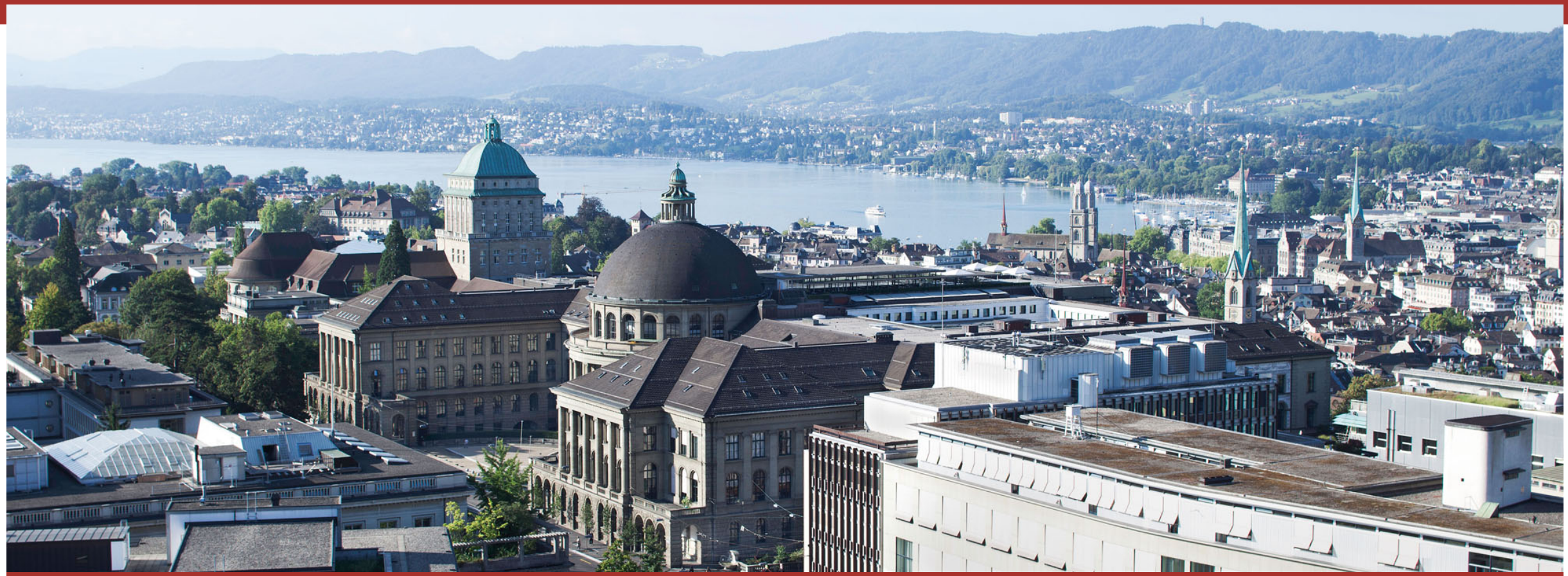


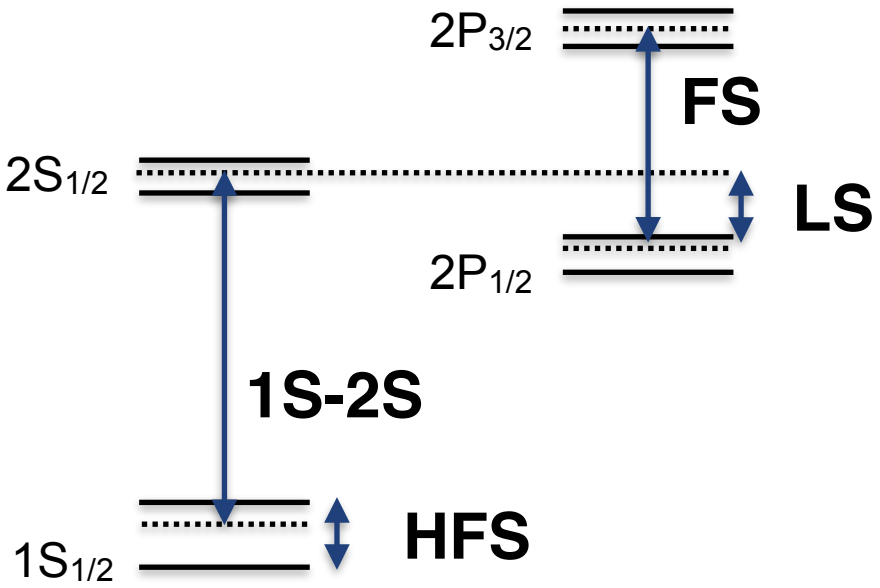
Current Status of Muonium Spectroscopy and prospects at HiMB - HiMB Physics Case Workshop - 8th of April 2021

Paolo Crivelli, Institute for Particle Physics and Astrophysics, ETH Zurich

Muonium Spectroscopy

MEASURED TRANSITIONS

→ Hyperfine splitting (HFS)
→ 1S-2S transition (1S-2S)
→ Lamb shift (LS)
→ Fine structure (FS)



MAIN RESULTS

→ Test of bound state QED free of finite size effects
→ Best determination of the muon mass and muon magnetic moment
→ Determination of the fine structure α
→ Best determination of the q_e/q_μ ratio
→ Searches for New Physics

