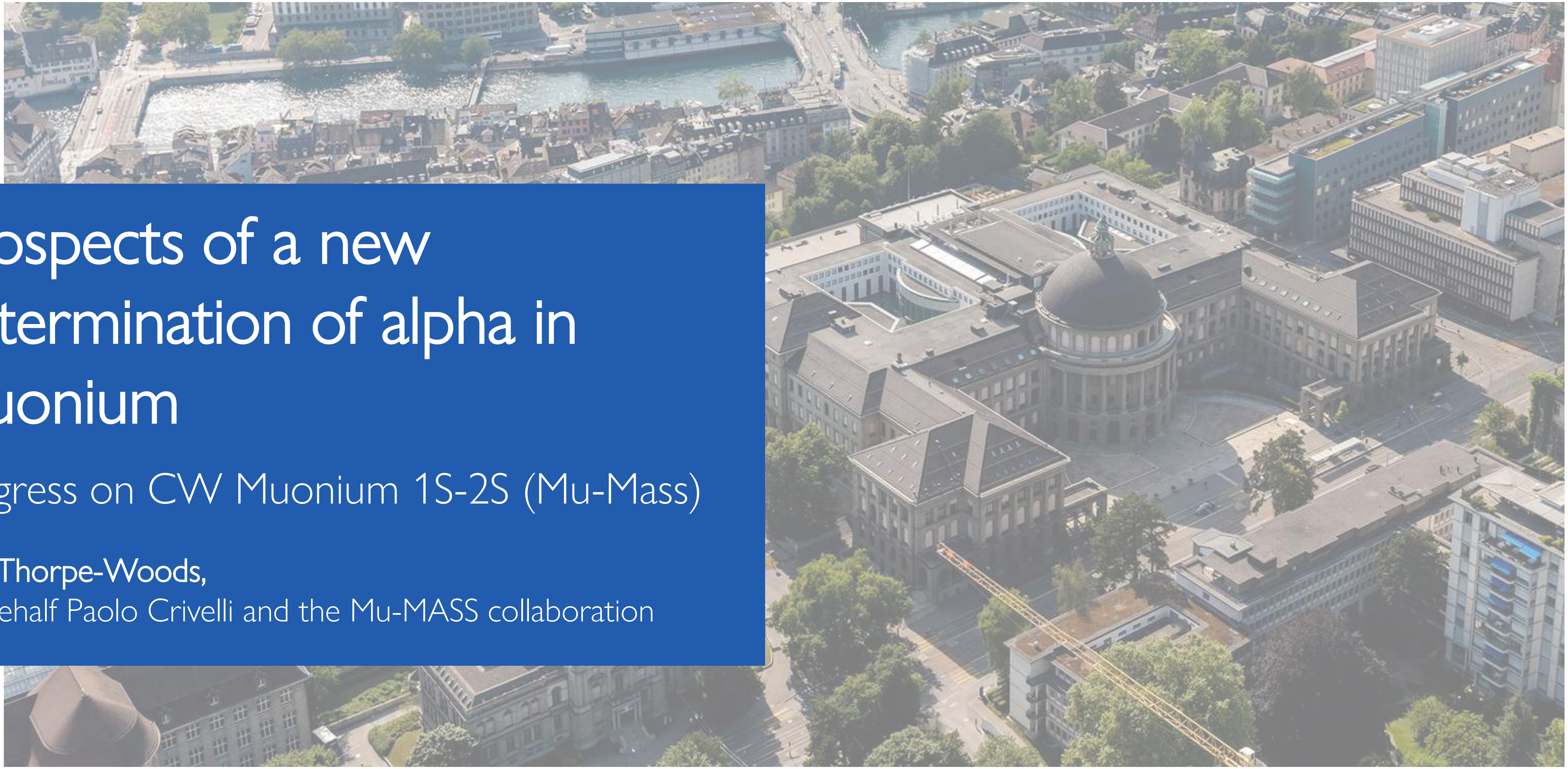


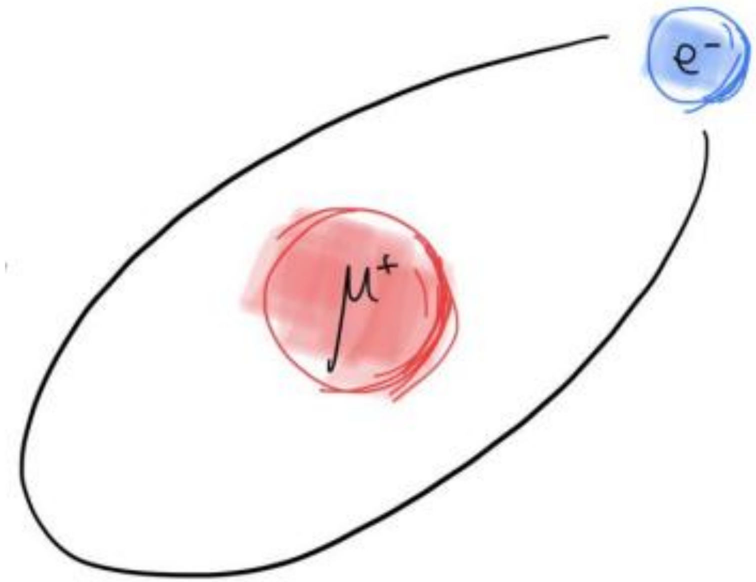
Prospects of a new determination of alpha in muonium

Progress on CW Muonium 1S-2S (Mu-Mass)

Ted Thorpe-Woods,
on behalf Paolo Crivelli and the Mu-MASS collaboration

Leptonic atoms & Muonium

- Leptonic atoms: QED bound states containing only charged (anti)leptons
- Why? Simple atomic systems which are devoid of finite size effects
- Muonium (M) : μ^+-e^- bound state
- Lifetime of ~ 2.2μs (limited by muon)



$$m_M \sim \frac{1}{9} m_H$$

Current status of Theory and Experiments

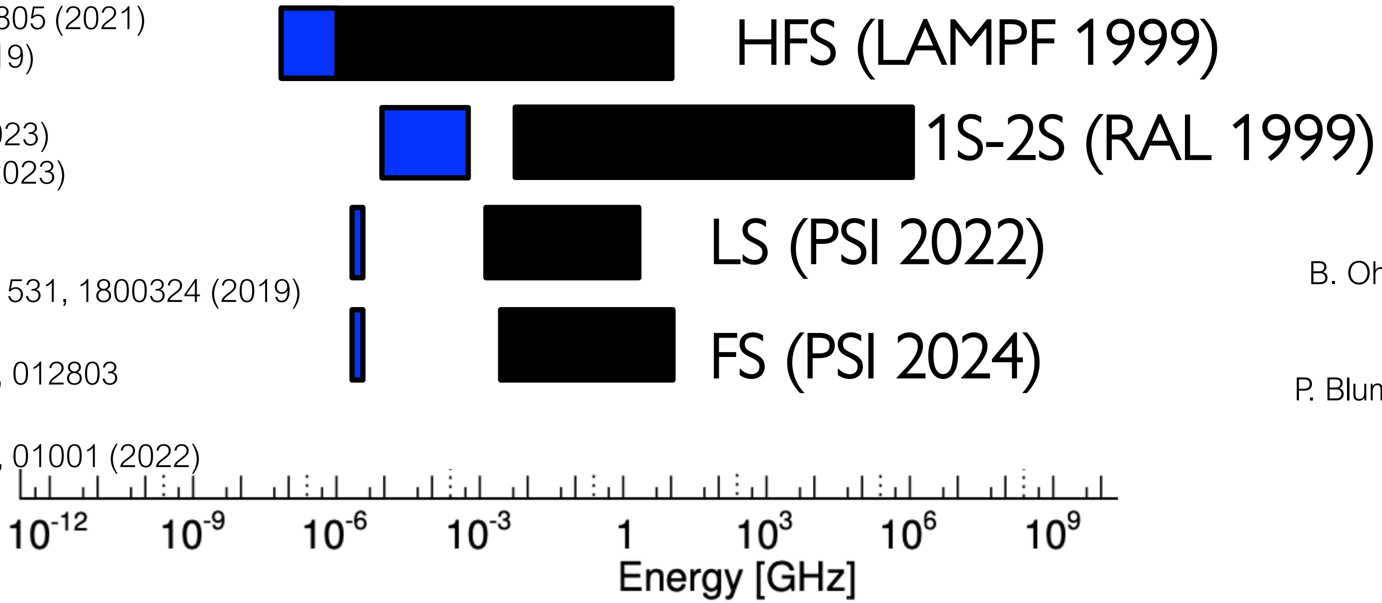
Karshenboim et al. PRA 103, 022805 (2021)
Eides, Phys. Lett. B 795, 113 (2019)

Adkins et al. PRL130, 023004 (2023)
I. Cortinovis et al., EPJD 77, 66 (2023)

V.A. Yerokhin, et al. Ann. der Phys. 531, 1800324 (2019)

M. Heides et al. PRA 105 (2022) 1, 012803

G. Janka et al. EPJ Web Conf. 262, 01001 (2022)



Liu et al. PRL82, 711 (1999)

Meyer et al. PRL84, 1136 (2000)

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

P. Blumer et al, paper in preparation

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

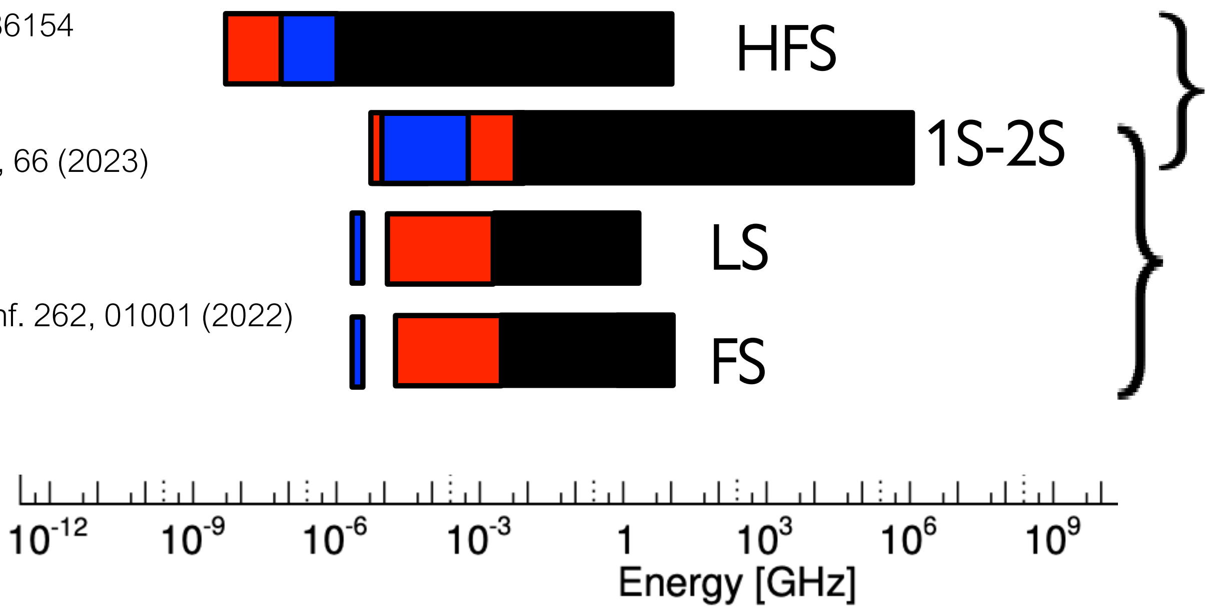
THEORY ▮ UNCERTAINTY DUE TO UNCALCULATED b-QED TERMS (LEFT EDGE)
UNCERTAINTY FROM KNOWLEDGE m_μ/m_e (RIGHT EDGE)

Muonium Spectroscopy – expected

S. Kanda et a. PLB 815 (2021) 136154

I. Cortinovis, PC, et al., EPJD 77, 66 (2023)

G. Janka, PC, et al. EPJ Web Conf. 262, 01001 (2022)



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)

Fine structure constant from M HFS (formalism)

- The theoretical formula for HFS in muonium has the form

$$\Delta\nu_{HFS} = \nu_F \left[1 + F\left(\alpha, Z\alpha, \frac{m_e}{m_\mu}\right) + \Delta\nu_{weak} + \Delta\nu_{hadr}\right] + \sigma_{th}$$

- With Fermi energy defined as

$$\nu_F = \frac{16}{3} Z^4 \alpha^2 \frac{m_e}{m_\mu} \left(\frac{m_r}{m_e}\right)^3 cR_\infty$$

M. I. Eides, S. G. Karshenboim, and V. A. Shelyuto, Phys. Rep. 342, 63 (2001)

- This depends on α and $r = \frac{m_\mu}{m_e}$ as

$$\nu_F \propto \alpha^4 \qquad \nu_F \propto \frac{r^2}{(1+r)^3}$$

- These allow us to define logarithmic sensitivities. These are convenient for resolving uncertainty propagation through

$$\frac{\sigma_\nu}{\nu} \approx S_x \frac{\sigma_x}{x}$$

$$S_\alpha \equiv \frac{\partial \ln \nu}{\partial \ln \alpha} \qquad S_r \equiv \frac{\partial \ln \nu}{\partial \ln r}$$

$$S_\alpha \simeq 4 \qquad S_r = \frac{2-r}{1+r} \simeq -0.986 \text{ (using r } \simeq 206.768)$$

Fine structure constant from M HFS (current)

- To extract determine the uncertainty on α extracted from the HFS of M, we consider uncertainty of the components:
  1. Experimental Uncertainty HFS: **51Hz**
  2. Theoretical uncertainty σ_{th} : $\approx$ 85Hz
  3. Uncertainty on r (for theory): $\sigma_r/r \approx 1.16 \times 10^{-7}$
  4. Hadronic & weak shifts < 2Hz uncertainty (neglect)

Liu et al. PRL82, 711 (1999)

M. I. Eides, S. G. Karshenboim, and V. A. Shelyuto, Phys. Rep. 342, 63(2001)

V.I Korobov, et al. *Phys.Part.Nucl.* 55 (2024)
S. Karshenboim et al. *Eur.Phys.J.D* 75 (2021)
V.A. Shelyuto, *Phys.Rev.D* 97 (2018)

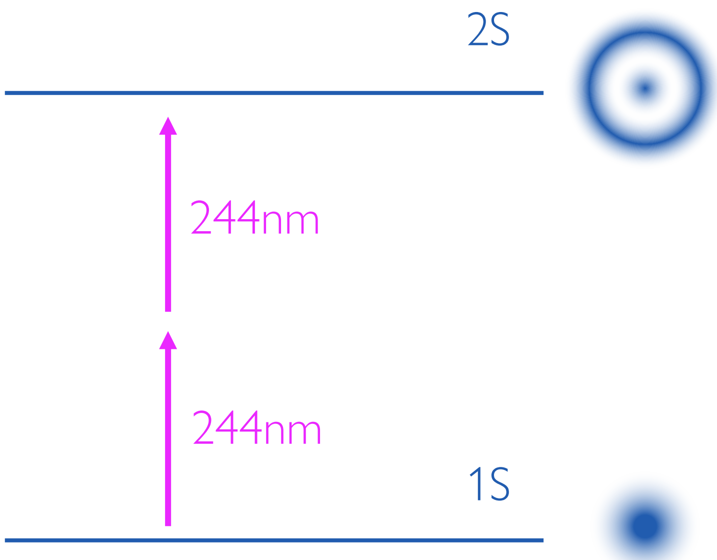
M. Eides, *PRA53*, 2953 (1996)

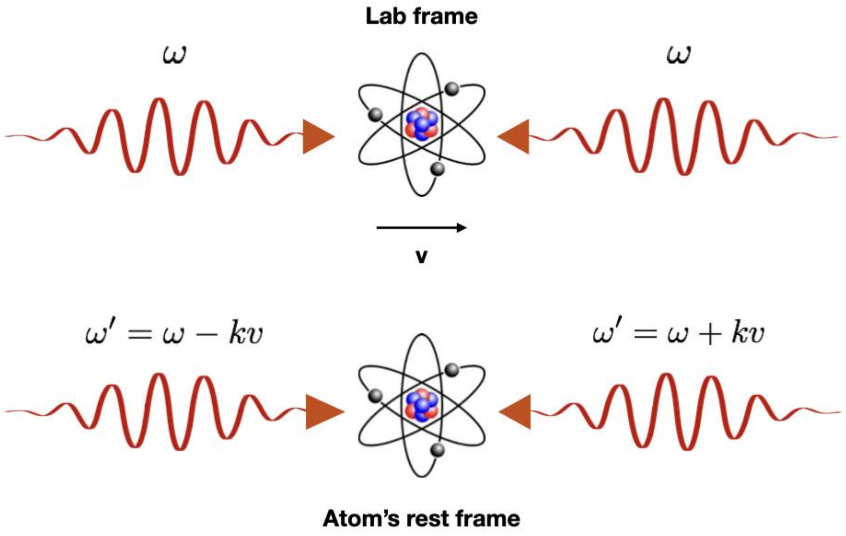
- Using S_r we can map σ_r onto uncertainty on HFS theory $\sigma_{th\ (r)} = |S_r|\nu \frac{u(r)}{r} \approx 511\ \mathrm{Hz}$
- Theory-experiment comparison has total uncertainty $\sigma \approx \sqrt{85^2 + 51^2 + 511^2} \approx 520\mathrm{Hz}$
- We can map this onto α using $\frac{\sigma_\alpha}{\alpha} \approx \frac{1}{|S_\alpha|}\frac{u_\nu}{\nu} \approx \frac{1}{4}\frac{5.2 \times 10^2}{4.4633 \times 10^9} \approx 29\mathrm{ppb}$

This is dominated by the uncertainty in r !

