ETH zürich

Institute for Particle Physics
and Astrophysics

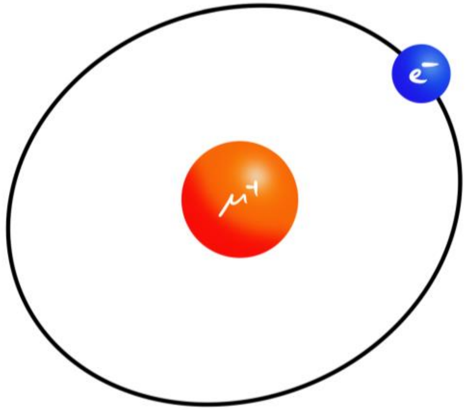
Status of Mu-MASS – Preliminary results of the Muonium Fine Structure

Philipp Blumer on behalf of the Mu-MASS collaboration
Group of Prof. Dr. Paolo Crivelli, ETHZ

Muonium (M) – a purely leptonic system

Discovered in 1960 (Hughes) by detecting muonium spin (Larmor) precession in magnetic field

Devoid from nuclear size effects
- excellent candidate to test bound-state QED
- probe fundamental constants
- look for new physics (Lorentz/CPT violation, new muonic forces, new bosons, ...)



$\tau_{\mathrm{M}} = 2.2\ \mu\mathrm{s}$

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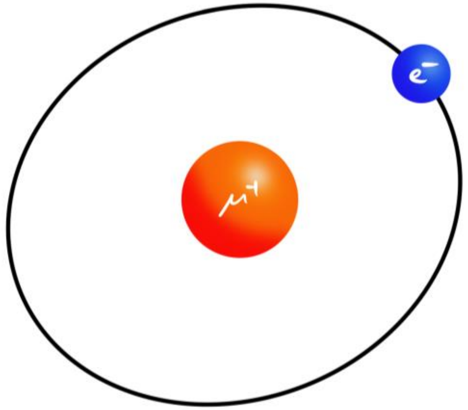
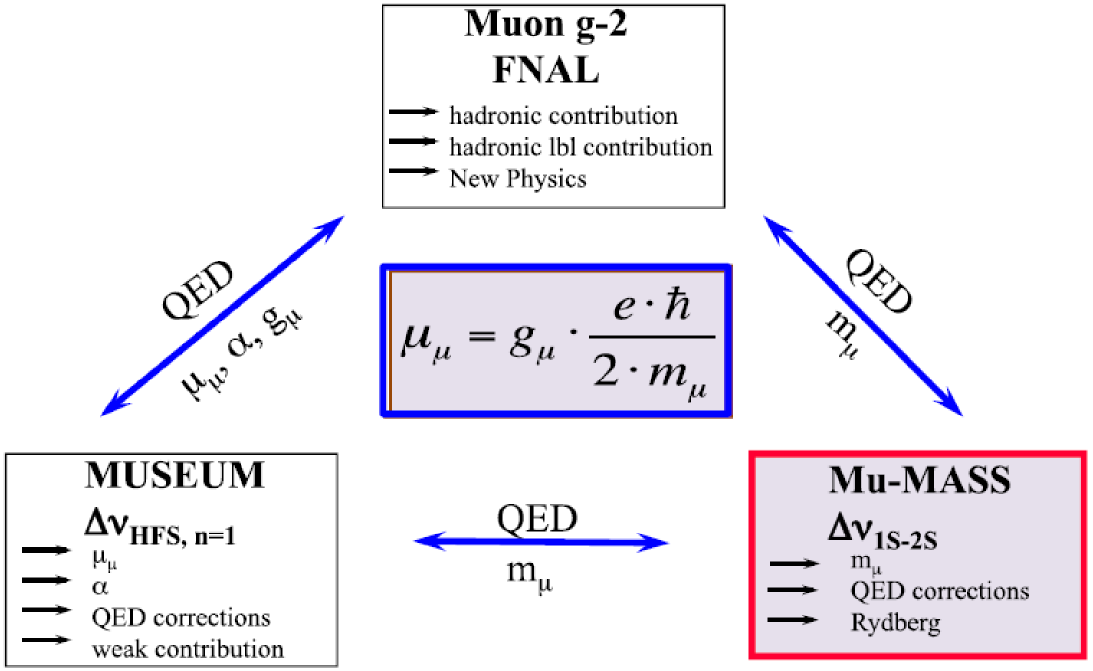
- Gravitational probe of second generation charged leptons: ongoing by LEMMING at PSI
- 1S HFS: ongoing by MUSEUM at JPARC
- 1S – 2S: ongoing by **Mu-MASS** at PSI
- $2S_{1/2} - 2P_{1/2}$: ongoing by **Mu-MASS** at PSI
- $2S_{1/2} - 2P_{3/2}$: ongoing by **Mu-MASS** at PSI

