Precise spectroscopy of muonium hyperfine structure at J-PARC

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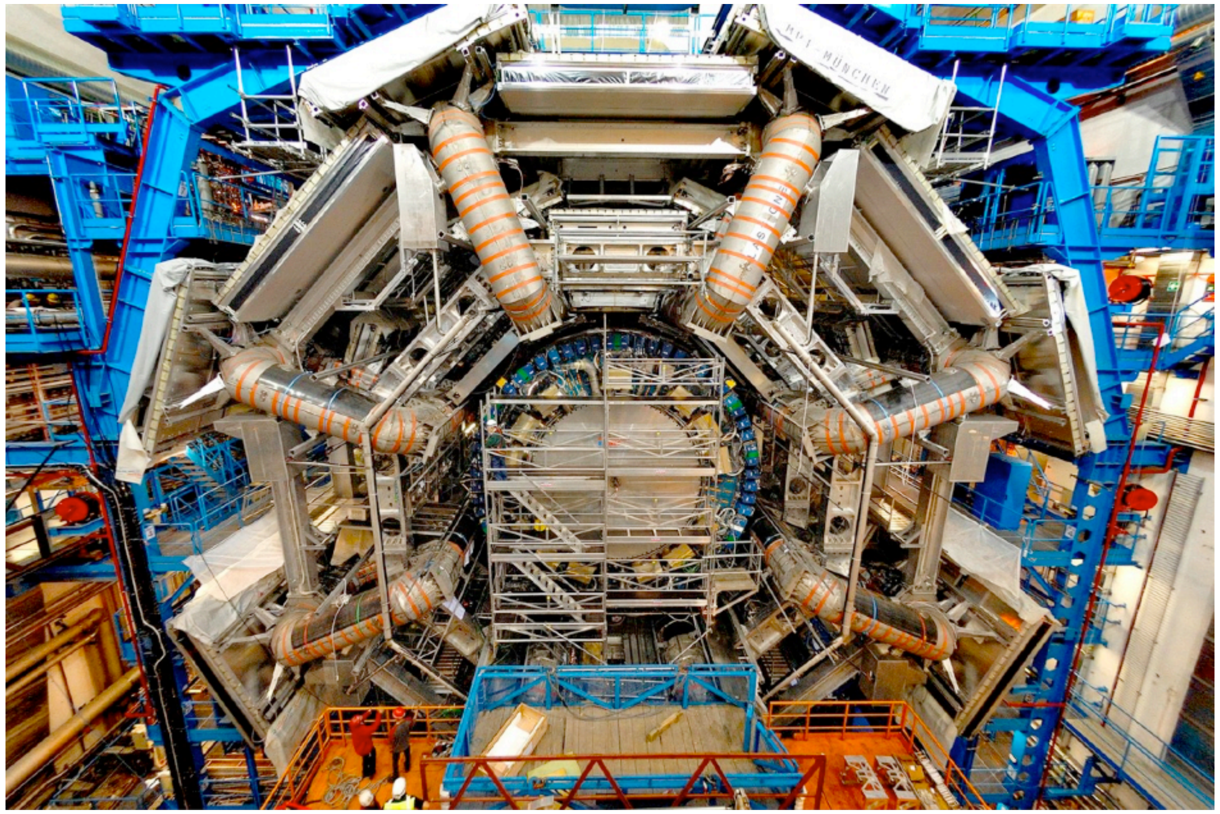
for MuSEUM collaboration

Standard Model tests and BSM searches

- Standard Model of particle physics is “Best" theory we have
- However, still many open questions…
  e.g. neutrino mass, muon *g*-2, proton radius, …
- Search for physics beyond the Standard Model

Direct search:
High energy experiments



ATLAS@LHC

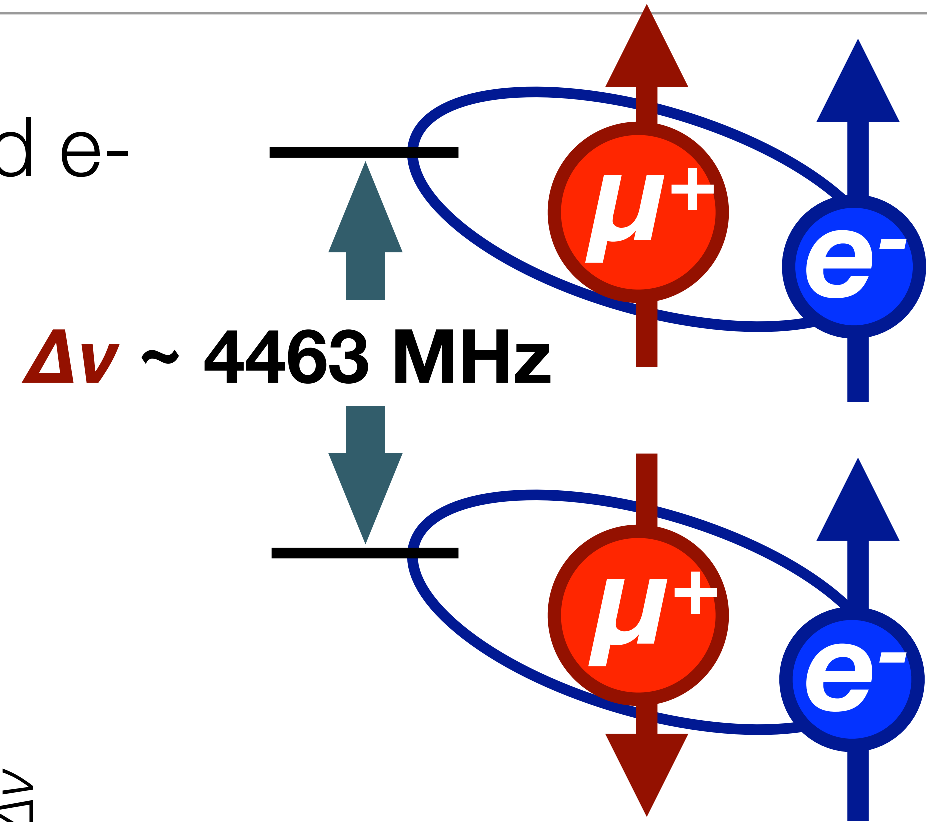
Indirect search:
High precision measurements

