Mu-MASS (MuoniuM lAser SpectroScopy)

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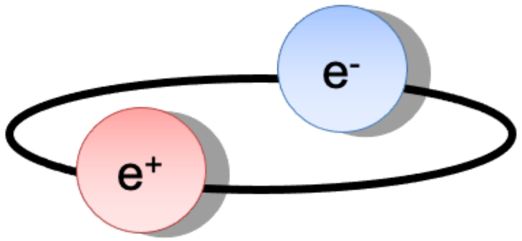
https://www.psi.ch/en/ltp/mu-mass

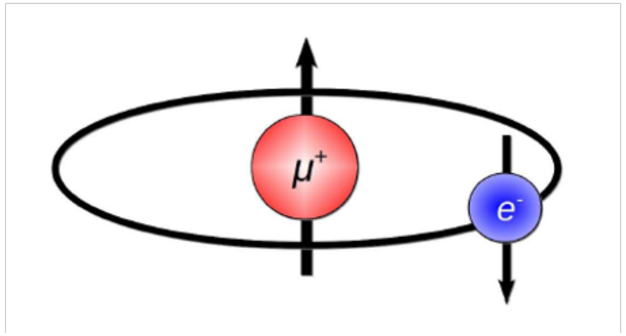
Latest results and status of the Mu-MASS experiment at PSI

PREN WORKSHOP -23rd of June 2022 , Paris

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

Motivations to study leptonic atoms - Positronium and Muonium



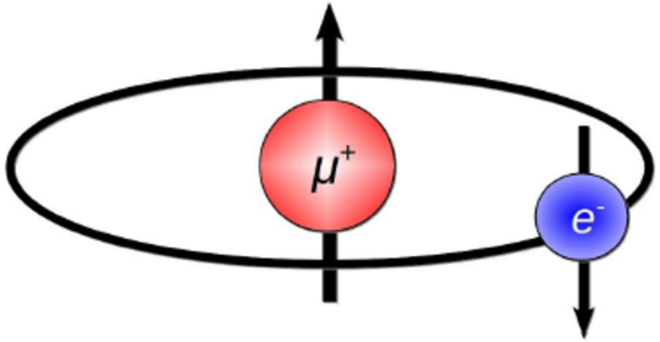


- Being **purely leptonic**, devoid of uncertainties from nuclear size effects present in normal atoms. Therefore, any deviation between theory and measurements could be a signal of New Physics.
- Muonic sector under the spot light: **recent muon g-2 and LHCb results** hints for possible deviations from SM predictions
- Interestingly, for **positronium** fine and hyperfine splitting intervals there are **some discrepancies** which deserve further scrutiny.
- Moreover, from these measurements very important values of **fundamental constants** can be extracted such as the muon mass and muon magnetic moment.

The muonium (M)

Vernon Hughes
1921-2003

M (positive muon-electron bound state)
Predicted in 1957 (Friedmann, Telegdi, Hughes)
Unstable with lifetime of 2.2 μs.
Main decay channel: $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$



Discovered in 1960 (Hughes) by **detecting muonium spin (Larmor) precession** in an external magnetic field perpendicular to the spin direction.

Actually M is not a real -onium atom (particle-antiparticle system).
The true muonium bound state would be $\mu^+\mu^-$ yet to be discovered…

How to produce muons?

