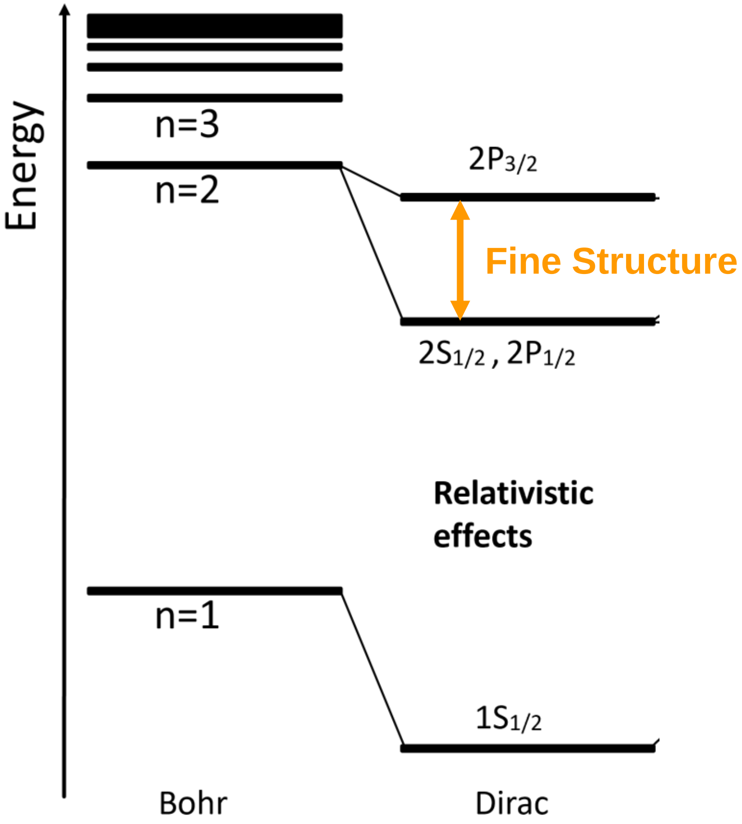
PAUL SCHERRER INSTITUT

Gianluca Janka, on behalf of the Mu-Mass collaboration :: CNM/LMU :: Paul Scherrer Institute

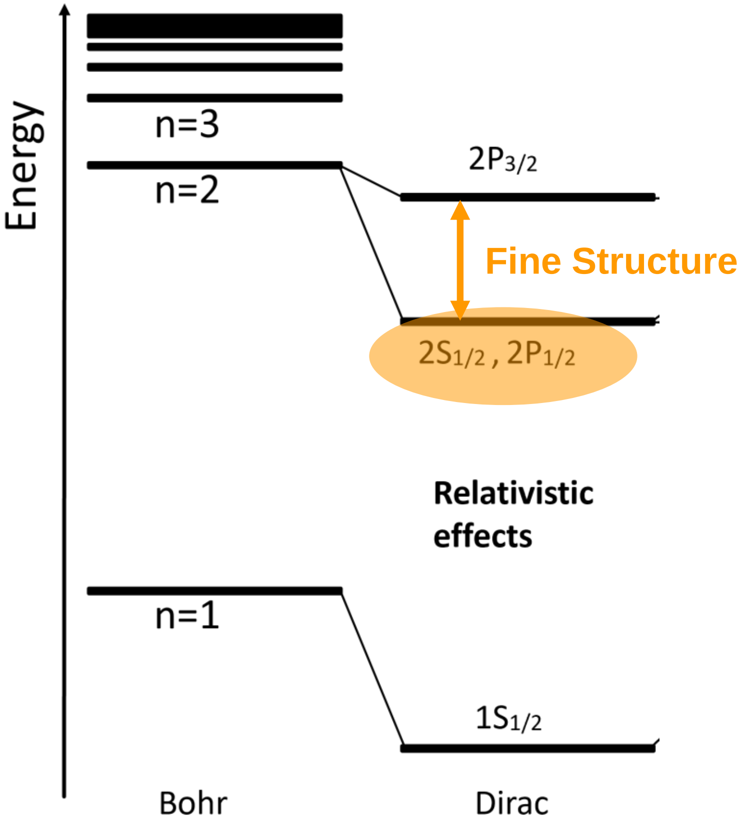
Precision Measurements of the Lamb Shift and Fine Structure in Muonium

MIP 2025, 18.05.2025

History of the Lamb Shift



History of the Lamb Shift



What about $2S_{1/2}$ and $2P_{1/2}$?

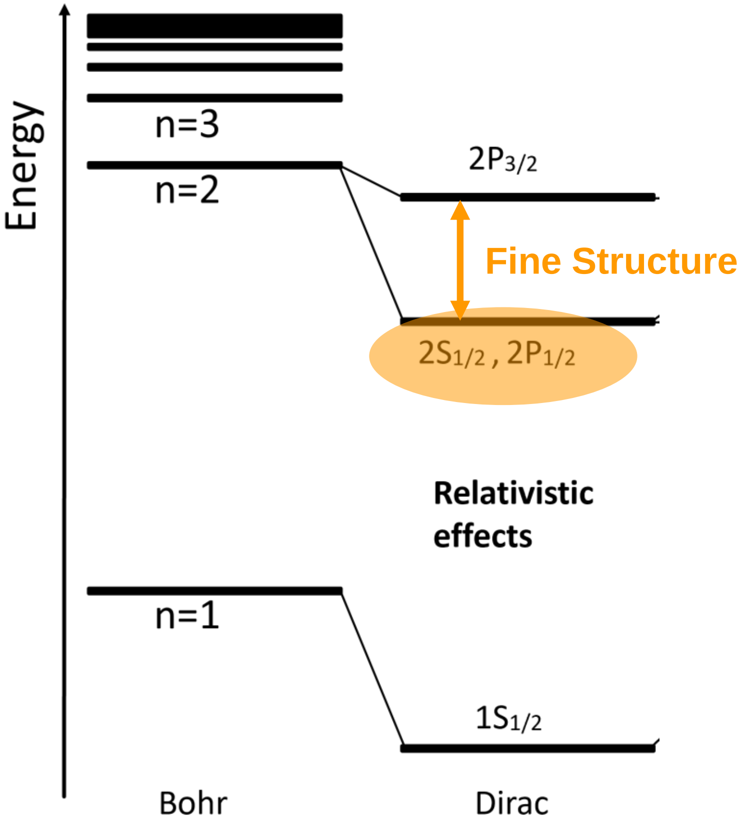
Experiments:

- Houston (1934), Williams (1938) had first evidence of splitting

First Explanation:

- Idea of $2S_{1/2}$ energy level slightly raised by Pasternack (1938)

History of the Lamb Shift



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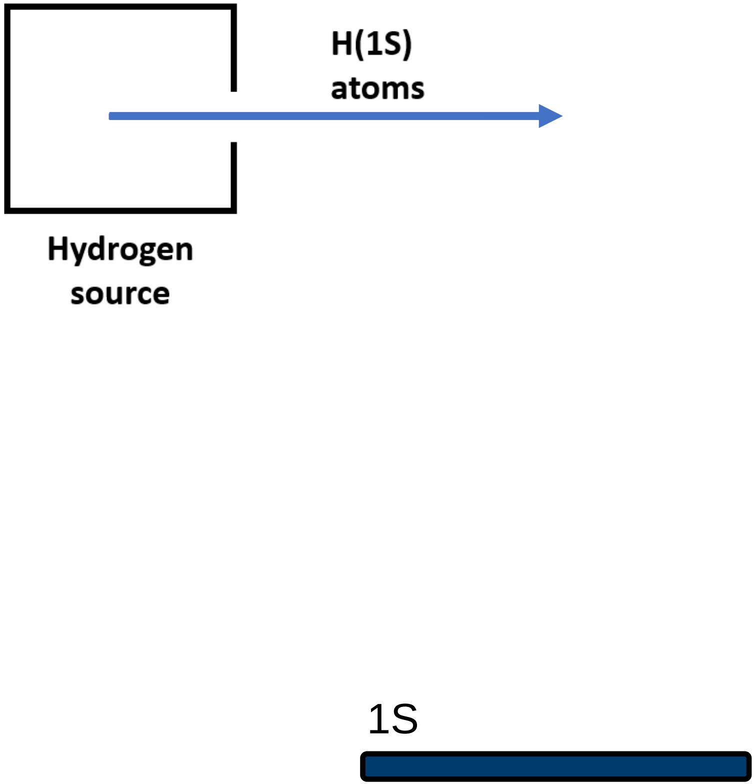
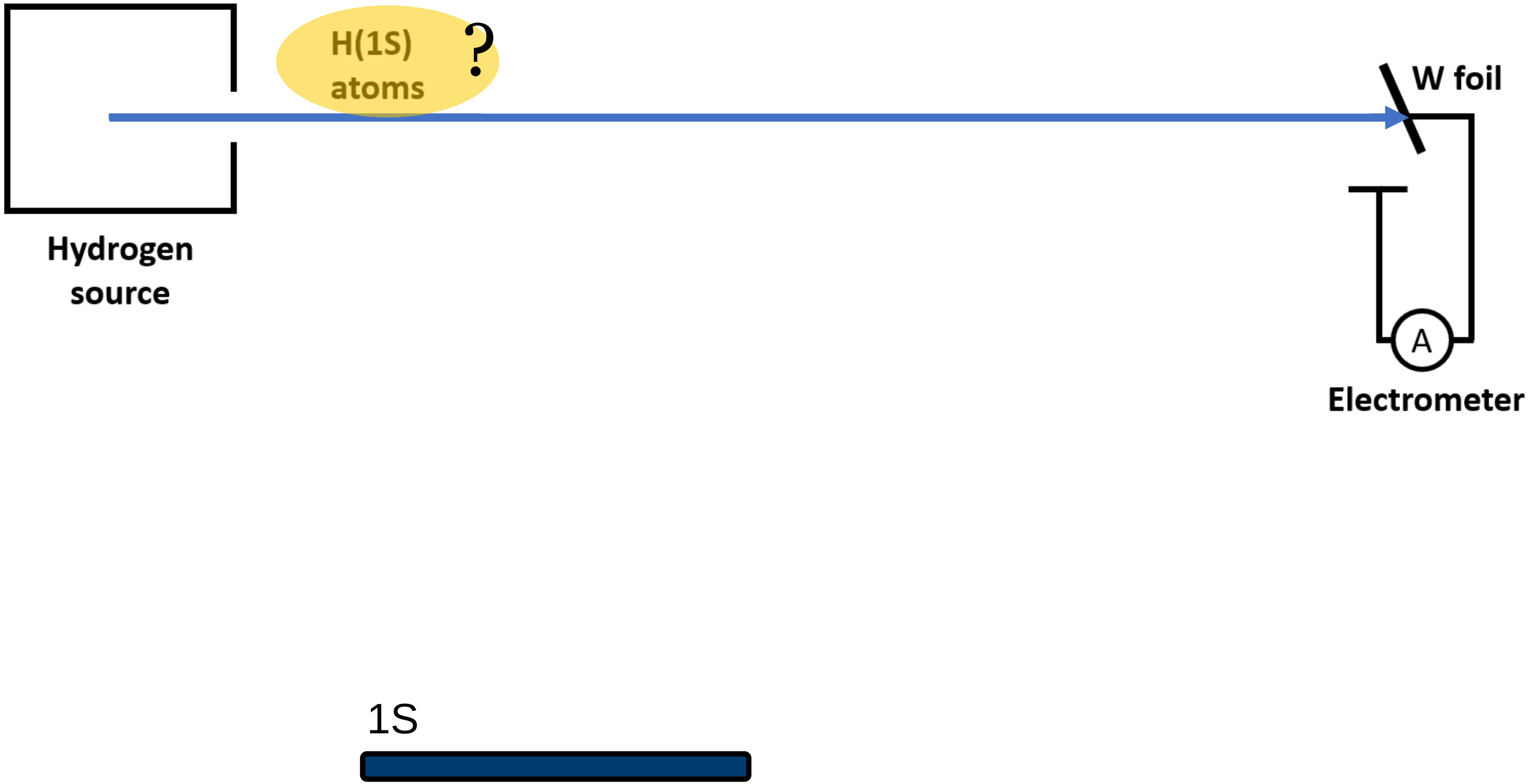
... but they were ignored!
and 2nd world war started...

