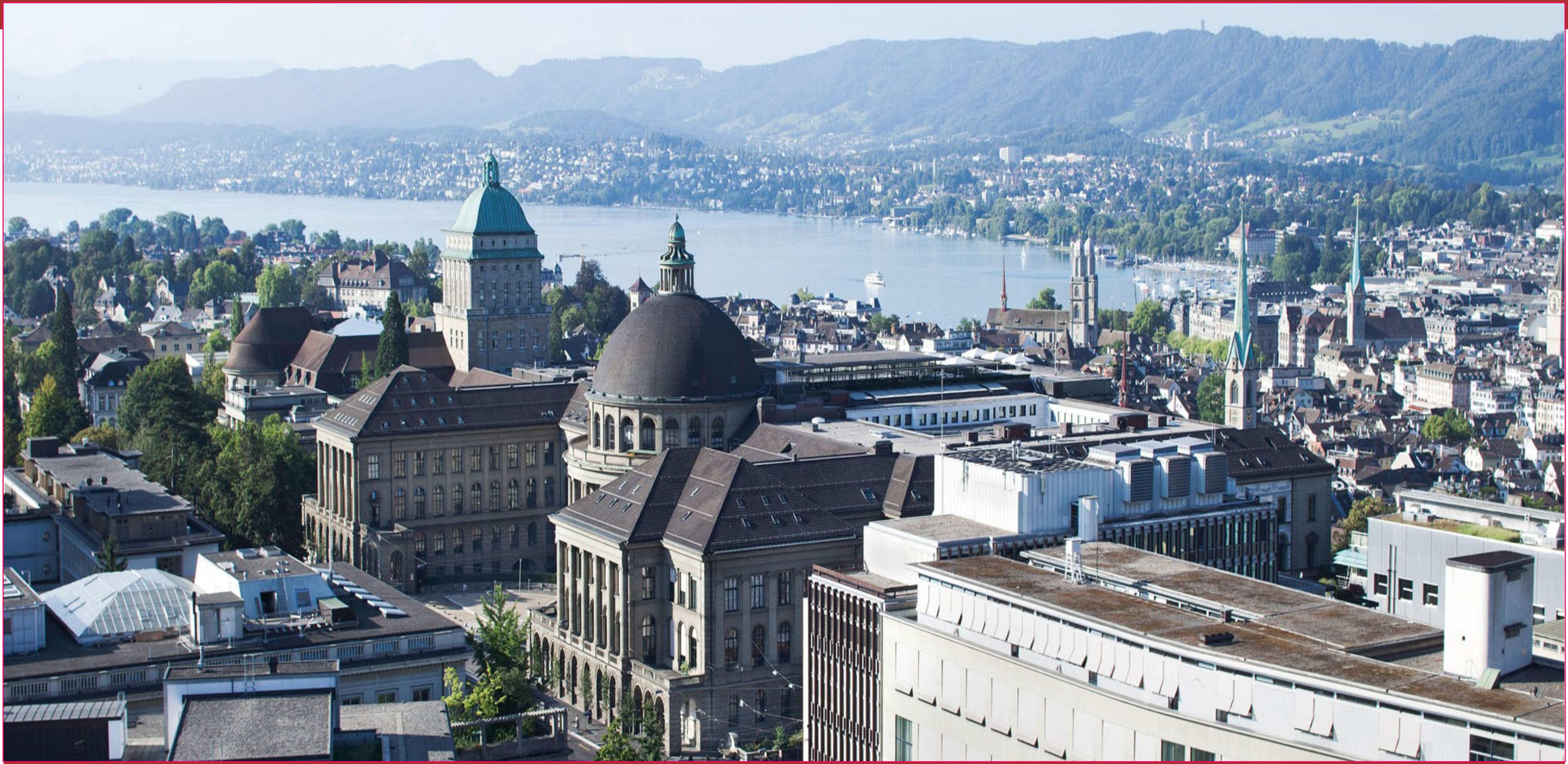


Positronium and Muonium 1S-2S laser spectroscopy

- SSP2018 Aachen, 13th of June 2018

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

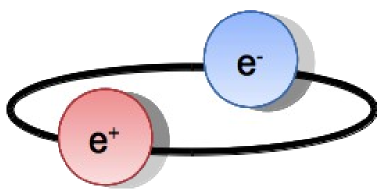
Leptonic atoms

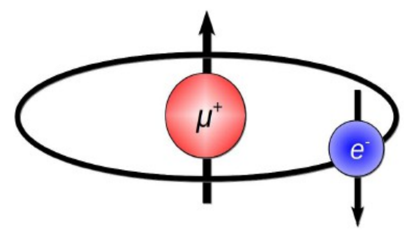
Talk R. Pohl (Thursday)

Precise bound state QED test free from finite size effects

Test fundamental symmetries and search for new physics

C. Vigo et al PRD D 97, 092008 (2018).





Positronium (Ps)

Muonium (Mu)

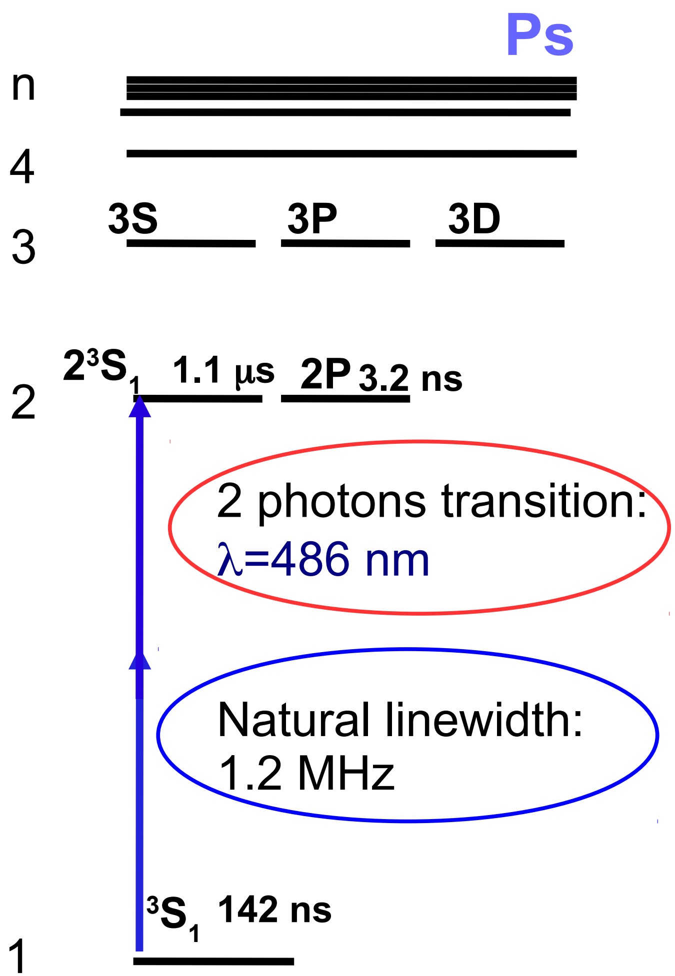
Fundamental constants

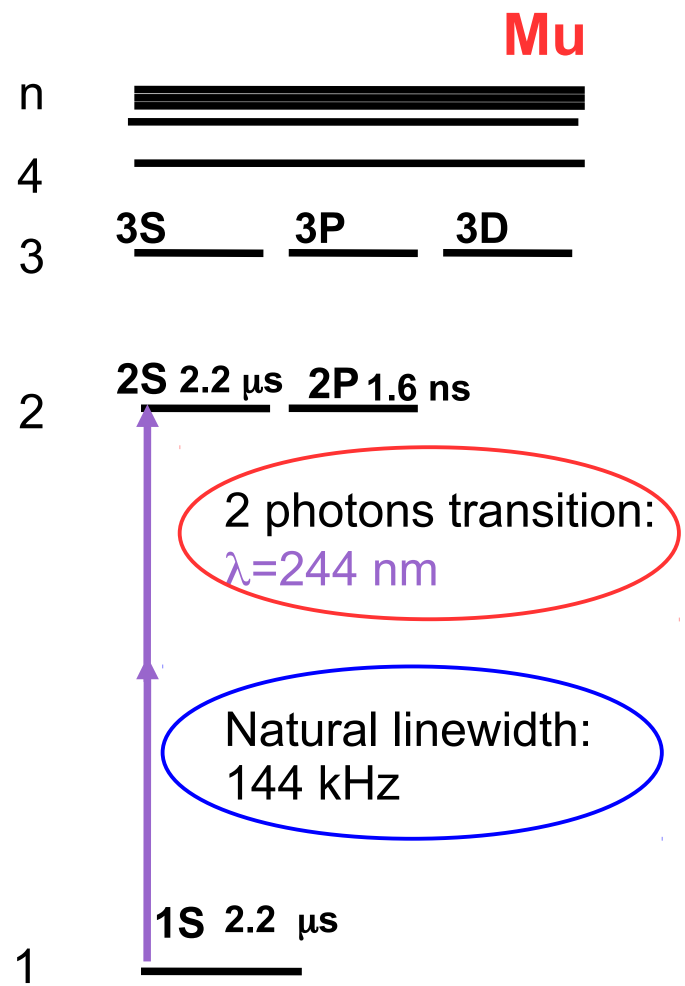
Test effect of gravity on anti-matter

Talk Seo (Friday)

Applications in material science

Energy levels

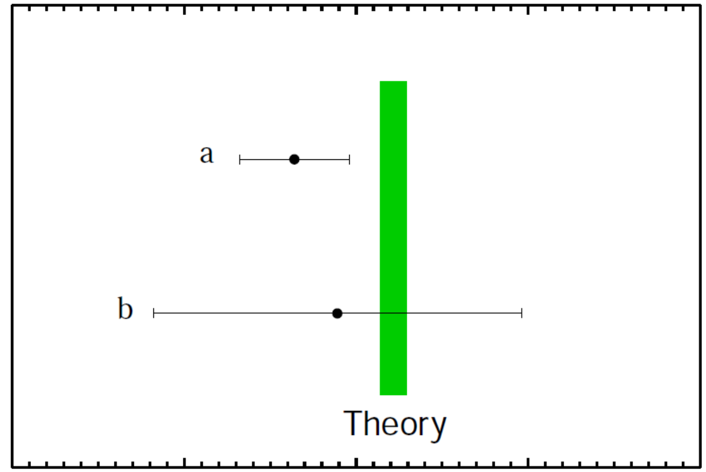




$$R_M = R_\infty \left(\frac{1}{1 + m/M} \right) = \begin{cases} R_\infty/2, & \text{for Ps.} \\ 0.995 \cdot R_\infty, & \text{for Mu.} \end{cases}$$

Positronium 1S-2S measurement

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



Theory: $\nu^{theory} = 1233607222.2(6)$ MHz

K. Pachucki and S. G. Karshenboim, Phys. Rev. A60, 2792 (1999),
K. Melnikov and A. Yelkhovsky, Phys. Lett. B458, 143 (1999)¨.
Adkins, Kim, Parsons and Fell, PRL 115 233401 (2015)

Experiments: $\nu^{a} = 1233607216.4(3.2)$ MHz

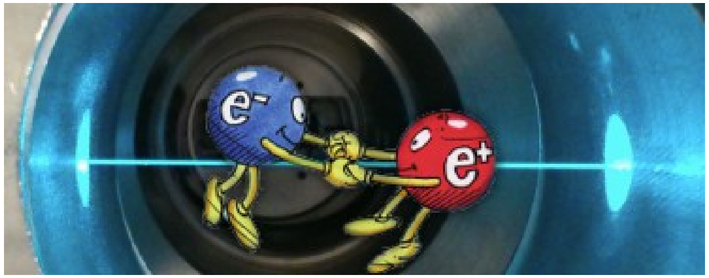
M. S. Fee et al., Phys. Rev. Lett. 70, 1397 (1993)
S. Chu, A. P. Mills, Jr. and J. Hall, Phys. Rev. Lett. 52,1689 (1984)

New measurement ongoing at ETHZ: goal 0.5 MHz

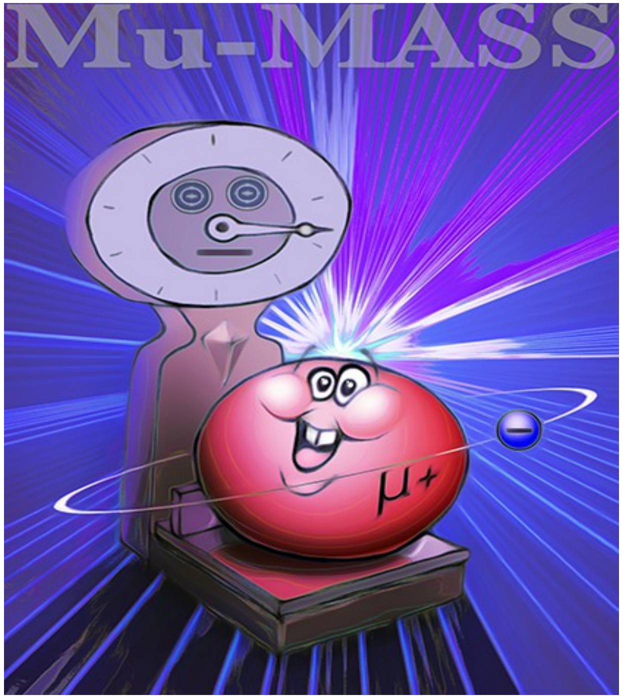
1) Check QED calculations ($\alpha^7 m$)

2) Stringent test of SME

3) Positron to electron mass ratio



Muonium 1S-2S measurement



Experiment:

$$\Delta\nu_{1S2S}(\text{expt.}) = 2455528941.0(9.8)\ \text{MHz}$$

Meyer et al. PRL84, 1136 (2000)

Theory:

$$\Delta\nu_{1S2S}(\text{theory}) = 2455528935.4(1.4)\ \text{MHz}$$

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

Improvement by 3 orders of magnitude seems possible!

