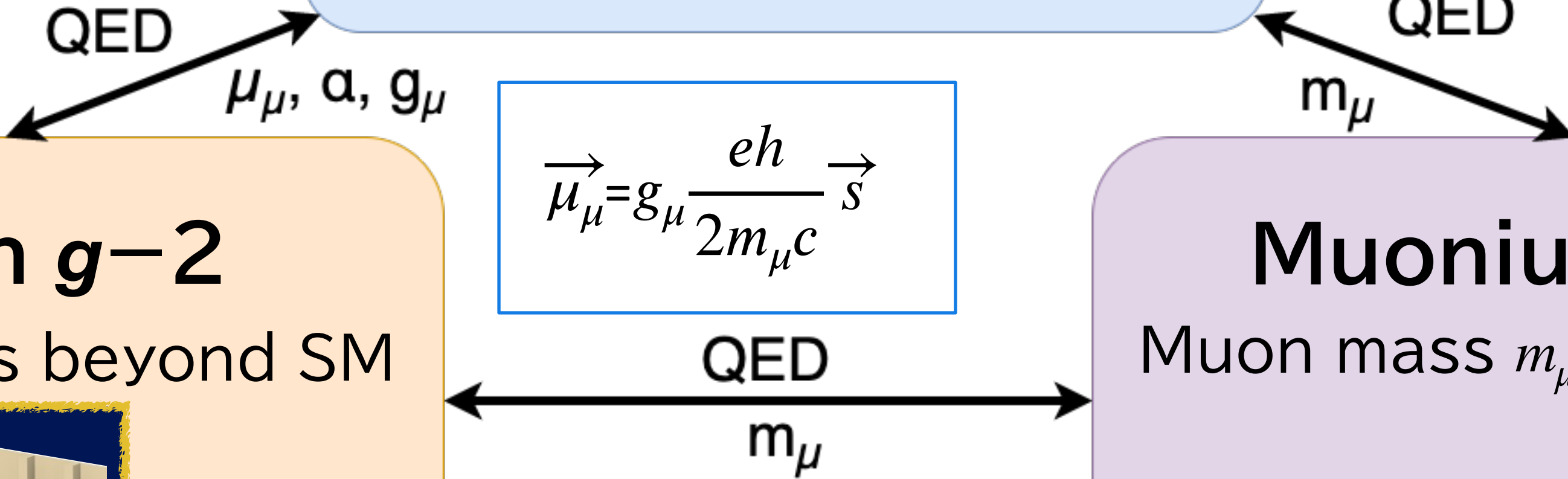
$$\vec{\mu}_\mu = g_\mu \frac{eh}{2m_\mu c} \vec{s}$$

Muonium 1s-2s
 Muon mass m_μ

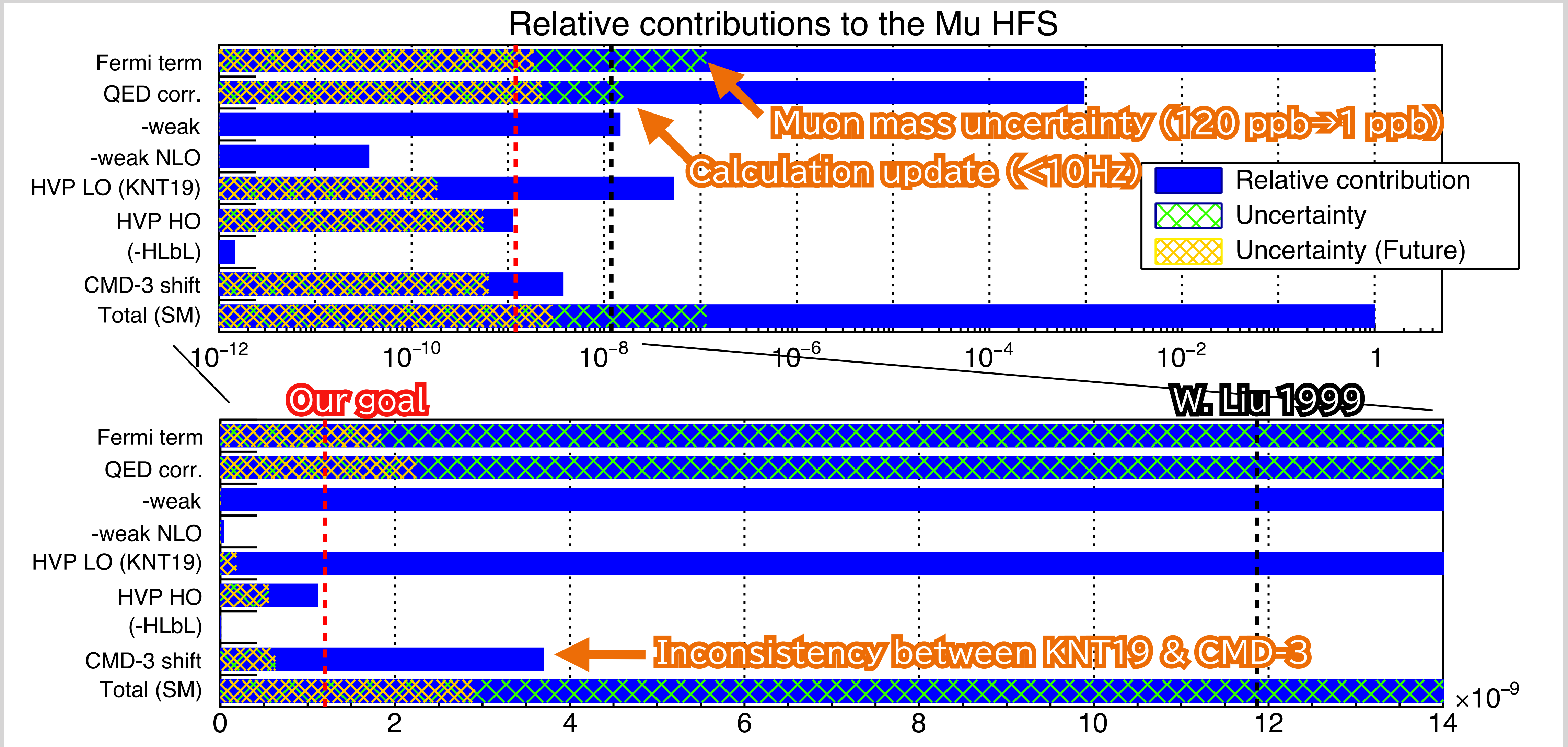


Mu-MASS

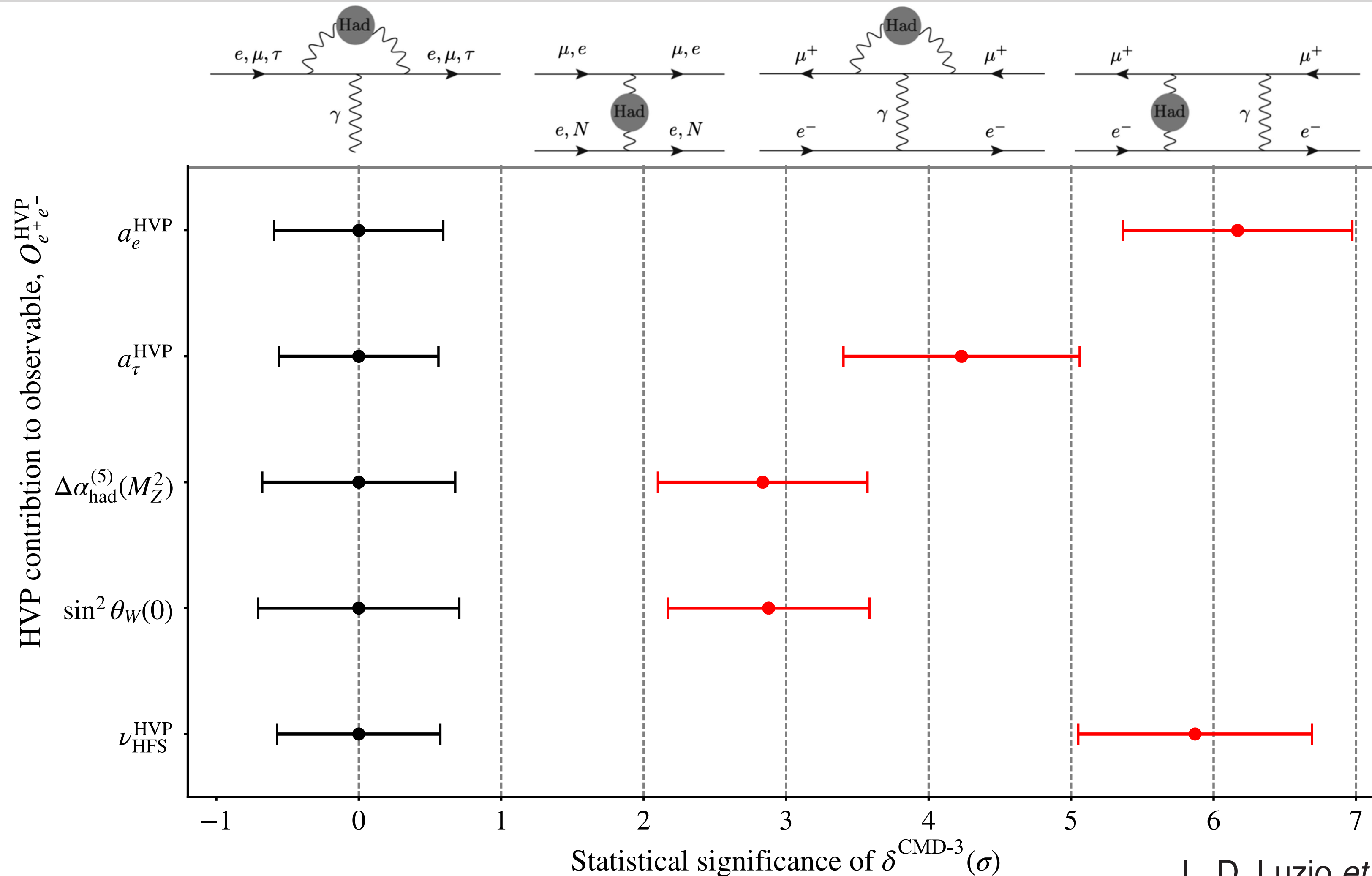
AMuLET



Theoretical Calculations

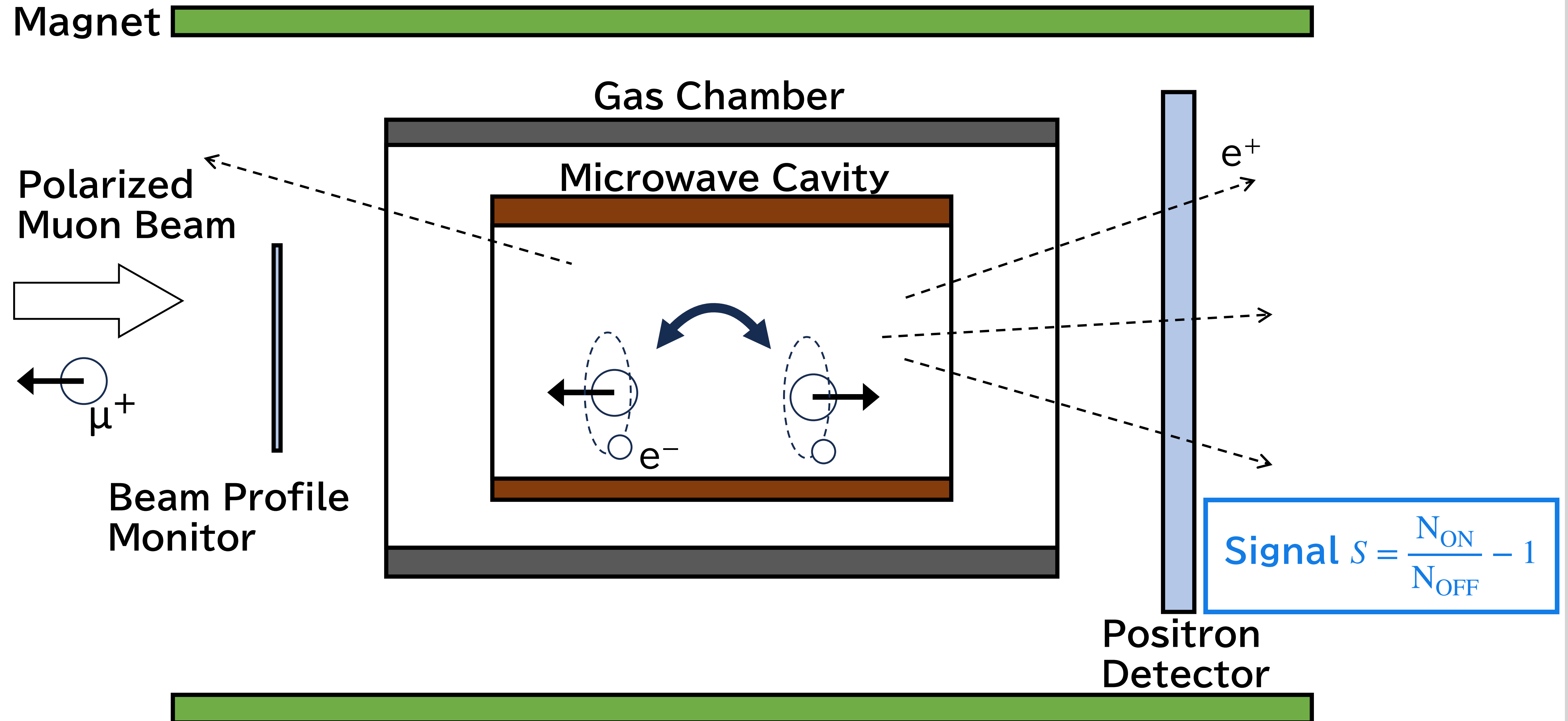


HVP (KNT19 vs CMD-3)



Difference	Exp. Prec.
$(6.0 \pm 1.0) \times 10^{-14}$	12.6×10^{-14}
$(7.4 \pm 1.7) \times 10^{-8}$	$\sim 10^{-6}$ (Belle-II)
$(1.4 \pm 0.5) \times 10^{-4}$	0.5×10^{-4} (FCC-ee)
$(7.4 \pm 1.7) \times 10^{-8}$	$\sim 10^{-5}$ (FCC-ee)
$(16.5 \pm 2.8) \text{ Hz}$	$\sim 5 \text{ Hz}$ (MuSEUM)