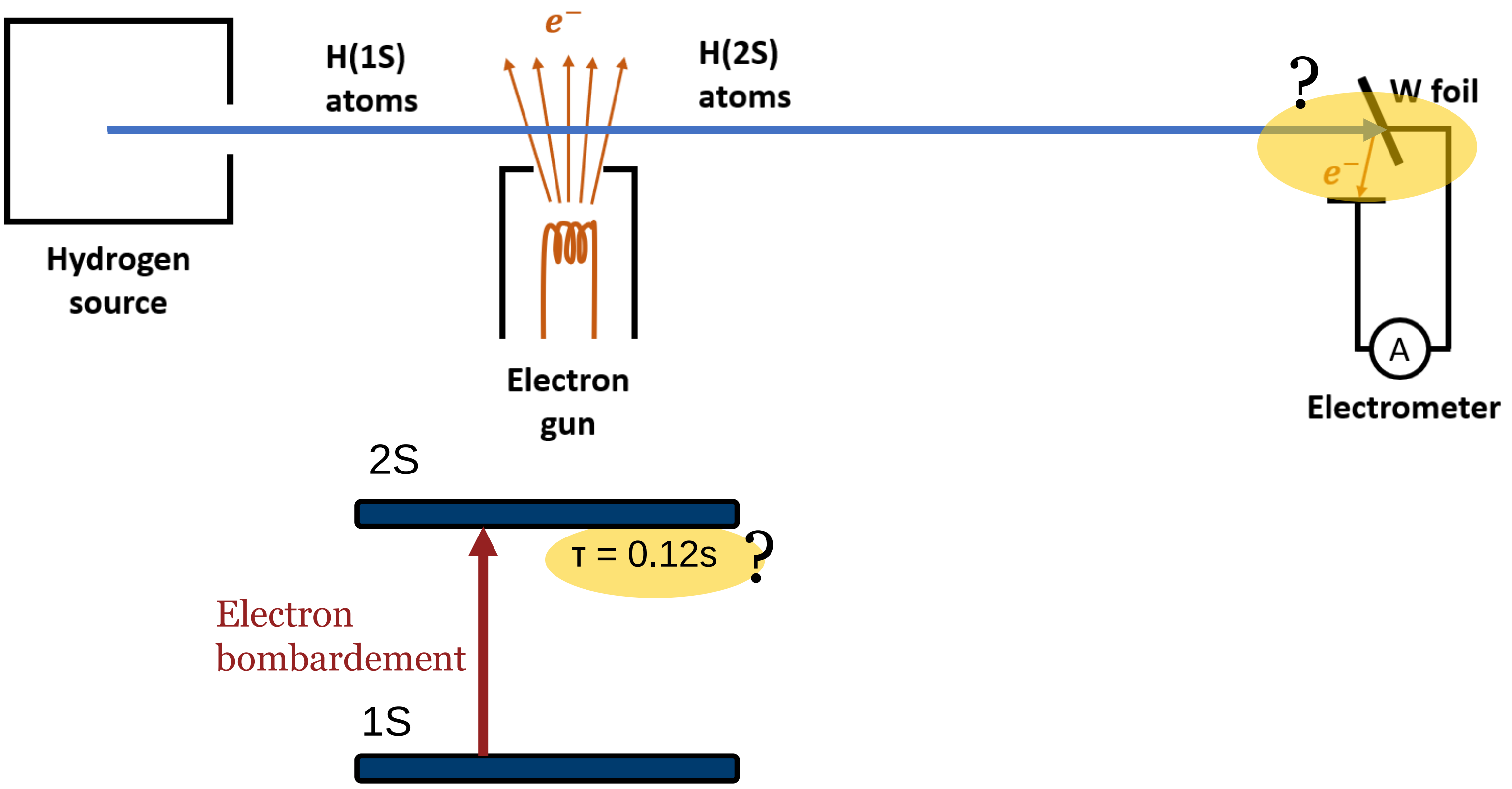
History of the Lamb Shift



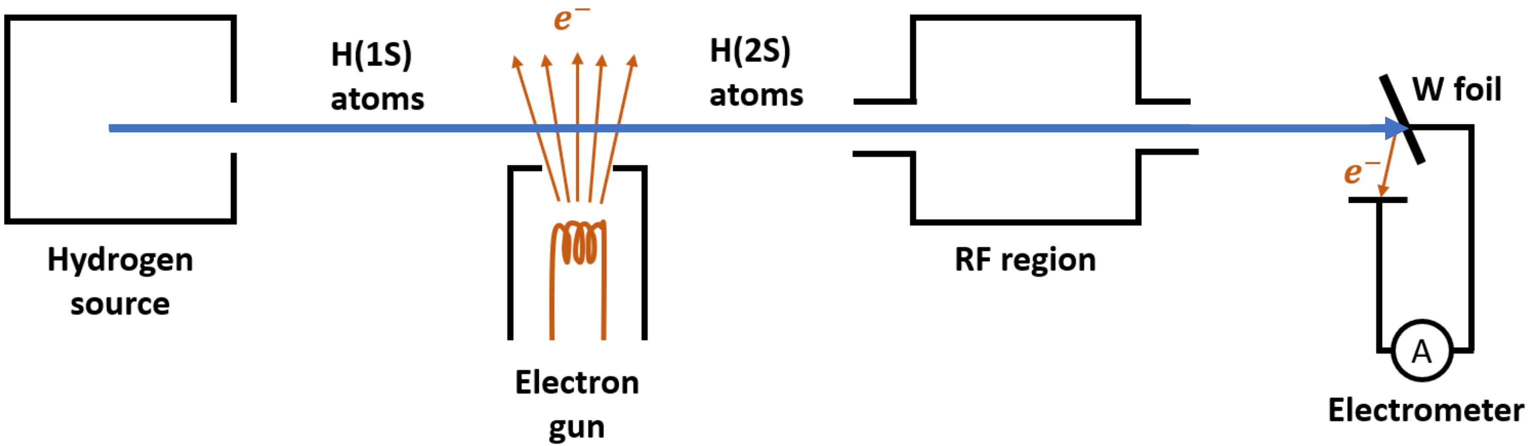
History of the Lamb Shift

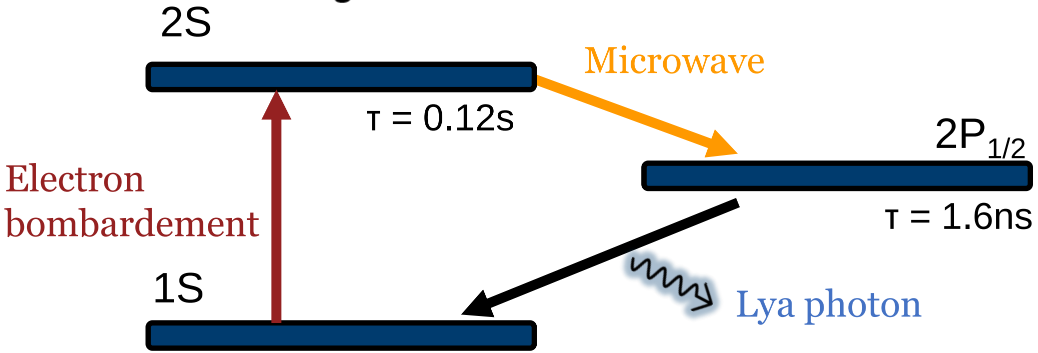


History of the Lamb Shift

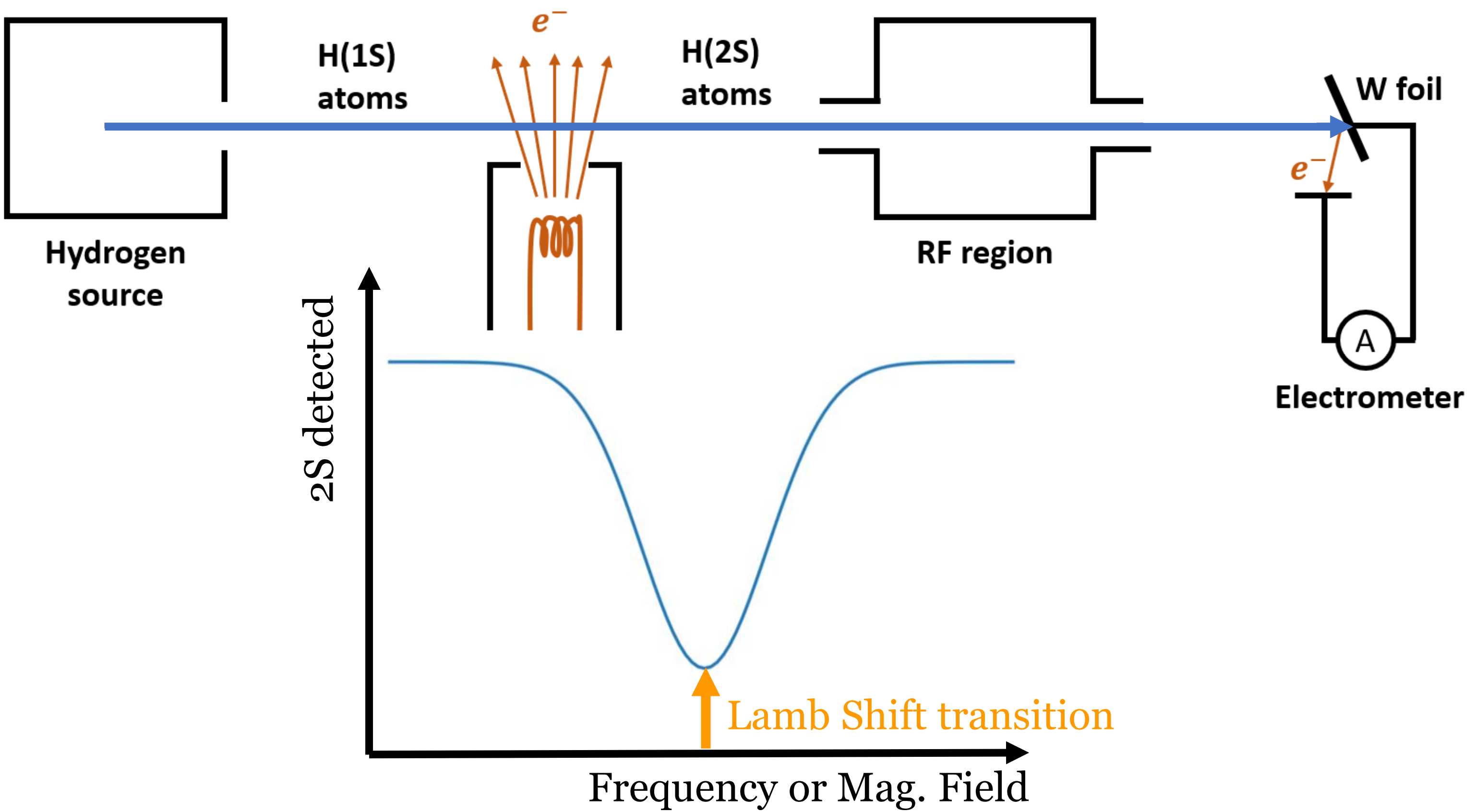


History of the Lamb Shift





History of the Lamb Shift



History of the Lamb Shift

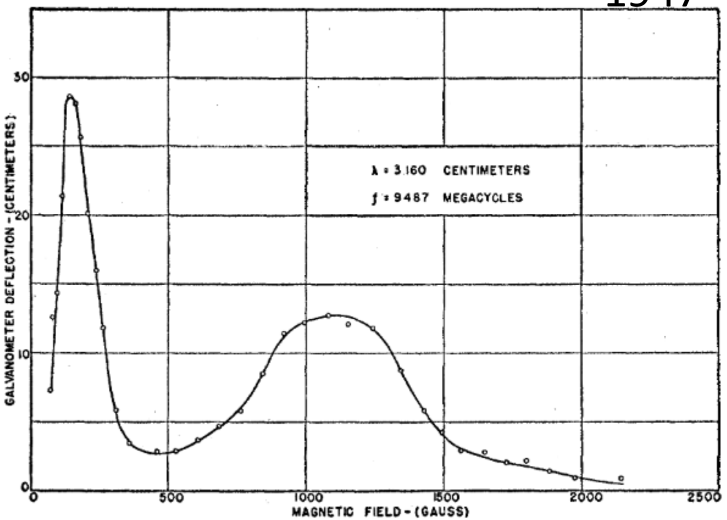
PHYSICAL REVIEW VOLUME 72, NUMBER 3 AUGUST 1, 1947