Muonium Spectroscopy

MEASURED TRANSITIONS

→ Hyperfine splitting (HFS)
→ 1S-2S transition (1S-2S)
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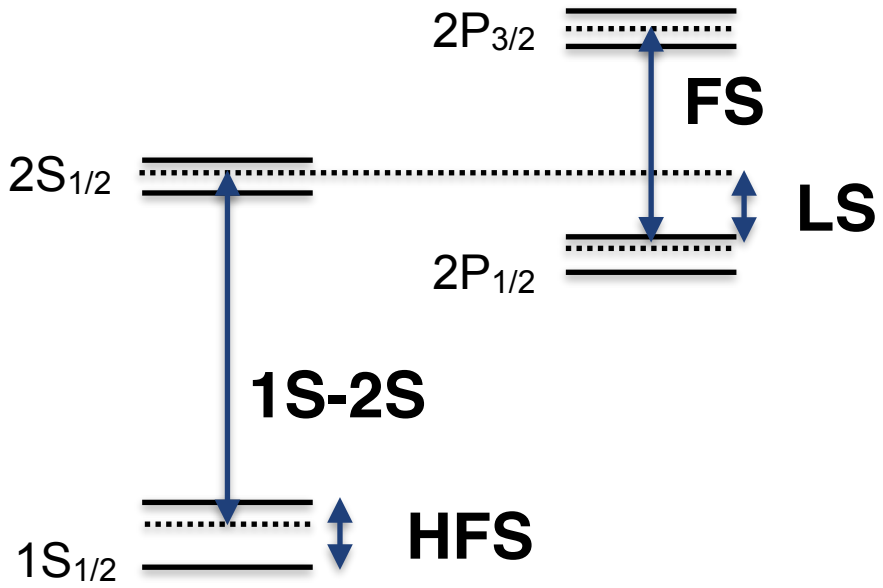
SEE TALK OF KLAUS JUNGMANN @ 16:50



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SEE TALK OF YOTAM SOREQ @ 17:25

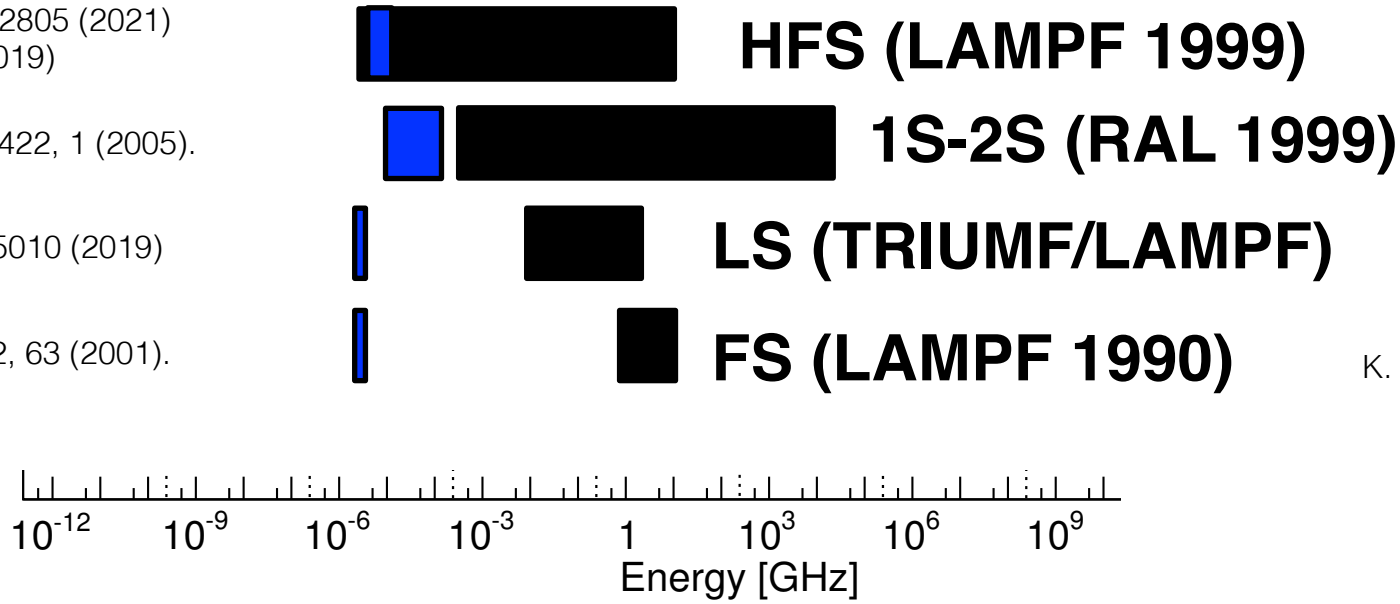
Muonium Spectroscopy - Theory vs Exp. Results

Karshenboim et al. PRA 103, 022805 (2021)
Eides, Phys. Lett. B 795, 113 (2019)

S. G. Karshenboim, Phys. Rep. 422, 1 (2005).

C. Frugiuele et al., PRD 100, 015010 (2019)

M. I. Eides et al., Phys. Rep. 342, 63 (2001).



Liu et al. PRL82, 711 (1999)

Meyer et al. PRL84, 1136 (2000)

C .J. Oram et al., PRL 52, 910 (1984)
K. Woodle et al., PRA 41, 93 (1990)

K. S. Kettel, PhD Thesis, LA—11893-T (1990)

EXP. ▮ **UNCERTAINTY (LEFT EDGE)**
MEASURED QUANTITY (RIGHT EDGE)

THEORY ▮ **UNCERTAINTY DUE TO UNCALCULATED b-QED TERMS (LEFT EDGE)**
UNCERTAINTY FROM KNOWLEDGE m_μ/m_e (RIGHT EDGE)