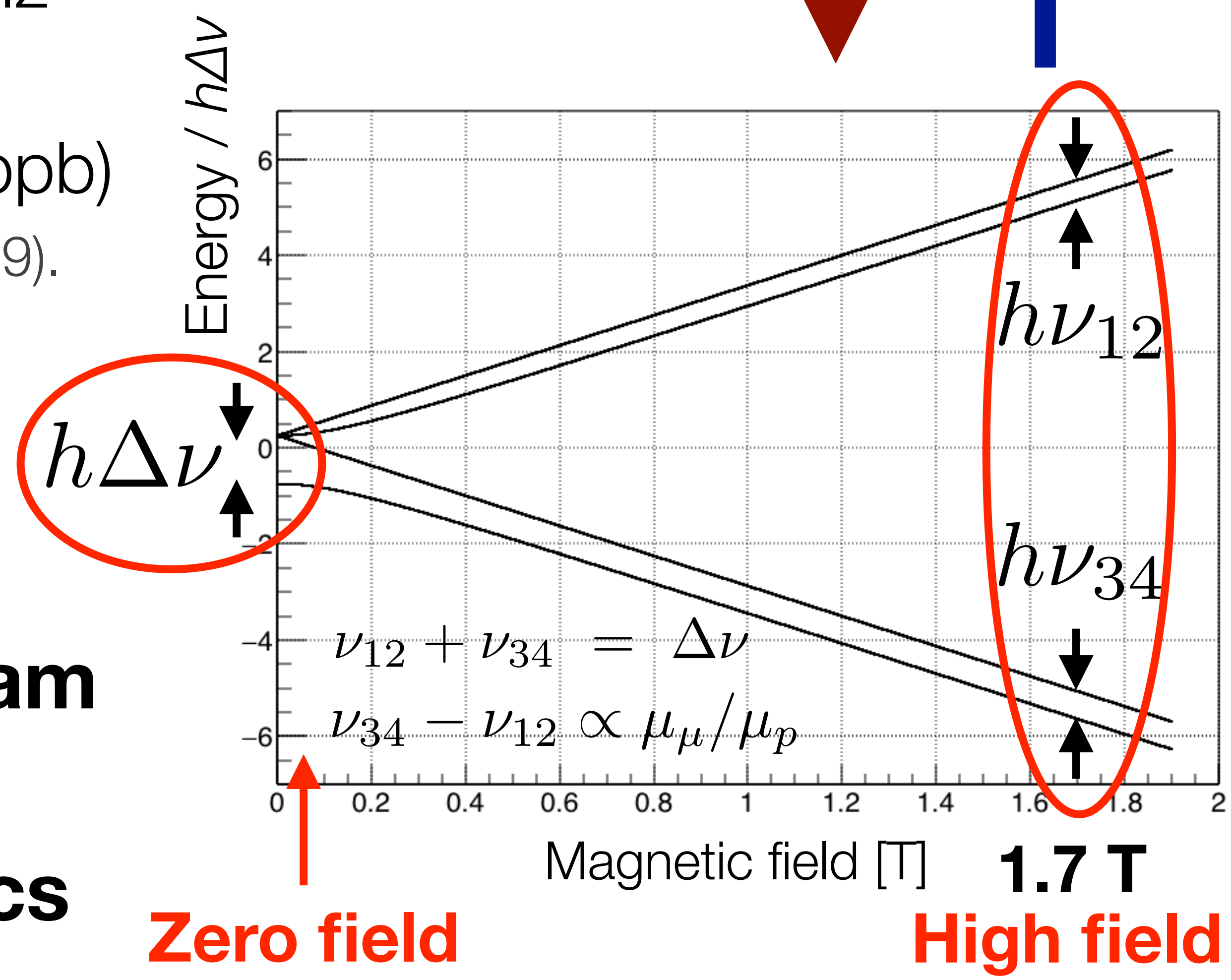
MuSEUM@J-PARC

Precision spectroscopy of Muonium HFS

- Muonium - the bound state of μ+ and e-
- Two independent methods:
  - Zero field measurement
  - High field measurement
- World record @LAMPF
  - $\Delta\nu$ (HF) = 4.463 302 765 (53) GHz (12 ppb)
  - μ_μ / μ_p = 3.183 345 13 (39) (120 ppb)

    W. Liu *et al*., Phys. Rev. Lett. **82,** 711 (1999).
- **MuSEUM's Goal: x10 improvement**
  - **Using the world's highest intensity pulsed muon beam at J-PARC**
    - **200 times more statistics**