Fine Structure of the Hydrogen Atom by a Microwave Method* **

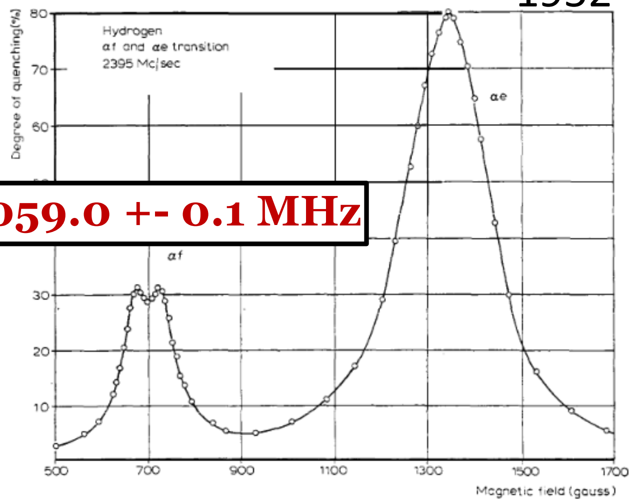
WILLIS E. LAMB, JR. AND ROBERT C. RETHERFORD
Columbia Radiation Laboratory, Department of Physics, Columbia University, New York, New York

(Received June 18, 1947)

1947



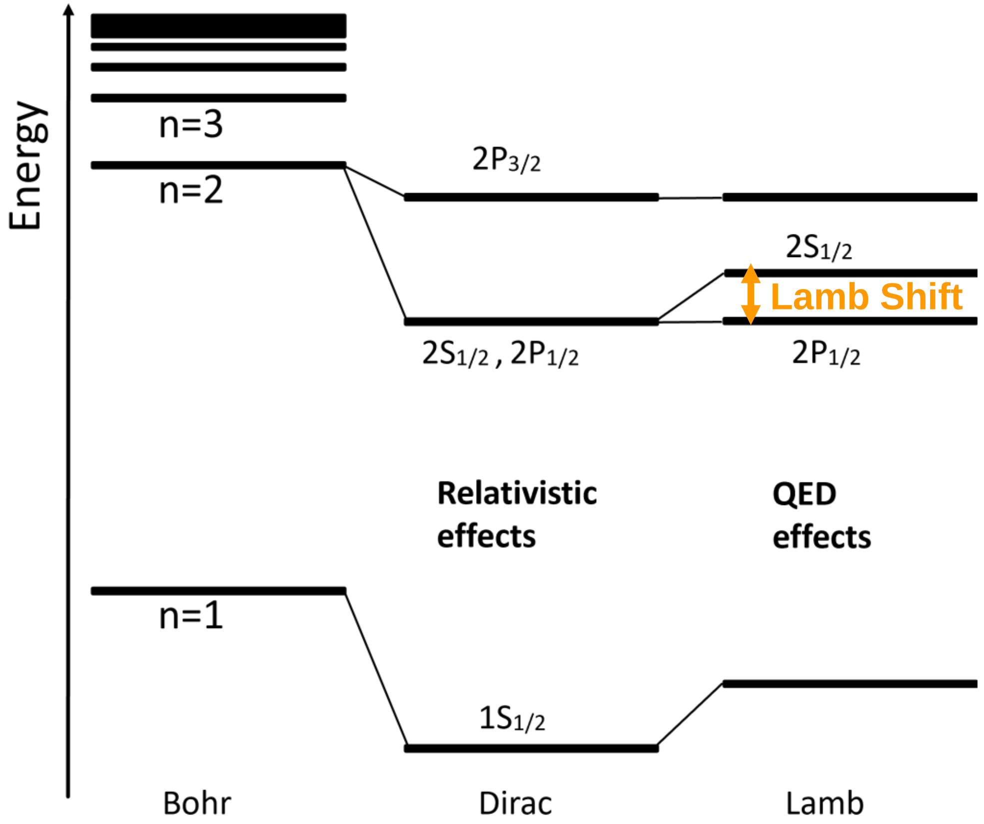
1952



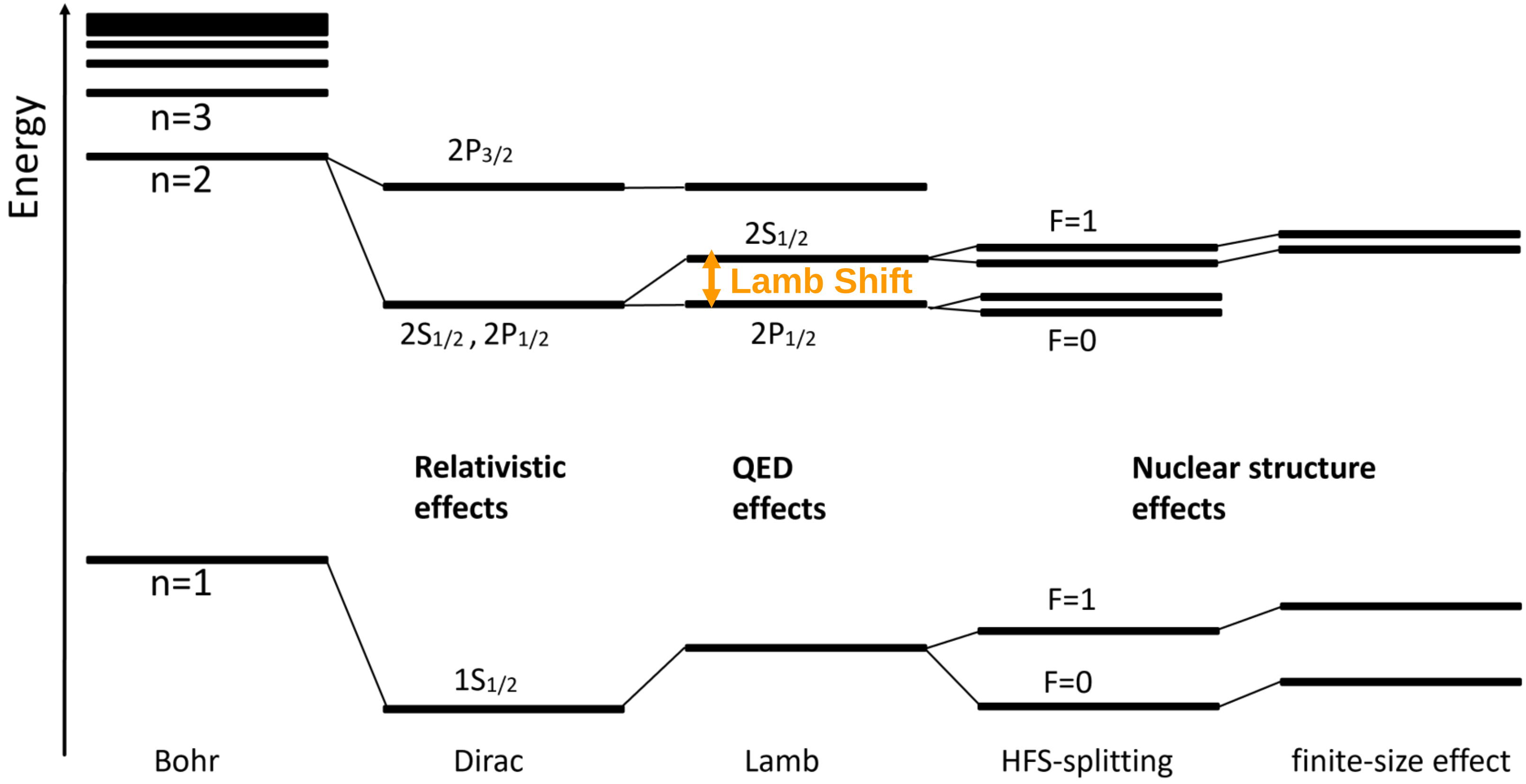
1059.0 +- 0.1 MHz

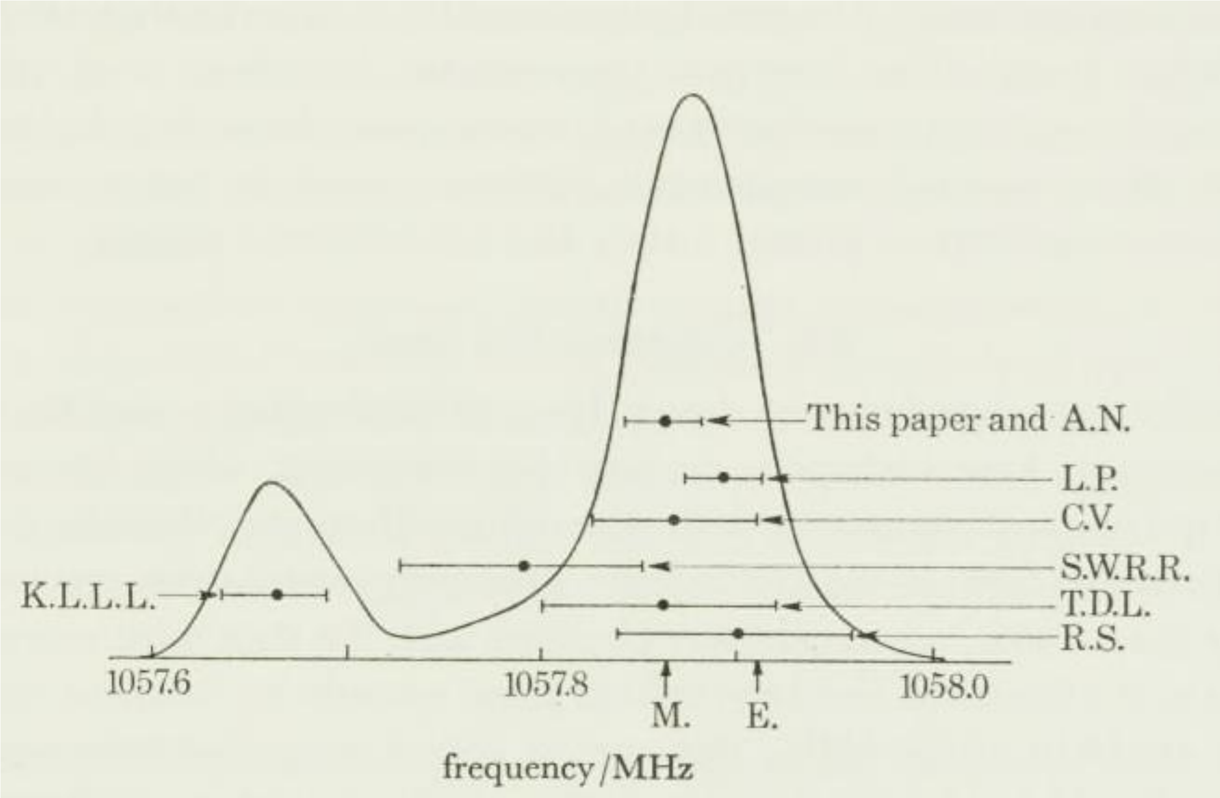
Fig. 7. Observed resonance curves for hydrogen.

History of the Lamb Shift



History of the Lamb Shift




This paper and A.N.
L.P.
C.V.
S.W.R.R.
T.D.L.
R.S.
K.L.L.L.
1057.6
1057.8
1058.0
M.
E.
frequency/MHz

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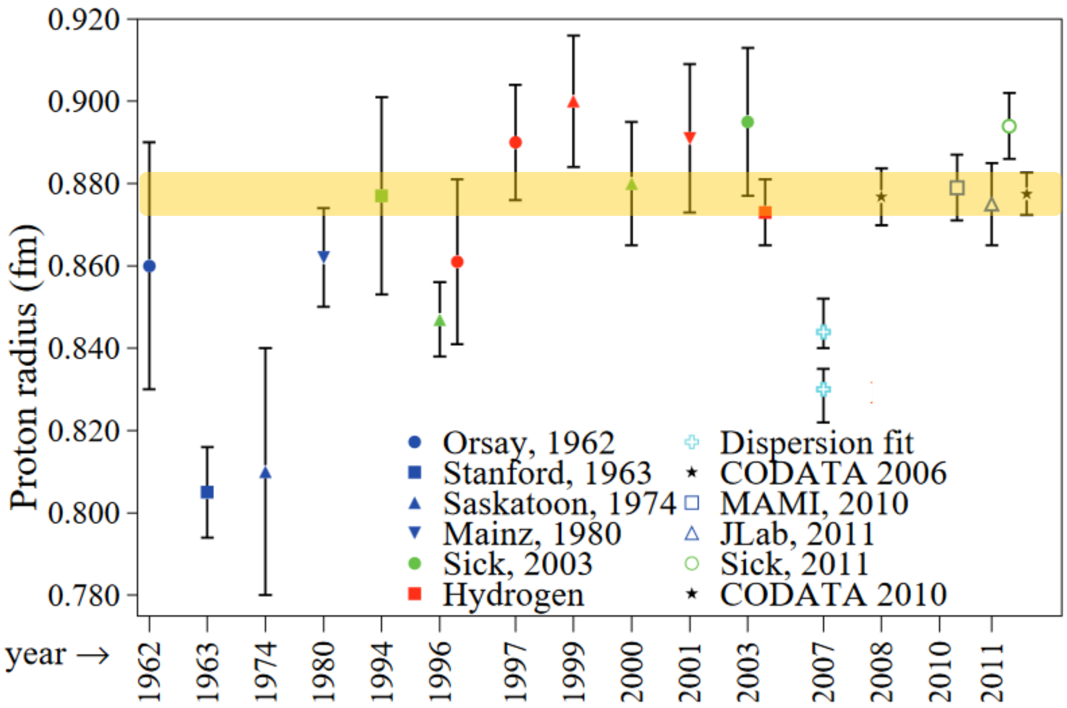
https://arxiv.org/pdf/1301.0905.pdf

Proton Charge Radius



What to do?