The 1S-2S transition

- To gain knowledge of atom energy structure: probe it with electromagnetic radiation
- The 1S-2S transition is the provide the gold standard for precision spectroscopy
  - Meta-stable (long lifetime, resulting in narrow linewidth)
  - Doppler free to first order in cavity
- A key goal of MuMASS: measure the 1S-2S of Muonium with a CW laser
- This can be used to extract the muon-electron mass ratio!





Muon-electron mass ratio from Muonium 1S-2S

- How does the uncertainty of r extracted from the 1S-2S transition frequency scale with the precision of the spectroscopy?

- Again, we can use logarithmic sensitivities:

$$\nu_{1S-2S}^{\mathrm{Mu}} \propto \frac{r}{1+r} R_\infty c \times \left[1 + \Delta_{\mathrm{QED}} + \cdots\right]$$

$$S_r^{(1S-2S)} \equiv \frac{\partial \ln(\nu_{1S-2S})}{\partial \ln r} = \frac{1}{1+r}$$

- Using this to map uncertainty in 1S-2S transition frequency

$$\frac{\sigma_r(r)}{r} = (1+r)\frac{\sigma_v}{\nu} \approx 208\frac{\sigma_v}{\nu}$$

- A 10kHz uncertainty in the 1S-2S frequency translated into $\frac{\sigma_r(r)}{r} \approx 0.85\text{ppb}$

Fine structure constant from M HFS (Prospective)

- As stated in a previously Theory-experiment comparison can extract alpha with precision

$$\sigma \approx \sqrt{85^2 + 51^2 + 511^2} \approx 520\text{Hz} \quad \rightarrow \quad \frac{\sigma_\alpha}{\alpha} \approx 29\text{ppb}$$

- However, if we assume prospective targets:
  - MuMASS (1S–2S): $\sigma_r/r \approx 1\text{ppb} \rightarrow \sigma_{th\,(r)} \approx |S_r|\nu \times 10^{-9} \approx 4.4\text{Hz}$
  - MuSEUM (HFS): experimental σ_{exp} ≈ 5 Hz. – MuSEUM talk tomorrow
  - Theory remainder: σ_{th} ≈ 5 Hz (QED higher orders refined, realistic?)

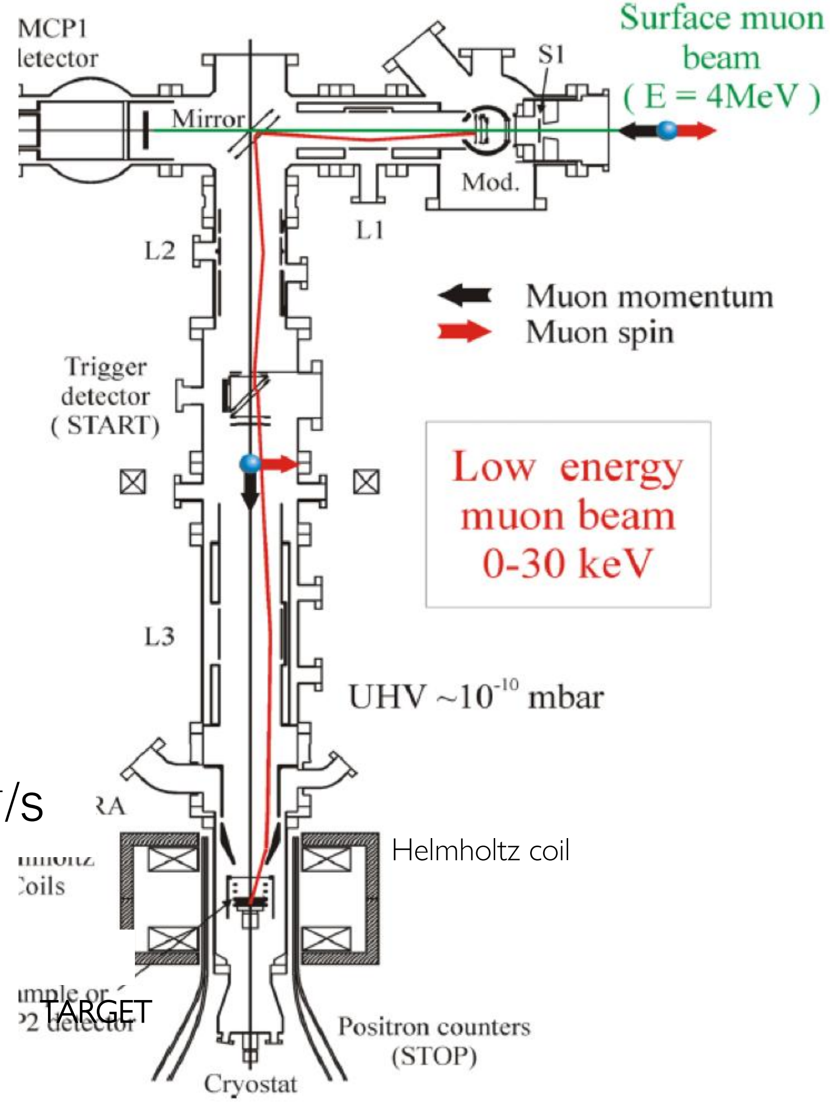
$$\sigma \approx \sqrt{5^2 + 5^2 + 4.4^2} \approx 8.6\text{Hz} \quad \rightarrow \quad \frac{\sigma_\alpha}{\alpha} \approx 0.5\text{ppb}\,!$$

- Whilst still not as good as state-of-the-art atom-interferometry determinations, this provides an independent measurement from muonium spectroscopy

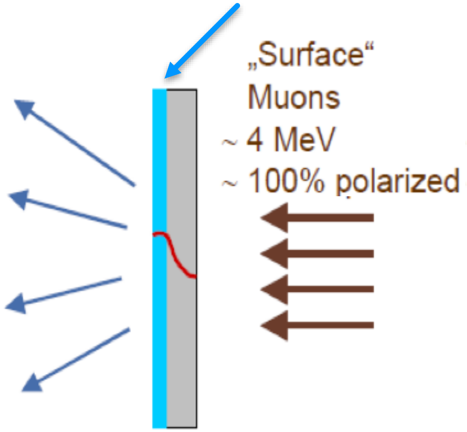
The PSI low energy muon beam (LEM)