L. D. Luzio *et al*, Phys. Rev. Lett. **134**, 011902 (2025)



Current Status of High-Field Experiment

Superconducting 3T Magnet

Installed H1 experimental area in Nov. 2023



Magnetic Field Probe

Standard probe

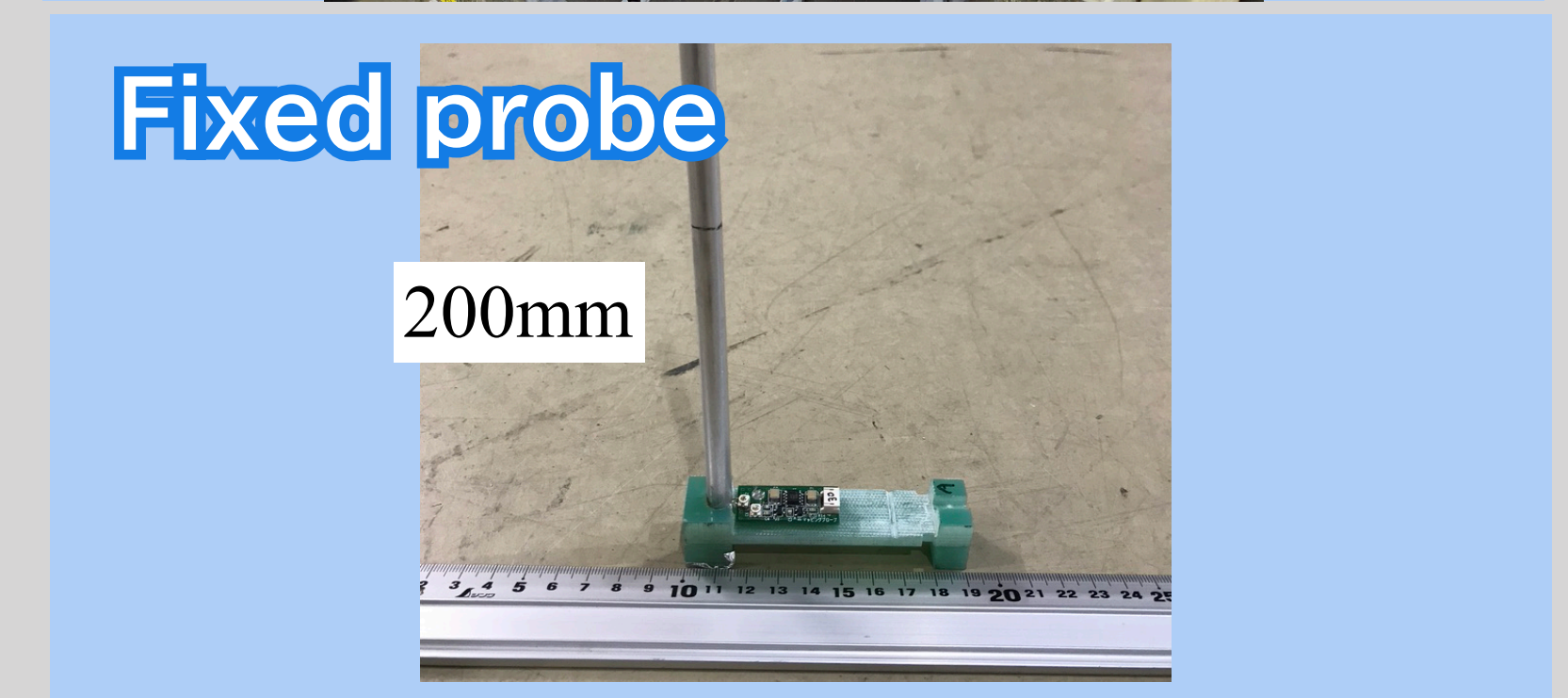
- Precision | 15 ppb

Field camera

- 24 ch rotating NMR probe
- Fast magnetic field mapping

Fixed probe

- Monitoring magnetic field stability

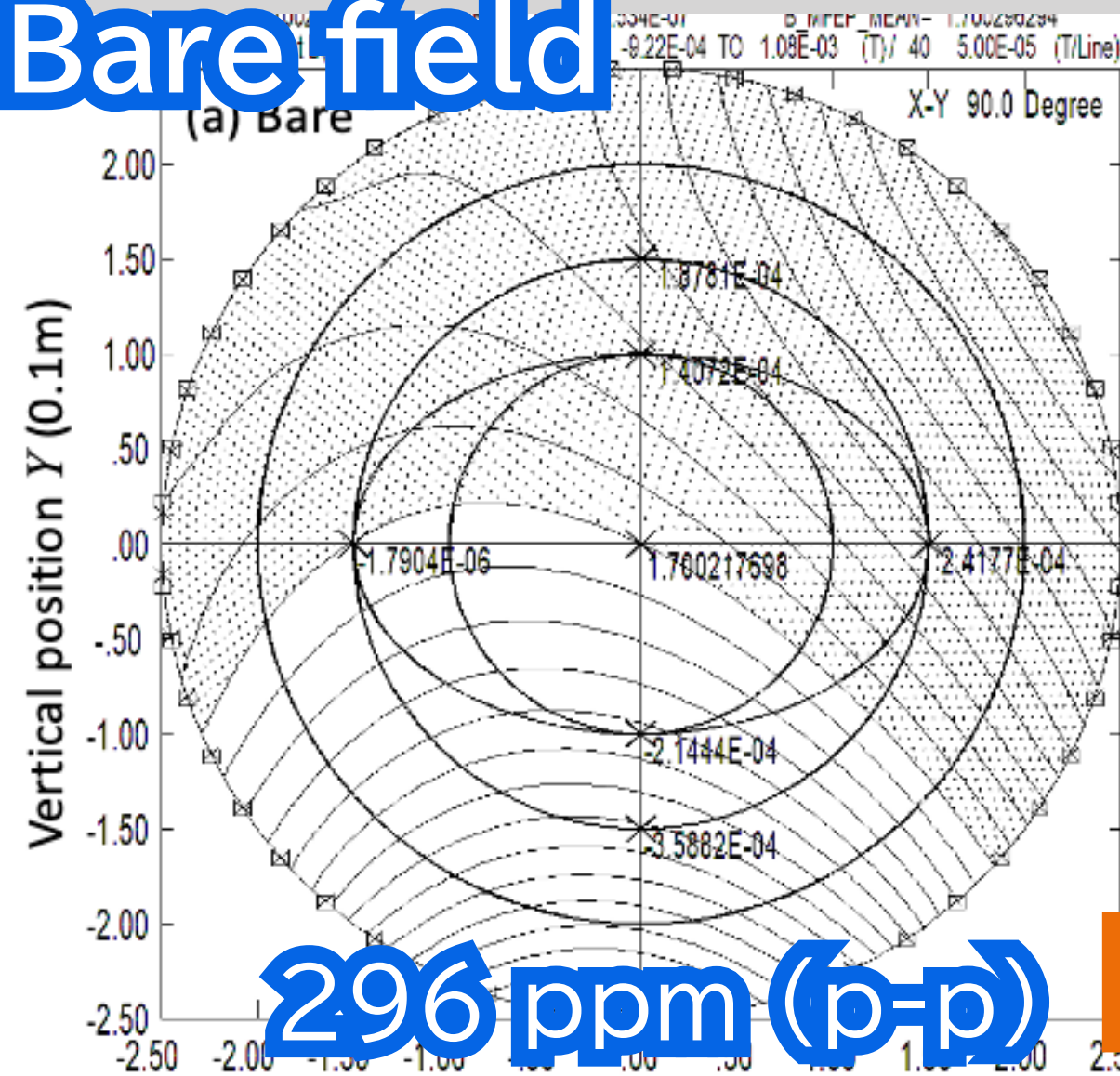


Field Homogeneity / Stability

Fe/Ni shim plate

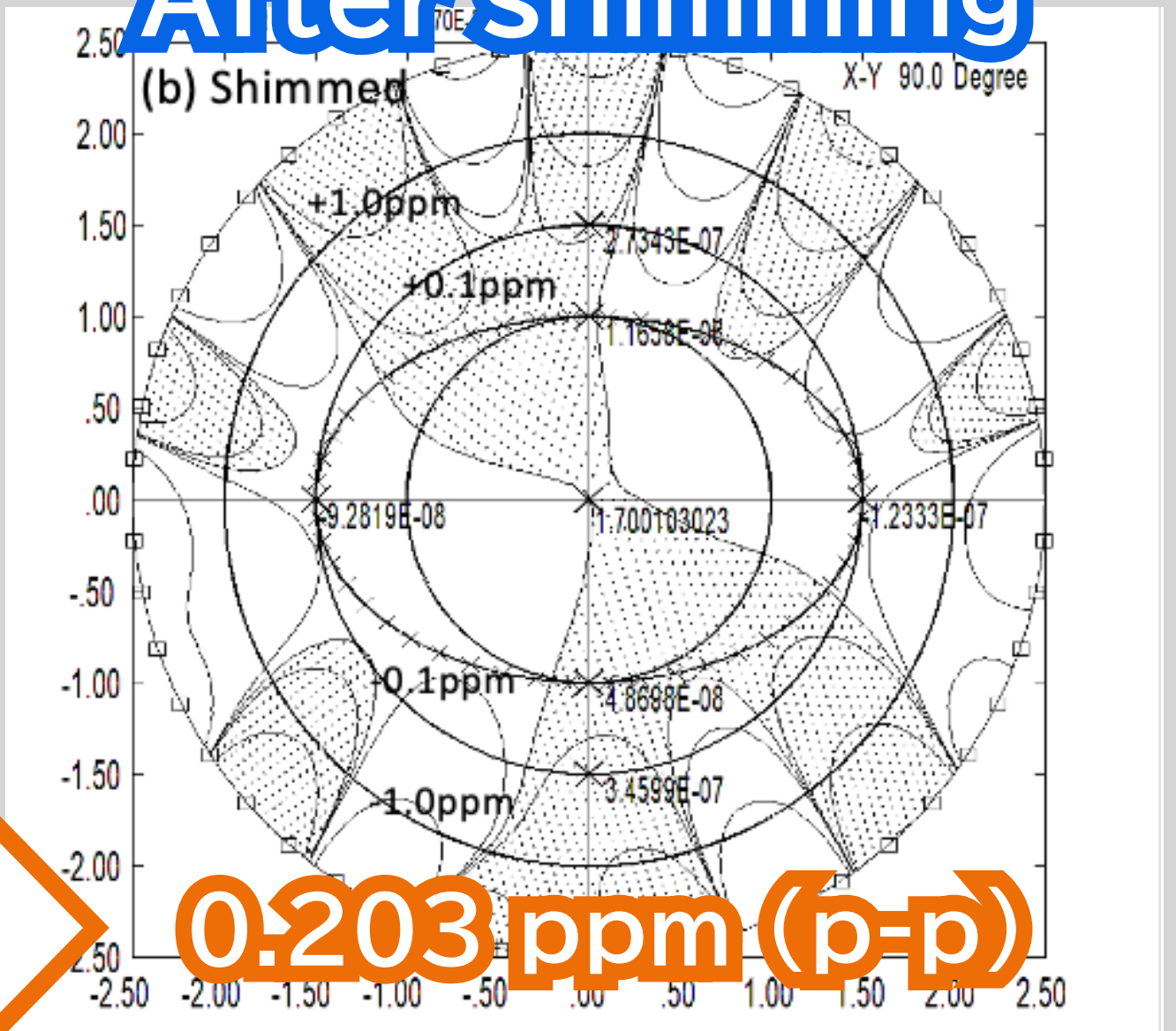


Bare field



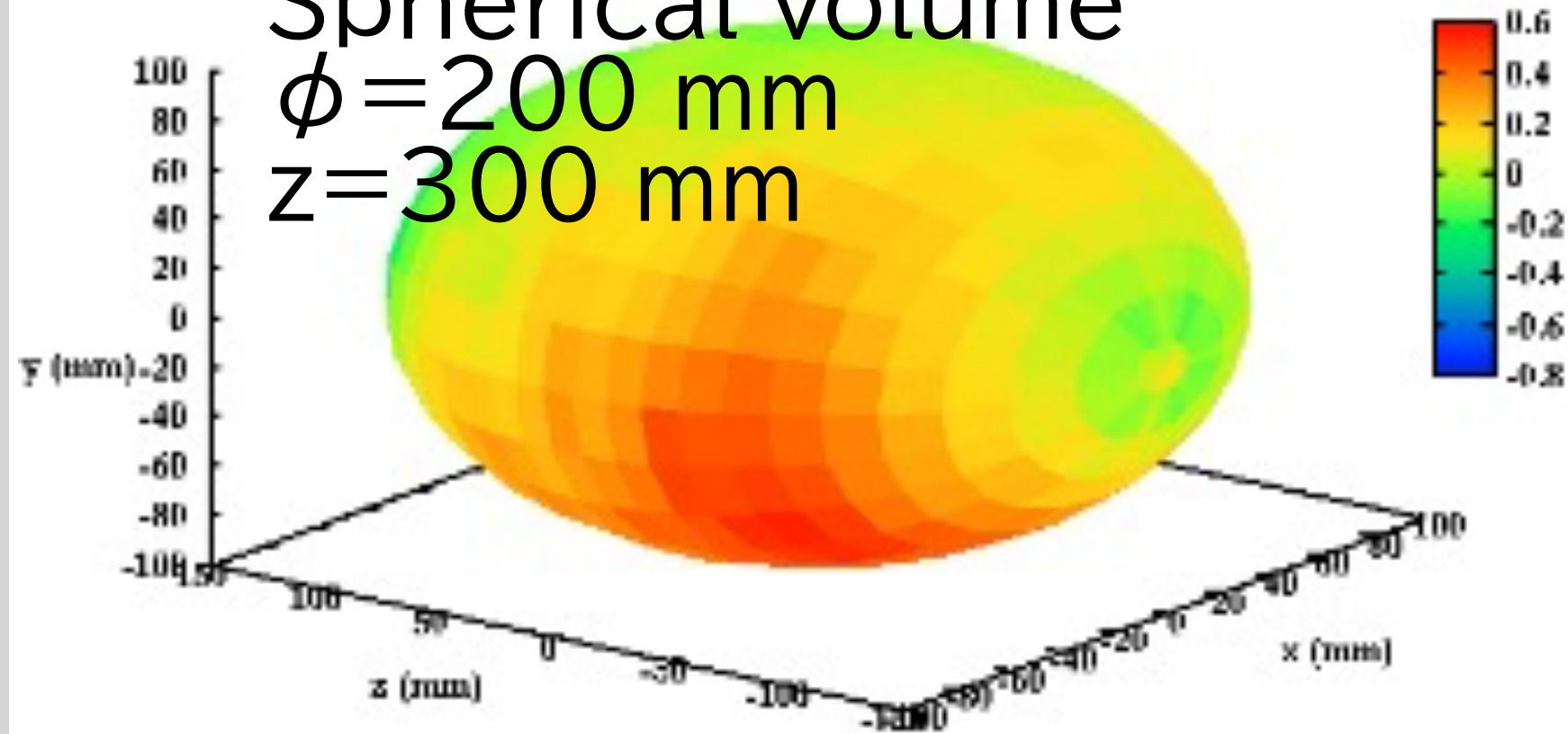
296 ppm (p-p)