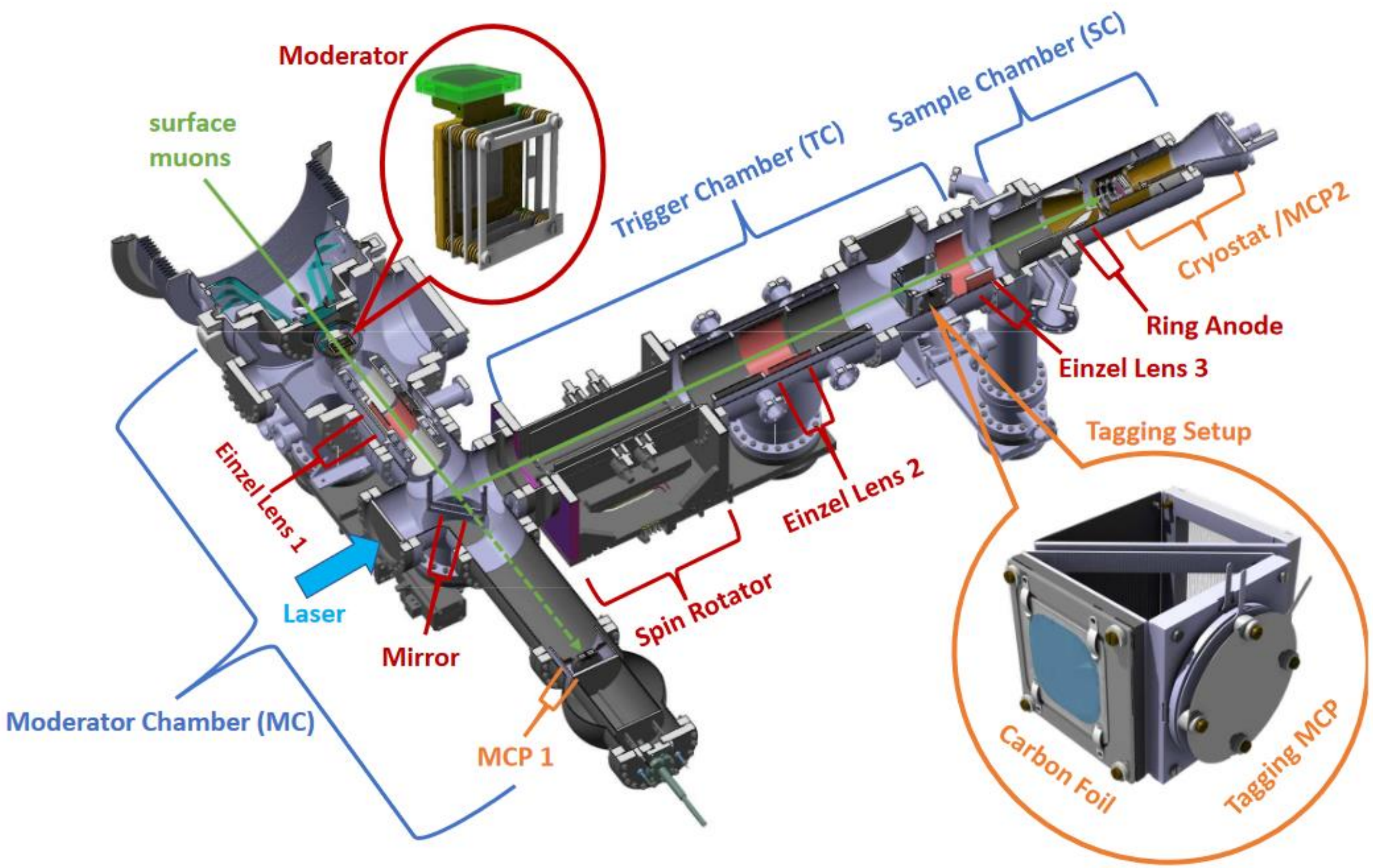


$\tau_M = 2.2\ \mu s$



Low Energy Muon (LEM) beam at Paul Scherrer Institute (PSI)

- Surface muon beam: $\sim 4\ \mathrm{MeV}$
- Cryogenic Ne/Ar moderator
- $3\ \mathrm{kHz}\ \mu^+$ rate at $1 - 30\ \mathrm{keV}$
- Muonium formation via carbon foil or mesoporous SiO_2



Mu-MASS main goal and principle

Doppler free laser spectroscopy of M 1S-2S

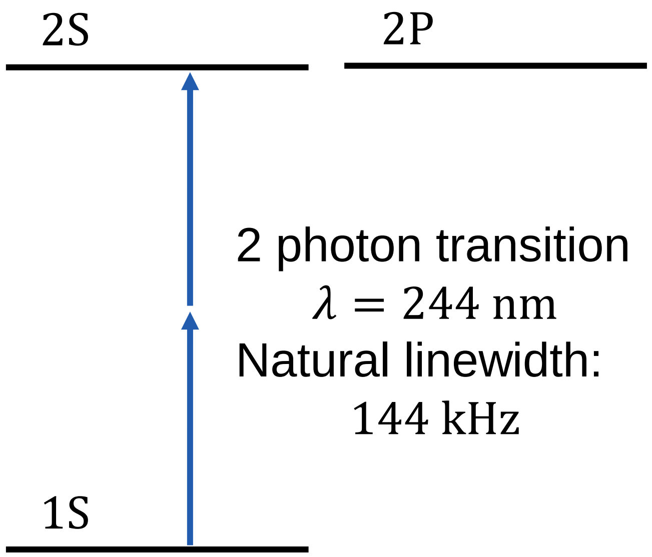
$$\Delta\nu_{1S-2S}(\text{expt.}) = 2455528941.0(9.8)\text{MHz}$$

Meyer et al. PRL 84, 1136 (2000)

$$\Delta\nu_{1S-2S}(\text{theory}) = 2455528935.4(1.4)\text{MHz}$$

Collected in I. Cortinovis et al. EPJD 77, 66 (2023)

Limited by knowledge of muon mass. QED calculations at 6kHz.



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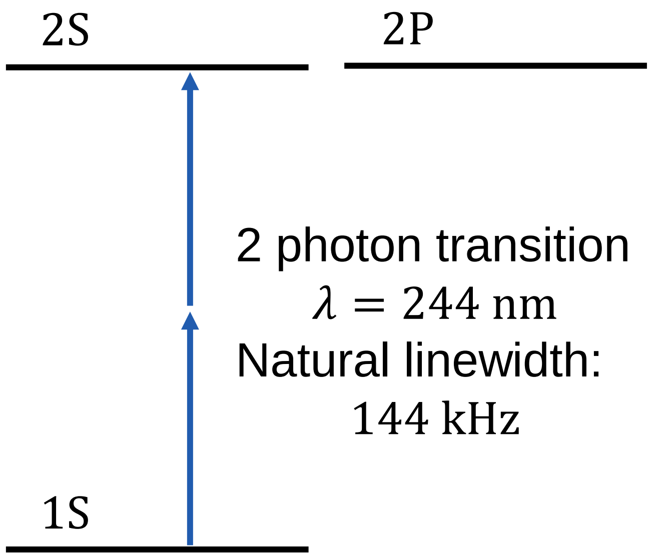
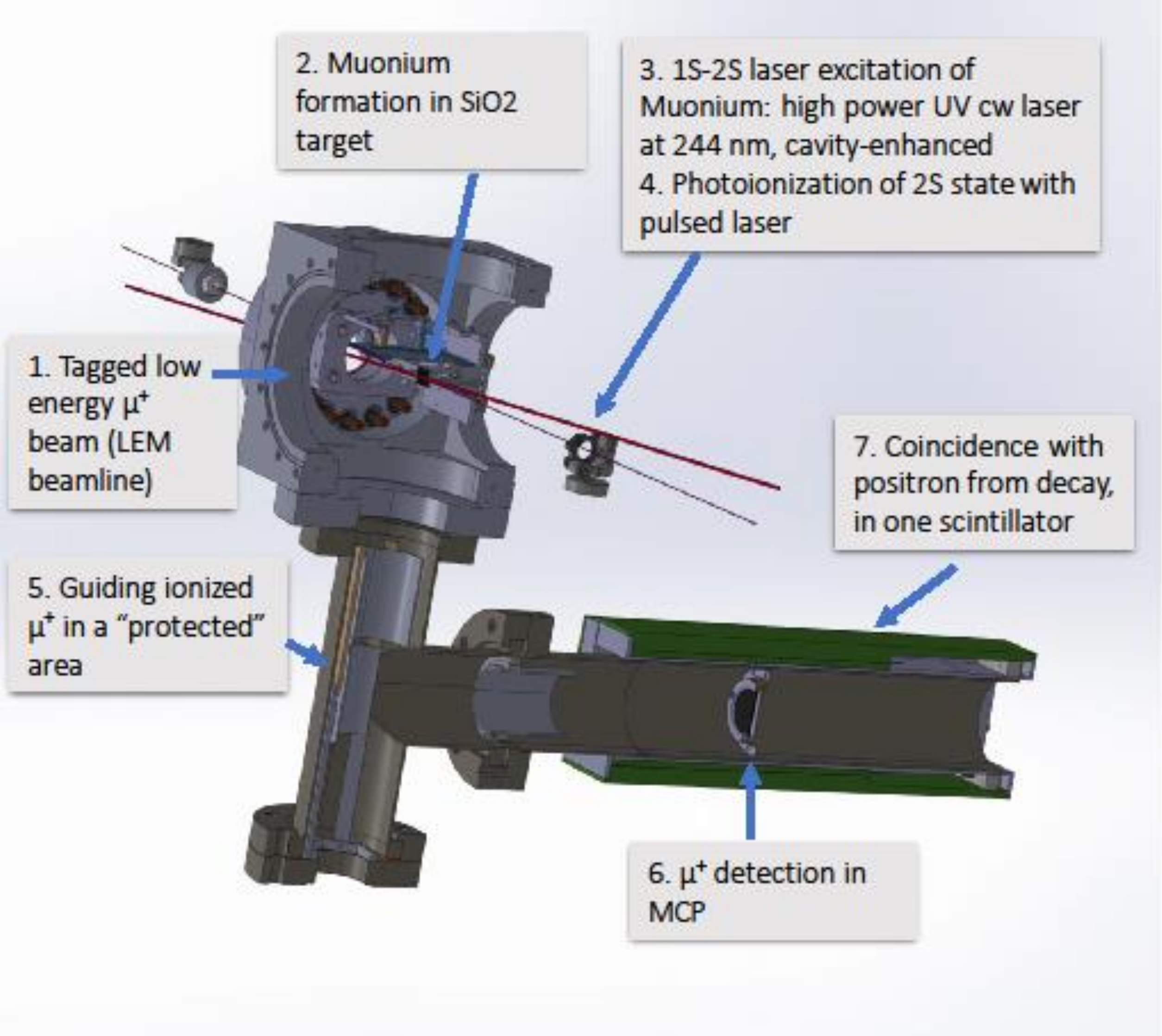