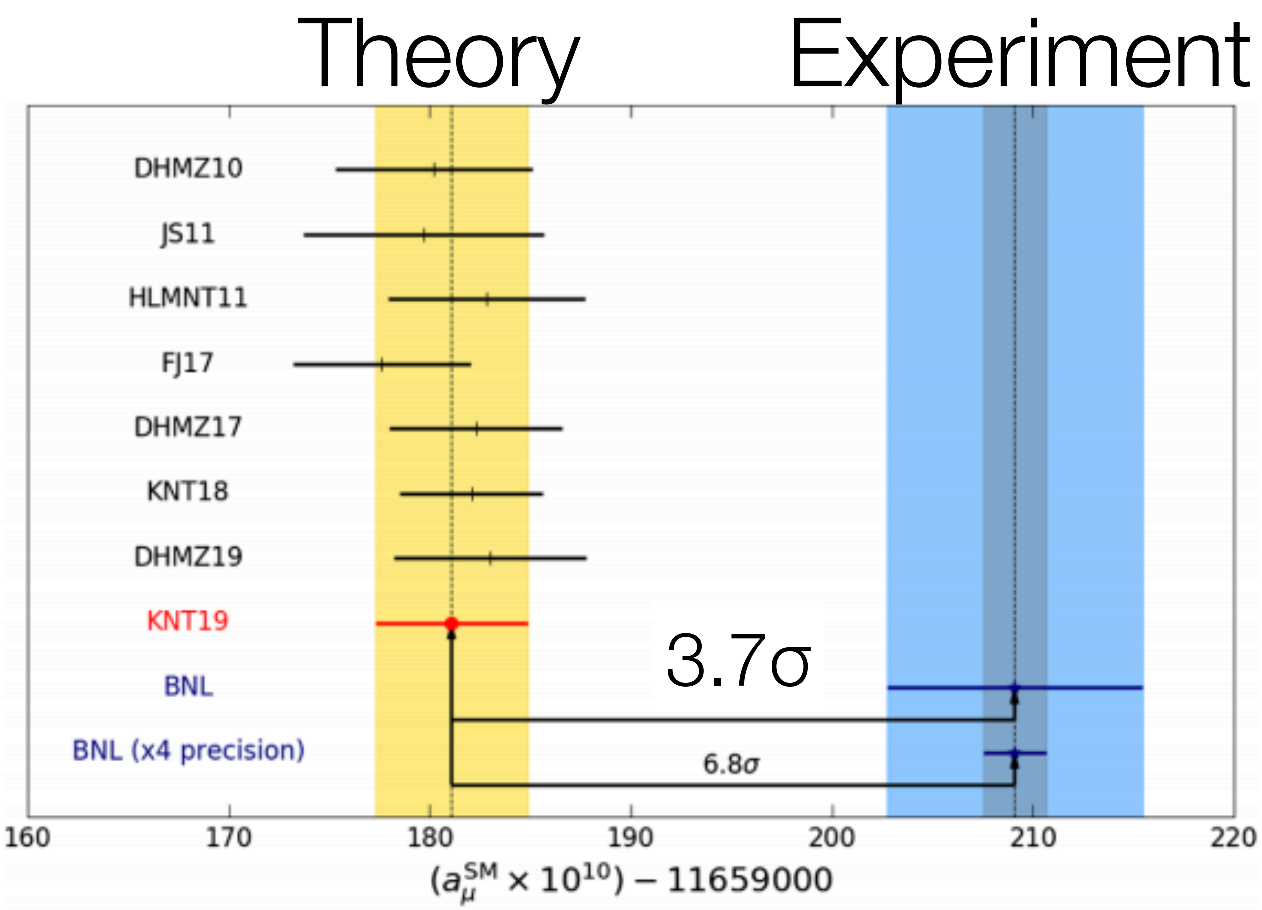




Physics Motivation of MuHFS Measurement

- **MuHFS(Δ*ν*) measurement**
  - **Validation for bound-state QED !**
    - $\Delta\nu$ (HF) = 4.463 302 765 (53) GHz (12 ppb)
      W. Liu *et al*., Phys. Rev. Lett. **82,** 711 (1999).
    - $\Delta\nu_{th}$ = 4.463 302 868 (271) GHz (63 ppb)
      P.J. Mohr *et al*., ReV. Mod. Phys. **88**, 035009 (2016).
  - Precise comparision between experiment and theory
  - Search for new particles, test of Lorentz invariance, and lepton universality

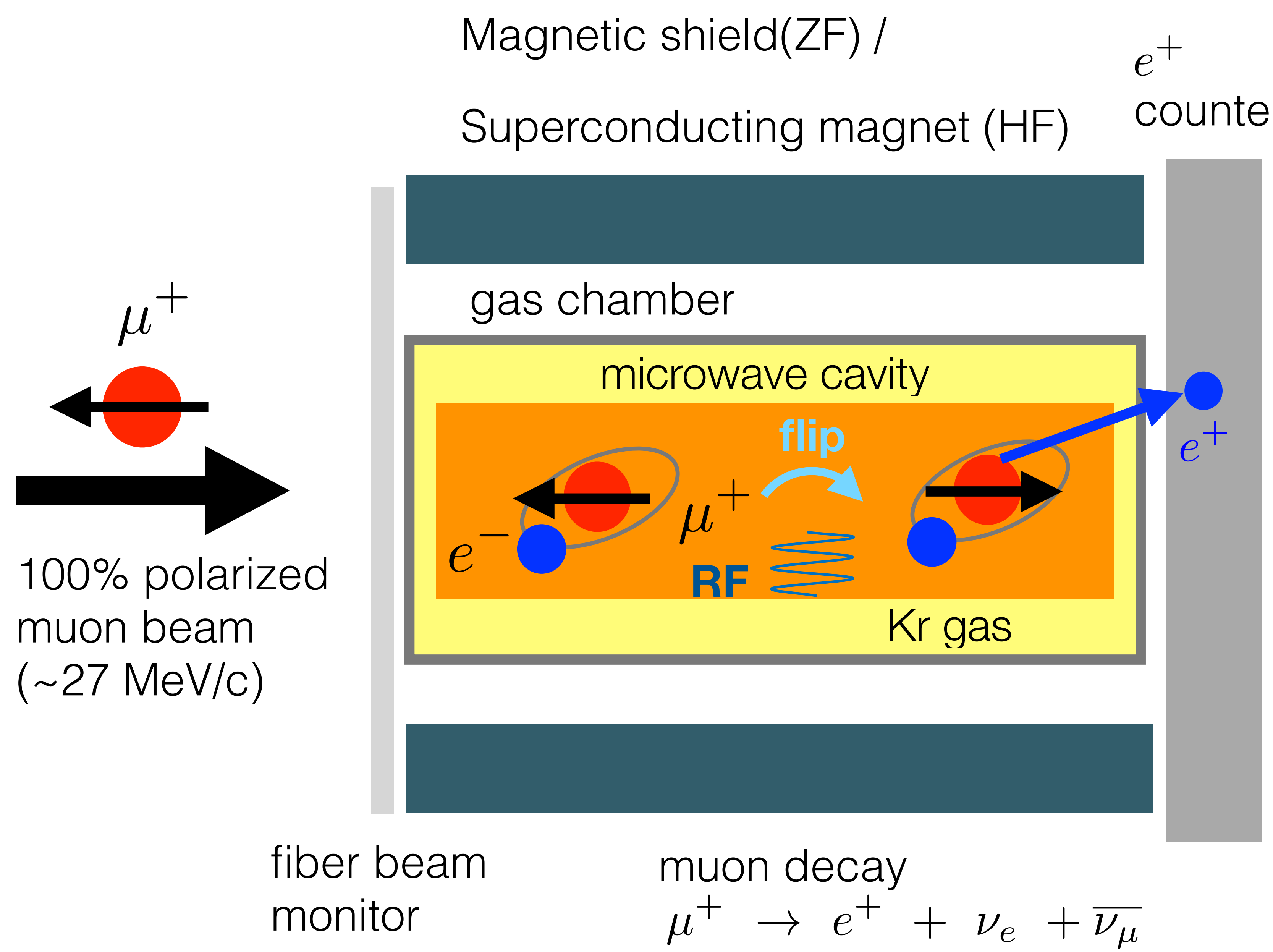
- **μ_μ / μ_p measurement**
  - Essential parameter to determine the muon g-2
  - 3.7 σ discrepancy between theory and exp.
  - New muon g-2 experiments at FNAL and J-PARC
  - MuHFS uncertainty : 30 ppb out of 540 ppb.



