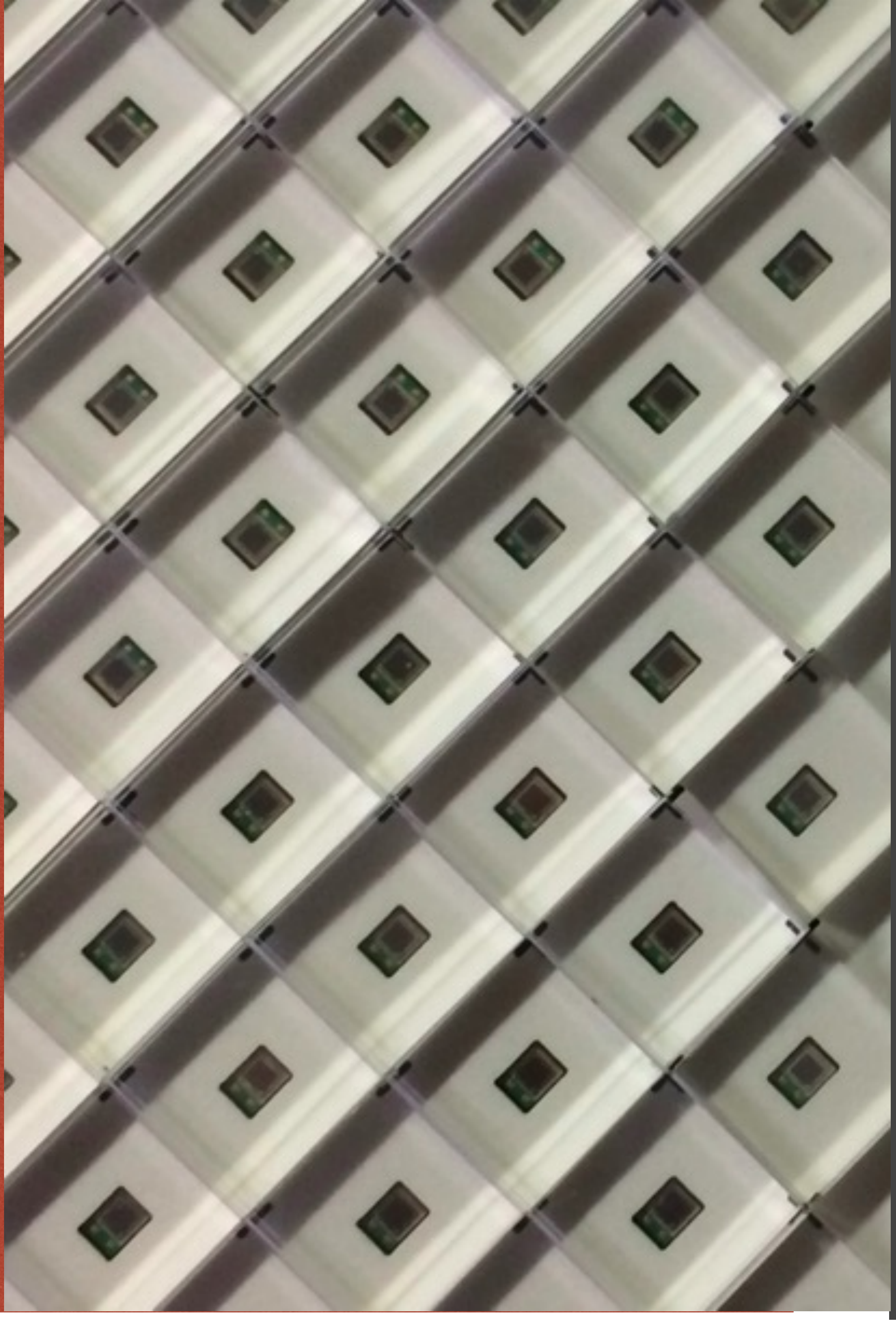
Muonium Hypefine Measurement at J-PARC



Sohtaro Kanda / THE UNIVERSITY OF TOKYO

kanda@post.kek.jp

2016. 09. 12 at INPC2016

MuSEUM Collaboration

MuSEUM

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

東京大学
THE UNIVERSITY OF TOKYO

KEK

J-PARC

RIKEN

JAEA

ICU

Yamanashi Univ.

Osaka Univ.

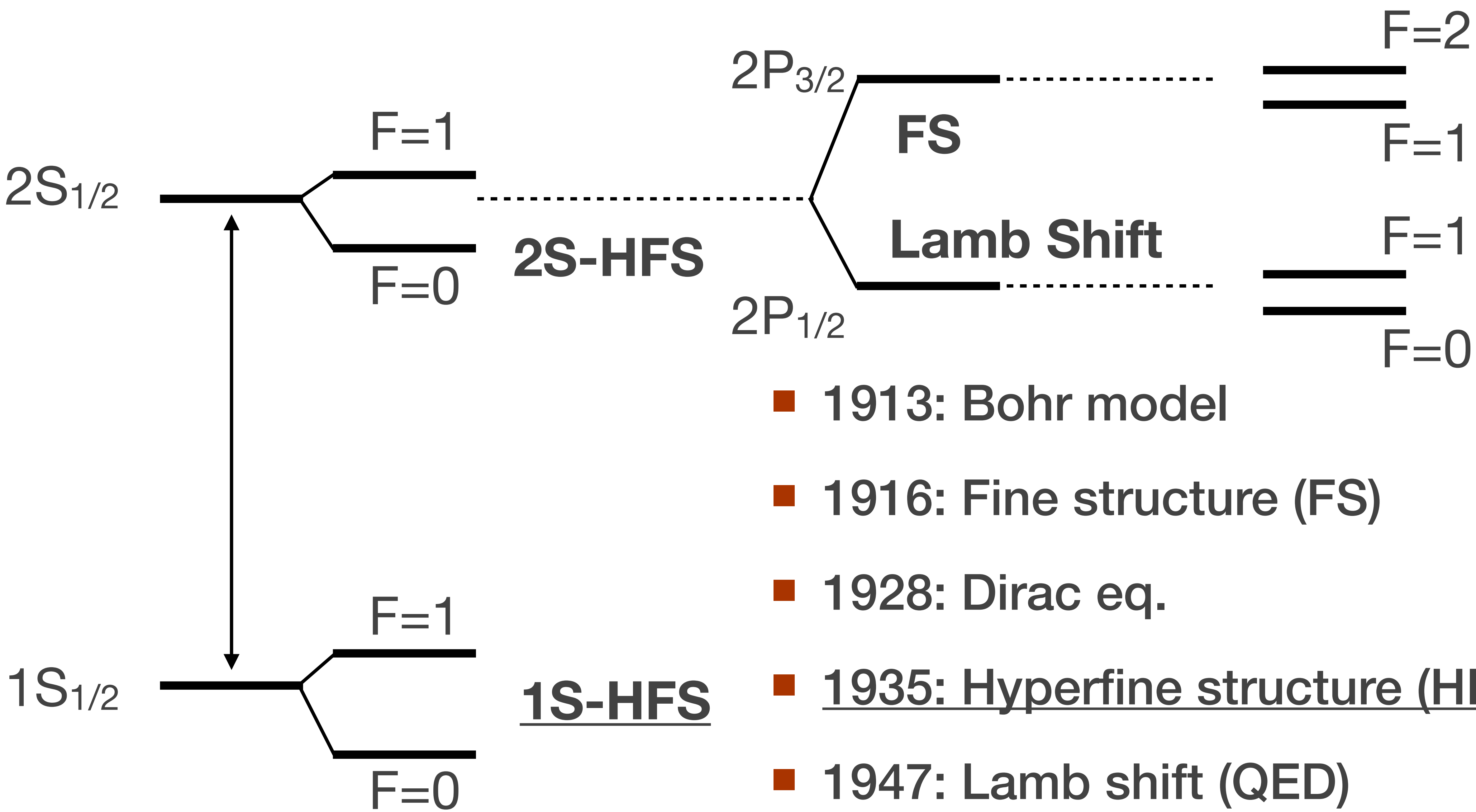
UMASS

Univ. of Massachusetts

5 Universities, 4 Institutions, 40 people

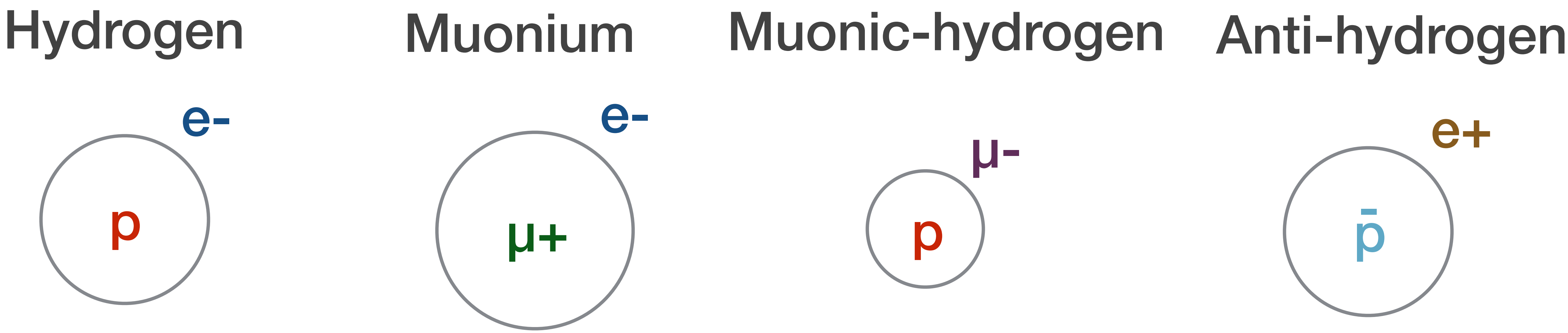
Hydrogen Atom Spectroscopy

- **The progress of hydrogen atom spectroscopy had brought evolution of quantum mechanics**



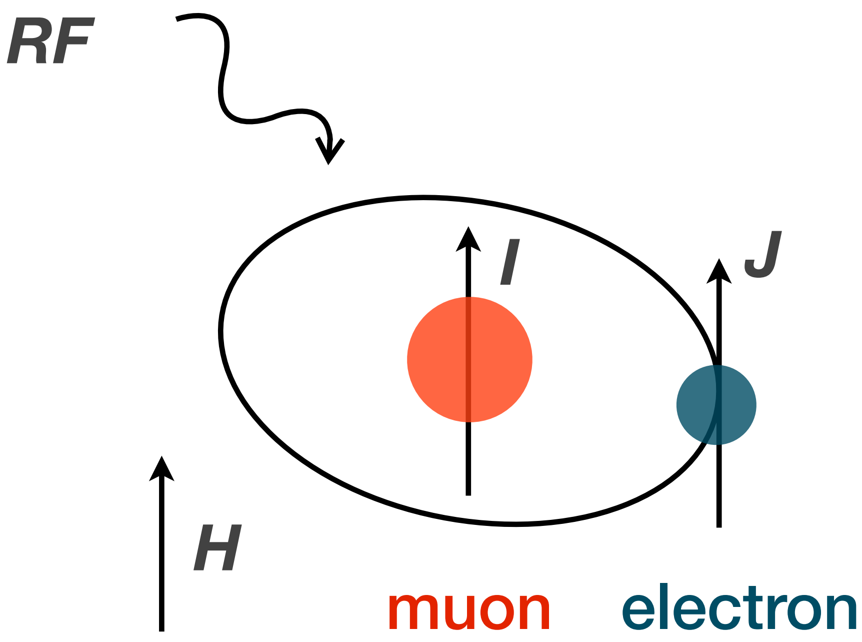
- **1913: Bohr model**
- **1916: Fine structure (FS)**
- **1928: Dirac eq.**
- **<u>1935: Hyperfine structure (HFS)</u>**
- **1947: Lamb shift (QED)**

HFS of Hydrogen-Like Atoms



System	Outcome	Precision
Hydrogen	Galactic motion (21 cm line)	The most precise experiment (2.1 ppt) Limited theoretical precision (1.2 ppm)
Muonium	**Muon mass, Muon g-2 Lorentz invariance test, Dark photon search**	**Precise experiment (12 ppb) Precise theory (63 ppb)**
Muonic-hydrogen	Proton radius, Muon catalyzed fusion	Not measured yet (proposed experiment's goal is 1%)
Anti-hydrogen	Test of CPT invariance	Not measured yet (proposed experiment's goal is 1 ppm)

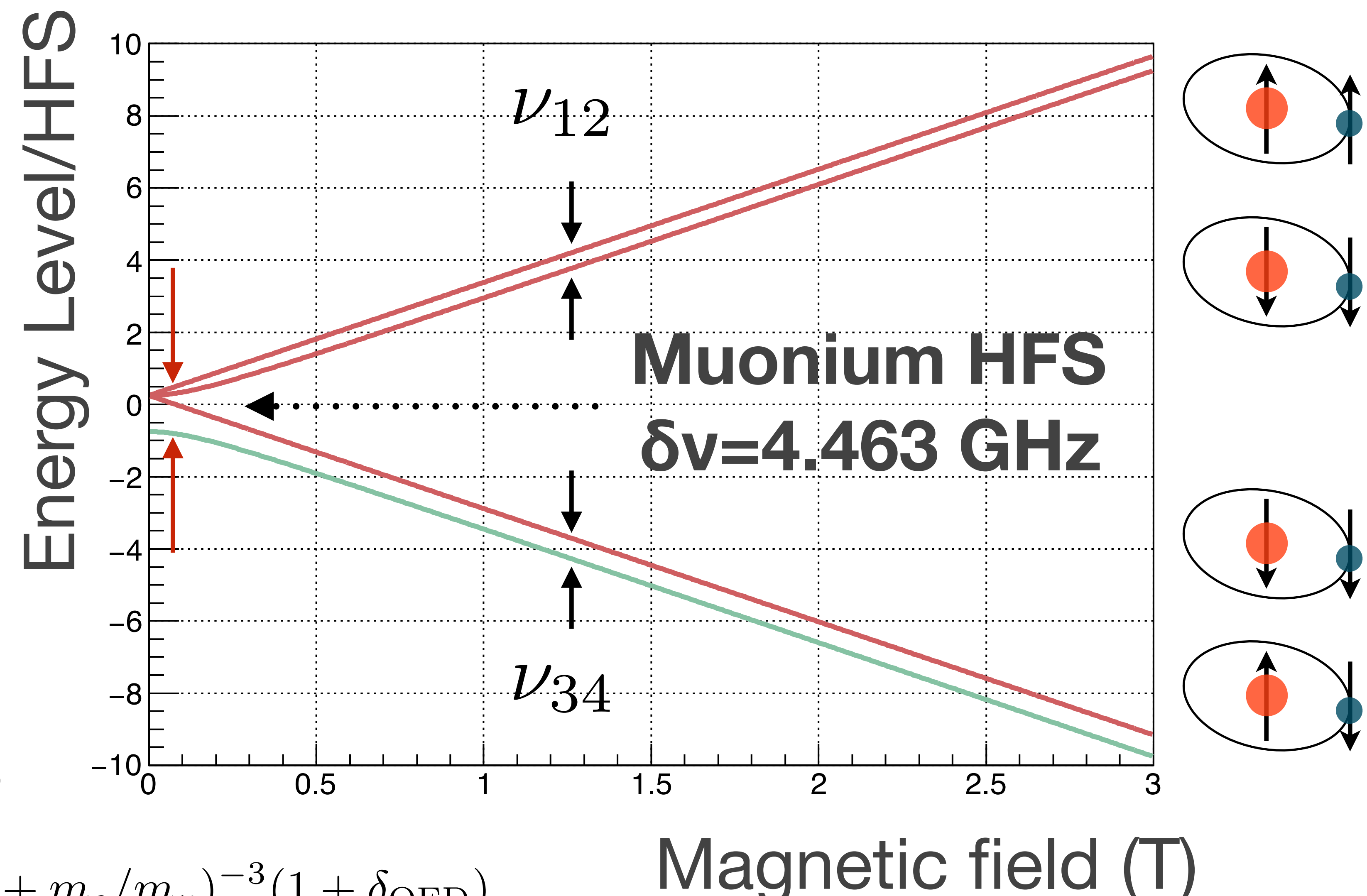
Muonium Energy Levels



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

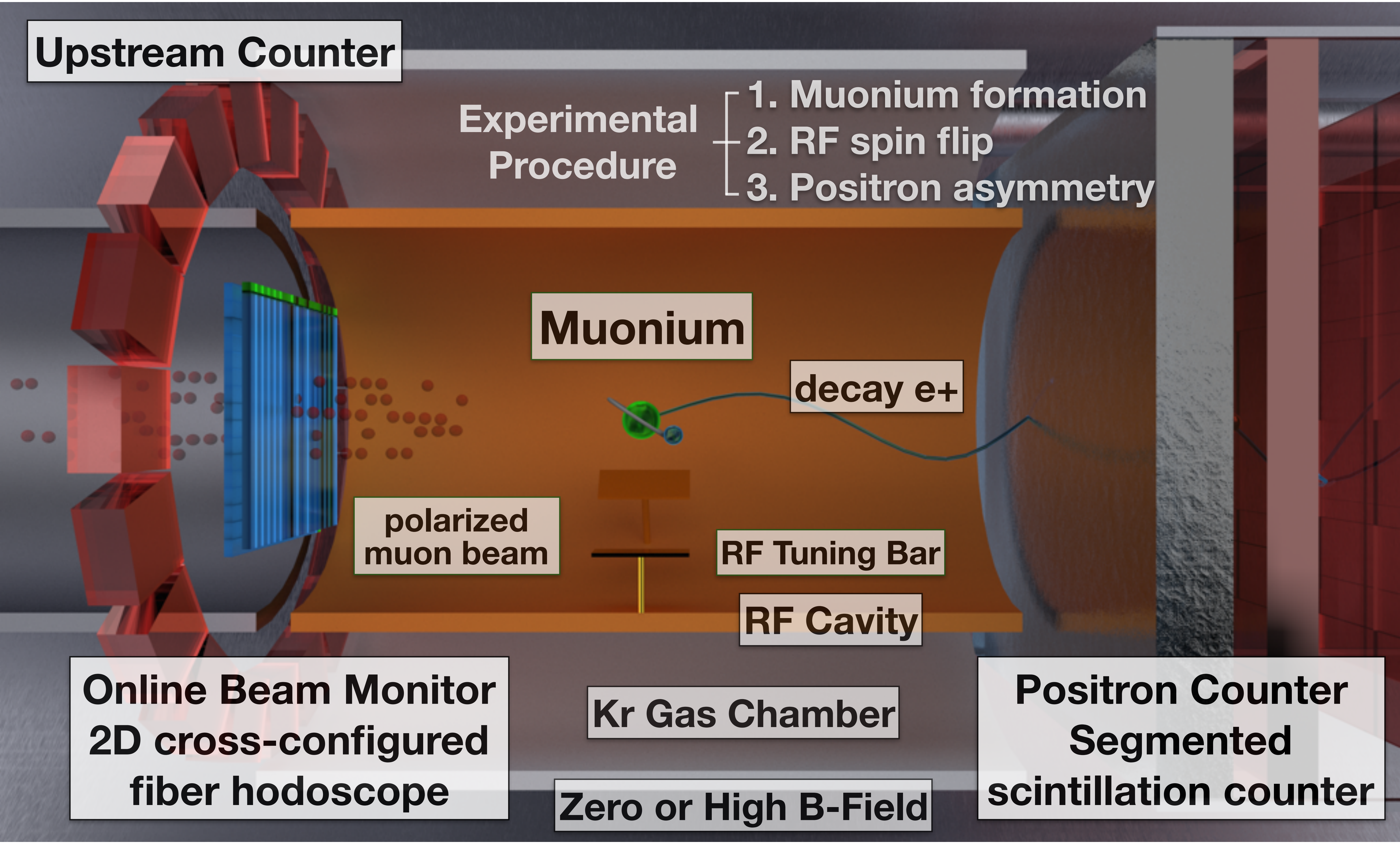
$$\nu_{12} - \nu_{34} \propto \mu_\mu / \mu_\mathrm{p}$$

or $\delta_\nu = (\frac{16}{3}\alpha^2 R_\infty c g_e g'_\mu)(1 + m_e/m_\mu)^{-3}(1 + \delta_{\mathrm{QED}})$

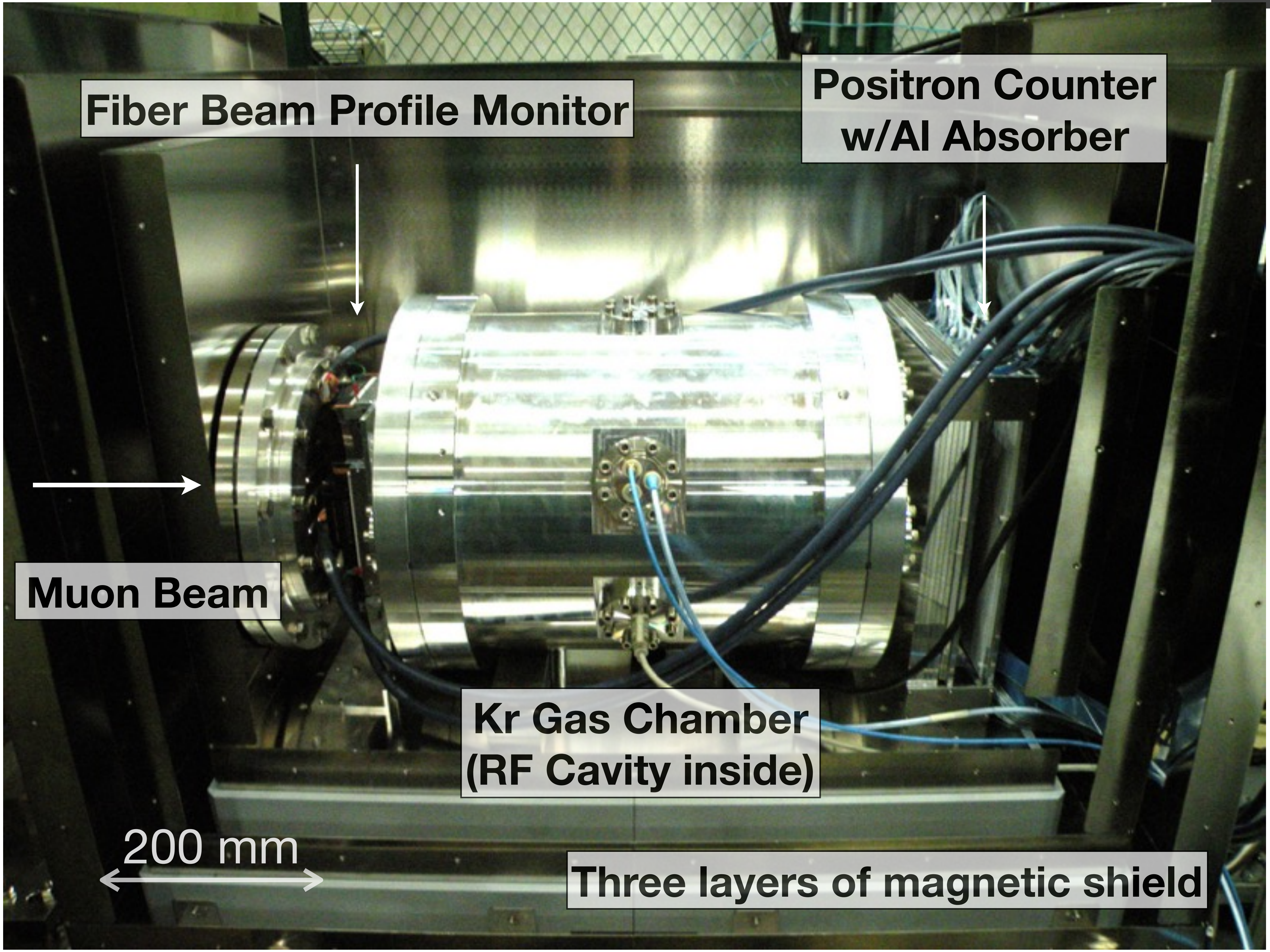


- Direct measurement at zero magnetic field (δv)
- Indirect measurement under a high magnetic field (ν_{12} and ν_{34})
- **Our goal is x10 improvement for both experiments**