After shimming



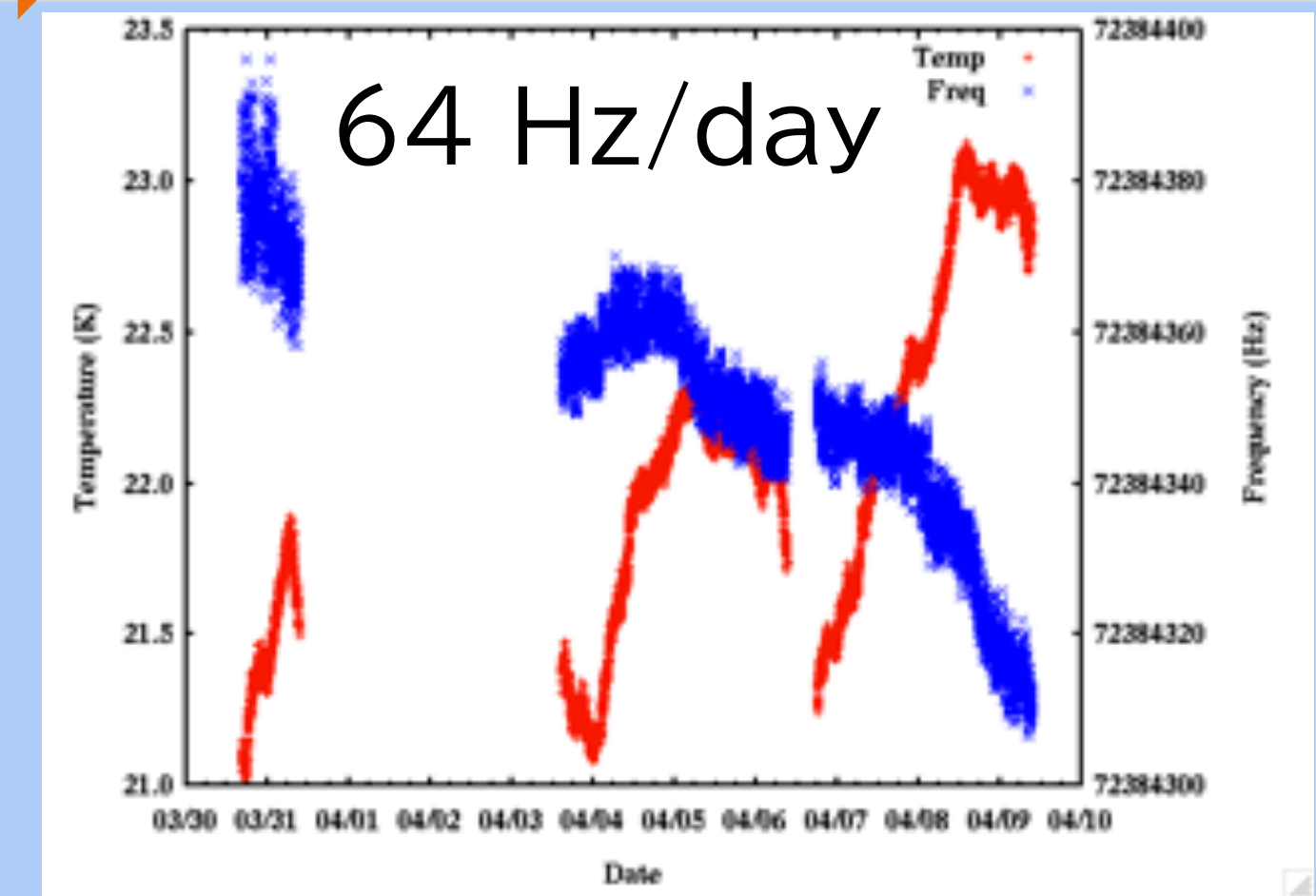
0.203 ppm (p-p)

Spherical volume
 $\phi = 200$ mm
 $z = 300$ mm



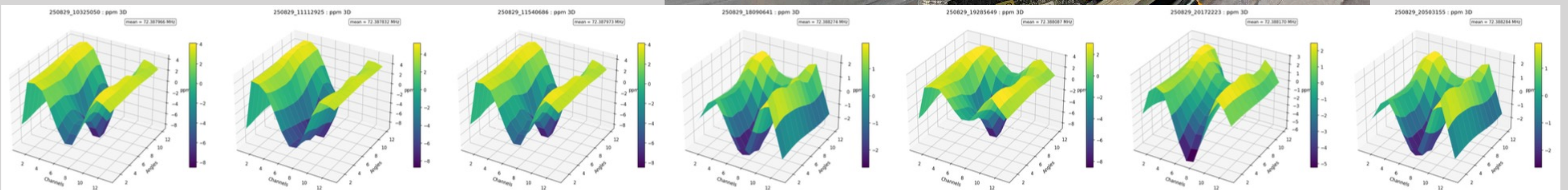
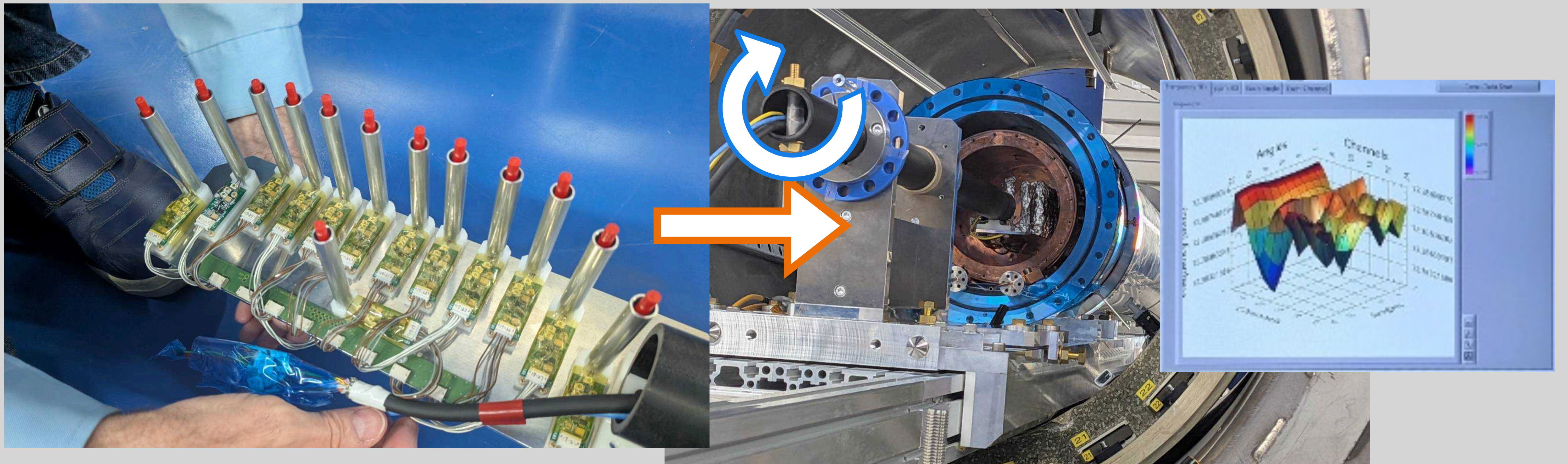
Field Stability

