Positronium and Muonium two photon laser spectroscopy

Paolo Crivelli

Institute for Particle Physics and Astrophysics, ETH Zurich

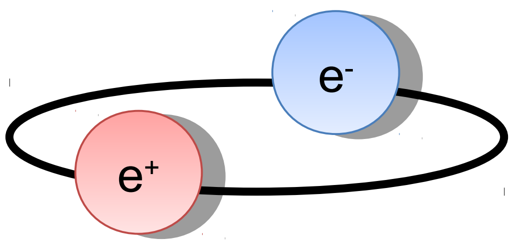
LEAP 2018- 16th of March 2018 – Paris (France)

Leptonic atoms

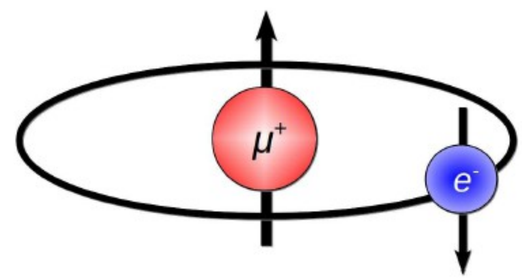
Precise test of bound state QED free from finite size effects

Fundamental constants

Positronium (Ps)



Muonium (Mu)



Test of the fundamental symmetries and search for new physics

See talks Vargas and Moskal

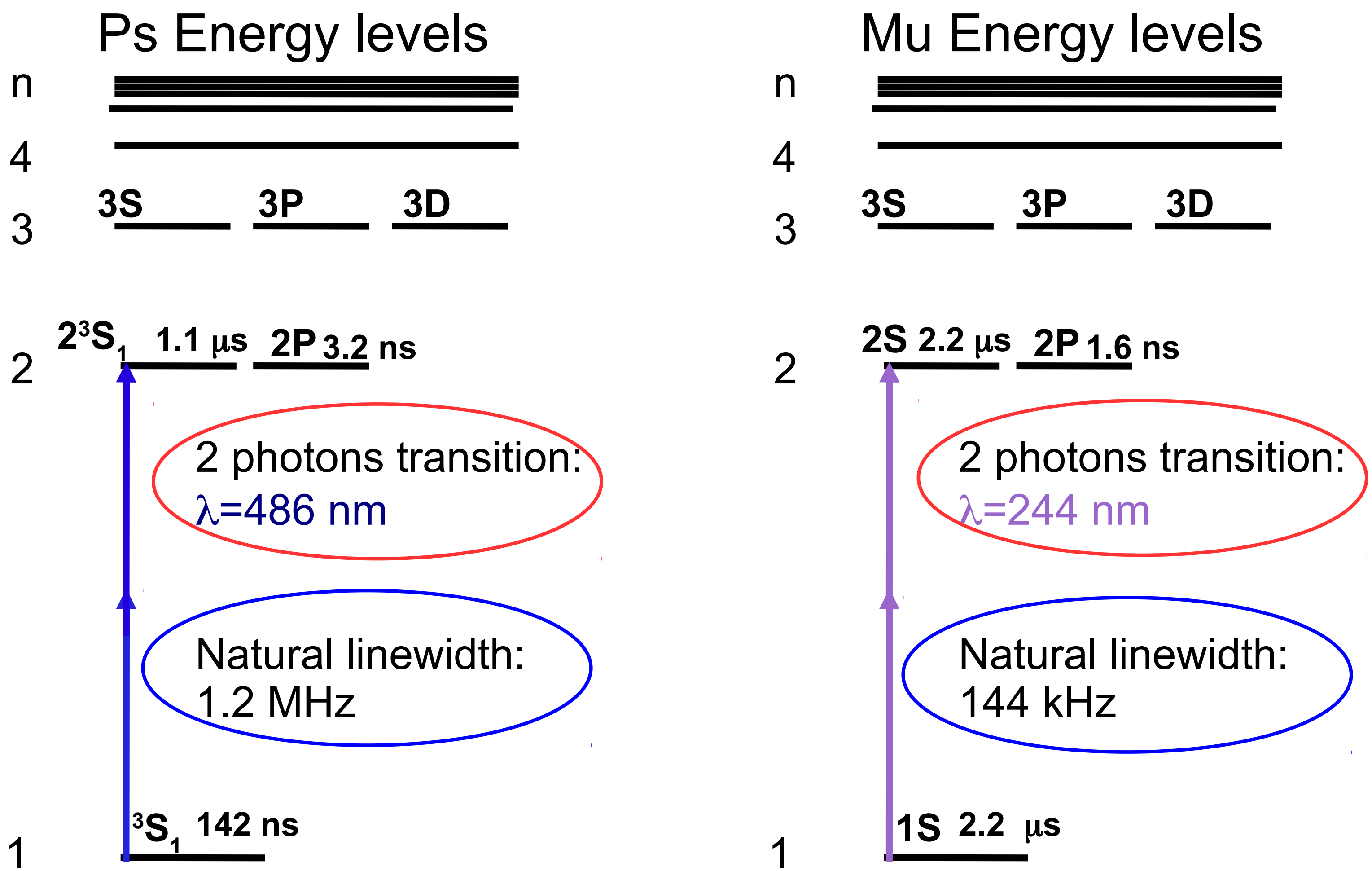
TODAY: arXiv:1803.05744 [hep-ex]

Applications in material science

Test the effect of gravity on anti-matter

See talk A. Soter

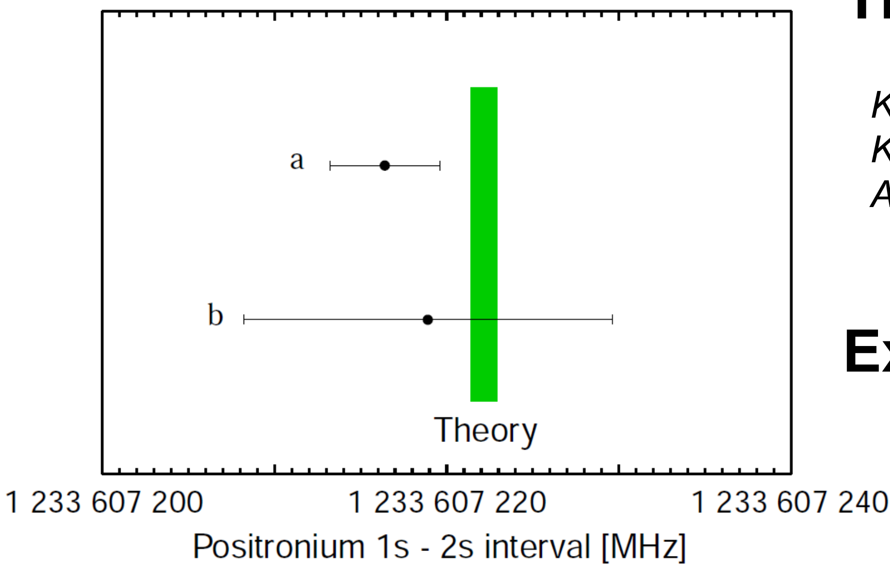
Ps/Mu energy levels



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

Positronium 1S-2S transition

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

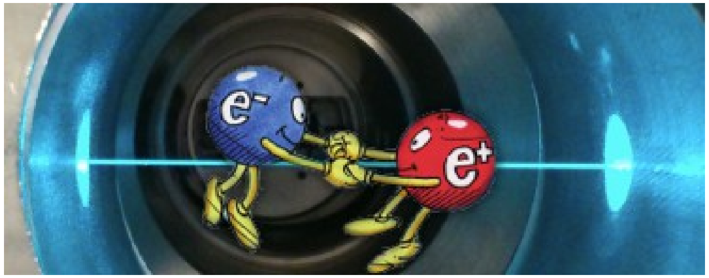
M. S. Fee et al., Phys. Rev. Lett. 70, 1397 (1993)
S. Chu, A. P. Mills, Jr. and J. Hall, Phys. Rev. Lett. 52,1689 (1984)

New measurement ongoing at ETHZ: goal 0.5 MHz

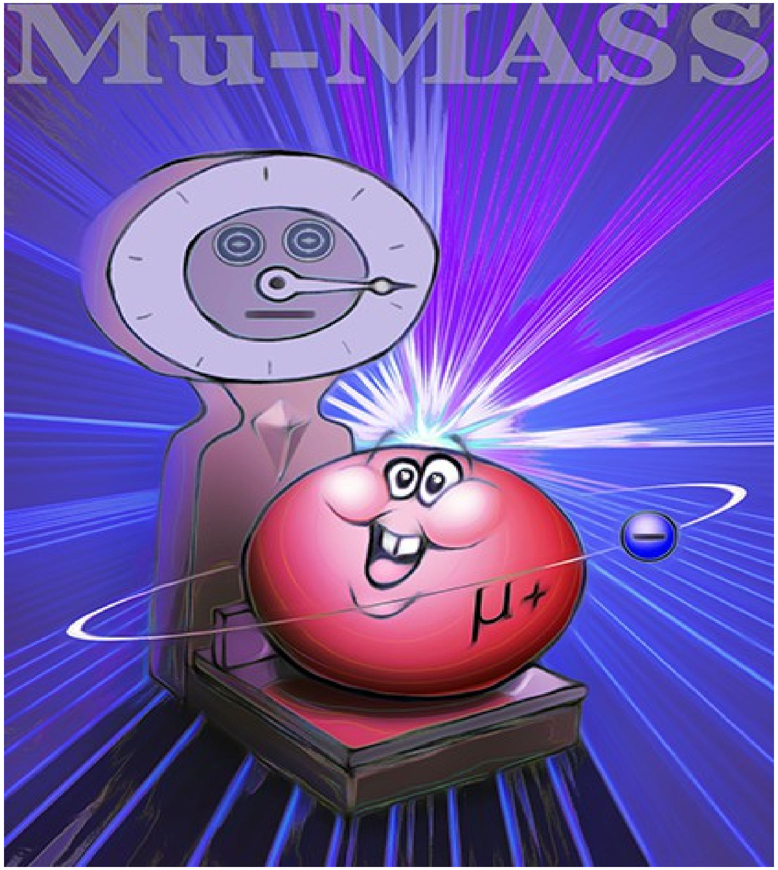
1) Check QED calculations ($\alpha^7 m$)

2) Stringent test of SME See talk A.Vargas

3) Positron to electron mass ratio



Muonium 1S-2S spectroscopy



Experiment:

$$\Delta\nu_{1s2s}(\text{expt.}) = 2\,455\,528\,941.0(9.8)\ \text{MHz}$$

Meyer et al. PRL84, 1136 (2000):

Theory:

$$\Delta\nu_{1s2s}(\text{theory}) = 2\,455\,528\,935.4(1.4)\ \text{MHz}$$

Limited by knowledge of muon mass.
QED calculations at 20 kHz

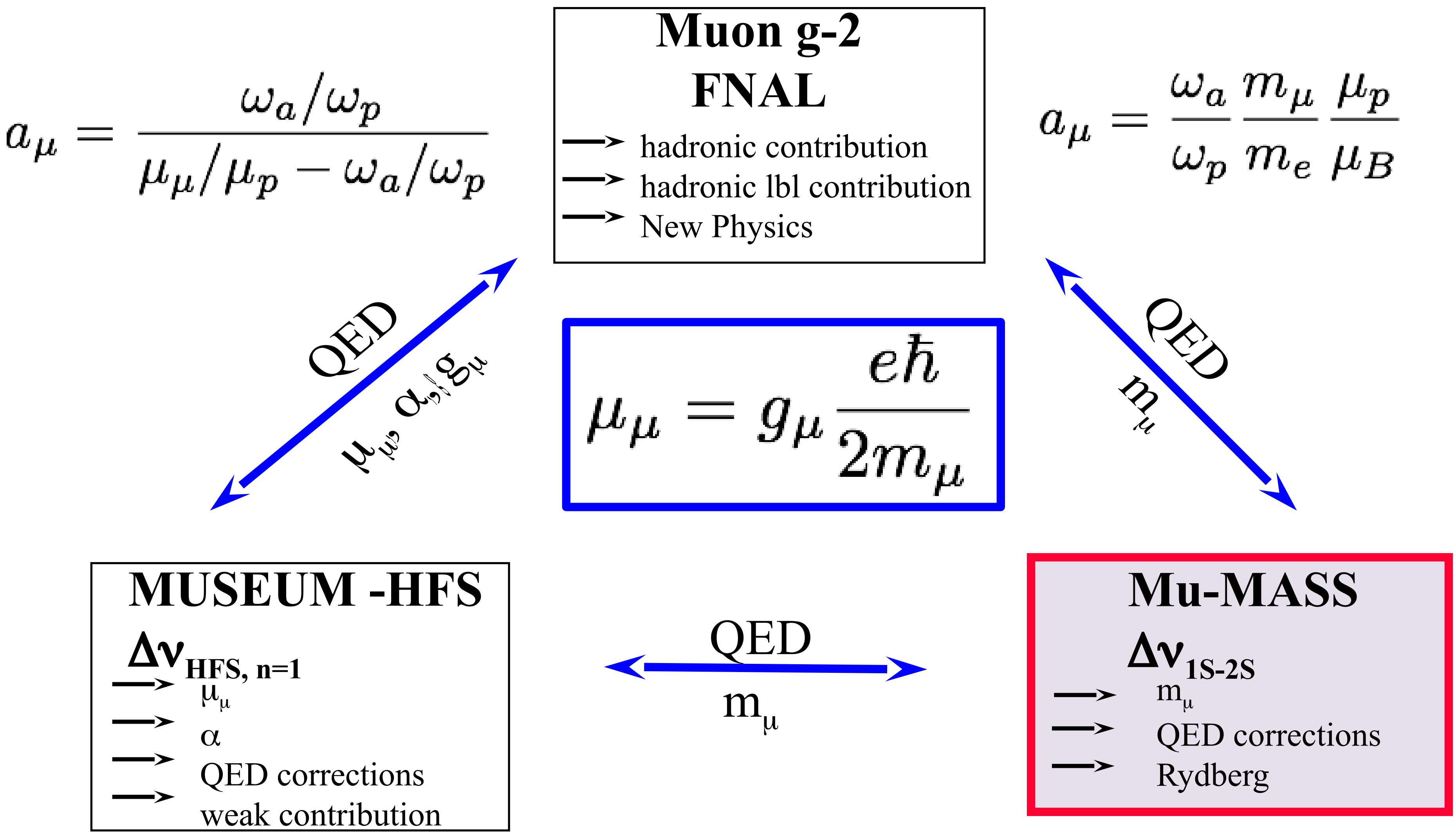
S. G. Karshenboim, Phys. Rep. 422, 1 (2005)

Reduced mass contribution:
1.187 THz (4800 ppm)

