Current status of precise measurement of muonium hyperfine structure in high magnetic field at J-PARC MUSE

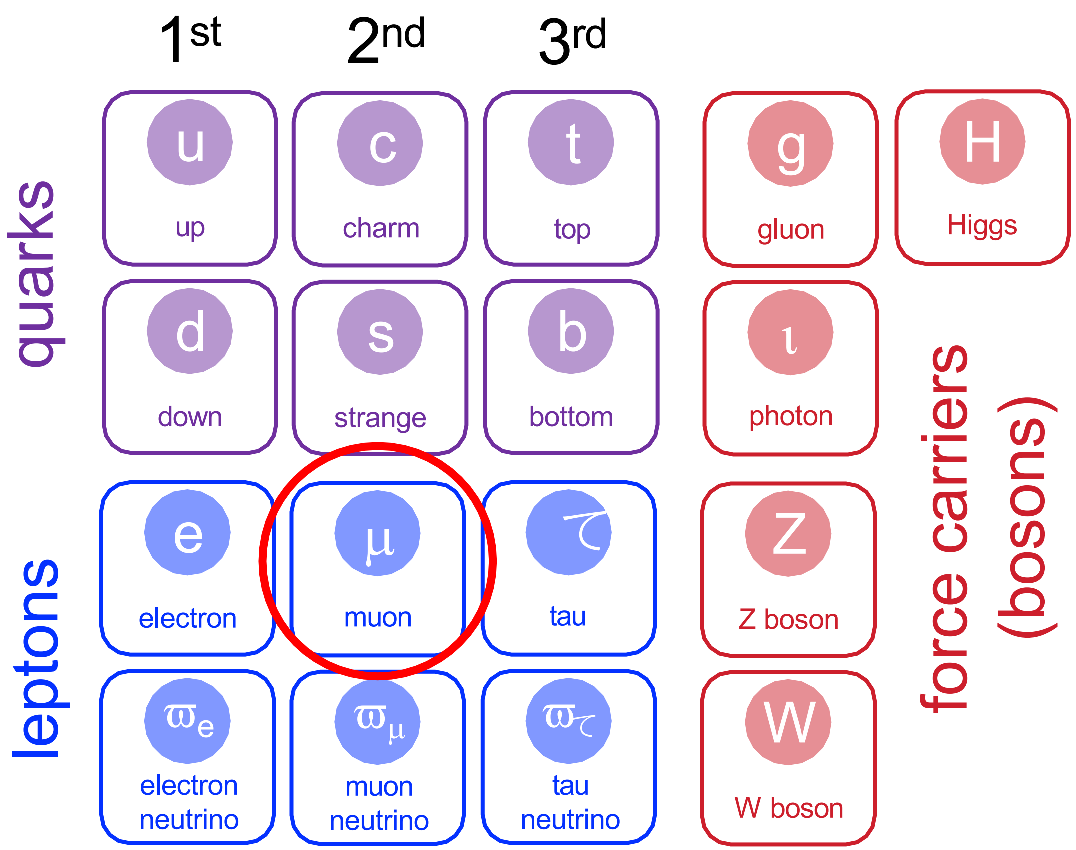
Koichiro SHIMOMUA KEK IMSS
on behalf of MuSEUM group

2025 June 26 NEWS colloquium

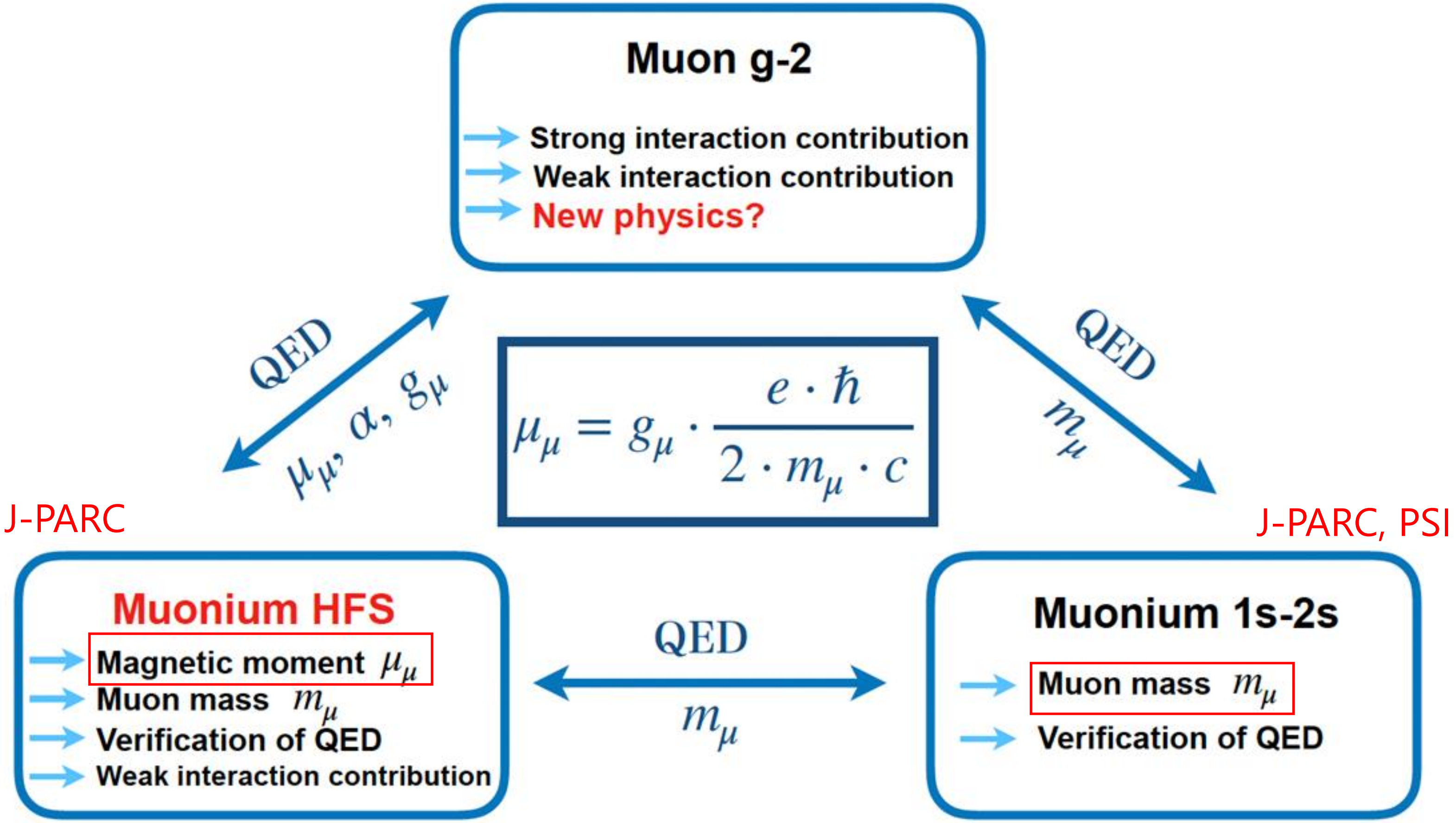
Contents

THE MUON IS A GREAT PROBE

- **“Goldilocks” mass**:
  - — **More sensitive** to virtual particles than electron
  - — Light enough so **no hadronic decays**
- **Unstable**:
  - — Decay: $\mu^+ \longrightarrow e^+\nu_e\bar{\nu}_\mu$
  - — Long lifetime so easy to make and store
- **Self-analyzing decay**
  - — High energy decay positron preferentially emitted in muon spin direction



Jungmann's triangle



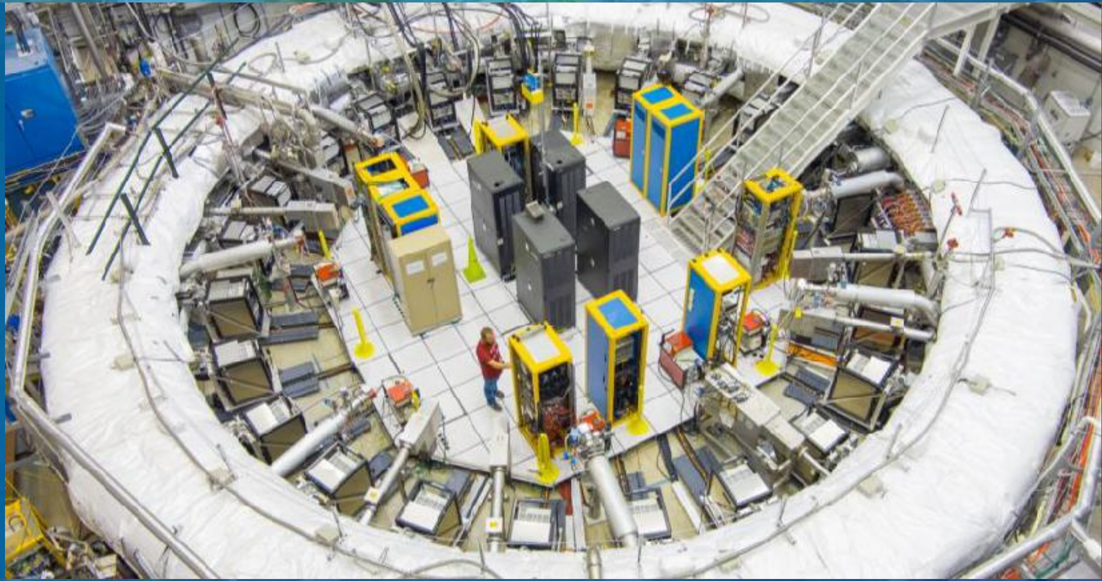
Independent test of g-2 is possible by combining Mu HFS and 1S-2S.

C. Delaunay et.al. Phys. Rev. Lett. 127, 251801 (2021)

Precision is not good...

17 JUNE 2025

A FINAL MOMENT FOR THE MUON

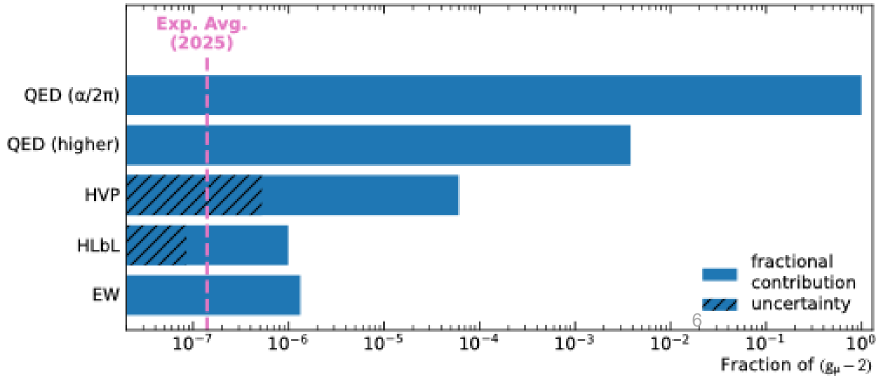


PETER WINTER
Muon g-2 Co-Spokesperson
Argonne National Laboratory

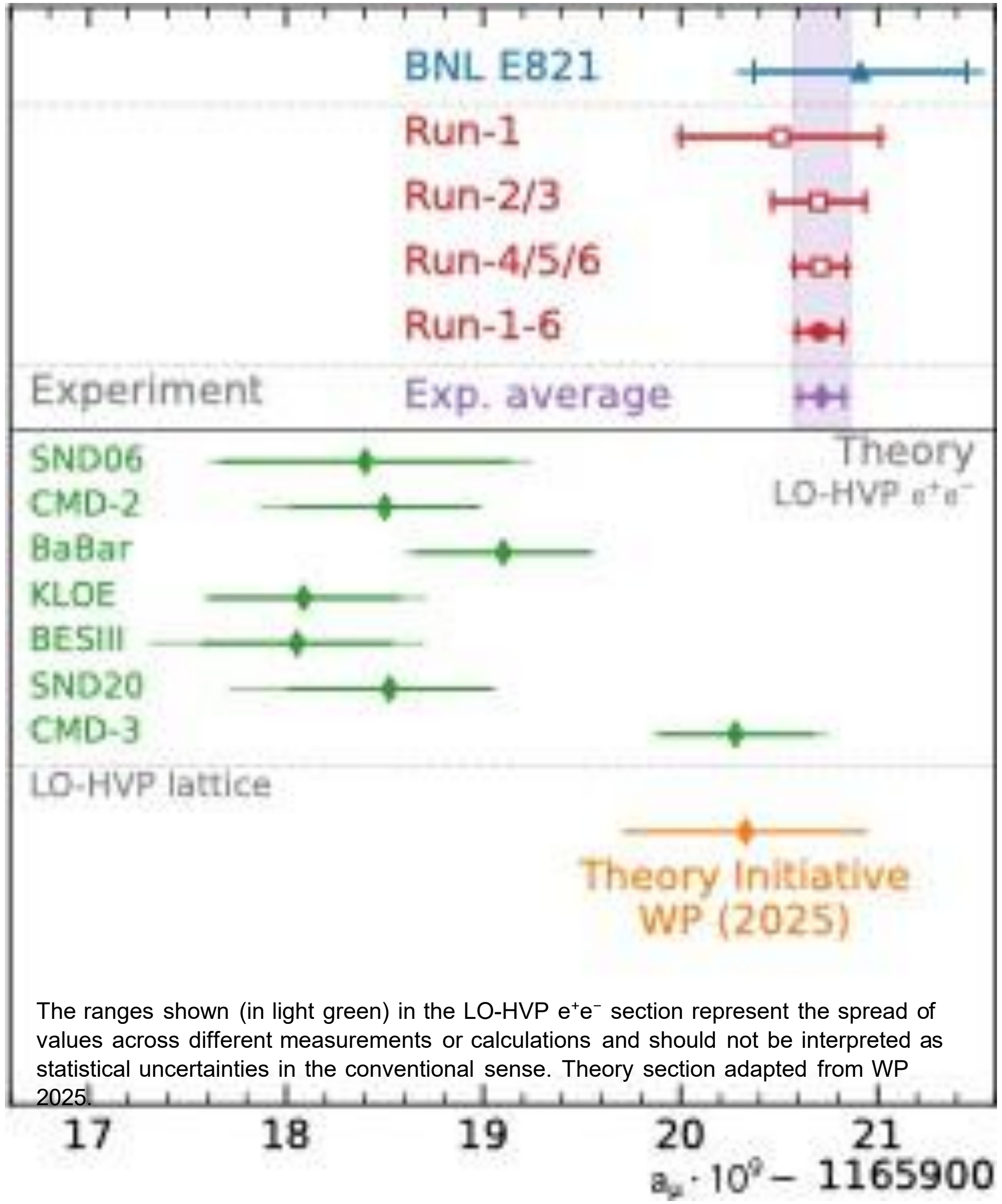
SUMMARY

$$a_\mu(\text{Run}-1-6) = \mathbf{0.001165920705(148)}$$

- **Most precise determination of a_μ for many years to come**
- 127 ppb measurement tests all Standard Model contributions

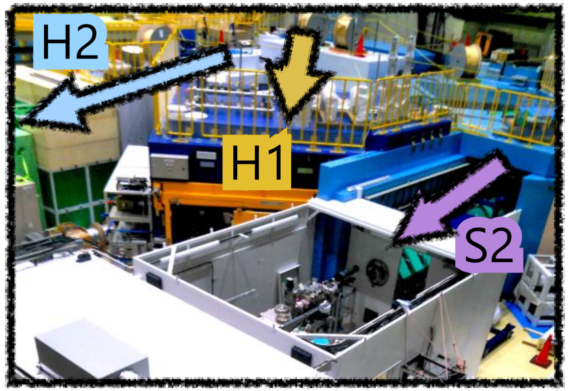


- Benchmark for models with new particles or forces (BSM)



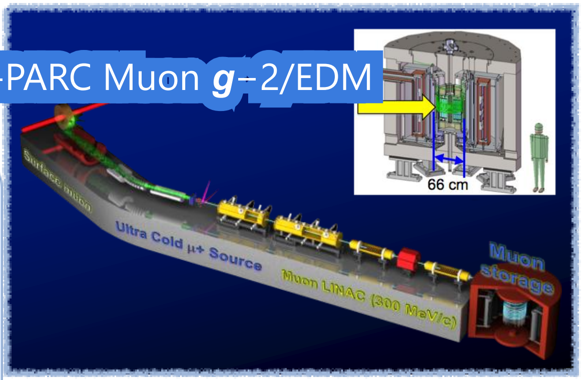
The ranges shown (in light green) in the LO-HVP e^+e^- section represent the spread of values across different measurements or calculations and should not be interpreted as statistical uncertainties in the conventional sense. Theory section adapted from WP 2025.

Muon Precision Measurement in J-PARC MLF



Muon $g-2$

New Physics beyond SM



QED

μ_μ, α, g_μ

QED

m_μ

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

Muonium (muonic He) HFS

Muon magnetic moment μ_μ

CPT for muon mass

QED

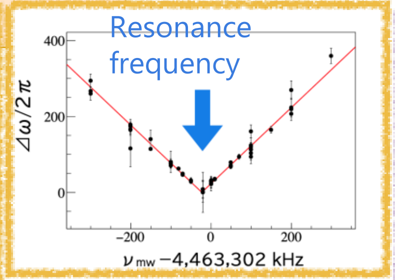
m_μ

Muonium 1s-2s

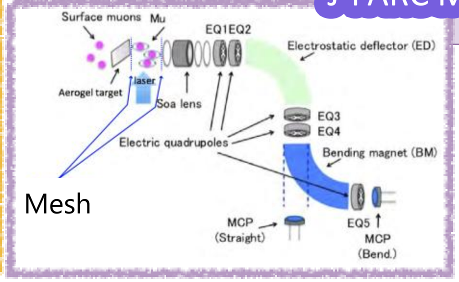
Muon mass m_μ

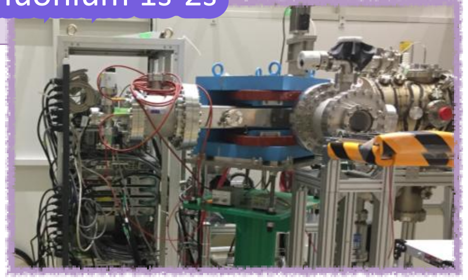
By K.Jungmann

MuSEUM

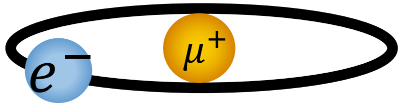


J-PARC Muonium 1s-2s





Muonium Hyperfine Structure (MuHFS)

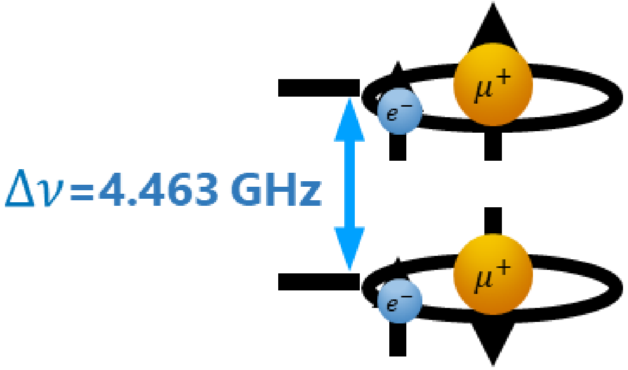


- Muonium (Mu, M)
  - Purely leptonic hydrogen-like atom
  - Relatively long lifetime = 2.2 μs
    - ✓ o-Ps = 140 ns
  - Precise calculations of level structure are available because there is no Finite-Volume effect

Examples of other binary systems

Hydrogen (H) **Positronium (Ps)**

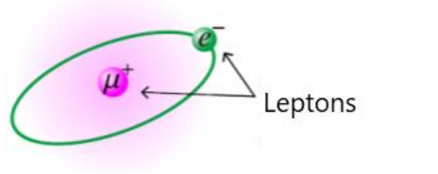
- Muonium hyperfine structure (MuHFS)



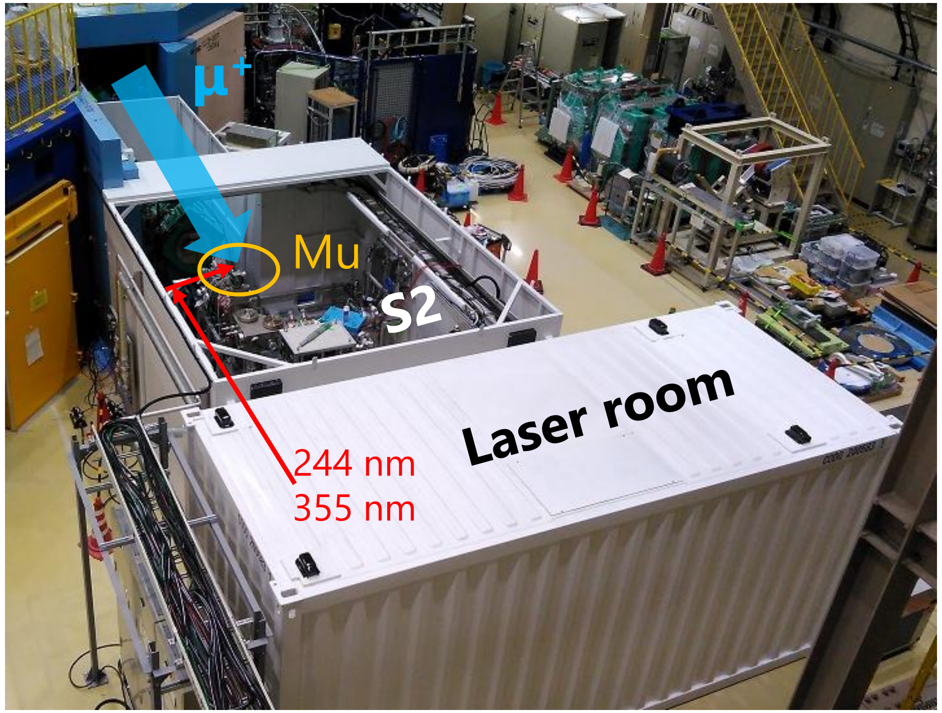
Hyper fine spectral structure of muonium atoms is produced by the magnetic dipole interaction between positive muon and electron

