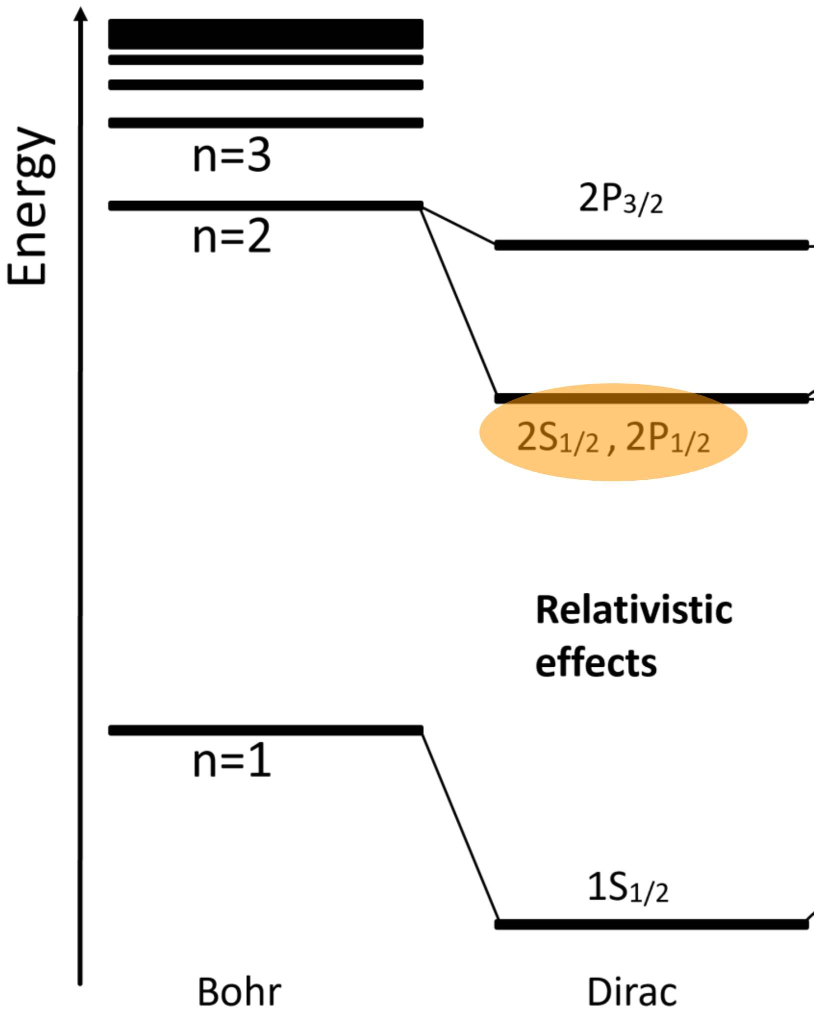
Towards Improving the Precision of the Lamb Shift Measurement in Muonium

Gianluca Janka, on behalf of the Mu-MASS collaboration

Searching for New Physics at the Quantum Technology Frontier,

03.07.2023

Lamb Shift

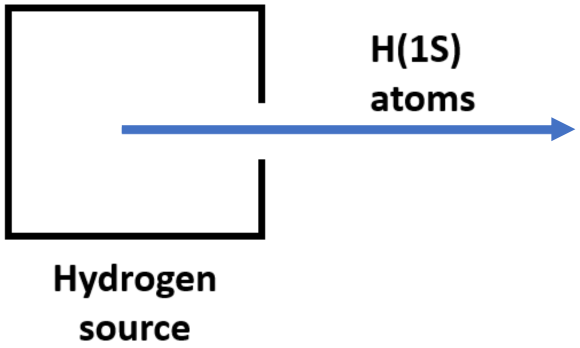


What about $2S_{1/2}$ and $2P_{1/2}$?

- Same energy according to Dirac
- Experimental evidence for a splitting found in early 1930s, nothing conclusive

Lamb Shift

W. E. Lamb and R. C. Retherford.
Phys. Rev., 72:241–243, 1947.



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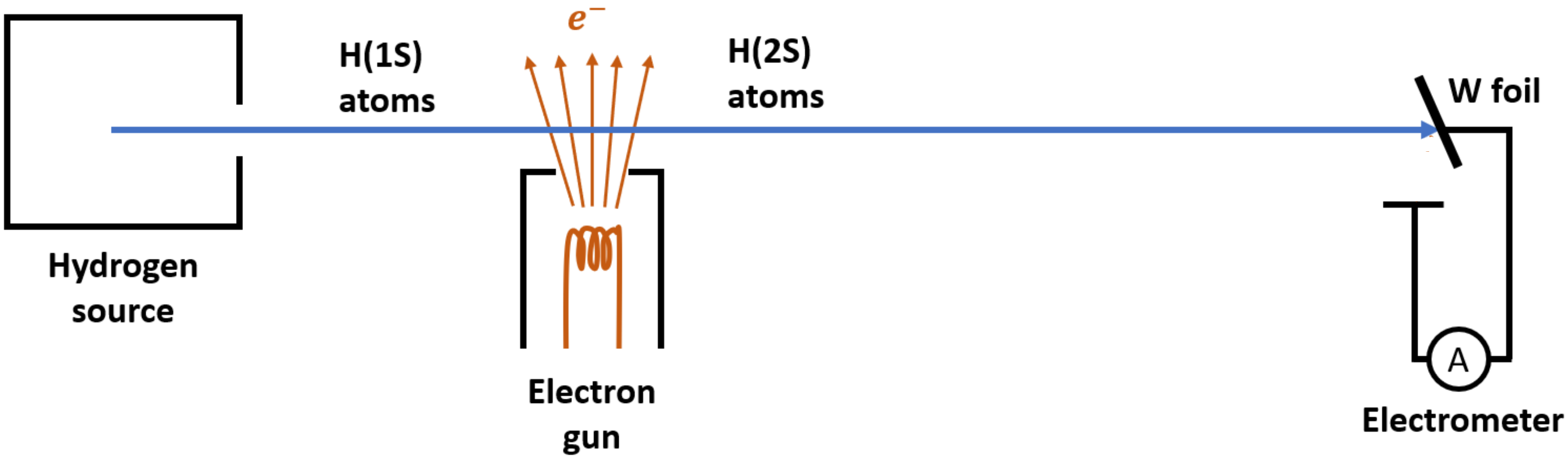

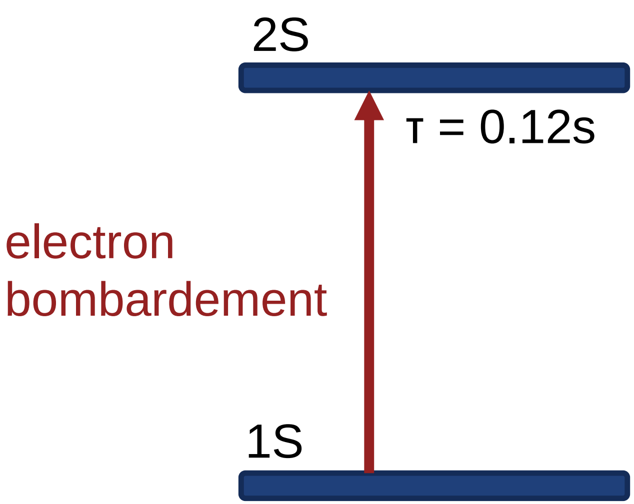

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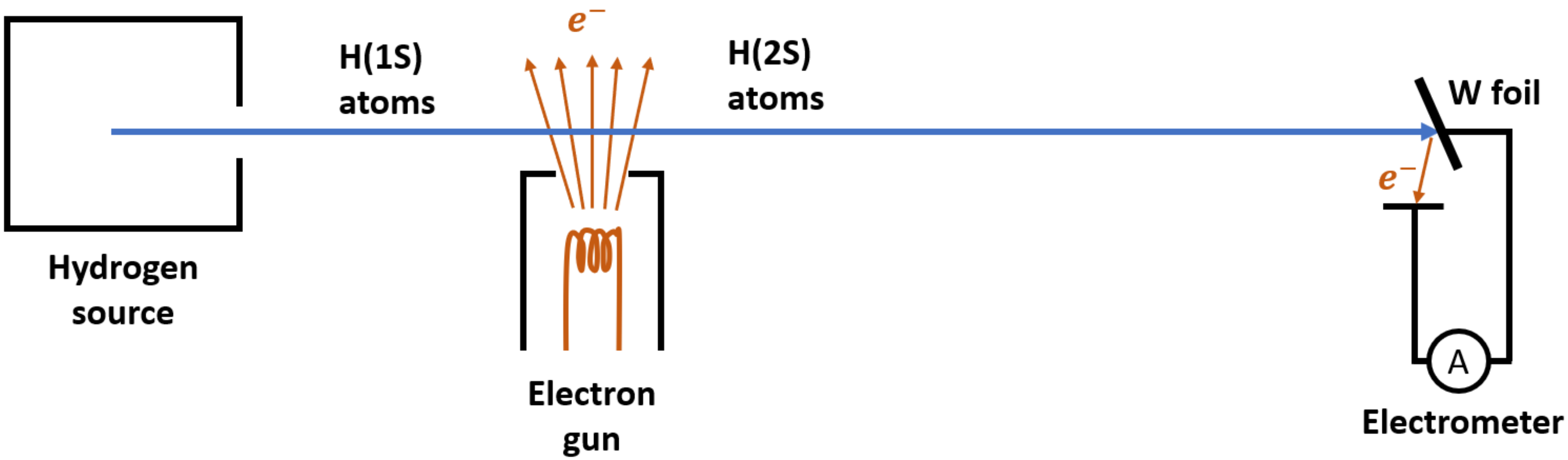

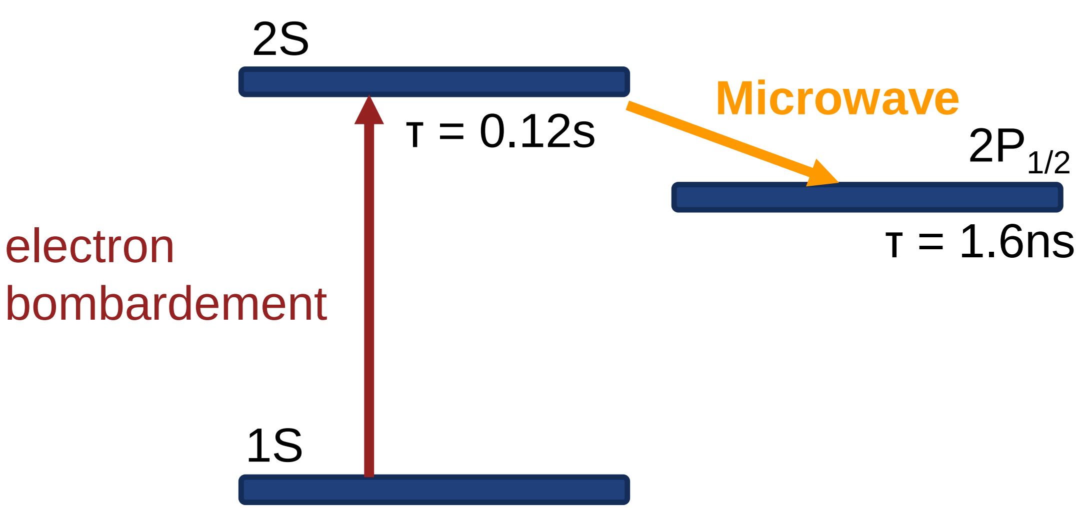

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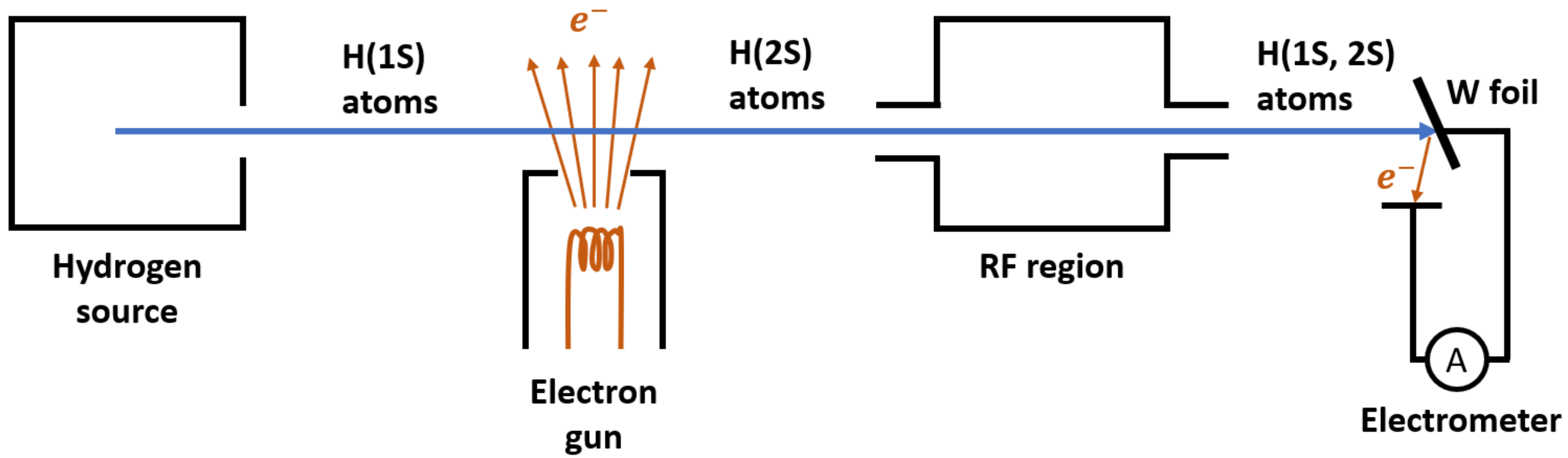

