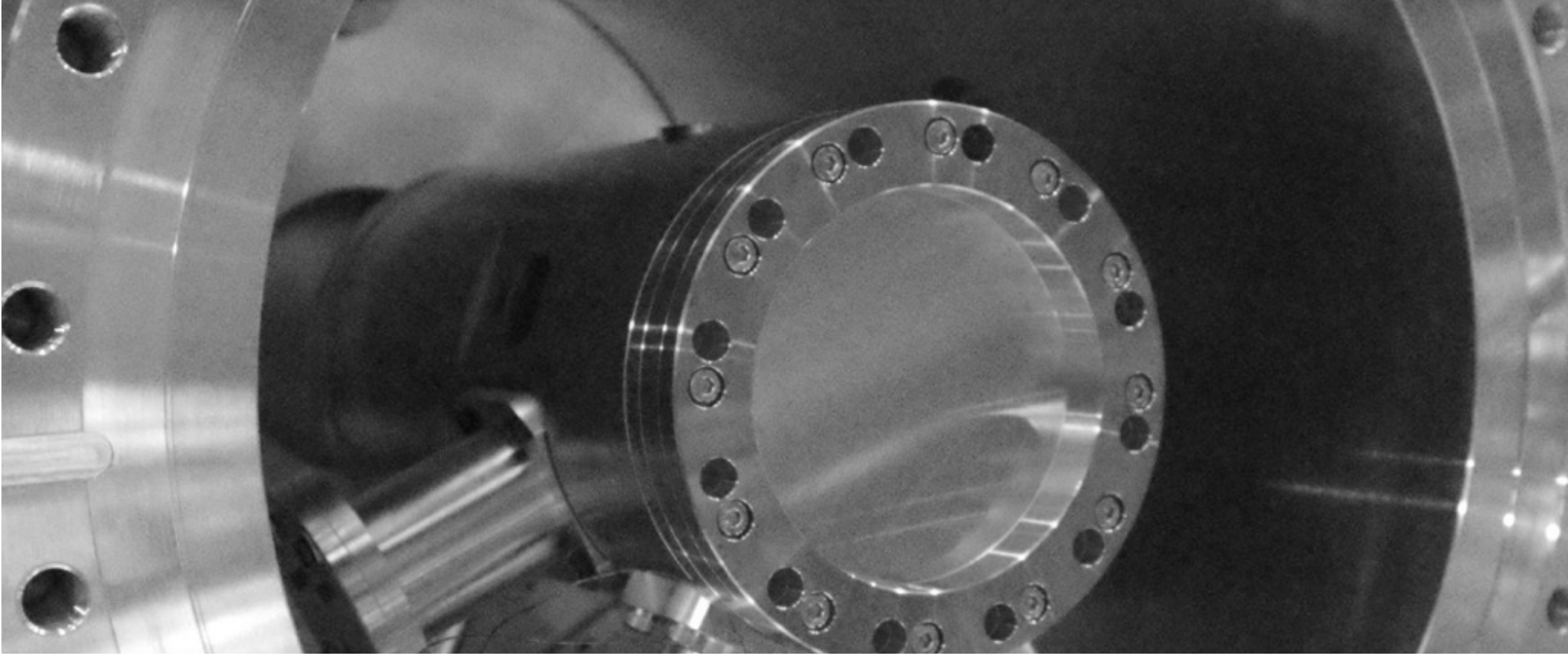
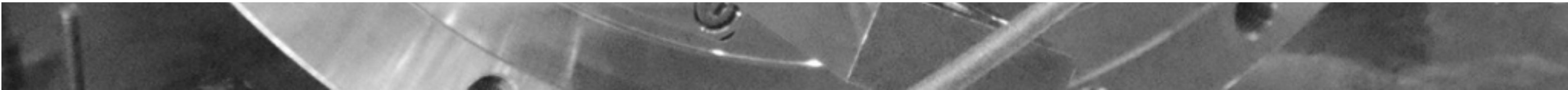


Precise Measurement of the Muonium HFS at J-PARC MUSE

Y. Ueno for MuSEUM Experiment



Agenda

- MuSEUM
  - Introduction of the Experiment
  - Physics Motivation
- Experimental Apparatuses
  - J-PARC MUSE: Intense Pulsed Muon Beam
  - Other Apparututses
  - Systematic Uncertainties
- Current Status
  - Resonance Signal Observed in June 2016
- Future Prospect

MuSEUM Collaboration

MuSEUM

MuSEUM

東京大学
THE UNIVERSITY OF TOKYO

KEK

J-PARC

RIKEN

JAEA

ICU

Univ. of Yamanashi

Osaka Univ.

UMASS

TOHOKU UNIVERSITY

Collaborators

M. Aoki[A], Y. Fukao[B], Y. Higashi[C], T. Higuchi[C], H. Iinuma[B], Y. Ikedo[B], K. Ishida[D], T.U. Ito[F], M. Iwasaki[D], R. Kadono[B], O. Kamigaito[D], S. Kanda[E], D. Kawall[G], N. Kawamura[B], A. Koda[B], K.M. Kojima[B], M.K. Kubo[H], Y. Matsuda[C], T. Matsudate[C], T. Mibe[B], Y, Miyake[B], T. Mizutani[C], K. Nagamine[B], S. Nishimura[E], K. Nishiyama[B], T. Ogitsu[B], R. Okubo[B], N. Saito[B], K. Sasaki[B], S. Seo[C], K. Shimomura[B], P. Strasser[B], M. Sugano[B], M. Tajima[C], K.S. Tanaka[I], T. Tanaka[C], D. Tomono[J], H.A. Torii[C], E. Torikai[K], A. Toyoda[B], K. Ueno[B], Y. Ueno[C], D. Yagi[C], A. Yamamoto[B], M. Yoshida[B]

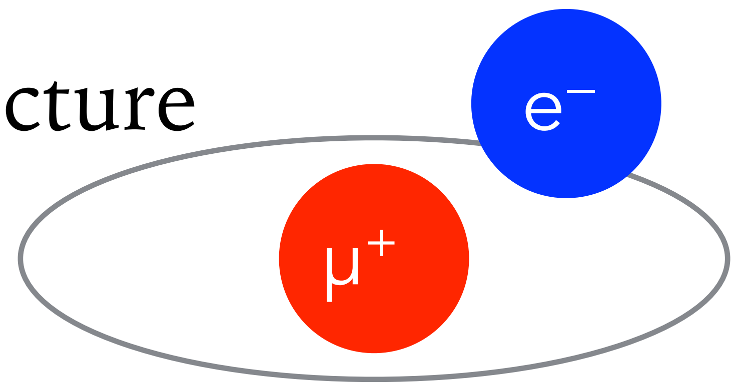
Universities and Institutions

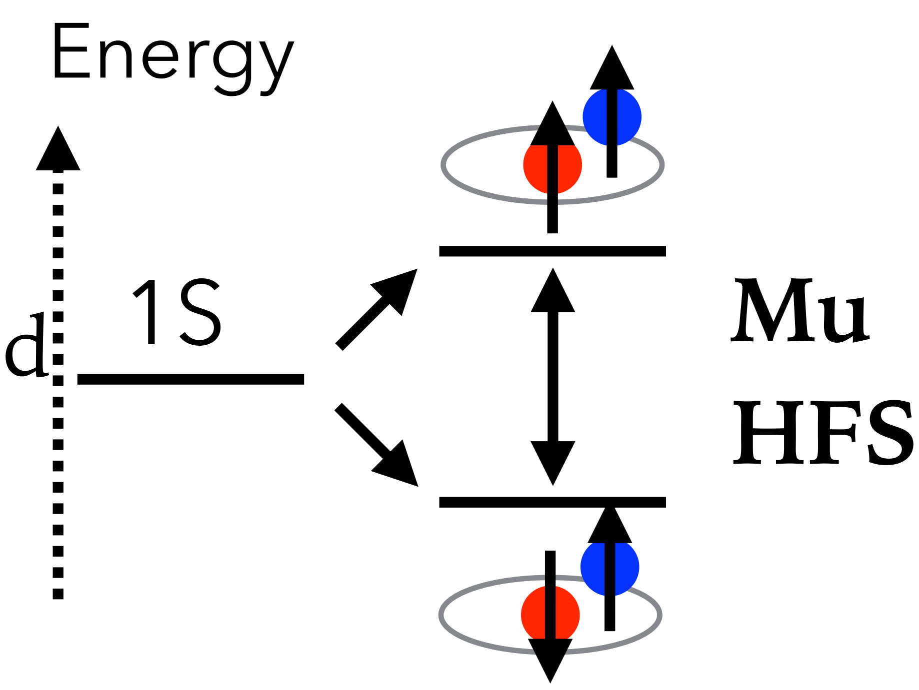
Osaka University[A], KEK[B], Graduate School of Arts and Sciences, University of Tokyo[C], RIKEN[D], Department of Physics, University of Tokyo[E], JAEA[F], University of Massachusetts[G], ICU[H], Tohoku University[I], RCNP[J], University of Yamanashi[K]

6 Universities, 4 Institutions: 45 people

MuSEUM

- **Mu**onium **S**pectroscopy **E**xperiment **U**sing **M**icrowave
  - Spectroscopy of muonium hyperfine structure
- Muonium: bound state of μ^+ and e$^-$
  - Hydrogen-like atom
  - Purely-leptonic: no proton
  - Theoretical value: precisely calculated
- Motivations:
  - Test of the bound-state QED
  - Determination of the muon magnetic moment/mass
  - New particle search, CPT/Lorentz violation search





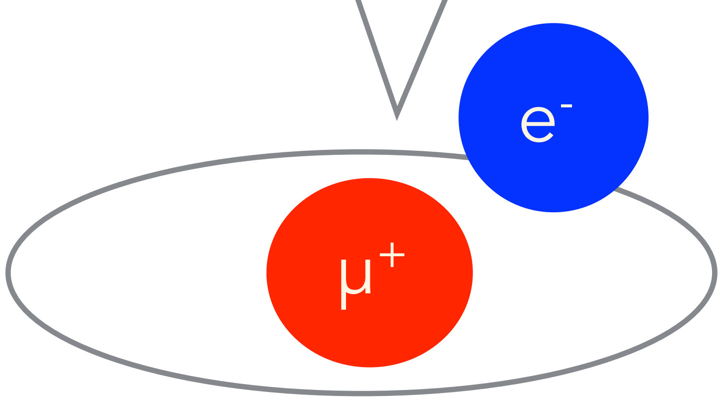
Theoretical Values of Mu and H

- Comparison of the theoretical values of Mu and H HFS

$\Delta\nu_{th}$ = 4. 463 302 891 (272) GHz

61 ppb

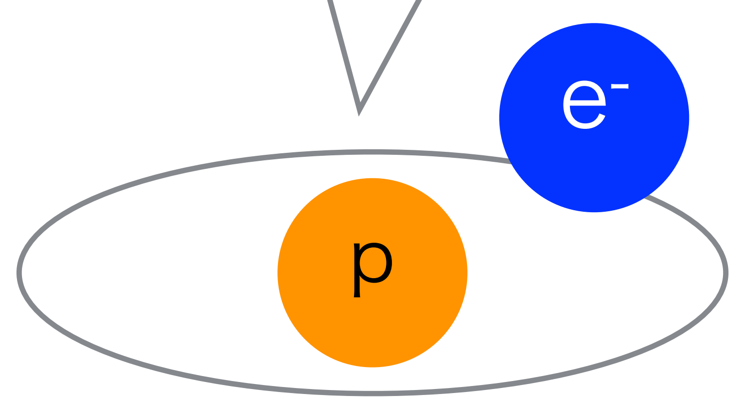
D. Nomura and T. Teubner,
Nucl. Phys. B 867 236 (2013)