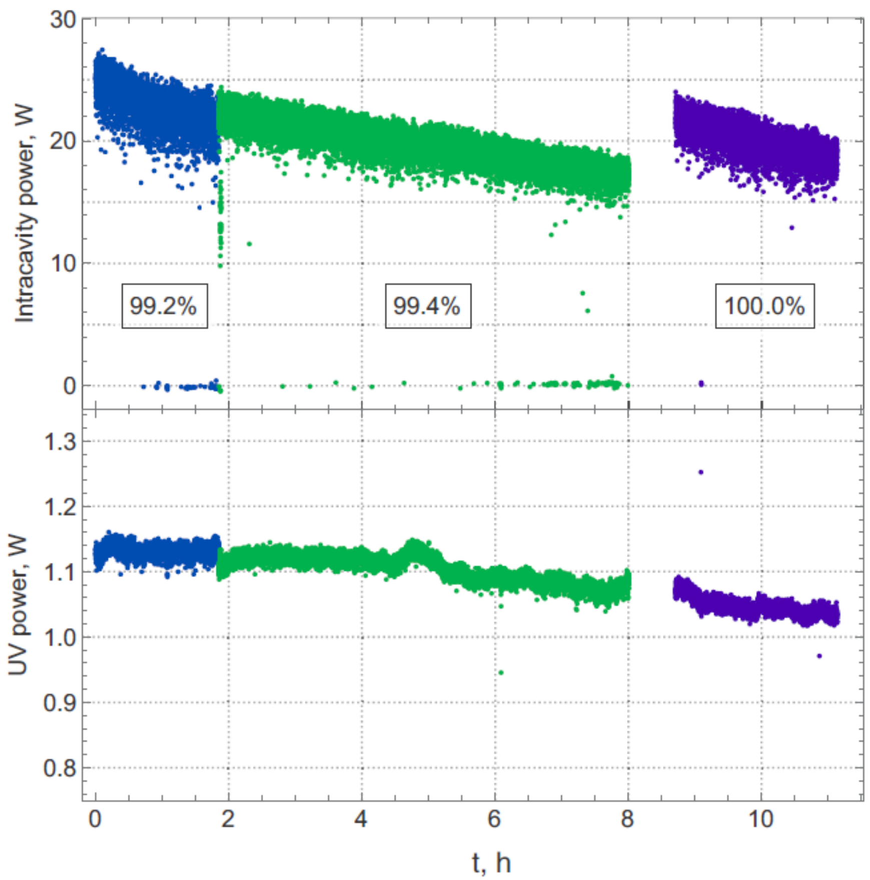
2022 beamtime at PSI

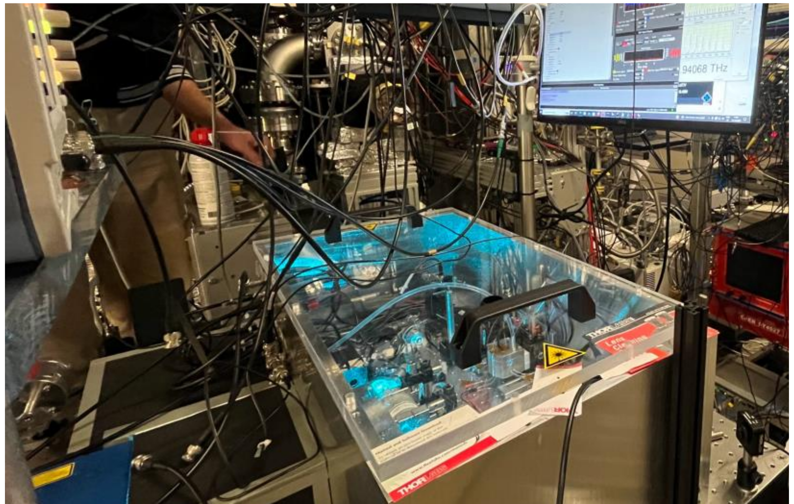
Laser development:

- Enhancement Fabry-Perot cavity: up to 40W in lab at ETHZ
  → 10x higher power than commercially available
- MgF_2 coated mirrors for in-vacuum operation
  → recover damaged optics by flowing oxygen over the mirrors

  Z. Burkley et al., Opt. Express 29, 27450 (2021)
- Pulsing cavity's internal power
  → about 1μs using an acousto-optic modulator (AOM)
- Additionally reducing background noise in other detectors

  N. Zhadnov et al., Opt. Express 31, 28470 (2023)
- Installation at LEM beamline: 40h
- Total measurement time: 65h
- Background: 0 events





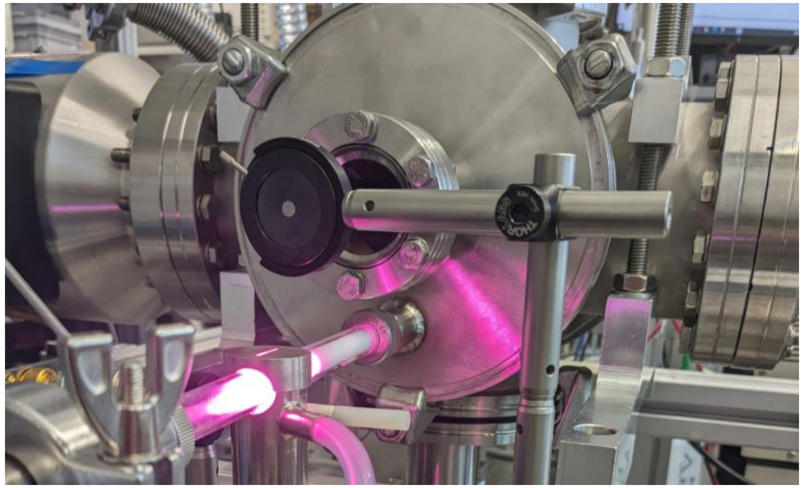
Mu-MASS 1S-2S prospects

Project restarted in summer 2024

- New PhD and postdoc

Systematic checks at ETHZ lab using hydrogen beam:

- Select fast H using chopper mimicking μ^+
- Custom tagging system to minimize impact of laser induced background on LEM tagging detector



