Mu-MASS experiment at PSI

Ben Ohayon

Mu-MASS collaboration (PI P. Crivelli)

Institute for Particle Physics and Astrophysics

ETH Zürich

QUARTET

Marie Skłodowska-Curie Actions No. 101019414

Swiss National Science Foundation

No. 197346

European Research Council

Established by the European Commission

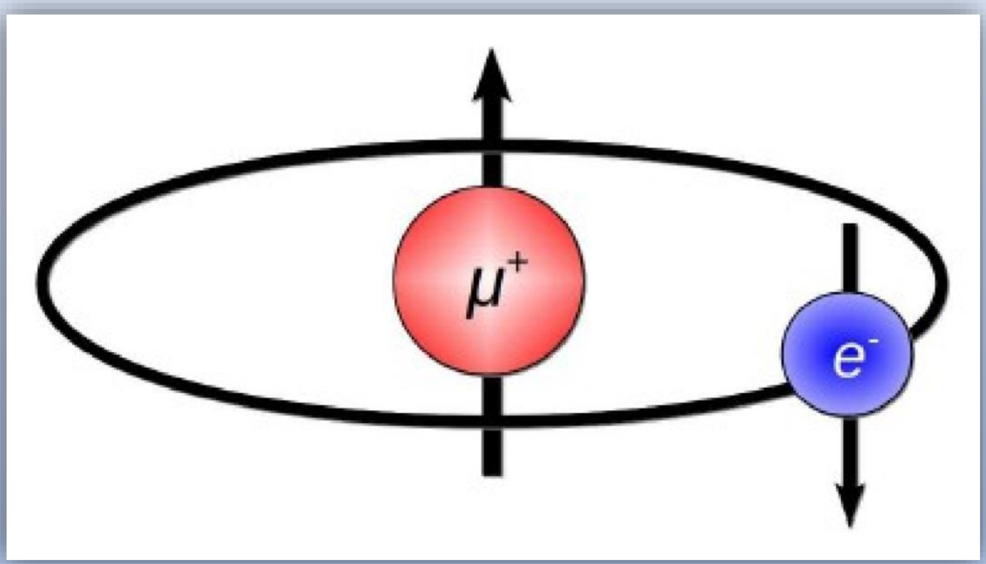
818053-Mu-MASS

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

bohayon@ethz.ch

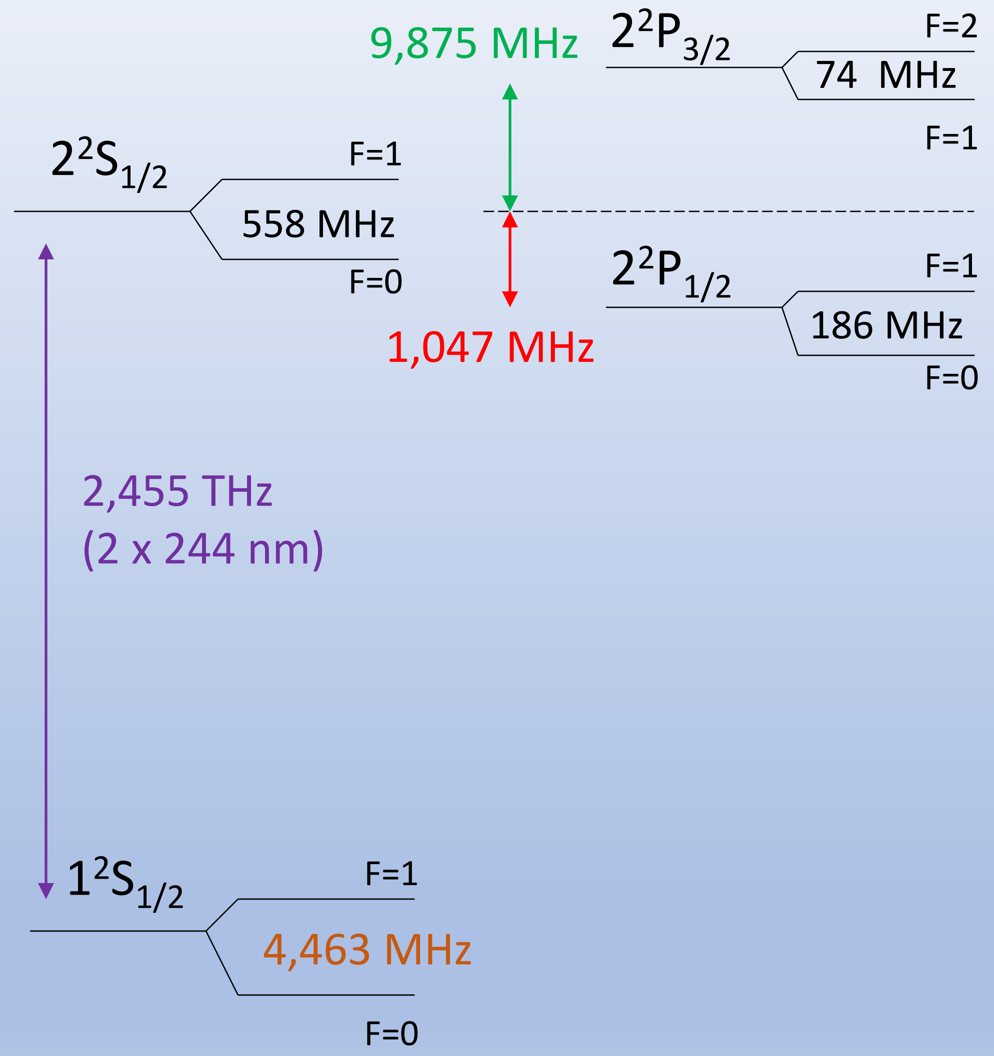
Muonium 101

- Along with Ps, simplest two body system
- Straightforward comparison of theory and experiment
- Lifetime 2.2 us (144 kHz) – limits methods
- Muons produced in accelerators (limited statistics), at high energy (few MeV)