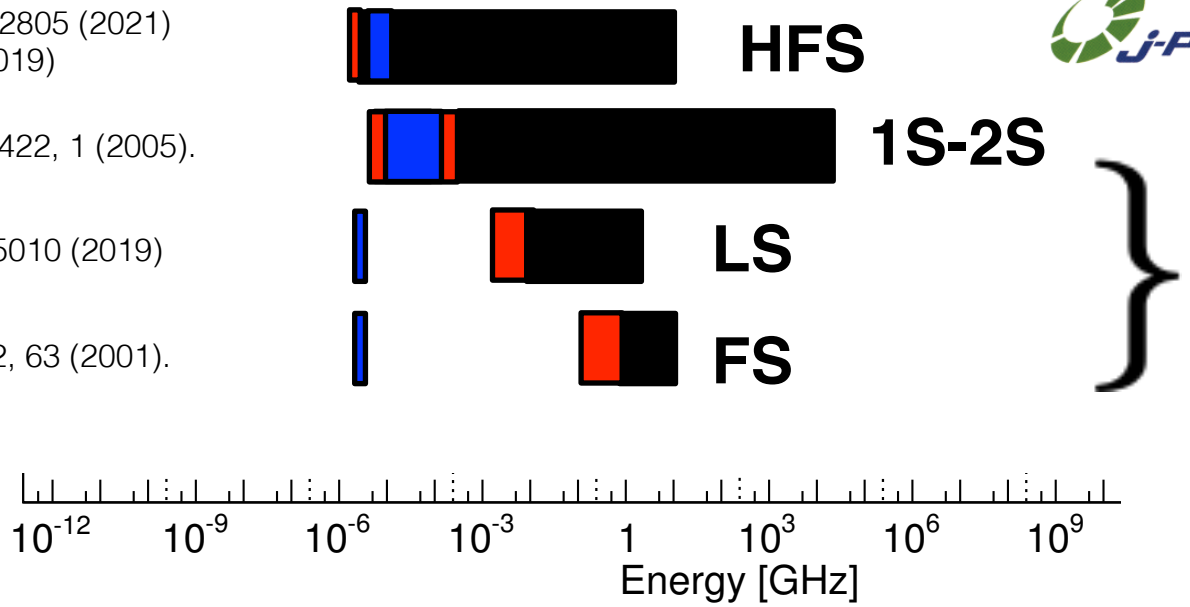
Muonium Spectroscopy - Theory vs ongoing Exp.

Karshenboim et al. PRA 103, 022805 (2021)
Eides, Phys. Lett. B 795, 113 (2019)

S. G. Karshenboim, Phys. Rep. 422, 1 (2005).

C. Frugiuele et al., PRD 100, 015010 (2019)

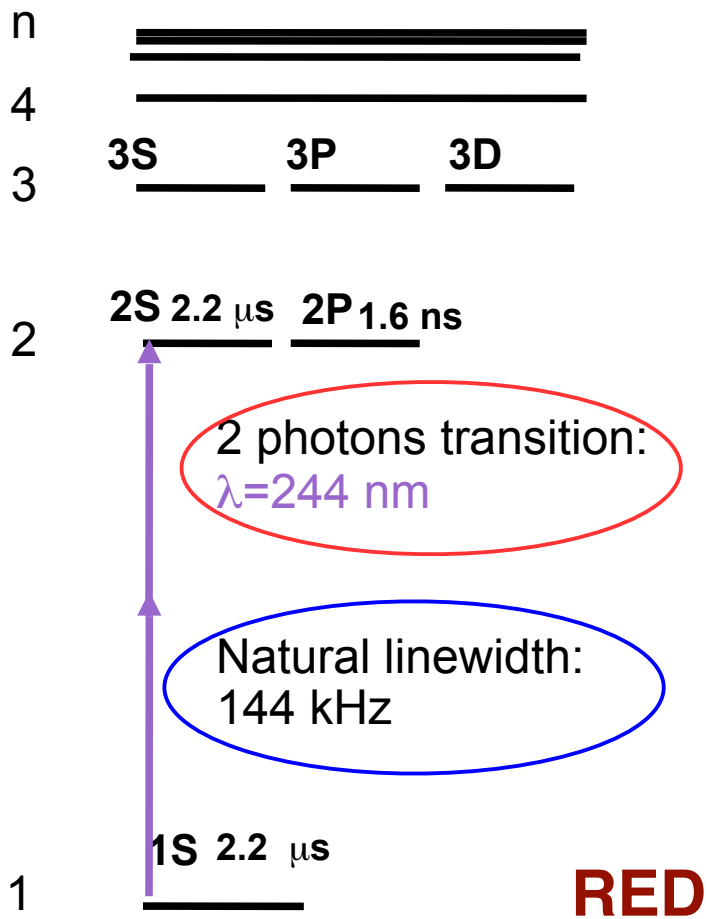
M. I. Eides et al., Phys. Rep. 342, 63 (2001).



EXP. **PROJECTED UNCERTAINTY (LEFT EDGE)**
MEASURED QUANTITY (RIGHT EDGE)

THEORY **UNCERTAINTY DUE TO UNCALCULATED b-QED TERMS (LEFT EDGE)**
UNCERTAINTY FROM KNOWLEDGE m_μ/m_e (RIGHT EDGE)

Muonium 1S-2S: current status theory/experiment



$$\Delta\nu_{1S2S}(\text{expt.}) = 2455528941.0(9.8)\ \text{MHz}$$

Meyer et al. PRL84, 1136 (2000)

$$\Delta\nu_{1S2S}(\text{theory}) = 2455528935.4(1.4)\ \text{MHz}$$

Limited by knowledge of muon mass.
QED calculations at 20 kHz *S. G. Karshenboim, Phys. Rep. 422, 1 (2005)*

REDUCED MASS CONTRIBUTION: 1.187 THz (4800 ppm)