Preliminary schedule June 2025:

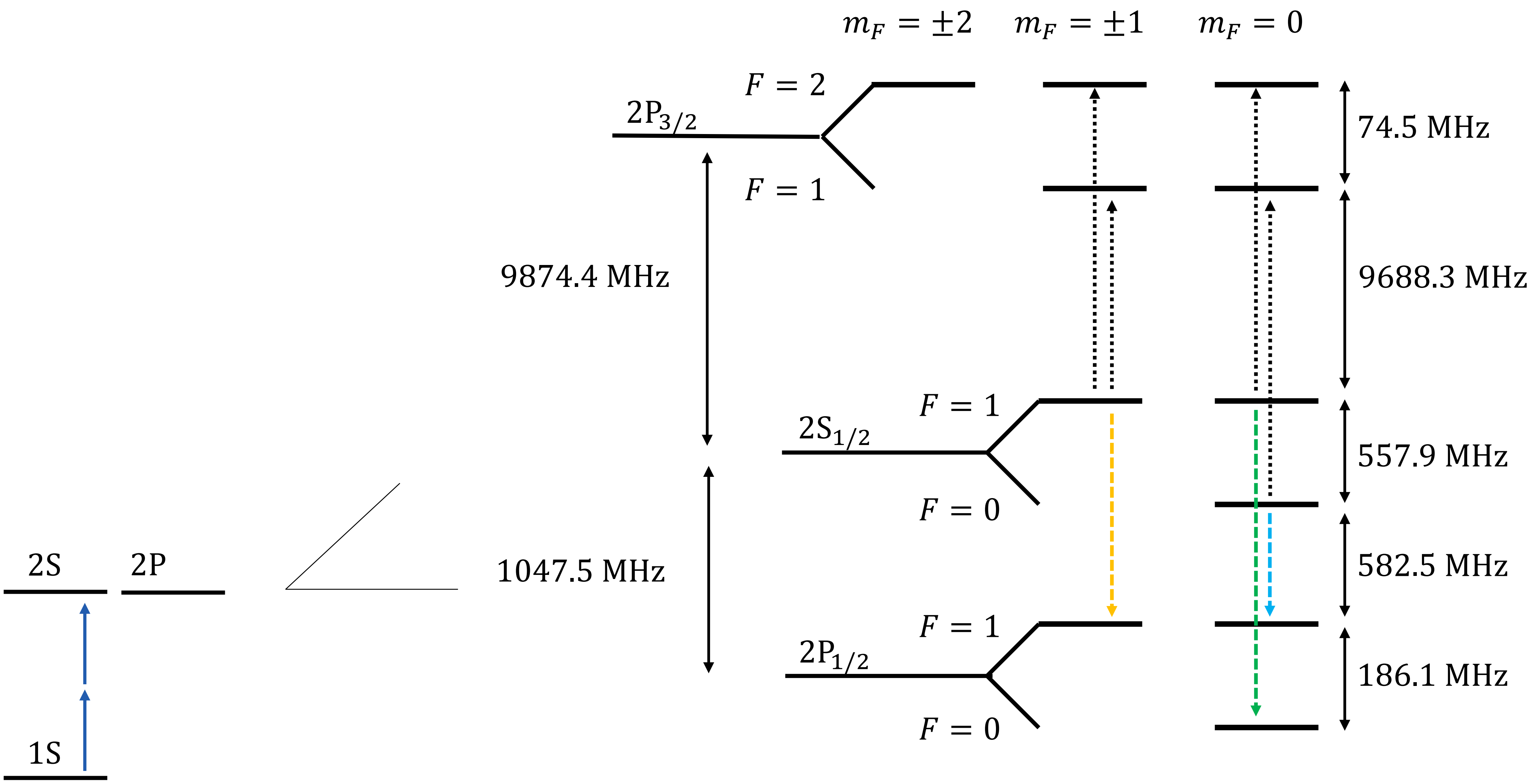
- 10 days with 25W laser power: $\delta_{\nu_{1S-2S}} = 600\text{kHz}$
- Experiment statistically limited

→ Laser at 50W increases the signal rate by factor 4

→ HiMB & muCool to increase Mu rate by factor 1000

→ Aim 10kHz uncertainty

Muonium Lamb shift using a transmission line:



Muonium Lamb shift at LEM, 2022

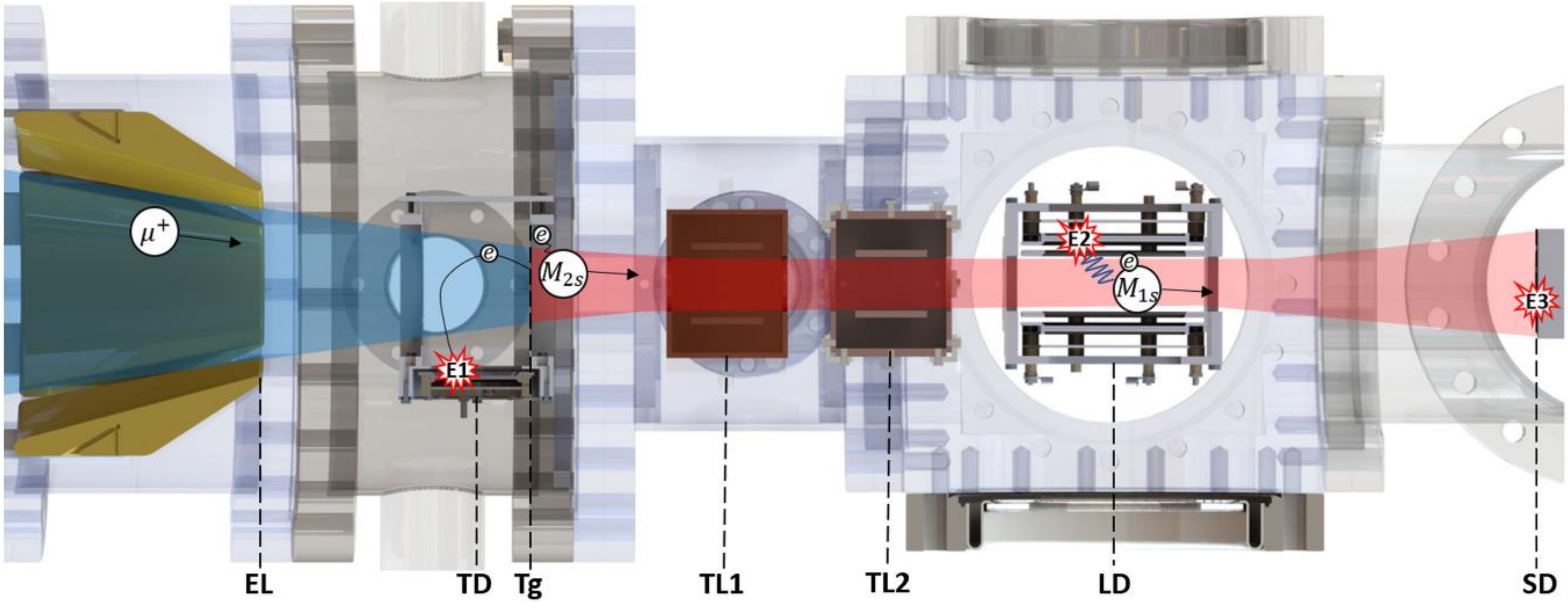
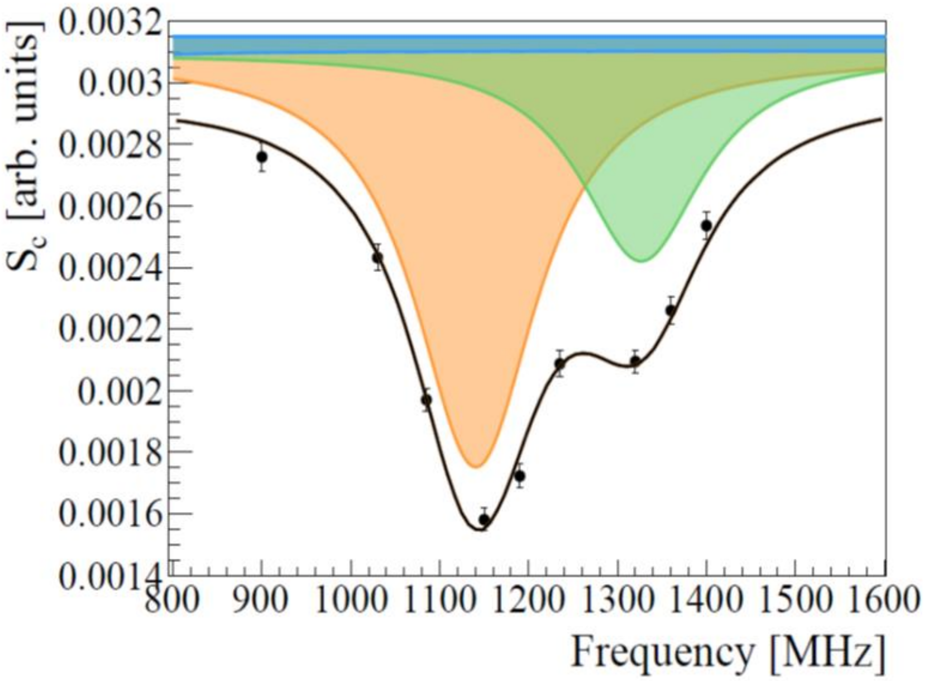
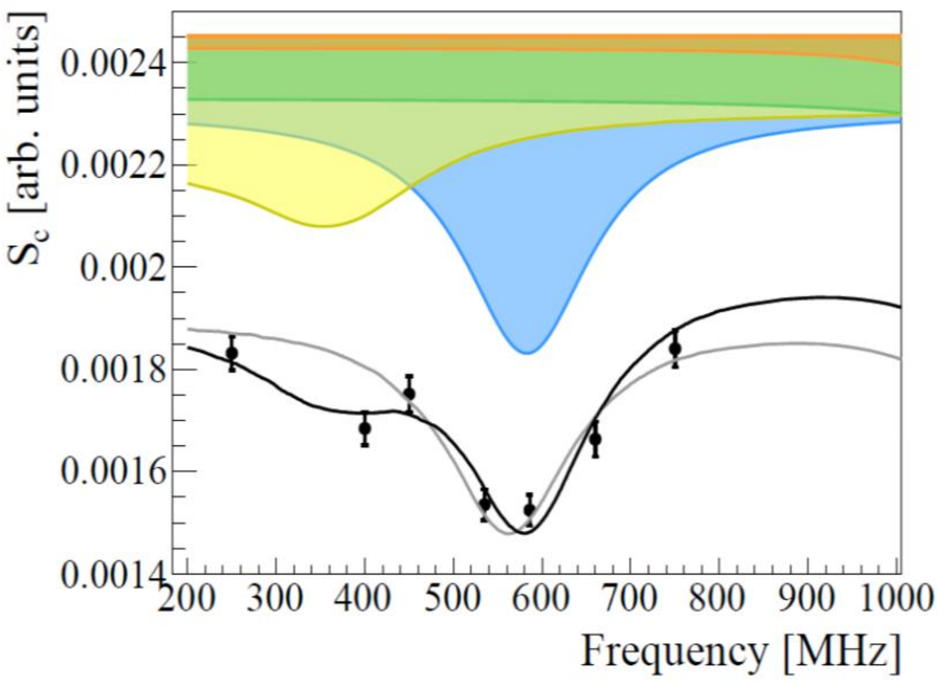


FIG. 1. Main elements of the experimental system. Conical electrostatic lens (EL), tagging detector (TD), carbon foil target (Tg), transmission line (TL), Lyman-alpha detector (LD), stop detector (SD). The normalization signal is given by the coincidence between an event in TD (E1) and SD (E3) within the expected time of flight, while a valid event includes also a reading in LD (E2).

Muonium Lamb shift at LEM, 2022





$$\Delta\nu_{2S_{1/2}-2P_{1/2}}(\text{expt.}) = 1047.2(2.5)\,\text{MHz}$$

B. Ohayon, G. Janka, et al., PRL 128, 011802 (2022)

$$\Delta\nu_{2S_{1/2}-2P_{1/2}}(\text{theory}) = 1047.498(1)\,\text{MHz}$$

G. Janka et al., EPJ Web Conf. 262, 01001 (2022)

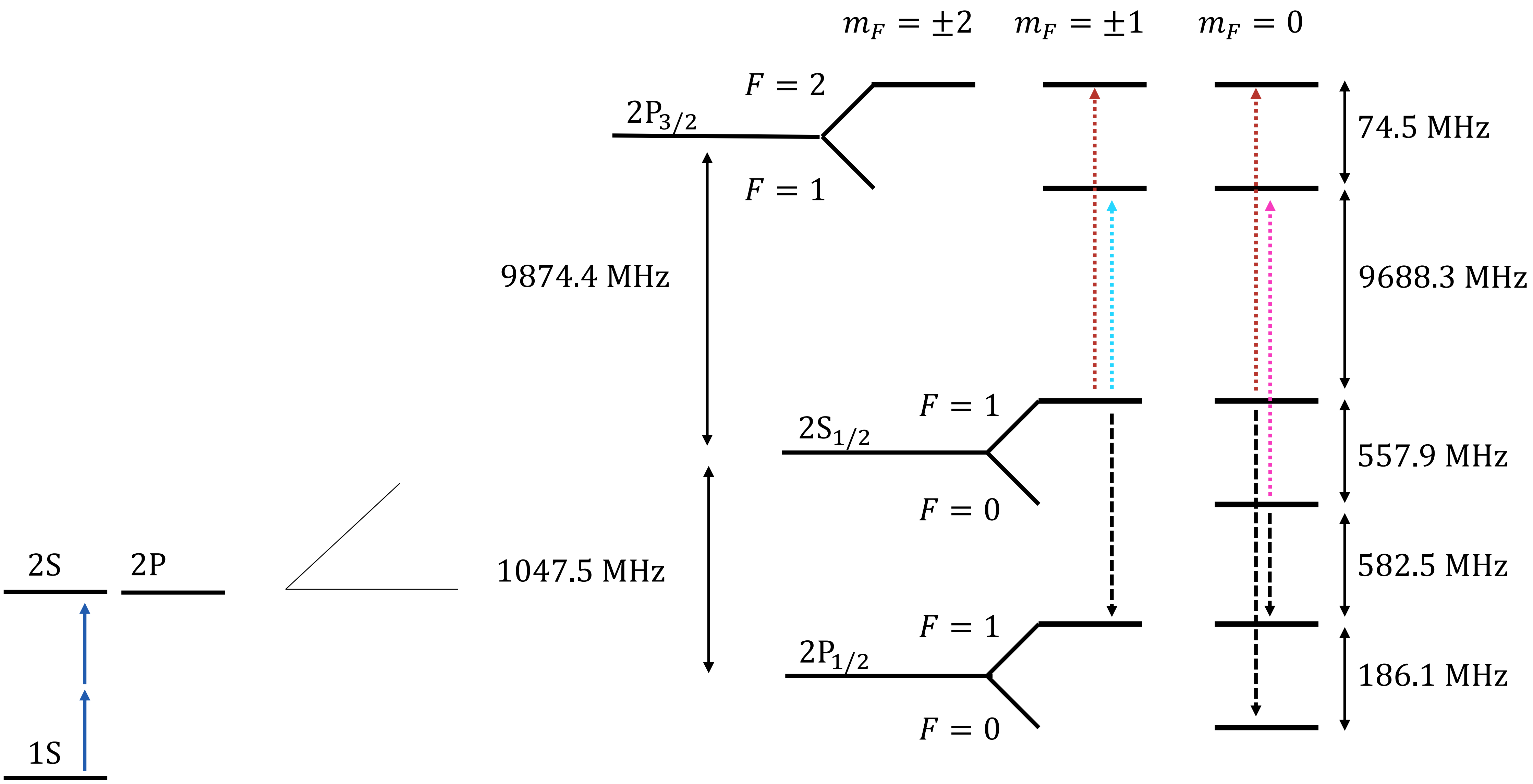
$$\Delta\nu_{2S_{1/2}-2P_{1/2}}(\text{expt.}) = 1045.5(6.8)\,\text{MHz}$$
$$\Delta\nu_{2S_{1/2},\text{HFS}}(\text{expt.}) = 559.6(7.2)\,\text{MHz}$$