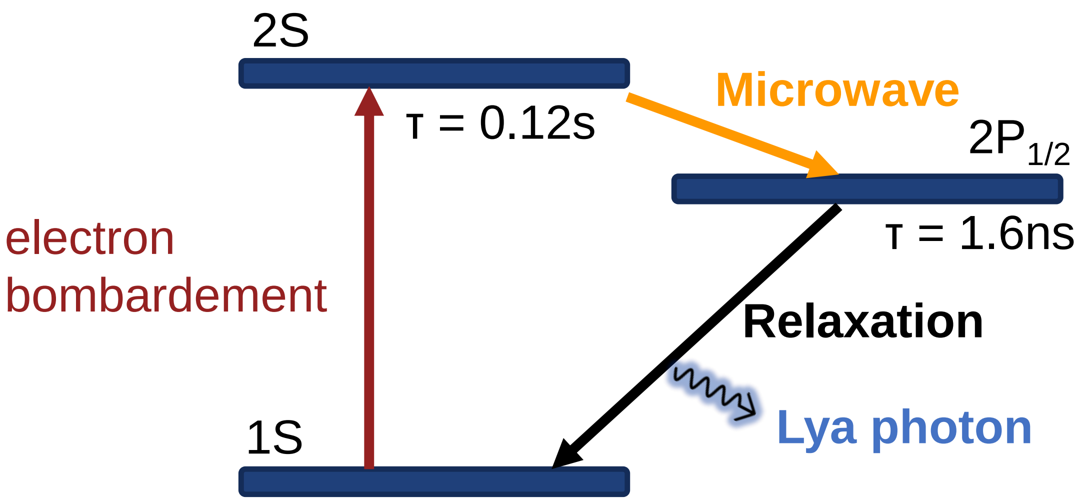

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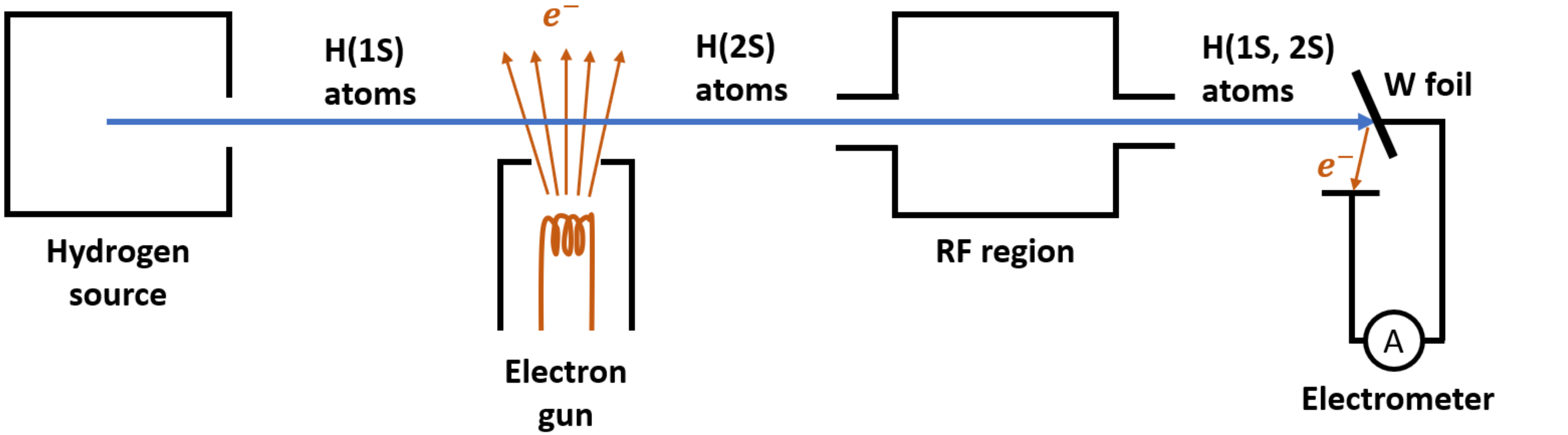
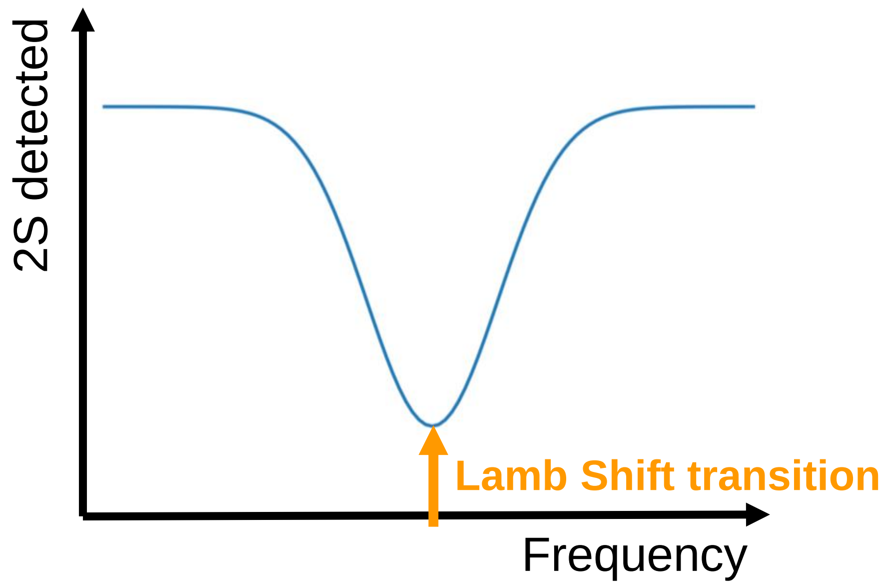
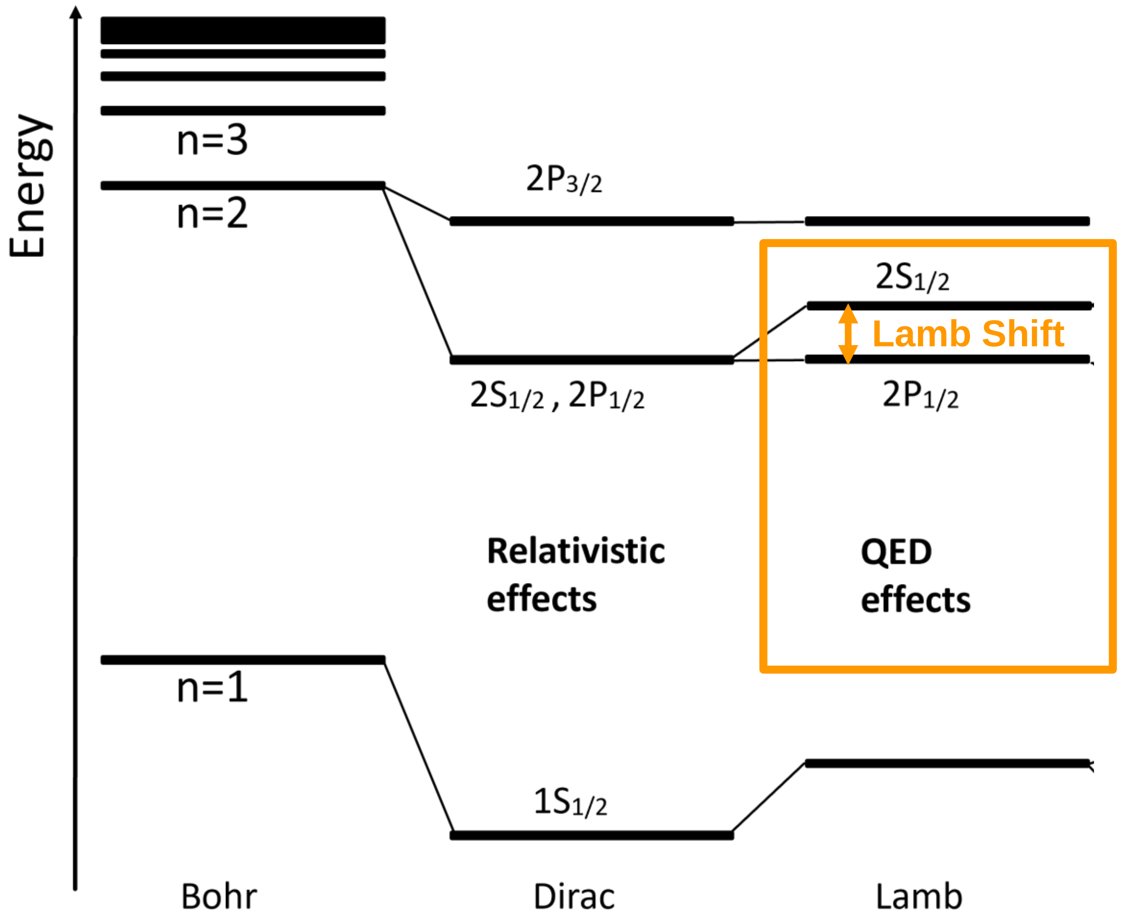


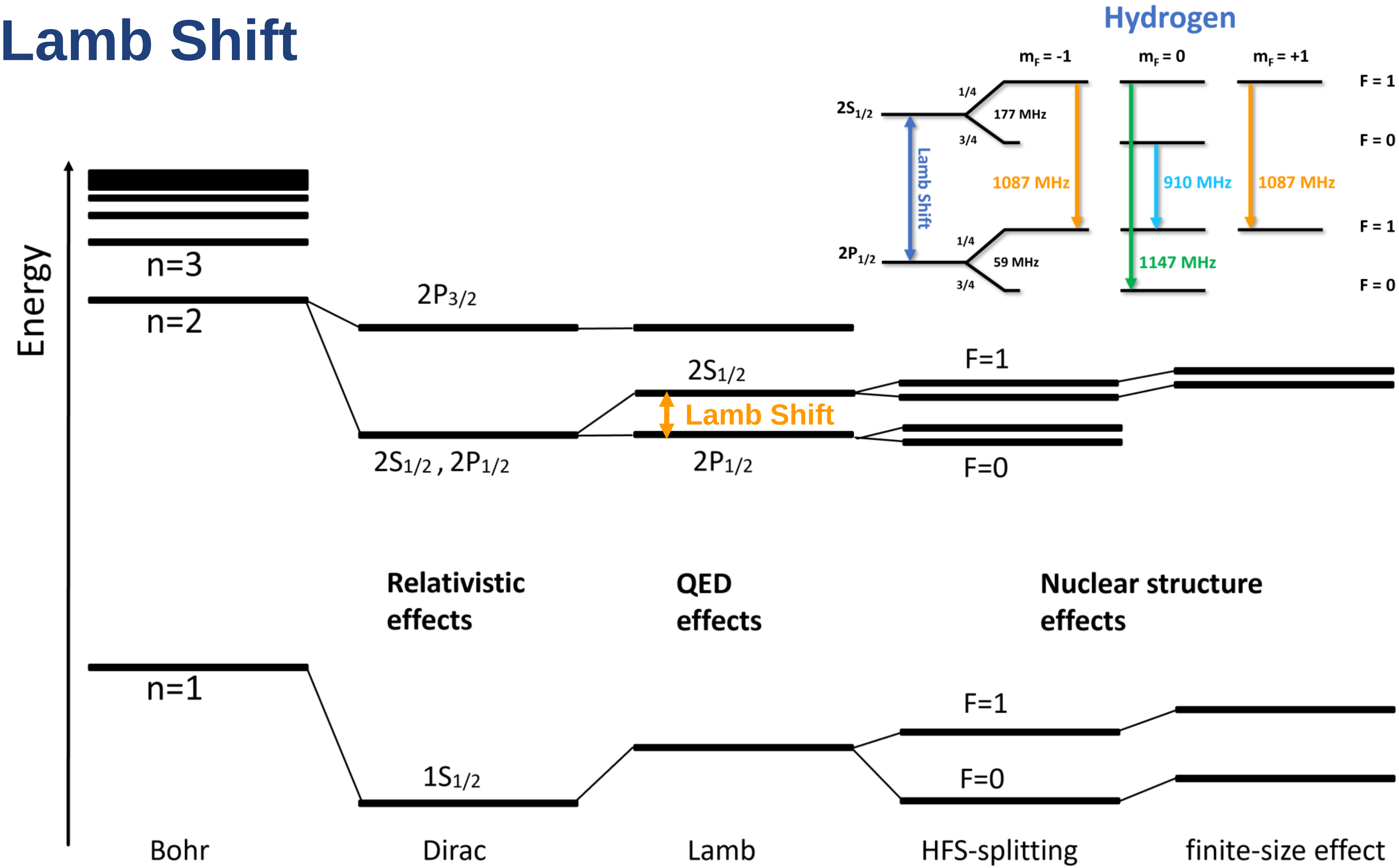


Lamb Shift



Fundamental discovery for the development of QED

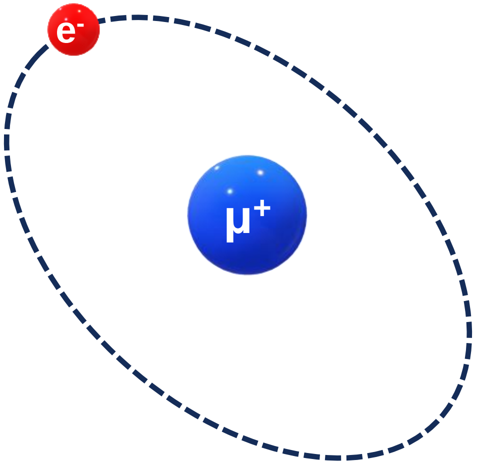
Lamb Shift



Hydrogen
$m_F = -1$
$m_F = 0$
$m_F = +1$
F = 1
F = 0
F = 1
F = 0
$2S_{1/2}$
$2P_{1/2}$
1/4
3/4
177 MHz
59 MHz
Lamb Shift
1087 MHz
910 MHz
1087 MHz
1147 MHz
Energy
n=3
n=2
n=1
$2P_{3/2}$
$2S_{1/2}$, $2P_{1/2}$
$2S_{1/2}$
$2P_{1/2}$
Lamb Shift
F=1
F=0
$1S_{1/2}$
F=1
F=0
Relativistic effects
QED effects
Nuclear structure effects
Bohr
Dirac
Lamb
HFS-splitting
finite-size effect

Lamb Shift of Muonium

Muonium (M)