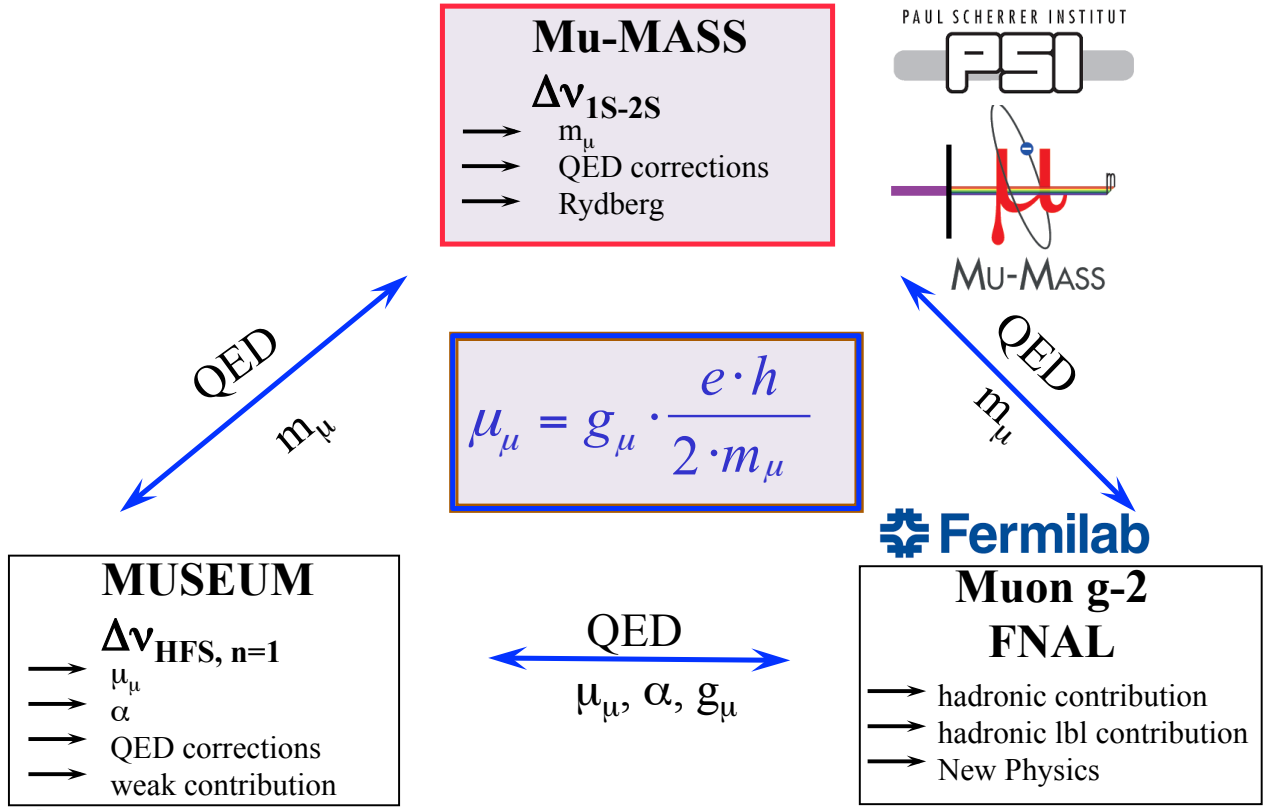
$$m_{\mu^+}/m_{e^-} = 206.76838(17)$$

Mu-Mass: Goal and Output

Mu-MASS: Measure **1S-2S transition** with Doppler free laser spectroscopy
GOAL: improve by 3 orders of magnitude (10 kHz, 4 ppt)

OUTPUT

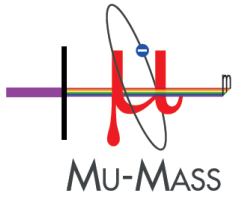
→ **Muon mass @ 1 ppb**
→ Ratio of q_e/q_μ @ 1 ppt
→ Search for New Physics
→ **Test of bound state QED (1×10^{-9})**
→ **Rydberg constant @ ppt level**
→ New determination of α @ 1 ppb
→ Input to muon g-2



Adapted from K. Jungmann, DPG 2017 (Mainz)

Mu-MASS: muonium laser spectroscopy prospects @ HiMB

	RAL (1999)	Mu-MASS Phase1	Mu-MASS Phase2	Mu-MASS Phase 3 **HiMB**
μ^+ beam intensity	3500×50 Hz	5000 s^{-1}	> 9000 s^{-1}	5×10^5 s^{-1}
μ^+ beam energy	4 MeV	5 keV	5 keV	5 keV
M atoms	600 s^{-1} @ 300K	1000 s^{-1} @ 300 K	1800 s^{-1} @ 100 K	$1. \times 10^5$ s^{-1} @ 100 K
Spectroscopy	Pulsed laser	CW	CW	CW
Experimental linewidth	20 MHz	1 MHz	300 kHz	300 kHz
Laser chirping	10 MHz	0 kHz	0 kHz	0 kHz
Residual Doppler shift uncert.	3.4 MHz	0 kHz	0 kHz	0 kHz
2nd-order Doppler shift uncert.	44 kHz	15 kHz	1 kHz (corrected)	$<$ 1 kHz (corrected)
Frequency calibration uncert.	0.8 MHz	$<$ 1 kHz	$<$ 1 kHz	$<$ 1 kHz
Background events	2.8 events/day	1.6 events/day	1.6 events/day	1.6 events/day
Total number of 2S events	99	1000 (10 d)	$>$ 7000 (40 d)	$> 1 \times 10^6$ (10 d)
Statistical uncertainty	9.1 MHz	$<$100 kHz	10 kHz	1 kHz
Total uncertainty	9.8 MHz	$<$100 kHz (linewidth/10)	10 kHz (linewidth/30)	1 kHz (linewidth/300)