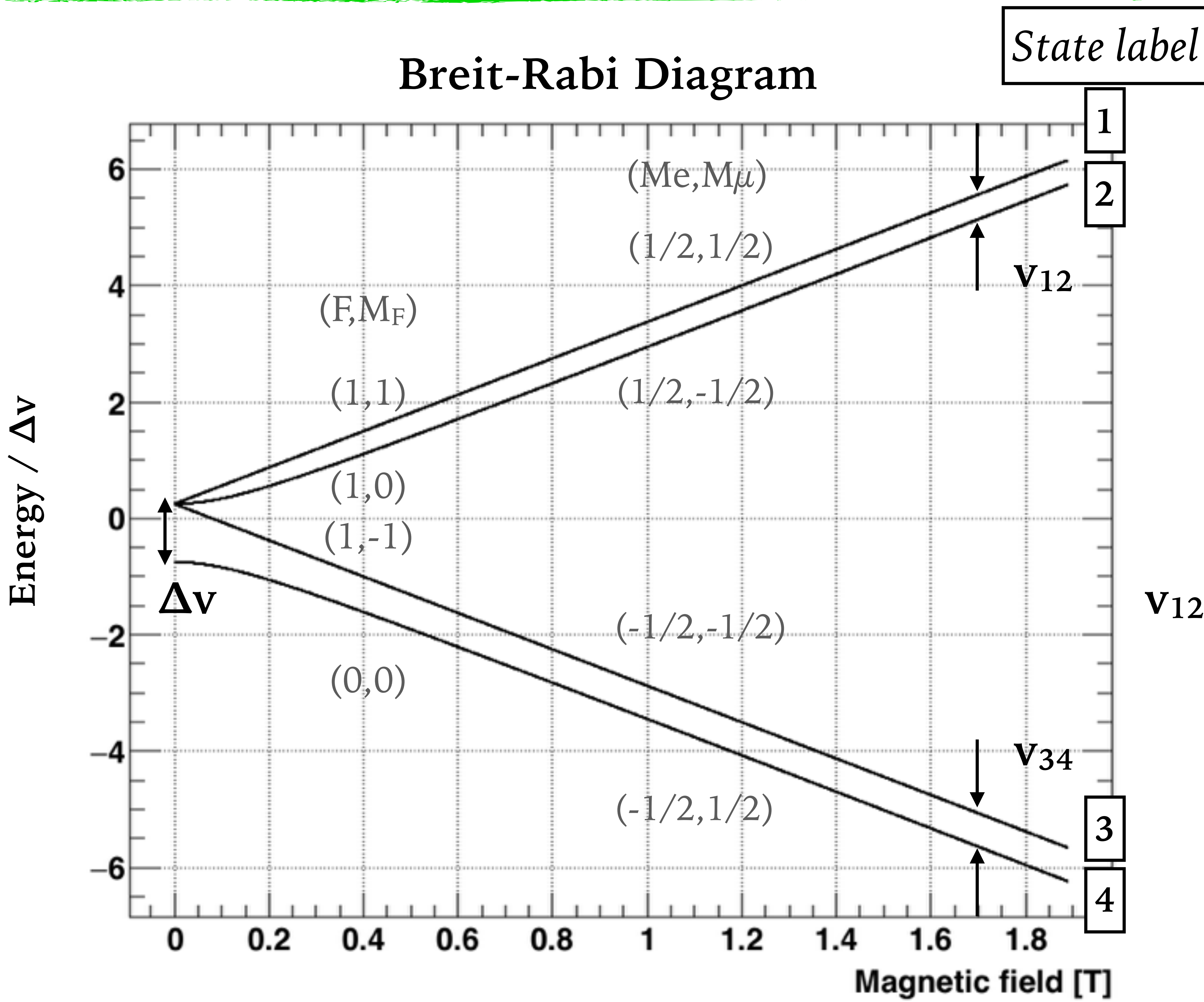
$\Delta\nu_{th}$ = 1. 420 403 1 (8) GHz

560 ppb

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

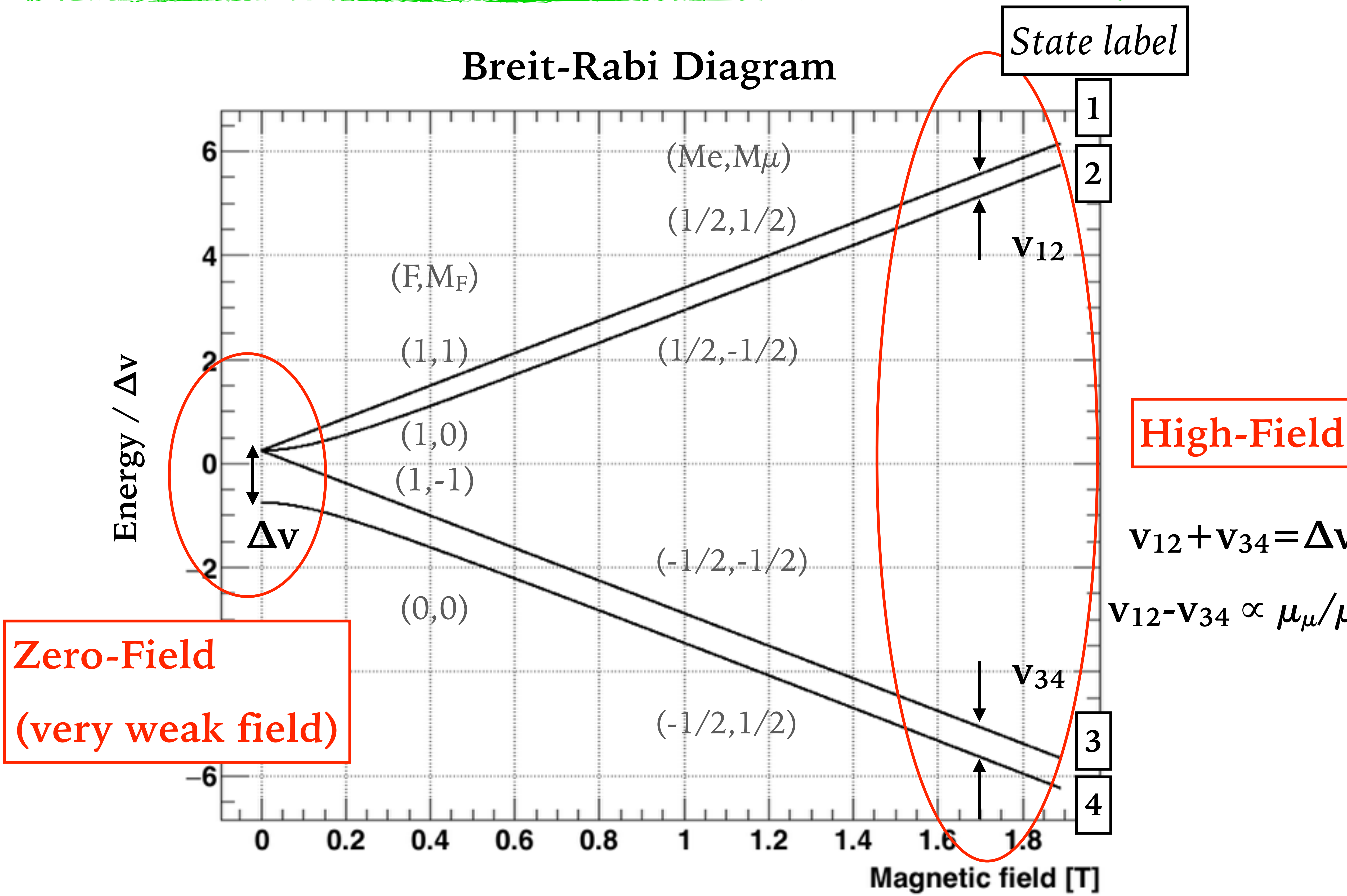


MuSEUM: Zeeman Splitting



$v_{12}+v_{34}=\Delta v$

MuSEUM: Zeeman Splitting



$v_{12}+v_{34}=\Delta v$

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

MuSEUM: High Field

- 1.7 T field generated by SC magnet
- Measurements for two different frequencies
- Obtain two different physical quantities
  - $\nu_{12} + \nu_{34} = \Delta\nu$ at zero field
  - $\nu_{12} - \nu_{34} \sim \mu_\mu/\mu_\text{p}$ (m_μ/m_p)

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

- World record: 4.463 302 776(51) GHz (12 ppb) at LAMPF (Los Alamos Meson Physics Facility)
- μ_μ/μ_p = 206. 768 276(24) (120 ppb)
- Essential input parametr for the muon g–2

talks by

T. Mibe

D. Flay

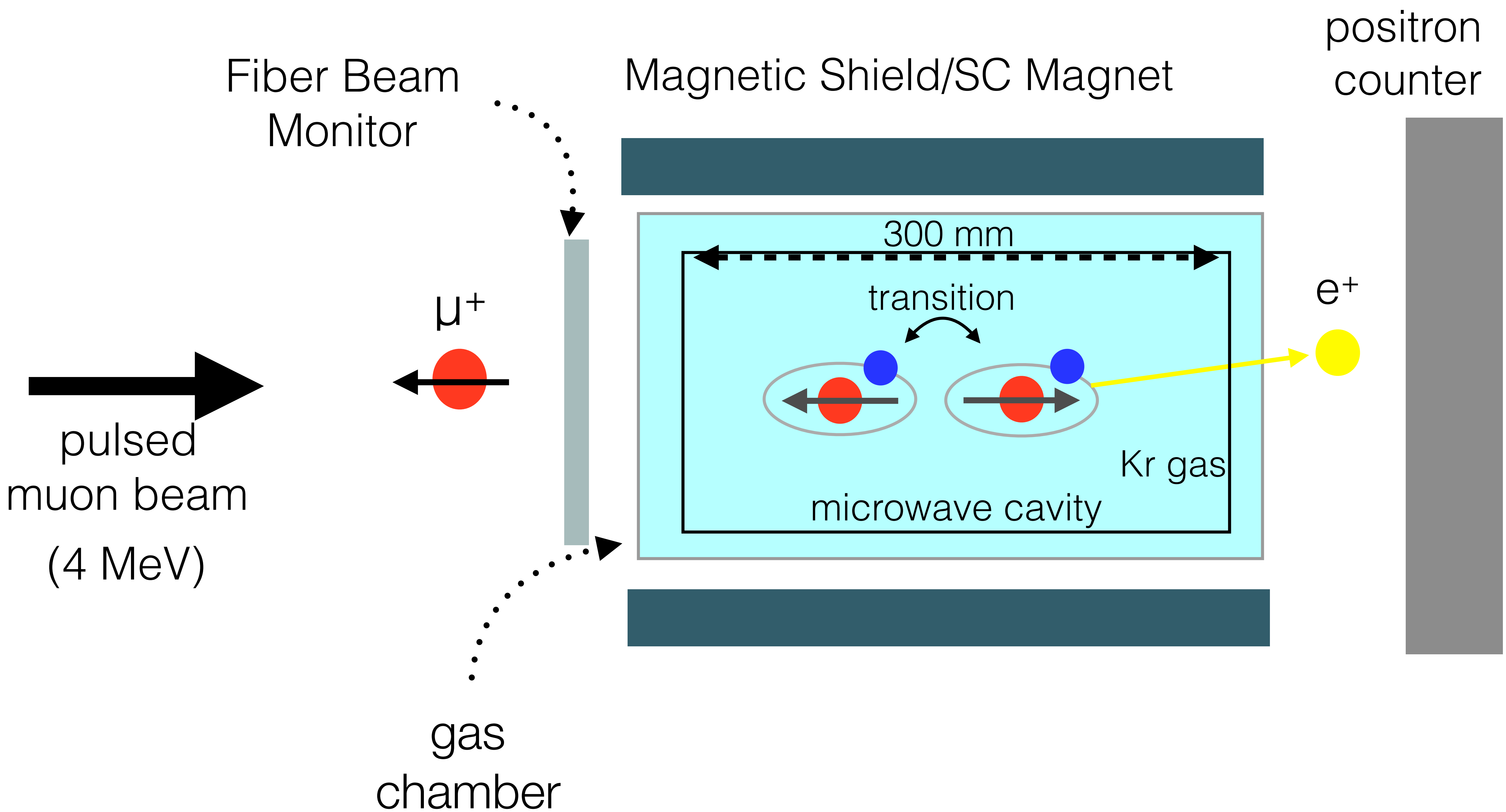
MuSEUM: Zero Field

- Field less than 100 nT (1 mG)
- Complementary measurement with different systematic uncertainties
- Different constraint on CPT/Lorentz invariance (mentioned in following slide)
- Best record 4.463 3022(14) GHz (300 ppb)

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

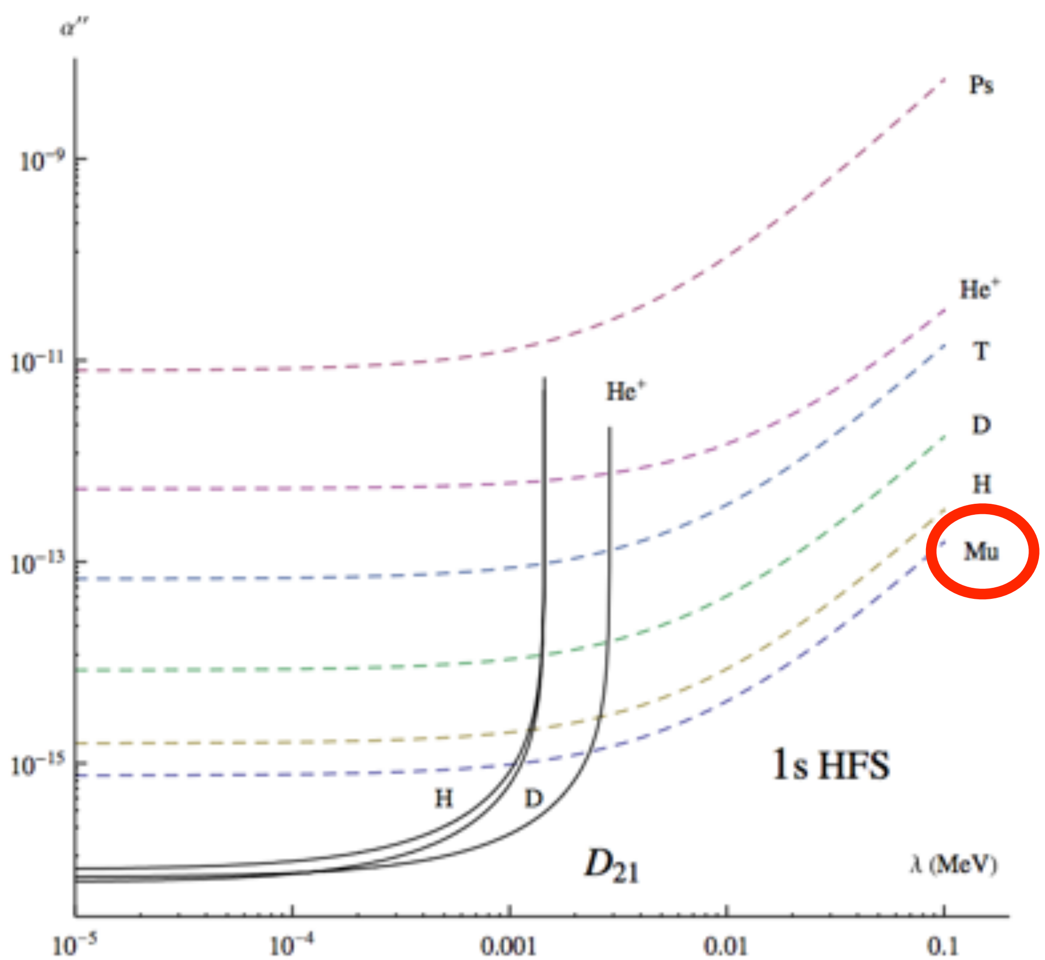
- **MuSEUM Goal**: ten-fold improvements for the both measurements at zero field and in high field

Procedure


Fiber Beam Monitor
Magnetic Shield/SC Magnet
positron counter
300 mm
transition
μ+
e+
pulsed muon beam
(4 MeV)
Kr gas
microwave cavity
gas chamber

MuSEUM: New Particle Search

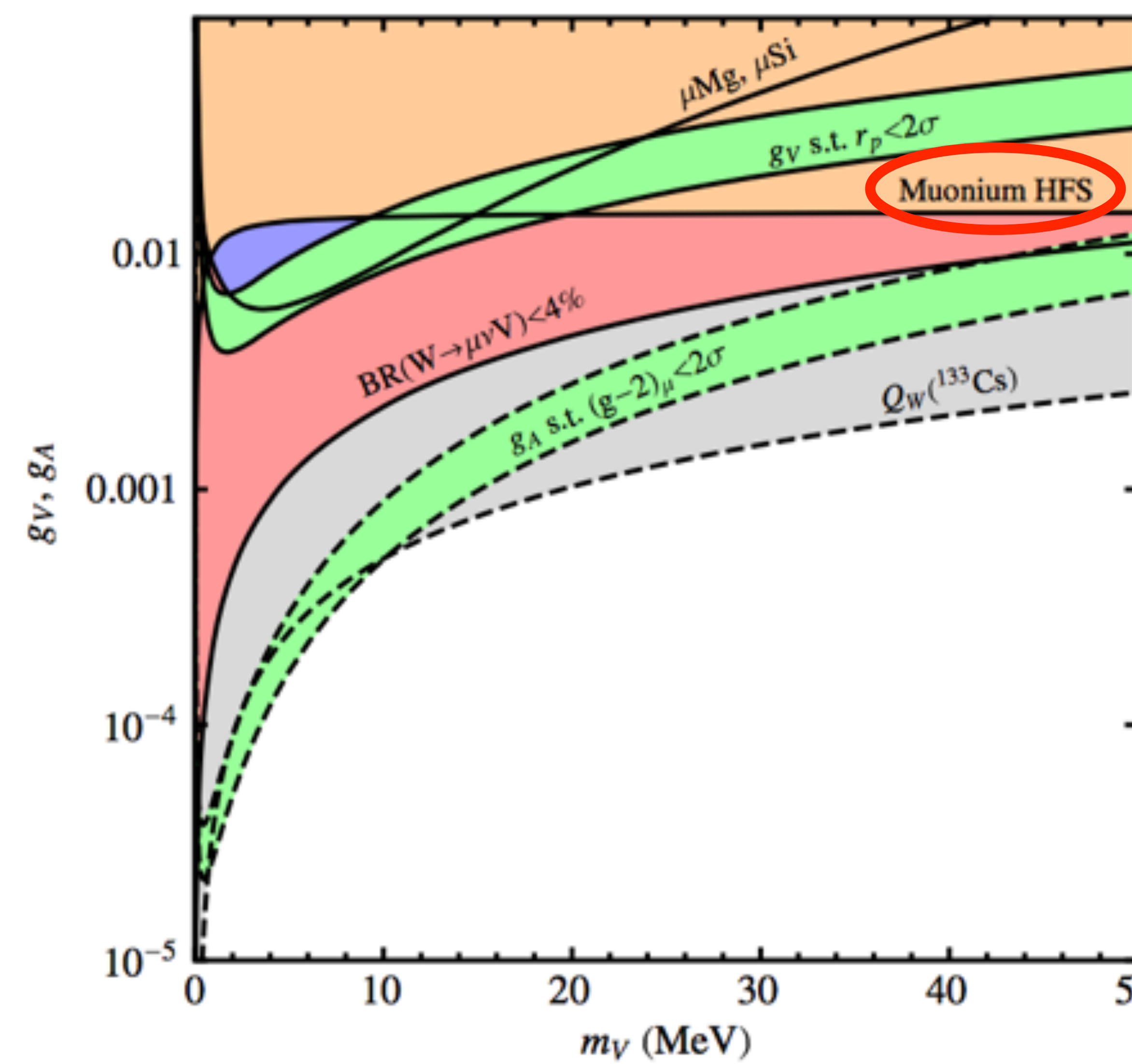
- Muonium HFS is sensitive to some new particles



Pseudovector boson

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

the red circle added by YU



Dark force

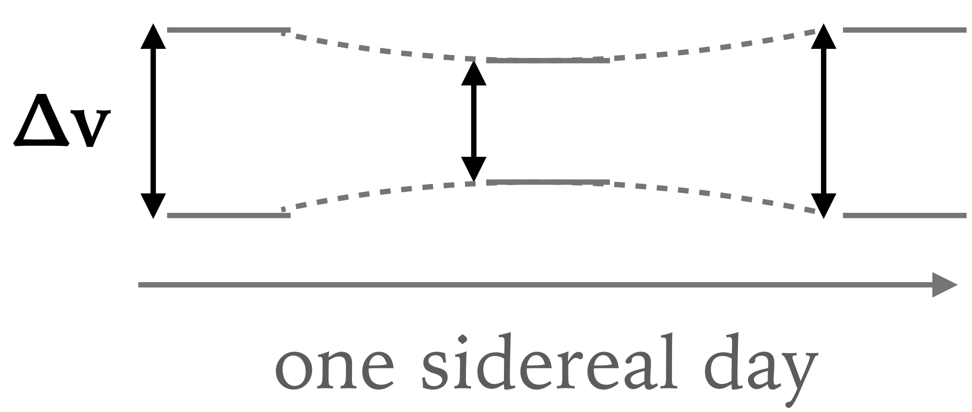
S. G. Karshenboim, *PRD* **90**, 073004 (2014)