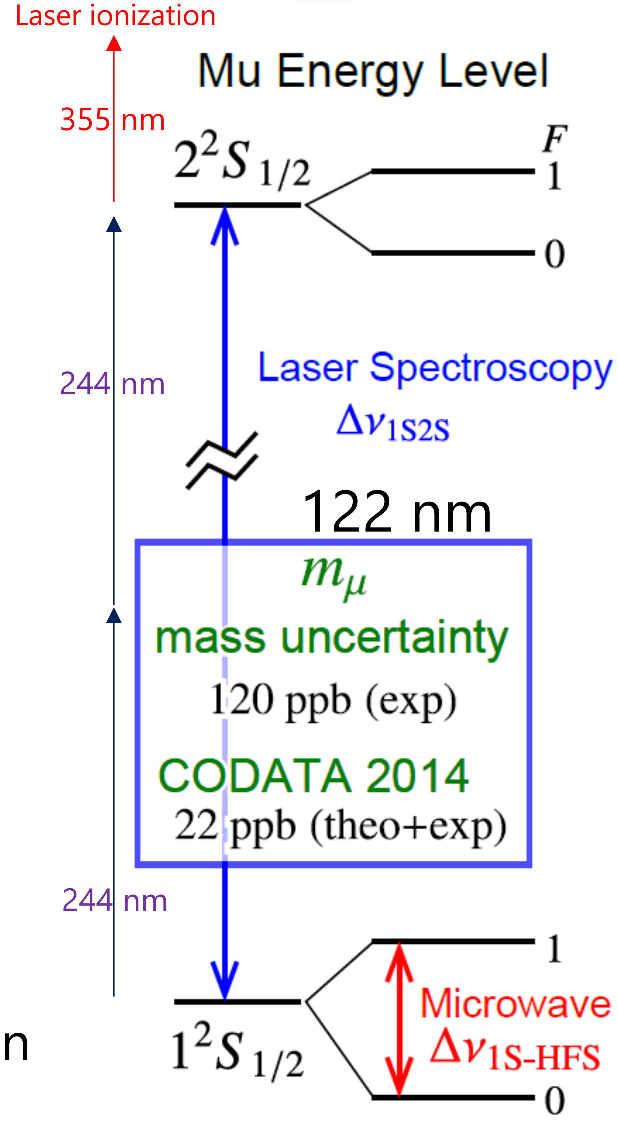
Mu 1S-2S @J-PARC

Muonium (Mu)



- Conducted at the 2nd branch of S-line
  - ✓ S-line is a surface muon beamline (10^6 μ^+/s)



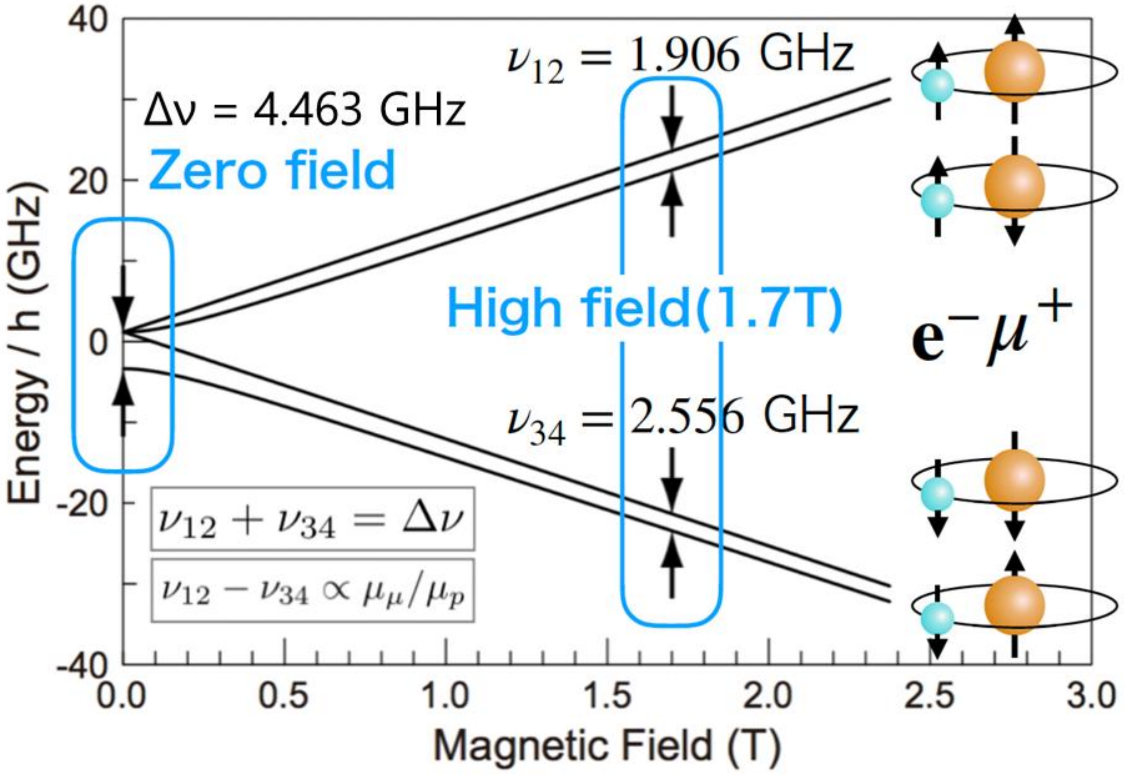


$$\Delta\nu_{1S2S} \simeq \frac{3\alpha^2}{8h} m_e c^2 \left(1 + \frac{m_e}{m_\mu}\right)^{-1}$$

mass

Goal:
10 kHz precision
Δm_μ = 1 ppb

HFS measurement at high field



$$\nu_{12} = -\frac{\mu_\mu B}{h} + \frac{\Delta\nu}{2}\left[(1+x) - \sqrt{1+x^2}\right]$$

$$\nu_{34} = +\frac{\mu_\mu B}{h} + \frac{\Delta\nu}{2}\left[(1-x) + \sqrt{1+x^2}\right]$$

x is proportional to magnetic field B

$$x = \frac{(\mu_\mu - \mu_e)B}{h\Delta\nu} \qquad \text{NMR: } B = \frac{h\nu_p}{2\mu_p}$$

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

$$\frac{\mu_\mu}{\mu_p} = \frac{4\nu_{12}\nu_{34} + \nu_p \frac{\mu_e}{\mu_p}(\nu_{12} - \nu_{34})}{\nu_p\left[\nu_p \frac{\mu_e}{\mu_p} - (\nu_{12} - \nu_{34})\right]}$$

$\Delta\nu_{HFS}$ = 4. 463 302 765(53) GHz (12 ppb)

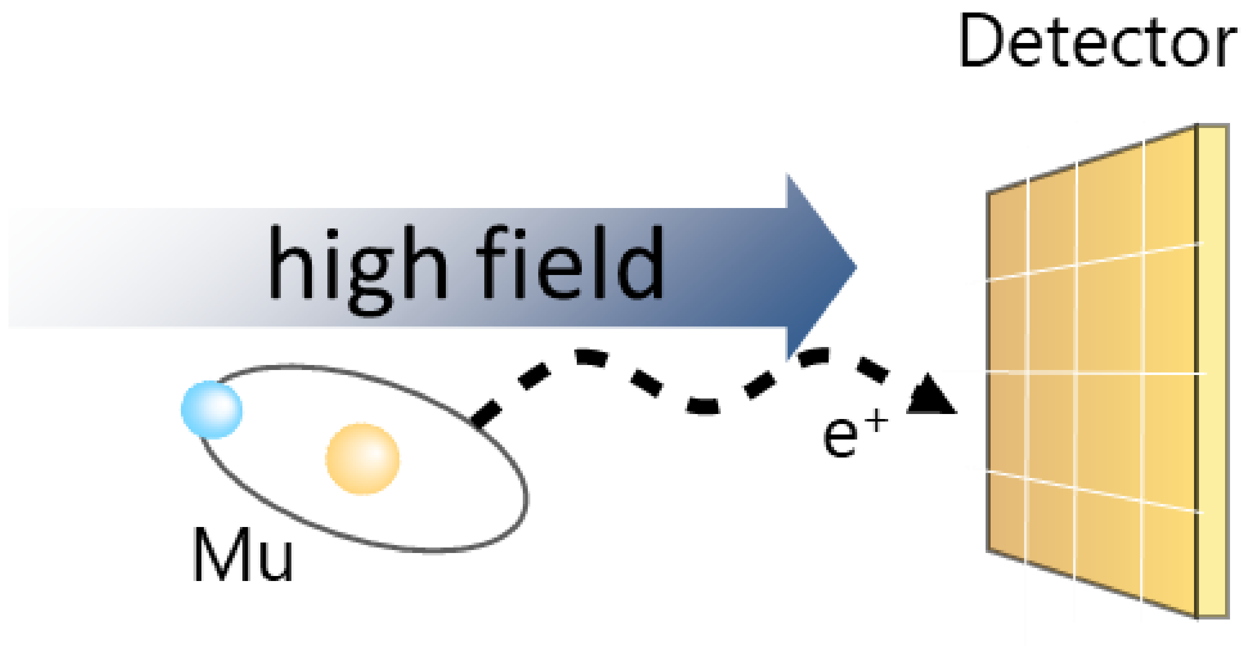
W. Liu et al., Phys. Rev. Lett. 82 711 (1999)

$$\mu_\mu/\mu_p = 3.18334513(39)(120\text{ppb})$$

W. Liu et al., Phys. Rev. Lett. 82 711 (1999)

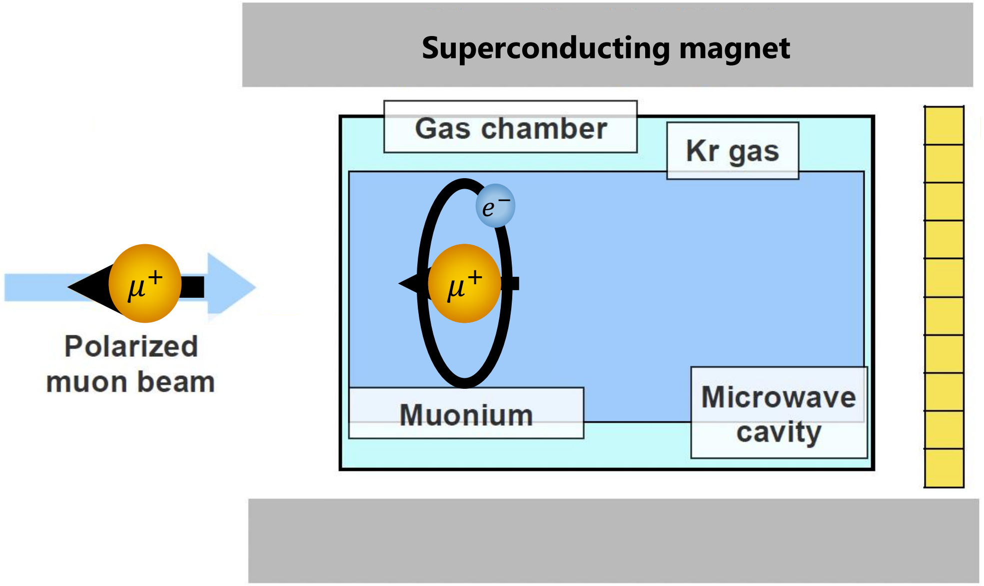
Other advantage of high field measurement

- Magnetic focusing of decay positron trajectories increases detection efficiency by several factors



Experimental setup

- Muonium production



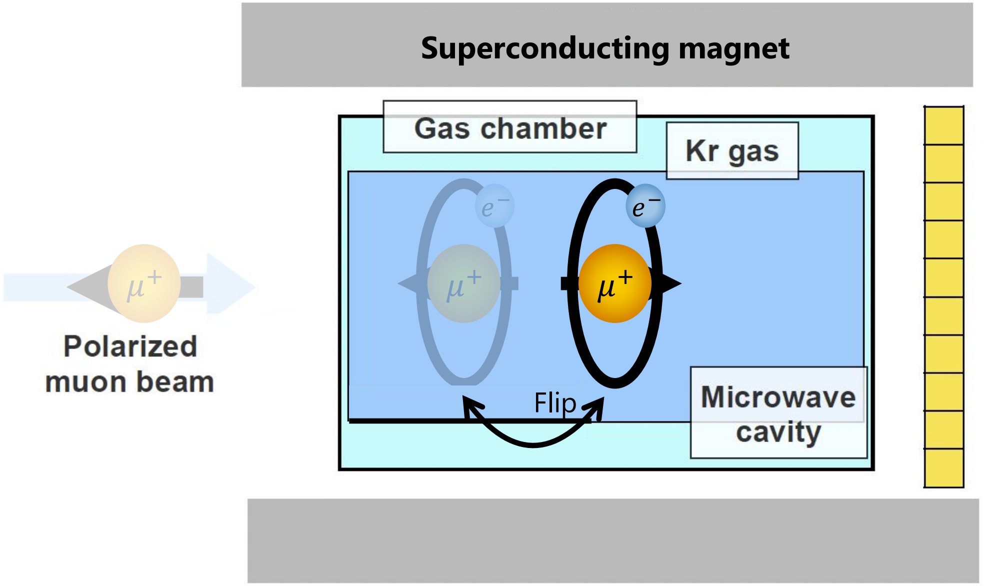
Muons strip electrons from Kr to form muonium

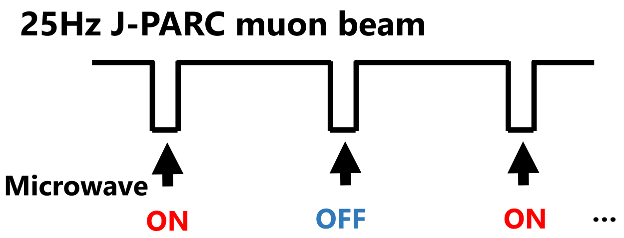
$$\mu^+ + \mathrm{Kr} \rightarrow \mathrm{muonium} + \mathrm{Kr}^-$$

- Kr has ionization energy close to muonium
- Inert gas
- High purity can be achived

Experimental setup

- Spin flip by applying microwaves



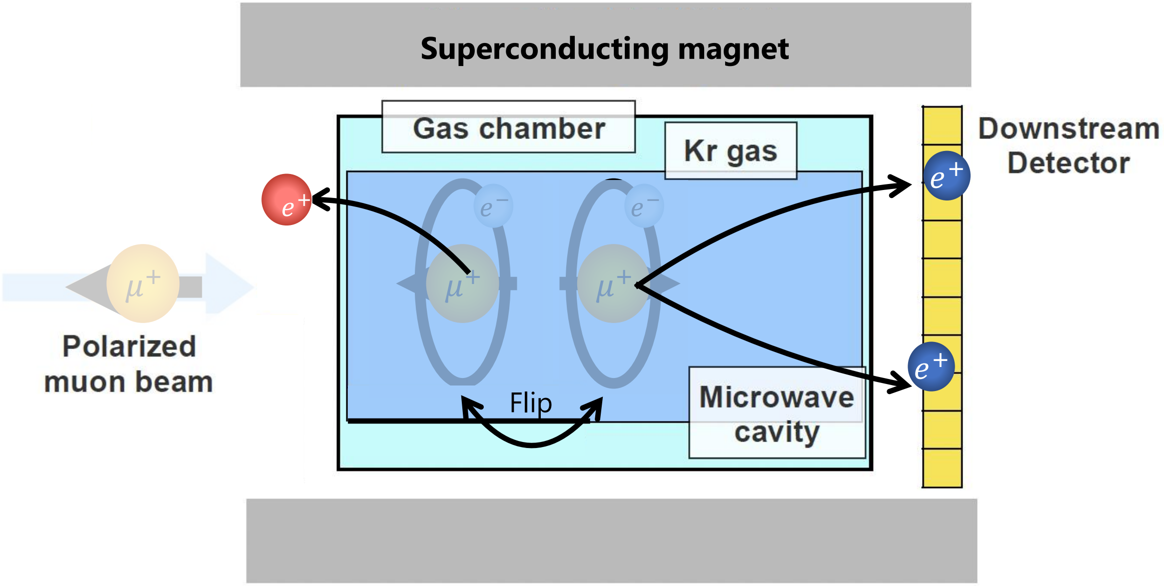


- Turning microwave on and off alternately

- If the microwave frequency is equal to the energy difference (ν_{12} or ν_{34}), muon spin is flipped

Experimental setup

- Decay positrons are counted by downstream detector



- Positrons are emitted preferably in the muon spin direction
- Signal = N_{on}/N_{off} -1
- By sweeping the microwave frequency, resonance curves are obtained.

Previous experiments

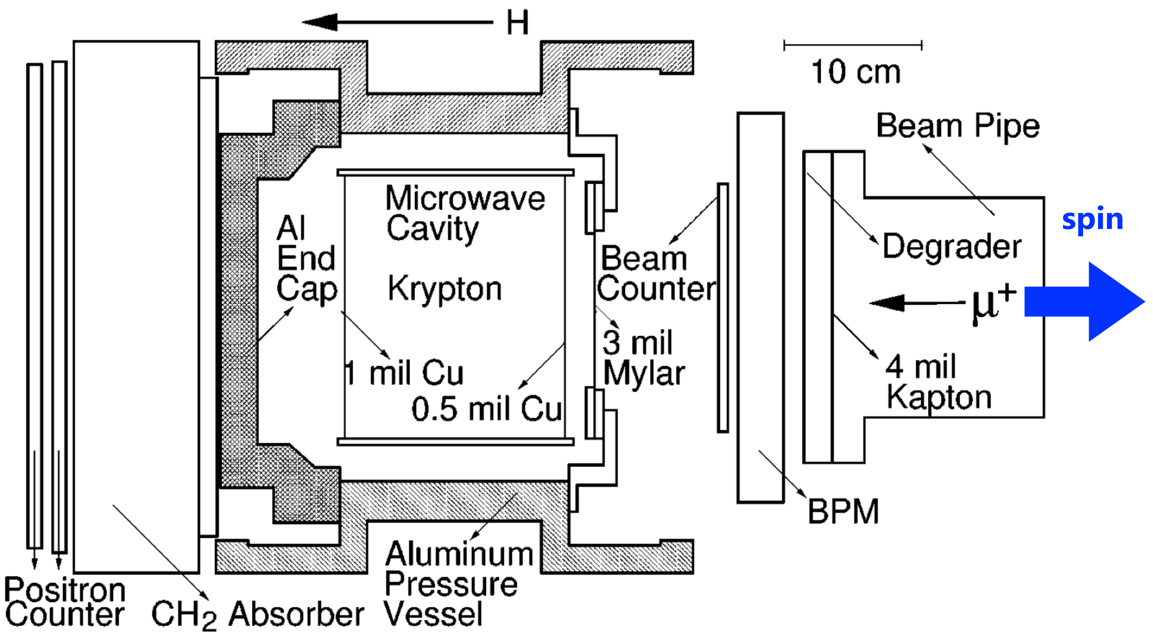
Time	Group	$\Delta\nu$	ppm	B field (T)
1961	Yale-Nevis	5500^{+2900}_{-1500} MHz		0.01-0.58
1962	Yale-Nevis	4 461.3(2.0) MHz	450	1.1353
1964	Yale-Nevis	4 463.24(12) MHz	27	0.5
1966	Yale-Nevis	4 463.18(12) MHz	27	2.7×10^{-4}
1969	Yale-Nevis	4 463.26(4) MHz	9.0	3×10^{-4}
1969	Chicago	4 463.317(21) MHz	4.7	1.1353
1970	Chicago	4 463.302 2(89) MHz	2.0	1.1353
1971	Yales-Nevis	4 463.308(11) MHz	2.5	3×10^{-4} and 1×10^{-6}
1973	Chicago-SREL	4 463 304.4(2.3) kHz	0.5	0
1975	LAMPF	4 463 302.2(1.4) kHz	0.3	very weak
1977	LAMPF	4 463 302.35(52) kHz	0.12	1.36
1982	LAMPF	4 463 302.88(16) kHz	0.036	1.36
1999	LAMPF	4 463 302.765(53) kHz	0.012	1.7

- Precision improved greatly in the 1970s due to the improvement of beam facilities.
- Current world record is Liu(1999) at LAMPF.

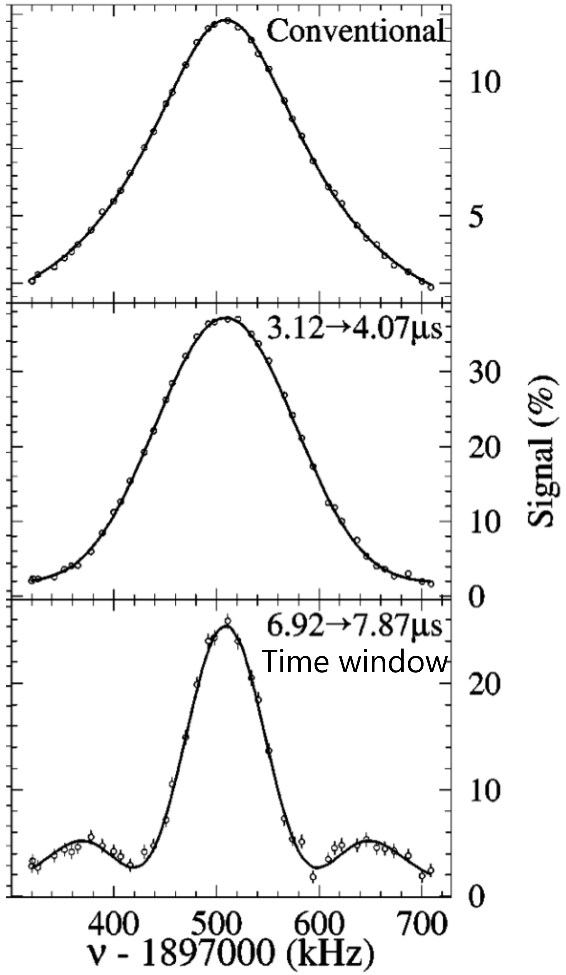
W. Liu et al., Phys. Rev. Lett. 82 711 (1999)

$\Delta\nu_{HFS}$ = 4. 463 302 765(53) GHz (12 ppb)

$\mu_\mu/\mu_p = 3.18334513(39)(120\text{ppb})$



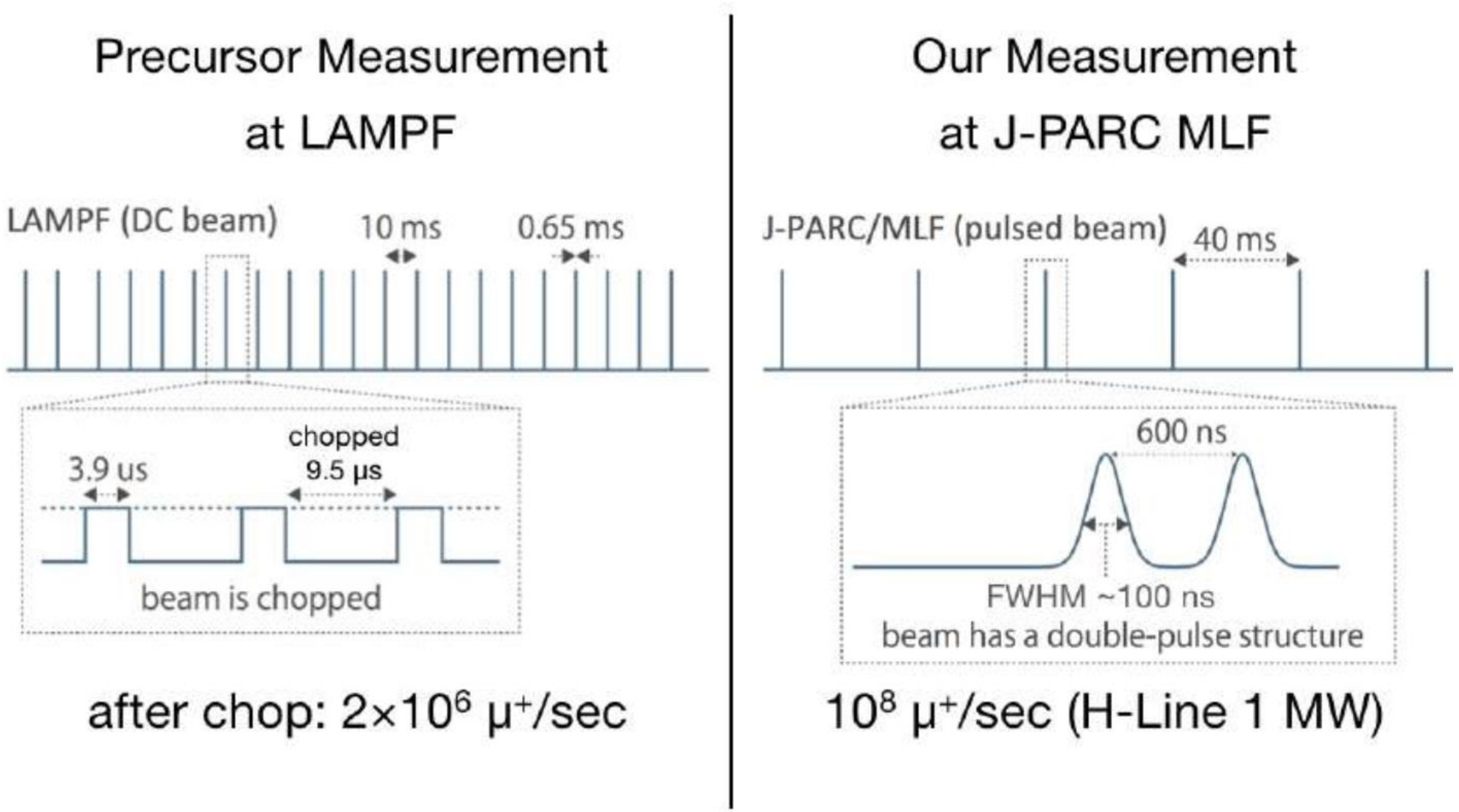
Resonance curve



Statistically limited

→ New high-intensity muon experiments at J-PARC (53→8 Hz)

