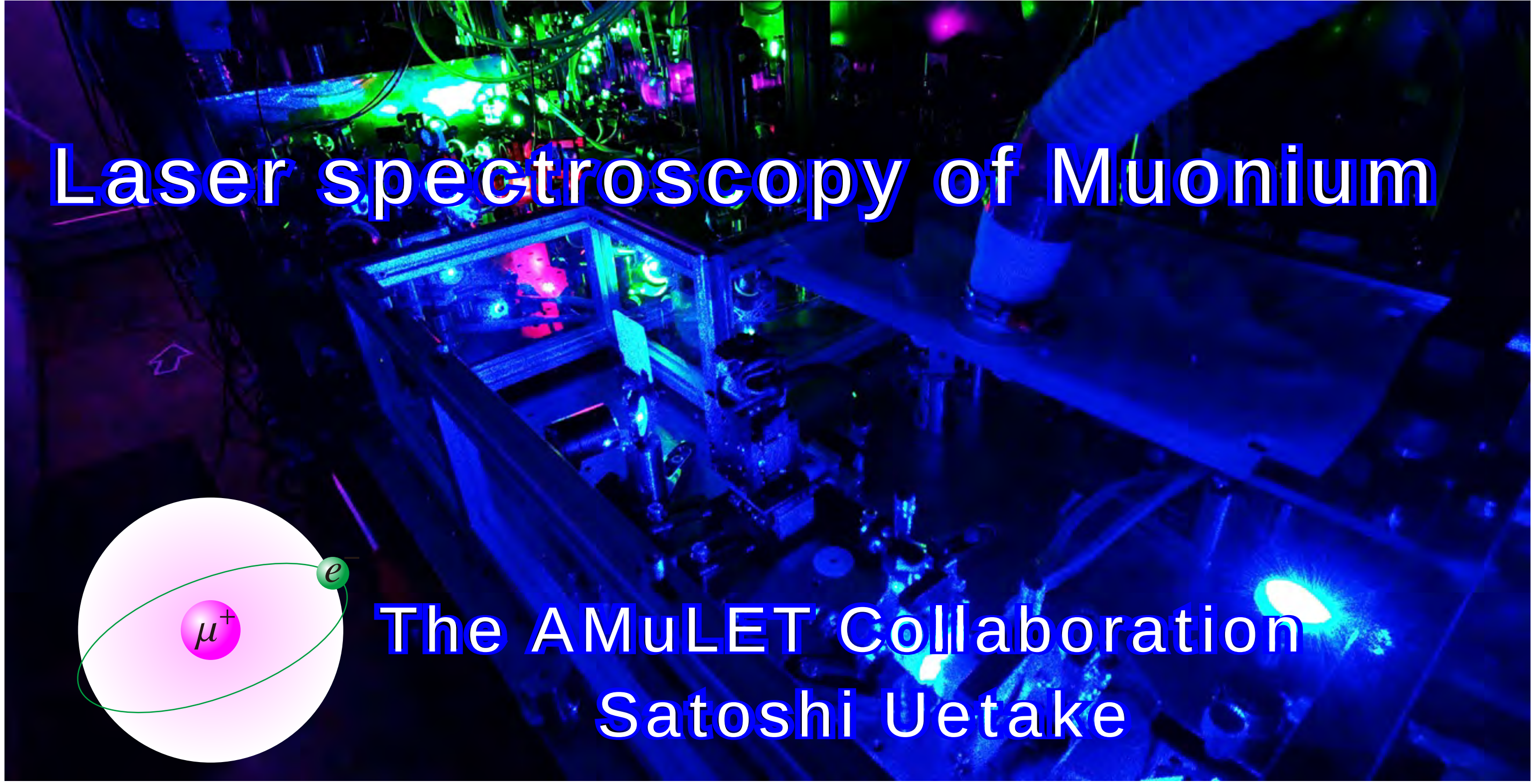



RIIS Okayama University[A]

Riken[B], KEK KEK[C], The University of British Columbia[D],

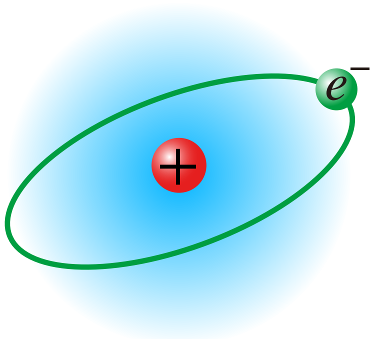
Nagoya University[E] Peking University[F]

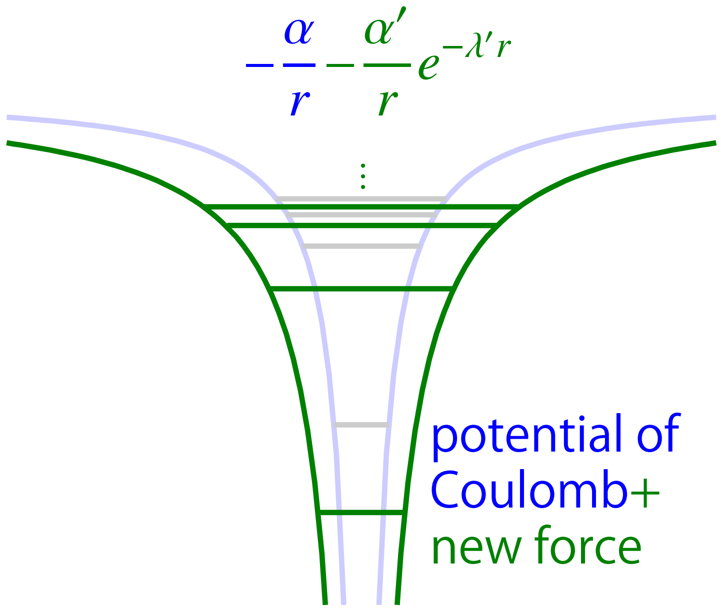
Collaborators:

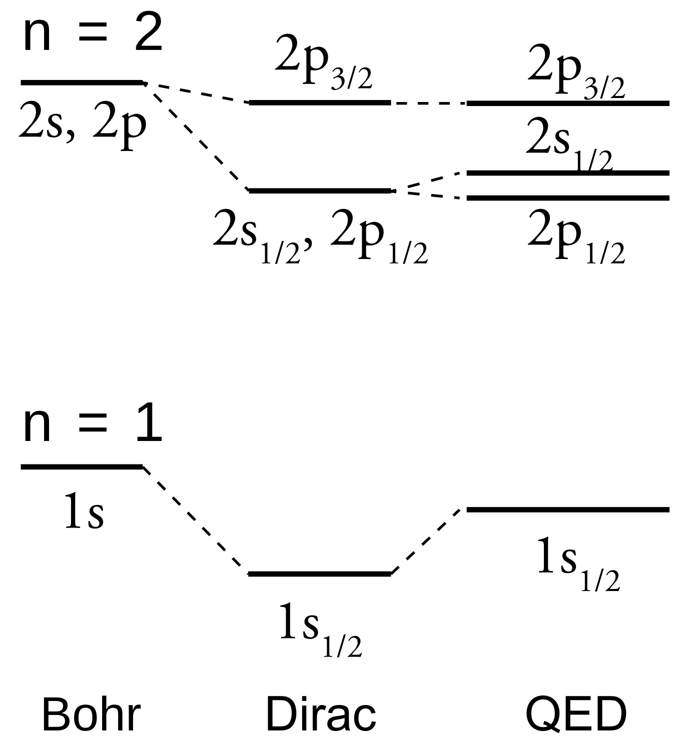
T. Adachi[B], R. Endo[A], H. Hara[A], T. Hiraki[A], Y. Ikedo[C], Y. Imai[A], K. Ishida[C], S. Kamal[D], S. Kamioka[C], N. Kawamura[C], M. Kimura[C], A. Koda[C], T. Masuda[A], T. Mibe[C], Y. Miyamoto[A], K. Shimomura[C], P. Strasser[C], K. Suzuki[E], S. Yamamoto[A], T. Yamazaki[C], M. Yoshida[C], K. Yoshimura[A], C. Zhang[F]

Advanced Muonium Laser Experiment at Tokai

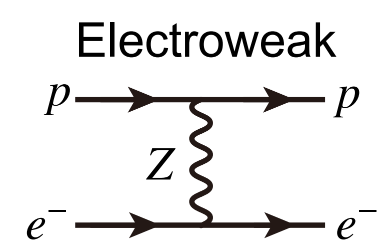
# Fundamental Physics with Spectroscopy of Hydrogen-like Atoms

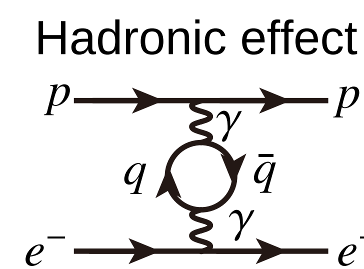



- Hydrogen-like Atoms: Simplest bound-system
  - Precise theoretical calculation of energy levels is possible
    →Quantum Mechanics / QED development
  - Energy levels correspond to forces between
    positive/negative charge



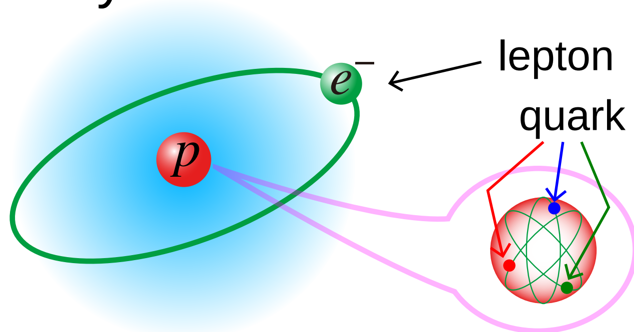

**Compare Precise experiment / theoretical calculation**

↓

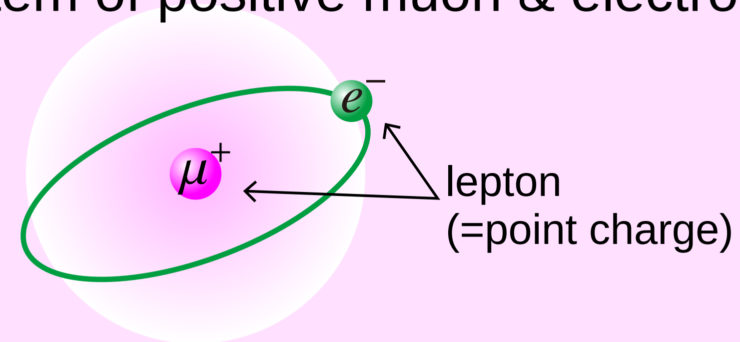
**Precision test of the Standard Model is possible**

# Hydrogen vs Muonium (purely leptonic system)

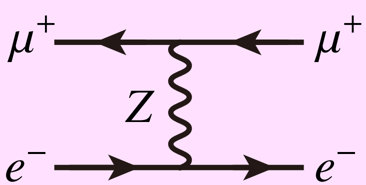
H [Hydrogen (ep)]：lifetime >$10^{34}$ yrs
Bound system of Proton & Electron



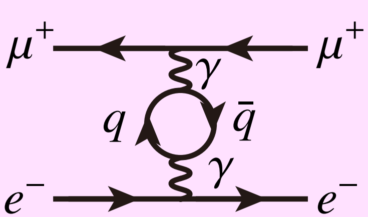

Mu [Muonium ($\mu^+e^-$)]：lifetime 2.2μs
Bound system of positive muon & electron




| | | |
|---|---|---|
| Composite particle of Hadrons and lepton | Components / Structure | only Leptons (point charges) |
| Large | Uncertainty from Nuclear structure | No |
| Difficult | Precise theoretical calculation | Yes |




$1^{st}$ order Electroweak
-65 Hz
PRA 53, 2953 (1996)
Phys. Lett. B **795**, 113 (2019)