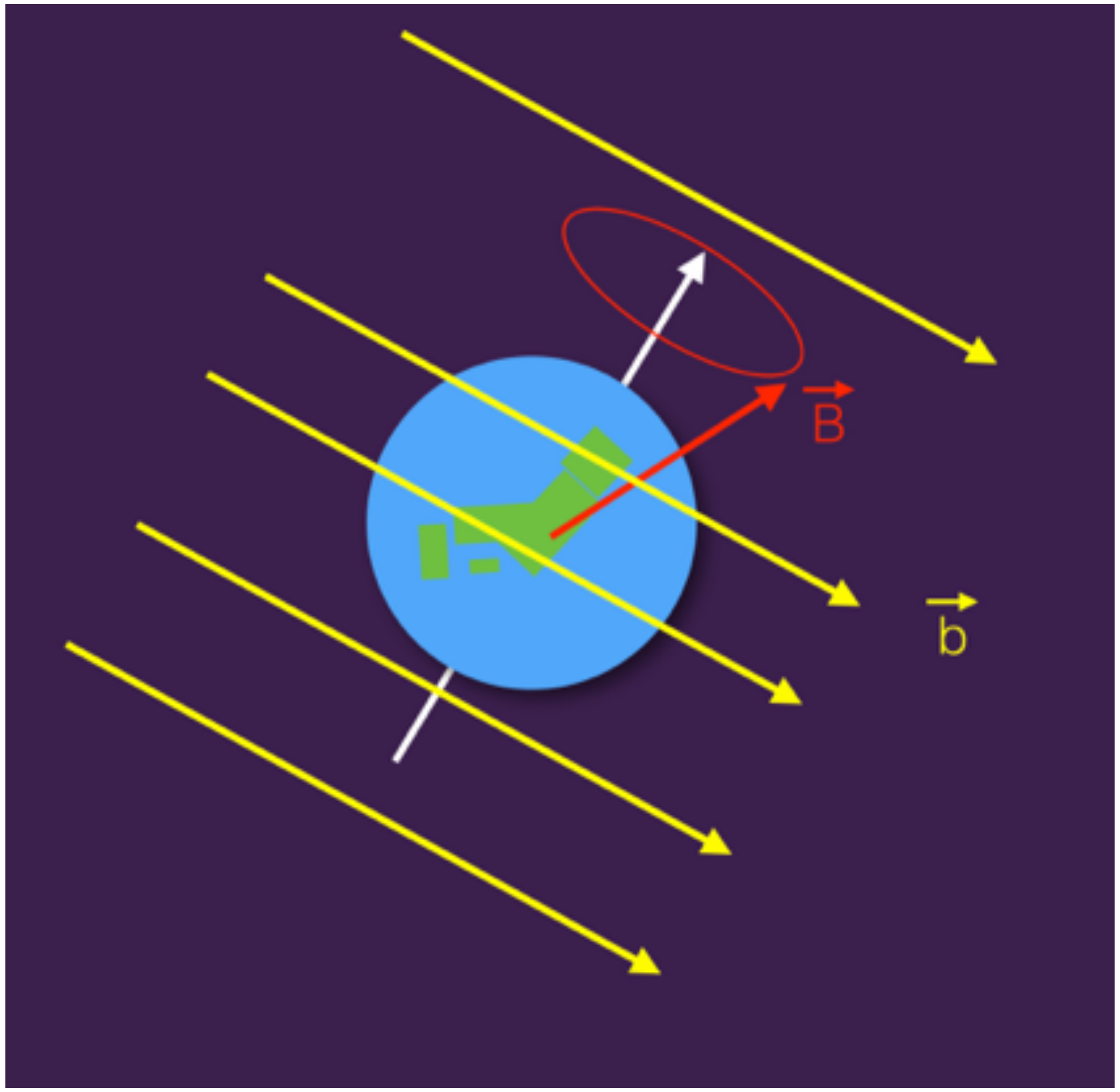
the red circle added by YU

MuSEUM: CPT and Lorentz Invariance

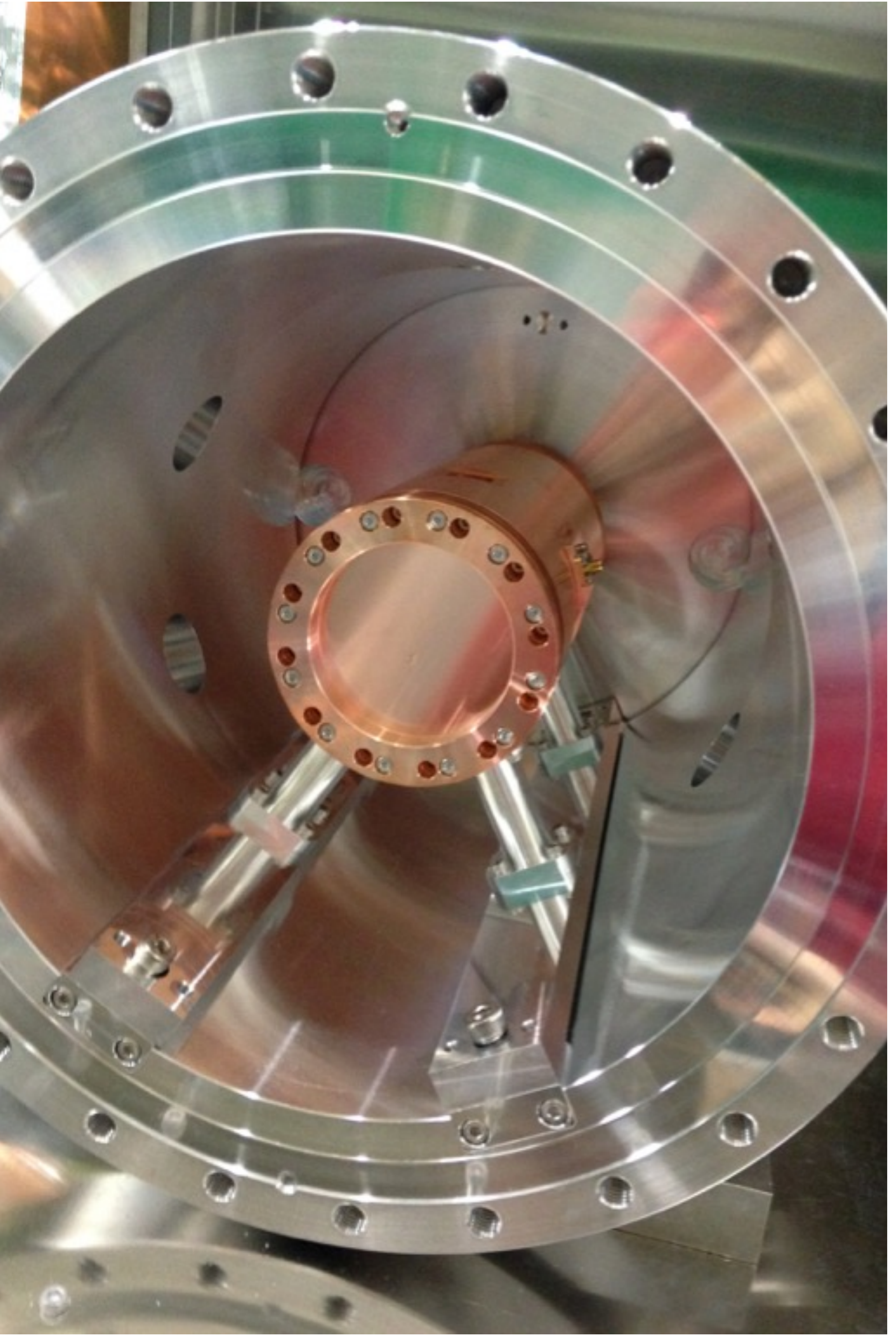
- CPT (Lorentz) violating background field can be detected as **sidereal** (or annual) **oscillation of the hyperfine frequency**
- Constraint on Standard Model Extension(SME) parameters

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





Apparatus




J-PARC
LINAC
Synchro-
tron
3 GeV Proton
MLF
MUSE
Dai Jingū Shrine
大神宮(宗教法人)
Buddhist Temple
村松虚空蔵尊
星月
野ばら
沼田屋旅館
さくらや旅館
村松海岸

J-PARC MLF MUSE

- J-PARC MLF (Material and Life science Facility) MUSE(Muon Science Establishment)
- D-Line: **1.0×10^7 muon/sec** (in case of 1 kW operation)
- H-Line (under construction): **1.0×10^8 muon/sec**
- The most **intense pulsed muon beam**
- Pulsed strucuture is favorable for efficient resonance analysis utilizing the information of the beam timing
- Note: the uncertainty of the world-record experiment at LAMPF is mostly from the statistics (>90%)

Superconducting Magnet for 1.7 T Field

- Bore diameter 925 mm
- Field uniformity is 1 ppm

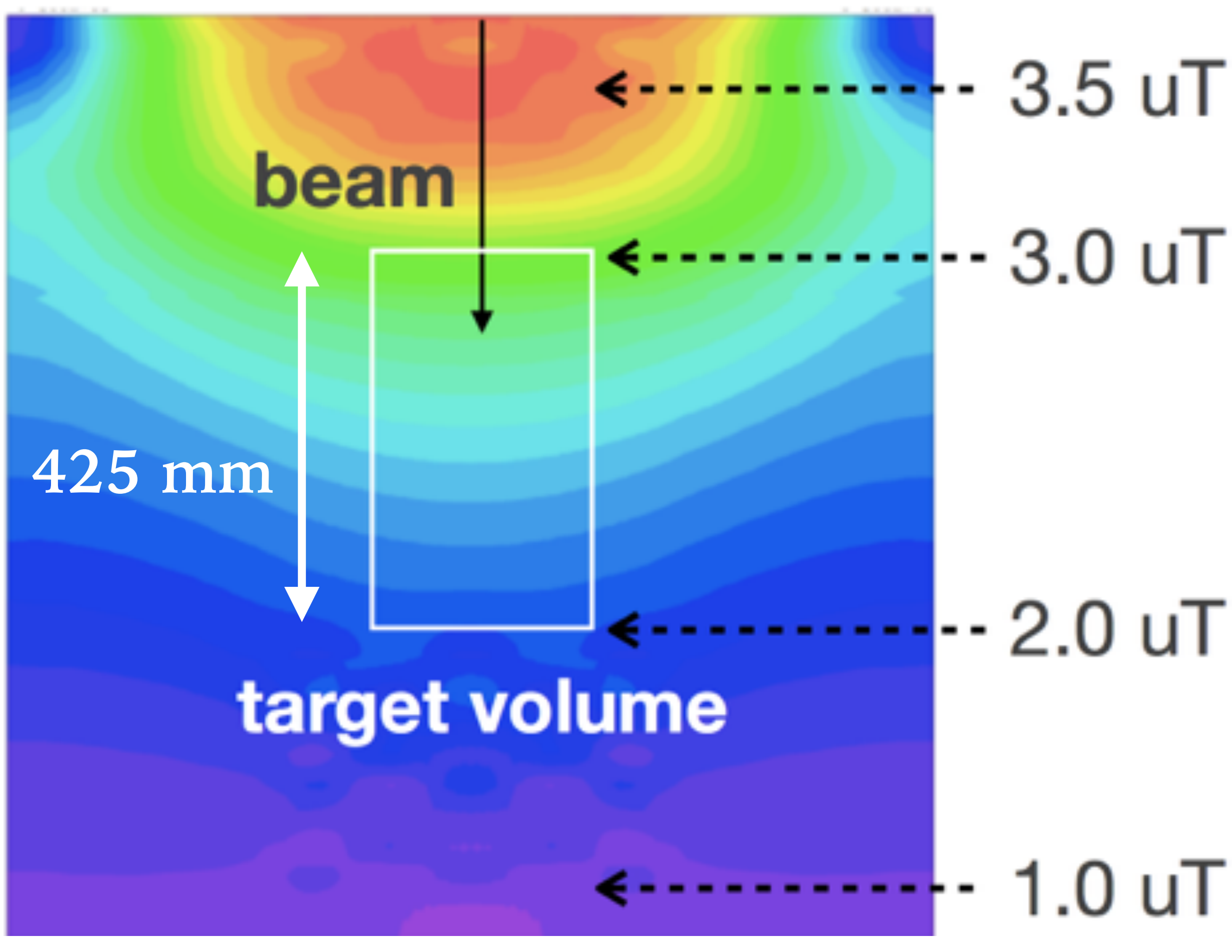
P. Strasser, *et al.*, *Hyp. Int.* *(2016) 237:124*

- Field time stability was measured: 0.03 ppm/hour over 10 days period

Shield for Magnetic Field

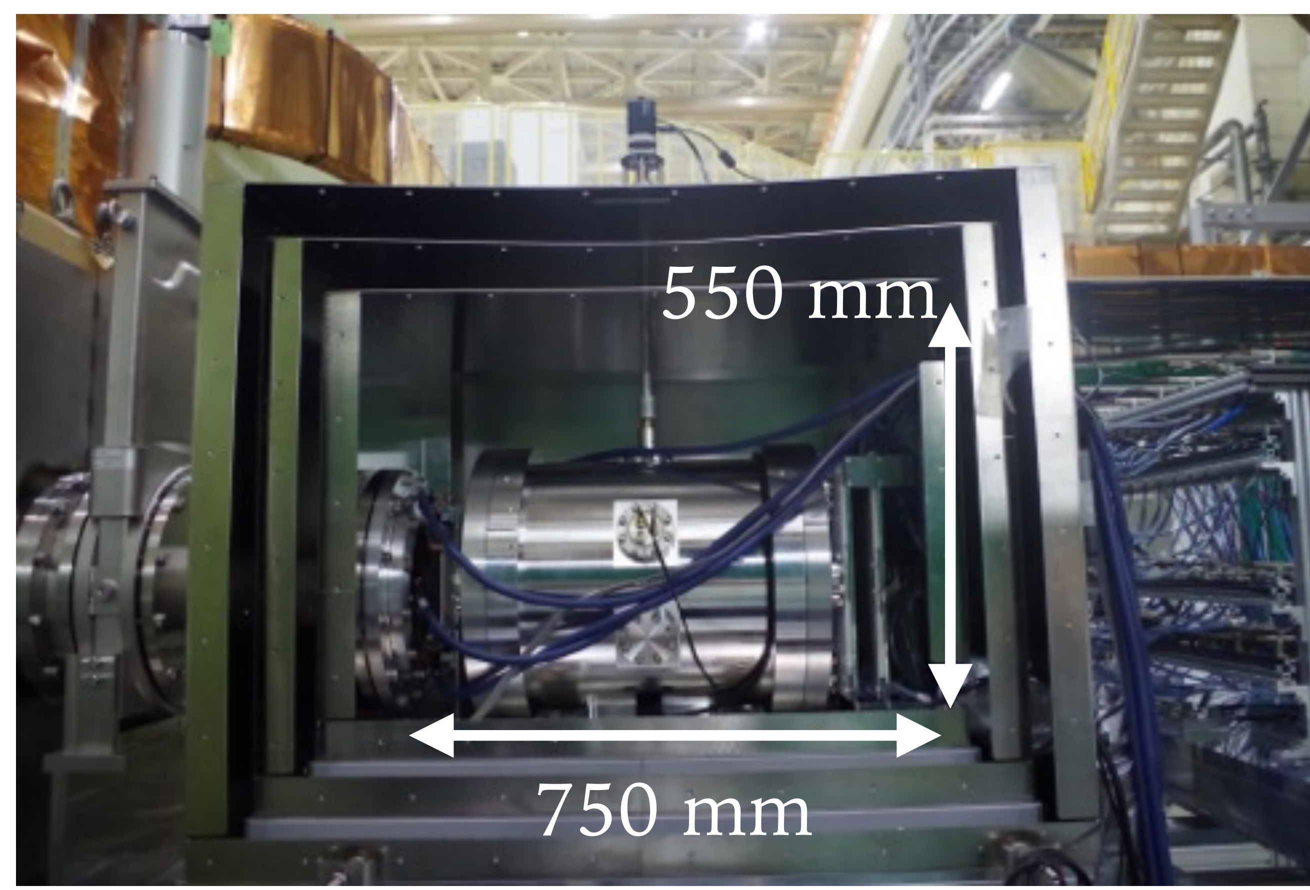
- ➤ Stray field from magnets in the beam line as well as the earth's magnetic field
- ➤ Three layers of a box-shaped permalloy shield is employed to suppress **the field less than 100 nT**