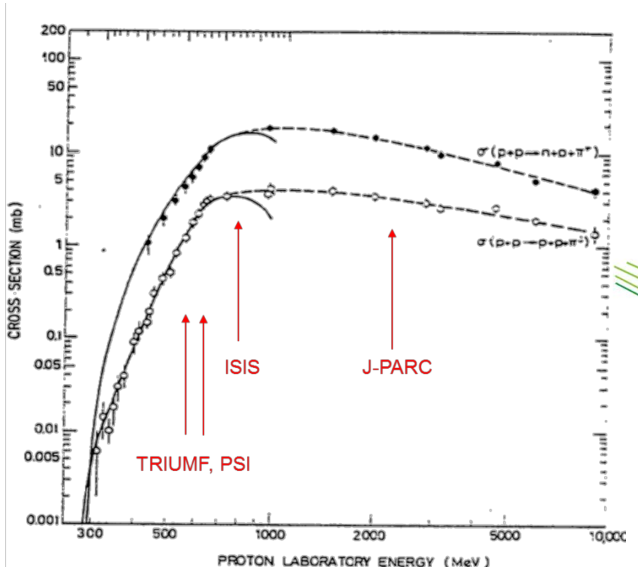
$p^+ + p^+ \rightarrow p^+ + n + \pi^+$

$p^+ + n \rightarrow n + n + \pi^+$

$p^+ + p^+ \rightarrow p^+ + p^+ + \pi^0$

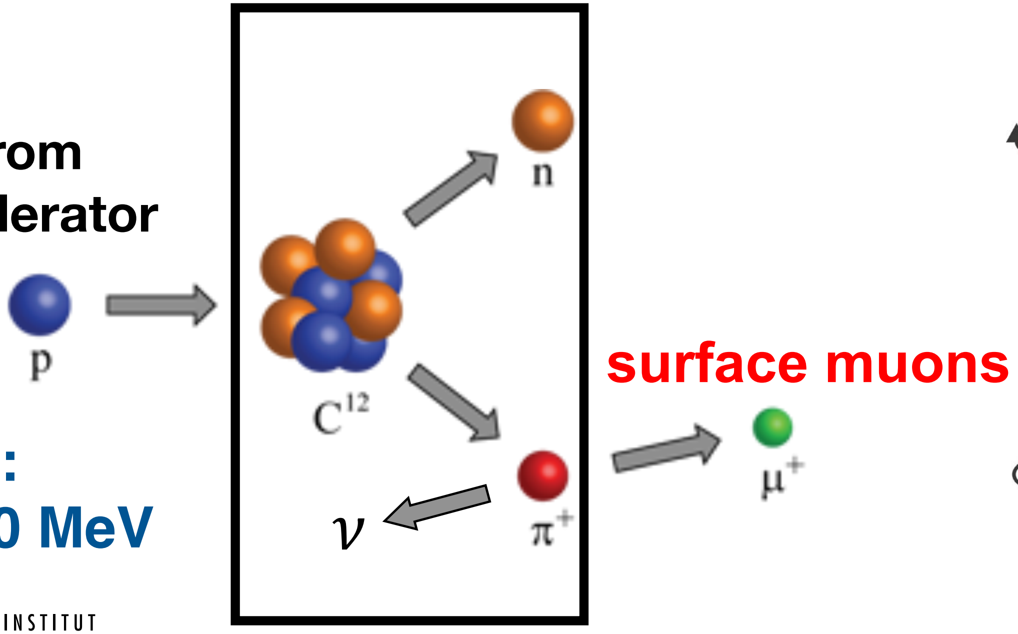
$p^+ + n \rightarrow p^+ + n + \pi^0$

$p^+ + n \rightarrow p^+ + p^+ + \pi^-$



Surface muon production

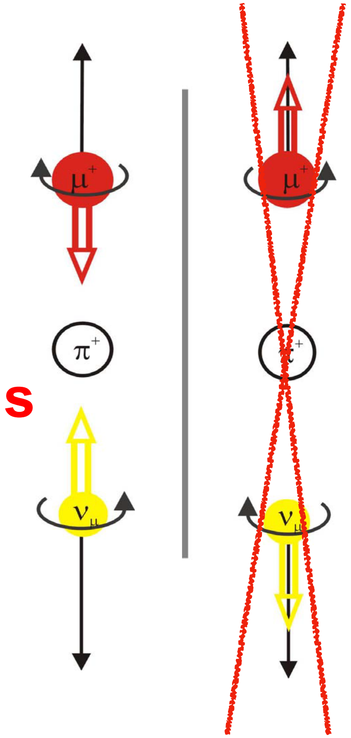
From accelerator



At PSI:
E_p=590 MeV

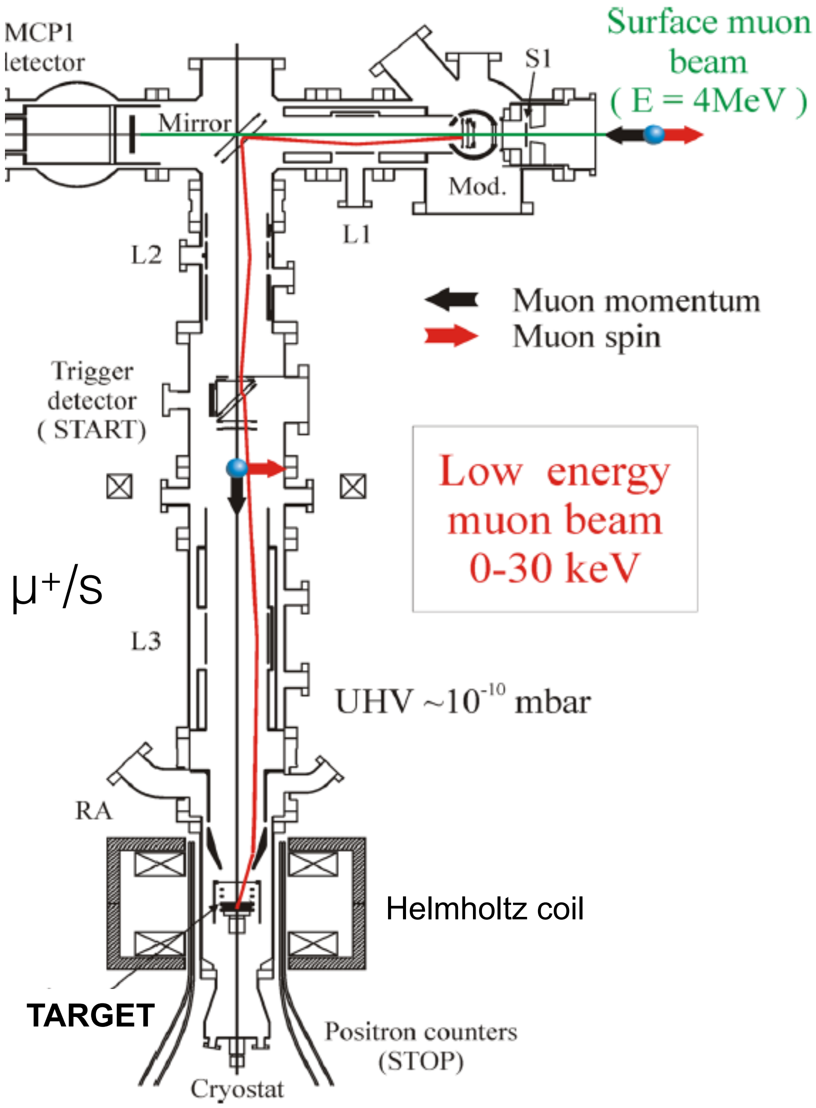
PAUL SCHERRER INSTITUT

Pion decay kinematics

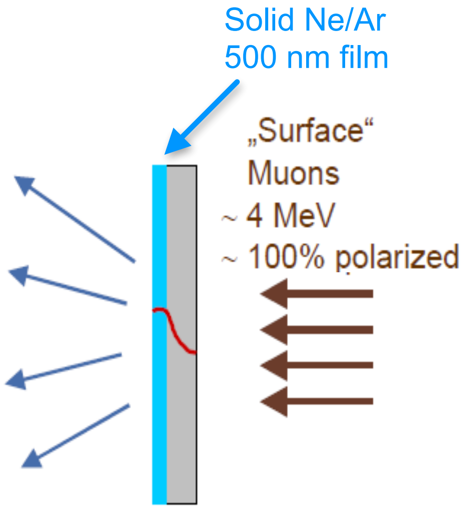


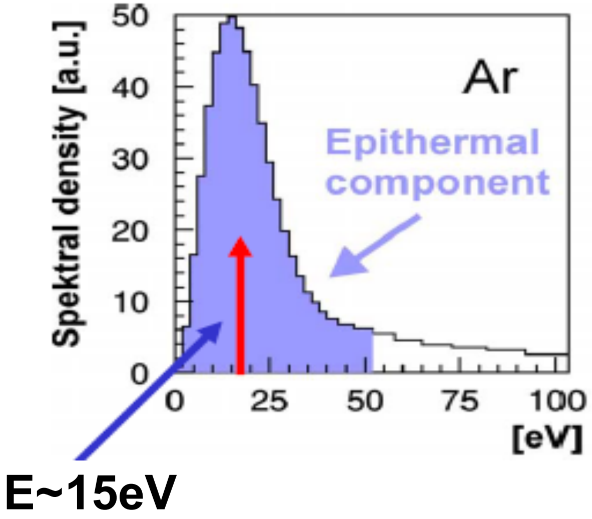
Generation of **100% polarized** (parity violation)
mono-energetic muon beams (E=4 MeV, p=29 MeV/c)

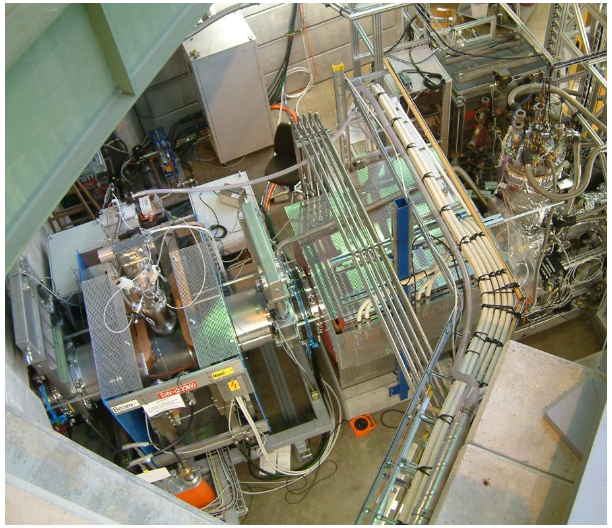
The PSI low energy muon beam (LEM)



Up to 2×10^4 μ^+/s



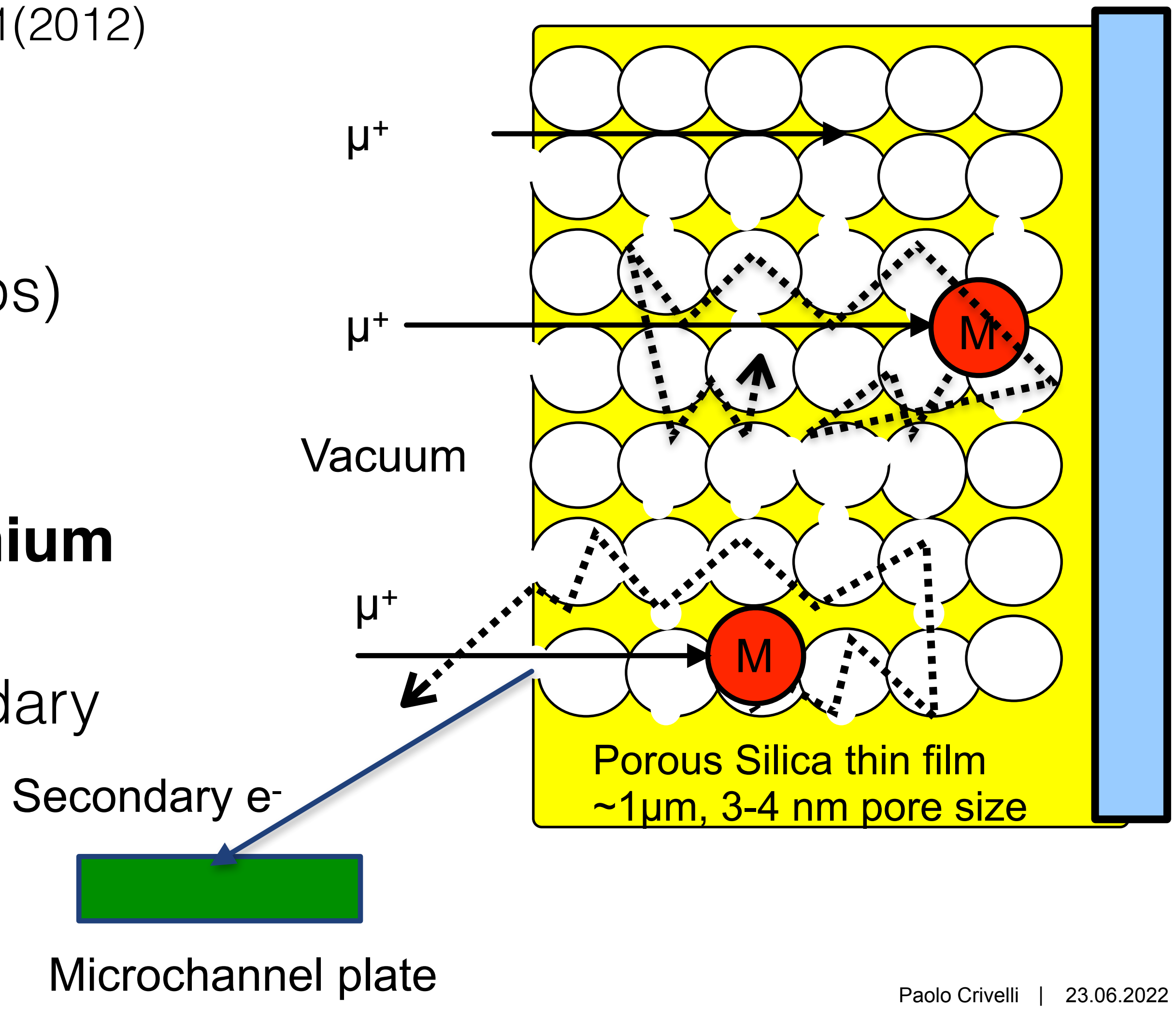




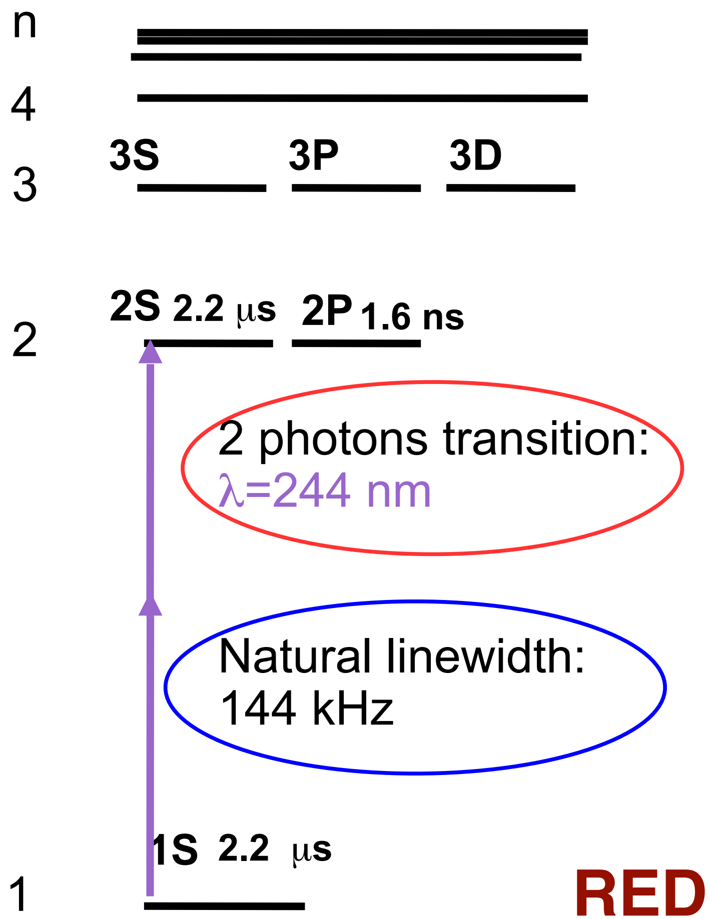
Muonium (&positronium) formation in porous SiO_2 films

P. Crivelli et al., PRA 81, 053622 (2010), D. B. Cassidy, P. Crivelli PRA81, 039904 (2010)
A. Antognini, P. Crivelli et al., PRL 108, 143401(2012)

- Muon implanted with keV energies (Requires low energy muon beam)
- Rapidly thermalises in the bulk (~ps)
- M formation and diffusion in the interconnected pore network
- Up to **20(40)% @100(250)K muonium in vacuum per incoming muon**
- Single muon tagging using secondary electrons (few ns)