0.003 ppm/h achieved

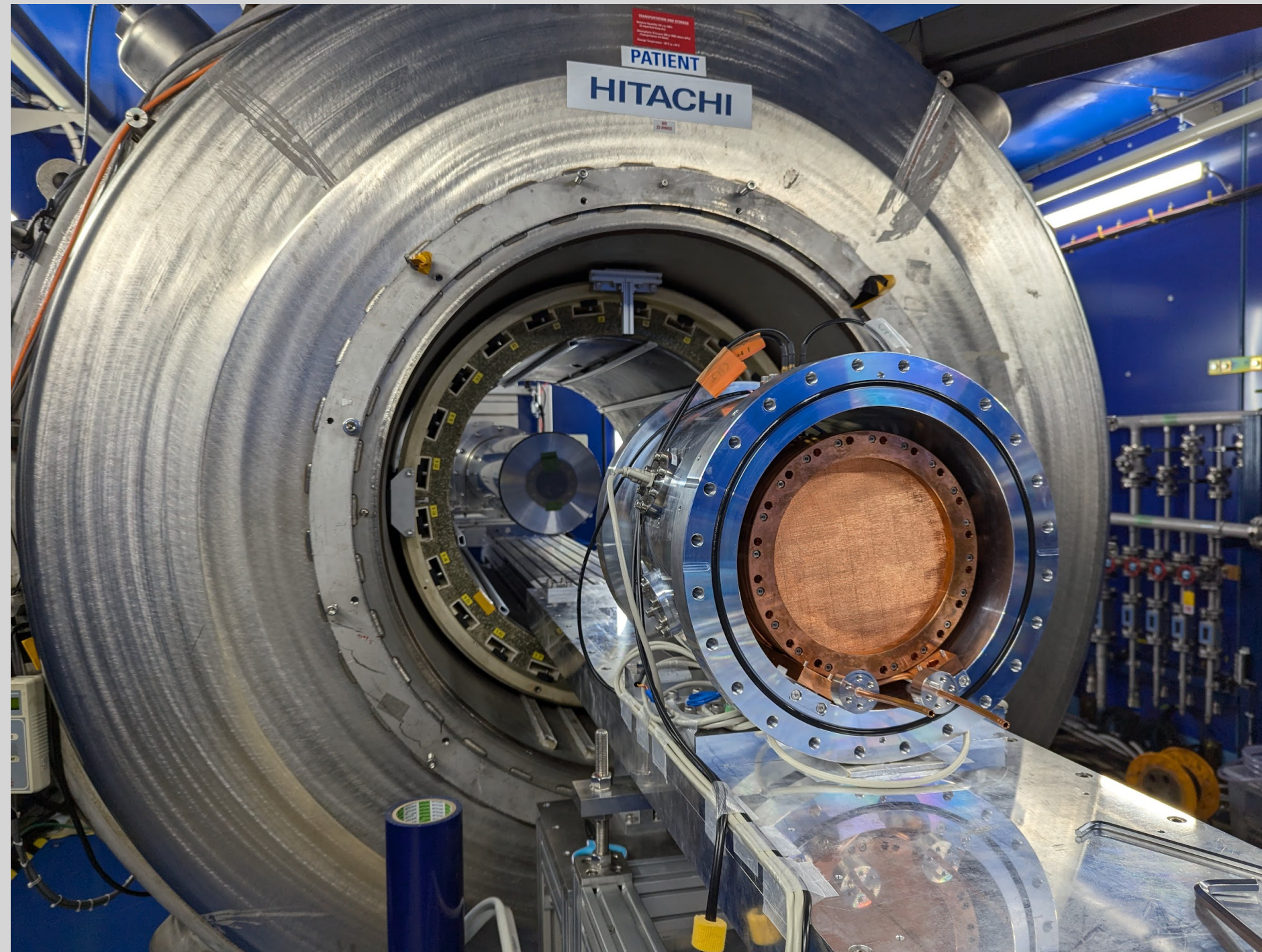


Inner Field Camera

Small camera to estimate material effect

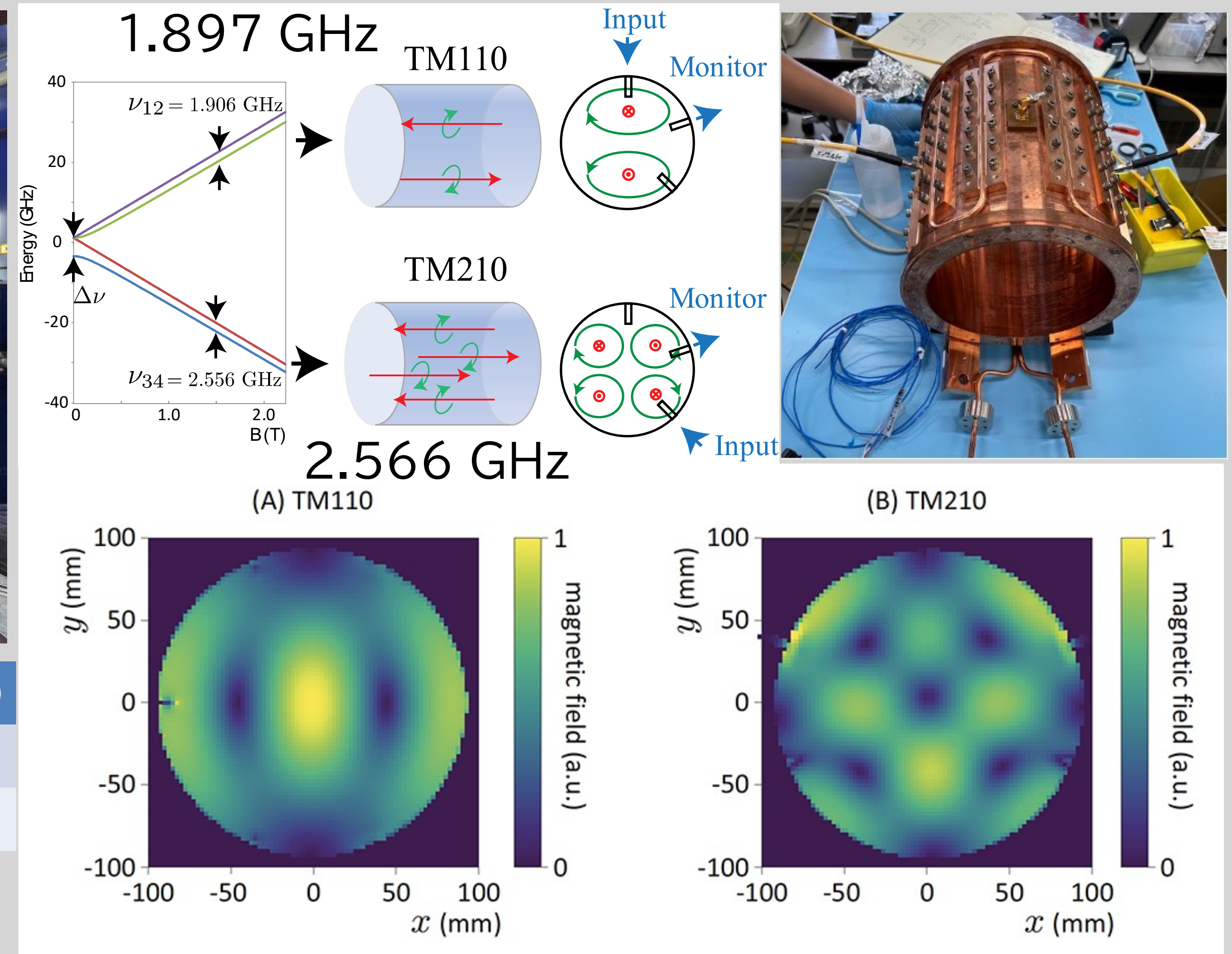


Microwave Cavity



Modes	Q (measured)	Q (simulation)
TM110	11,300	29,700
TM210	8,050	28,900

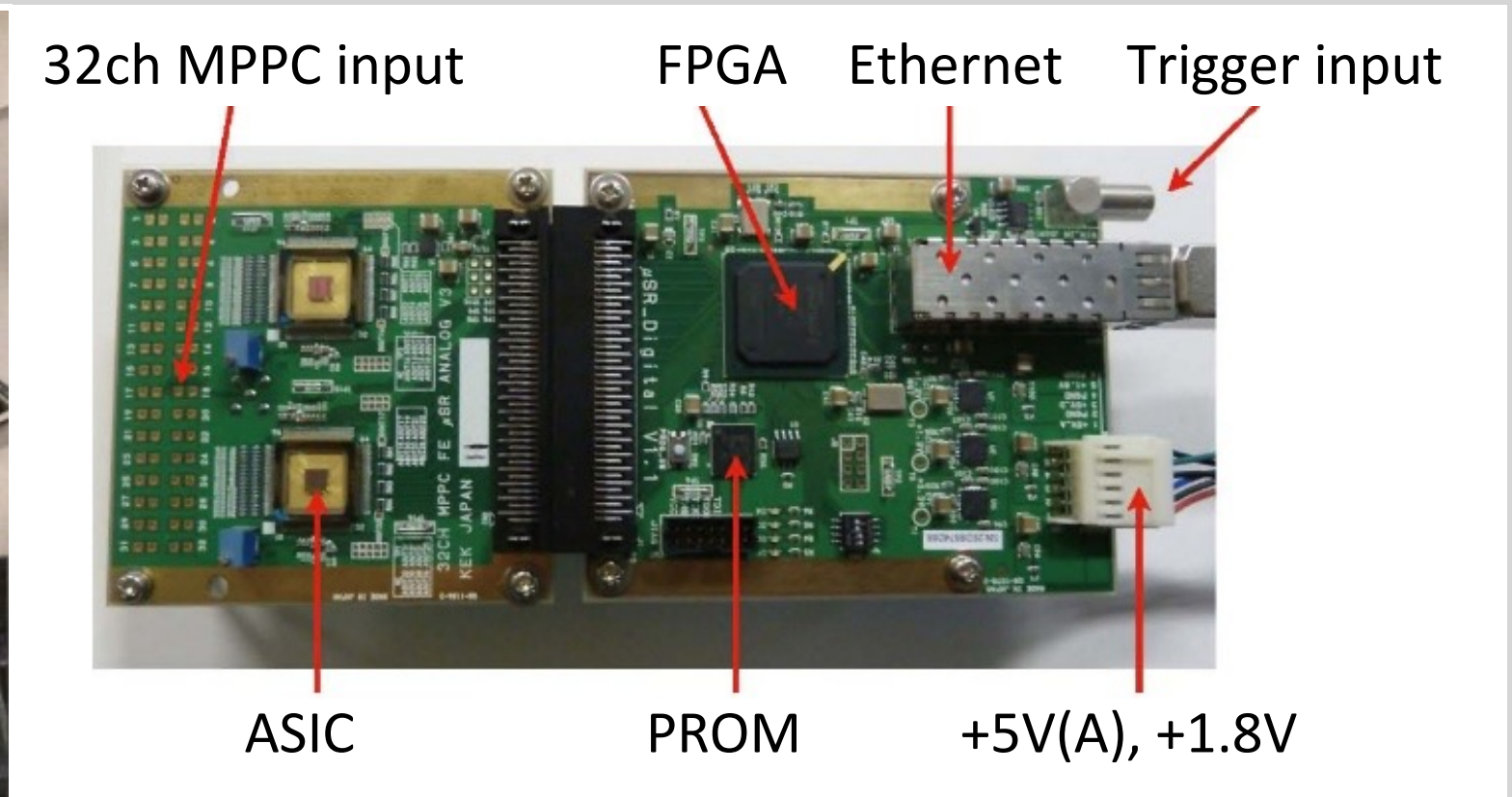
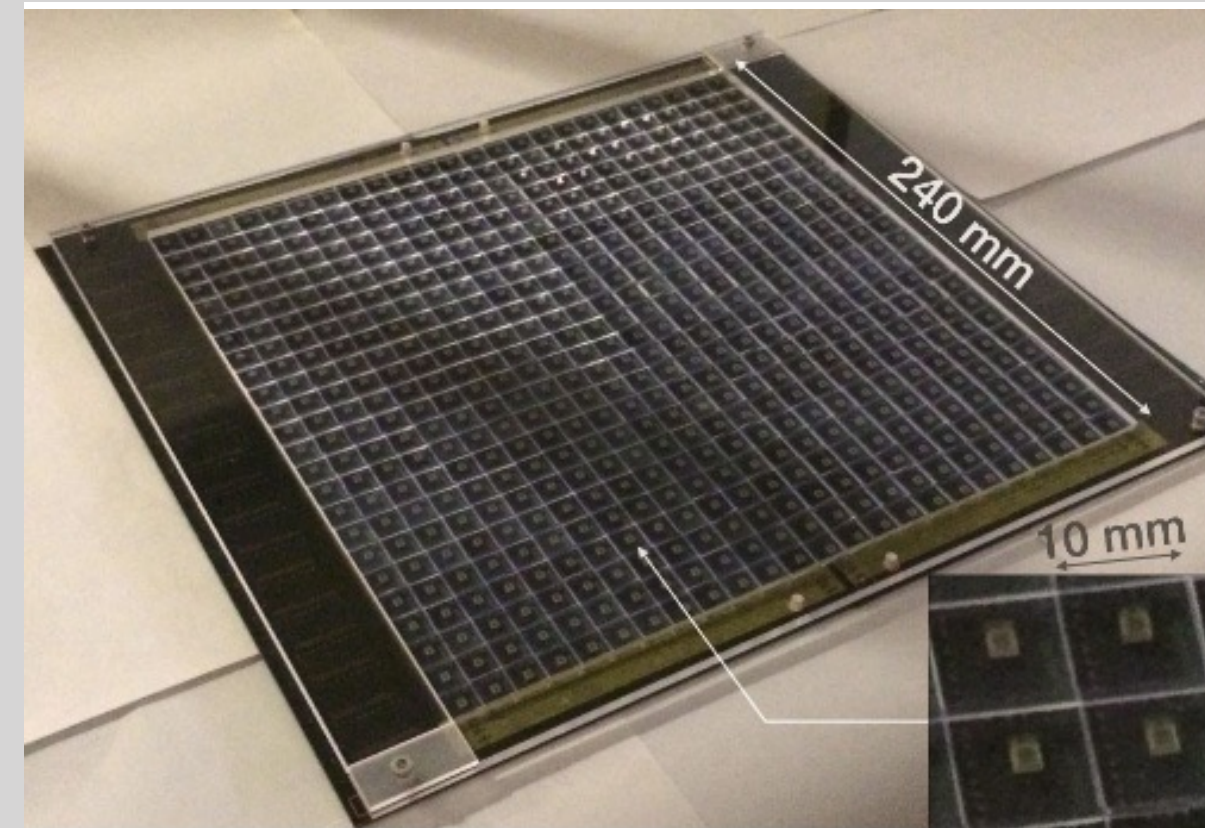
Re-tuning in progress



Detectors

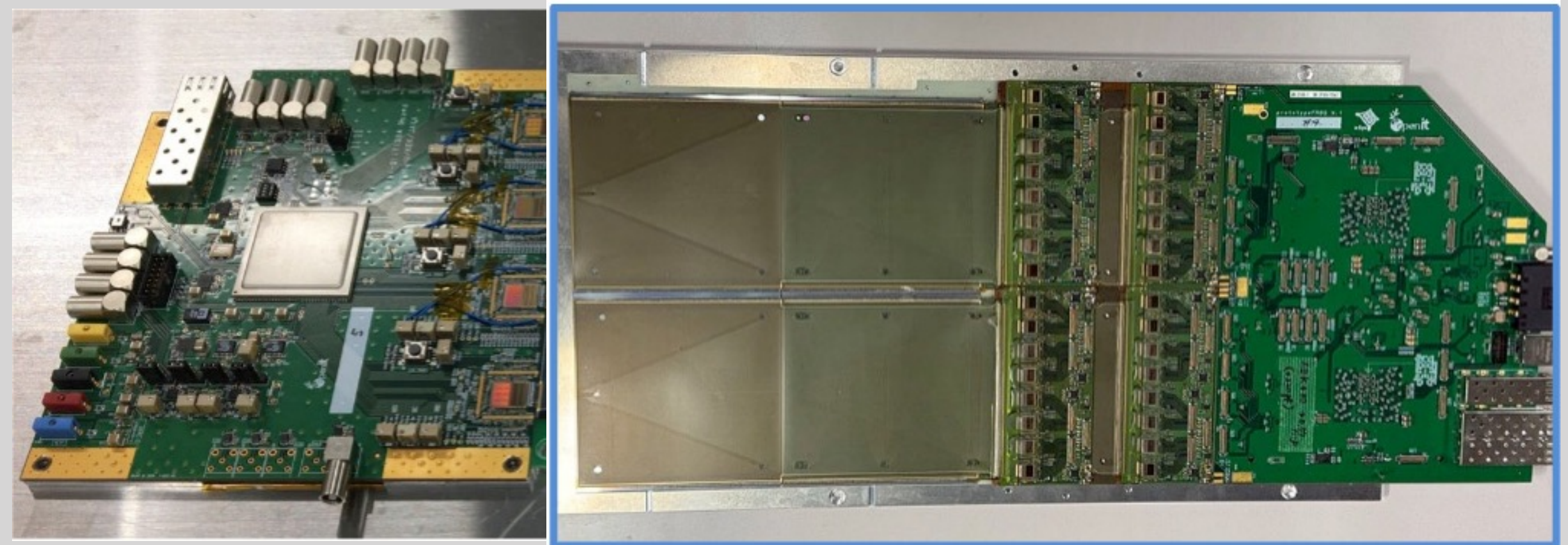
SiPM + Scintillator

- 24×24 segments
- Unit cell |
10 mmsq. × 3 mmt

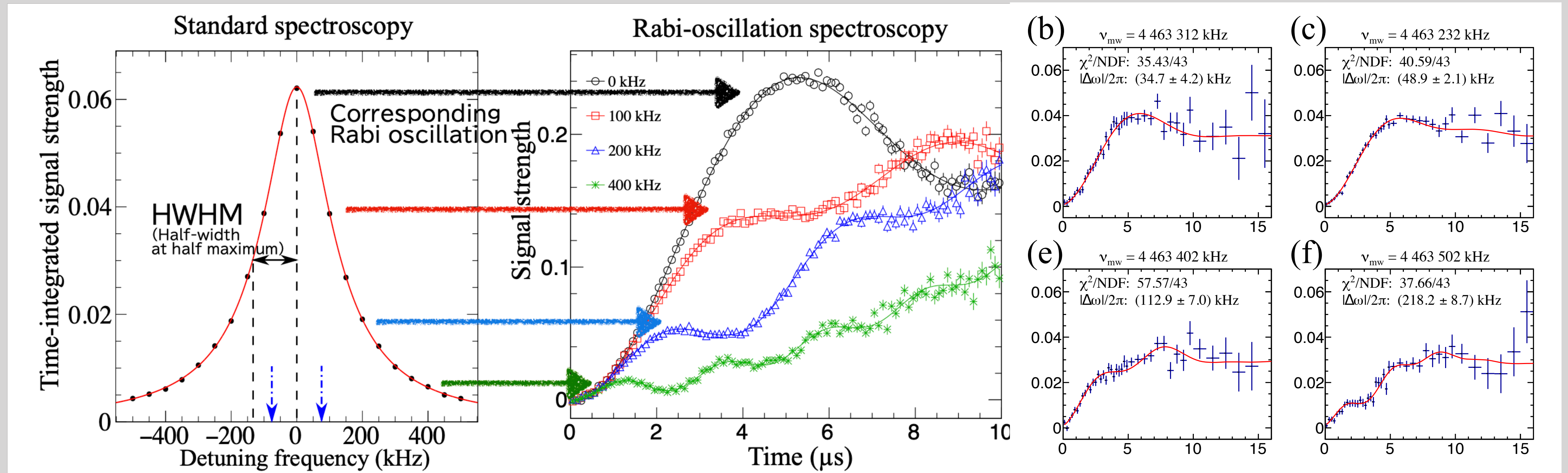


J-PARC g-2/EDM SSSD

- 512×2 strips
- Strip size |
48.575 mm × 0.19 mm
- High-rate capability

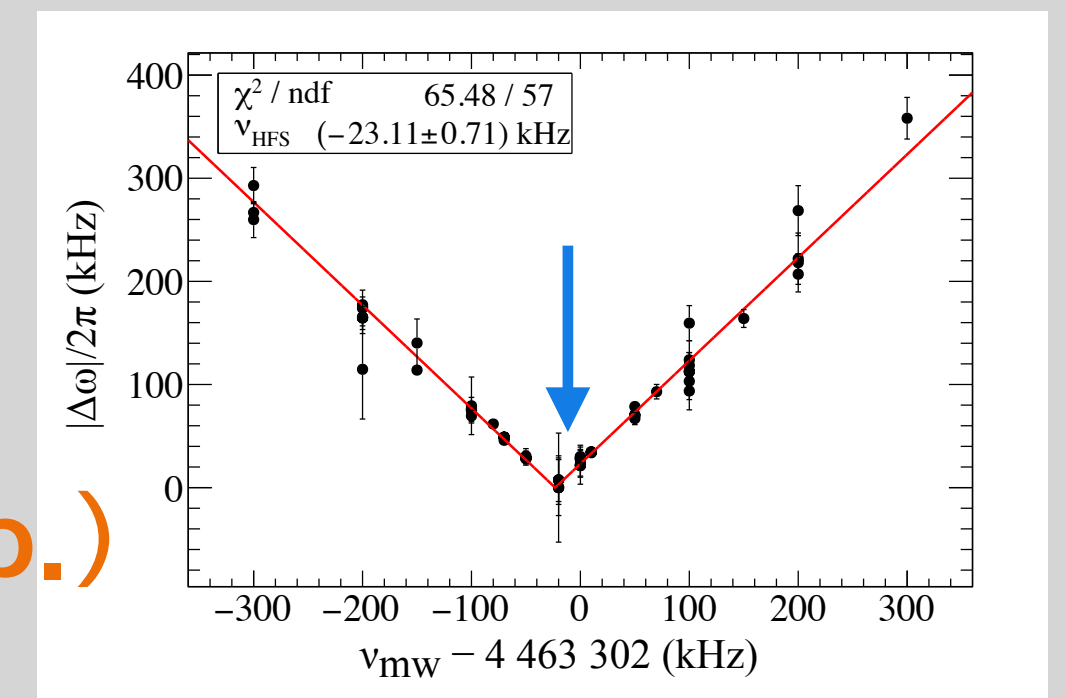


Rabi-Oscillation Spectroscopy



- No frequency sweeping
- Microwave power obtained as fitting parameter
- Stat. Uncertainty improves factor 2-3

160 ppb
(WR of ZF exp.)



Slow Control & Monitor

Microwave monitors
Pressure gauge
Etc...