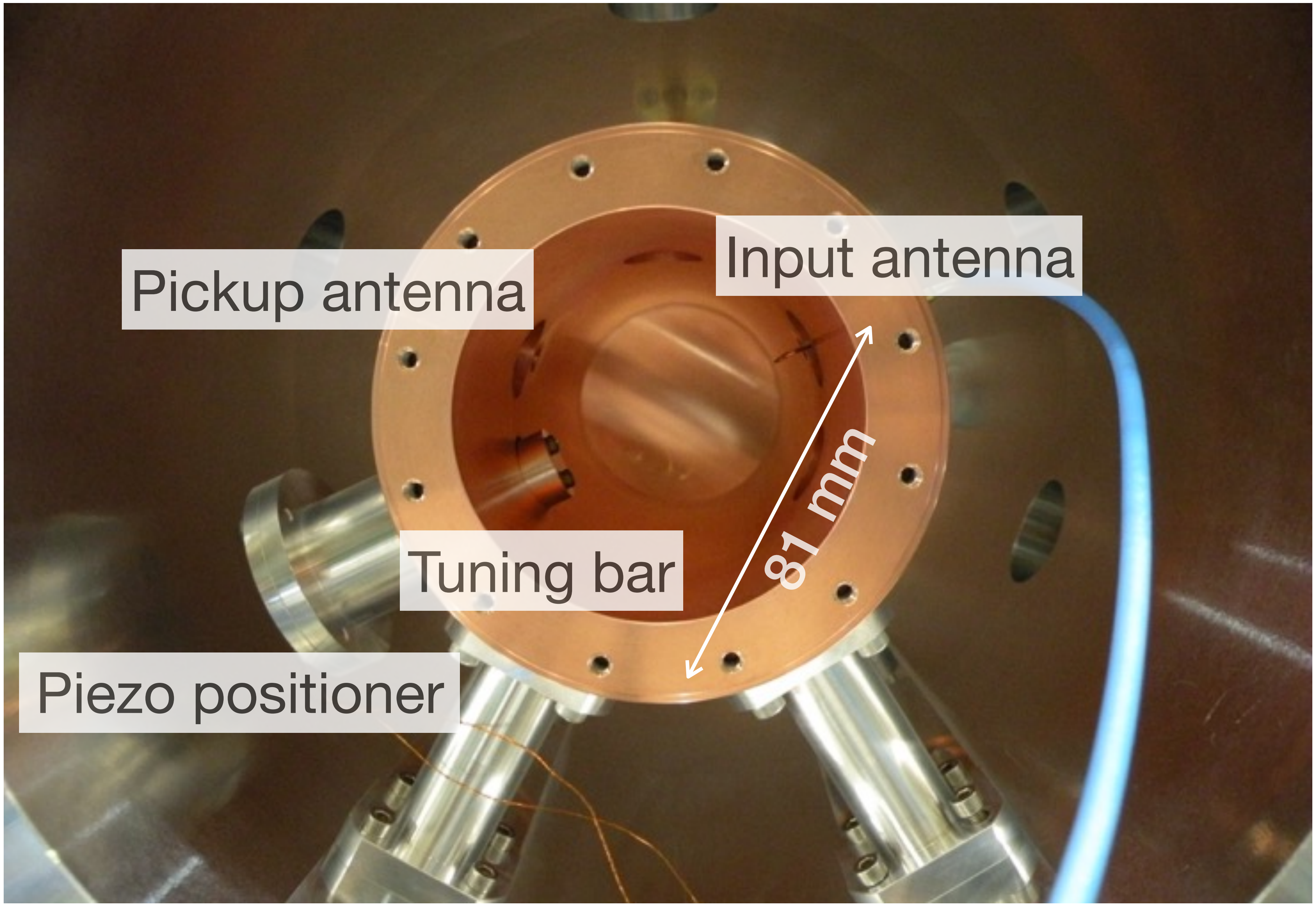
Experimental Overview



Resonance Measurement Setup

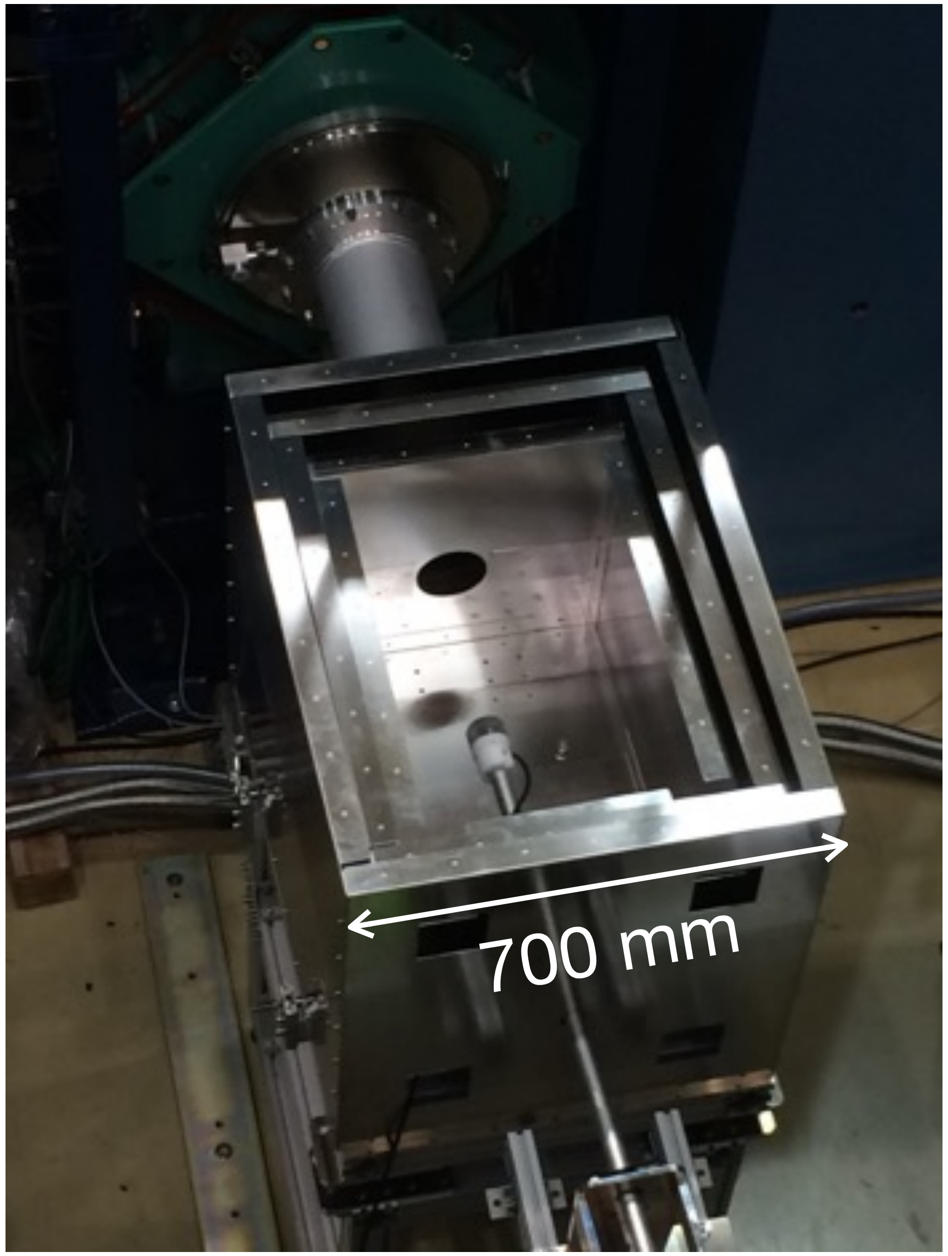


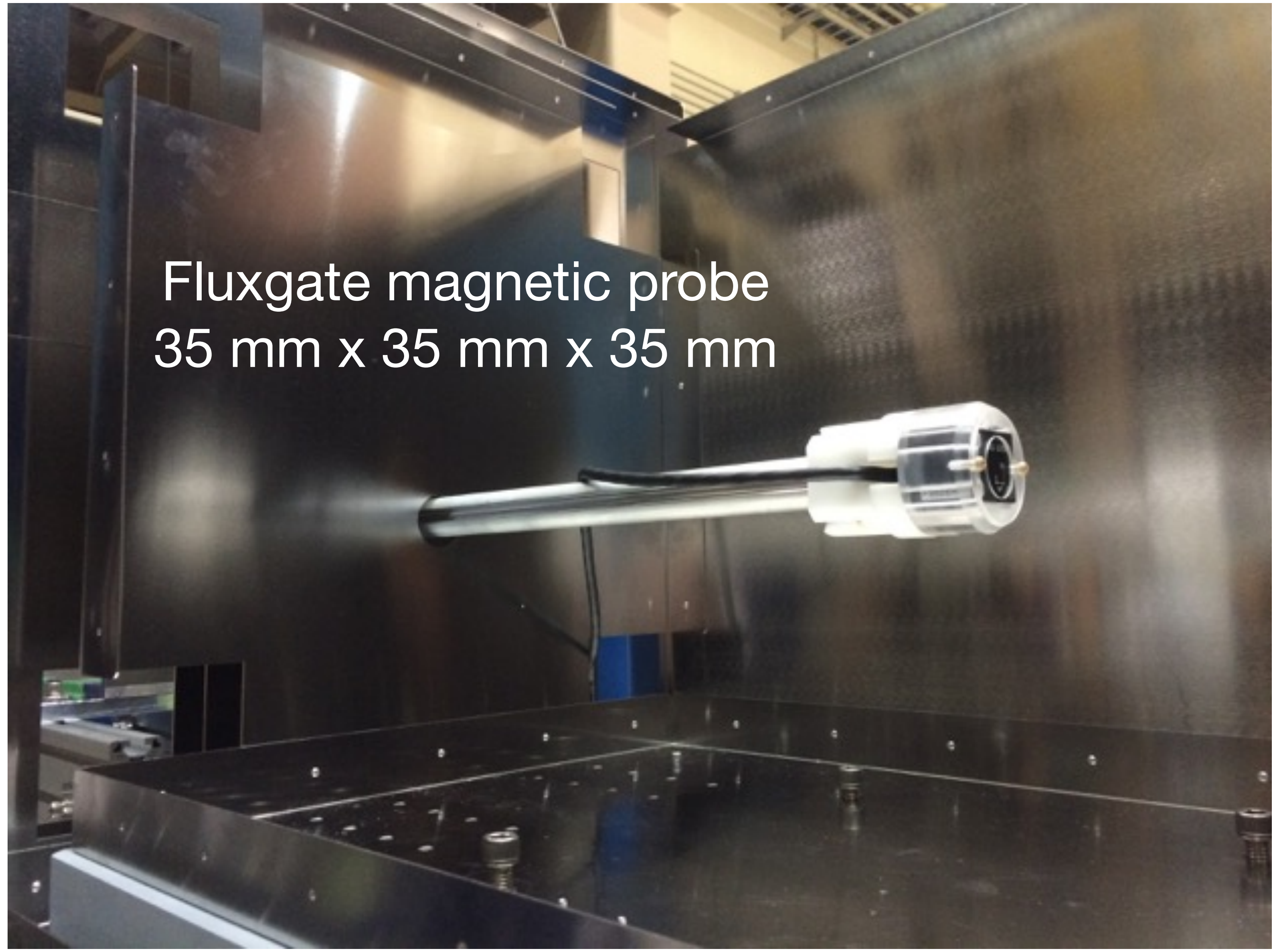
Inside of the Gas Chamber



- TM110 mode at 4.463 GHz, +-1 MHz tuning by a piezo positioner
- Expected Q-value is 10000, microwave power is up to 3 W

Magnetic Shield and Field Probe

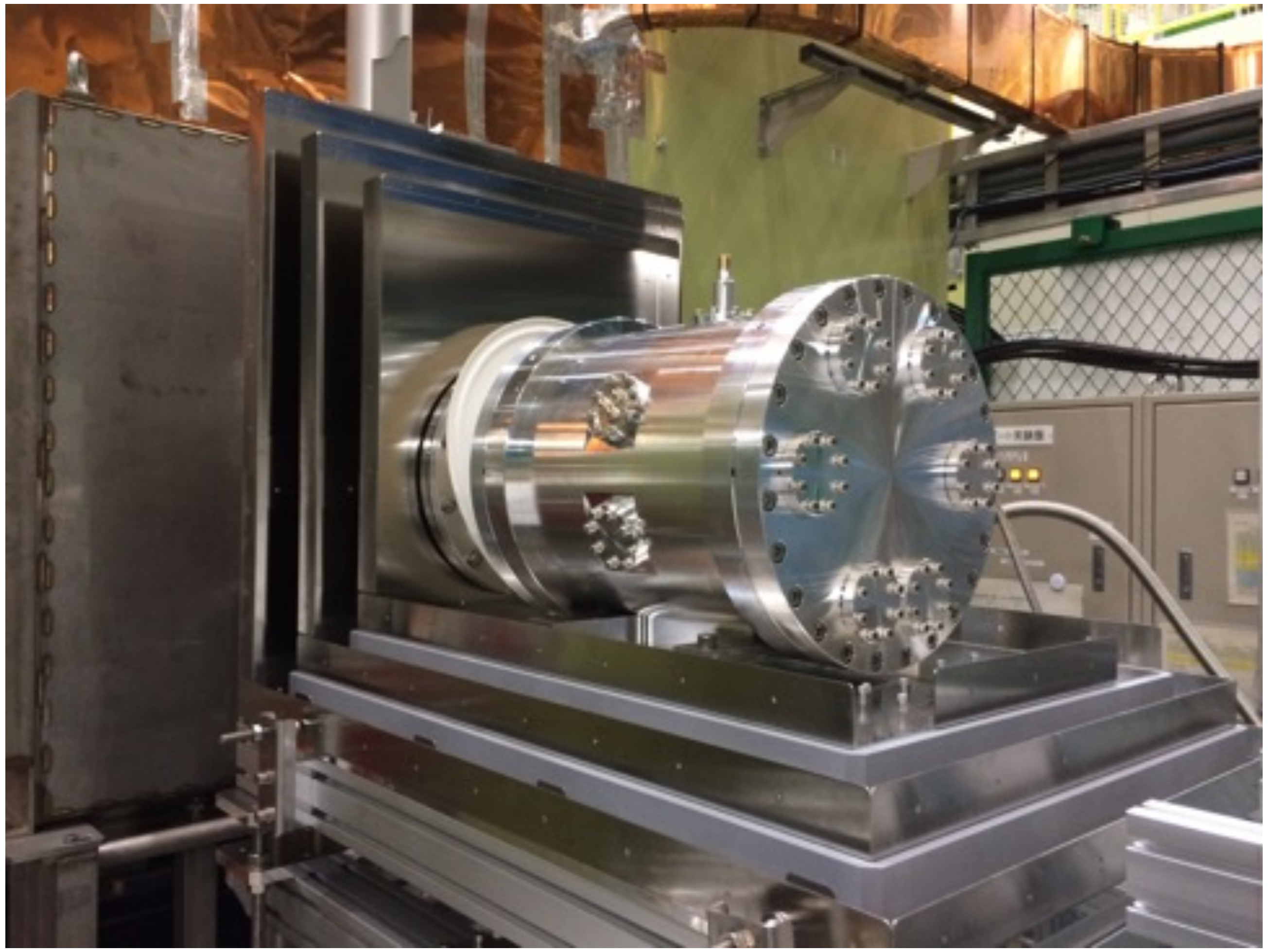




- **B-Field was suppressed from 3000 nT to 80 nT**
- **Field gradient was suppressed to be acceptable (30 nT~80 nT)**

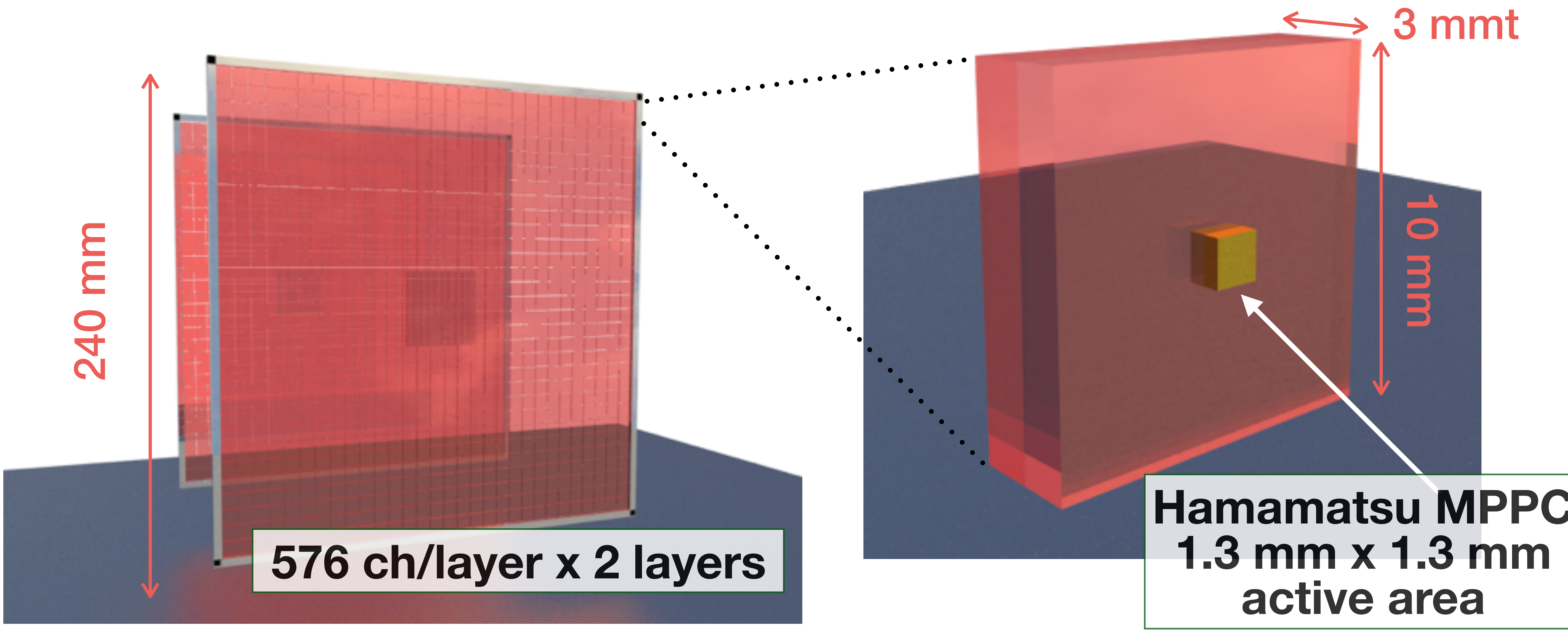
S. Kanda, RIKEN Accelerator Progress Report Vol.49 (in press)

Gas Chamber and Gas Handling



- 425 mm length, 280 mm diameter, 100 µm Al beam window
- Pressure range is from 1e-4 Pa to 2e5 Pa
- Gas pressure is monitored by a capacitance gauge
- Gas purity is measured by Q-Mass spectrometer

Segmented Positron Counter

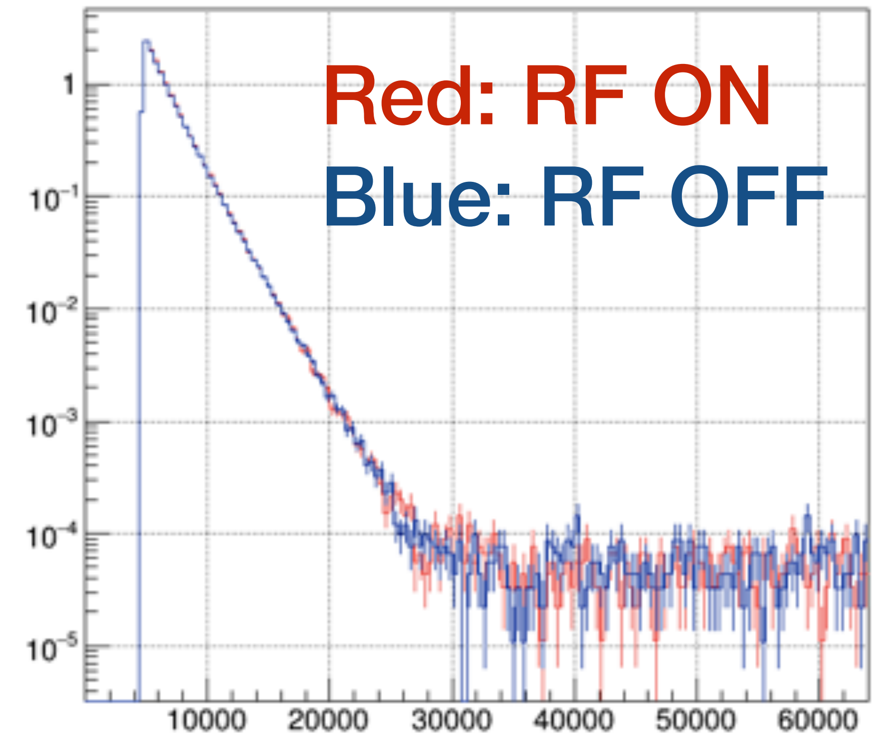


- Segmented scintillation counter with SiPM readout
- Unit cell is 10 mm x 10 mm x 3 mmt
- 240 mm x 240 mm area, 1152 ch. in total
- High rate capability is required (100 M muon/s at 1 MW)

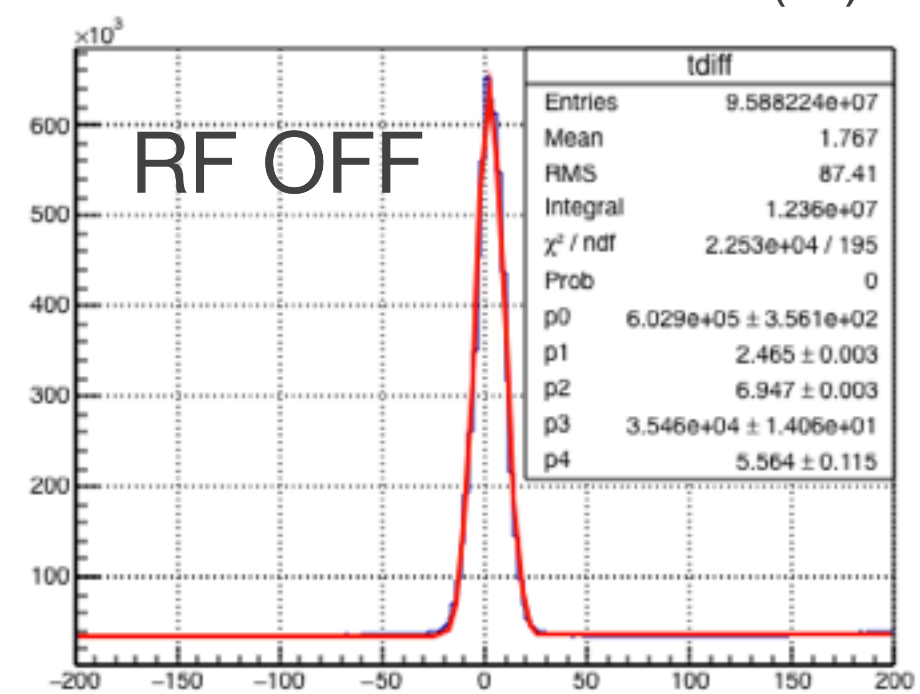
S. Kanda, PoS(PhotoDet16)039 (2016)

Data Taking and Analysis

- Gas chamber is filled with Kr target gas
- RF signal generator setting and cavity resonance tuning
- Data taking with RF ON or OFF
- Decay positron counting (A)
- Coincidence analysis with near and far detector layer (B)
- Taking the ratio Non/Noff
- Change RF frequency

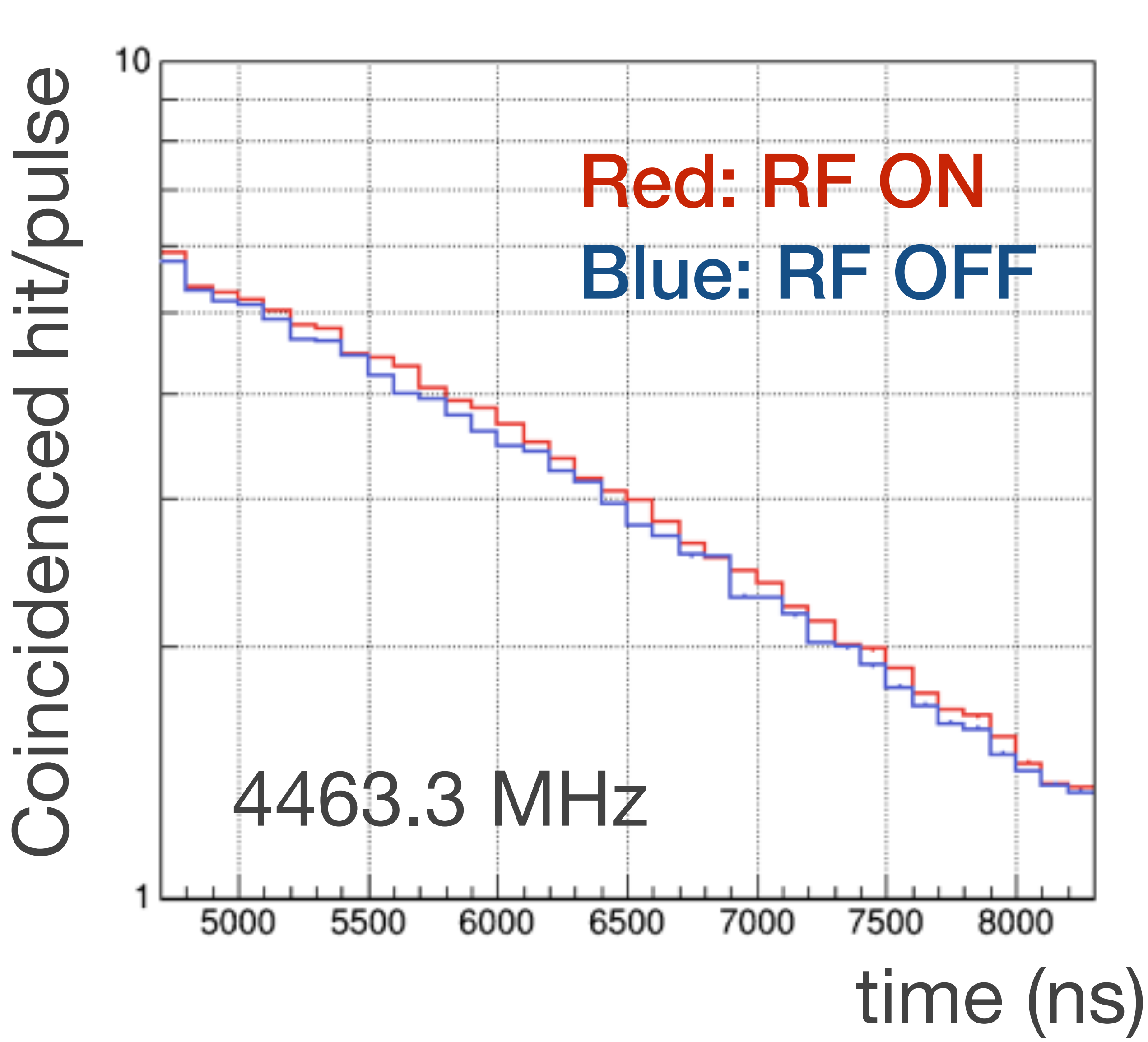


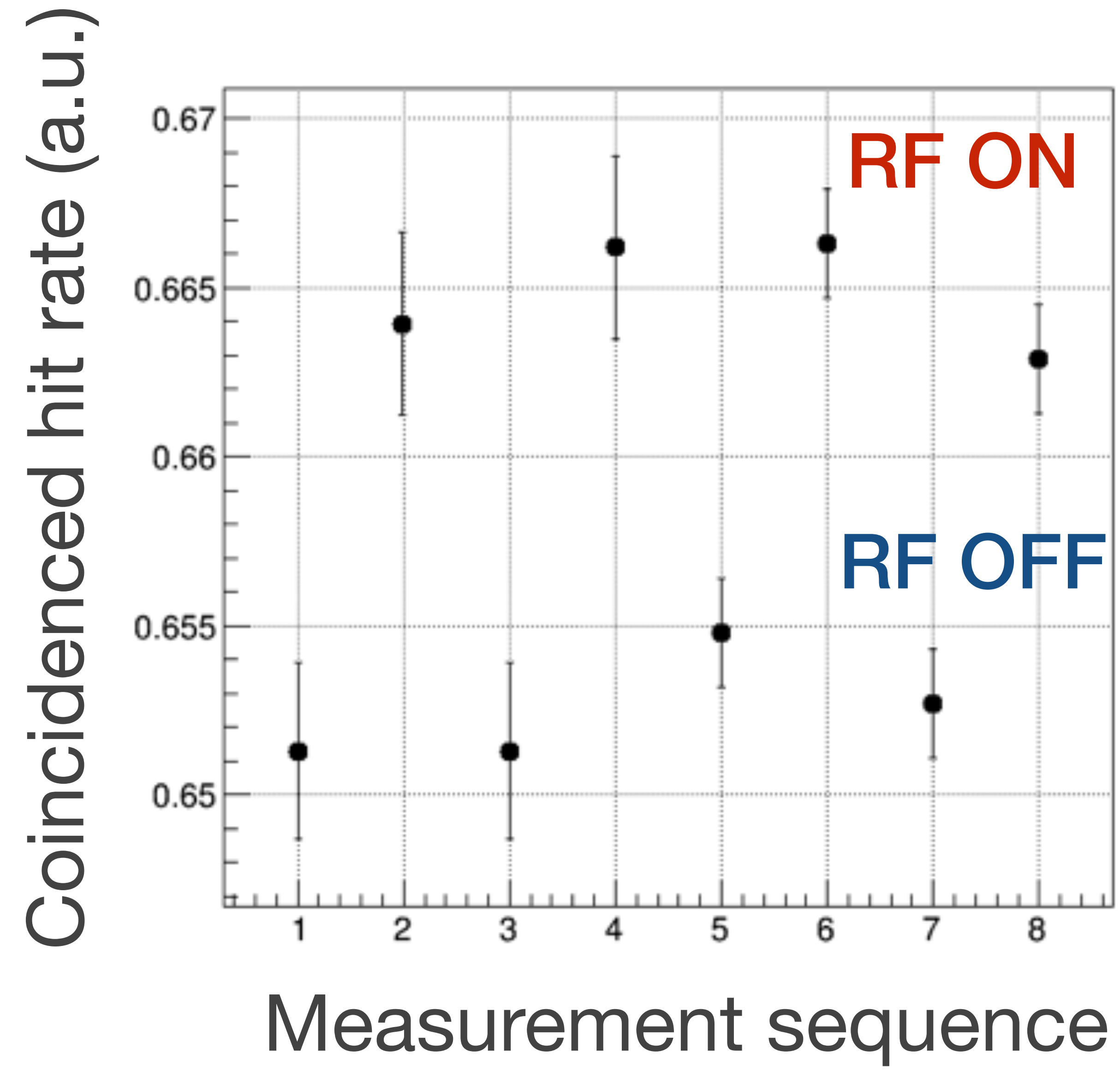
(A)



(B)

Positron Counting

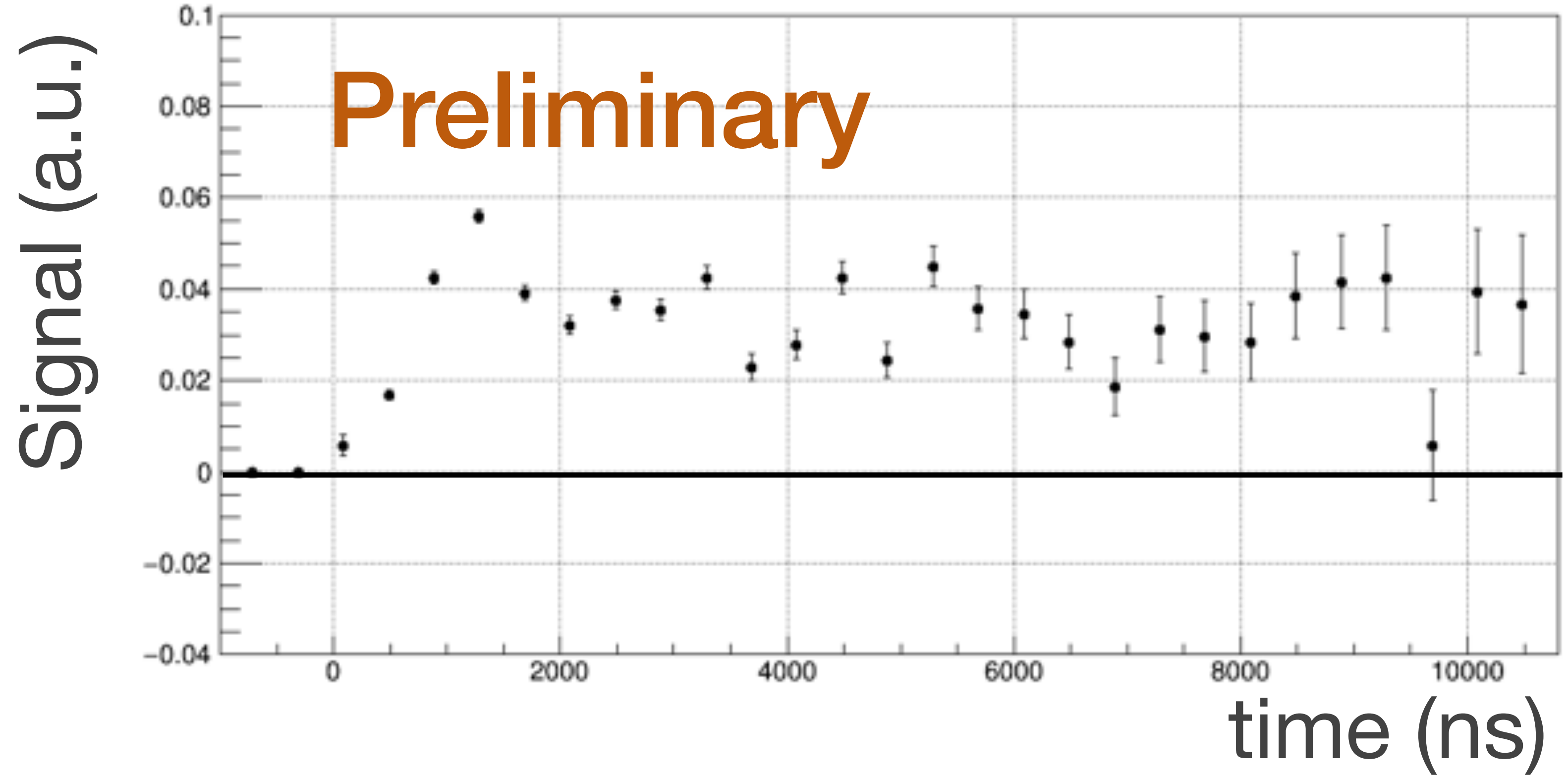




- RF was switched in 1 minute cycle
- Number of coincidenced decay positron was analyzed
- Each runs were normalized by the number of beam pulse