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 6 kHz

I. Cortinovis et al. (manuscript in preparation for the PSAS 2022 proceedings)

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

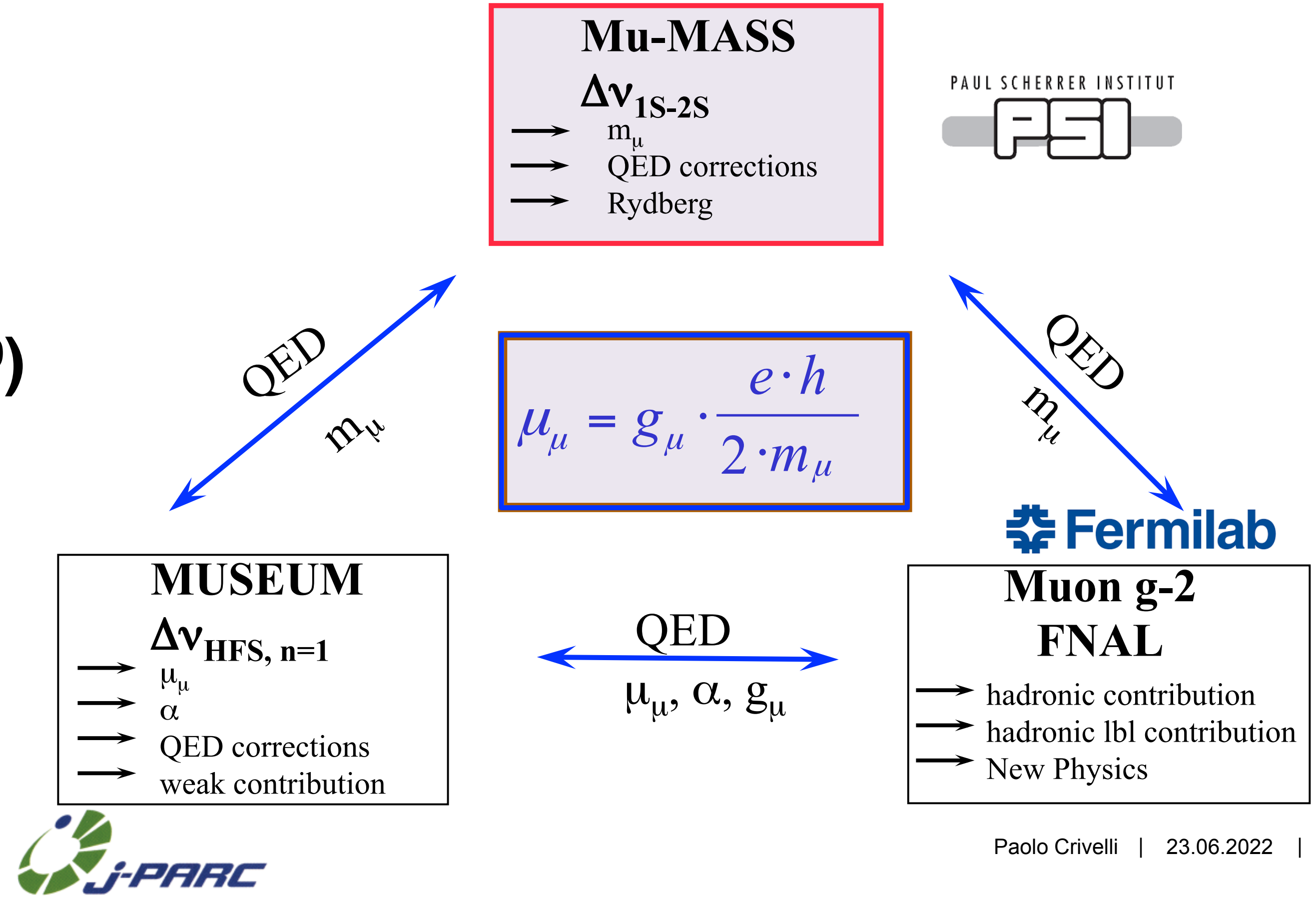
→ Search for New Physics

→ **Test of bound state QED (1×10^{-9})**

→ Input to muon g-2 theory

→ **Rydberg constant @ ppt level**

→ New determination of α @ 1 ppb



Mu-MASS: methodology

Low energy μ^+ beam

↓

Muonium production

↓

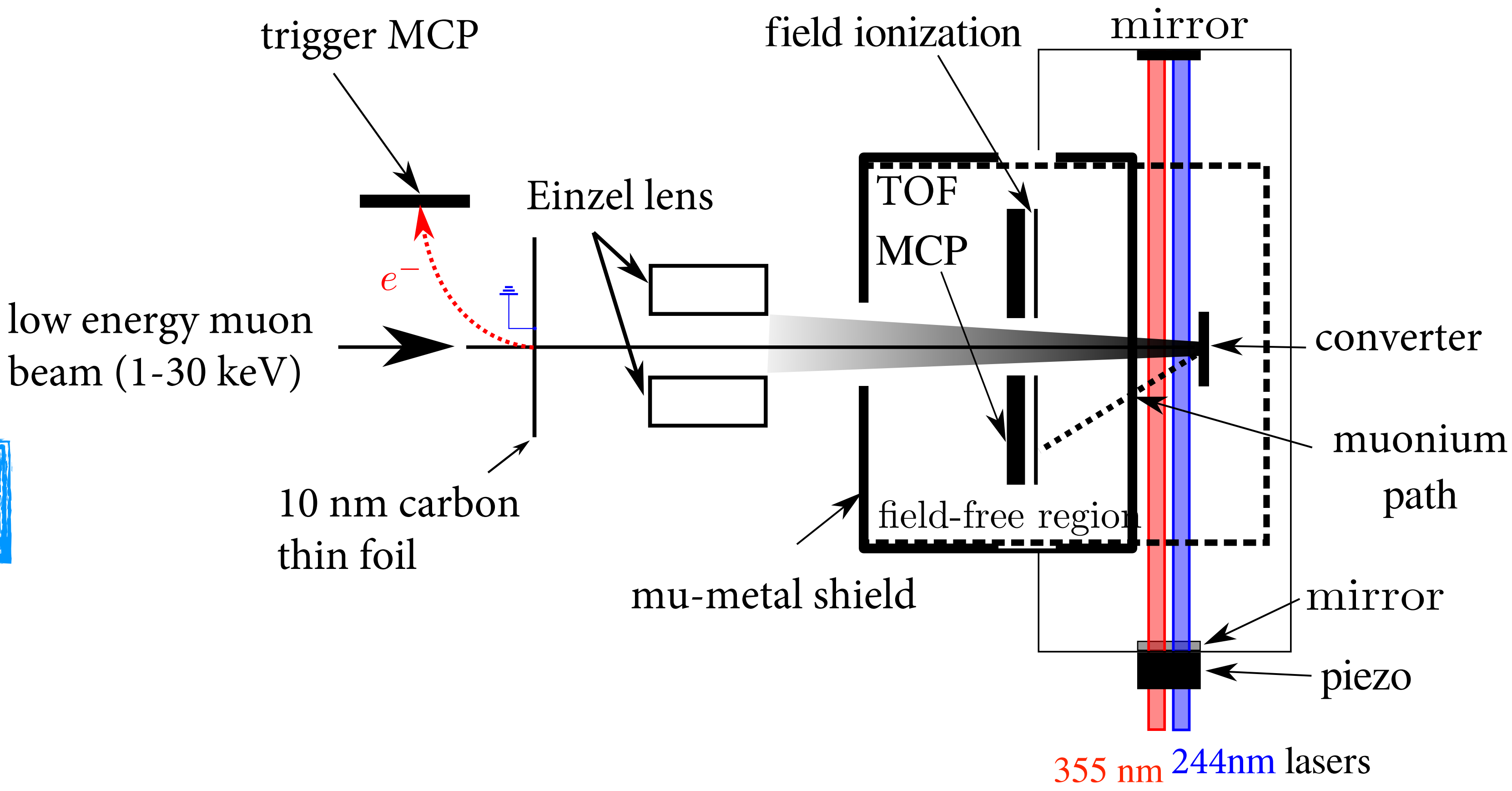
Muonium 2S excitation

↓

Muonium pulsed 355 nm PI

↓

μ^+ detection in MCP+
e+ detection in scintillator



Mu-MASS: experimental scheme

3. 1S-2S laser excitation of Muonium: High power UV CW laser at 244 nm, cavity-enhanced to >20 W of stable intracavity power
4. Photoionization of 2S state with pulsed laser

Opt. Express 29, 27450 (2021)

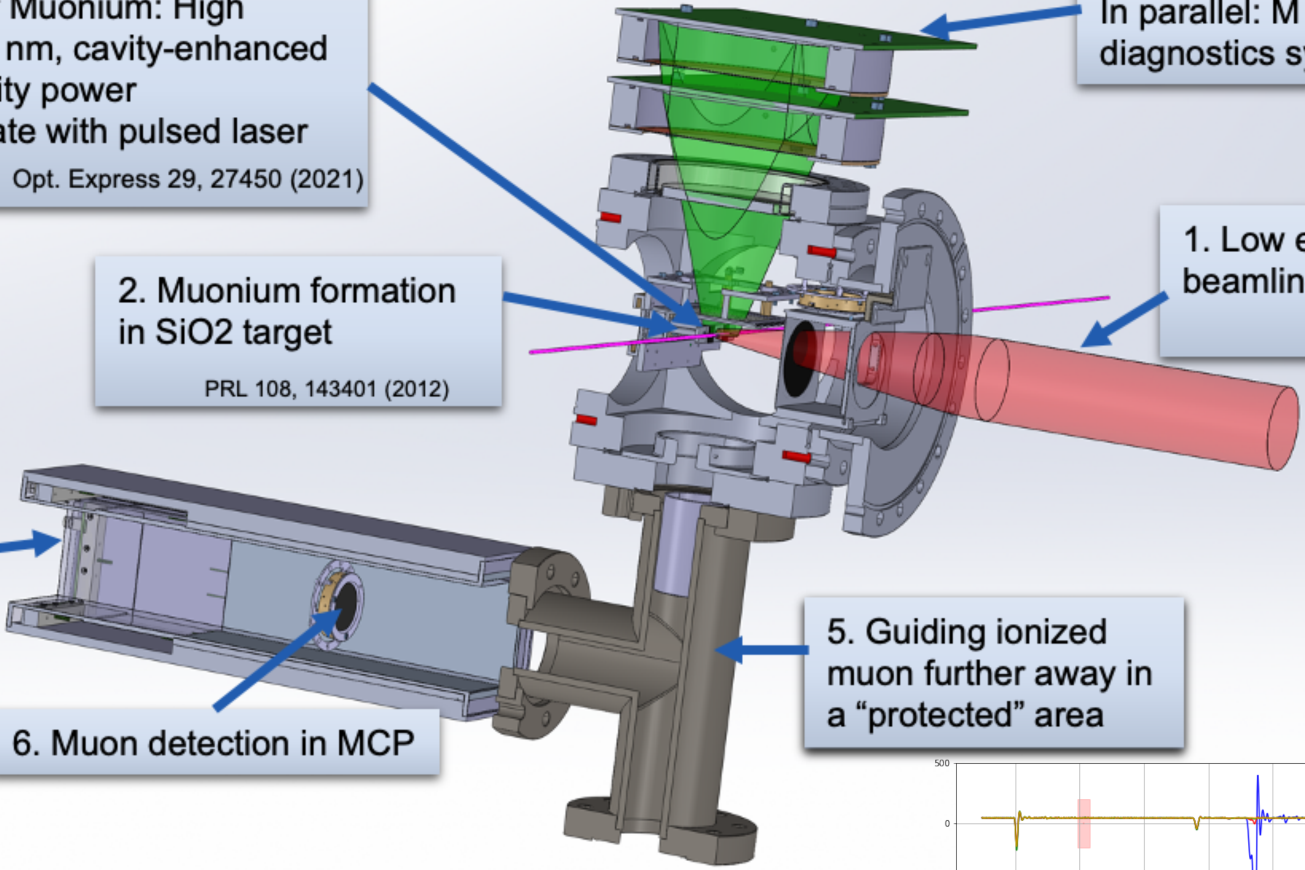
In parallel: M formation diagnostics system