Fundamental constants in muon sector

Talks Mott, Denig, Stoeckinger (Tuesday)

$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$

Muon g-2
FNAL

- → hadronic contribution
- → hadronic lbl contribution
- → New Physics

$$a_\mu = \frac{\omega_a}{\omega_p}\frac{m_\mu}{m_e}\frac{\mu_p}{\mu_B}$$

QED
μ_μ, α, g_μ

$$\mu_\mu = g_\mu \frac{e\hbar}{2m_\mu}$$

QED
m_μ

MUSEUM -HFS

$\Delta\nu_{HFS, n=1}$

- → μ_μ
- → α
- → QED corrections
- → weak contribution

QED
m_μ

Mu-MASS

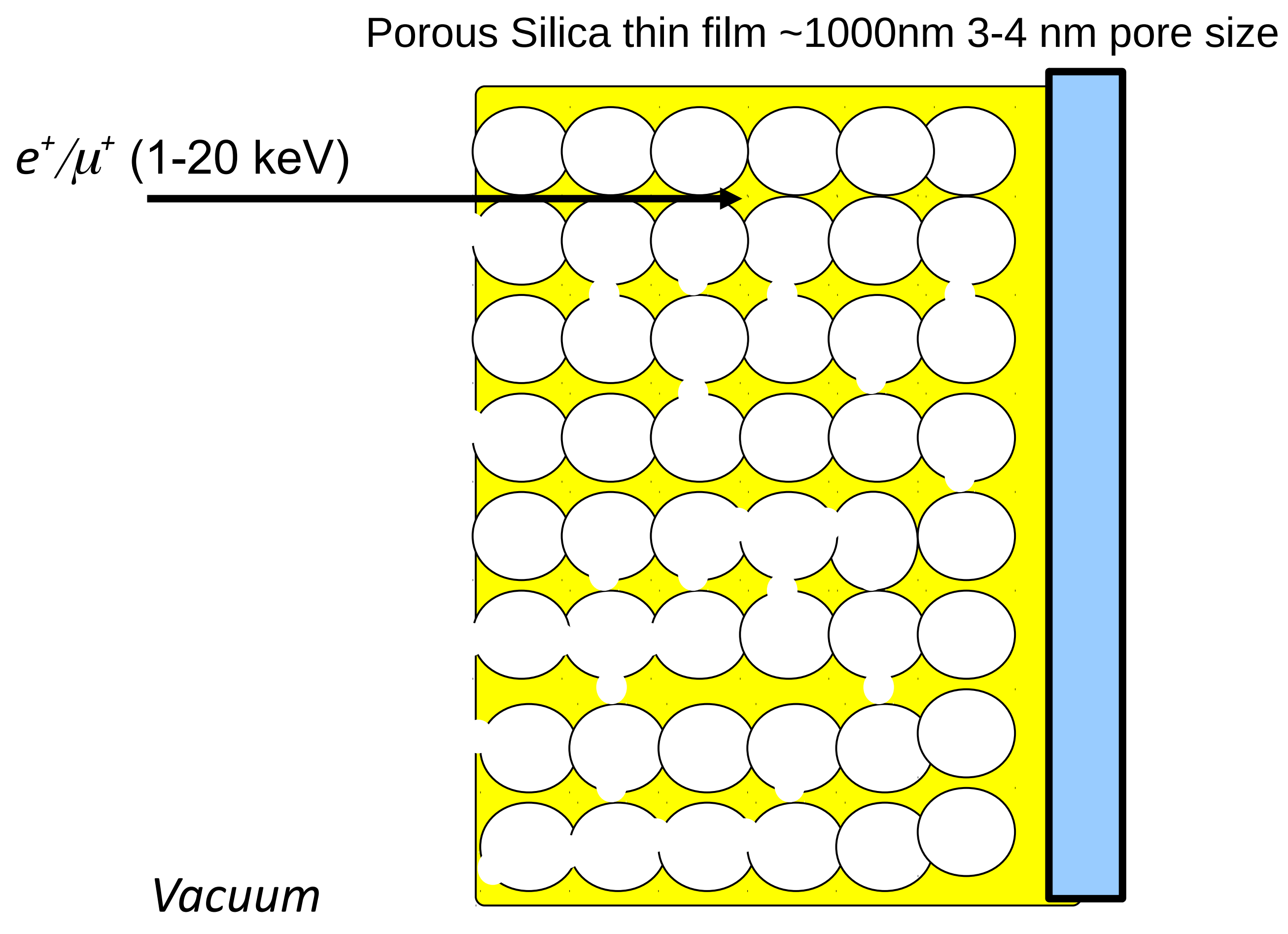
$\Delta\nu_{1S\text{-}2S}$

- → m_μ
- → QED corrections
- → Rydberg

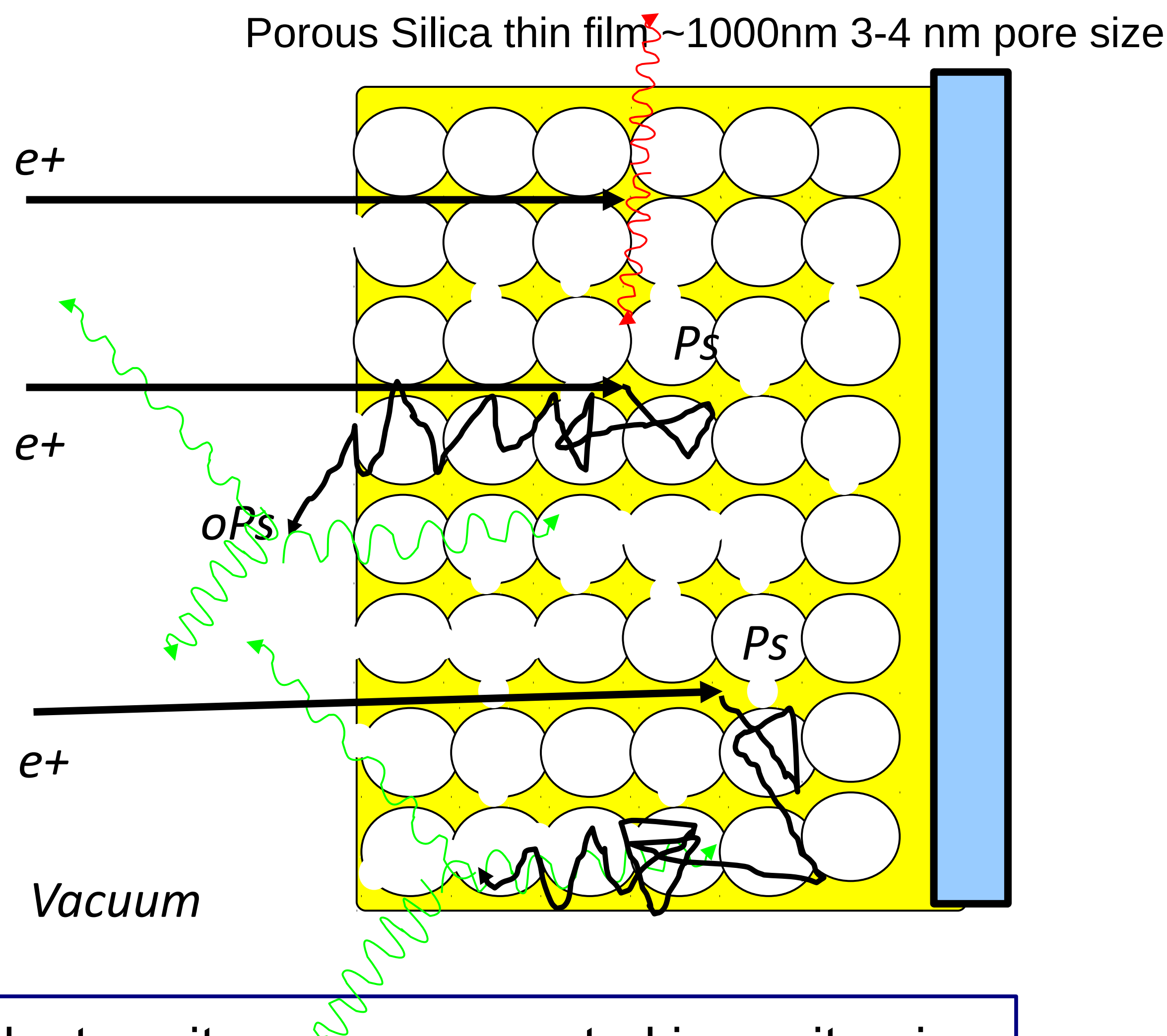
Talk Seo (Friday)

Adapted from K. Jungmann, DPG 2017 (Mainz)

Positronium/muonium formation



Positronium formation



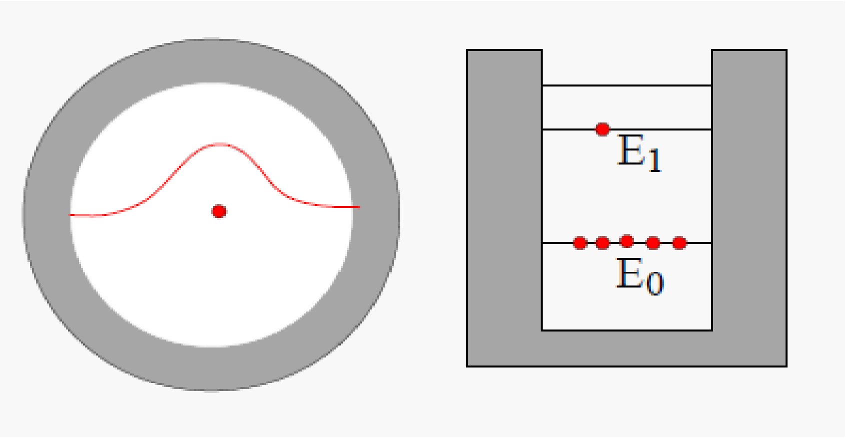
30% of the incident positrons are converted in positronium emitted into vacuum with 40 meV (almost 10^5 m/s).

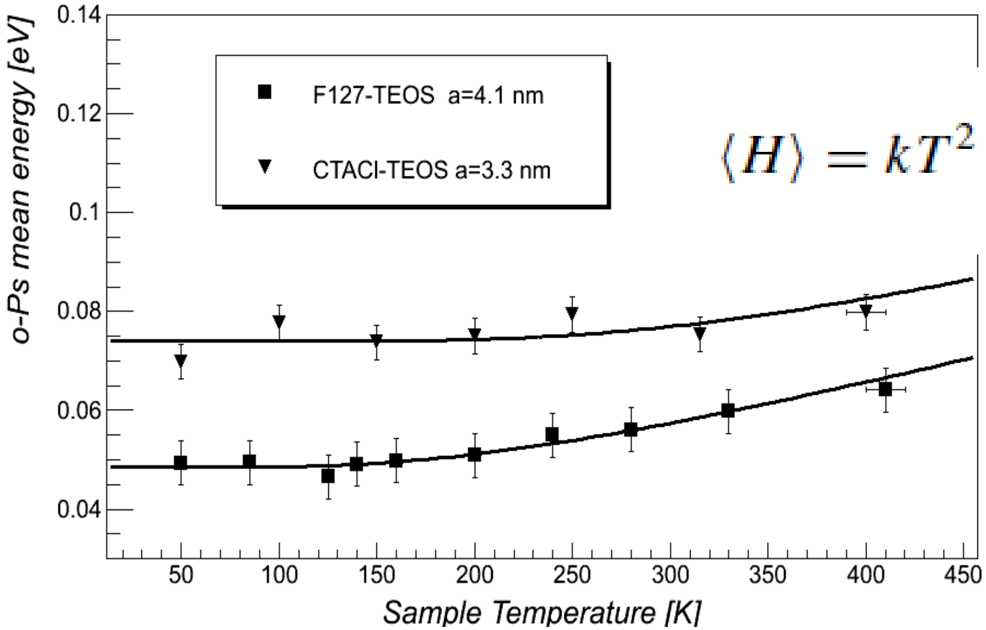
P. Crivelli et al. , Phys. Rev. A81, 052703 (2010)

Positronium formation

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

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



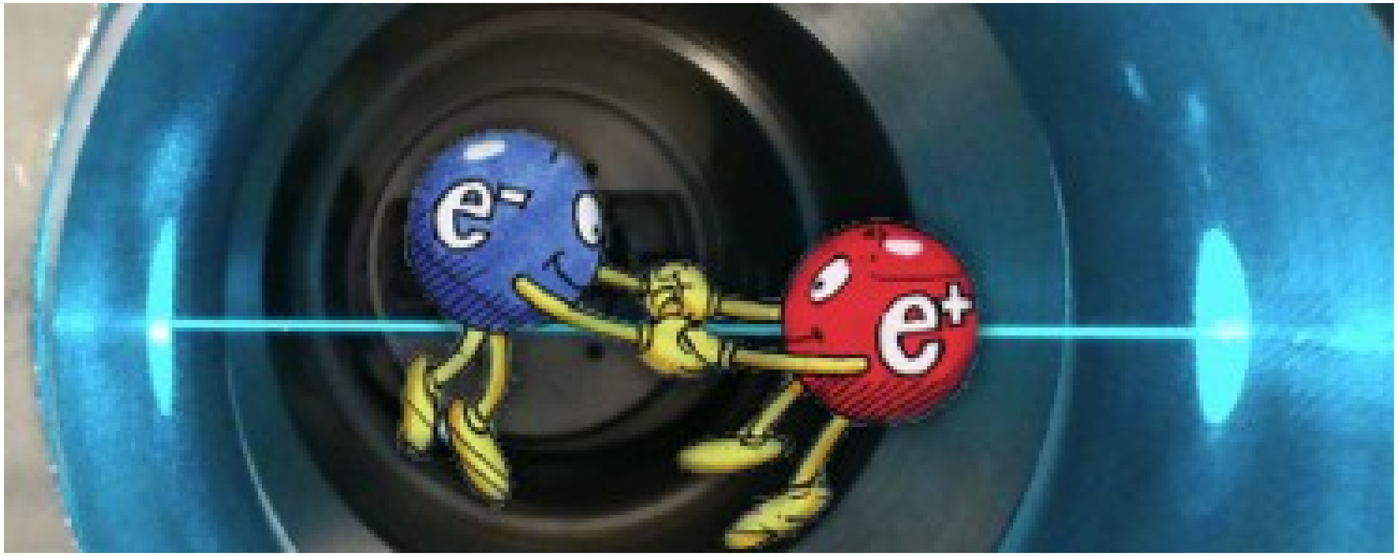


$$\langle H\rangle = kT^2\left(\frac{1}{Z(a)}\frac{dZ(a)}{dT} + \frac{1}{Z(b)}\frac{dZ(b)}{dT} + \frac{1}{Z(c)}\frac{dZ(c)}{dT}\right)$$

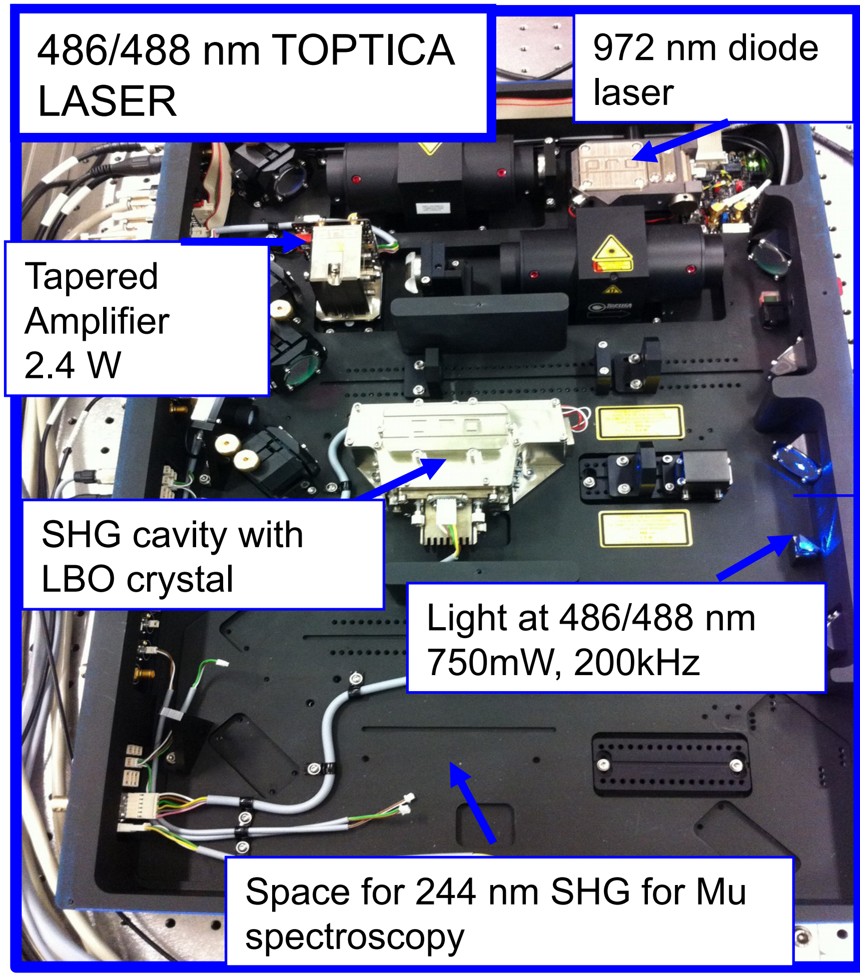
$$Z(a) = \sum_{n=1}^{\infty} e^{-\frac{h^2 n^2}{8ma^2}/kT},$$