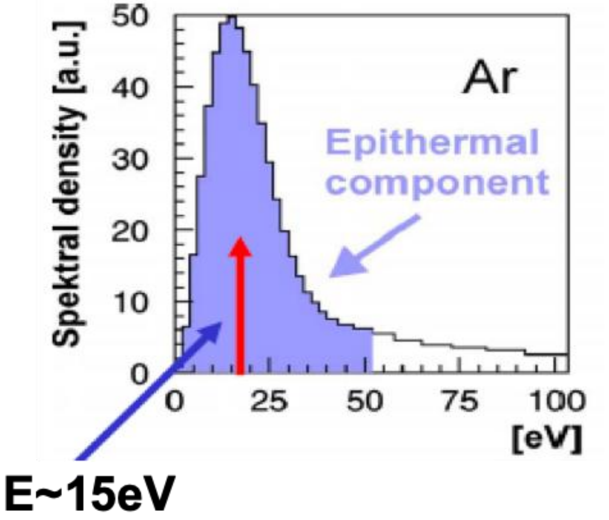
https://www.psi.ch/en/low-energy-muons

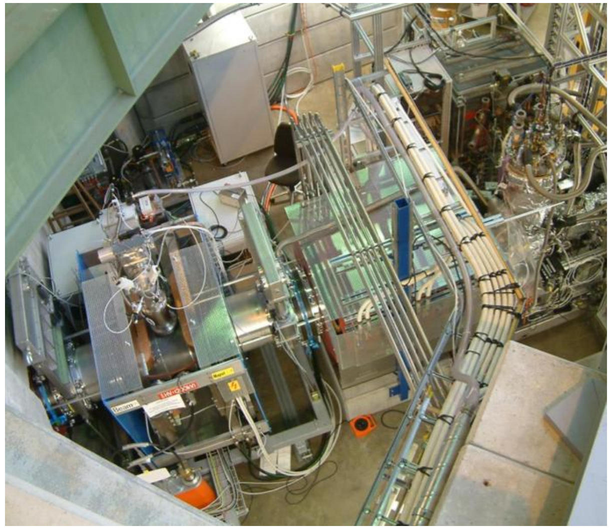
PAUL SCHERRER INSTITUT



Up to 5x10^3 μ^+/s







Mu-MASS timeline

2018 | 2019 | 2020 | 07/21 | 12/22 | 6/23 | 12/23 | 6/23 | 3/25 | 11/25 | 6/26

1.5W UV CW laser developed

Engineering runs PSI

M Lamb Shift

Pulsed CW technique developed

1S-2S attempt

Diffusion studies 1

Diffusion studies 2

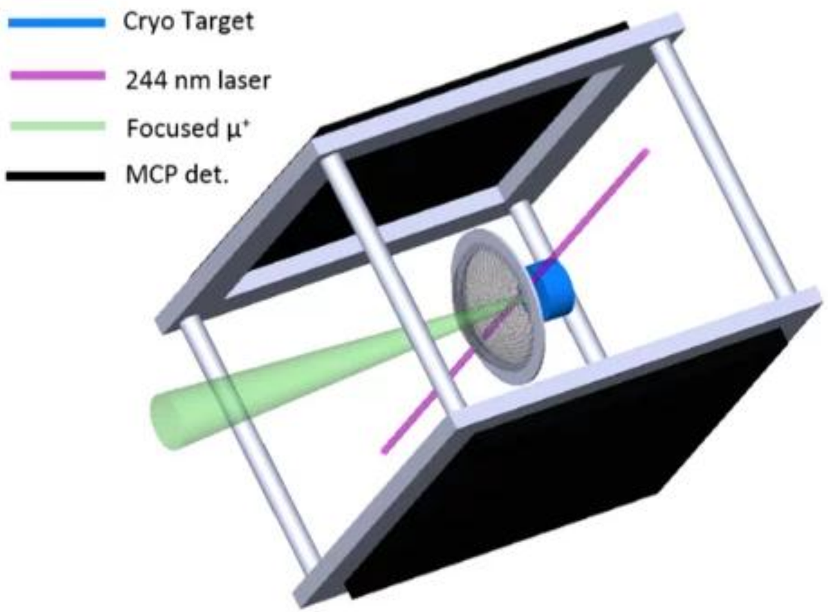
M Fine structure

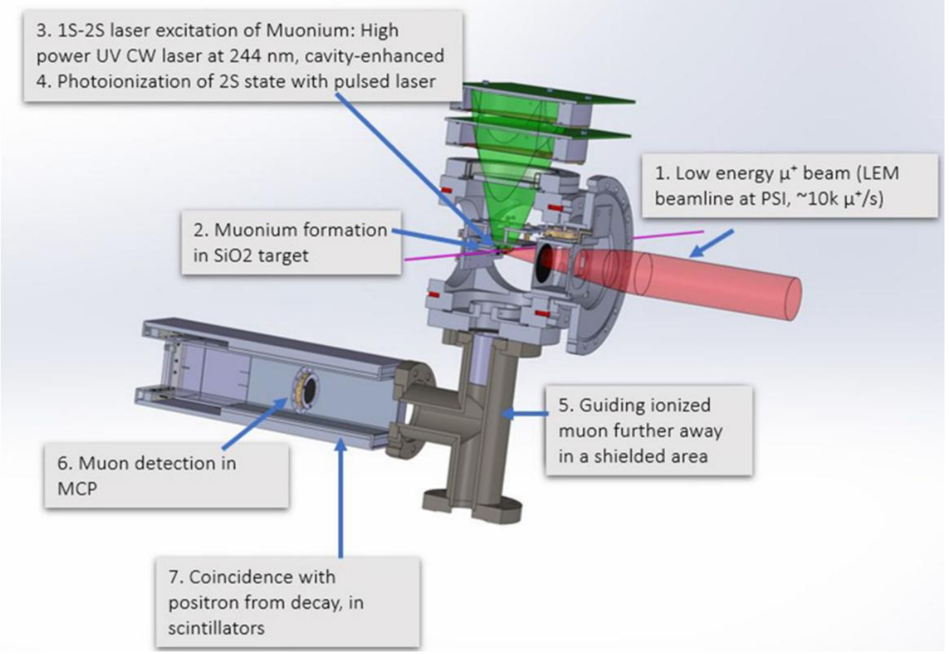
FA upgrades

Hydrogen commissioning

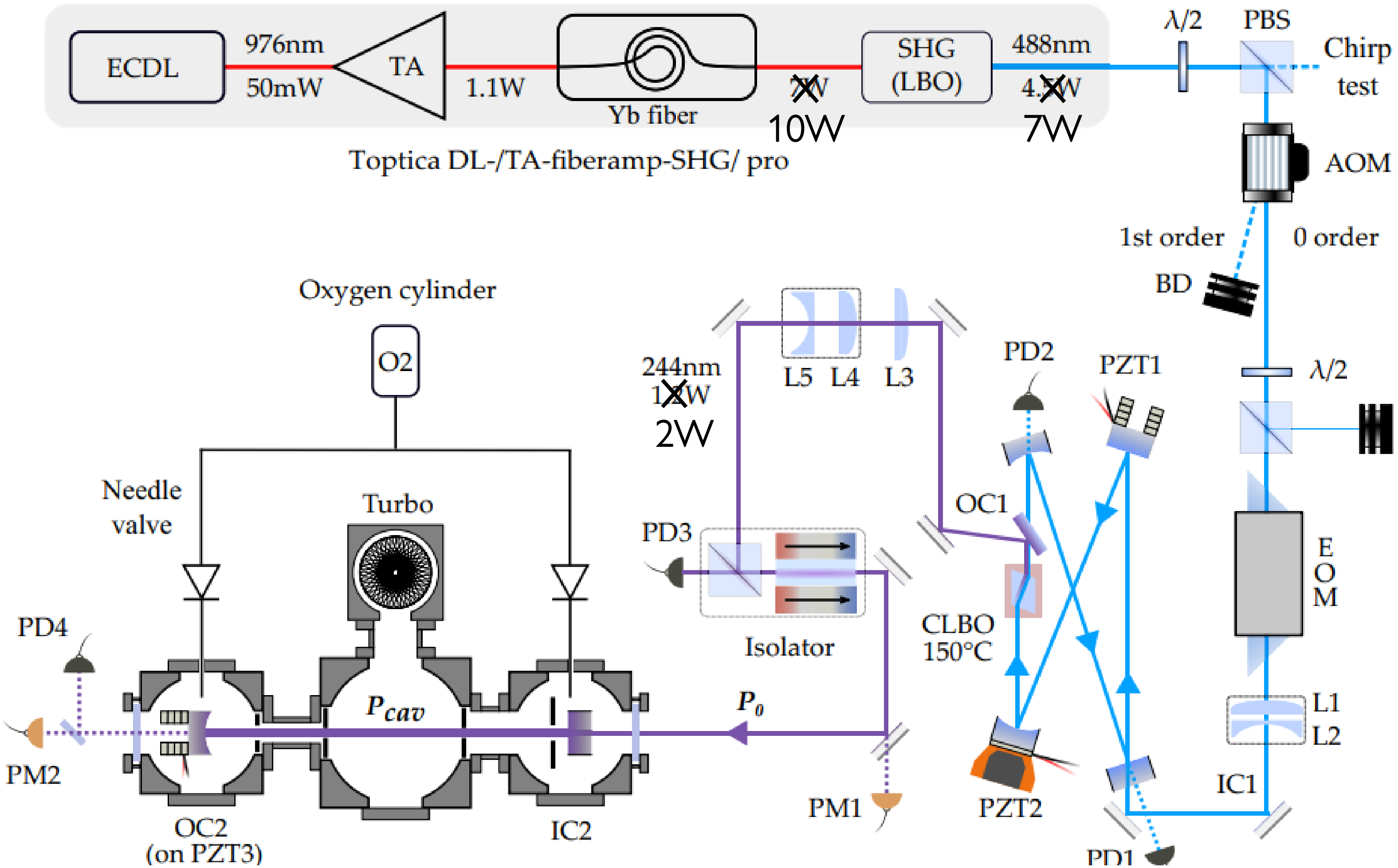
Beamtime

Beamtime





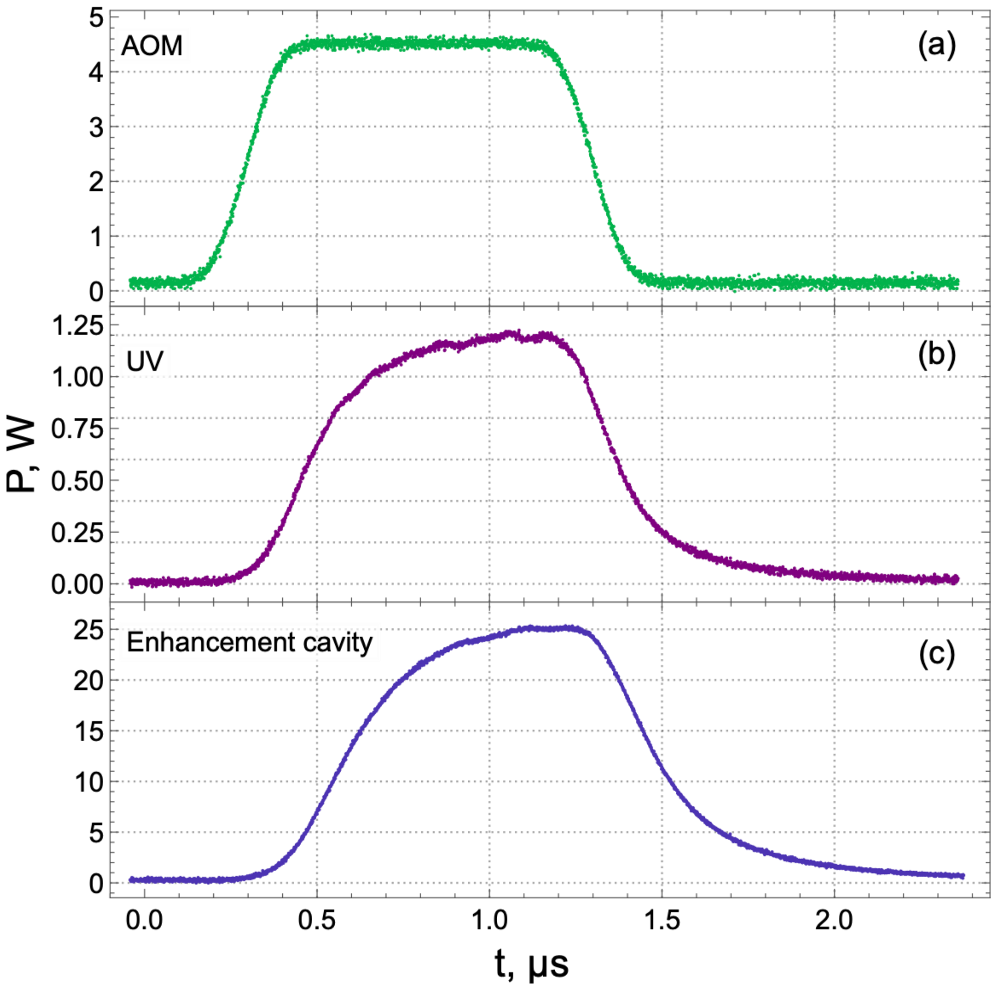
Upgraded 244nm laser system



N Zhadnov et al, Optics Express 31, 17(2023)

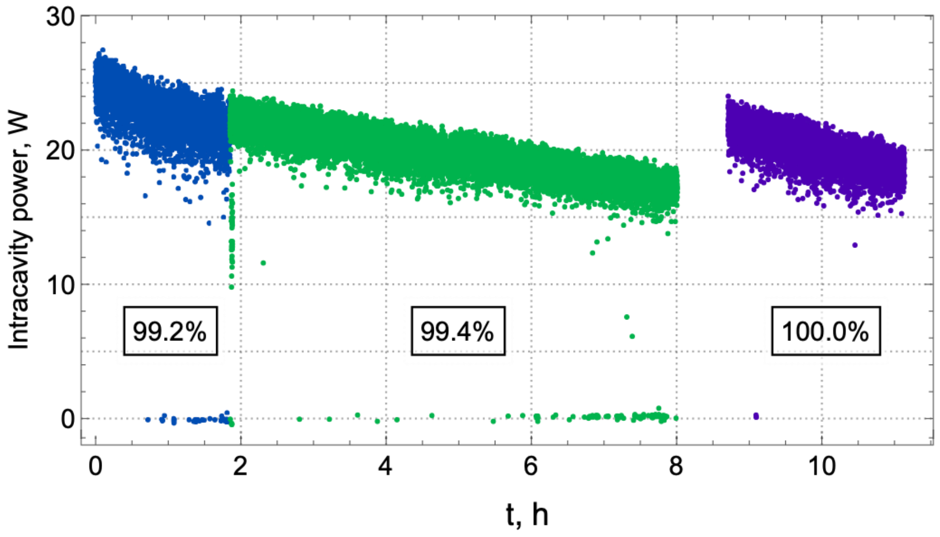
- 976nm light amplified to 10W via sequential TA and FA
- Frequency doubled to 7W of 488nm
- Second frequency doubling to ~2W of 244nm within custom made cavity with CLBO
- Enhanced to 30-40W within MuMASS

Pulsed CW technique



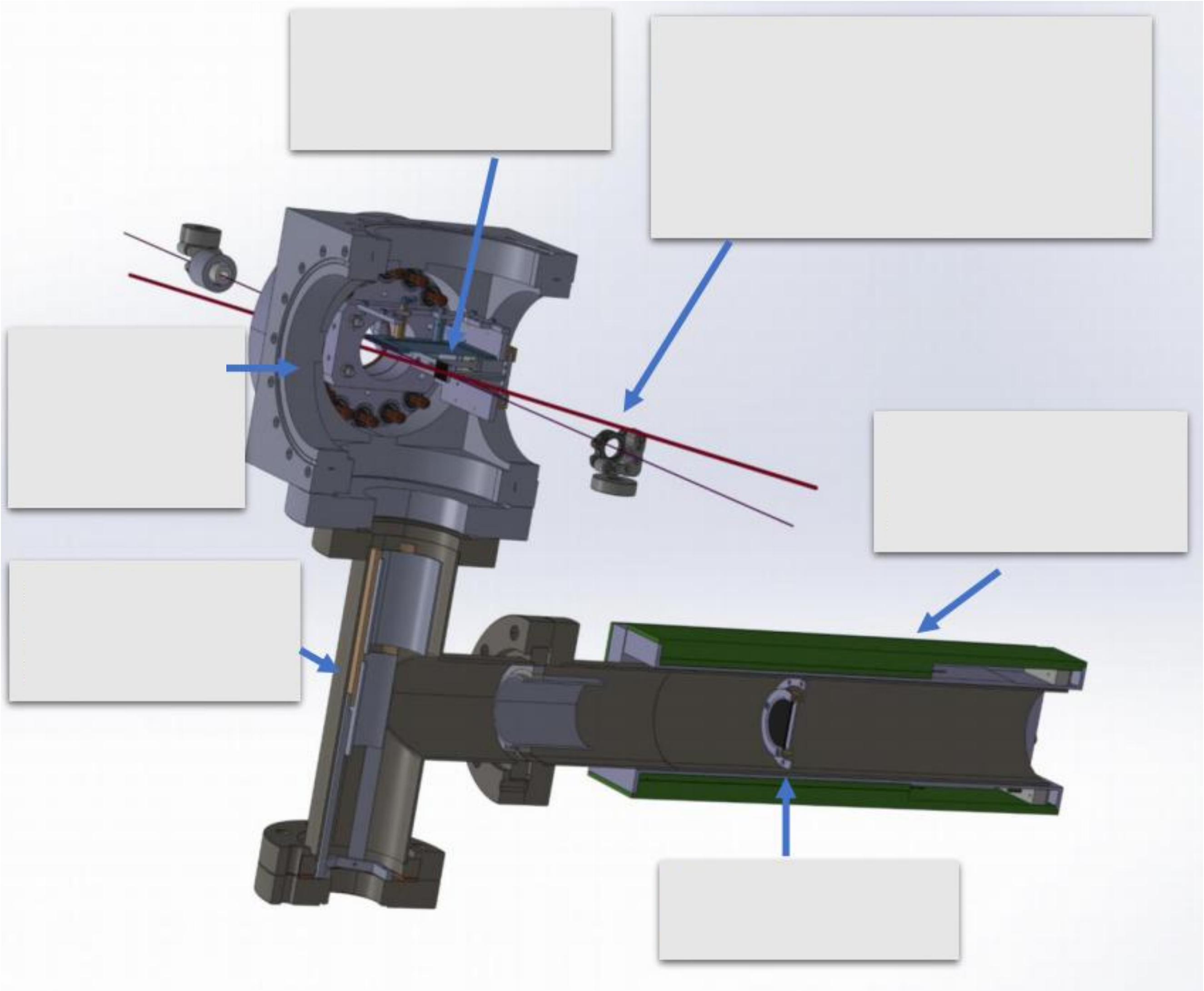
N Zhadnov et al, Optics Express 31, 17(2023)

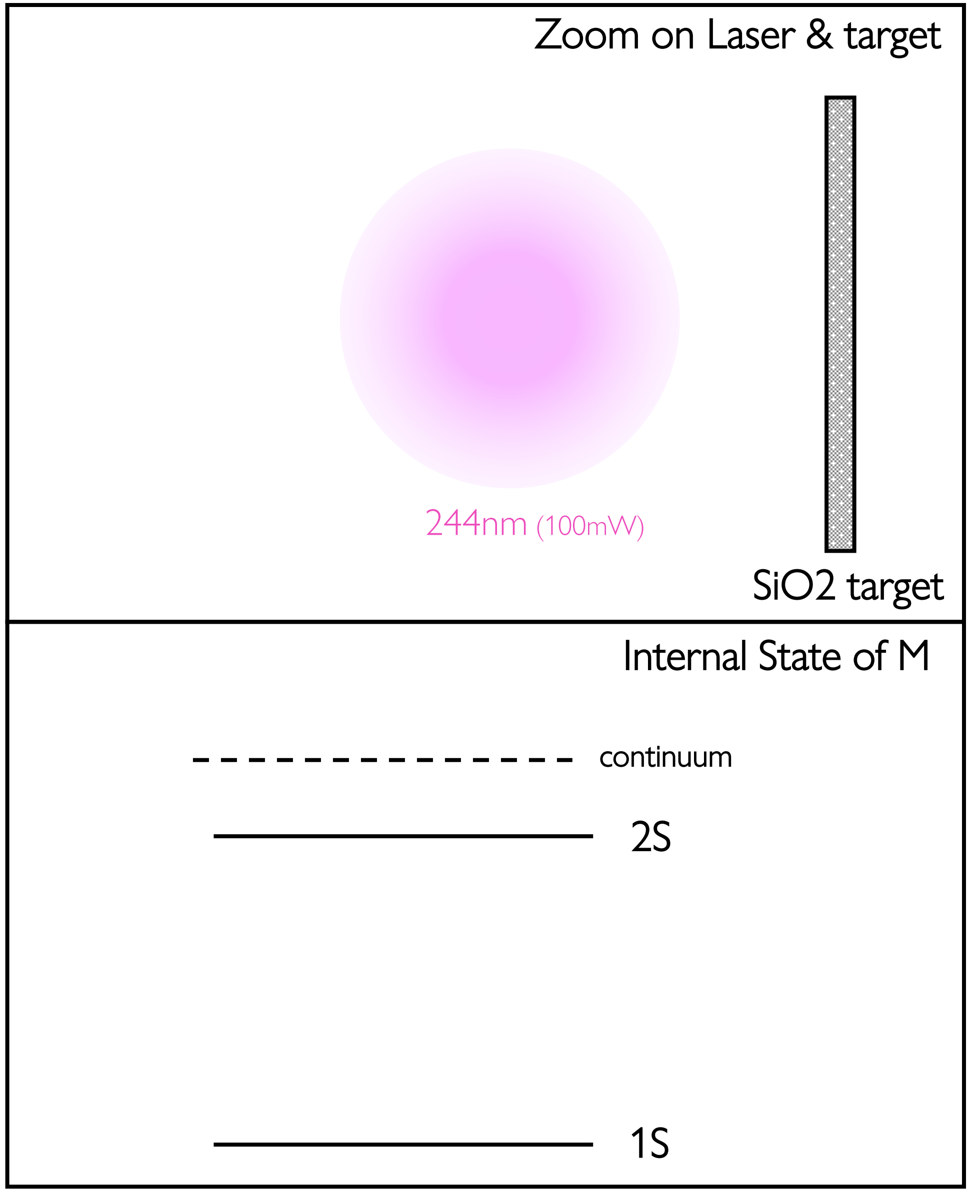
- 1-2W of CW 244nm light (enhanced to 30W) is an extremely harsh optical environment
- Degrades optics, adds background
- Solution: Pulse CW power when needed
- Previously: AOM; Now: Pockles Cell + AOM



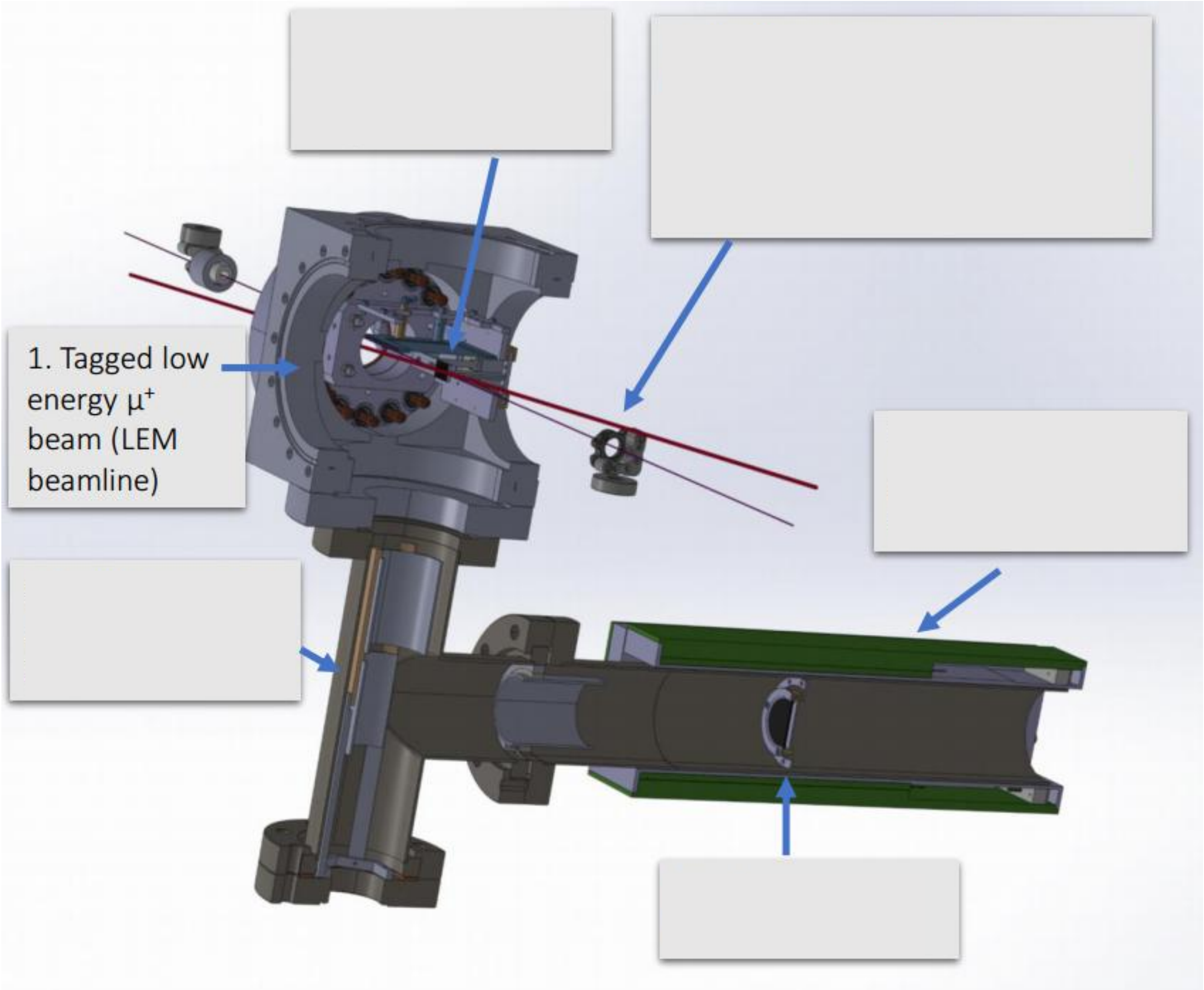
Can operate consistently for days, with occasional O_2 treatment