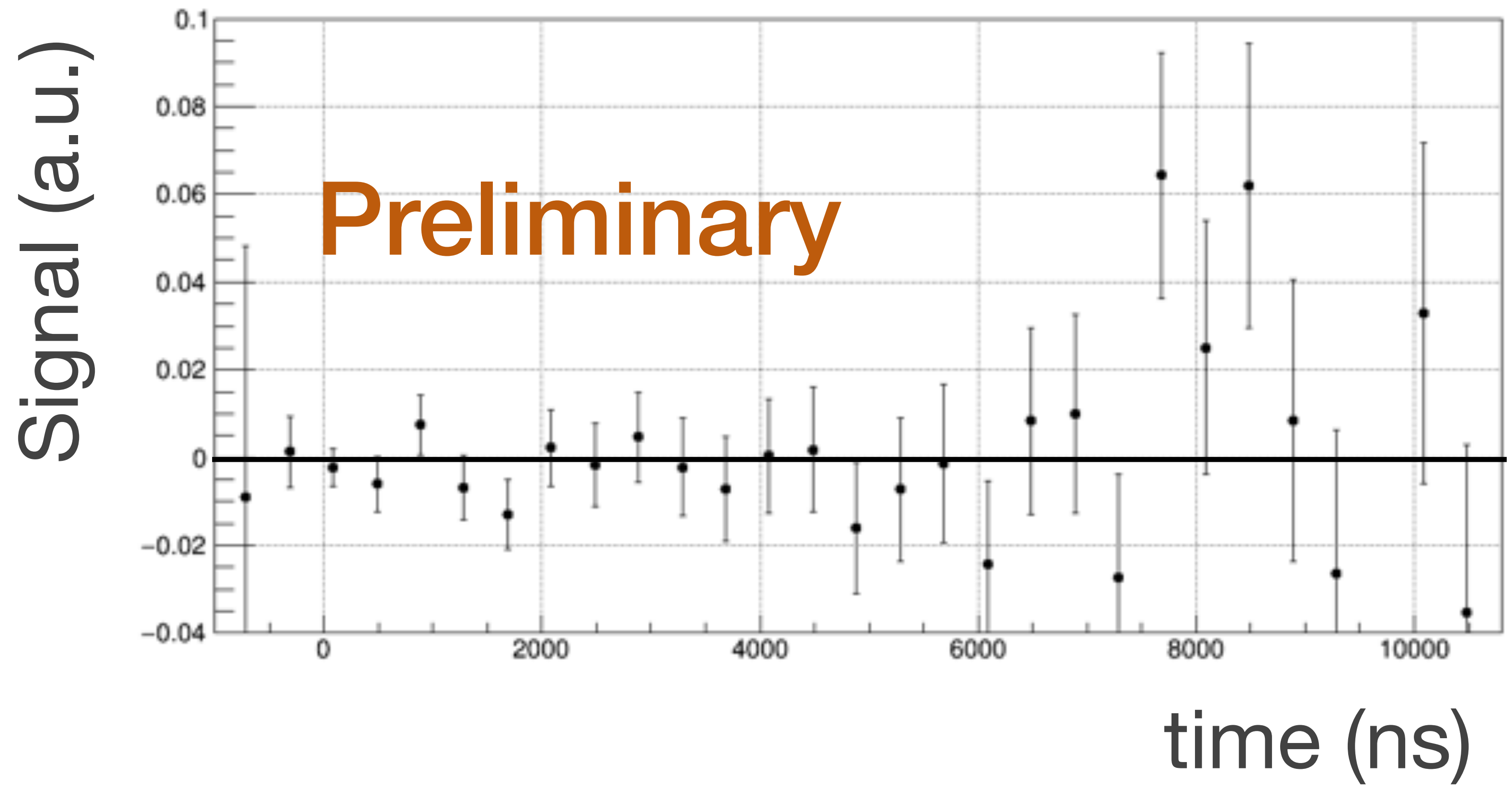
Time Dependent Spin Flip Signal

Near at Resonance
4463.1 MHz
RF frequency
1.0 Kr atm
27.4 MeV/c muon

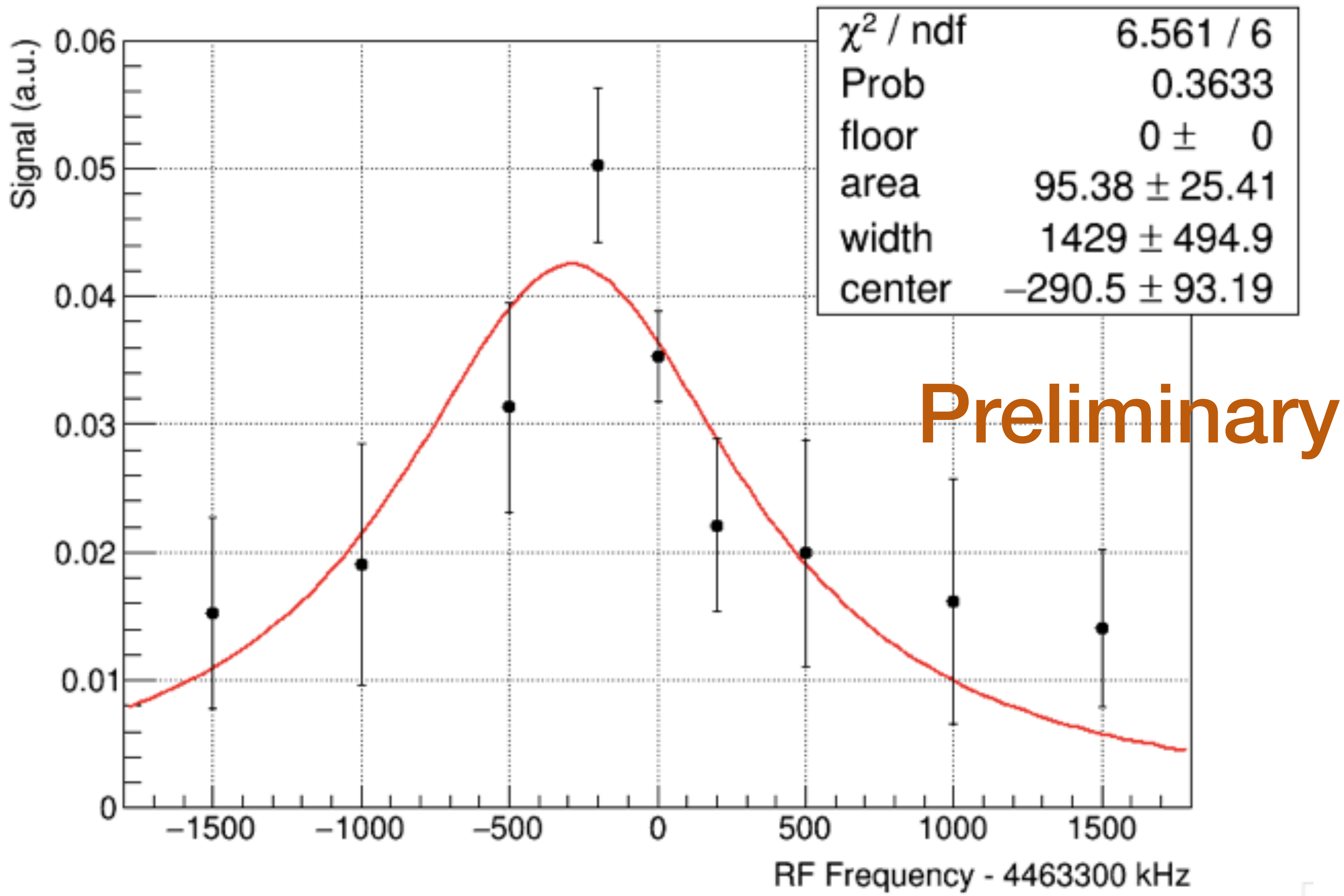


Off-Resonance
RF frequency was
far detuned
1.0 Kr atm
27.4 MeV/c muon

Signal = ON/OFF-1



Resonance Lineshape

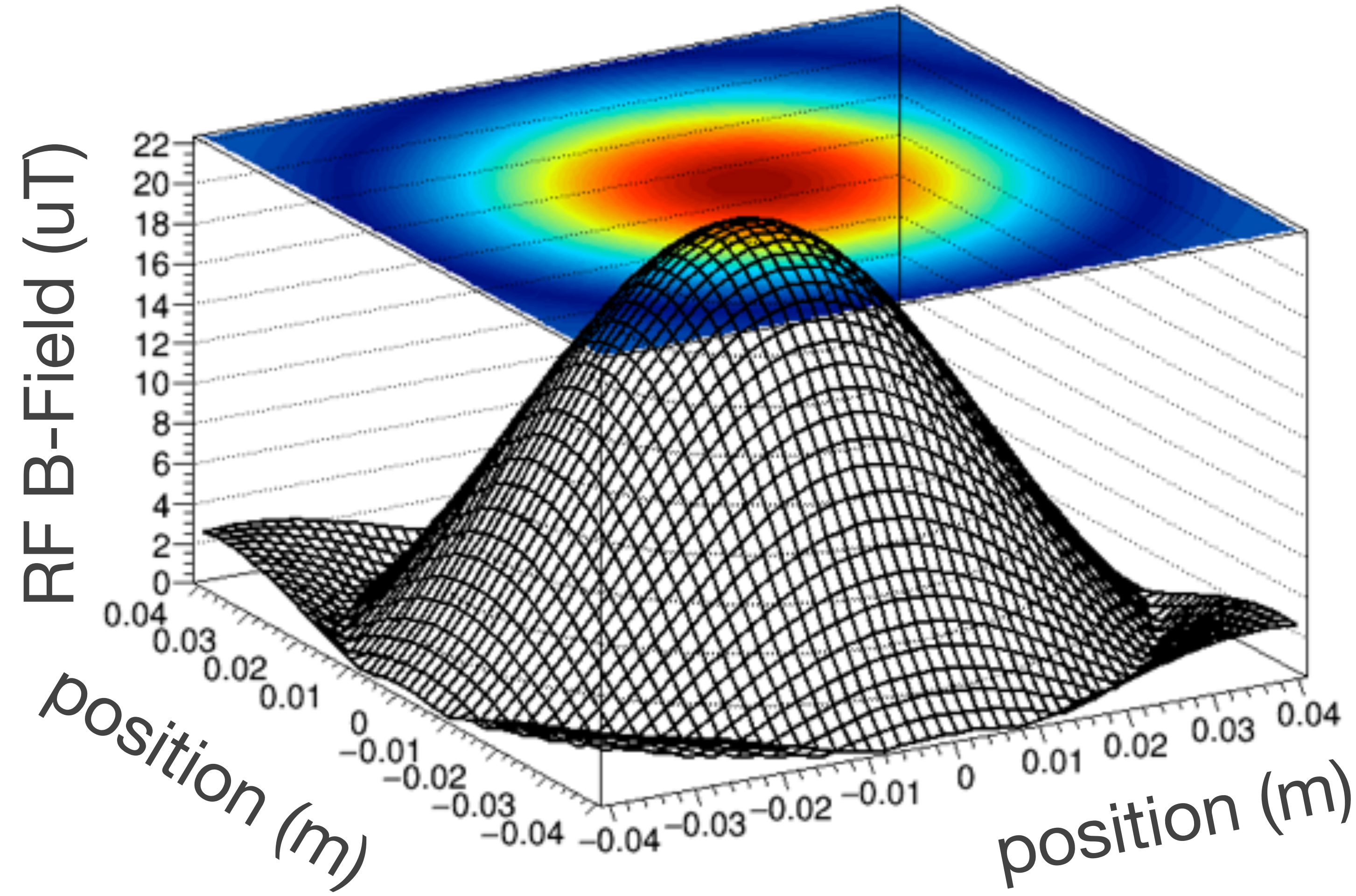


- Muonium HFS resonance was observed
- Fitted by Lorenzian and freq. center was 4463.01+-0.09 MHz
- Expectation from precursor experiments is 4463.0 MHz

Summary and Prospects

- Muonium HFS measurement is one of the high sensitivity experiments for beyond standard model physics
- The first physics measurement of muonium HFS at “zero” magnetic field was performed
- Muonium HFS resonance was observed at 1.0 atm Kr gas pressure with 27.4 MeV/*c* muon beam
- Obtained HFS frequency was 4463 MHz and consistent w/ previous experimental result
- B-field uniformity, RF stability, gas purity were good enough
- Data analysis will be updated very soon
- Next zero field experiment is scheduled after summer shut down

RF Cavity

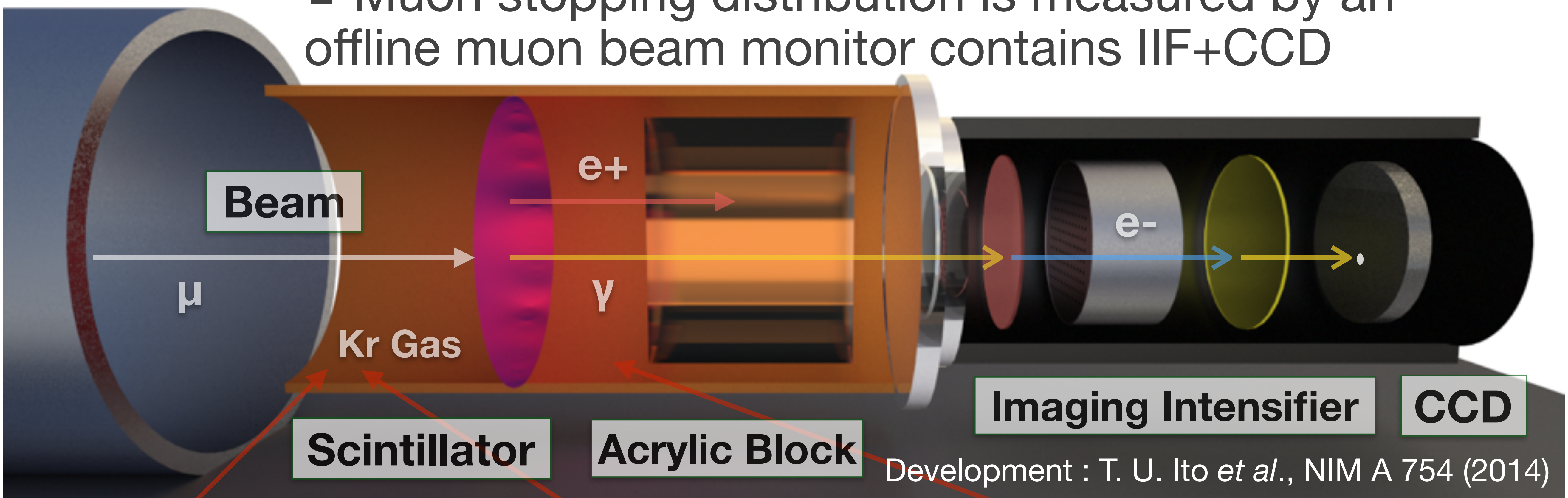


Calculated RF B-Field map

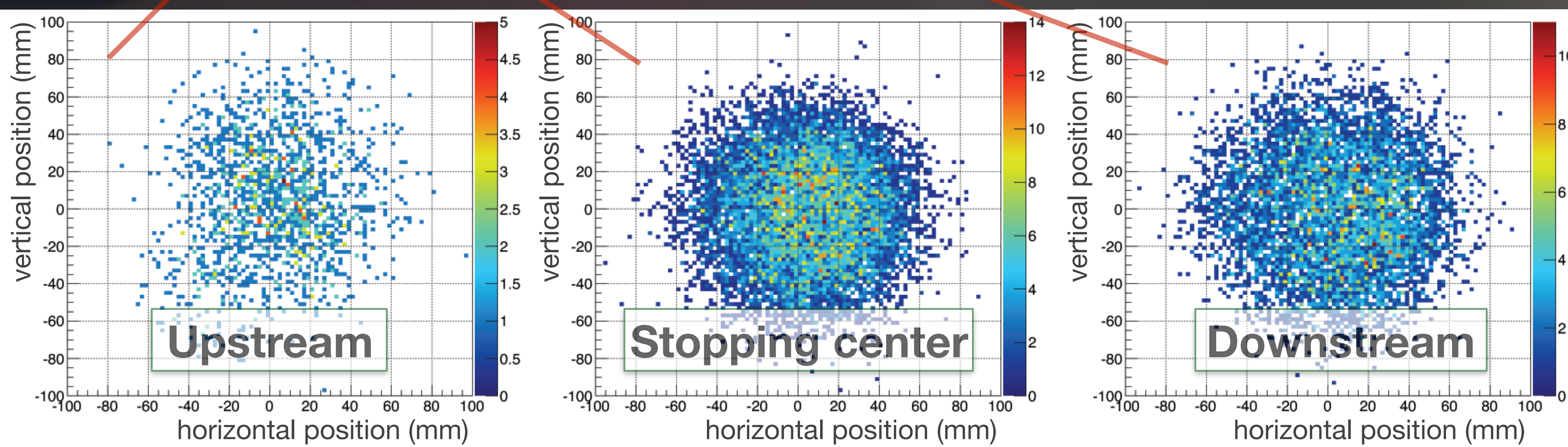
- 230 mm length, 81 mm diameter, made of pure copper
- TM110 mode at 4.463 GHz, +-1 MHz tuning by a piezo positioner
- Expected Q-value is 10000, microwave power is up to 3 W

Target Beam Profile Monitor

- Muon stopping distribution is measured by an offline muon beam monitor contains IIF+CCD

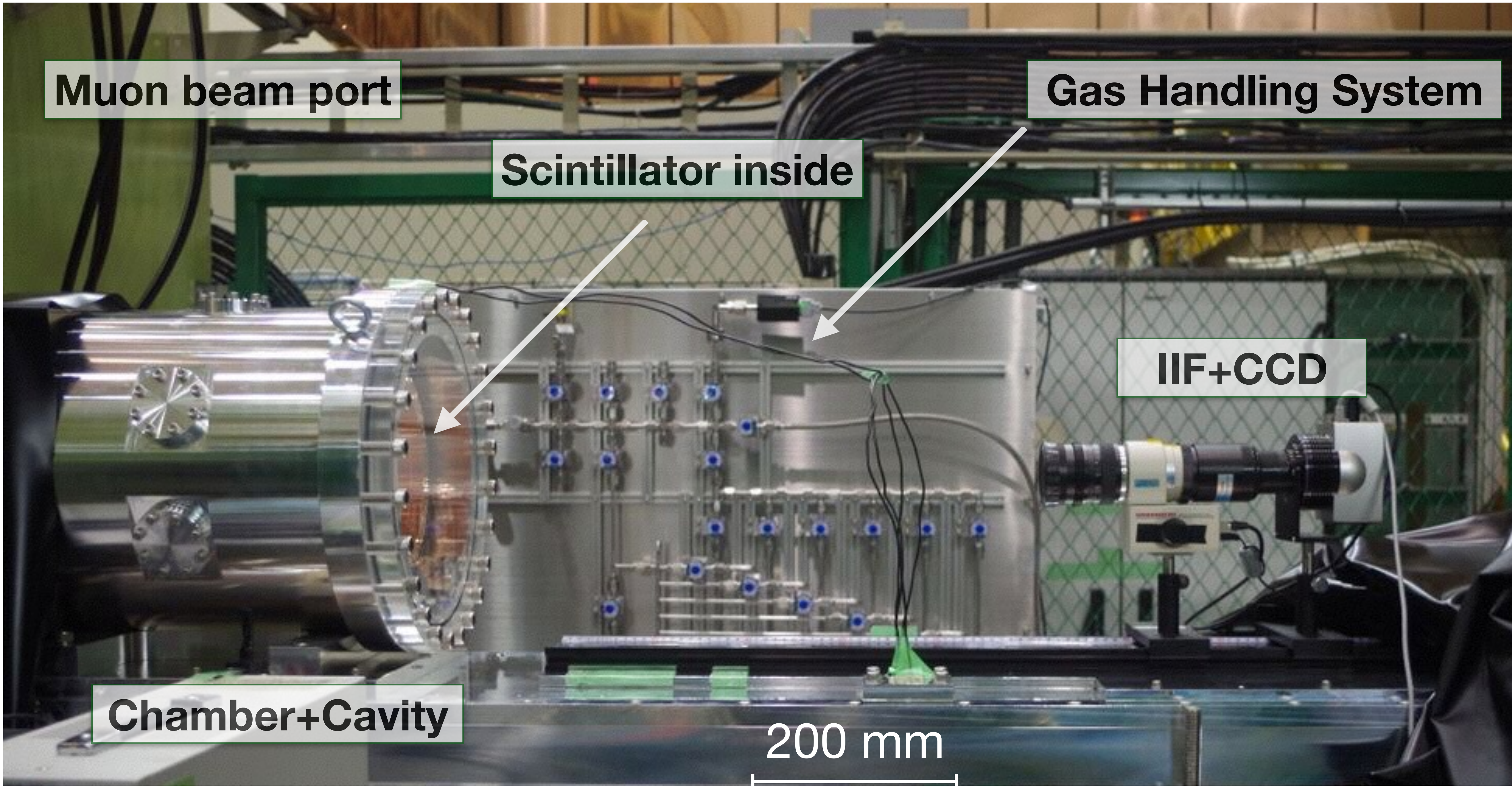


Development : T. U. Ito *et al*., NIM A 754 (2014)



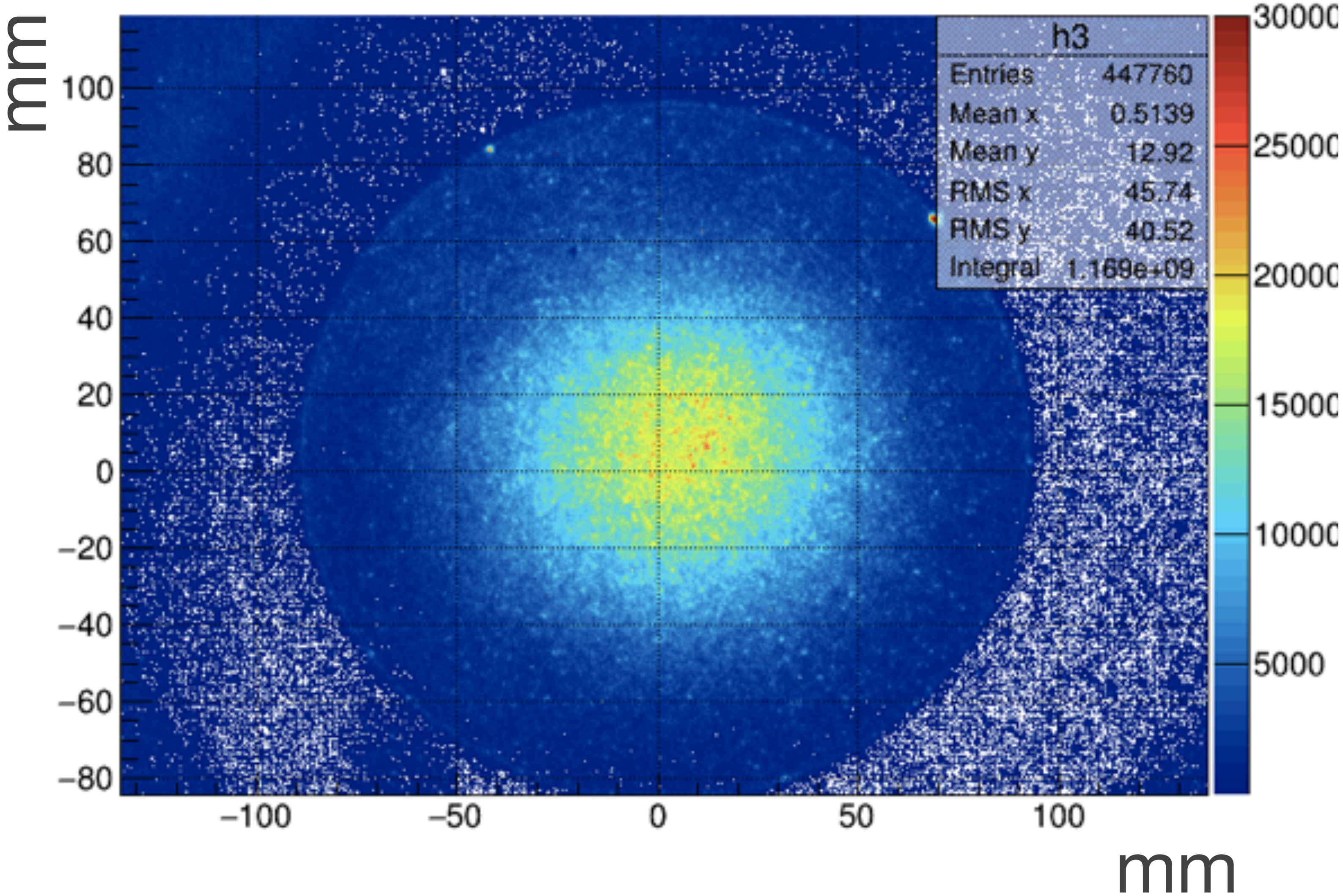
Simulated muon stopping distribution

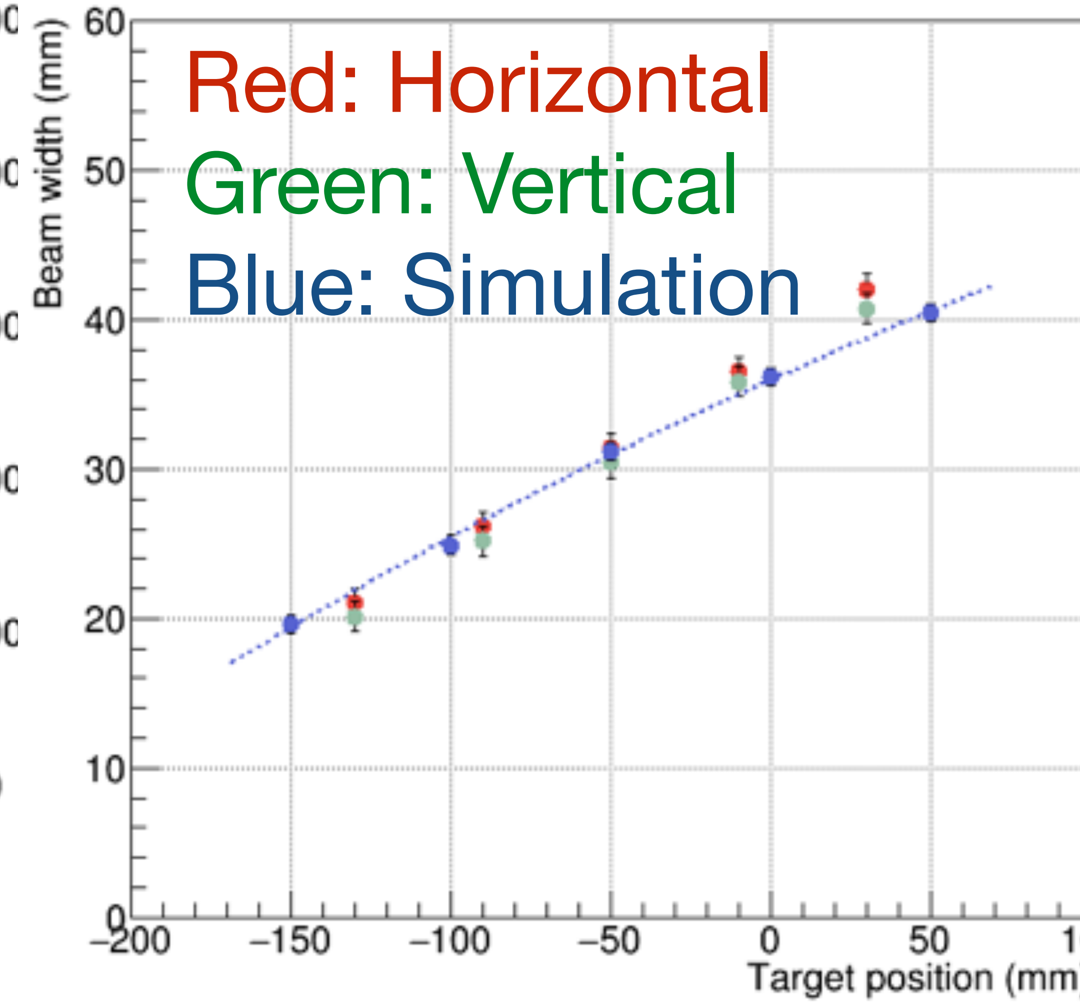
Beam profile measurement setup



- Measurement was performed at 0.3, 0.5 1.0 Kr gas pressure

Measured Beam Profile





- Muon beam profile was measured and fitted by two-dimensional Gaussian function
- Good agreement with simulation
- Reconstruction of three-dimensional distribution is ongoing