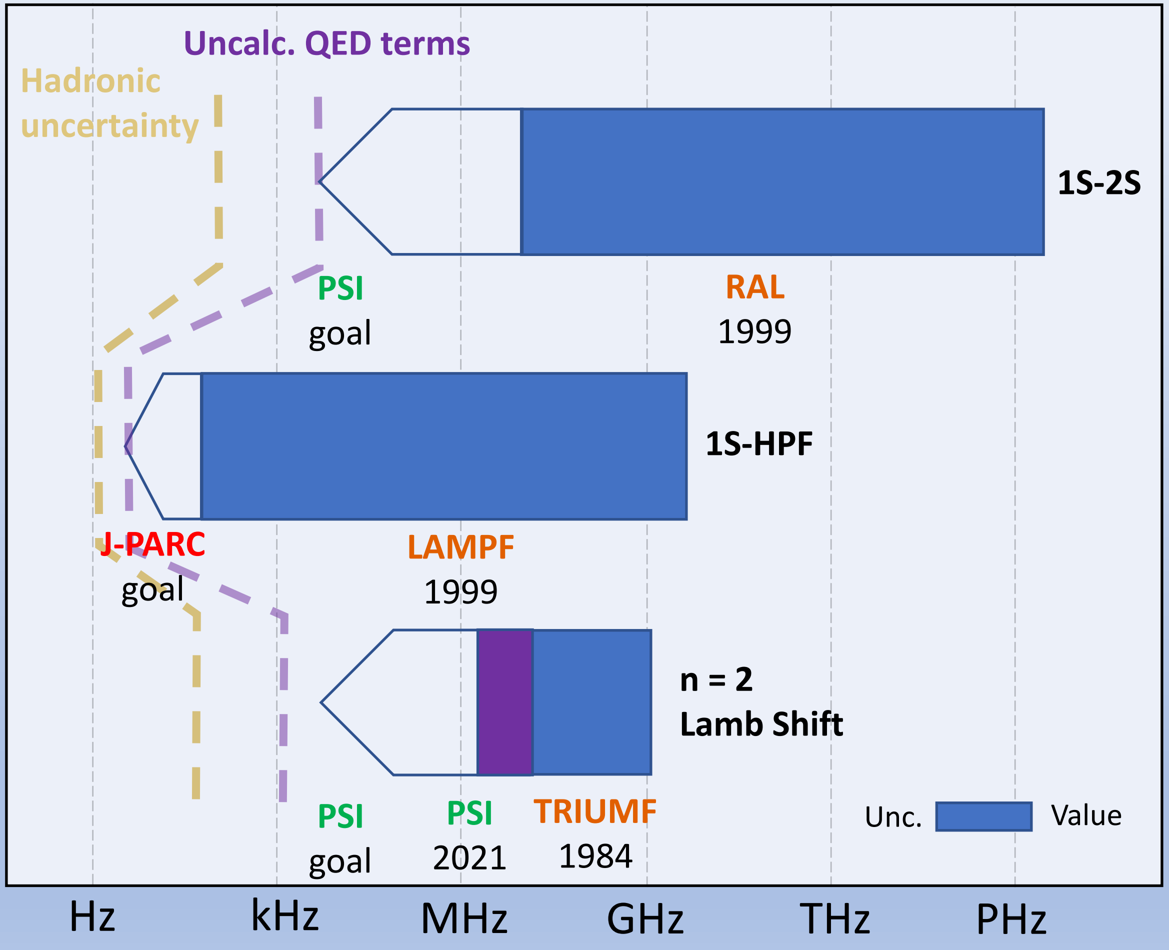


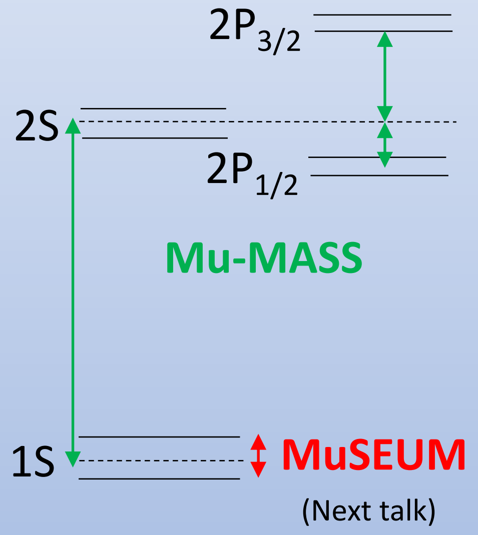
Energy levels:

- Similar Gross- and Fine-structure as H
- Enhanced recoil corrections $m_p/m_\mu \approx 9$
- Larger hyperfine structure by ≈ 3
- No (known) finite size effects
- Smaller Hadronic contributions



Overview of Muonium spectroscopy:





What is it good for?

- Determination of Fundamental constants
- QED tests
- New physics searches

ETH zürich

Determination of fundamental constants:

Mu-MASS goal:

- Gross structure $\propto R_\infty(1+\frac{m_e}{m_\mu})$ — 4 ppt
- ➢ Given R_∞, get q_{μ^+}/q_{e^-} — 4 ppt
- ➢ Assume $q_{\mu^+} = q_{e^-}$, get $\frac{m_e}{m_\mu}$ — 2 ppb

$$\nu_{1S-2S} = \frac{3}{4}\frac{R_\infty c}{(1+m_e/m_\mu)}[1+\delta_{1S-2S}]$$

MuSEUM goal:

- Ground state hyperfine structure:
- ➢ Given R_∞,a_μ, α, get $\frac{m_e}{m_\mu}$ — 1 ppb

Combined:

- ➢ Given R_∞, $\frac{m_e}{m_\mu}$,a_μ, get α — 1 ppb
- ➢ Given R_∞, $\frac{m_e}{m_\mu}$, α, get a_μ — 2 ppm

$$\nu_{HFS} = \frac{16}{3}(1+a_\mu)\frac{m_e}{m_\mu}\frac{R_\infty c\alpha^2}{(1+m_e/m_\mu)^3}[1+\delta_{HFS}]$$