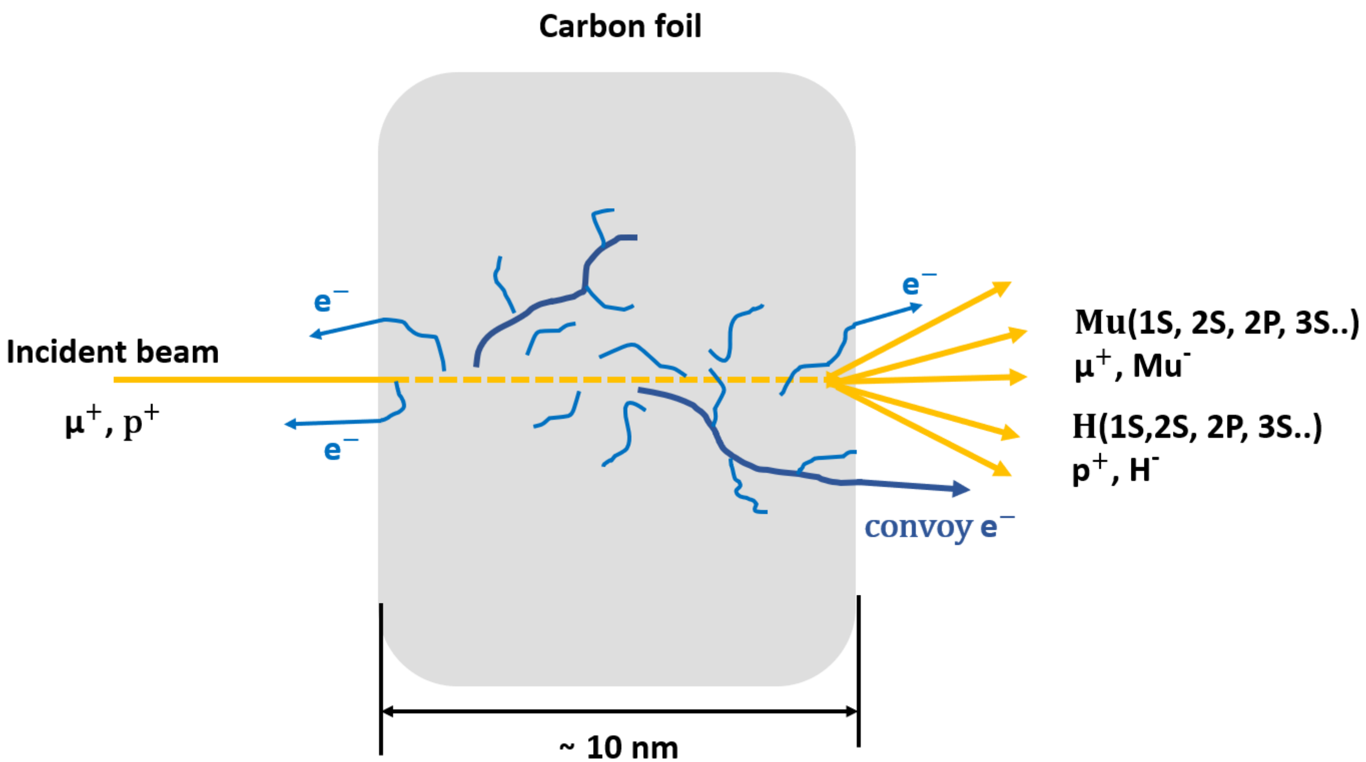
- Prediction of M in 1957 by Friedmann, Hughes, Telegdi, detected in 1960

- M is purely leptonic, free from finite size effects

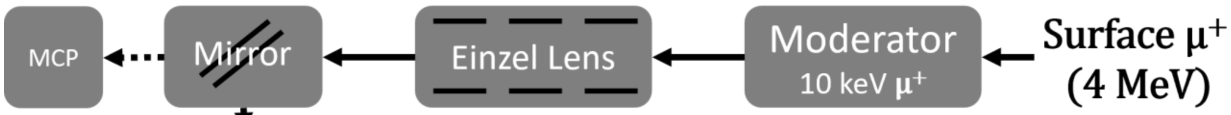
  → **excellent candidate to test bound-state QED**

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

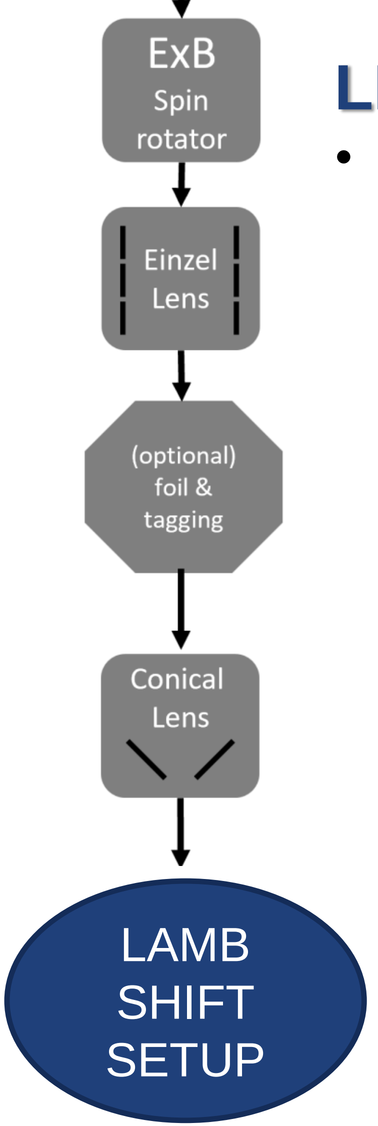
2S Muonium formation: Beamfoil technique



LEM beamline @ PSI



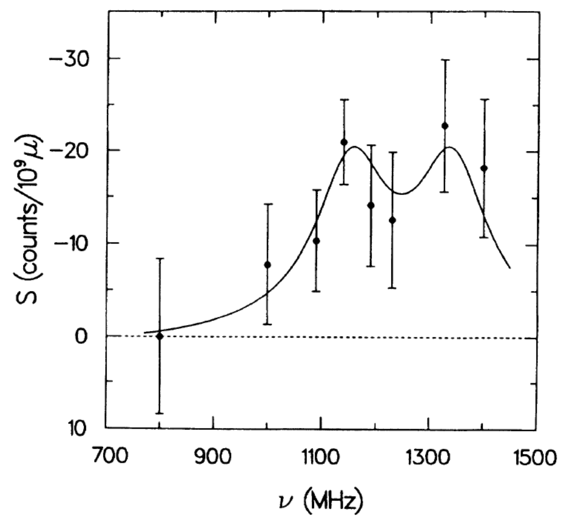
PAUL SCHERRER INSTITUT



LEM beamline @ PSI

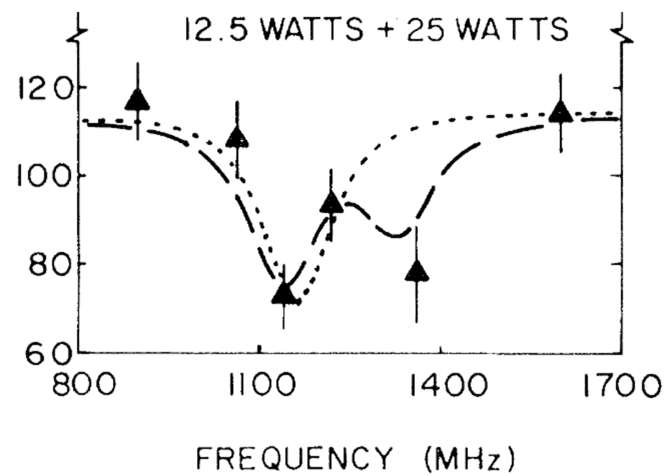
- delivers high rate μ+ (around 5 – 10 kHz), with energies adjustable from 2 to 20 keV
  → **unique!**
  → … **and exactly what we need!**

1042(22) MHz



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

1070(13) MHz



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

2S Muonium formation at LEM

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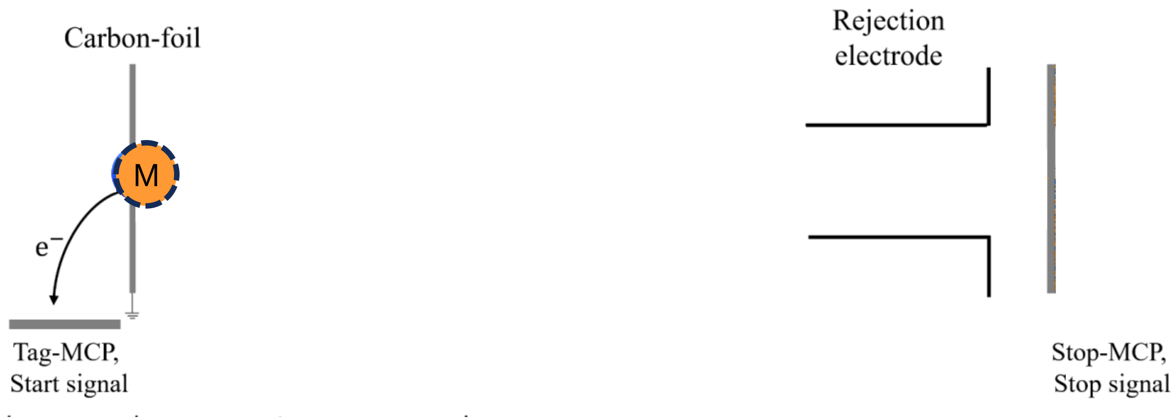
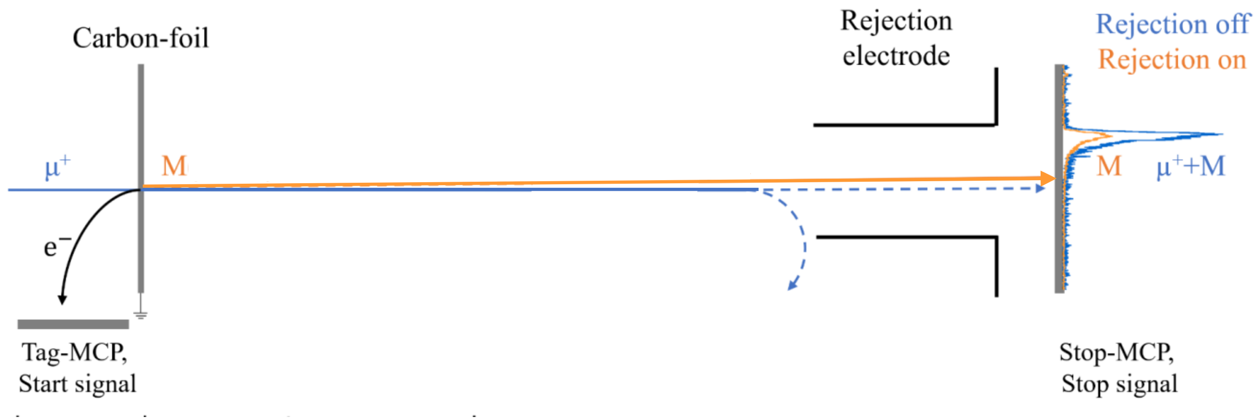
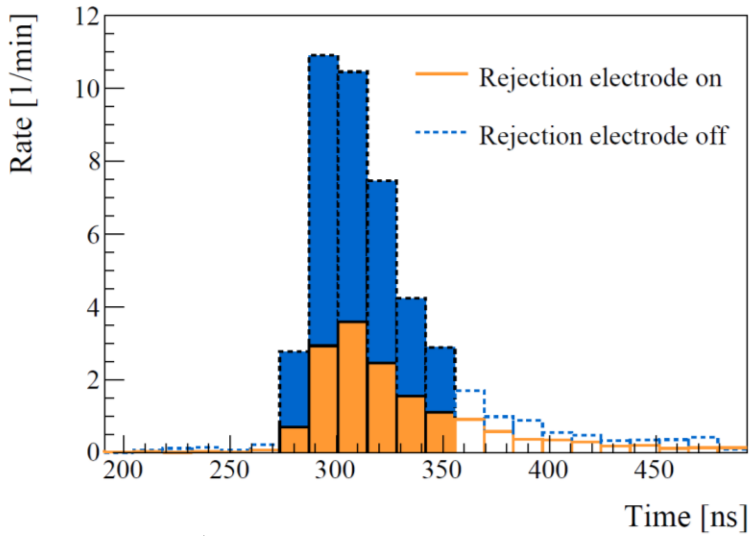
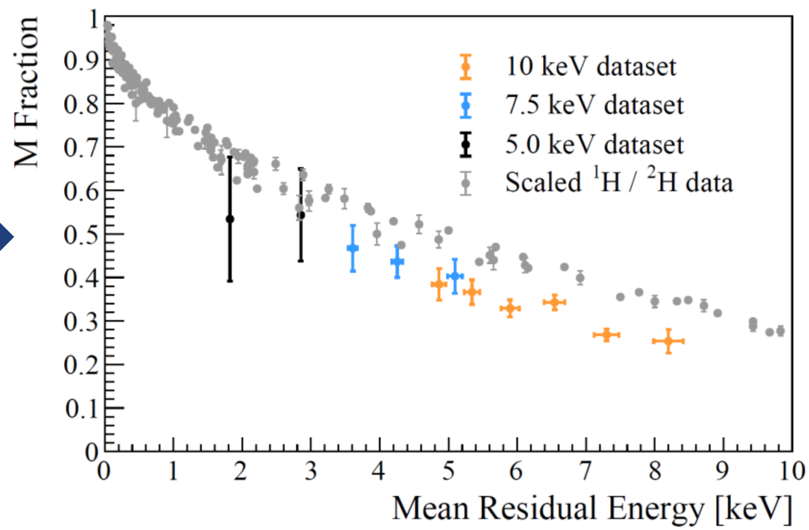