Muonium HFS and Muon g-2

- More than three standard deviations discrepancy between theoretical prediction and experimental result

$$a_{\mu\mathrm{Exp}} = 11659208.9(6.3)$$ G.W. Bennet *et al*., PRD, 73, 072003 (2006)

$$a_{\mu\mathrm{Theory}} = 11659181.8(4.9)$$ M. Davier *et al*., Eur. Phys. J. C 73, 2453 (2013)

$$\delta a_\mu = 27.2(8.0)$$

- Muonium HFS is on of the two experimental inputs

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

R : From muon spin precession

λ : From muonium HFS

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

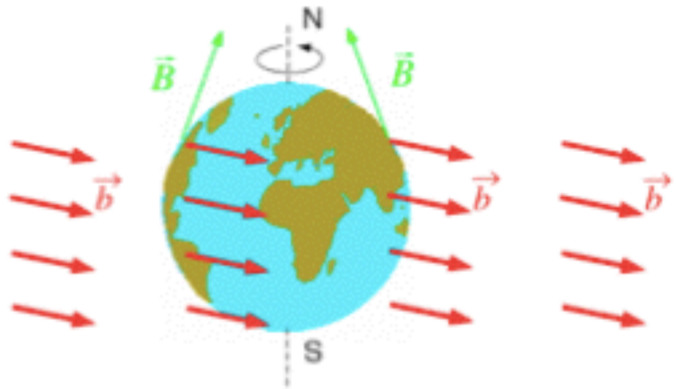
540 ppb

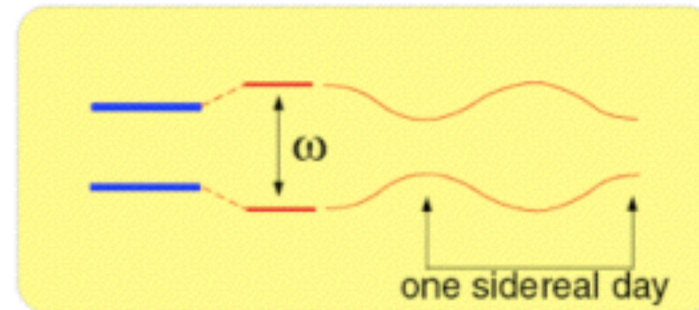
26 ppb

The possible clue to the new physics

Search for Lorentz Violation

- **Sidereal oscillation of transition frequency**

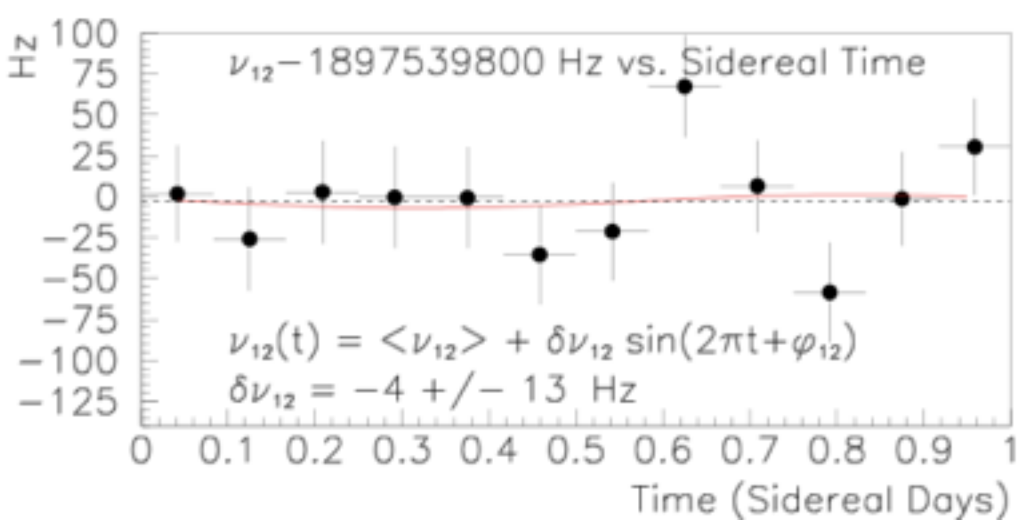


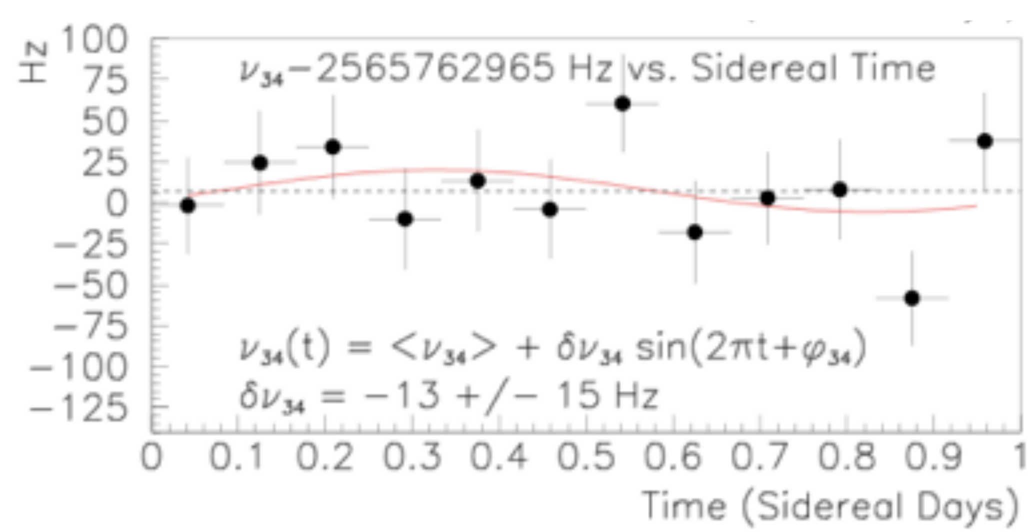


cited from
R. Bluhm’s slide

R. Bluhm, V.A. Kostelecký, and C. Da Lane, Phys. Rev. Lett. 84, 1098 (2000)

- **The most recent experimental result**



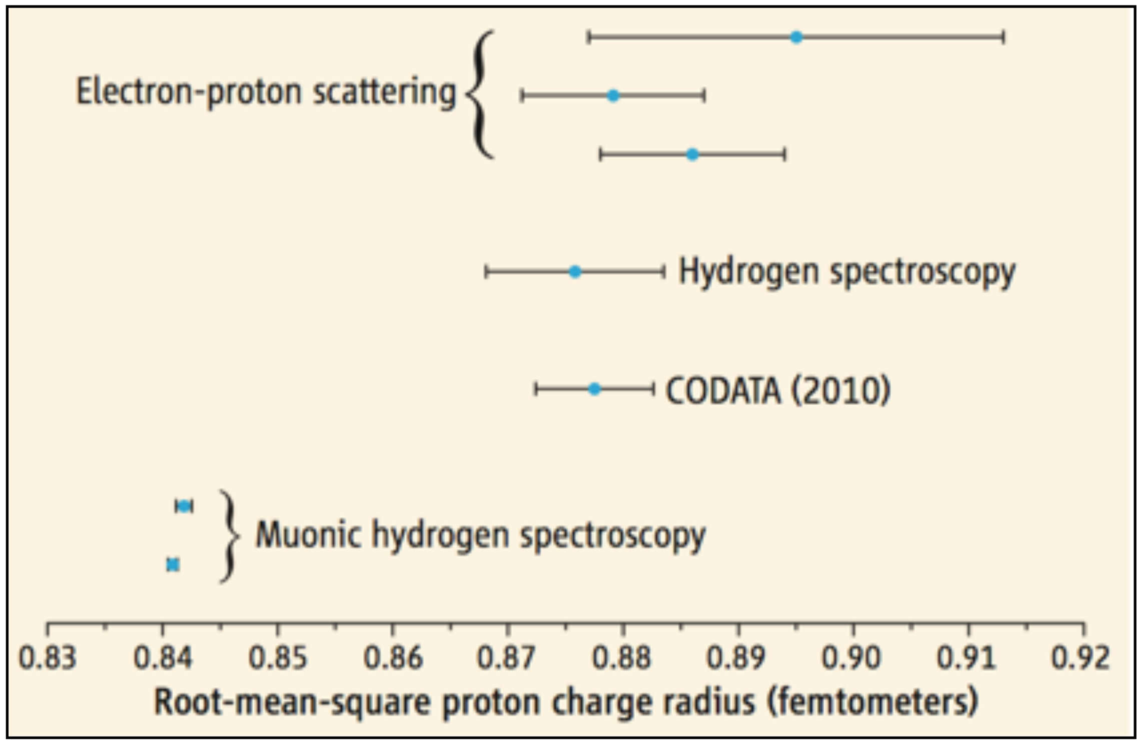


$$|\sin\chi|\sqrt{(\tilde{b}_X^{\mu})^2 + (\tilde{b}_Y^{\mu})^2} \lesssim 2 \times 10^{-22}\ \mathrm{GeV}$$

V.W. Hughes *et al*., Phys.Rev.Lett.87, 111804 (2001)

Proton Radius Puzzle

- The discrepancy between the muonic hydrogen result and the CODATA value remains with the difference being 7σ



- Proton charge radius

$$r_p \equiv -6\frac{dG_E}{dQ^2}|_{Q^2=0}$$

- Zemach radius (convolution of charge and magnetic distribution)

$$R_p = \int d^3r\, r \int d^3r'\, \rho_E(\mathbf{r}-\mathbf{r}')\, \rho_M(\mathbf{r}')$$

- Zemach radius can be obtained from muonium HFS and hydrogen HFS

$$E_{\rm HFS}(e^- p) = (1 + \Delta_{\rm QED} + \Delta_R^p + \Delta_S)E_F^p,$$

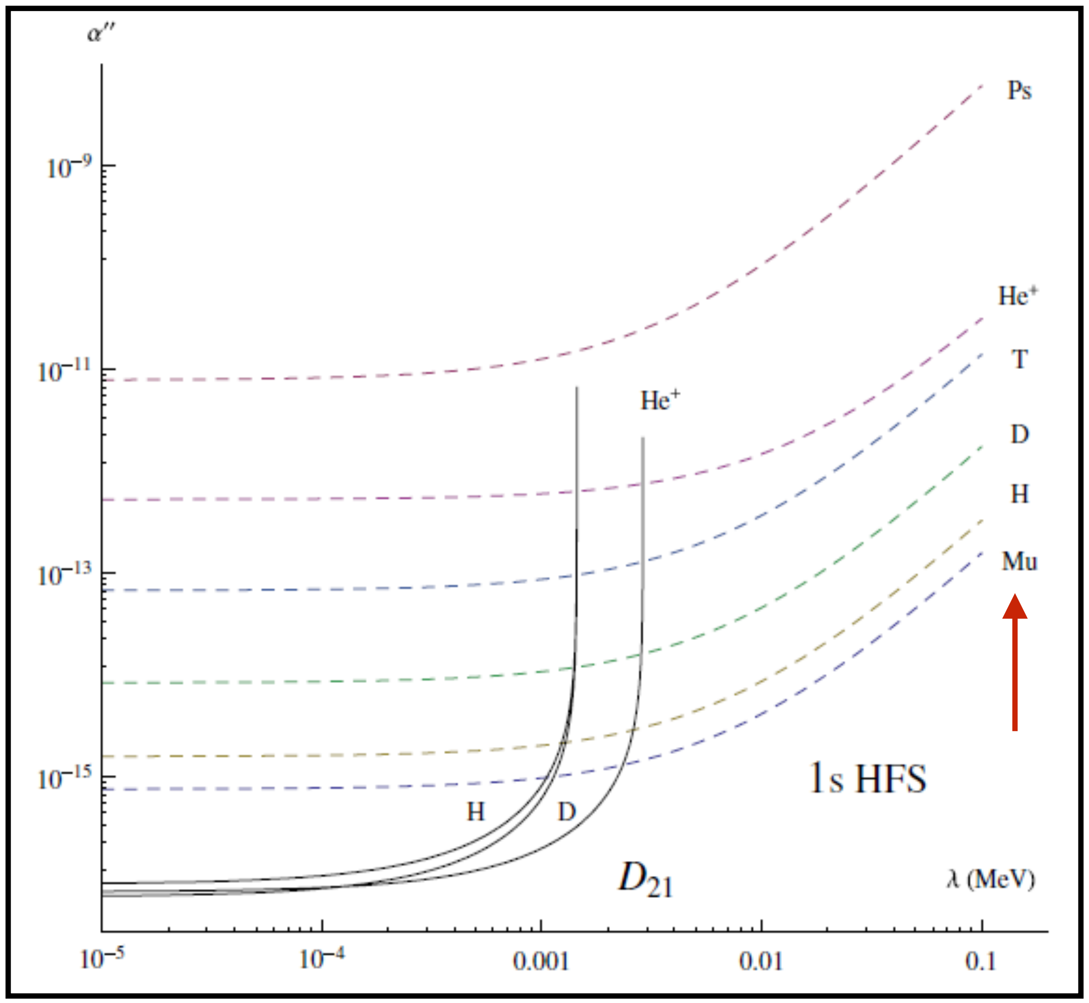
$$E_{\rm HFS}(e^- \mu^+) = (1 + \Delta_{\rm QED} + \Delta_R^\mu)E_F^\mu.$$

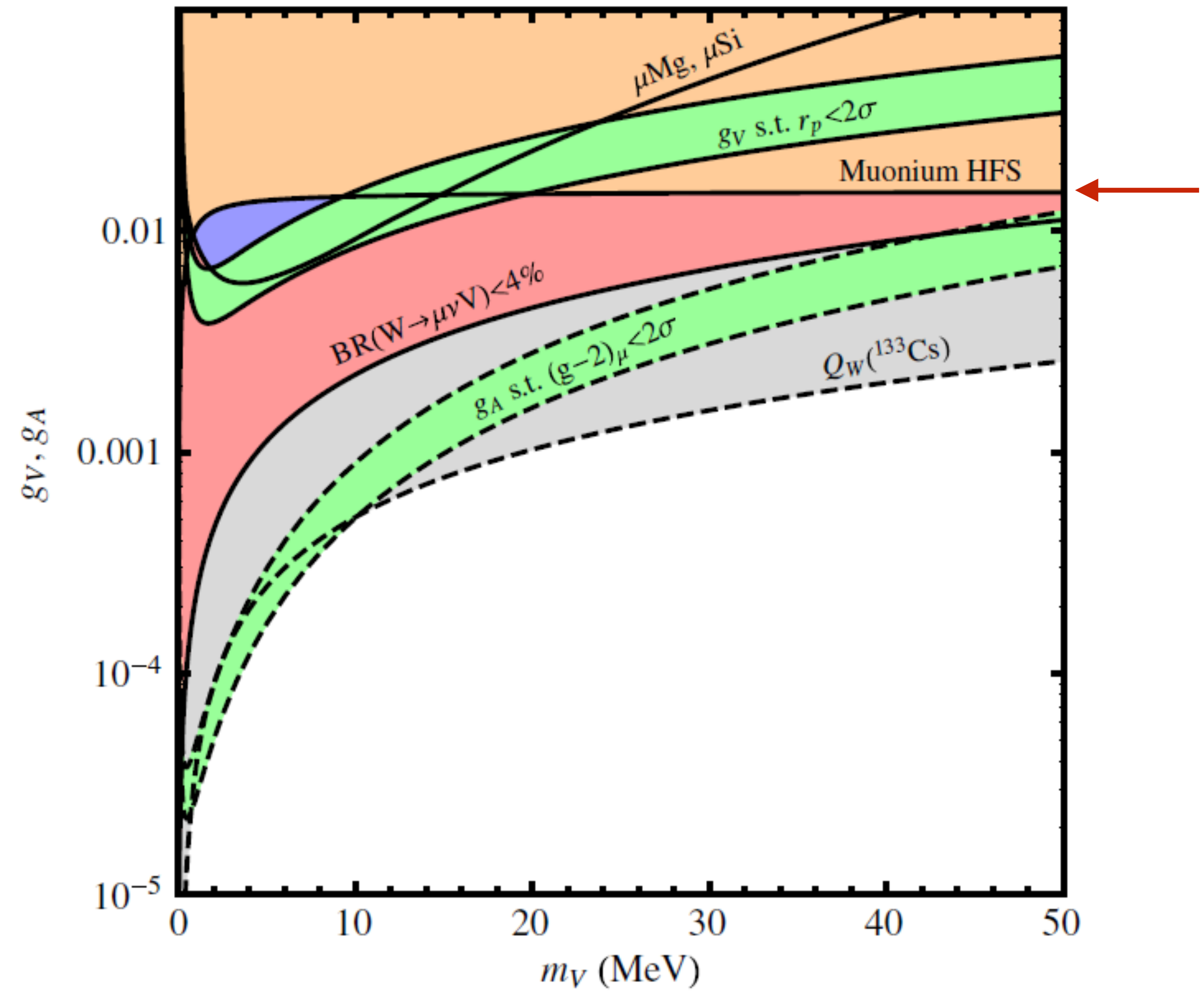
ΔQED: QED correction term
Δs: proton structure term
ΔR: recoil term
E_F: Fermi energy

S.J. Brodsly *et al*., Phys. Rev. Lett. 94, 022001 (2005)

Search for Exotic Interaction

- **Muonium HFS constraints "dark" force carriers**





light pseudo-vector boson

S. G. Karshenboim, PRL, 104, 220406 (2010)

massive vector boson

S. G. Karshenboim, PRD, 90, 073004 (2014)

Precision of Muonium HFS

- **Experimental data**

$$\Delta E_{\mathrm{HFS\ Exp}} = 4.463302765(53)\ \mathrm{GHz}$$ **(12 ppb)**

W. Liu *et al*., PRL, 82, 711 (1999)

- **Theoretical value**

$$\Delta E_{\mathrm{HFS\ Theory}} = 4.463302891(272)\ \mathrm{GHz}$$ **(63 ppb)**

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

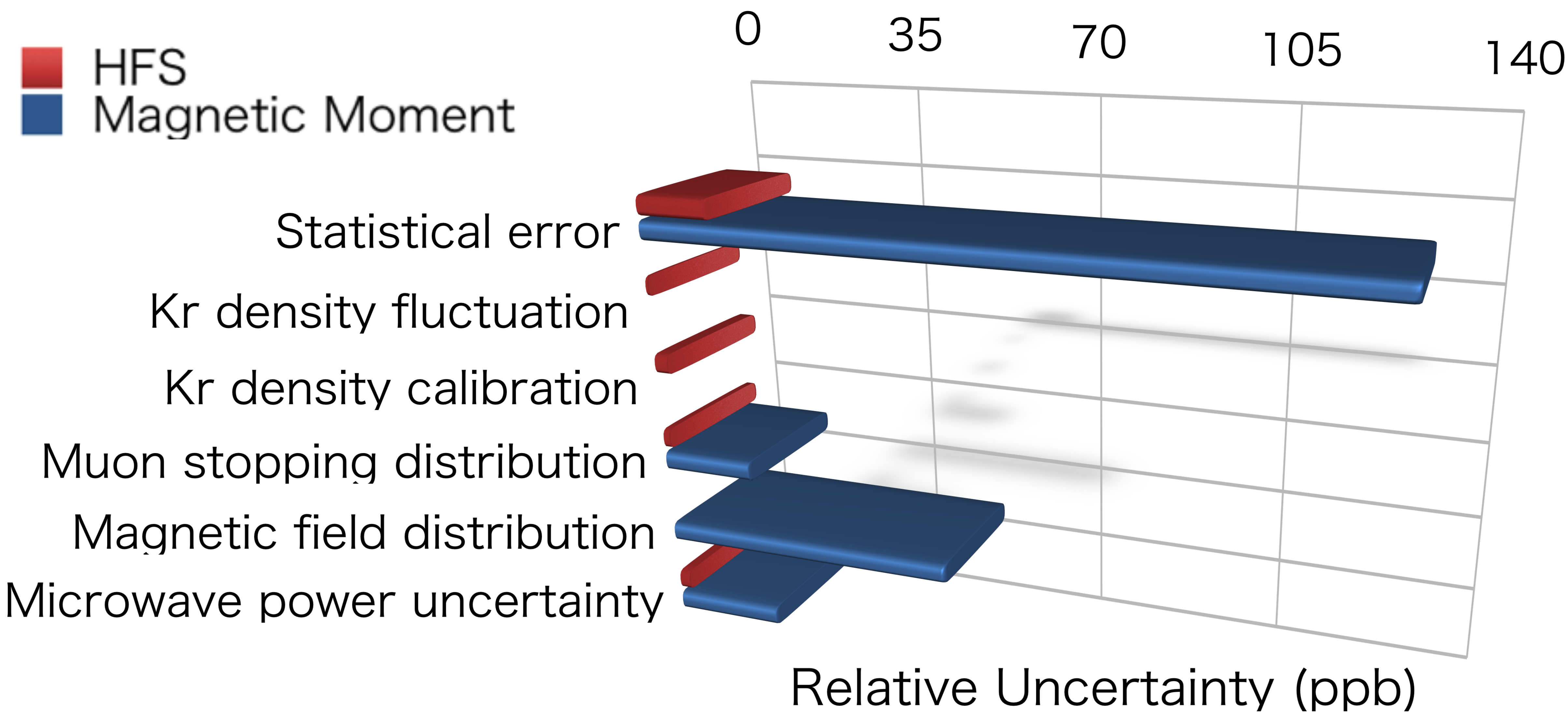
And more updates for higher order contributions

eg. M.I. Eides and V.A. Shelyuto, PRL 112, 173004 (2014)

The most precise test of bound state QED

Uncertainties in the most recent exp.

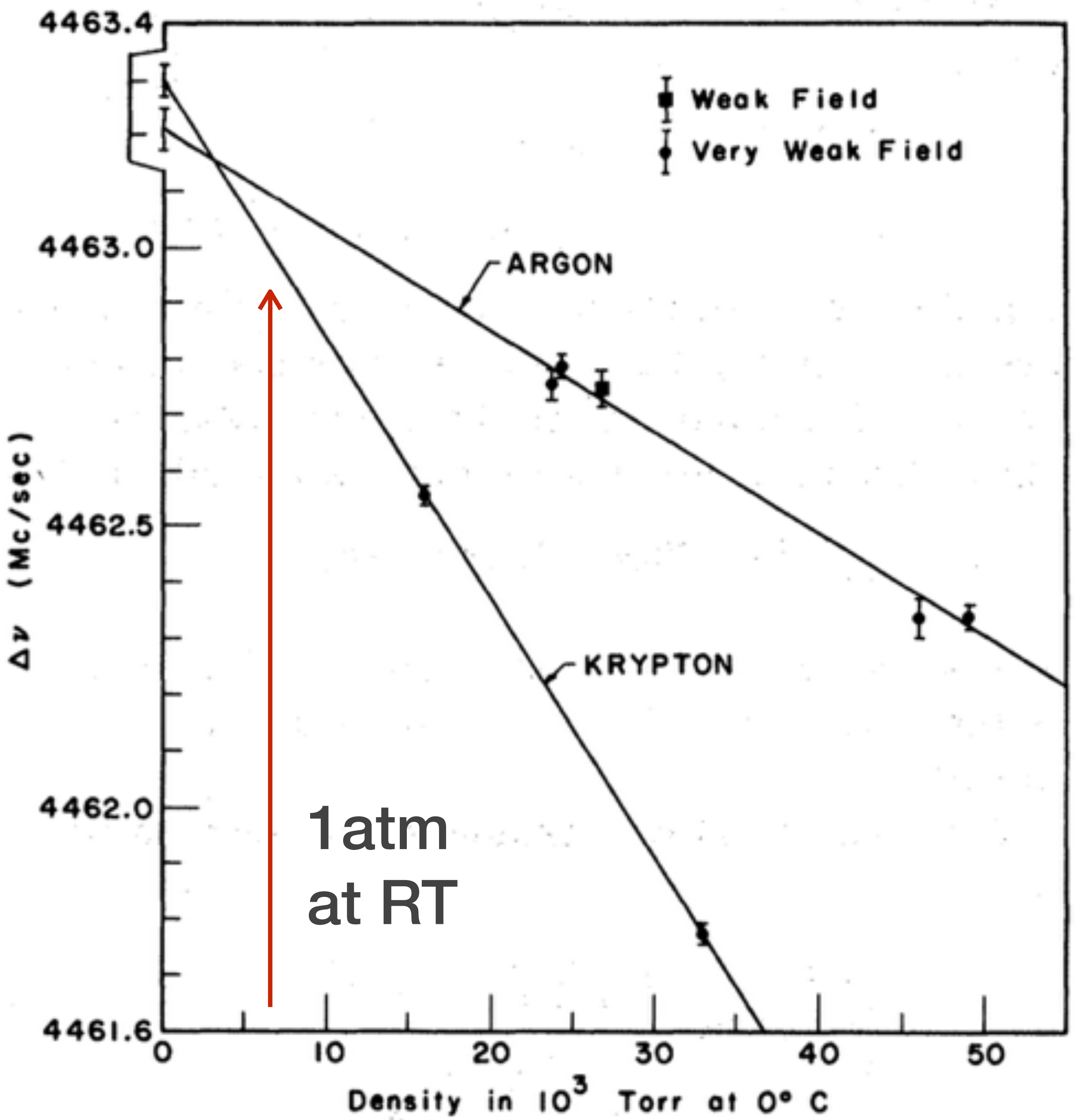
- Experimental precision was mostly statistically limited



- Understanding of systematics was limited by measurement time

Our goal is x10 improvement with x200 of statistics

Systematic effect with gas density



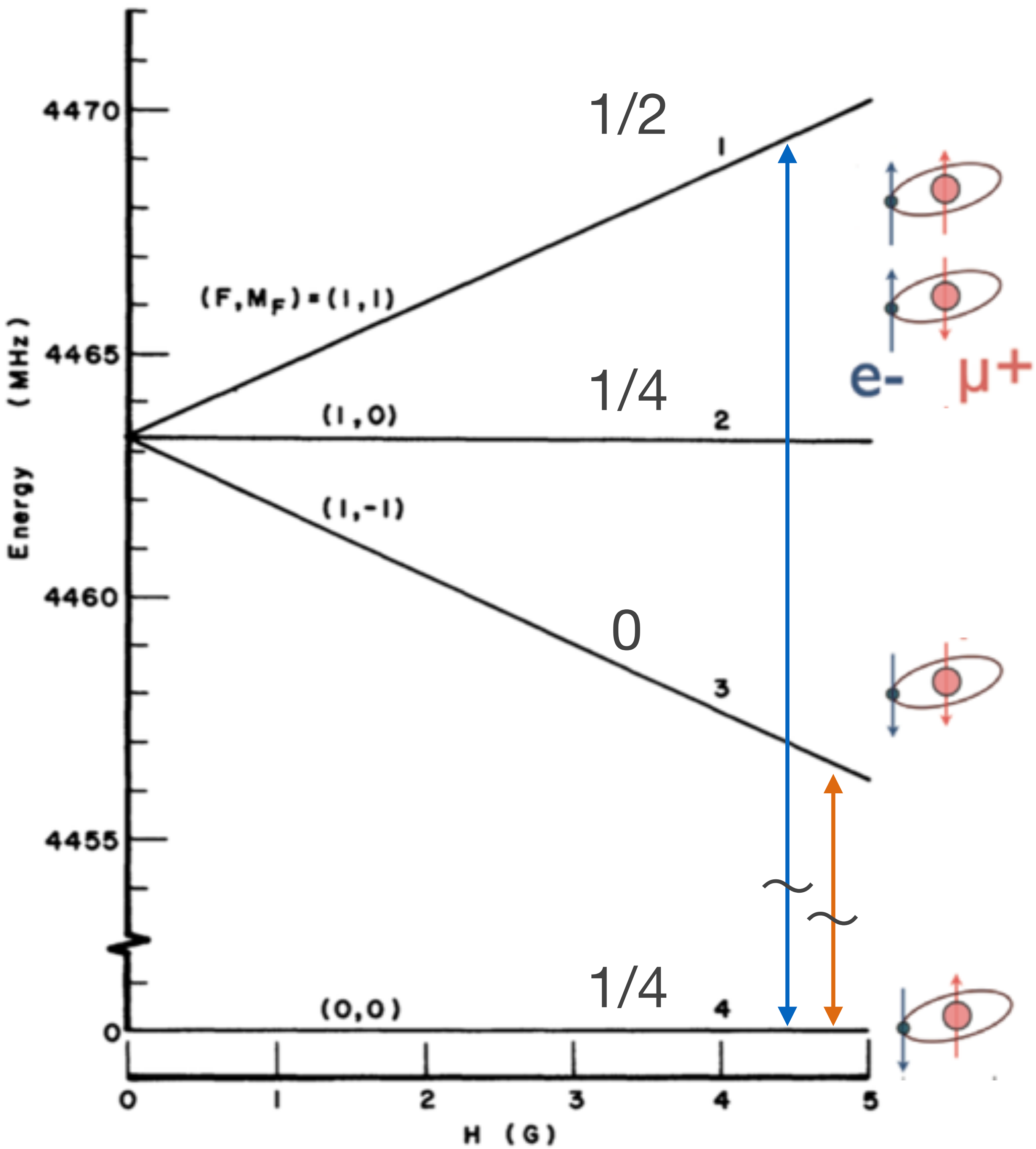
4463 MHz is expected in 1.0 atm Kr case

P.A. Thompson *et al*., PRL, 22, 5 (1969)163

- Transition frequency depends on target gas pressure due to atomic collisional shift
- HFS at zero gas density is obtained by extrapolation
- Pressure dependence extrapolation is source of systematic uncertainty
- Previous experiments were performed at high gas pressure
- We aim to perform at low gas pressure (less than 1 atm)

Systematic effect with B-Field

F: total angular momentum of muonium quantum number
M_F: associated magnetic quantum number



- At “zero” field, these four states are not degenerated
- Transition frequency depends on static B-field
- In the low field limit, 14 nT/Hz shift is expected
- The most recent zero field exp. case was 200 nT
- We aim to improve the field uniformity to 100 nT