A. Keshavarzi *et al*., Phys. Rev. D. **101**, 014029 (2020).

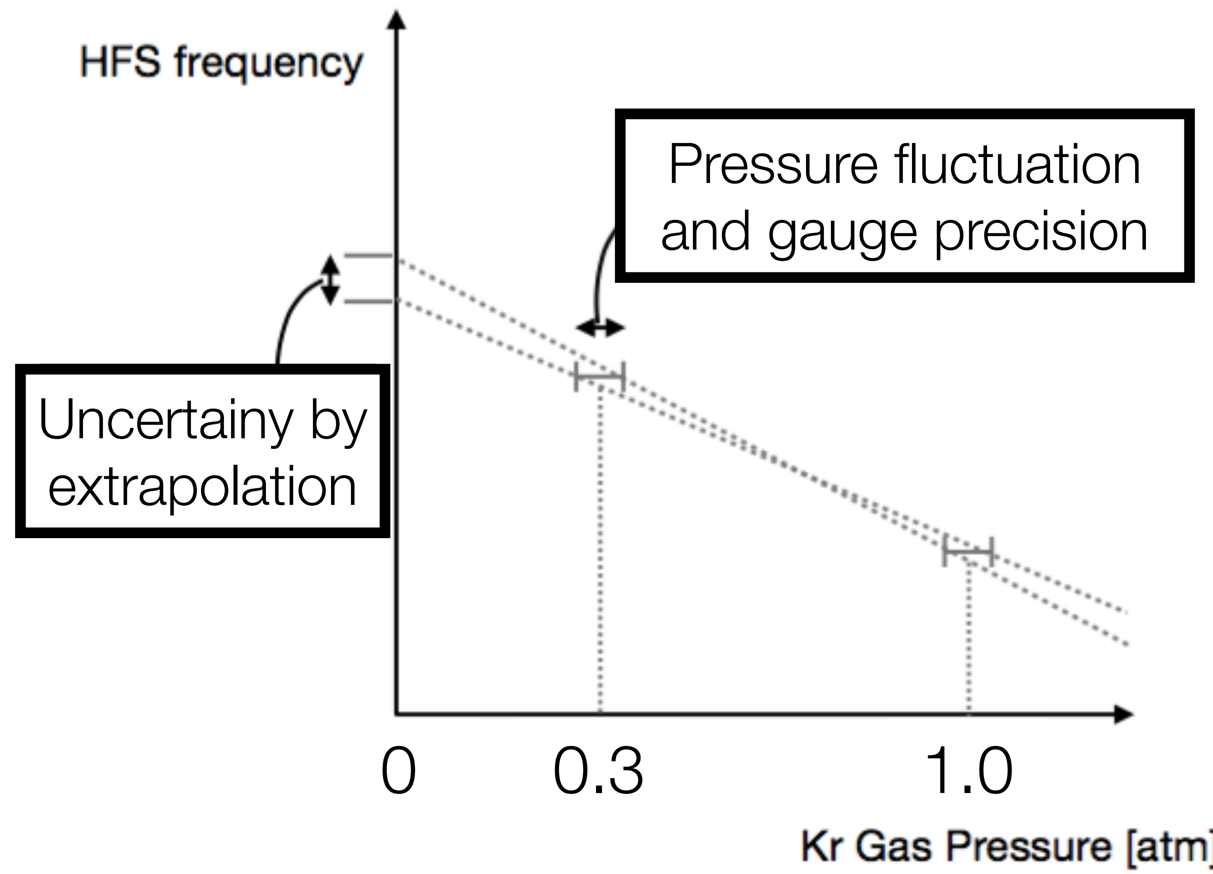
Experiment Procedure

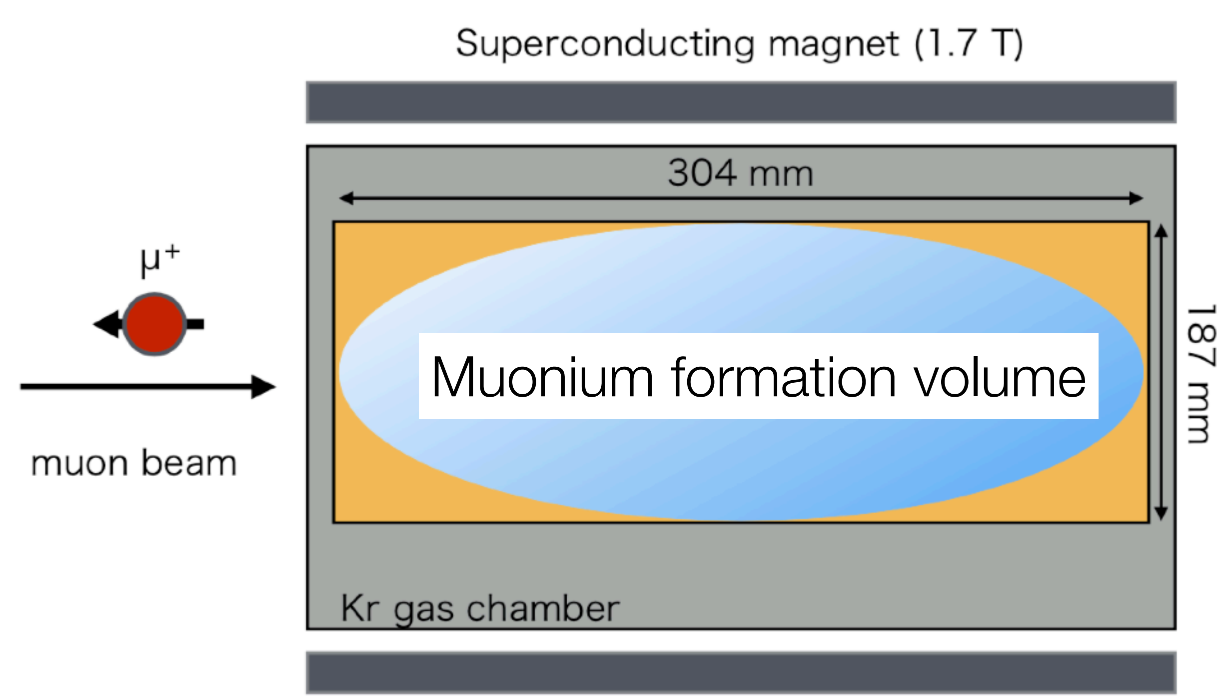
- **Muon beam injection to Kr gas and muonium formation**
- **Hyperfine transition by irradiation of microwave and muon spin flip**
- **Muon decay and positron emission correlated to muon spin**
- **Taking the ratio of positron time spectrum between RF ON and OFF**