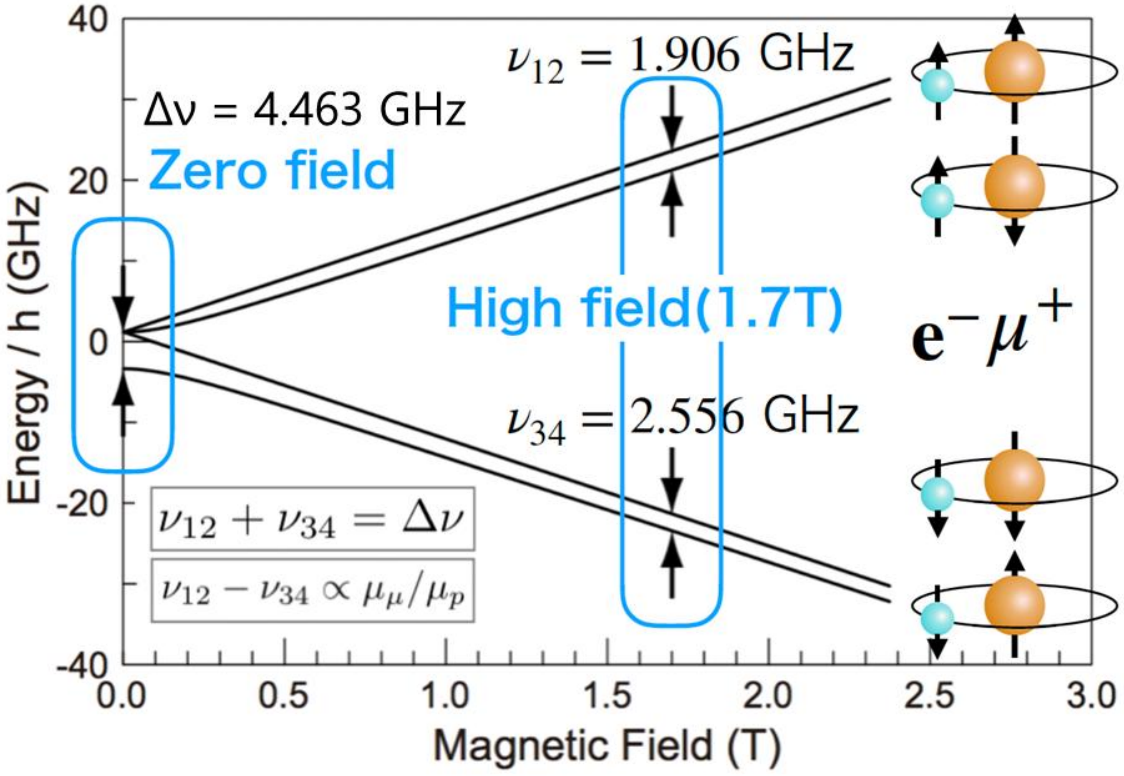
Comparison of the beam structures



MuSEUM experiment at J-PARC

*MuSEUM = **Mu**onium **S**pectroscopy **E**xperiment **U**sing **M**icrowave*

HFS measurement at high field



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x is proportional to magnetic field B

$$x = \frac{(\mu_\mu - \mu_e)B}{h\Delta\nu}$$

NMR: $B = \frac{h\nu_p}{2\mu_p}$

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

$$\frac{\mu_\mu}{\mu_p} = \frac{4\nu_{12}\nu_{34} + \nu_p\frac{\mu_e}{\mu_p}(\nu_{12}-\nu_{34})}{\nu_p\left[\nu_p\frac{\mu_e}{\mu_p}-(\nu_{12}-\nu_{34})\right]}$$

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W. Liu et al., Phys. Rev. Lett. 82 711 (1999)

Papers on MuSEUM

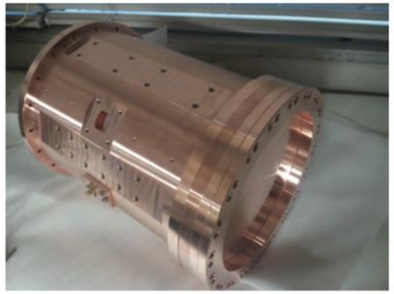
ZF and HF cavity

PTEP

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. Iwasaki[3], O. Kamigaito[3], S. Kanda[4,5,6], N. Kawamura[4,5,6], Y. Matsuda[2], T. Mibe[5,6,7], S. Nishimura[4,5], N. Saito[5,8], N. Sakamoto[3], S. Seo[2,3], K. Shimomura[4,5,6], P. Strasser[4,5,6], K. Suda[3], 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

Physics Letters

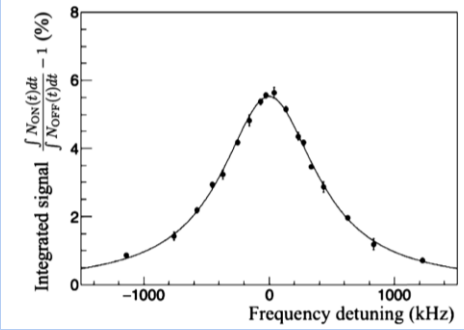
Contents lists available at ScienceDirect

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. Torii[i], A. Toyoda[b,d,e], Y. Ueno[a]



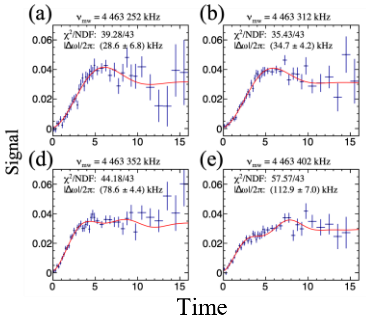
Rabi-oscillation spectroscopy

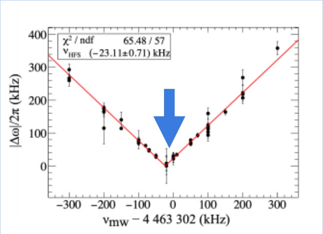
PHYSICAL REVIEW A **104**, L020801 (2021)

Letter

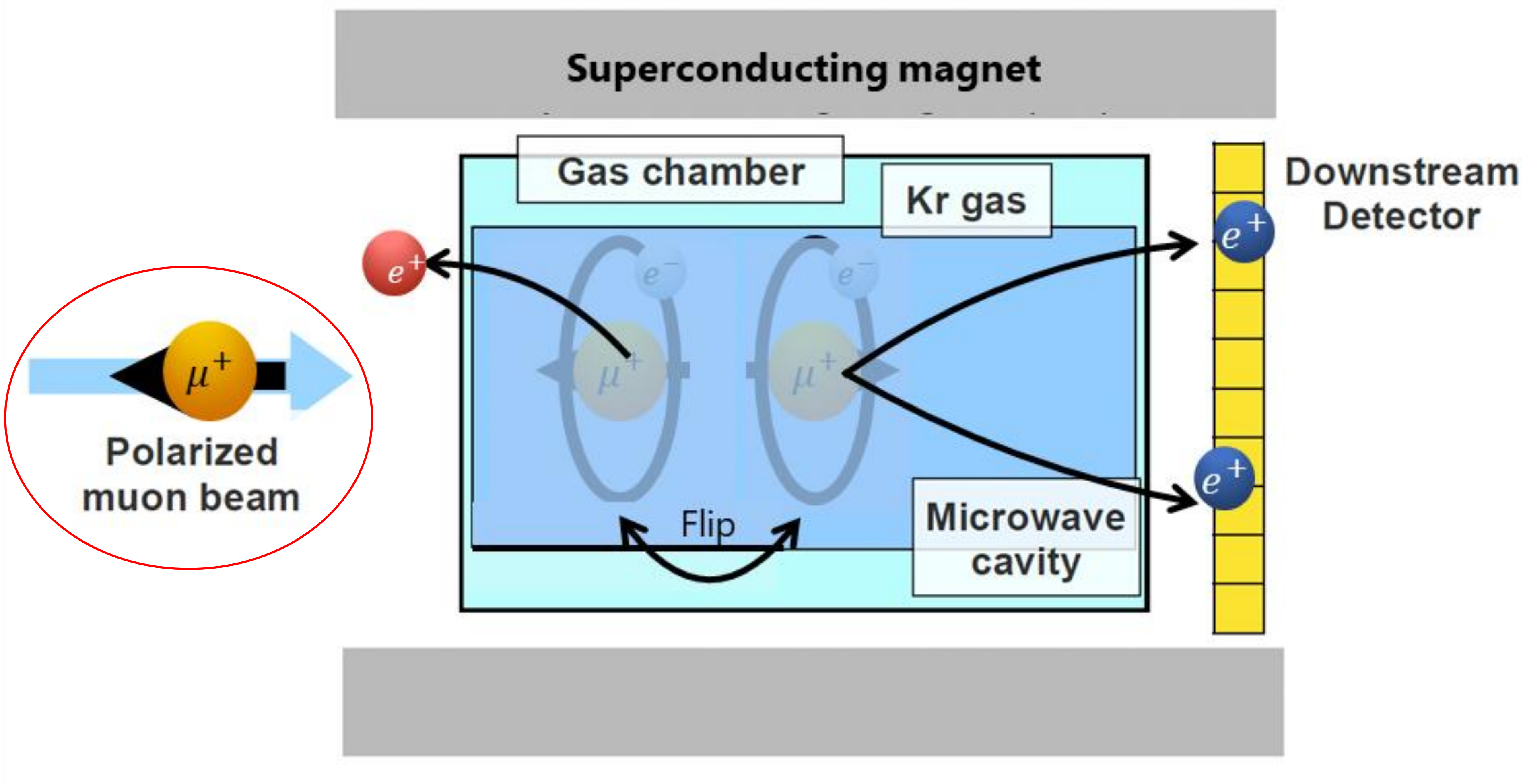
Rabi-oscillation spectroscopy of the hyperfine structure of muonium atoms

S. Nishimura,[1,2,*] H. A. Torii,[3] Y. Fukao,[1,2,4] T. U. Ito,[2,5] M. Iwasaki,[6] S. Kanda,[6] K. Kawagoe,[7] D. Kawall,[8] N. Kawamura,[1,2,4] N. Kurosawa,[1,2] Y. Matsuda,[9] T. Mibe,[1,2,4] Y. Miyake,[1,2,4] N. Saito,[1,2,4,3] K. Sasaki,[1,2,4] Y. Sato,[1] S. Seo,[6,9] P. Strasser,[1,2,4] T. Suehara,[7] K. S. Tanaka,[10] T. Tanaka,[6,9] J. Tojo,[7] A. Toyoda,[1,2,4] Y. Ueno,[6] T. Yamanaka,[7] T. Yamazaki,[1,2,4] H. Yasuda,[3] T. Yoshioka,[7] and K. Shimomura[1,2,4]
(MuSEUM Collaboration)





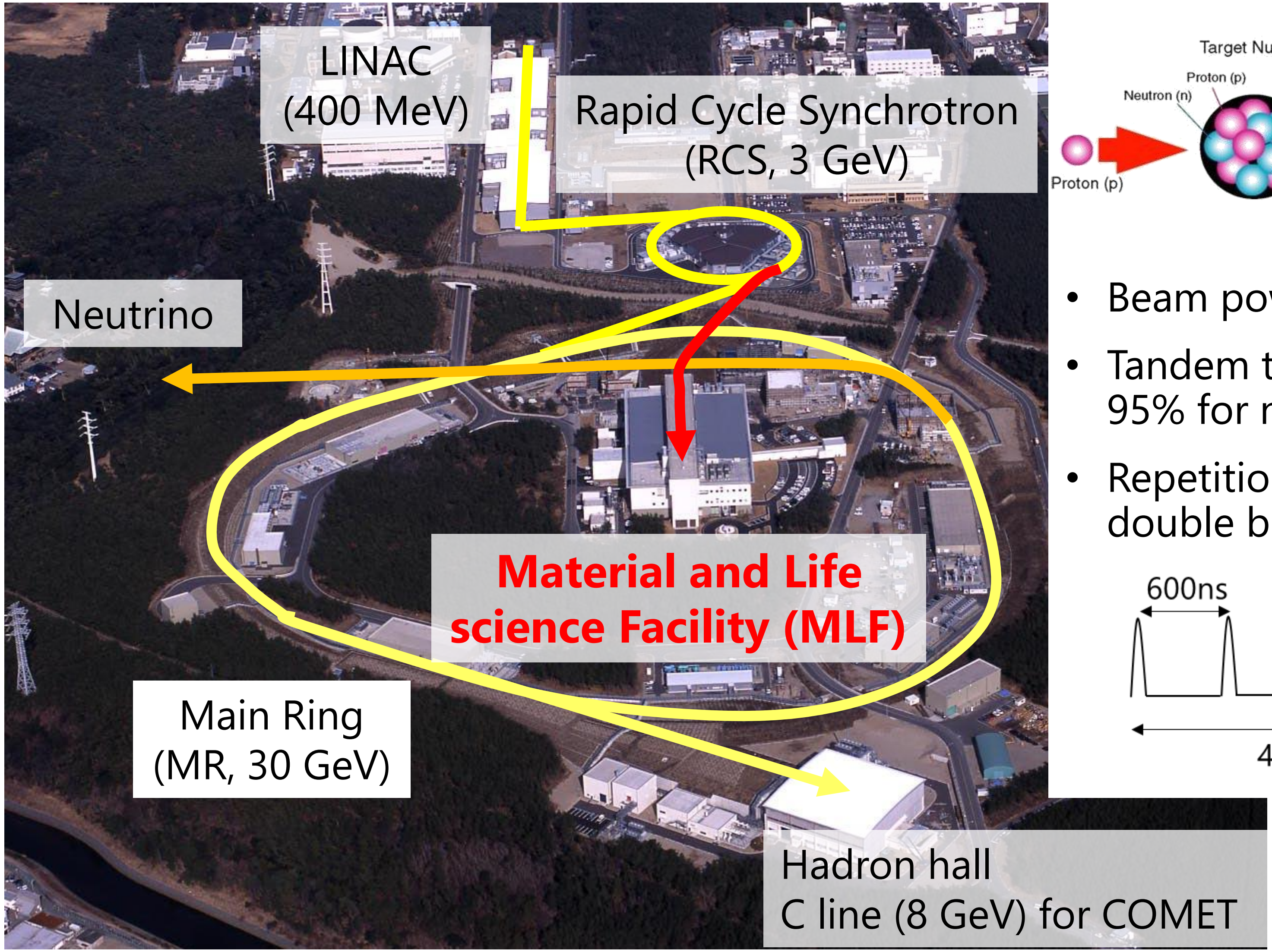
Polarized muon beam

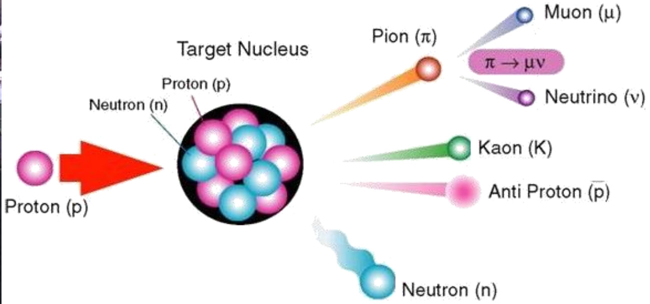


- High-intensity pulsed muon beam of H-line at J-PARC MLF

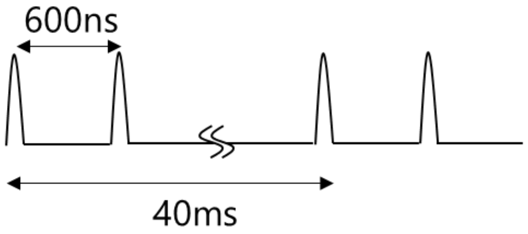
J-PARC

J-PARC (Japan Proton Accelerator Research Complex)





- Beam power 1 MW
- Tandem target: 5% for μ, 95% for n
- Repetition rate 25 Hz, double bunches



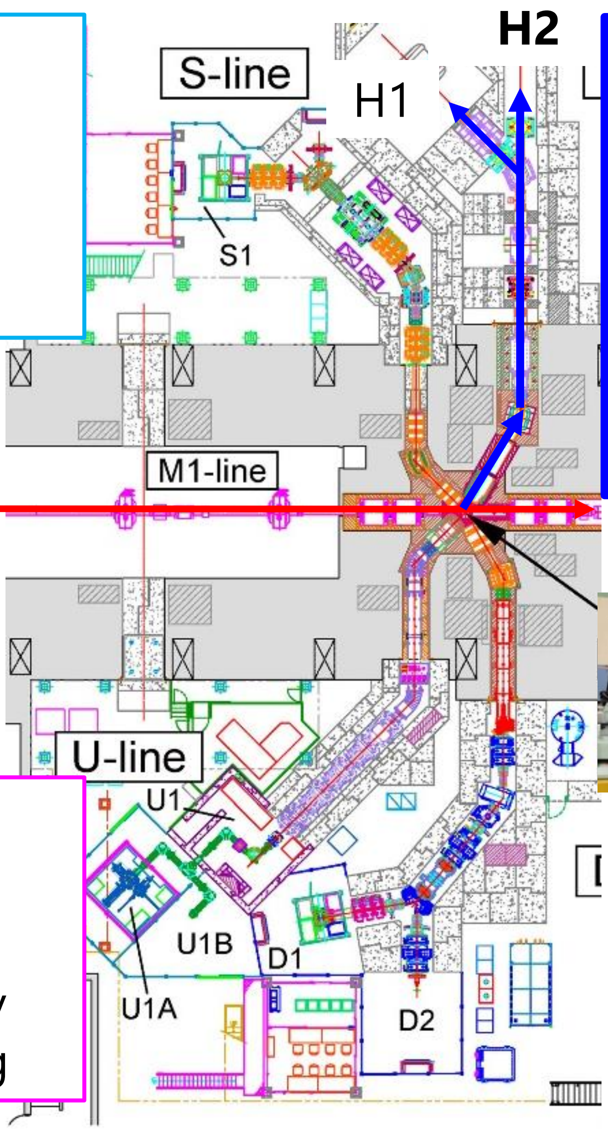
J-PARC muon facility

- MUSE (MUon Science Establishment) in the MLF

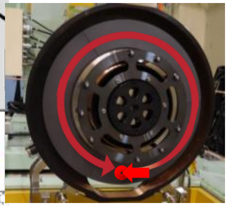
<u>S line</u>
- surface μ^+
- S1 for μSR
- S2 for Mu 1S-2S
- S3/S4 are planned

3GeV proton from RCS

2e15 /s @1MW



<u>H line</u>
- **surface μ^+ (~10^8 μ^+/s)**, cloud μ^+/μ^-, e^-
- **for high intensity & long beamtime** experiments
- H1 for DeeMe & MuSEUM
- H2 for g-2/EDM & TμM

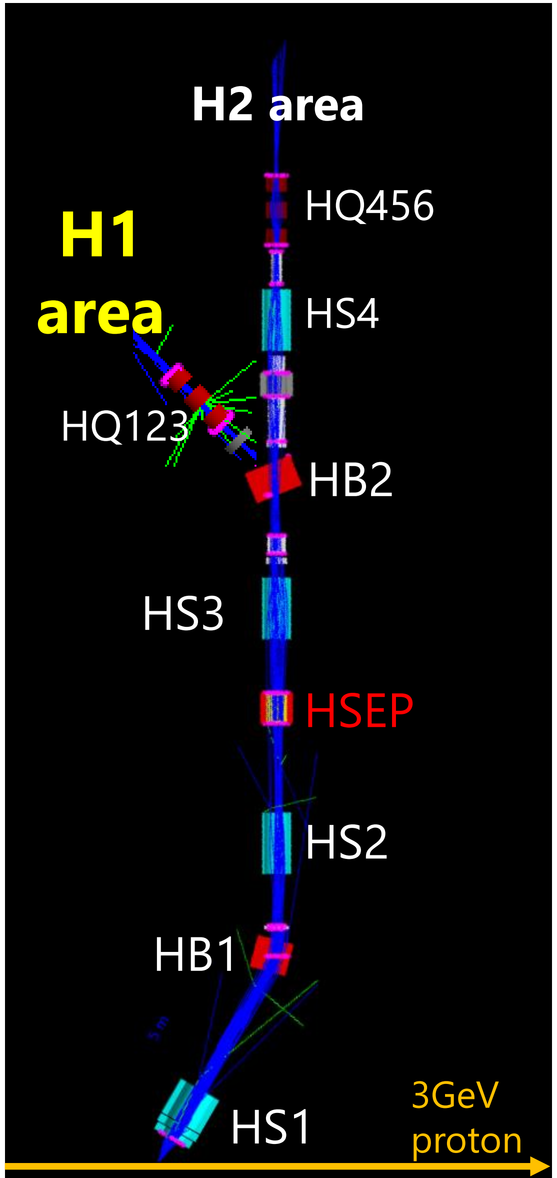


Muon target
(graphite, ^{t}20mm)
Rotating target

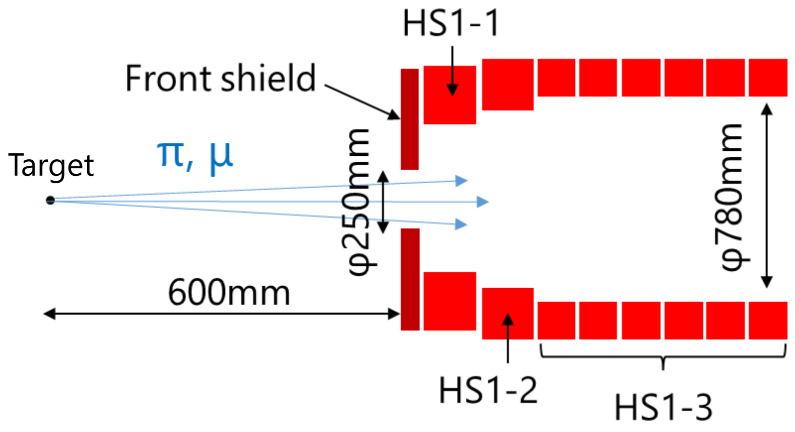
<u>U line</u>
- ultra slow μ^+
- U1A for nm-μSR
- U1B for μ microscopy
- under commissioning