Experimental Overview

Formation of Muonium

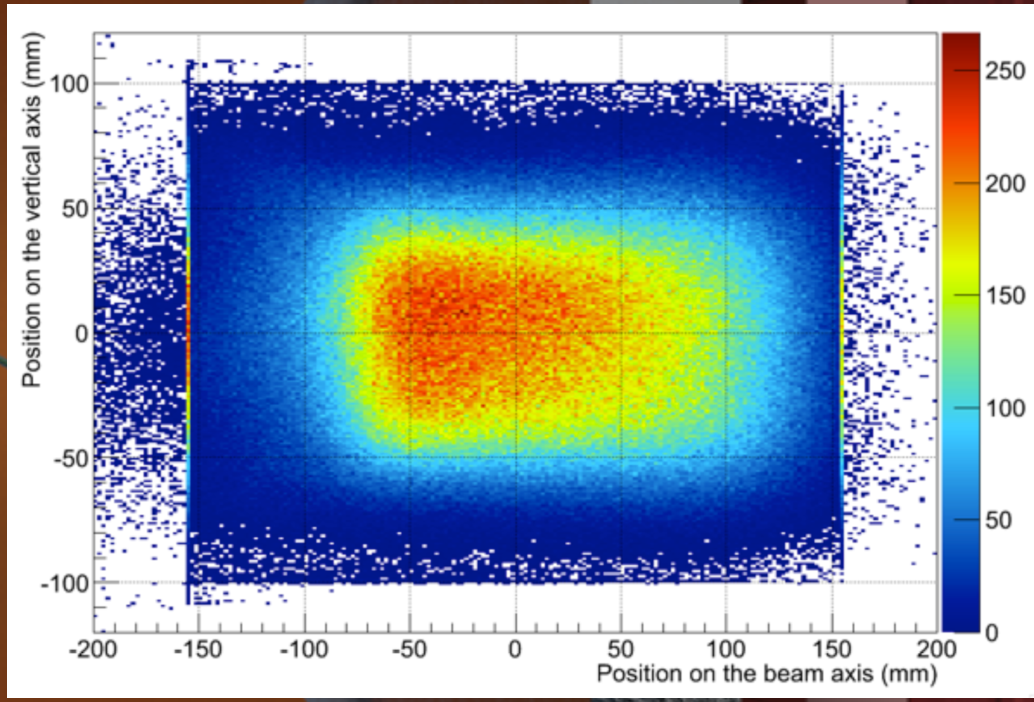
Experimental Procedure
- 1. Muonium formation
- 2. RF spin flip
- 3. Positron asymmetry

Polarized muon loses its kinetic energy in Kr gas

Stopped muon captures an electron from Kr gas

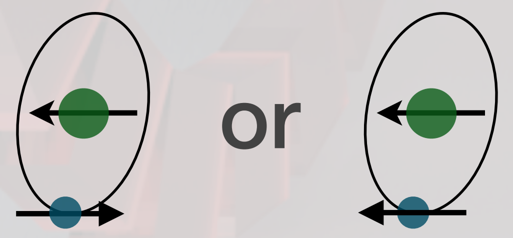
muon

electron



Simulated muon stopping position

Possible initial states



Kr Gas Chamber

1.7 T Magnet

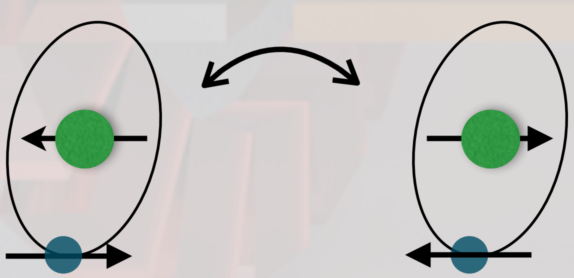
RF Spin Flip

Experimental Procedure
1. Muonium formation
2. RF spin flip
3. Positron asymmetry

A magnetic field of microwave is introduced into a muonium formation volume

Microwave induces muon spin flip and states time development

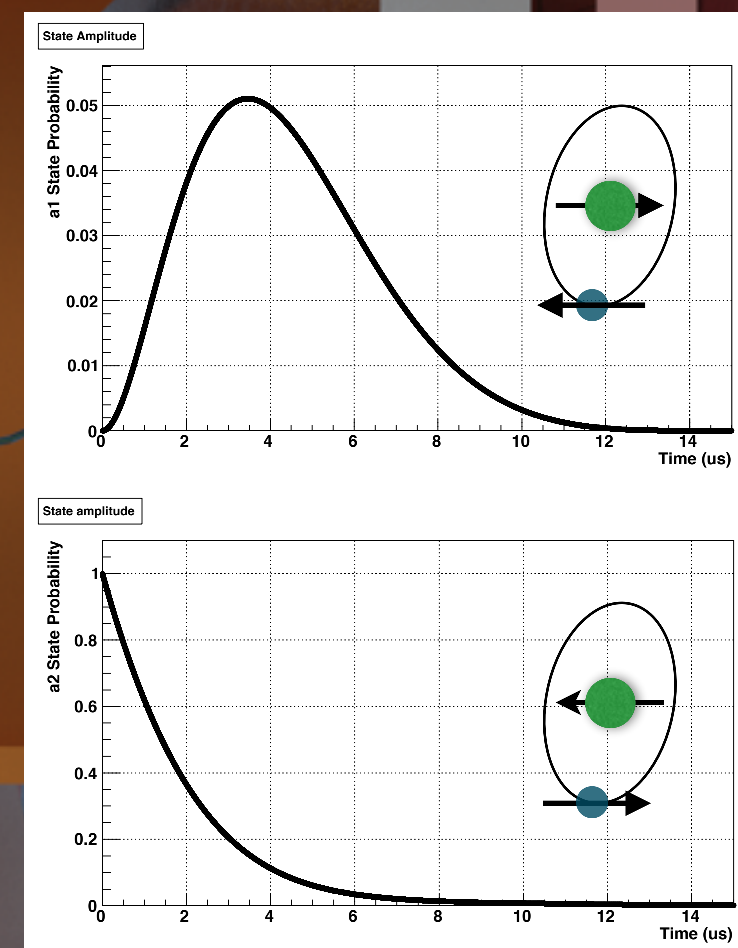
Muon spin flip



RF

RF Tuning Bar

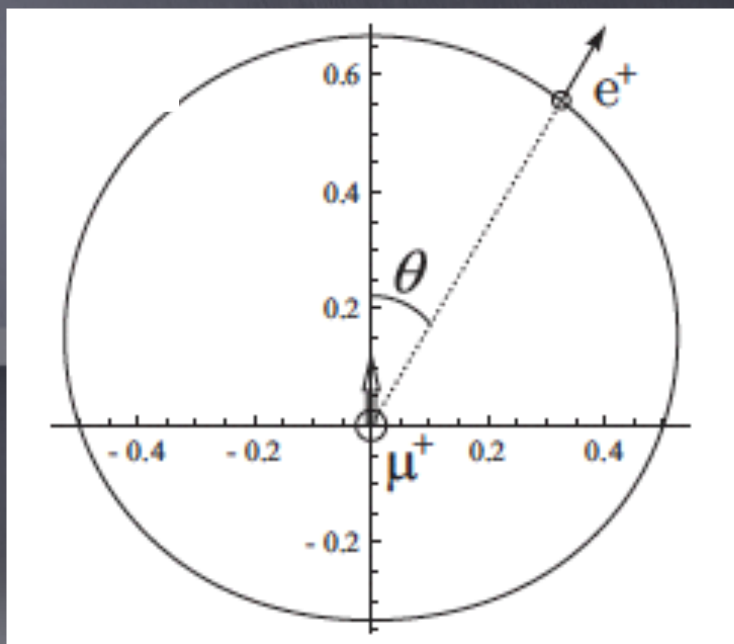
RF Cavity



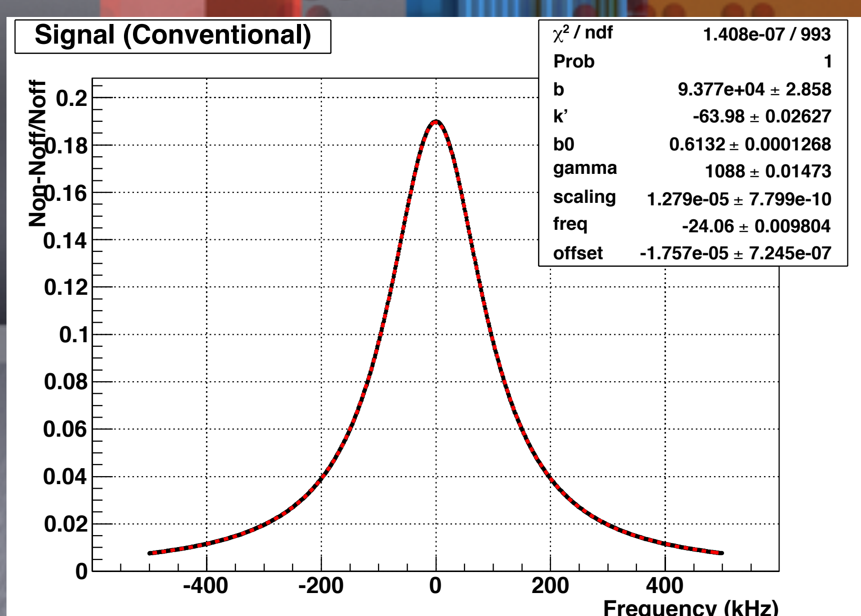
Calculated state population

Decay Positron Asymmetry

Experimental Procedure
1. Muonium formation
2. RF spin flip
3. Positron asymmetry



Positron decay asymmetry



Simulated resonance line

There is the correlation between the positron momentum and the muon spin direction (more positrons in parallel to muon spin)

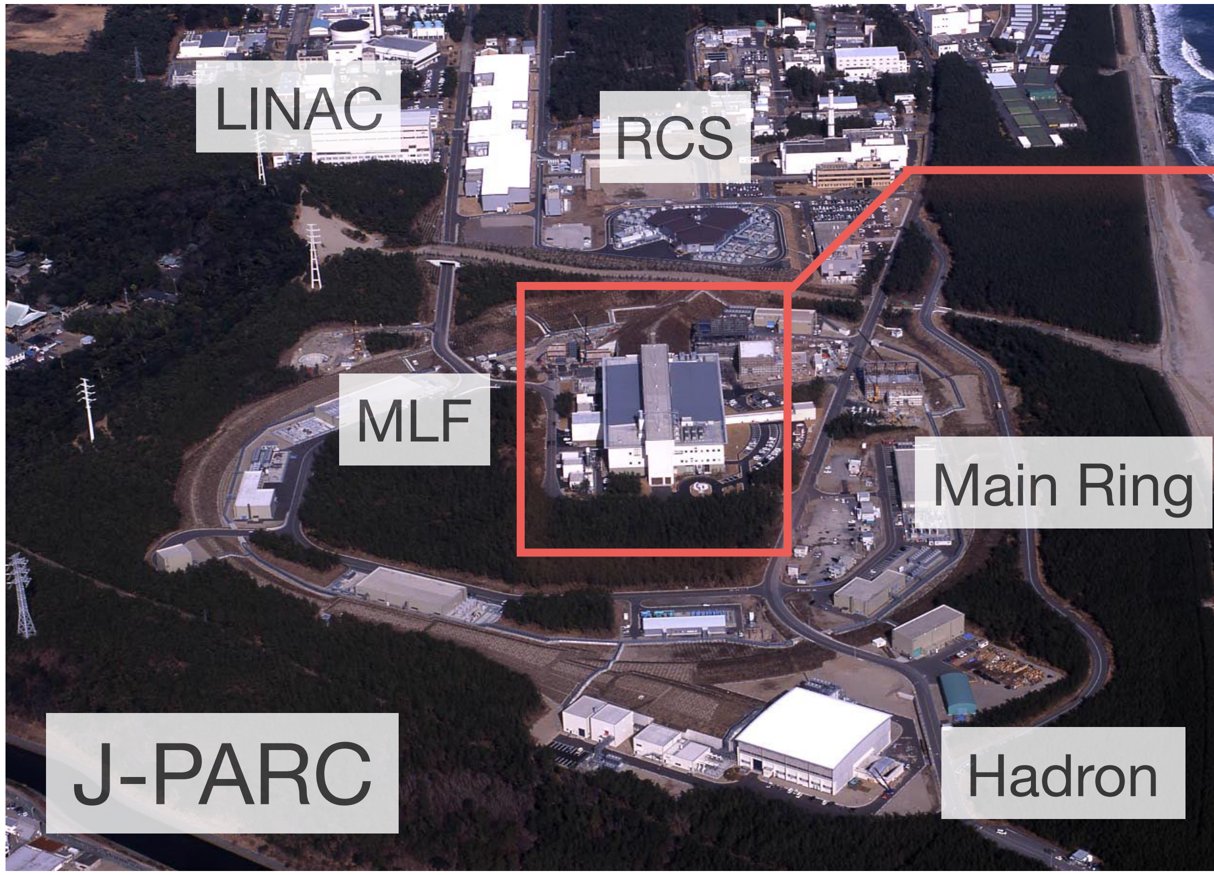
On resonance, positron counting is enhanced due to muon spin flip

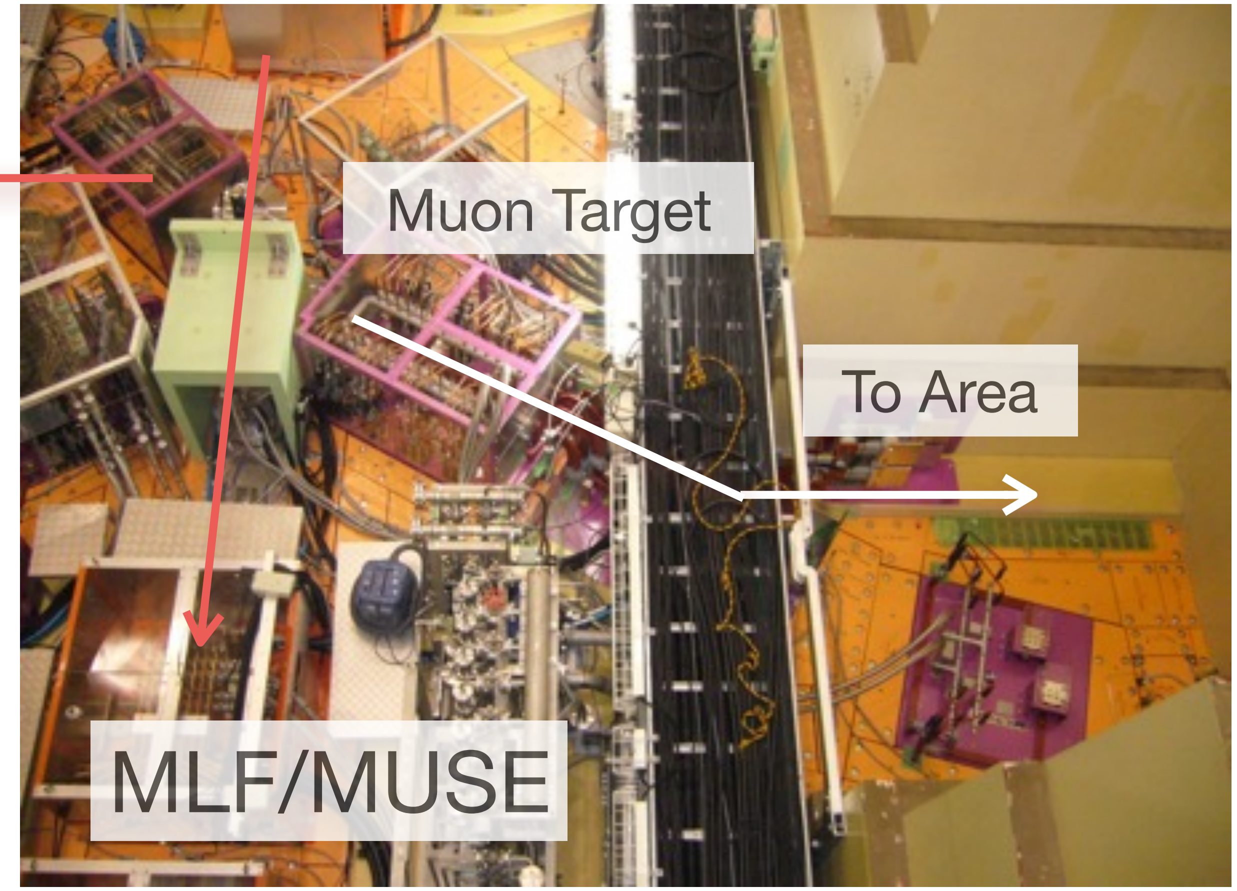
High Field Exp. and “Zero” Field Exp.

	High Field	**Zero Field**
B-Field	Superconducting solenoid 1.7 T measured by NMR probes	**Magnetic field less than 0.1 μT measured by fluxgate probe**
RF	1.906 GHz and 2.556 GHz TM110 and TM210 189 mm diameter	**4.463 GHz** **TM110 (or Higher order modes)** **81 mm diameter (TM110 case)**
Detector	**Common for both experiments**	
World Record of HFS	12 ppb (53 Hz) W. Liu *et al*., PRL, 82, 711 (1999)	**300 ppb (1.4 kHz)** **Casperson *et al*.,** **Phys. Lett. B, 59, 397 (1975)**
MuSEUM Goal	x10 improvement	**x2 improvement (1st phase)** **x10 improvement (2nd phase)**

The Apparatus

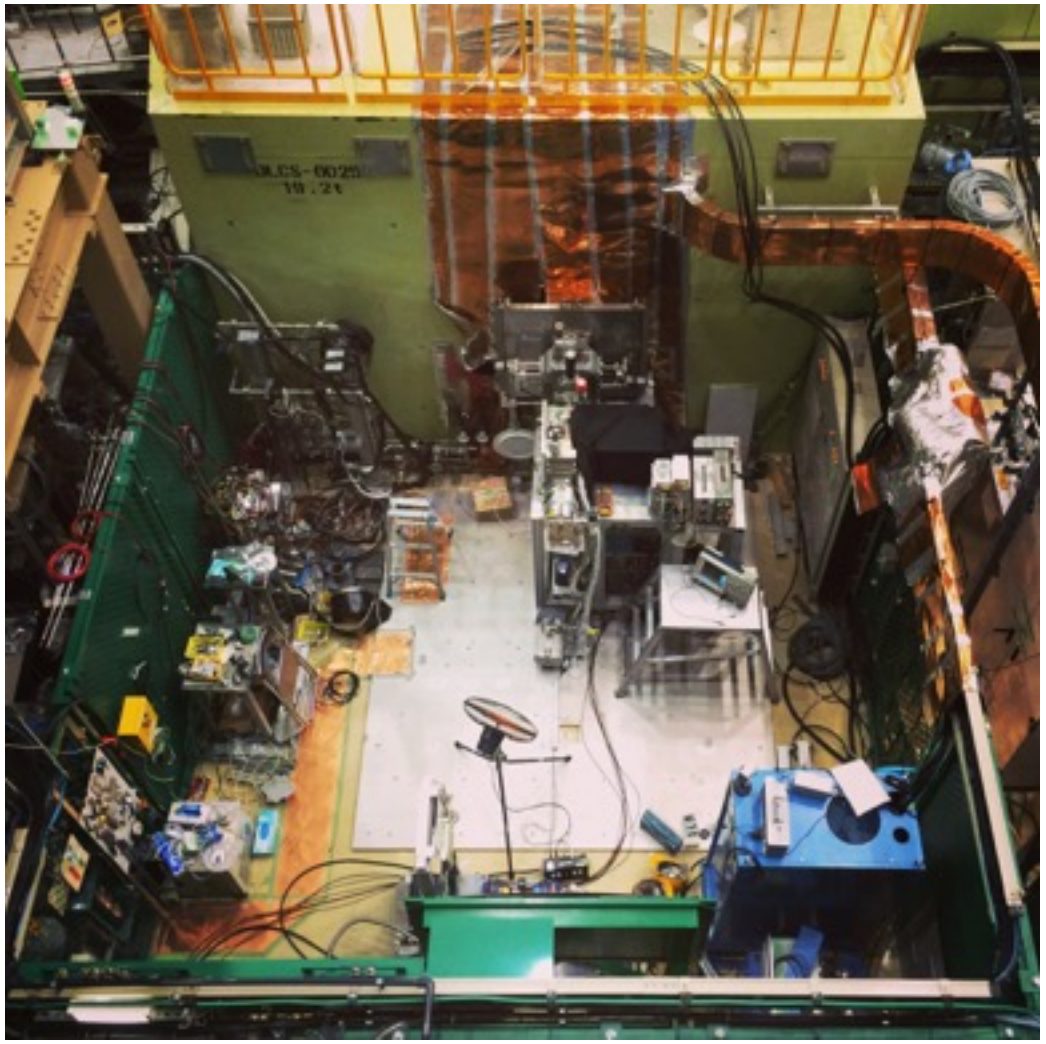
J-PARC and MLF/MUSE

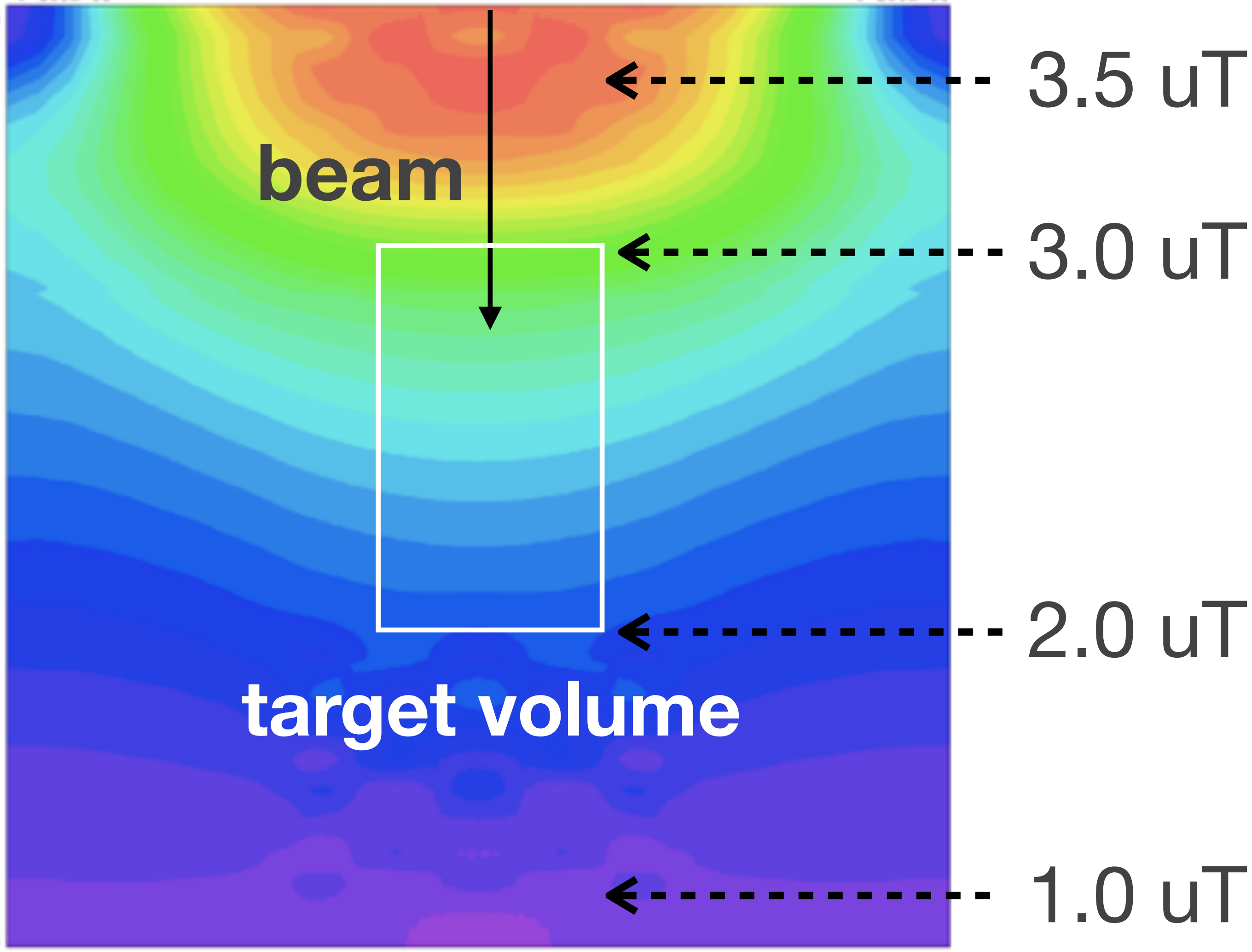




- The highest intensity pulsed proton beam
- RCS (Rapid Cycle Synchrotron) provides 25Hz, 3 GeV proton beam
- MLF (Material and Life science Facility) has graphite target for muon production at MUSE (Muon Science Establishment)
- Typical beam intensity is 20 Tera protons/sec at 200 kW power

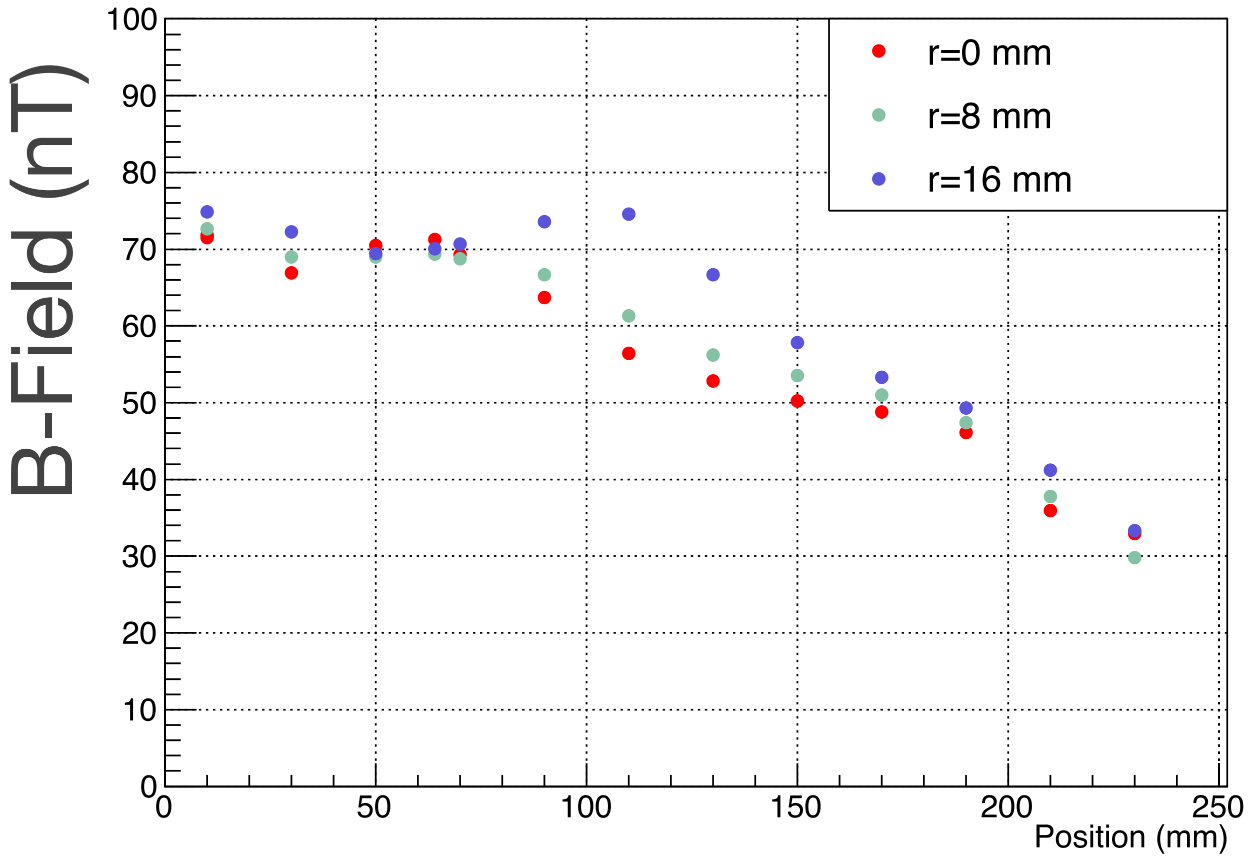
D2 Experimental Area

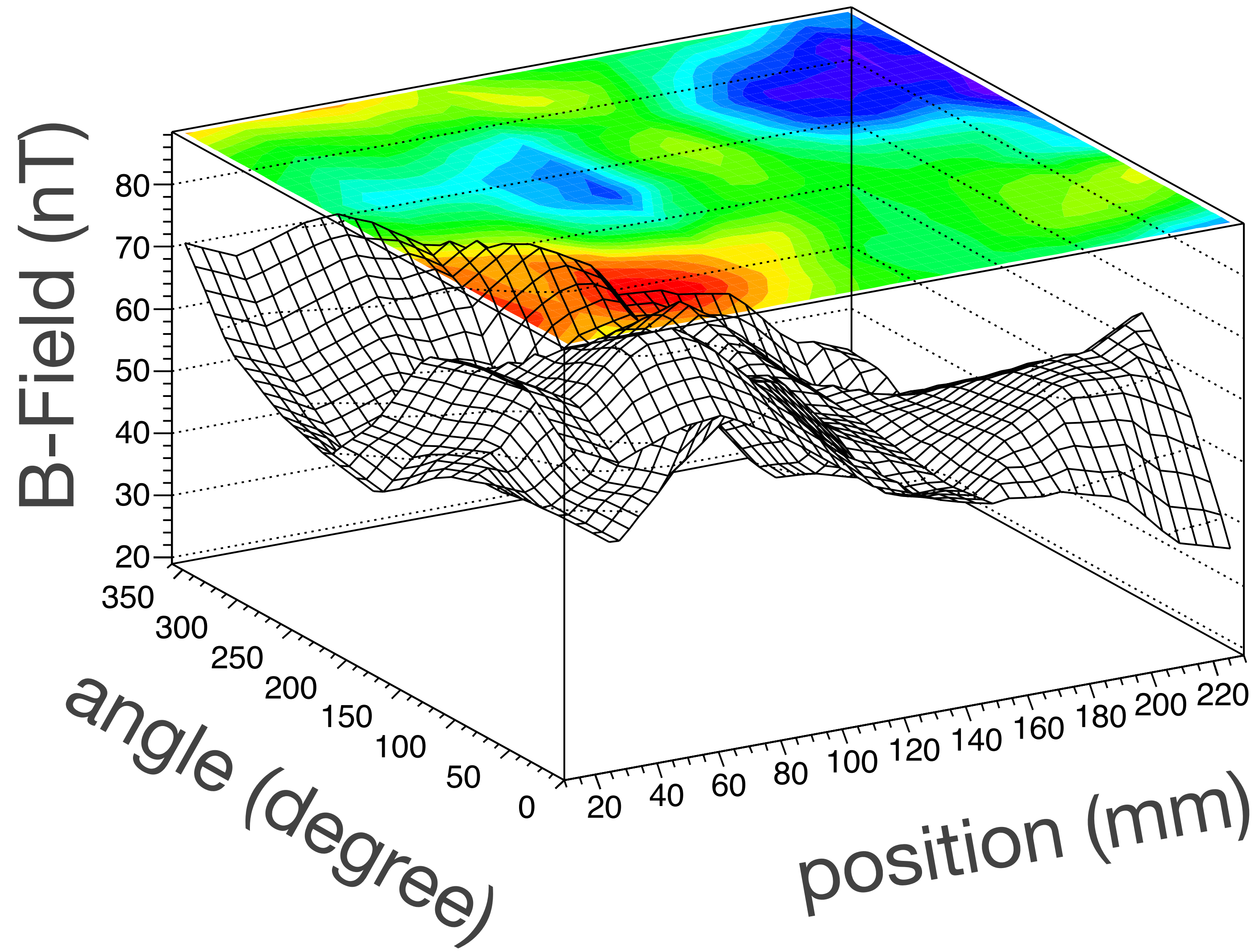




- Multi-purpose decay/surface muon beam line
- Typical beam intensity is 2 Million muons/sec at 200 kW power
- Leakage field from beam line components should be suppressed
- Requirement for field uniformity is 100 nT