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

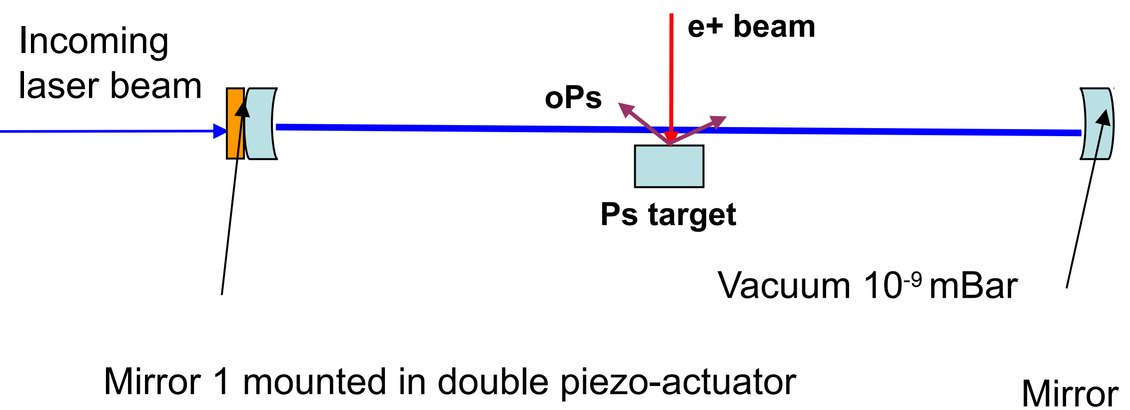
Laser spectroscopy



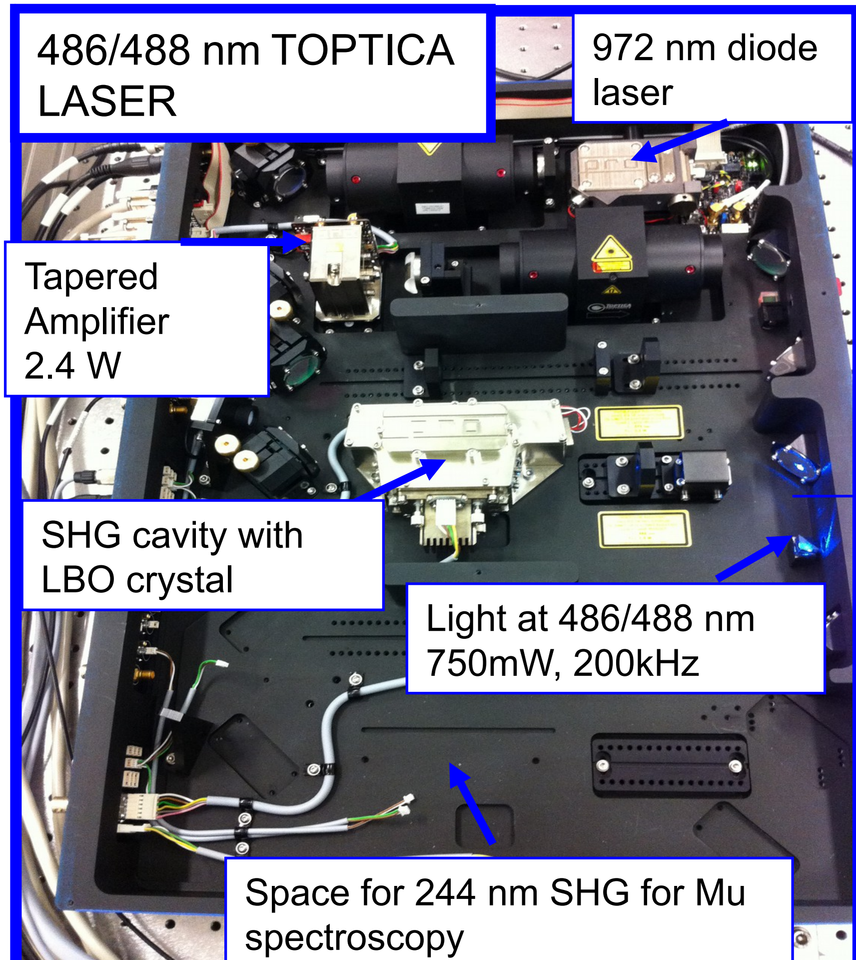
The laser system



<u>Requirements</u>:
- High power (~kW) at 486 nm -> detectable signal
- Long term stability (continuous data taking ~days)
- Scanning of the laser ± 100 MHz

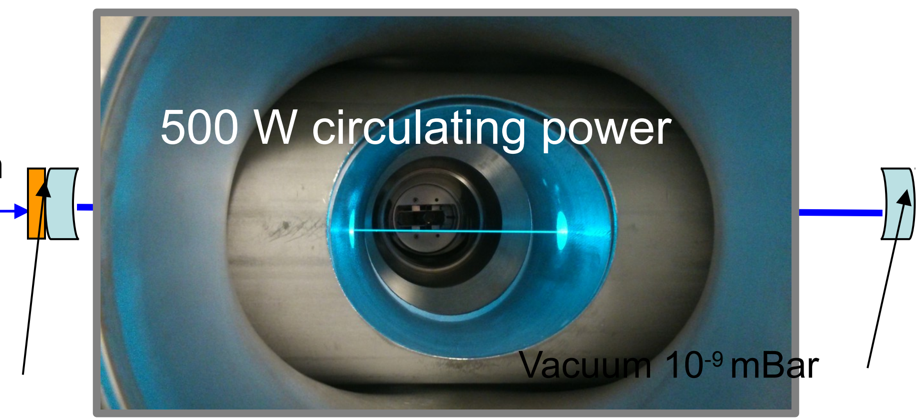


The laser system



<u>Requirements</u>:
- High power (~kW) at 486 nm -> detectable signal
- Long term stability (continuous data taking ~days)
- Scanning of the laser ± 100 MHz

Incoming laser beam



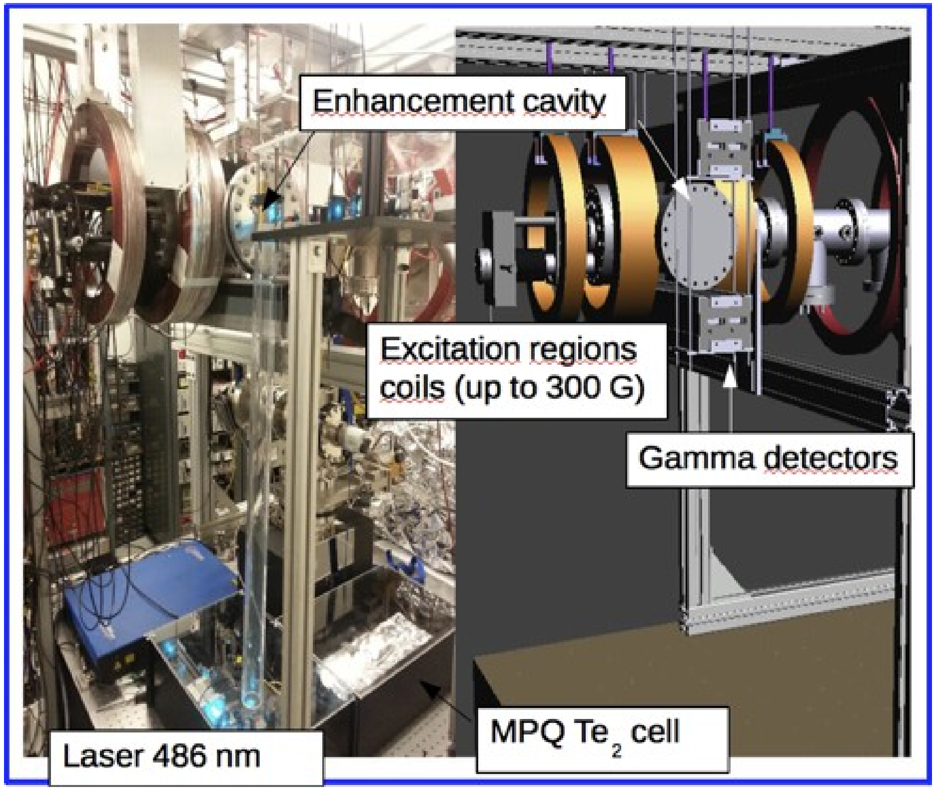
Mirror 1 mounted in double piezo-actuator

Mirror 2

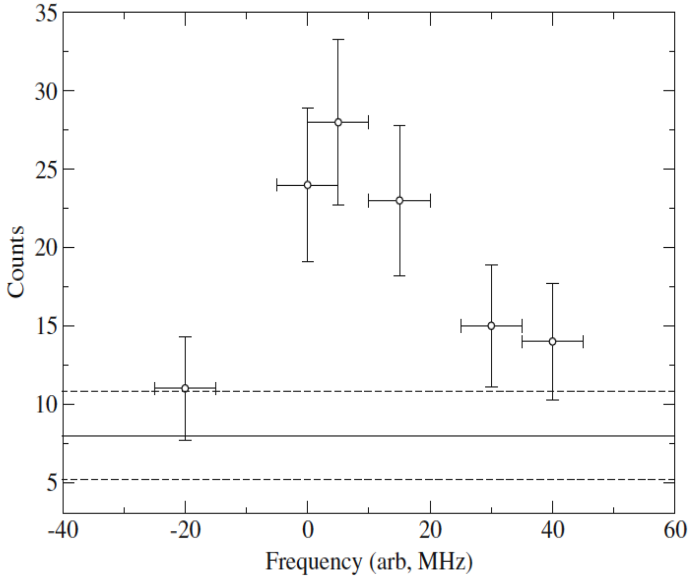
High finesse resonator for power build up
500 mW → 1 kW

Detection of Ps annihilation in the 2S state

CW slow positron beam setup



D.Cooke, PC et al, Hyp. Interact. 233 (2015) 1-3, 67



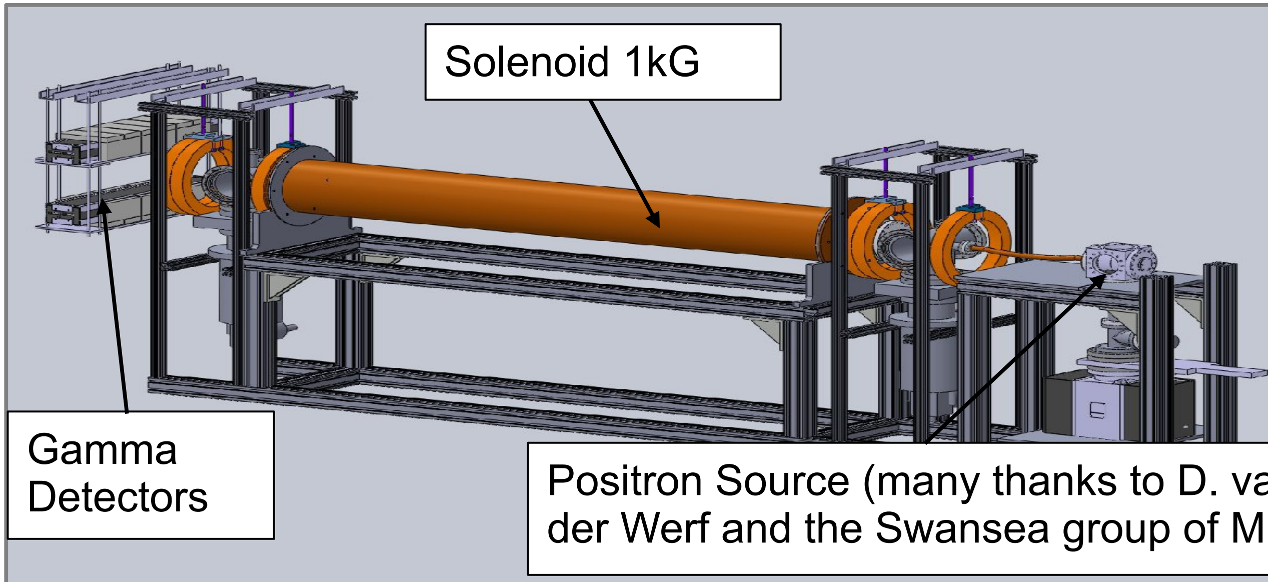
→ **S/N ratio should be improved.**

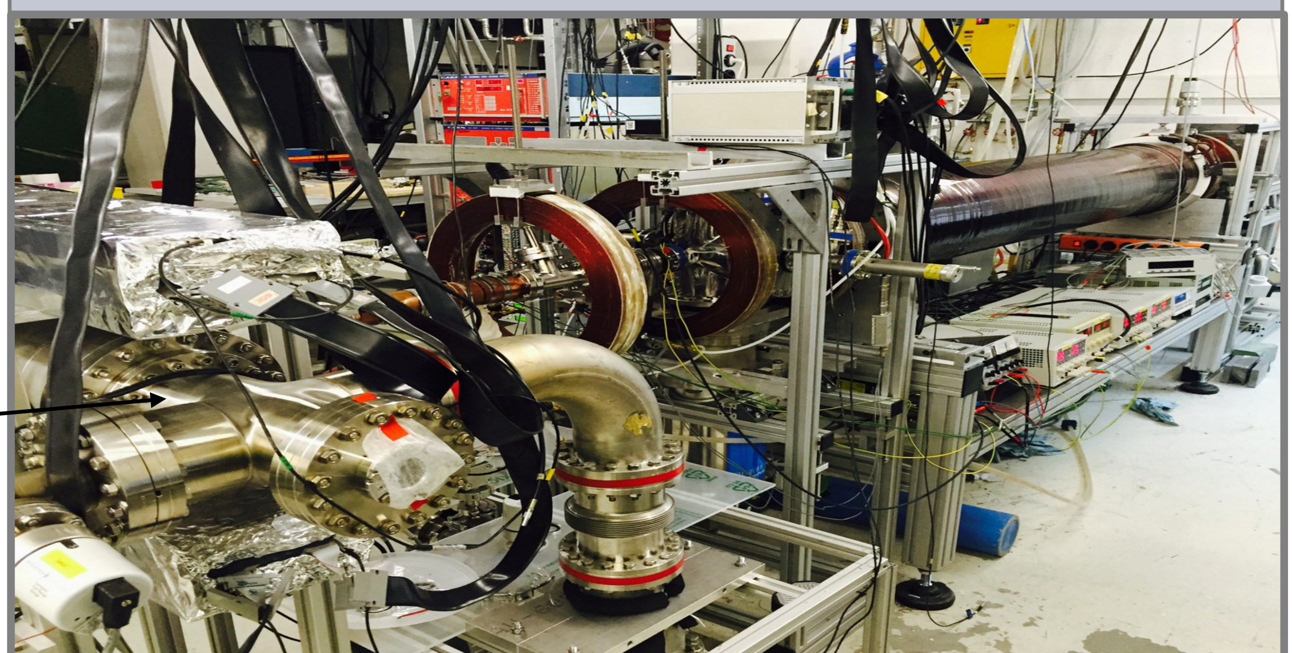
Use bunched beam (buffer gas trap)