2. Muonium formation in SiO2 target

PRL 108, 143401 (2012)

1. Low energy μ^+ beam (LEM beamline at PSI, ~10k μ^+/s)

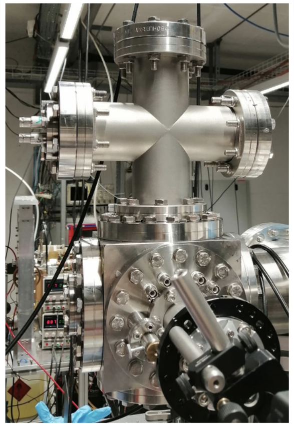
JINST 10, P10025 (2015)



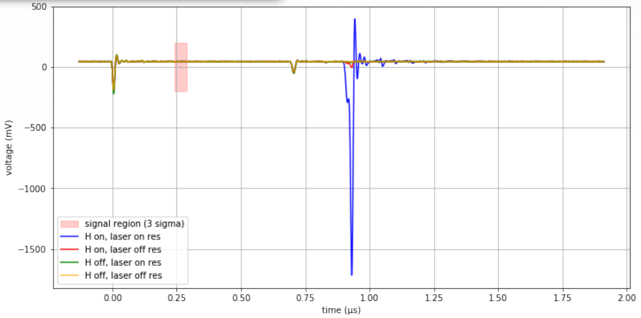
7. Coincidence with positron from decay, in scintillators

6. Muon detection in MCP

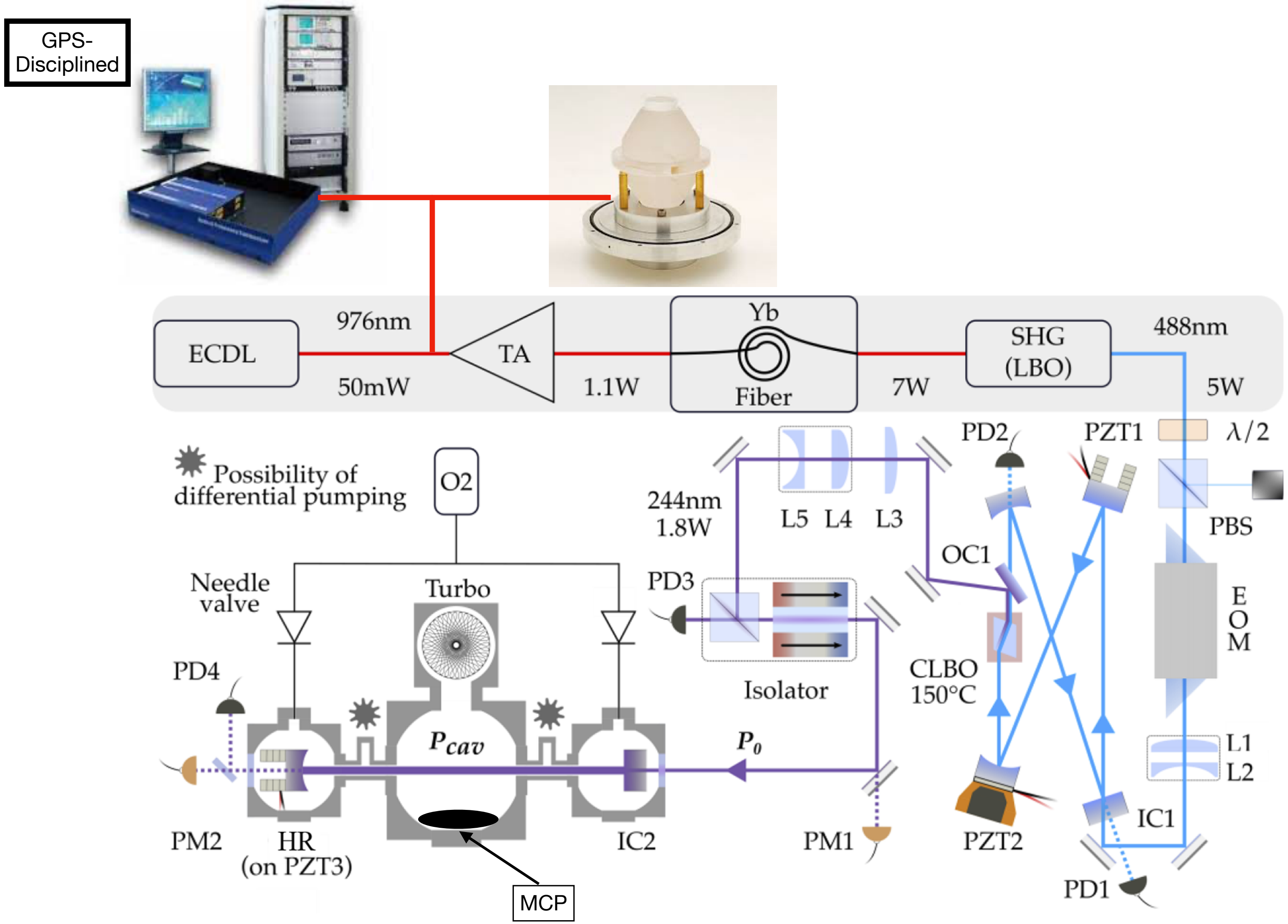
5. Guiding ionized muon further away in a “protected” area

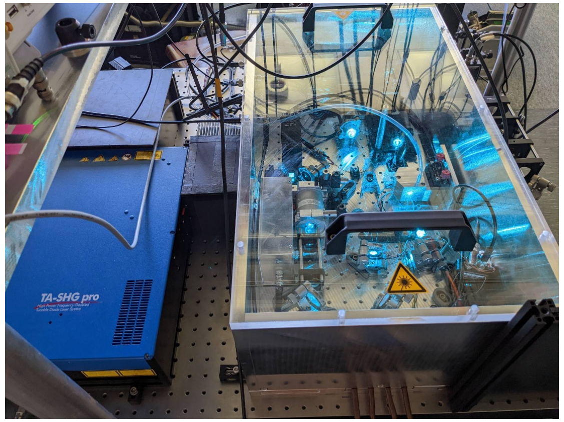


Commissioning with residual hydrogen in vacuum chamber+ pulsed UV laser

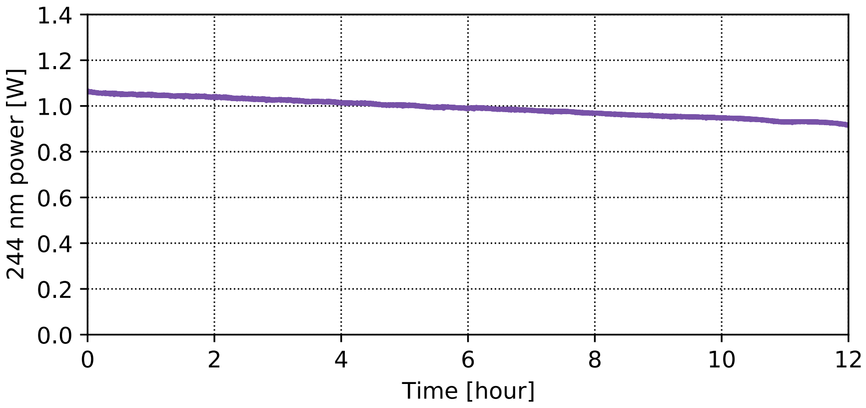


Mu-MASS: Laser system





Stable 1W UV operation



More than 1.8W UV max. output

Designed based on Z. Burkley, A. D. Brandt, C. Rasor, S. F. Cooper, and D. C. Yost, Appl. Opt., 58(7):1657–1661 (2019)

Mu-MASS: Laser system

About 500 mW input **20 W in enhancement cavity** with new CaF_2 substrate and MgF2/ LaF3 dielectric coating minimising the need for O_2 to prevent neon moderator degradation (vs SiO2, HfO2/Al2O3)