← Control

Slowdash 

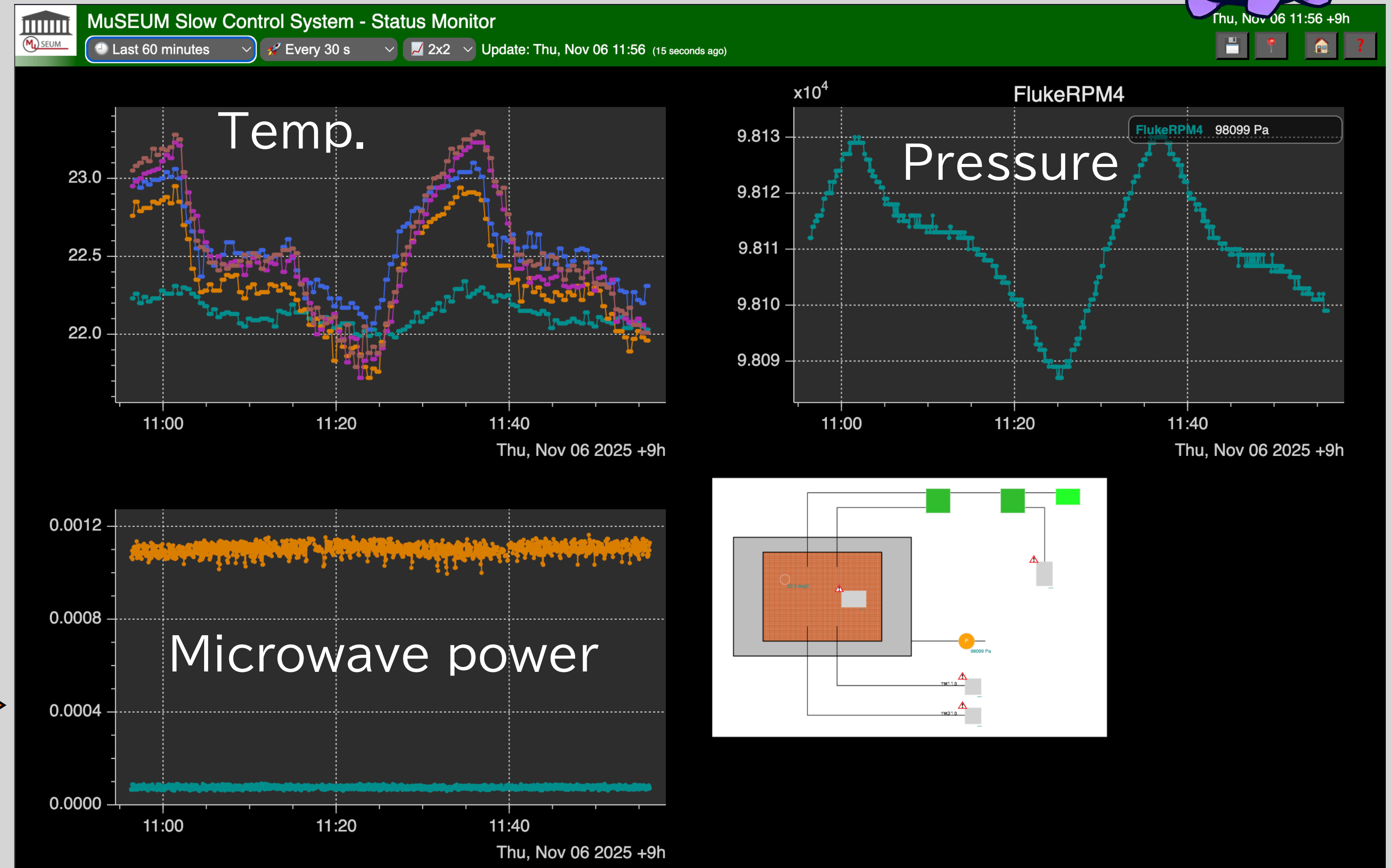
↓ Data



↓

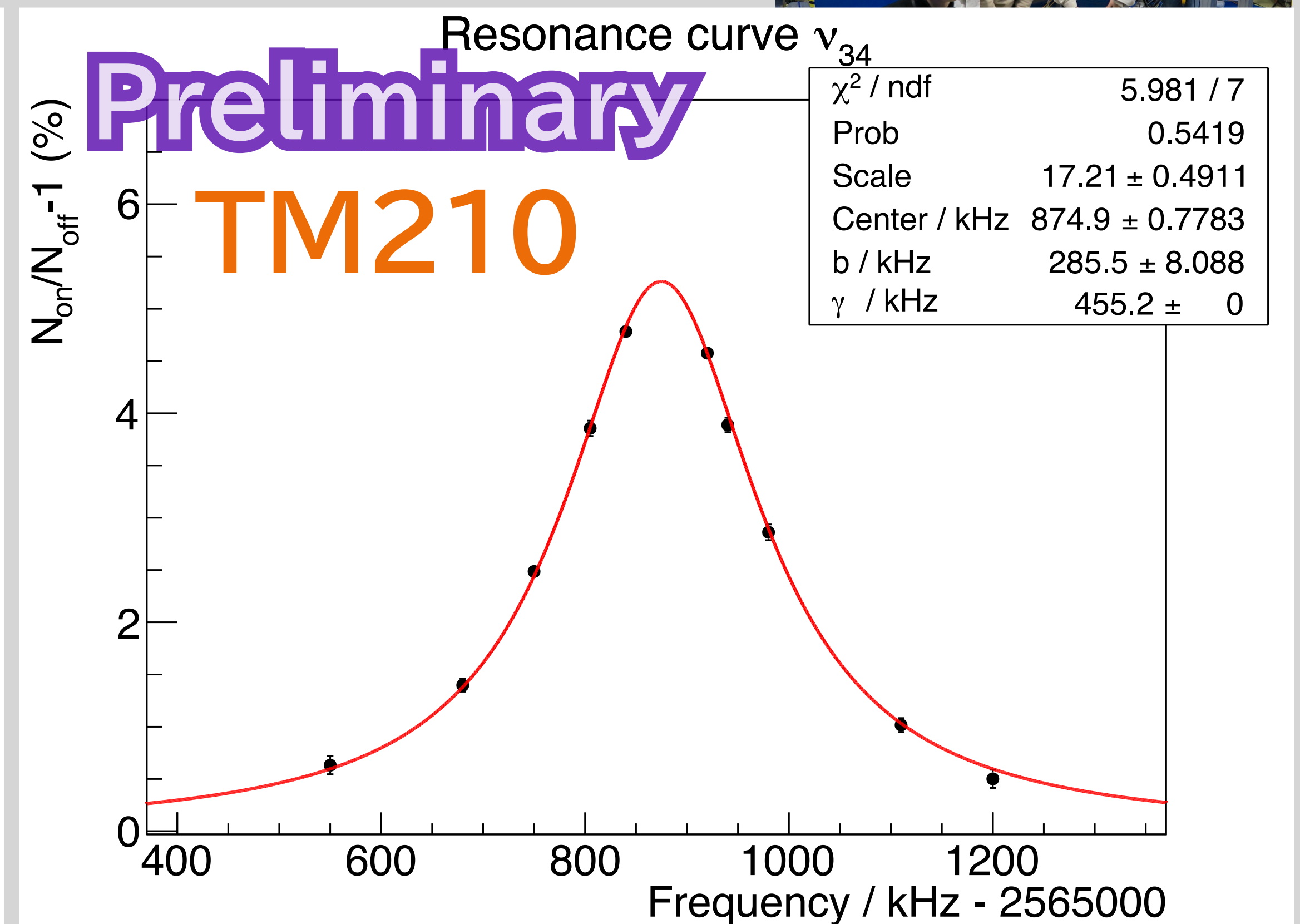
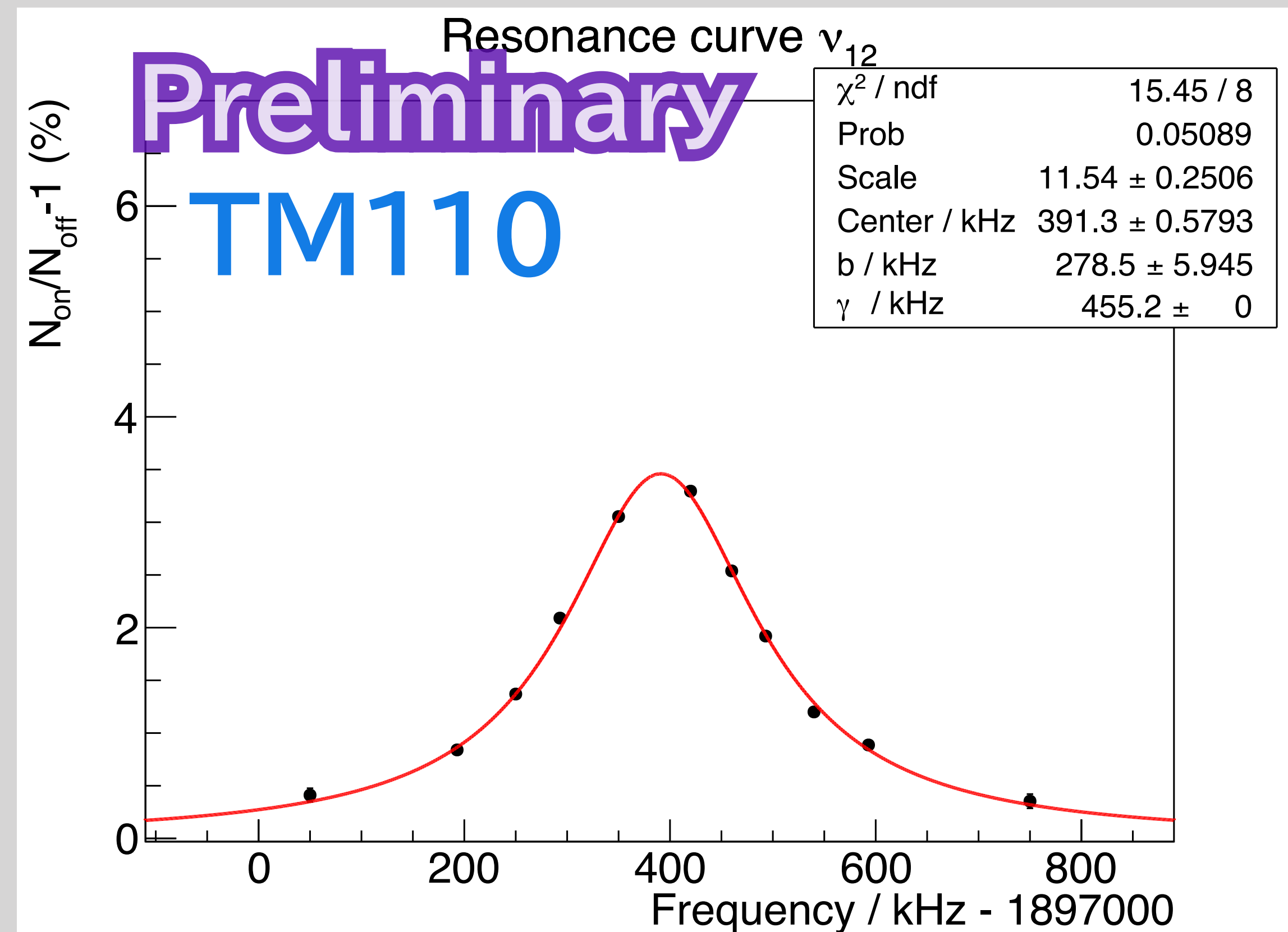
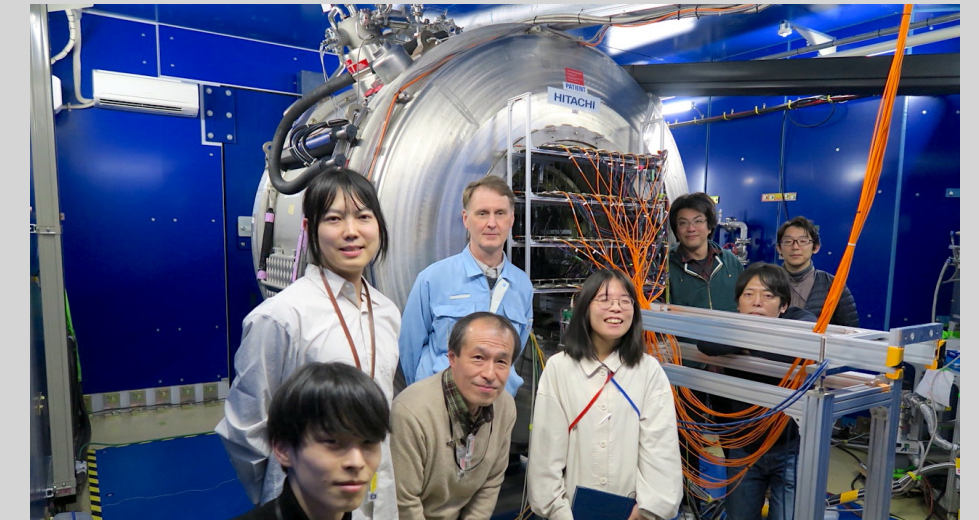