Expected B-field from the beam line



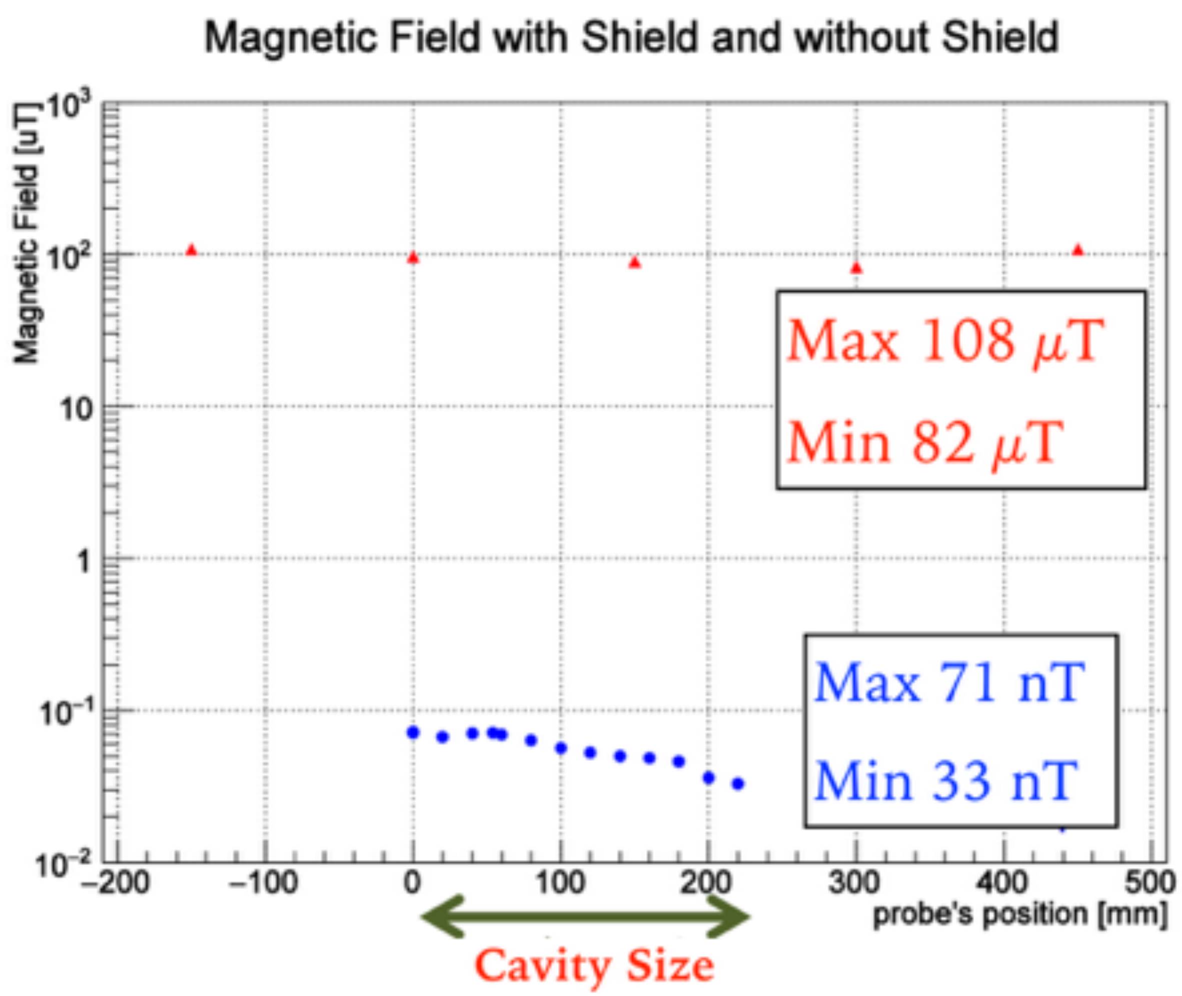
K. S. Tanaka, Ph. D. Thesis, Univ. of Tokyo (2016)

Shield and gas chamber

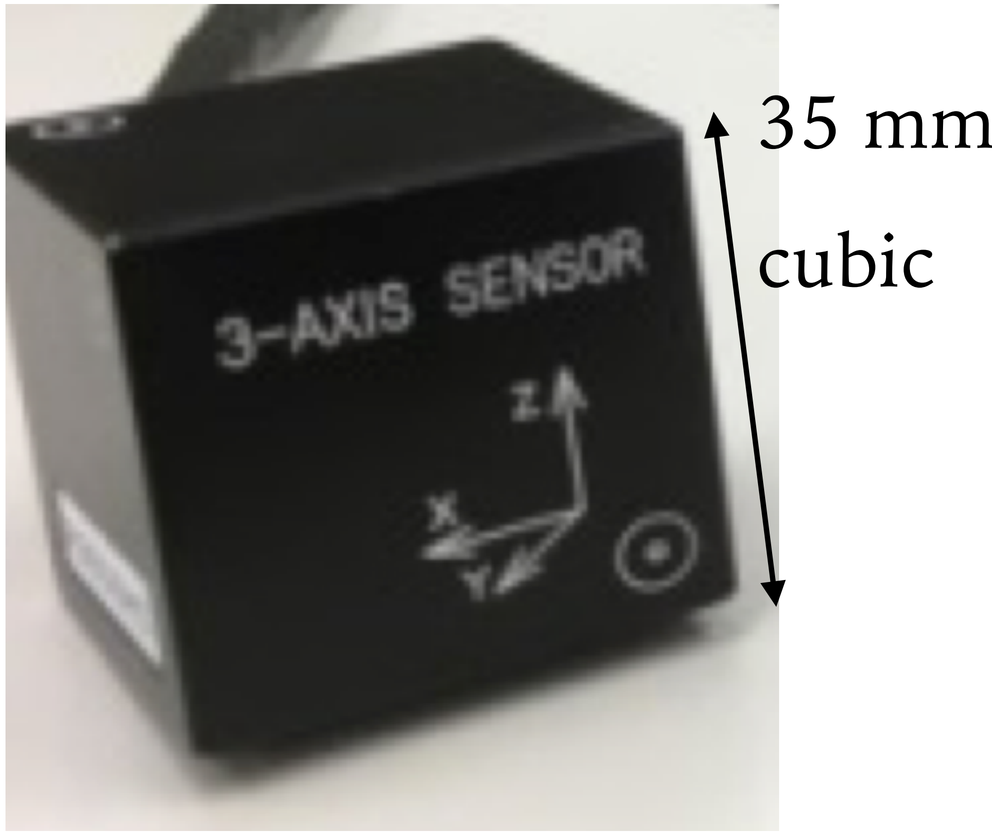


Flux Gate Probe

- Three-axis flux gate probe is used for B-field measurement
- 0.5 nT precision for each axis, linearity 5 nT
- Field was mesured after the resonance measurement
- Analysis in detail is ongoing: to be shown later



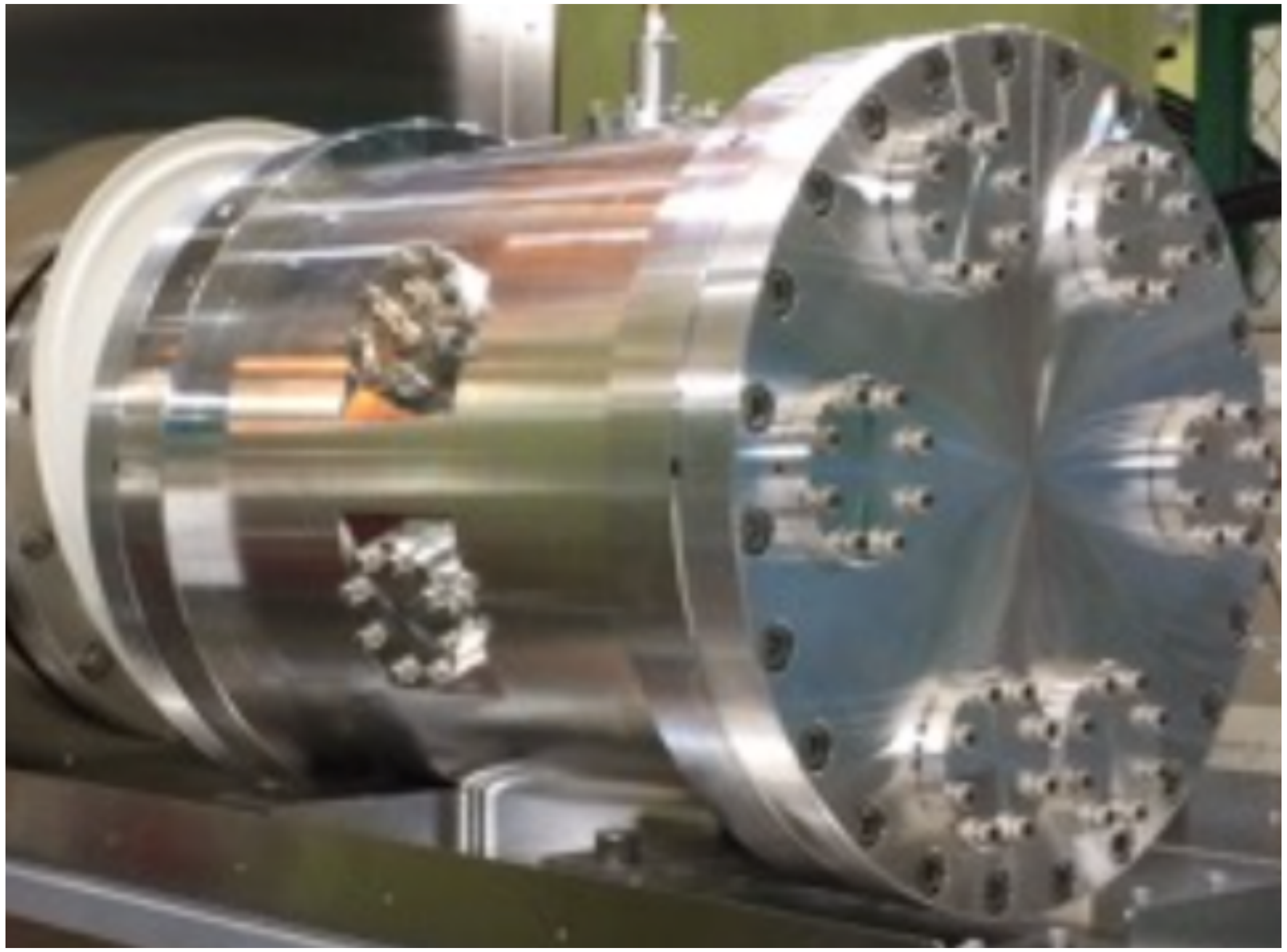
Flux gate probe



Krypton Gas Target

- Inner diameter: 280 mm, length: 425 mm
- Pressure is monitored by a capacitance gauge (silicon gauge RPM4-AD will be used in near future)
- Purity is measured by a Q-MASS spectrometer

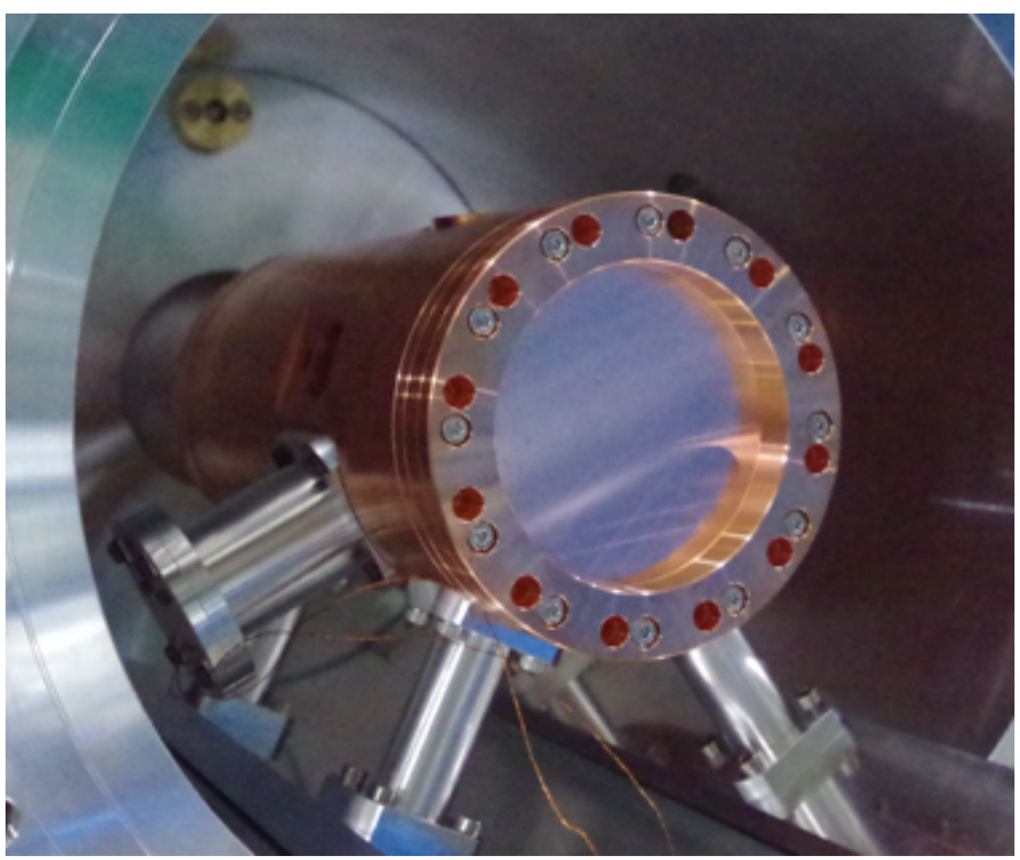
- Collosions of the muonium with Kr shift the resonance frequency
- Extrapolation to the vacuum
- The systematic uncertainty from the collisonal shift is 9 Hz