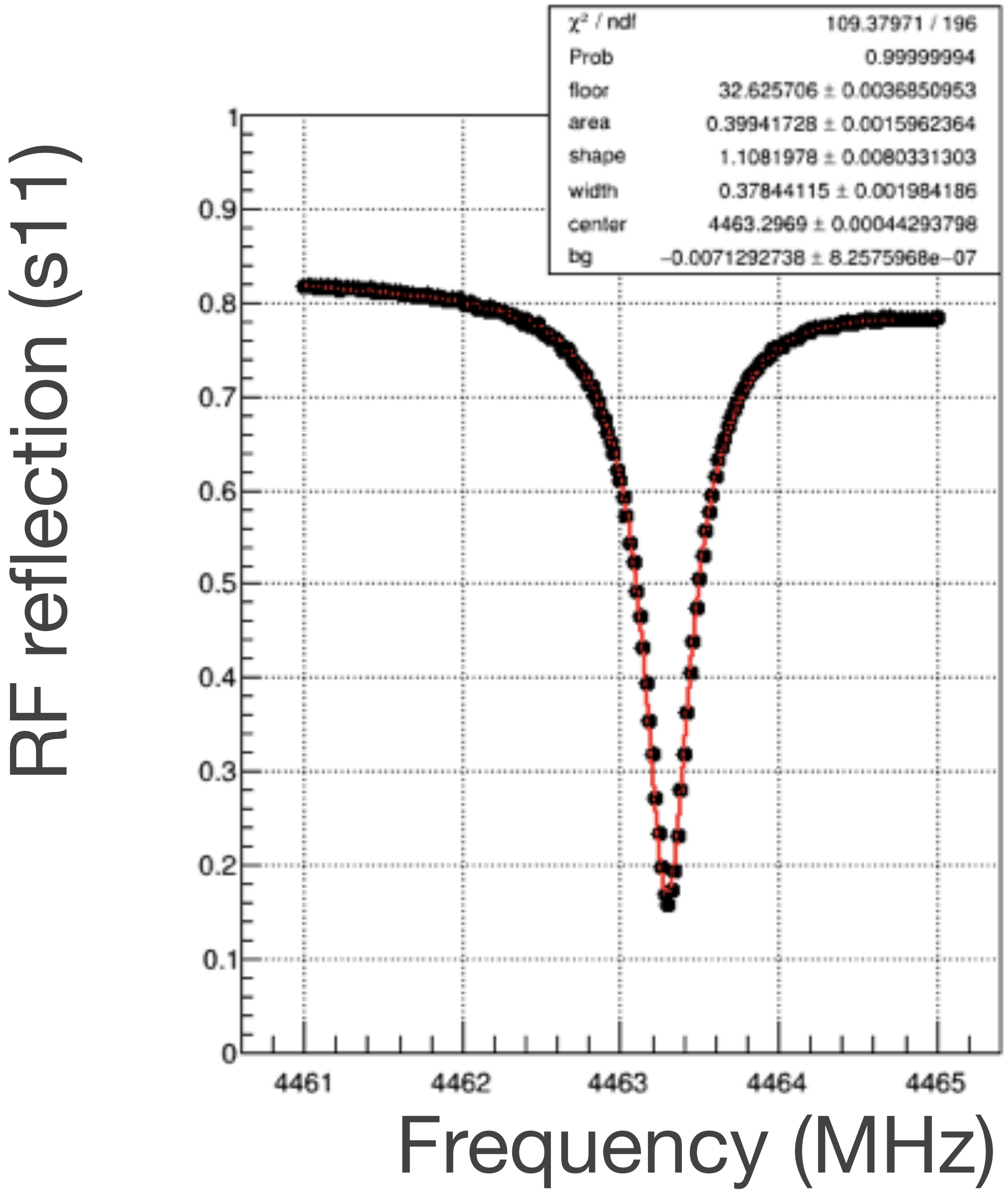
Magnetic Field Distribution

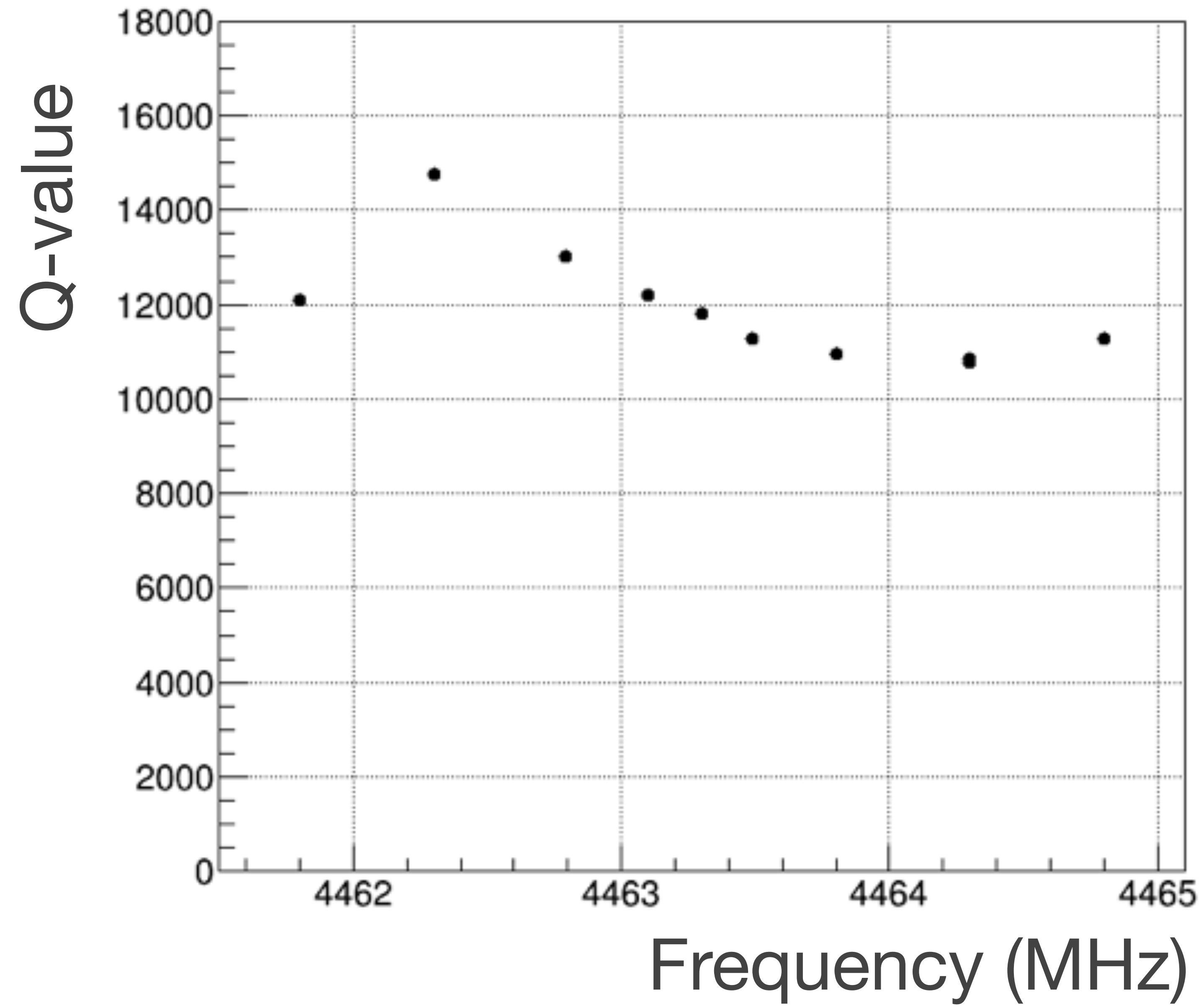




- B-field in the target volume was ranged from 30 nT to 80 nT
- Field gradient was suppressed to be acceptable

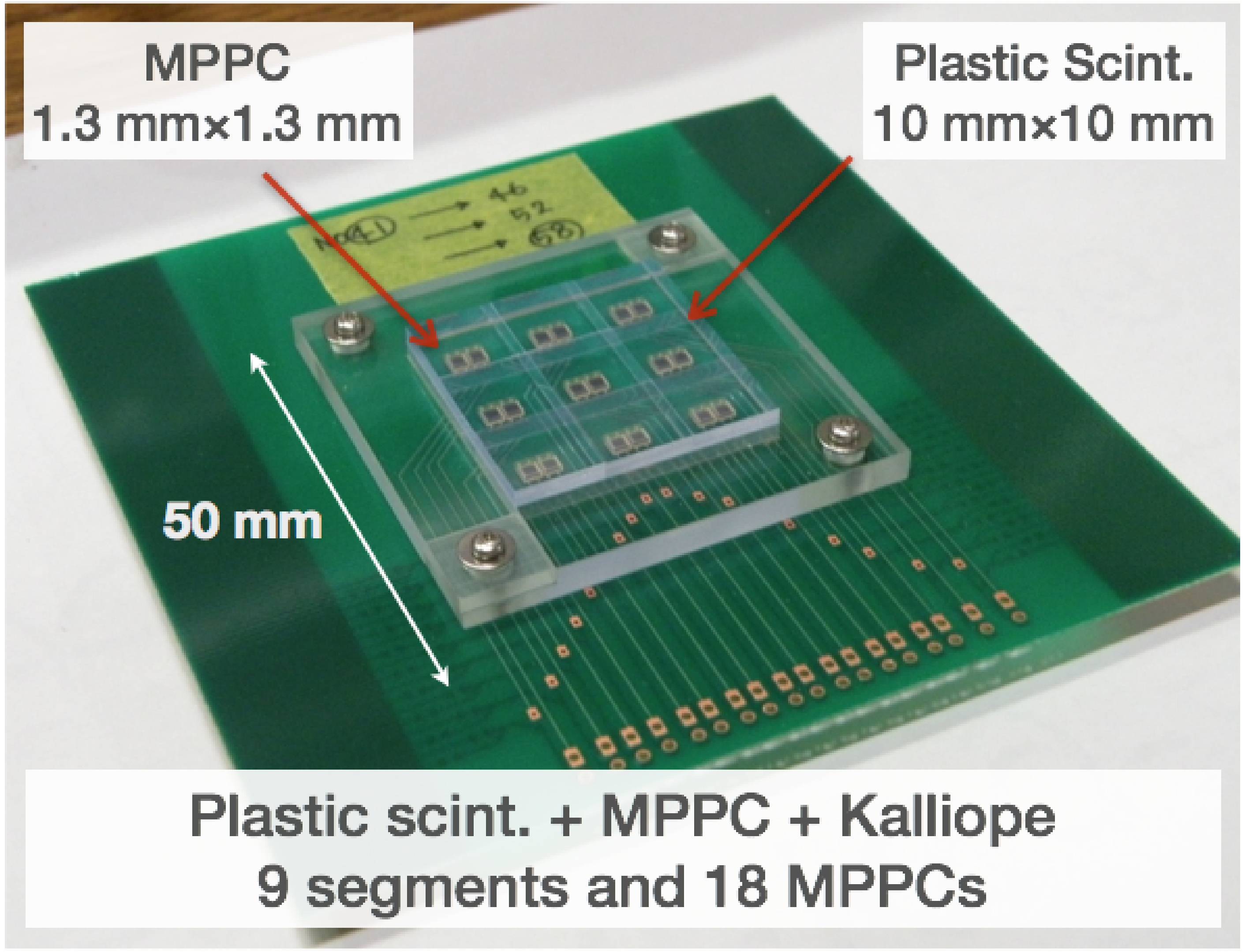
RF Cavity Resonance

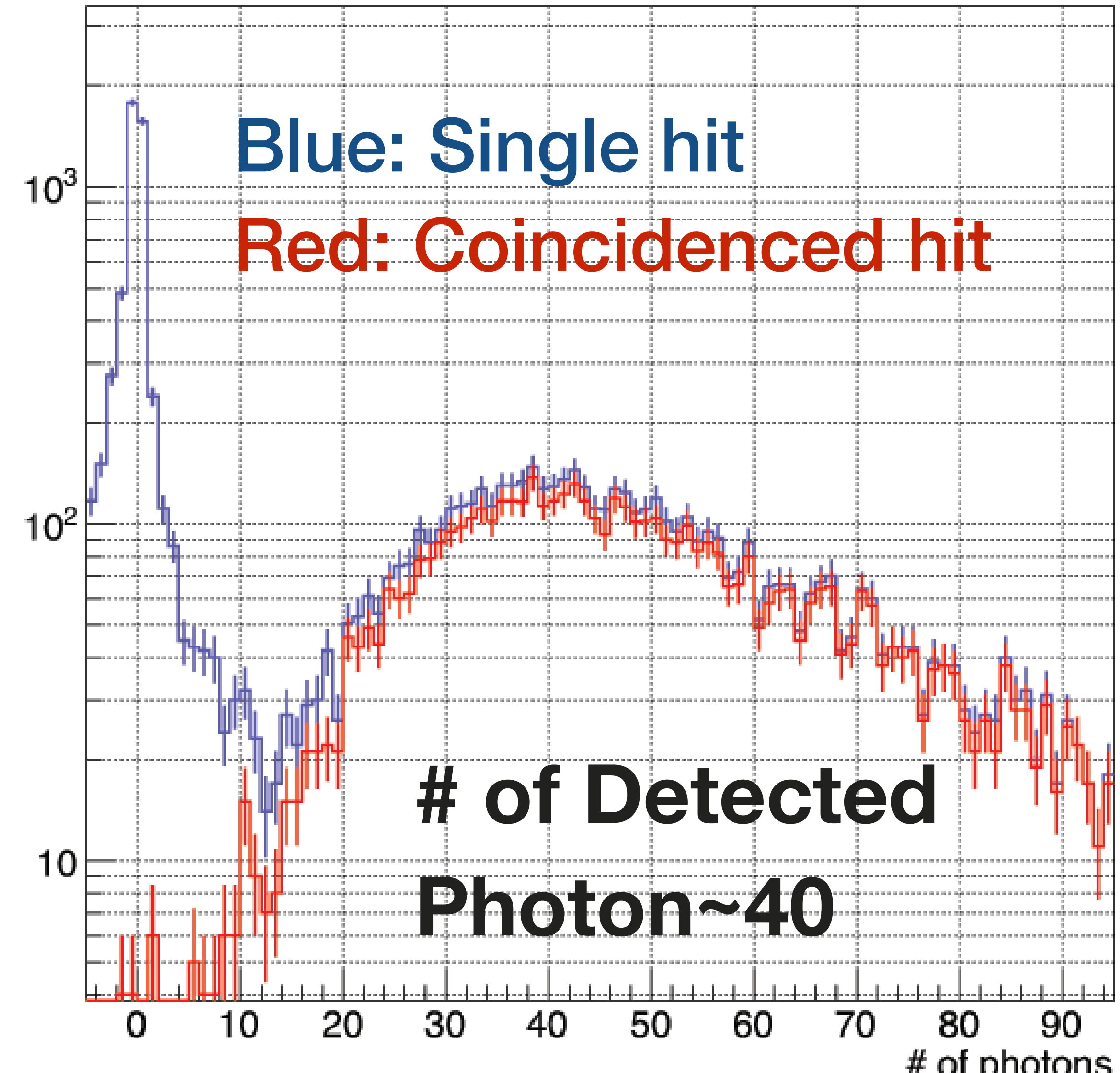




- Cavity resonance was observed and fitted by pseudo-Voigt function to evaluate its characteristics
- Q-value was high enough and mostly flat in the sweep region

Prototype Development

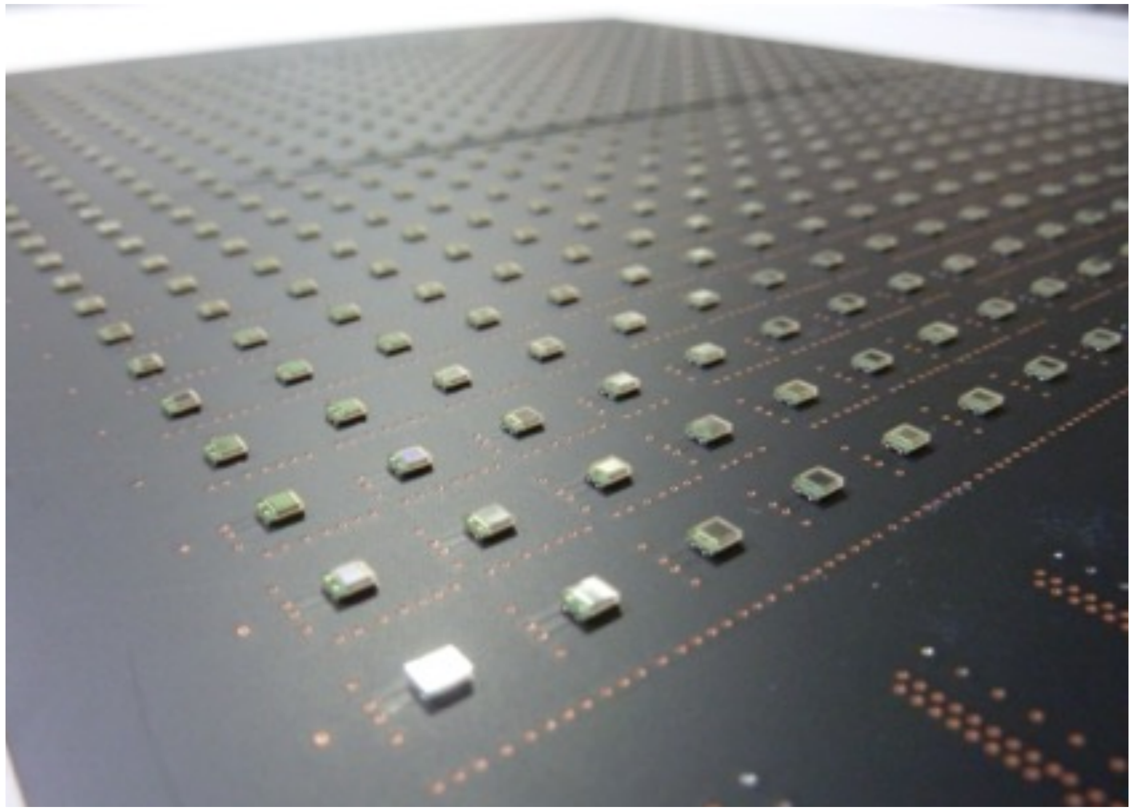


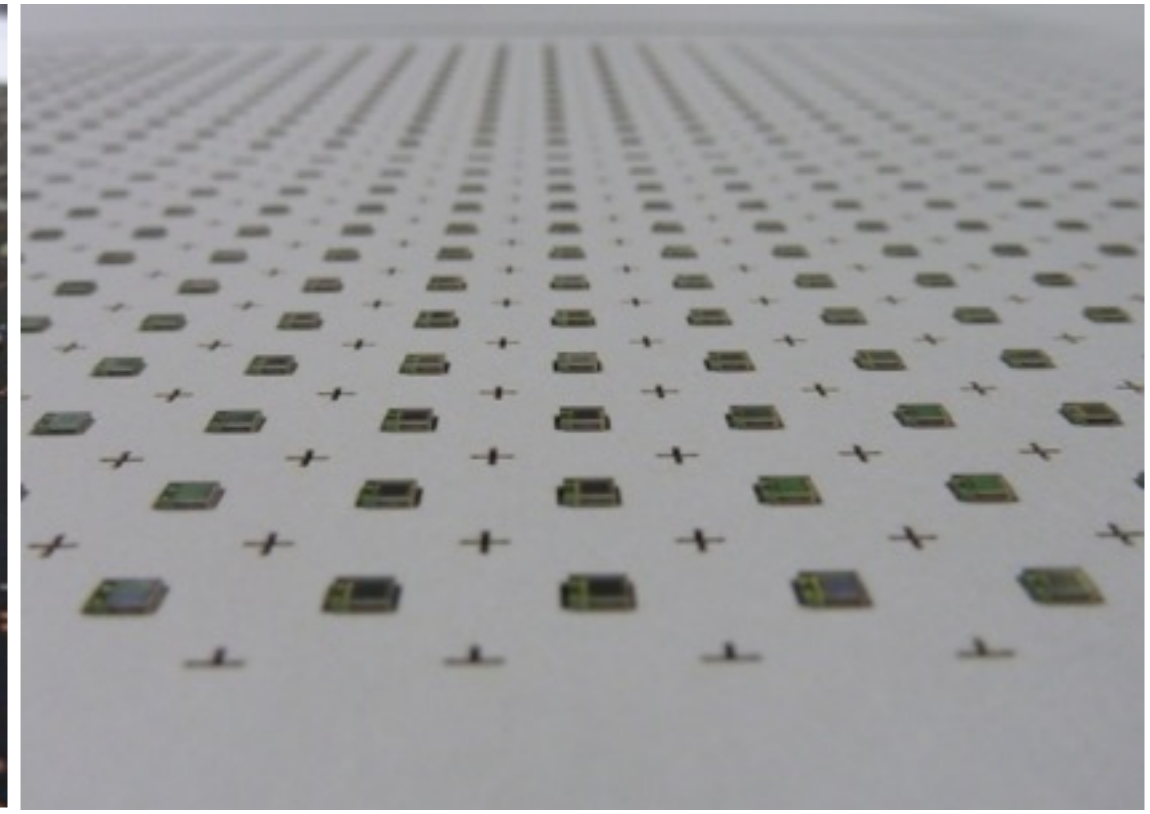


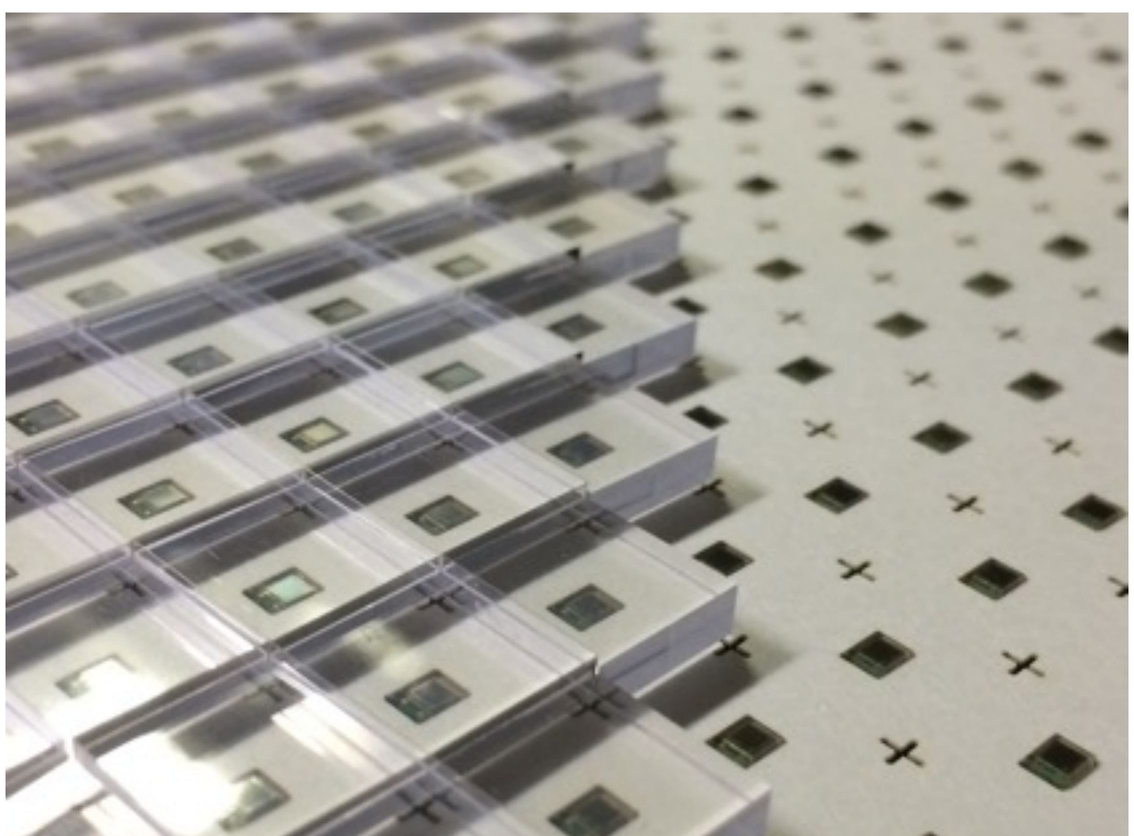
- Nine segments prototype was developed and tested
- Photon yield positron was measured and high enough
- High-rate capability was also tested and good enough

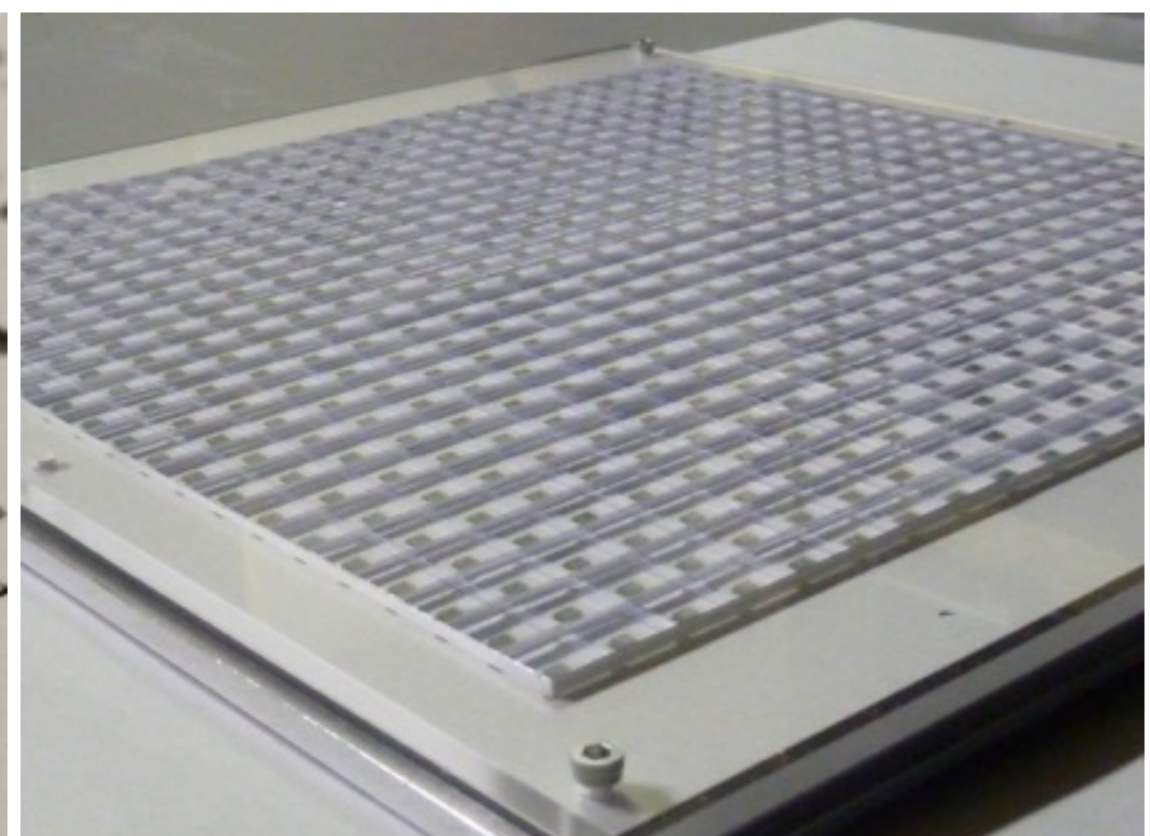
S. Kanda *et al.*, JPSP Conf. Proc., 8, 025006 (2015)