→

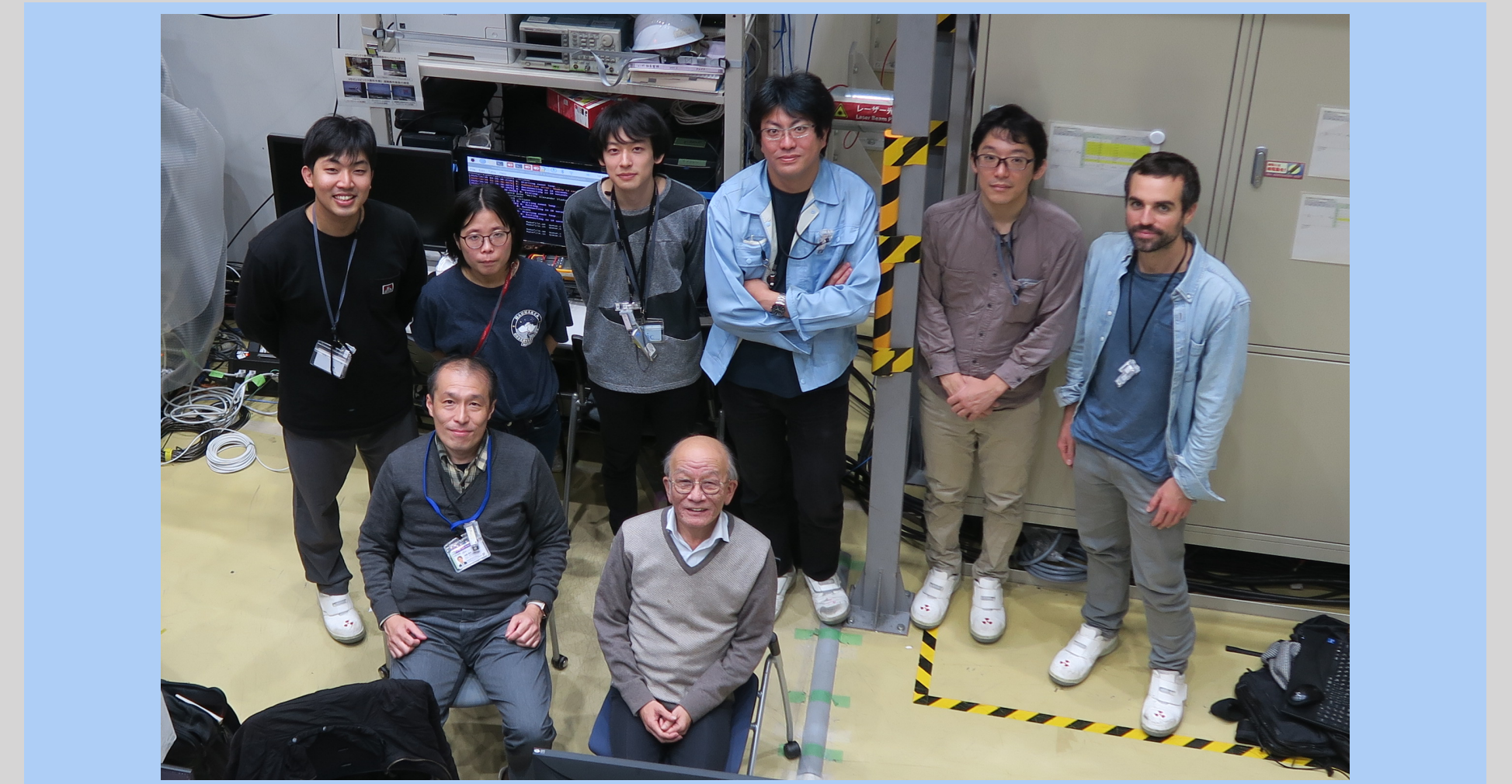
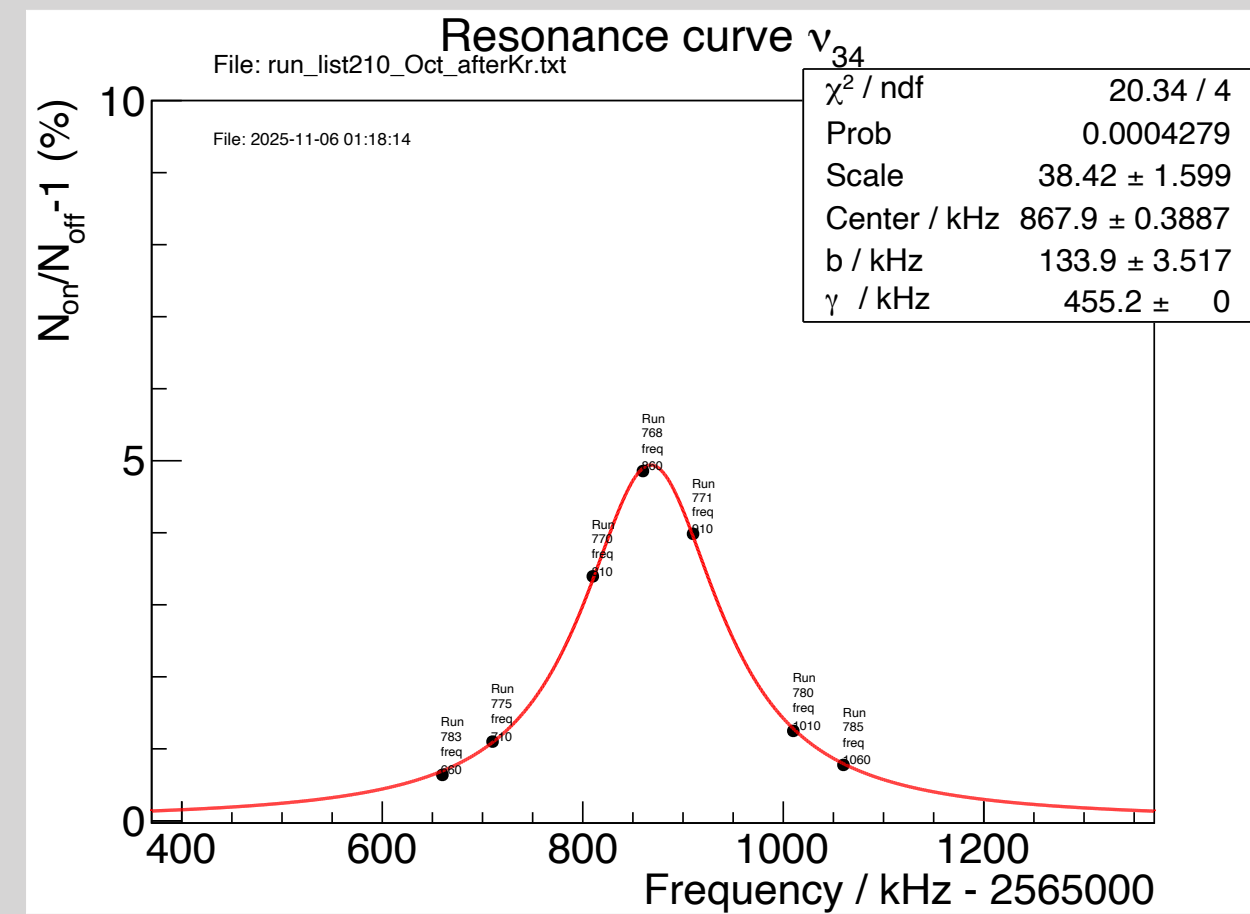
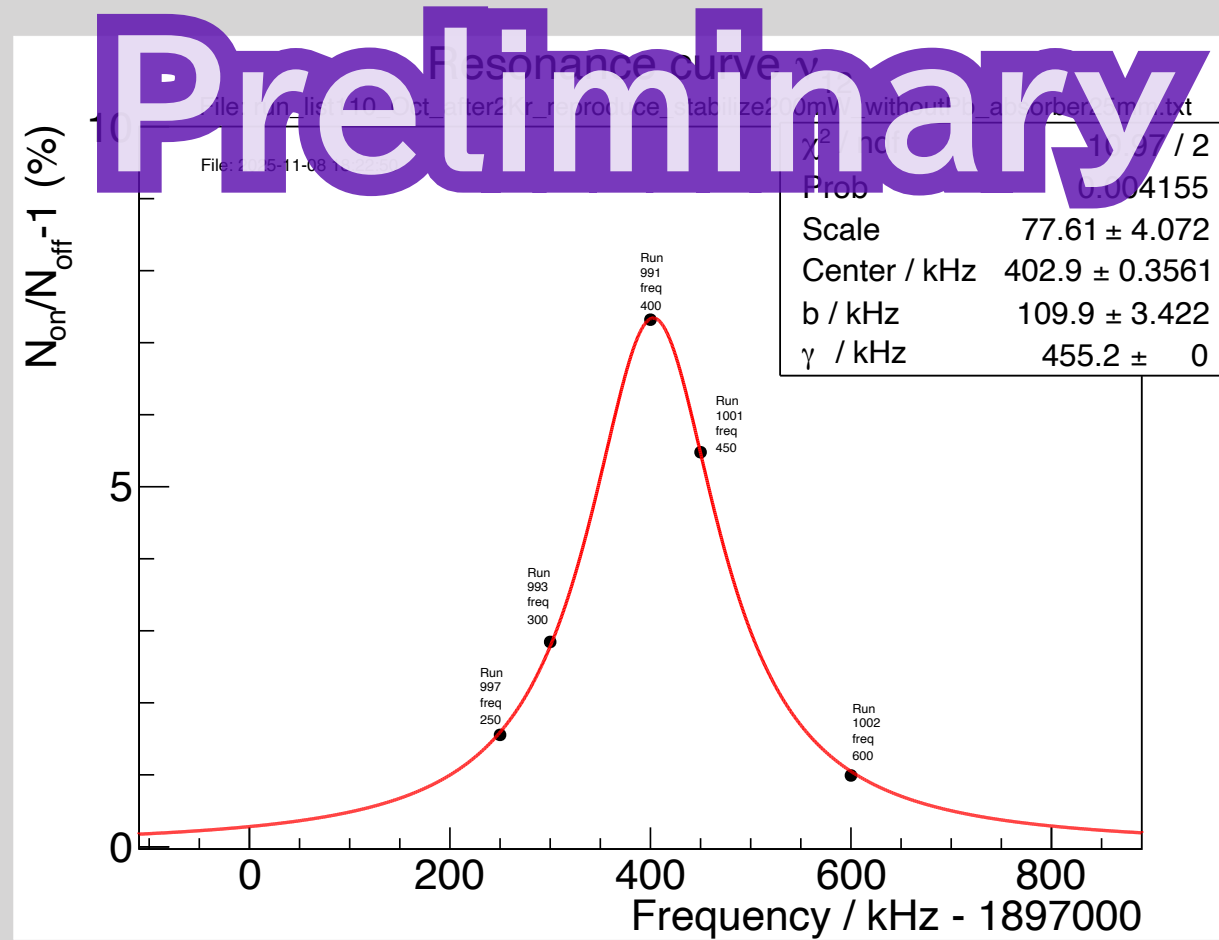


First Resonance Observation

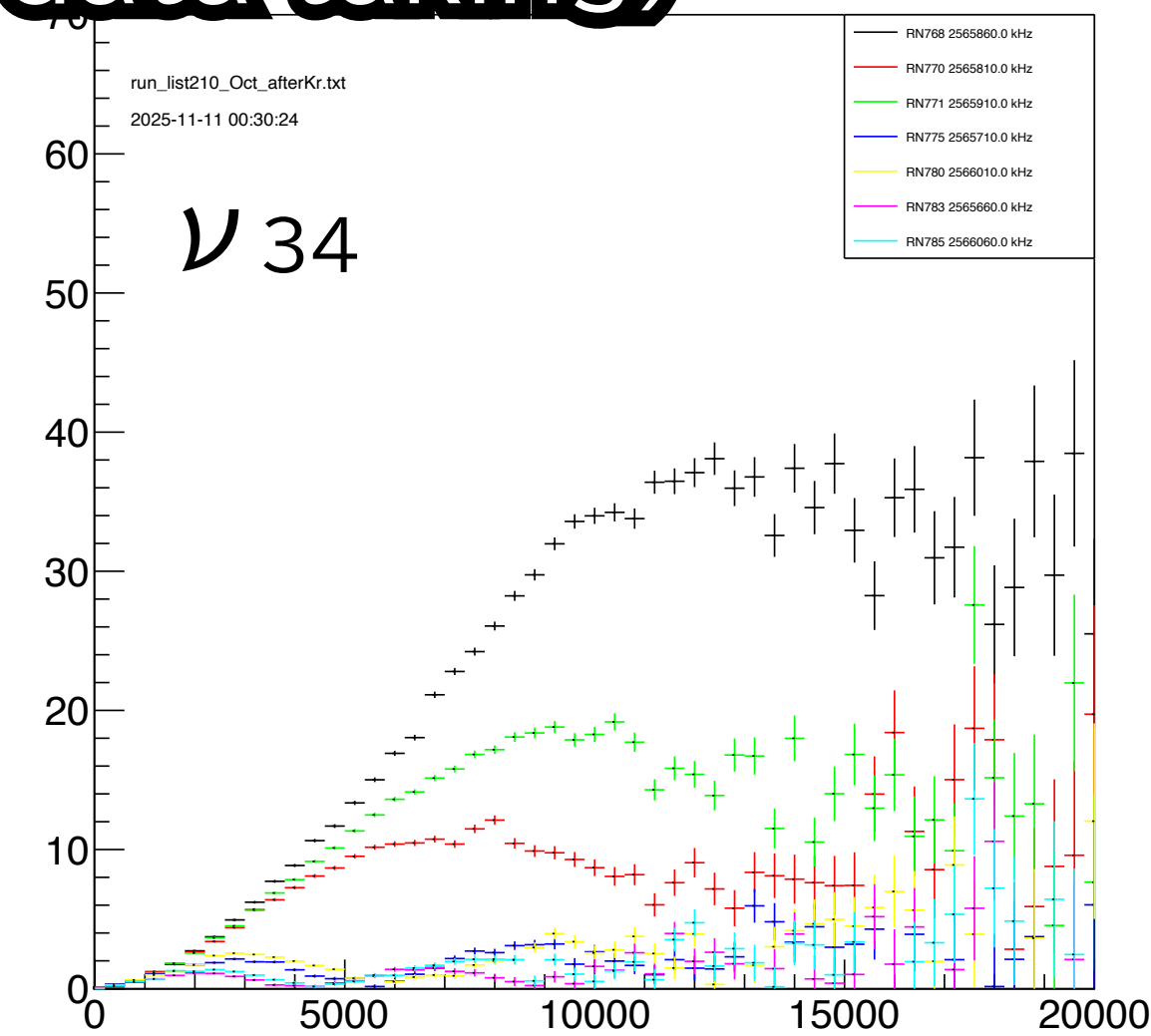
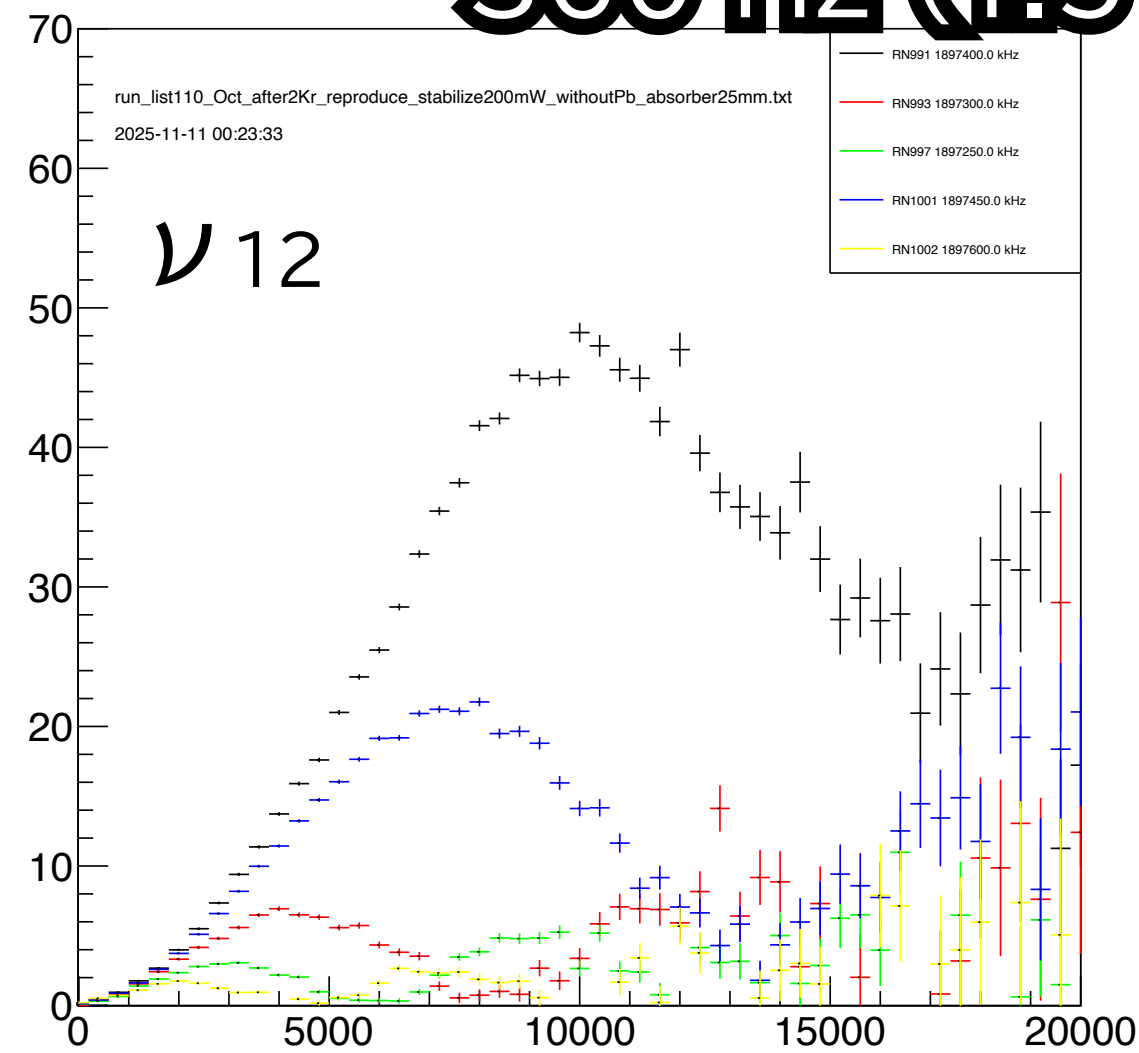
Conducted in Feb. 2025



Second Measurement (Nov. 2025)



360 Hz (1.5 h data taking)



100 days data taking	x40
Rabi-oscillation spectroscopy	x 3
Higher gas purity	x 1.5
Higher microwave power	x 2
Beam Power 800 kW \rightarrow 1 MW	x 1.2

Stat. uncertainty < 1 Hz (0.22 ppb)

Systematical Uncertainty (Expected)