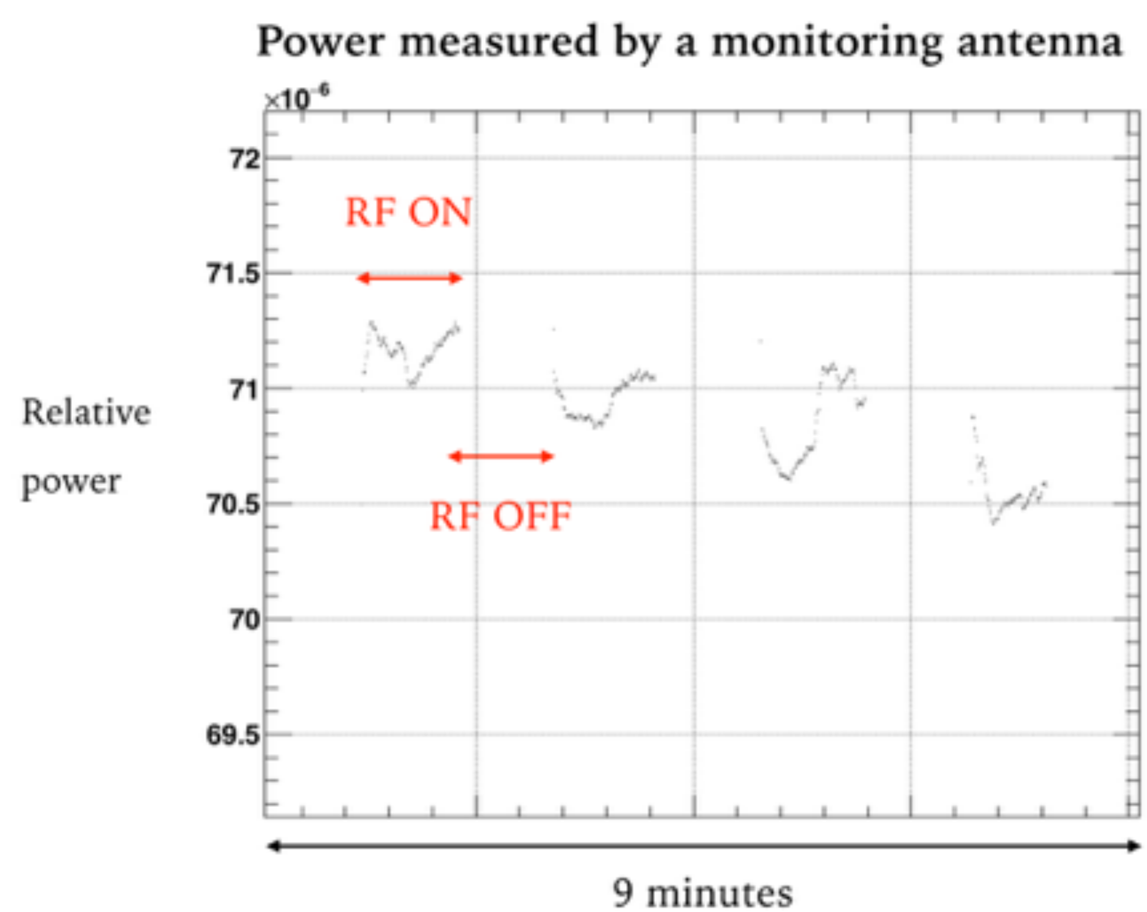


K. S. Tanaka, Ph. D. Thesis, Univ. of Tokyo (2016)

Microwave Cavity and RF system

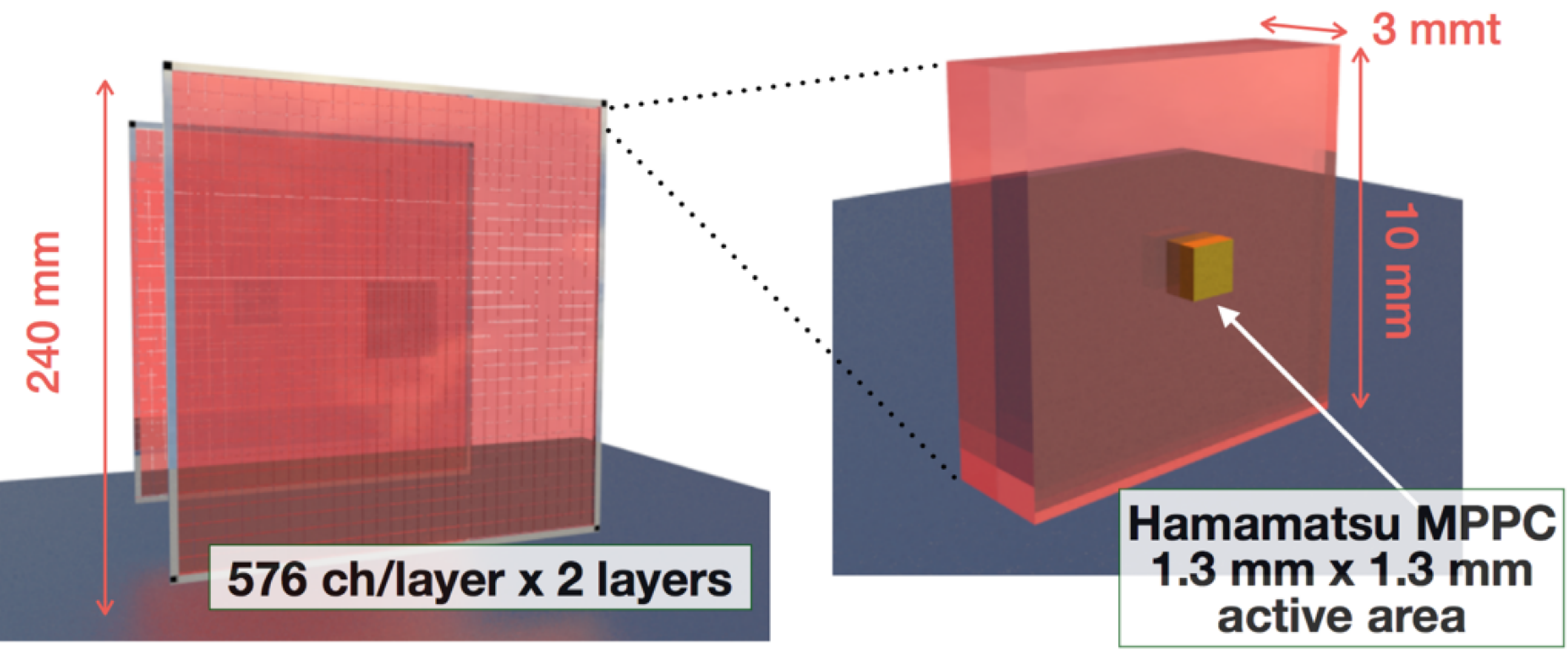
- Copper microwave cavity (diameter: 81 mm, length: 230 mm)
- Microwave is generated from a signal generator and amplified by two amplifier (3 W in cavity)
- Power stability is monitored by a dedicated monitoring antenna during the measurement





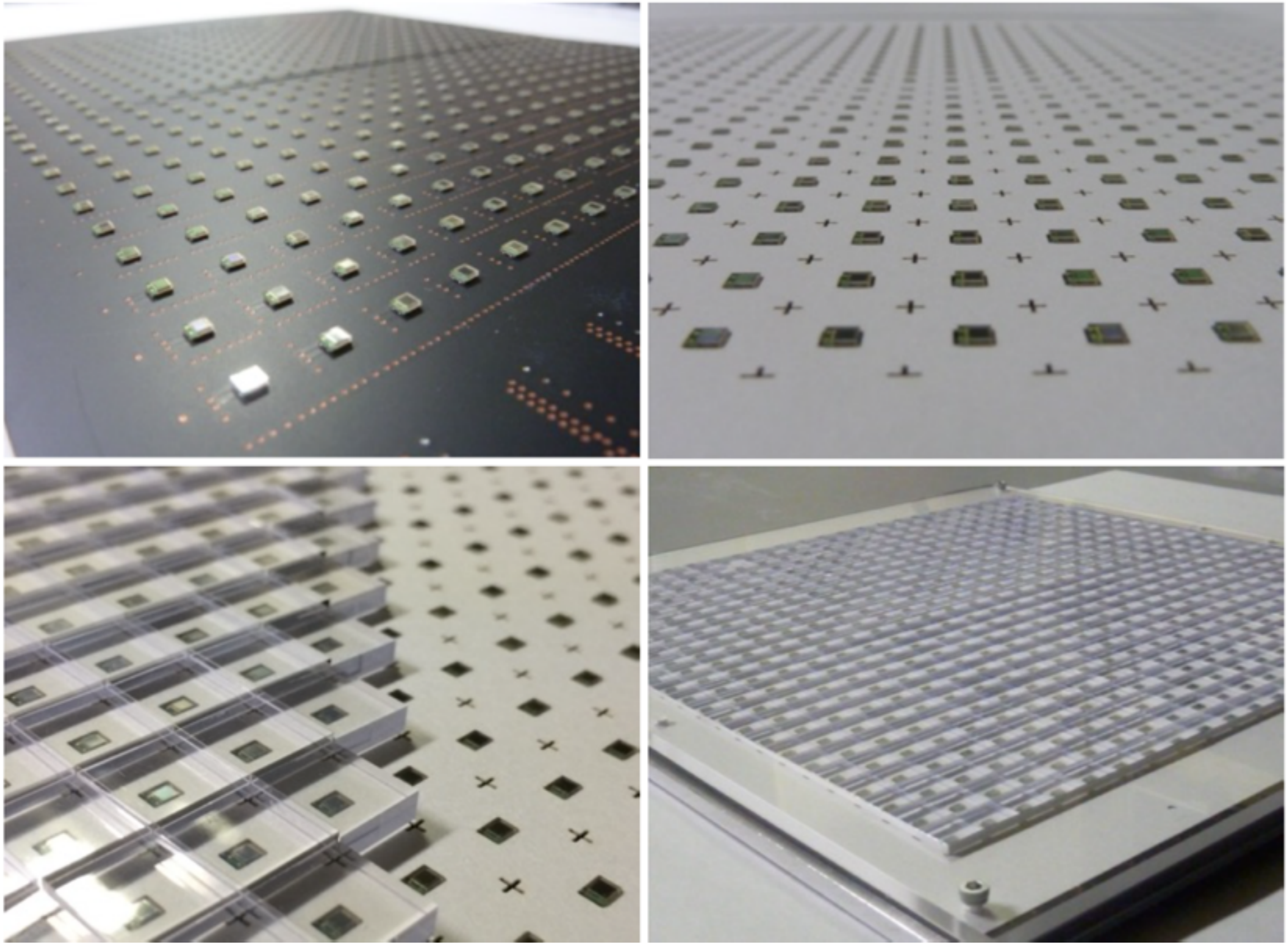
Positron Detector

- Segmented (10 mm×10 mm×3mmt) Scintillator, readout: Hamamatsu MPPC (Si photomultiplyer)
- Two layers of 240 mm × 240 mm detector



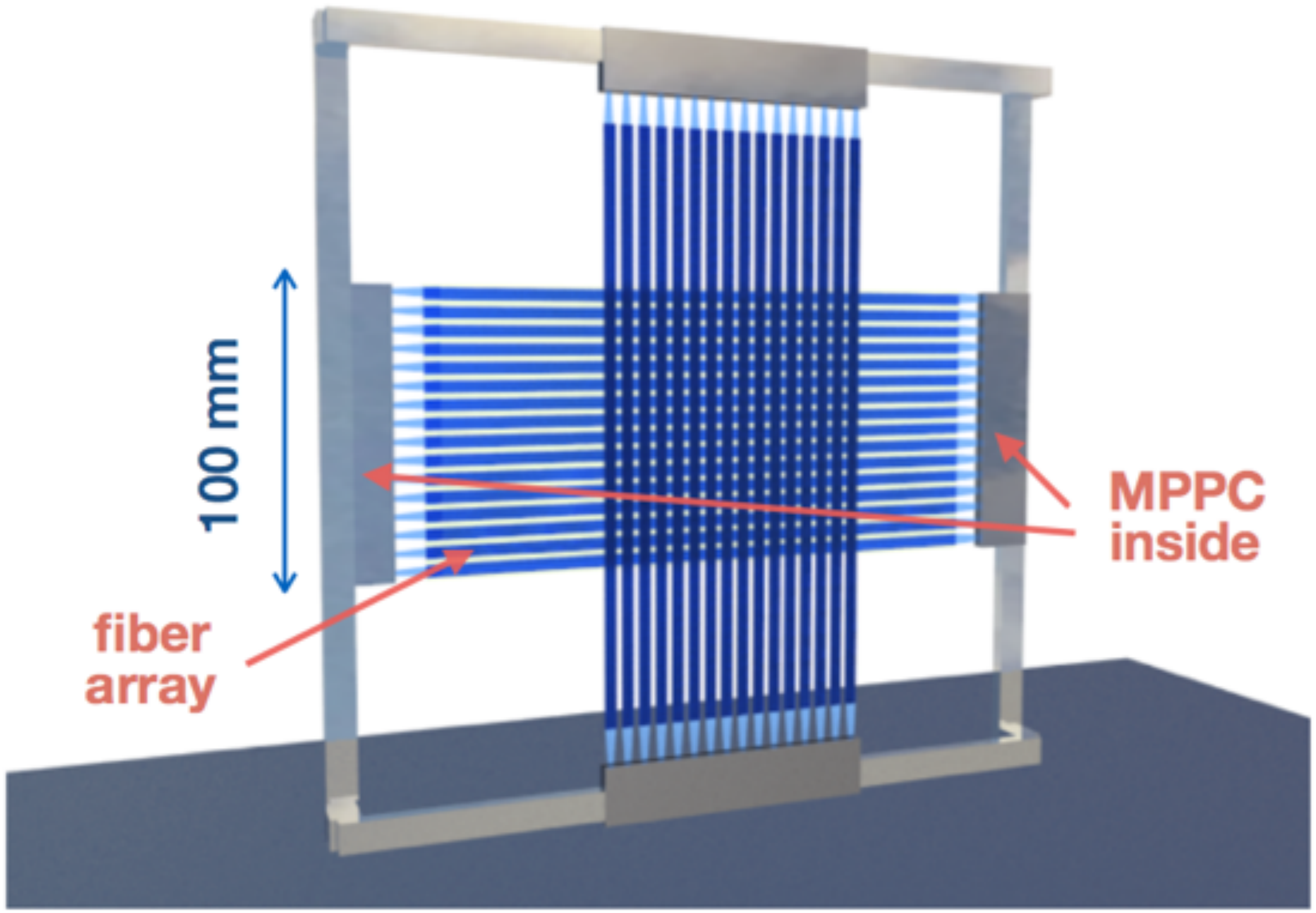
S. Kanda, PoS (PhotoDet2015) 039 (2016)

Positron Detector



FBPM (Fiber Beam Profile Monitor)

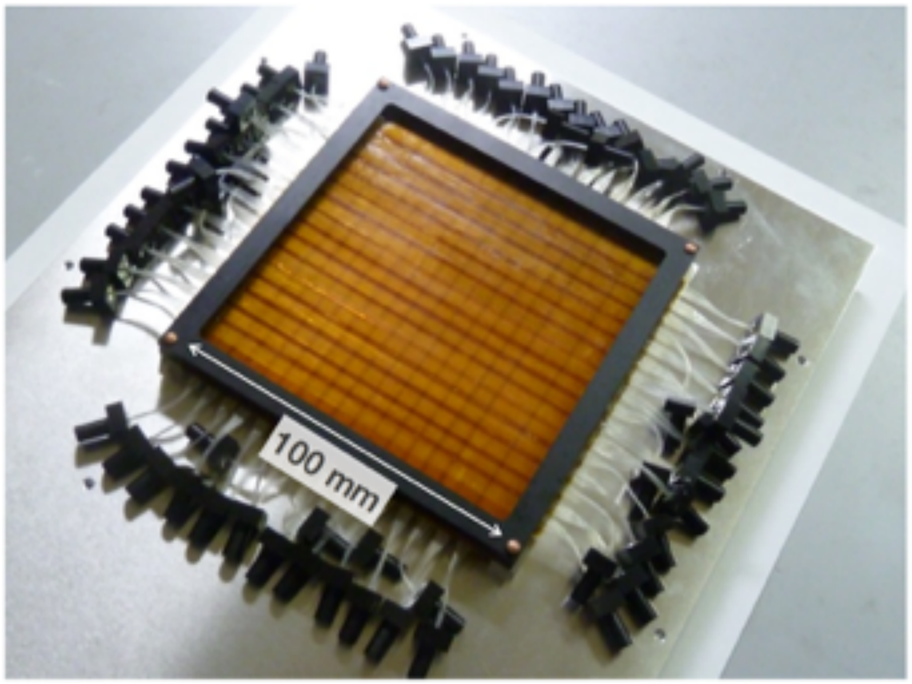
- Thin (100 μm) Scintillation Fibers and MPPC (SiPM)



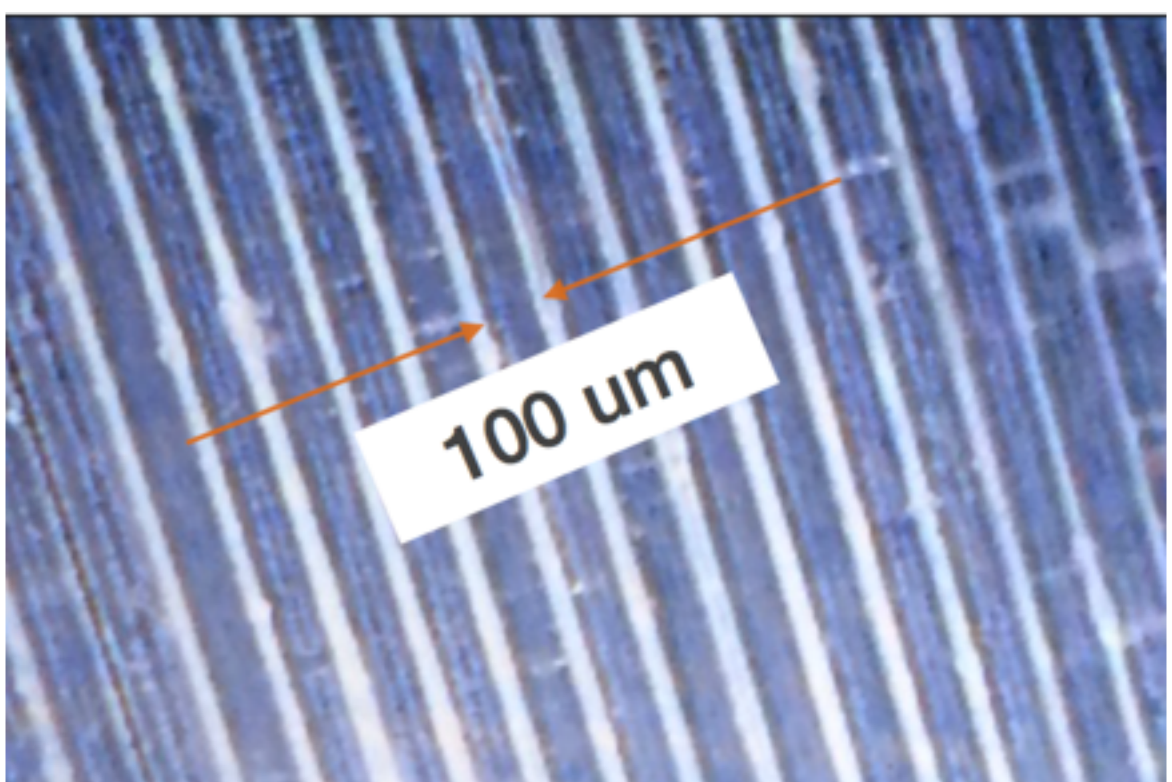
- Cross-configured fiber hodoscope with SiPM readout
- To be placed in front of the target chamber
- Online monitoring of beam profile and intensity
- Minimum amount of material is required (4 MeV muon)