See S. Nishimura's talk up next

bohayon@ethz.ch

MuMASS + MuSEUM = QED test at the ppb level

M. Eides: PLB 795, 10 2019

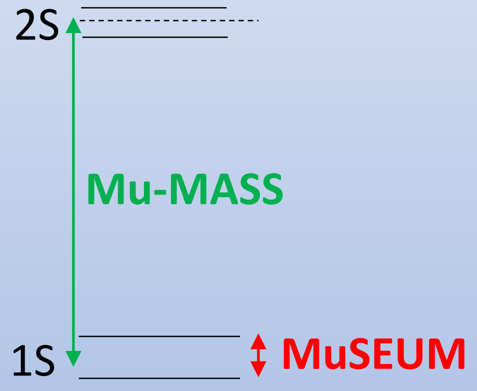
$$\Delta\nu^{\mathrm{th}}_{\mathrm{HFS}} - \Delta\nu^{\mathrm{ex}}_{\mathrm{HFS}} = 96(\cancel{5}1_{\mathrm{ex}})(5\cancel{1}1_{\mathrm{mass}})(\cancel{7}0_{\mathrm{QED}})\,\mathrm{Hz}$$

5 4 7

MuSEUM goal

Mu-MASS goal

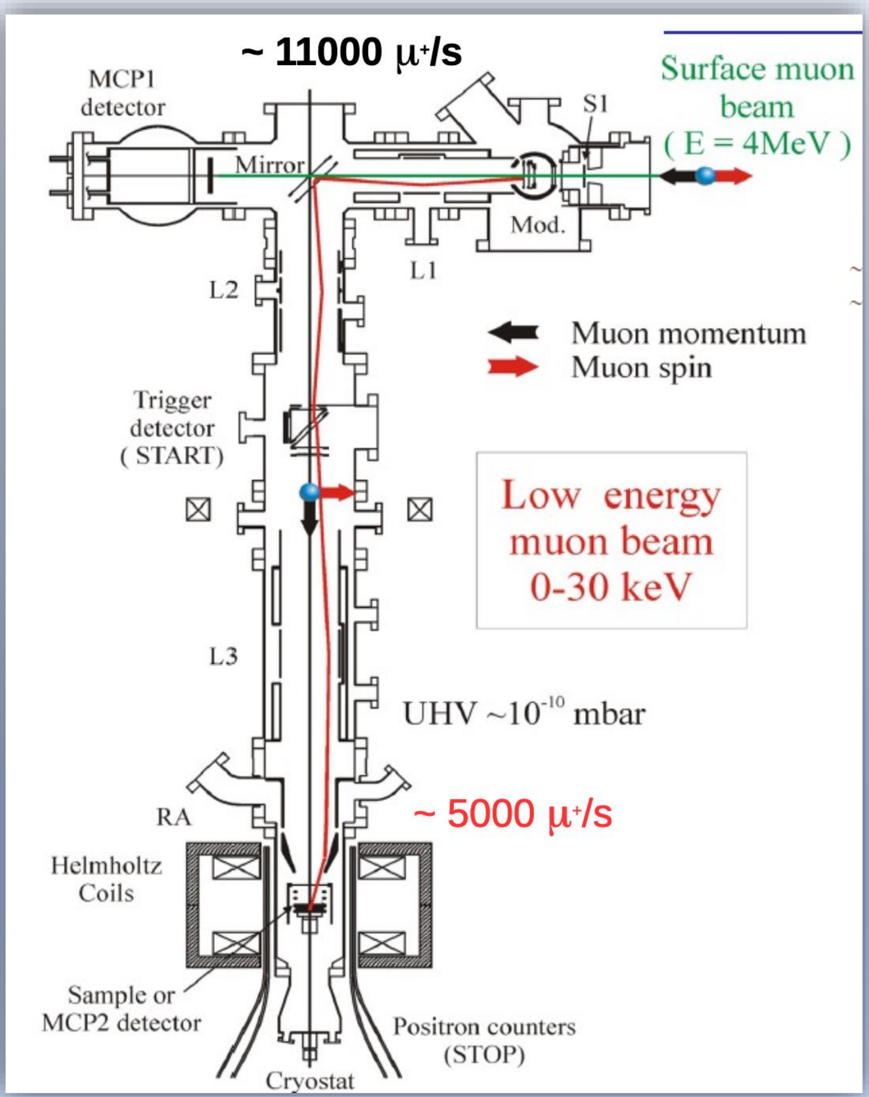
Theory Goal 7 Hz.
Hadronic ‘wall’ 1 Hz.

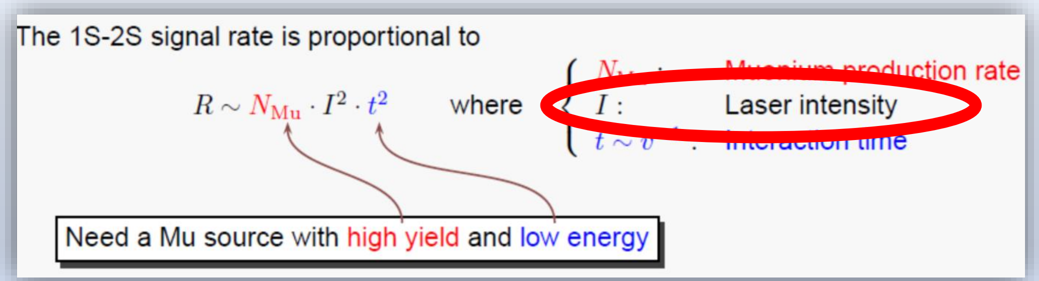


How do we get there?

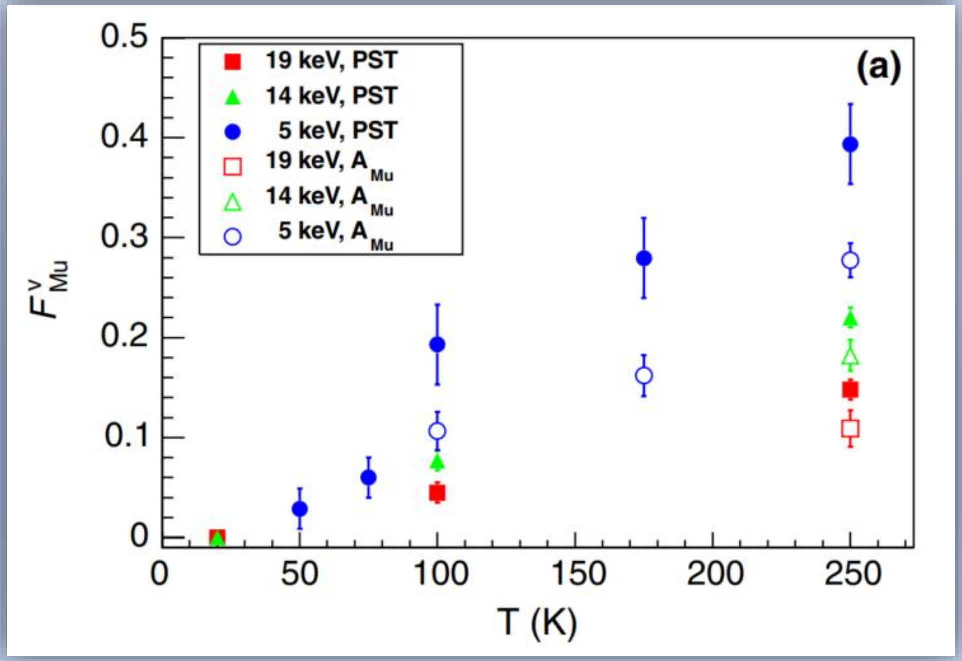
How to measure 1S-2S to 10 kHz?