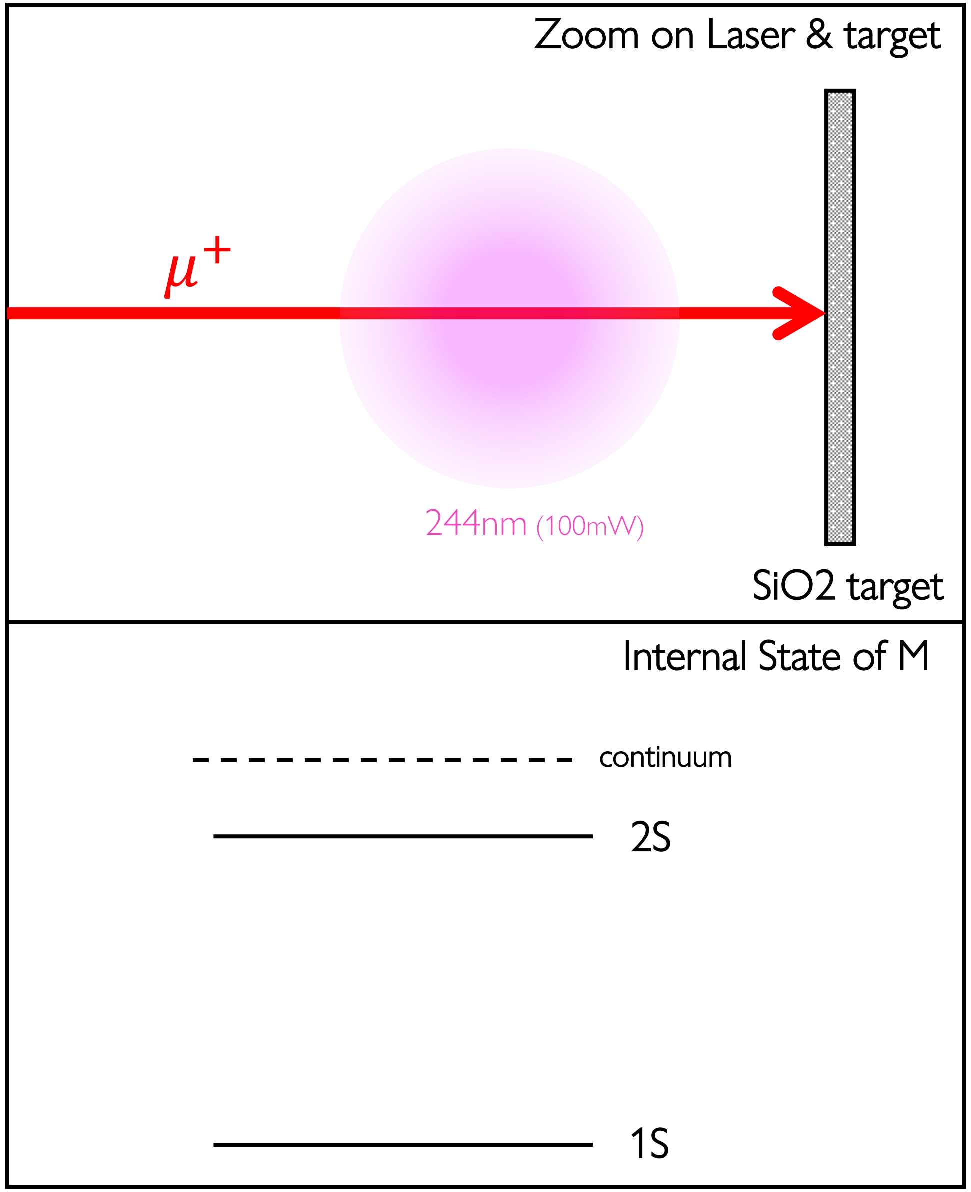
Mu-Mass experimental setup



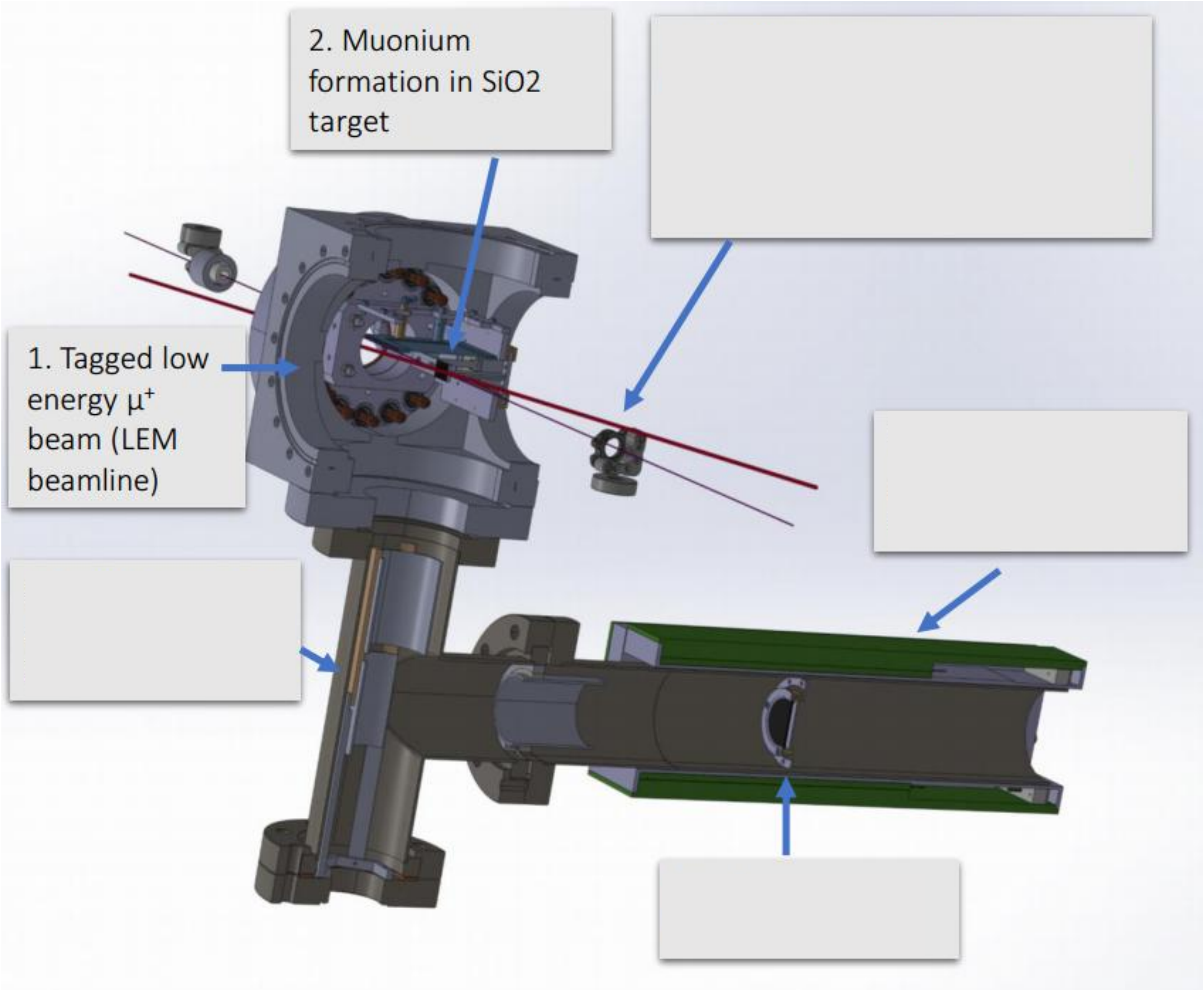


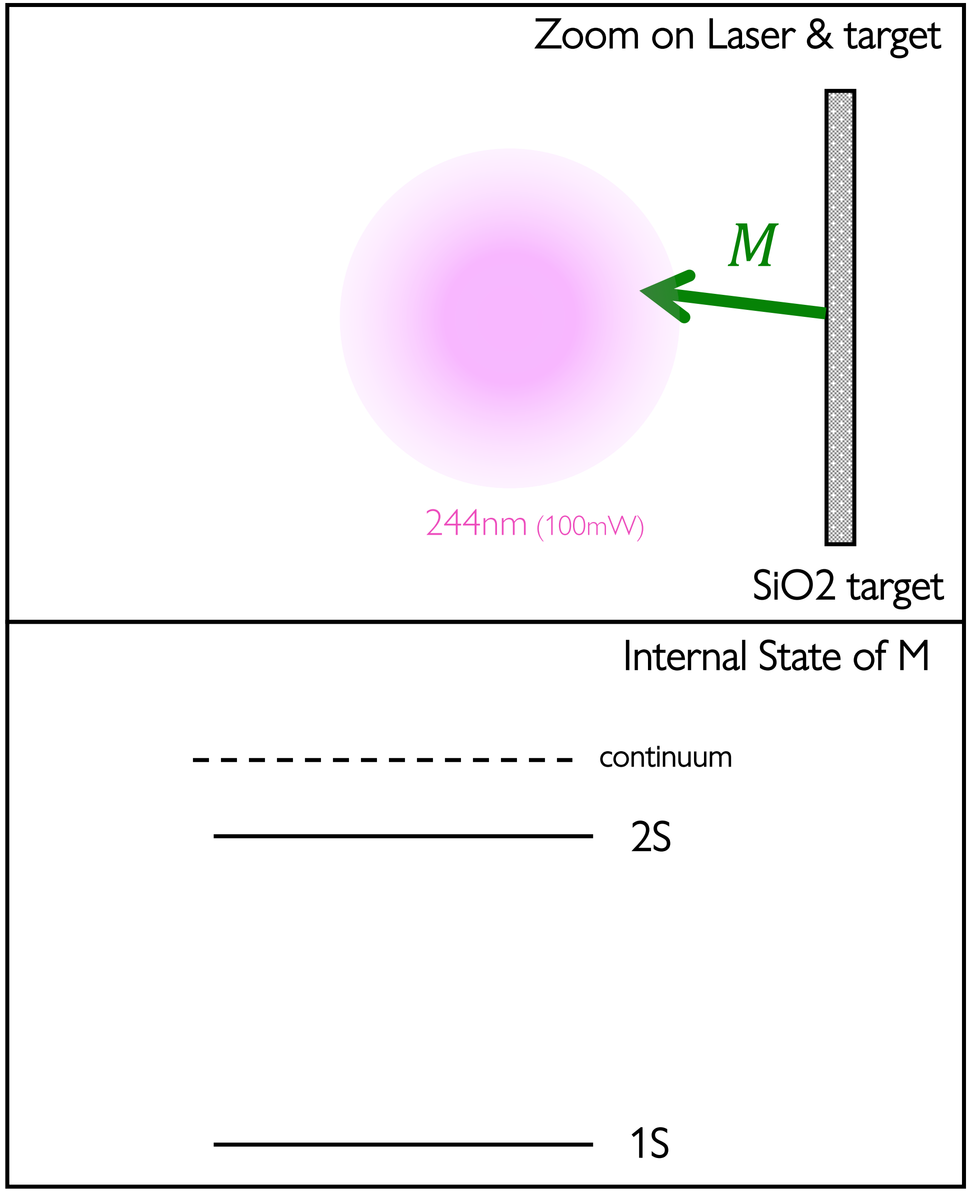
Mu-Mass experimental setup



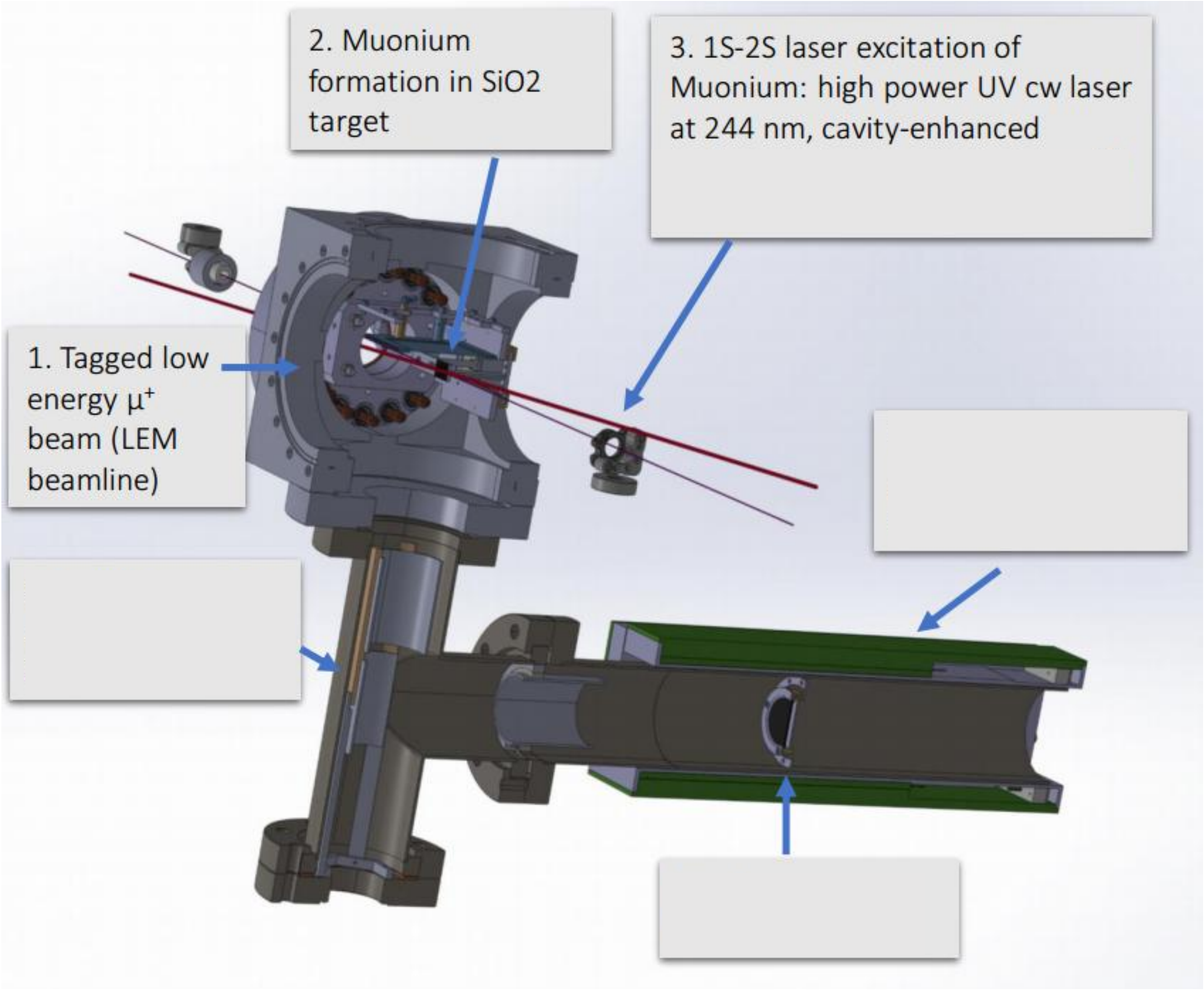


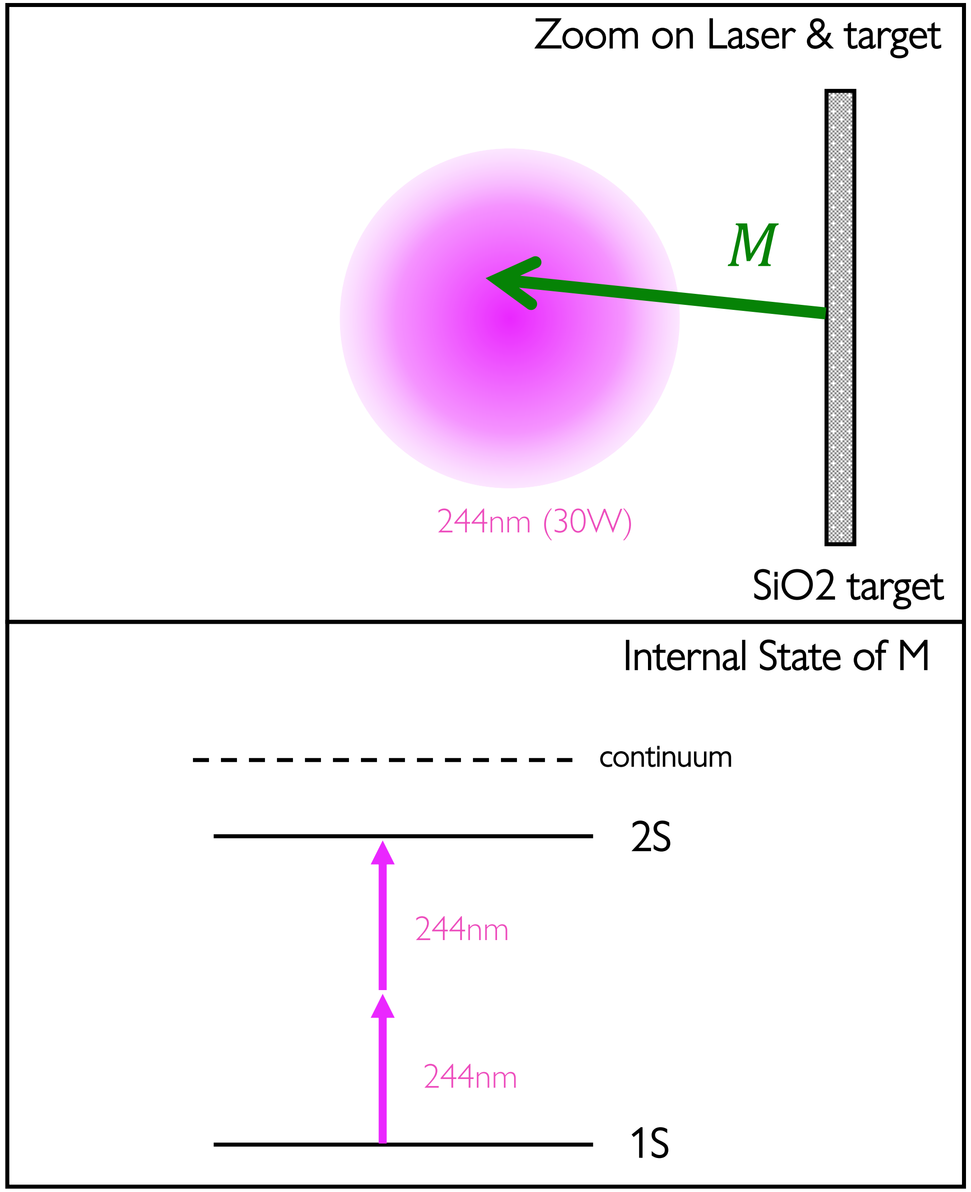
Mu-Mass experimental setup



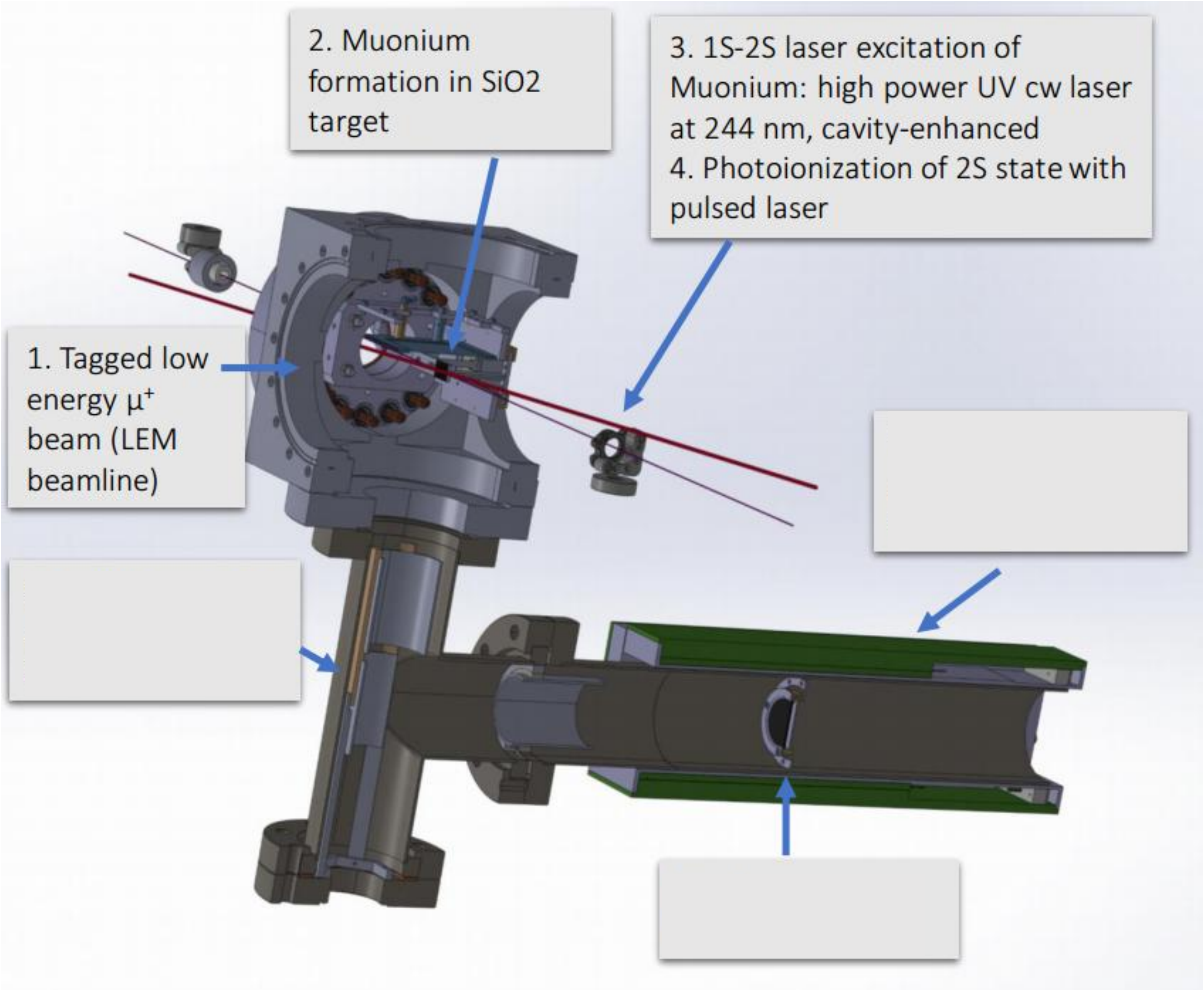


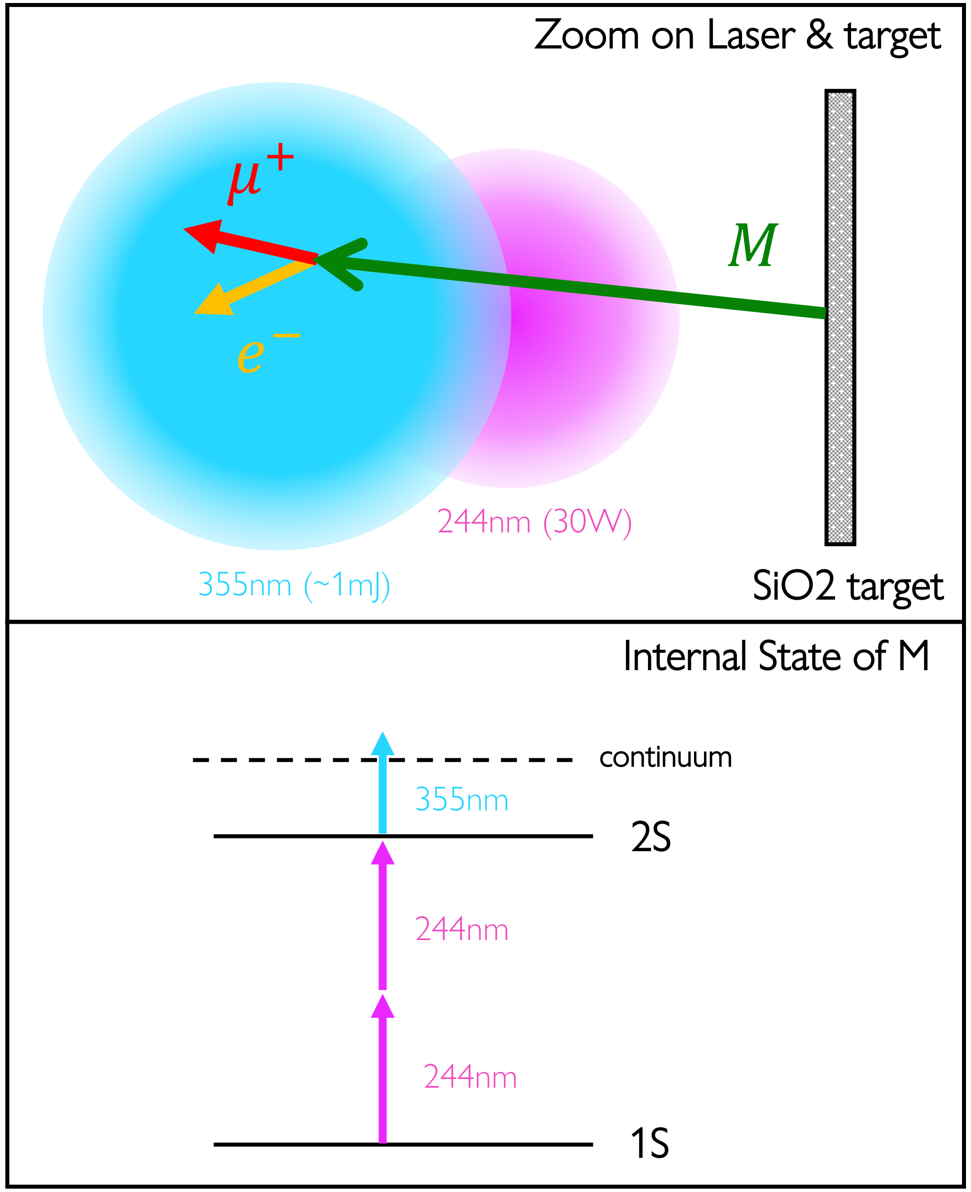
Mu-Mass experimental setup



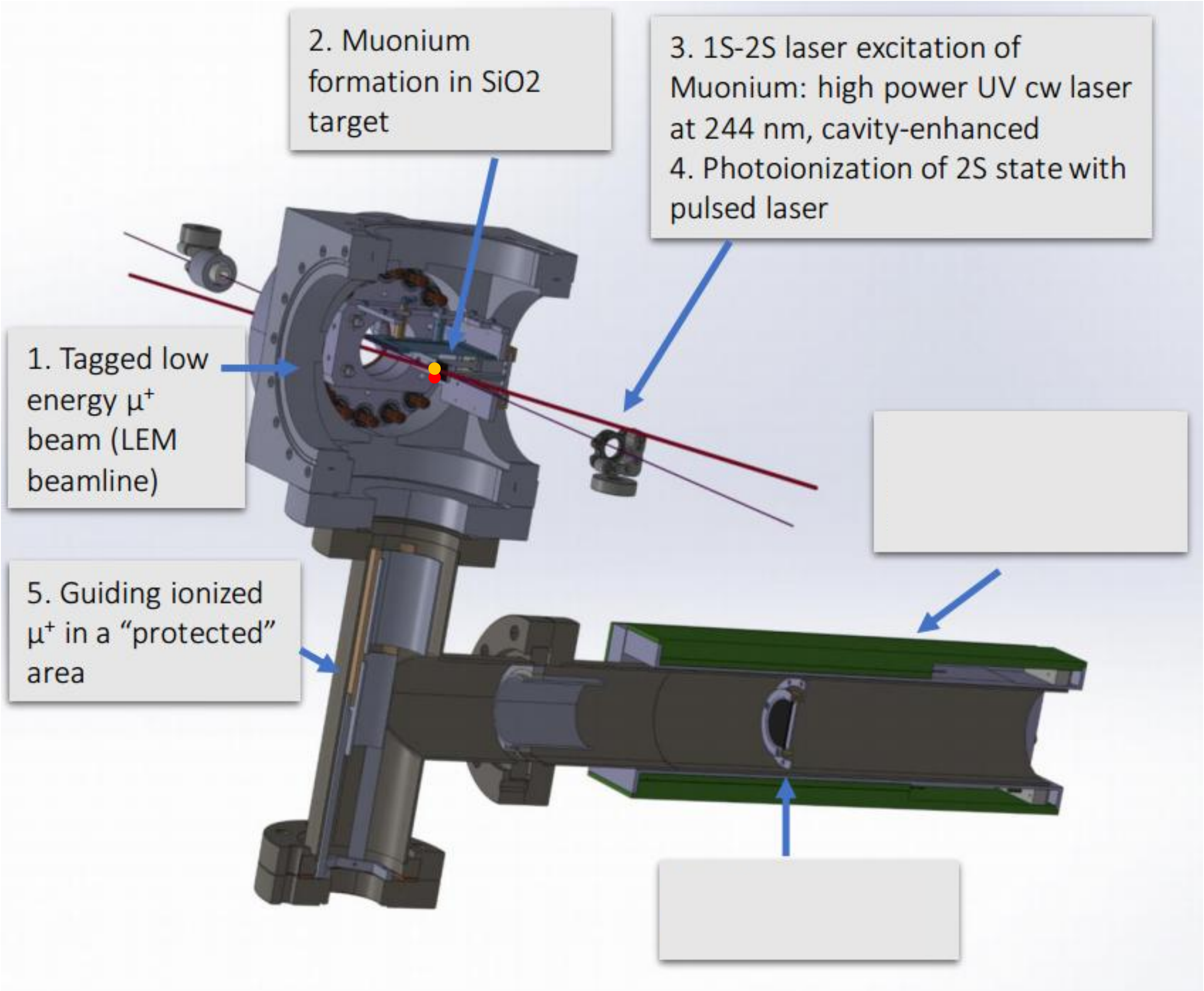


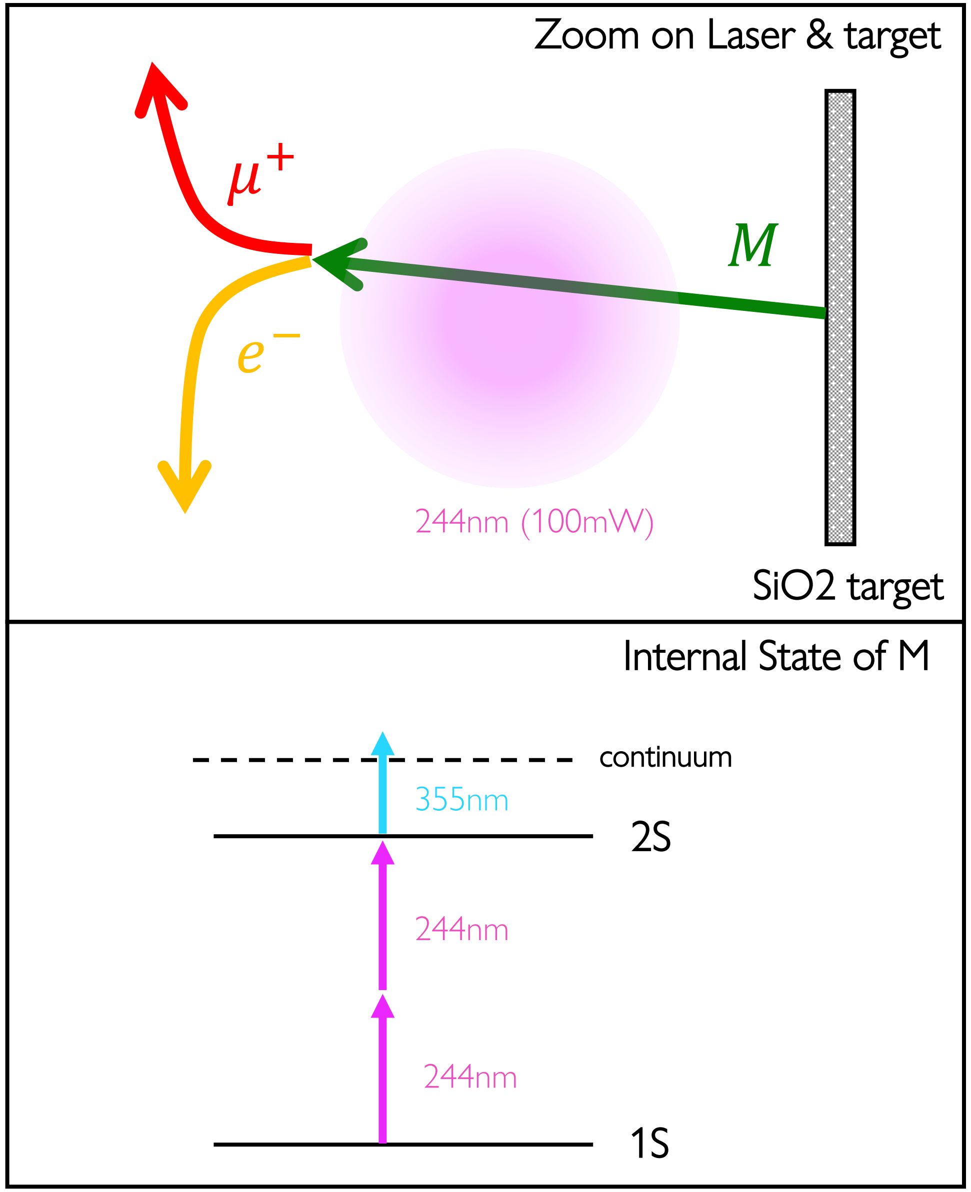