→ Noise from **accidentals** reduced by 2 orders of magnitude

→ Reduction and correction of **systematic** effects

New beamline based on a buffer gas trap

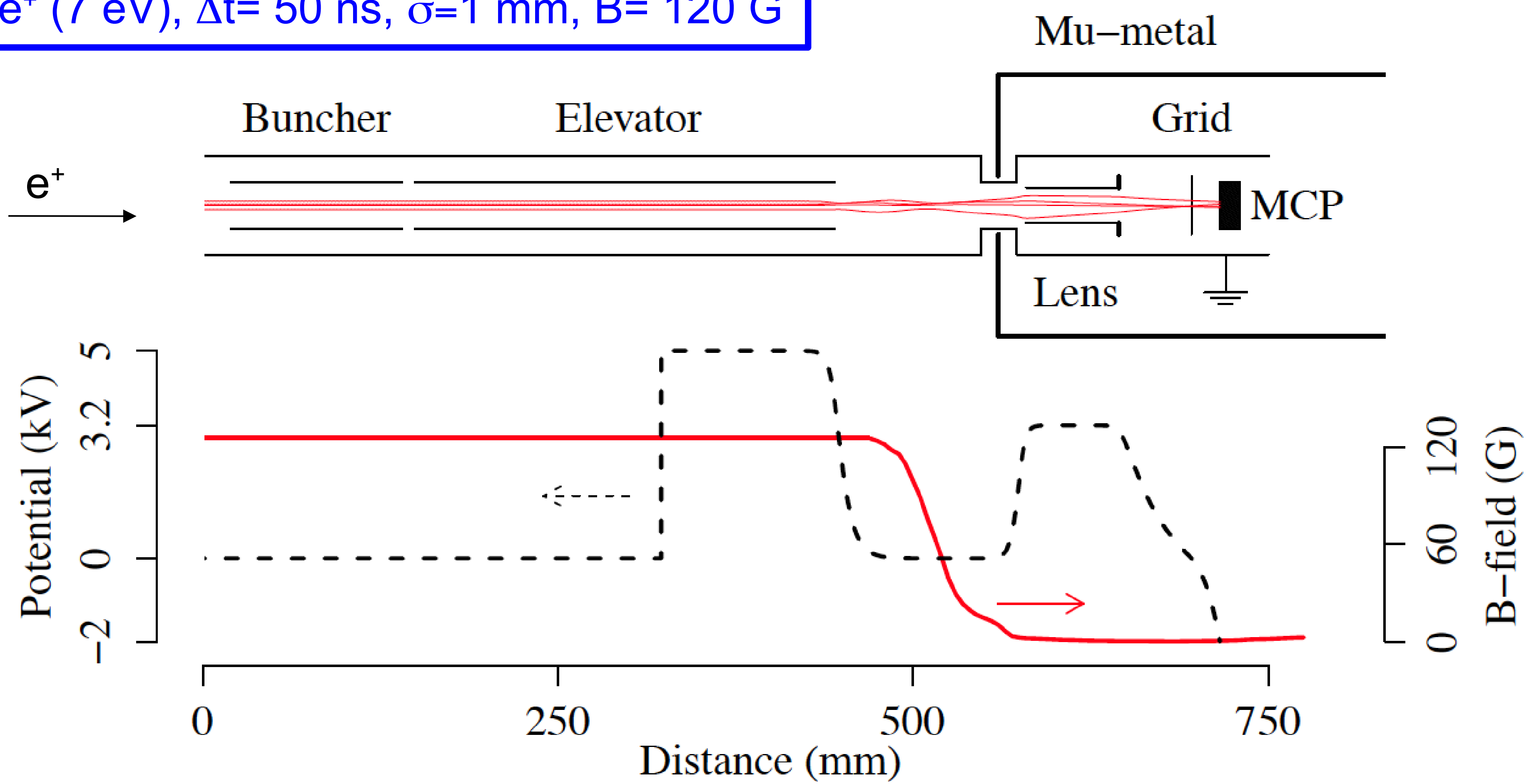




Bunching and extraction to a field free region

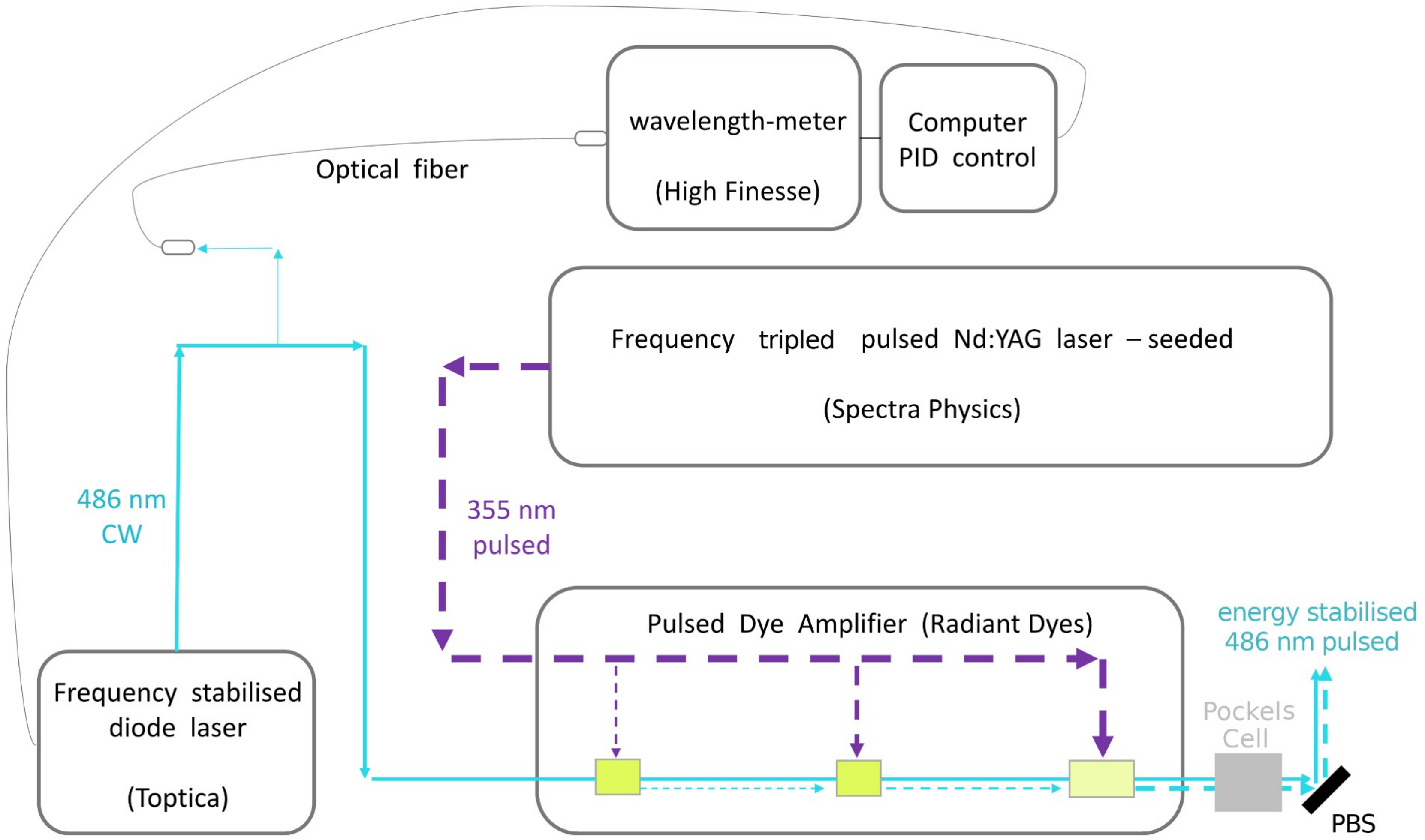
D. A. Cooke PC et al. , J. Phys. B: At. Mol. Opt. Phys. 49 014001 (2016)