2S Muonium formation at LEM

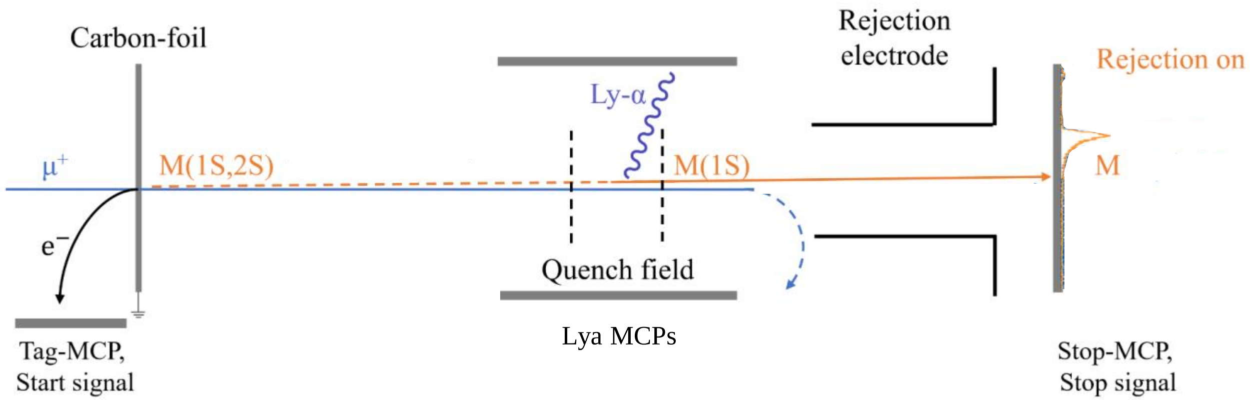


Rejection electrode on/off to show Muonium formation

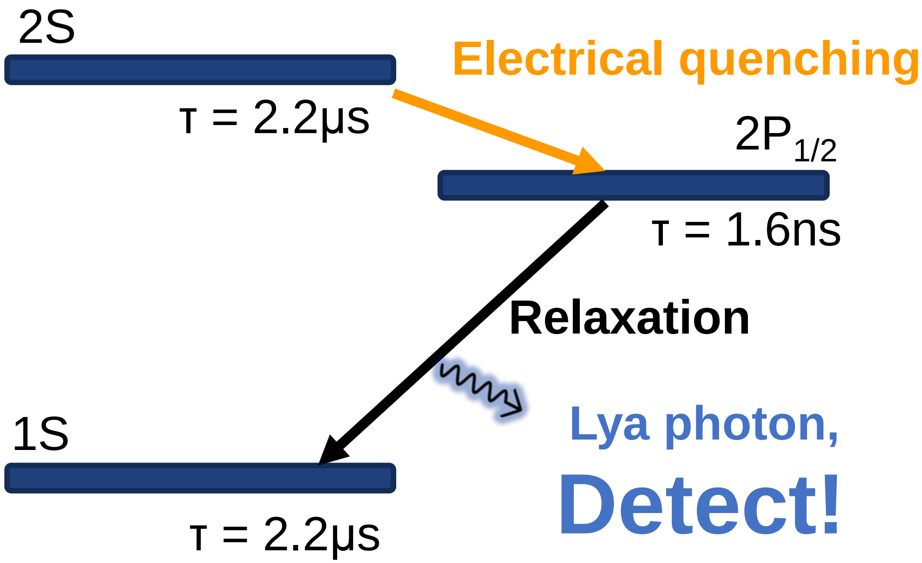




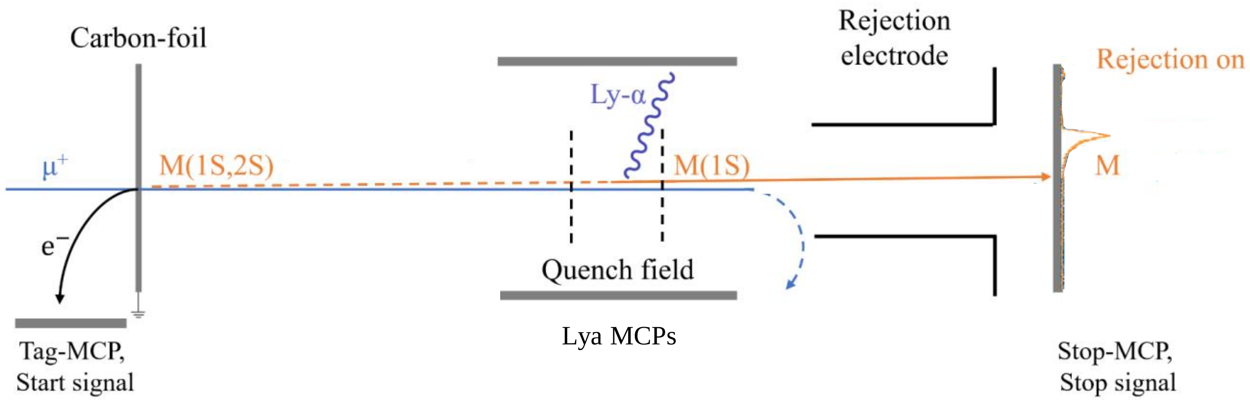
2S Muonium formation at LEM



Lya setup with quenching on/off to show M(2S) formation



2S Muonium formation at LEM



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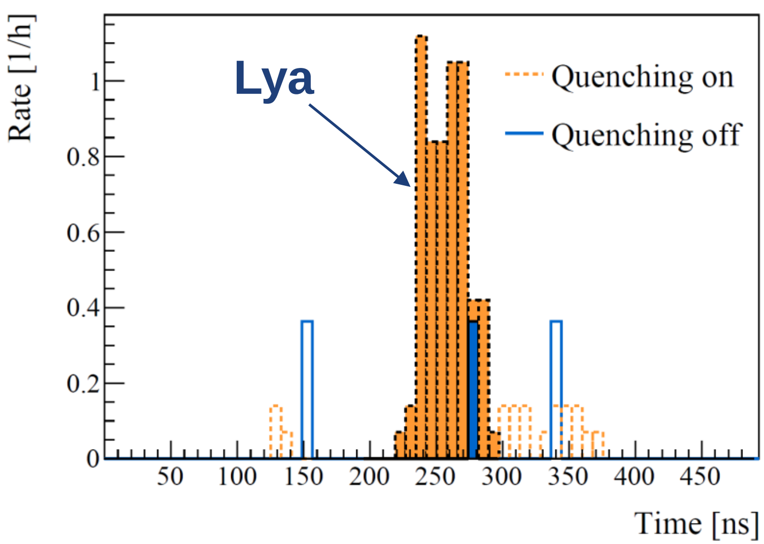
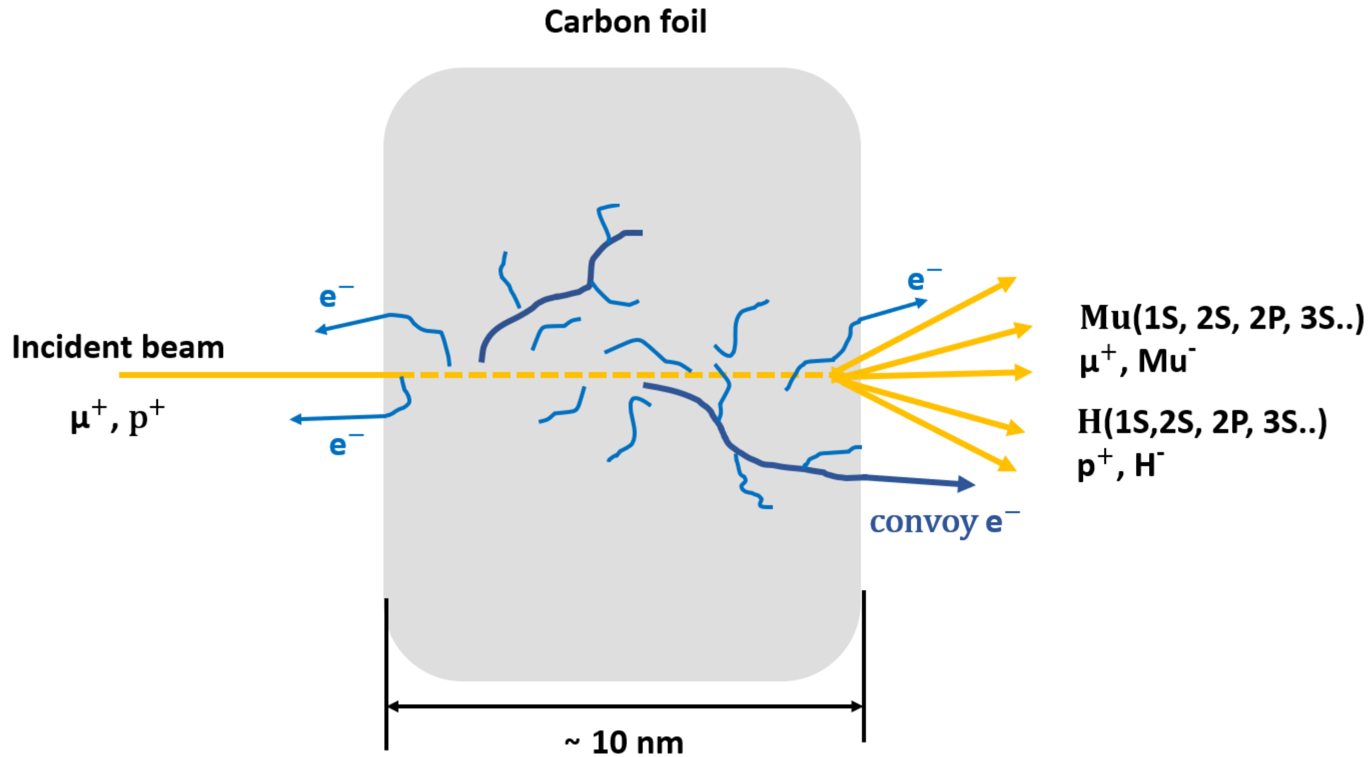


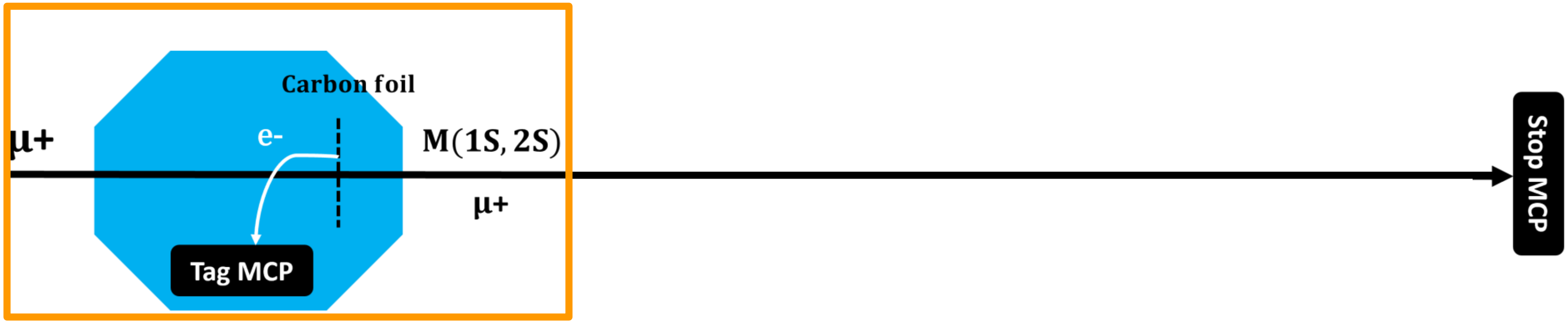
→ M(2S) beam suitable for Lamb shift measurement

→ (GBAR Lya setup is commissioned)

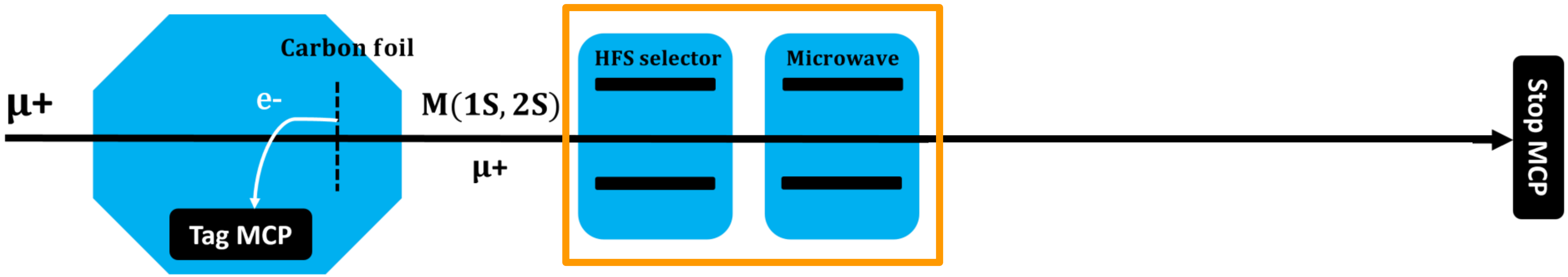
G. Janka et al. Eur. Phys. J. C, 80(9):804, 2020