Mu-Mass experimental setup



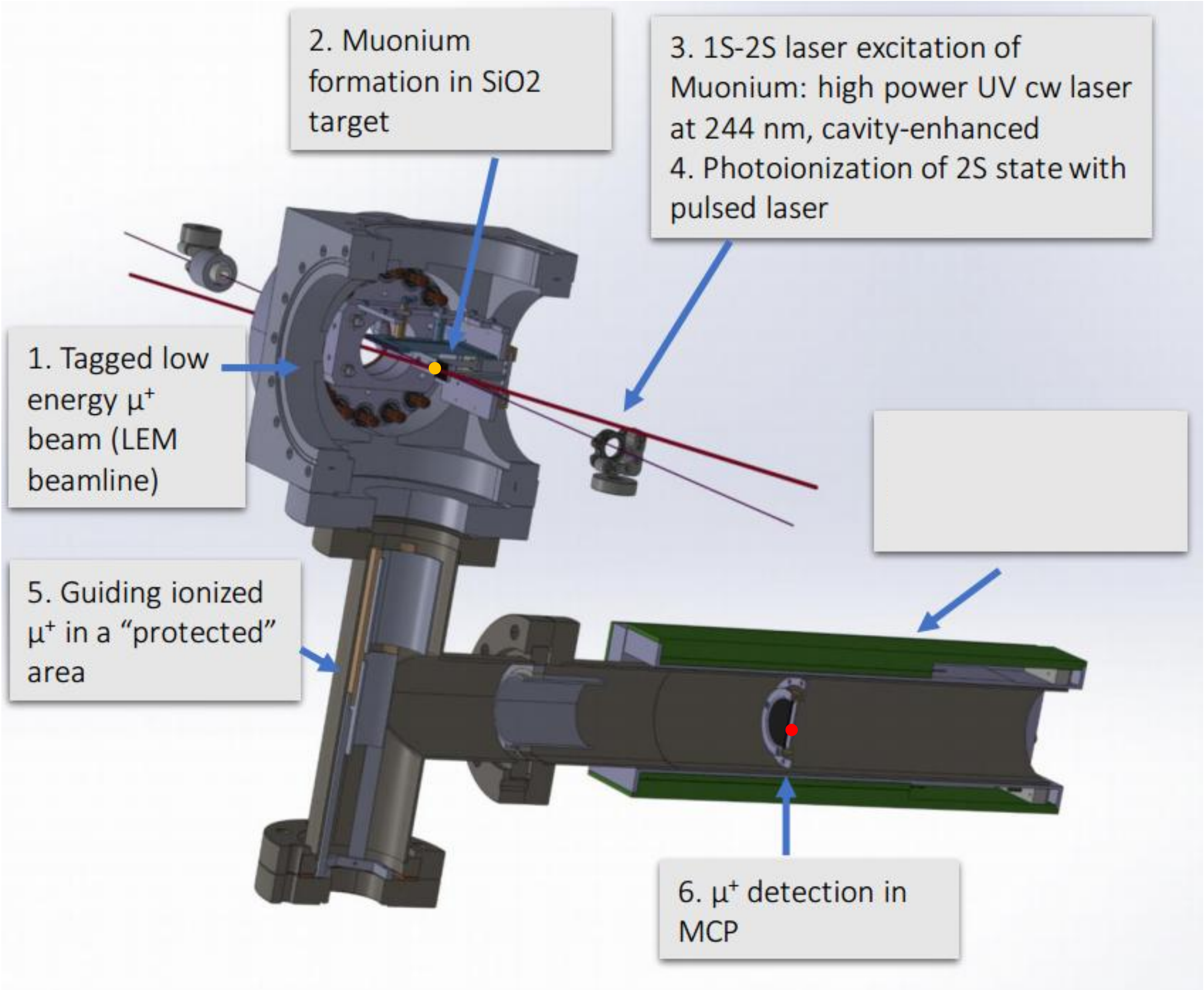


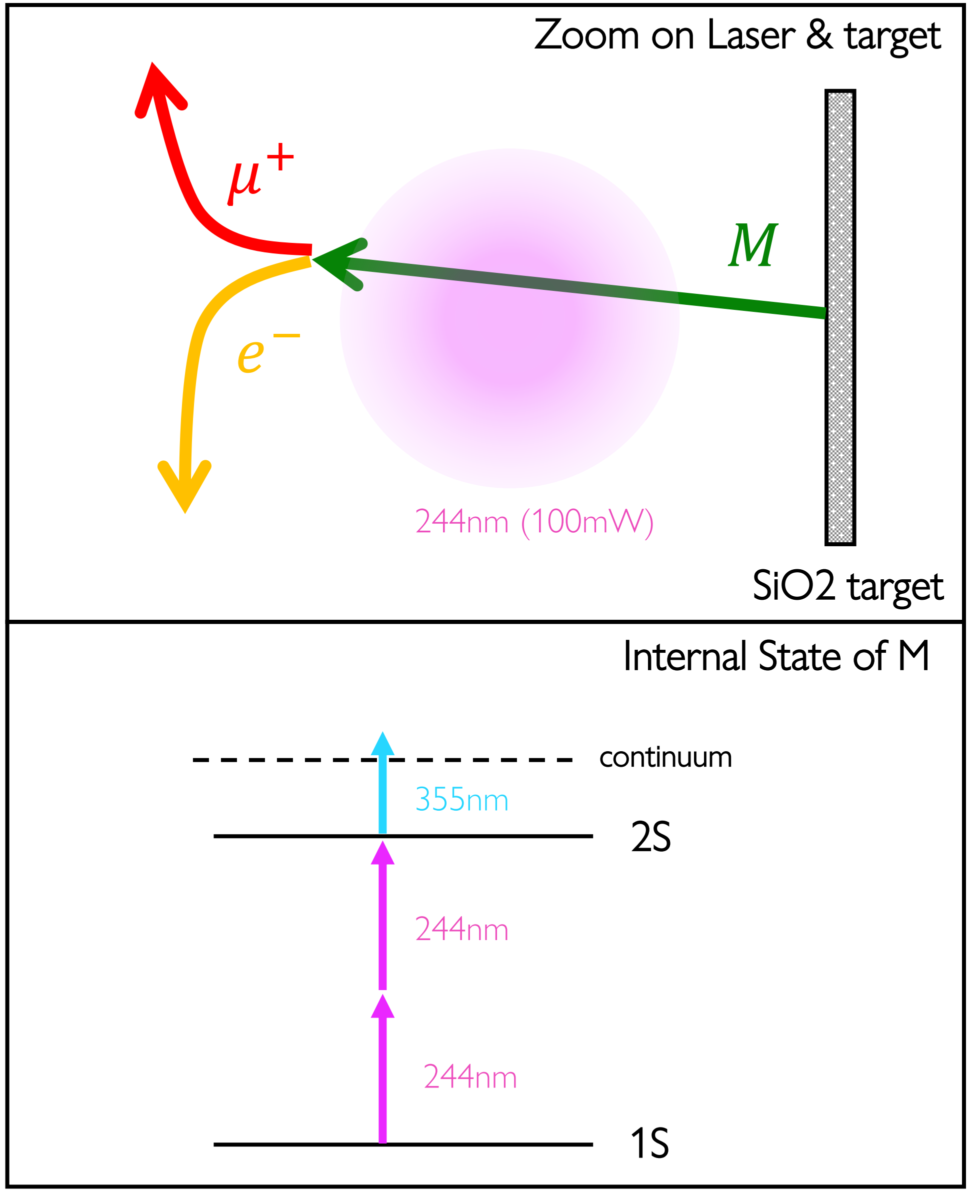
Mu-Mass experimental setup



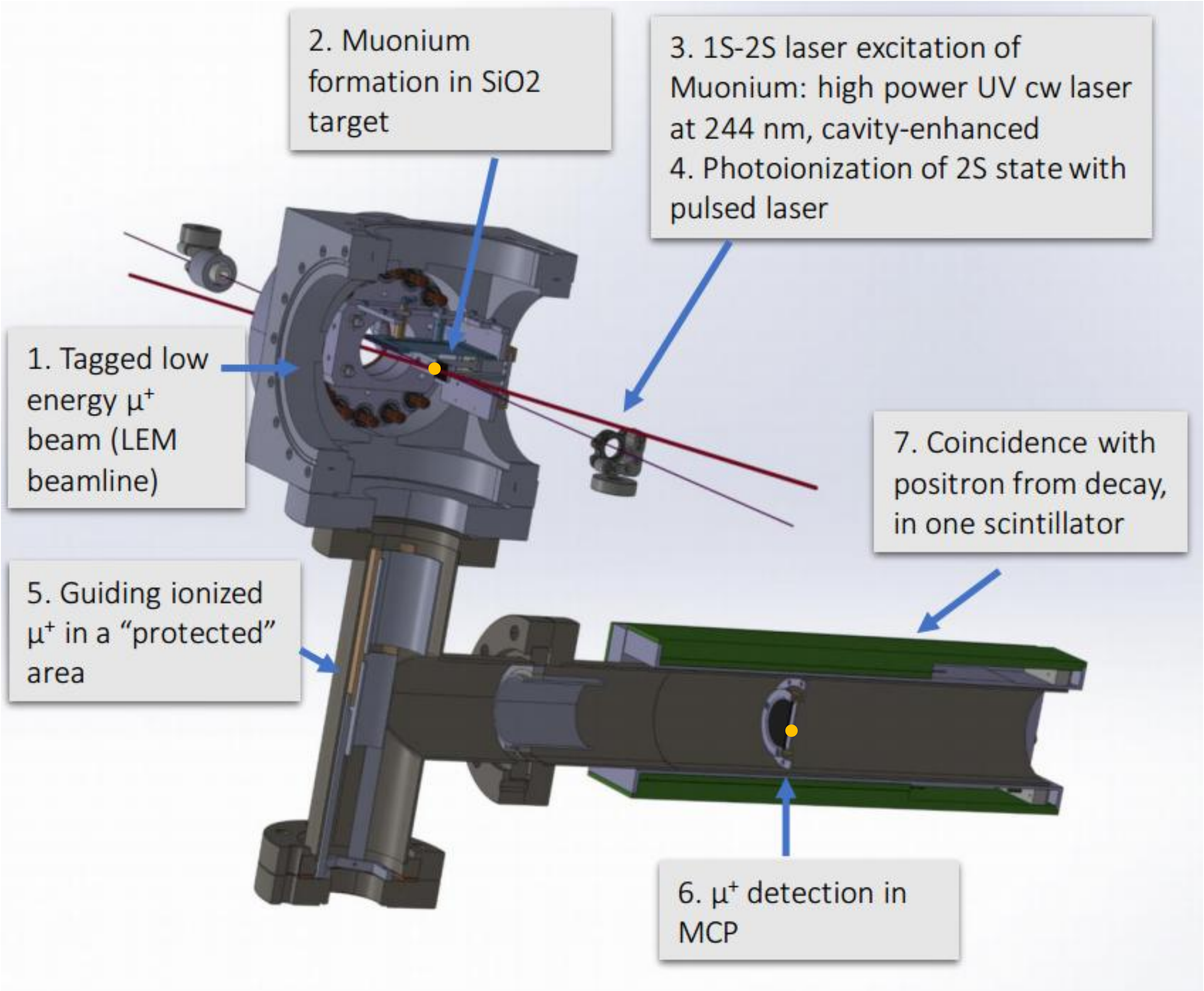


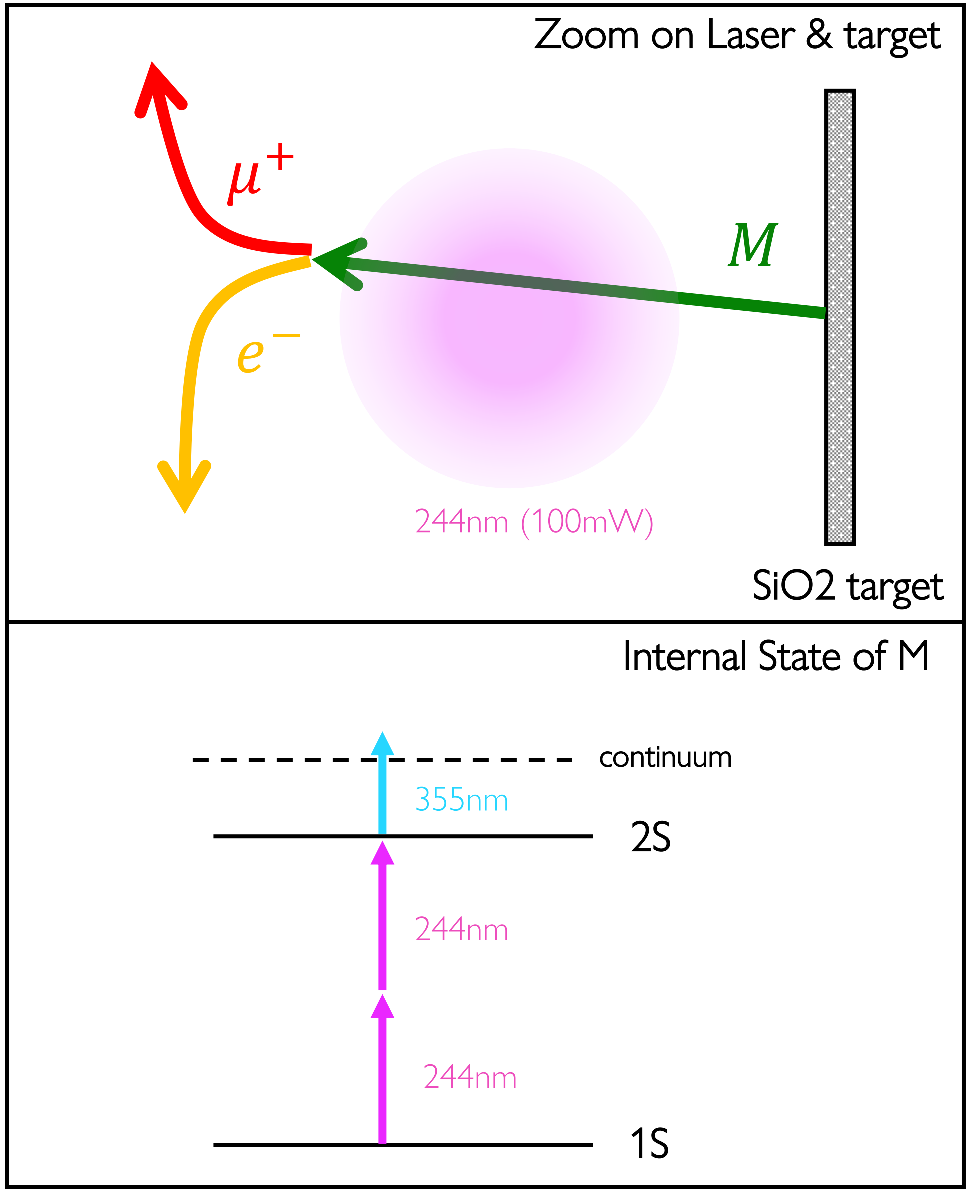
Mu-Mass experimental setup



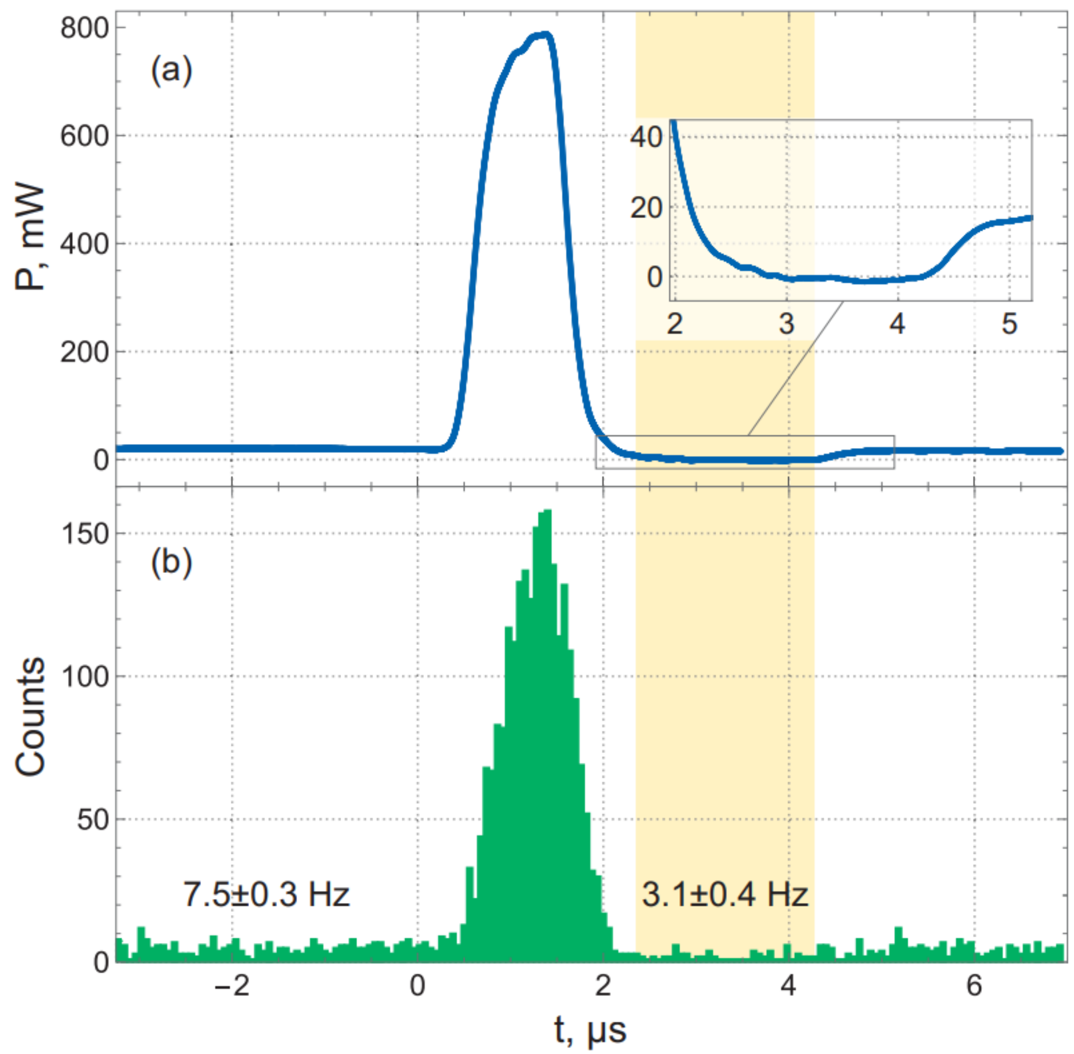


Mu-Mass experimental setup





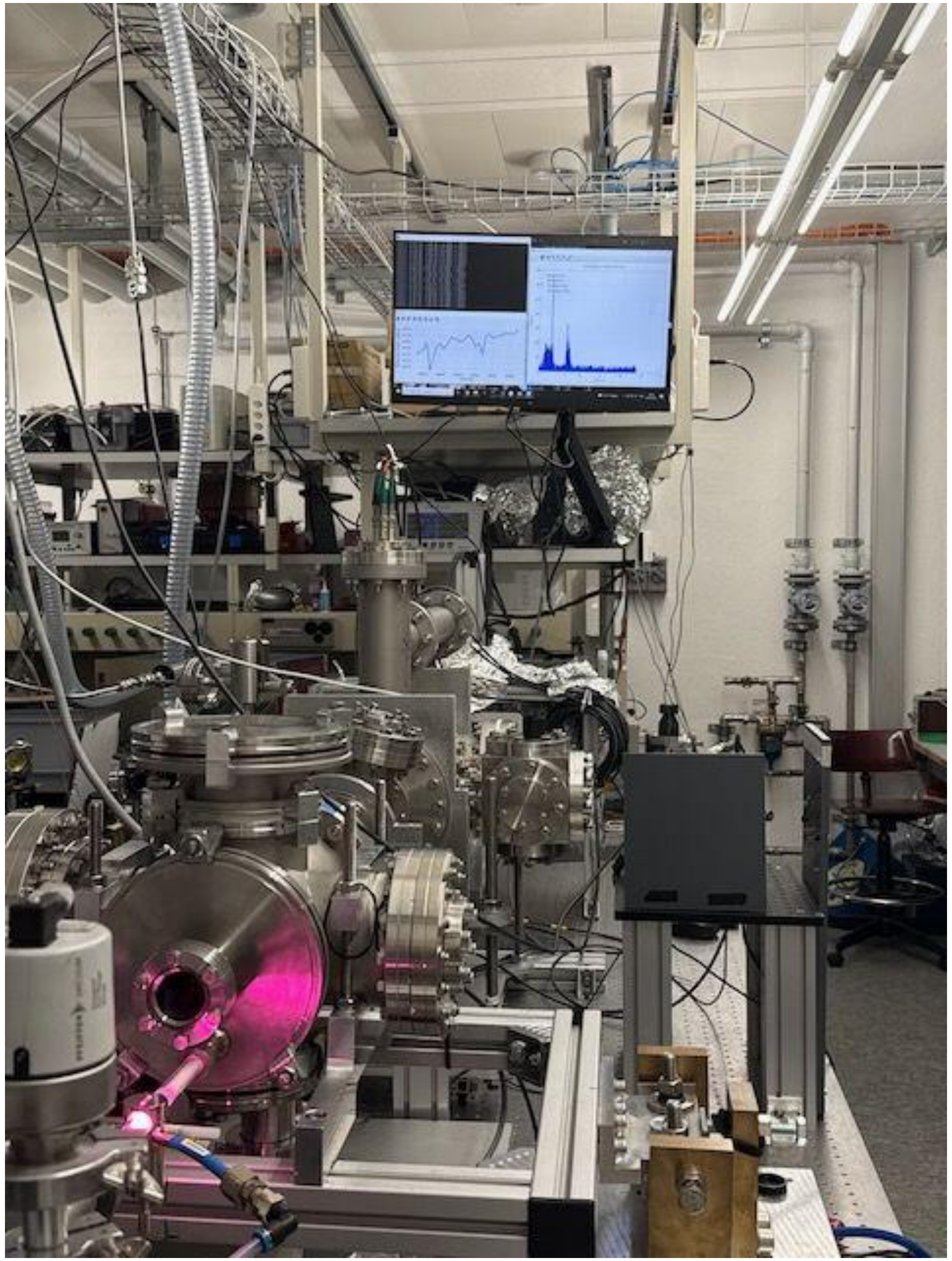
2022 campaign



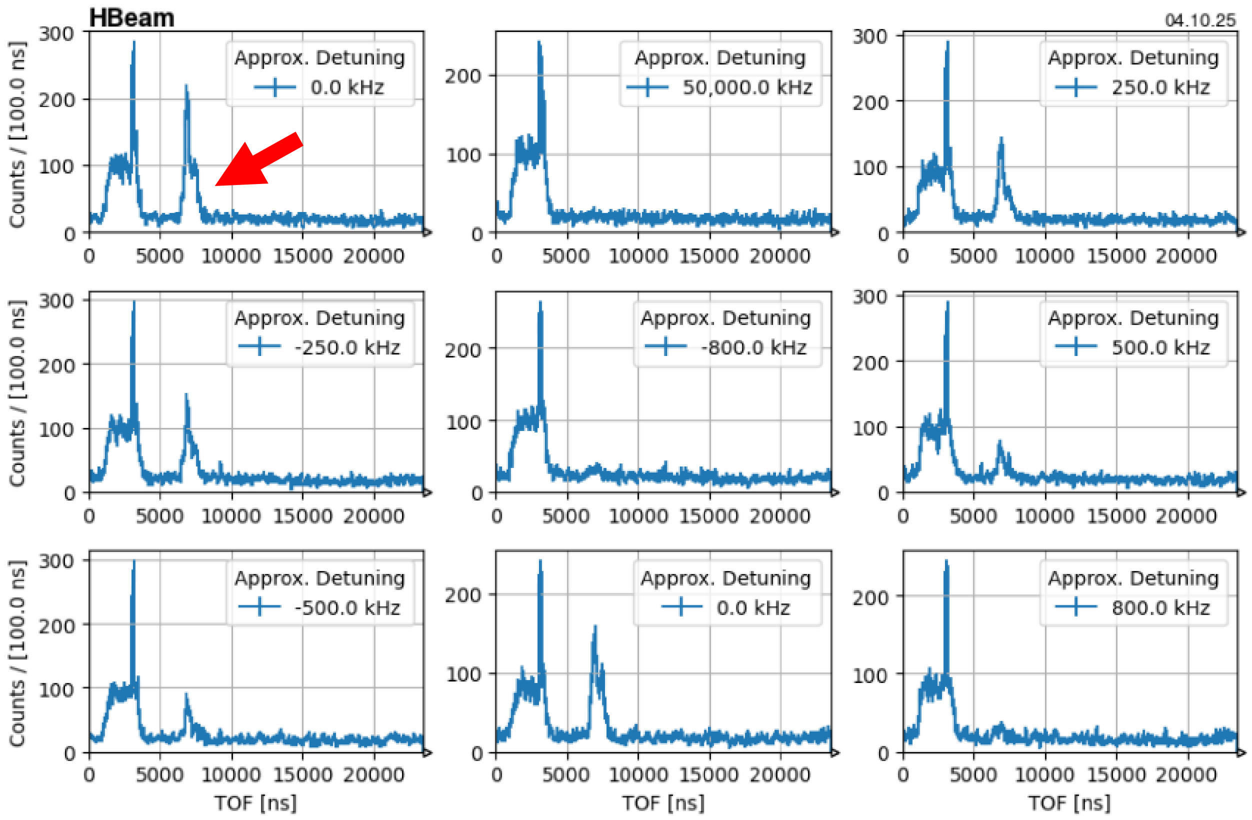
- 2022 campaign (5 days of muon beam) unfortunately did not see any signal