Uncertainty of proton charge radius is limiting impact of hydrogen spectroscopy…

Stay with hydrogen,
measure some transitions more precisely
and extract (another) proton radius

What to do?

Uncertainty of proton charge radius is limiting impact of hydrogen spectroscopy…

Stay with hydrogen,
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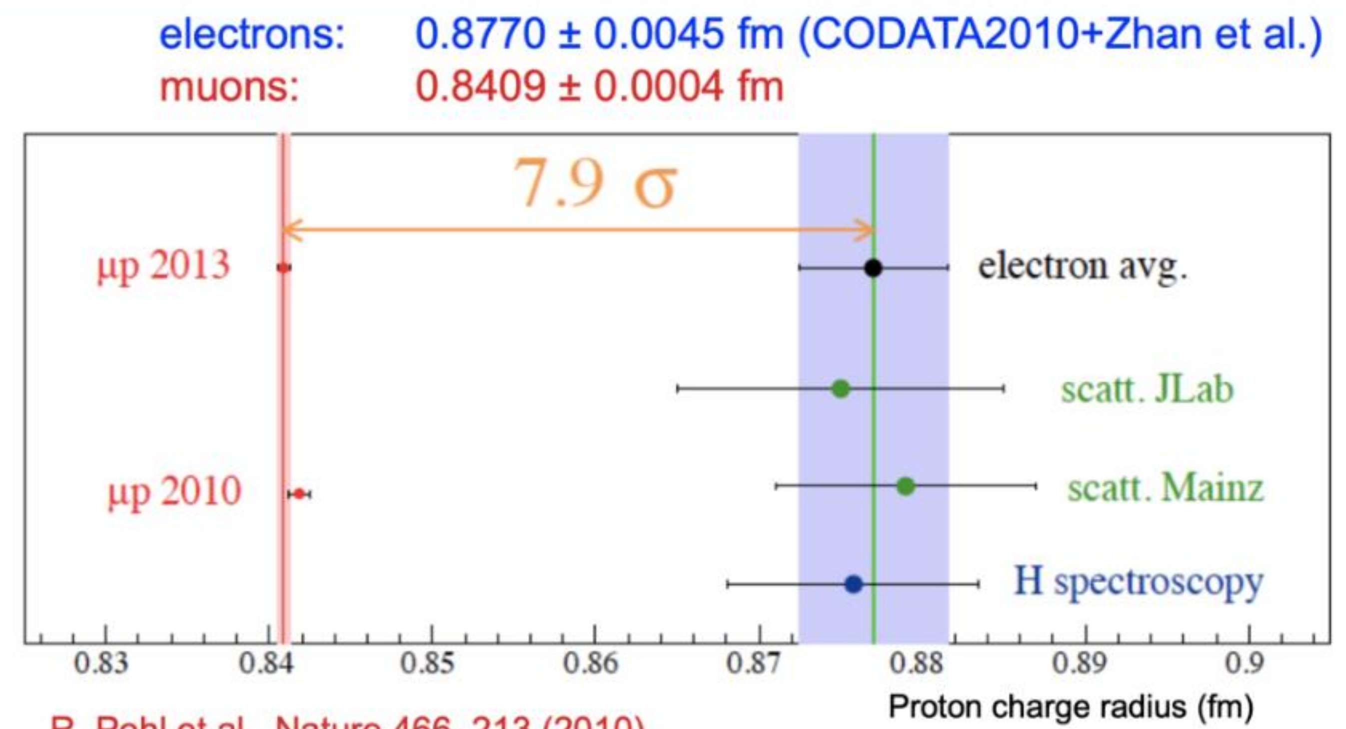
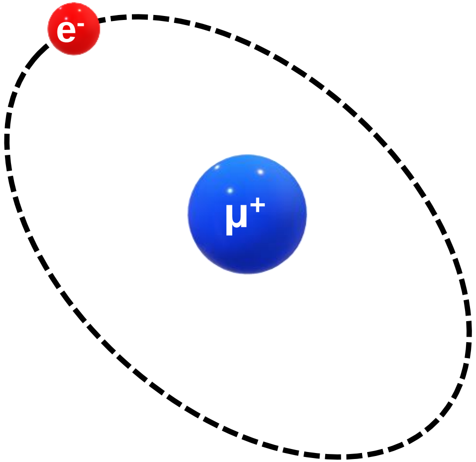
Move to exotic atoms

Proton Charge Radius Puzzle



R. Pohl et al., Nature 466, 213 (2010)
A. Antognini et al., Science 339, 417 (2013)

Muonium



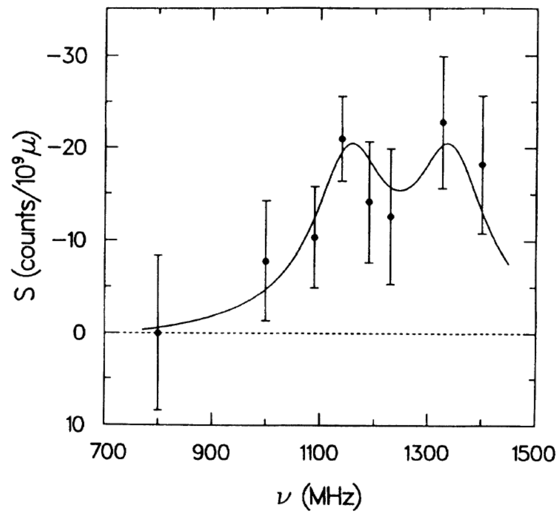
Muonium is purely leptonic, free from finite size effects

→ **excellent candidate to test bound-state QED**

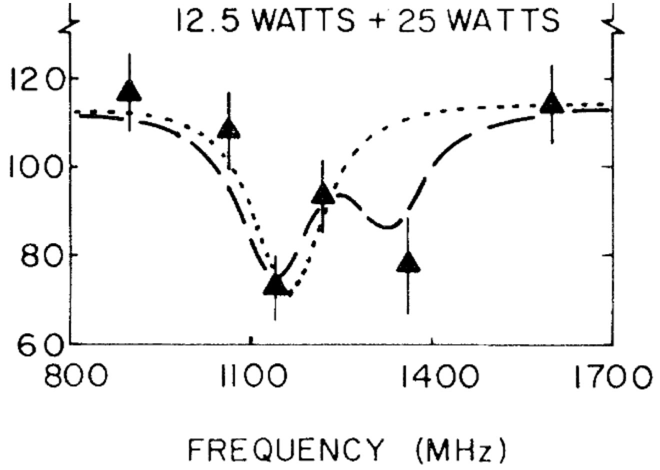
→ **any deviation between theory and measurements hint of New Physics**

Early Muonium Lamb Shift

1042(22) MHz



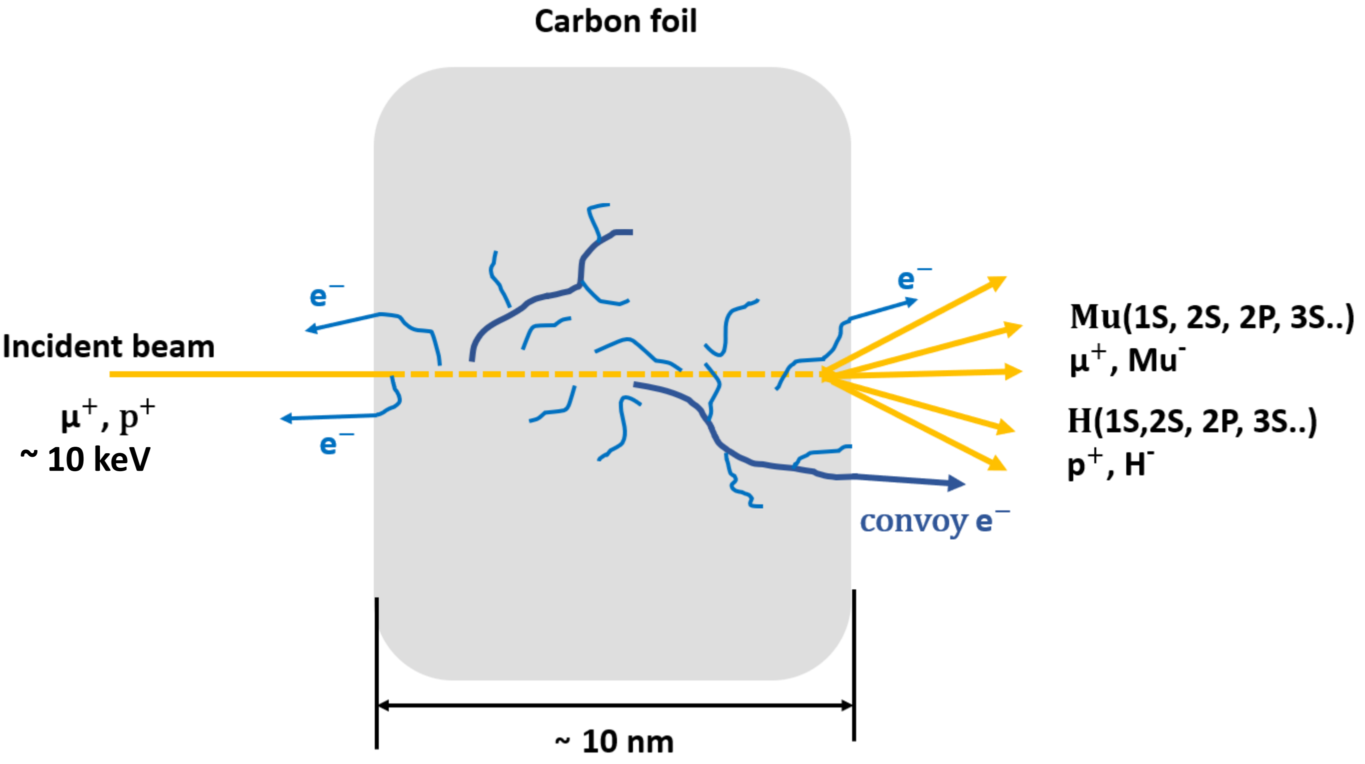
1070(13) MHz



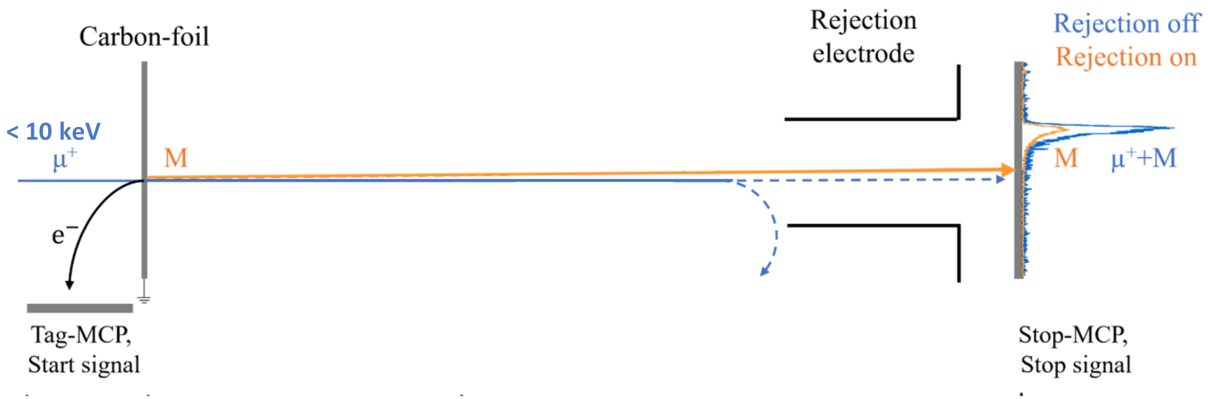
@ **LAMPF**: K. Woodle, et al., Phys. Rev. A 41, 93 (1990).