Dominant sources of systematics

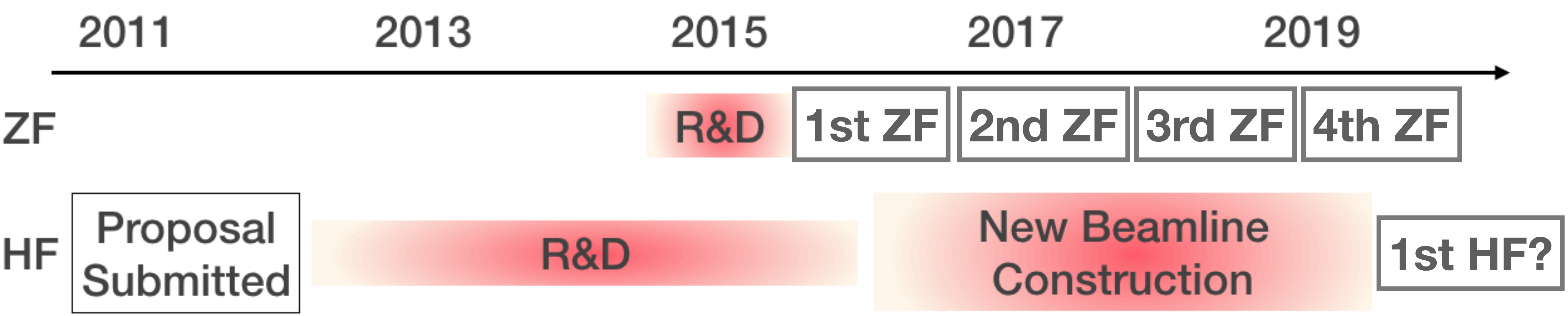
- Pressure shift of the hyperfine structure due to atomic collisions between Mu and Kr atoms
  - Need to extrapolate MuHFS in vacuum from data at various pressures
  - **Uncertainty arising from gas pressure was dominant**
  - **Low pressure is preferable**
- High field homogenity is required for a high-field exp.
  - **Requirement: <1 ppm homogeneity** of 1.7 T in the spheroid volume where muonium atoms form
  - **Precise magnetic probe is necessary** (**Goal** : **10 ppb precision**)

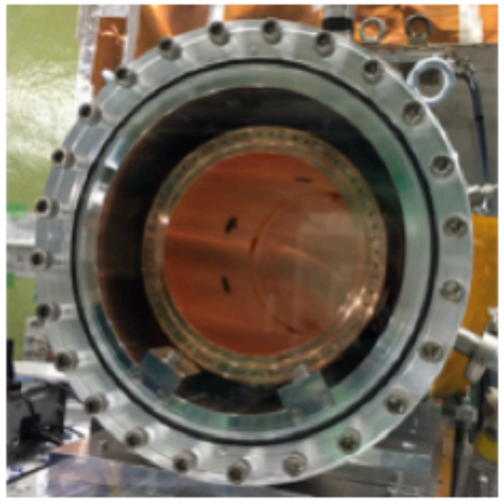




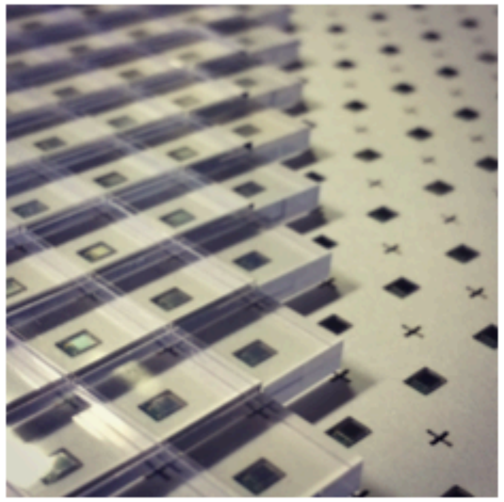
Status of MuSEUM

- **Zero field : Demonstration at existing beamline**
- **High field : Highest precision experiment at dedicated beamline under construction**