⇨ $m_{\mu^+}/m_{e^-} = 206.768\,38(17)$

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

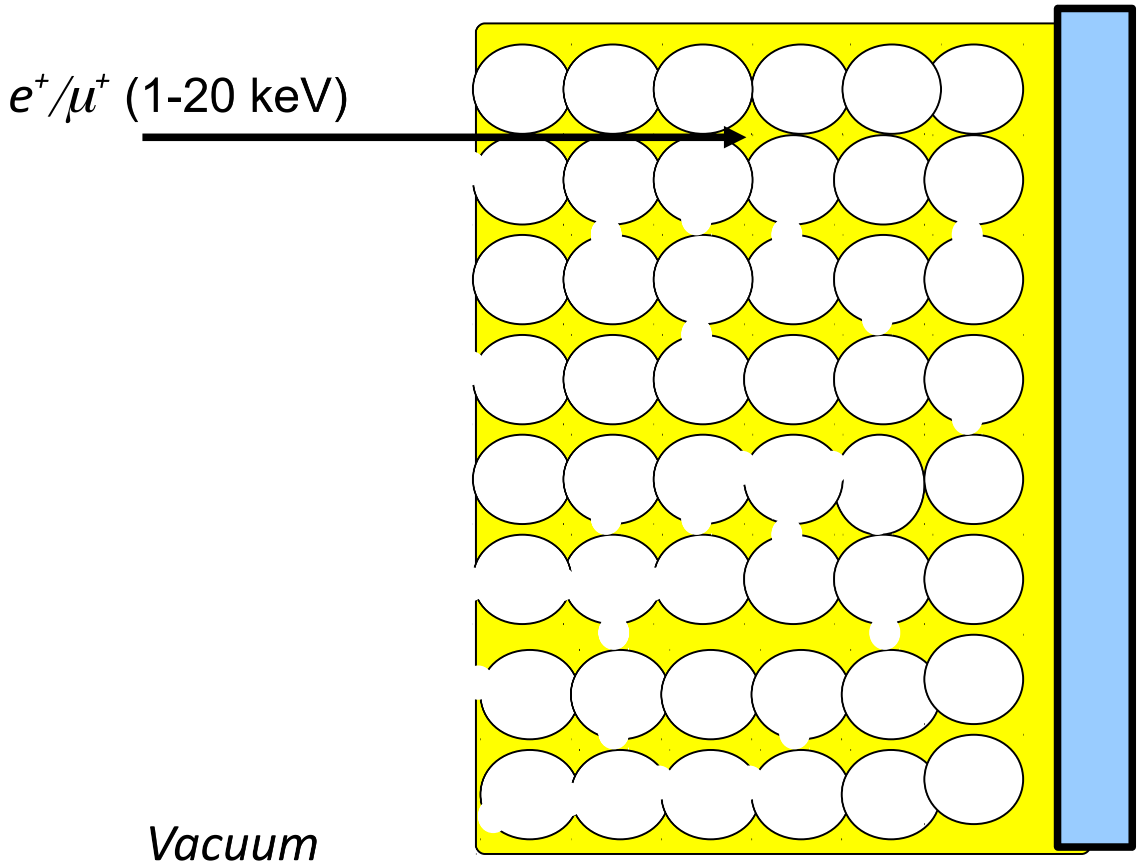
Muonium 1S-2S spectroscopy



Adapted from K. Jungmann
DPG 2017 (Mainz)

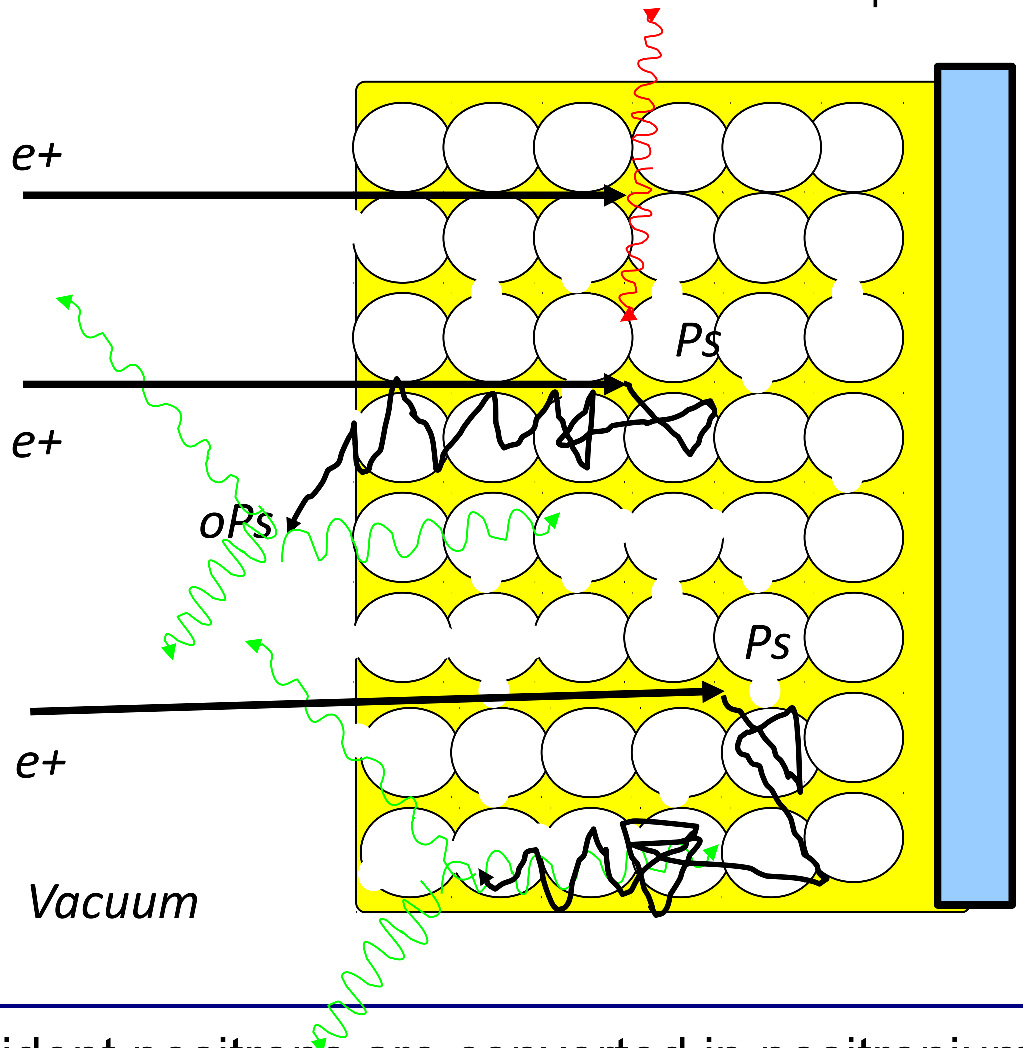
Positronium/Muonium formation

Porous Silica thin film ~1000nm 3-4 nm pore size



Positronium formation

Porous Silica thin film ~1000nm 3-4 nm pore size



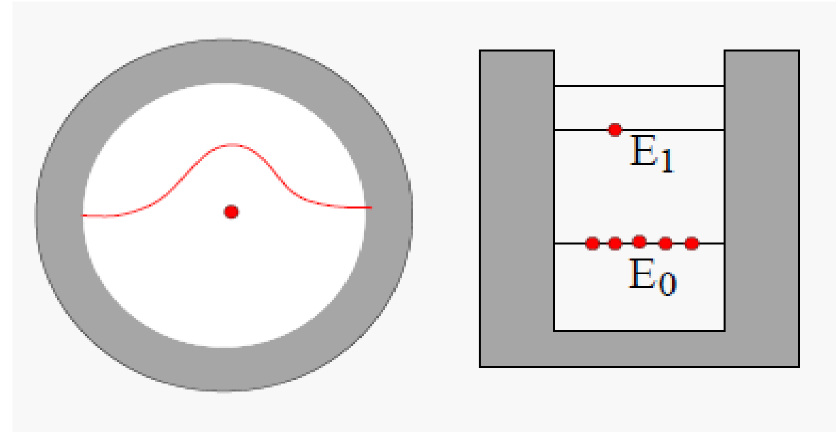
30% of the incident positrons are converted in positronium emitted into vacuum with 40 meV (almost 10^5 m/s).

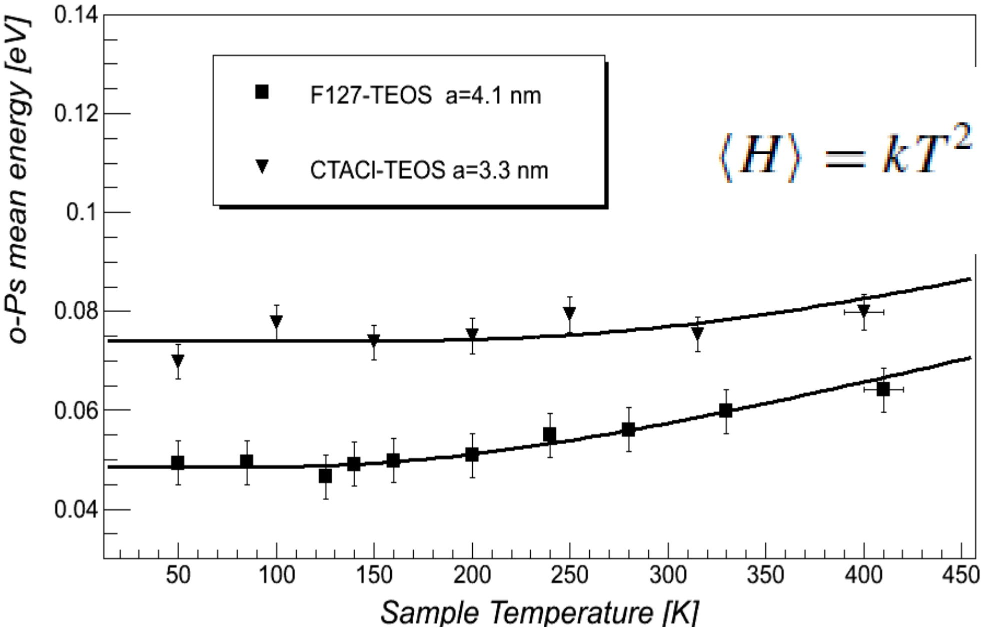
P. Crivelli et al. , Phys. Rev. A81, 052703 (2010)

Ps as a particle in a box

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

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



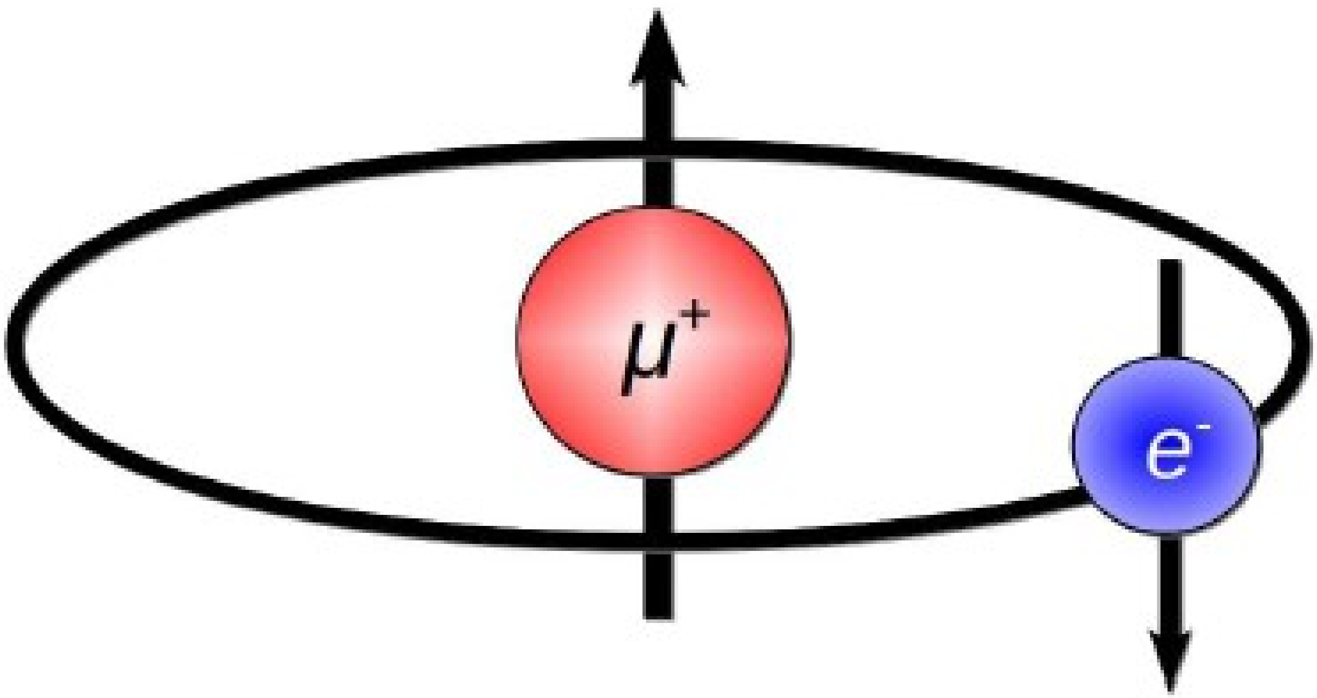


$$\langle H\rangle = kT^2\left(\frac{1}{Z(a)}\frac{dZ(a)}{dT} + \frac{1}{Z(b)}\frac{dZ(b)}{dT} + \frac{1}{Z(c)}\frac{dZ(c)}{dT}\right)$$

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

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

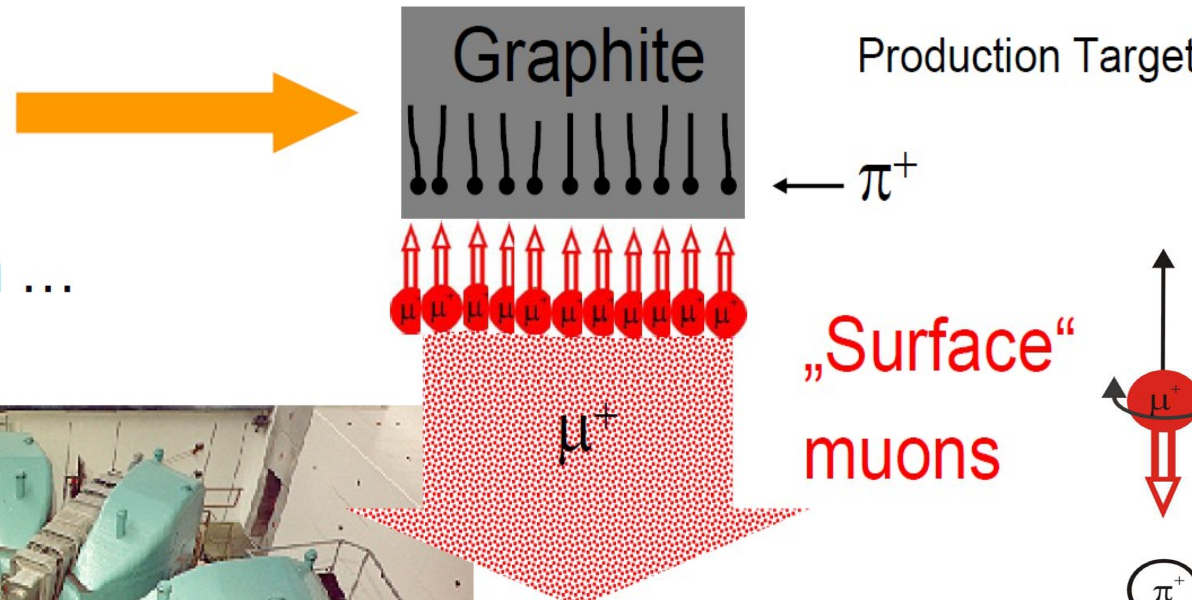
Muonium (Mu)