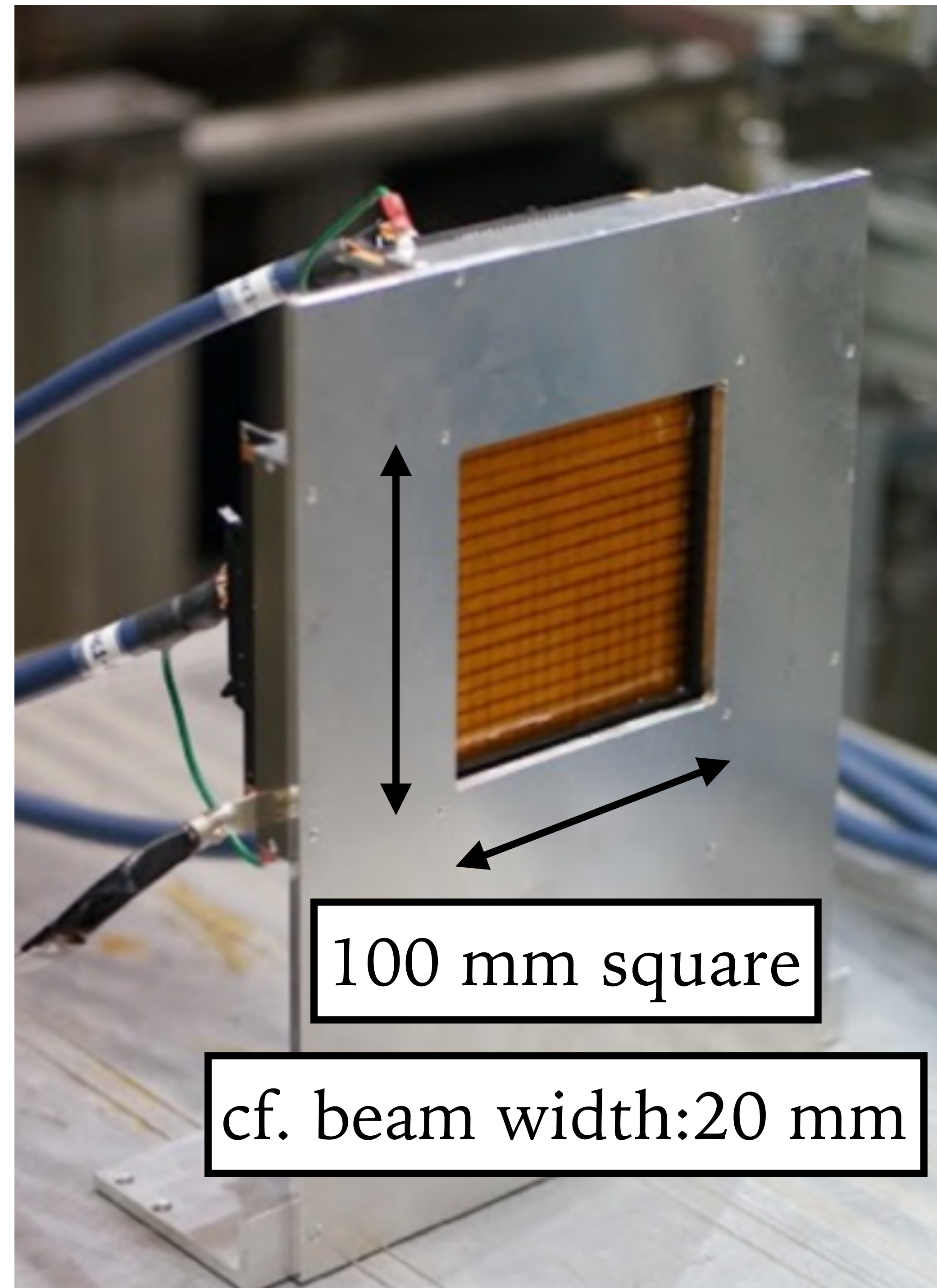
FBPM (Fiber Beam Profile Monitor)

- Thin (100 μm) Scintillation Fibers and MPPC (SiPM)



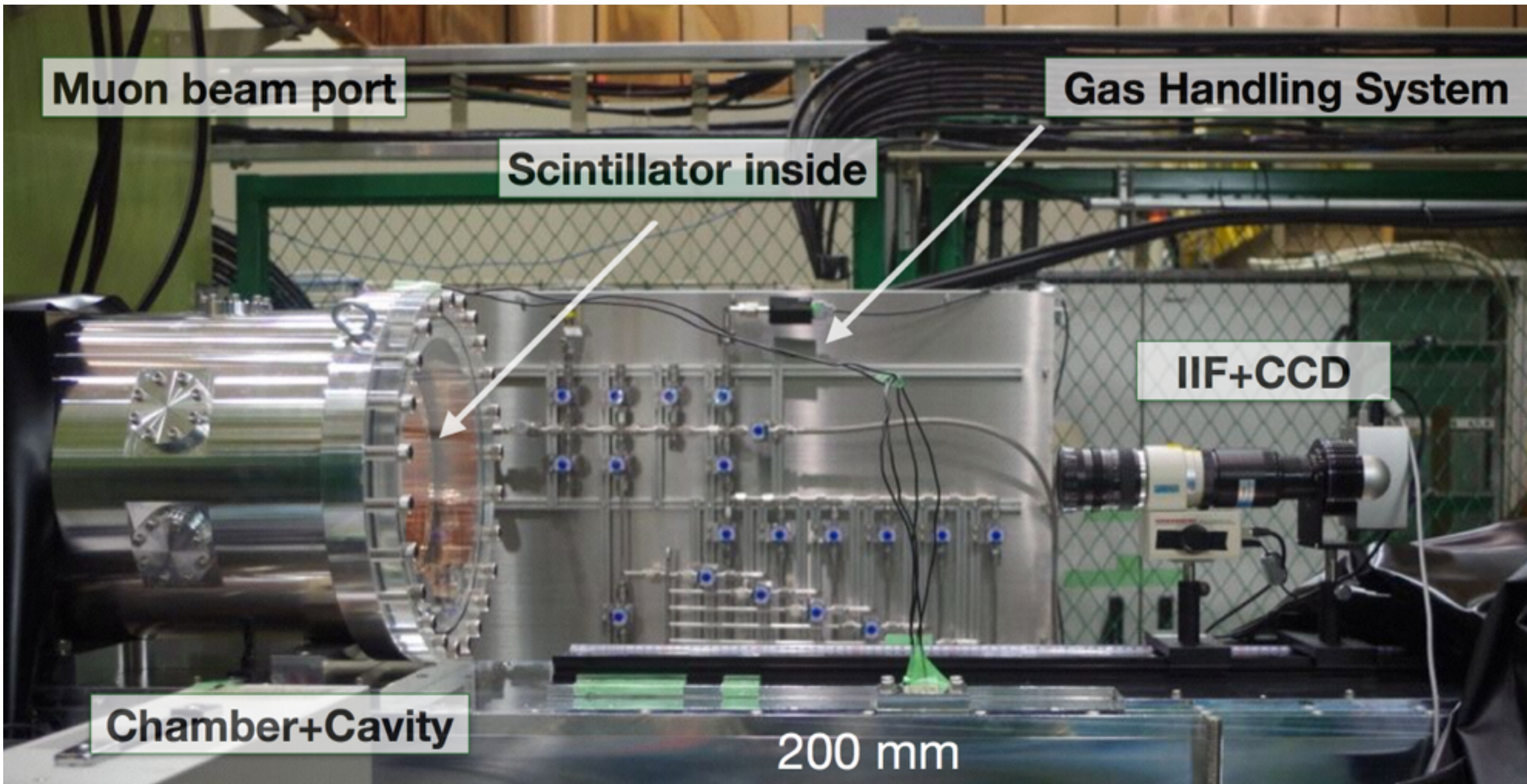
100 mm x 100 mm active area, 32 ch. for each direction (x-y)





TBPM (Target Beam Profile Monitor)

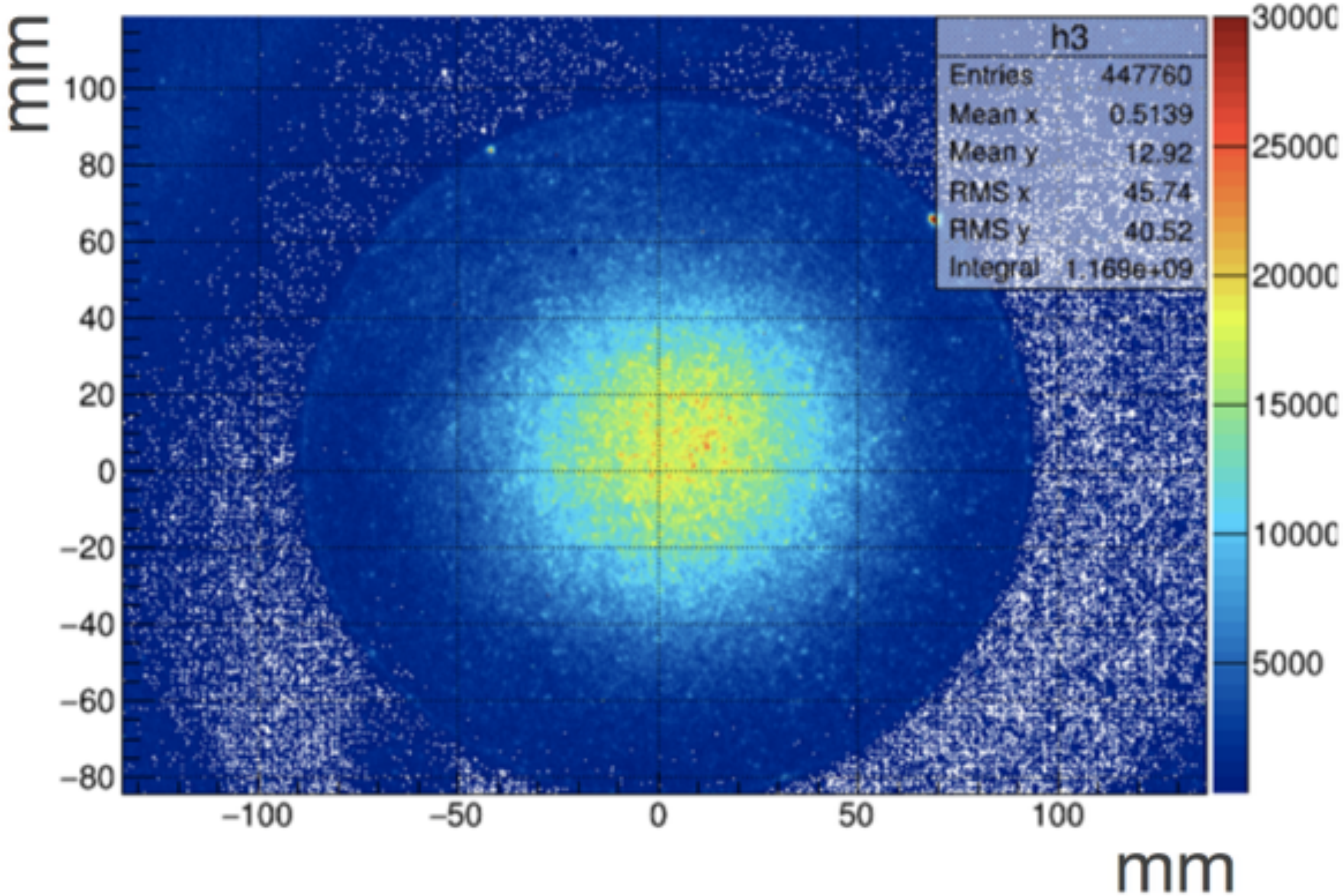
- Offline measurement of 3D beam profile
- Plastic Scintillator + CCD Camera



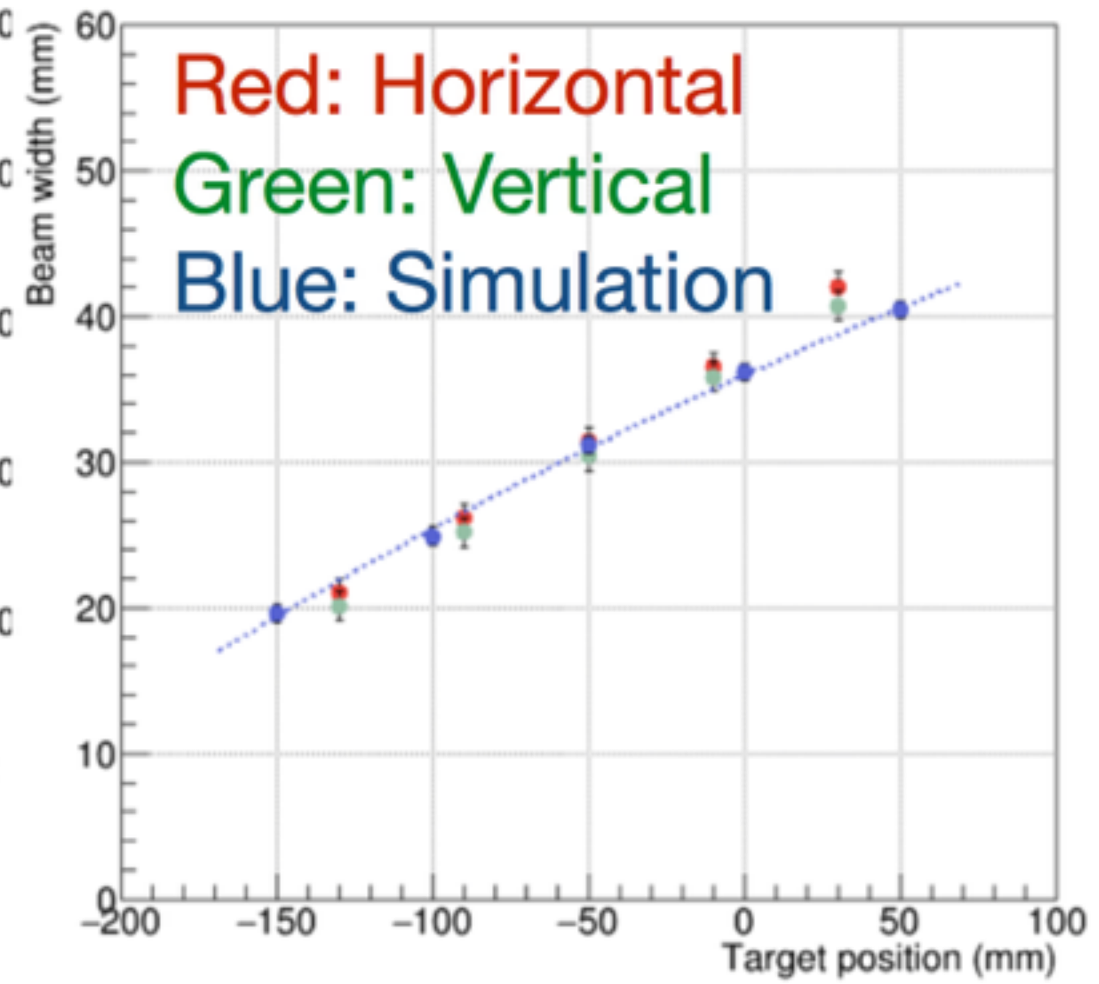
TBPM (Target Beam Profile Monitor)