@ **TRIUMF**: C .J. Oram et al. Phys. Rev. Lett. 52, 910 (1984).

What they would have needed…
… and exactly what LEM offers!



Comissioning of Setup at LEM, PSI (2019)



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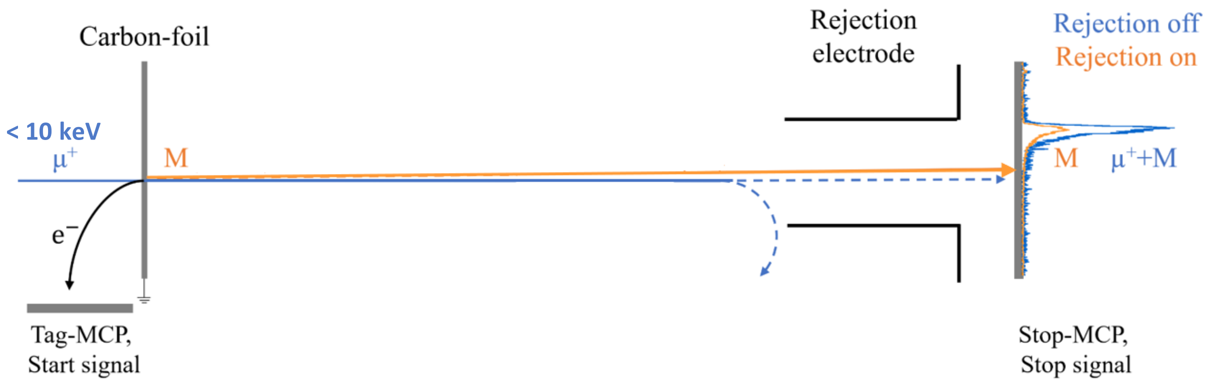
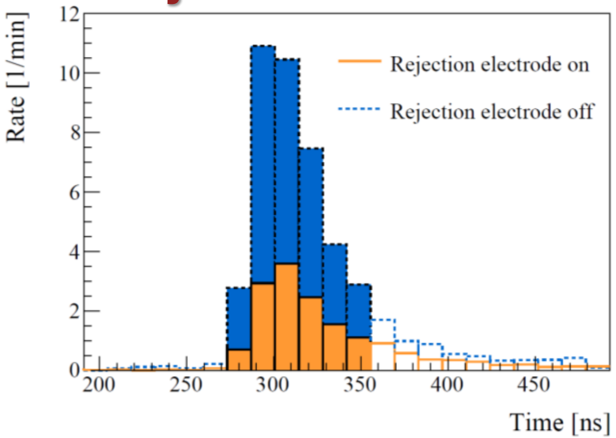


Rejection electrode on/off to show Muonium formation



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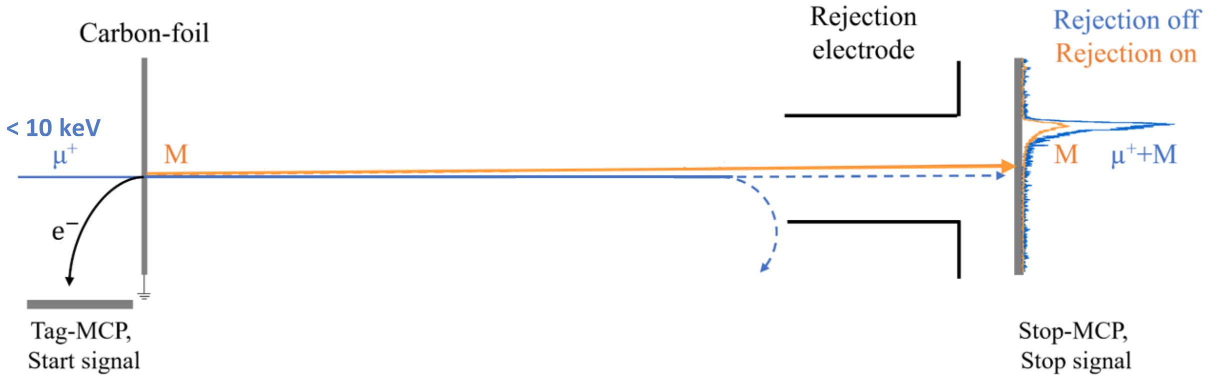

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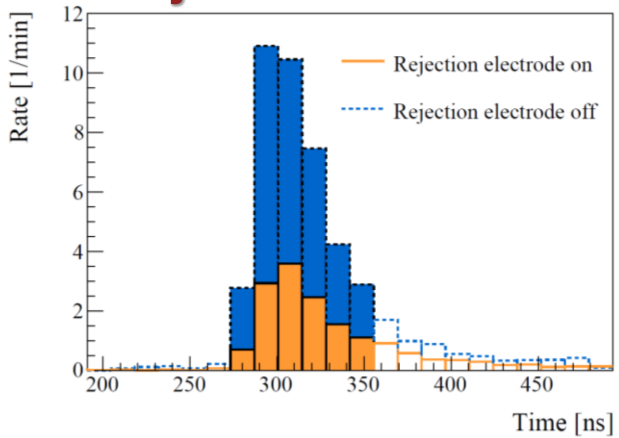

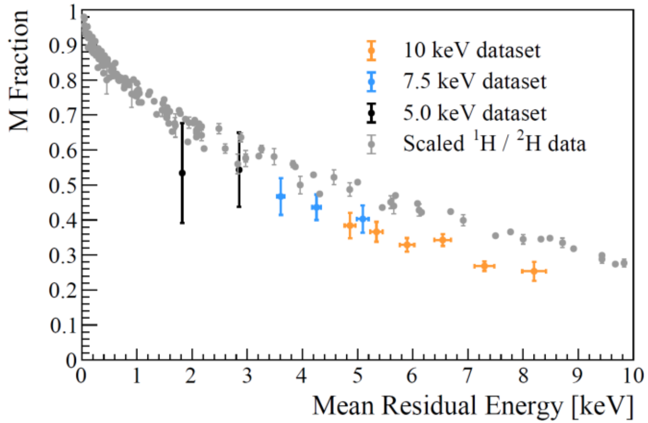

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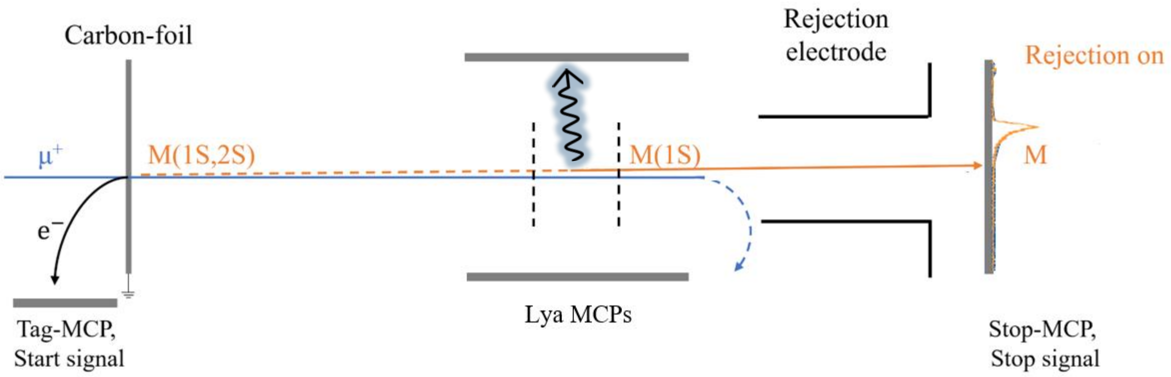

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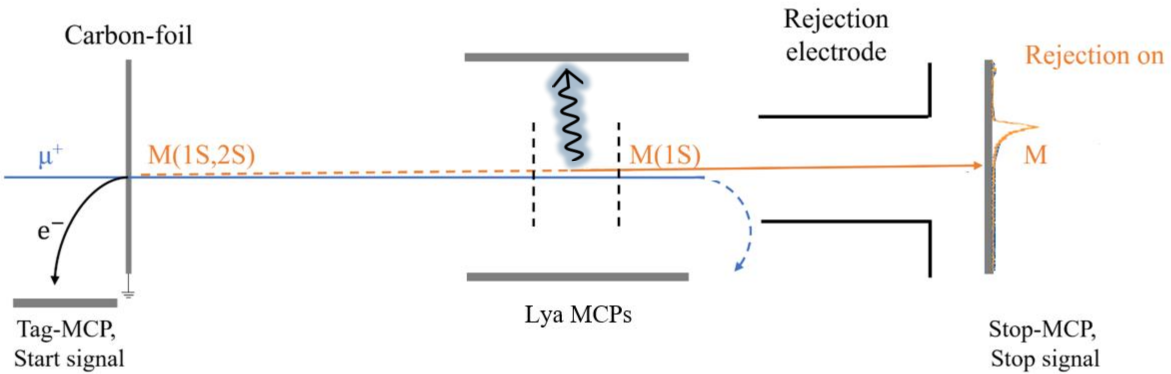

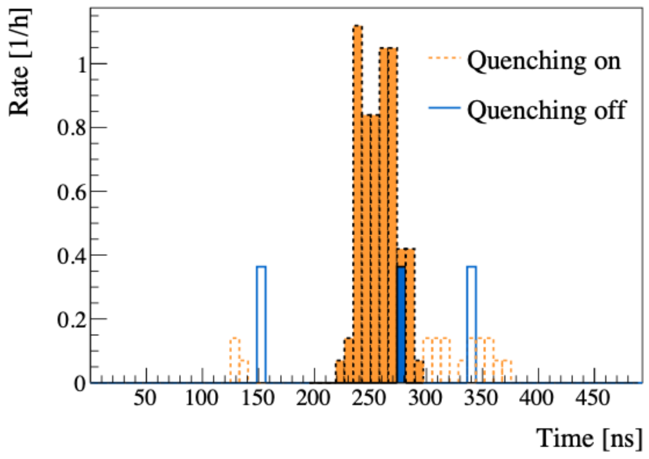

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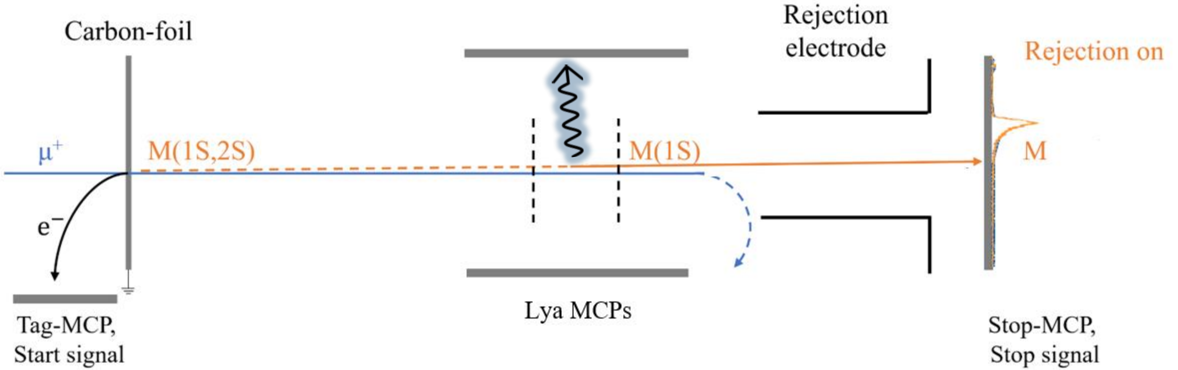