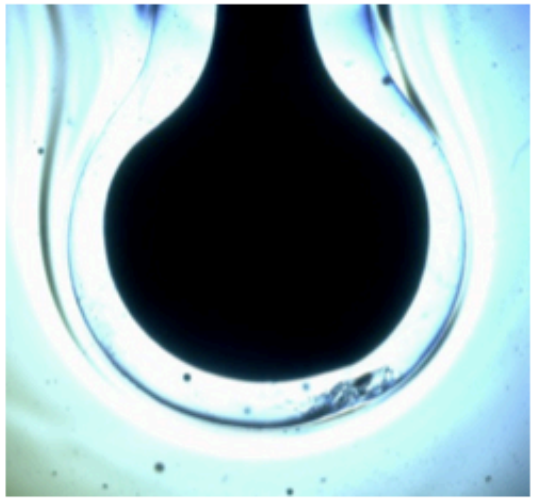


RF Cavity

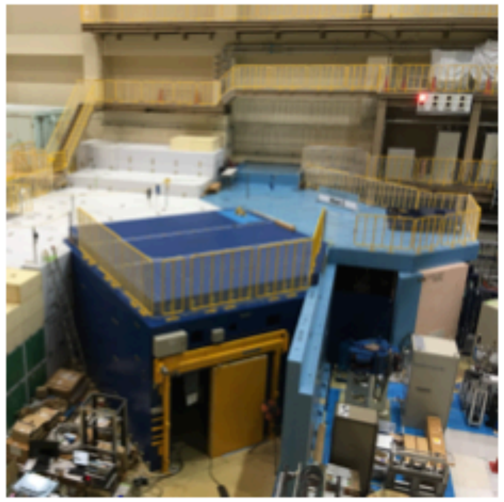


Detector

Magnet



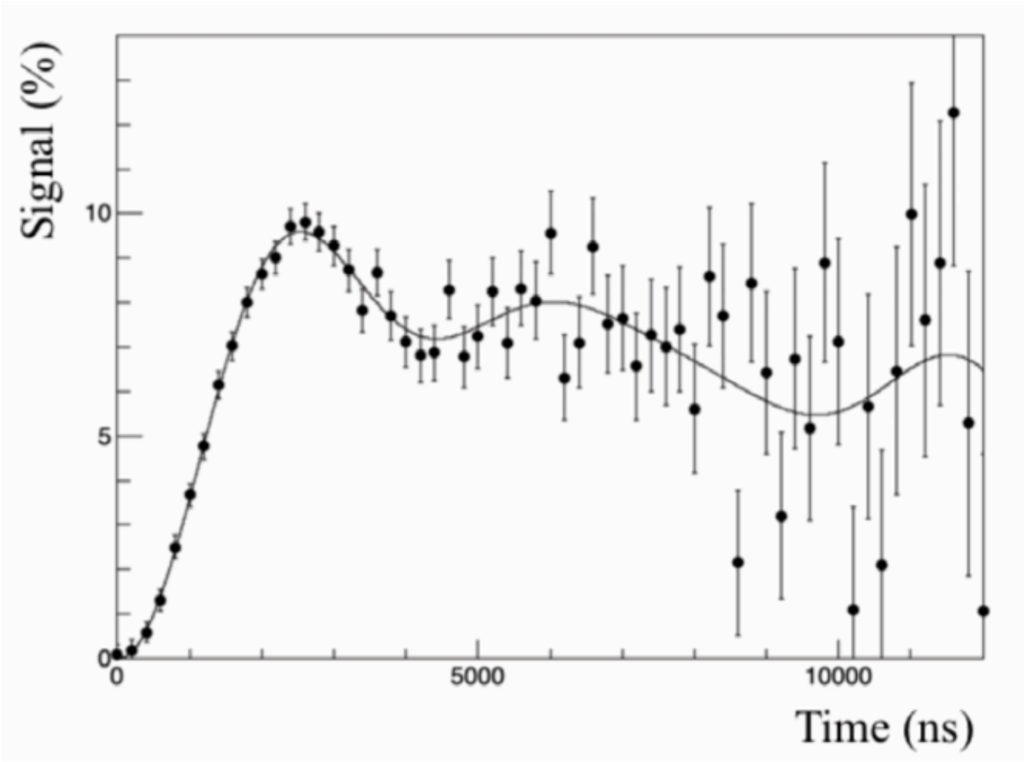
Field probe



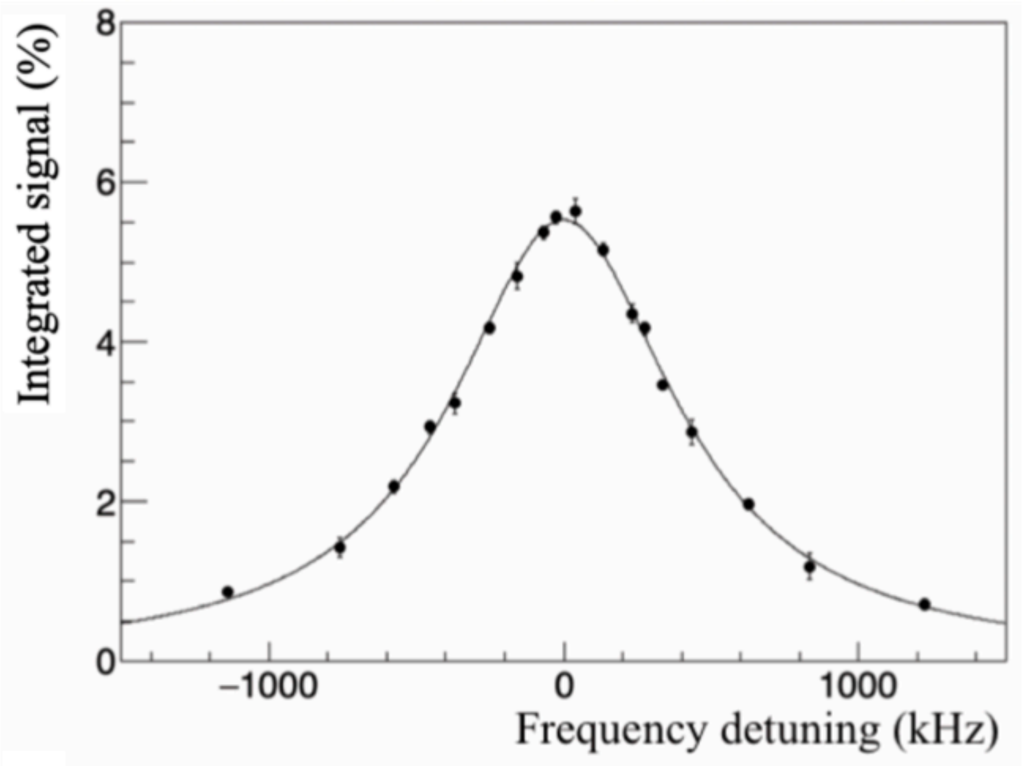
New beamline

Beamtime from 2016 to 2018

- 1st Beamtime in 2016
- First succesfull observation of the MuHFS resonance with pulsed beam at a near-zero magnetic field
  - S/N was limited due to a small microwave cavity.
  - High pressure was necessary for muon stopping (1.0 atm)
- 2nd & 3rd Beamtime in 2017, 2018
- High precision measurement at lower gas pressure with a larger cavity
  - Even at low pressure (0.3 atm), pressure shift systematics remains.