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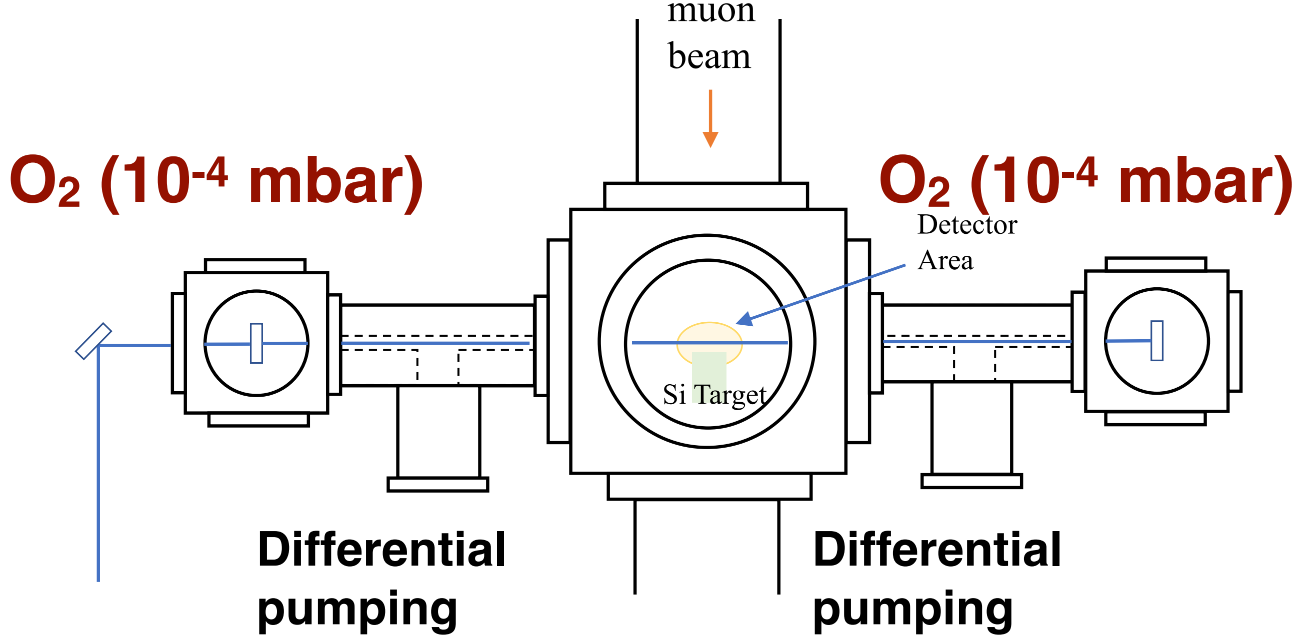
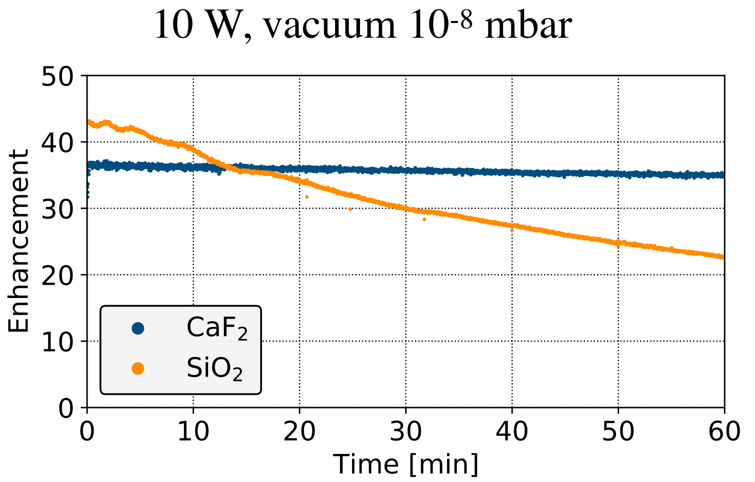
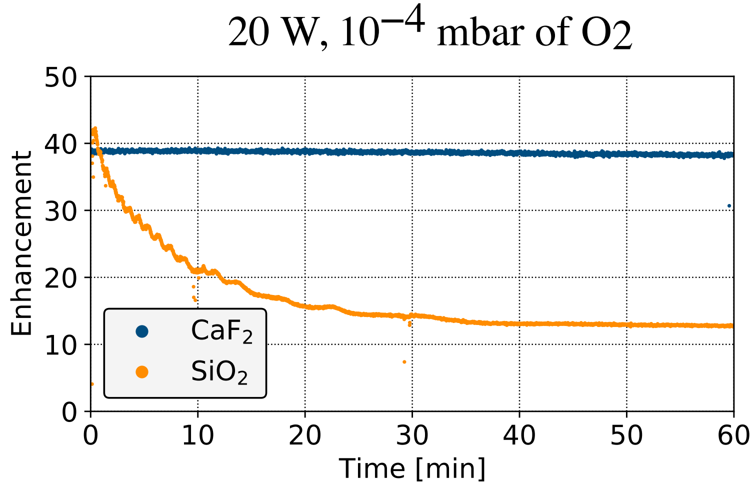




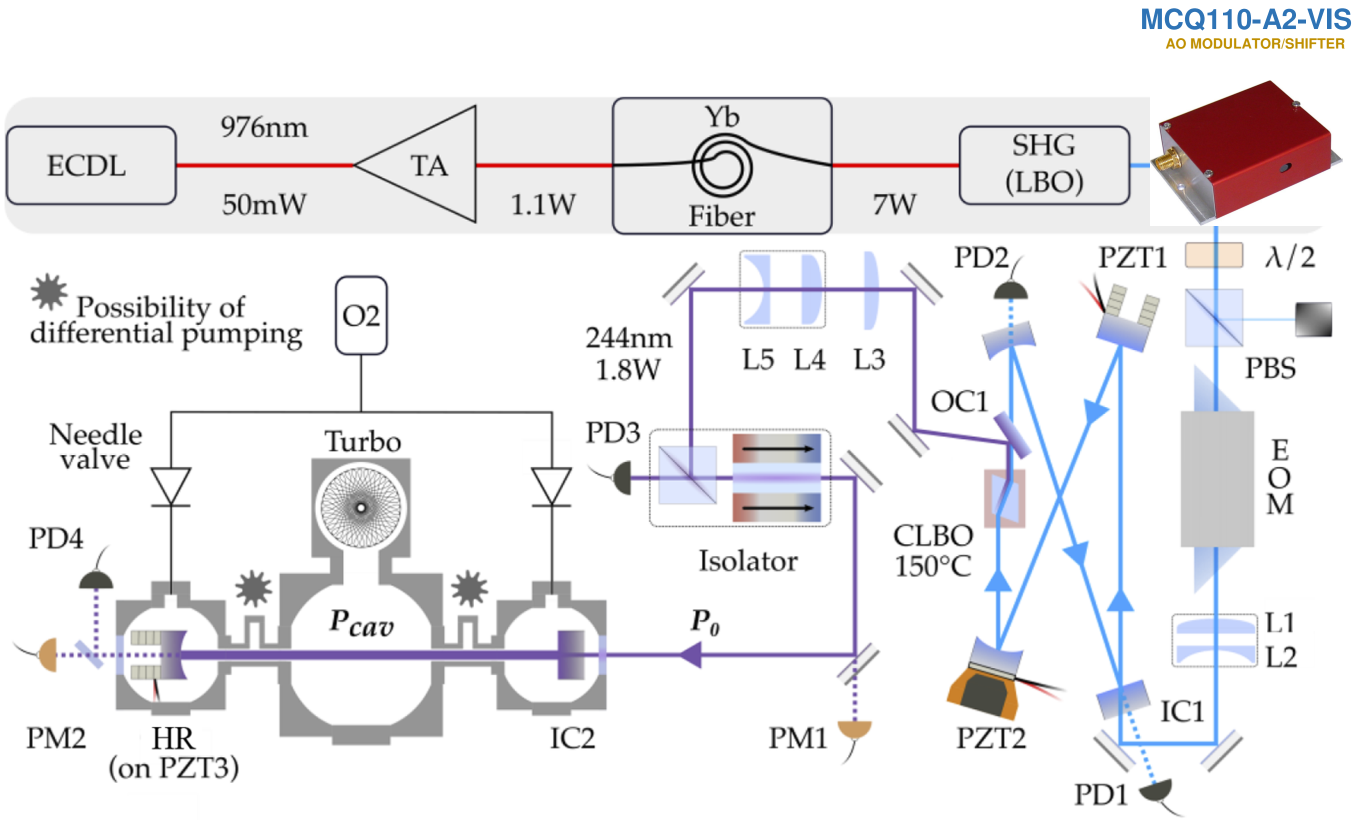


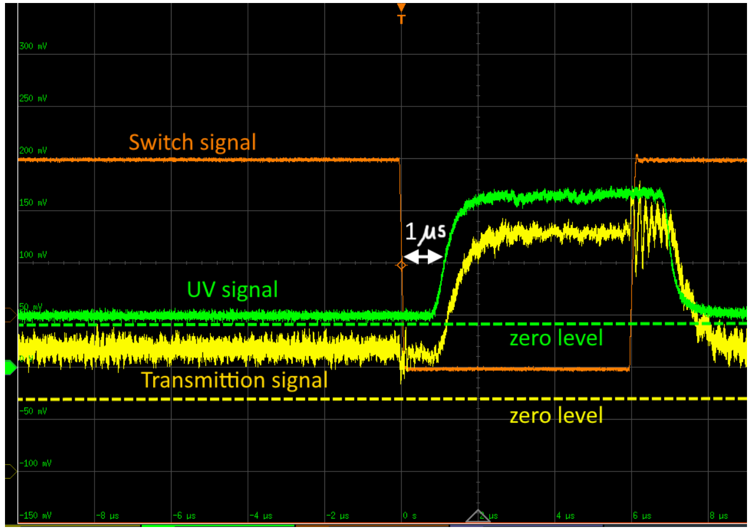
Z. Burkley, L. de Sousa Borges, B. Ohayon, A. Golovozin, J. Zhang, and P. Crivelli Opt. Express 29, 27450 (2021)

Mu-MASS: enhancement cavity QCW operation

Tagged muon rate ~ 5 kHz and TOF ~1 microsecond -> duty cycle 0.5 %

“Laser on demand” reduce average power 0.5% * 40W = 200mW in cavity and to ~ 0.5% * 1W = 5mW @ UV output





Preliminary tests very promising!

Summary and outlook for 1S-2S measurement

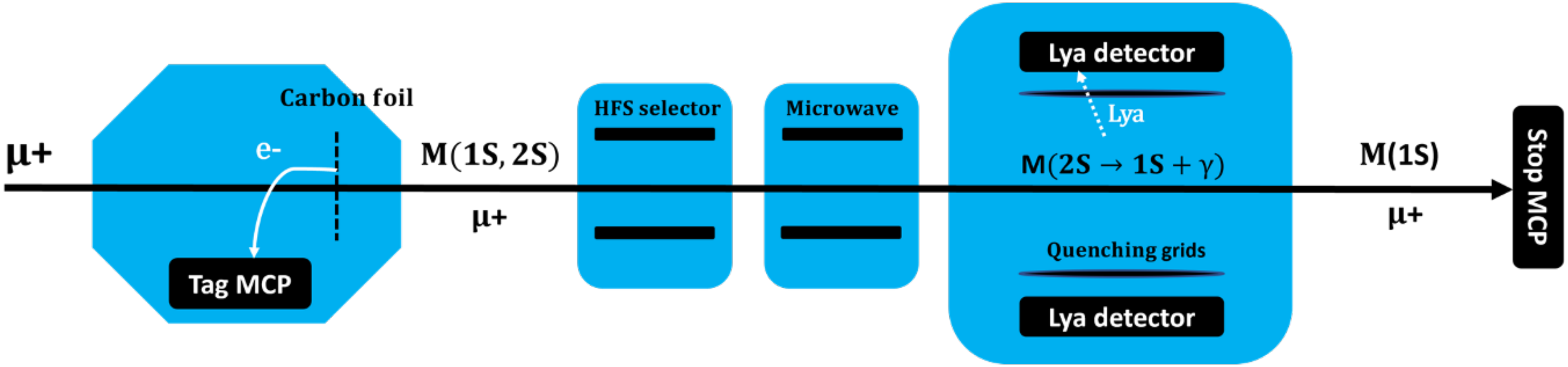
CURRENT STATUS:

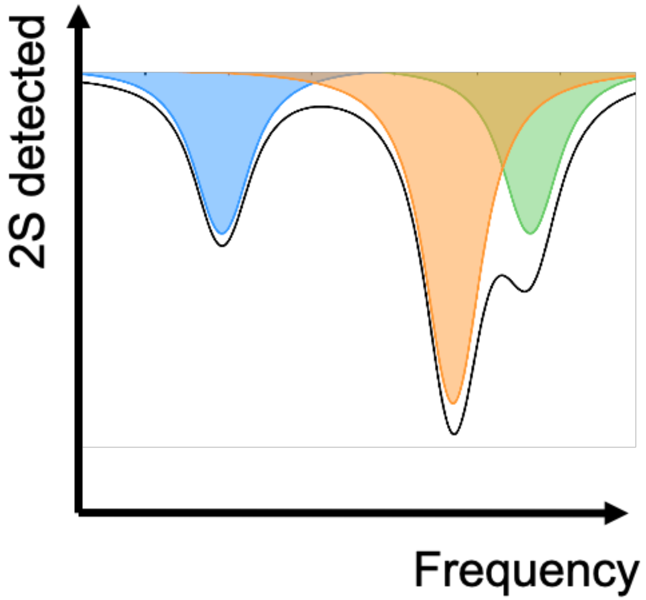
- Detection of 2S states achieved but S/N has to be improved
- Laser system, 20W circulating power achieved
- Frequency reference for the experiment is ready.
- Last November 2021 first attempts to excite 1S-2S transition using a pulsed laser detecting the PI muons + decaying positron -> all sort of problems…
-

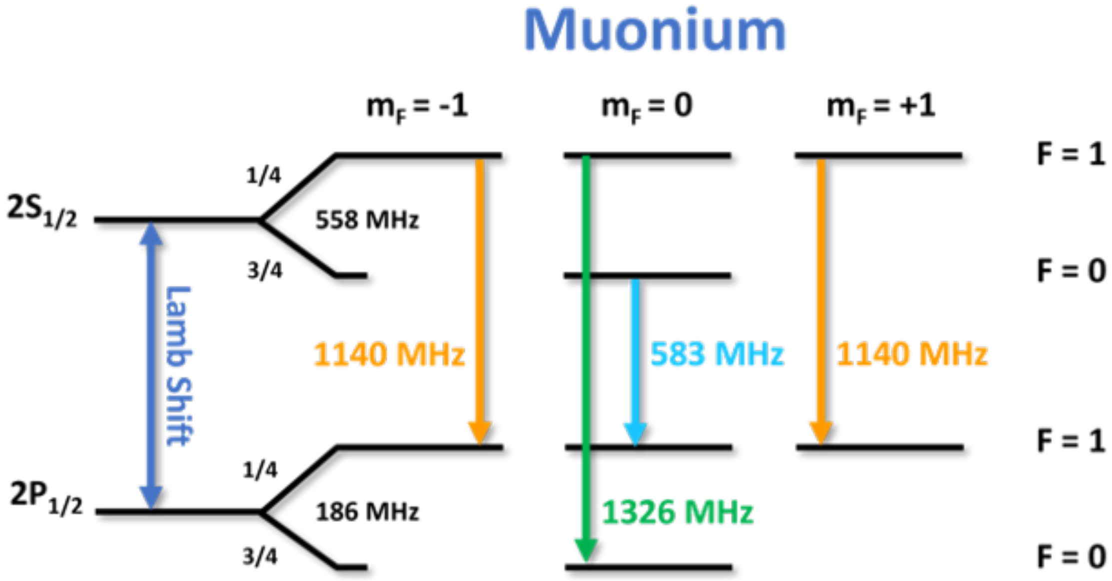
OUTLOOK 2022-:

- Next week: 5 days beam-time to test improved detection scheme (basically BKG measurement) + M diagnostic
- December beam-time: combine for the first time CW laser system + experiment at LEM

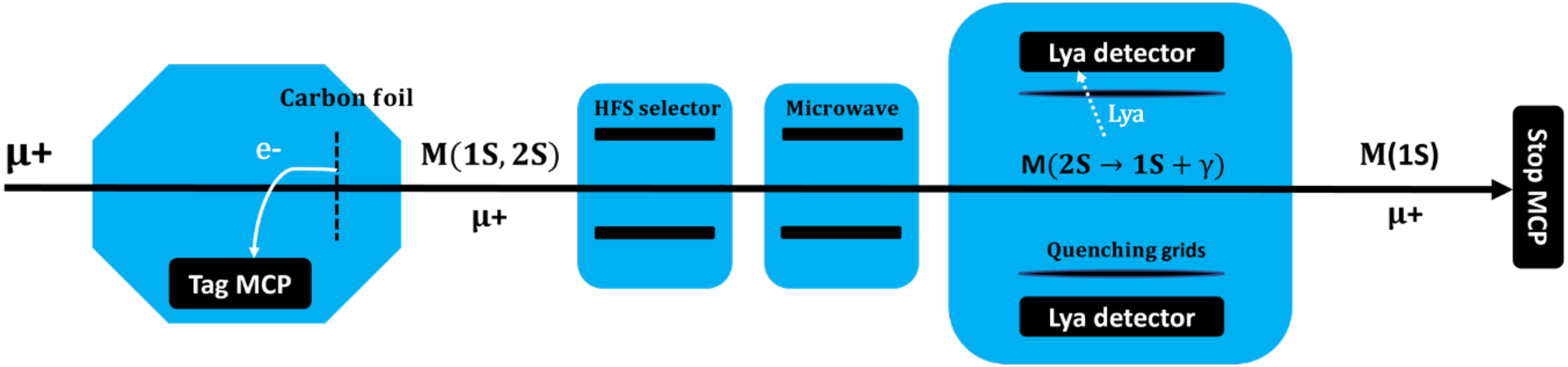
Muonium Lamb shift measurement in Mu-MASS