e^+ (7 eV), Δt= 50 ns, σ=1 mm, B= 120 G

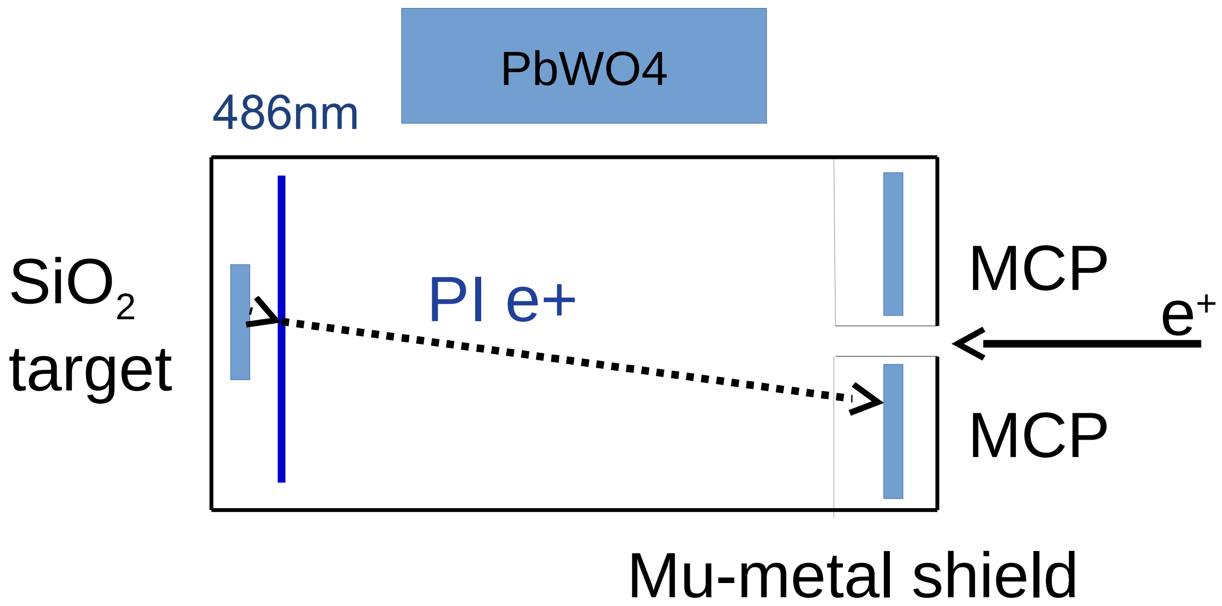


ON TARGET (@ground): Δt= 1 ns, σ=1 mm, B<0.1 G, 90 % efficiency

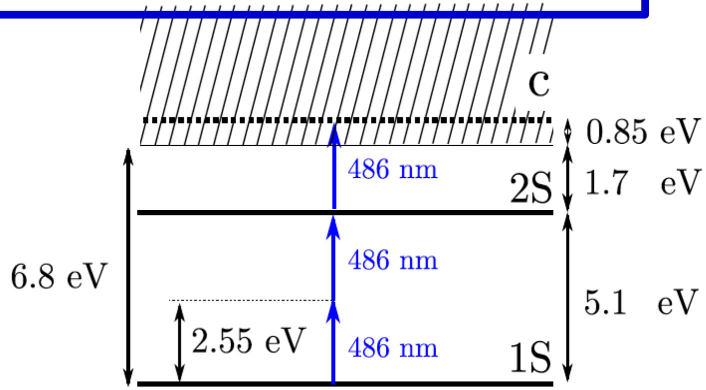
Pulsed laser system for Ps excitation



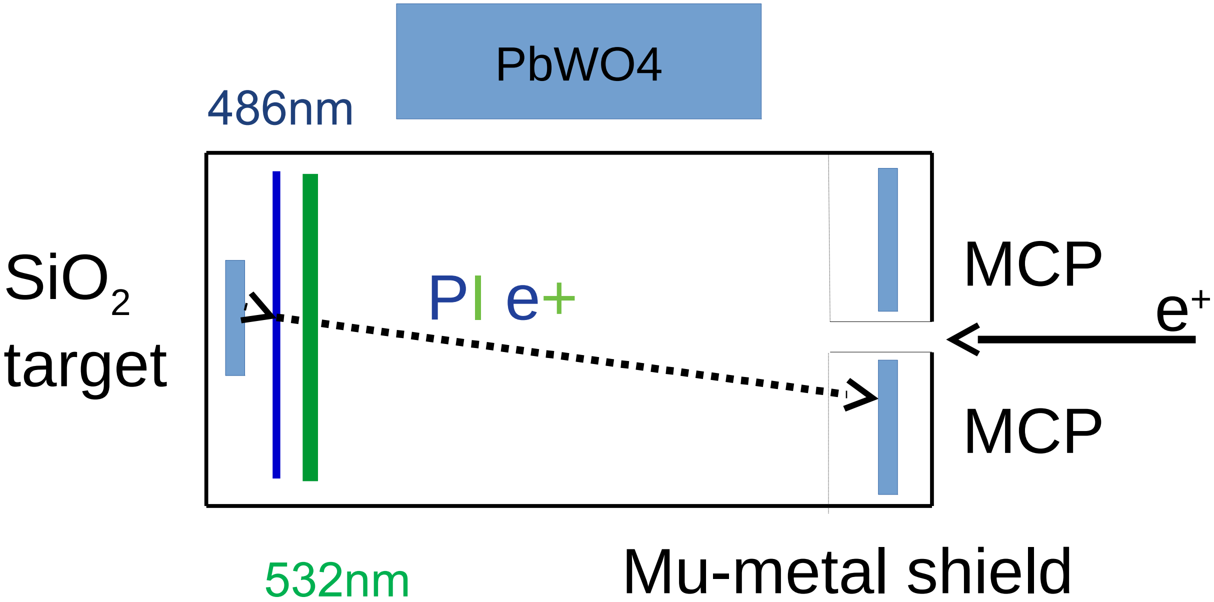
Detection schemes for Ps 2S excitation



Direct photo-ionization in the exciting laser

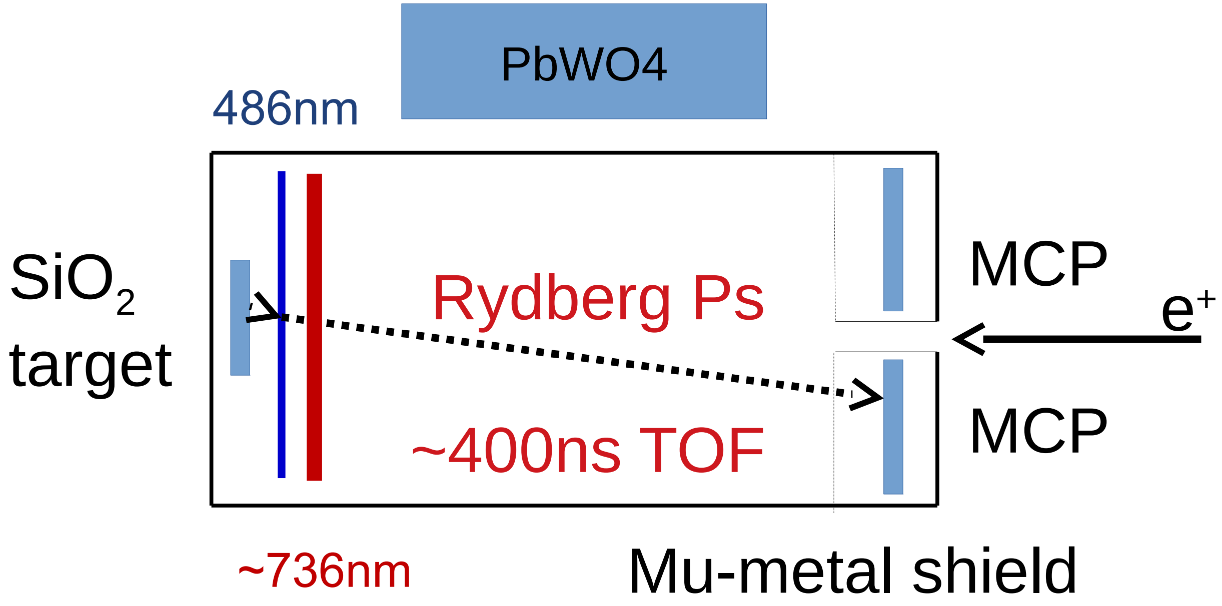


Detection schemes for Ps 2S excitation



2S photo-ionization in separate laser

Detection schemes for Ps 2S excitation



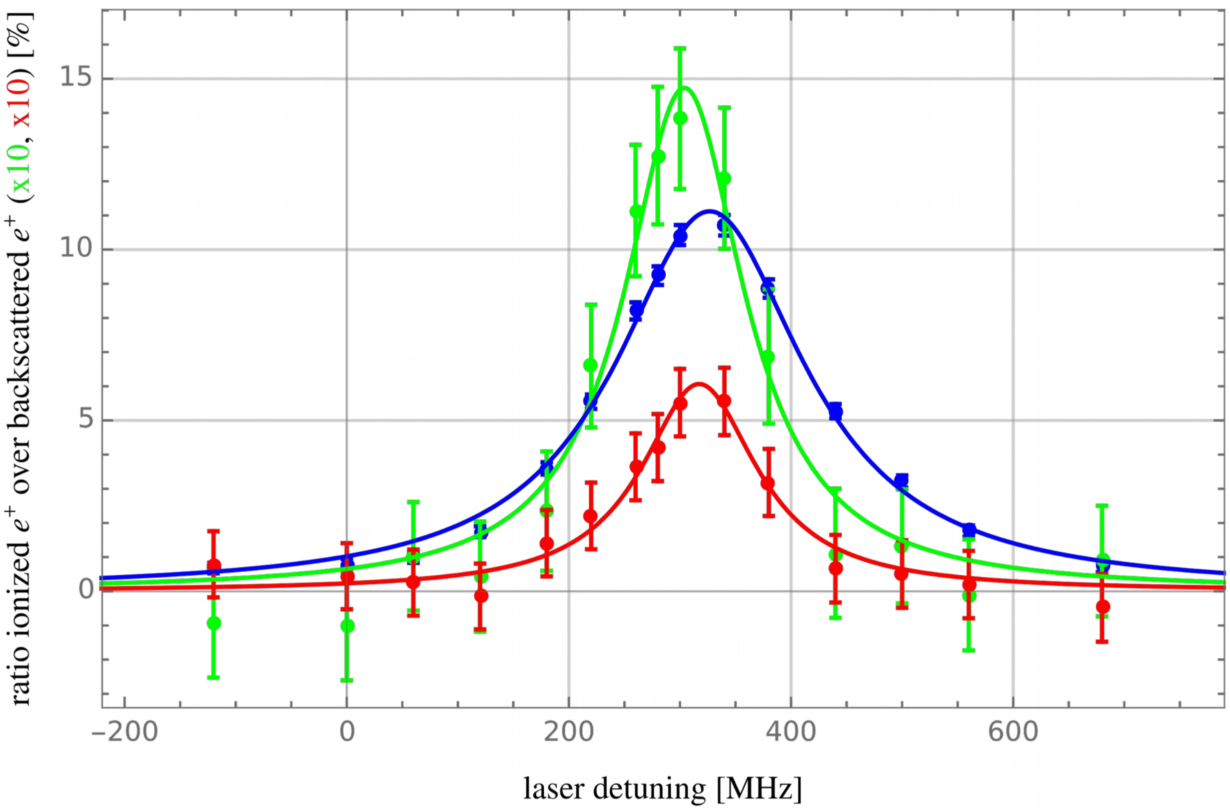
2S → Rydberg (e.g. 20P) and field ionization on MCP

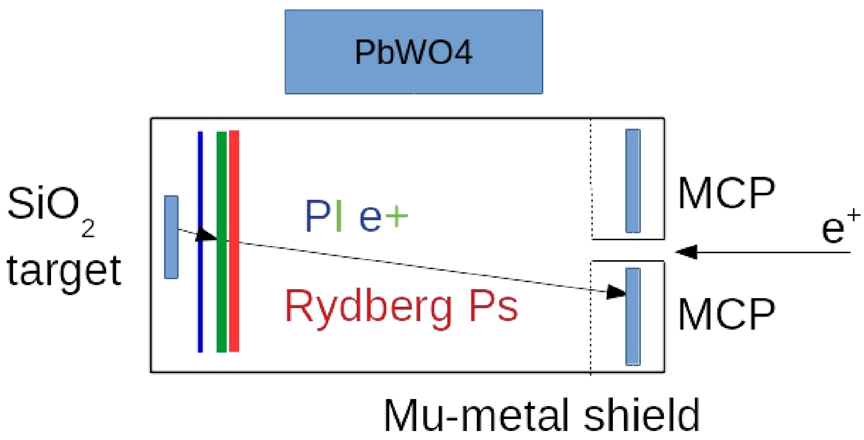
allows for correction of second order doppler shift (main systematic!)

$$\Delta\nu_{D2} = \nu_0 \frac{v^2}{2c^2}$$

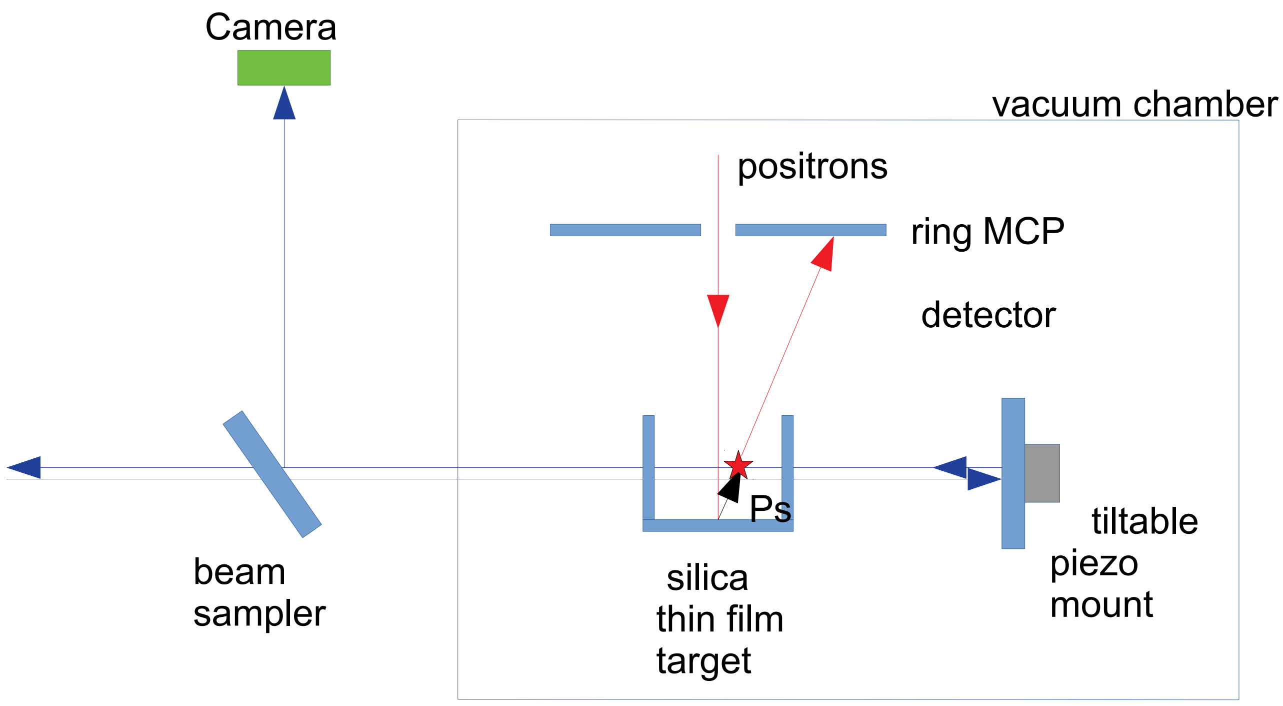
Detection schemes for Ps 2S excitation

M. Heiss, et al arXiv:1805.05886

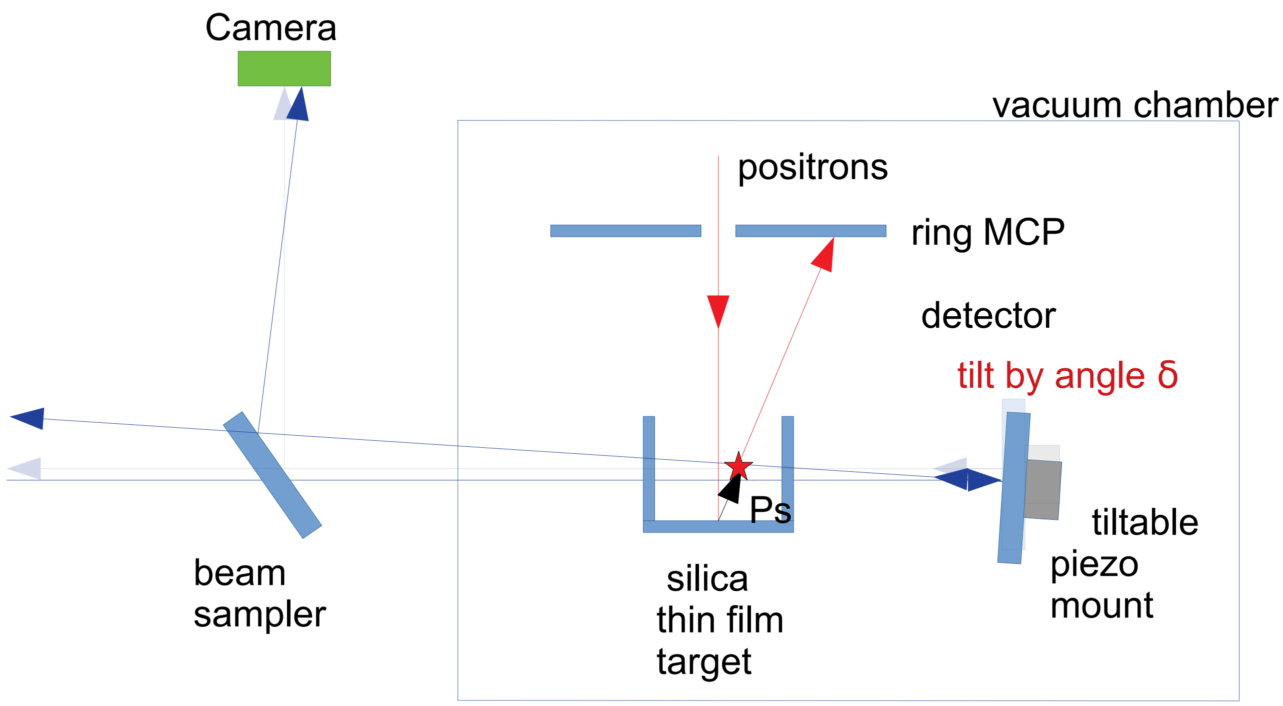




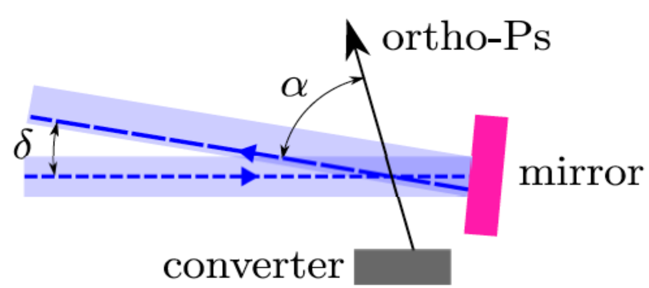
"Quasi" Doppler free excitation → velocity distribution

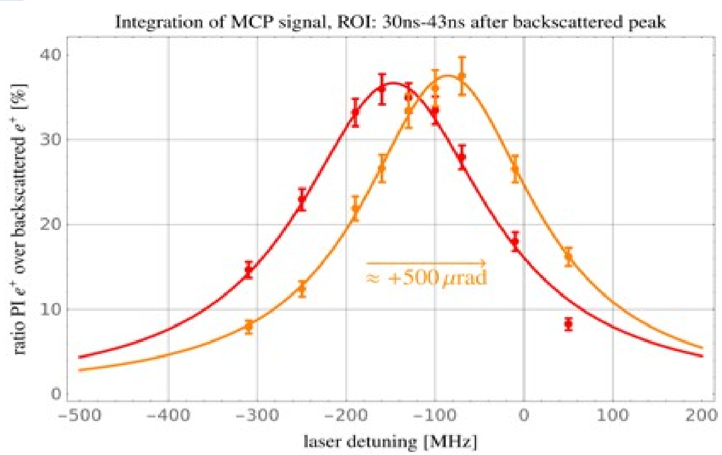


"Quasi" Doppler free excitation → velocity distribution



$$\Delta\nu \propto v_{Ps}\cdot\delta$$





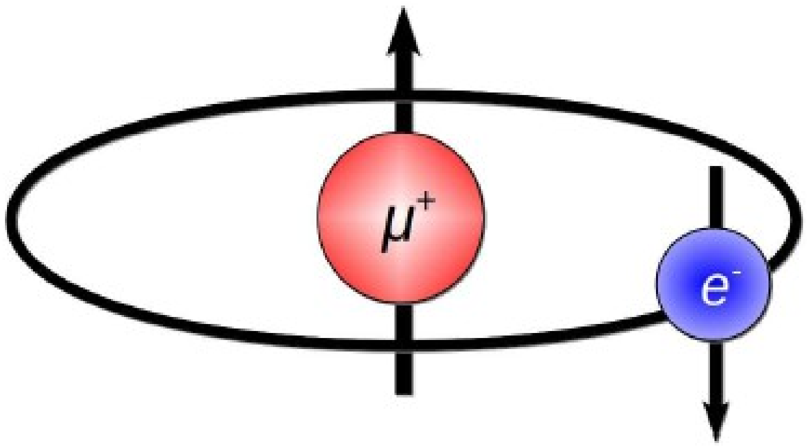
Outlook of 1S-2S Ps spectroscopy

NEXT STEPS
→ Combine CW laser with bunched positron beam.
→ Absolute frequency reference: upgrade with output @ 972 nm frequency comb of Prof. Esslinger group (ETHZ).

GOAL: current source (10000 Ps/pulse @ 40 meV)
→ Measurement of 1S-2S of Ps at a level about 5×10^{-10}
→ Check QED calculation, SME test (sidereal variations)

POTENTIAL IMPROVEMENTS
→ GBAR LINAC
→ Colder Ps source?