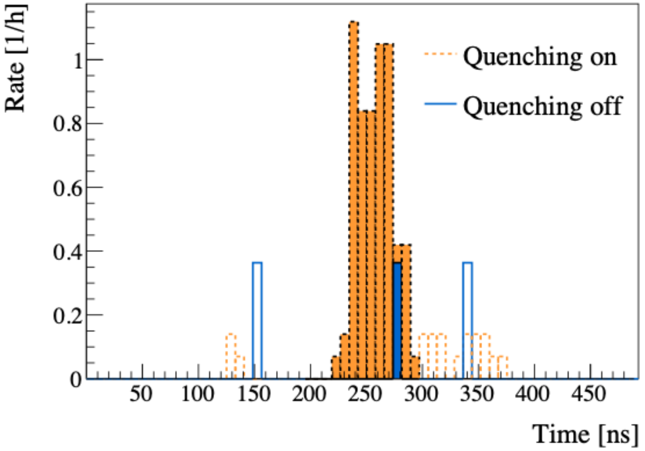


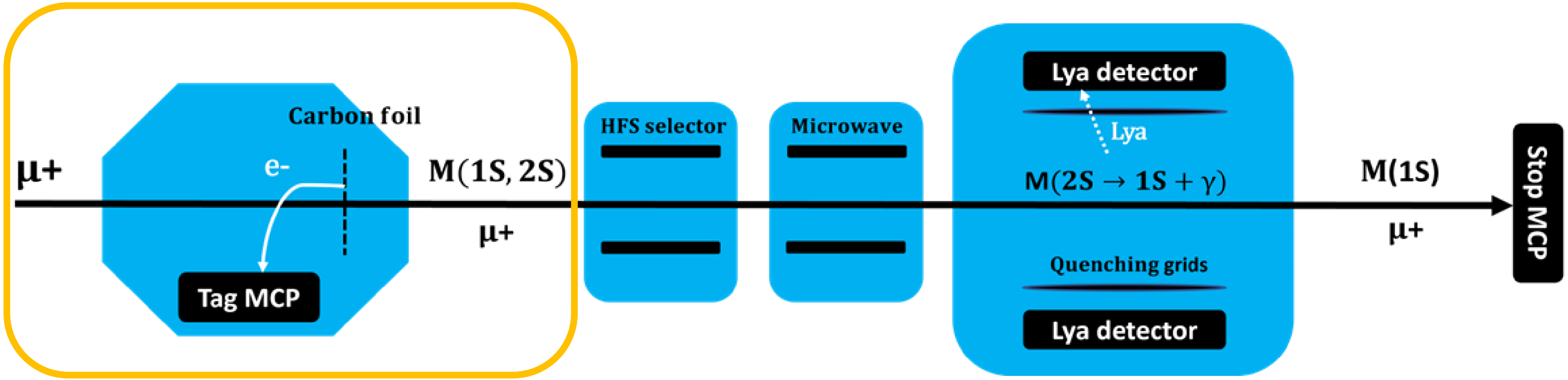
Table 1 Summary of values extracted from different incident energies E_{inc}. MPE is the Most Probable Energy for M that traversed the foil and reached the Stop-MCP

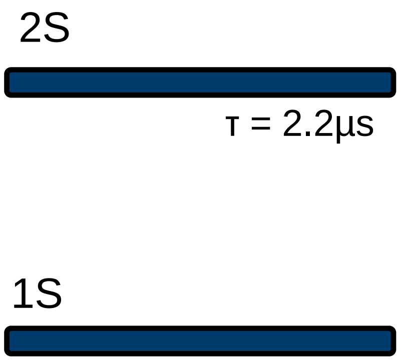
E_{inc} (keV)	MPE (keV)	f_{M/μ^+} (%)	$f_{2\mathrm{S}/\mathrm{M}}$ (%)	R_{μ^+} (kHz)	$R_{2\mathrm{S}}$ (Hz)
5.0	2.7 ± 0.1	56.8 ± 9.0	–	1.45	$83^* \pm 21$
7.5	4.7 ± 0.2	43.2 ± 2.4	11 ± 4	2.07	100 ± 30
10.0	7.0 ± 0.3	31.8 ± 0.8	10 ± 3	2.84	90 ± 30

For $R_{2\mathrm{S}}$ at 5 keV, $f_{2\mathrm{S}/\mathrm{M}} = 10 \pm 2$ % was assumed (see text)

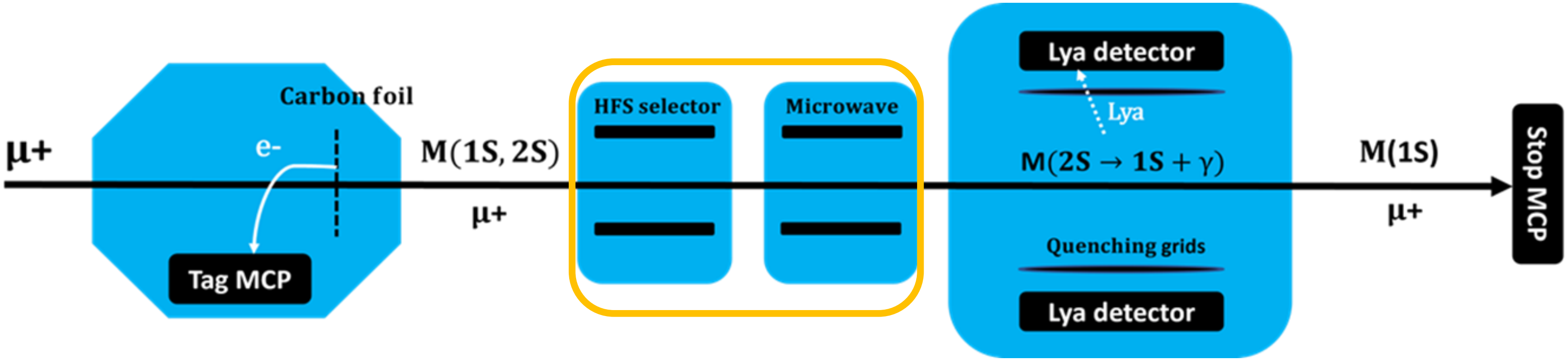
G. Janka et al., Eur. Phys. J. C (2020) **80**: 804