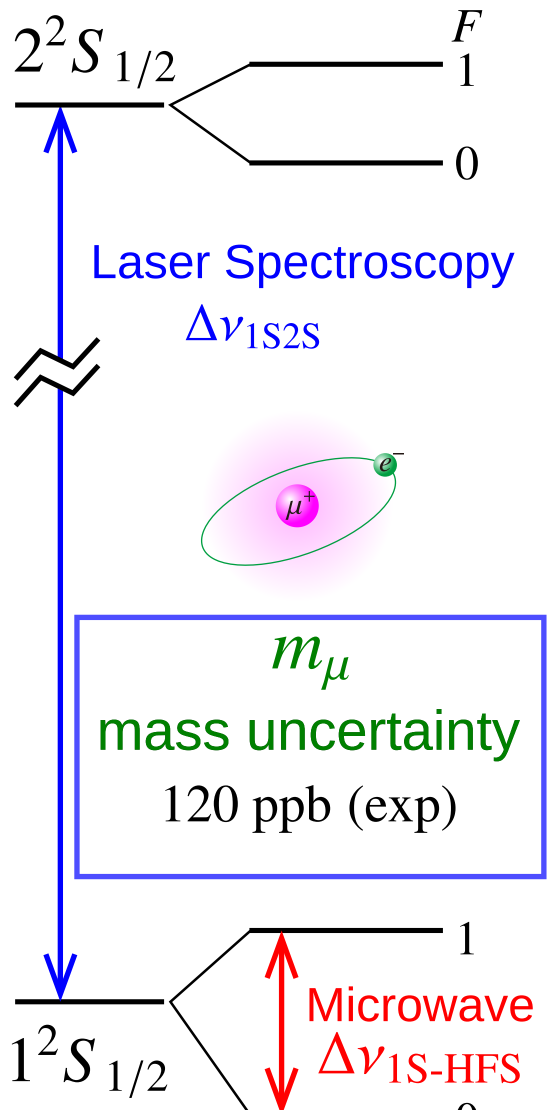

Vacuum polarization
(hadronic) +232.7(1.4) Hz
Nucl. Phys. B 867, 236 (2013), Sov. J. Nucl. Phys. 53, 626(1991)

- Ultra-precision Test of the Standard Model
- **Found discrepancy between theo. & exp.?**

**→May be evidence of Physics Beyond the Standard Model**

# Present Precision

Mu Energy Level




$m_\mu$
mass uncertainty
120 ppb (exp)

electron mass uncertainty
$m_e$ 0.3 ppb ($10^{-9}$)

**1S-2S Laser Spectroscopy** $\Delta\nu_{\mathrm{1S2S}} \simeq \frac{3\alpha^2}{8h} m_e c^2 \left(1 + \frac{m_e}{m_\mu}\right)^{-1}$ (mass: $m_\mu$)

**Reduced mass contribution: 1.2 THz (0.48%)**

Precise measurement of 1S-2S transition frequency

☞ Precise determination of muon mass $m_\mu$

QED error:[4]
$\mathcal{O}(m_\mu \alpha^8 \ln^3 \alpha)$
$\sim$ 10 kHz

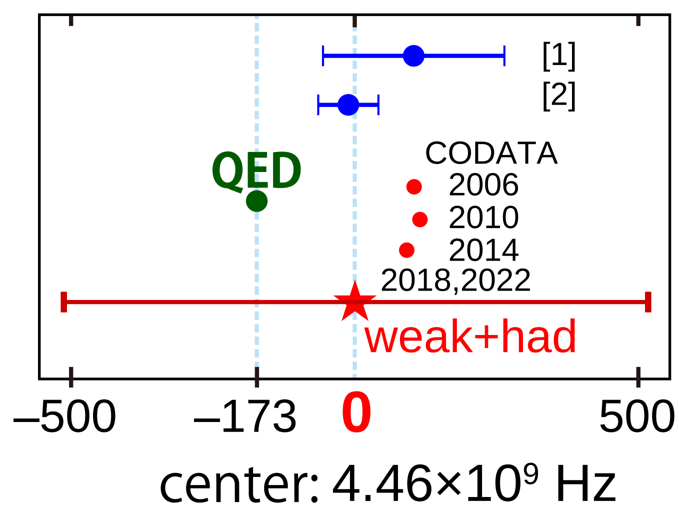
**1S-HFS microwave spectroscopy**

$$\Delta\nu_{\mathrm{1S\text{-}HFS}} \simeq \frac{16}{3}\alpha^2 c R_\infty \frac{m_e}{m_\mu}\left(1 + \frac{m_e}{m_\mu}\right)^{-3}$$

mass

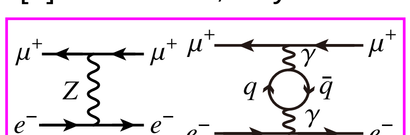
Uncertainty
Exp : 160 Hz [1]
53 Hz [2]

Theory: 515 Hz [3]
muon mass uncertainty
(120 ppb) → 511 Hz





[1] F.G. Mariam *et al.*, PRL 49, 993 (1982)
[2] W. Liu *et al.*, PRL 82, 711 (1999)
[3] M. I. Eides, Phys. Lett. B **795**, 113 (2019)

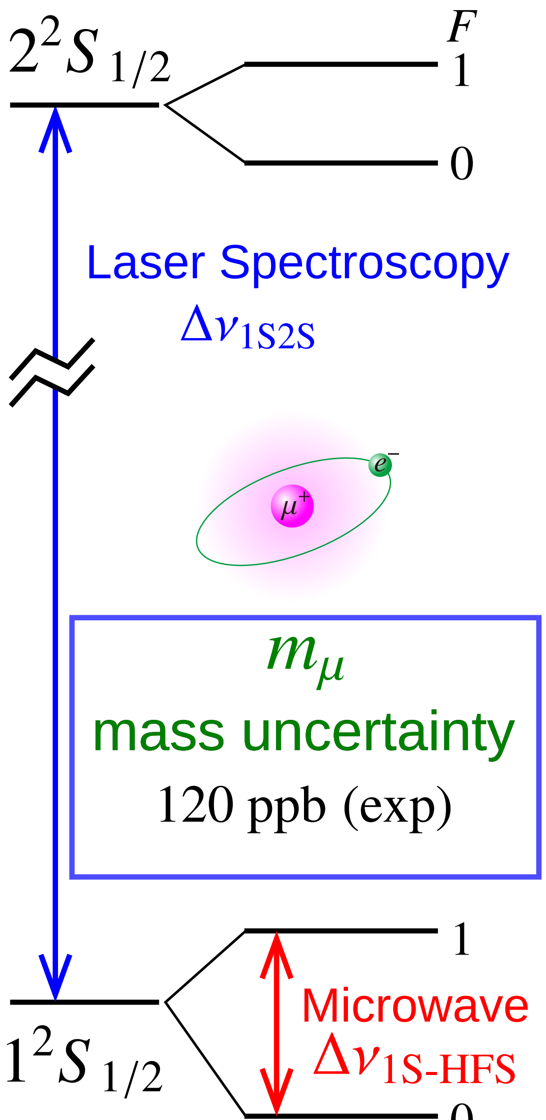




**Electroweak Frequency shift: -65 Hz**
**Hadronic vacuum polarizaiton: +237.7 Hz**


[4] M. I. Eides, Phys. Rept. **342**, 63 (2001)

# Present Precision and Our Goal

Mu Energy Level




electron mass uncertainty

$m_e$ 0.3 ppb ($10^{-9}$)

## 1S-2S Laser Spectroscopy

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

mass

**1S-2S Goal**

**u[$\Delta\nu_{1S2S}$]$_{exp.}$: 100 kHz**

**(RAL 1999: 9.8 MHz[1])**

[5] V. Meyer *et al.*, PRL **84**, 1136 (2000)

**Goal (a) : 1S-2S Spectroscopy**

**Reduce the mass uncertainty**

**120 ppb ➔ 8 ppb**

## 1S-HFS microwave spectroscopy

$$\Delta\nu_{1S\text{-}HFS} \simeq \frac{16}{3}\alpha^2 c R_\infty \frac{m_e}{m_\mu}\left(1 + \frac{m_e}{m_\mu}\right)^{-3}$$

mass

Uncertainty

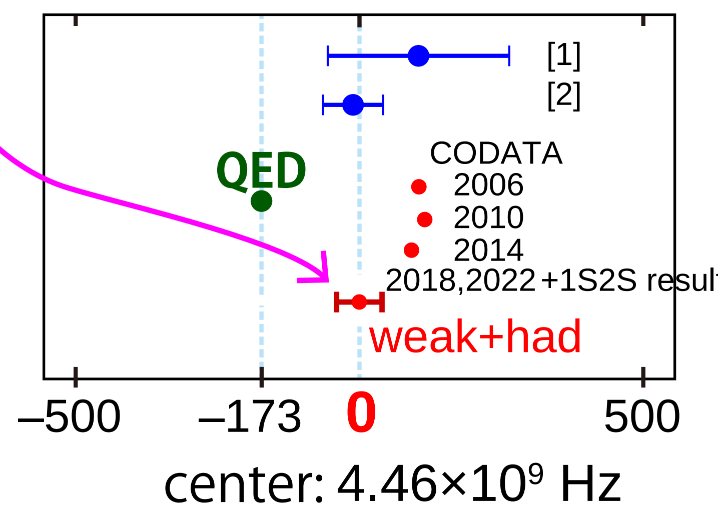
Exp : 160 Hz [1]

53 Hz [2]

Theory: ~~515 Hz~~[3] 40 Hz

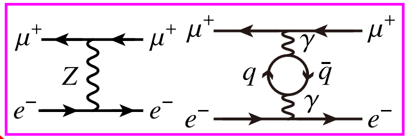
muon mass uncertainty

(120 ppb) → 511 Hz





[1] F.G. Mariam *et al.*, PRL 49, 993 (1982)
[2] W. Liu *et al.*, PRL 82, 711 (1999)
[3] M. I. Eides, Phys. Lett. B **795**, 113 (2019)


**Electroweak Frequency shift: -65 Hz**

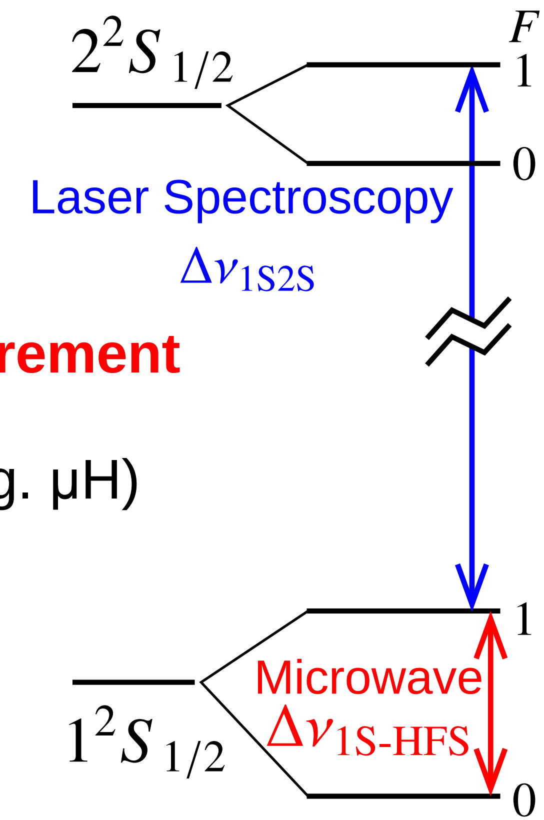
**Hadronic vacuum polarizaiton: +237.7 Hz**


[4] M. I. Eides, Phys. Rept. **342**, 63 (2001)

# The Limited Robustness of the Muon Mass

- **Muon mass measurements**

| Experiment | uncertainty | discussed paper |
| --- | --- | --- |
| LAMPF 1982 | 360 ppb | CODATA1998 [1] |
| LAMPF 1999 | 120 ppb | CODATA2002 [2] |




- **Muon mass is determined by $\Delta\nu_{1S\text{-}HFS}$ : only one measurement**

- **Same quantity ← Different method / Different Labs.** (e.g. μH)
  - **Improve reliability of Fundamental Constants**
  - **► $m_\mu$ determined by 1S-2S transition**

[1] Rev. Mod. Phys. 72, 351 (2000); [2] Rev. Mod. Phys. 77, 1 (2005)
(LAMPF: Clinton P. Anderson Meson Physics Facility at Los Alamos)

**CODATA recommended values of the fundamental physical constants: 2018***

Eite Tiesinga†

*Joint Quantum Institute and Joint Center for Quantum Information a College Park, Maryland 20742, USA*
*and National Institute of Standards and Technology, Gaithersburg,*

Peter J. Mohr,‡ David B. Newell,§ and Barry N. Taylor‖

*National Institute of Standards and Technology, Gaithersburg, Mar*

(published 30 June 2021)

E. Tiesinga *et al.*, Rev. Mod. Phys. **93**, 025010 (2021), p. 58

A perusal of the input data in Table XXI shows there is only one input datum for some quantities, and some are decades old. Measurements of the same quantity by different methods in different laboratories help to identify unknown systematic effects, thereby improving the reliability of the input data. The six magnetic-moment ratios, items D32 to D37 in the table, are obvious examples of old data. The muon mass is currently only determined by essentially one measurement. It would be useful if researchers kept in mind the limited robustness of the data set on which CODATA adjustments are based in planning research.