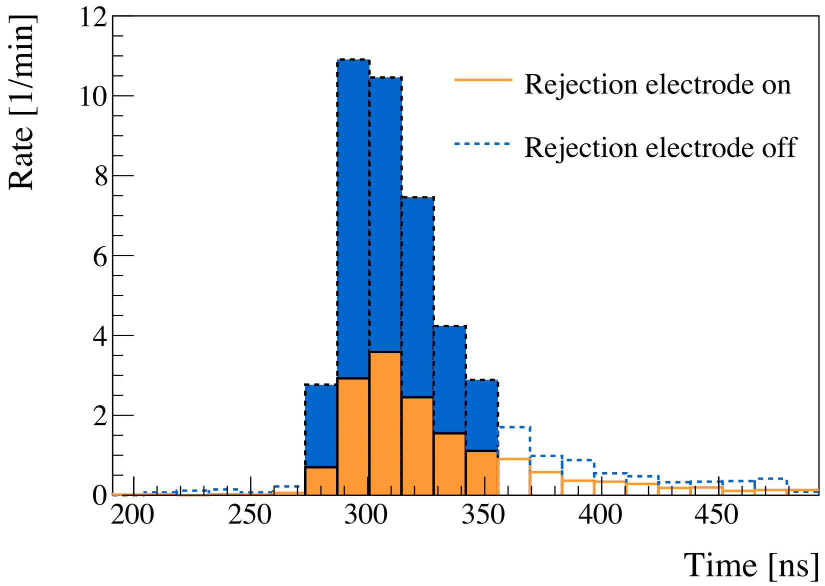


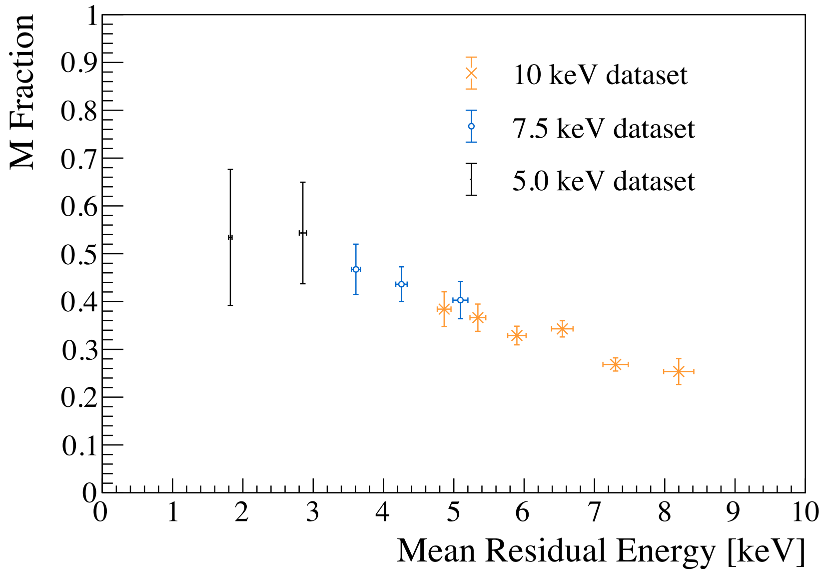




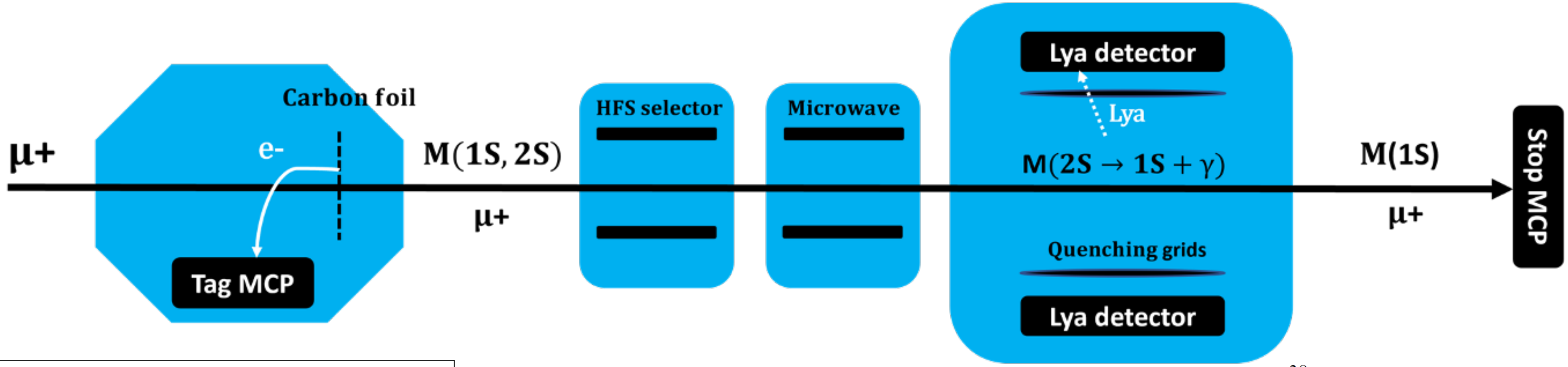
Muonium formation with a C-foil

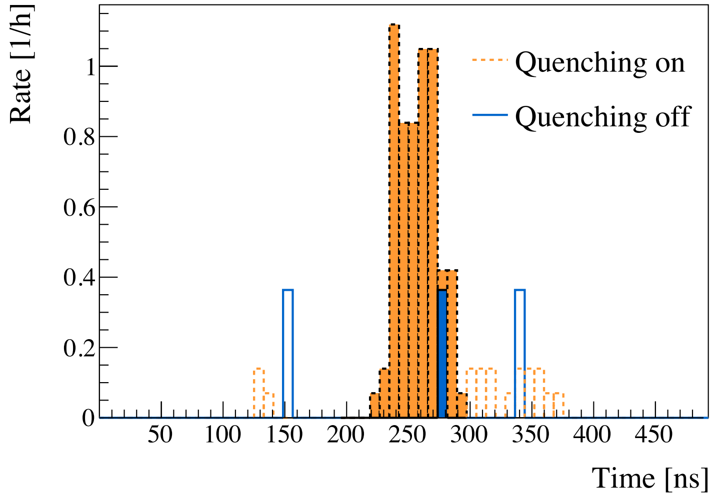






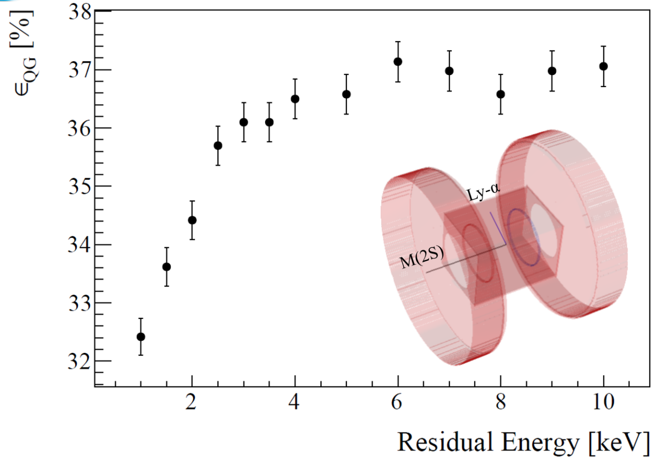
Detection of muonium in 2S state from C foil





Quenching efficiency and geometrical acceptance from MC + detection efficiency confirms $1/n^3$ scaling

$$f_{M(n=2)/M(n=1)} = (10 \pm 2)\%$$



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

Muonium Lamb shift

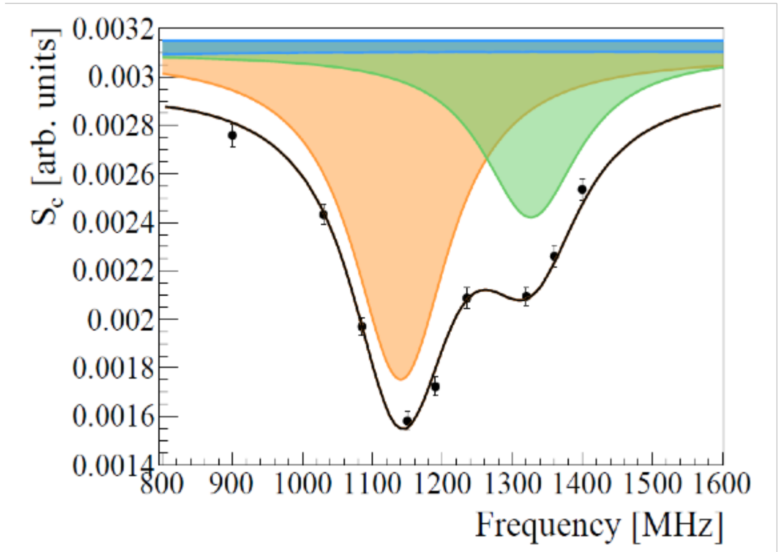
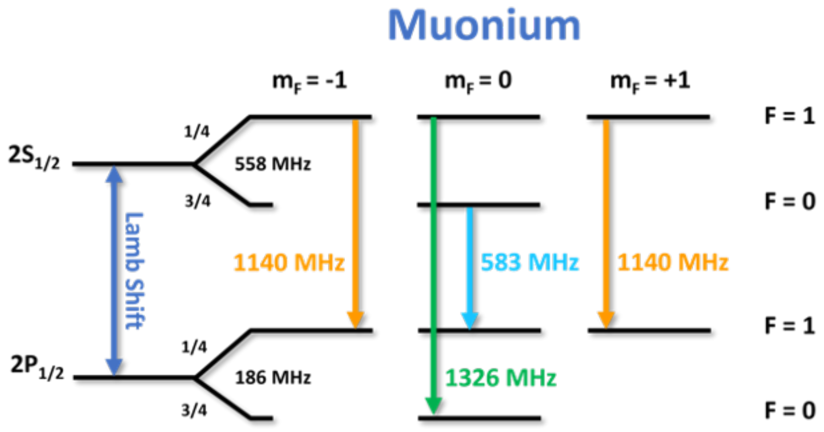


TABLE I. Central values and uncertainty contributions in MHz.

	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
2nd-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



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

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**

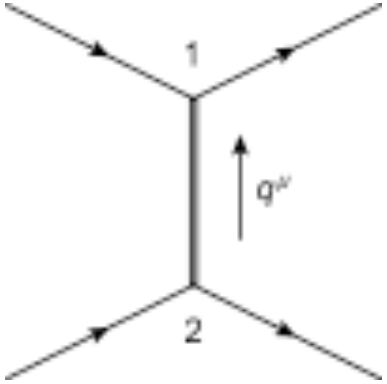
Searches for new bosons via positronium and muonium spectroscopy

- New bosons could mediate new forces resulting in shifts of Ps and M energy levels.

C Frugiuele et al., Phys. Rev. D100, 015010 (2019)

- Scattering between two fermions described by different potentials (scalar-scalar, vector-vector…)

P.Fadeev et al.,Phys. Rev. A 99, 022113 (2019)



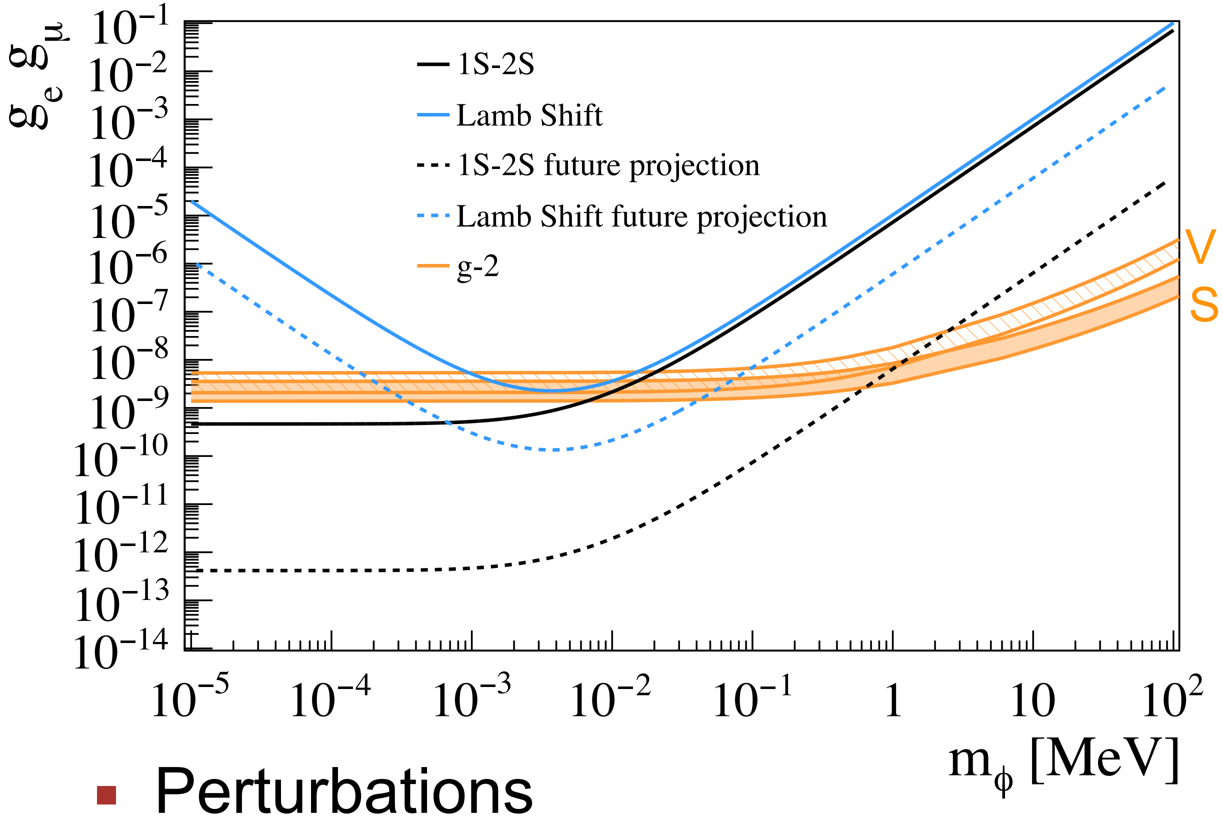
- We focus on the scalar-scalar potential: $V_{ss}(\vec{r}) = -g_1^s g_2^s \frac{e^{-Mr}}{4\pi r}$

- Leading order corrections: $\langle V_{ss} \rangle = -\frac{g_1^s g_2^s}{4\pi} F_{n,l}^1(M)$

$$F_{n,l}^k(M) = \langle \frac{e^{-Mr}}{r} \rangle_{n,l}, \; k = 1$$

	$l = 0$	$l = 1$	$l = 2$
$n = 1$	$\frac{4}{a_0(Ma_0+2)^2}$	X	X
$n = 2$	$\frac{2M^2a_0^2+1}{4a_0(Ma_0+1)^4}$	$\frac{1}{4a_0(Ma_0+1)^4}$	X
$n = 3$	$\frac{4(243M^4a_0^4+216M^2a_0^2+16)}{9a_0(3Ma_0+2)^6}$	$\frac{64(9M^2a_0^2+1)}{9a_0(3Ma_0+2)^6}$	$\frac{64}{9a_0(3Ma_0+2)^6}$