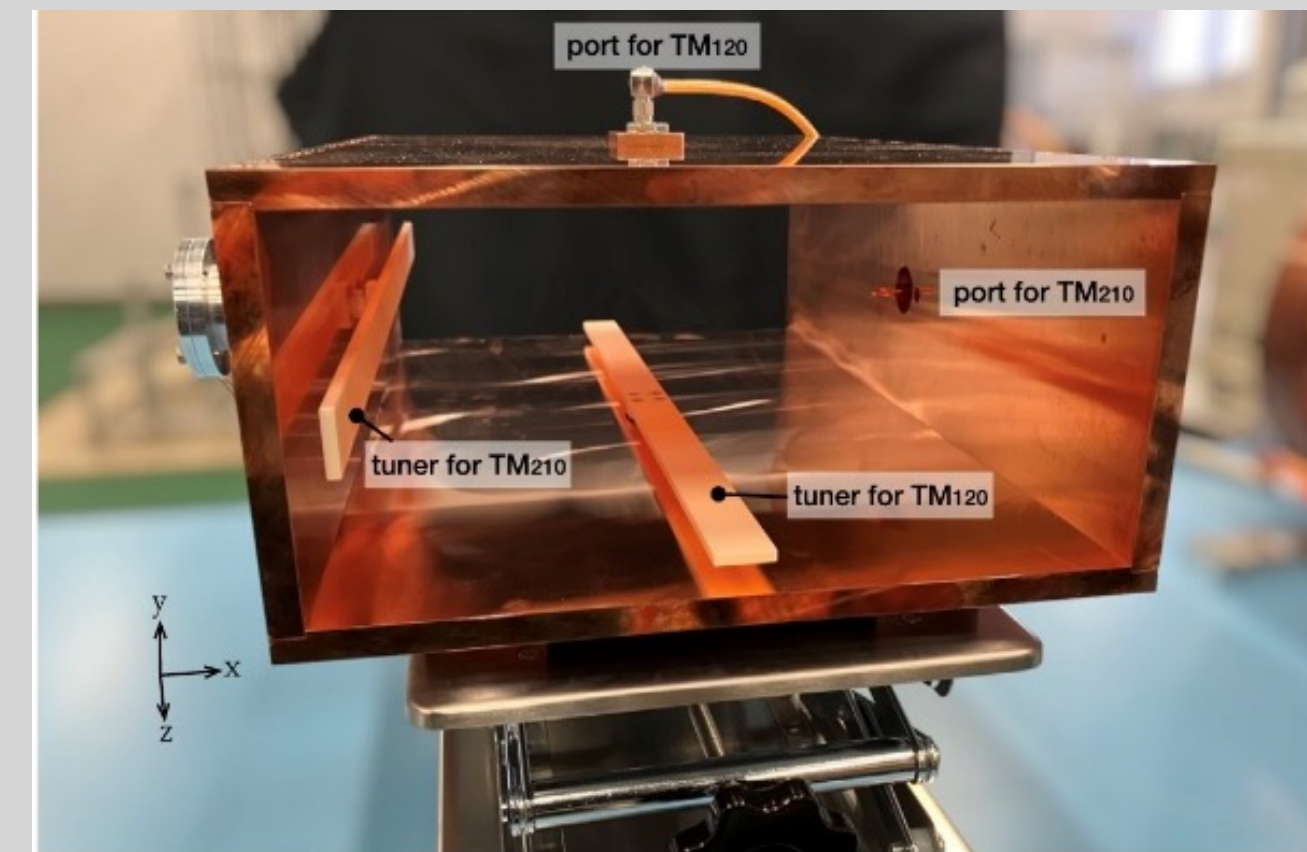
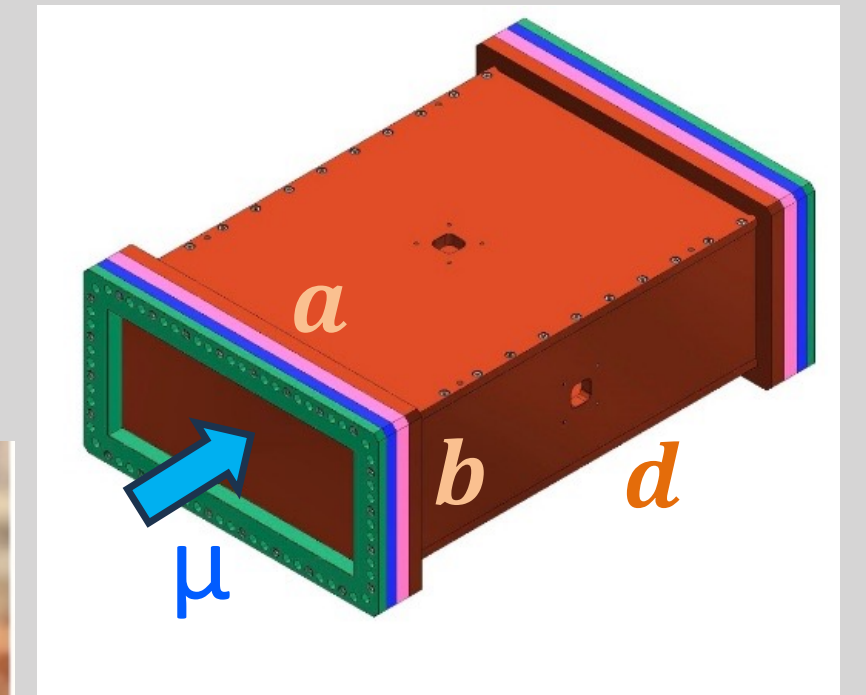
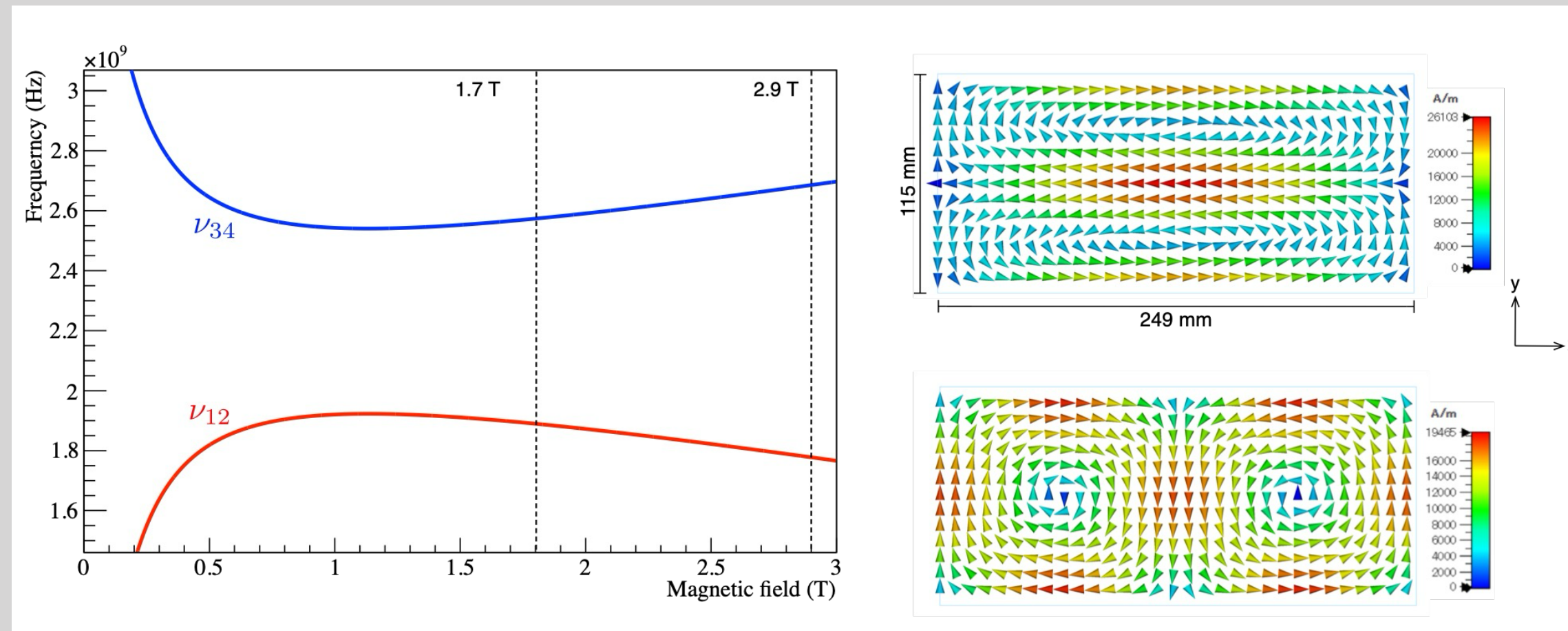
Contributions	Precision	ν_{12} and ν_{34}	$\delta(\Delta\nu_{\text{HFS}})$	$\delta(\mu_{\mu}/\mu_p)$
Magnetic Field	15 ppb		< 0.1 ppb	8 ppb
RF power	< 0.1 %	< 1 Hz	0.2 ppb	2 ppb
Kr gas temperature	0.2 deg.	< 2 Hz	0.4 ppb	4 ppb
Kr gas pressure	1 Pa	1 Hz	0.2 ppb	0 ppb
H impurity	< 50 ppm	1 Hz	0.5 ppb	0 ppb
Quadratic dependence	@0.3 atm	< 1 Hz	0.1 ppb	0.5 ppb
Muonium position (x,y)	1 mm	3 Hz	0.6 ppb	6 ppb
Muonium position (z)	1 mm	< 1 Hz	0.2 ppb	2 ppb
Beamline	10 ⁻⁴	< 1 Hz	0.2 ppb	2 ppb
Detector pile-up		0.3 Hz	< 0.1 ppb	< 1 ppb
Total			~ 1.0 ppb	~ 11 ppb

Toward Further Improvement

Rectangular Cavity

$$F_{mnl} = \frac{c}{2\sqrt{\mu_r \epsilon_r}} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{l}{d}\right)^2}$$

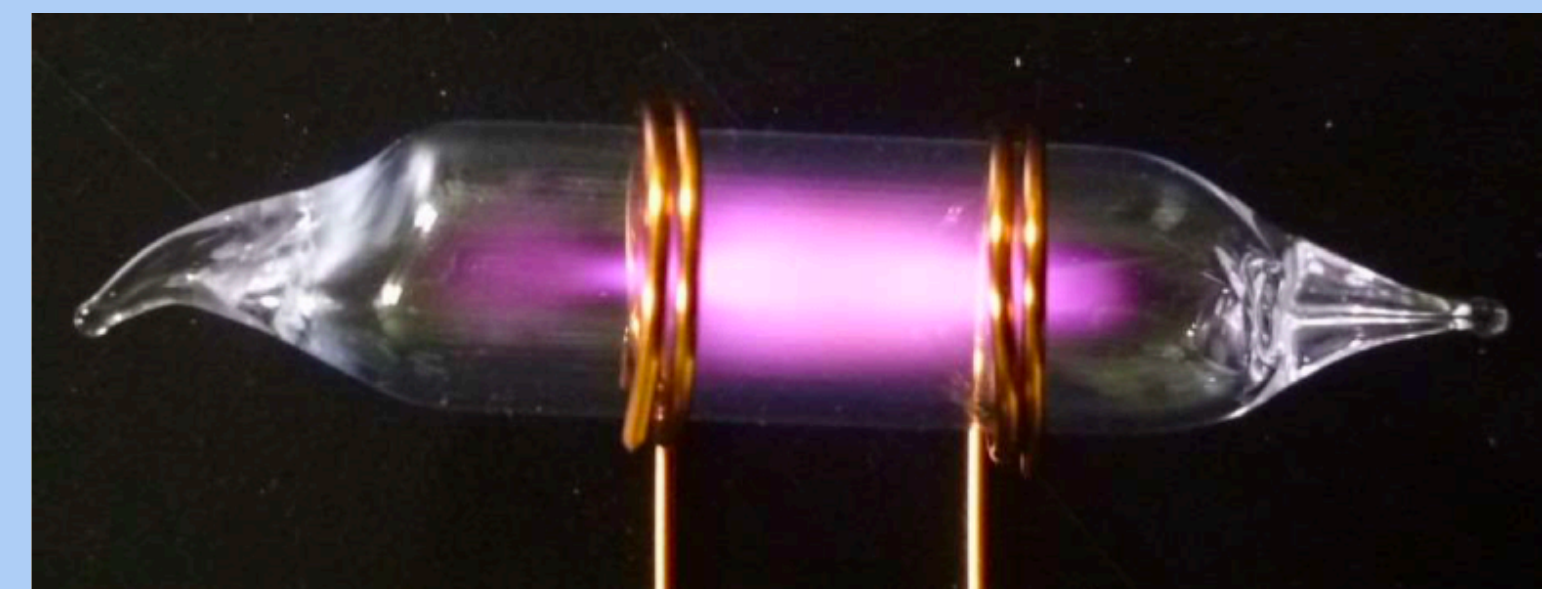
- Improve μ_μ/μ_p determination at higher field



R. Iwai *et al.*, Nucl. Instrum. Meth. A **134**, 169434 (2024)

^3He NMR Probe

- Improve shielding effect
- Higher precision (0.1 ppb)



Summary

Muonium HFS

- Goal $\Delta \nu \sim 1$ ppb
- Key to solve the muon puzzle
- High-Field Measurement is ongoing



Backup

Statistical Uncertainty (ZF)