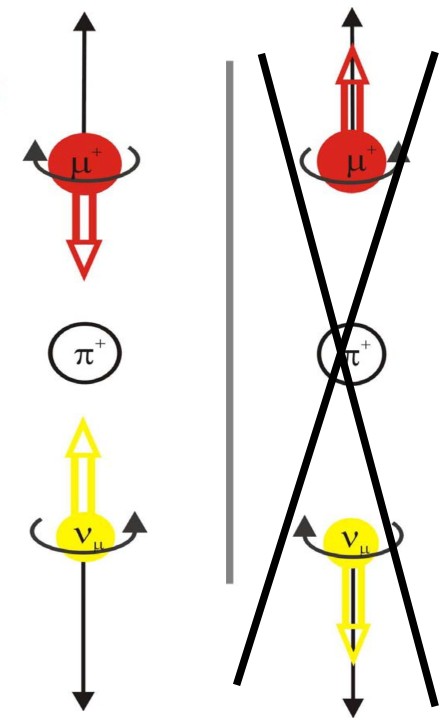
Polarized surface muon beam generation

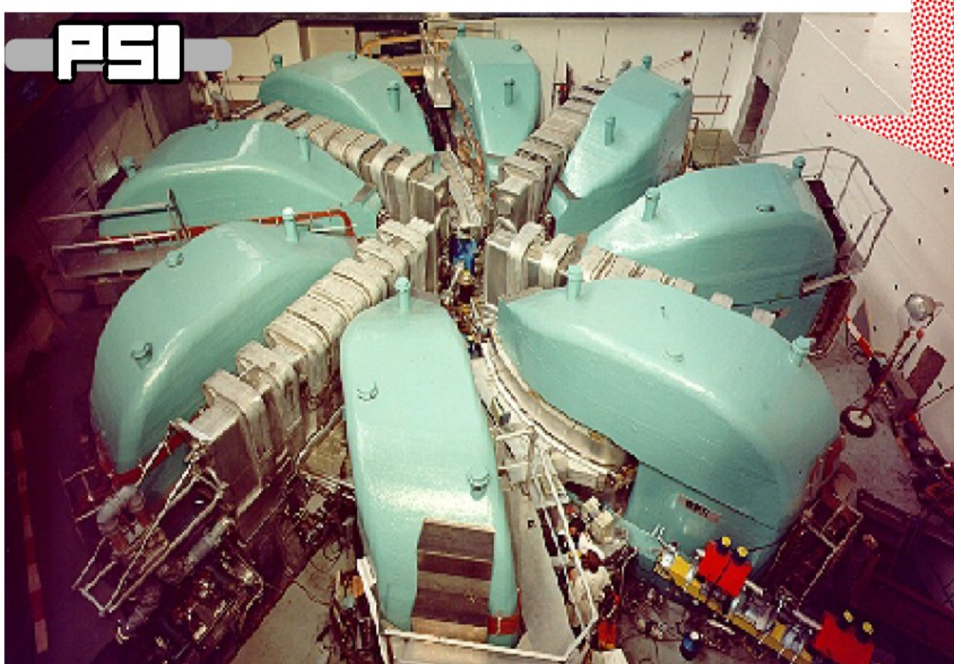
2.2 mA $\cong$ 1.4 10^{16} Protons/sec

with 600 MeV



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





~10^7- 10^8 μ^+/sec

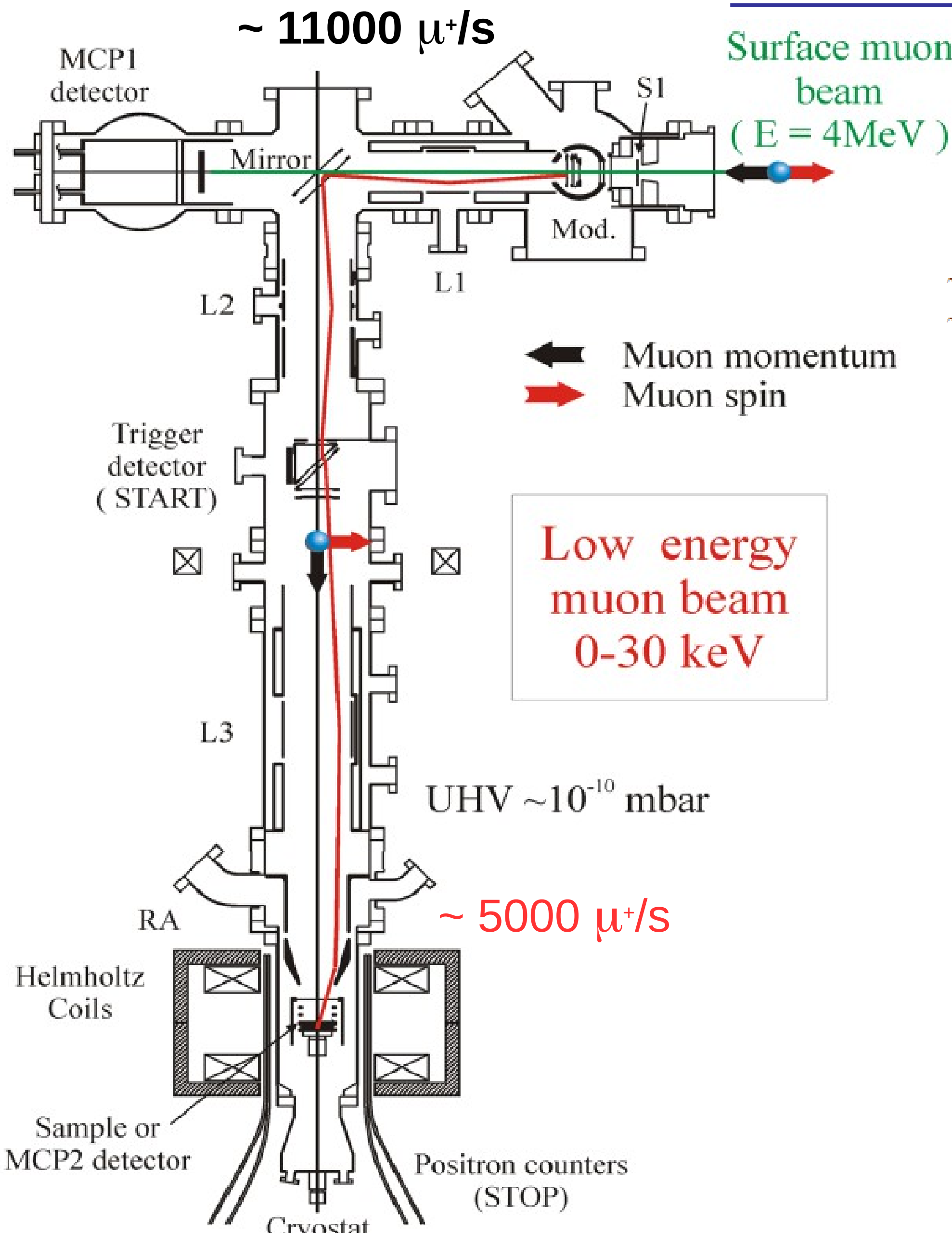
100 % pol.

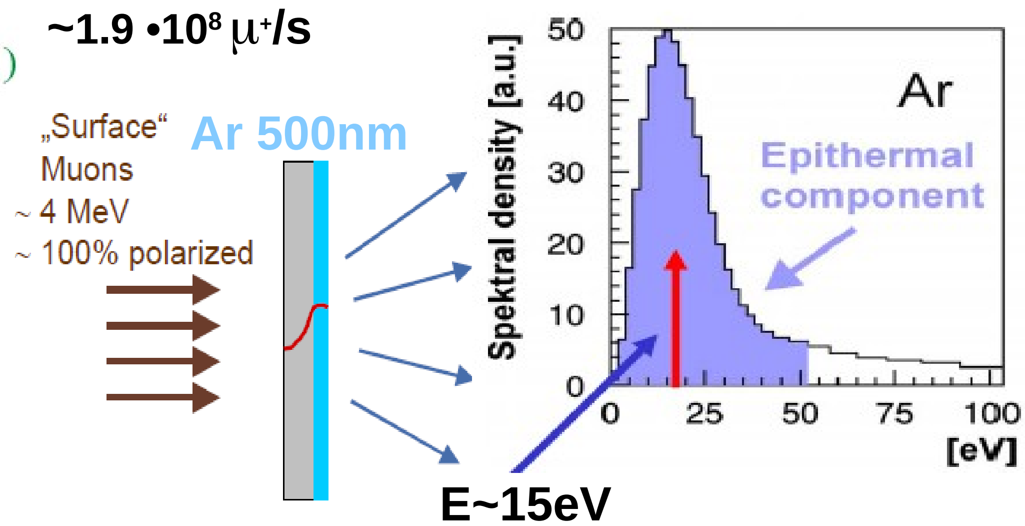
~ 4 MeV

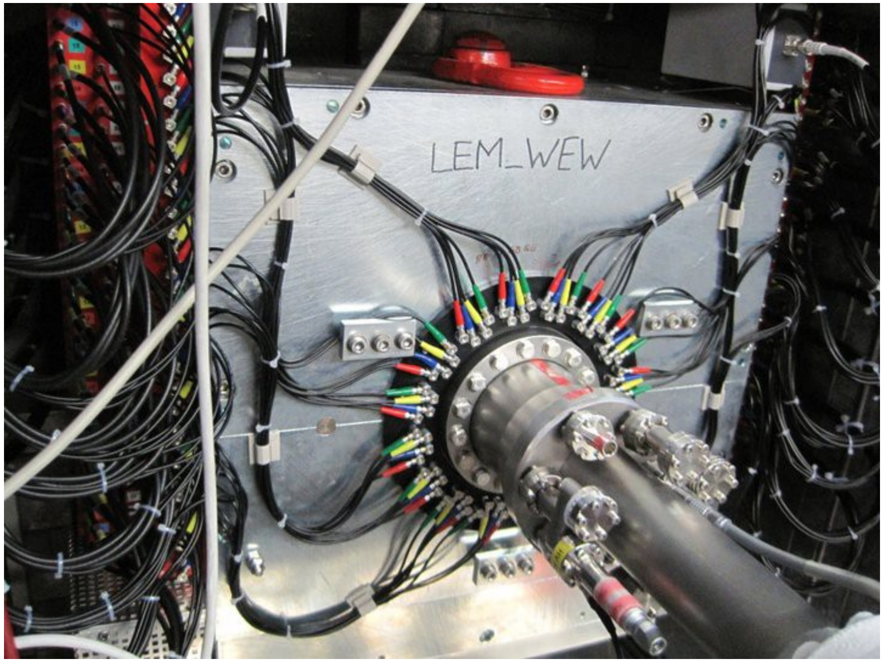
generally used for “bulk” condensed matter studies