  - Reduction of factor 7 in flux due to laser interaction with muon trigger
  - Unexpectedly short muonium formation time lead to unoptimised timing
  - These problems have been addressed since
- Pulsing scheme allowed experiment to be operated continuously for 80 hours
- Detection scheme with pulsing reduced experimental background to < 1 background count per day)

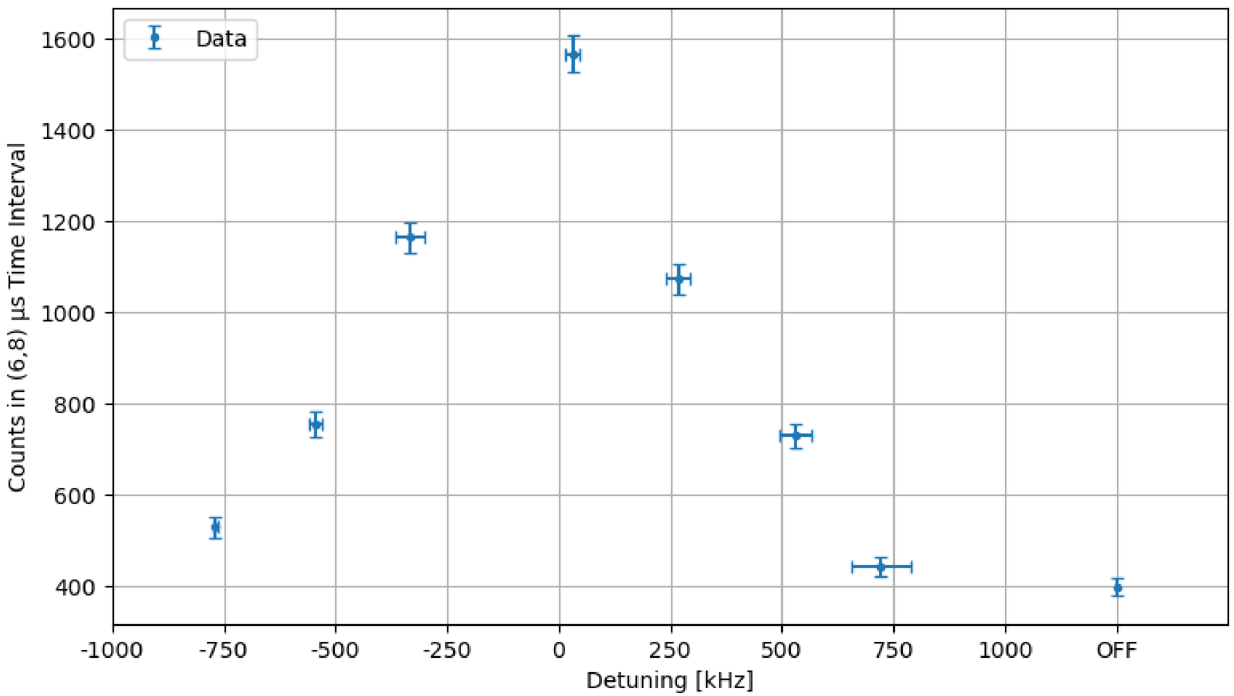
Commissioning with Hydrogen

