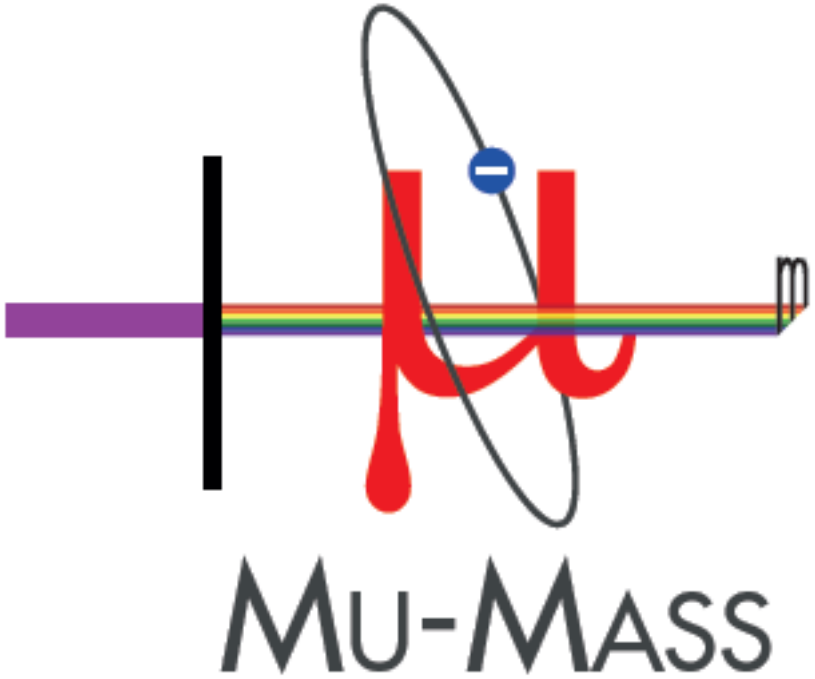


Mu-MASS (MuoniuM lAser SpectroScopy)

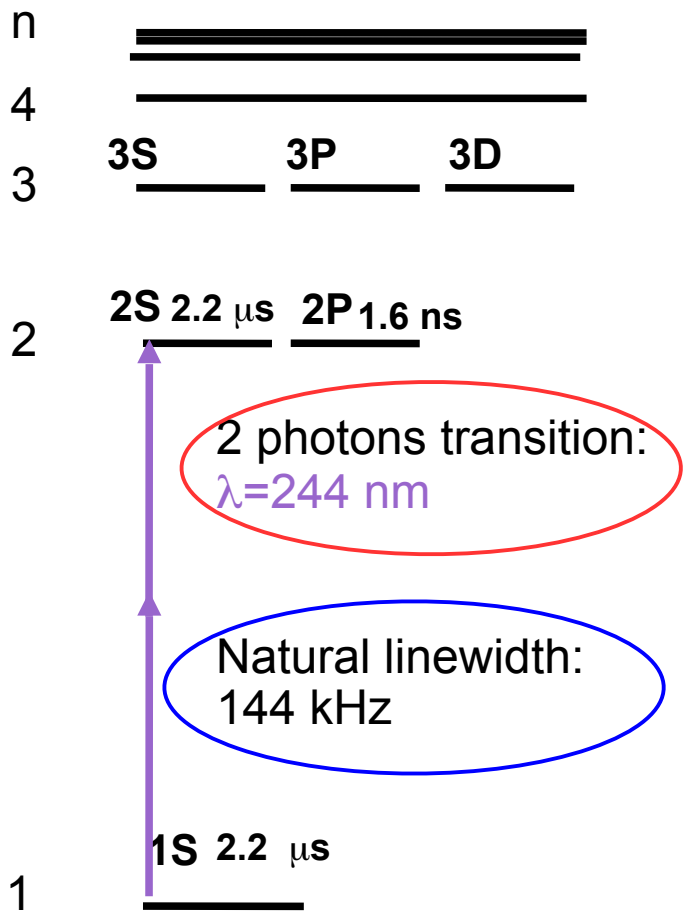
P. Crivelli, L. Gerchow, A. Golovizin, M. Heiss, G. Janka
ETH Zurich, Institute for Particle Physics and Astrophysics (IPA), 8093 Zurich, Switzerland
A. Amato, T. Prokscha, Z. Salman, A. Suter
PSI, Laboratory for Muon Spin Spectroscopy (LMU), 5232 Villigen, Switzerland
A. Antognini, K. Kirch
PSI, Laboratory for Particle Physics (LTP), 5232 Villigen, Switzerland and
ETH Zurich, Institute for Particle Physics and Astrophysics (IPA), 8093 Zurich, Switzerland
A. Knecht, A. Soter
PSI, Laboratory for Particle Physics (LTP), 5232 Villigen, Switzerland
Z. Burkley, D. Yost
Colorado State University (CSU), Colorado, USA

R-19-01.1 - MuoniuM lAser SpectroScopy (Mu-MASS)

BV50 User meeeting - 29th of January 2019

Paolo Crivelli, ETH Zurich, Institute for Particle Physics and Astrophysics, 8093 Zurich (Switzerland)

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 20 kHz

S. G. Karshenboim, Phys. Rep. 422, 1 (2005)

Reduced mass contribution:1.187 THz (4800 ppm)

$$m_{\mu^+}/m_{e^-} = 206.76838(17)$$

Byproduct: $q_{\mu^+}/q_{e^-} = -1 - 1.1(2.1) \times 10^{-9}$

MU-MASS

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

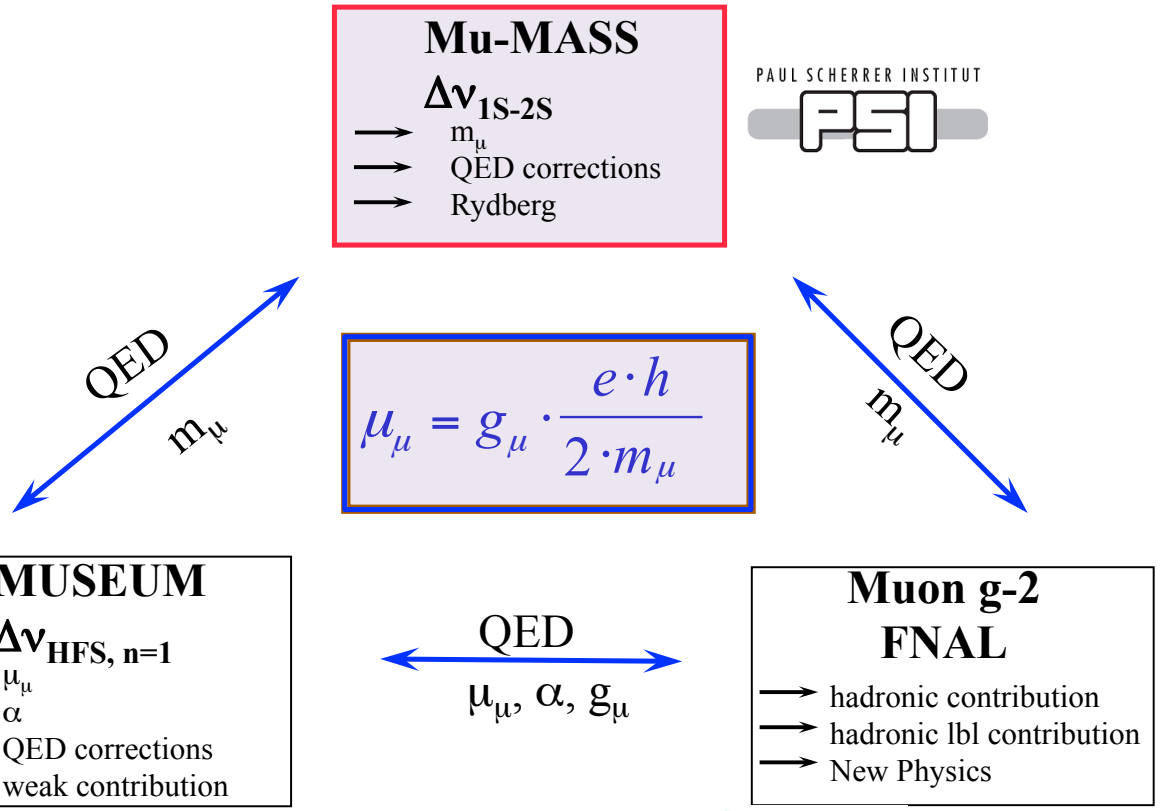
Mu-Mass

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})**
→ **Rydberg constant @ ppt level**
→ New determination of α @ 1 ppm
→ Input to muon g-2



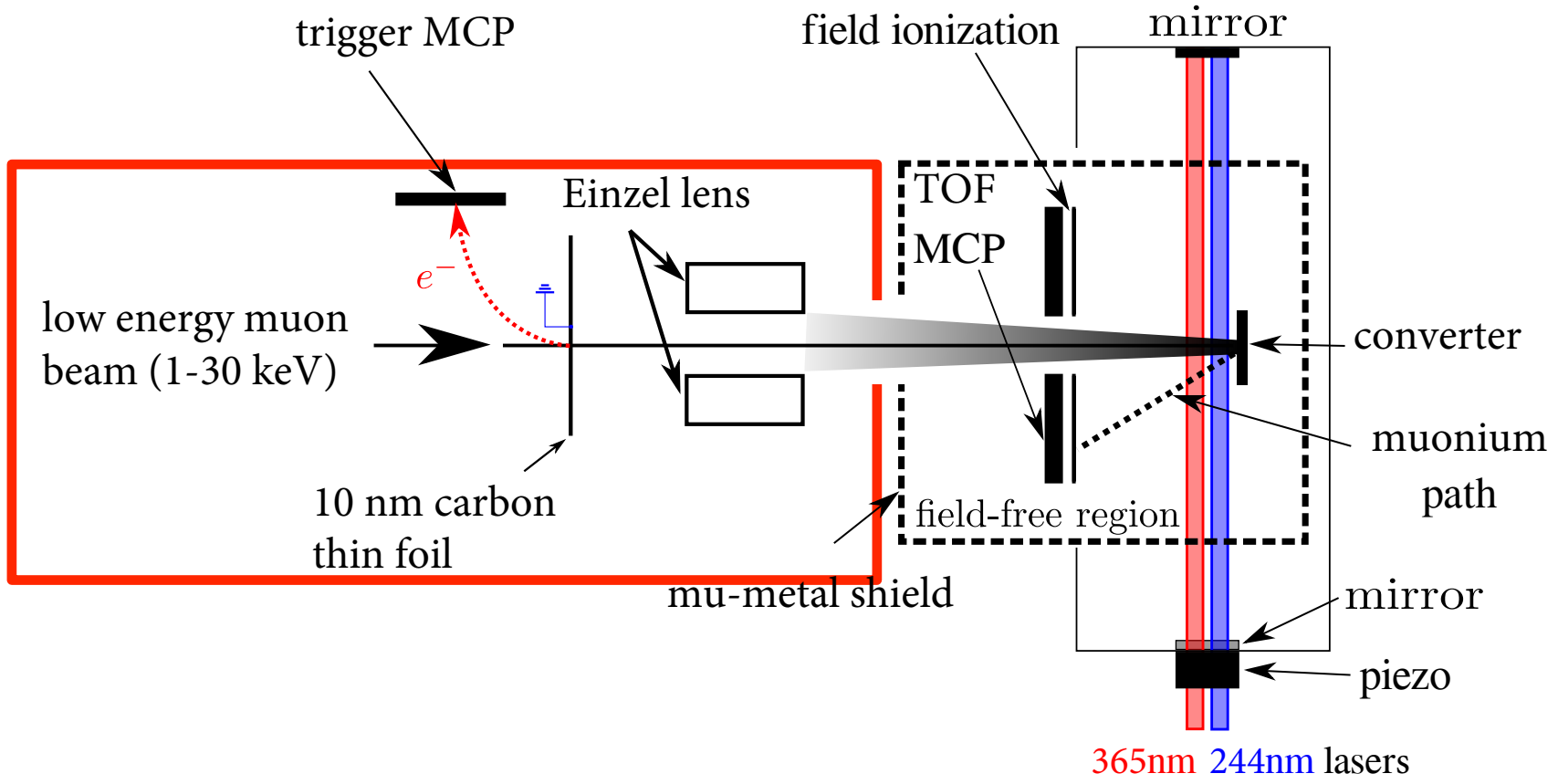
Mu-Mass

Adapted from K. Jungmann, DPG 2017 (Mainz)