For thin film studies: eV-30 keV

Low energy muon (LEM) beam @PSI

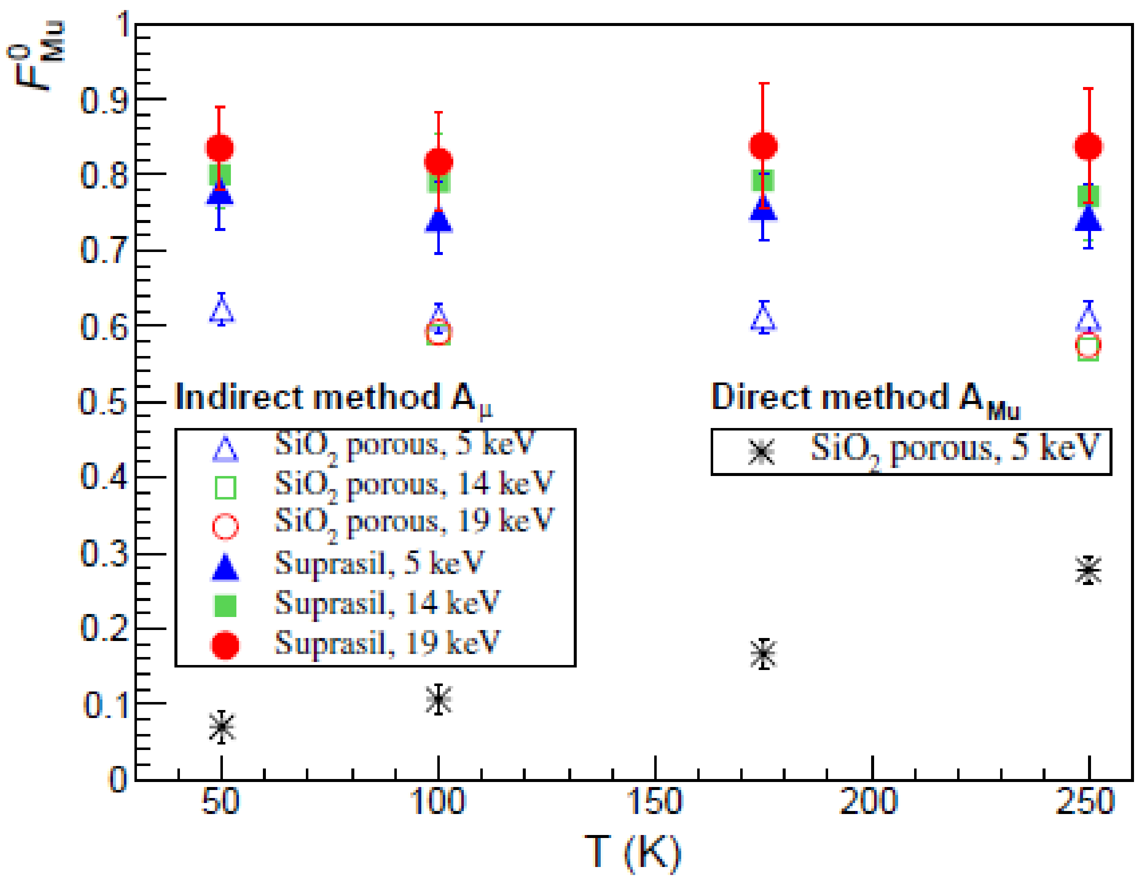






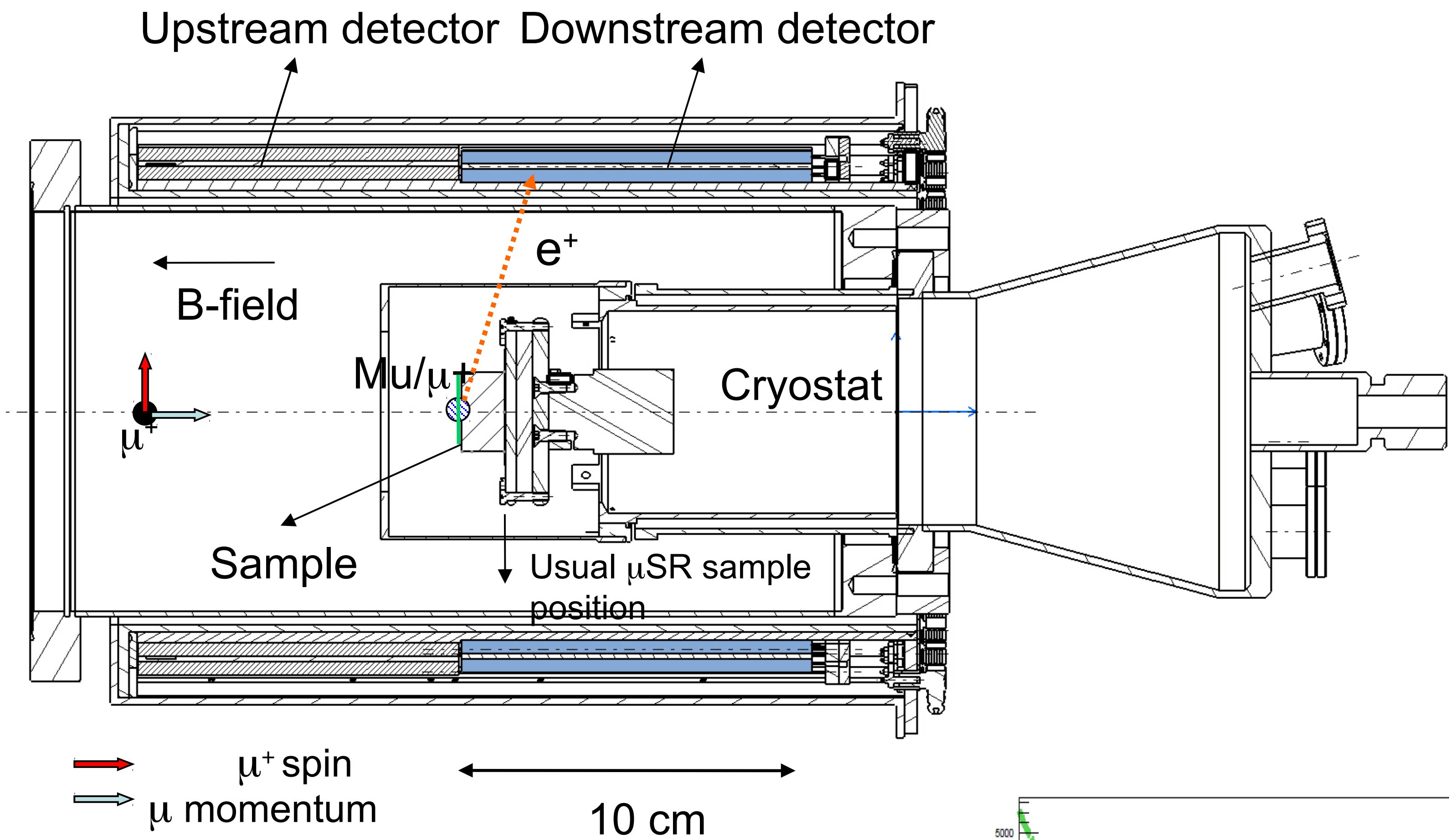
MuSR results for SiO2 porous and bulk

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

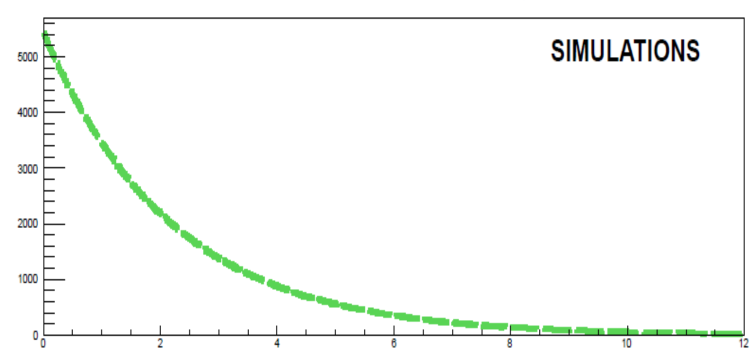


MuSR → Mu is formed but is this emitted in vacuum?

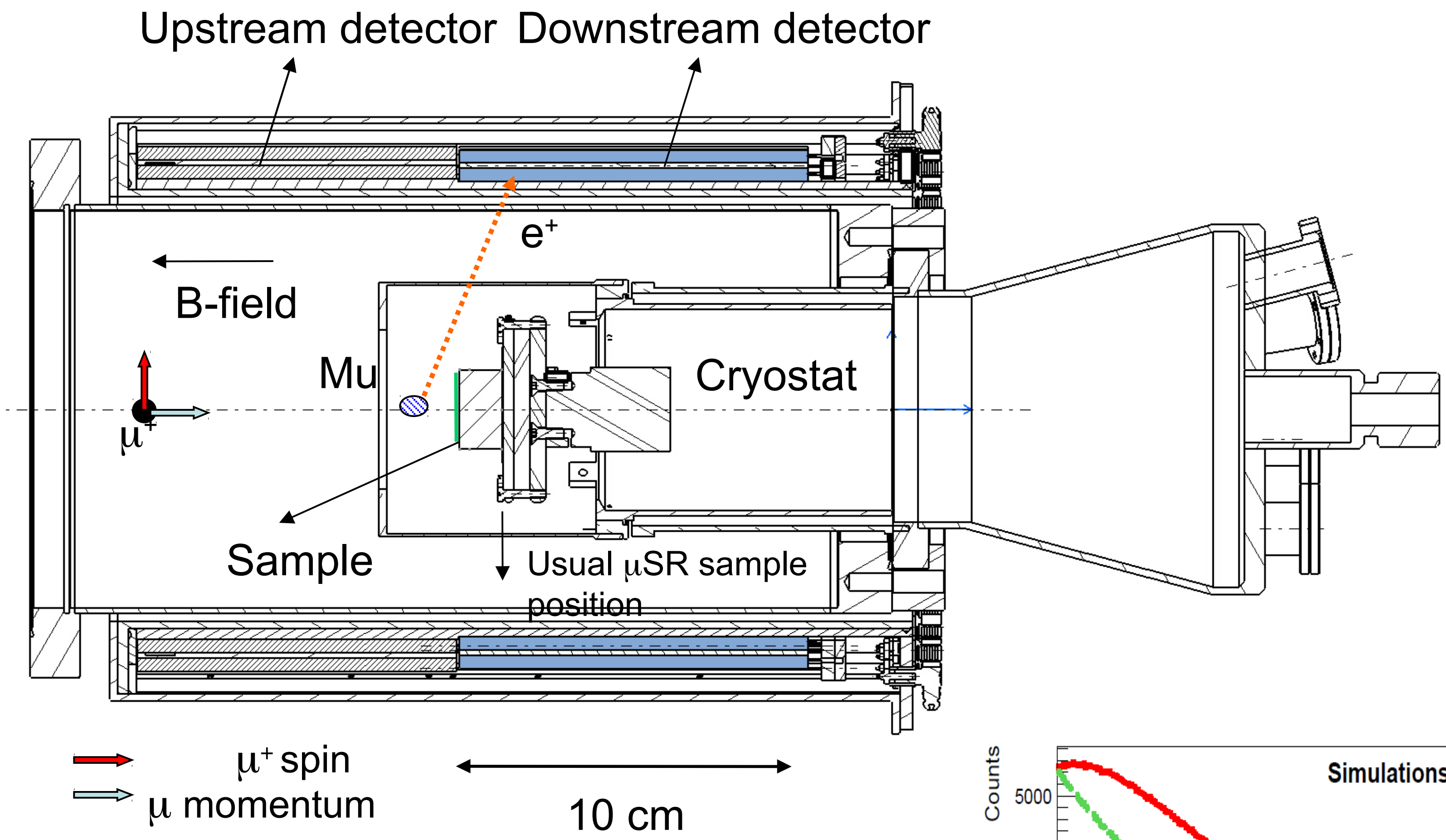
Positron shielding technique (PST)



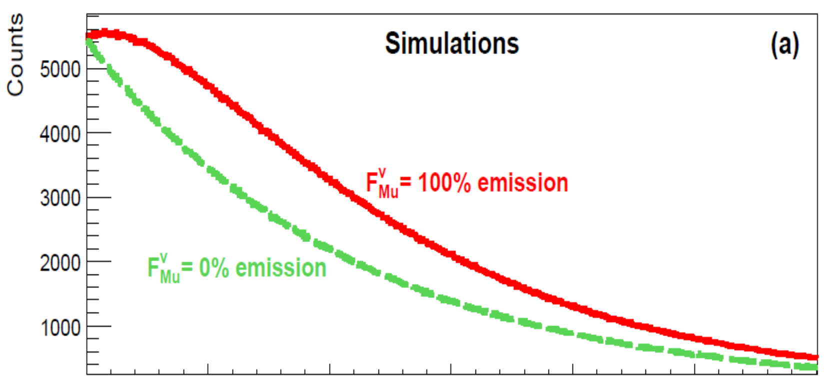
No emission into vacuum



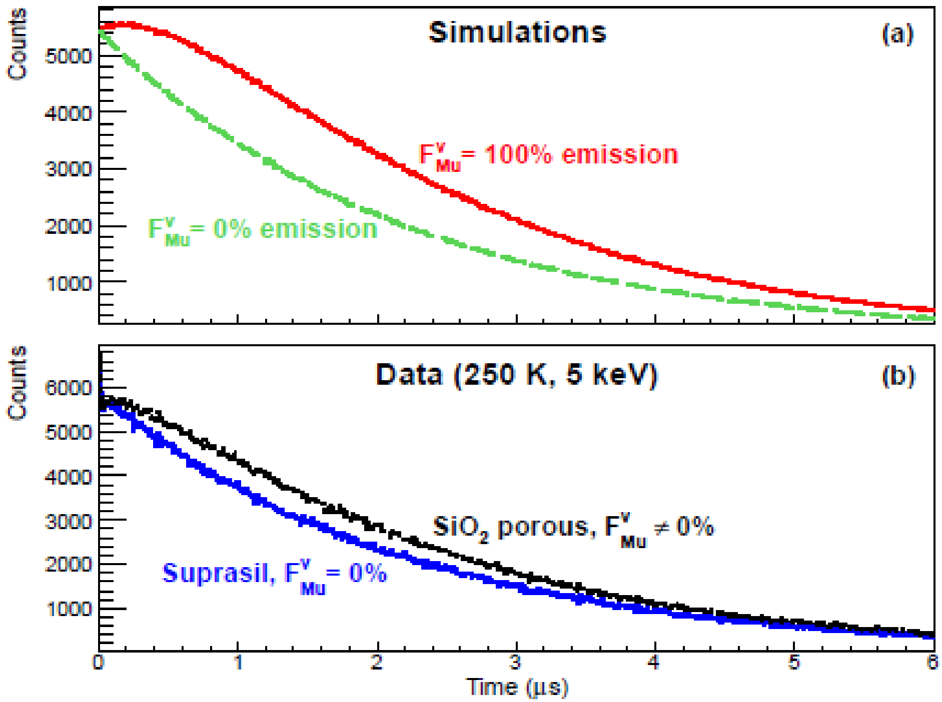
Positron shielding technique (PST)

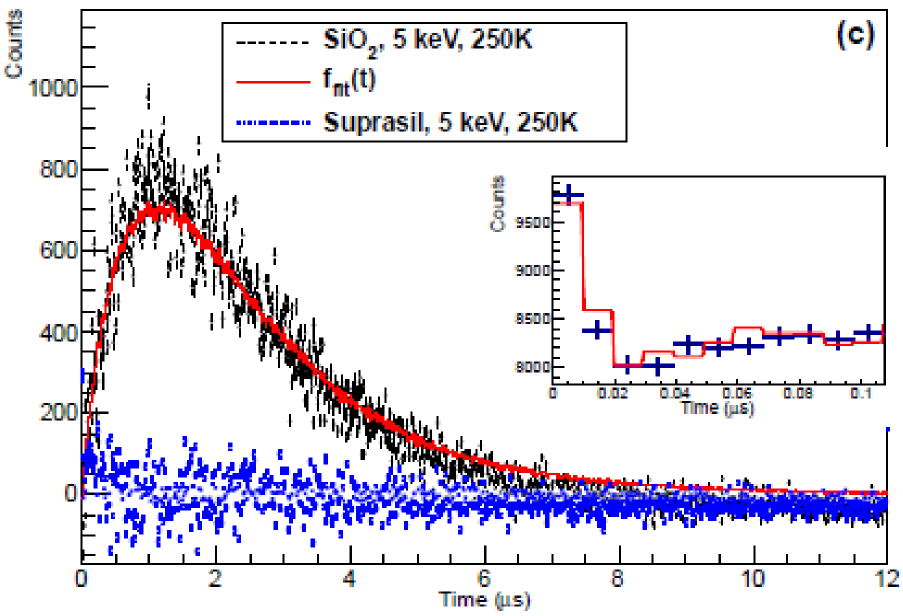


Emission into vacuum



PST principle



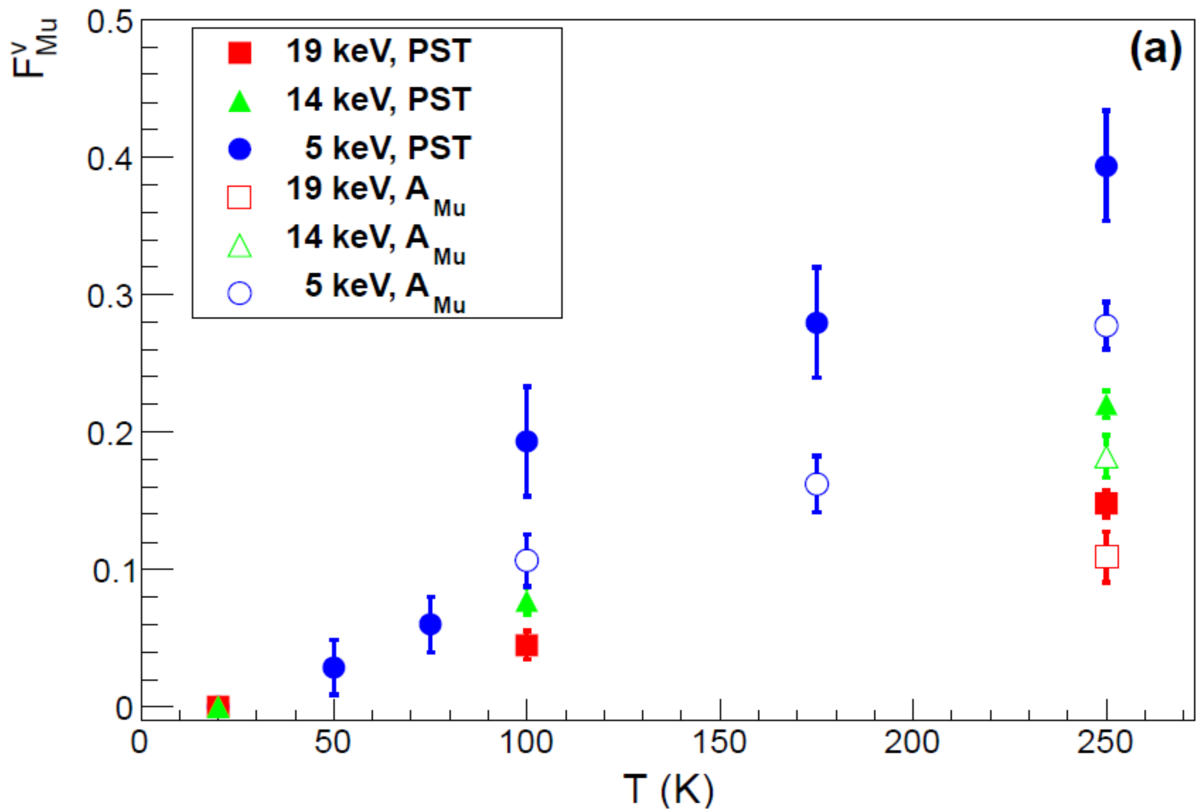


$$f_{\rm fit}(t) = n[(1 - F^{v}_{Mu})f_0(t) + F^{v}_{Mu}f_{100}(t)] + n_{pp}f_{pp}(t)$$