# Previous Mu 1S-2S Experiments (1)

- S. Chu et al., Phys. Rev. Lett. **60**, 101 (1988) [KEK, Japan]

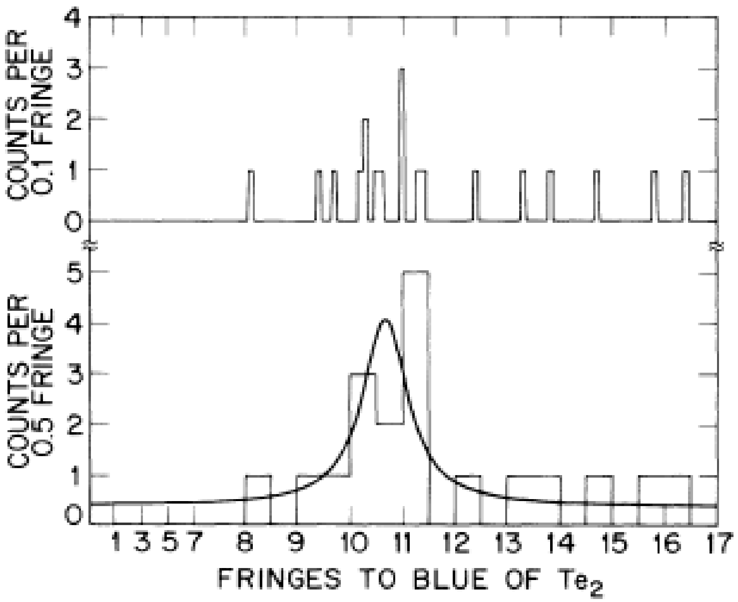



FIG. 4. Frequency spectrum for all the runs (16 h) taken in the manner of Fig. 3. A Lorentzian is fitted to the individual events shown at the top of the figure

- The first observation of Mu 2S resonance
- Obtained by 16 hours measurement
- Only $F = 1 \rightarrow F' = 1$ is observed

- K. Jungmann et al., Z. Phys. D **21**, 241 (1991) [RAL, UK]

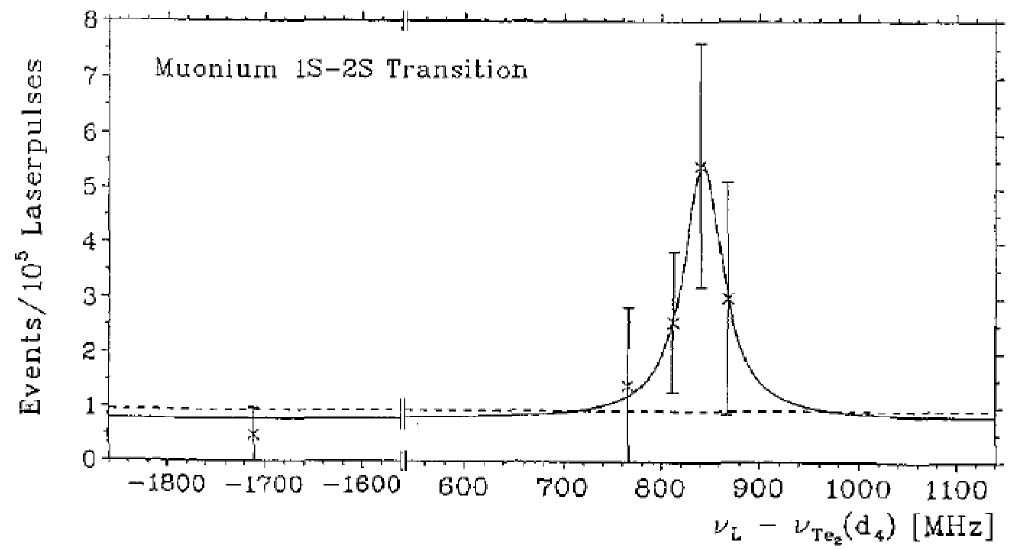
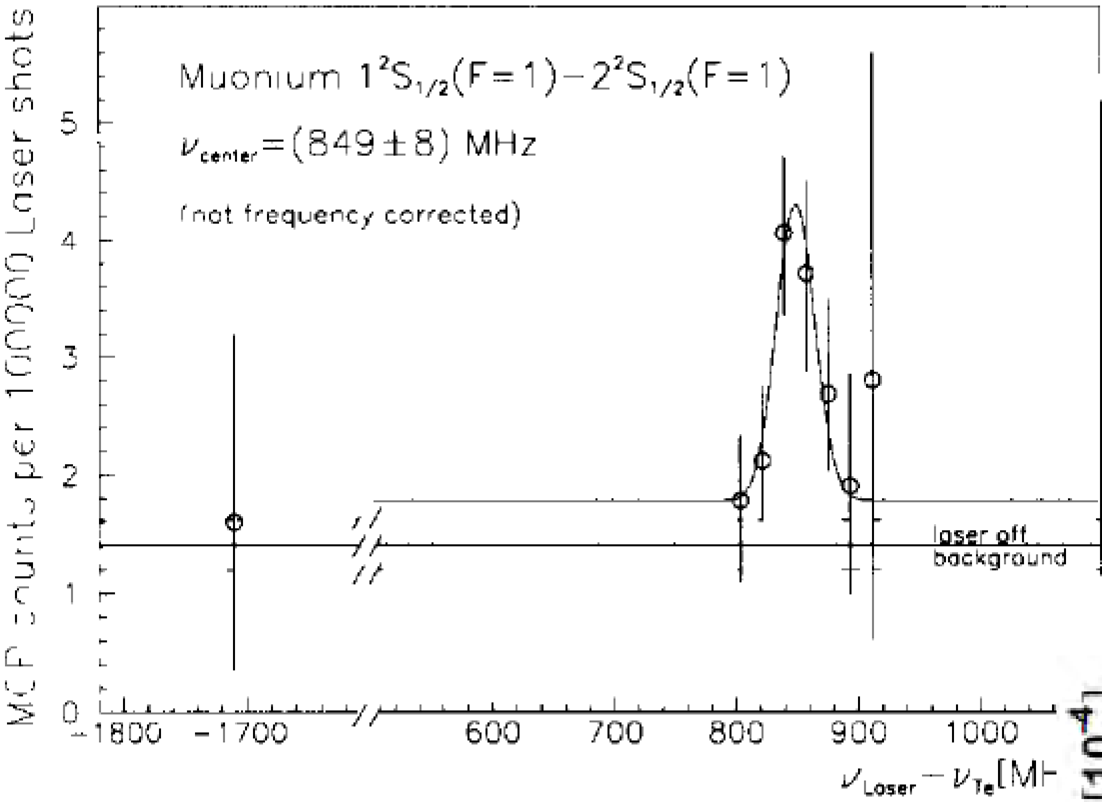



**Fig. 4.** Doppler-free muonium 1*S*–2*S* signal. The dashed line indicates the background count level in the laser off phase in agreement with the counting rate observed when the laser is tuned by 2.5 GHz below resonance. The frequency scale corresponds to the offset of one quarter of the 1*S*–2*S* transition frequency from the tellurium $d_4$ line

- Transition frequency: (stat) (syst)
  2 455 528 016 (58) (43) MHz
- Signal rate $5 \times 10^{-5}$ /pulse
- Only $F = 1 \rightarrow F' = 1$ was observed

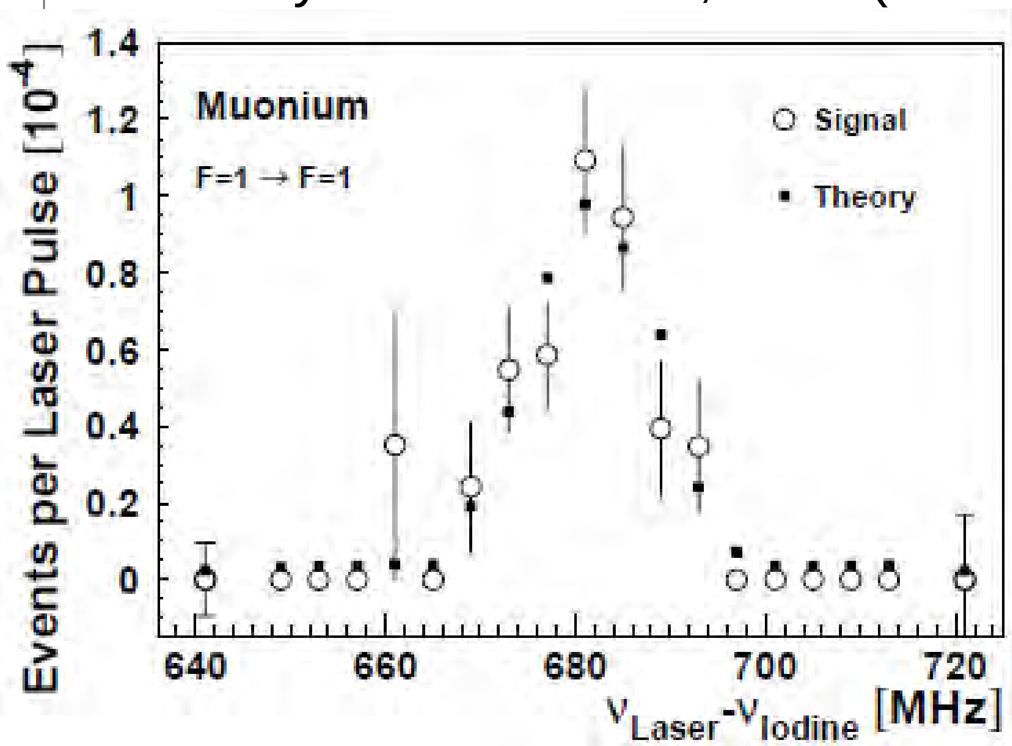
# Previous Mu 1S-2S Experiments (2)

- F. E. Maas et al., Phys. Lett. A **187,** 247 (1994)




- Transition frequency: (stat) (syst)
  2 455 529 002 (33) (46) MHz
- Signal rate: $4\times10^{-5}$ /pulse ($1\text{x}10^{-3}$ cps)
- Only $F=1\rightarrow F'=1$ was observed

- V. Meyer et al., Phys. Rev. Lett. **84**, 1136 (2000)




- 1S-2S transition frequency was measured (9.8 MHz uncertainty)
- Signal rate: $1\times10^{-4}$ /pulse ($2.5\text{x}10^{-3}$ cps)
- Only $F=1\rightarrow F'=1$ was observed
- 99 events total was obtaind with 33 hours measurement