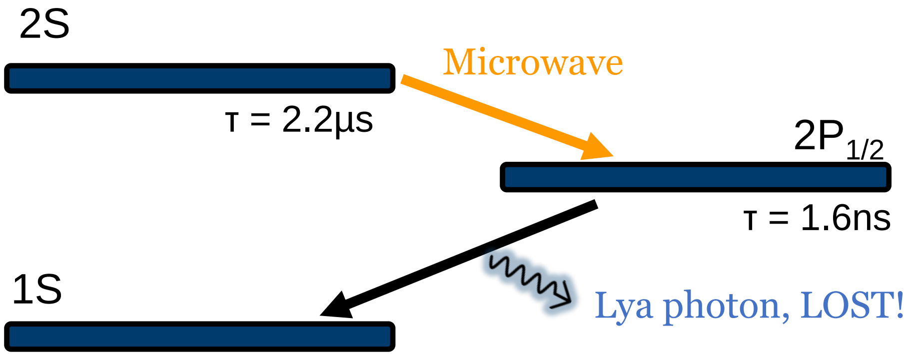
Lamb Shift of Muonium at LEM, PSI



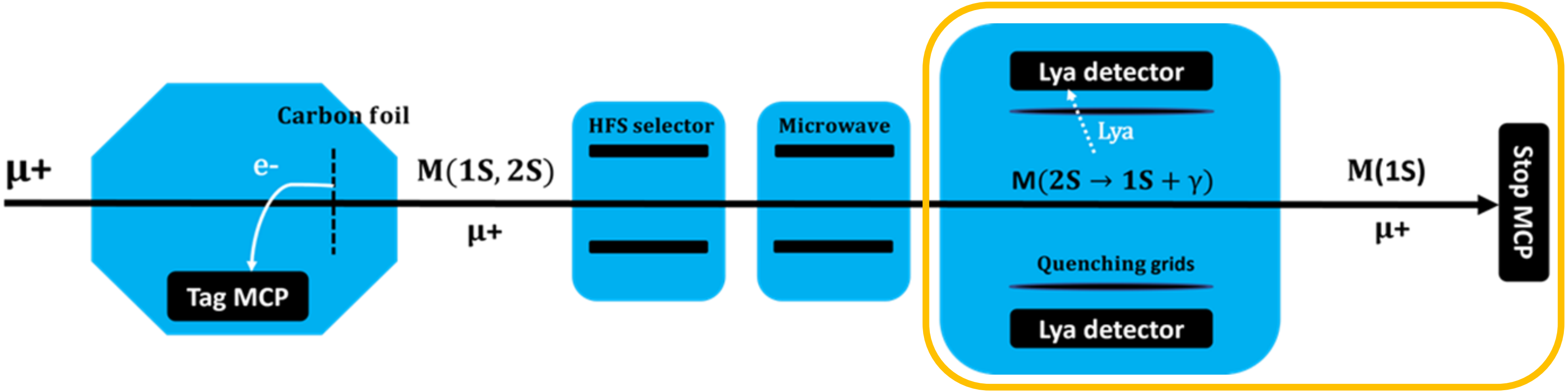


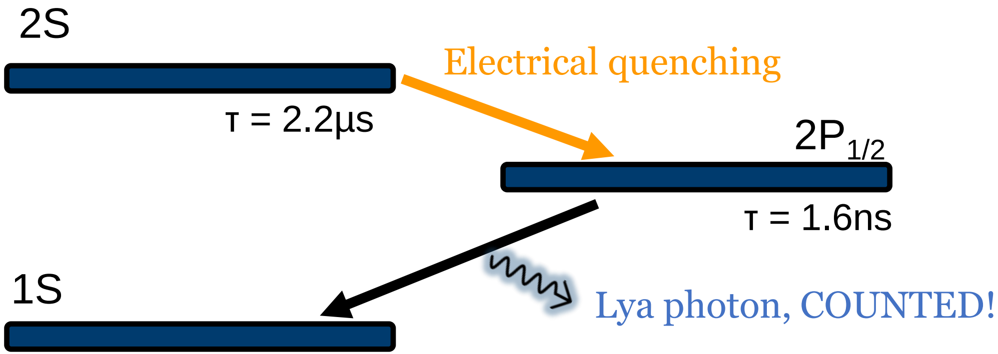
Lamb Shift of Muonium at LEM, PSI





Lamb Shift of Muonium at LEM, PSI





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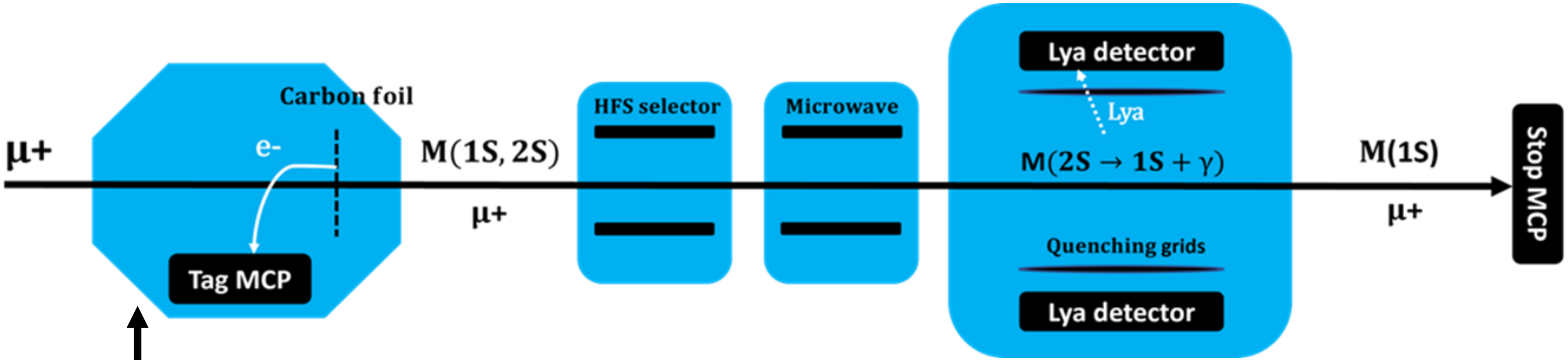
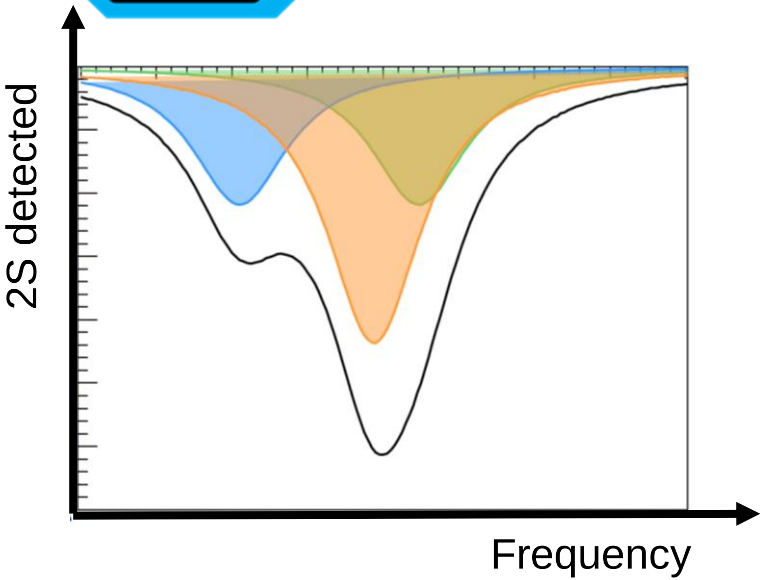
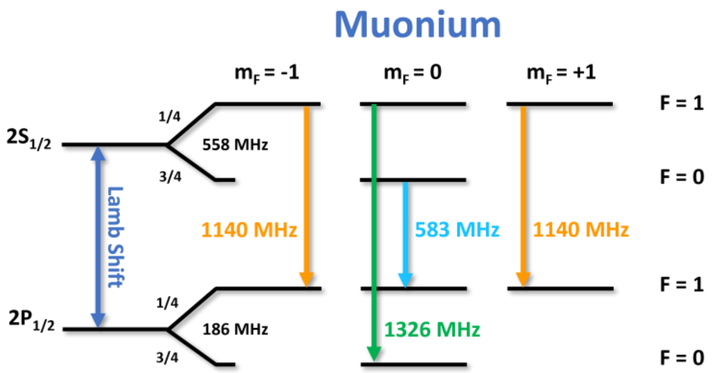
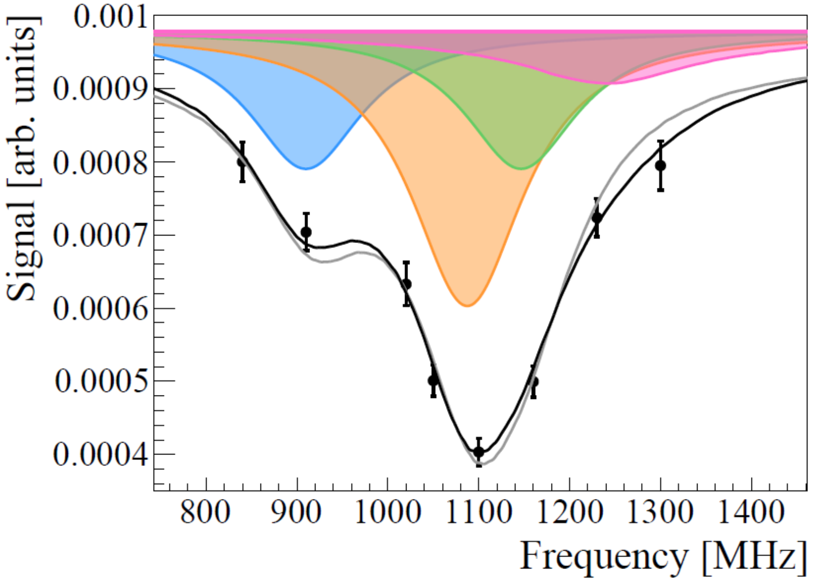
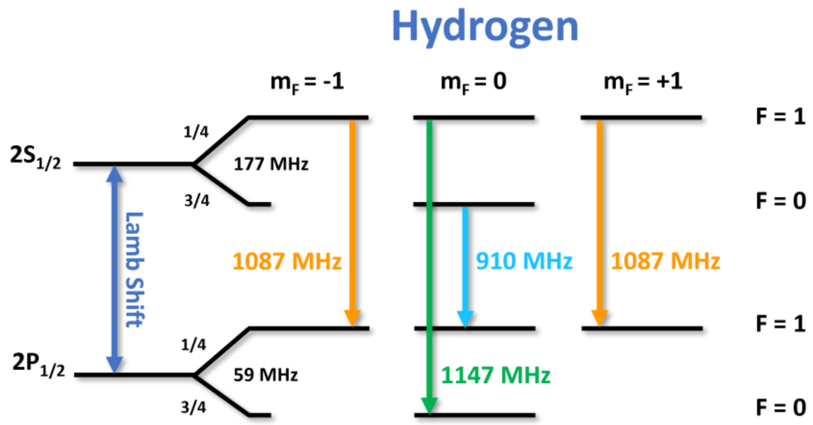






Lamb Shift of Hydrogen at LEM, PSI (2021)



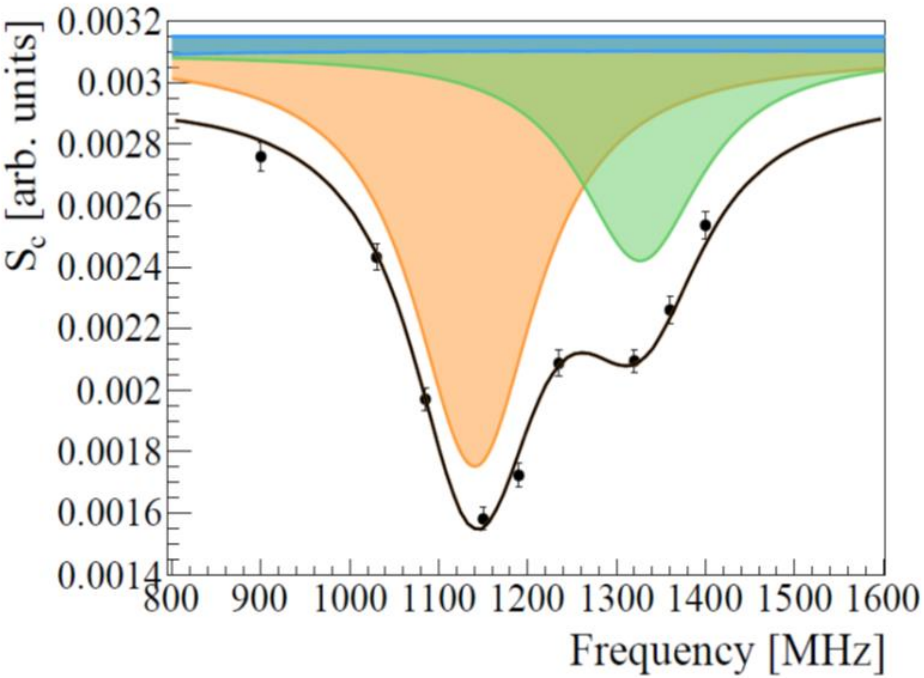


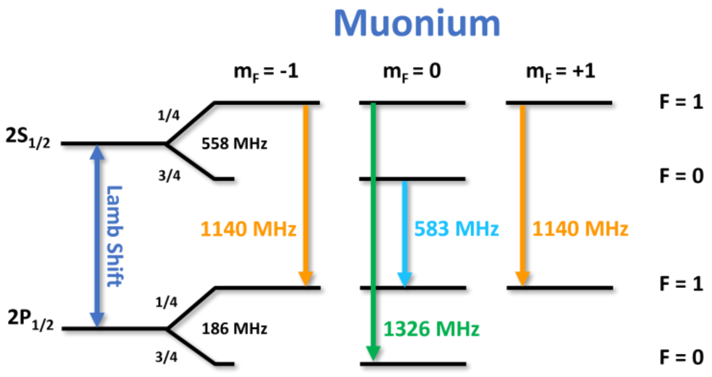
First tests with proton beam:

→ Microwave and Lya-Detection setup works as expected

→ Contamination in beam from higher n states (4S seen, 3S expected), needs to be taken into account for Muonium measurements as well

Lamb Shift of Muonium at LEM, PSI (2021)





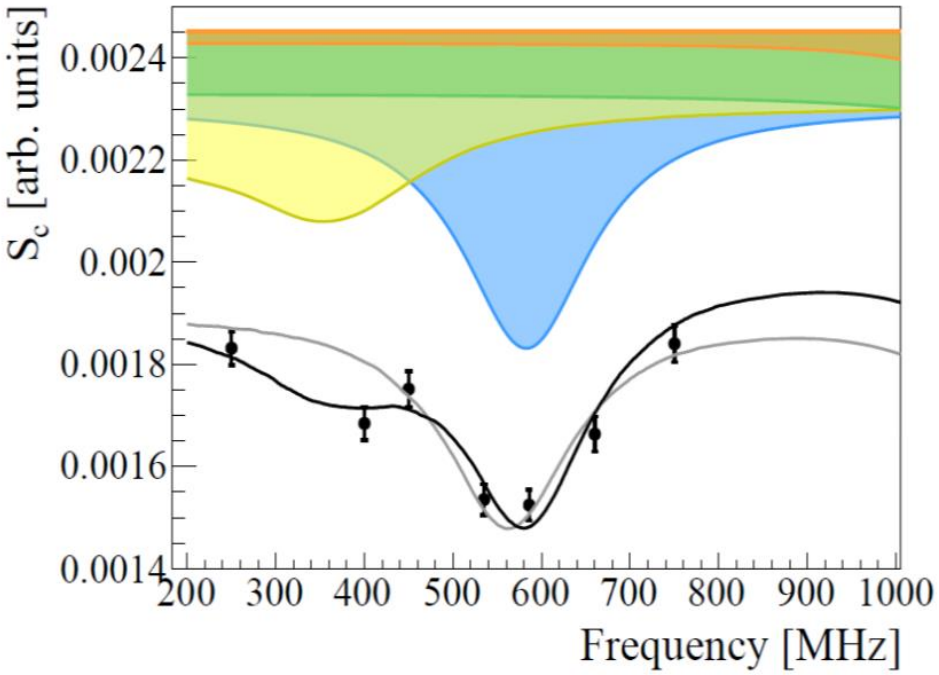
LS at 1047.2(2.5) MHz

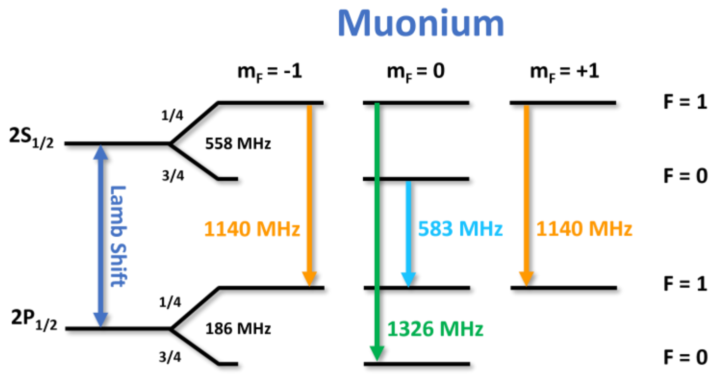
Theory at 1047.498(1) MHz

- → Limited by statistics
- → Agrees well with theory
- → **Precision not enough yet to test b-QED**

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

Lamb Shift of Muonium at LEM, PSI (2021)





LS at 1045.5(6.8) MHz

2S HFS at 559.6(7.2) MHz

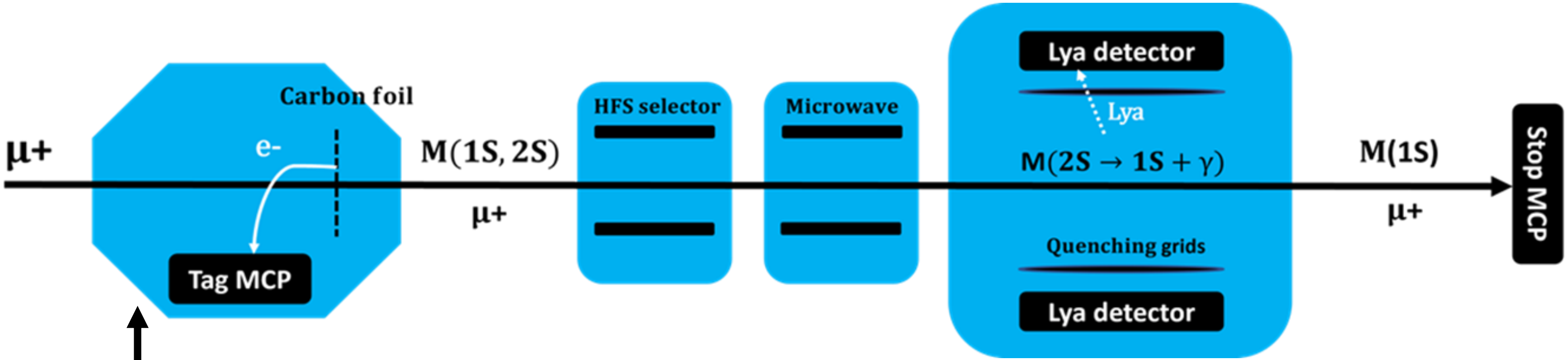
→ First time observation of F=0 → F=1 transition in Mu