J-PARC J-PARC Fermilab

Mu-MASS: methodology

Low energy μ^+ beam

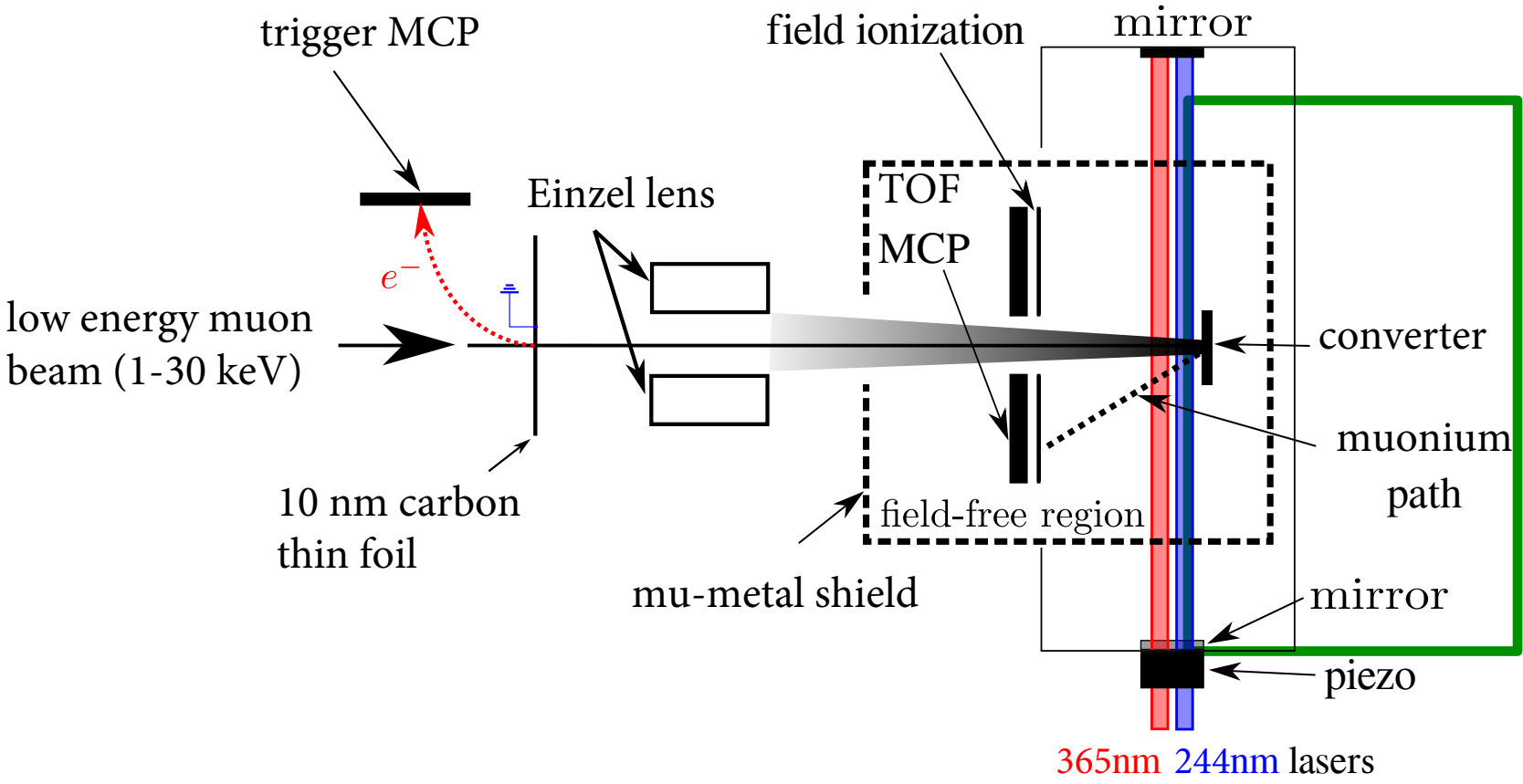


Mu-MASS: methodology

Low energy μ^+ beam

↓

Muonium production



Mu-MASS: methodology

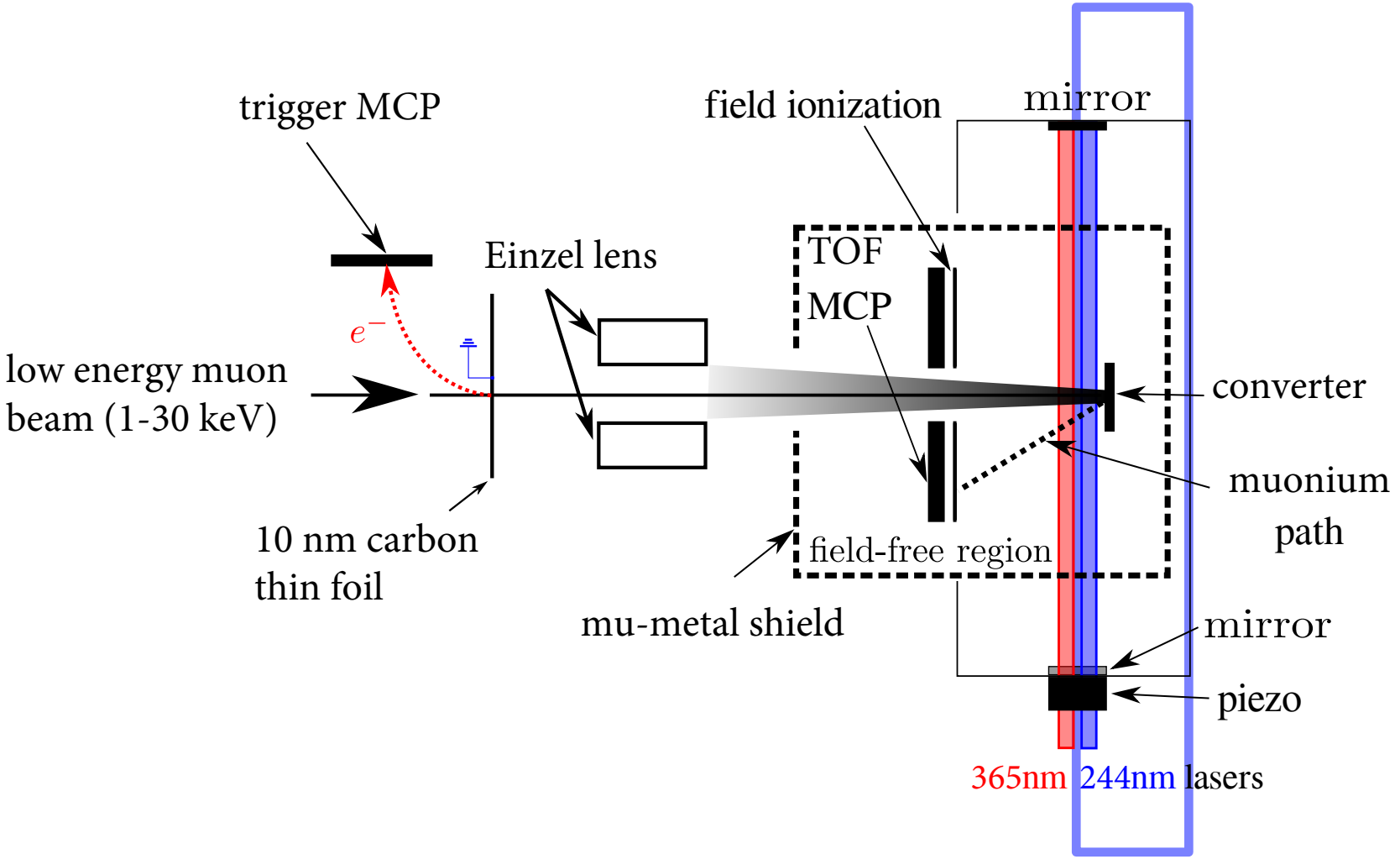
Low energy μ^+ beam

↓

Muonium production

↓

Muonium 2S excitation



Mu-Mass

Mu-MASS: methodology

Low energy μ^+ beam

↓

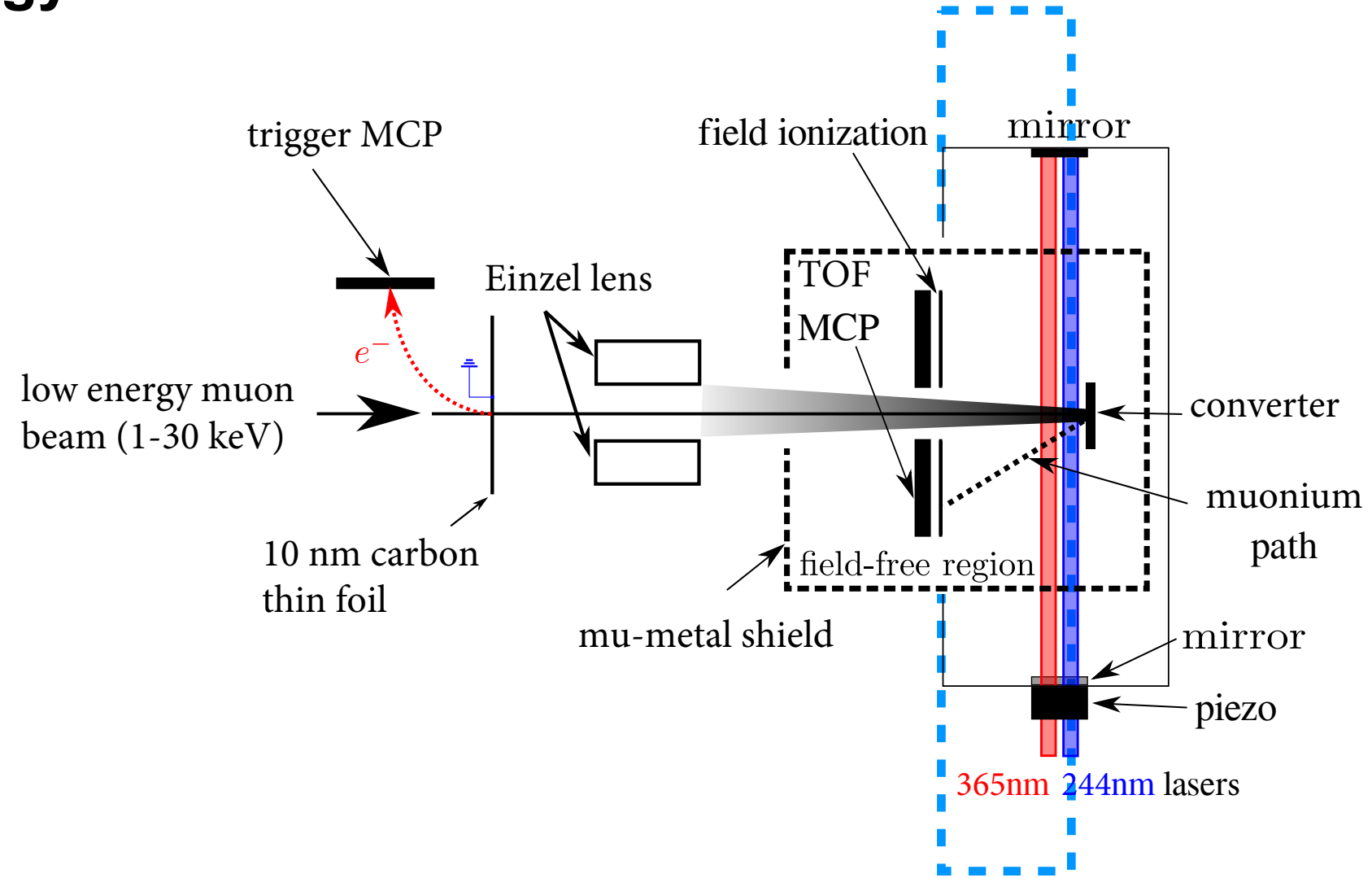
Muonium production

↓

Muonium 2S excitation

↓

Muonium 20P excitation



Mu-Mass

Mu-MASS: methodology

Low energy μ^+ beam

↓

Muonium production

↓

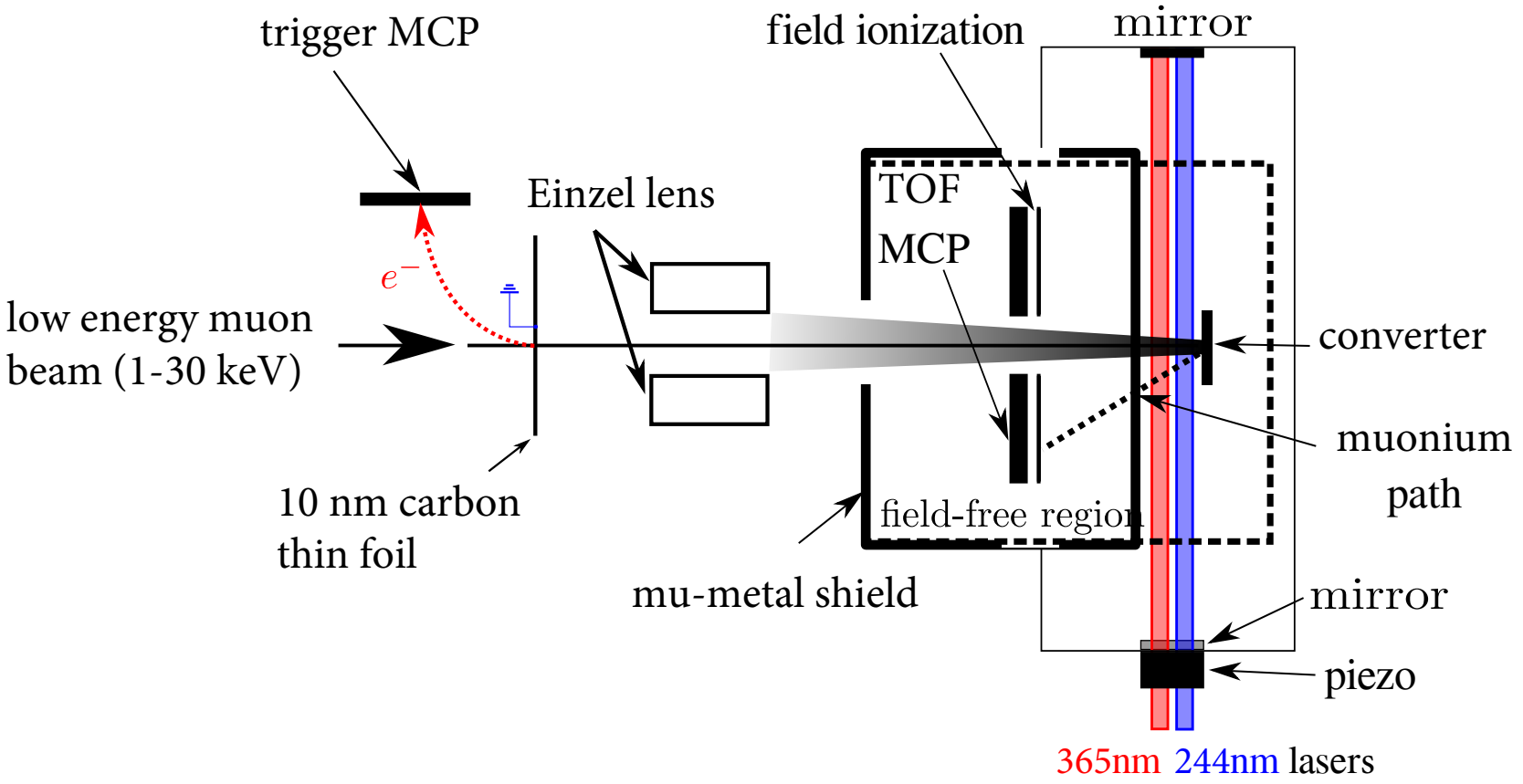
Muonium 2S excitation

↓

Muonium 20P excitation

↓