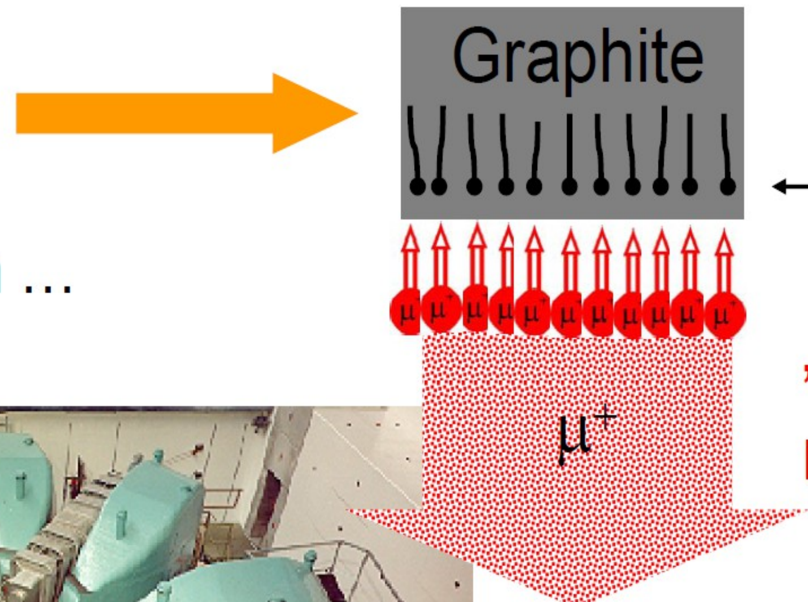
Muonium formation



Polarized surface muon generation

2.2 mA ≅ 1.4 10^{16} Protons/sec

with 600 MeV

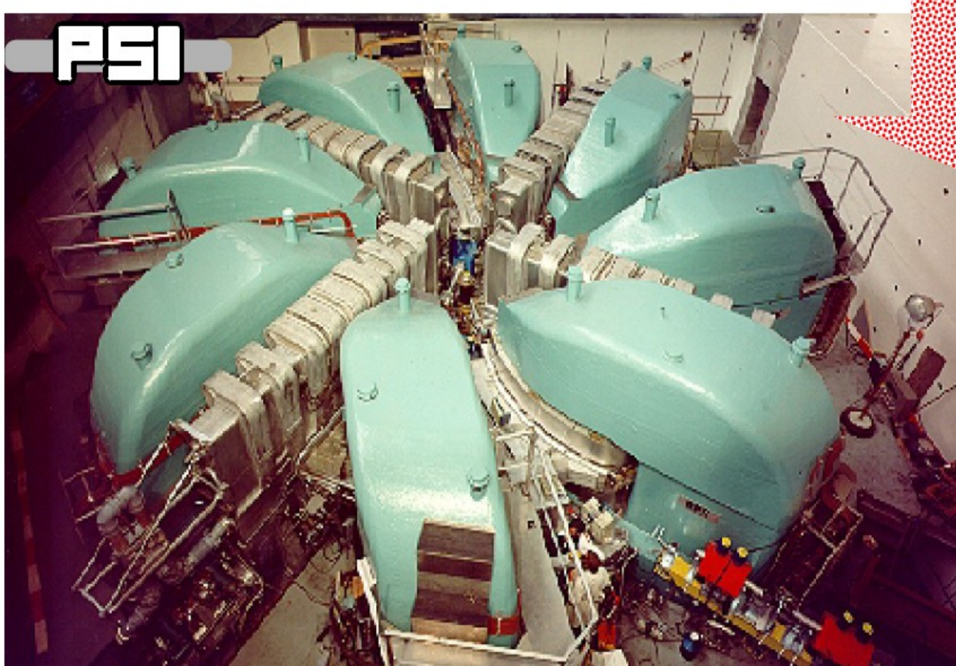


Production Target

$\leftarrow \pi^+$

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

„Surface“ muons



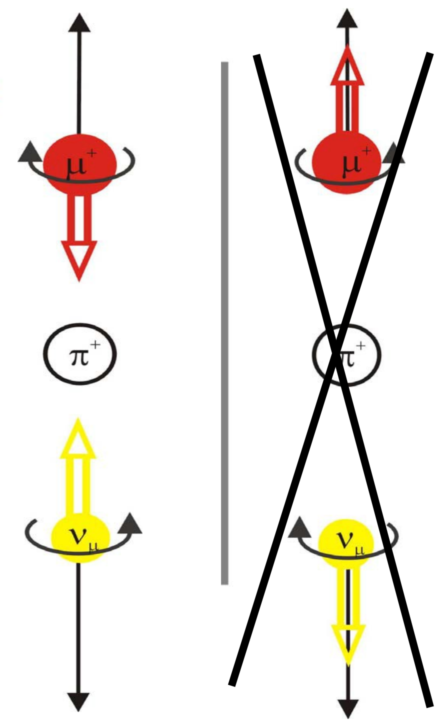
~10^7- 10^8 μ^+/sec

100 % pol.

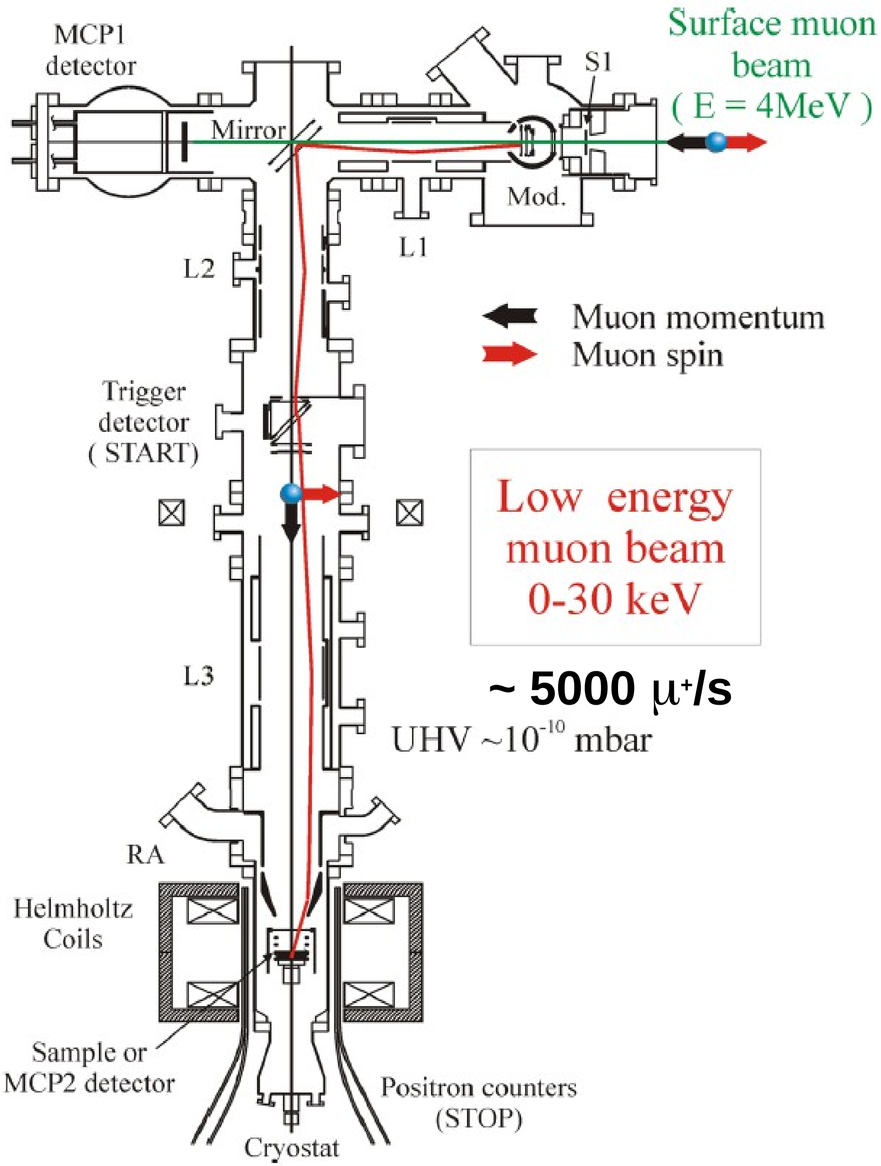
~ 4 MeV

generally used for “bulk” condensed matter studies

For thin film studies: eV-30 keV

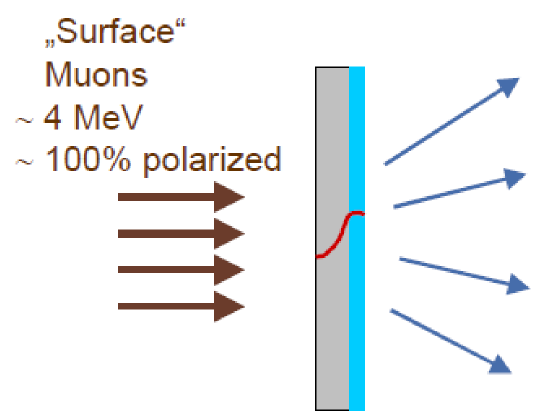


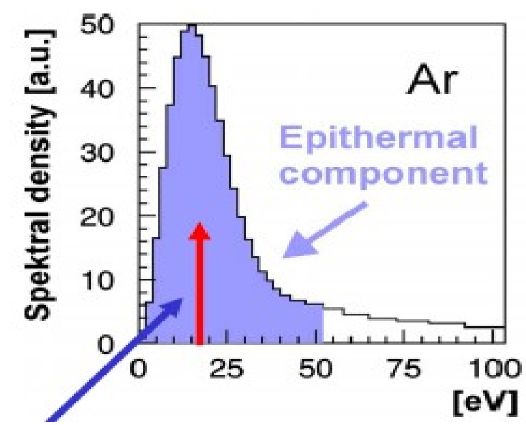
Low energy muon (LEM) beam line at PSI



~ 5000 μ^+/s

~1.9 x 10^8 μ^+/s

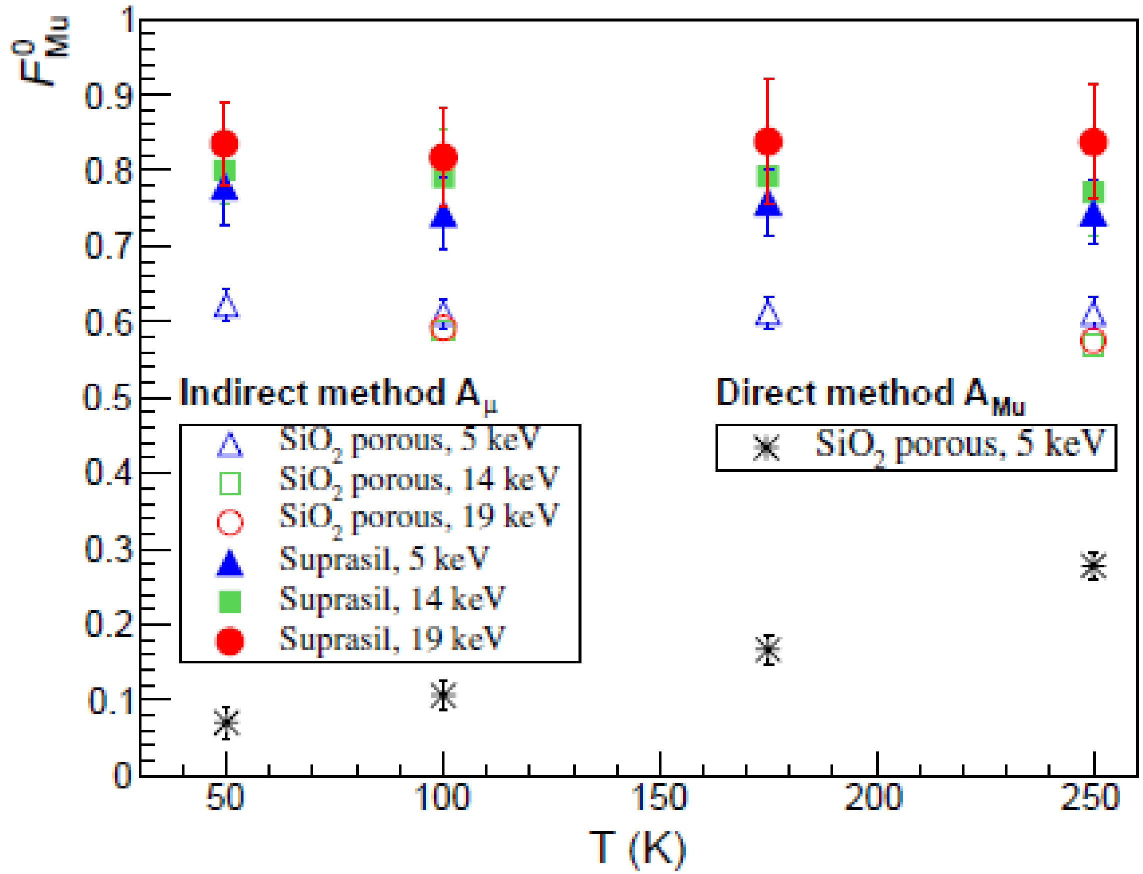




E~15eV

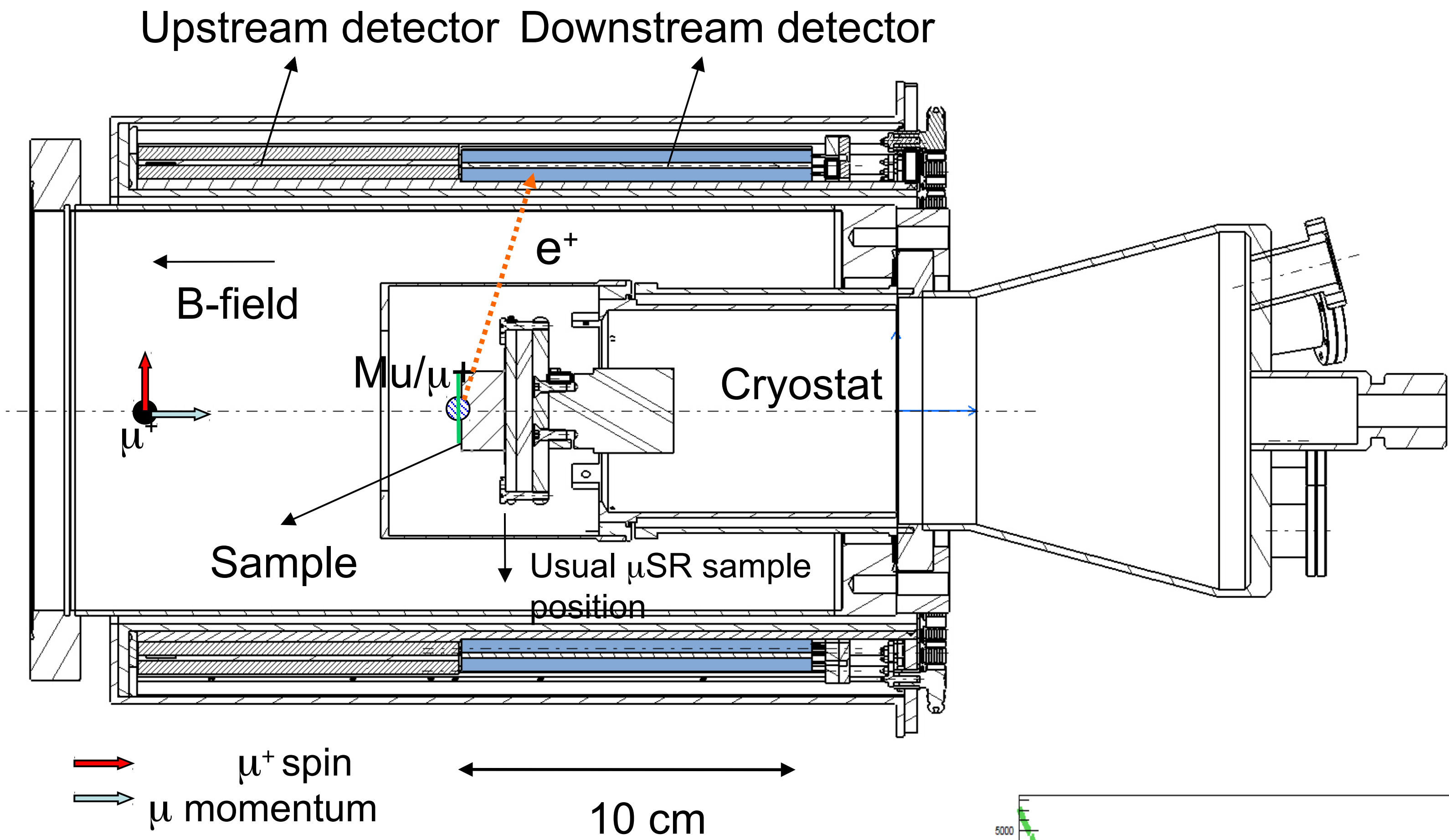
muSR results for porous and bulk SiO2

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

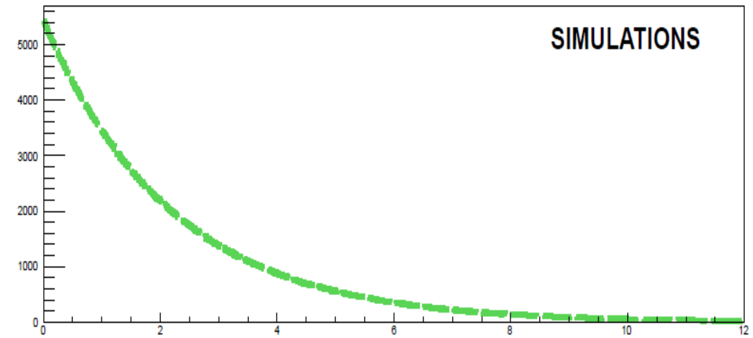


MuSR → Mu is formed but is this emitted in vacuum?