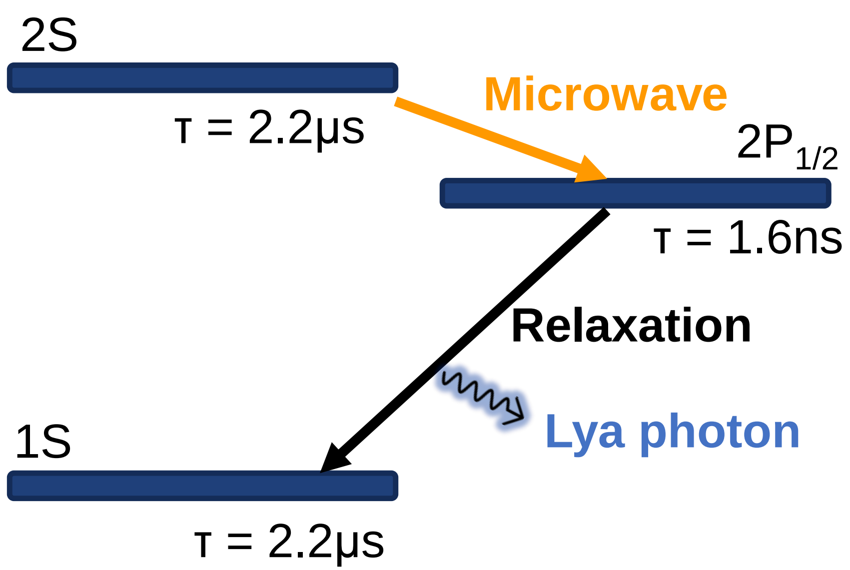
Lamb Shift of Muonium: Principle



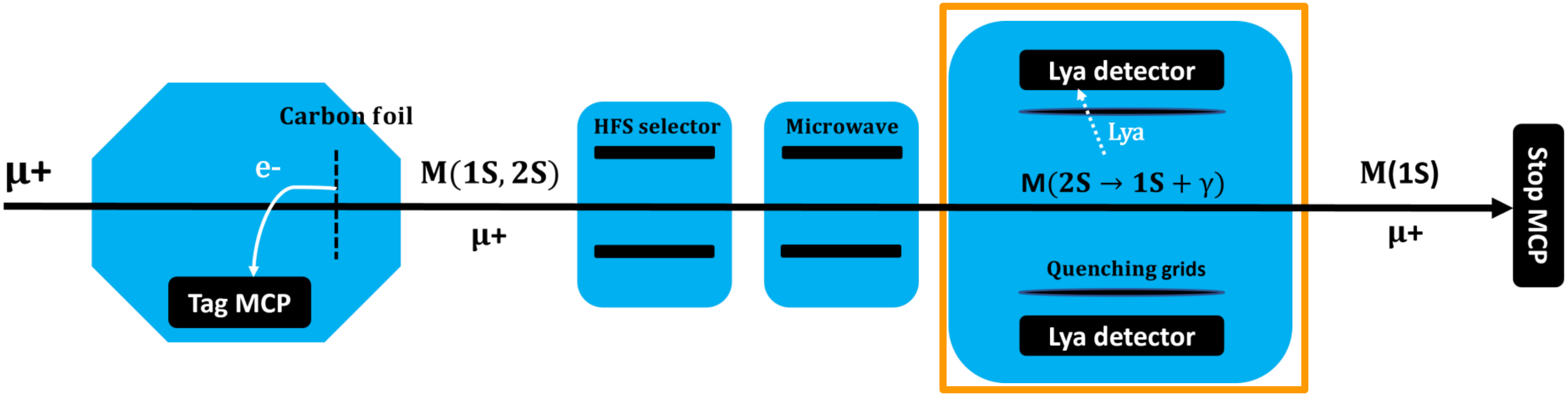


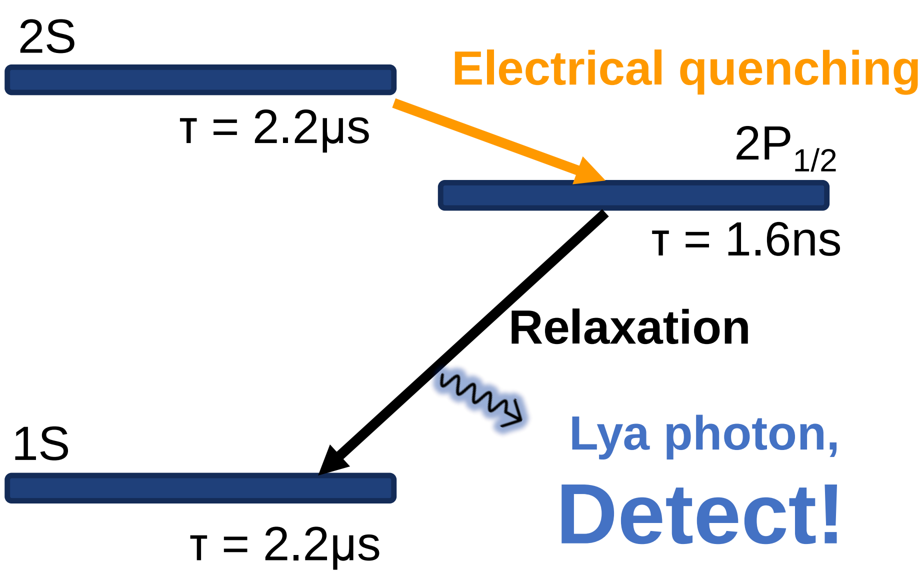
Lamb Shift of Muonium: Microwave

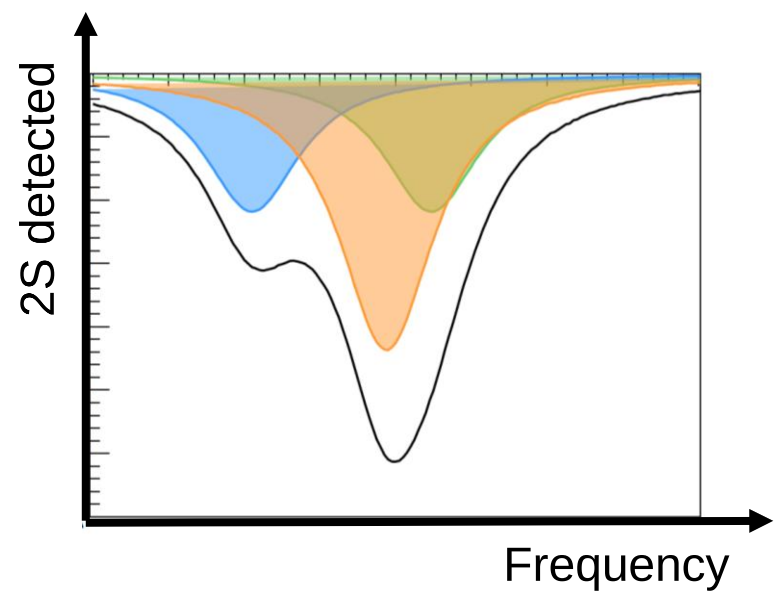




Lamb Shift of Muonium: Principle



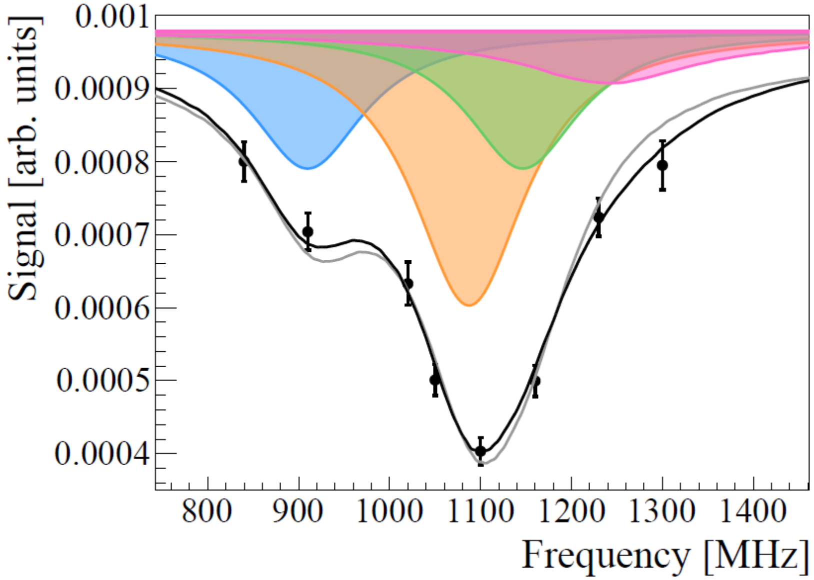


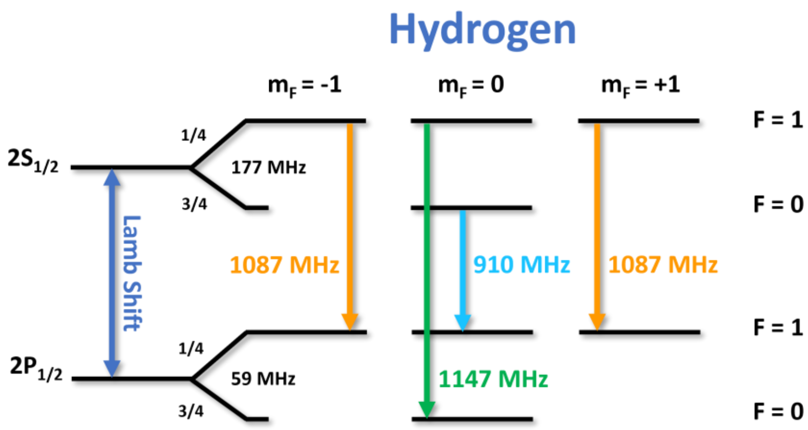


The journey begins...

Lamb Shift of Hydrogen with Mu-MASS

Hydrogen





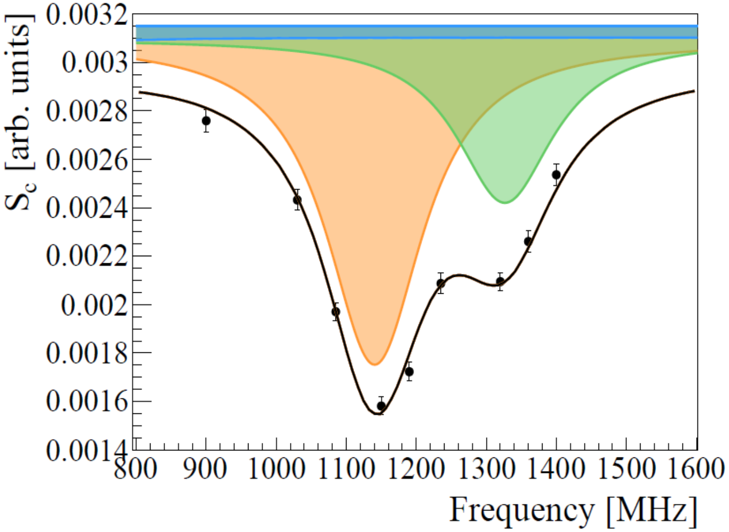
First tests with proton beam:

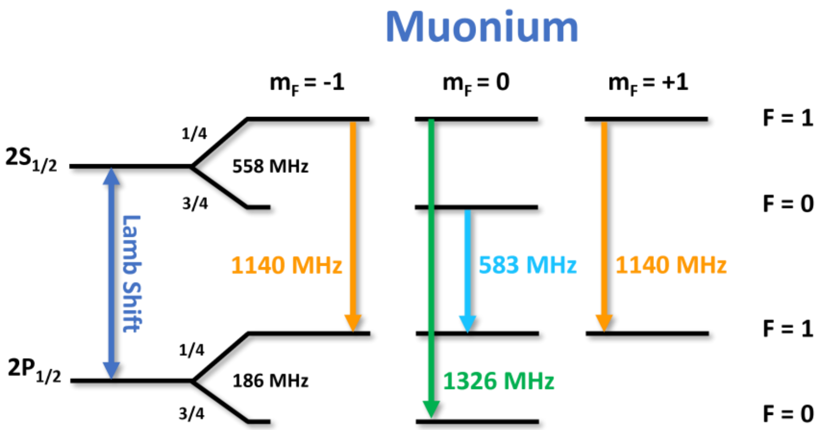
→Microwave and Lya-Detection setup works as expected

→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 with Mu-MASS

Muonium





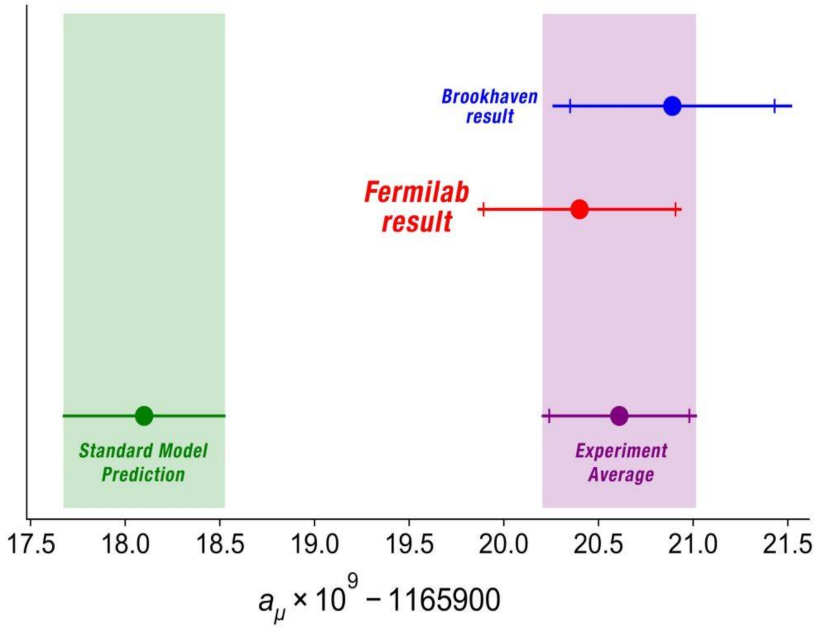
LS at 1047.2(2.5) MHz
Theory at 1047.498(1) MHz

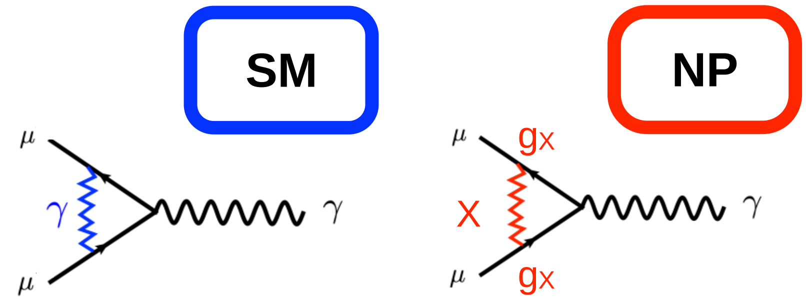
G. Janka et al., EPJ Web Conf. 262 (2022)

→ Limited by statistics
→ Agrees well with theory
→ **Precision not enough to test b-QED, but constrains new physics**