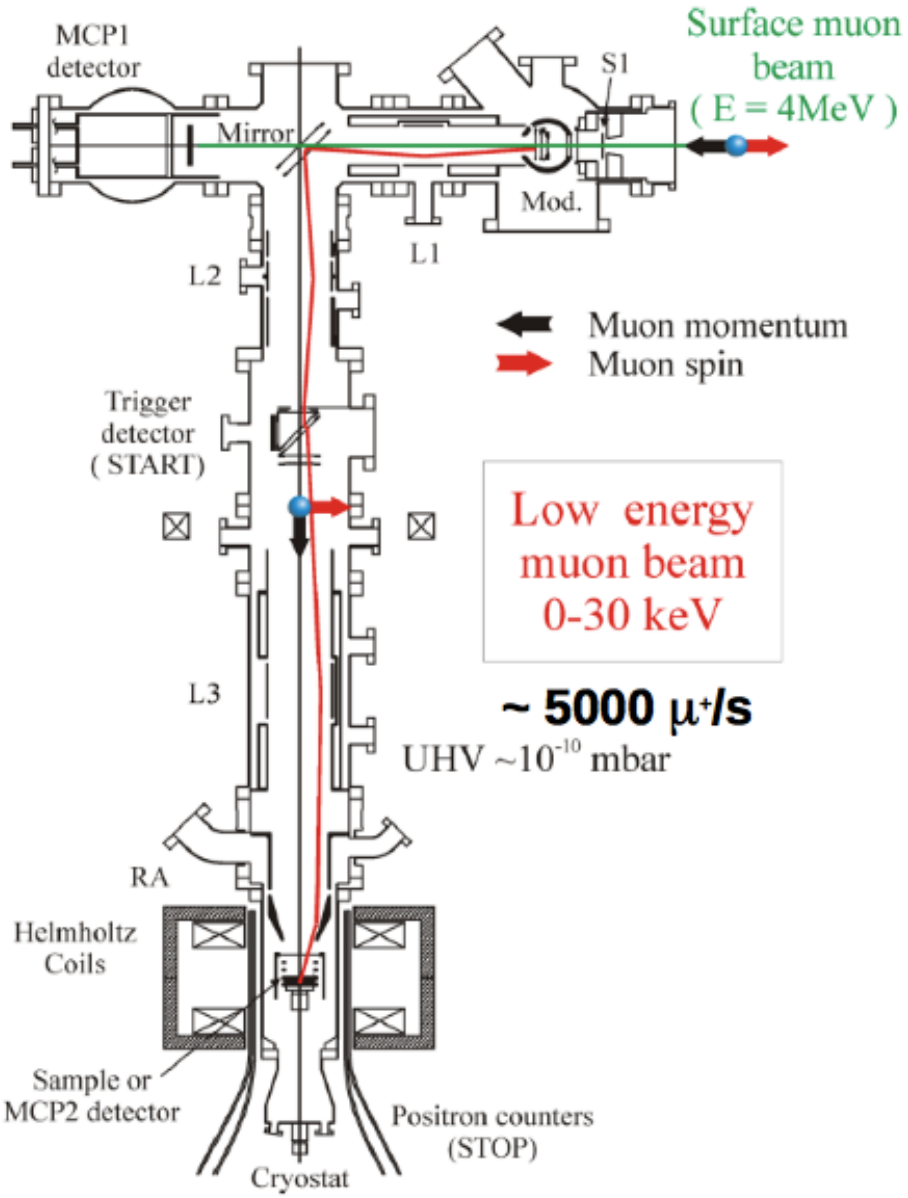
Muonium field ionisation
μ^+ detection



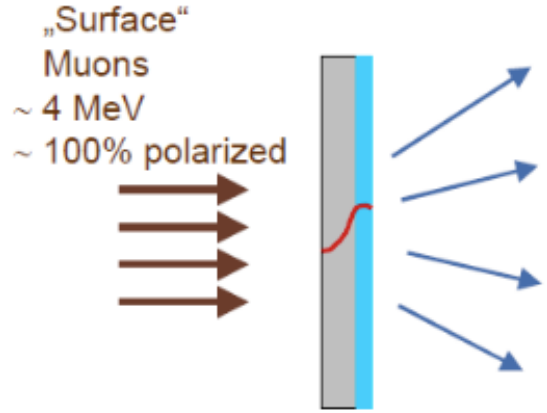
Mu-Mass

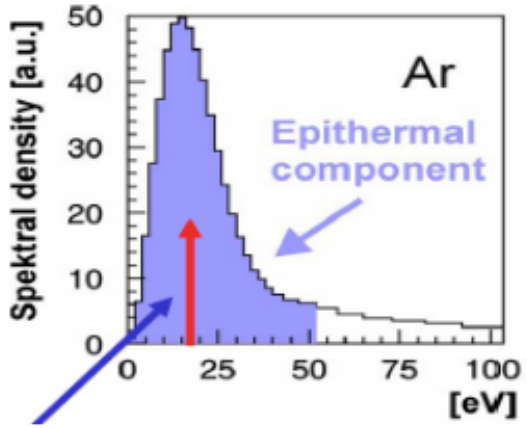
Low energy muon (LEM) beam line at PSI

PAUL SCHERRER INSTITUT
PSI



~1.9 x 10^8 μ^+/s

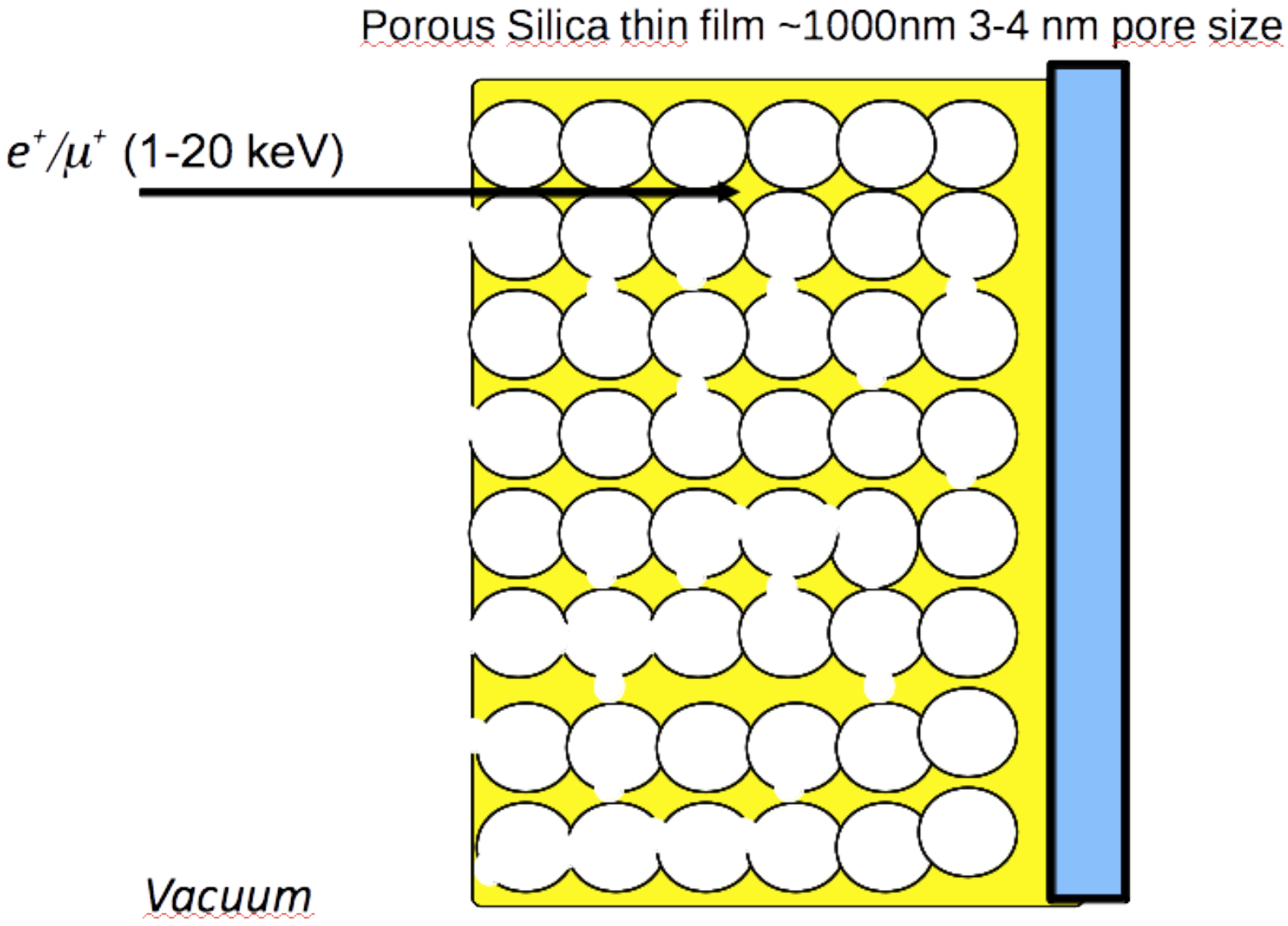




E~15eV

MU-MASS

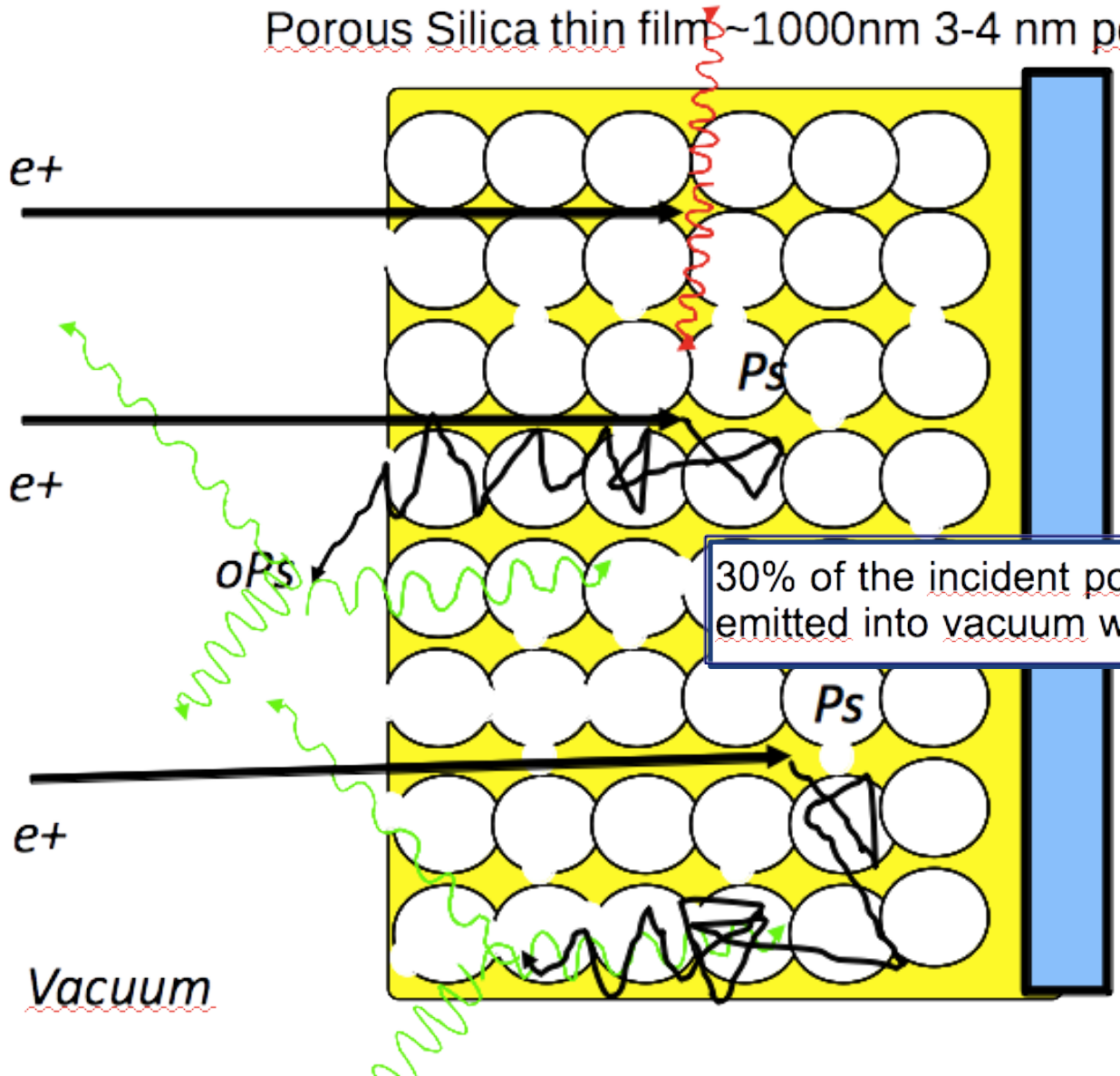
Porous silica targets: Positronium/Muonium formation



MU-MASS

Positronium formation

P. Crivelli et al. , Phys. Rev. A81, 052703 (2010)



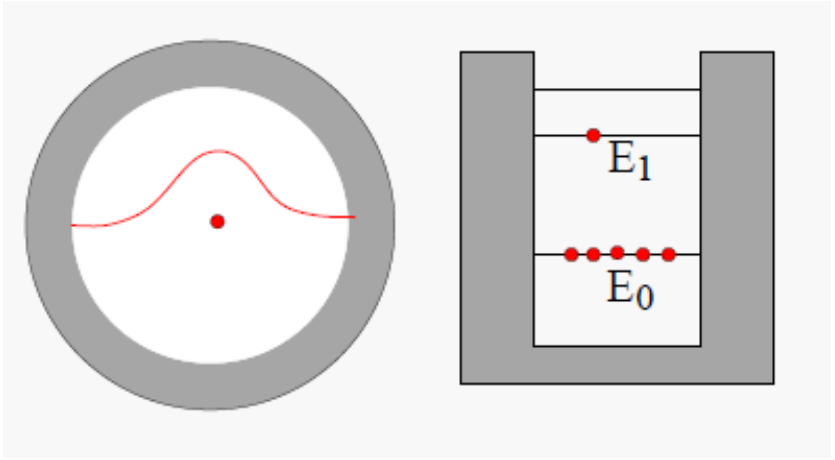
30% of the incident positrons are converted in positronium emitted into vacuum with 40 meV (almost 10^5 m/s).