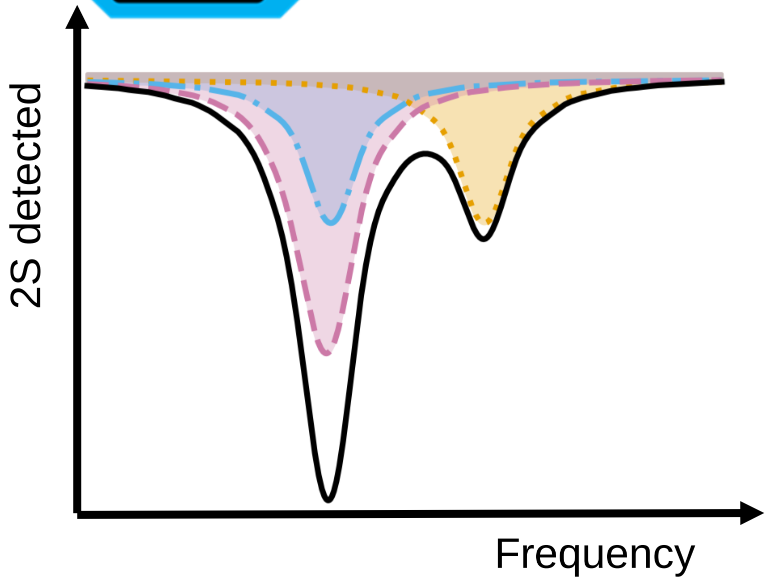
→ First time extraction of 2S HFS in Mu

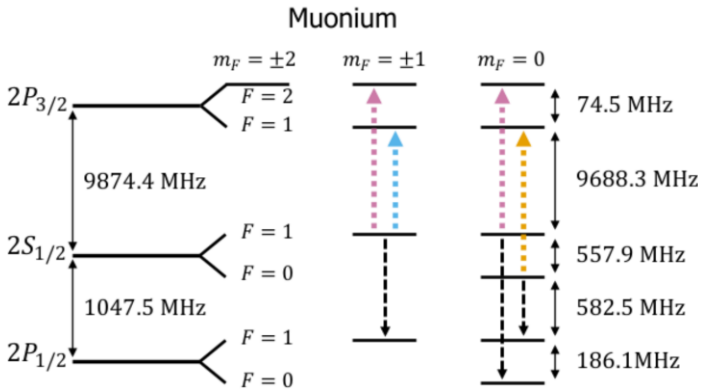
→ First time detection of Mu(3S)

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

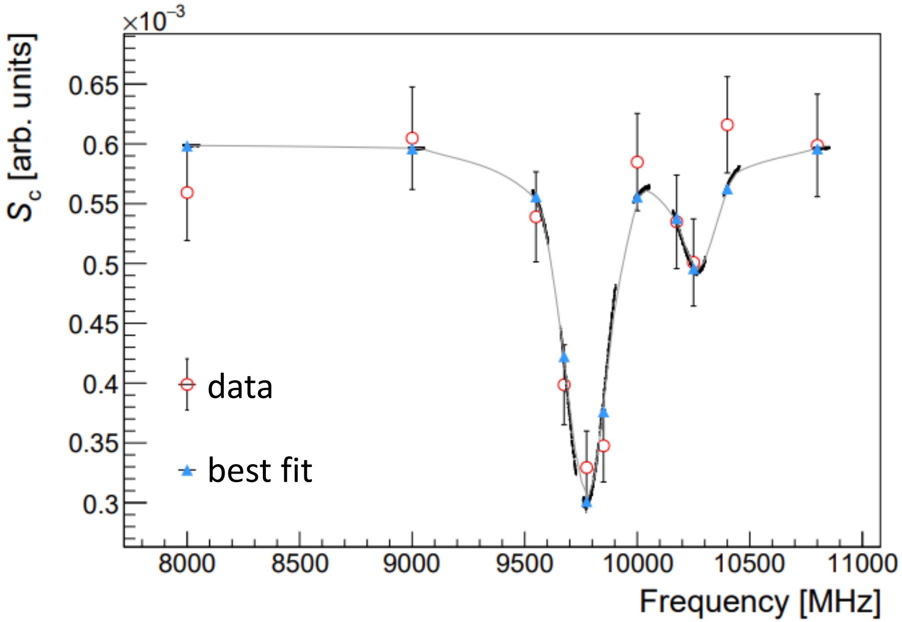
Fine Structure of Muonium at LEM, PSI (2024)

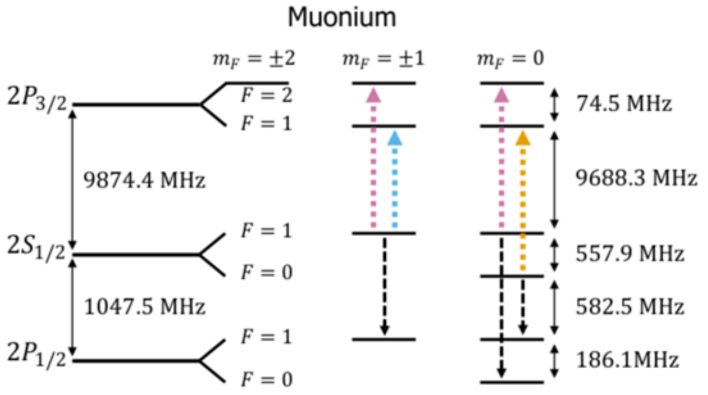






Fine Structure of Muonium at LEM, PSI (2024)





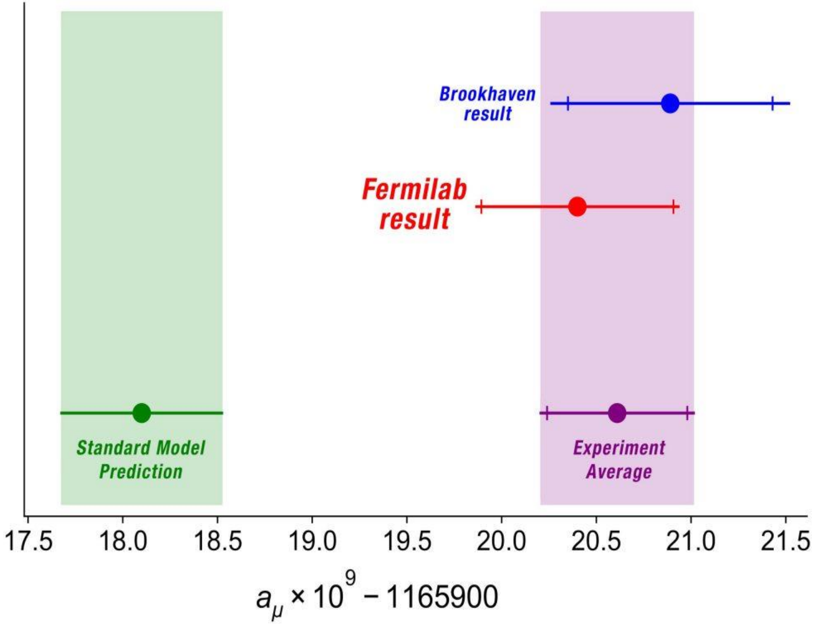
FS at 9871.0(7.0) MHz

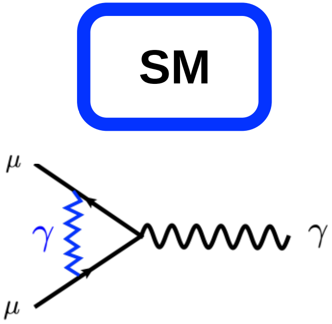
Theory at 9874.367(1) MHz

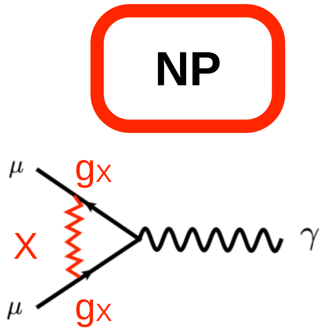
- → Limited by statistics
- → Agrees well with theory
- → **Precision not enough yet to test b-QED**

P. Blumer, G. Janka et al., Manuscript in prep.

Looking for New Physics, g-2



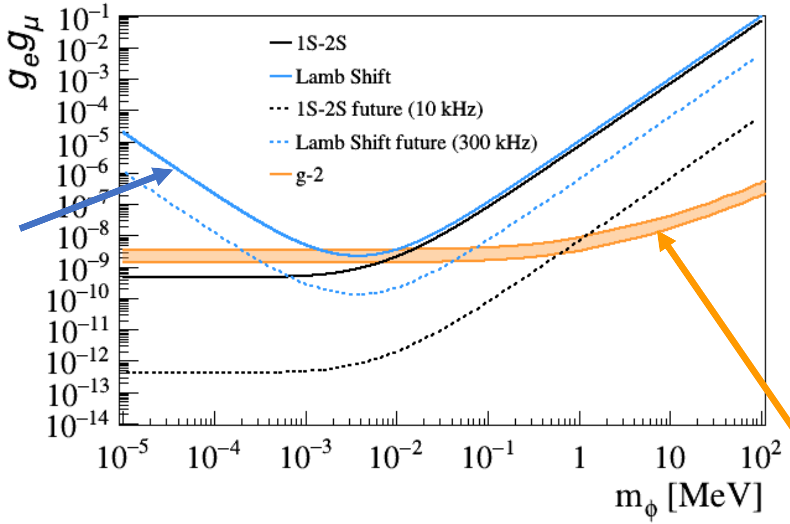




$$V_{ss}(\vec{r}) = -g_1^s g_2^s \frac{e^{-Mr}}{4\pi r}$$

Looking for New Physics, g-2

$$V_{ss}(\vec{r}) = -g_1^s g_2^s \frac{e^{-Mr}}{4\pi r}$$



Bands: region suggested by **$(g\text{-}2)_\mu$**

B. Abi, et al. Phys. Rev. Lett. 126, 141801 (2021)

combined with bound from **$(g\text{-}2)_e$**

L. Morel et al, Nature 588, 61 (2020),

R. H. Parker et al., Science 360, 191 (2018).

D. Hanneke et al. e Phys. Rev. Lett. 100, 120801 (2008)

Looking for New Physics, CPT Violation

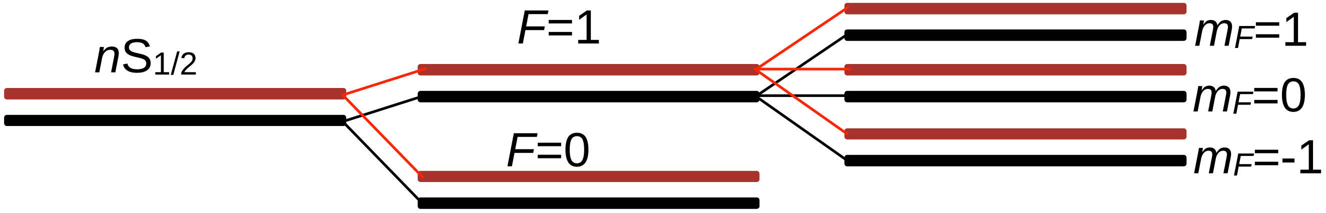
$$\mathfrak{L}_{\mathrm{SME}} = \underbrace{\mathfrak{L}_{\mathrm{SM}} + \mathfrak{L}_{\mathrm{GR}}}_{\text{Conventional physics}} + \underbrace{\mathfrak{L}_{\mathrm{LV}}}_{\text{Lorentz violation}}$$

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

Lorentz-violating contribution

Conventional case

$$\epsilon = \epsilon_0 + \boxed{\delta\epsilon}$$



Looking for New Physics, CPT Violation

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

Lorentz and CPT

Only Lorentz

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

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

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Outlook: Motivation!

- Precision not enough to test b-QED, **yet**
  - **200 kHz: Barker-Glover correction**
  - **50 kHz: Nuclear Self Energy correction**
  - **< 50 kHz: many mass-dependent terms**

- No solution yet to matter-antimatter asymmetry
  - **Keep on probing models beyond the Standard Model (e.g. SME)**

- Currently still limited by statistics, not systematics! Improving μ, Mu, Mu(2S) rates!
  - Thinner carbon foil (sub nm thickness)
  - Upgrade of muE4 beamline L. Zhou et al., Phys. Rev. Accel. Beams 25, 051601 (2022)
  - **MuCool** @ PSI to produce low-energy muon beam A. Antognini et al., SciPost Phys.Proc. 5 (2021)
  - **HIMB upgrade** @ PSI to increase μ+ flux (talk by A. Knecht)

M. Aiba et al., arXiv:2111.05788

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Thank you for your attention!

MU-MASS