MAIN OUTPUTS

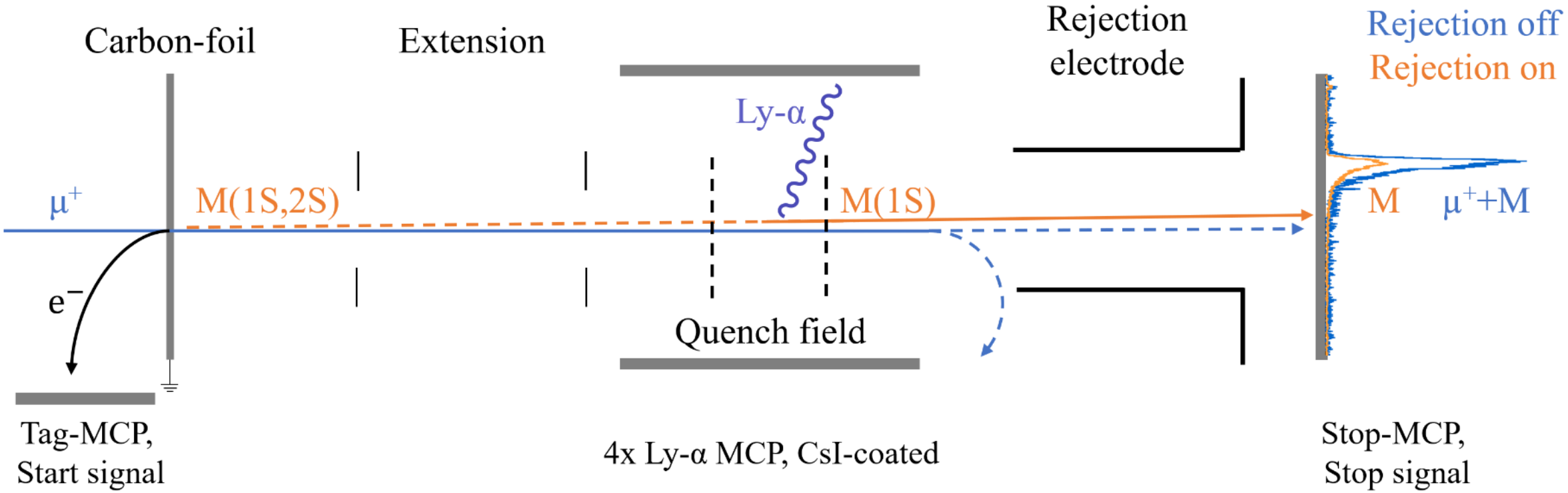
→ Muon mass @ 0.1 ppb/ determination of Rydberg constant @ < ppt level /test NP

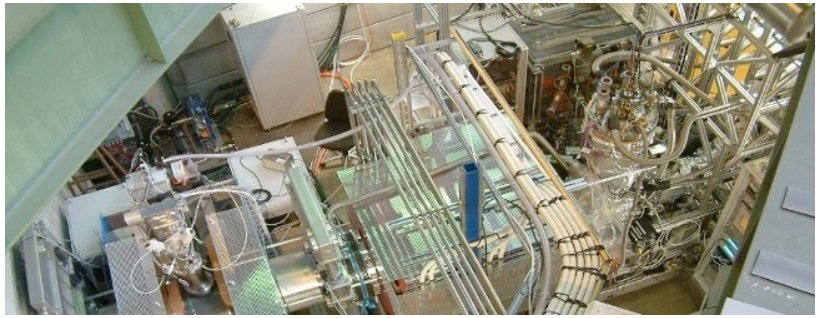
PROBE **ADDITIONAL TRANSITIONS 1S-3S, 2S-8D, 2S->Rydberg:**

- Combining determination of 1S-2S @ 1 kHz and 2S-8D @ 10 kHz R test of b-QED + NP

SEE TALKS OF DYLAN YOST @ 17:10 AND BEN OHAYON @ 17:50

Detection of the 2S states (beamtime at LEM Dec. 2019)