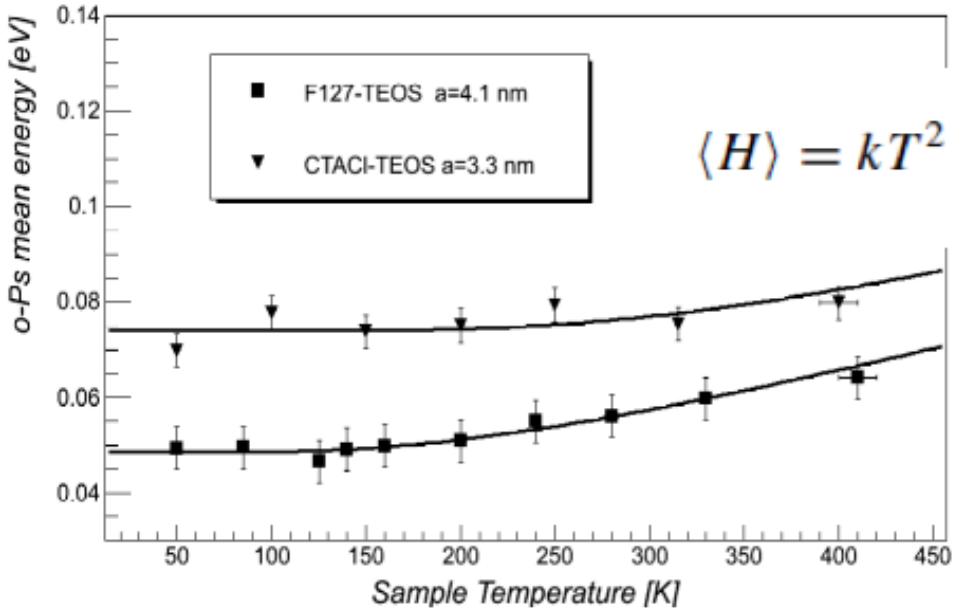
MU-MASS

Positronium results

$$\lambda_{Ps} = 0.9\,\mathrm{nm}\sqrt{1\,\mathrm{eV}/E_{Ps}}$$

$$E_{\mathrm{Ps}} = \frac{h^2}{2m\,d^2} \approx 0.8\,\mathrm{eV}(1\,\mathrm{nm}/d)^2$$





$$\langle H \rangle = kT^2 \left(\frac{1}{Z(a)} \frac{dZ(a)}{dT} + \frac{1}{Z(b)} \frac{dZ(b)}{dT} + \frac{1}{Z(c)} \frac{dZ(c)}{dT} \right)$$

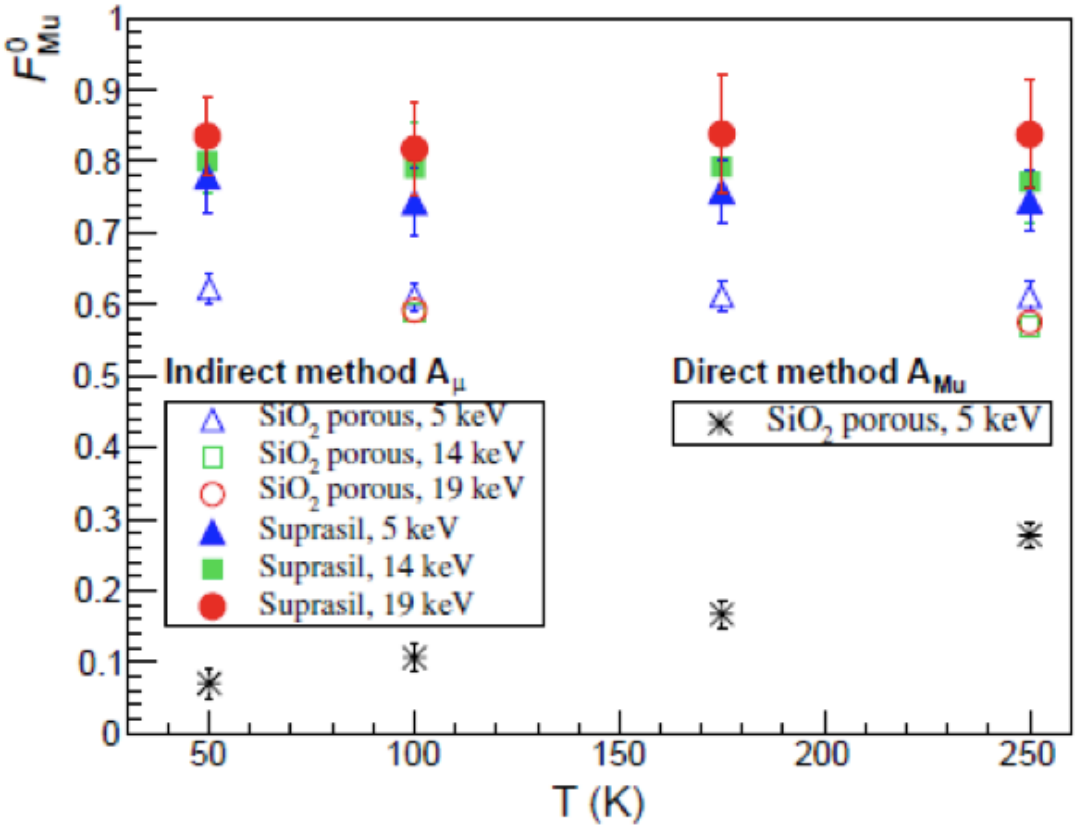
$$Z(a) = \sum_{n=1}^{\infty} e^{-\frac{h^2 n^2}{8ma^2}/kT},$$

MU-MASS

P. Crivelli et al. , Phys. Rev. A81, 052703 (2010)

muSR results for porous and bulk SiO2

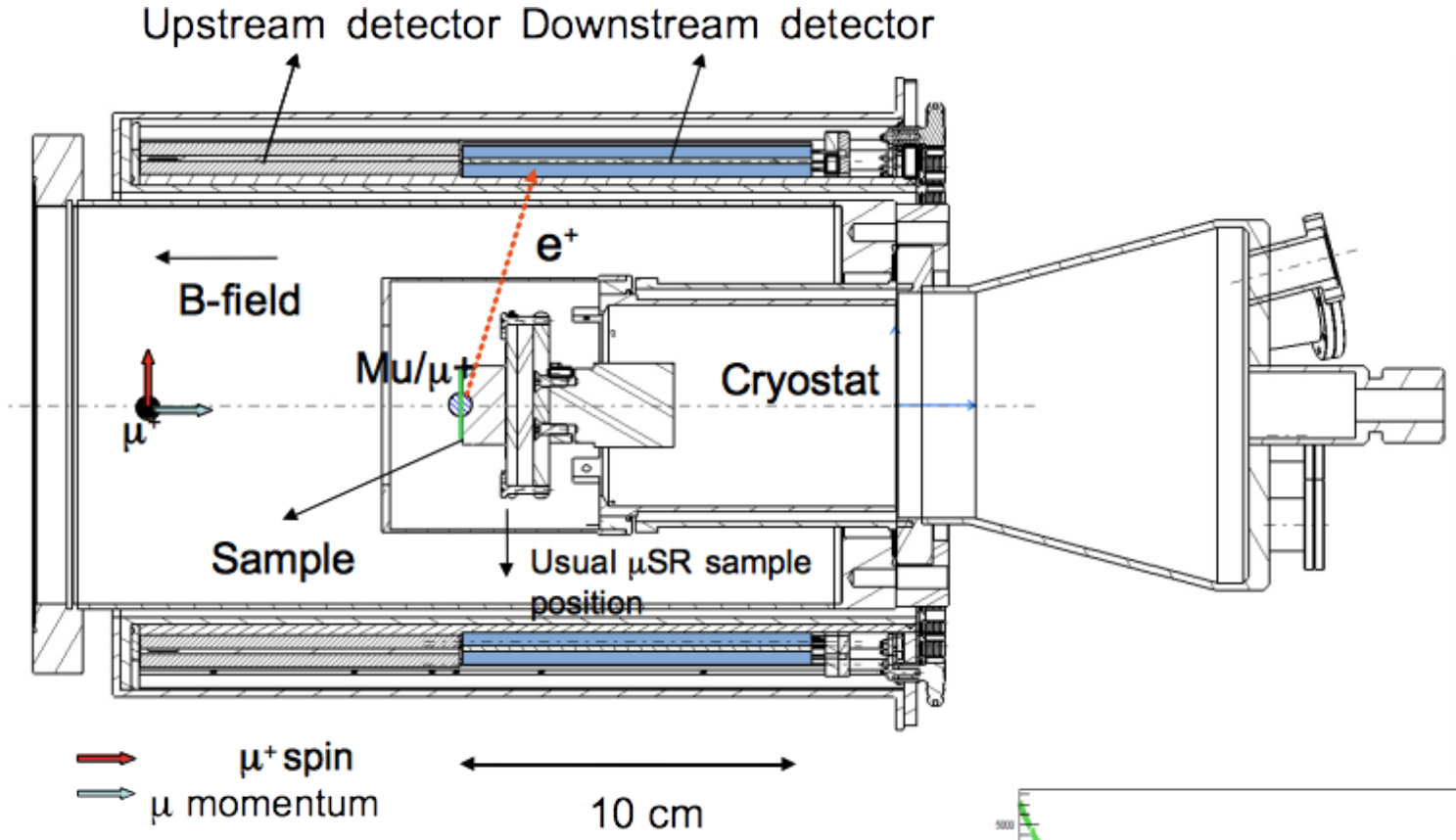
Larmor frequency: $\omega_{Mu} \simeq 103\,\omega_{\mu+}$



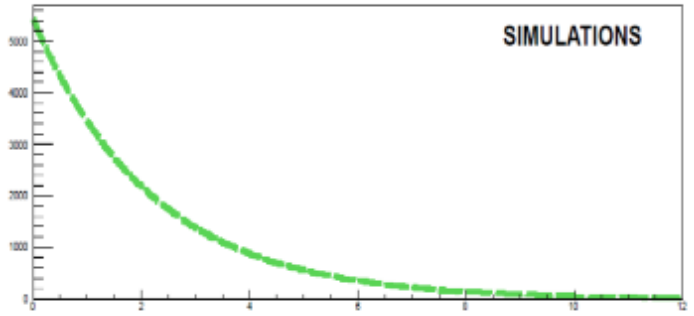
MuSR → Mu is formed but is this emitted in vacuum?

MU-MASS

Positron shielding technique (PST)

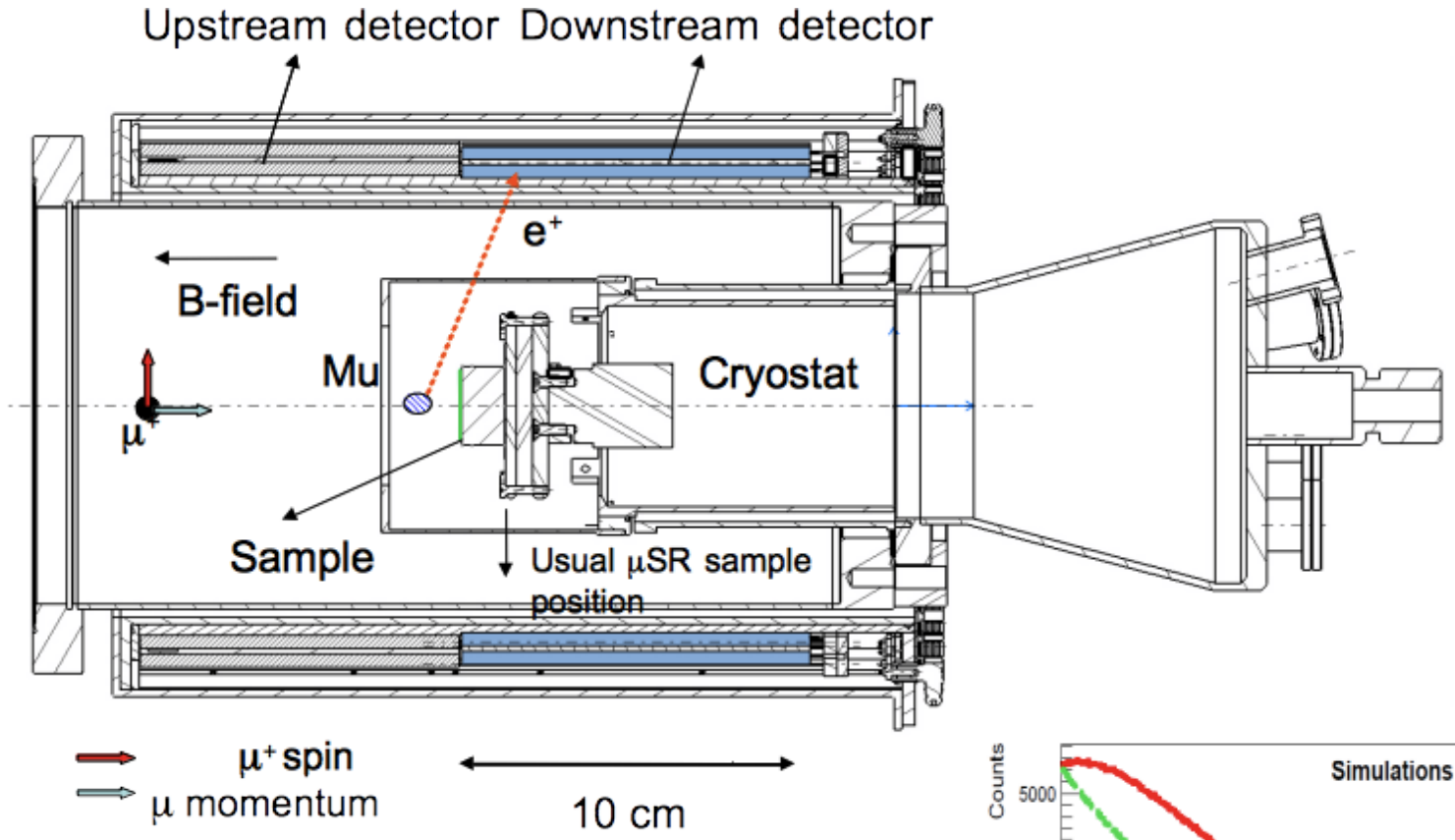


No emission into vacuum

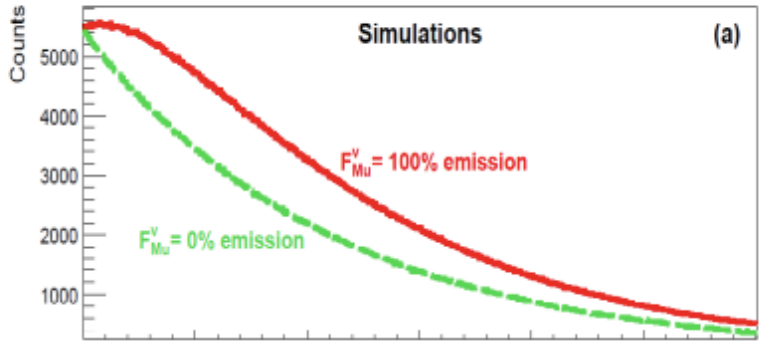


MU-MASS

Positron shielding technique (PST)