<u>D line</u>
- decay μ^+/μ^-, surface μ^+
- D1 area for μSR
- D2 for variety of science

H-line



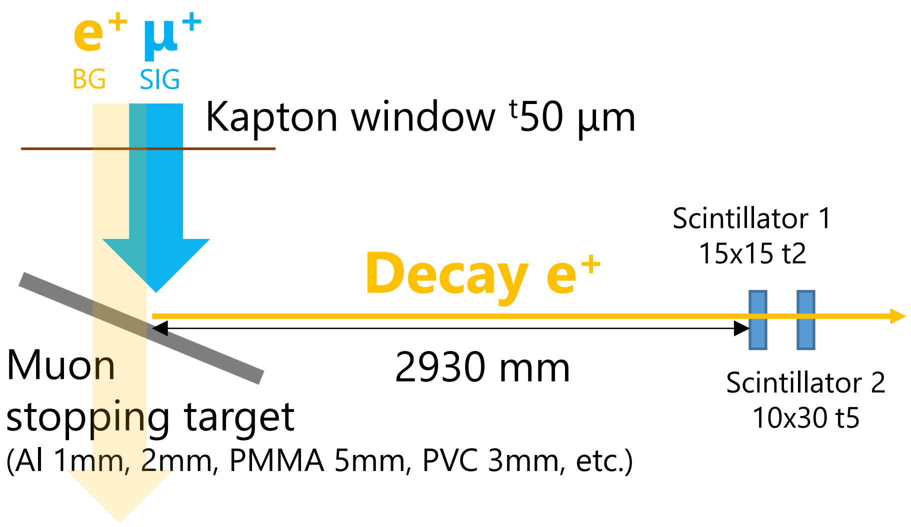
- H line is a high intensity muon beamline which can deliver both of surface μ^+ (~10^8 μ/s) and cloud μ^+/μ^-.
  - First beam at H1 in 2022 and at H2 in 2025
  - HS1 : large acceptance capture solenoid



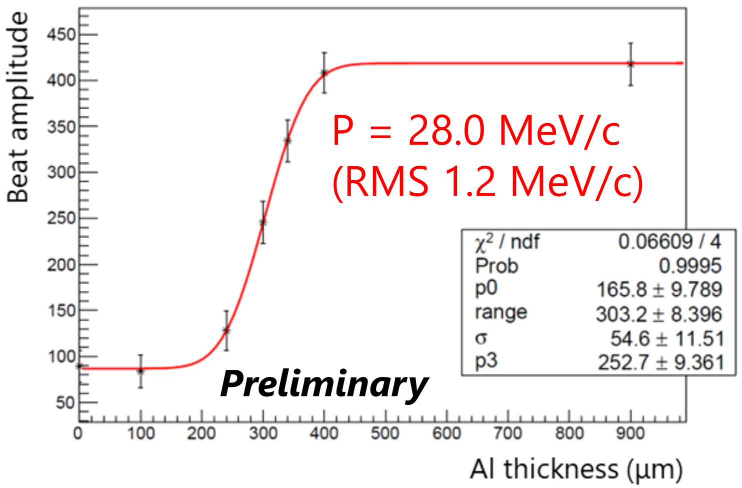
Spec.
HS1-1 : 0.37T
HS1-2 : 0.31T
HS1-3 : 0.60T
*Normal conducting
*Good radiation resistance (MIC)

  - HS2,3: Two superconducting solenoid with opposite polarities
  - HSEP : DC separator (Wien filter) to reduce e^+/e^- background
  - HQ123: Q-triplet for H1 area
  - HS4 and HQ456: Solenoid and Q-triplet for H2 area

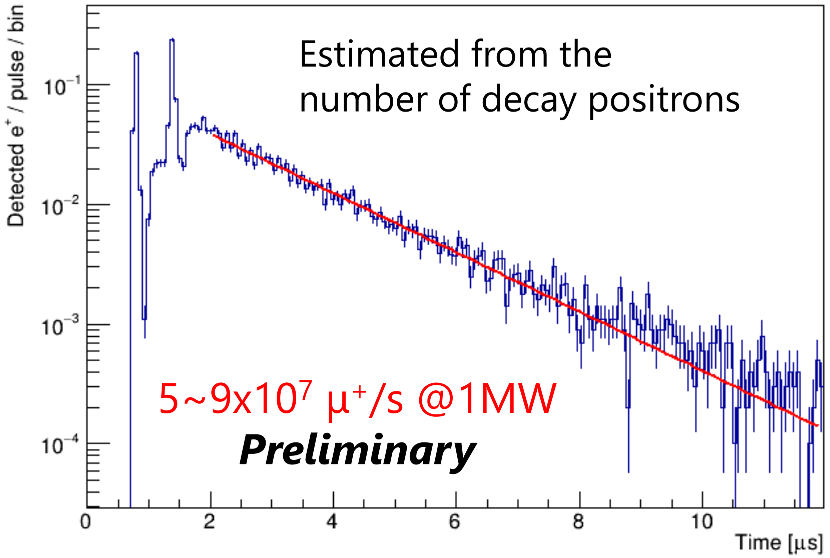
Beam commissioning at H1



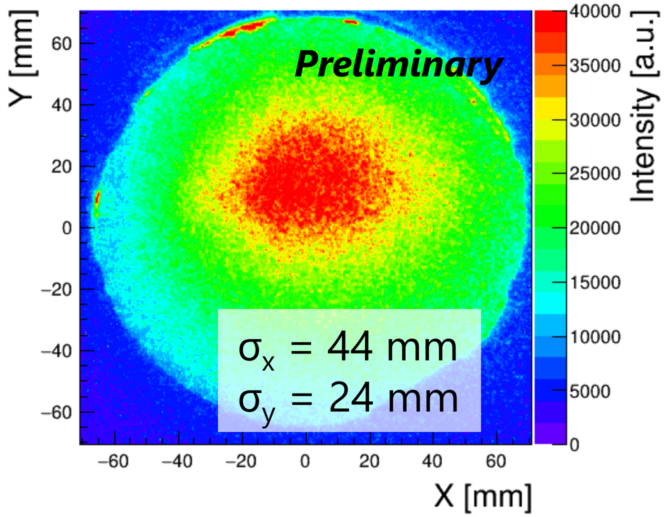
Momentum of surface muons estimated from μ^+ range in Al target



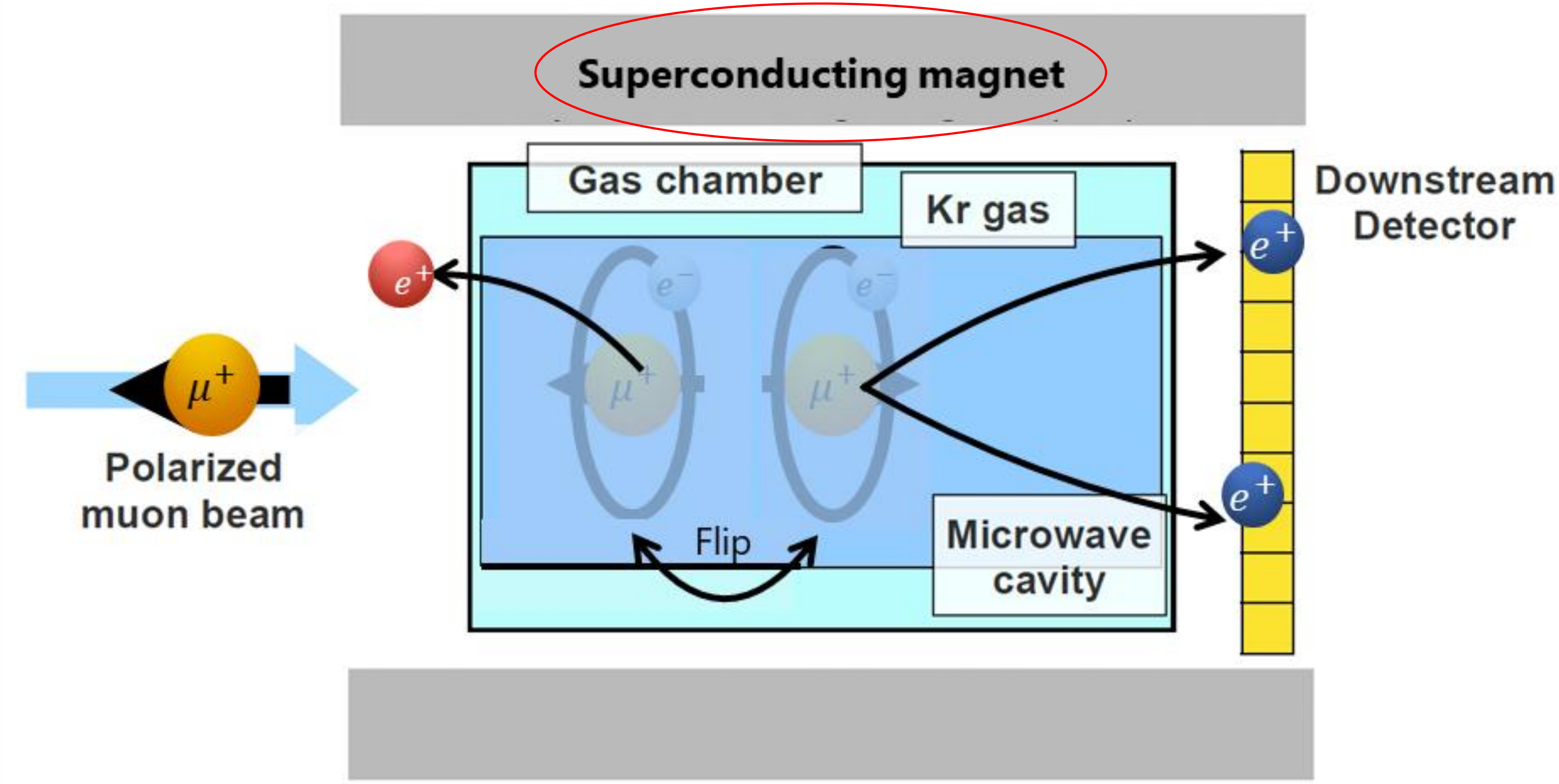
Surface muon intensity



A typical profile of surface μ^+



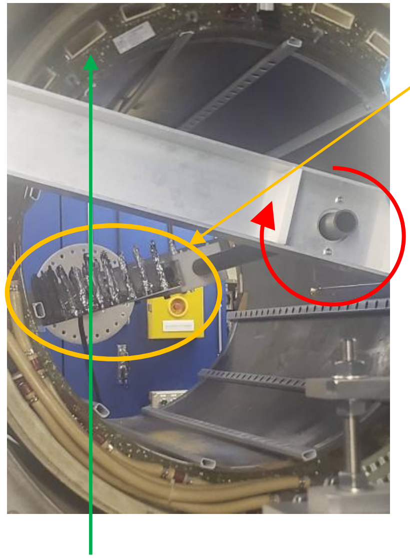
Superconducting magnet



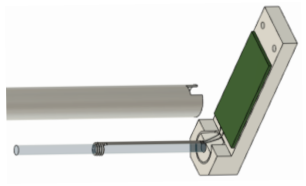
- 1.7 T with uniformity < ±0.1 ppm is necessary

Superconducting MRI magnet

- A superconducting MRI magnet was moved to the H1 area.
- Ramped up to 1.7 T and measured magnetic field using NMR probes.



24 NMR probes

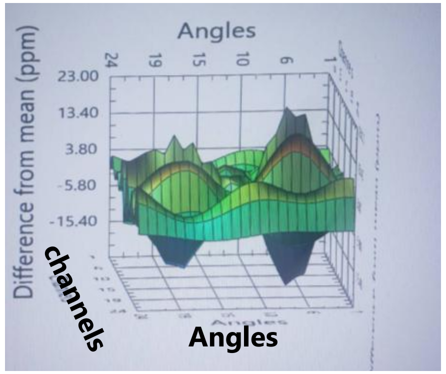


Rotating by 24 steps

→ **576 points**

Space for a shim tray

Raw field data

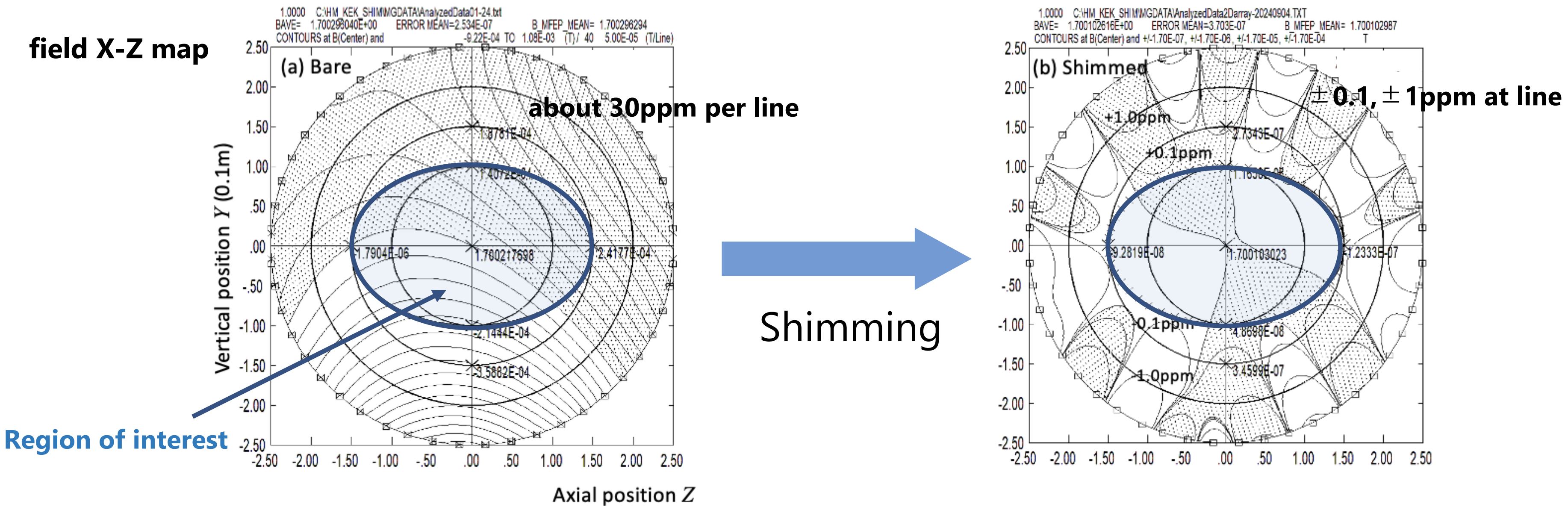


Shimming

24 shim trays x 24 shim pockets
0.5 x 30 x 40 mm Fe and Ni plate
Coarse shimming w/ ramp up and down
Fine shimming w/o ramp up and down

Uniformity after shimming

- Uniformity < ±0.1 ppm was achieved after shimming

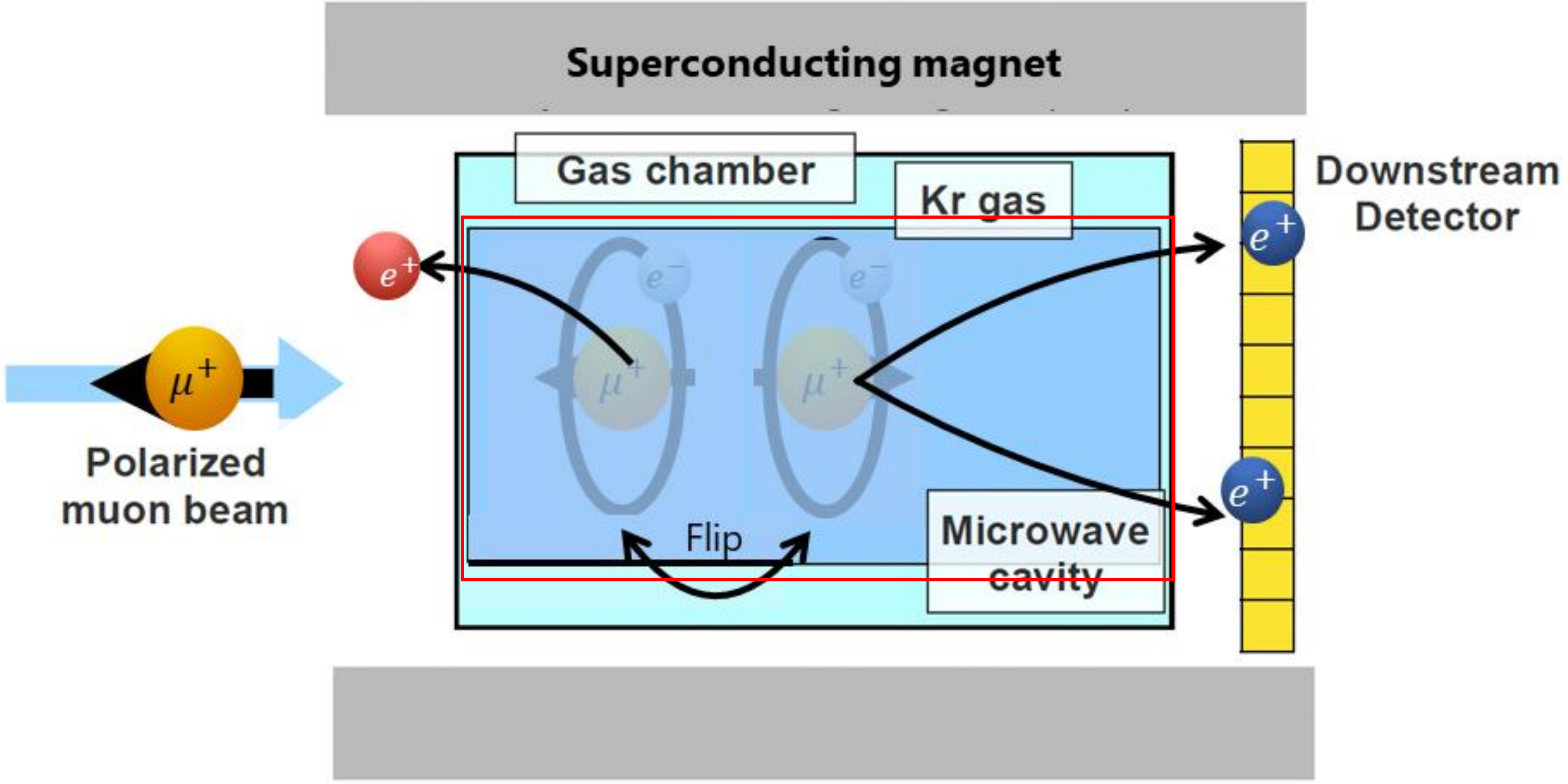


Magnetic field	Fe Volume(cc)	Homogeneity(ppm) 20-30cm-DSS
Bare field	C1, 700.05	295.59
After C1	C2, 48.77	8.9182
After C2	F1, (29)	0.5281
Before F1	F1 28.08	0.6854
After F1	F1 1.020	0.5712
After F2	F3 0.249(Ni)	0.2506
After F3		0.2033

2 coarse shimming

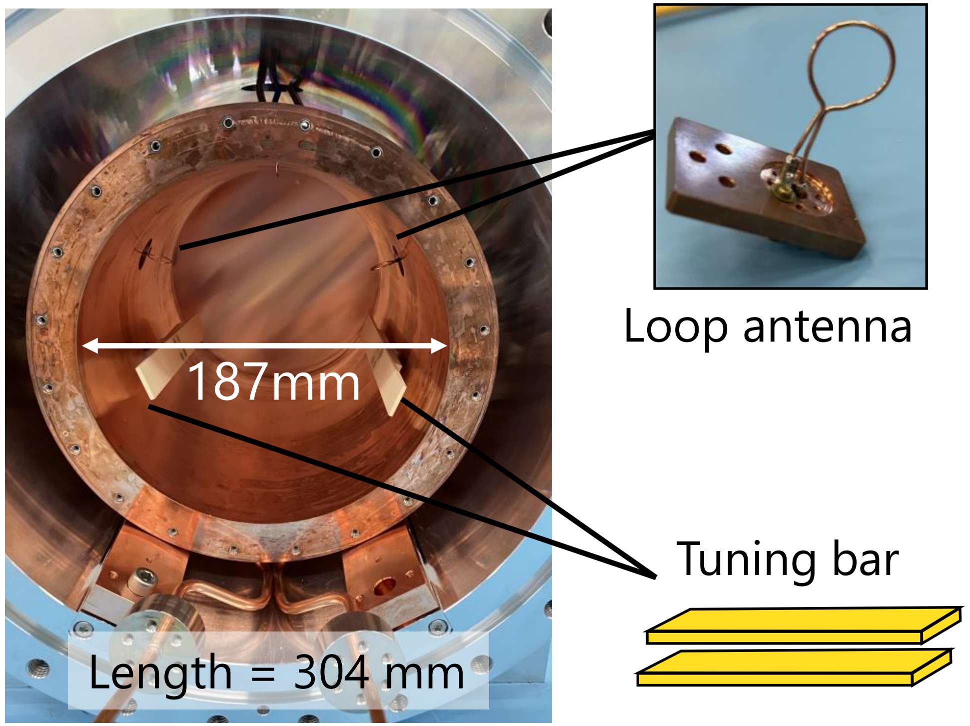
3 fine shimming

Microwave cavity

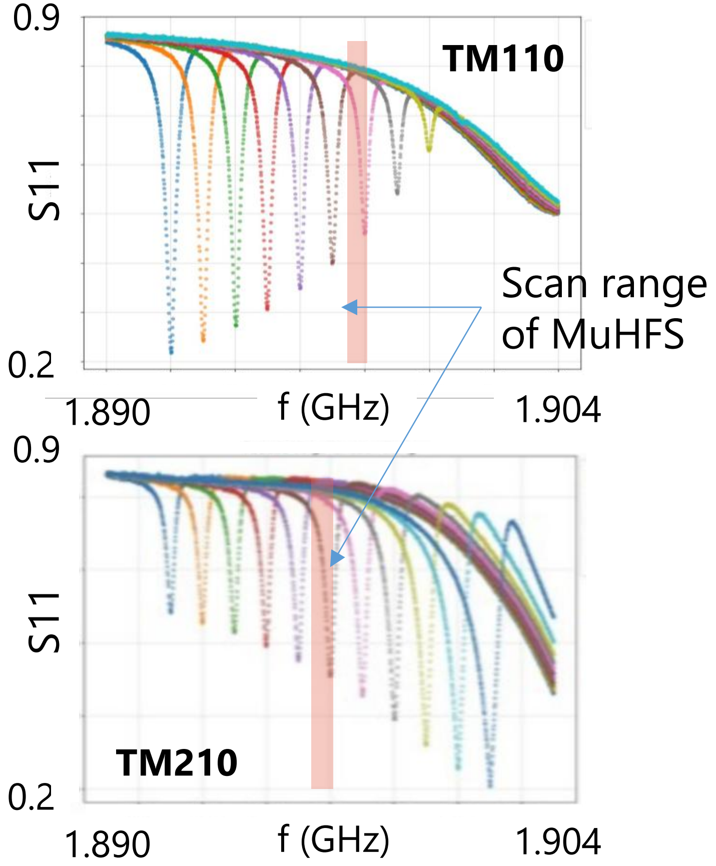


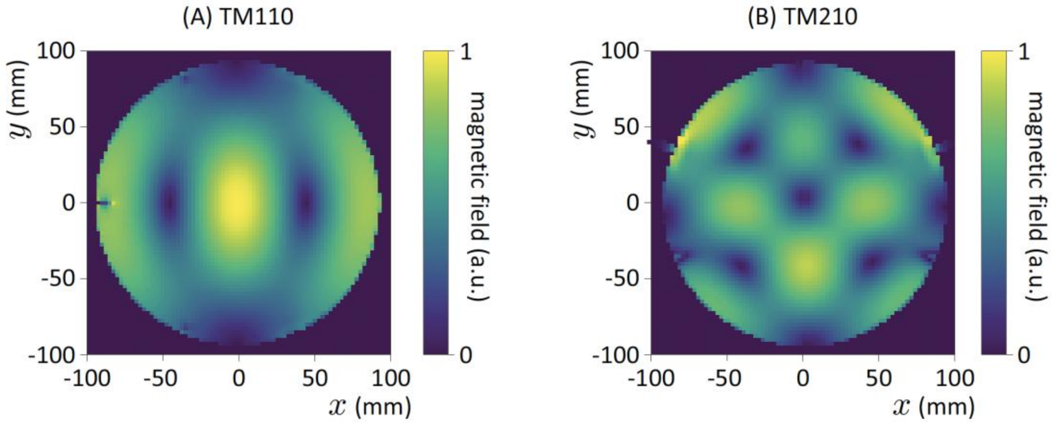
- TM110: ν_{12} = 1.90 GHz, TM210: ν_{34} = 2.57 GHz
- Q-value > 10,000 is necessary in both mode