Muonium spectroscopy as a probe for new muonic forces



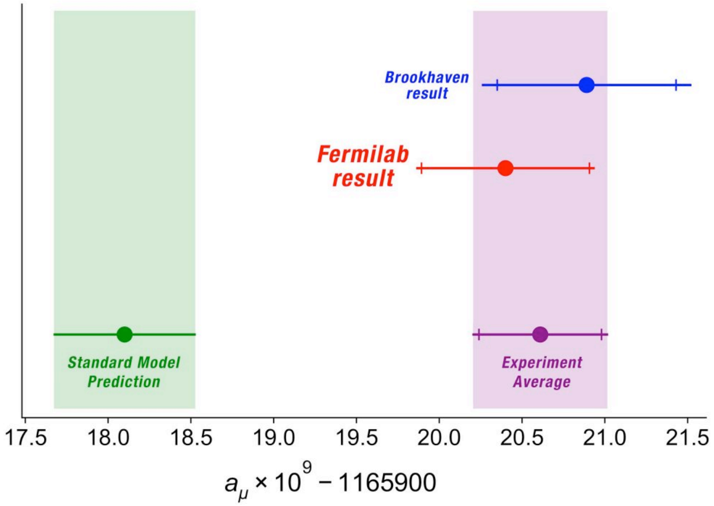
- Perturbations

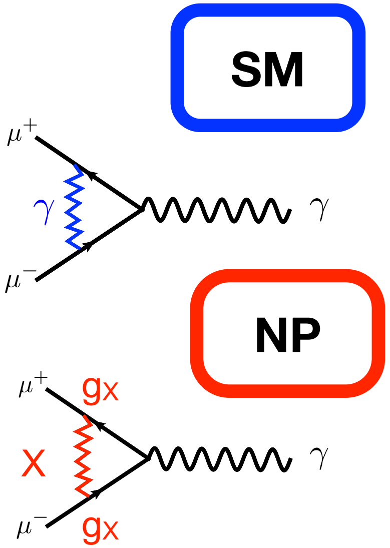
$$\Delta E_{ss}(2S^0 \to 1S^0) = \frac{g_1^S g_2^S}{4\pi}\left(\frac{4}{a_0(Ma_0+2)^2} - \frac{2M^2a_0^2+1}{4a_0(Ma_0+1)^4}\right)$$

$$\Delta E_{ss}(2S^0 \to 2P^0) = \frac{g_1^S g_2^S}{4\pi}\left(\frac{1}{4a_0(Ma_0+1)^4} - \frac{2M^2a_0^2+1}{4a_0(Ma_0+1)^4}\right)$$

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

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

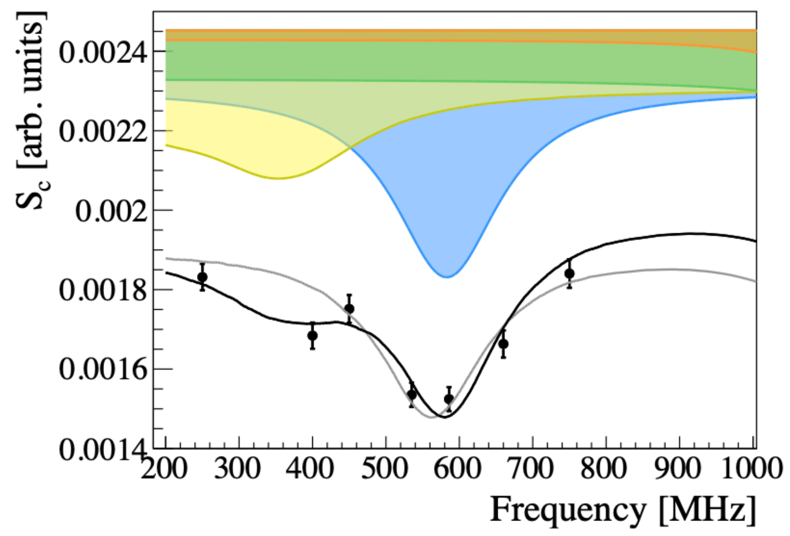


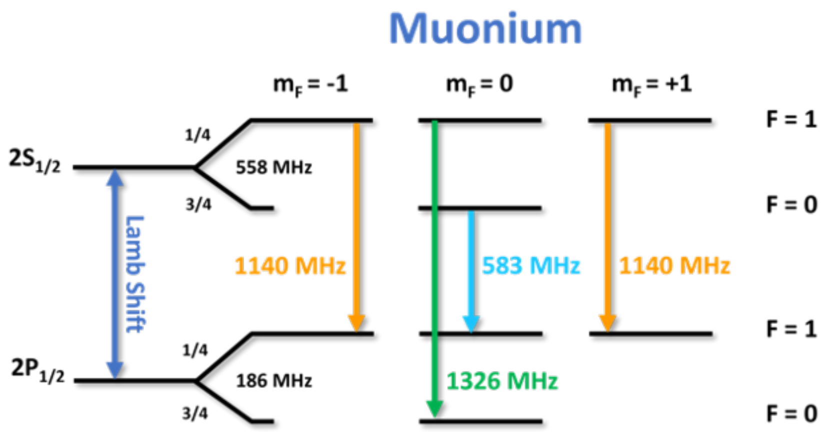


combined with bound from **$(g\text{-}2)_e$**

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)

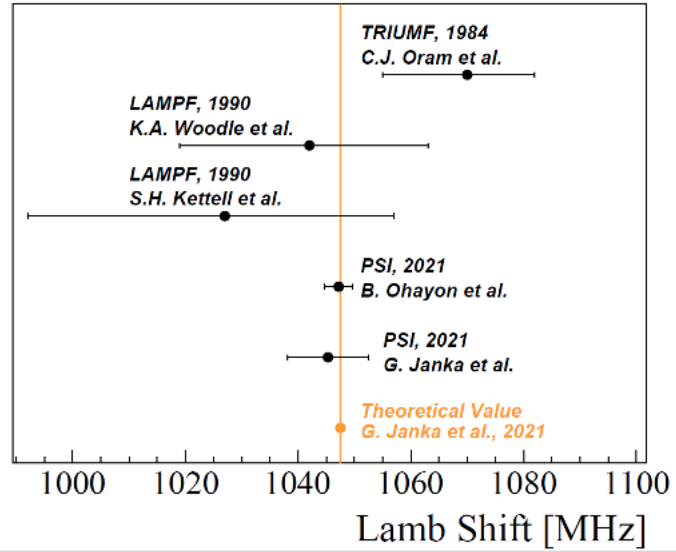
Measurement of $2S_{1/2}$,F=0 → $2P_{1/2}$,F=1 transition in Muonium





First time:
- Measurement of **$2S_{1/2}$, F=0 → $2P_{1/2}$, F=1** at **580.6(6.8) MHz**
- Extraction of **2S HFS** at **559.6(7.2) MHz**
- Detection of **M(3S)**

→ LS at 1045.5(6.8) MHz



G. Janka et al., arXiv:2205.06202 (2022)

Outlook - Muonium Lamb shift

$2S_{1/2}$, F=1 → $2P_{1/2}$, F=1 transition: most precise determination limited by statistics

$2S_{1/2}$, F=0 → $2P_{1/2}$, F=1 transition:

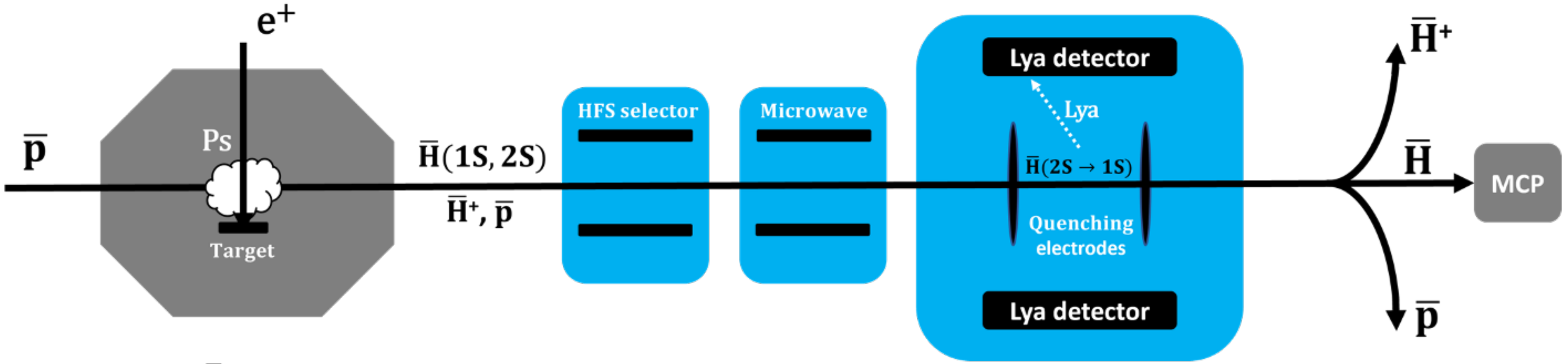
- Not competitive yet with most precise determination due to statistics
- Most promising transition for high precision measurements

Lowering uncertainty by another order of magnitude:
allows to probe larger region for $(g-2)_\mu$ and further probe SME (fine structure could also be measured with same uncertainty if interesting from SME perspective)
< 160 kHz to probe b-QED (Barker-Glover), not in reach in hydrogen LS yet

→ **reachable with minor changes:**
changing Muonium formation target
eliminating 3S & 4S contribution with weak electrical field

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

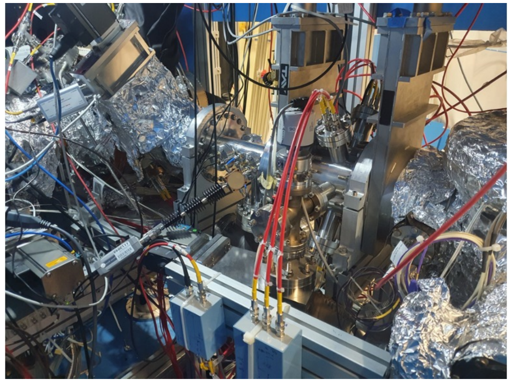
Prospects for Antihydrogen Lamb shift measurement in GBAR

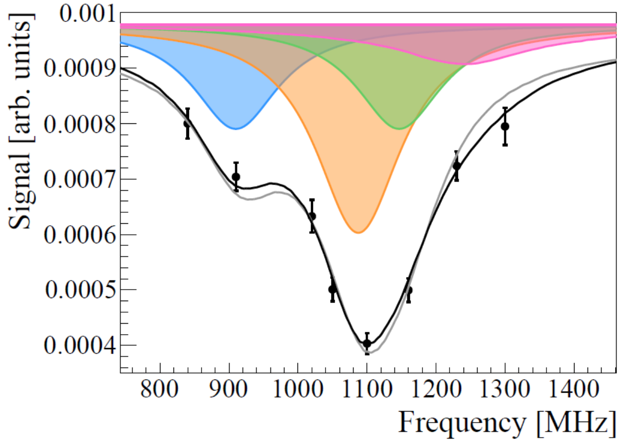


H̄ formation cross-section calculations:
C. M. Rawlins et al., Phys. Rev. A 93, 012709 (2016)
M. Charlton et al., Phys. Rev. A 104, L060803 (2021)

H̄ Lamb Shift:
P. Crivelli et al., Phys. Rev. D 94, 052008 (2016)

- Setup commissioned with H at in GBAR using protons on a C foil





G. Janka, PhD thesis 2022, ETHZ, https://doi.org/10.3929/ethz-b-000536696

Ready to measure H̄ Lamb shift as soon as H̄ available in GBAR.
At level of 100 ppm we can determine the antiproton charge radius at 10% level

Thank you!

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