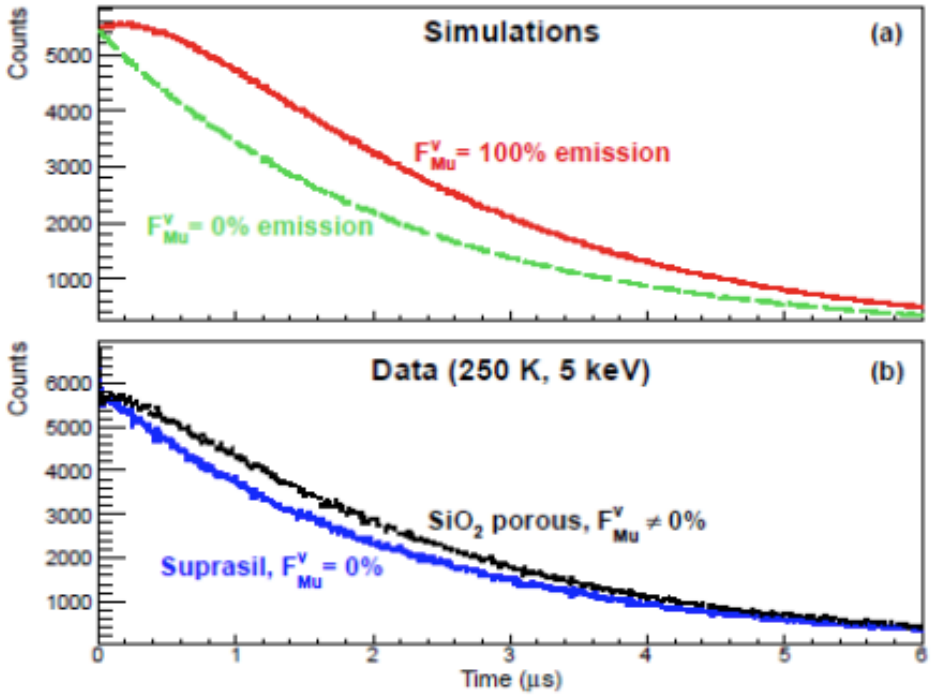


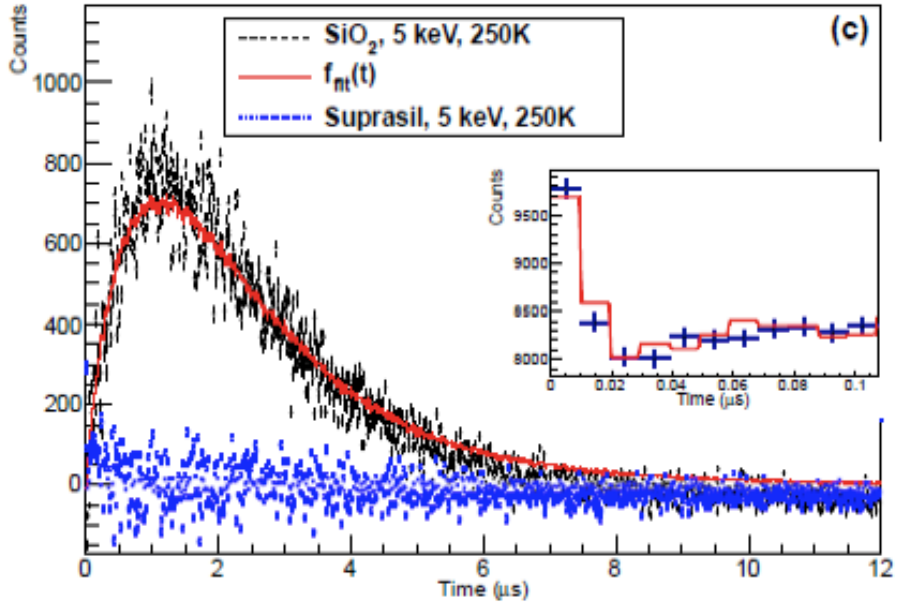
Emission into vacuum



Mu-Mass

PST → vacuum yield





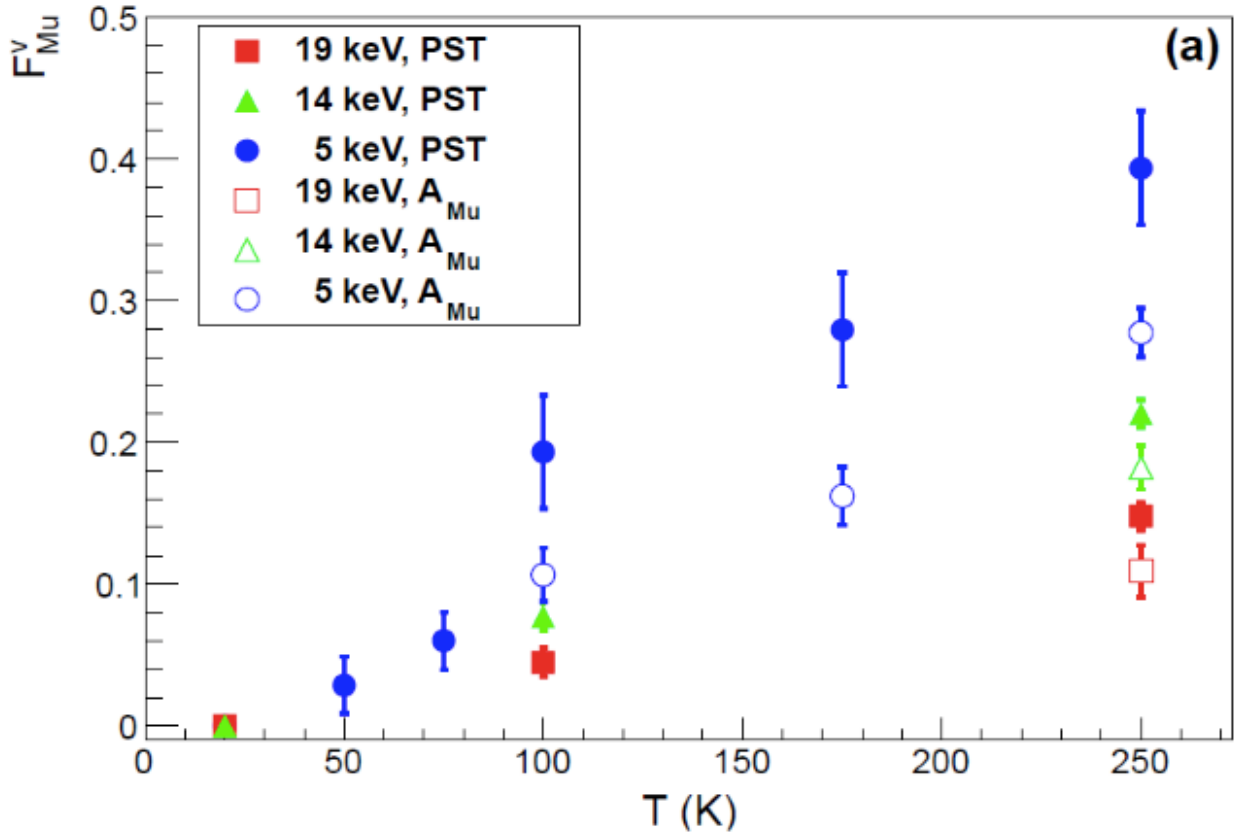
$$f_{\text{fit}}(t) = n[(1 - F^v_{Mu}) f_0(t) + F^v_{Mu} f_{100}(t)] + n_{pp} f_{pp}(t)$$

MU-MASS

Vacuum Yield: F^{v}_{Mu}

PST results

A.Antognini, P. Crivelli, T. Prokscha et al. PRL108,143401(2012)

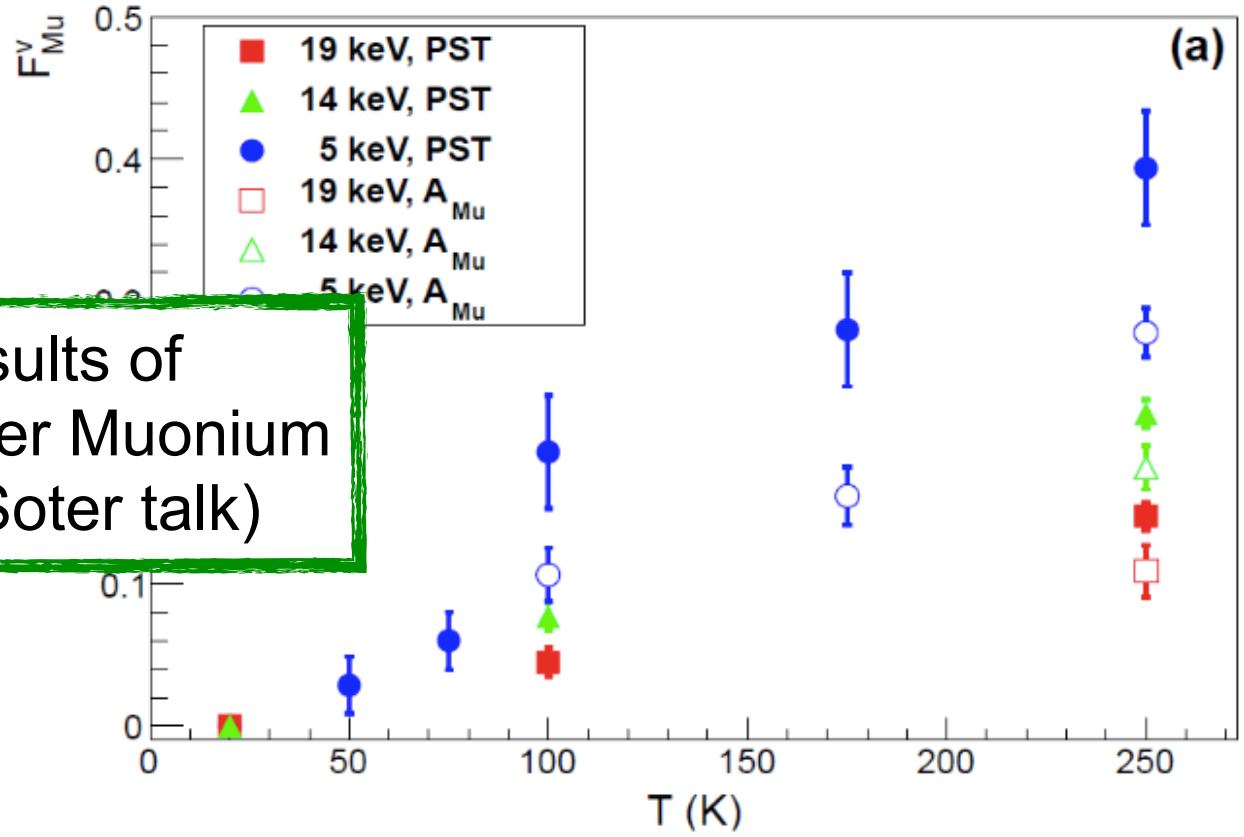


$(38\pm4)\%$ at 250 K and $(20\pm4)\%$ at 100 K for 5 keV

MU-MASS

PST results

A.Antognini, P. Crivelli, T. Prokscha et al. PRL108,143401(2012)



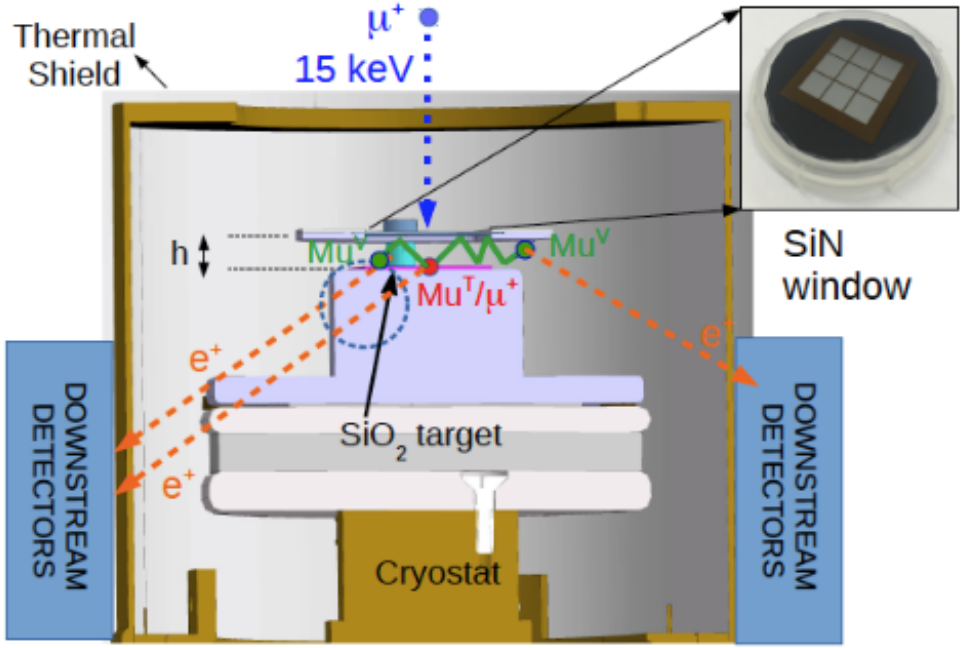
Promising results of production of colder Muonium source (see A. Soter talk)

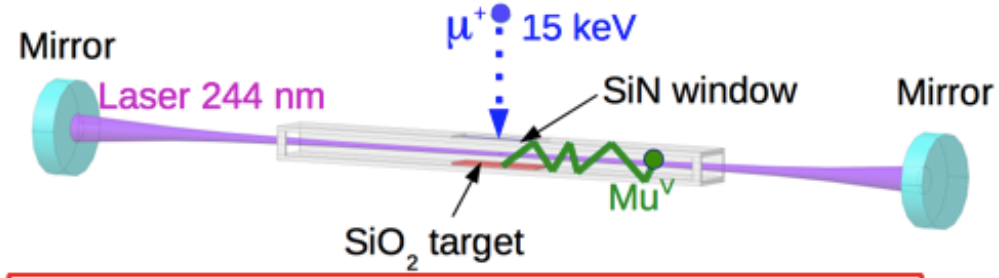
$(38\pm4)\%$ at 250 K and $(20\pm4)\%$ at 100 K for 5 keV