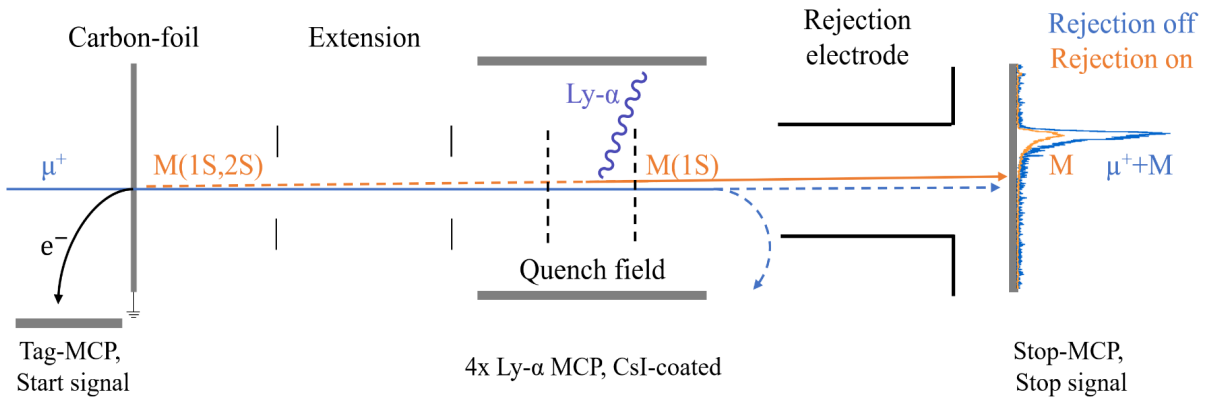


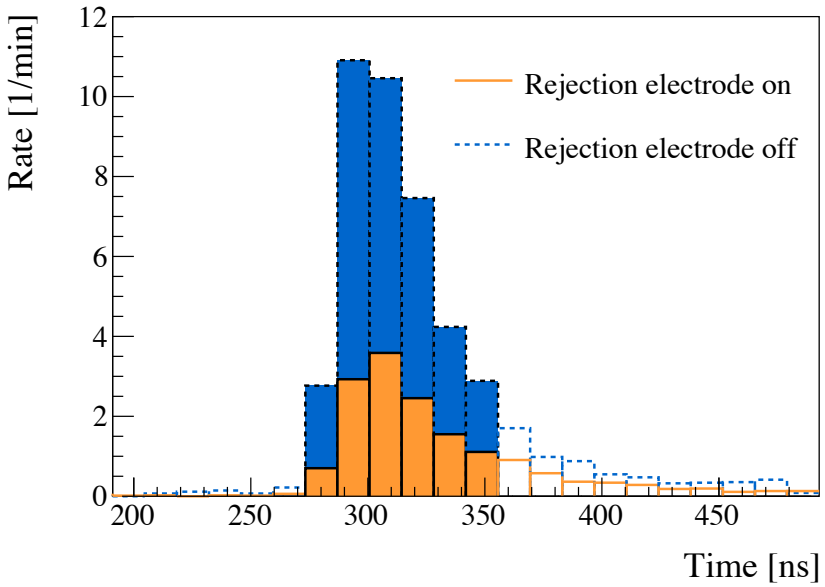


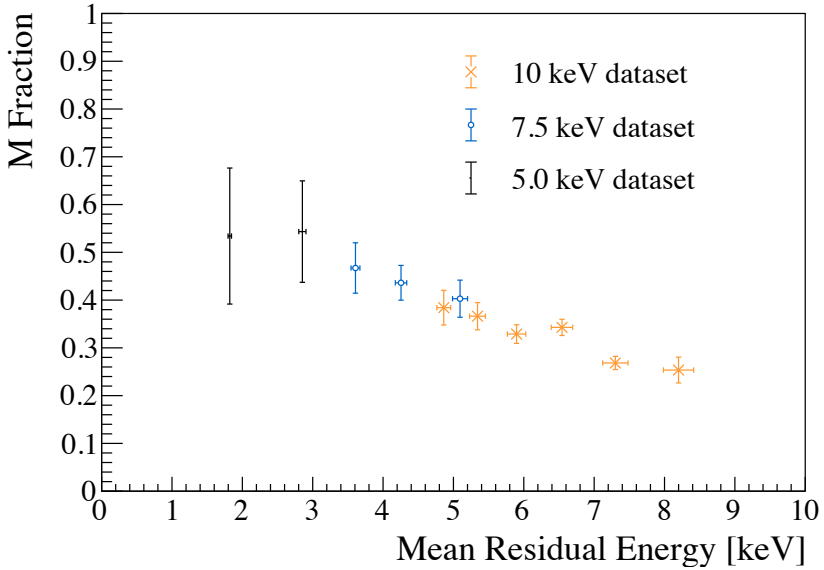
Low Energy Muons (LEM)