Low Energy Muons (LEM) beamline @ PSI:



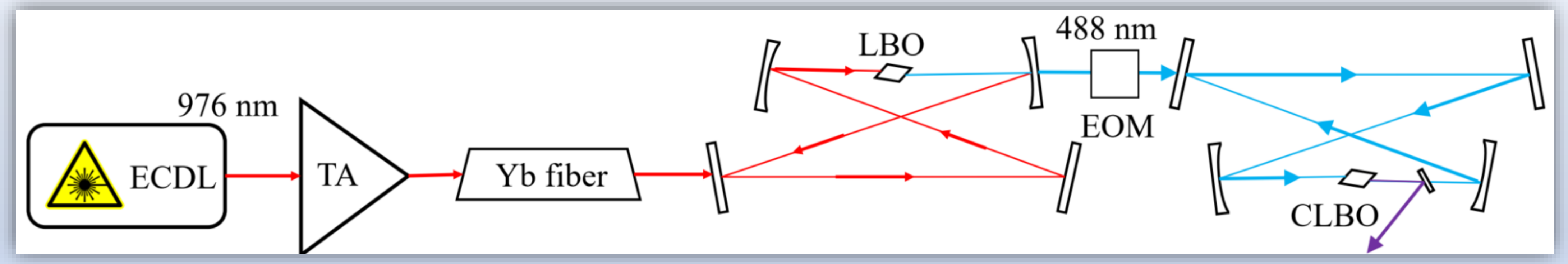


Efficient Muonium emission into vacuum:



A. Antognini et. al. PRL 108, 143401 (2012)

Intense CW 244 nm laser:



Z. Burkley, *et. al.* Applied optics 58.7: 1657-1661 (2019)

> 0.8 W stable on the day timescale

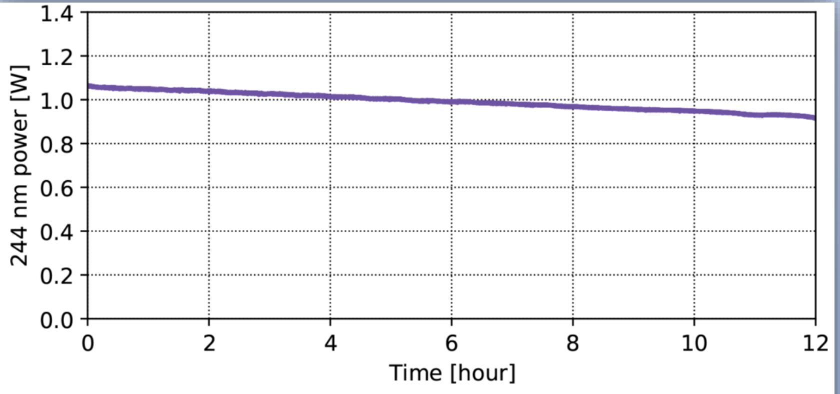


Fig. 2. Performance of the 244 nm laser system over long time scales. The laser can output 1 W of 244 nm power over several hour time scales without degradation of the CLBO crystal. We attribute the slow degradation observed to damage of the output coupler.

Cavity enhancement

~ 10W intracavity power in UHV

~ 20W intracavity power in 10^{-3} mbar O_2

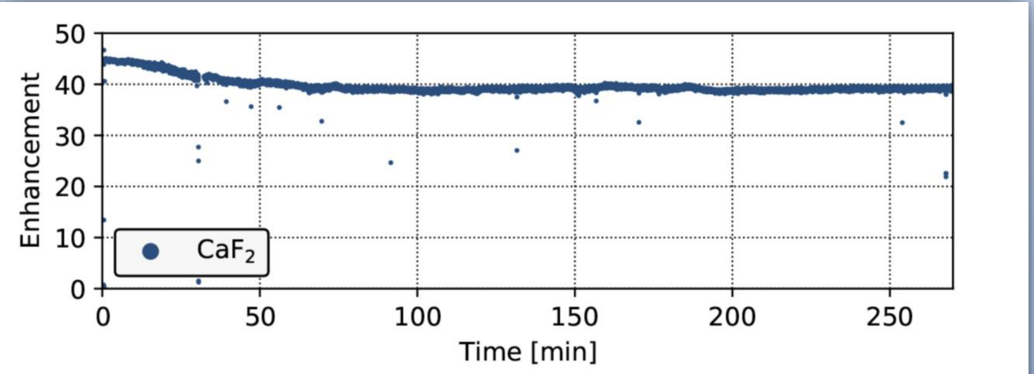
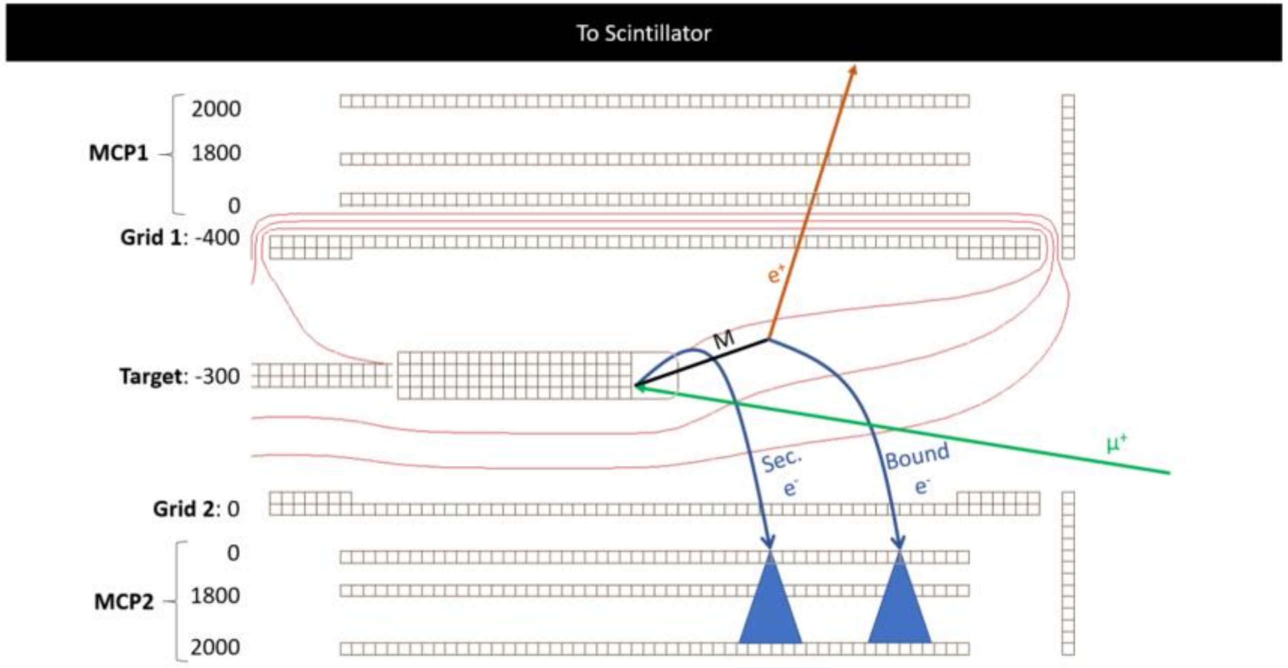