MU-MASS

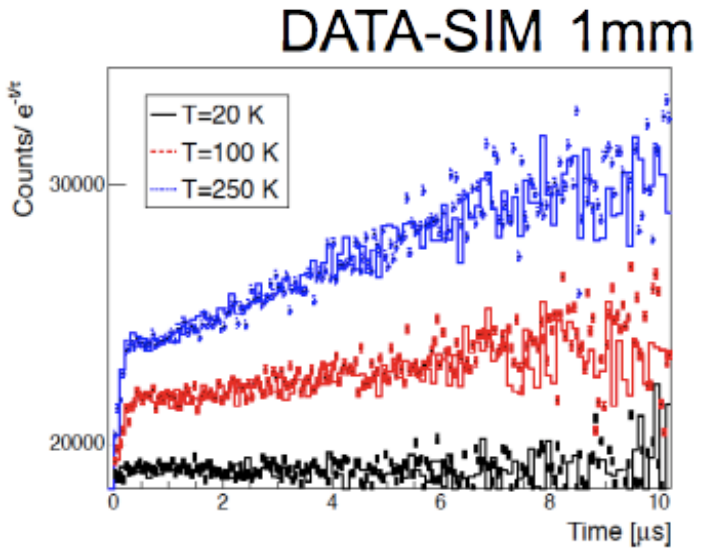
Muonium confinement

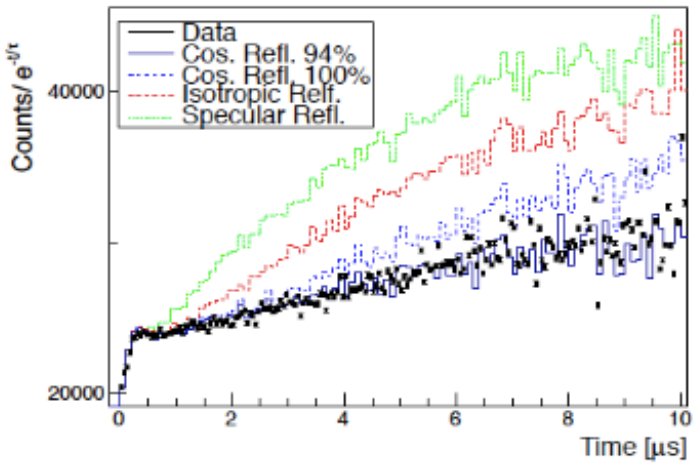
K. S. Khaw, A. Antognini, T. Prokscha, K. Kirch, L. Liszkay, Z., Salman, P. Crivelli, PRA 94, 022716 (2016)





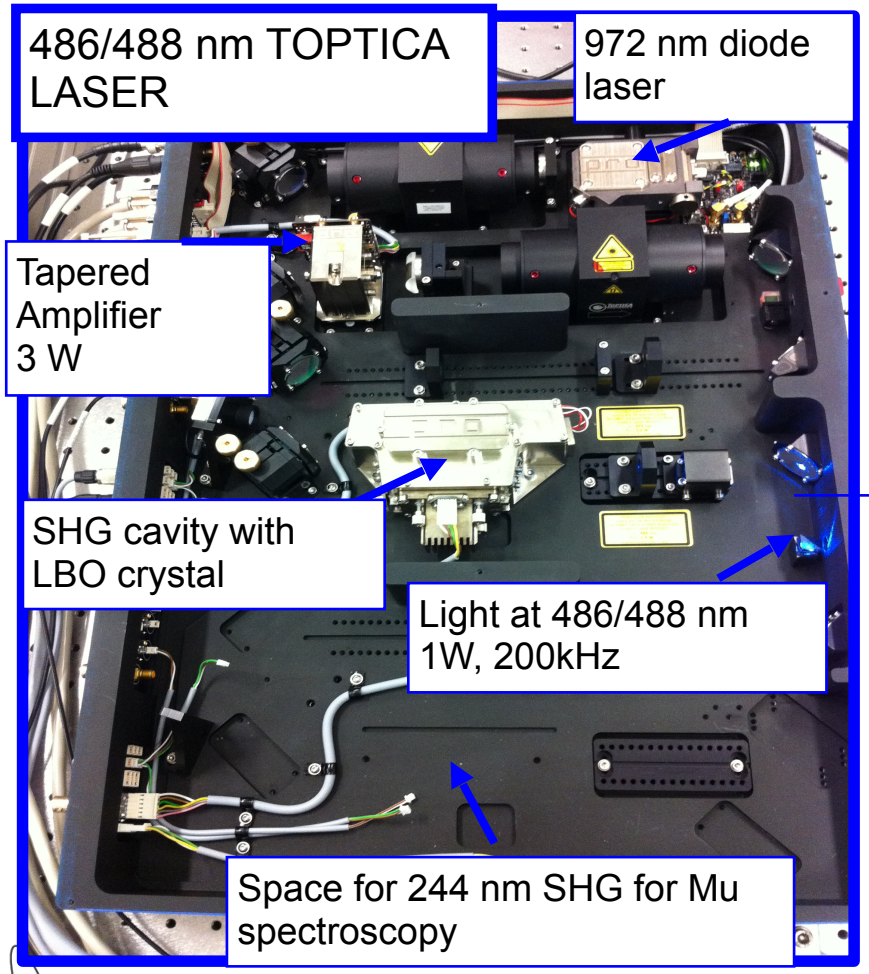
Factor 5 enhancement in exc. probability