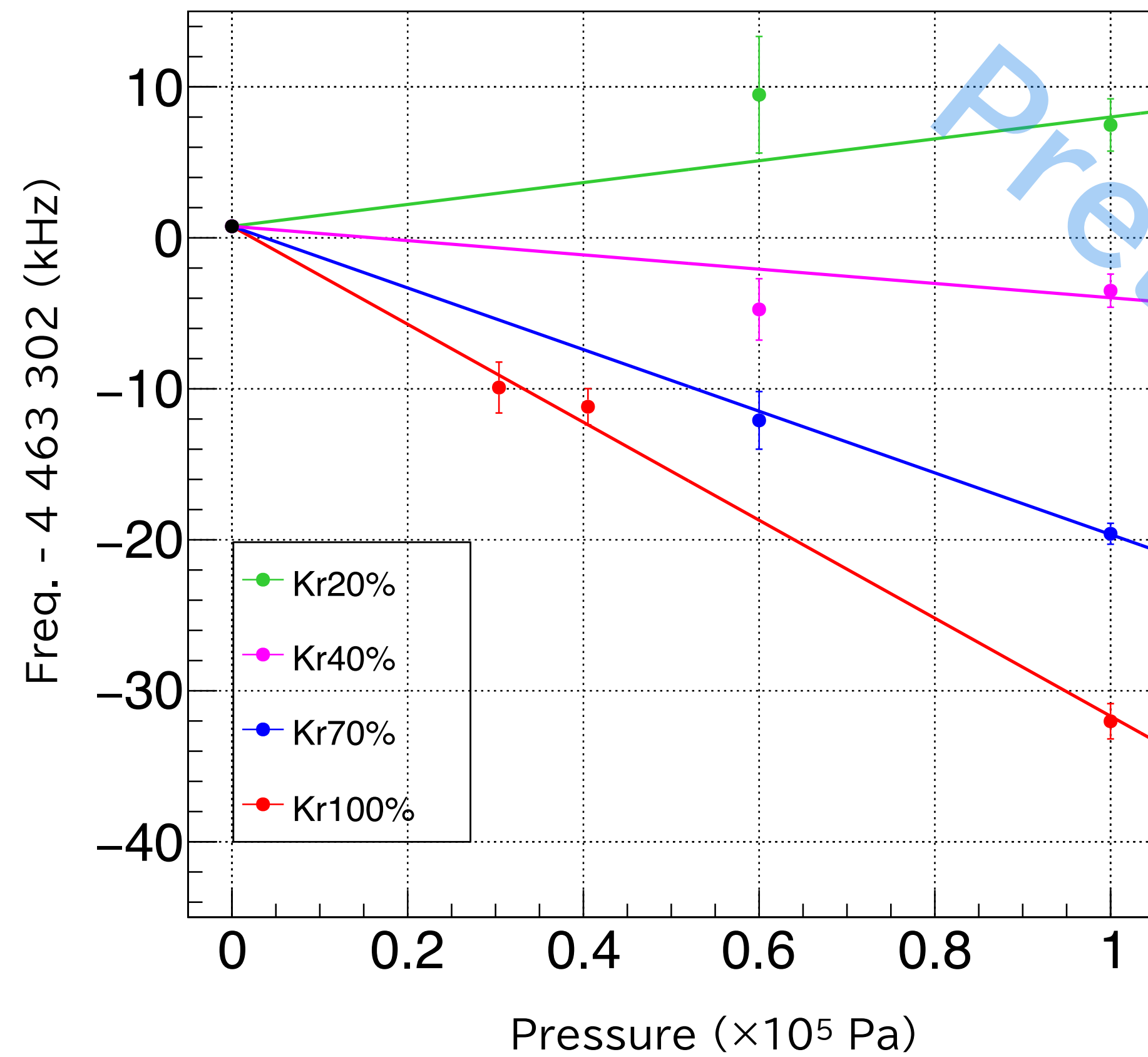
Item	June 2017	June 2018 (Kr 0.7 atm only)	Prospects
Analysis method	Rabi-oscillation spectroscopy	Rabi-oscillation spectroscopy	Rabi-oscillation spectroscopy
Beam line	D line	D line	H line (D line×10)
Beam power	150 kW	525 kW	1 MW
Measurement period	31 hours	42.5 hours	30 days
Microwave cavity	TM220 (not stable)	TM220	TM220
Detector area	98.77×98.77 mm ²	98.77×98.77 mm ²	98.77×98.77 mm ² ×4
Statistic Uncertainty	3,100 Hz 690 ppb	710 Hz 160 ppb	19 Hz 4 ppb

Status of Software Development

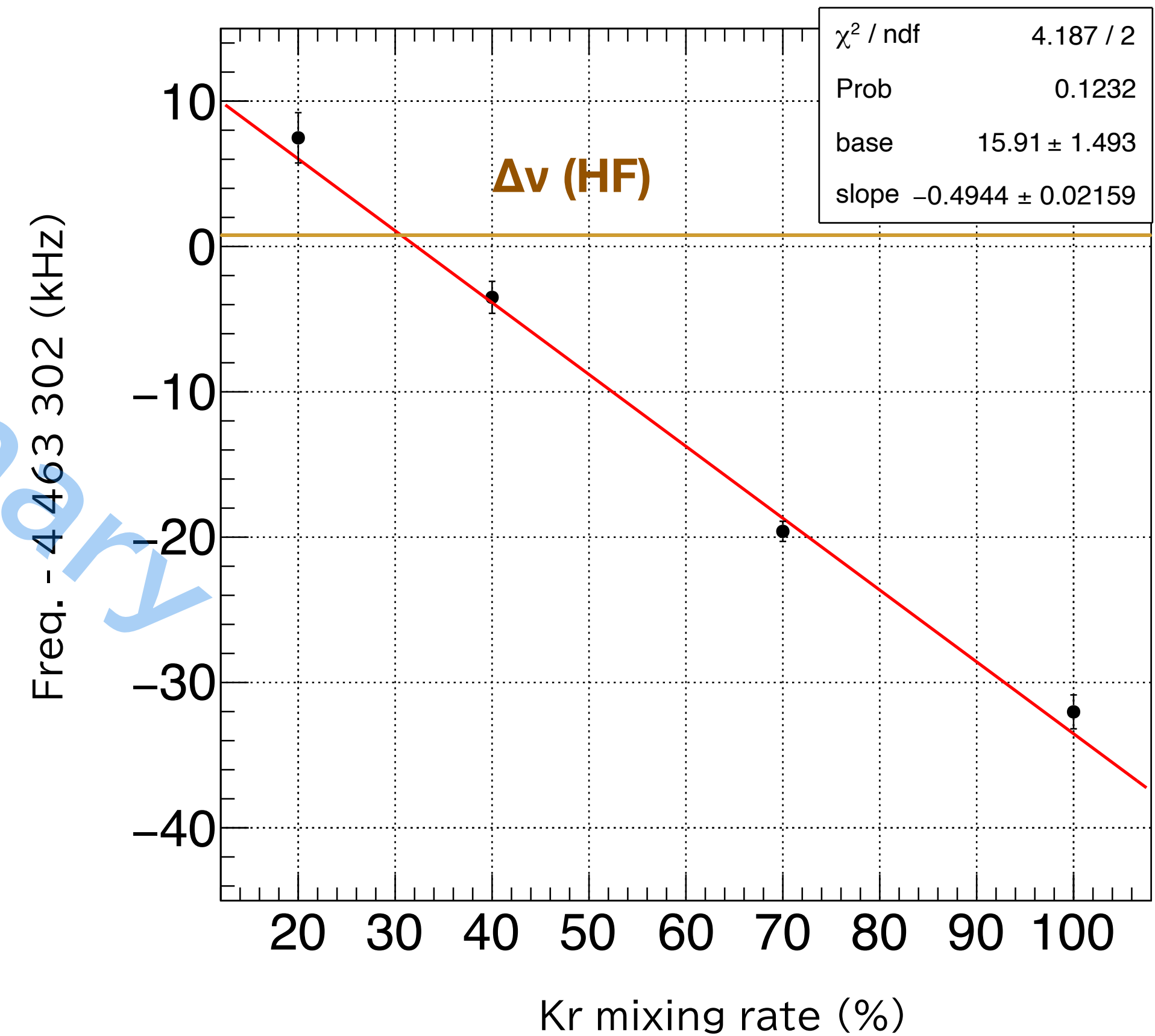
	Connection Test	Controller	Operator	Implementation
Thermometer	✓	✓	✓	✓
Pressure gauge	✓	✓	✓	✓
Signal generator	✓	✓	✓	
VNA	✓	✓		
Piezo cntl.	✓			
MW monitor	✓	✓	✓	✓
MW switch	✓			
DAQ			✓	
Field probe	✓	✓	✓	
Blind analysis	-			

Kr-He Mixture Gas

Pressure dependence of Mu HFS



Mixing ratio dependence (1 atm)



MuSEUM Experiment Timeline

2011

- Muonium HFS proposal submitted

2017

- Mu HFS resonance measured at zero field @ Kr 1 atm

2018

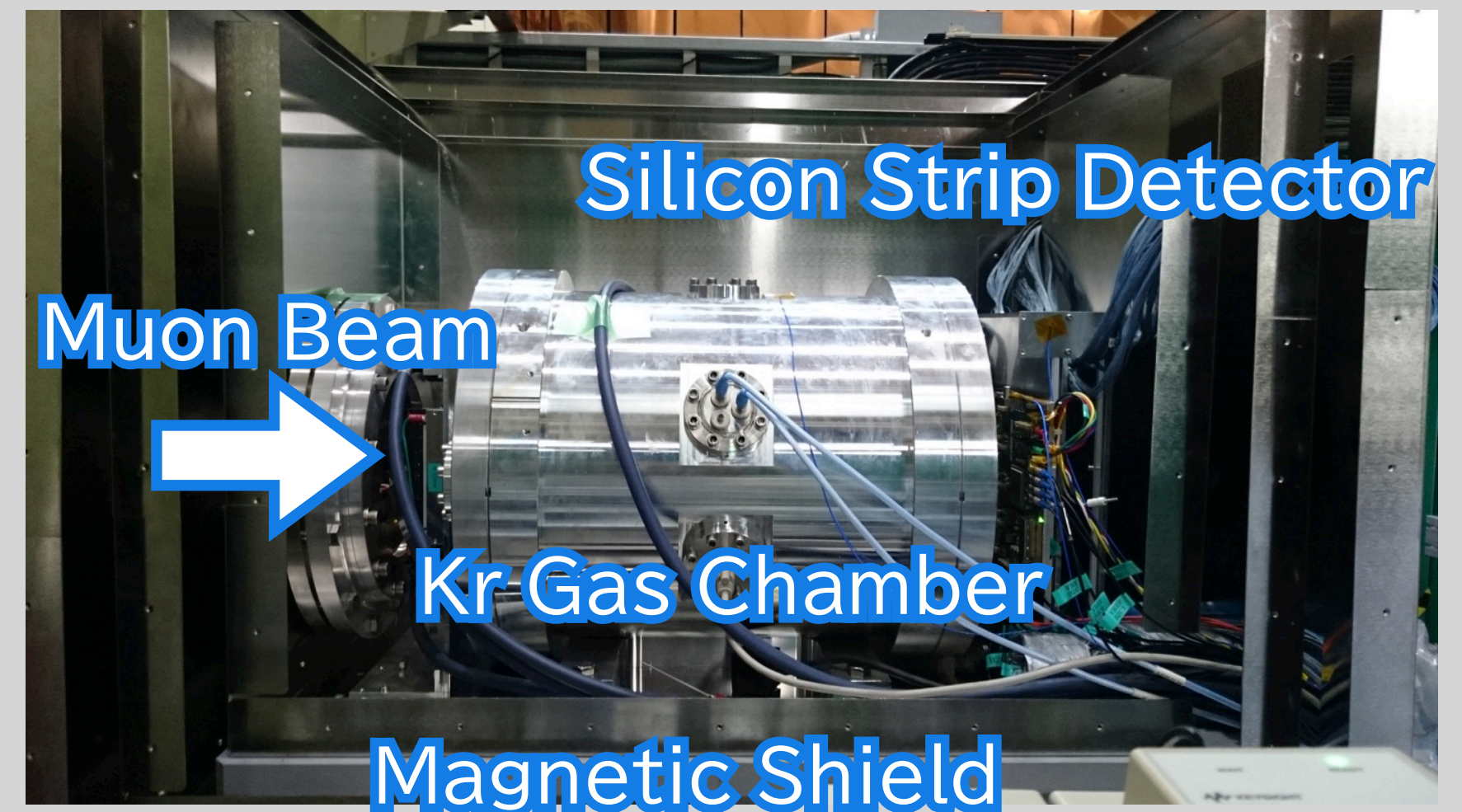
- Measurement @ Kr 0.3, 0.4, 0.7 atm
- Development of Rabi-oscillation spectroscopy

2019

- Measurement with Kr-He mixture gas
- Upgrade with silicon strip detector

2022~

- H-line commissioning
- High-field measurement



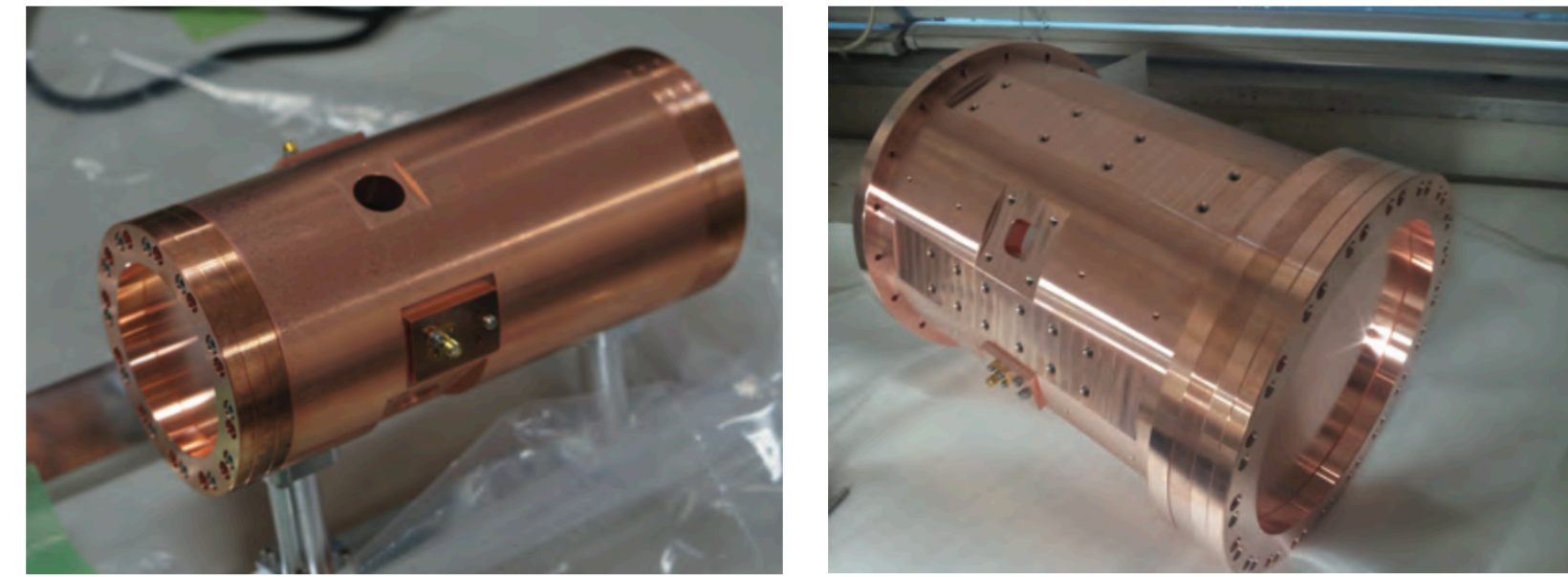
MuSEUM Publications

ZF and HF cavity

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. Iwasaki³, O. Kamigaito³, S. Kanda^{4,5,6}, N. Kawamura^{4,5,6}, Y. Matsuda², T. Mibe^{5,6,7}, S. Nishimura^{4,5}, N. Saito^{5,8}, N. Sakamoto³, S. Seo^{2,3}, K. Shimomura^{4,5,6}, P. Strasser^{4,5,6}, K. Suda³, 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



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. Toriiⁱ, 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. Torii³, Y. Fukao^{1,2,4}, T. U. Ito^{2,5}, M. Iwasaki⁶, S. Kanda⁶, K. Kawagoe⁷, D. Kawall⁸, N. Kawamura^{1,2,4}, N. Kurosawa^{1,2}, Y. Matsuda⁹, T. Mibe^{1,2,4}, Y. Miyake^{1,2,4}, N. Saito^{1,2,4,3}, K. Sasaki^{1,2,4}, Y. Sato¹, S. Seo^{6,9}, P. Strasser^{1,2,4}, T. Suehara⁷, K. S. Tanaka¹⁰, T. Tanaka^{6,9}, J. Tojo⁷, A. Toyoda^{1,2,4}, Y. Ueno⁶, T. Yamanaka⁷, T. Yamazaki^{1,2,4}, H. Yasuda³, T. Yoshioka⁷ and K. Shimomura^{1,2,4}
(MuSEUM Collaboration)