Fig. 7. 10^{-3} mbar of O_2, 16 W intra-cavity power with fluoride-IC (CaF_2).

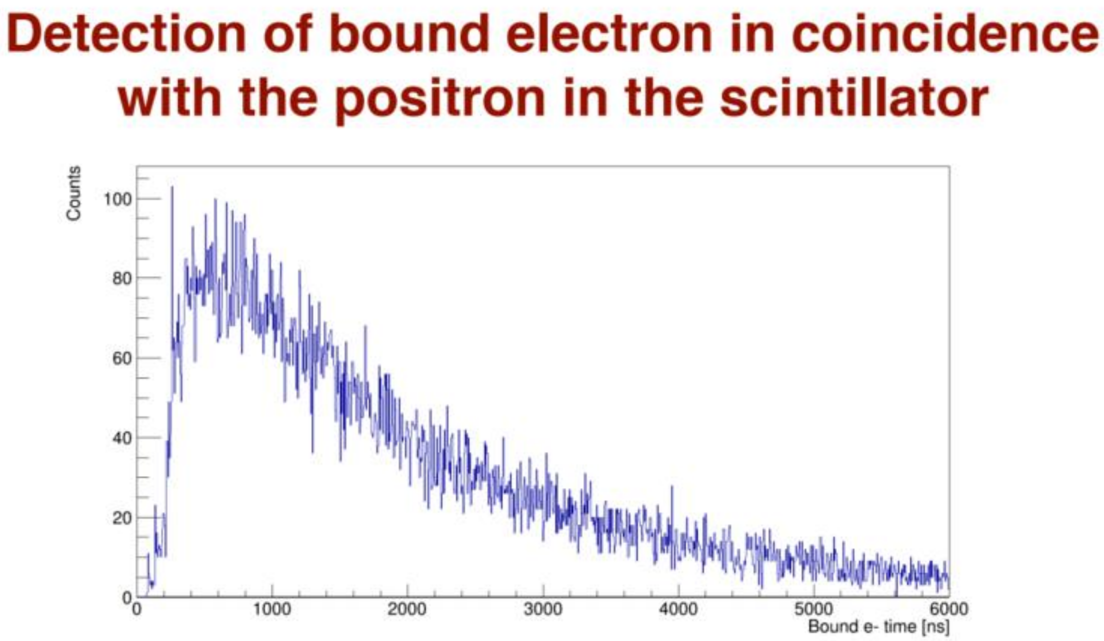
Z. Burkley, *et. al.* Optics Express 29 (17), 26287-27960 (2021)

ETH zürich

Mu-MASS detection system:



Test December 2020



Test pulsed detection scheme Nov. 2021

Lamb shift in M and H:

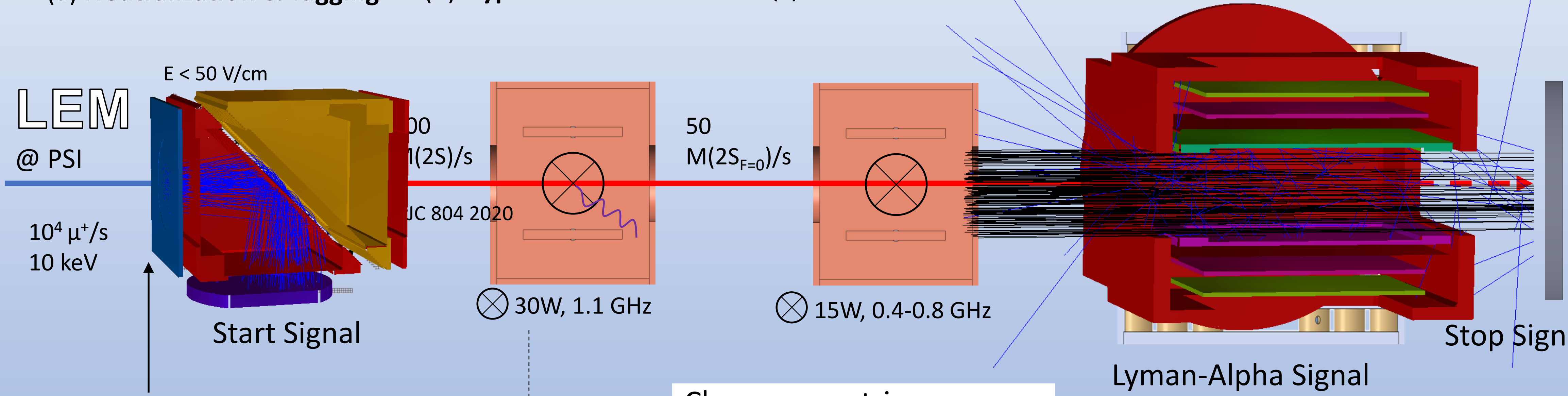
- An interesting opportunity?
- At 200 kHz, LS in M sensitive to high-order QED recoil not resolved in H