PAUL SCHERRER INSTITUT PSI

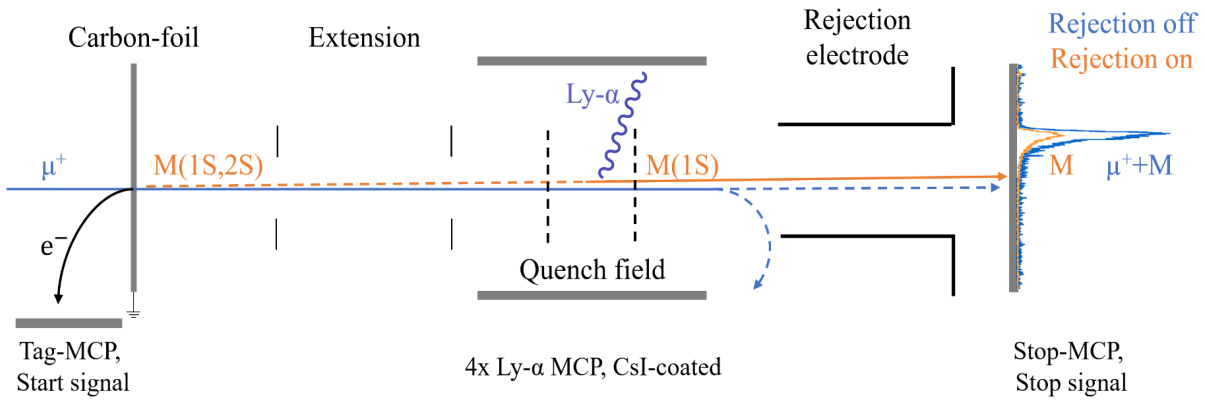
Muonium formation with a C-foil

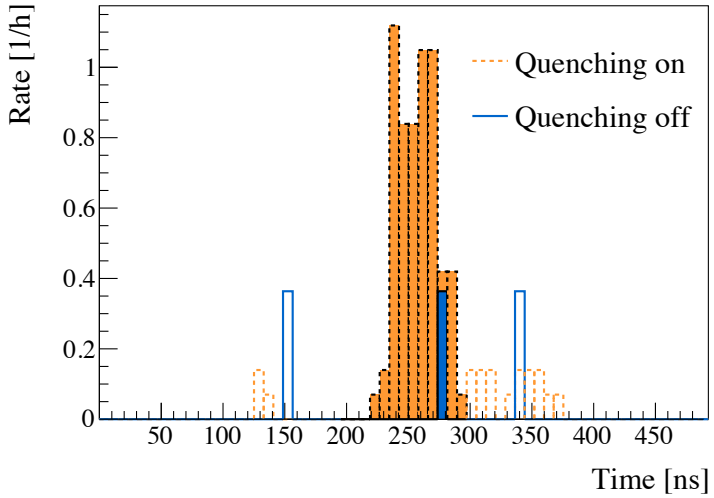






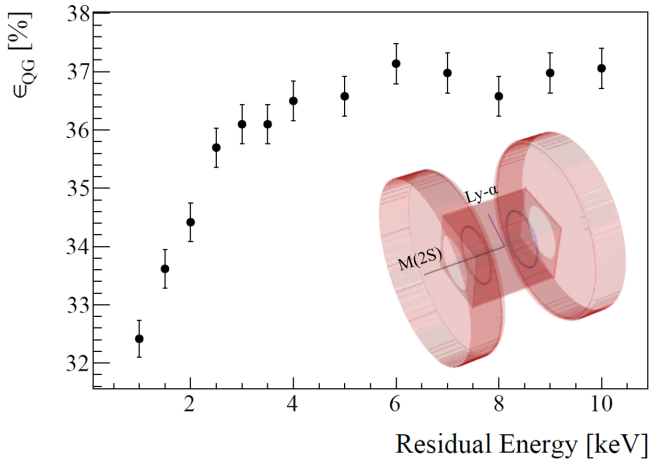
Detection of muonium in 2S state





Quenching efficiency and geometrical acceptance from MC

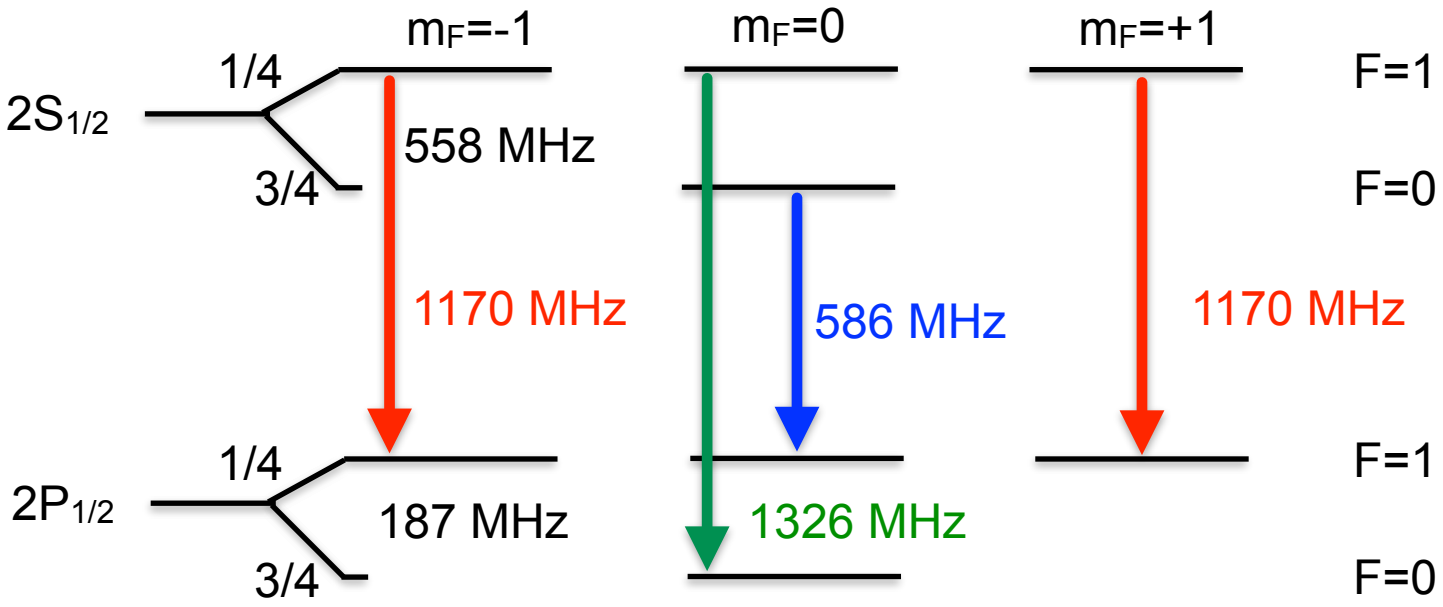
$$f_{2S/M} = 10 \pm 2\%$$



INTENSE 2S M BEAM -> POSSIBILITY TO IMPROVE THE M LAMB SHIFT

G. Janka et al., Eur. Phys. J. C (2020) 80: 804

Muonium Lamb shift



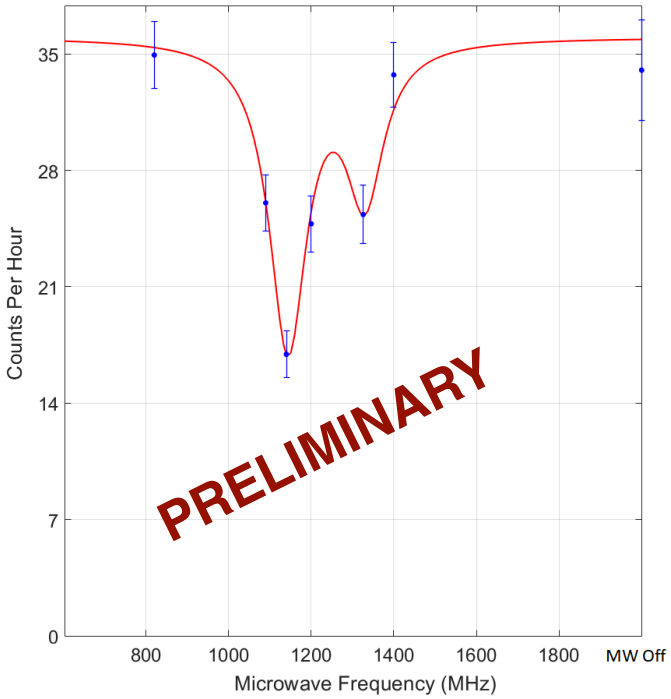
THEORY $(E(2S_{1/2}) - E(2P_{1/2}))^{\mathrm{th}}_{\mathrm{Mu}} = 1047.284(2)\ \mathrm{MHz}.$

C. Frugiuele, J. Perez-Ríos, C. Peset, Phys. Rev. D 100, 015010 (2019)
M. I. Eides, H. Grotch, and V. A. Shelyuto, Phys. Rep. 342, 63 (2001).

EXPERIMENT $(E(2S_{1/2}) - E(2P_{1/2}))^{\mathrm{exp}}_{\mathrm{Mu}} = 1042(22)\ \mathrm{MHz}.$

C .J. Oram et al. Phys. Rev. Lett. 52, 910 (1984). DOI 10.1103/PhysRevLett.52.910. @ TRIUMF
K. Woodle, et al., Phys. Rev. A 41, 93 (1990). DOI 10.1103/ PhysRevA.41.93 @ LAMPF