Microwave cavity

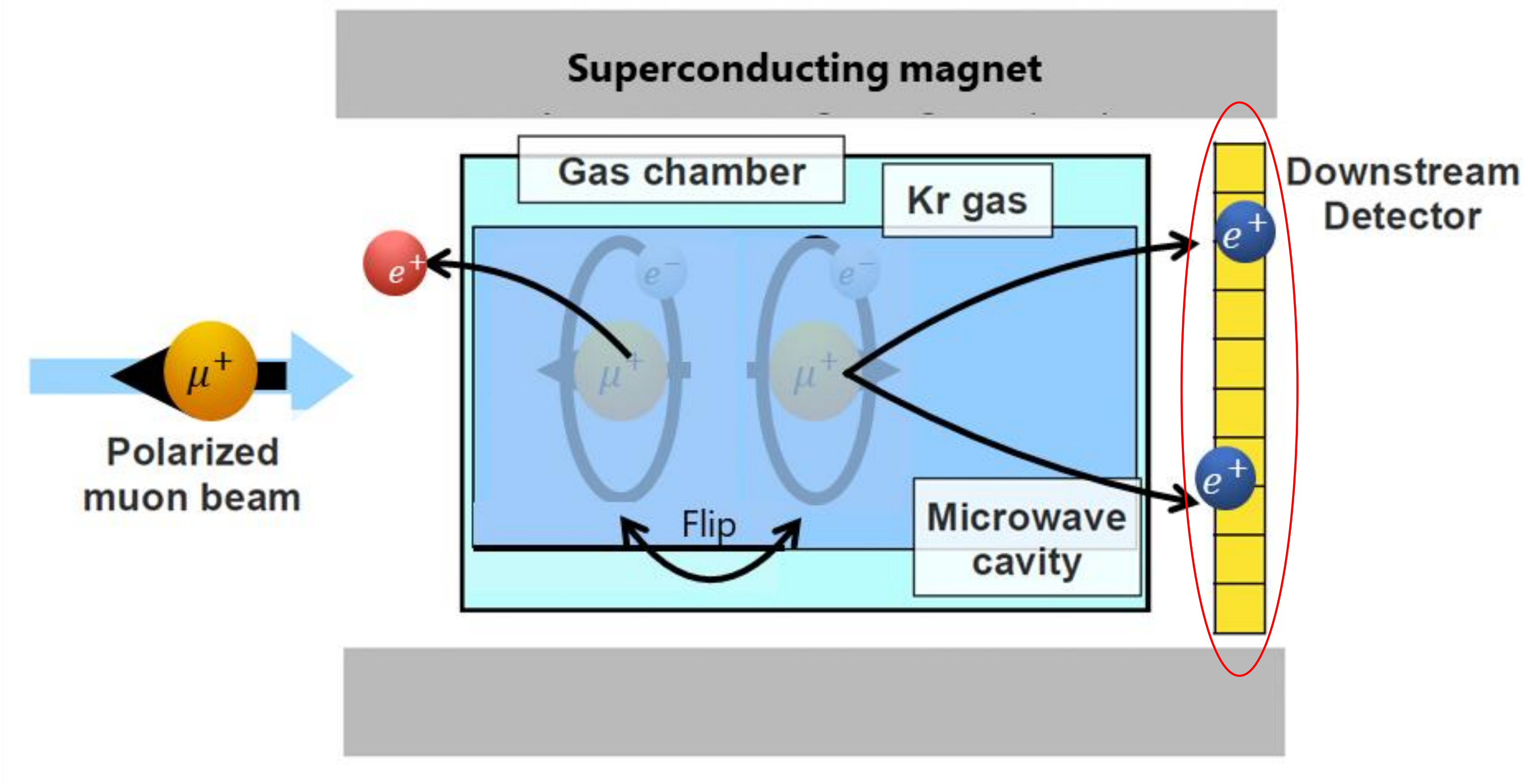


- TM110: f_0=1.90 GHz, Q~5,000
- TM210: f_0=2.57 GHz, Q~6,700
- These modes can be tunable independently.





Detector

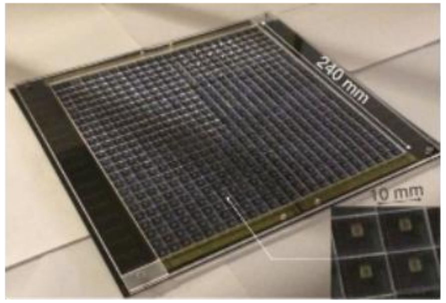


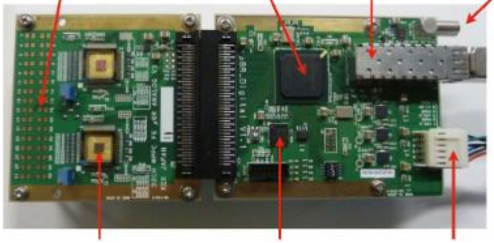
- High-granularity and DAQ speed are necessary.

Detector

Positron Counter (1)

Segmented Scintillation Detector





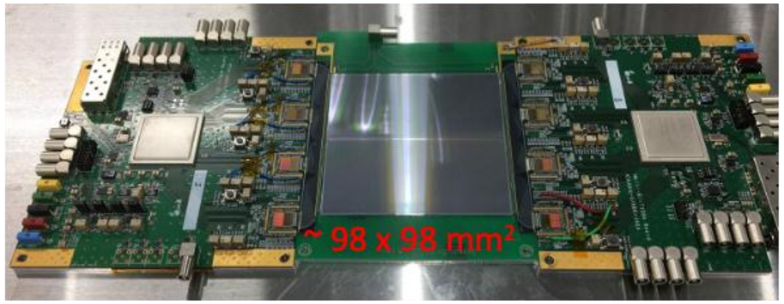
Plastic scintillator + MPPC(SiPM) + Kaliope readout circuit

- Unit cell: 10 mm × 10 mm × 3 mm^t
- Area: 240 mm × 240 mm
- 24x24 segments x 2 layers = 1152 ch

- High-rate capability
- Pileup loss at 3 MHz/ch ~ 2%

Positron Counter (2)

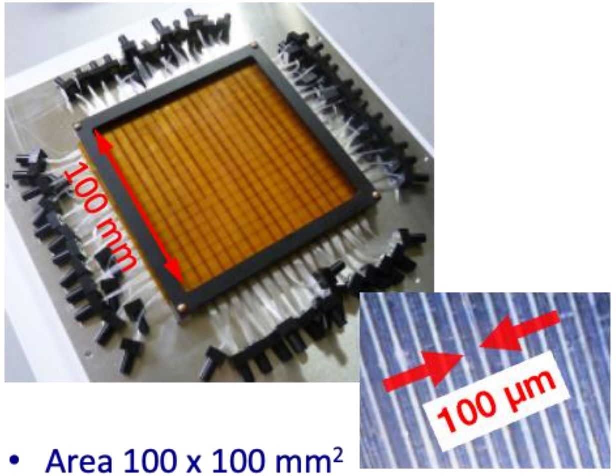
Silicon Strip Detector



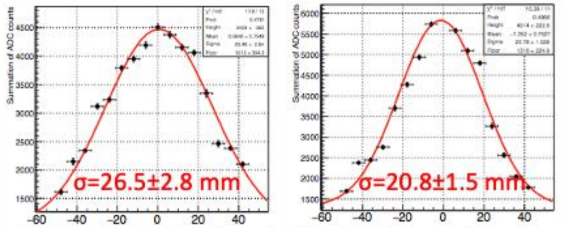
- Readout chips (SliT128A, 128 ch/chip)
- Developed for J-PARC g−2/EDM experiment
- Highly-segmented
- High-rate capability (S/N ~ 21)

- Strip pitch: 0.19 mm
- Strip length: 48.575 mm
- No. of strips: 512 x 2 blocks
- Thickness: 0.32 mm

Muon Beam Profile Monitor

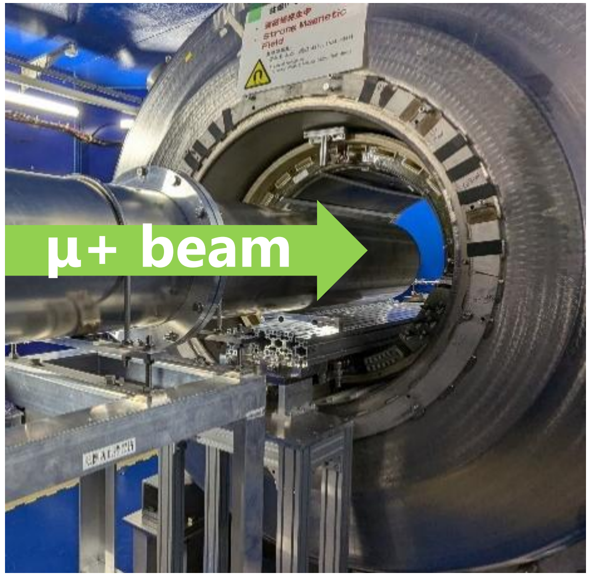


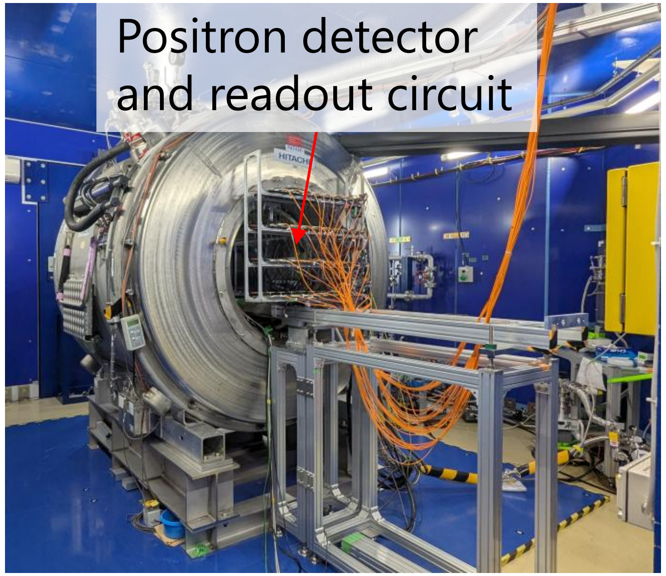
- Area 100 x 100 mm^2
- 100-μm fiber hodoscope (16 ch x 2)
- 3 x 3mm^2 active area MPPC with 15-μm pixel pitch
- EASIROC readout



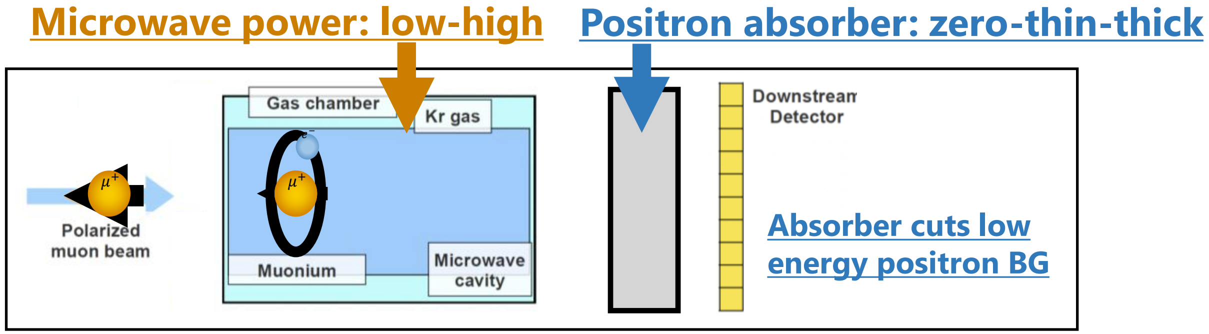
Our first measurement at high field

- Jan 30 – Feb 18 in 2025. Due to the trouble of the neutron target, the proton beam power was only 100 kW.

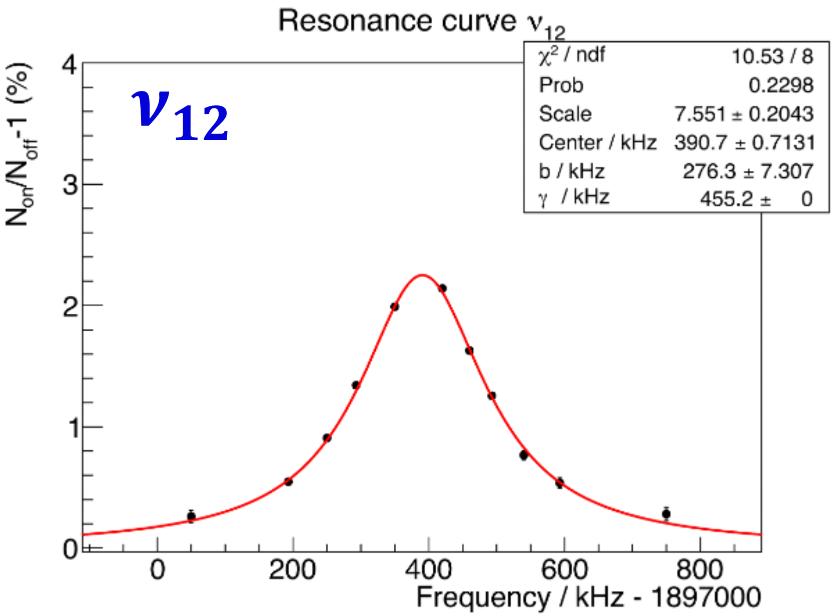


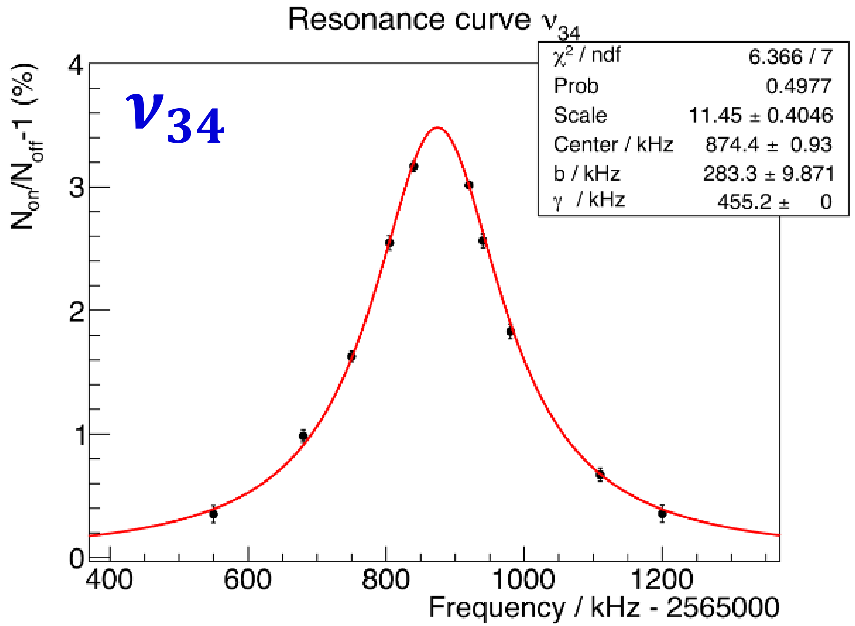


- Data were obtained under several conditions. Detailed analysis is underway.



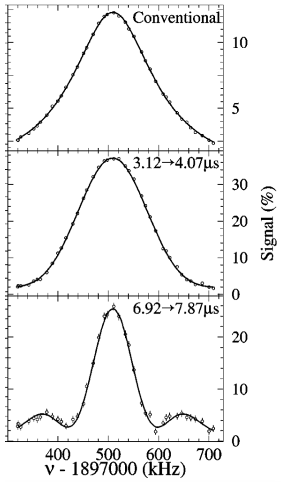
Our first result at high field





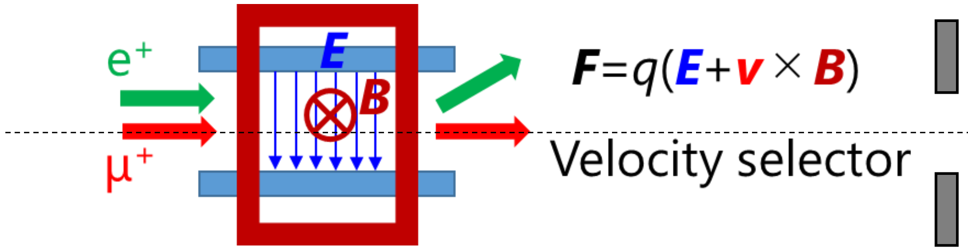
- 2 days with 100 kW proton beam
- Statistical error of Δν is 1100 Hz
- To achieve an accuracy of 8 Hz (our goal),
  - 1 MW beam power (x√10)
  - Rabi-oscillation spectroscopy (x2) → backup slides
  - 100 days (x√50)
  - S/N improvement (x3)

Liu (1999)



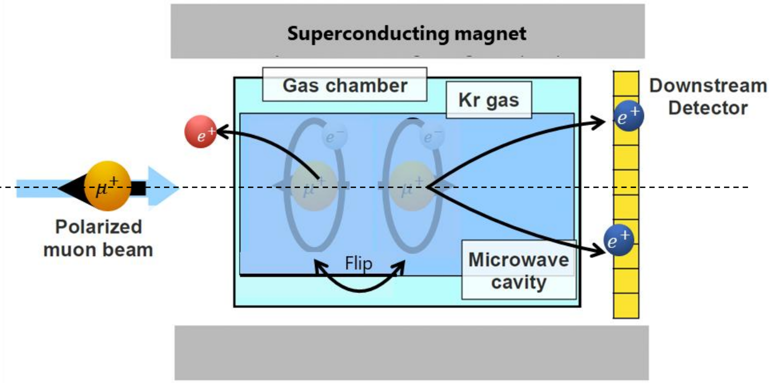
To-do list to achieve precise measurement

- S/N improvement
  - Improve Q-factor (Q_{110}~5,000, Q_{220}~6,700) and coupling of MW cavity
    - Liu(1999): Q_{110}=14,000, Q_{220}=19,000
  - Find best thickness of absorber from 100 kW data and simulation
  - Install slits to cut e+ contamination



Wien filter (DC separator)
in the beamline

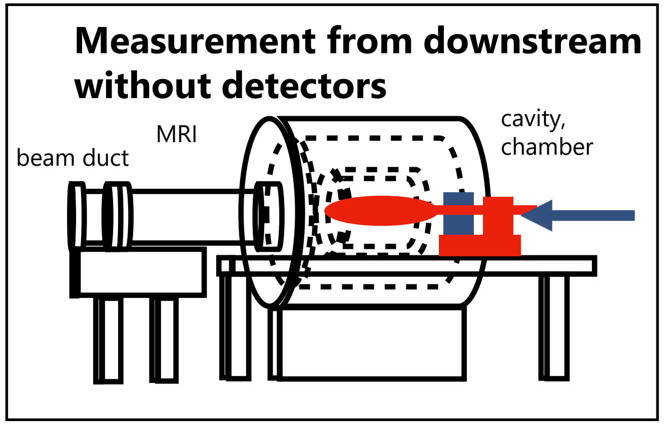
Slits

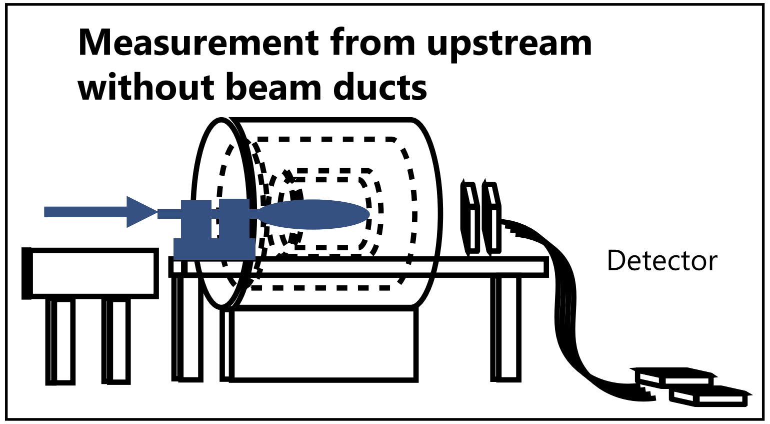


- Stabilization, monitoring, etc.
  - MW stored in the cavity
  - Gas pressure
  - Temperature
- DAQ system with 1 MW beam power

To-do list to achieve precise measurement

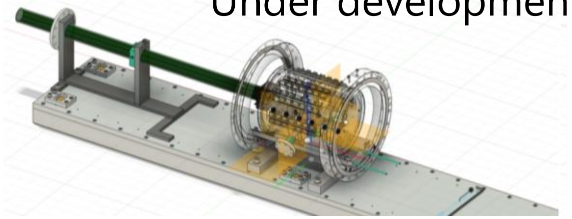
- Inner field measurement
  - The current magnetic field measurements are performed without experimental equipment (duct, chamber, cavity, detector, etc.)
  - A small multi-probe field camera is being developed to measure actual magnetic field





- Measurements from upstream and downstream are combined to evaluate the influence of all equipment.