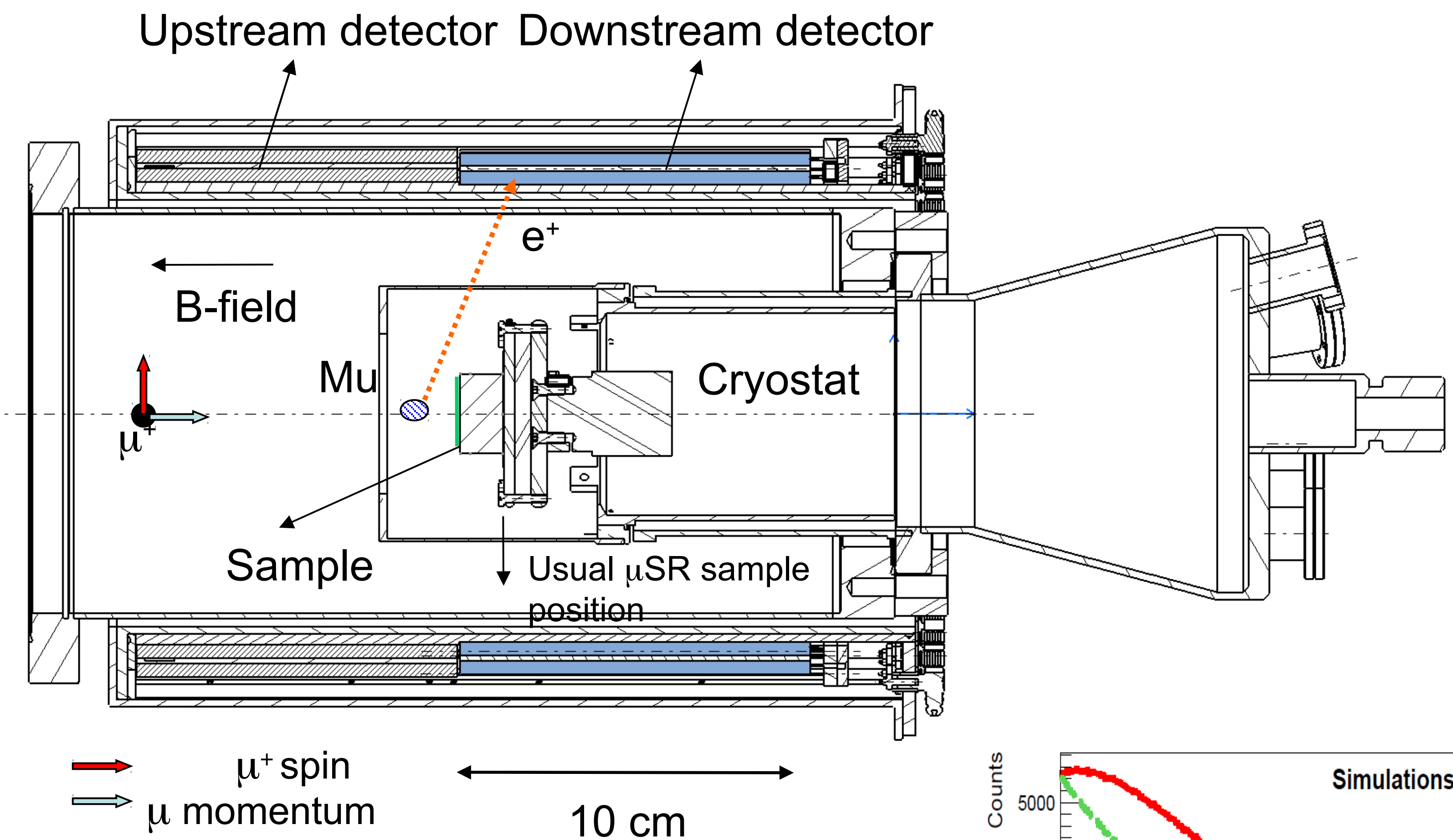
Positron shielding technique (PST)



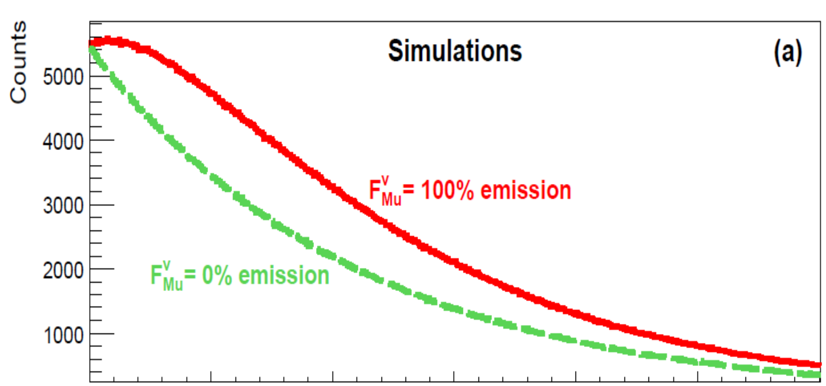
No emission into vacuum



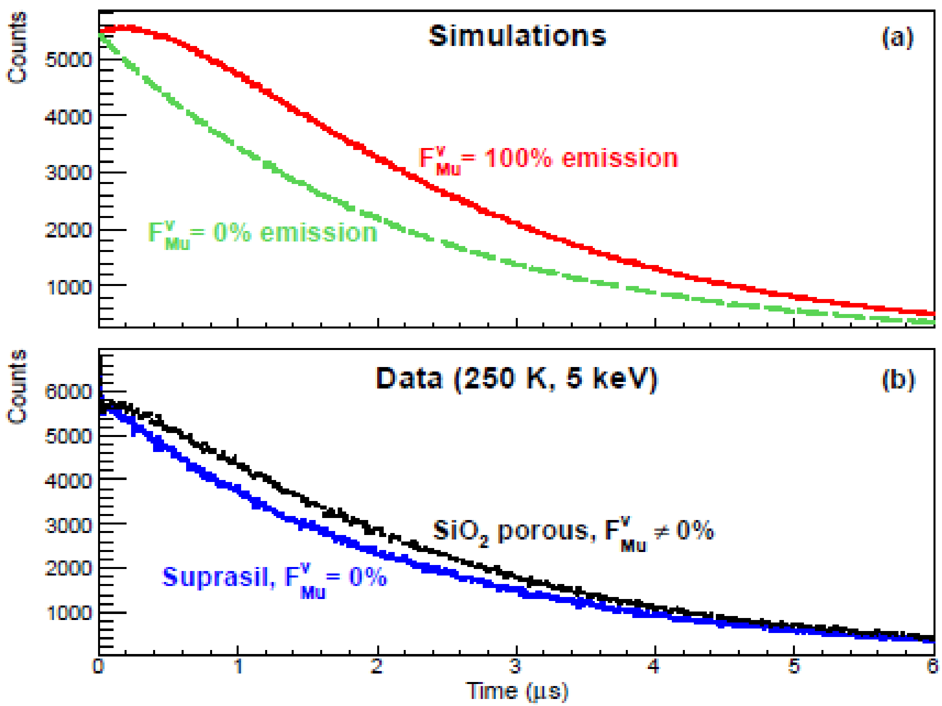
Positron shielding technique (PST)

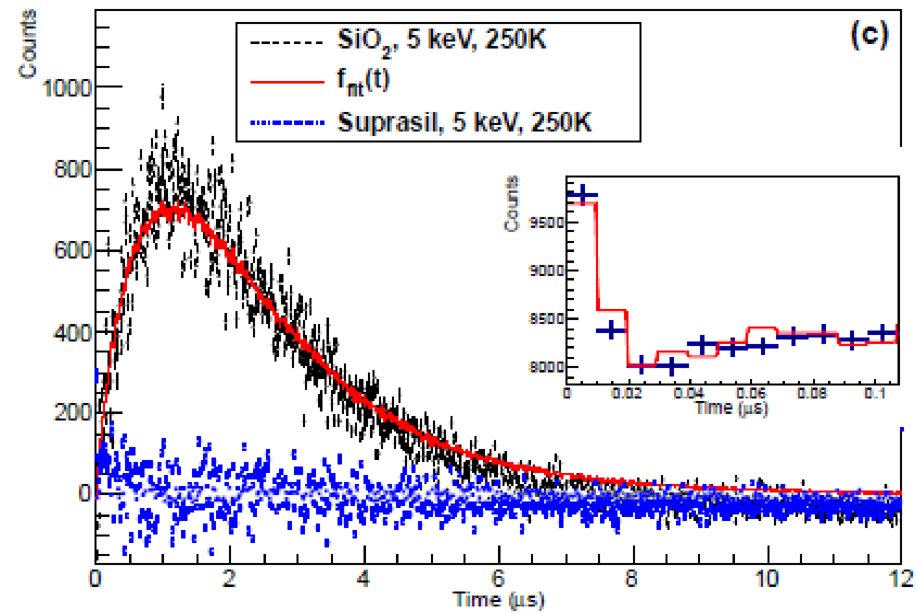


Emission into vacuum



PST principle



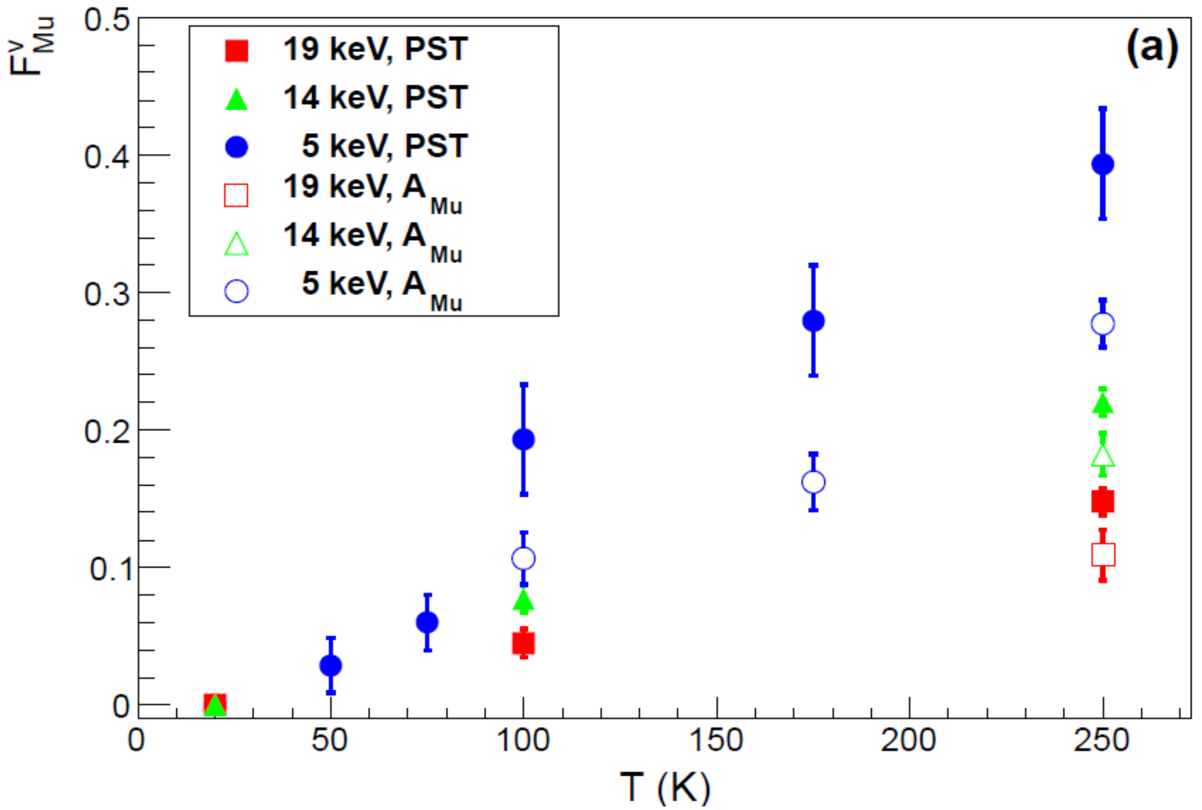


$$f_{\text{fit}}(t) = n[(1 - F^{v}_{Mu})f_0(t) + F^{v}_{Mu}f_{100}(t)] + n_{pp}f_{pp}(t)$$