- To optimize the experiment, we have been doing hydrogen 1S-2S spectroscopy
- Apparatus is identical
  - Lower laser power (No FA gain at 243nm)
  - No positron detection in scintillator
- $\sim 10^{16}$ **atoms/s** ; Spectrum in ~ 1 hour



Detection of Hydrogen 1S-2S

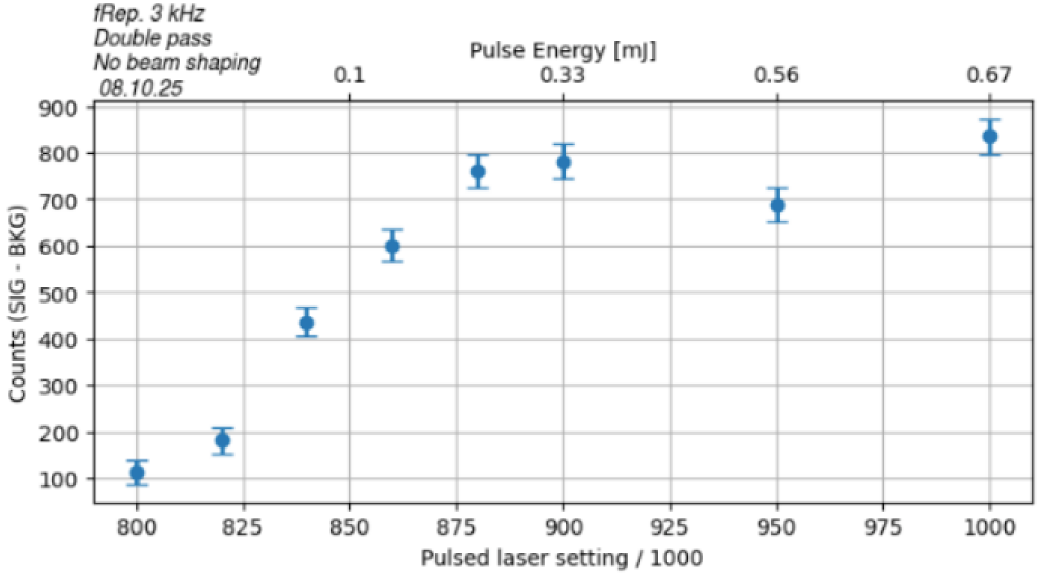


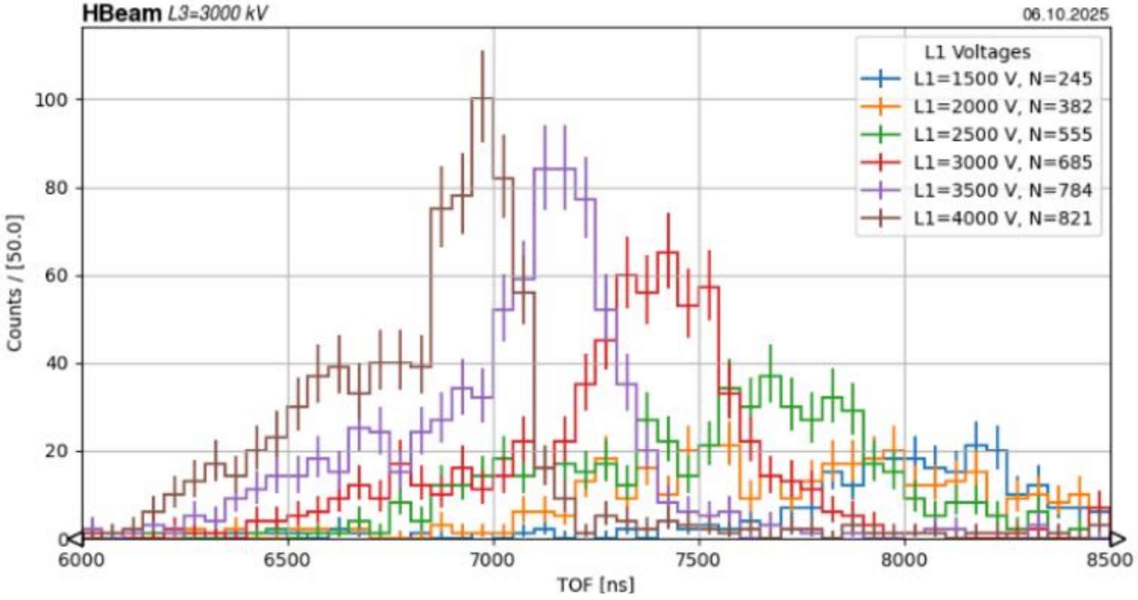


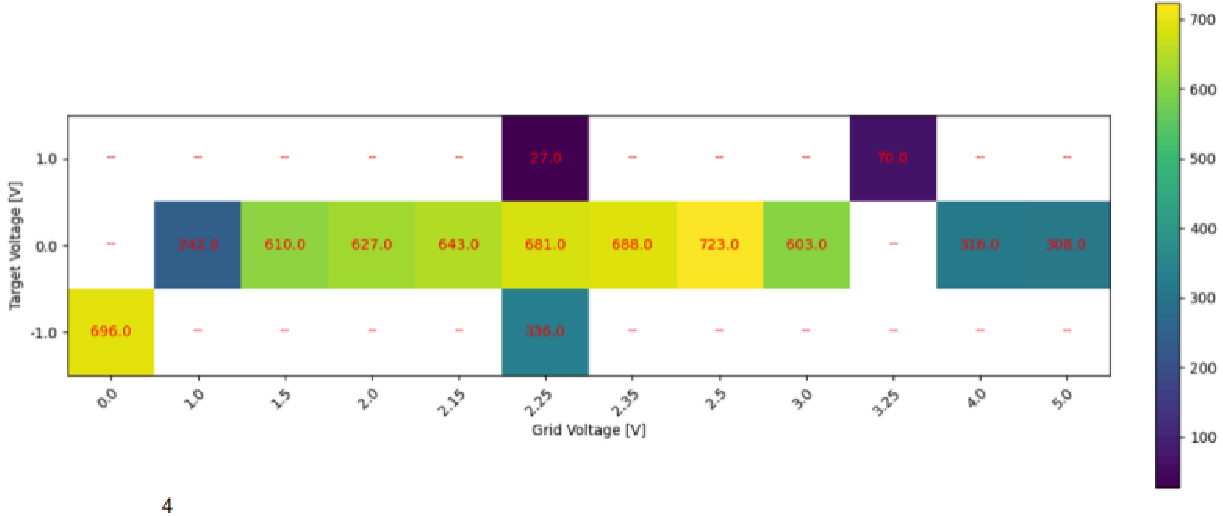
- We see distinctive second peak which indicates 1S-2S of hydrogen
- Can measure the 1S-2S spectrum of hydrogen