Under development



Summary

- The measurement of MuHFS at J-PARC (MuSEUM experiment) aims to measure MuHFS with an accuracy of 8 Hz and test the SM (QED+QCD+Weak) and search for new physics contributions in combination with new Mu 1S-2S experiments.

- MuSEUM group performed a test run with 100 kW beam in Jan 2025.
  - ν_{12} and ν_{34} resonances were observed clearly.
  - S/N was worse than expected.
  - Detailed analysis and effort to improve S/N and reduce systematic uncertainty are ongoing.

Backup slides

Analysis method

Conventional

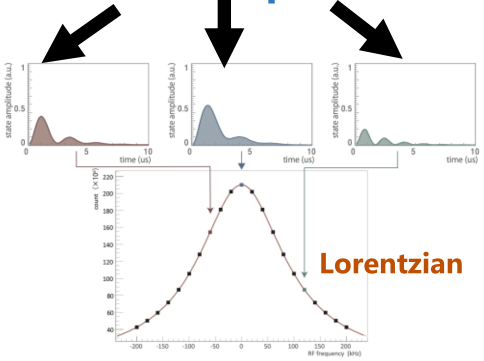
Asymmetry $=(N_{on}-N_{off})/N_{off}$

$$\propto \frac{2|b|^2}{\omega'^2 + 4|b|^2 + \gamma^2}$$

↓muon life

↑detune ↑Microwave power

Rabi oscillation time spectrums of different frequencies

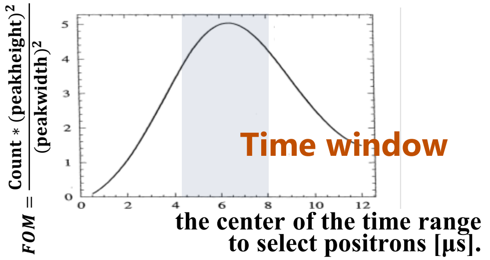


Old muonium

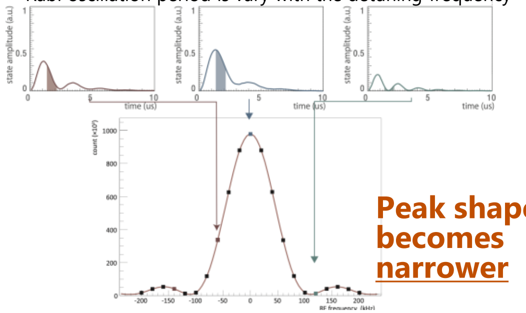
＊Used in Liu (1999)

＊Time window

FOM of old muonium method at a certain Microwave power



Rabi oscillation period is vary with the detuning frequency

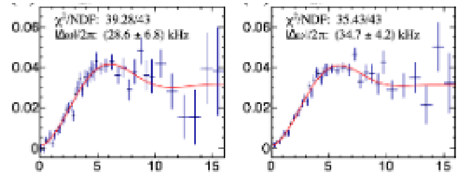


Peak shape becomes narrower

Rabi-oscillation spectroscopy

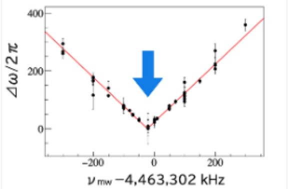
＊Used in our zero-field exp. (2017)

Fitting the Rabi oscillation itself with detuning frequency from the center as a parameter.



fitting function to zero-field exp.↓

$$S(t) = \frac{N_{ON}(t)}{N_{OFF}(t)} - 1 = A\left(\frac{G^+}{\Gamma}\cos G^- t + \frac{G^-}{\Gamma}\cos G^+ t - 1\right),$$



$$G^{\pm} = \frac{\Gamma \pm \Delta\omega}{2},$$

$$\Gamma = \sqrt{(\Delta\omega)^2 + 8|b|^2},$$

The distribution of microwave power and muon stopping ratio are needed

But can improve statistical uncertainty by 3.2 times compared to the conventional method.

Uncertainties

	$\delta\Delta\nu^{\mathrm{MuSEUM}}$ [Hz]		$\delta\Delta\nu^{\mathrm{LAMPF}}$ [Hz]
	Conventional	**Old Muonium**	**Old Muonium**
Statistical uncertainty	3.0	1.7	60 (dominant)
Magnetic field inhomogeneity	1.4	3.0	0
Muon stopping distribution	3.5	2.5	5
Microwave power	2.0	0.7	9
Magnetic probe calibration	0		0
Bloch-Siegert shift	1.2		2.8
Off-resonant mode	8.7	under discussion	
Kr pressure variation	2.8		2
Kr temperature variation	4.8		11
Pressure gauge accuracy	1.2		11
Second-order pressure shift	0		8.5
Impurities	0.016		10
Total	**11.7**	**11.3**	**64.3**

Pressure Dependence

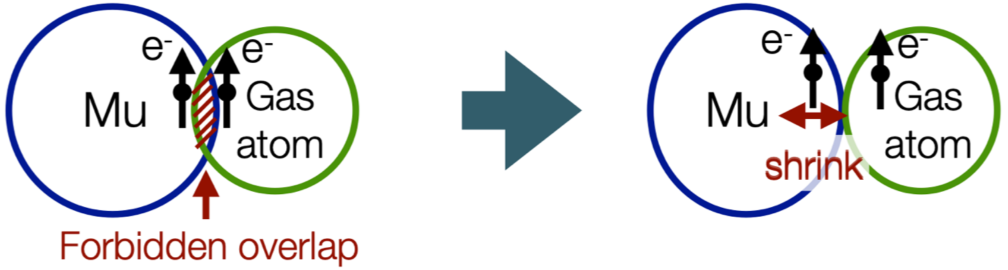
HFS changes when atoms are present in the surroundings !

➢ **Measure the pressure dependence and extrapolate to vacuum !**

Atomic collision effect

- Atomic collision effect consists of two effects.
  - **Pauli exclusion effect** -> Decrease e^- density at muon.
    -> **Increase transition freq.**

Short Range Interaction



  - **van der Waals interaction effect** -> Increase e^- density at muon.
    -> **Decrease transition freq.**

Long Range Interaction

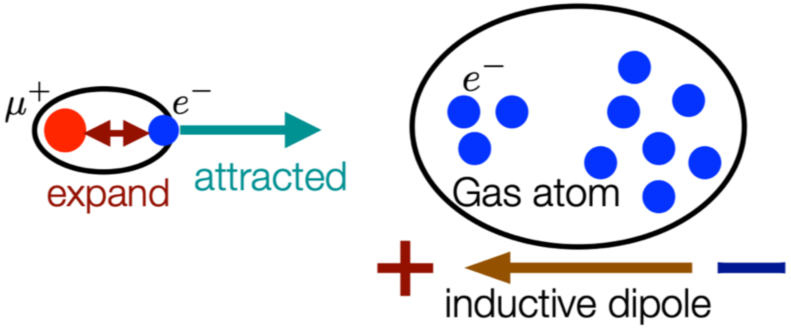


Figure borrowed from
S. Seo slide for ICHEP2020

Muon Precision Measurement with the Penning Trap at J-PARC

2025/05/30

Shoichiro Nishimura[1,2], Yukinori Nagatani[1,2], Takayuki Yamazaki[1,2], Patrick Strasser[1,2], Koichiro Shimomura[1,2], Ken-ichi Sasaki[1,2], Masatoshi Hiraishi[1,2], Amba Dat Pant[1,2], Hiroto Kokubo[3], Hiromi Iinuma[3], Taihei Adachi[4], Makiko Nio[4], Hirotaka Okabe[1,2], Takashi Higuchi[5]

[1]KEK IMSS, [2]J-PARC Center, [3]Ibaraki Univ., [4]RIKEN, [5]Kyoto Univ.

Muon Precision Measurements

MuSEUM

Jungmann's triangle

Muonium HFS

Muon magnetic moment μ_μ

Fine-structure constant α

QED

μ_μ, α, g_μ

QED

m_μ

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

Muon *g*−2

New Physics beyond SM

QED

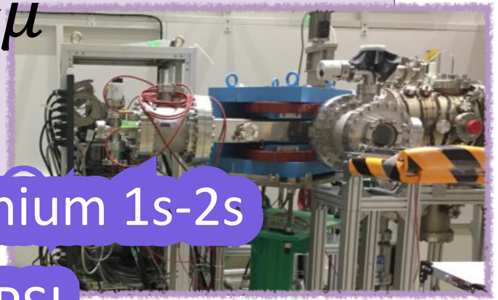
m_μ

Muonium 1s-2s

Muon mass m_μ

J-PARC Muon *g*−2/EDM

E989 @ FNAL

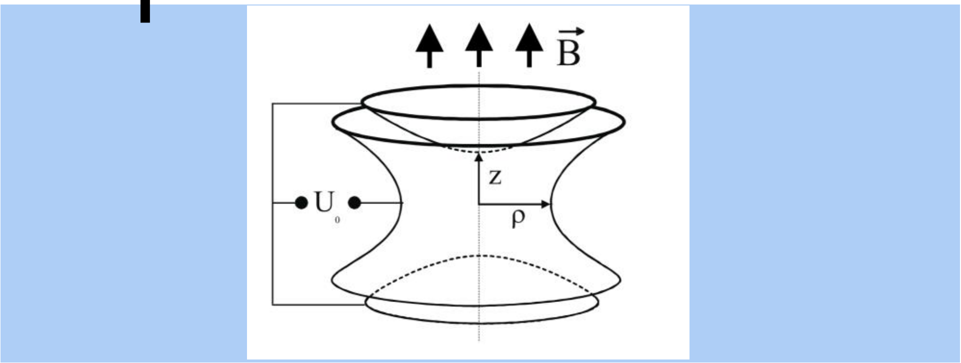


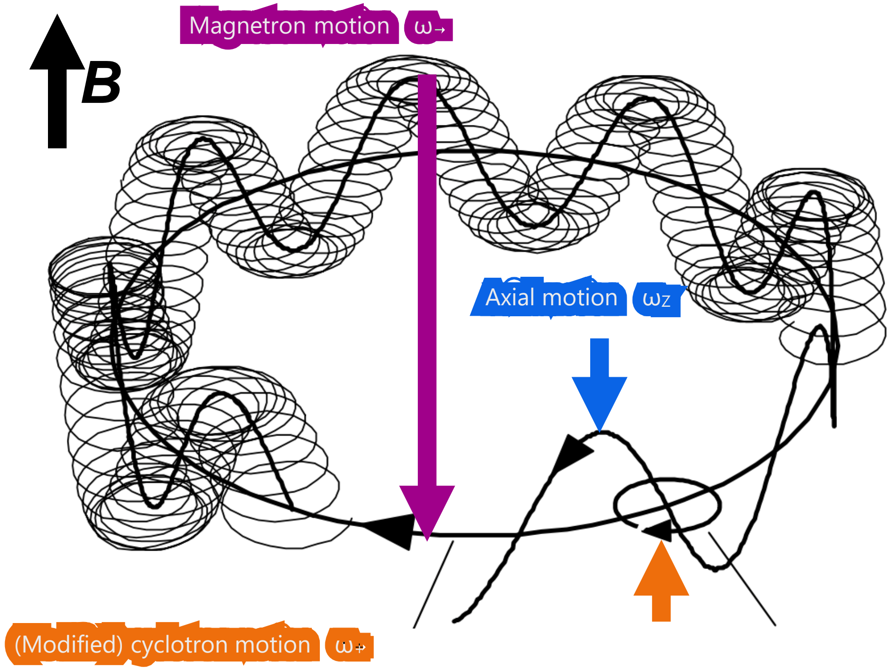
J-PARC Muonium 1s-2s

Mu Mass @ PSI

Electric & Magnetic Trap

- Penning Trap
  - Trap particle with E & B Field
  - Muon trap | 1st time
- Motion in the Trap
  - Cyclotron motion
  - Axial motion
  - Magnetron motion
    - E × B drift





J. Dilling, Ph.D. thesis, Rupertus Carola University of Heidelberg, Germany

Muon Penning Trap Experiment

- Goal |
- Mass q/m (～1ppb)
- Magnetic moment (～1ppb)
- Lifetime (～1ppm)

Mass	105.658 375 5(23) MeV	22 ppb
Magnetic moment	$-4.490\,448\,30(10)\times10^{-26}$ J/T	22 ppb
Lifetime	$2.196\,9811(22)\times10^{-6}$ s	1.0 ppm

CODATA 2022

- First step｜Verification of Muon trapping in vacuum

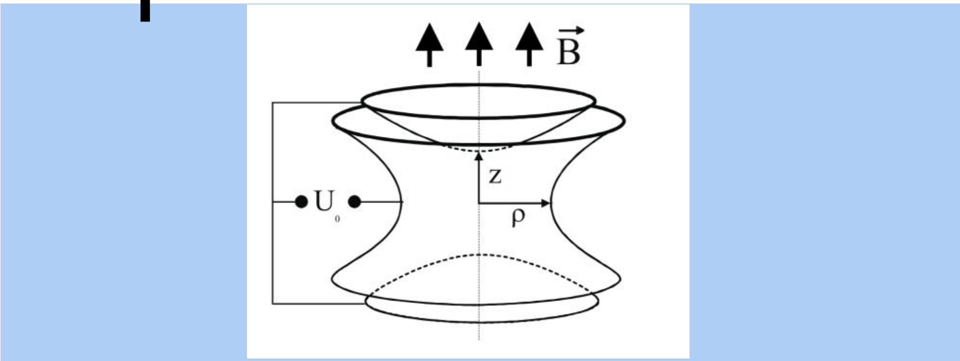
- The key of Muon Penning Trap experiment
- Measuring oscillation frequency of short-lived particle
- Generating high-intensity slow muon beam

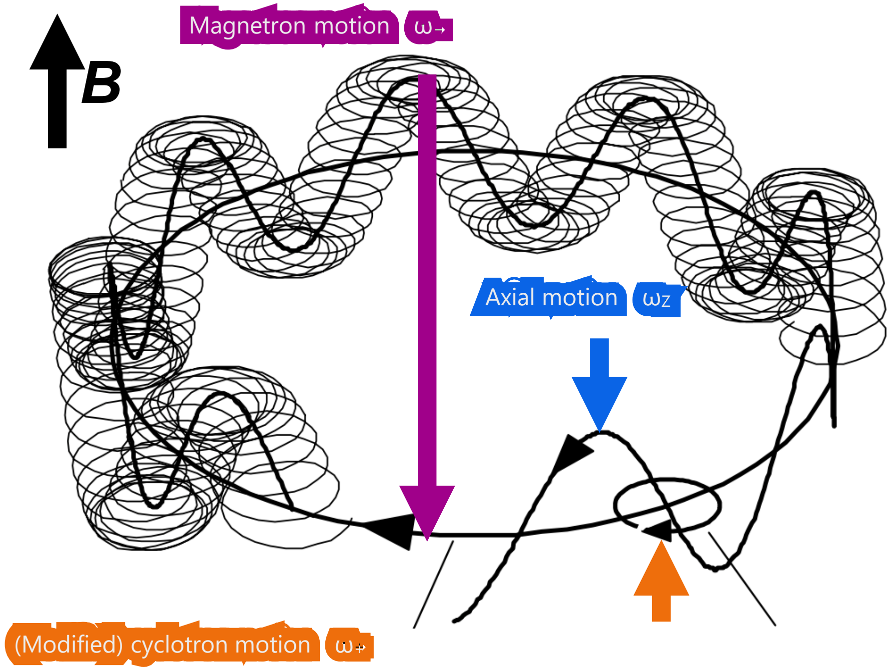
Realized by high-intensity muon beam at J-PARC MUSE

Proposal 1 | Ultra-slow muon

Electric & Magnetic Trap

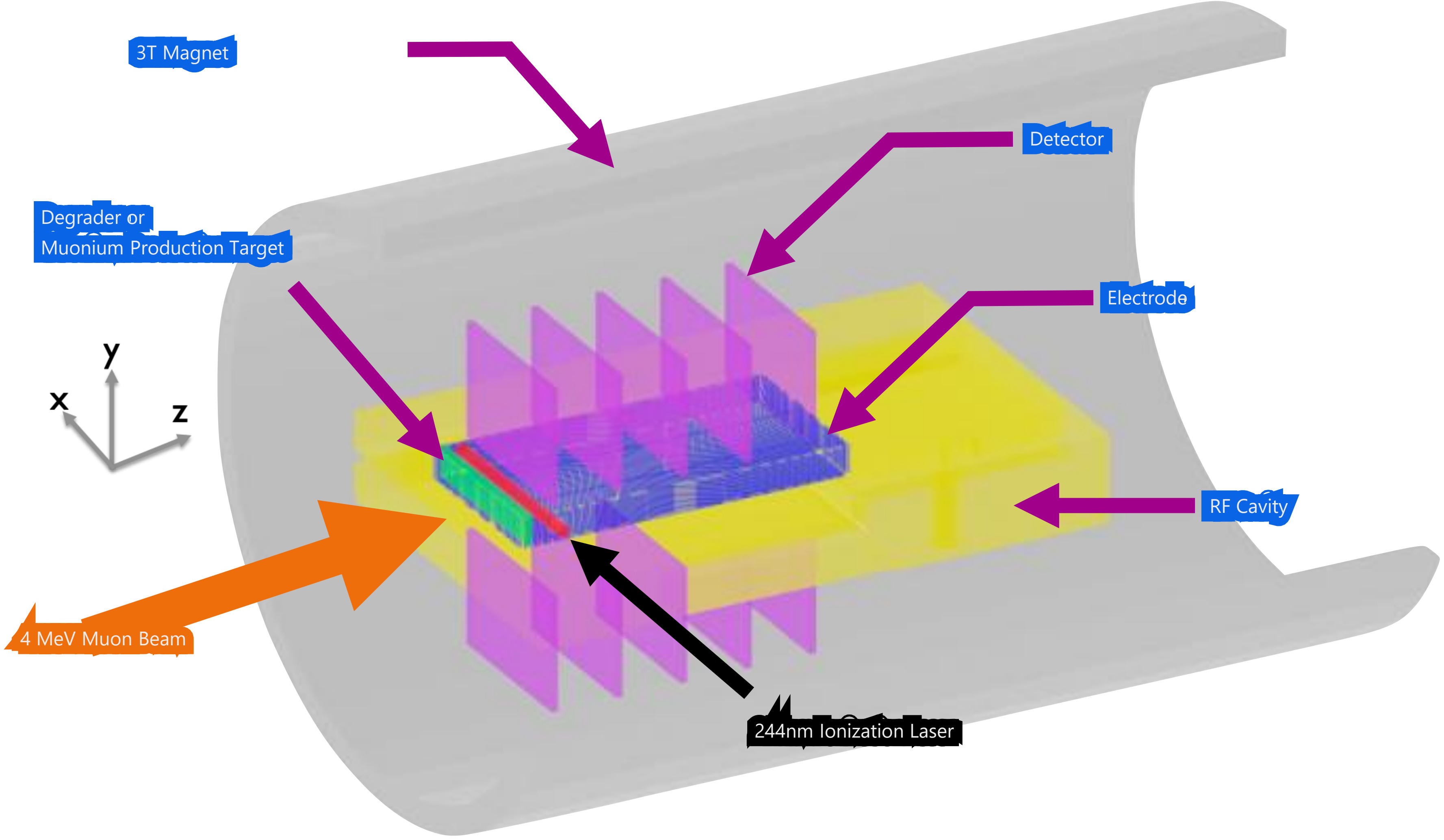
- Penning Trap
  - Trap particle with E & B Field
  - Muon trap | 1st time
- Motion in the Trap
  - Cyclotron motion
  - Axial motion
  - Magnetron motion
    - E × B drift