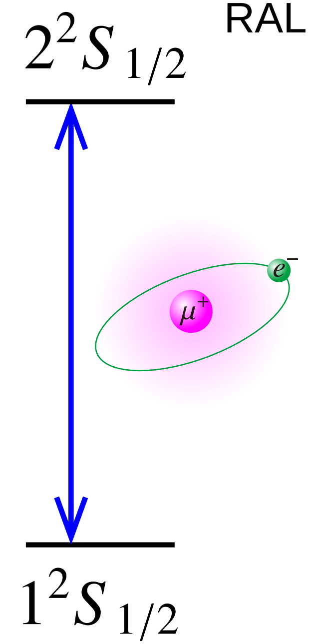
# Uncertainty in the Previous Research

RAL: Rutherford Appleton Laboratory

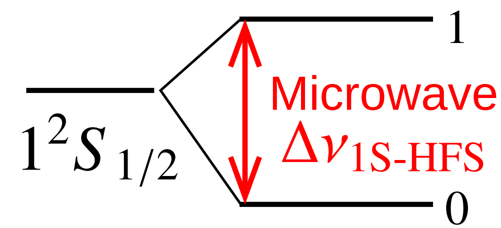
**RAL Result: 2 455 528 941.0(9.8) MHz**

$u_r[m_\mu/m_e] = 820$ ppb

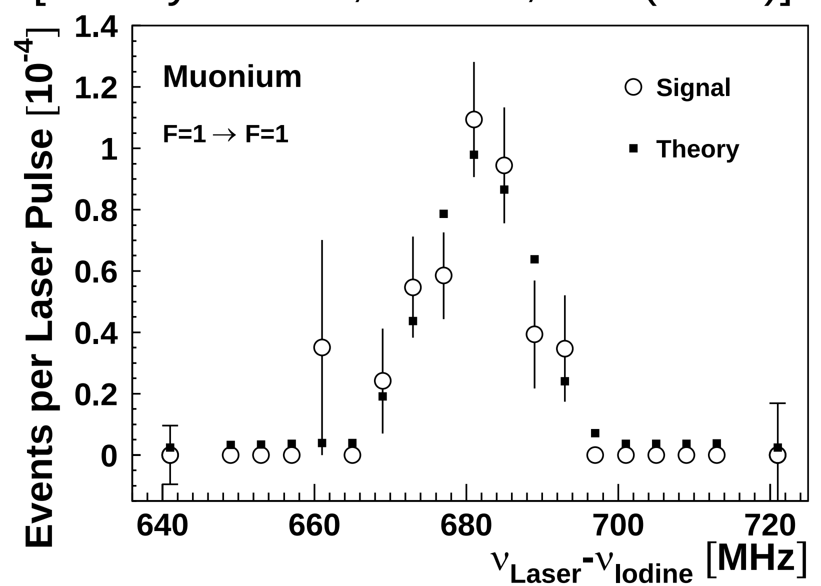
| | **RAL(1999)** |
|---|---|
| $\mu^+$ intensity | 3500 × 50 Hz (0.17MHz) |
| Mu yield | 4,000 cps |
| Laser / Linewidth | pulsed / ~8 MHz |
| Peak signal rate (Number of signals) | $2.5\times10^{-3}$ cps (99 for 33 hrs) |
| | Uncertainty |
| Statistics | 9.1 MHz |
| Residual doppler | 3.4 MHz |
| Freq. calibration | 0.84 MHz |
| Freq. lock stability | 0.5 MHz |
| Line shape calc. | 1.2 MHz |
| Total | 9.8 MHz |




**CODATA2022**
**120 ppb (exp)**



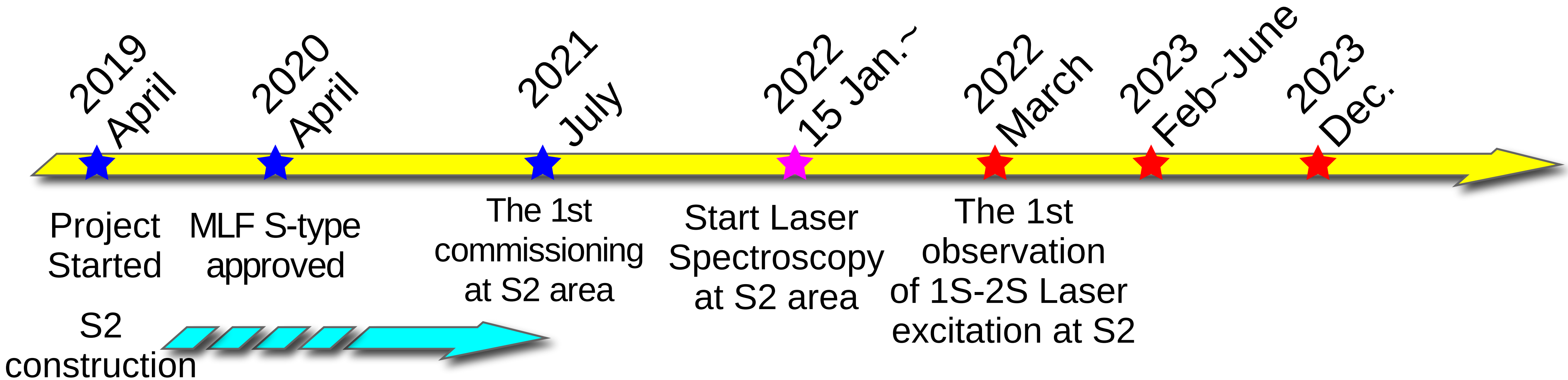

[V. Meyer et al., PRL84,1136(2000)]




(Peak rate: 0.0025 cps)

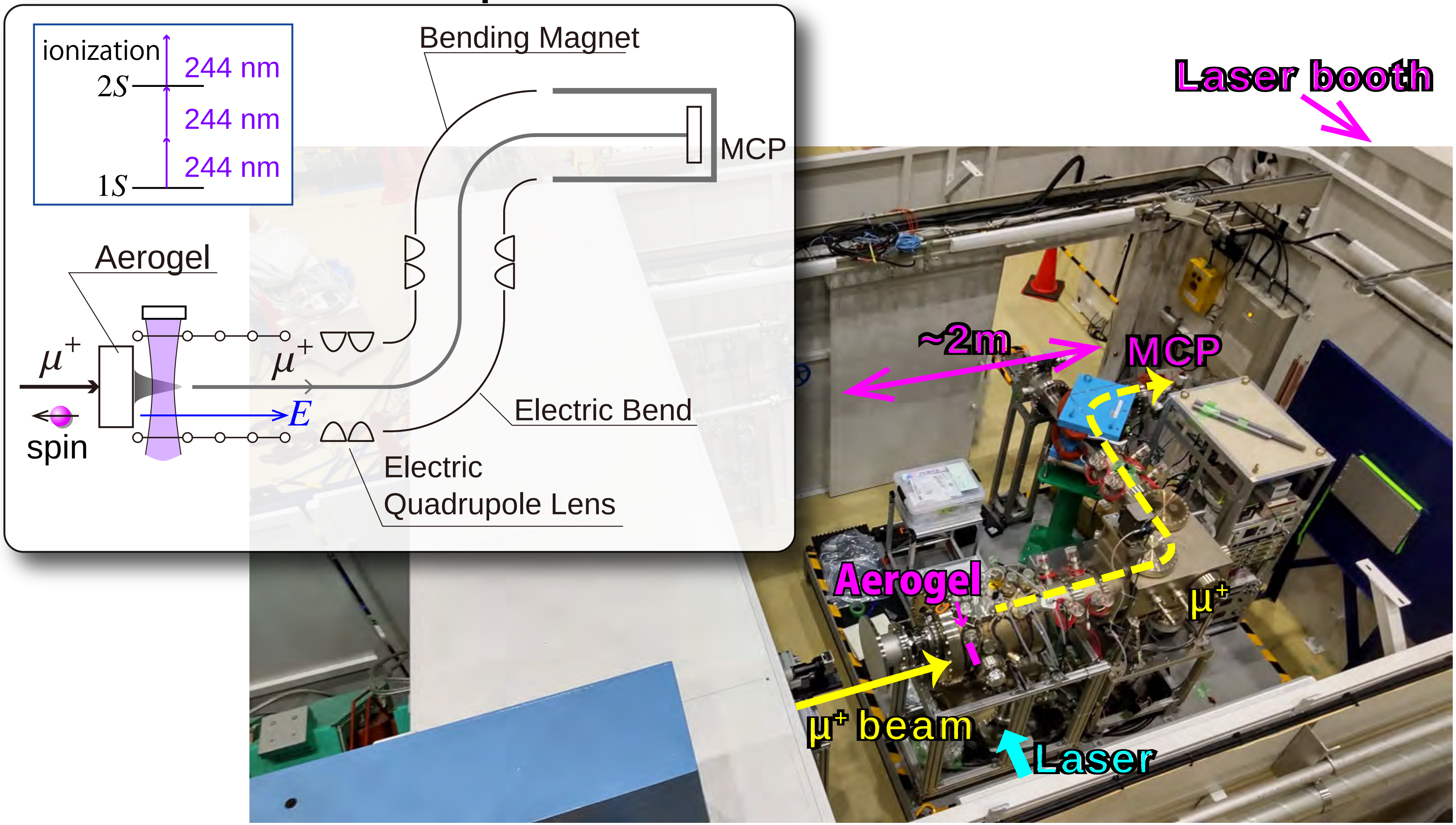
Reduce these uncertainty is the key to our expeiriment

# Project History of Mu 1S-2S Spectroscopy @J-PARC



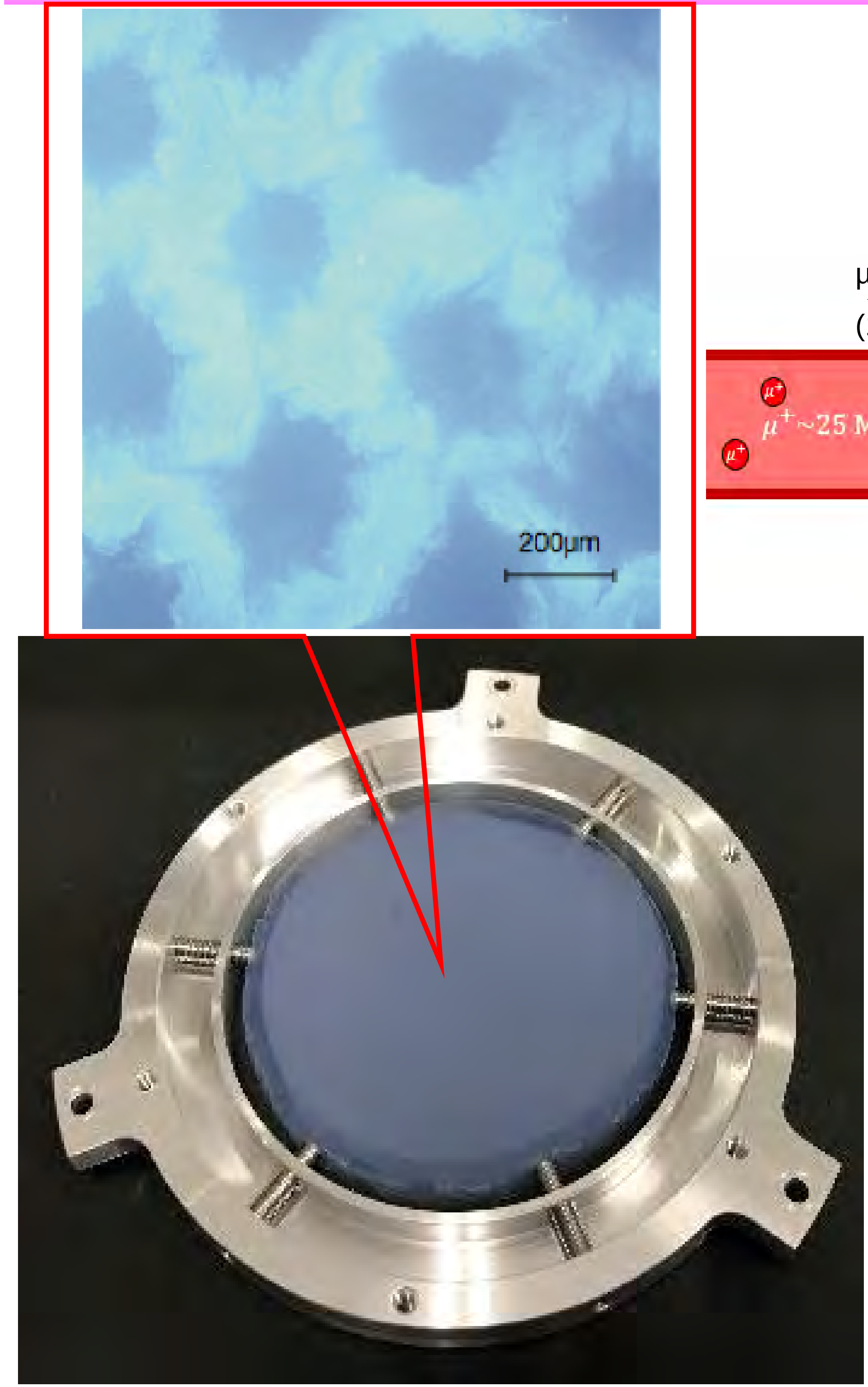

- 2019 Project Start (Grant-in-Aid for Scientific Research(S) adopted)
- 2020 MLF S-type research project, Start S2 area construction
- 2021.7 The 1st beam comissioning at S2 area
- 2022.1 Start laser spectroscopy experiment
- 2022.3 The 1st observation of 1S-2S laser excitation
- 2023.2~6 experiment
- 2023.11 Improve laser system (higher laser power)
- 2023.12 experiment: x300 signal rate obtained
- 2024.4 Grant-in-Aid for Scientific Research(S) adopted again
- 2025.4 Laser spectroscopy with Optical Cavity