- Cross-sectional distribution: in good agreement with simulation
- Longitudinal distribution: analysis is underway

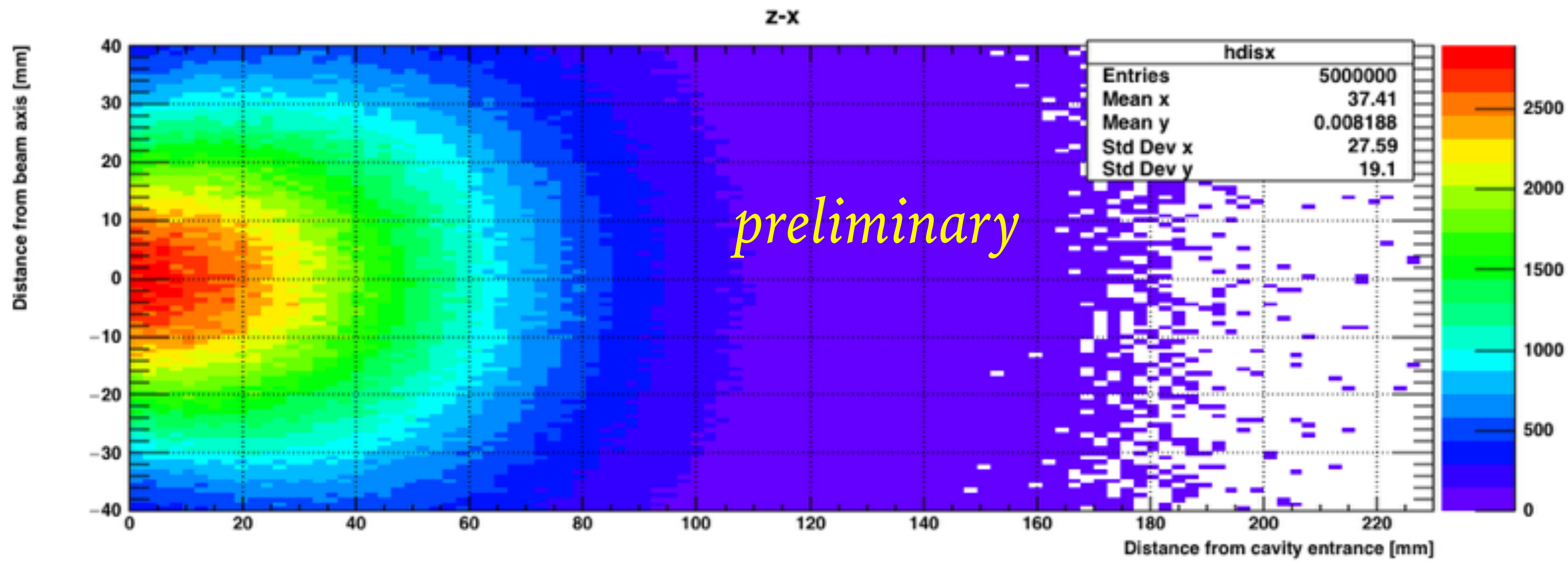
Cross-sectional view of the beam

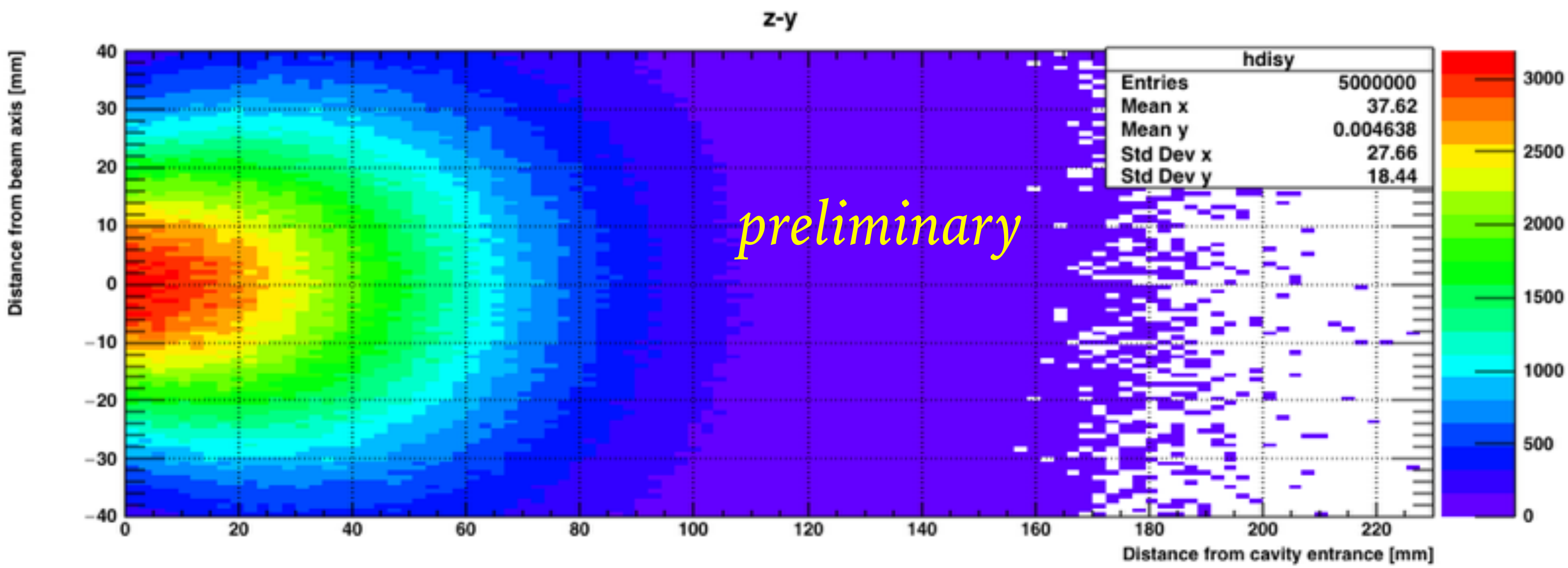


Beam width



TBPM (Target Beam Profile Monitor)

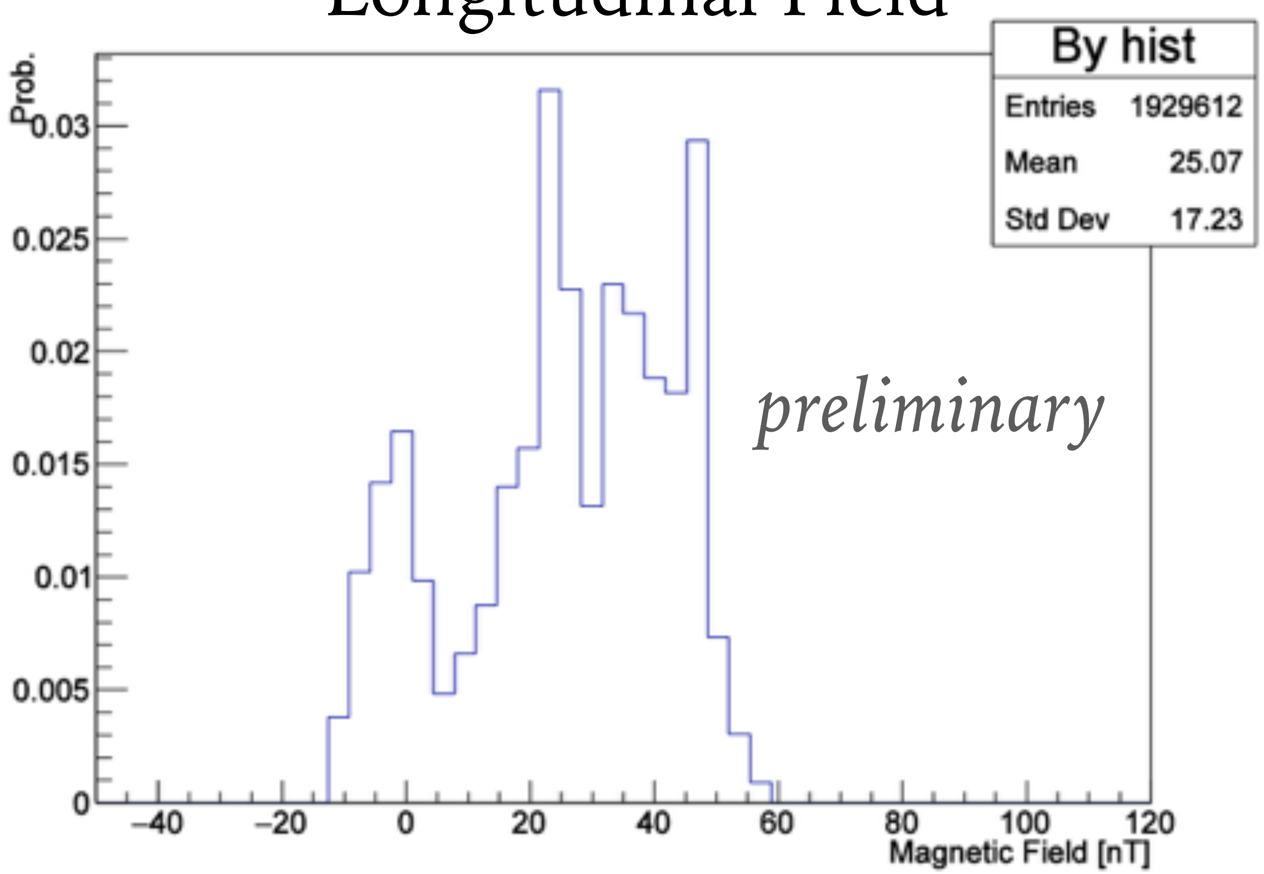




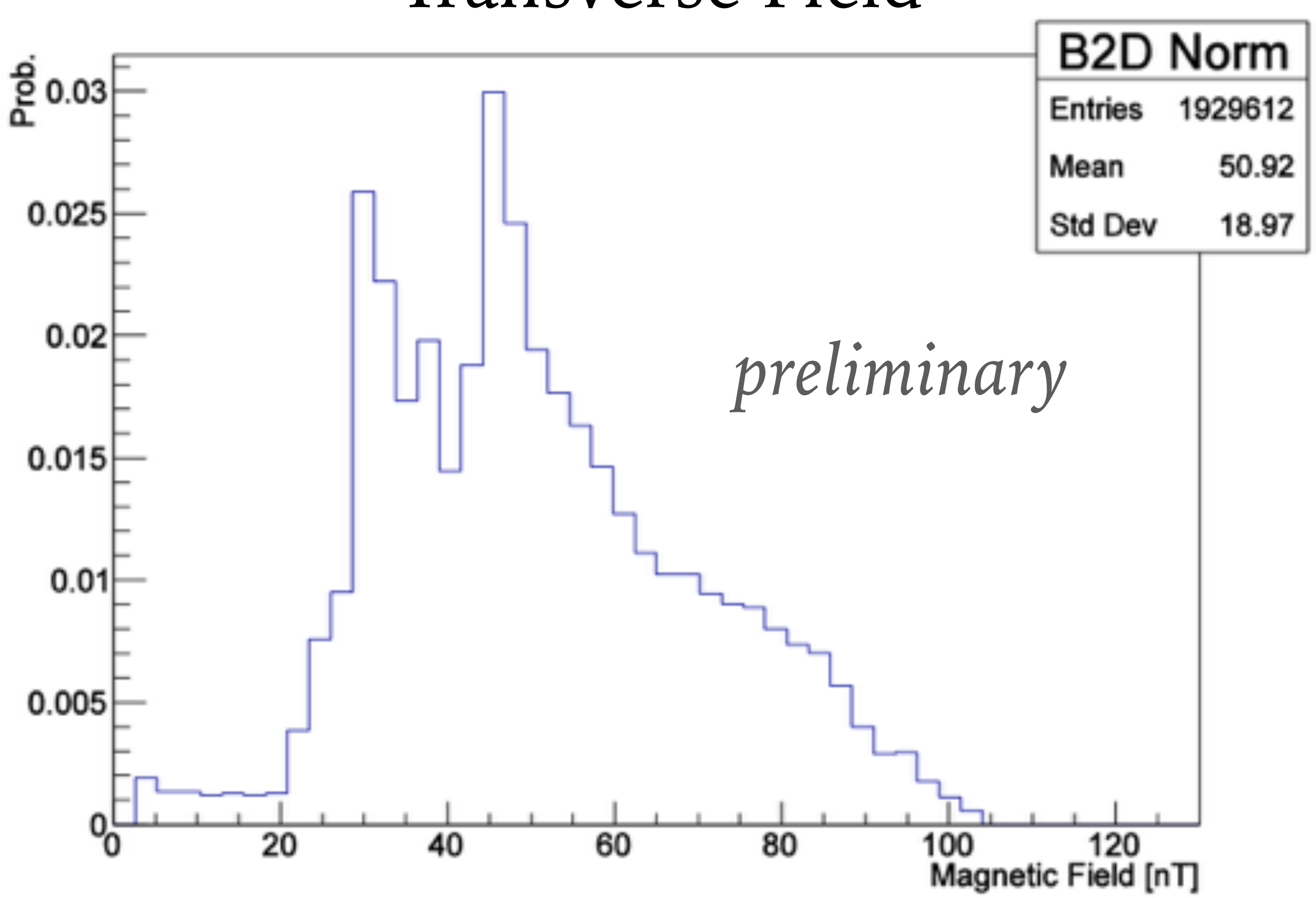
TBPM (Target Beam Profile Monitor)

- combined analysis with magnetic field measured by the flux gate probe is ongoing
- longitudinal field: less than 60 nT
- transverse field: spin rotation is less than 1° per 2.2 μs (μ life)