Segmented Positron Counter



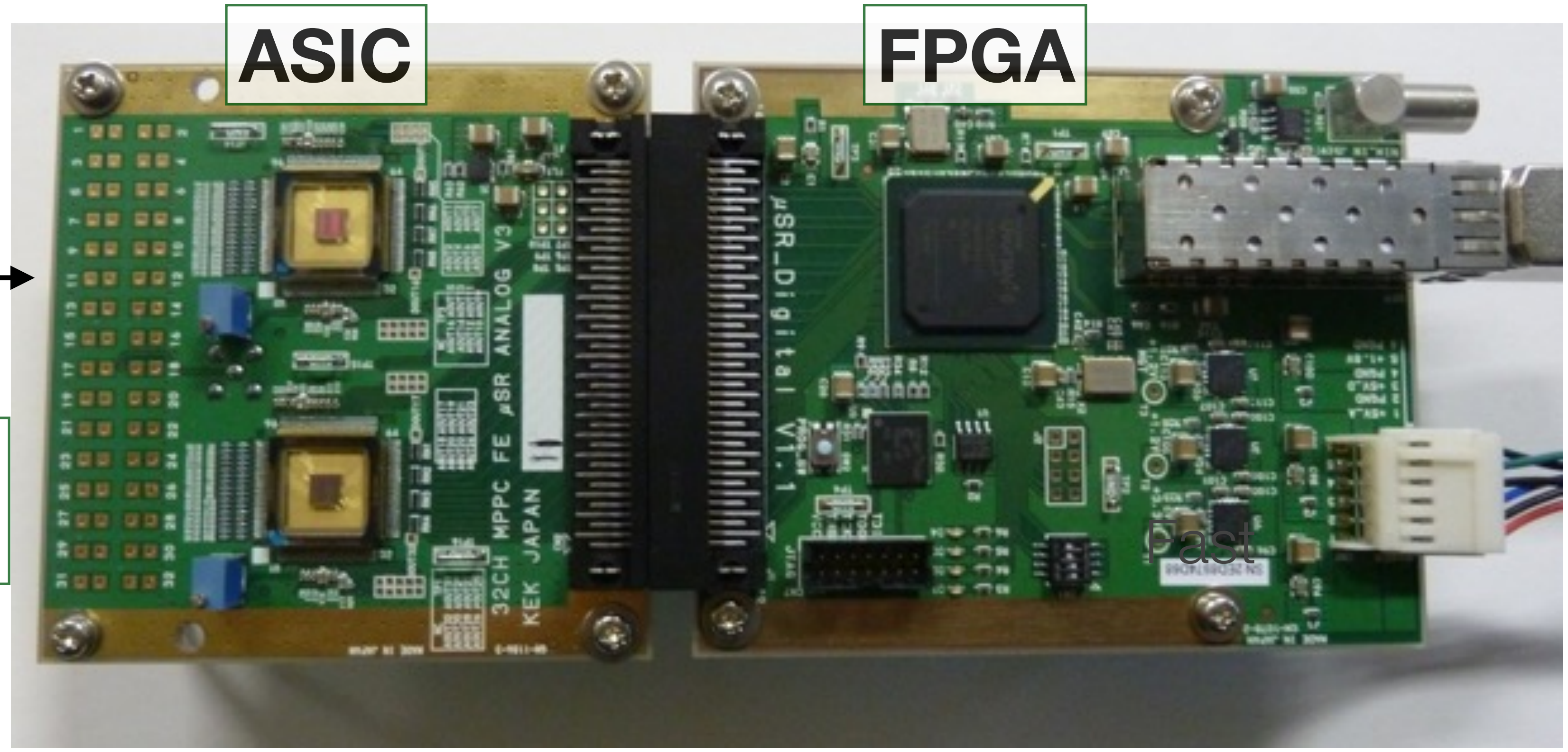






Readout Electronics

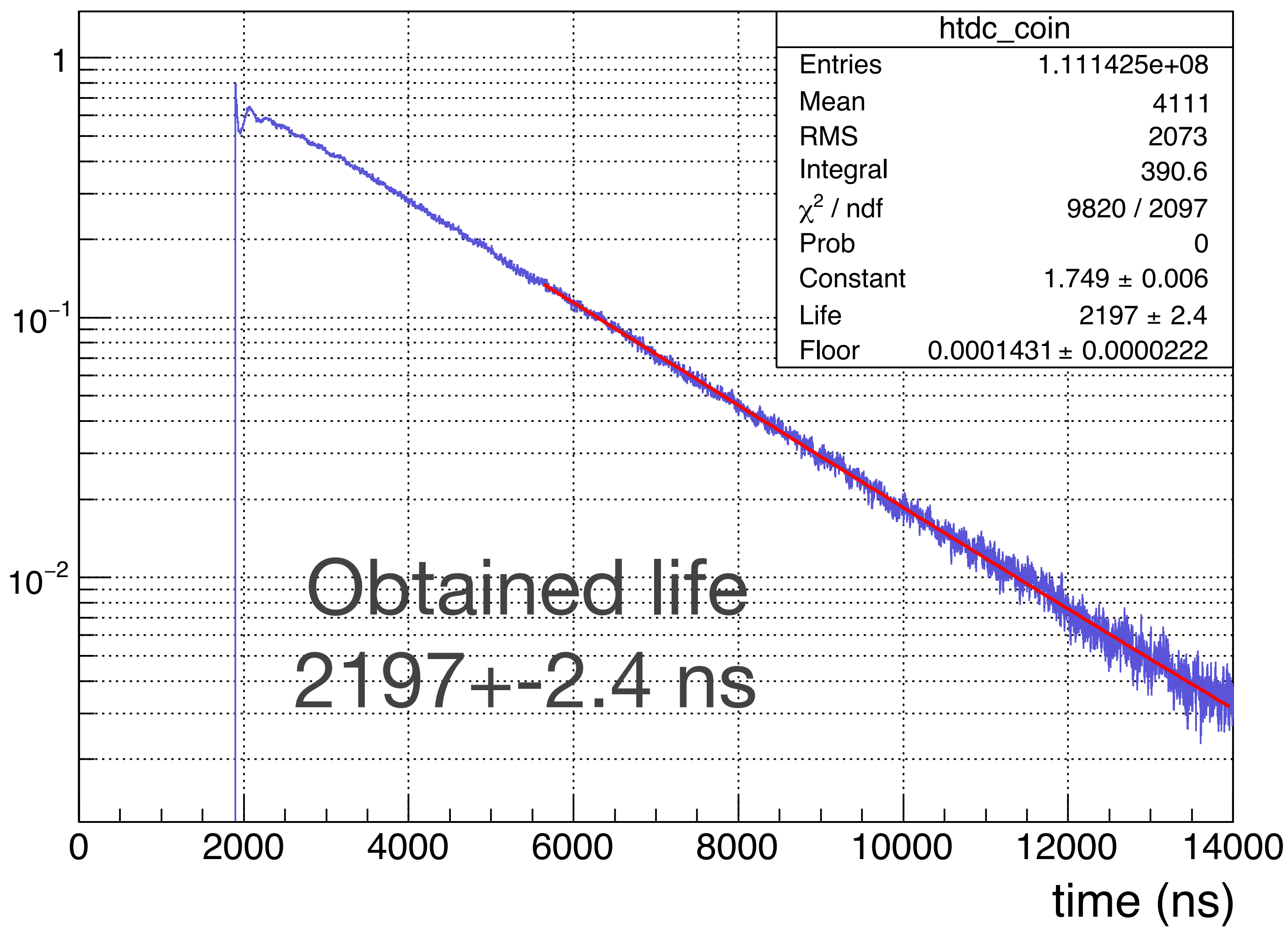
- KEK Advanced Linear and Logic-board Integrated Optical detectors for Positrons and Electrons

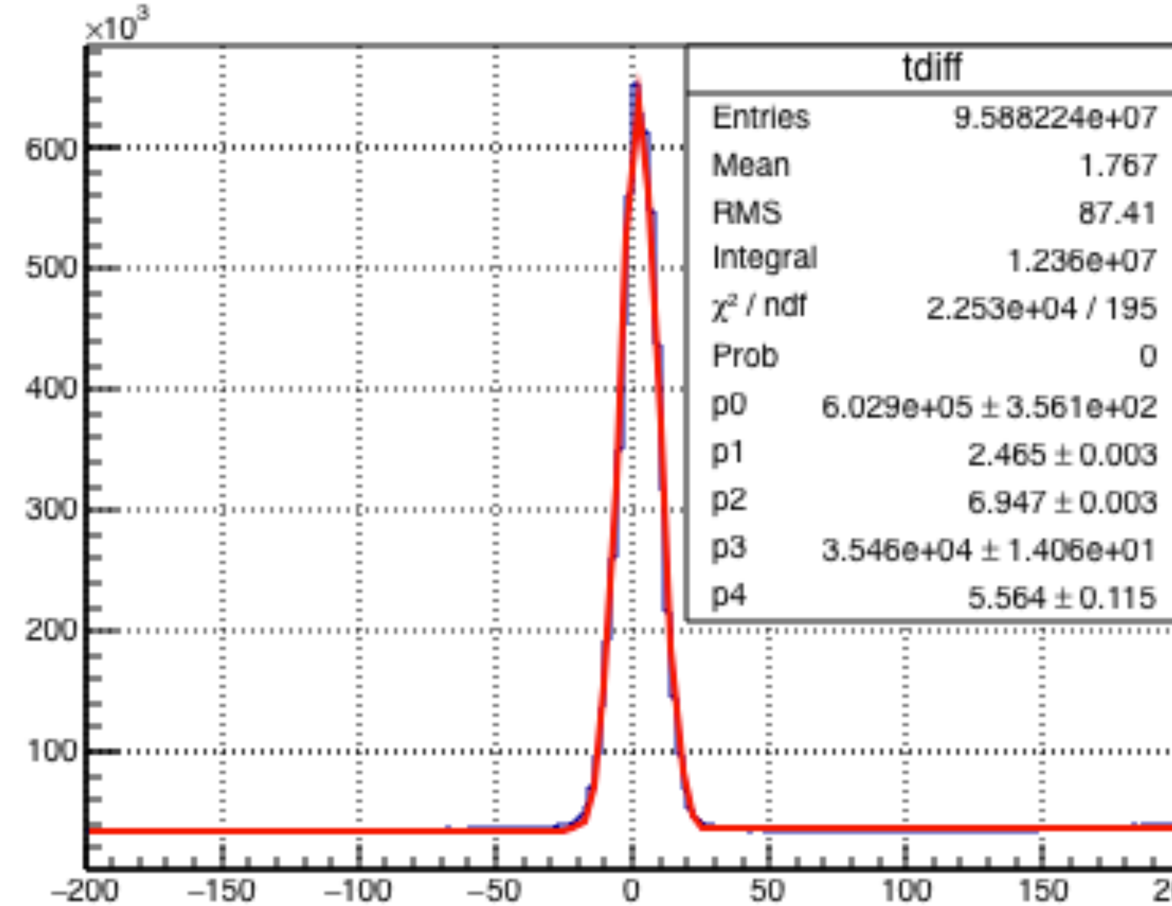


- 32ch inputs for MPPC
- ASIC implemented amplifier, shaper, discriminator
- FPGA programmed multi-hit TDC (common start)
- SiTCP data transfer

M. M. Tanaka, K. M. Kojima, T. Murakami, S. Kanda, C de la Taille and A. Koda, “MPPC frontend module for muon spin resonance spectrometer” (to be published)

Positron Time Spectrum

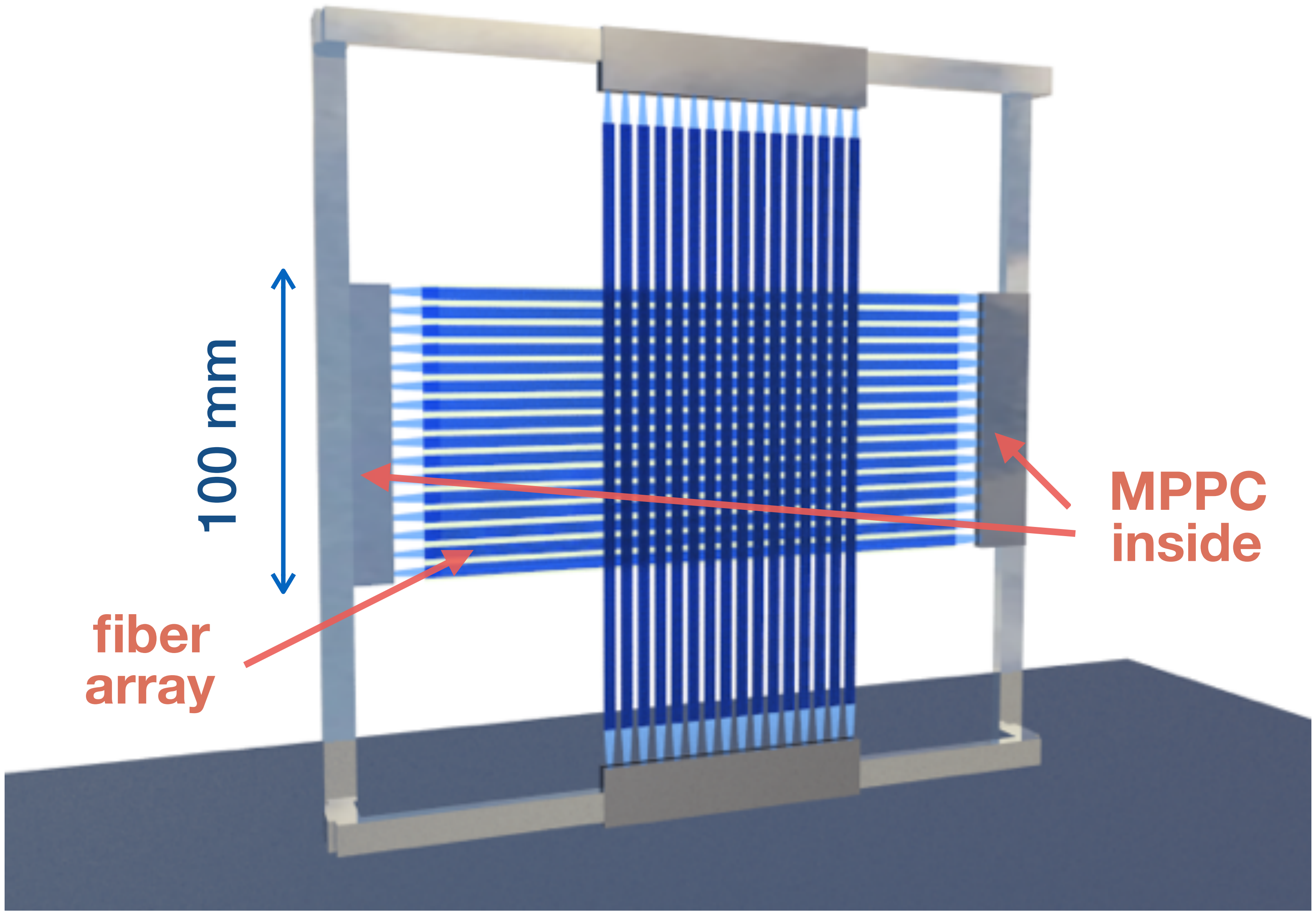




Coincidence time difference (ns)

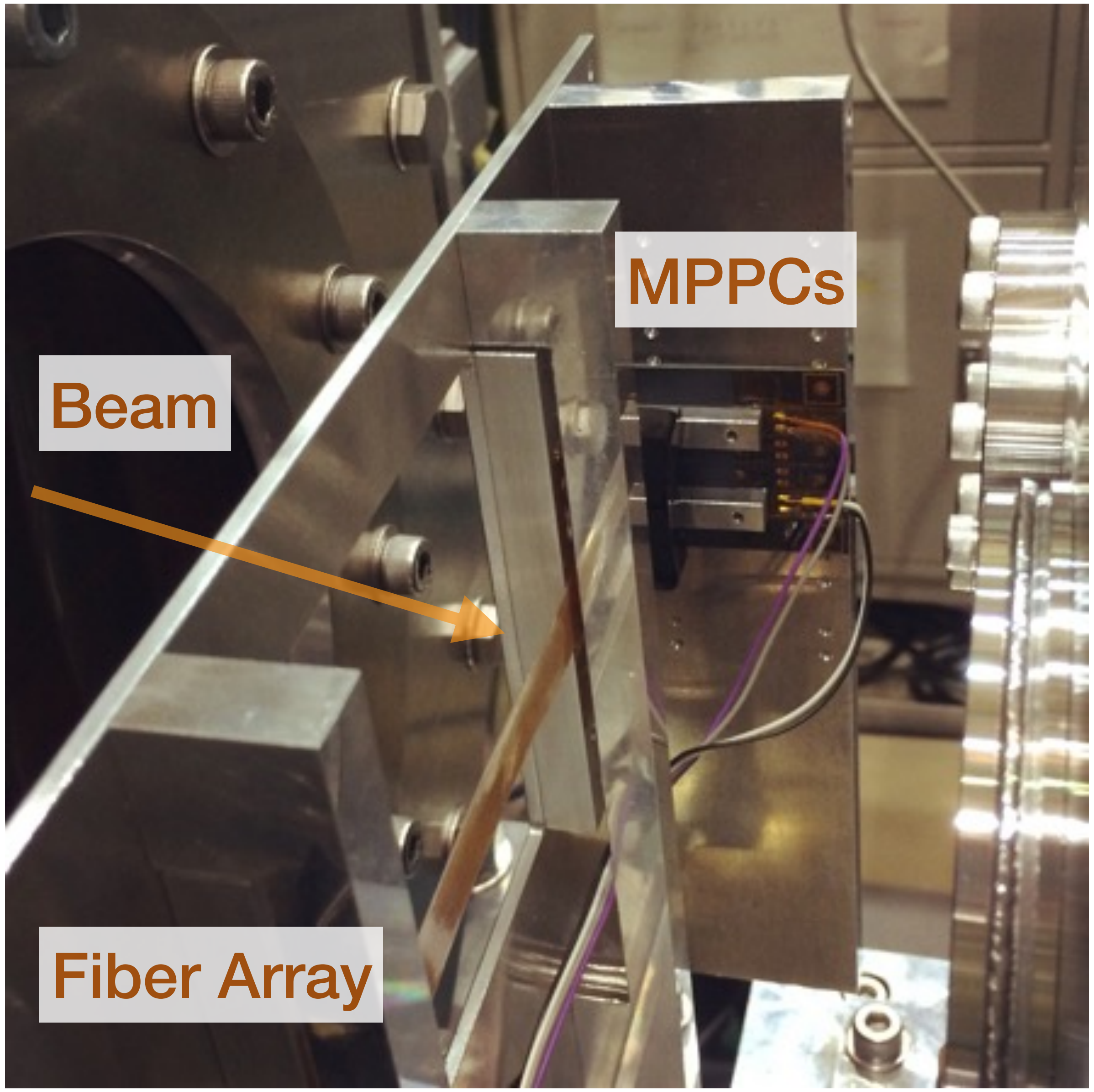
- Time spectrum of muon decay positron was measured by full-scale detector without significant event loss
- Timing resolution was estimated as 7 ns and good enough

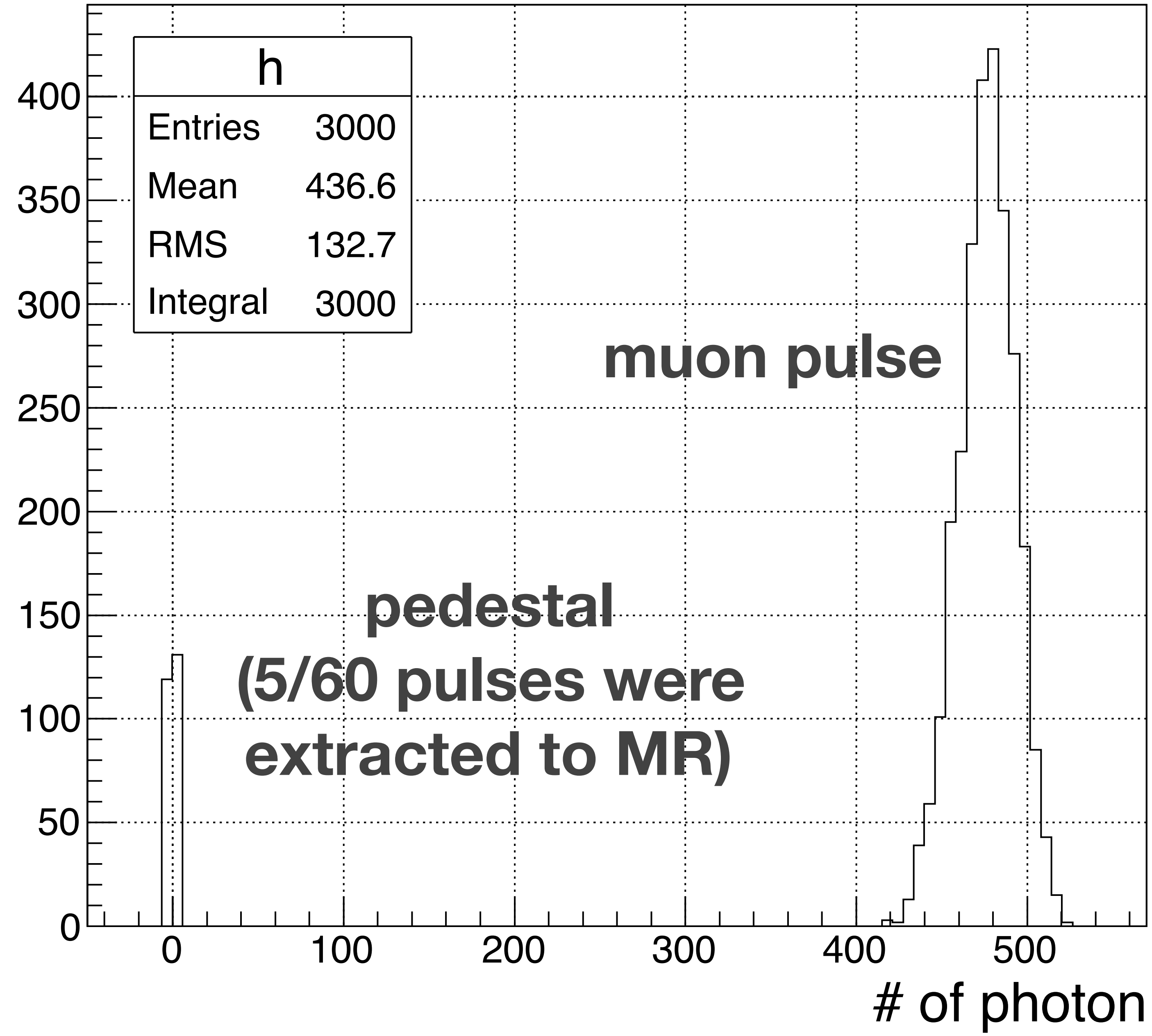
Fiber Beam Profile Monitor



- Cross-configured fiber hodoscope with SiPM readout
- To be placed in front of the target chamber
- Online monitoring of beam profile and intensity
- Minimum amount of material is required (4 MeV muon)

Prototype Development

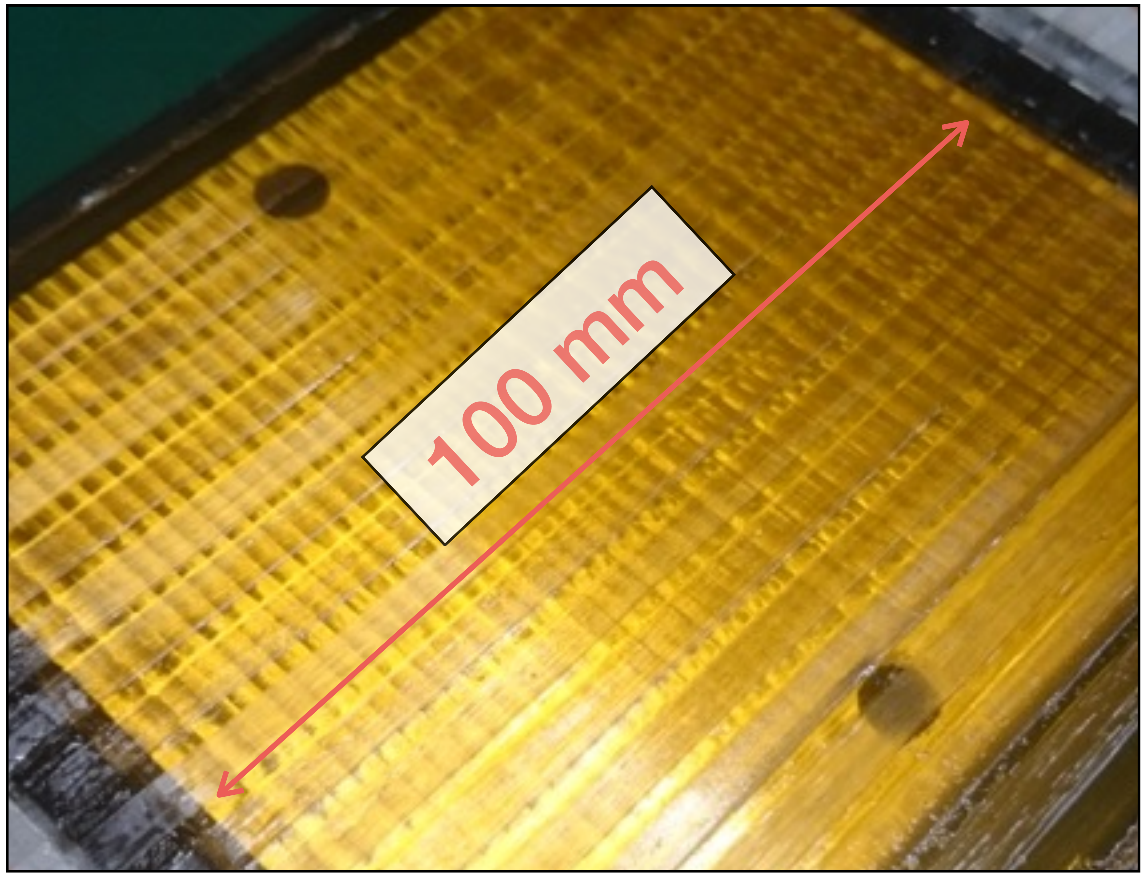


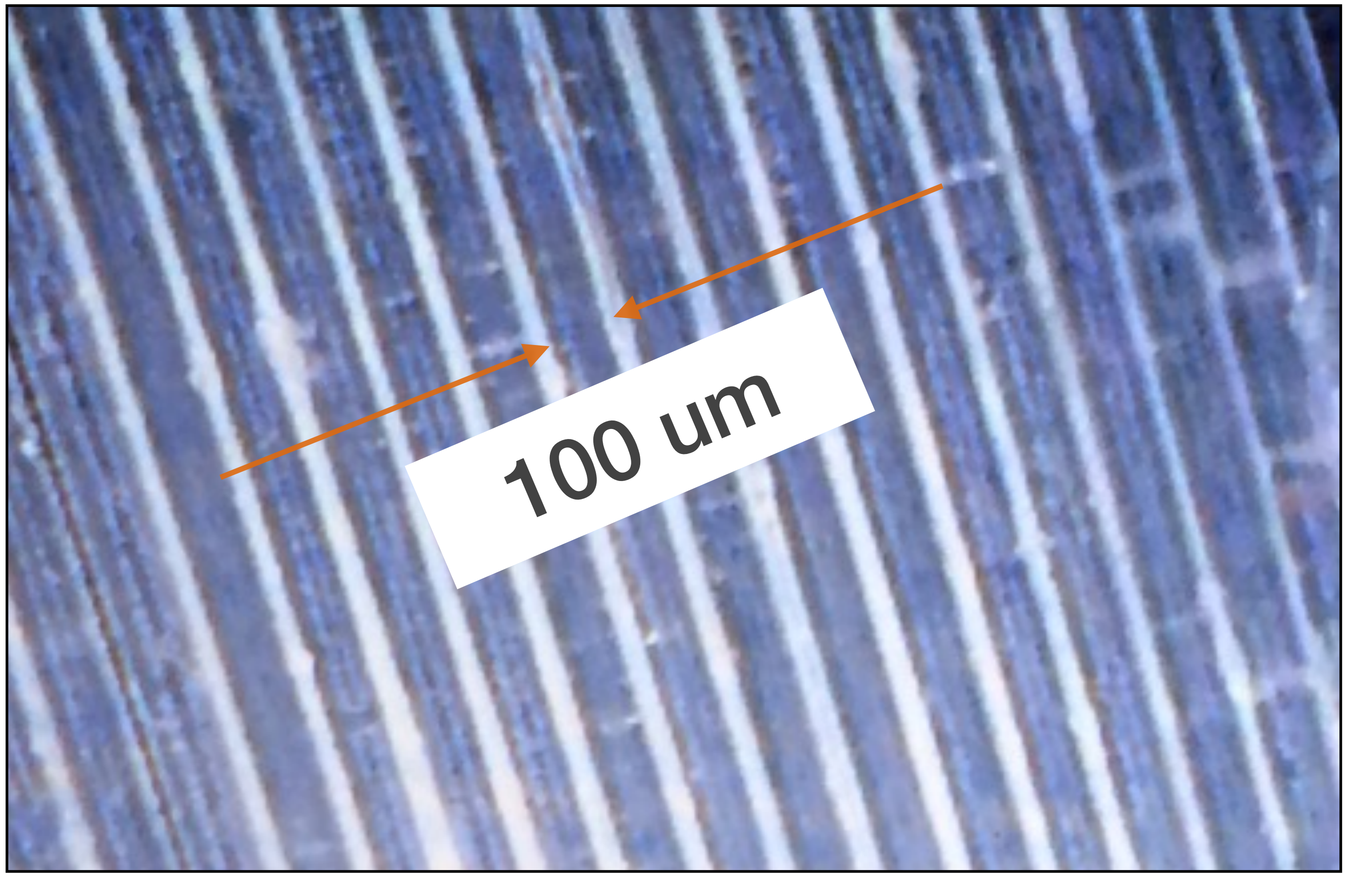


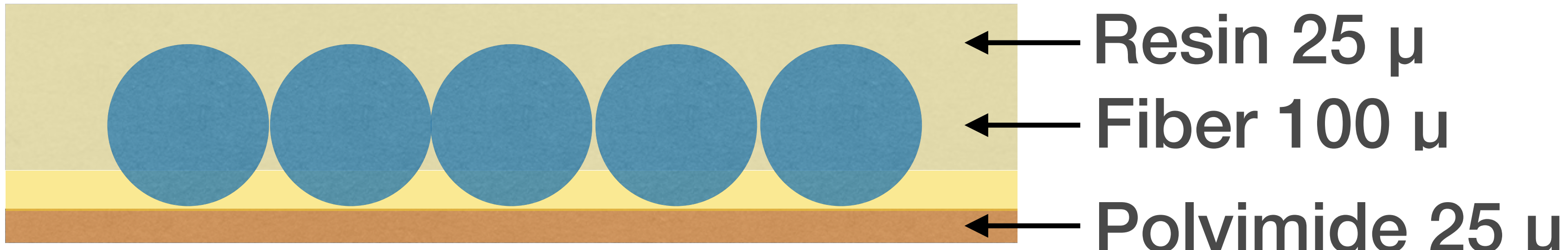
- Single band prototype was developed and tested by muon beam
- Photon yield positron was measured and high enough