Rough estimate based on:
VA Yerokhin, K Pachucki, V Patkóš - Annalen der Physik, 2019

	Highest order	$Z=1, M\to\infty$	
One loop:			
Self energy (SE)	$\alpha^5 ln(\alpha^{-2})$	1085.817	
Vac. Pol. (VP)	α^5	−26.897	
Two loop:			
SE-SE	α^6	0.265	
VP-VP	α^6	−0.237	
SE-VP	α^6	0.037	
		$Z=1, H$	$Z=1, M$
Reduced Mass	$\alpha^5 ln(\alpha^{-2})M^{-1}$	−1.646	−14.511
Rel. Recoil	$\alpha^5 ln(\alpha^{-2})M^{-1}$	0.357	3.131
Rel. Recoil (HO)	$\alpha^4 M^{-2}$	−0.002	−0.175
Off-diag. hfs	$\alpha^4 M^{-2}$	0.002	0.019
Rad. Recoil	$\alpha^6 M^{-1}$	−0.002	−0.013
Nuclear SE	$\alpha^5 ln(\alpha^{-2})M^{-2} ln(M)$	0.001	0.039
Finite Size	$\alpha^4 R^2$	0.138	0

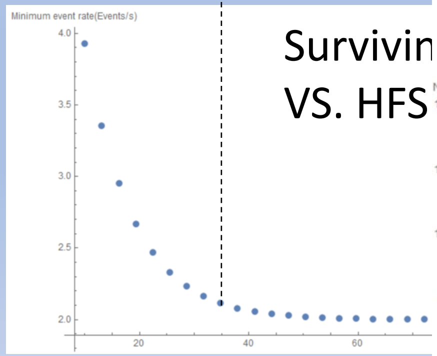
Muonium Lamb Shift: Methods

(a) **Neutralization & Tagging** (b) **Hyperfine-selection** (c) **Scan resonance** (d) **Quenching & detection** (e) **Back detector**

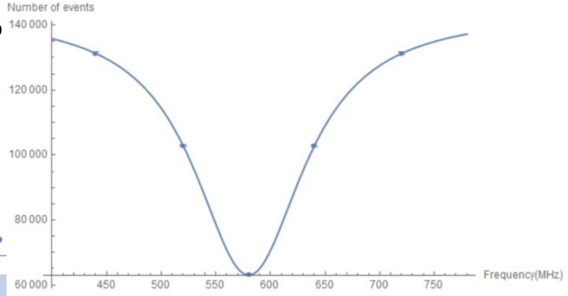


Total Efficiency ~10%

Survivin
VS. HFS



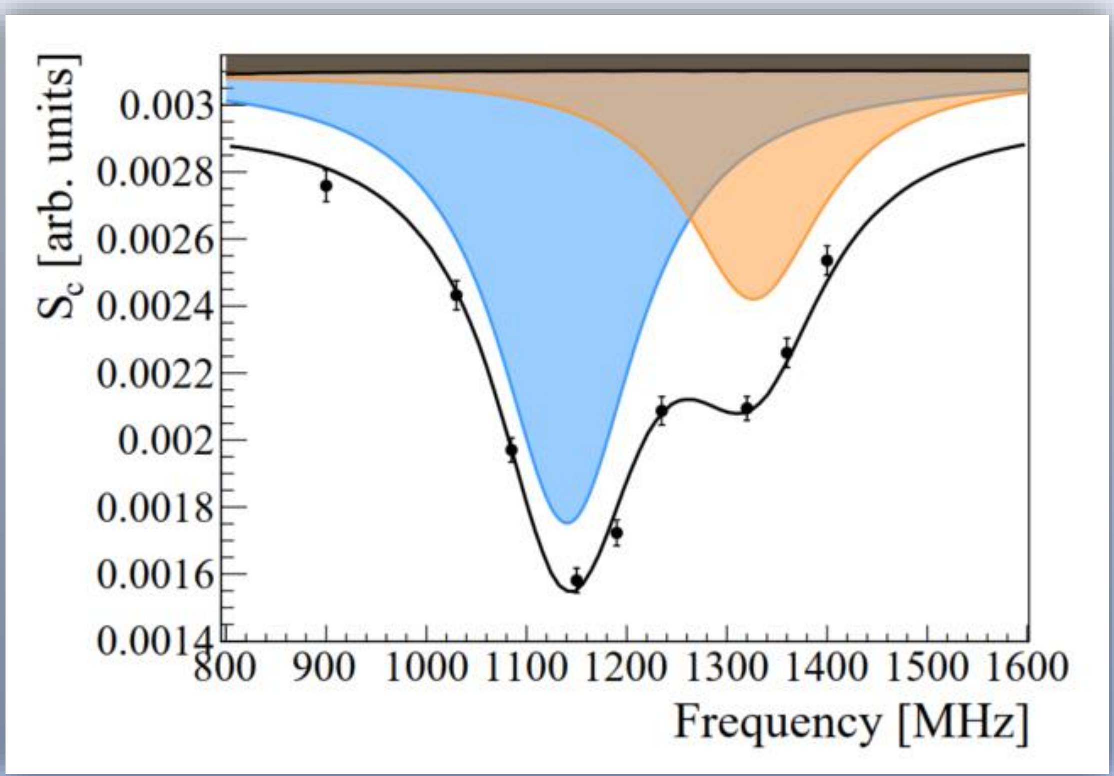
Clean symmetric resonance (unlike hydrogen)



bohayon@ethz.ch

LS Results:

arXiv:2108.12891



Factor 5.4 improvement over TRIUMF result in 48 hours of beamtime

	Central Value	Uncertainty
Fitting	1139.9	2.3
4S contribution		< 1.0
MW-Beam alignment		< 0.32
MW field intensity		< 0.04
M velocity distribution		< 0.01
AC Stark $2P_{3/2}$	+0.26	< 0.02
2^{nd}-order Doppler	+0.06	< 0.01
Earth's Field		< 0.05
Quantum Interference		< 0.04
$2S_{F=1}-2P_{1/2,F=1}$	1140.2	2.5
Hyperfine	−93.0	0.0
Lamb Shift	1047.2	2.5
Theoretical value [13]	1047.284	0.002