➡ **Vacuum Yield:** $F^{\rm v}_{\rm Mu}$

PST results

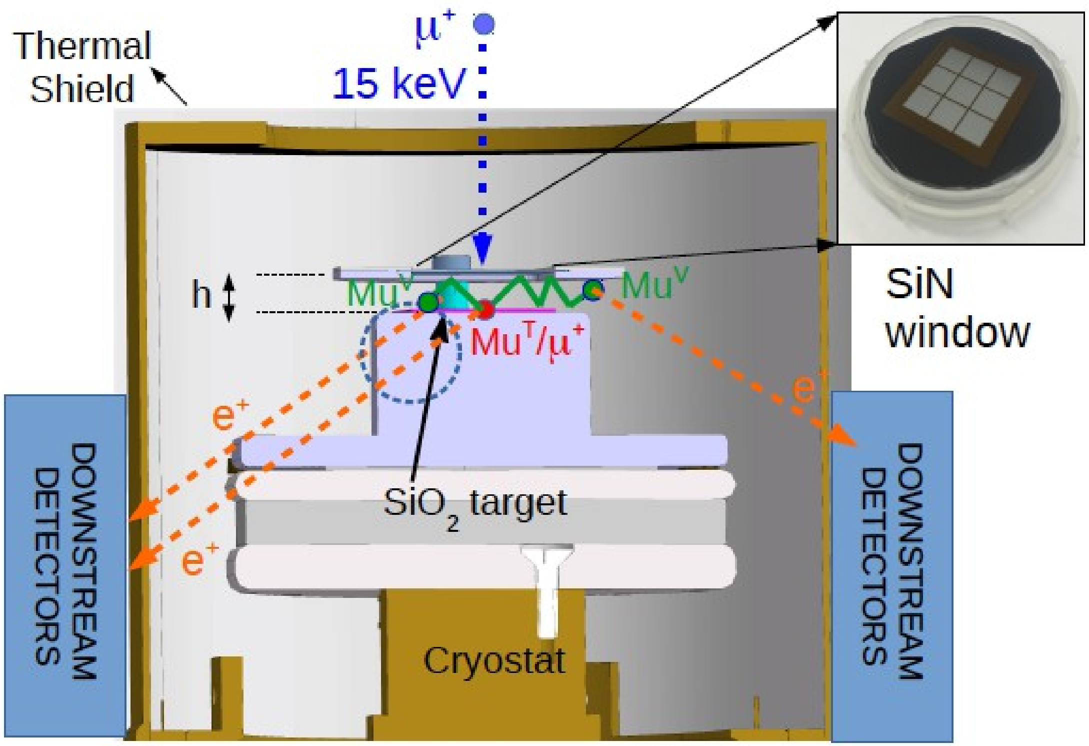
A. Antognini (ETHZ), P. Crivelli (ETHZ), K. S. Khaw (ETHZ), K. Kirch,(ETHZ/PSI), B Barbiellini (NU Boston), L. Liszkay (CEA),T. Prokscha (PSI), E. Morenzoni (PSI), Z. Salman (PSI), A. Suter (PSI), PRL 108, 143401 (2012)

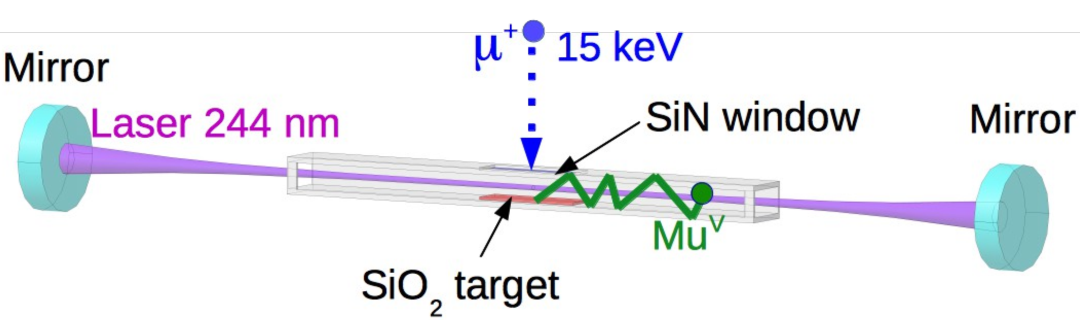


$(38\pm4)\%$ at 250 K and $(20\pm4)\%$ at 100 K for 5 keV

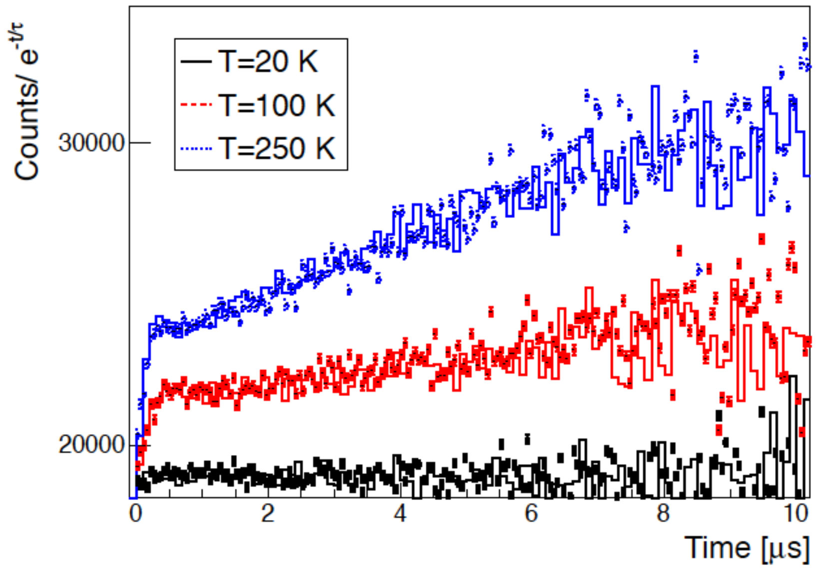
Muonium spatial confinement

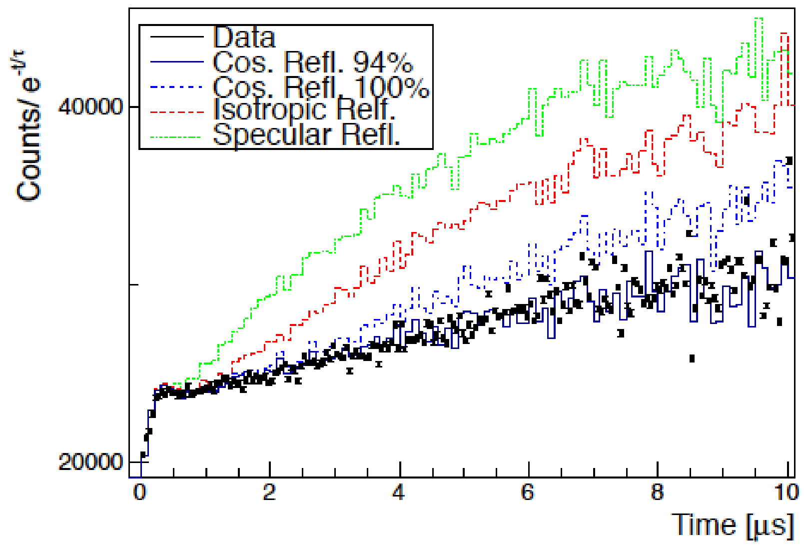
K. S. Khaw, A. Antognini, T. Prokscha, K. Kirch, L. Liszkay, Z., Salman, P. Crivelli, PRA 94, 022716 (2016)