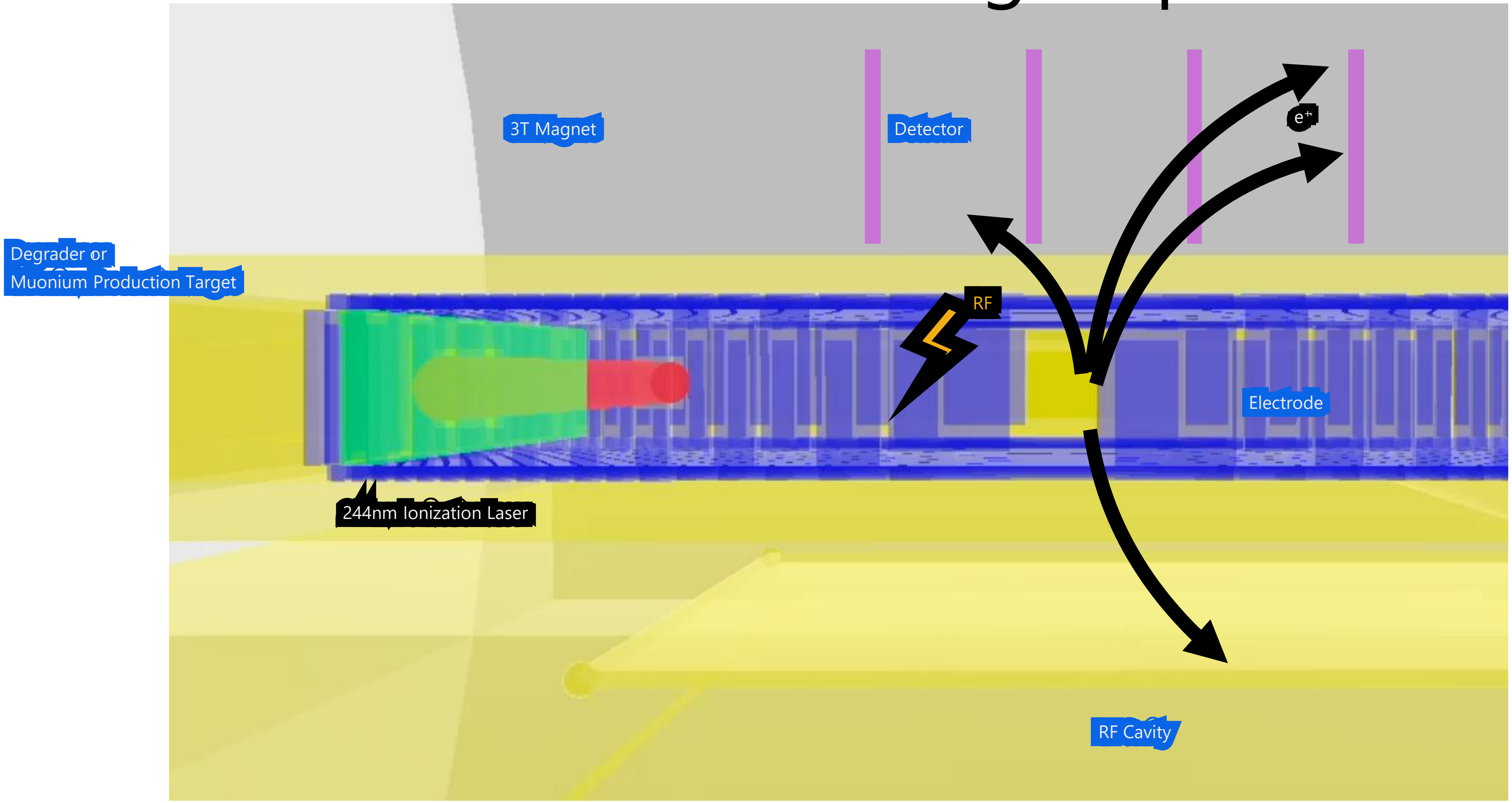


J. Dilling, Ph.D. thesis, Rupertus Carola University of Heidelberg, Germany

Schematic of Muon Penning Trap

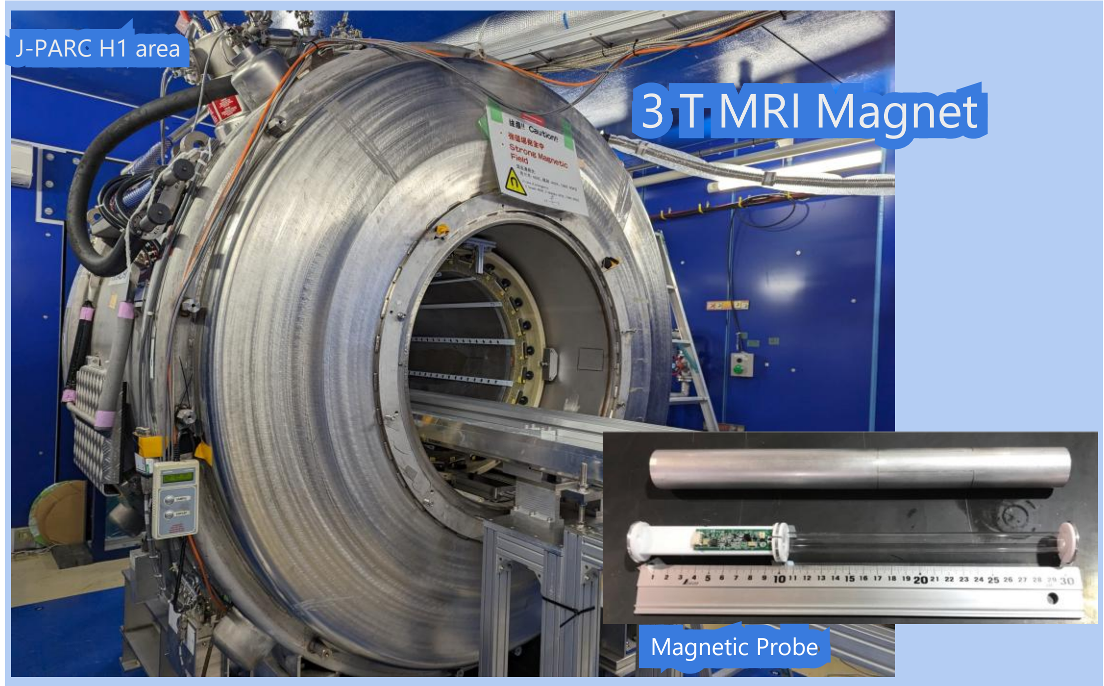


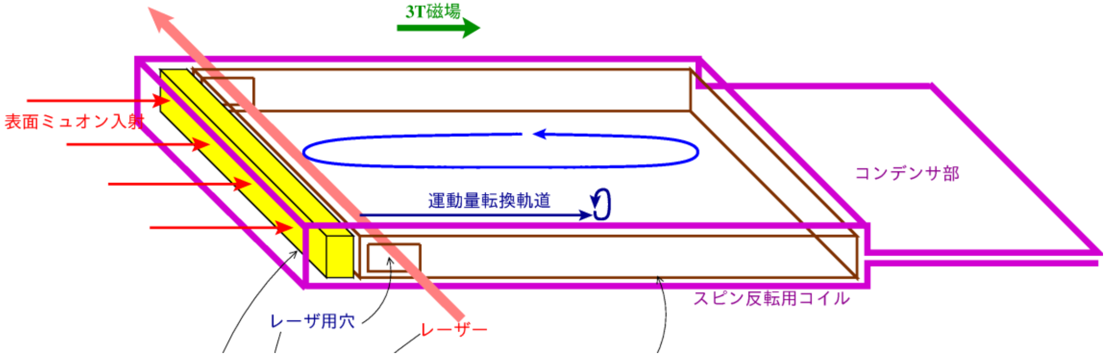
Schematic of Muon Penning Trap



Magnetic & Electric Fields

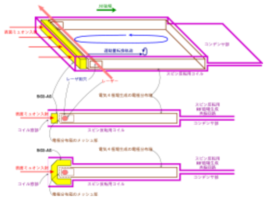
- Magnetic Field
  - 3 Tesla MRI Magnet developed by MuSEUM Group
  - Magnetic probe | 15 ppb
  - Field uniformity | 0.2 ppm p-p
- Quadrupole electric field
  - Rectangular electrode design in progress
  - Simple harmonic motion

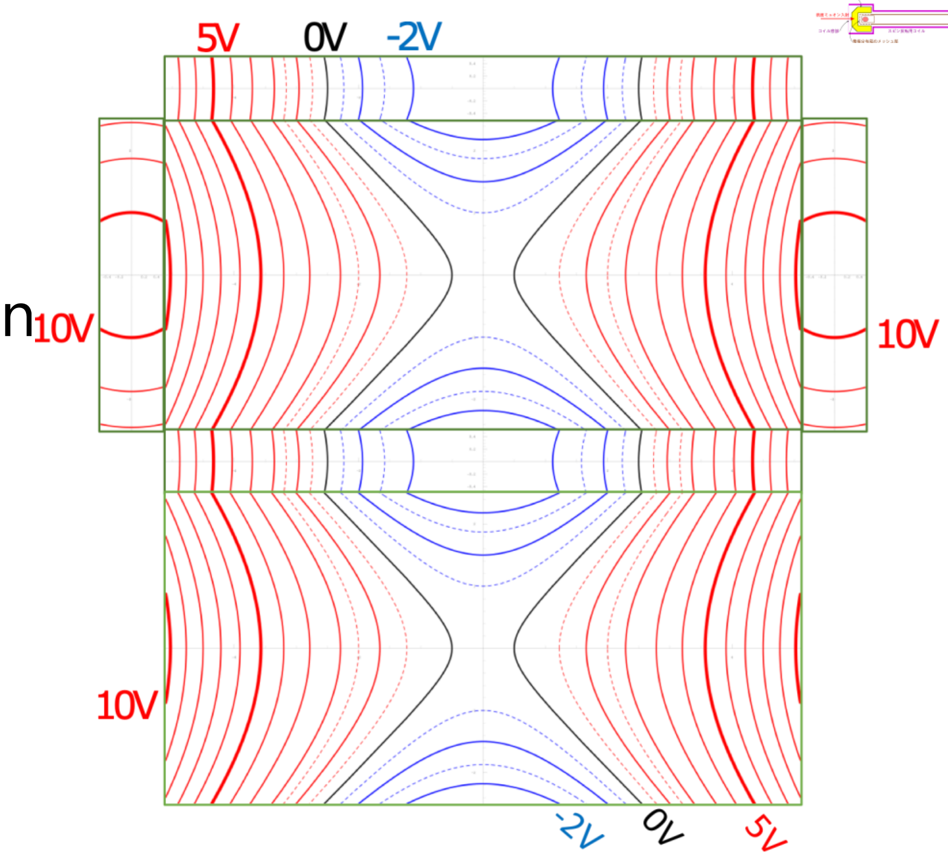




Rectangular Trap Electrode

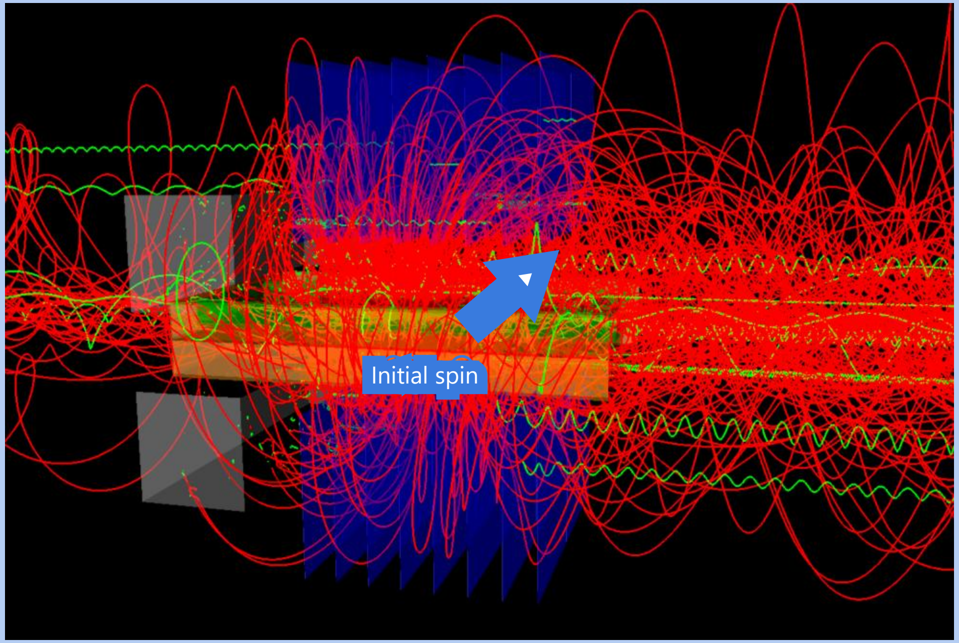
- Features
  - RF field can be stored from outside
  - Muonium polarization 100%
  - Ultra-slow muon directory trapped
  - Small spin flip coil
  - Low inductance & Low power operation





Detection of Decay Electron

- Simulation Condition
  - Magnetic Field | 2.9 T
  - Initial spin | Perpendicular to B field
  - Detector | 35 mm from trap region
- Larmor precession
  - 135.53 MHz/T × 2.9 T ＝ 393.037 MHz
  - Period | 2.55 ns
- Fitting result
  - $\Delta\gamma_\mu$ = 6 ppb with 10^{12} μ^+
  - Goal with 100 days measurement



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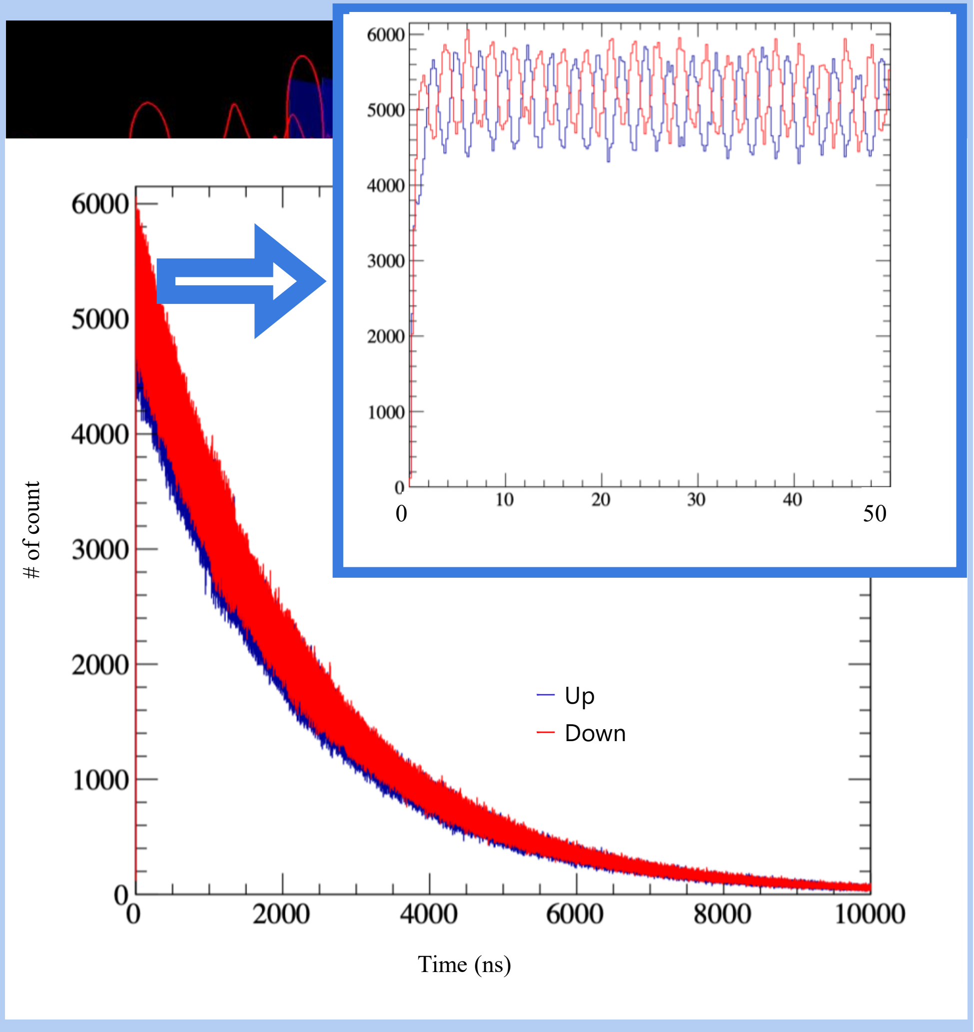

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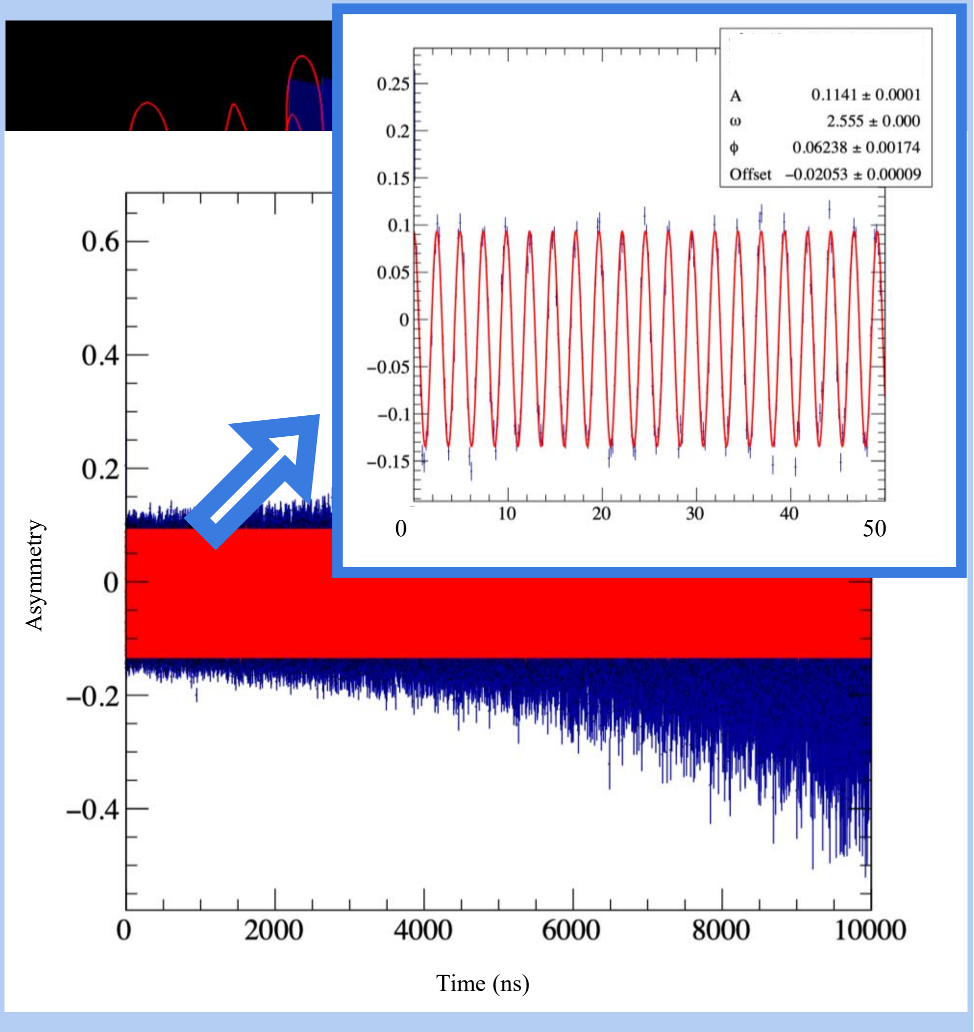
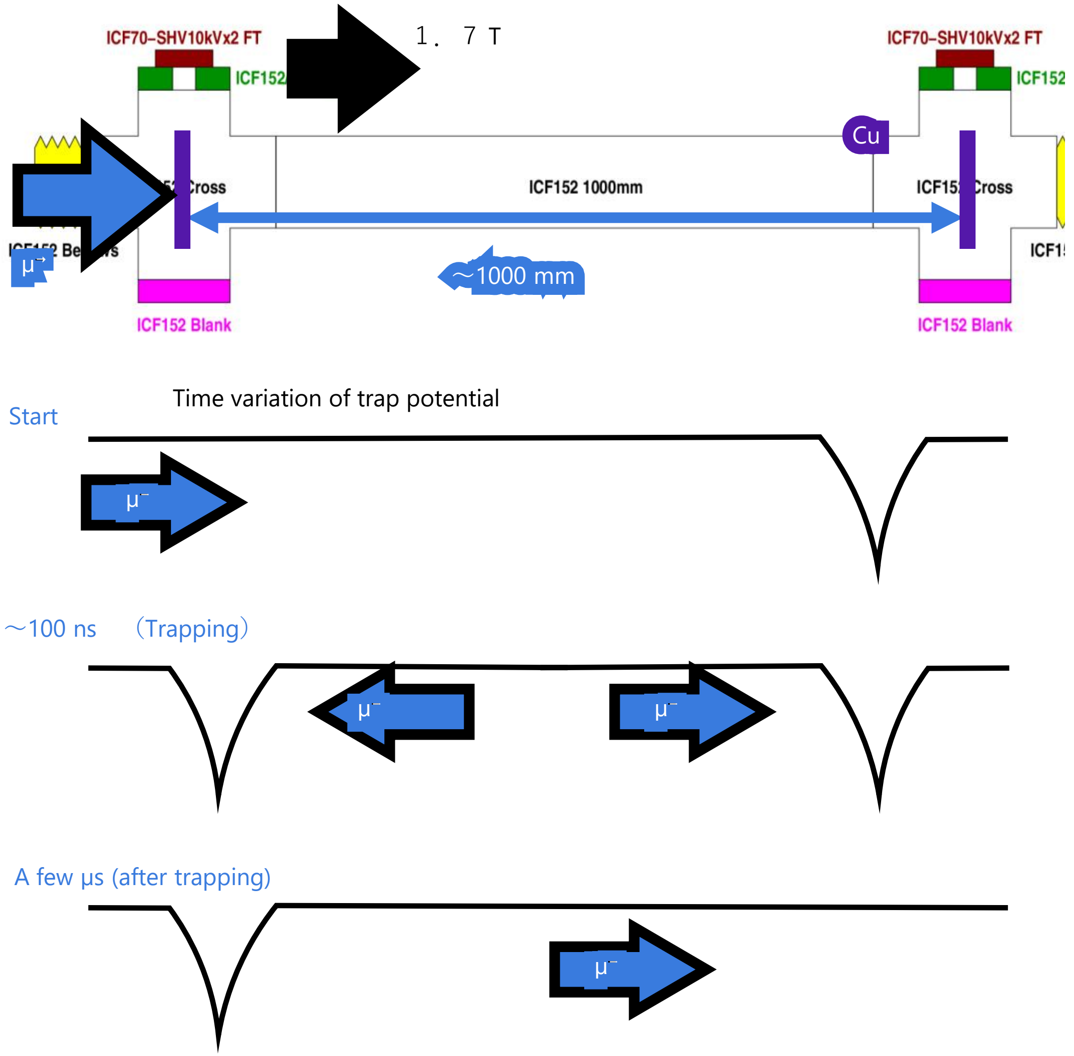
  - $\Delta\gamma_\mu$ = 6 ppb with 10^{12} μ^+
  - Goal with 100 days measurement



Proposal 2 | Using Degrader (Negative Muon Trap)

Test of Negative Muon Trap

- Trap μ⁻ in vacuum
  - Momentum | p～30 MeV/c
  - Degraded by Cu electrode
  - Trapping voltage | ～10 kV
  - Only detecting μ⁻ decay at downstream electrode
  - μ⁻ lifetime in Cu｜160 ns



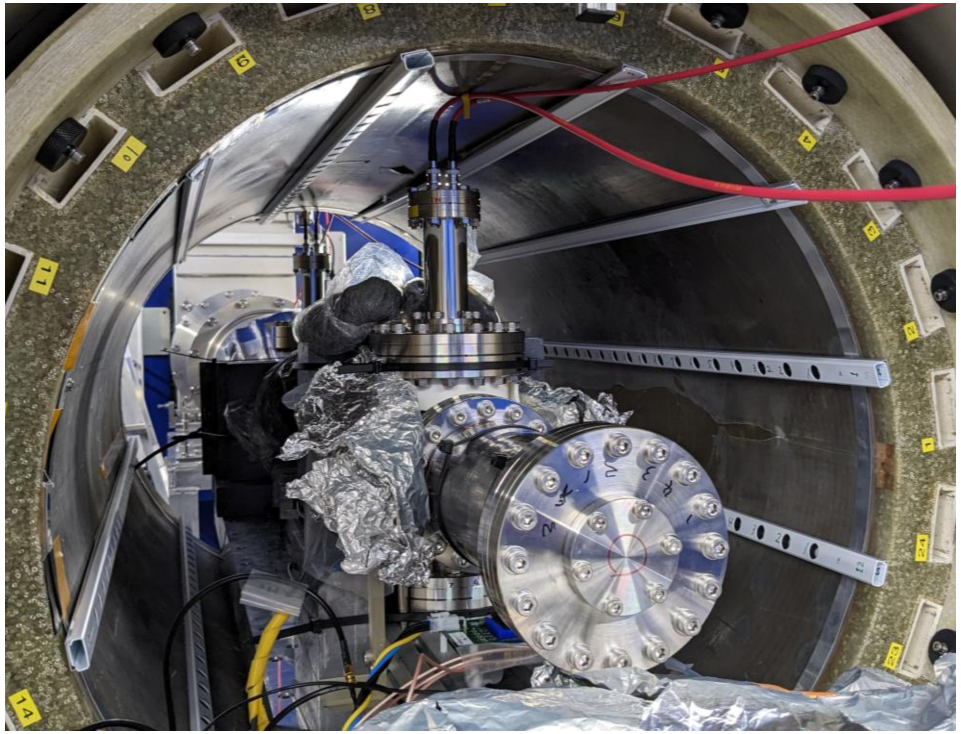
Untrapped muon | Disappear in short life