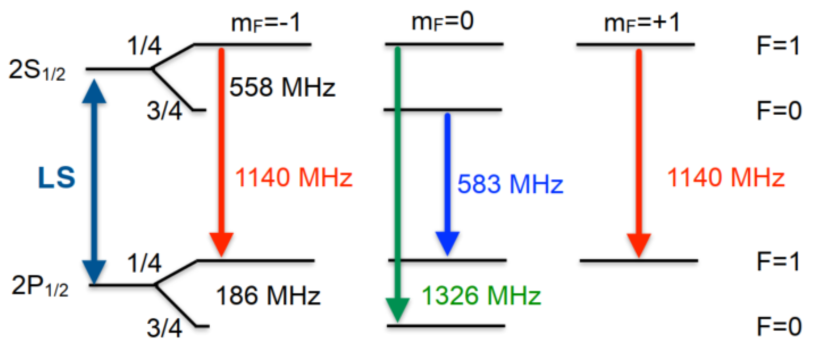
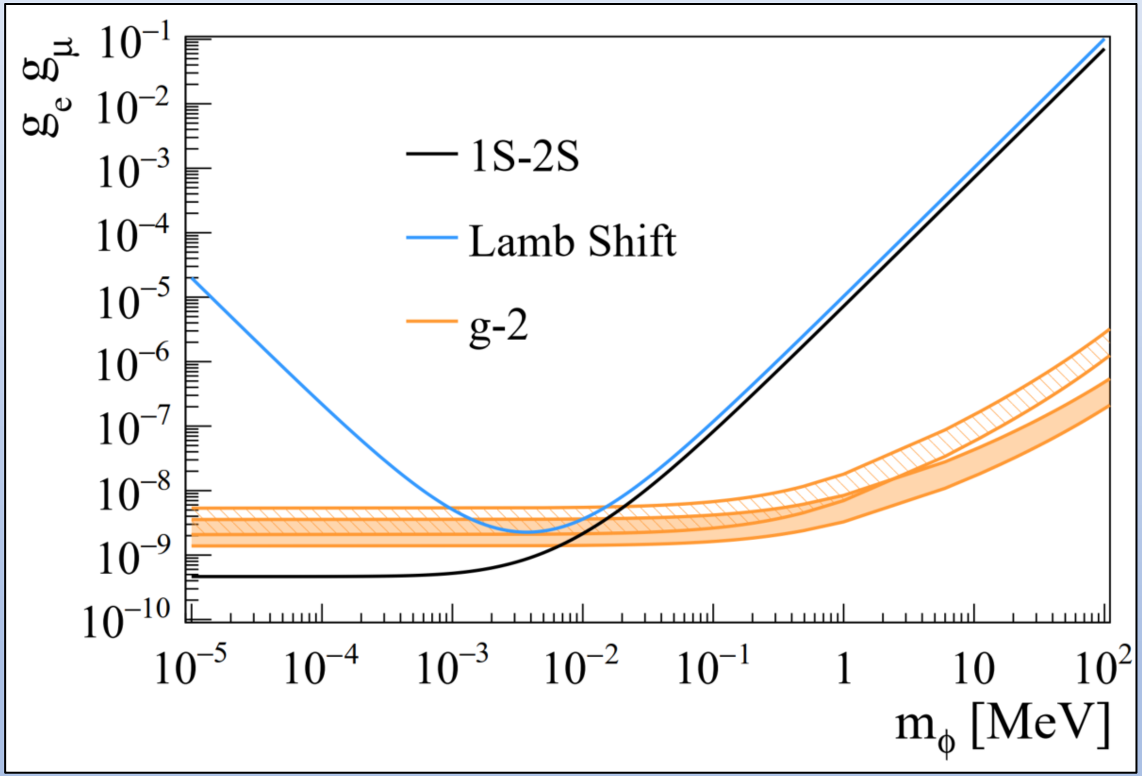


FIG. 2. Scheme of the M $2S_{1/2}-2P_{1/2}$ energy levels.

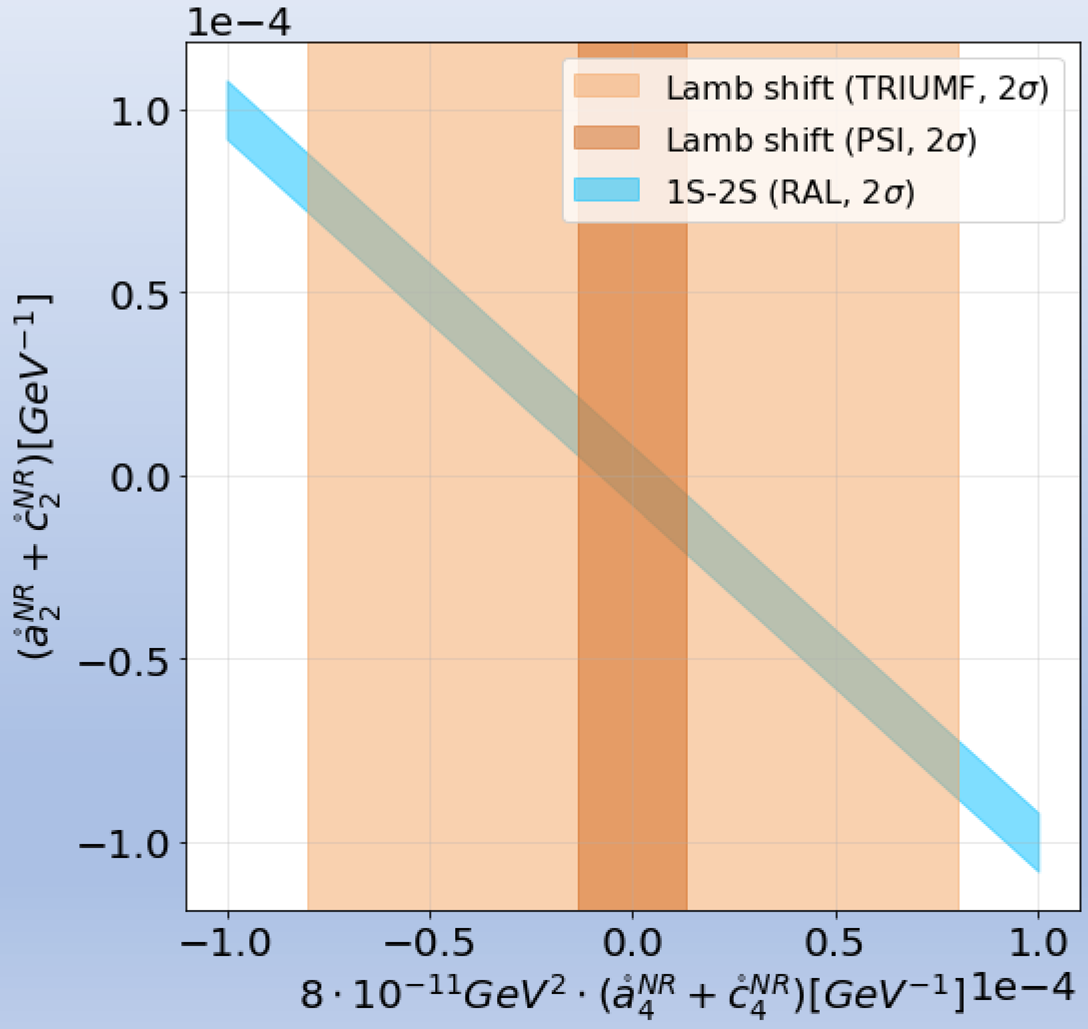
LS applications:

Search for **CPT & Lorenz violation** in the muonic sector:

Comparable limits to 1S-2S for new scalar/Vector particles:

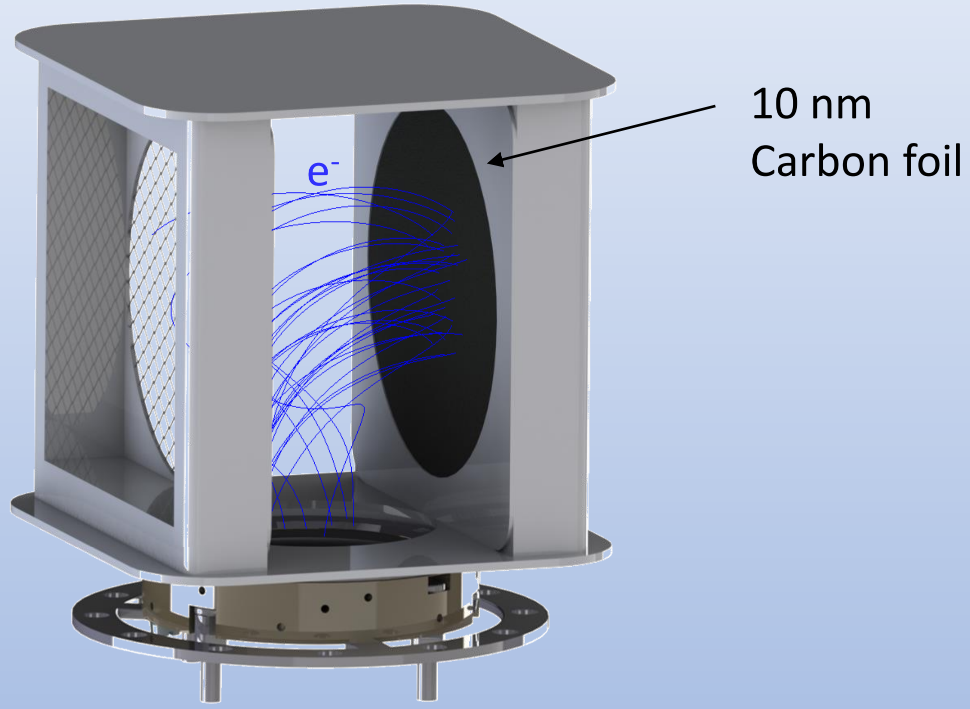


arXiv:2108.12891



LS outlook:

Statistics limited by scattering in foil target



Factor 15-25 higher statistics with **few-layer graphene foils** (0.3-1 nm)

	Central Value	Uncertainty
Fitting	1139.9	2.3
4S contribution		< 1.0
MW-Beam alignment		< 0.32
MW field intensity		< 0.04
M velocity distribution		< 0.01
AC Stark $2P_{3/2}$	+0.26	< 0.02
2^{nd}-order Doppler	+0.06	< 0.01
Earth's Field		< 0.05
Quantum Interference		< 0.04
$2S_{F=1}-2P_{1/2,F=1}$	1140.2	2.5
Hyperfine	−93.0	0.0
Lamb Shift	1047.2	2.5
Theoretical value [13]	1047.284	0.002

LS outlook:

Main systematics:

- Long-lived higher states (mainly 4S)
- ➢ Remove with weak DC field

- Residual 1st order Doppler shift
- ➢ Periodically switch MW direction

	Central Value	Uncertainty
Fitting	1139.9	2.3
4S contribution		< 1.0
MW-Beam alignment		< 0.32
MW field intensity		< 0.04
M velocity distribution		< 0.01
AC Stark $2P_{3/2}$	+0.26	< 0.02
2^{nd}-order Doppler	+0.06	< 0.01
Earth's Field		< 0.05
Quantum Interference		< 0.04
$2S_{F=1}-2P_{1/2,F=1}$	1140.2	2.5
Hyperfine	−93.0	0.0
Lamb Shift	1047.2	2.5
Theoretical value [13]	1047.284	0.002

Summary:

- New Era for Muonium spectroscopy

- Main experiments: Mu-MASS (PSI) and MuSEUM (JPARC)

  Determine Fundamental constants: $m_\mu, (R_\infty, \alpha, a_\mu)$
  QED Test at 1 ppb
  Complementary search for new physics

- New Lamb shift measurement. First improvement to M levels in 20 years!

- 2022-First CW excitation of M 1S-2S
- 2023-Imroved Lamb shift measurement by Order-of-magnitude