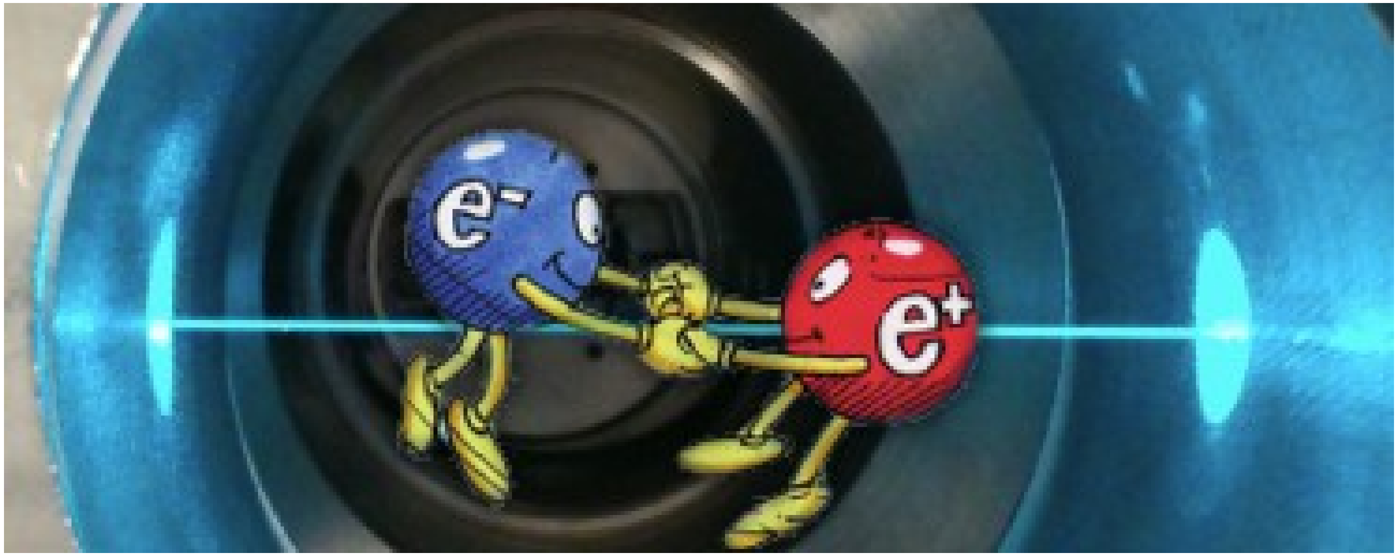
DATA-SIM 1mm



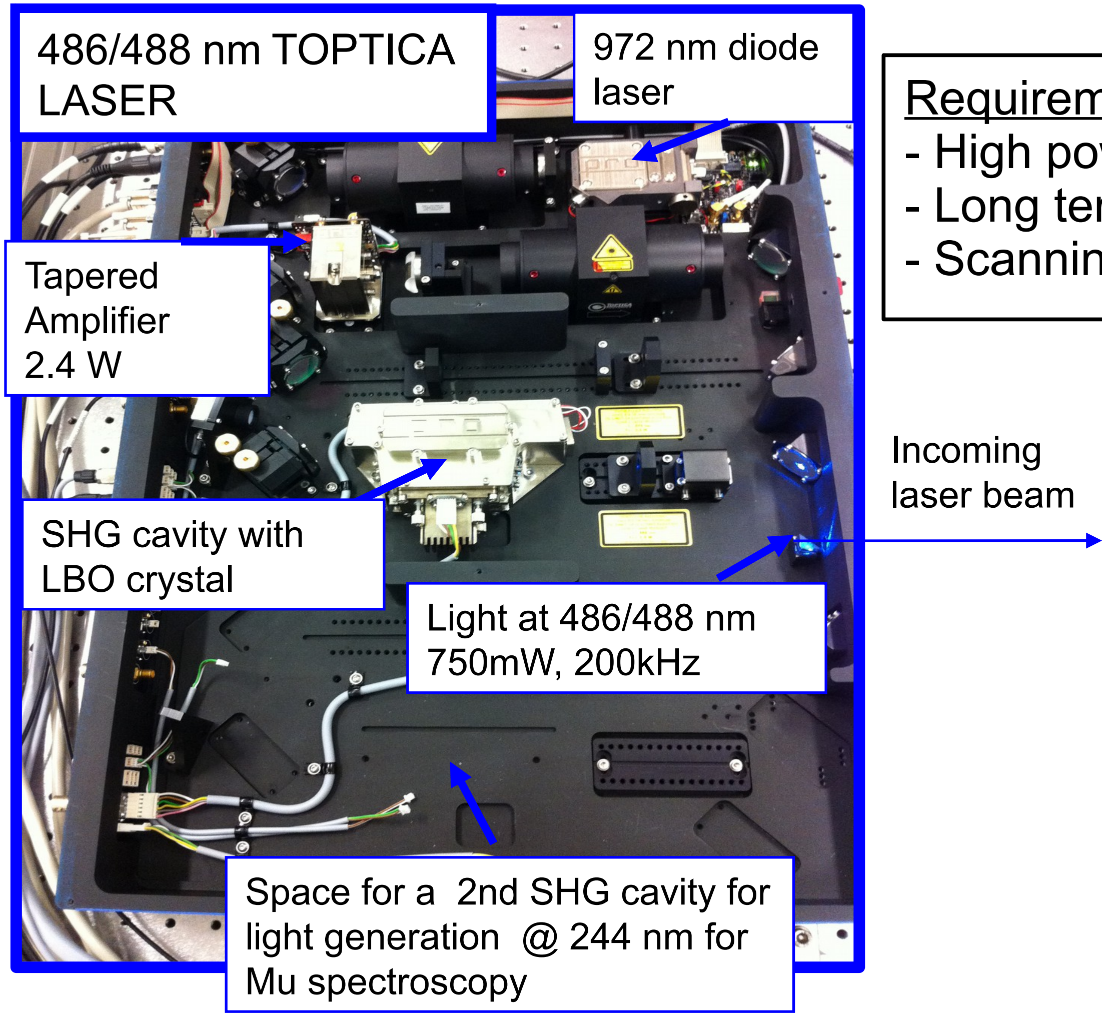


Factor 5 enhancement in exc. probability

Laser spectroscopy

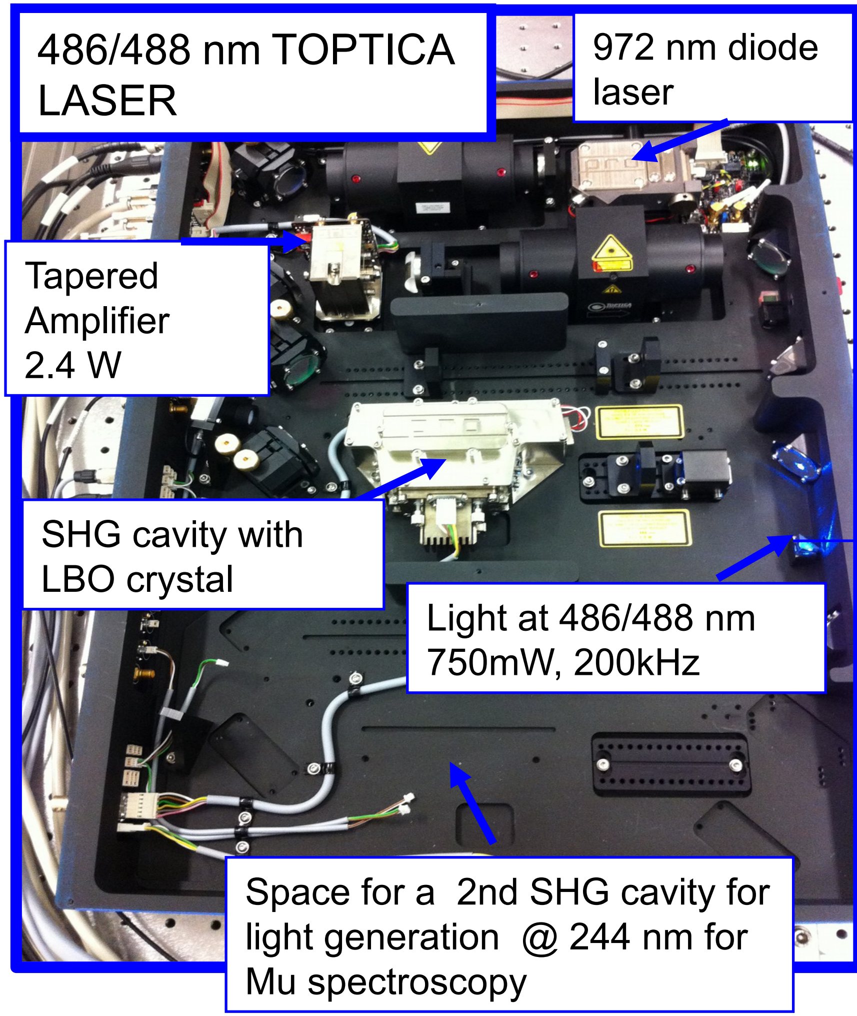


The laser system

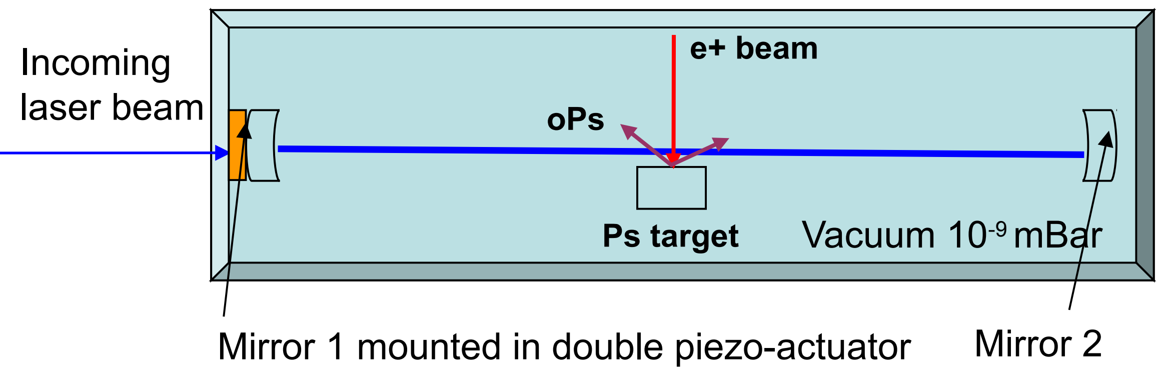


Requirements:
- High power (~kW) at 486 nm -> detectable signal
- Long term stability (continuous data taking ~days)
- Scanning of the laser ± 100 MHz

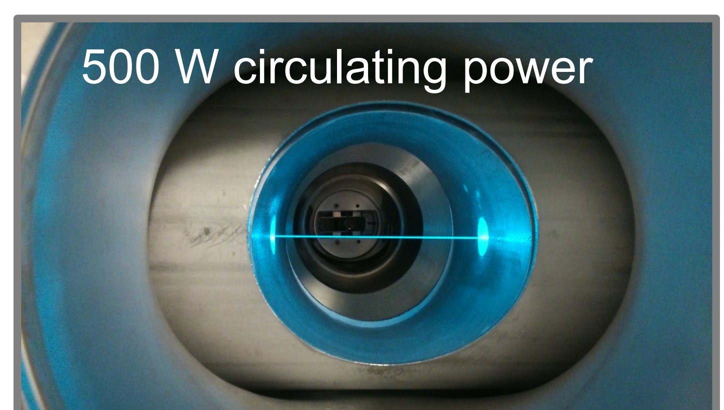
The laser system



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

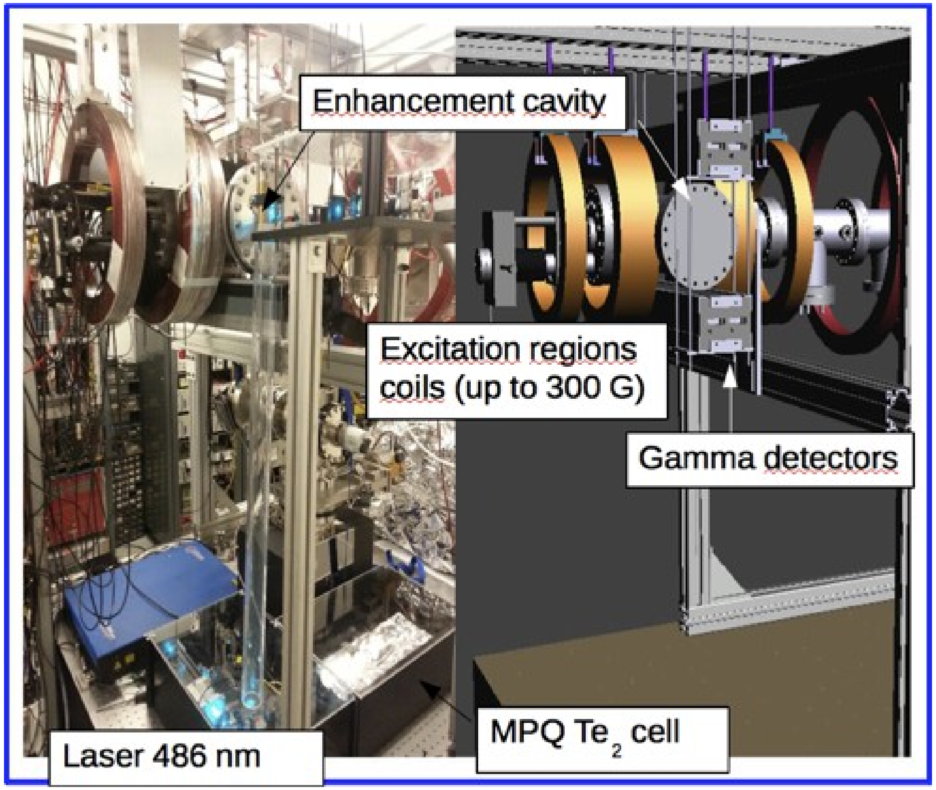


High finesse resonator for power build up
500 mW ⇒ 1 kW

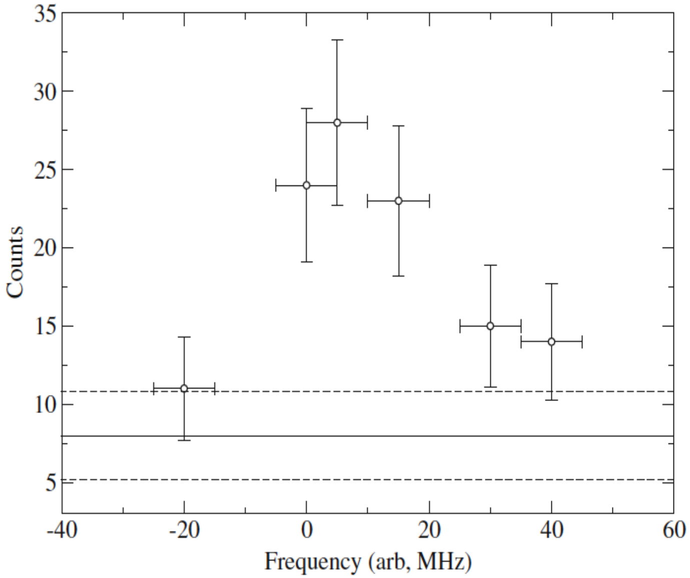


Detection of Ps annihilations in the 2S state

CW slow positron beam setup



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



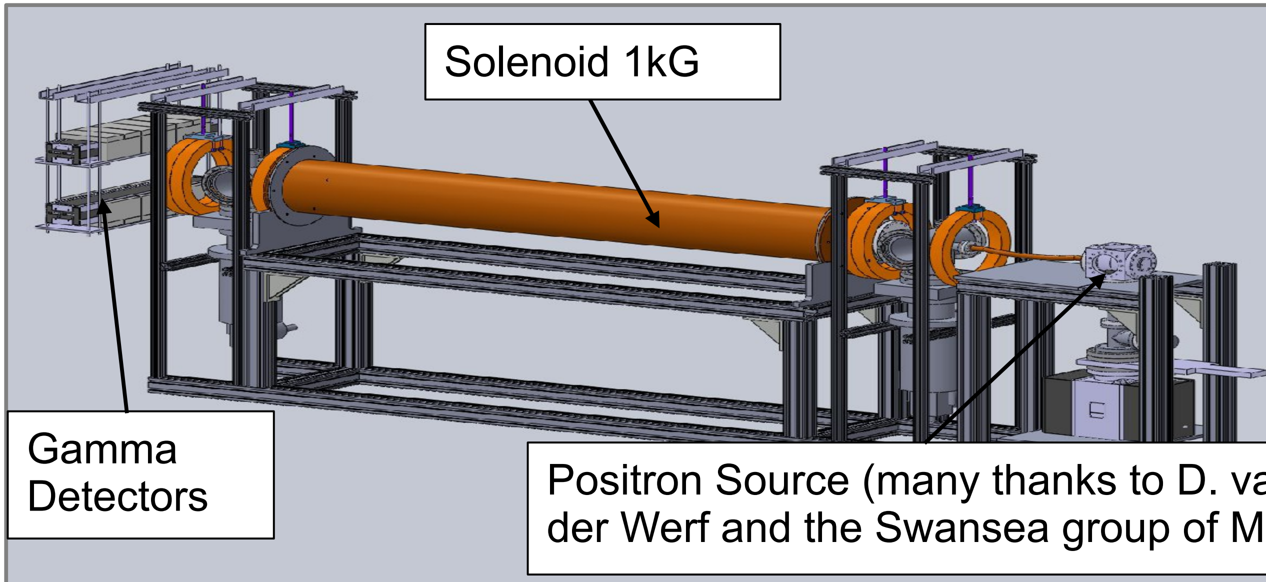
S/N ratio should be improved.

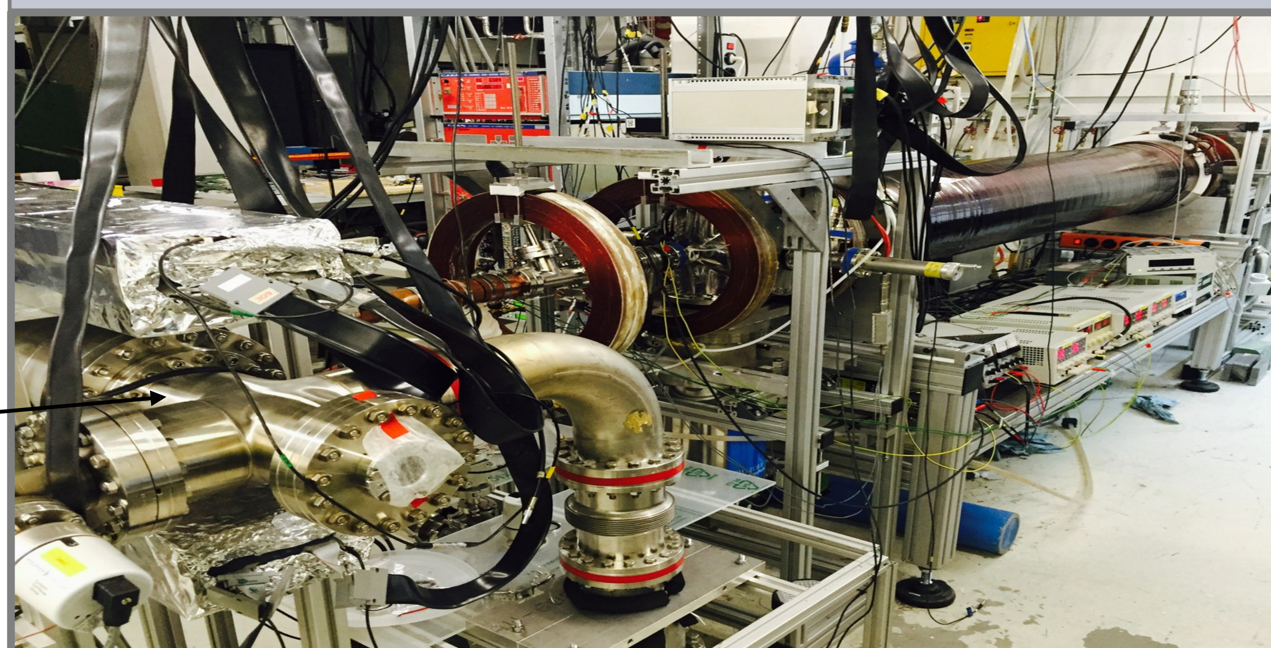
Use bunched beam (buffer gas trap)