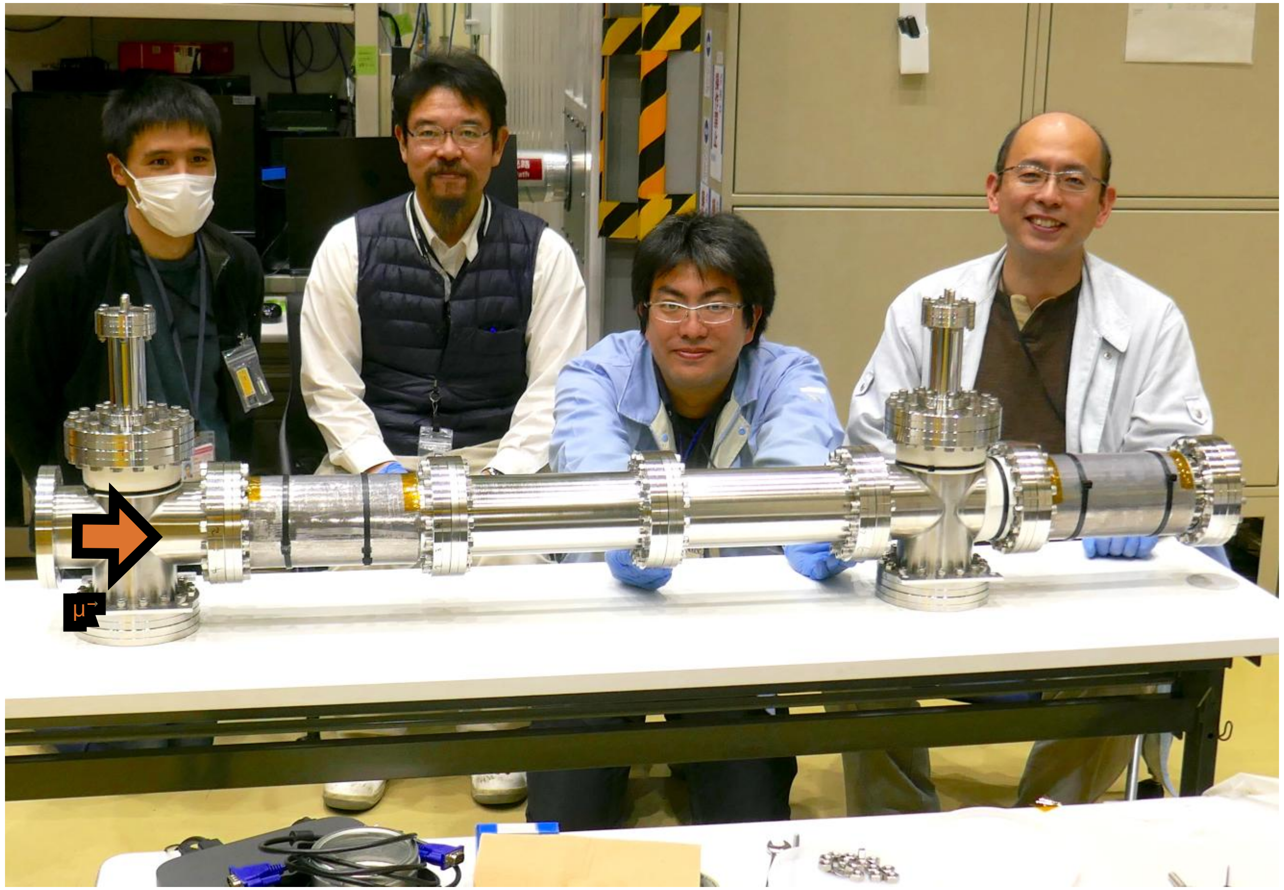
Trapped muon | Delayed signal

Set up of μ^- trap test

@H1 area

- 2023/12/23-25
- 2024/02/14-





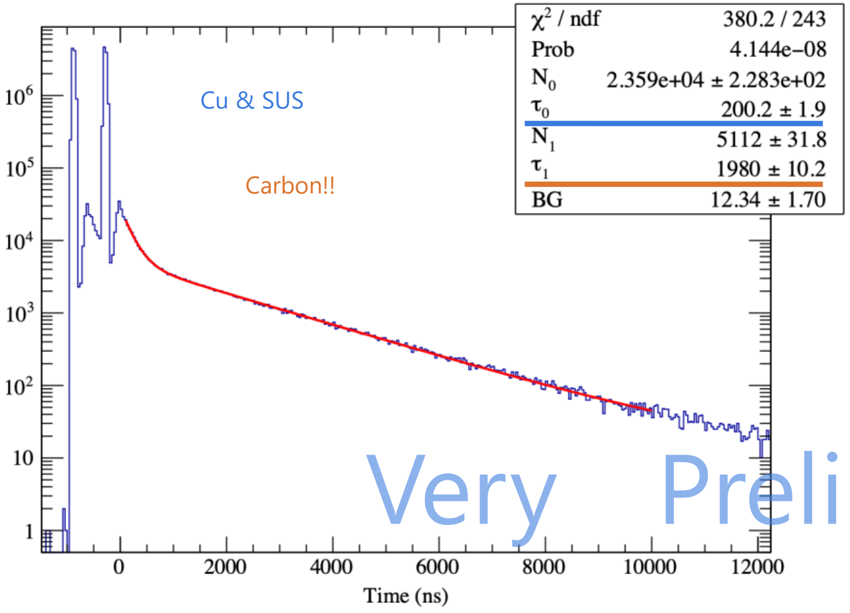
Results (First Trial)

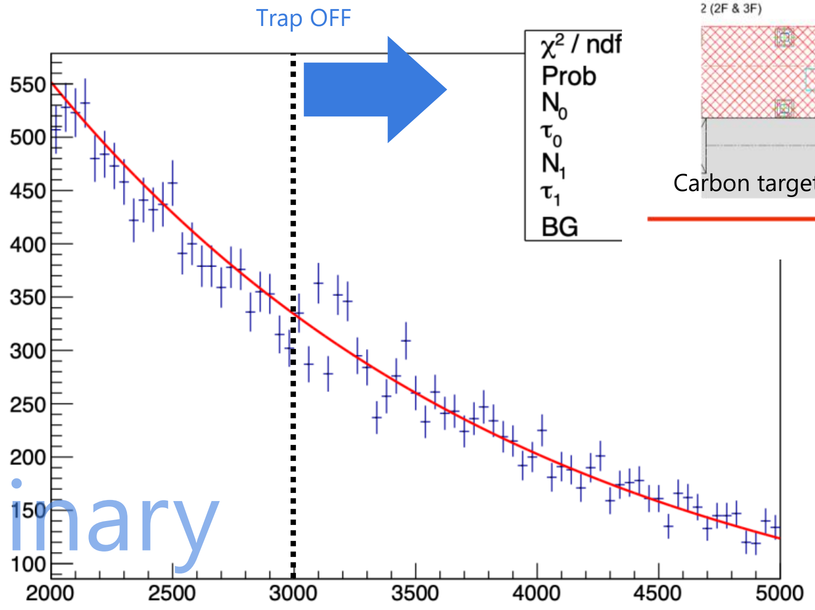
Condition

Momentum | 30 MeV/c

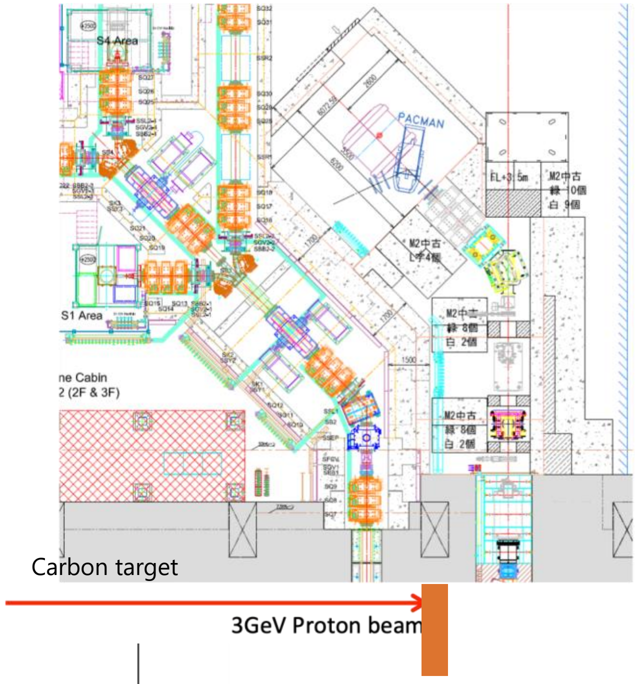
Trap electrode voltage | 6 kV

DC separator | 175 kV





Very Preliminary



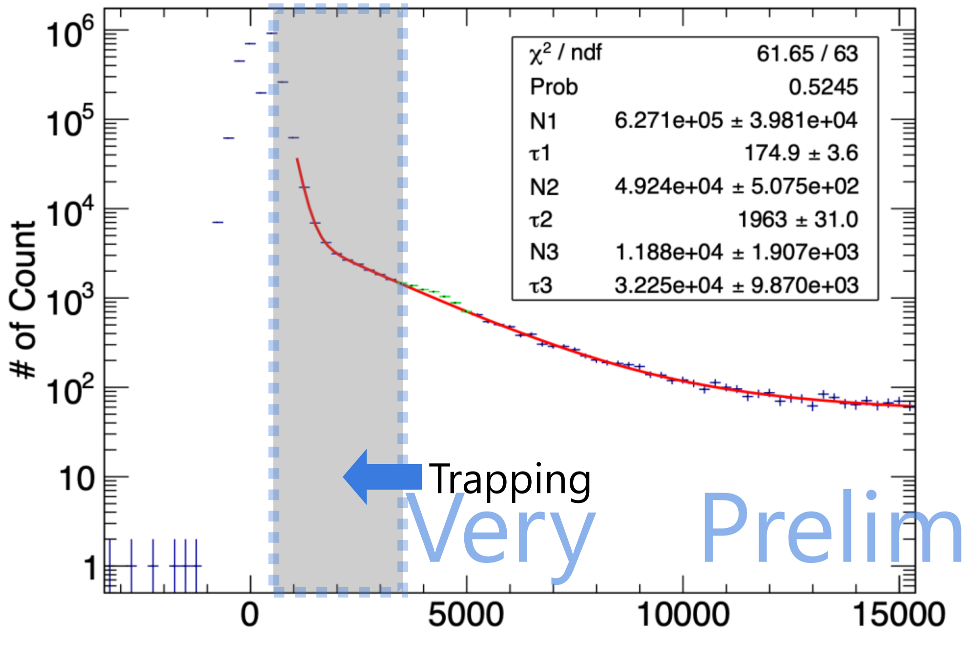
Results (After Improvement)

Condition

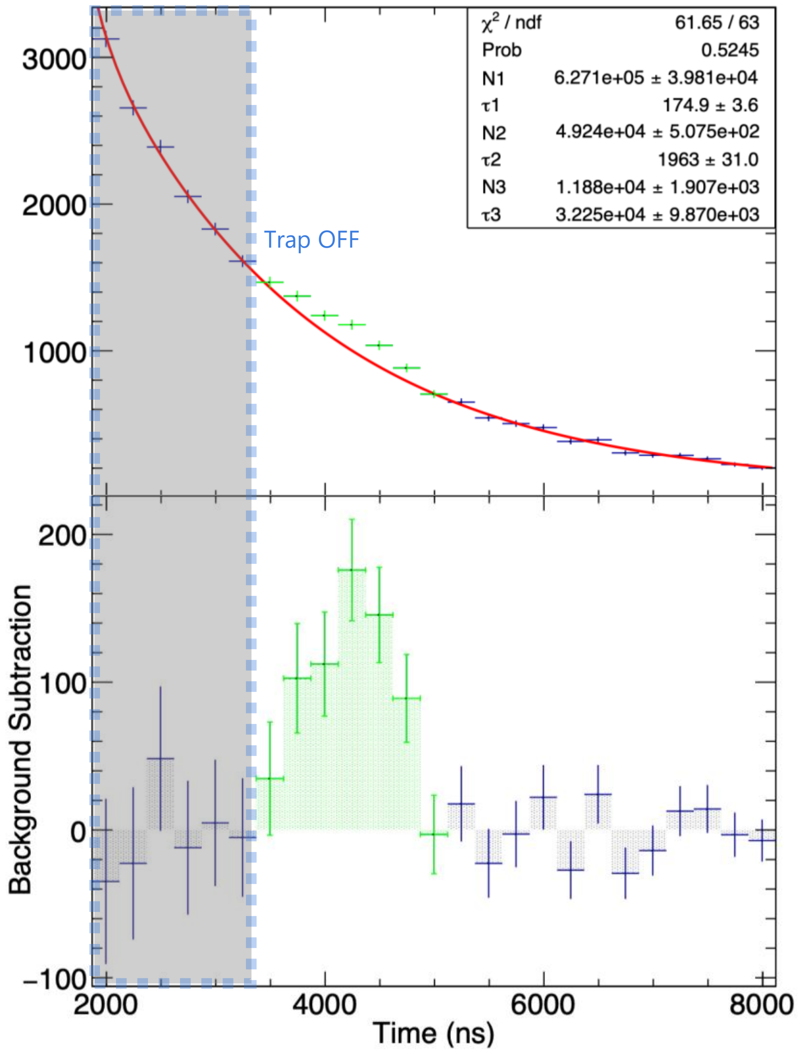
Momentum | 17 MeV/c

Trap electrode voltage | 6 kV

DC separator | 500 kV

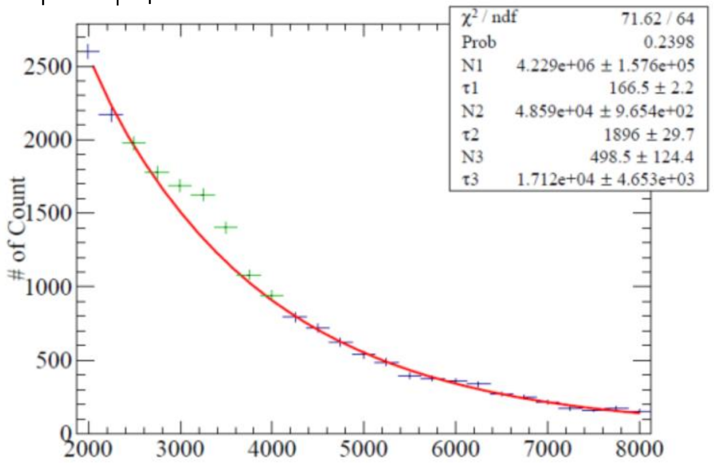


Very Preliminary

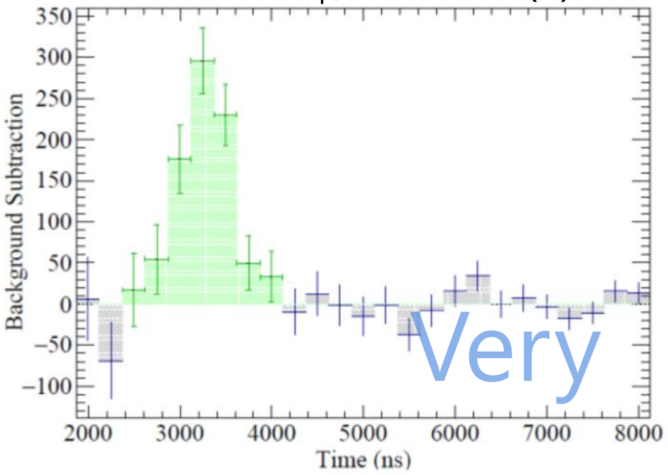


Dependence of Trap Time

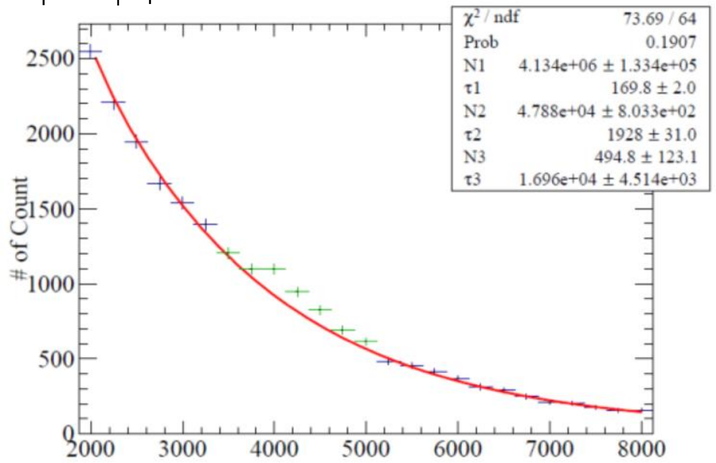
Trap time | 2 μs



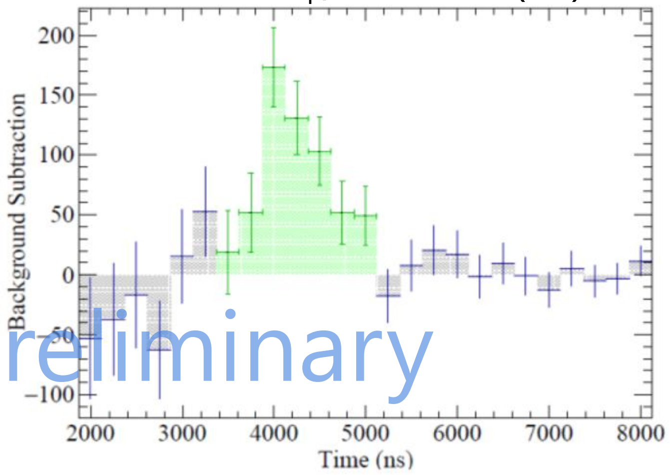
N_{trap}/N_{Cu}=0.66(8)%



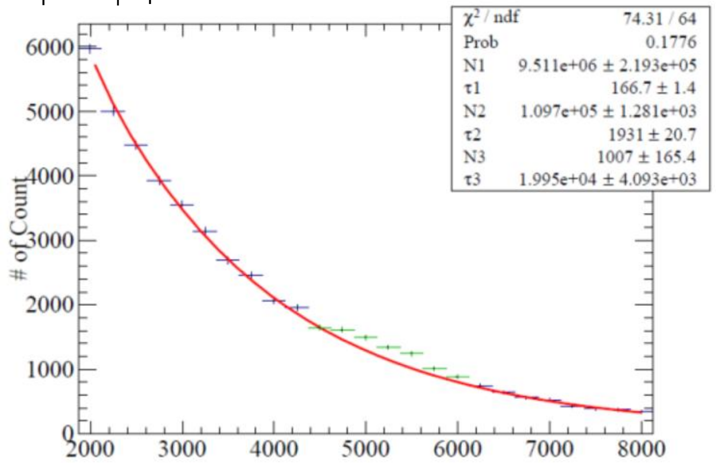
Trap time | 3 μs



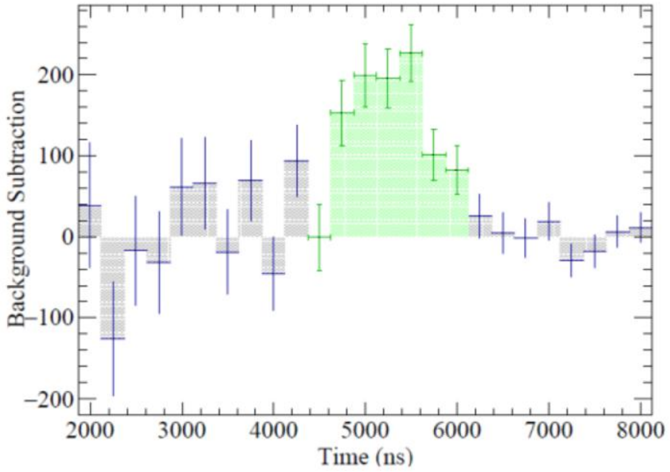
N_{trap}/N_{Cu}=0.71(10)%



Trap time | 4 μs



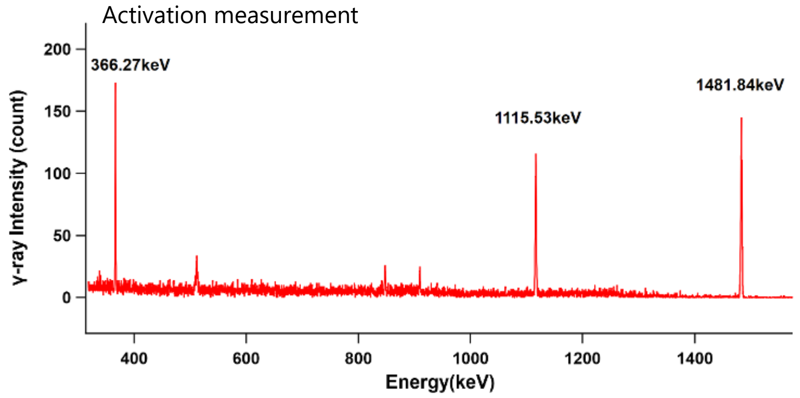
N_{trap}/N_{Cu}=0.82(8)%

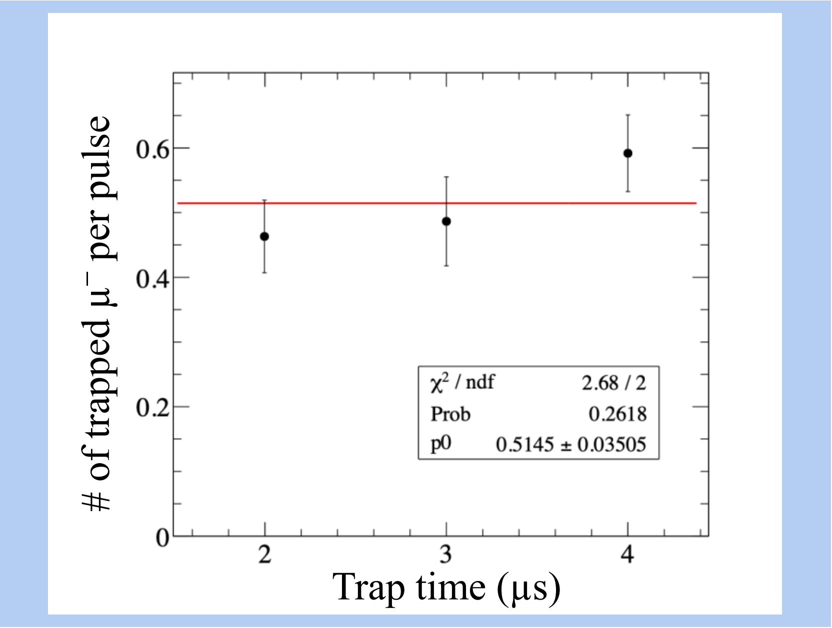


Very Preliminary

Trapping Ratio of Negative Muon

- Number of injected μ^-
  - Estimated by activation of Cu
  - 600 μ^-/pulse (p=17 MeV/c)
- Number of trapped μ^-
  - Detection efficiency estimated by Geant4
  - 0.52 μ^-/pulse





Trapped μ^- / Injected μ^- = 0.09 %

Summary & Prospects

- Muon Precision Measurement
- High-Intensity Slow Muon
  - Ultra-slow muon
  - Degraded muon
- Test of negative muon trap
  - μ^- trapped in vacuum
  - Trap efficiency 0.09%
- What's Next?
  - Measuring μ^- life time in vacuum
  - Anti-muonium production