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

Looking for New Physics: New Force





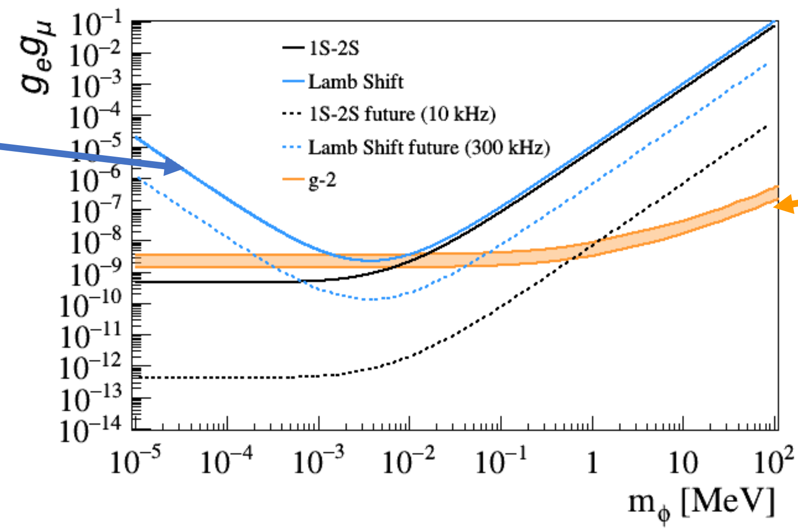
Bands: region suggested by **$(g\text{-}2)_\mu$**

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)

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



Looking for New Physics: SME

Additional energy term for Muonium Lamb Shift:

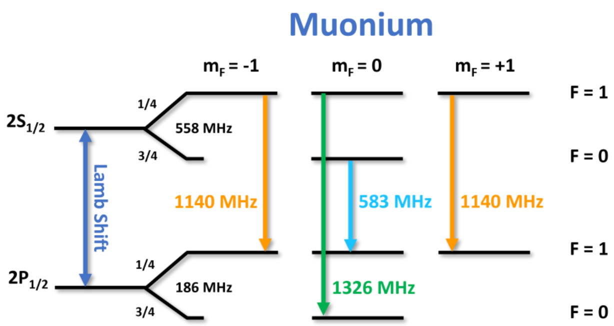
$$2\pi\delta\nu_{\text{Lamb}} = -\frac{2}{3}(\alpha m_r)^4(\mathring{a}_4^{\text{NR}} + \mathring{c}_4^{\text{NR}})$$

Lorentz and CPT ($\mathring{a}_4^{\text{NR}}$)   Only Lorentz ($\mathring{c}_4^{\text{NR}}$)

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

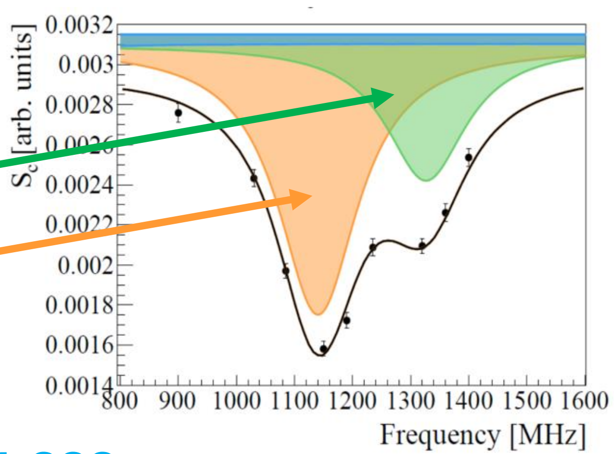
A. H. Gomes et al., Phys. Rev. D, 90:076009, 2014.

But wait...? Where is the transition F=0 to F=1?



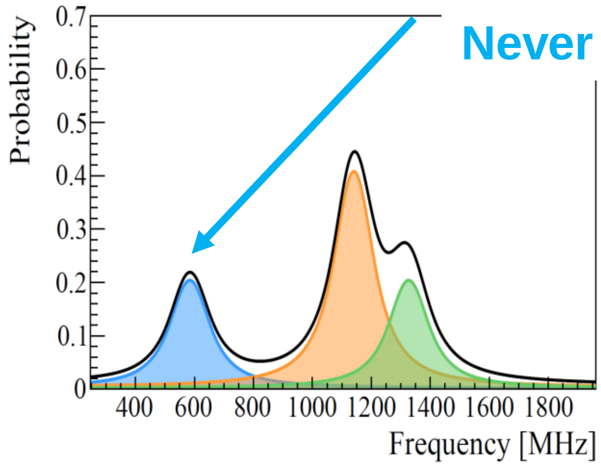
F=1 to F=0

F=1 to F=1

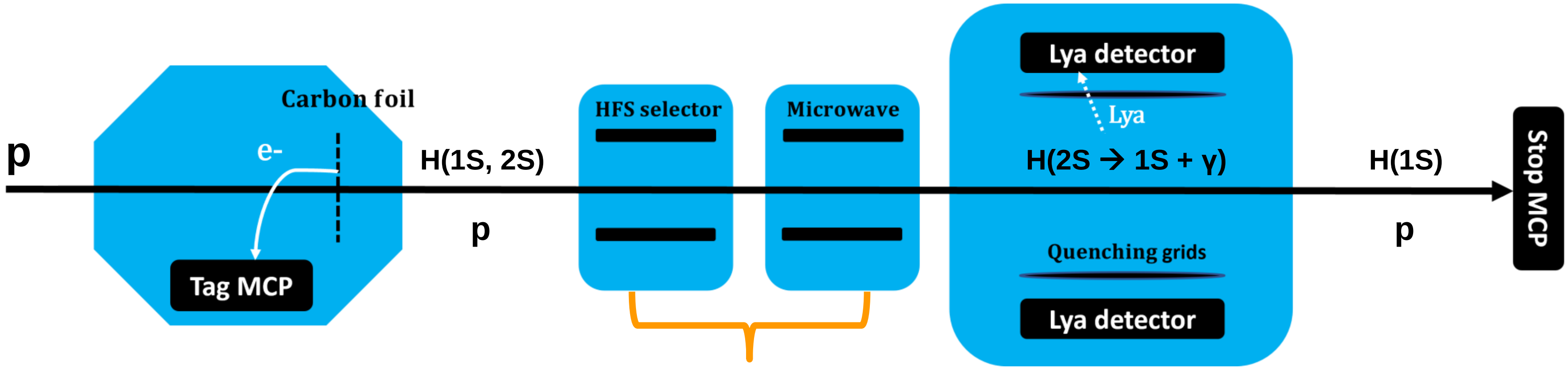


F=0 to F=1 ???

Never observed before in M...



Lamb Shift of Hydrogen: HFS Selector

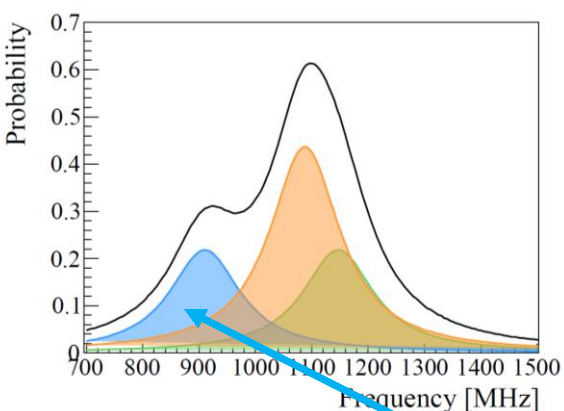


RF region

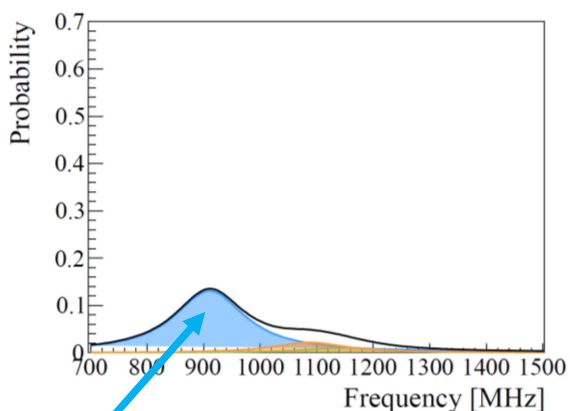
2S → 2P → 1S + $\gamma_{(122nm)}$

τ_{2S} = 0.12s, τ_{2P} = 1.6ns

Without HFS selector



With HFS selector



→ **reduces overall linewidth, background and line-pulling**

→ **simplifies analysis**

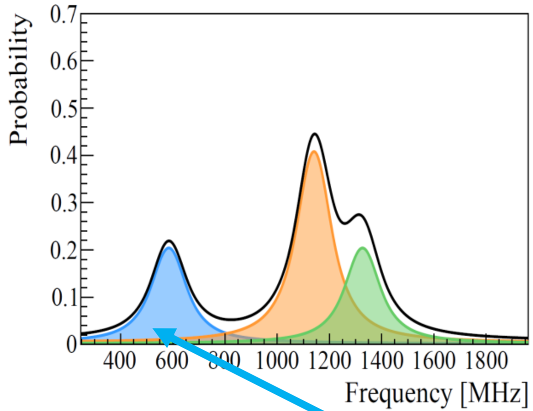
→ **reduces statistics**

F=0 to F=1:

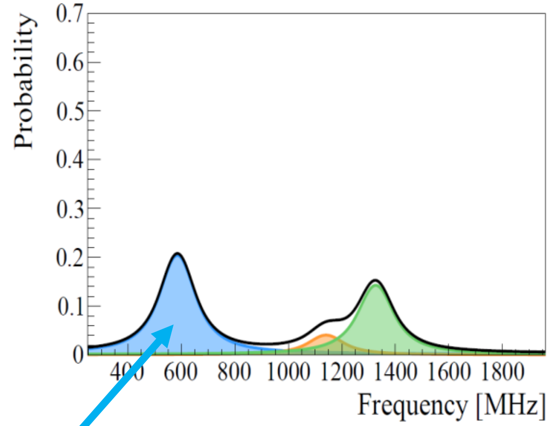
Most promising transition for precise measurement with H

Lamb Shift of Muonium: HFS Selector

Without HFS selector



With HFS selector

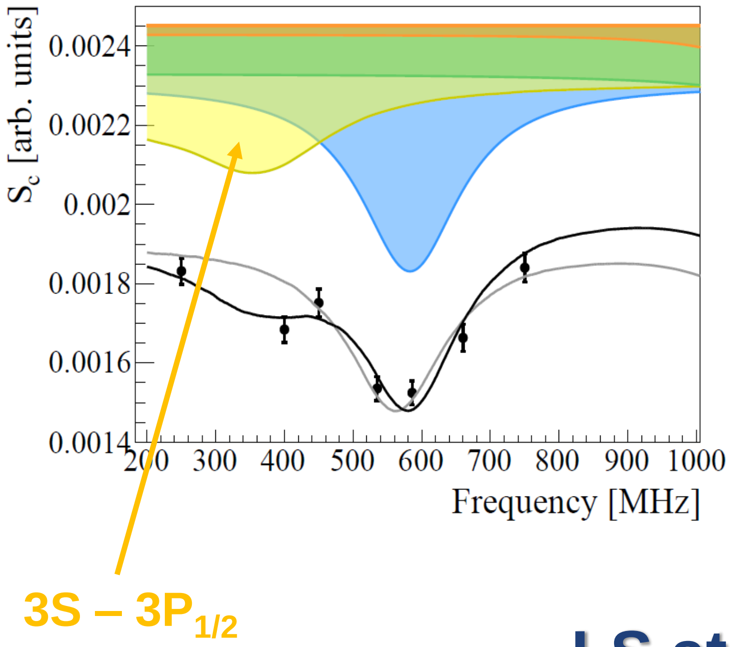


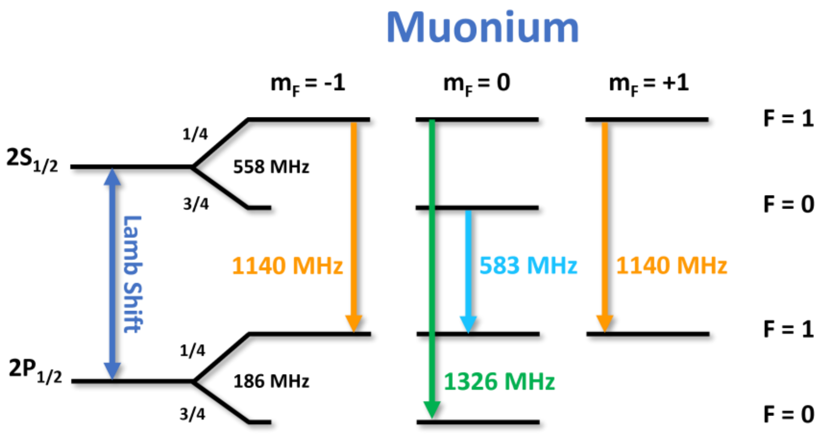
F=0 to F=1:
Also promising transition for precise measurement with Muonium

- →**HFS selector less crucial in Muonium due to more isolated F=0 to F=1 transition**
- →**reduces still background and line-pulling and simplifies analysis**
- →**reduces statistics**