First time extraction of 2S HFS in M

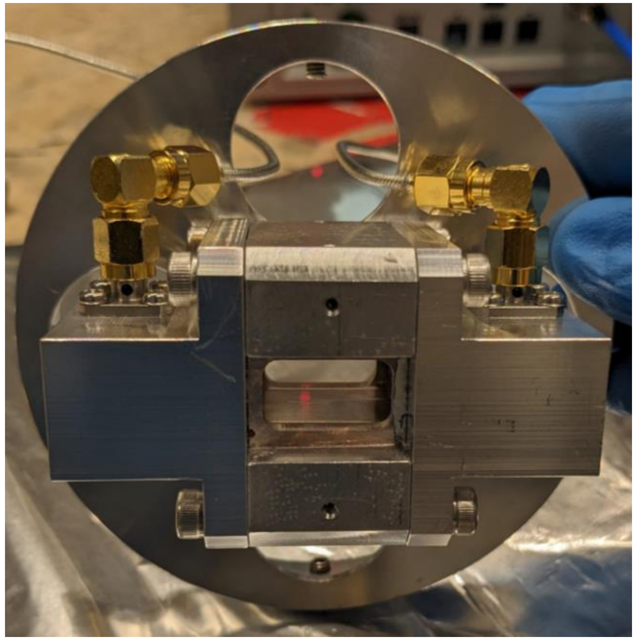
First time detection of M(3S)

G. Janka et al., Nature Commun. 13 (2022)

Muonium fine structure using a waveguide:



Muonium fine structure at LEM, 2024



First and only measurement:

- 1990 by S. H. Kettell at LAMPF
- Using microwave cavity
- Result: 9895^{+35}_{-30} MHz

Mu-MASS measurement in June 2024:

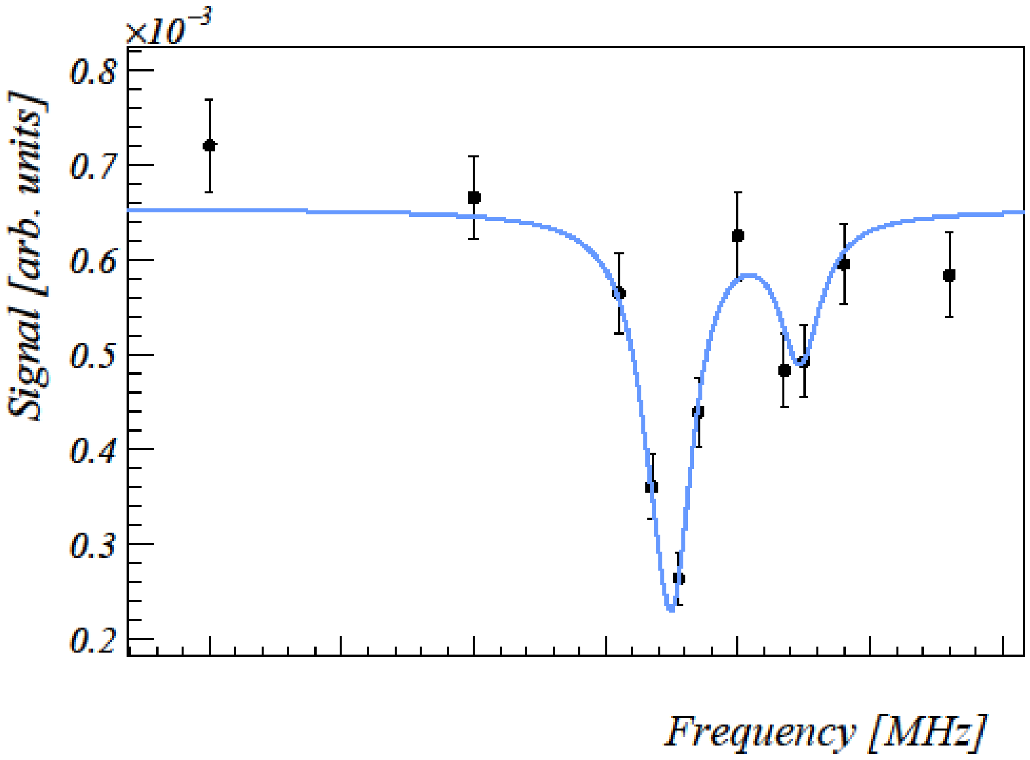
- 5d muon beamtime
- Thinner C-Foil: 7nm
- New Lyα-MCP
- Improved RF control
- Rectangular Waveguide (WR90)

→ Stronger E-Field with same input power compared to transmission line

Muonium fine structure at LEM, 2024

- Analysis ongoing → data still blinded
- Statistical uncertainty estimated by Lorentzian fit
- Systematics effects extracted from Hydrogen measurements

WG [V/cm]	Moderator	Stat. Uncertainty [MHz]	χ_r^2
60	Ar	25.1	0.73
60	Ne	18.9	0.74
30	Ne	15.4	1.18
30 / inverse	Ne	9.4	0.94
20	Ne	36.1	1.39
Total		7.0	