Rabi oscillation of Muonium



Resonance curve in 2017

S. Kanda et al., arXiv:2004.05862 [hep-ex]

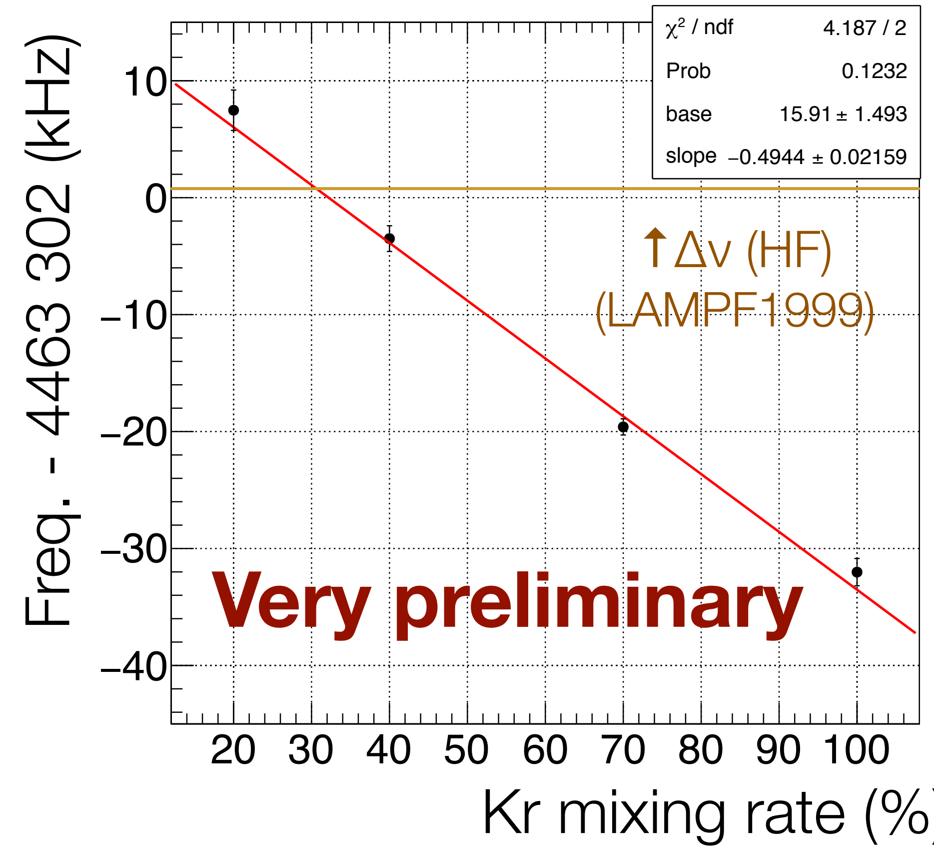
The latest beamtime in 2019

- The hypefine pressure shift may be canceled out by using Kr/He mixture gas
- Optimization of a gas mixture ratio was studied
  - We found an optimum at Kr:He=3:7.
- **Systematics due to gas pressure will be less than 1ppb**
  - **35 Hz (2018) -> a few Hz**
- **We achieved a world record in zero-field measurements:**
  - Preliminary result : 150 ppb stat. precision

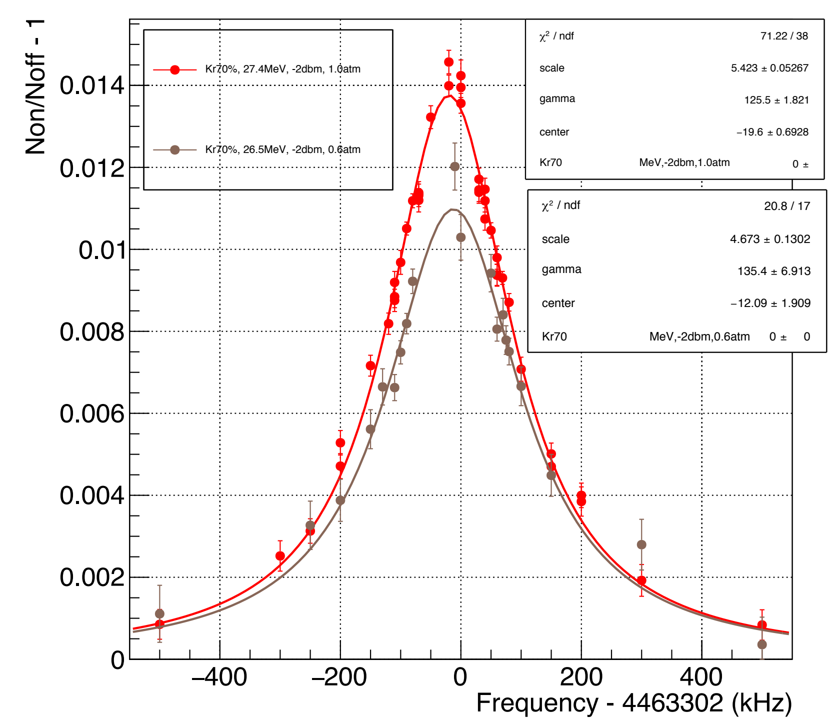
cf. World record of ZF@LAMPF

$\Delta\nu$ (ZF) = 4.463 3022 (14) GHz (300 ppb)