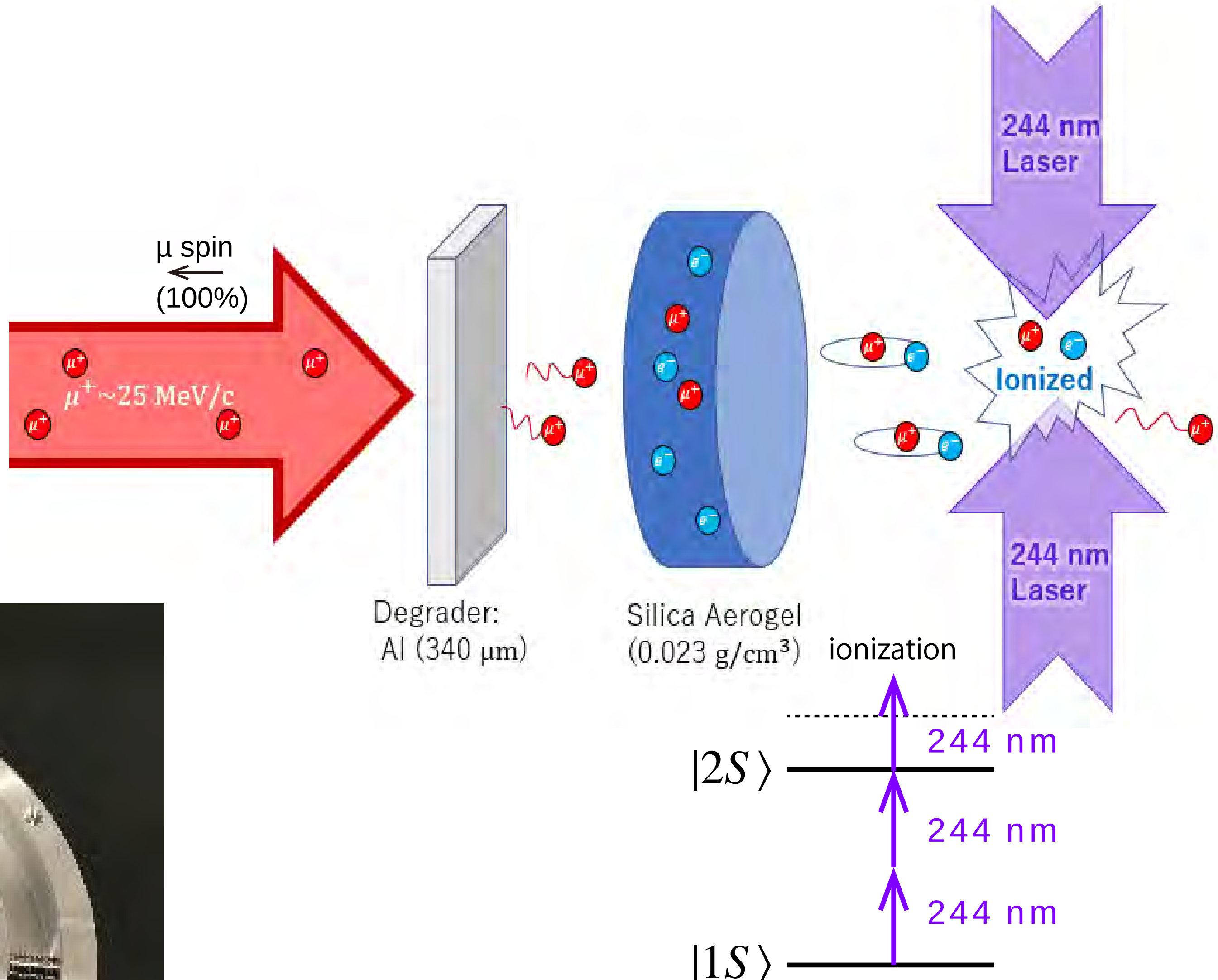
# Experiment Overview




- Muonium (Mu) is generated by Silica-aerogel in Slow-Muon Beam line (SMBL)
- Resonant Multi-Photon ionization (REMPI) signal of Mu by pulsed 244 nm laser is detected by MCP at the end of the SMBL
- Electric Bend and Magnet is used to eliminate background noise (high-energy $\mu^+$, $e^+$ etc.)
- Laser system is located next to the beam area (~7 m away) in the Laser booth

# Muonium formation target: Silica aerogel



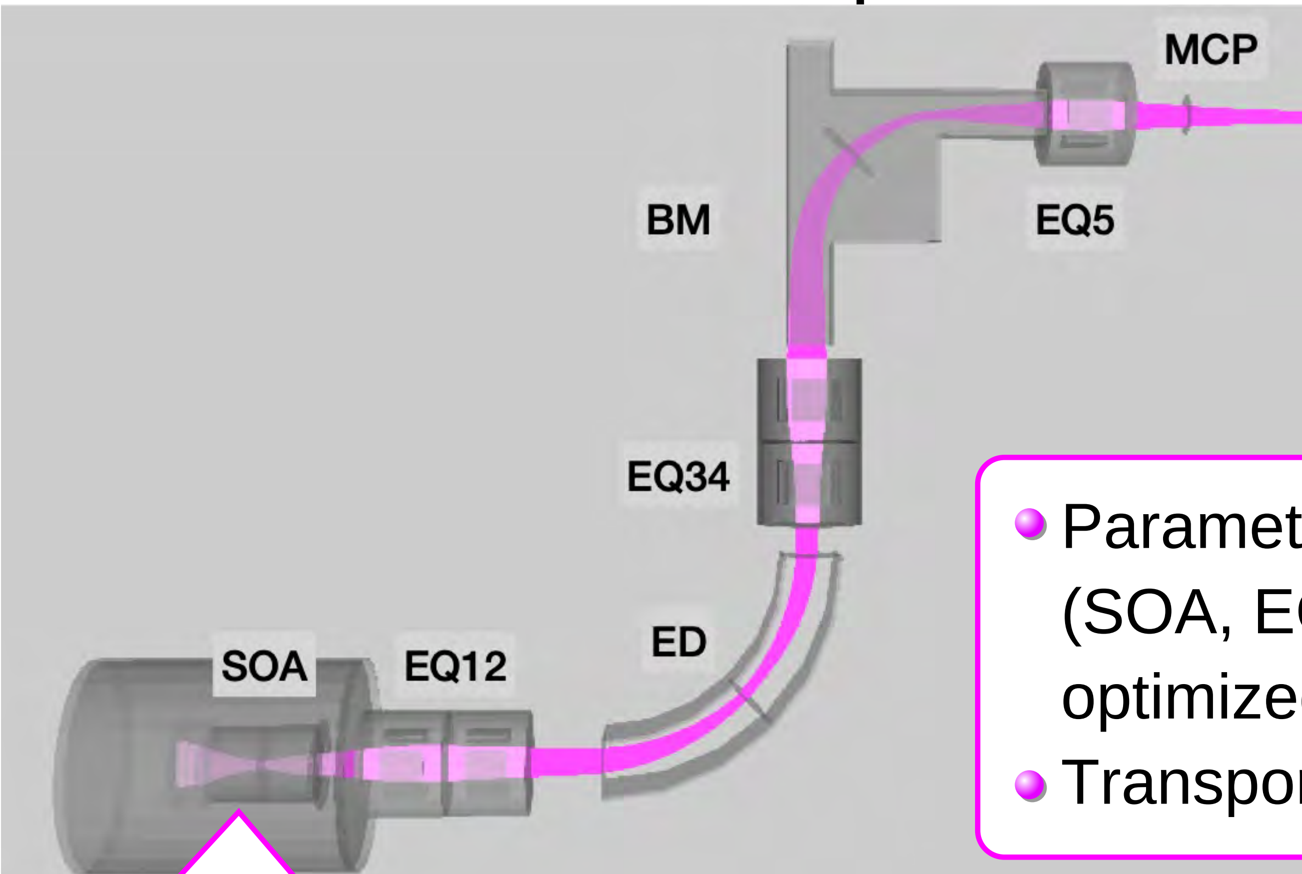




- Laser ablated silica aerogel
- Developed by the muon g-2/EDM experiment group at J-PARC [1]
- Mu yield ~2%

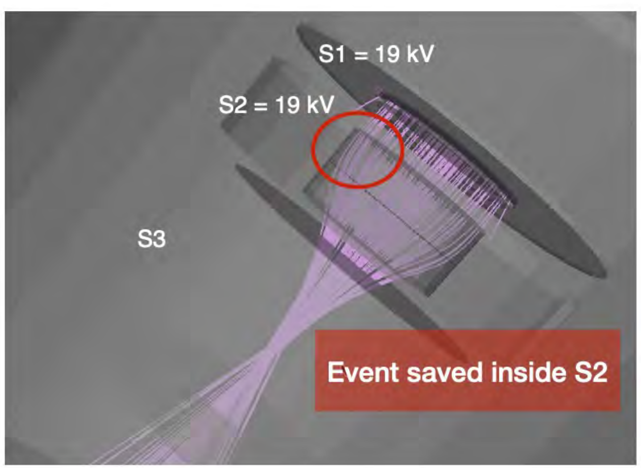
[1] Prog. Theor. Exp. Phys. 2020, 123C01