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

PST results

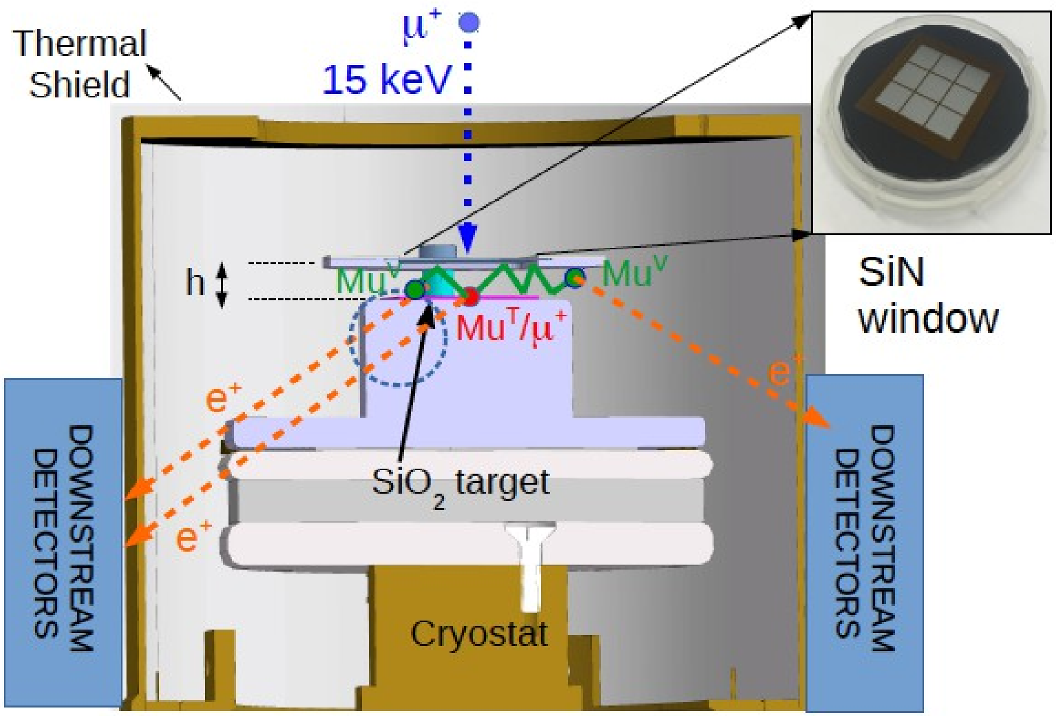
A. Antognini (ETHZ), P. Crivelli (ETHZ), K. S. Khaw (ETHZ), K. Kirch,(ETHZ/PSI), B Barbiellini (NU Boston), L. Liszkay (CEA),T. Prokscha (PSI), E. Morenzoni (PSI), Z. Salman (PSI), A. Suter (PSI), PRL 108, 143401 (2012)

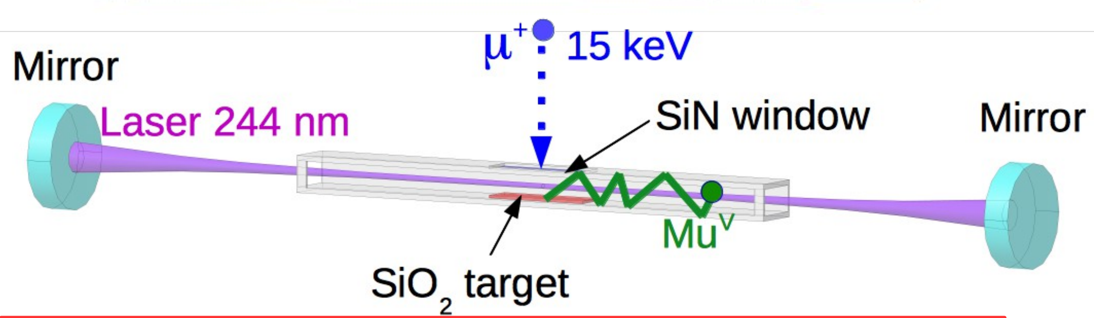


(38±4)% at 250 K and (20±4)% at 100 K for 5 keV

Muonium spatial confinement

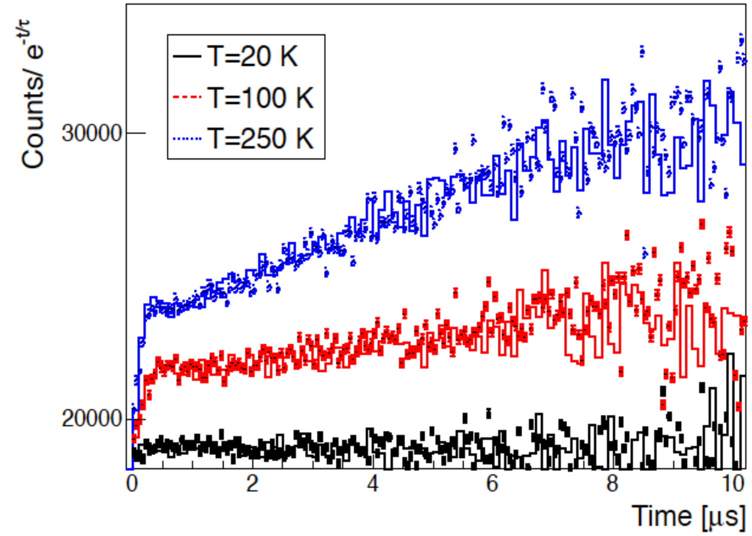
K. S. Khaw, A. Antognini, T. Prokscha, K. Kirch, L. Liszkay, Z., Salman, P. Crivelli, PRA 94, 022716 (2016)

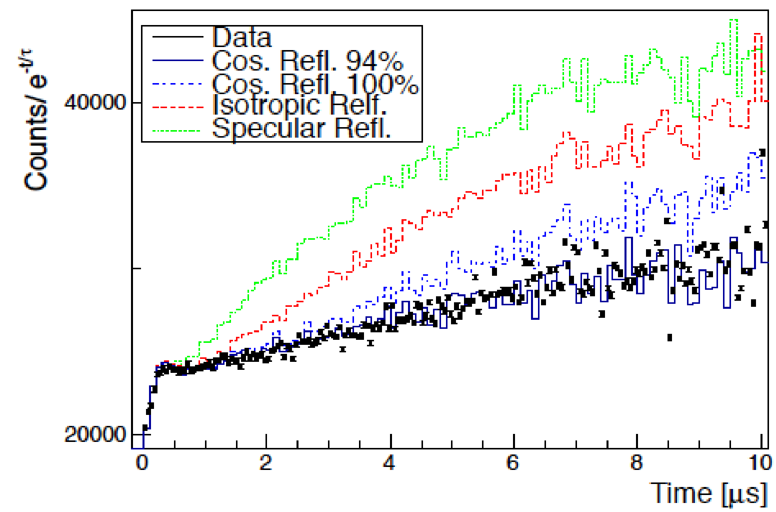




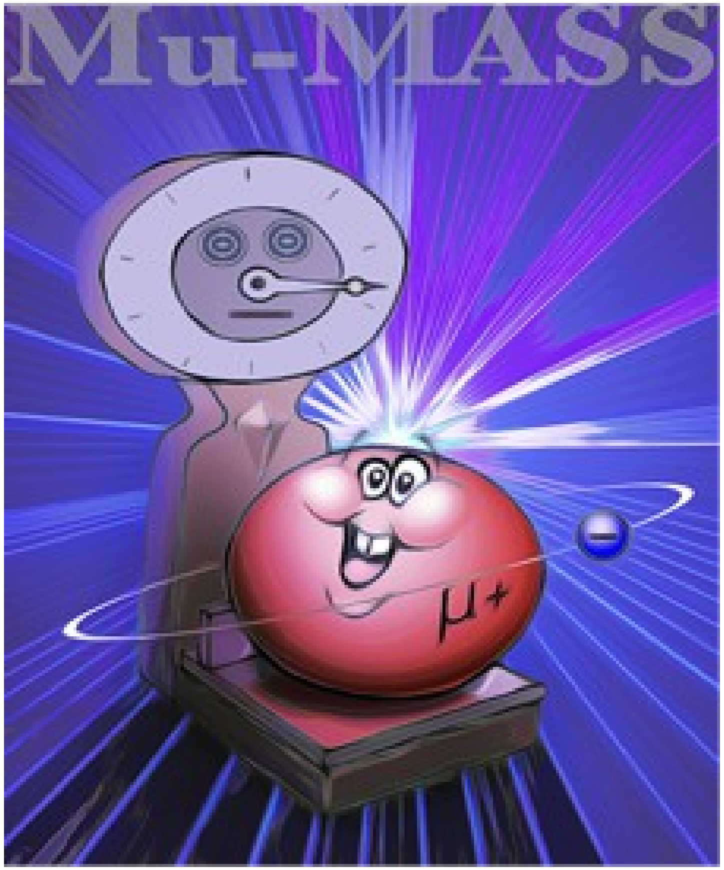
Factor 5 enhancement in exc. probability

DATA-SIM 1mm



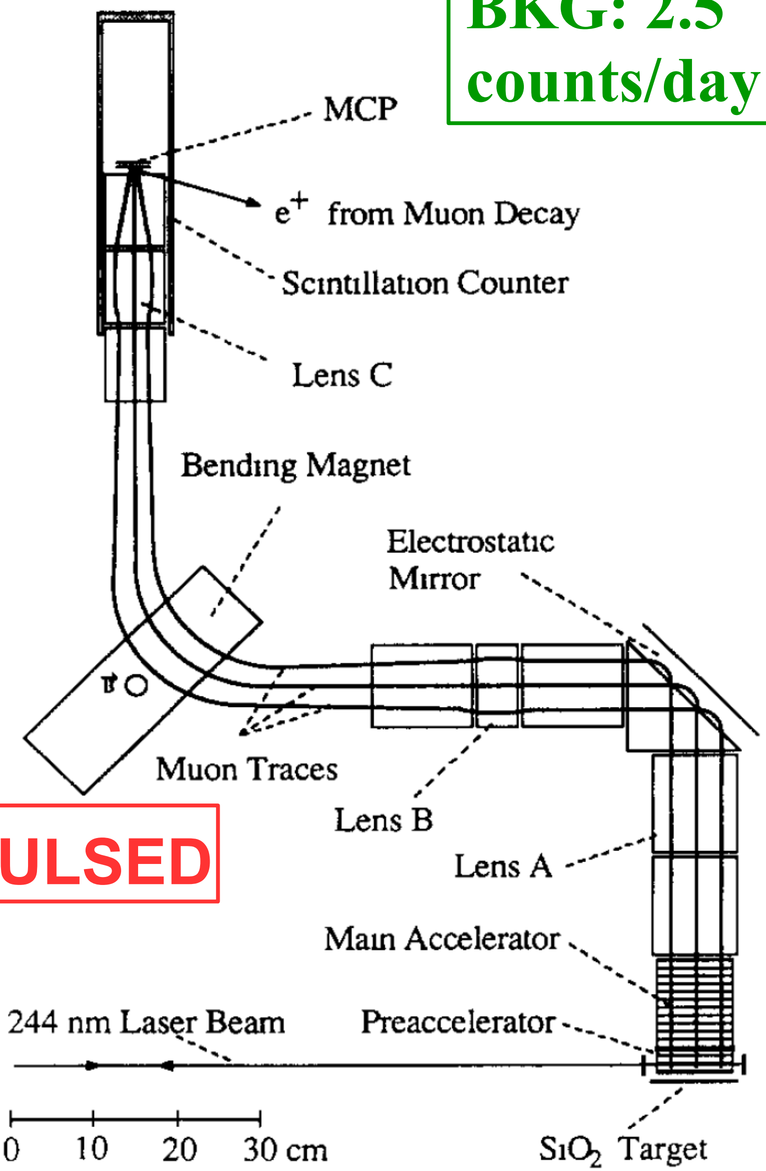


MuoniuM lAser SpectroScopy (Mu-Mass)

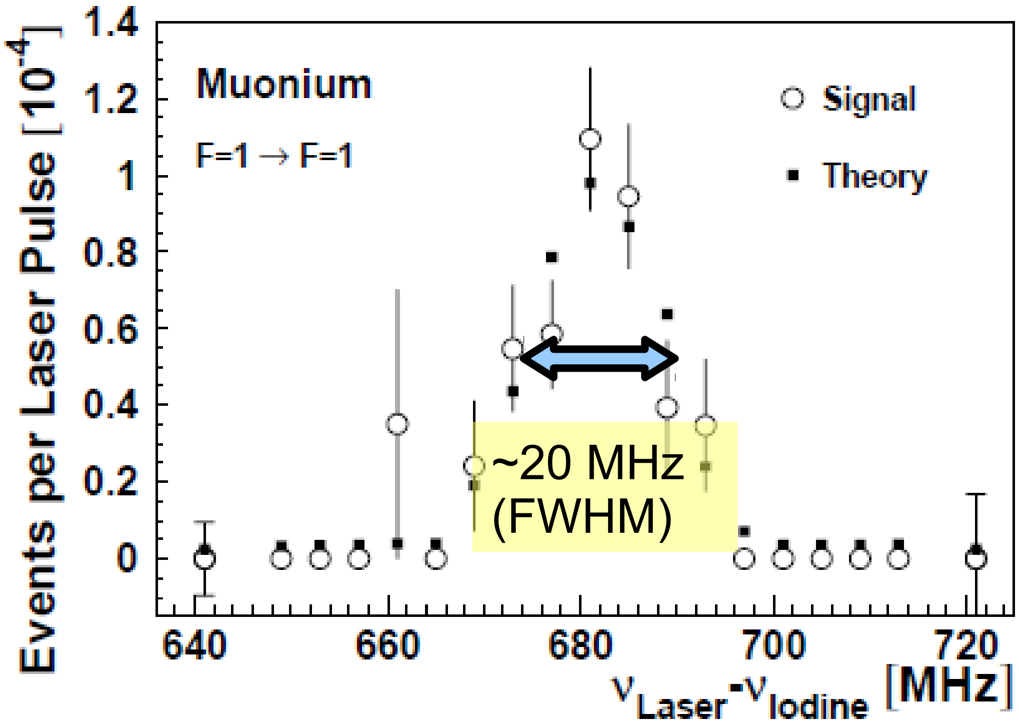


Current (1999) 1S-2S measurement

BKG: 2.5 counts/day



PULSED



F. Maas, Physics Letter A 187, 247 (1994)
Meyer et al. PRL84, 1136 (2000)

3500 mu+/pulse, 50 Hz, 80 Mu/pulse

1S-2S CW laser spectroscopy

The 1S-2S signal rate is proportional to

$$R \sim N_{\mathrm{Mu}} \cdot I^2 \cdot t^2$$

where

- N_{Mu} : Muonium production rate
- I : Laser intensity
- $t \sim v^{-1}$: Interaction time

Need a Mu source with high yield and low energy

Decrease requirements of laser intensity

Mu @ 100 K

HP 244 nm laser light

First CW spectroscopy

(Z. Burkley et al., Appl. Phys. B 123, 5 (2016) and F. Cooper et al. Optic Letters 43, 1375 (2018)

Pulsed vs CW spectroscopy

	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
M atoms	600 s^{-1} @ 300K	1000 s^{-1} @ 100 K	1800 s^{-1} @ 100 K
Spectroscopy	Pulsed laser	CW	CW
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
Total number of 2S events	99	1900 (10 d)	> 7000 (40 d)
Statistical uncertainty	9.1 MHz	<100 kHz	10 kHz
Total uncertainty	9.8 MHz	<100 kHz (linewidth/10)	10 kHz (linewidth/30)

For CW reduction of the transition linewidth by a factor >20!

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Systematic related to pulsed excitation eliminated

Pulsed vs CW spectroscopy

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→ Improvement in reach using the LEM beamline at PSI

Outlook – Muonium spectroscopy

NEXT STEPS
- Upgrade Ps laser with fiber amplifier and SHG (CLBO) + UV enhancement cavity.
- Develop laser: Mu(2S) → Mu* enhance the signal and measure atoms velocity.
- Test new targets for Mu prodution (in collaboration with PSI muon group)

GOAL:
→ Improve muon mass (1 ppb) adn q_μ/q_e (1 ppt)
Combined with HFS:
→ stringent test of bound state QED (rel. accuracy 1 ppt)
→ Rydberg costant free of finite size effects (few ppt), α (1 ppb)
→ Test of SME

POTENTIAL IMPROVEMENTS:
1S-2S results will be statistically limited
→ New low energy beam lines under development at PSI (Kirch group, ETHZ/PSI) and at JPARC → 2 orders of magnitude more low energy muons expected.

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IPA ETH zürich

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