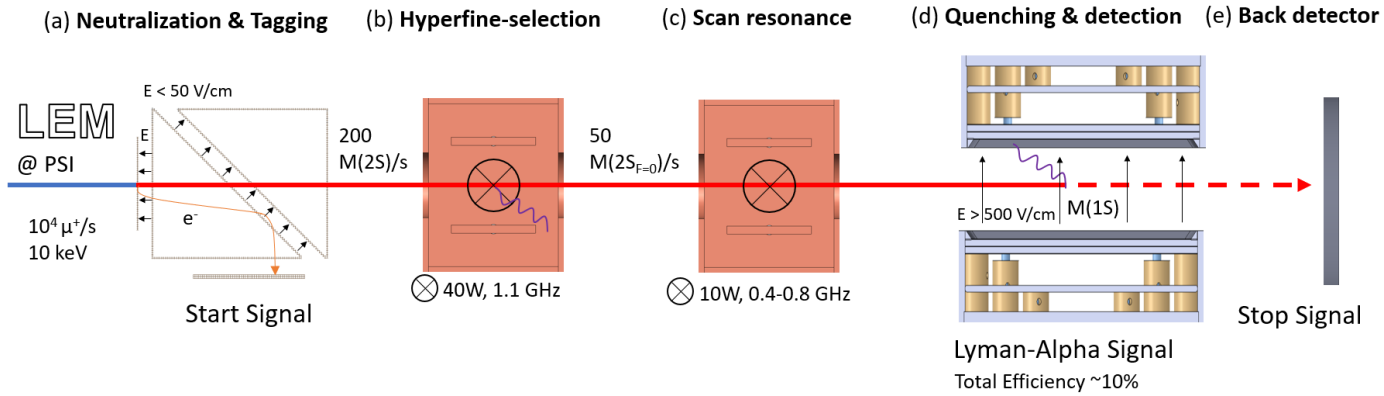
Results of the M Lamb shift (beamtime Dec. 2020) & Outlook (2021)



STATUS OF Mu-MASS LAMB SHIFT MEASUREMENT:

- RUN @LEM in June 2021 (5 days if approved)
- Dedicated tagging system under construction (reduce losses due to scattering in C-foil by factor 10)
- Probe isolated 586 MHz line
- LS projected accuracy around 1-2 MHz

40 HOURS DATA TAKING @LEM (10x statistics compared to TRIUMF)

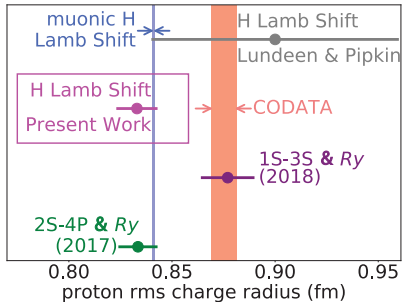


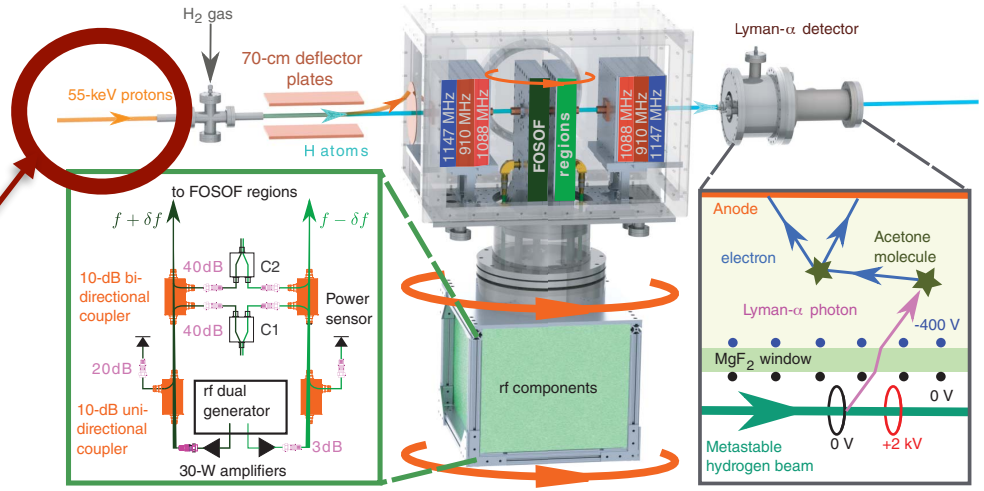
Prospects of Lamb shift at HiMB

A measurement of the atomic hydrogen Lamb shift and the proton charge radius

N. Bezginov[1], T. Valdez[1], M. Horbatsch[1], A. Marsman[1], A. C. Vutha[2], E. A. Hessels[1,*]
+ See all authors and affiliations

Science 06 Sep 2019:
Vol. 365, Issue 6457, pp. 1007-1012
DOI: 10.1126/science.aau7807





BEST LS DETERMINATION WITH H USING 55 keV protons

OUTLOOK at HiMB: **2 ORDERS** of magnitude larger **FLUX** with a better (**1mm**) defined beam

→ Using graphene instead of C-foil (10 nm -> 1nm) or charge exchange in a gas jet

→ Measurement of **LS few tens of kHz**

→ Measurement of **Fine Structure at 100 kHz**

Summary and outlook for M spectroscopy at HiMB

HiMB WOULD GREATLY EXPAND THE PHYSICS REACH OF Mu-MASS

- 1S-2S: CURRENT AIMED ACCURACY FROM 10 kHz → 1kHz
- LAMB SHIFT: CURRENT MEASUREMENTS around 7 MHz → few tens kHz
- FINE STRUCTURE (AS BYPRODUCT)
- NEW LASER TRANSITIONS SUCH AS 2S-8D WOULD BE POSSIBLE
- HFS? MORE?

Mu-MASS (MuoniuM lAser SpectroScopy)

P. Crivelli, Z. Burkley, I. Cortinovis, L. de Sousa Borges, L. Gerchow, A. Golovizin, G. Janka, B. Ohayon, C. Vigo
ETH Zurich, Institute for Particle Physics and Astrophysics (IPA), 8093 Zurich, Switzerland
T. Prokscha, Z. Salman, A. Suter, X. Ni
PSI, Laboratory for Muon Spin Spectroscopy (LMU), 5232 Villigen, Switzerland
A. Antognini, K. Kirch, A. Soter
PSI, Laboratory for Particle Physics (LTP), 5232 Villigen, Switzerland and
ETH Zurich, Institute for Particle Physics and Astrophysics (IPA), 8093 Zurich, Switzerland
A. Knecht
PSI, Laboratory for Particle Physics (LTP), 5232 Villigen, Switzerland
D. Yost
Colorado State University (CSU), Colorado, USA

https://www.psi.ch/en/ltp/mu-mass

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