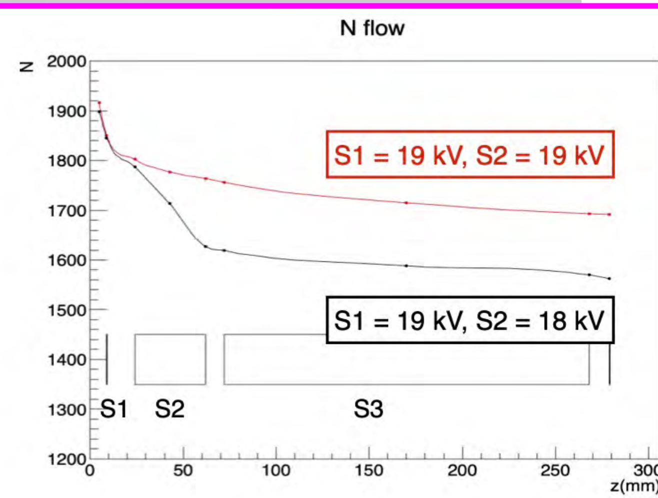
# SMBL Transportation Efficiency

SMBL: Slow Muon Beam Line



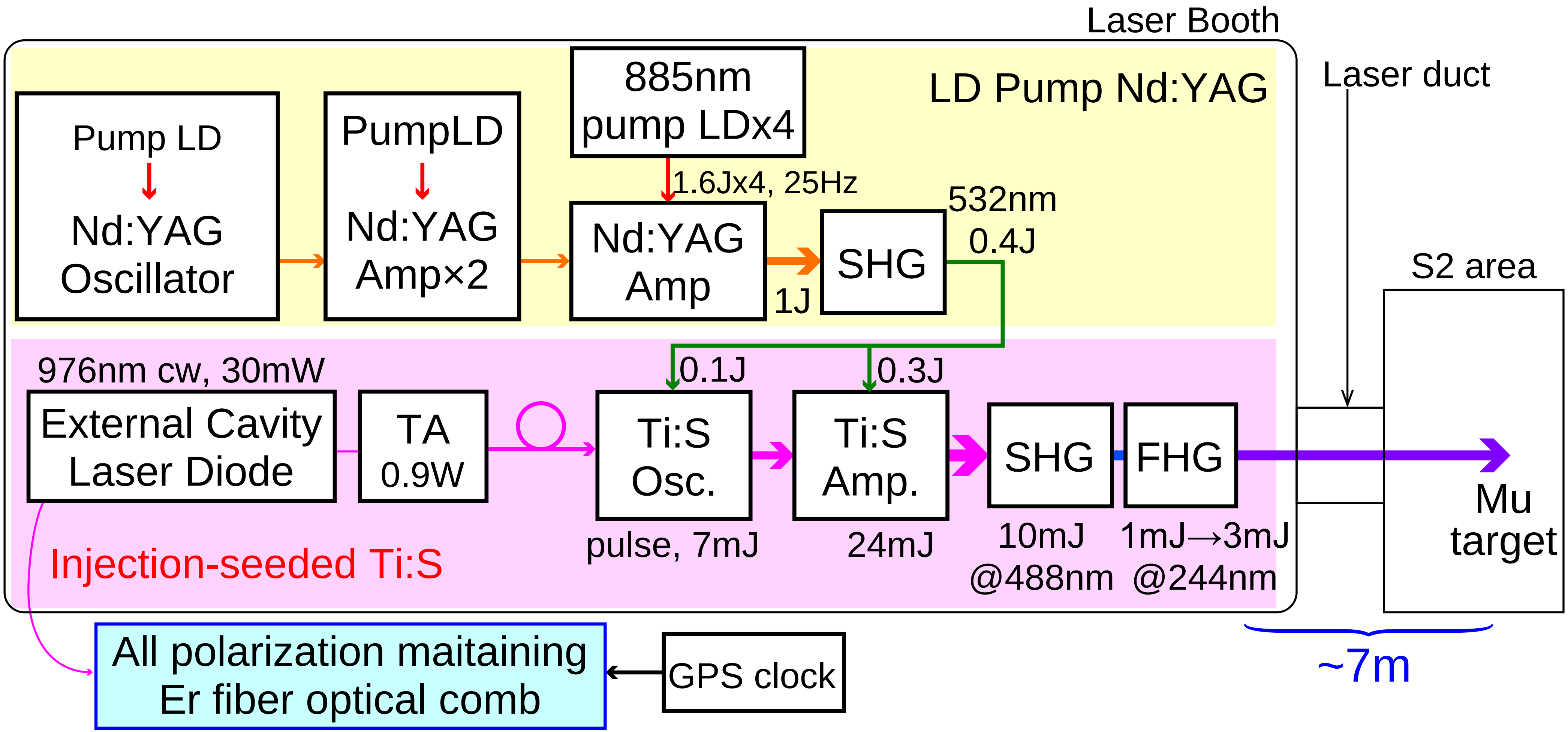

- Parameters of SMBL optics (SOA, EQ, ED, and BM) are optimized with musrSim program
- Transport Efficiency is ~0.651



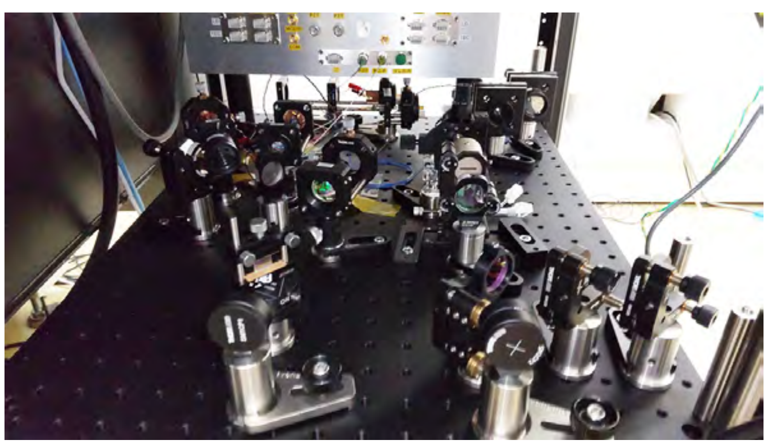




Ce Zhang, PhD Thesis; Ce Zhang et al., JPS Conf. Proc. 33, 011125 (2021)

# Setup of Laser System: Overview

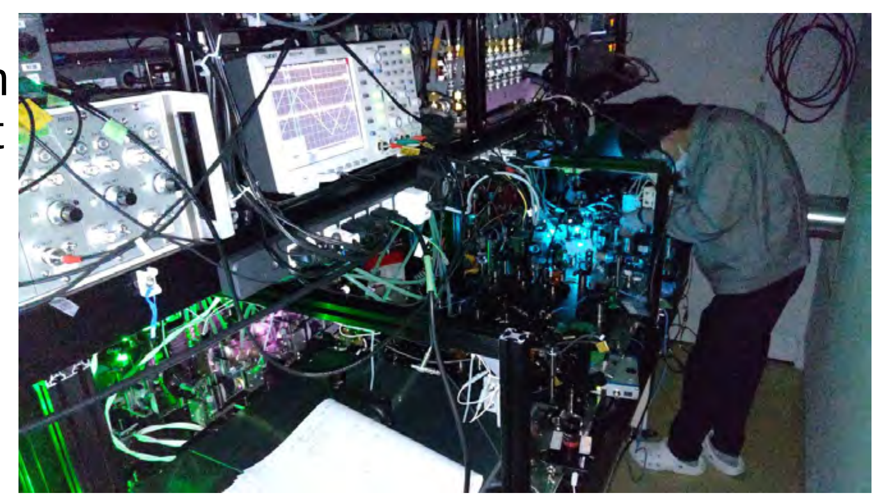



Frequency stability: $2\times10^{-11}$ (50 kHz) at 1000 s



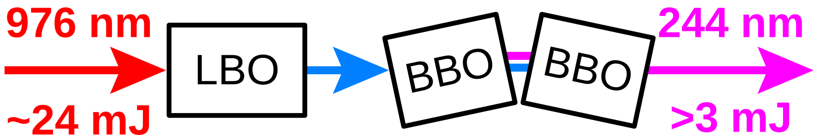
Fiber comb system '22 Dec 04~

244 Generation @S2 Laser hut '22 Jan~

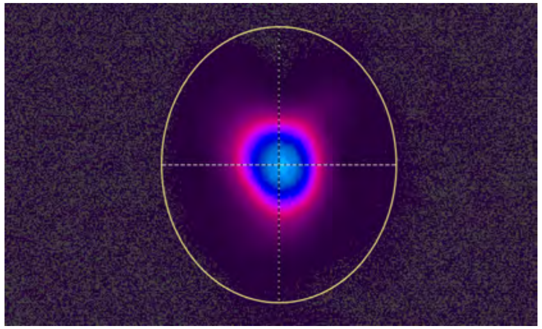


# Beam Quality of 244 nm DUV with BBO

- BBO with no AR coating [2023.12~]




2023.12/11

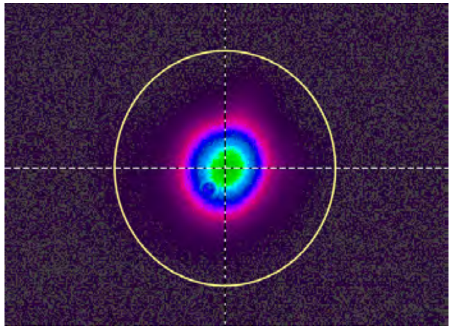


Sufficient beam quality

$$M^2 \lesssim 1.3$$

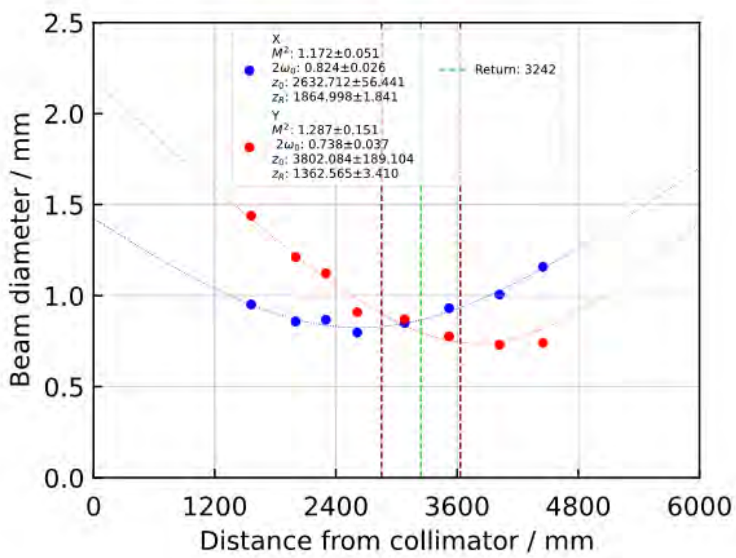
half a year later

2024.5/20



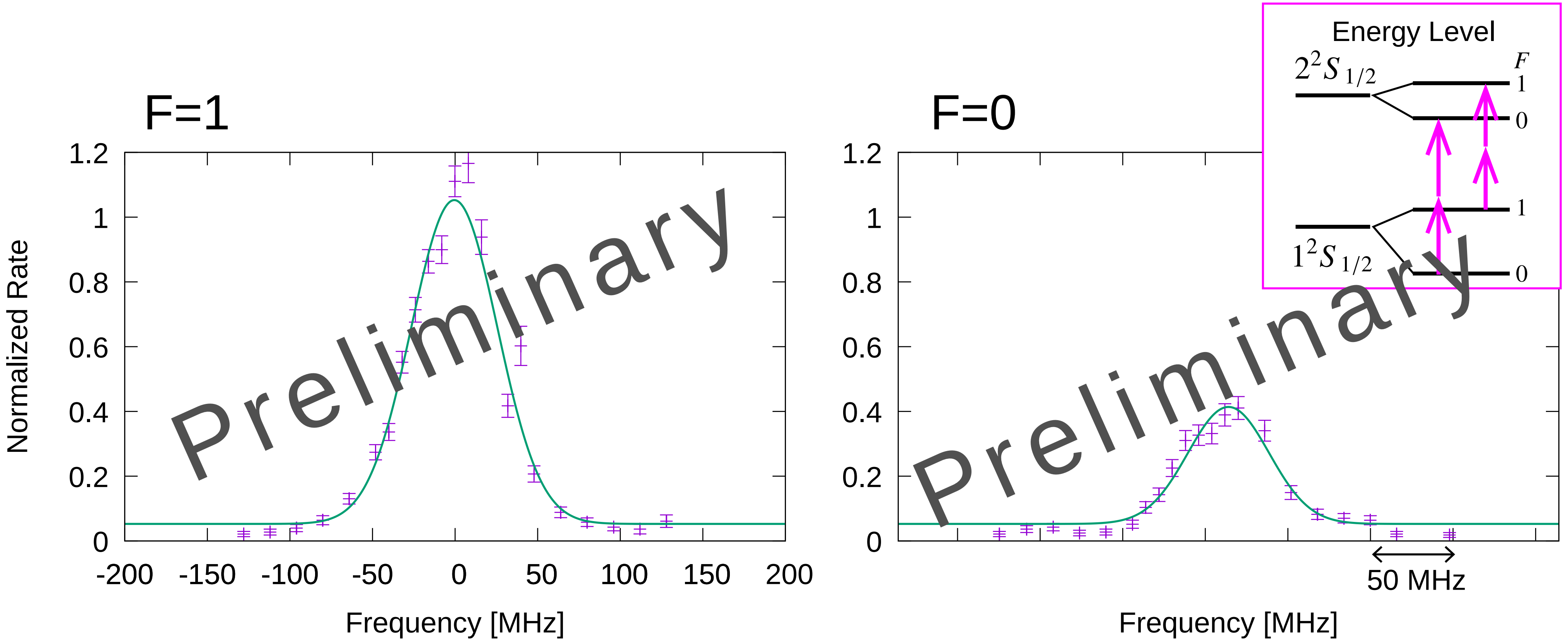
- More than 3 mJ output pulse energy is available
- Maintenance FREE!!