Use hydrogen to optimise Mu-MASS

1. Scan/Optimise experimental parameters
↓
2. Compare to Simion Simulations
↓
3. Select optimum parameters for muonium

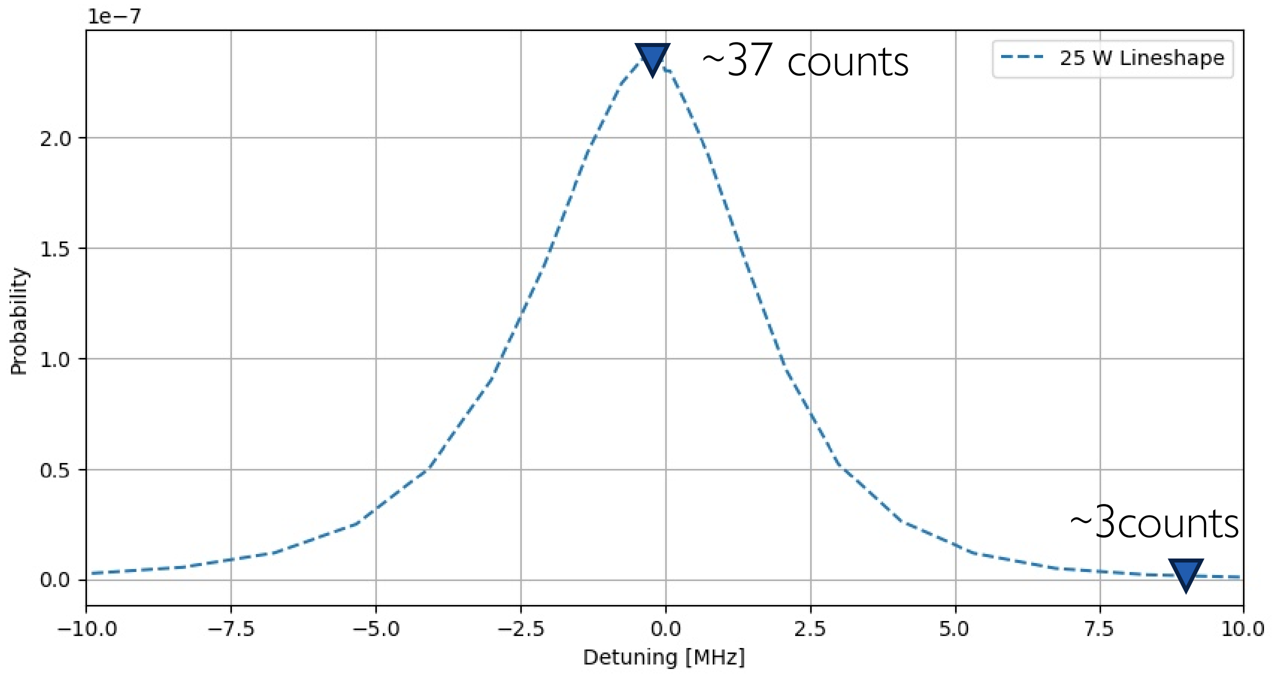






Beamtime Nov 2025

- We return in less than a month!
- Improvements since 2022:
  - More laser power
  - Faster laser pulsing
  - Active beam stablisation
  - Optimised setup via hydrogen



- We only have 7 days of beam + 3 of setup
  - We expect ~ 10 counts per day
  - Goal – observe on/off resonance comparision
  - Ask longer beamtime 2026
  - Long shutdown mid 2026

What next?

- Beamtime in November this year,
- Next year ect
- Improved muon rates: HIMB
- Better phase-space beams:
  - MuCOOL (muon beam phase-space compression)
  - SFHe sources (smaller initial M phase-space, Landau critical velocity: mono-energetic to the ~5% level)
- Alternative spectroscopic technique: Ramsey spectroscopy

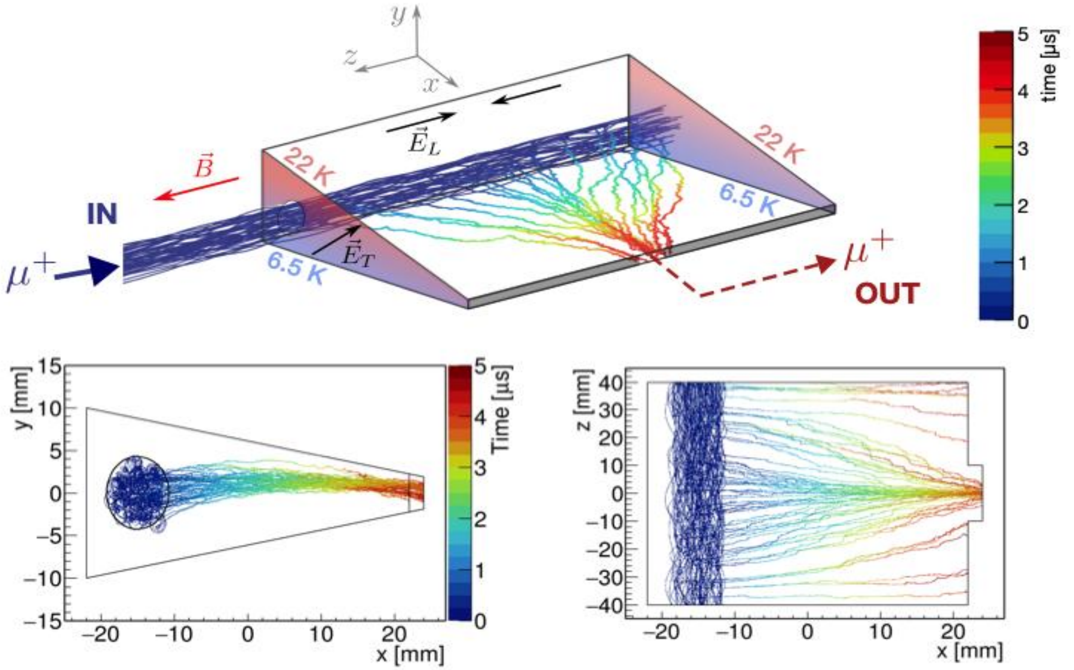
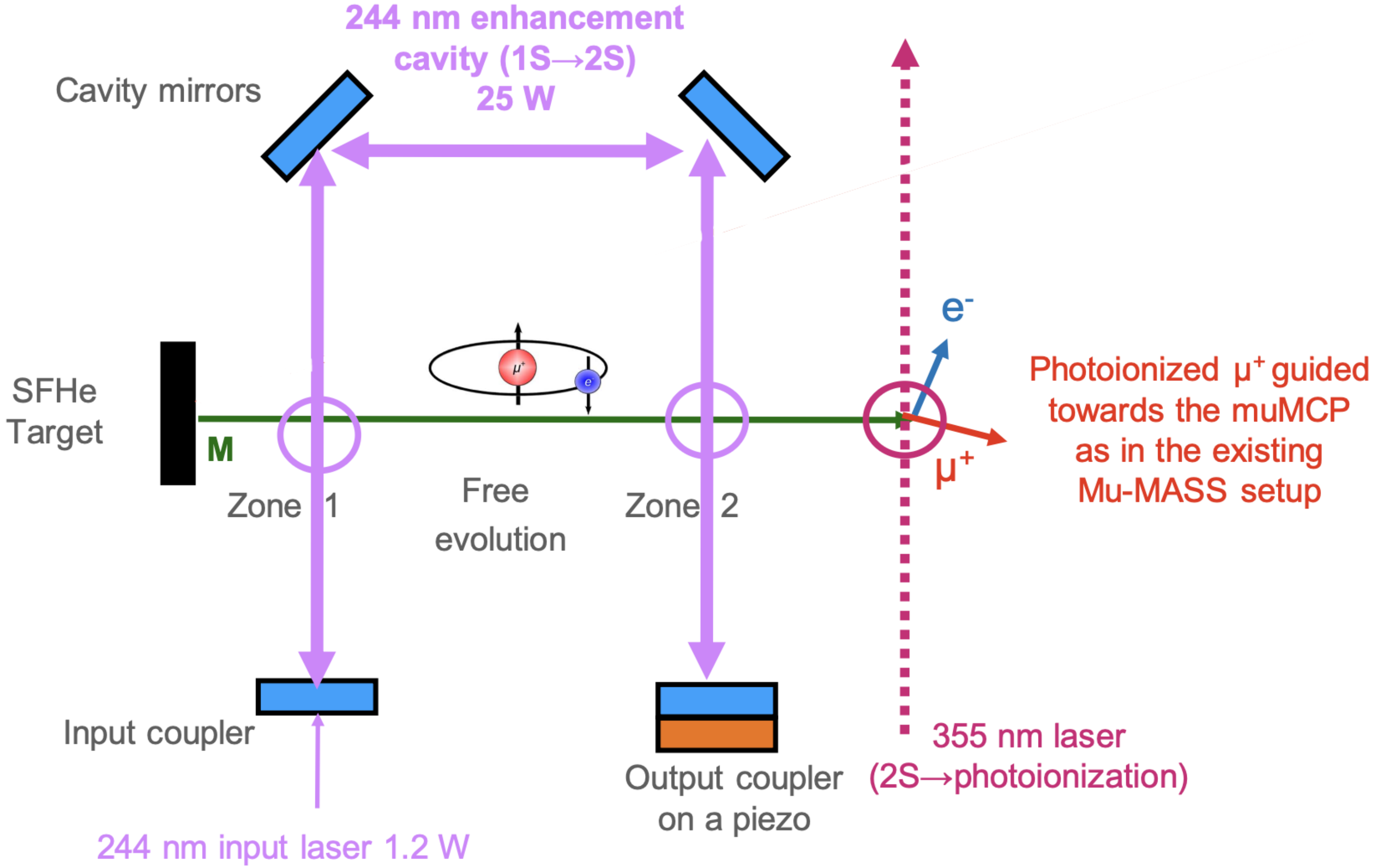


Fig 2 from "Phase space compression of a positive muon beam in two spatial dimensions", Antognini et al. 2024

A. Soter, A. Knecht SciPost Phys. Proc. 5, 031 (2021)
A. Soter, Physics of fundamental Symmetries and Interactions (2025)

SFHe Targets & Ramsey Spectroscopy of M

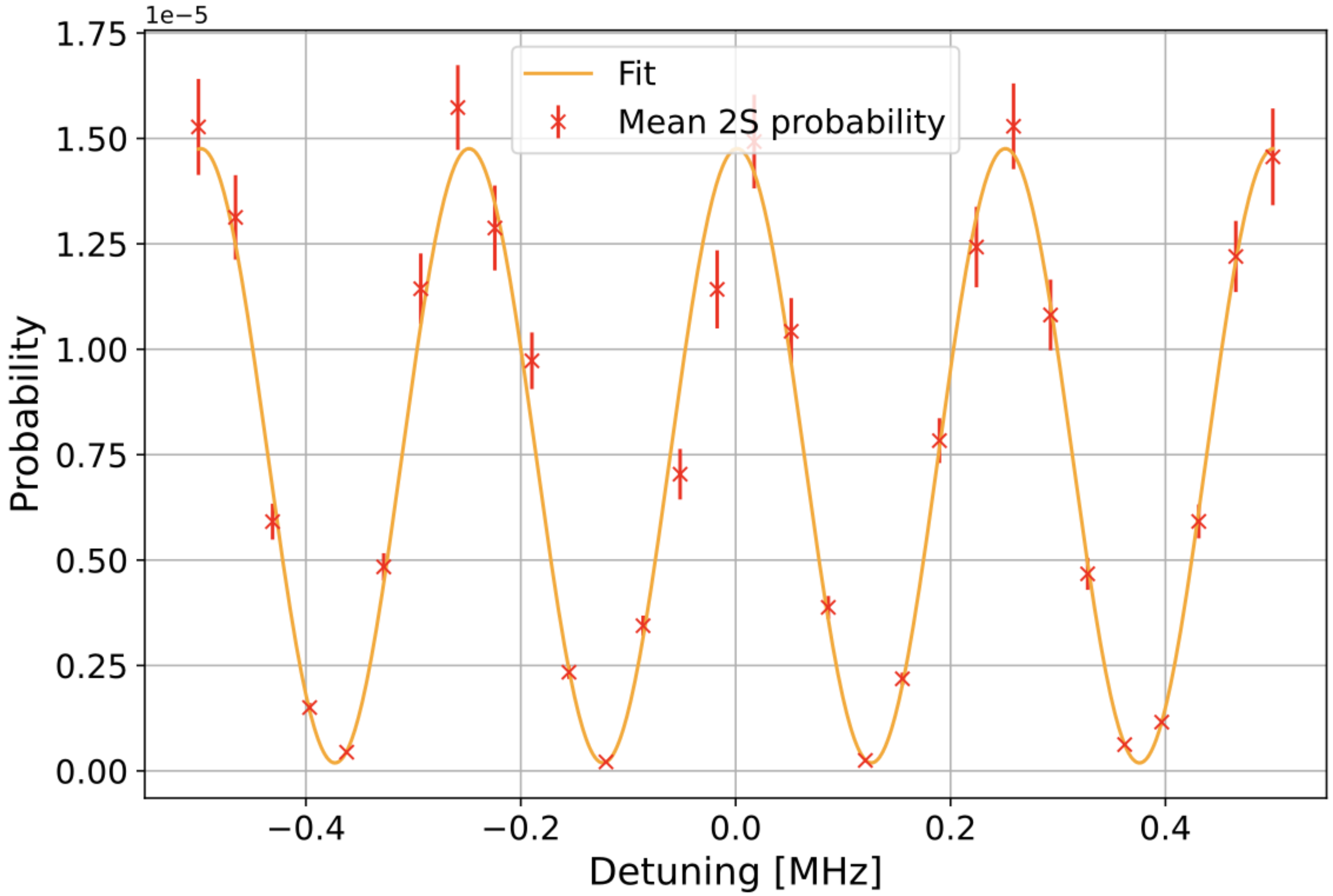
- Two interaction regions separated by longer free evolution
- Has been done with hydrogen
- For classical Ramsey, mono-energetic atoms, requires SFHe



Javary, E., Thorpe-Woods, E., Cortinovis, Mähring, M., de Sousa Borges, L., Crivelli, P. Eur. Phys. J. D 79, 15 (2025)
A. Huber, B. Gross, M. Weitz, and T. W. Hänsch, Phys. Rev. A 58 (1998)
Soter, A. Physics of fundamental Symmetries and Interactions (2025)

Simulated Ramsey Spectroscopy of M

- Monte Carlo simulation using expected parameters
- Result: Ramsey fringes with ~120kHz linewidths
- ~1kHz statistical uncertainty in 10 days of measurements
- Reduced AC Stark (Ramsey)
- Reduced 2nd Doppler (SFHe)



Javary, E., Thorpe-Woods, E., Cortinovis, Mähring, M., de Sousa Borges, L., Crivelli, P. Eur. Phys. J. D 79, 15 (2025)

Summary & conclusion

- Spectroscopy of M provides an independent route to measuring alpha
- Currently: multiple orders of magnitude less precise atom-interformetry
  - Limited by muon-electron mass ratio - improved in future by Mu-MASS
- Future spectroscopy results could determine alpha at a similar level
- We are currently commissioning Mu-MASS with hydrogen
- Planned Mu-MASS beamtime for this November – on/off resonance
  - Spectrum planned for future beamtime
- Following HIMB upgrades, Ramsey methods can 1S-2S spectroscopy precision even further





Thank you for listening!

European Research Council
Established by the European Commission

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Swiss National Science Foundation

Extra Slides