Lamb Shift of Muonium with Mu-MASS

Muonium





LS at 1045.5(6.8) MHz

2S HFS at 559.6(7.2) MHz

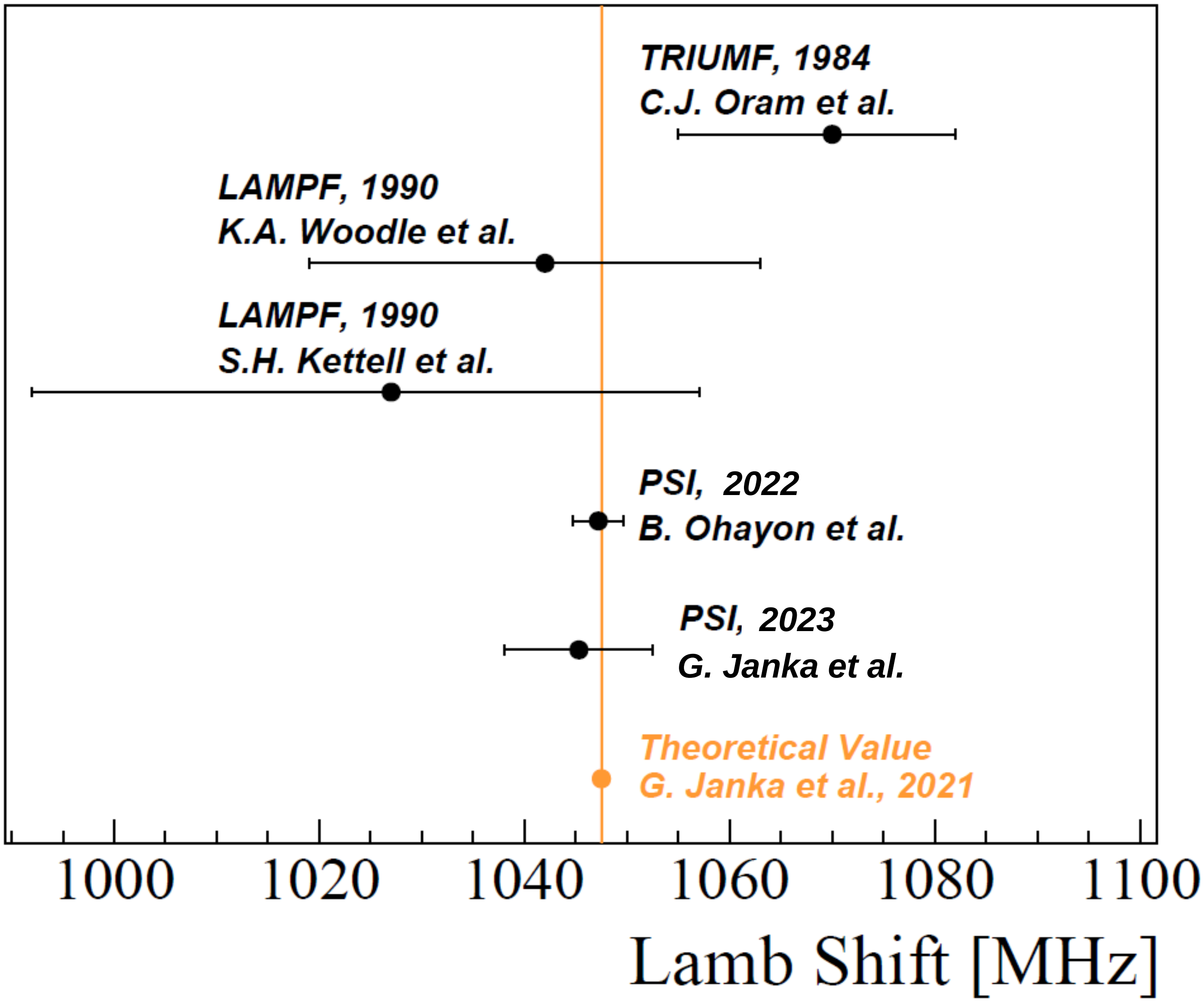
First time detection of M(3S)

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

→ **Promising, but suffers from 3S contamination**

→ **We can fix that!**

Lamb Shift of Muonium

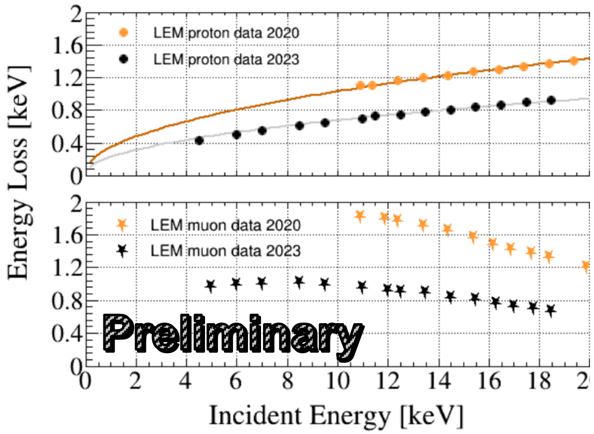


Outlook on Muonium Lamb Shift

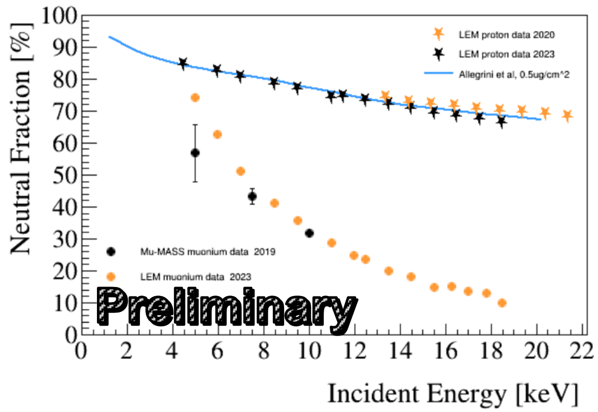
Increasing Muonium flux is key to improve uncertainty!

Change to thinner carbon foil (2.5ug/cm^2 to 0.5ug/cm^2)

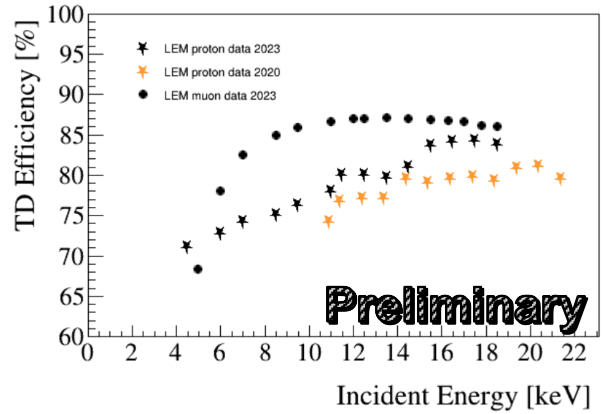
- **Tests with protons and muons very promising**



Significantly smaller energy loss



Similar neutral formation efficiency



Improved tagging efficiency

Measurement of M LS with new foil planned for June 2023, but unfortunately HIPA was broken during our beamtime...

Outlook on Muonium Lamb Shift

For all options, increasing Muonium flux is key to improve uncertainty!

- **Change to few layers of graphene (~1nm thickness)**
  - **To my knowledge not commercially available. Producing foils is an art!**
- **Upgrade of muE4 beamline (~ factor 3 in flux, expected 2025)**
  - **L. Zhou et al., Phys. Rev. Accel. Beams 25, 051601 (2022)**
- **MuCool beamline @ PSI**
  - **Would allow to use gas targets for M formation**
  - **A. Antognini et al., SciPost Phys.Proc. 5 (2021)**
- **HiMB upgrade @ PSI**
  - **Two orders of magnitude higher μ+ flux**
  - **M. Aiba et al., arXiv:2111.05788**

With **MuCool** beamline and **HiMB UPGRADES** @ PSI, measurements with uncertainty of the order of hydrogen would become feasible

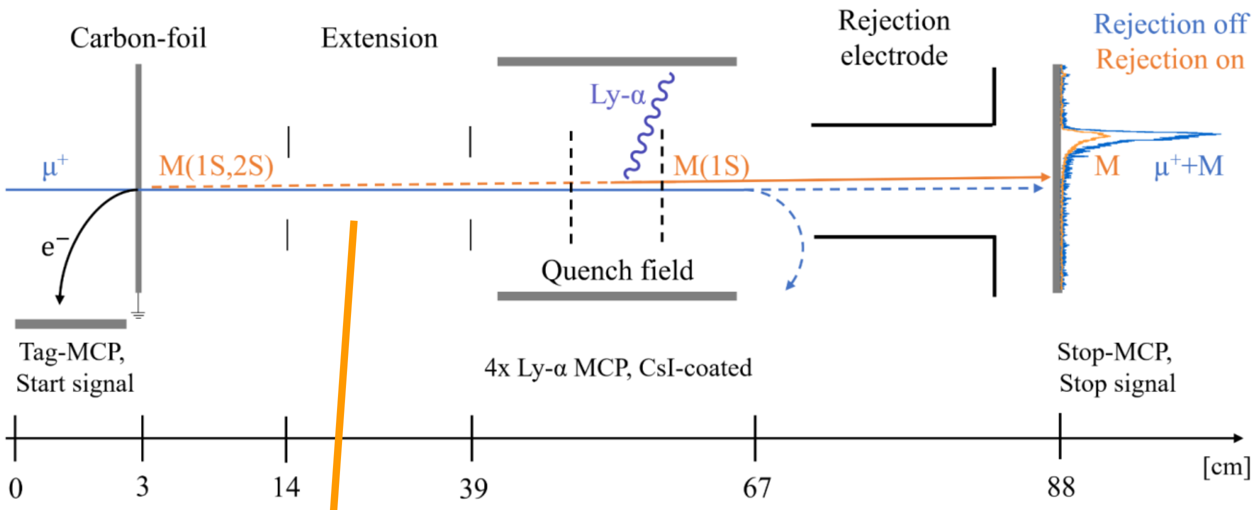
Thank you for your attention!

PAUL SCHERRER INSTITUT
PSI

MU-MASS

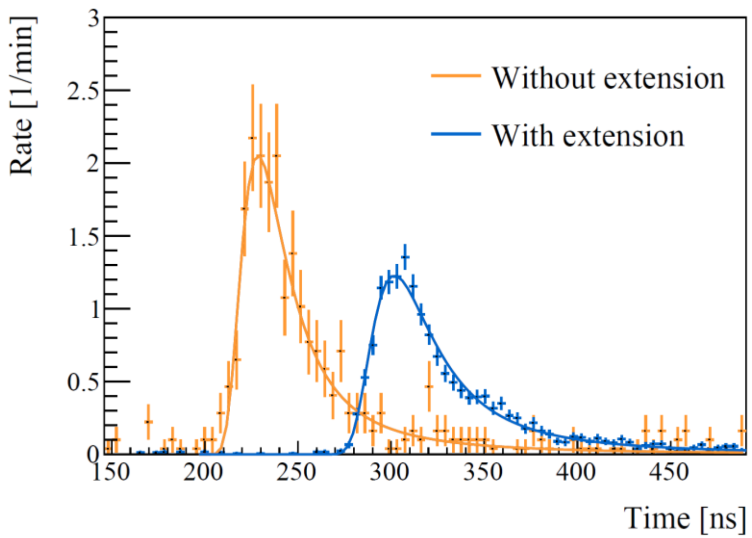
Backup Slides

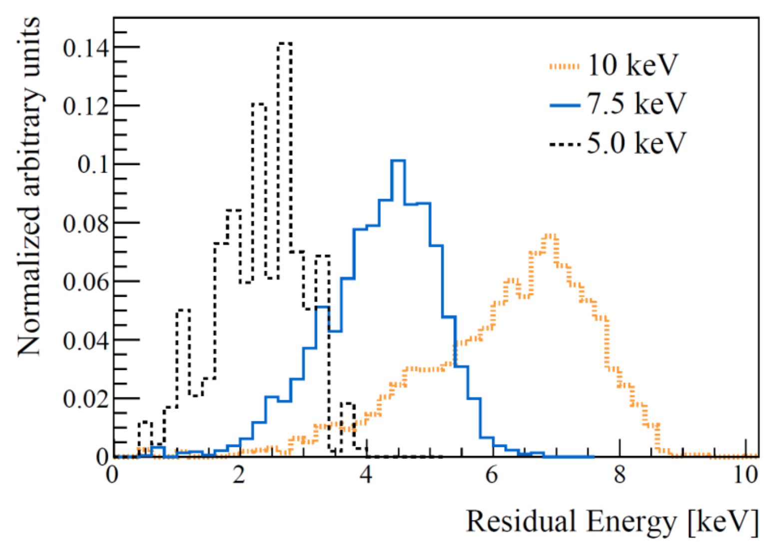
2S Muonium formation at LEM



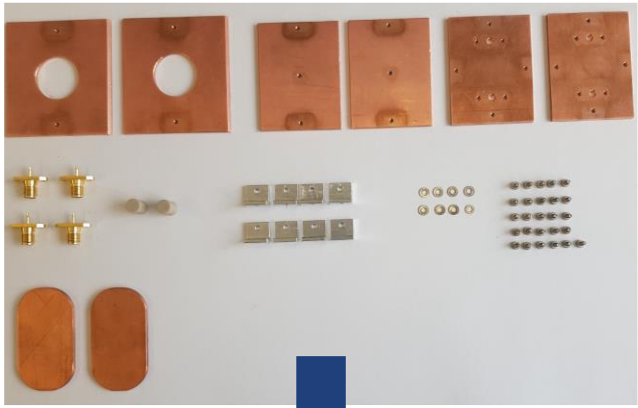
(1&2) **(3)** **(4)**

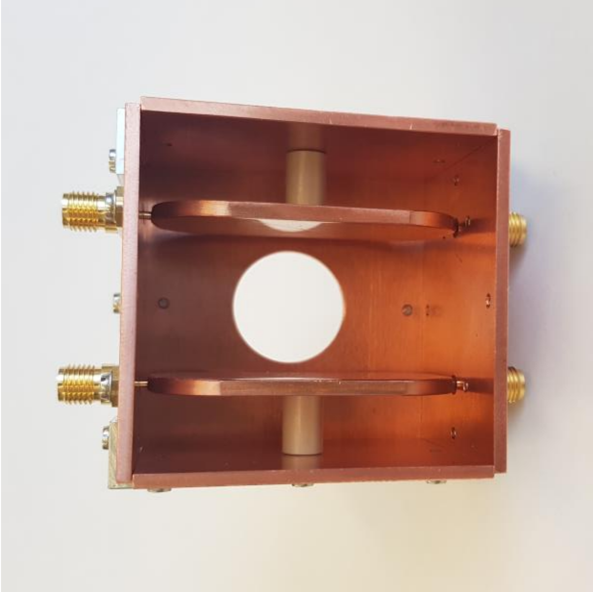
Extension to correct TOF spectra and extract energy loss