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

→ Reduction and correction of **systematic** effects

New beam line based on positron buffer gas trap

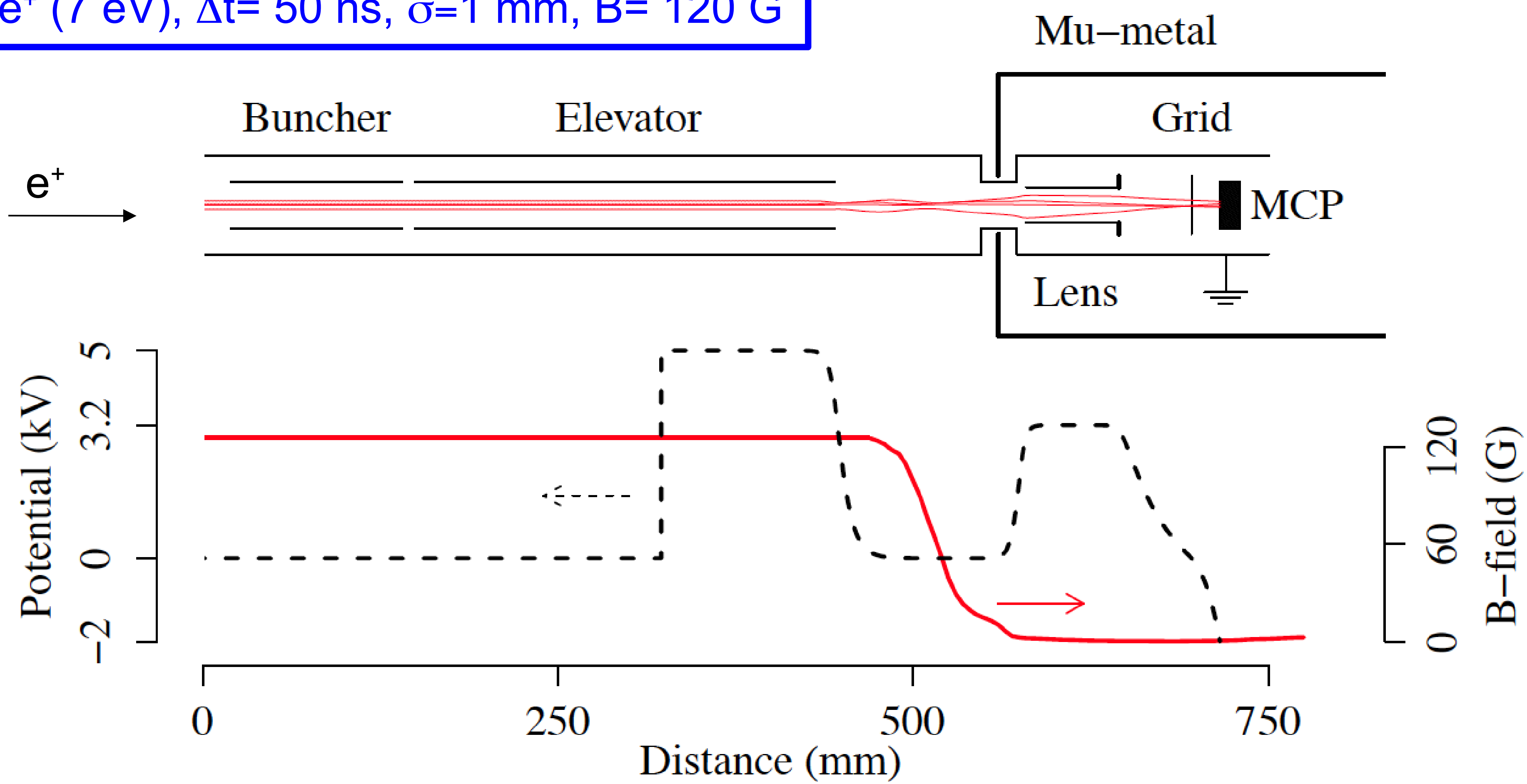




Bunching and extraction to a field free e-m region

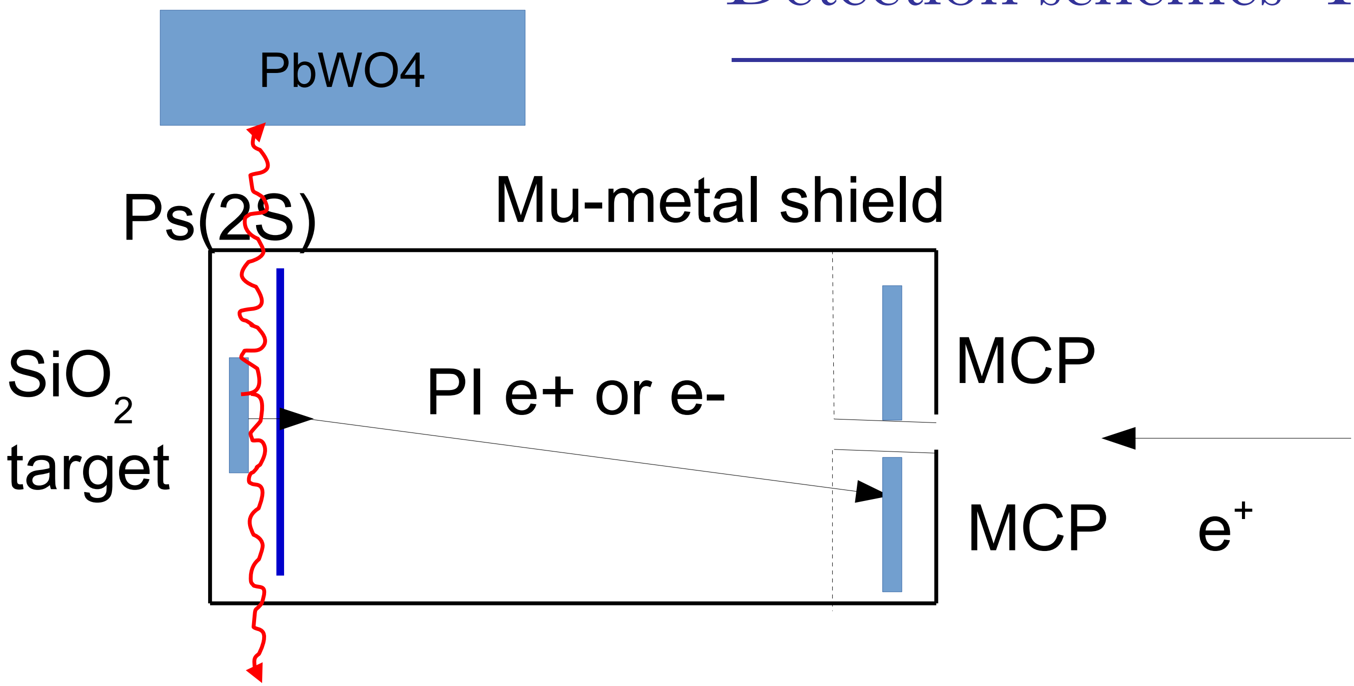
D. A. Cooke PC et al. , J. Phys. B: At. Mol. Opt. Phys. 49 014001 (2016)

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



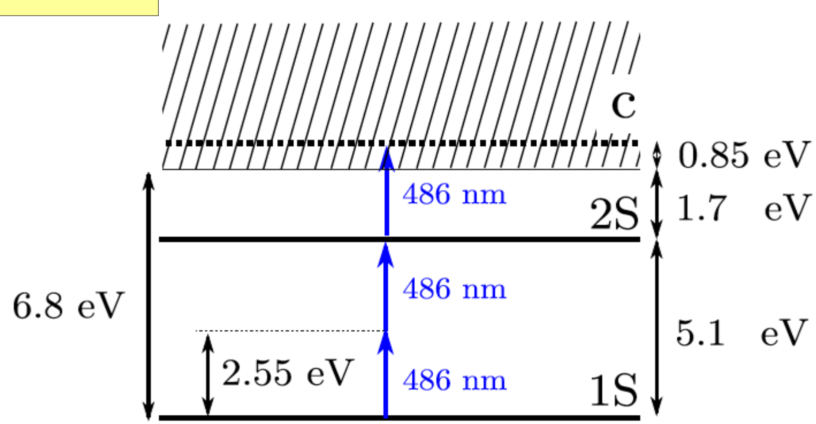
ON TARGET (@ground): Δt= 1 ns, σ=1 mm, B<0.1 G, 90 % efficiency

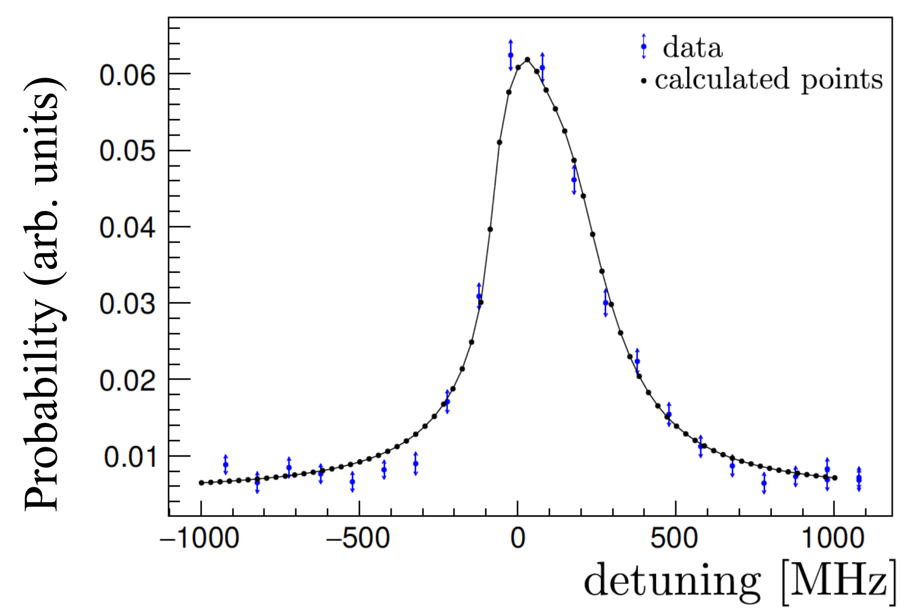
Detection schemes- PI in the 2S exc. Laser



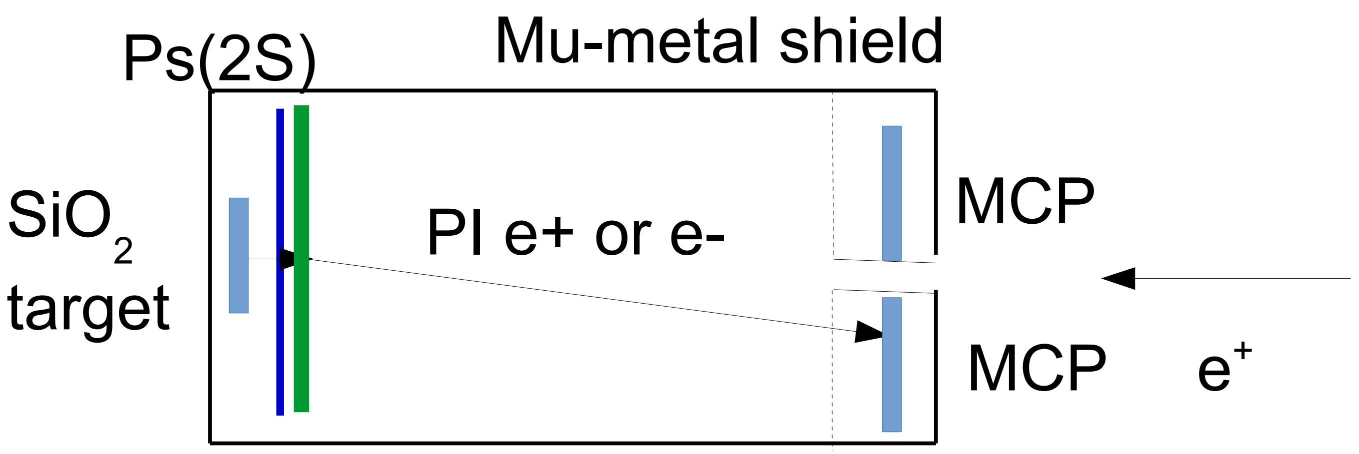
1) Photo-ionized Ps in the 2S excitation laser detected either by SSPALS or e^+ or e^- in an MCP