Looking for new physics: Standard Model Extension

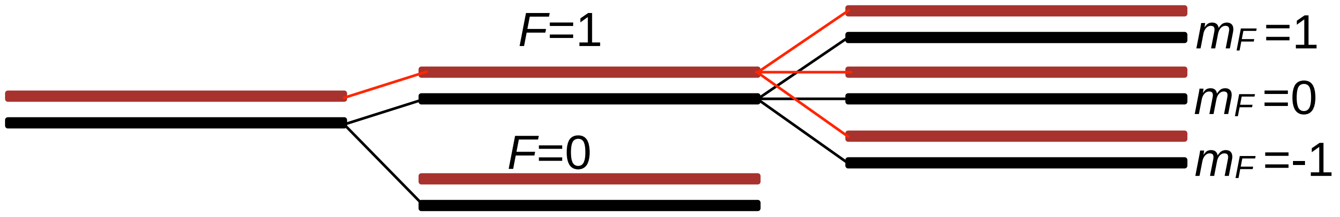
$$\mathfrak{L}_{\text{SME}} = \underbrace{\mathfrak{L}_{\text{SM}} + \mathfrak{L}_{\text{GR}}}_{\text{Conventional physics}} + \underbrace{\mathfrak{L}_{\text{LV}}}_{\text{Lorentz violation}}$$

Colladay and Kostelecky., PRD **55**, 6760 (1997)
Colladay and Kostelecky., PRD **58**, 116002 (1998)
Kostelecky., PRD **69**, 105009 (2004)

Lorentz-violating contribution

Conventional case

$$\epsilon = \epsilon_0 + \delta\epsilon$$



Looking for new physics: Standard Model Extension

$$2\pi\delta\nu_{\mathrm{Lamb}} = -\frac{2}{3}(\alpha m_{\mathrm{r}})^4(\mathring{a}_4^{\mathrm{NR}} + \mathring{c}_4^{\mathrm{NR}})$$

Lorentz and CPT ($\mathring{a}_4^{\mathrm{NR}}$)

Only Lorentz ($\mathring{c}_4^{\mathrm{NR}}$)

Transition	Coefficient	Constraint	
$1S_{1/2}$-$2S_{1/2}$	$\lvert\mathring{a}_2^{\mathrm{NR}}\rvert$	$< 8 \times 10^{-6}\ \mathrm{GeV}^{-1}$	
	$\lvert\mathring{c}_2^{\mathrm{NR}}\rvert$	$< 8 \times 10^{-6}\ \mathrm{GeV}^{-1}$	
	$\lvert\mathring{a}_4^{\mathrm{NR}}\rvert$	$< 1 \times 10^{5}\ \mathrm{GeV}^{-3}$	
	$\lvert\mathring{c}_4^{\mathrm{NR}}\rvert$	$< 1 \times 10^{5}\ \mathrm{GeV}^{-3}$	
Lamb shift	$\lvert\mathring{a}_4^{\mathrm{NR}}\rvert$	~~$< 1 \times 10^{6}\ \mathrm{GeV}^{-3}$~~	**< 1.7 x 10^5 GeV^{-3}**
	$\lvert\mathring{c}_4^{\mathrm{NR}}\rvert$	~~$< 1 \times 10^{6}\ \mathrm{GeV}^{-3}$~~	**< 1.7 x 10^5 GeV^{-3}**

A. H. Gomes et al., Phys. Rev. D, 90:076009, 2014.

Constrain additional coefficients with fine structure measurement

Mu-MASS spectroscopy prospects

Precision not enough to test b-QED, yet

- 200 kHz: Barker-Glover correction
- 50 kHz: Nucleus Self Energy correction
- < 50 kHz: many mass-dependent terms

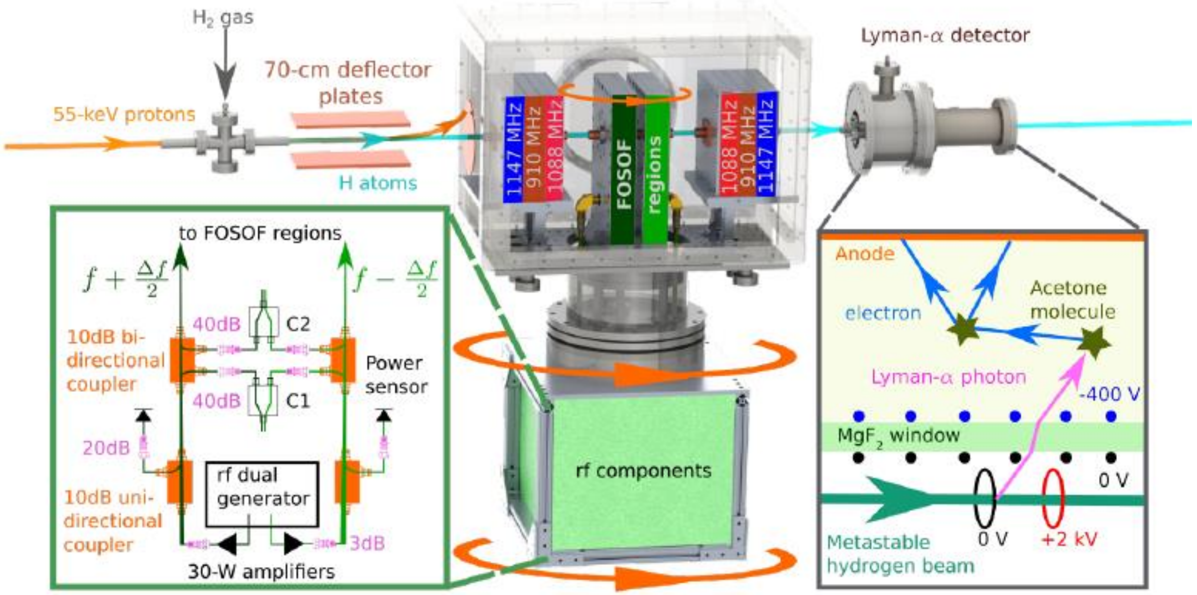
Currently still limited by statistics, not systematics

High Intensity Muon Beam:

- New target station with optimized design
- surface muon rate of $10^{10} s^{-1}$

muCool:

- Transform μ^+ beam from $4\mathrm{MeV}$ to $10\mathrm{keV}$
- Beam size reduction from $1\mathrm{cm}$ to $1\mathrm{mm}$



Bezginov et al., Science 365, 1007-1012 (2019)