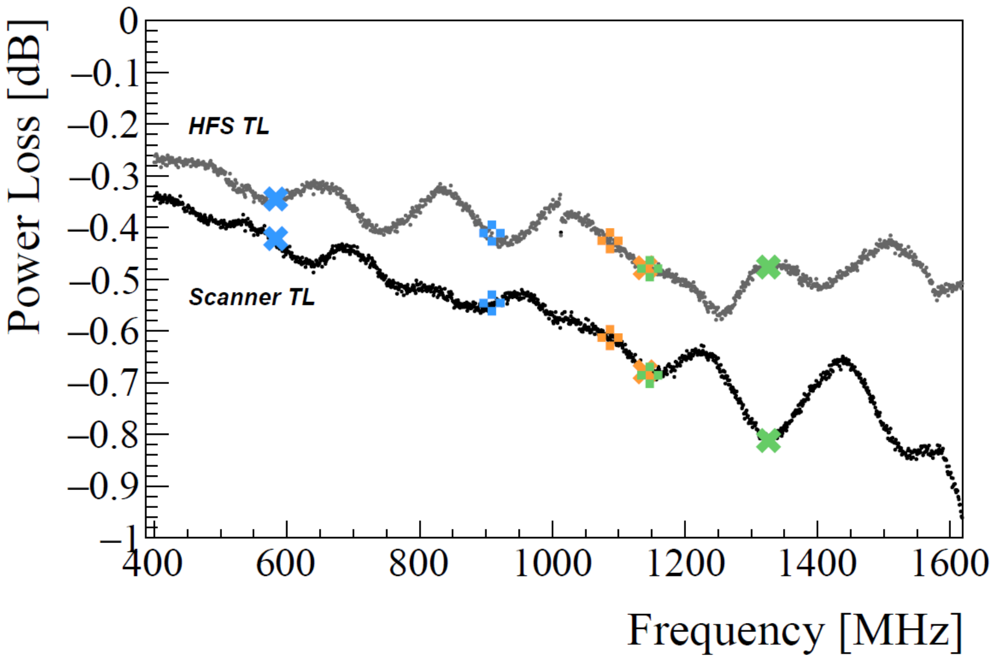


Lamb Shift of Muonium: RF Region

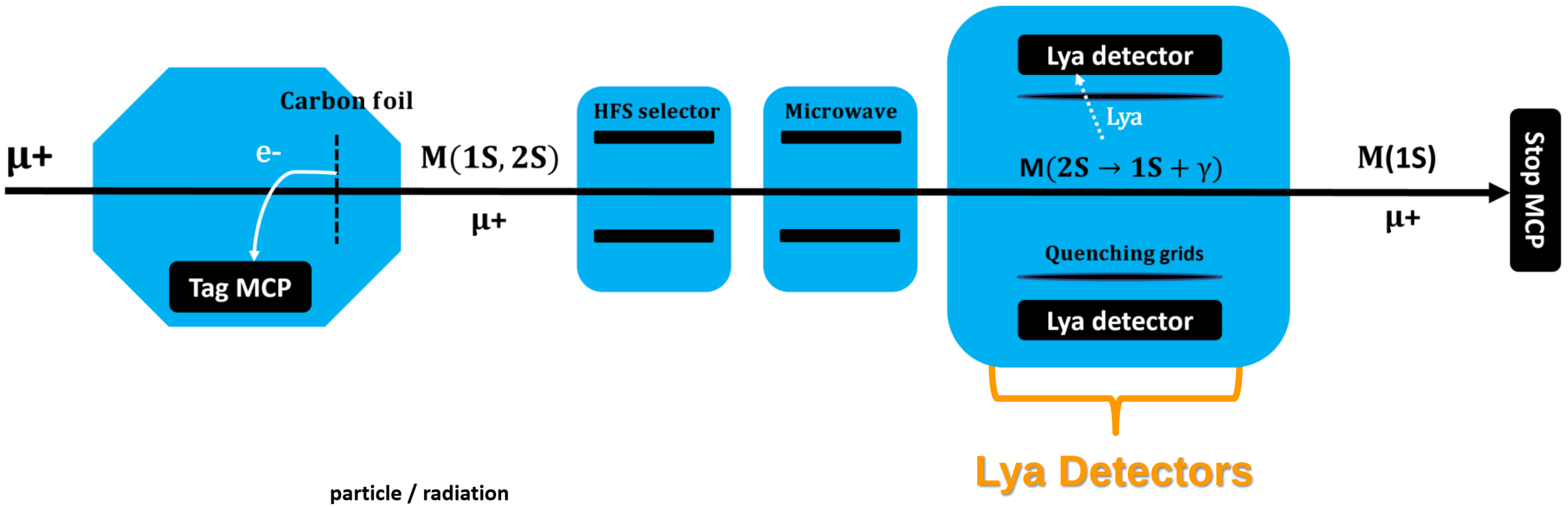


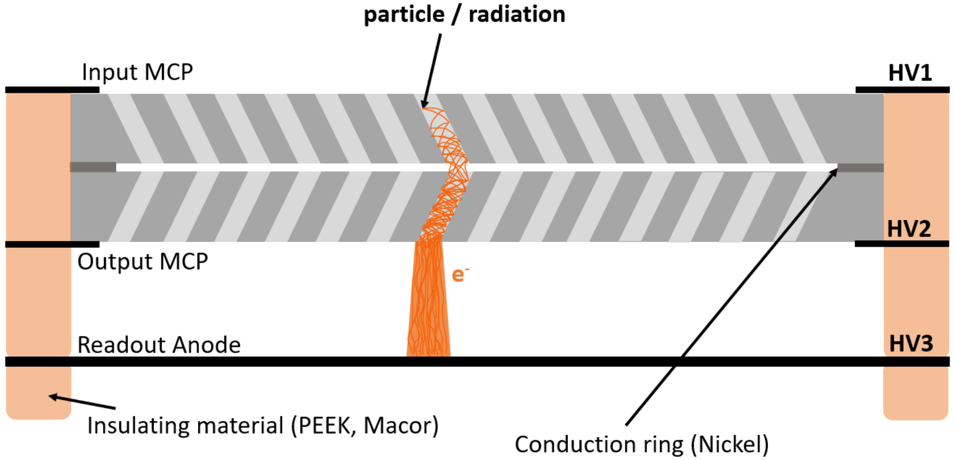


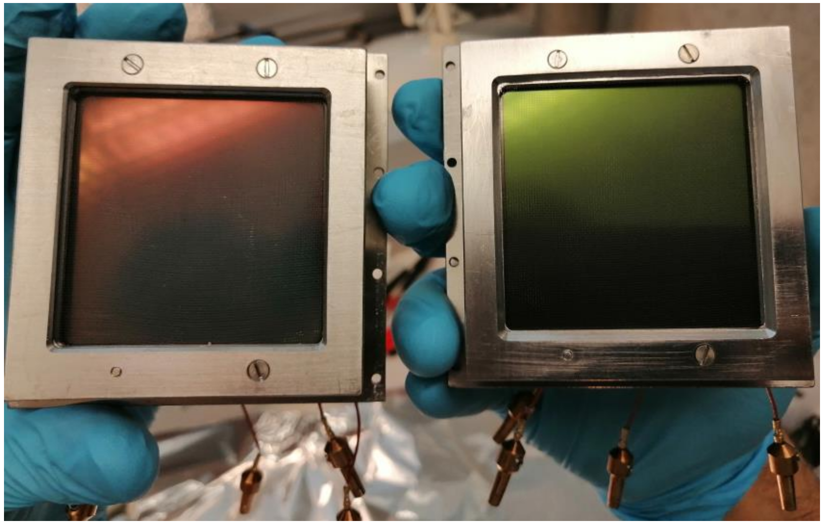
- Design of transmission line chosen, inspired by Lundeen and Pipkin
  S. R. Lundeen and F. M. Pipkin. Metrologia, 22(1):9–54, 1986.
- Trial & Error with VNA until power loss was minimized



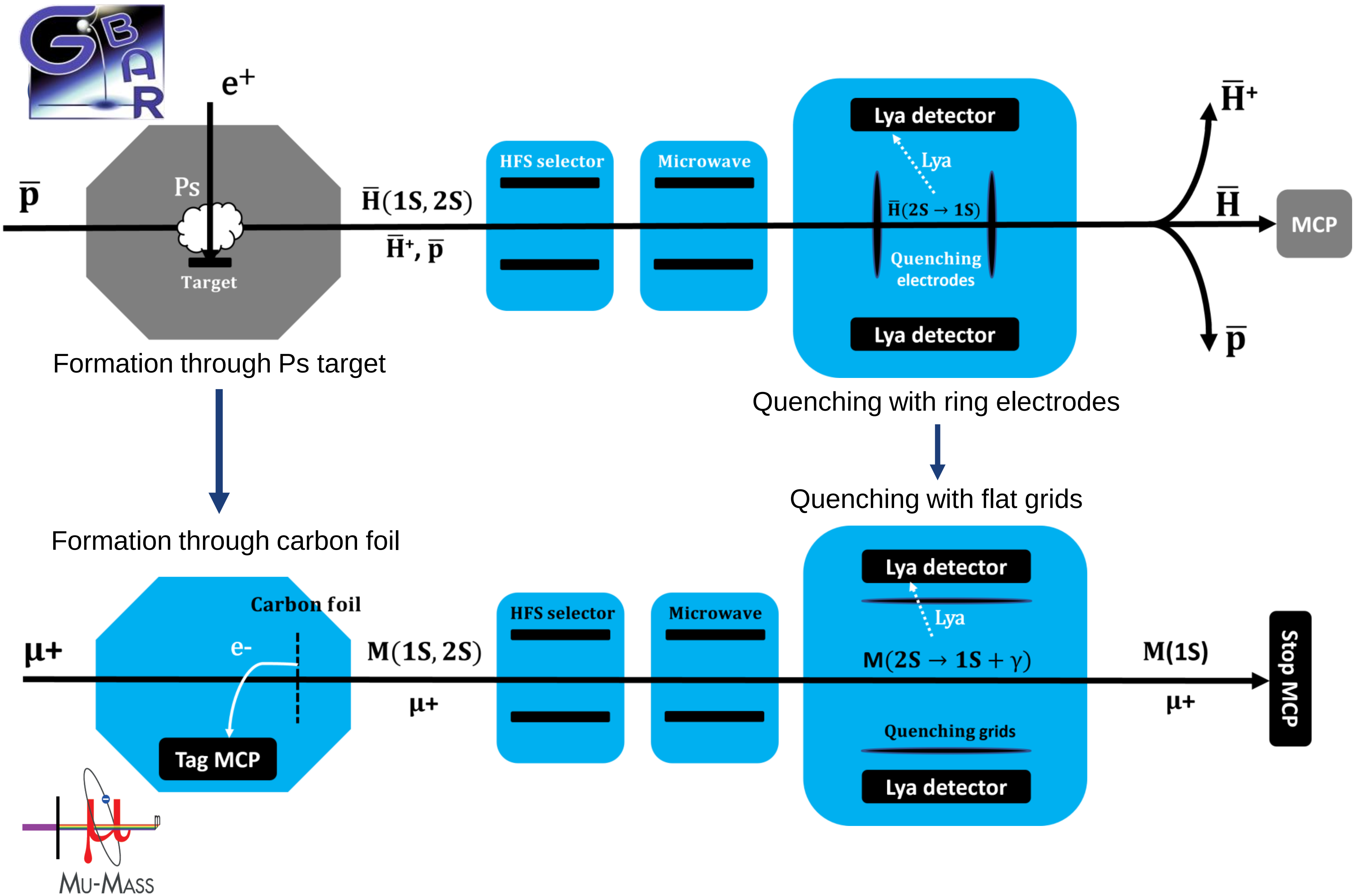
Lamb Shift of Antihydrogen: Detection Setup



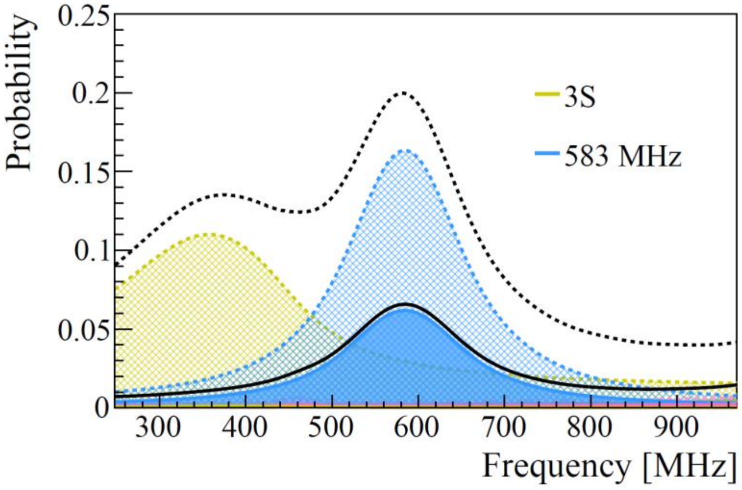




Lamb Shift of Muonium with Mu-MASS

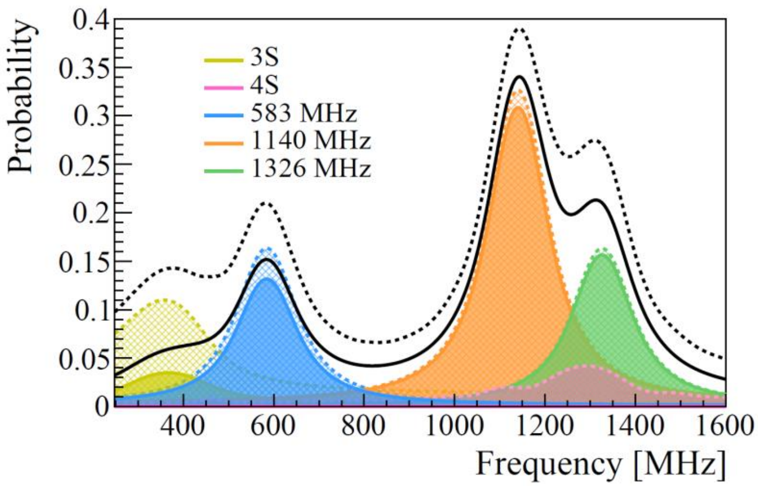


Options for upcoming M LS measurements



Option 1)
Additionally apply weak electrical field to quench 3S and measure F=0 to F=1 transition

- Cleanest way, least systematics expected
- Most promising for precision measurement
- Reduces also 2S F=0 population
- Needs higher M flux or an increase in beamtime



Option 2)
Additionally apply weak electrical field to quench 4S and measure F=1 to F=1 and F=1 to F=0 transition

- n=2 population less affected by electrical field
- Statistics much easier to gather
- Issue of line-pulling and necessity of good knowledge of line-shape still present
  → Systematics!

Option 3) Additionally apply weak electrical field to quench 4S, depopulate F=1 to F=0 transition with HFS selector and measure F=1 to F=1

- Reduced line-pulling by F=1 to F=0 transition, but still needs good knowledge of line-shape
- Need to extend beamline, which results in loss of M flux