S. Kanda, RIKEN Accelerator Progress Report Vo. 48 (2015)

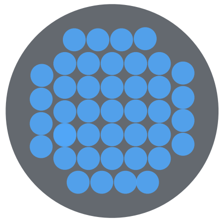
Scintillation Fiber Array





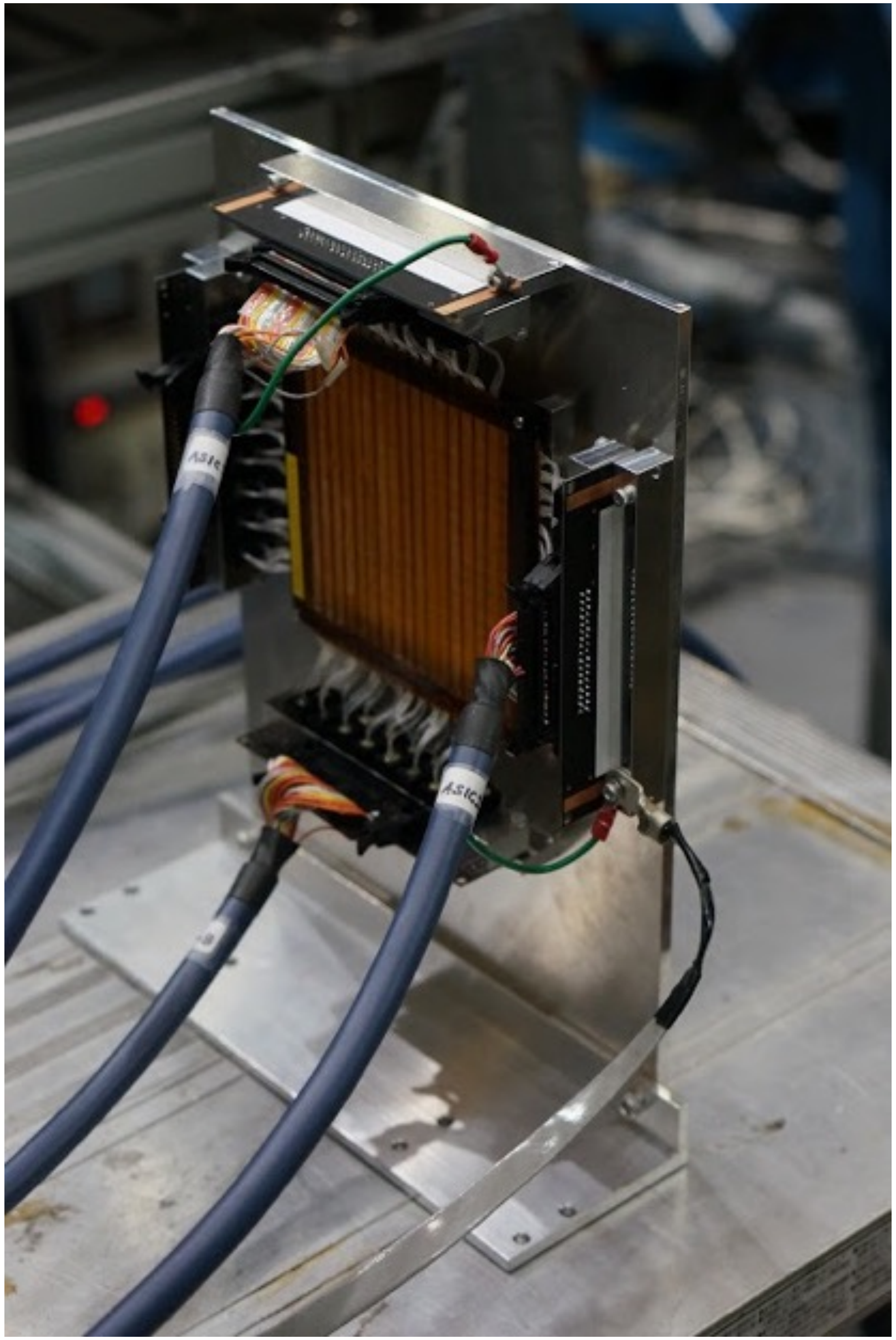


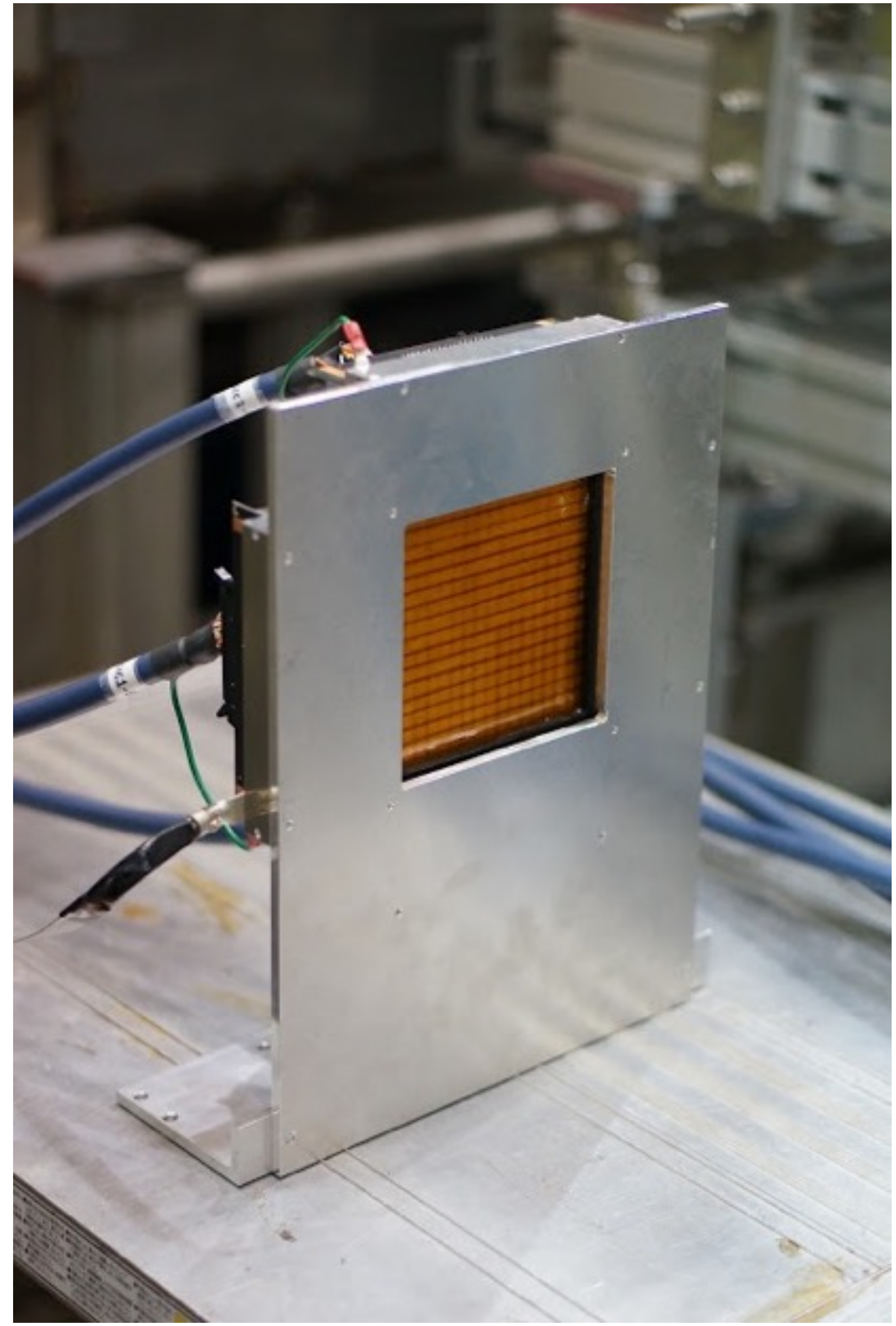
Fiber array layer structure



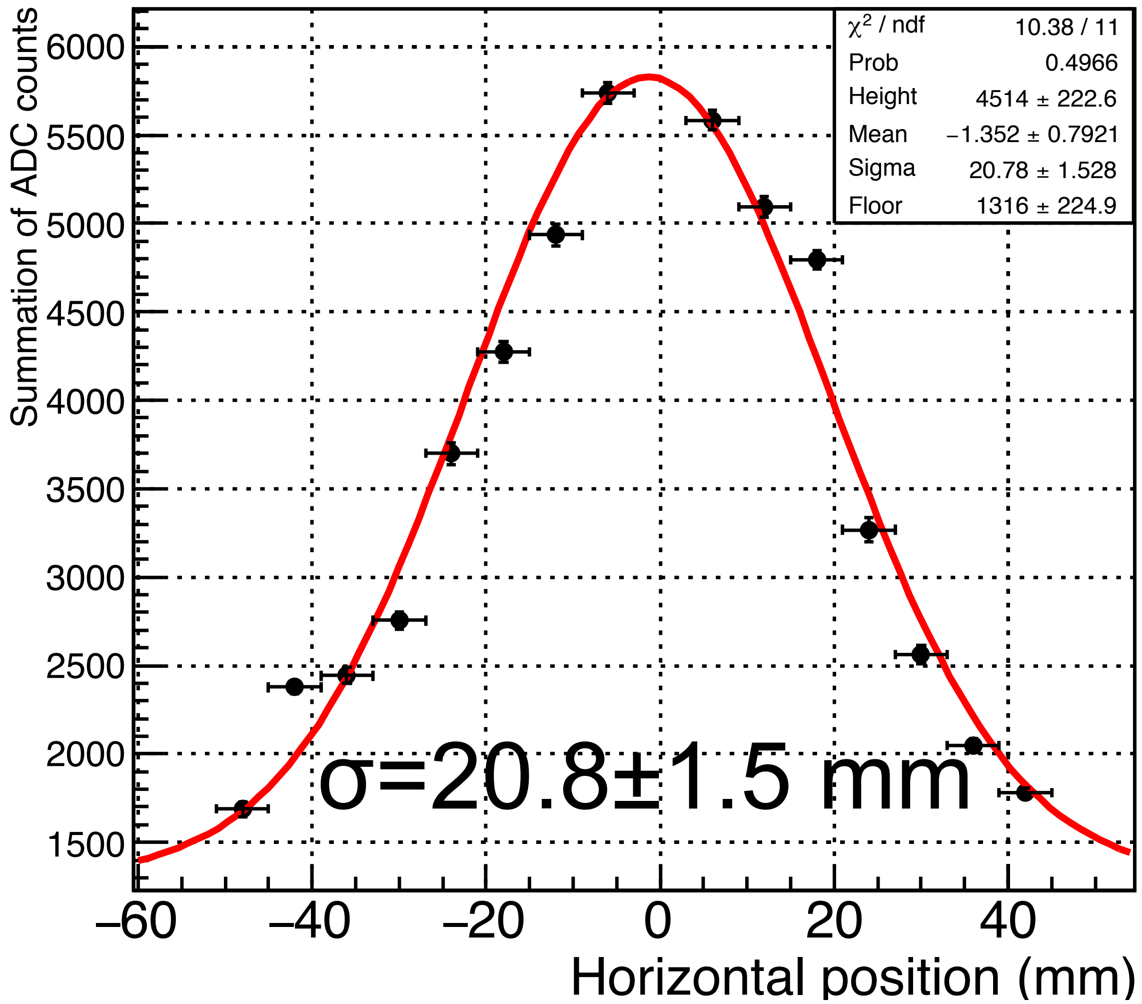
40 fibers are bundled for 1 ch. and connected to MPPC

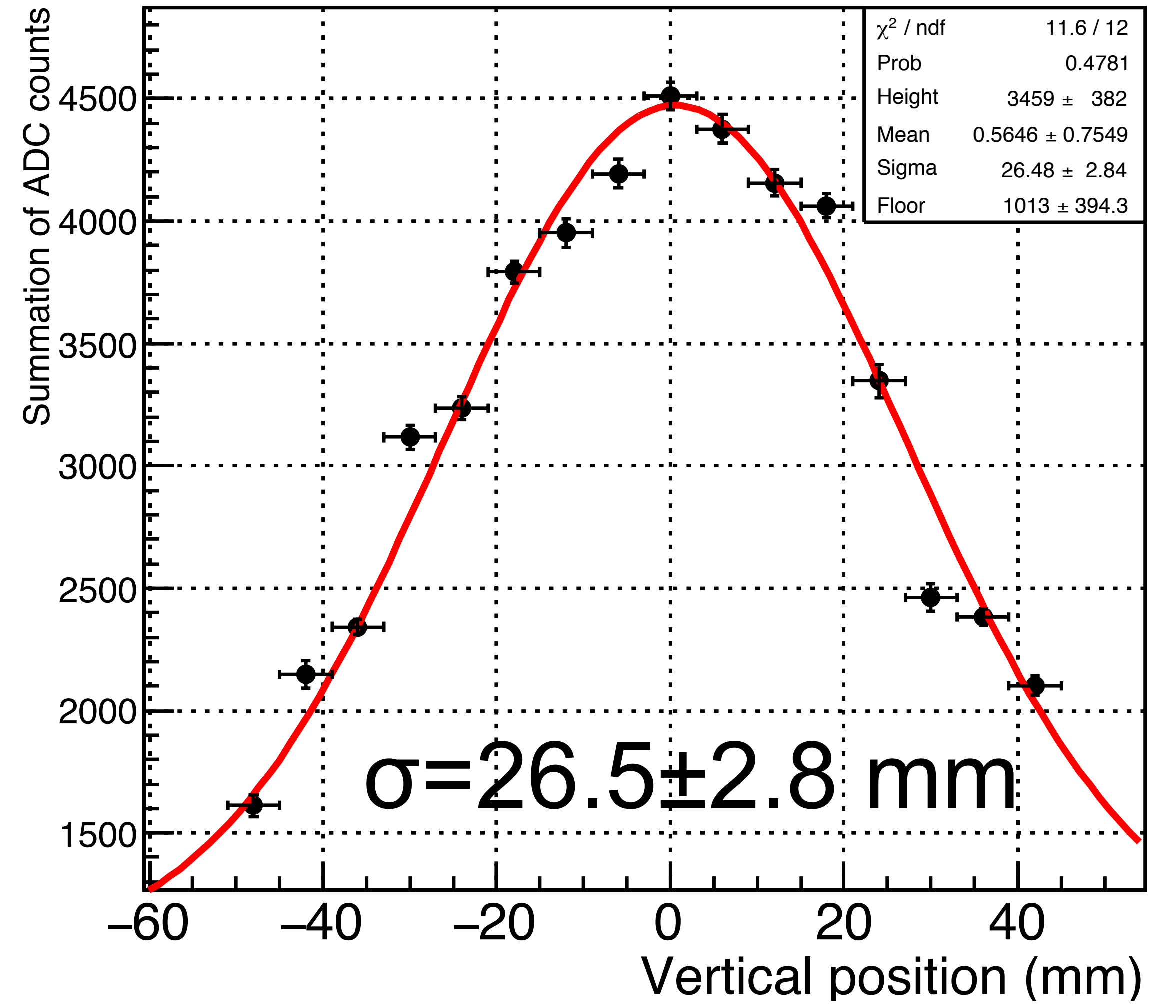
Fiber Beam Profile Monitor





Measured Beam Profile



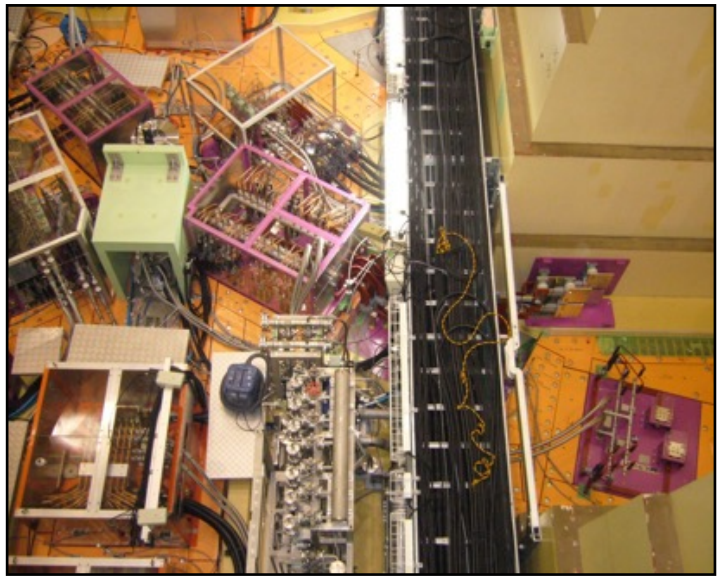


- **Muon beam profile was measured by fiber beam profile monitor**
- **Correction for light attenuation is to be applied**

S. Kanda and Y. Fukao, LEAP2016 conference

For High Field Experiment

- **H-Line; The highest intensity pulsed muon beam at J-PARC**



1×10^8 μ/s at 1 MW beam power (4M μ/pulse)

Optimization of beamline components is under study

Experimental area construction will be started in this summer

- **Superconducting magnet**

Field strength 1.7 T, Bore diameter 925 mm

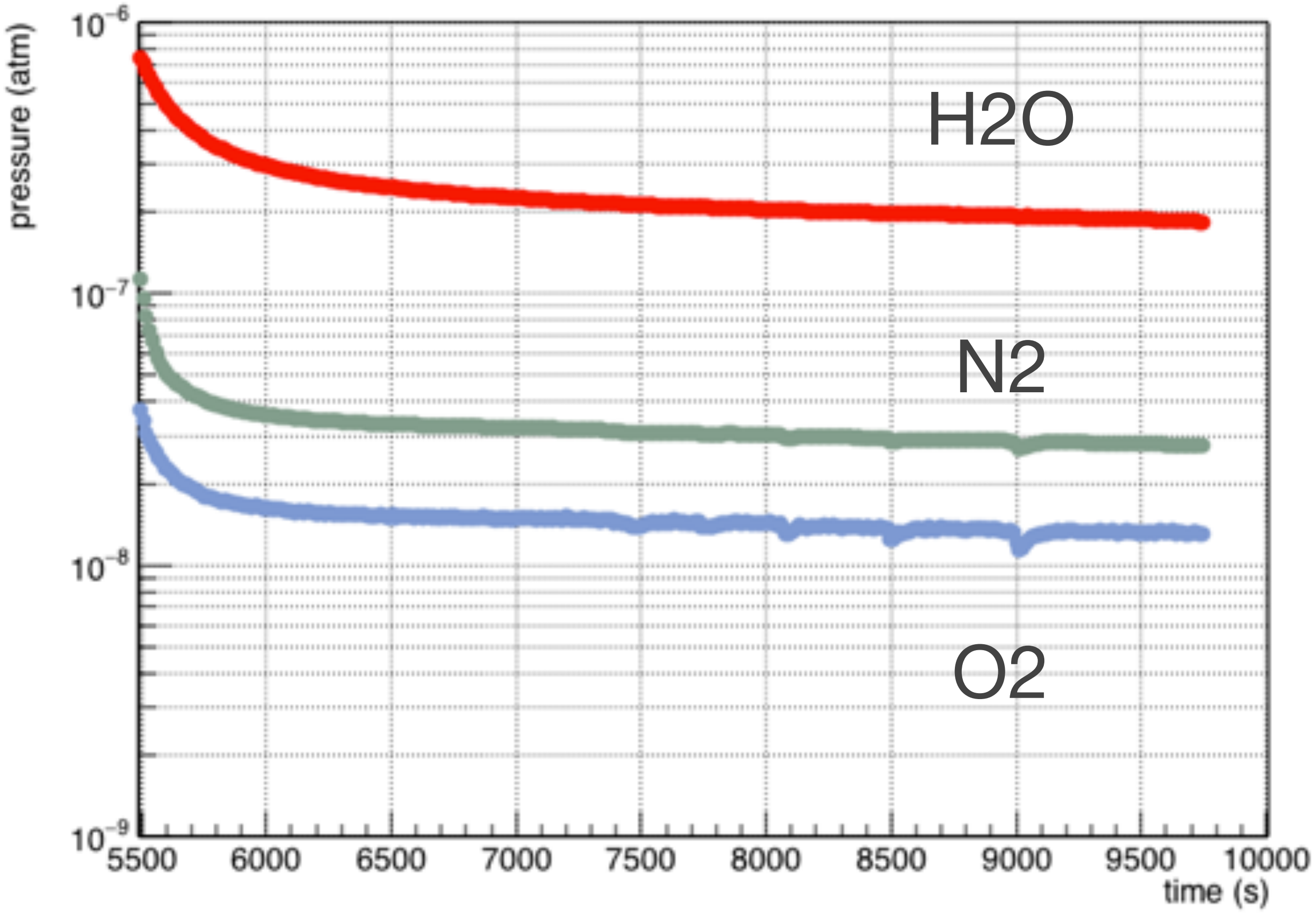
1 ppm uniformity in z300 mm, r100 mm region is required

Field shimming algorithm was developed and 1 ppm uniformity was achieved

Field monitoring by NMR probe in 30 ppb precision was achieved

Preliminary Result of the First Data Taking

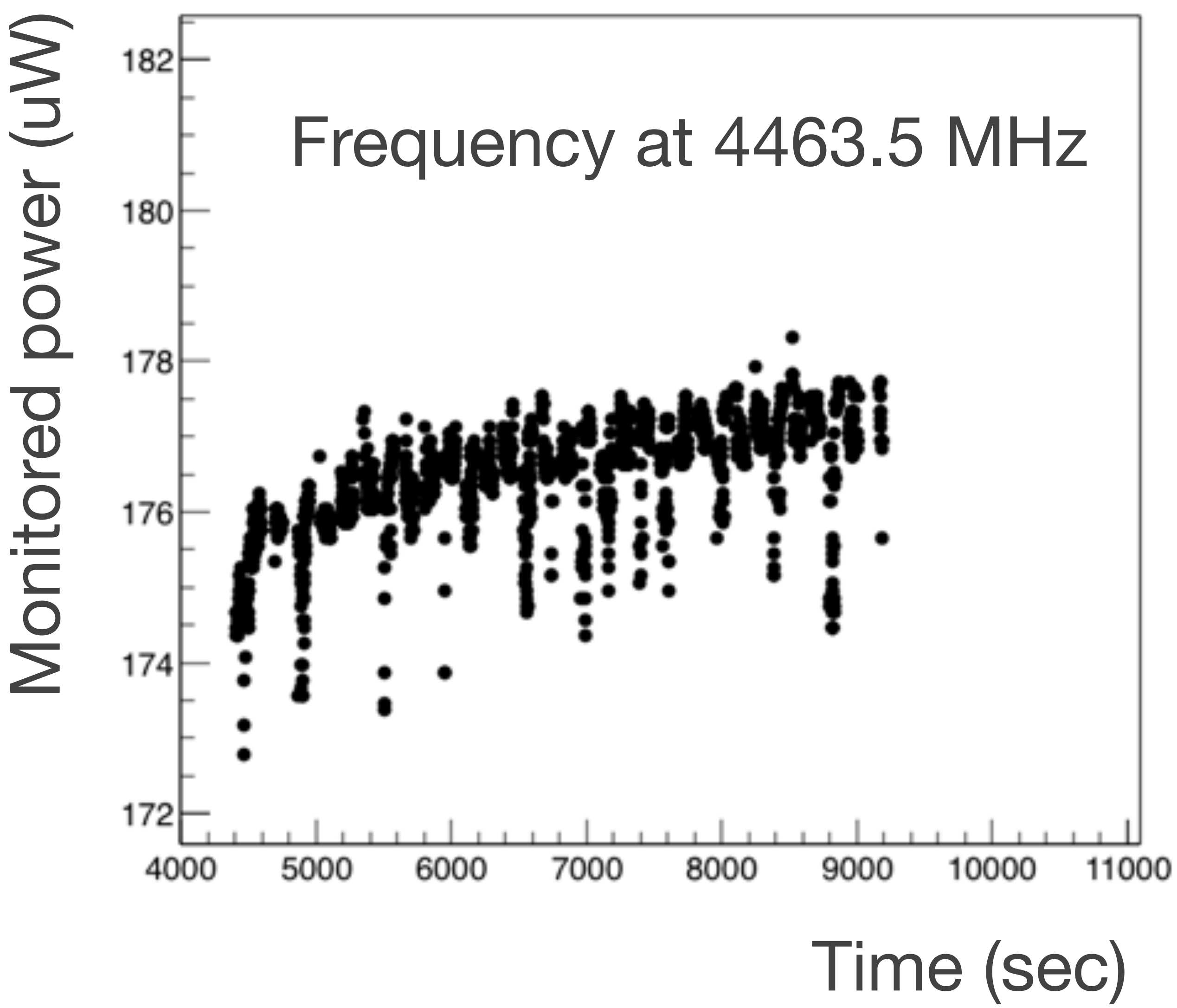
Systematic Uncertainties (Gas)

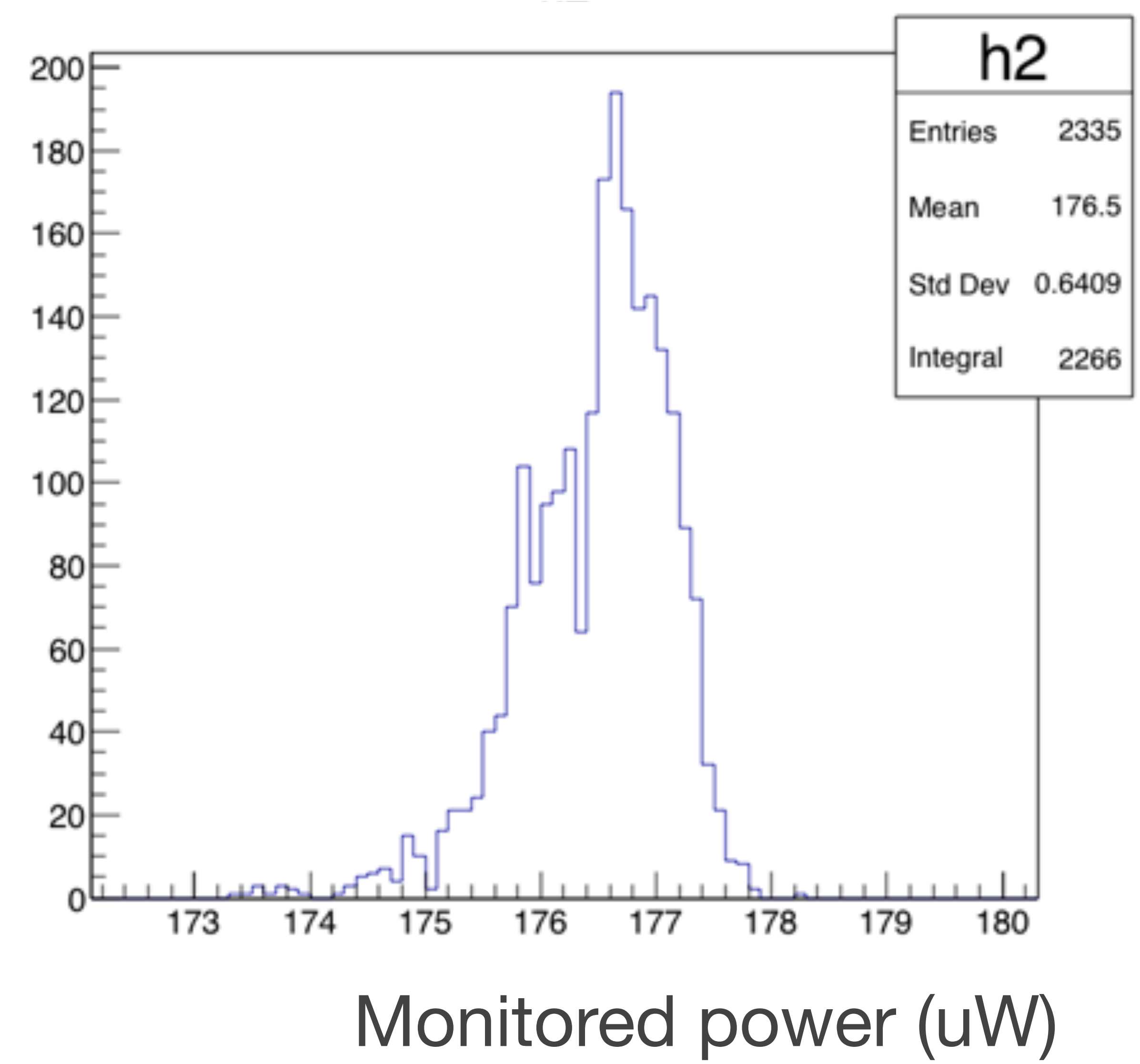


- Gas impurities was measured by a Q-Mass spectrometer
- Leakage rate and outgas pressure were measured by a cold cathode gauge
- Oxygen density was less than 1% of total pressure (~0.8%)

When we assume 0.1 Pa/hour of vacuum leakage
Gas exchange interval was shorter than 20 hours
2 Pa x 0.008 = 0.016 Pa of Oxygen
2 ppm at 1 atm case
Depolarization effect ~ 5% decrease of the spin flip signal

Systematic Uncertainties (RF)





Monitored RF power drifted due to temperature changing of the RF cavity
Some substructures were arising from the signal generator stability

RMS/Mean~0.4 %
(Less than 2% is acceptable)