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

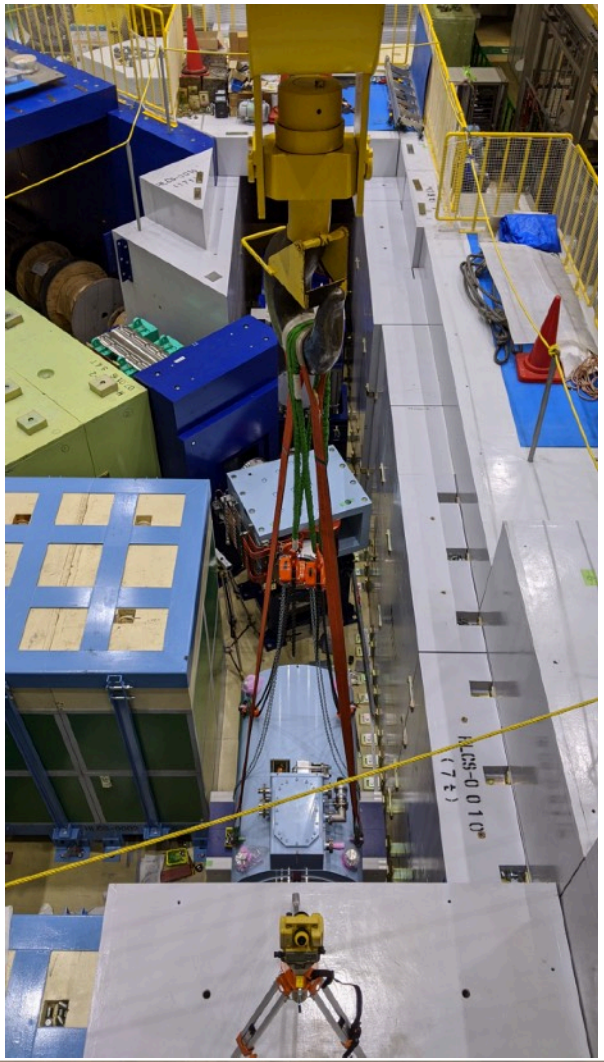


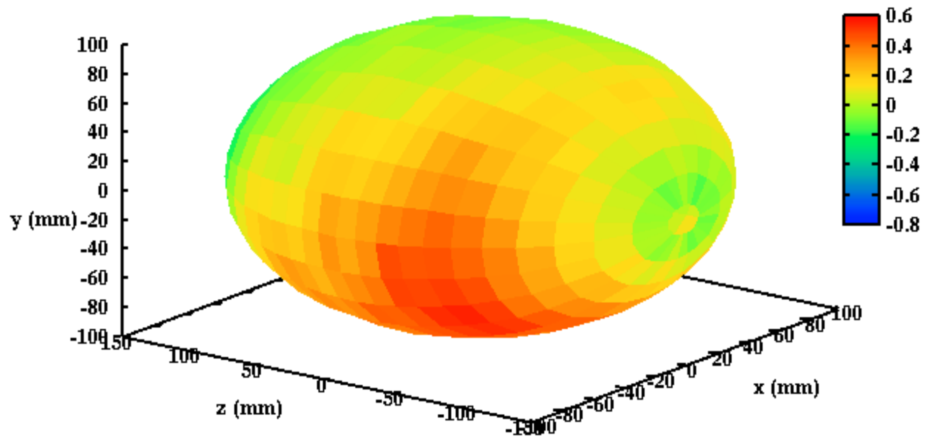
Kr rate dependence of transition freq. at 1.0×10^5 Pa



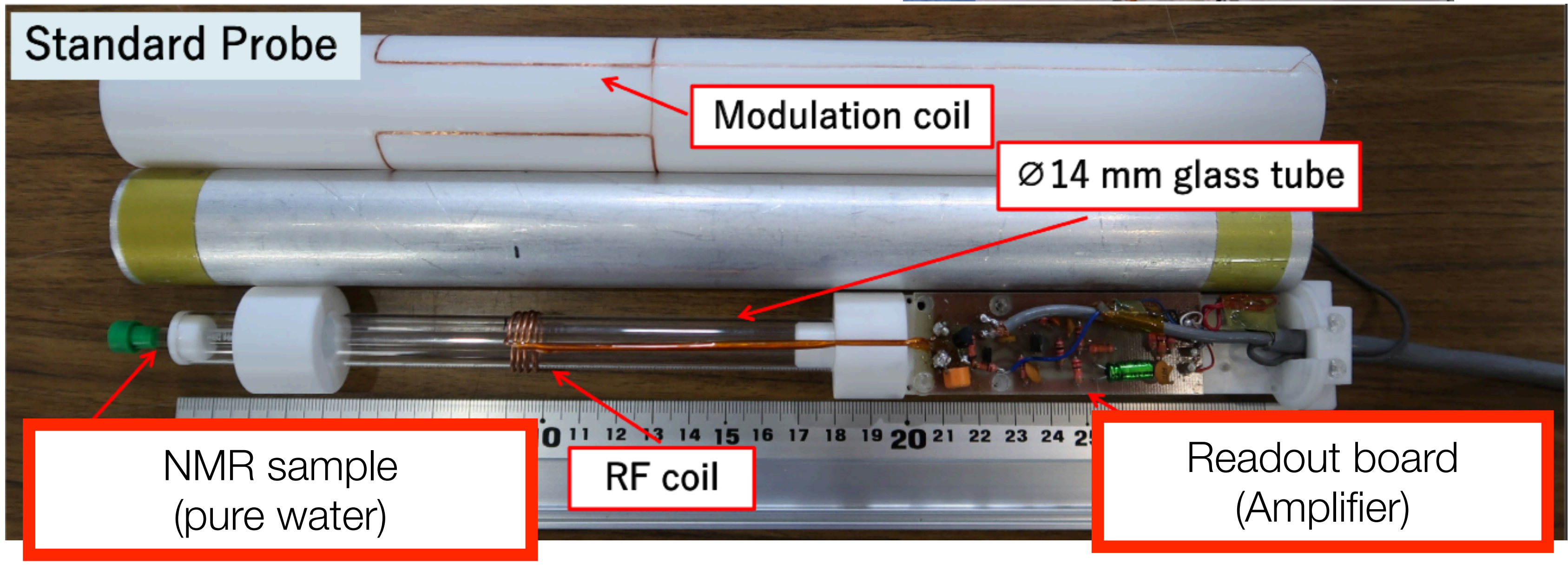
Preparation for High field Exp.

- **Beamline (H-Line: Yamazaki, Kawamura, Toyoda)**
  - A new dedicated beamline is under construction
  - We expect first beam in 2021
- **Magnetic Field (Sasaki, Abe)**
  - Achieved homogeneity: **±0.2 ppm in 1.7 T**
    (Recent result in 1.2 T: ±0.1 ppm has been achieved)
- **CW-NMR probe (Sasaki, Yamaguchi, Tanaka)**
  - Developping probes
    for an absolute value and field mapping
  - accuracy: **about 10 ppb achieved**(preliminary)
  - have performed cross calibration with Fermilab muon *g*-2 group





0.2 ppm homogeneity in spheroid:
r=100 mm, z=300 mm



H. Yamaguchi et al., IEEE Trans. Appl. Supercond. 29 5, 9000904 (2019)

Summary

- The hyperfine splitting of muonium is a unique probe to search for physics beyond the standard model.
- The MuSEUM collaboration aims to measure:
    - MuHFS with 1 ppb precision
    - μ_μ / μ_p. with 10 ppb precision
- We have performed experiments at a zero-field and established the principle.
- Preparations for a high-field experiment for the highest precision are in progress.

MuSEUM collaboration

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

- **Collaborators**

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