  No degradation was observed with 1 month operation (25Hz, 24 hours/day)




**High quality, maintenance free DUV laser system**

# Our Results: F=0→F'=0 Transition




- First observation of $F = 0 \rightarrow F' = 0$ transition in Muonium
- Peak signal rate (F=1): 0.66 cps
- All optical determination of 2S-hyperfine interval is under preparation

# Improvements

| | RAL(1999) | 2025-2026 Prospects |
|---|---|---|
| $\mu^+$ intensity | 3500 × 50 Hz (0.17MHz) | 1.7 MHz (J-PARC S2 area) |
| Mu yield | 4,000 cps | 40,000 cps |
| Laser / Linewidth | pulsed / ~8 MHz | pulsed / 17 MHz (@976nm) |
| Peak signal rate (Number of signals) | $2.5\times10^{-3}$ cps (99 for 33 hrs) | 0.7 cps (>500/hour on average) |
| | Uncertainty | Expected Uncertainty |
| Statistics | 9.1 MHz | ~0.5 MHz ✓ >x300 signal |
| Residual doppler | 3.4 MHz | Optical cavity |
| Freq. calibration | 0.84 MHz | } 0.05 MHz ✓ Optical Comb |
| Freq. lock stability | 0.5 MHz | |
| Line shape calc. | 1.2 MHz | x1/2 (TBC) |
| Total | 9.8 MHz | ~1 MHz $u_r[m_\mu/m_e] \simeq 80$ ppb |

**RAL Result: 2 455 528 941.0(9.8) MHz**

$u_r[m_\mu/m_e] = 820$ ppb

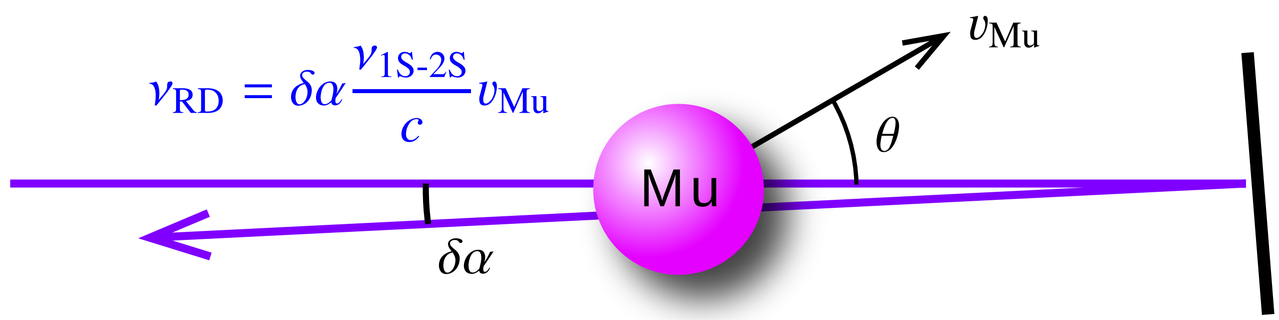
[V. Meyer et al., PRL84,1136(2000)]

**CODATA2022: 120 ppb (exp)**

Uncertainty 1 MHz
→Contribute to CODATA

# Residual Doppler Shift

- **Counter-propagating beams by a retro-reflected mirror**



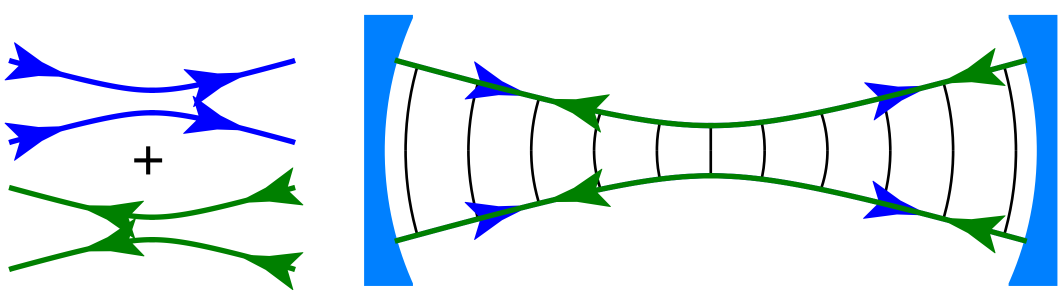

  - RAL

    $\delta\alpha \leq 55\ \mu\text{rad},\ v_{Mu} = 7400\ \text{m/s}$ → $\nu_{RD} = 3.4\ \text{MHz}$

  - Okayama

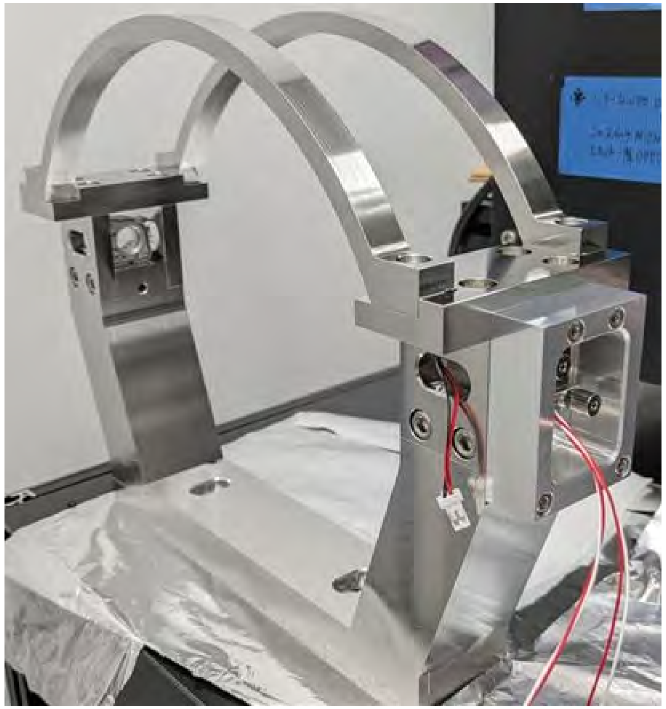
    $\delta\alpha \sim 60\ \mu\text{rad},\ v_{Mu} = 5500\ \text{m/s}$ → $\nu_{RD} \sim 3\ \text{MHz}$

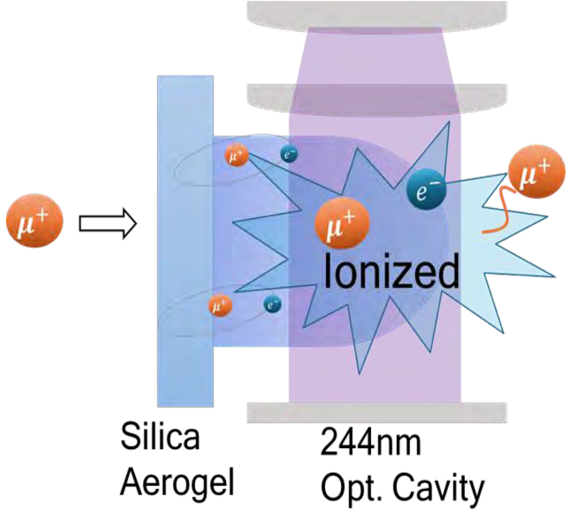
- **Counter-propagating beams in the Optical cavity**
  - Wavefronts of the cavity mode are in perfect alignment
  - Free from residual Doppler