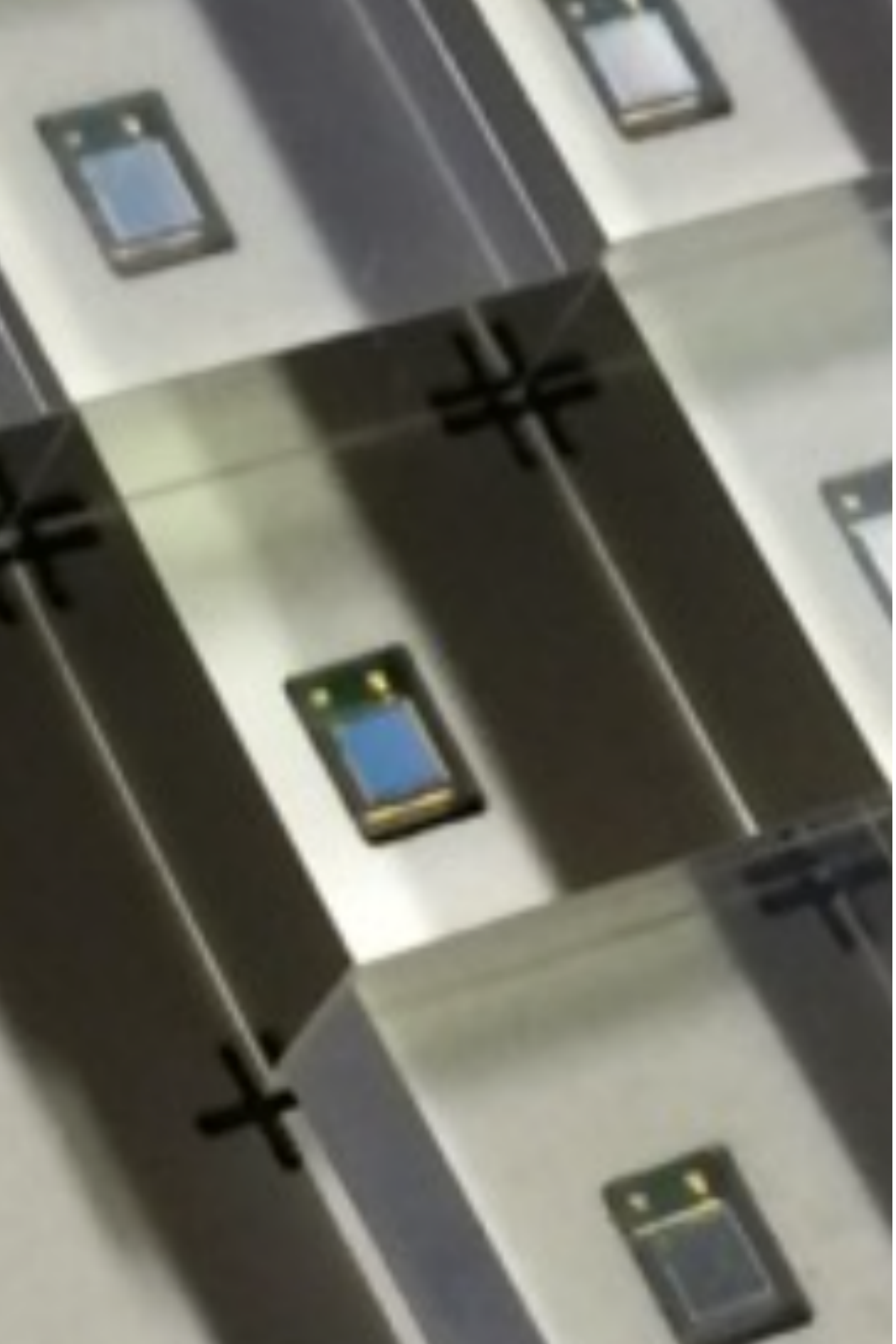
Longitudinal Field



Transverse Field

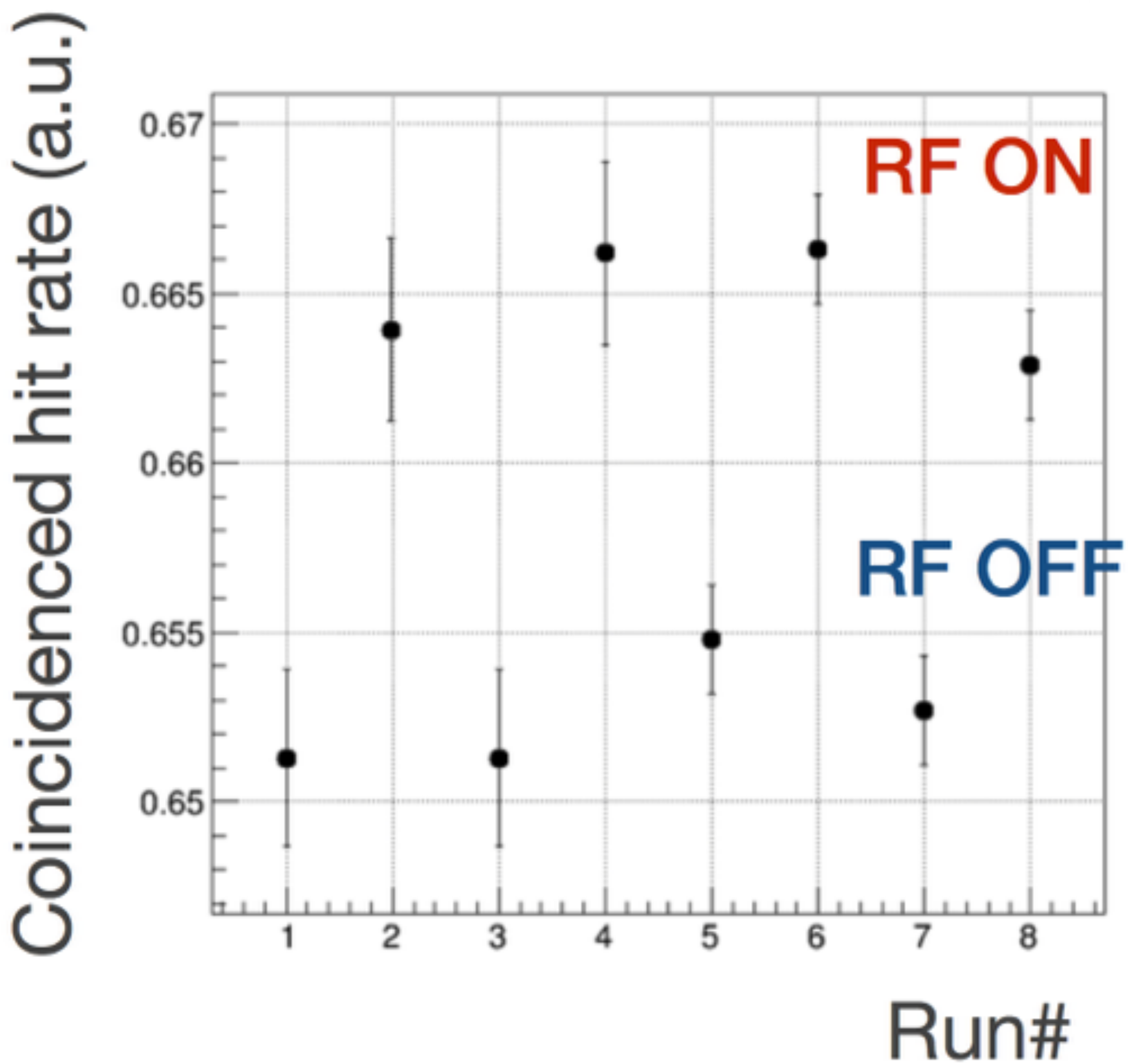


Latest Result



Beam Time in 2016 June

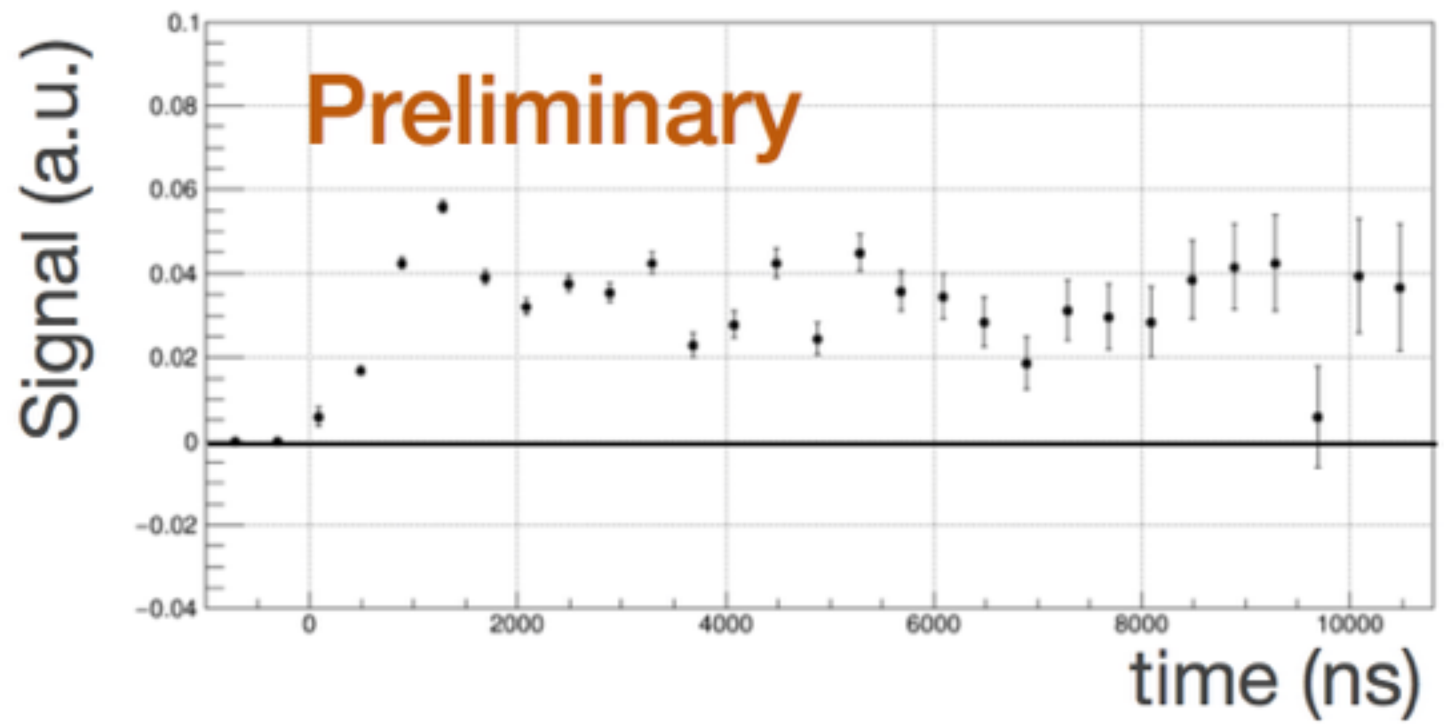
- ➤ RF ON/OFF repeated in cycle (1 min)
- ➤ Each run was normalized by the number of beam pulse



Time Dependent Signal

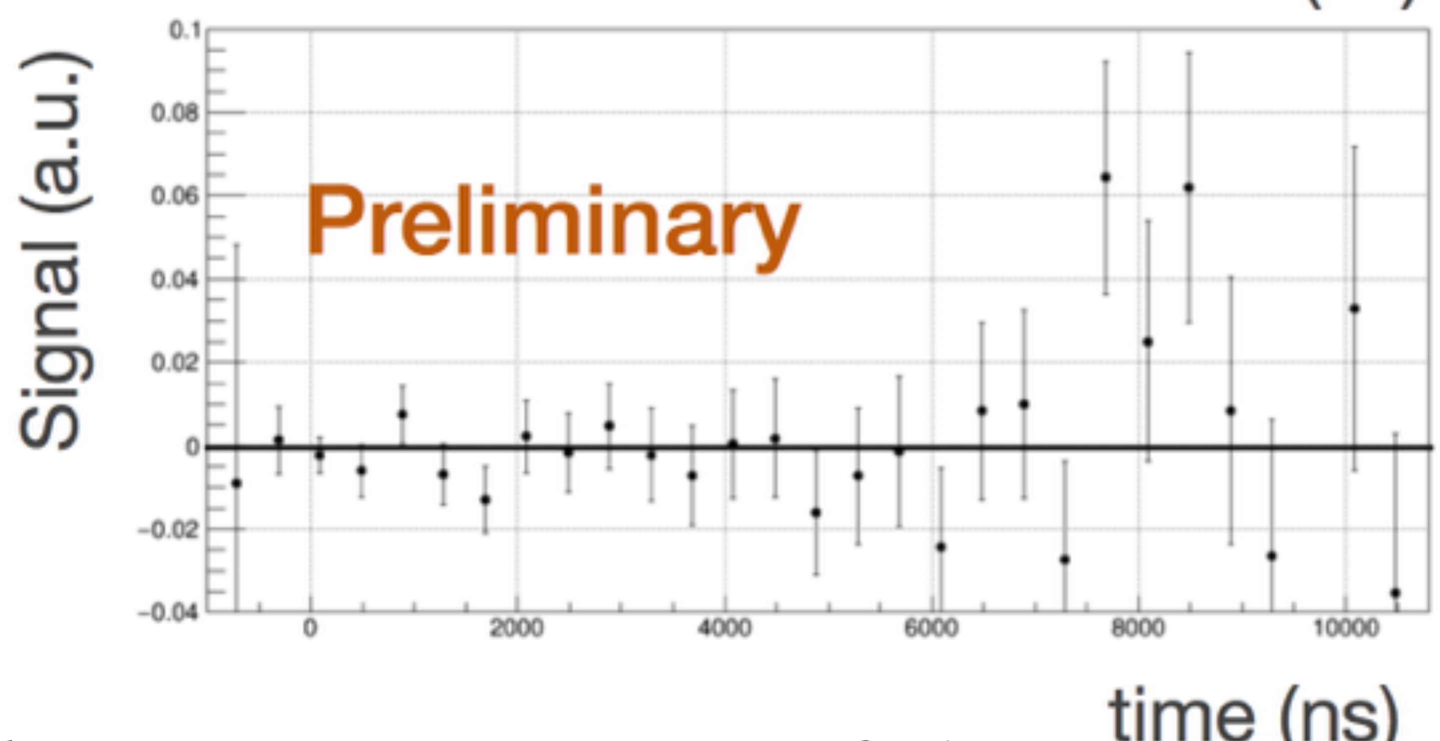
➤ Further analysis is in progress

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



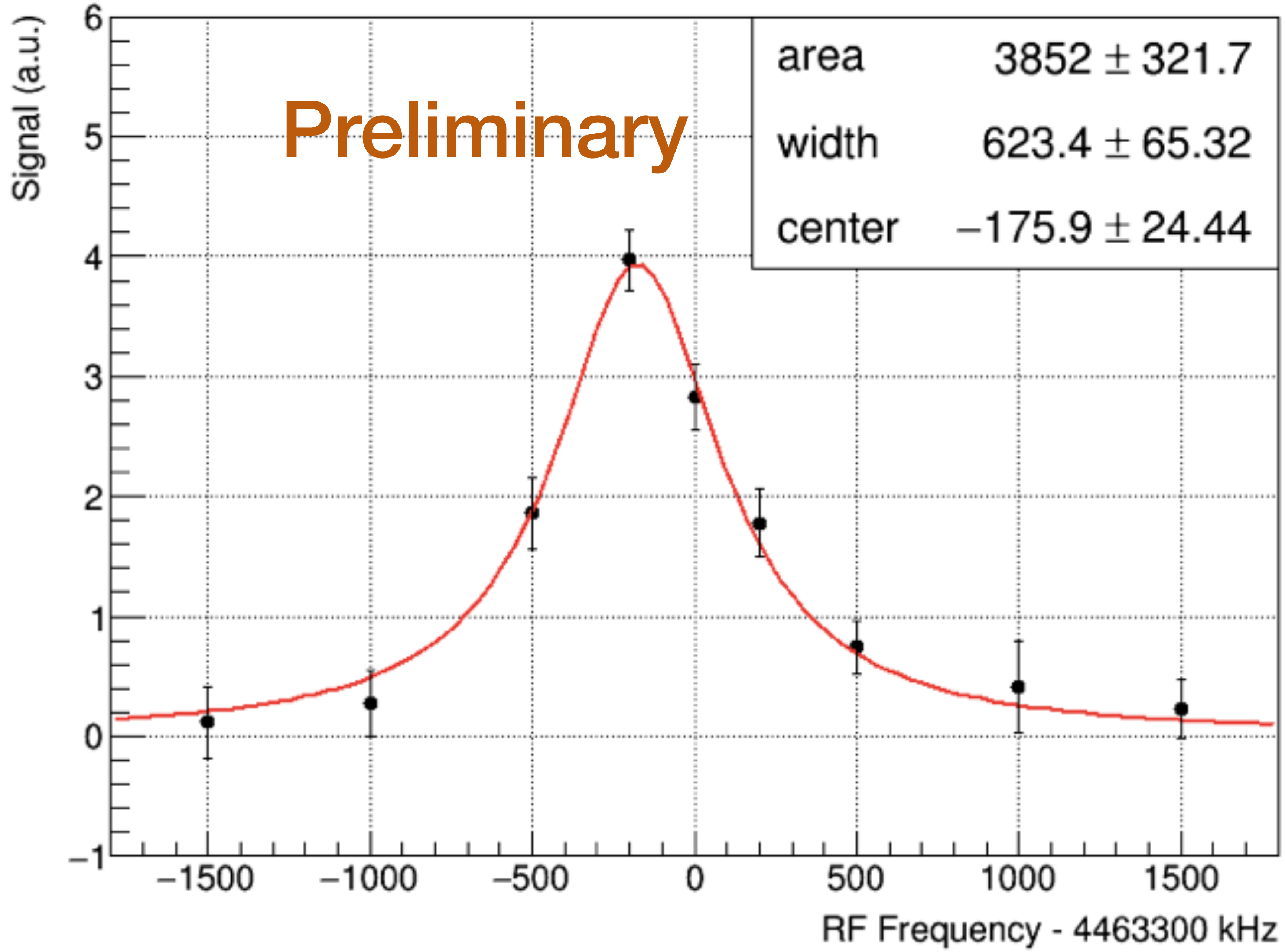
Off-Resonance
RF frequency was
far detuned
1.0 Kr atm
27.4 MeV/c muon

Signal = ON/OFF-1



Obeserved Resonance

- After 6 hours of data taking we observed the resonance
- Fit by Lorezian: further analysis is underway



Summary and Future Prospect

- MuSEUM experiment
  - The test of bound-state QED
  - Determination of the muon magnetic moment/mass
- 2016 June: First resonance signal was obeserved
  - further analysis is ongoing
- Future prospect
  - Next zero-field experiment in early 2017
  - H-Line will be ready in the FY 2017: the measurement in high field is going to be conducted