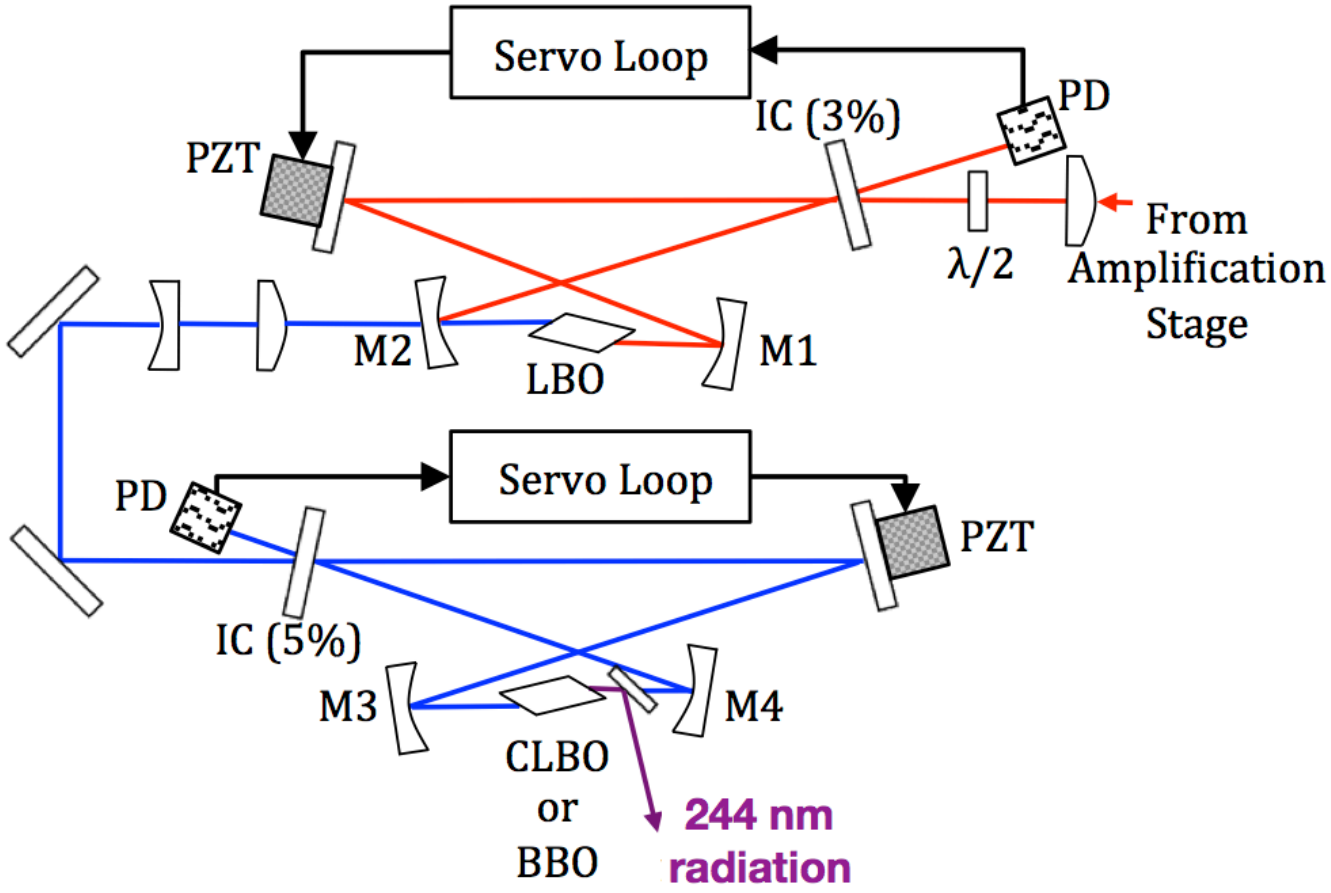




MU-MASS

Mu-MASS: Laser system

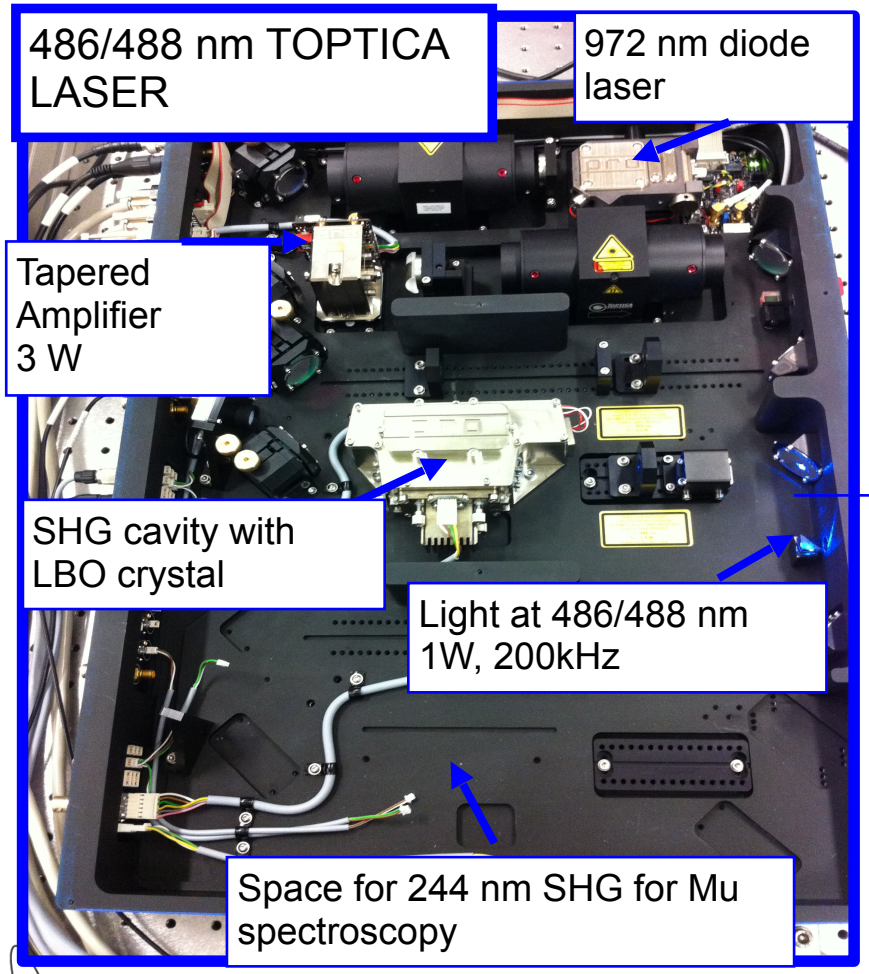


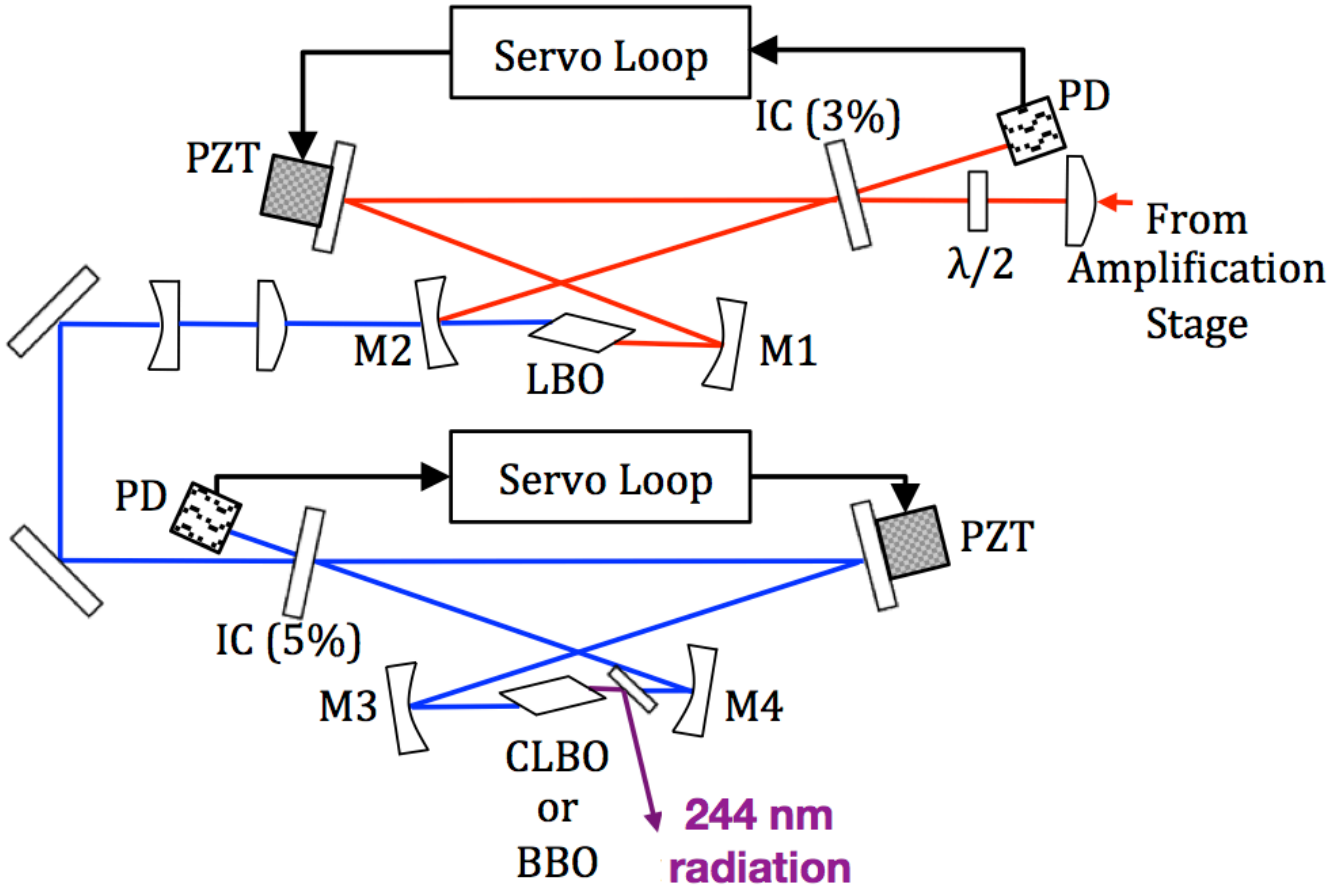


Upgrade laser system used for positronium

MU-MASS

Mu-MASS: Laser system

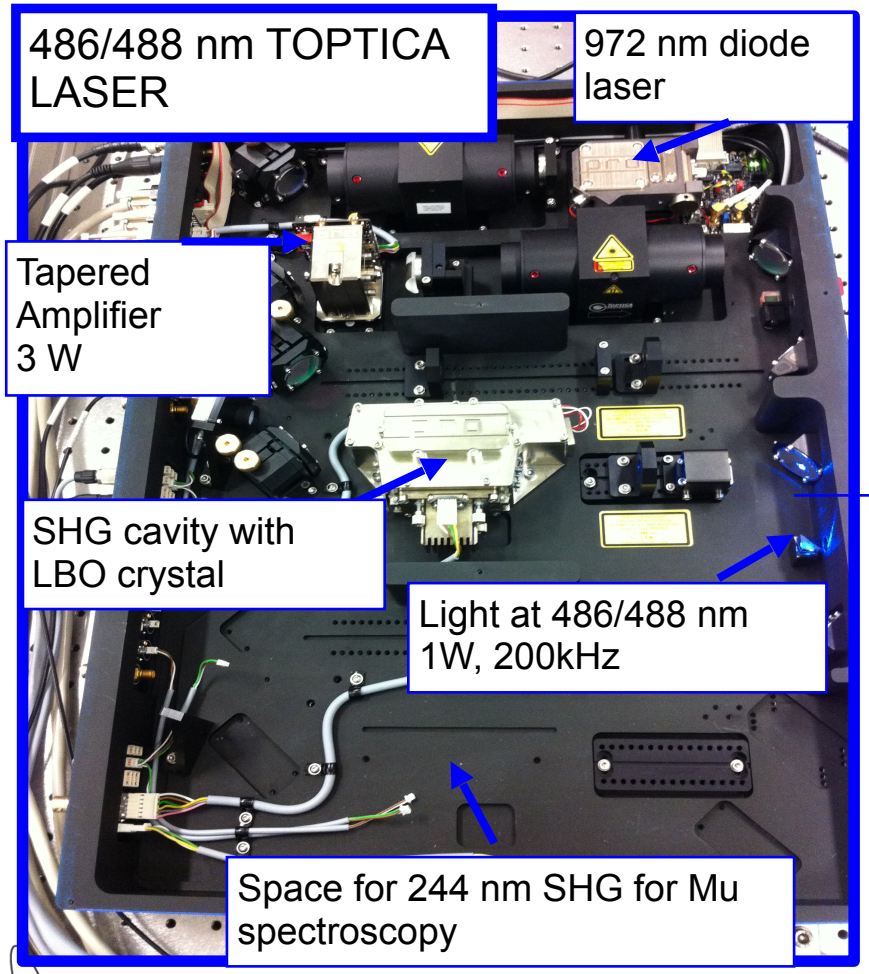




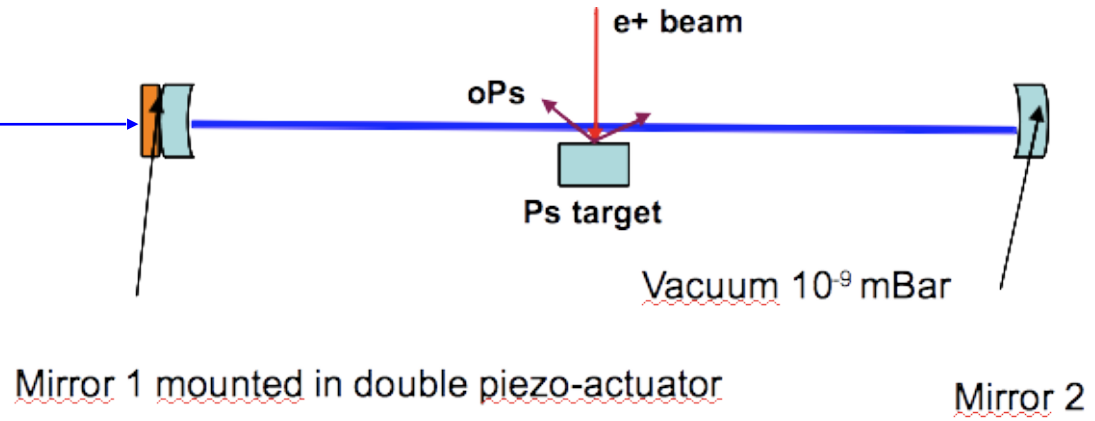
Our collaborators 1.4 W@244nm
https://arxiv.org/abs/1811.09874

Mu-Mass

Mu-MASS: Laser system

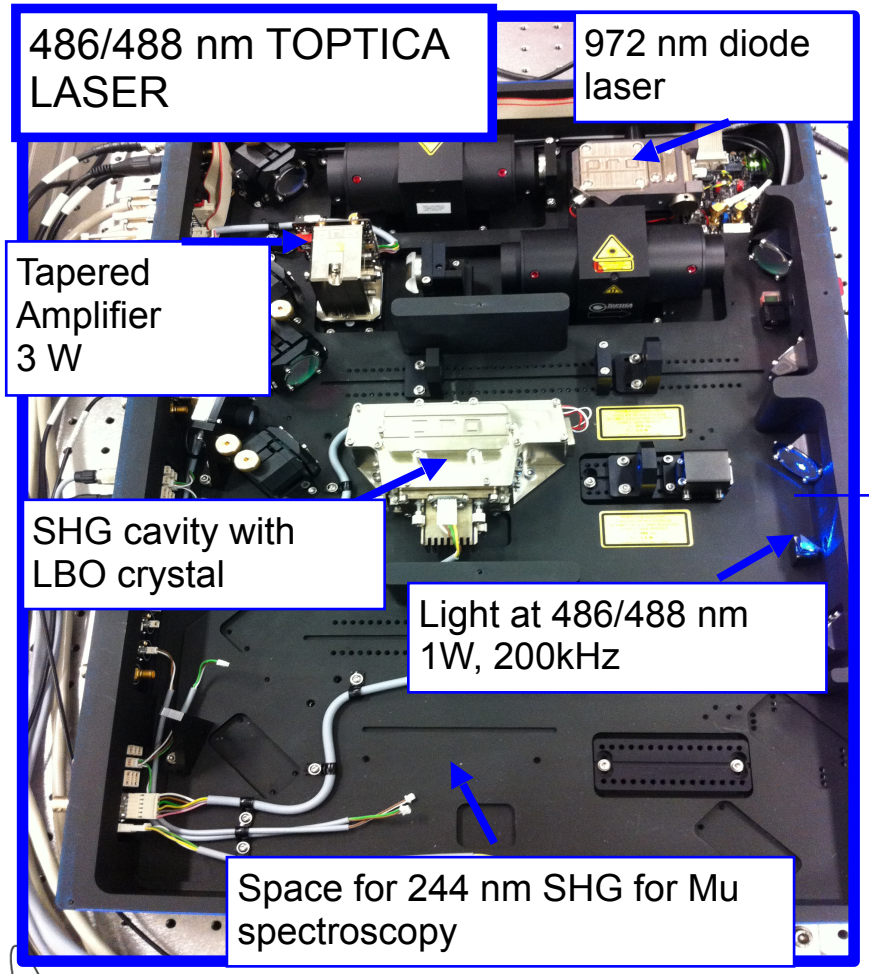


Use enhancement cavity as for Ps

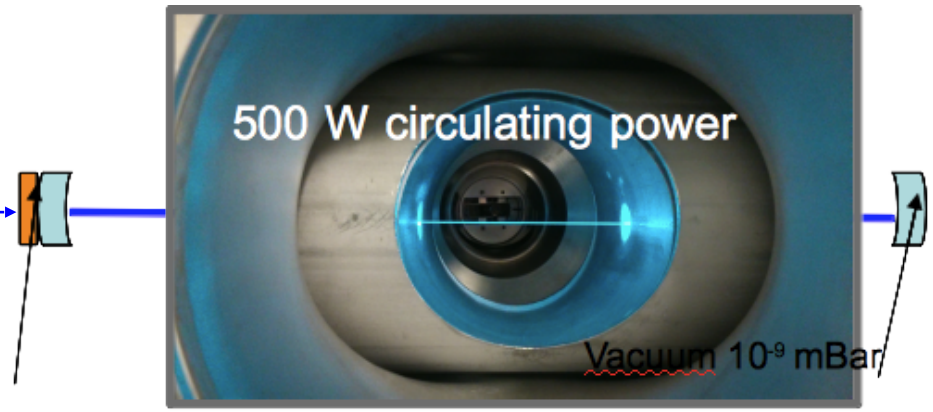


MU-MASS

Mu-MASS: Laser system



Use enhancement cavity as for Ps



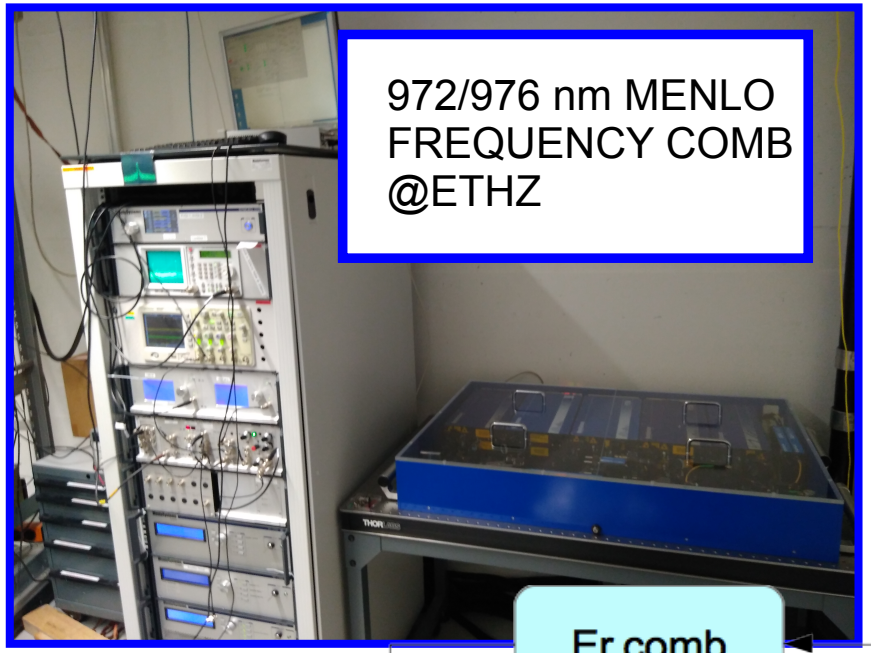
Mirror 1 mounted in double piezo-actuator