Summary

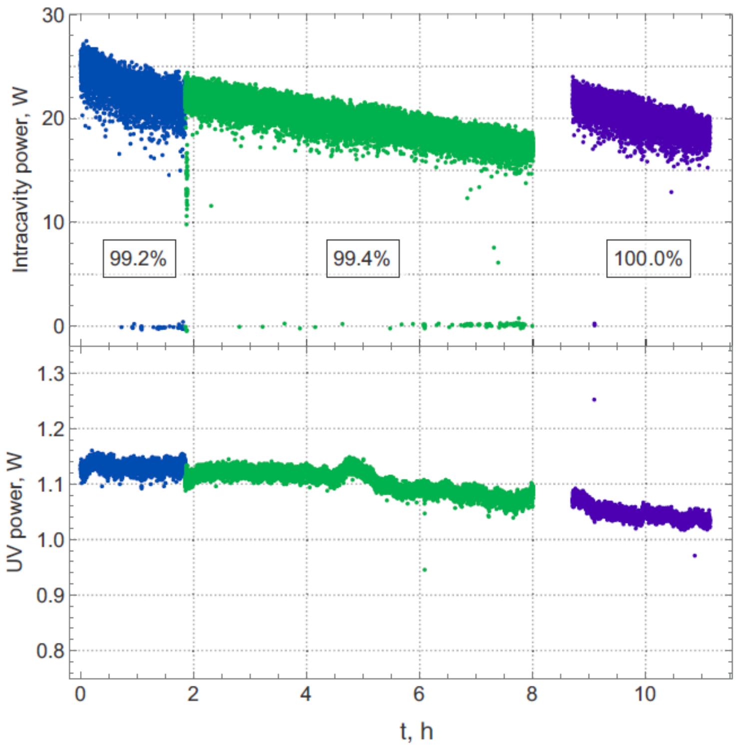
Dec. 2022 first full 1S-2S beamtime

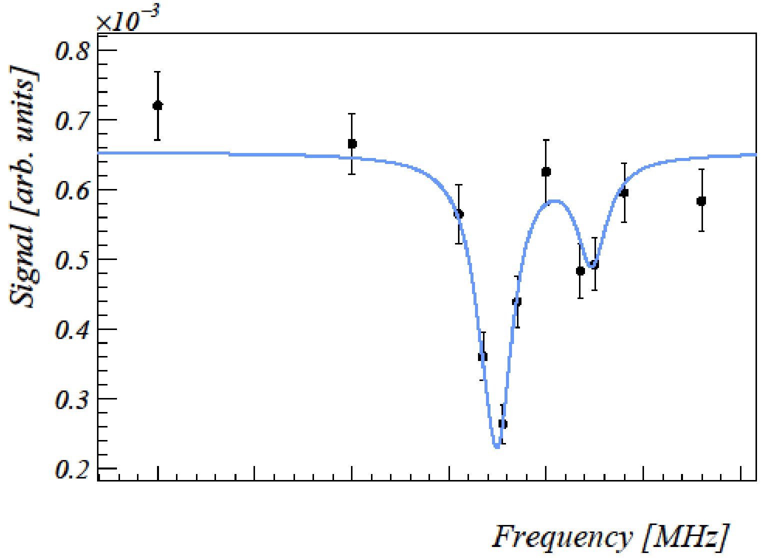
- Continuous measurement with in-vacuum cavity-enhanced UV laser at 20W
- Pulsing UV intensity to maximum only when atom inside cavity mode volume $\sim 1\mu s$
- During 3d measurement: 0 background events

→10 days with 25W laser power: $\delta_{\nu_{1S-2S}} = 600\text{kHz}$

RF spectroscopy at MHz level

- Increase statistics to probe bound-state QED
- Similar setup installed at CERN to measure antihydrogen Lamb shift and possibly fine structure
- Exploring FOSOF technique to increase precision



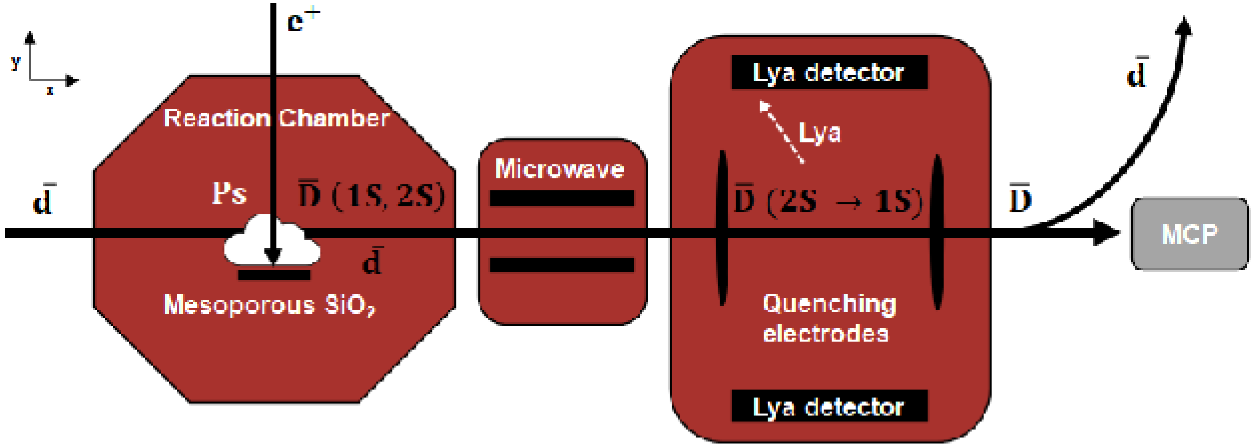


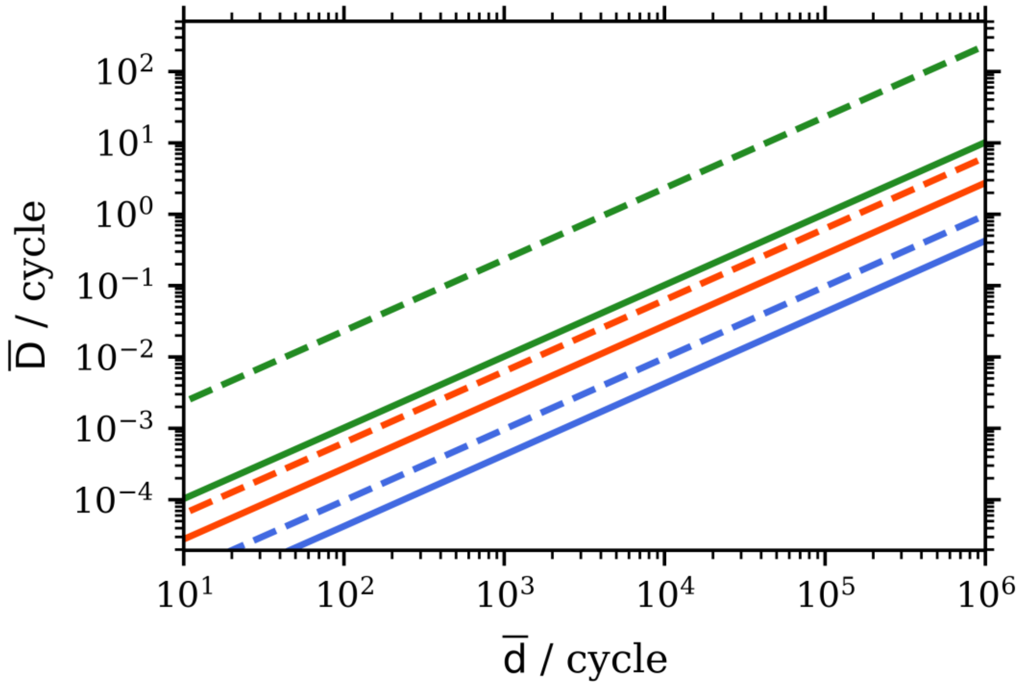
From PSI to CERN!

What about antimatter spectroscopy?

- Valuable tool in probing longstanding matter-antimatter asymmetry
- Similar Lamb shift apparatus installed and commissioned in 2021 with hydrogen at CERN
- Finite size effects (affects primarily S state)
- $\Delta E_{\mathrm{nucl}} = \frac{2}{3}\frac{(Z\alpha)^4}{n^3} m_{\mathrm{R}}^3 R_{\mathrm{p}}^2$
- At level of $1\mathrm{MHz}$ determine the antideuteron charge radius at 10% level

  → $\delta_\nu = \Delta\nu/\sqrt{N}$





arXiv:2410.00840v1

See also talk R. Caravita