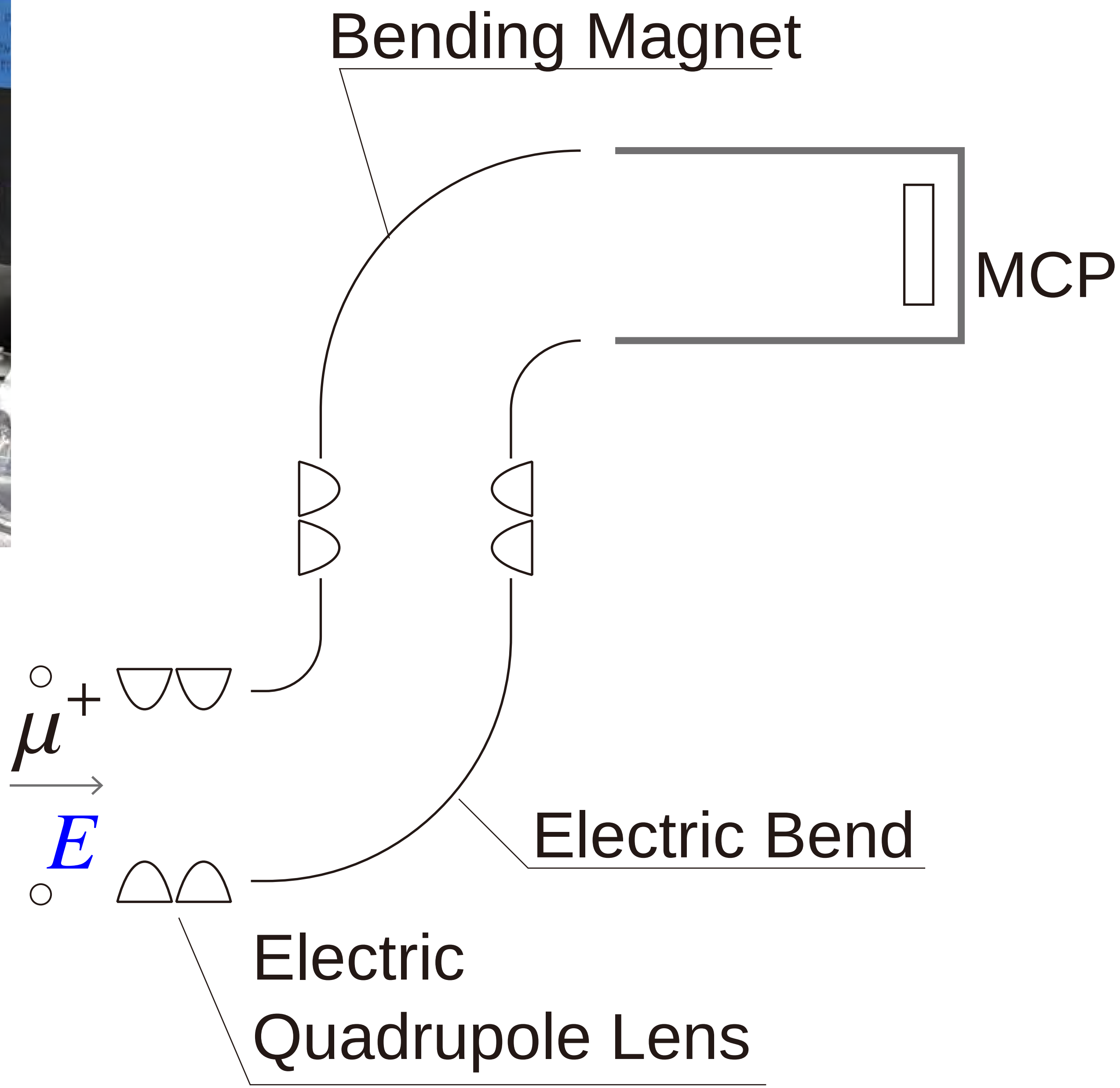


# Optical Cavity Design

- Optical cavity with rigid frame

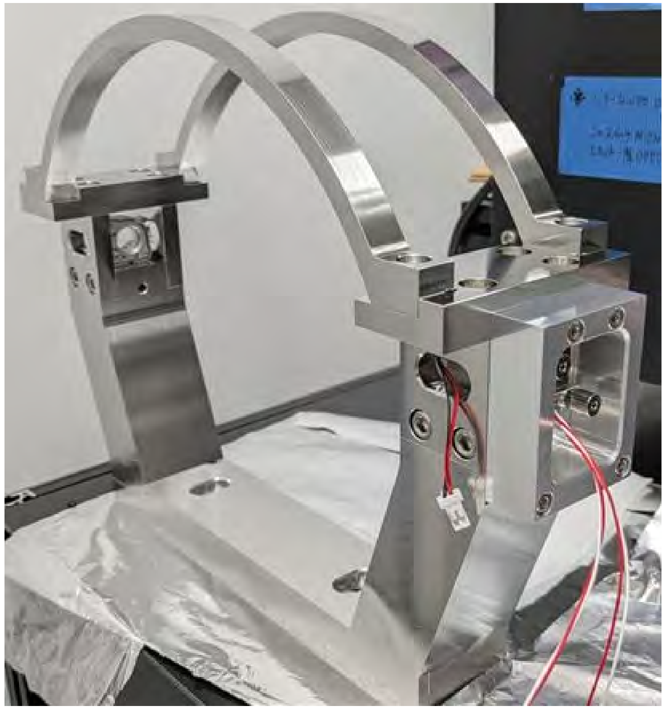


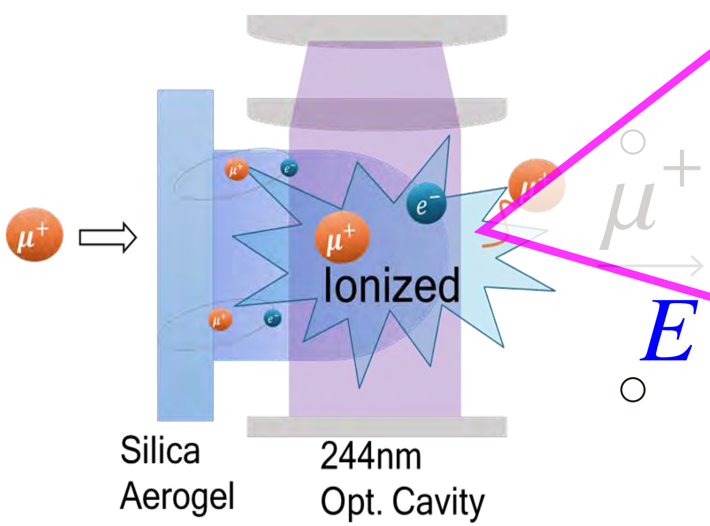


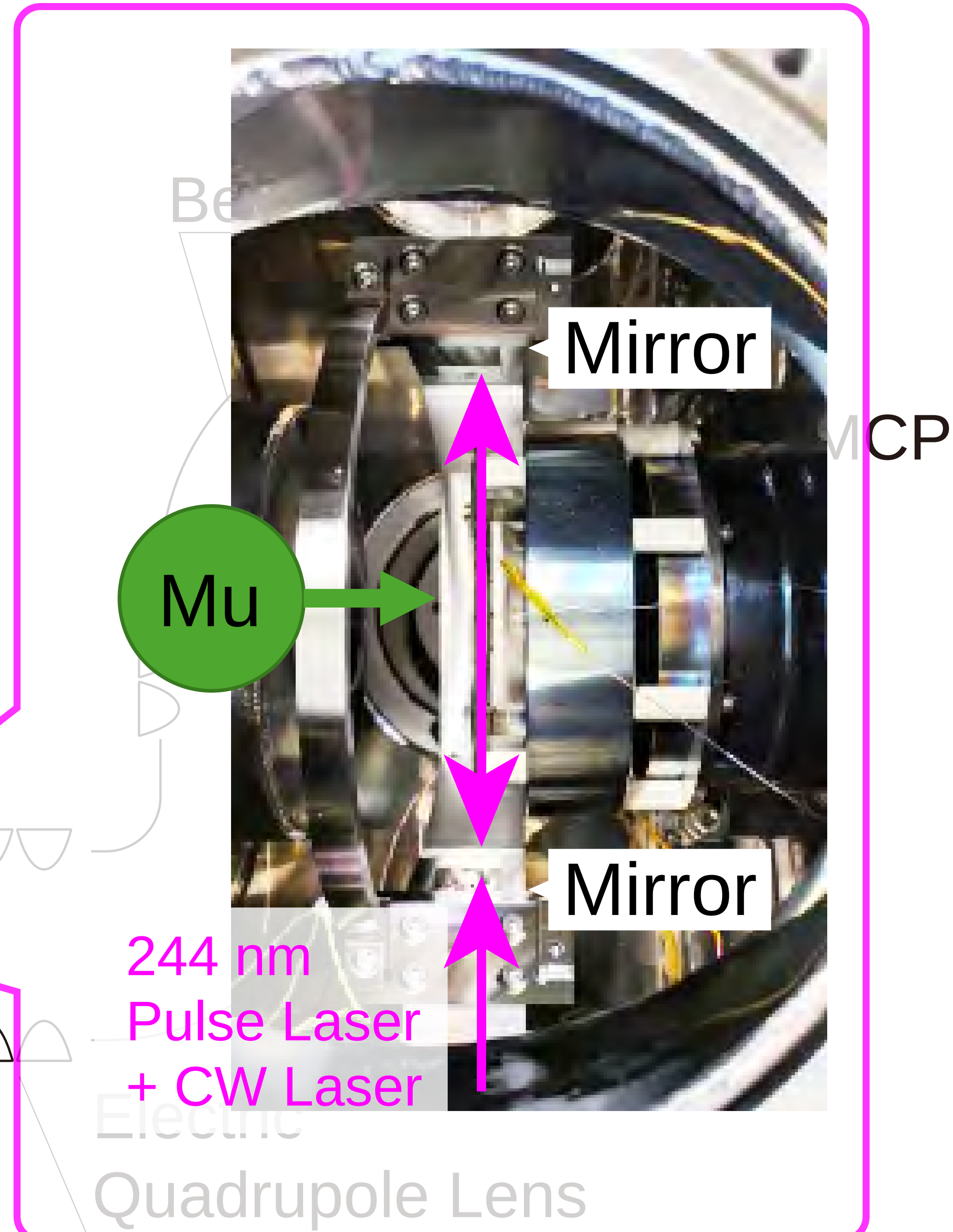



# Optical Cavity Design

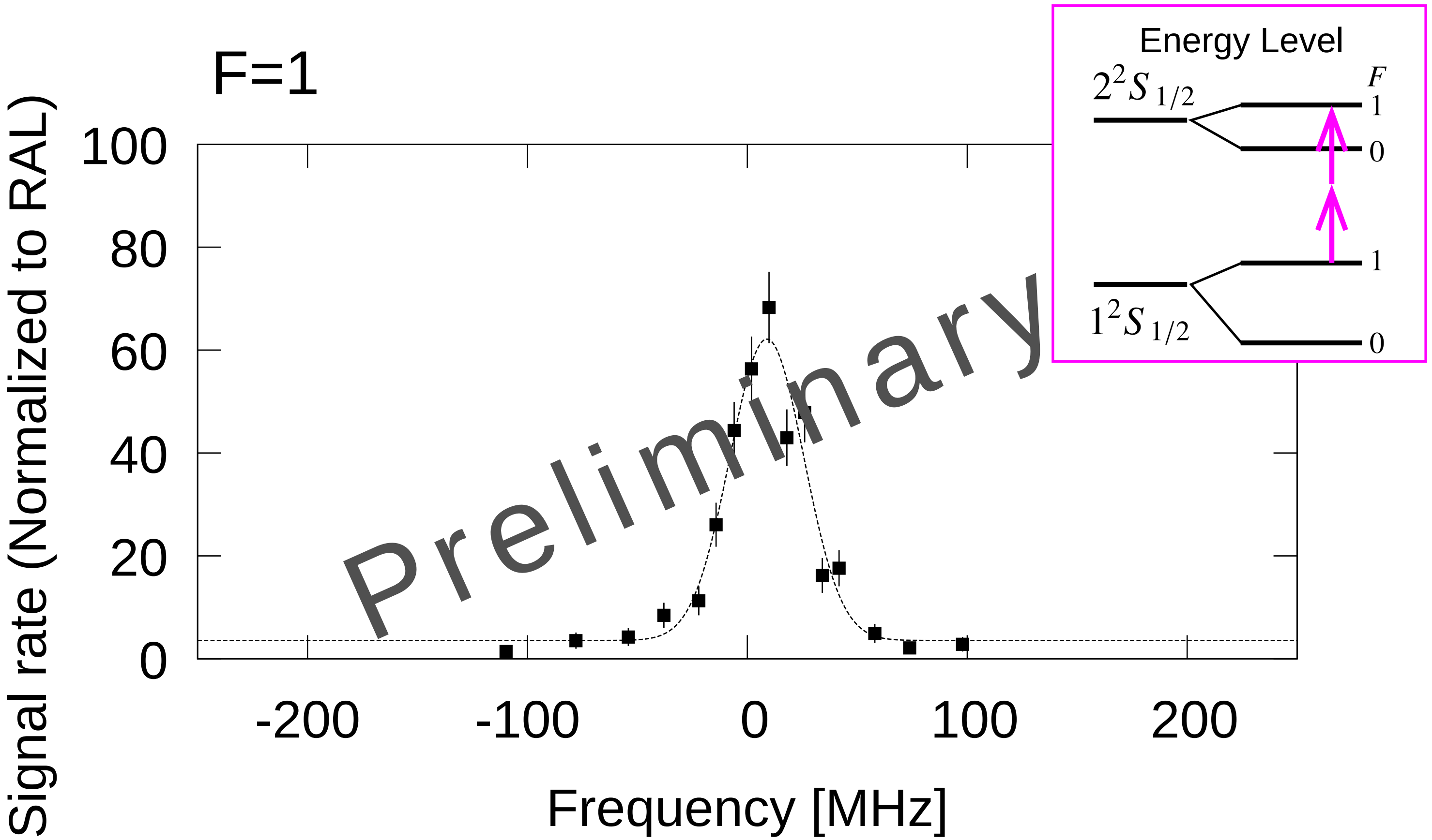
- Optical cavity with rigid frame





# 1S-2S Measurement in Optical Cavity




- Total 509 counts in 3 hours measurement
- Peak rate: 0.14 cps
- Linewidth: 40 MHz (~1/2 linewidth than RAL results)
- Signal rate will be increased in upcoming experiments (2025B, 2026)

# Summary

- Precise spectroscopy of Muonium:
  - A powerful way to search for BSM
- Mass uncertainty $u_r[m_\mu]$ of 120 ppb limits the theoretical calculation

- Muon mass $m_\mu$ can be determined precisely from laser spectroscopy of Muonium 1S-2S transition
  - 1 MHz Uncertainty of transition frequency $\rightarrow u_r[m_\mu]$ =80 ppb
    $\rightarrow$ Improve robustness of muon mass (fundamental constants)
  - 100 kHz Uncertainty $\rightarrow$ Precision test of SM would be possible

- Mu 1S-2S Laser spectroscopy at J-PARC
  - ☑ Signal rate of 300 times higher than RAL experiment
  - ☑ First observation of $F = 0 \rightarrow F' = 0$ transition
  - ☑ Laser spectroscopy in optical cavity

**Try to improve the measurement accuracy of 1S-2S interval in 2025-2026 experiments**