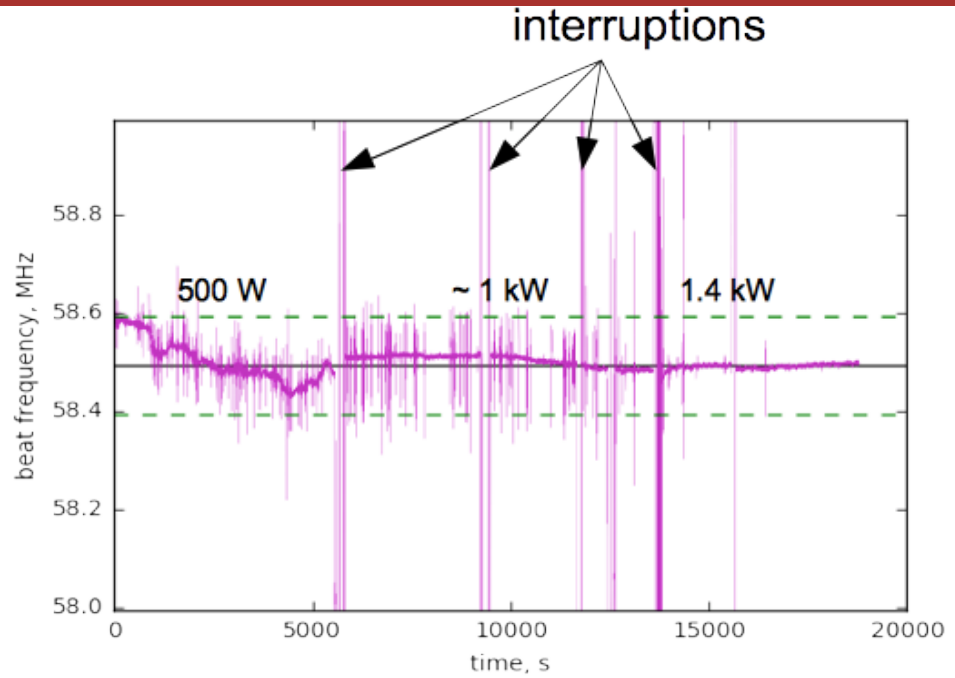
Mirror 2

High finesse resonator for power build up
500 mW ⟹ 1 kW

MU-MASS

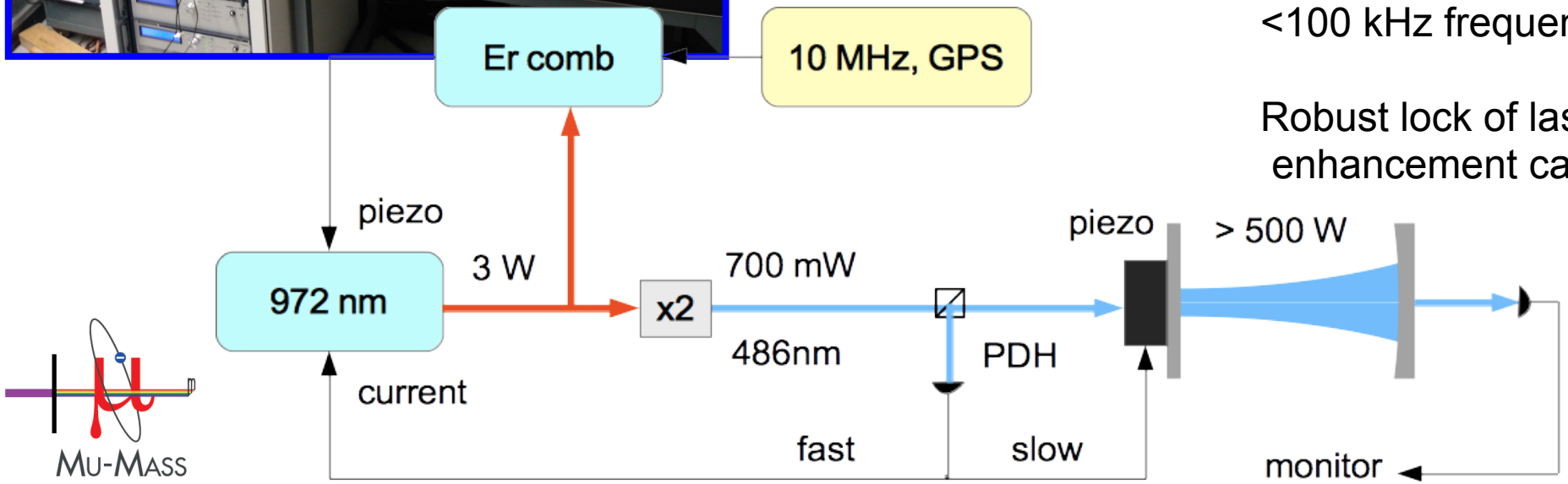
Frequency reference





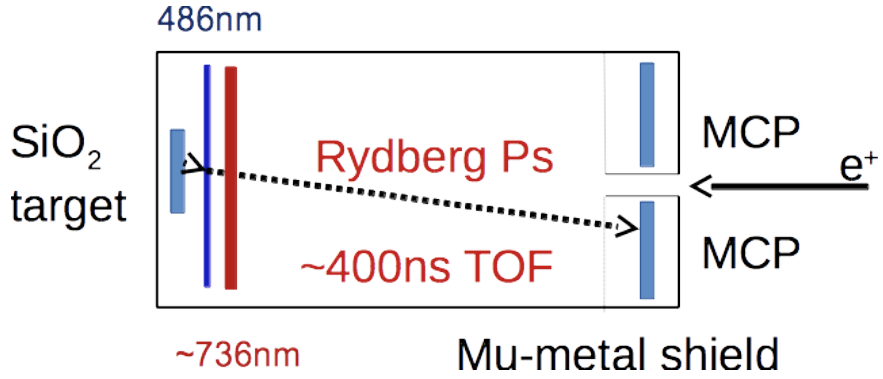
<100 kHz frequency stability over few hours

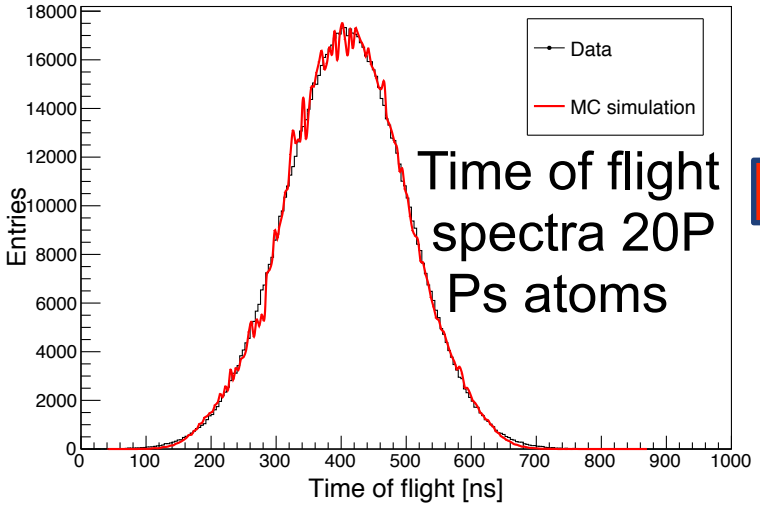
Robust lock of laser frequency and enhancement cavity



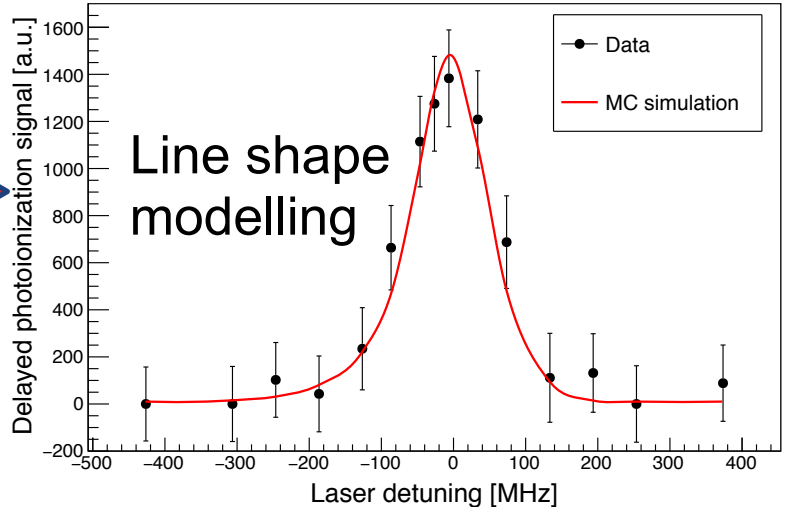
Detection of 2S excited states

Positronium 1S→2S→20P excitation & detection via field ionisation in an MCP, arXiv 1809.07854 (2018)





Atoms velocity



Transition frequency

IPA ETH zürich

Correction of second order doppler shift (main systematic!) $\Delta\nu_{D2} = \nu_0 \frac{v^2}{2c^2}$

Mu-Mass

Mu-MASS: feasibility

Low energy μ^+ beam → Existing LEM beam line

PAUL SCHERRER INSTITUT PSI

JINST 10, P10025 (2015)

Muonium production → ε = 20%@100 K

PRL108,143401(2012), PRA94,022716 (2016)

Muonium 2S excitation → >33 W circulating power @ 244 nm

Colorado State University

Opt. Express 43, 1375 (2018)

Muonium 20P excitation → 365 nm multi-pass laser cavity

Synergy with A. Antognini, ERC-2016-COG

Opt. Express 22,13050 (2014)

Muonium field ionisation
μ^+ detection → Precursor experiment: Positronium 1S-2S measurement

IPA ETH zürich

Hyp. Int 233, 67 (2015)

Mu-Mass

Previous results (RAL(1999))

	RAL (1999)	Mu-MASS Phase1	Mu-MASS Phase2
μ^+ beam intensity	3500 × 50 Hz	5000 s^{-1}	> 9000 s^{-1}
μ^+ beam energy	4 MeV	5 keV	5 keV
Temperature M atoms	300 K	100 K	100 K
Total number of 2S events	99	1900 (10 d)	> 7000 (40 d)
Spectroscopy	Pulsed laser	CW (25 W)	CW (50 W)
Experimental linewidth	20 MHz	750 kHz	300 kHz
Laser chirping	10 MHz	0 kHz	0 kHz
Residual Doppler shift uncert.	3.4 MHz	0 kHz	0 kHz
2nd-order Doppler shift uncert.	44 kHz	15 kHz	1 kHz (corrected)
Frequency calibration uncert.	0.8 MHz	< 1 kHz	< 1 kHz
Background events	2.8 events/day	1.6 events/day	1.6 events/day
Statistical uncertainty	9.1 MHz	<100 kHz	10 kHz
Total uncertainty	9.8 MHz	<100 kHz (linewidth/10)	10 kHz (linewidth/30)

Current best result

Mu-Mass

Mu-MASS vs RAL(1999) - New essential developments

	RAL (1999)	Mu-MASS Phase1	Mu-MASS Phase2
μ^+ beam intensity	3500 × 50 Hz	5000 s^{-1}	> 9000 s^{-1}
μ^+ beam energy	4 MeV	5 keV	5 keV
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2nd-order Doppler shift uncert.	44 kHz	15 kHz	1 kHz (corrected)
Frequency calibration uncert.	0.8 MHz	< 1 kHz	< 1 kHz
Background events	2.8 events/day	1.6 events/day	1.6 events/day
Statistical uncertainty	9.1 MHz	<100 kHz	10 kHz
Total uncertainty	9.8 MHz	<100 kHz (linewidth/10)	10 kHz (linewidth/30)

Improved muonium source (higher yield + lower temperature)

Continuous wave laser spectroscopy vs pulsed

Mu-Mass

Mu-MASS vs RAL(1999) - Line-width

	RAL (1999)	Mu-MASS Phase1	Mu-MASS Phase2
μ^+ beam intensity	3500 × 50 Hz	5000 s^{-1}	> 9000 s^{-1}
μ^+ beam energy	4 MeV	5 keV	5 keV
Temperature M atoms	300 K	100 K	100 K
Total number of 2S events	99	1900 (10 d)	> 7000 (40 d)
Spectroscopy	Pulsed laser	CW (25 W)	CW (50 W)
Experimental linewidth	20 MHz	750 kHz	300 kHz
Laser chirping	10 MHz	0 kHz	0 kHz
Residual Doppler shift uncert.	3.4 MHz	0 kHz	0 kHz
2nd-order Doppler shift uncert.	44 kHz	15 kHz	1 kHz (corrected)
Frequency calibration uncert.	0.8 MHz	< 1 kHz	< 1 kHz
Background events	2.8 events/day	1.6 events/day	1.6 events/day
Statistical uncertainty	9.1 MHz	<100 kHz	10 kHz
Total uncertainty	9.8 MHz	<100 kHz (linewidth/10)	10 kHz (linewidth/30)

Phase 1: Line-width 20 smaller

Phase 2: Line-width 100 smaller

MU-MASS

Mu-MASS vs RAL(1999) - Systematic effects

	RAL (1999)	Mu-MASS Phase1	Mu-MASS Phase2
μ^+ beam intensity	3500 × 50 Hz	5000 s^{-1}	> 9000 s^{-1}
μ^+ beam energy	4 MeV	5 keV	5 keV
Temperature M atoms	300 K	100 K	100 K
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Statistical uncertainty	9.1 MHz	<100 kHz	10 kHz
Total uncertainty	9.8 MHz	<100 kHz (linewidth/10)	10 kHz (linewidth/30)

Systematic related to pulsed excitation eliminated

Phase 1: no systematic effect to correct

Phase 2: systematic effects to be corrected

Mu-Mass

Time schedule and Milestones

Milestones	2019	2020	2021	2022	2023
Lasers development [ETHZ,CSU]					
Detectors development [ETHZ,LMU,LTP]					
Tests with H/D beam [ETHZ]					
Beamtime at LEM (+setup) [ETHZ,LMU,LTP]					
Phase1 data analysis and publications [ALL]					
Laser upgrade [ETHZ,CSU]					
Phase 2 beam time (+ setup) [ALL]					
Data analysis and publications [ALL]					
New M targets and beamline [ETHZ, LMU, LTP]					

Mu-MASS (MuoniuM lAser SpectroScopy)

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Core research team

	1 year	2 year	3 year	4 year	5 year
PostDoc 1 Laser developments Beam time (H/D beams + muons phase 1) Laser (244 nm) upgrade					
PostDoc 2 Detectors development and DAQ Beam time (H/D beams + muons phase 1) Data analysis					
PostDoc 3 Laser (244 nm) upgrade →50 W Phase 1 Beam time + data analysis Phase 2 Beam time + data analysis					
PhD 1 LEM optics/tagging/tests with p Beam time (H/D beams + muons phase 1) Data analysis/Writing thesis					
PhD 2 Phase 1 Beam time Optimization/Phase 2 Beam time Data analysis /Writing thesis					

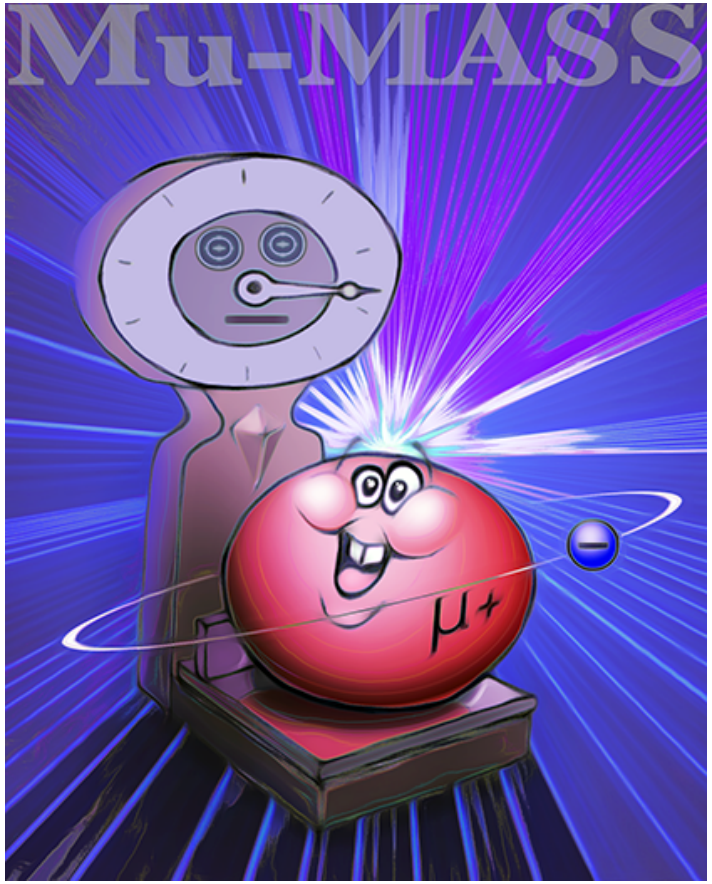
Phase 1 Phase 2

erc 818053 - Mu-MASS

Mu-Mass

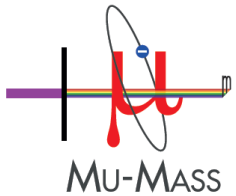
Summary

- Mu-MASS aims at improving 3 orders of magnitude on our current knowledge of the 1S-2S of Muonium
- Feasibility builds on expertise acquired during the last decade: Ps CW laser spectroscopy, cryogenic muonium production, high precision detectors development.
- Project funded by European Research Council: starting from February 2019.
- Phase 1: at LEM (2x2 weeks) end of 2020/2021.
- In parallel: development of new Mu cold targets
- Phase 2: Experiment would greatly profit of muCool beamline (see a A. Antognini talk)



MU-MASS

Thank you for attention! I will be happy to answer your questions.



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Mu-Mass

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