See talk Alonso



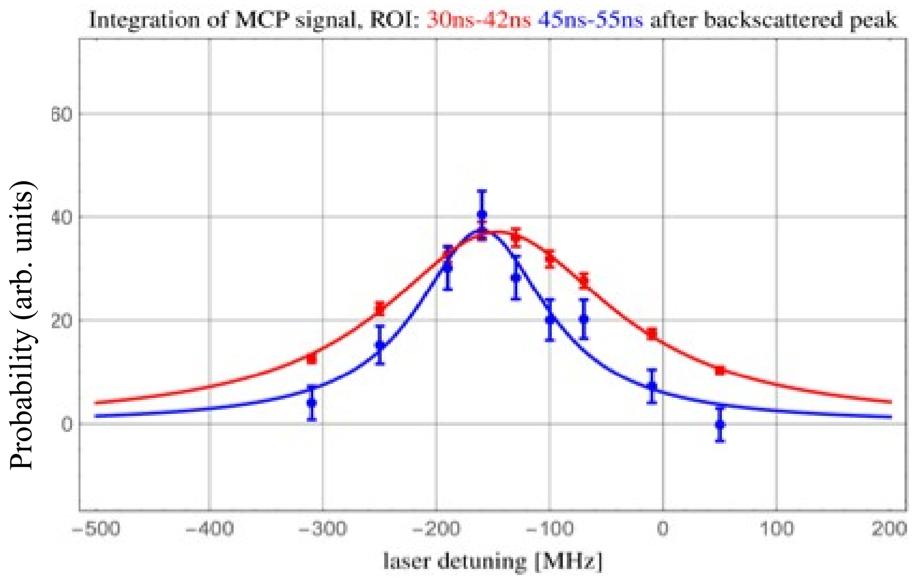


Detection schemes- external PI

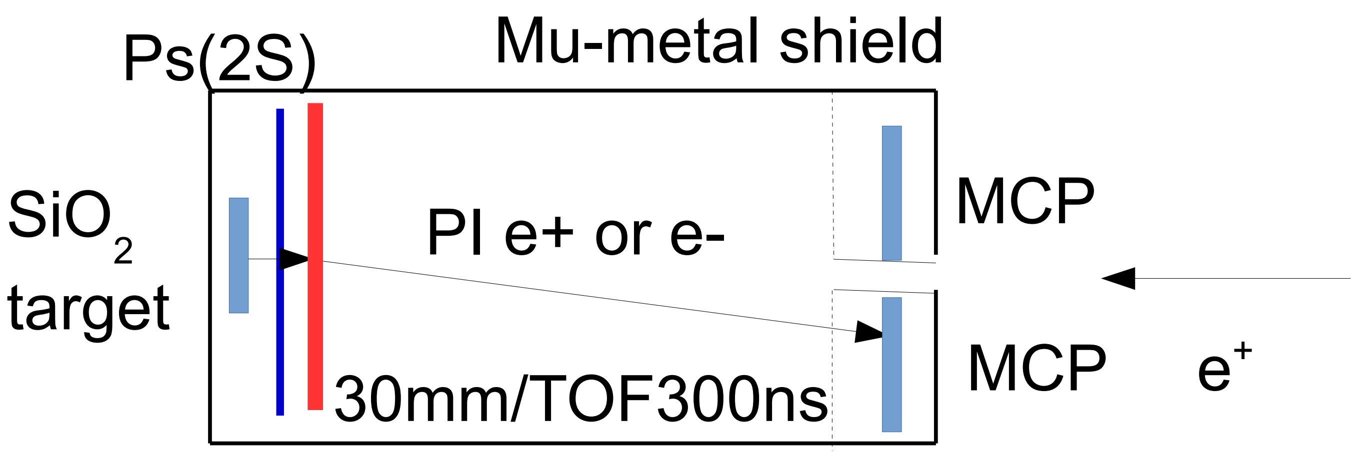


2) Photo-ionization: external laser 532 nm

Photo-ionization in 486 nm laser
2S photoionization with 532 nm laser



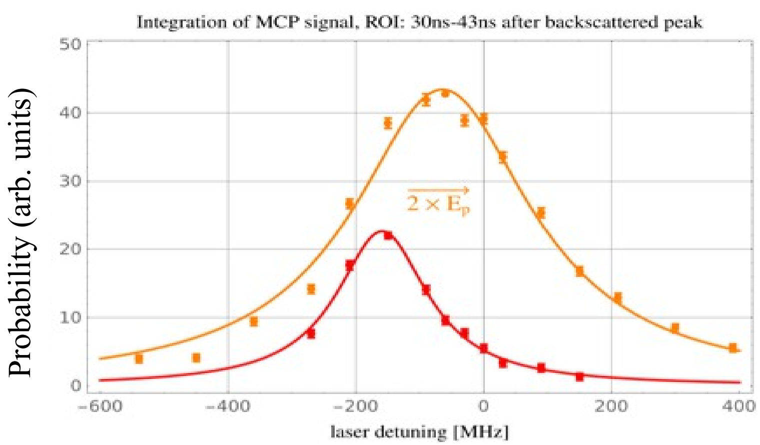
Detection schemes- field ionization of Ps*



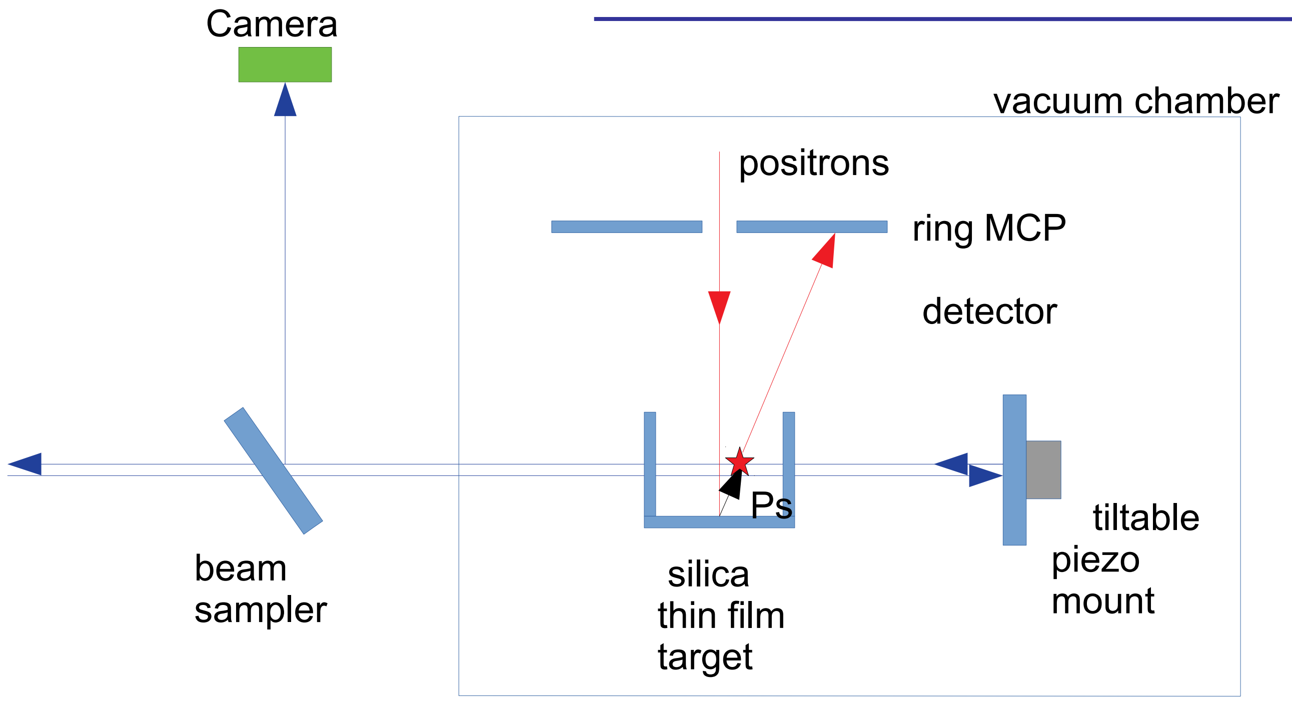
3) Excitation 2S->20P: laser at 735 nm detection via field ionization

→ correction for the 2nd order Doppler shift $\Delta\nu_{D2} = \nu_0 \frac{v^2}{2c^2}$

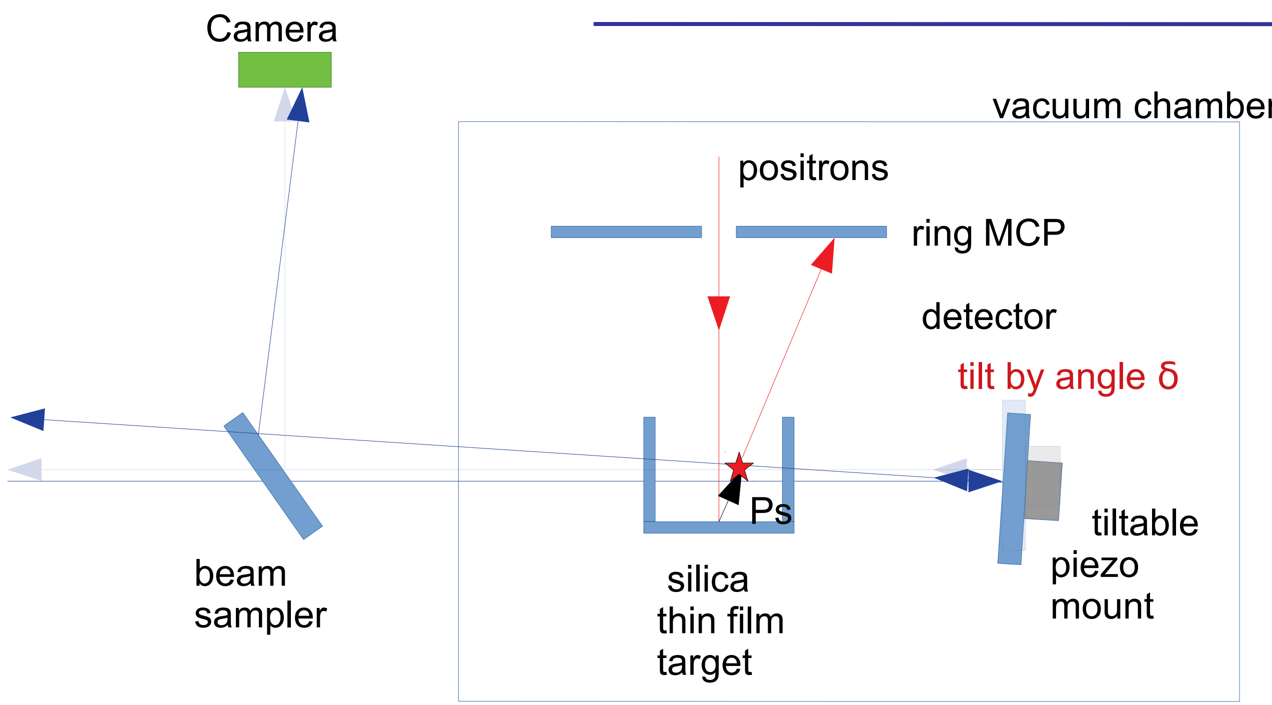
→ Other main systematic: AC Stark shift (corrected via extrapolation)



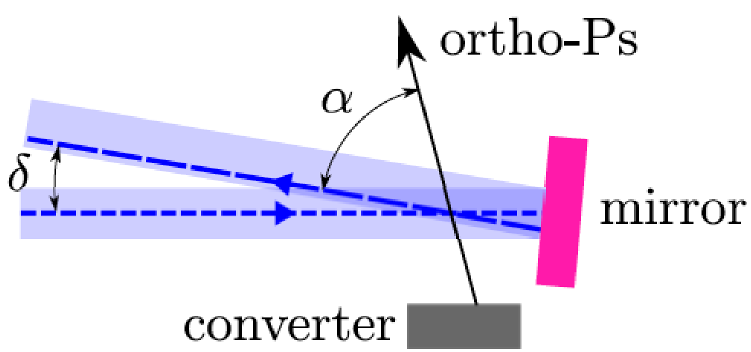
"Quasi" Doppler free excitation → Ps velocity distribution

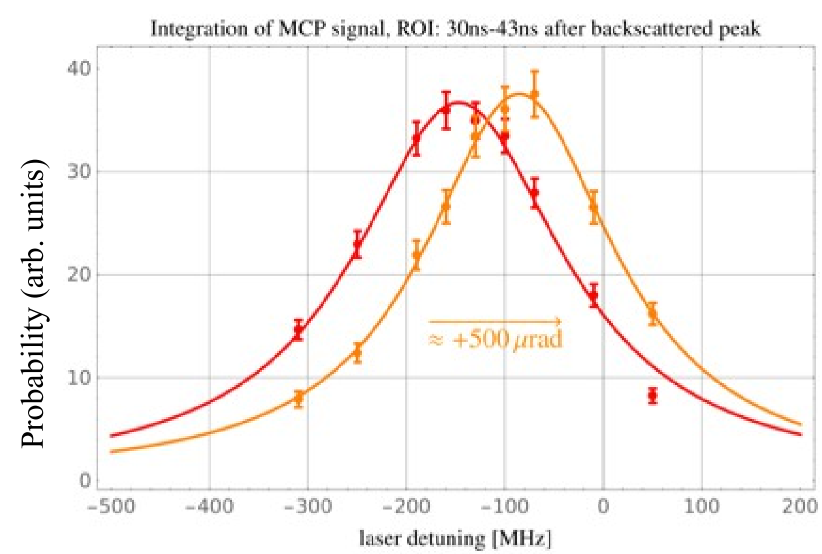


"Quasi" Doppler free excitation → Ps velocity distribution



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





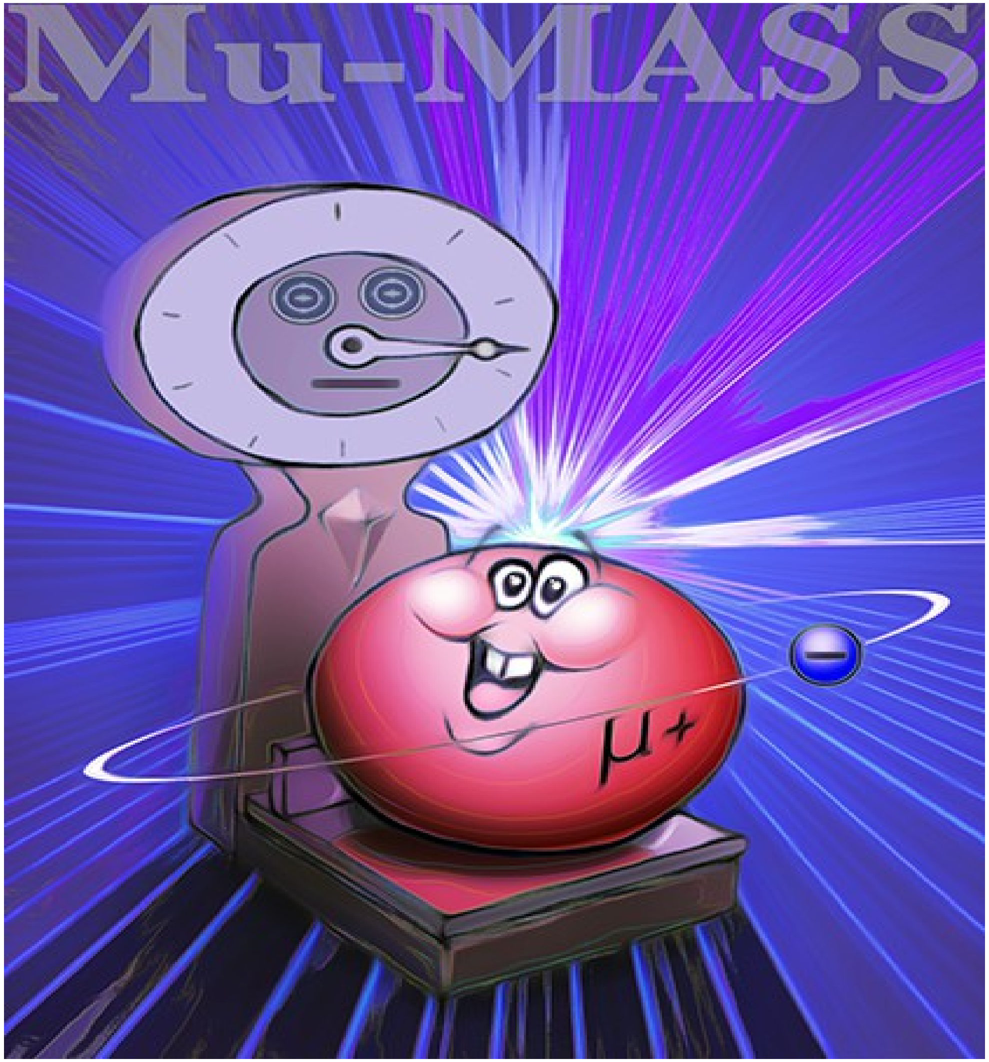
Outlook of 1S -2S experiment

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)

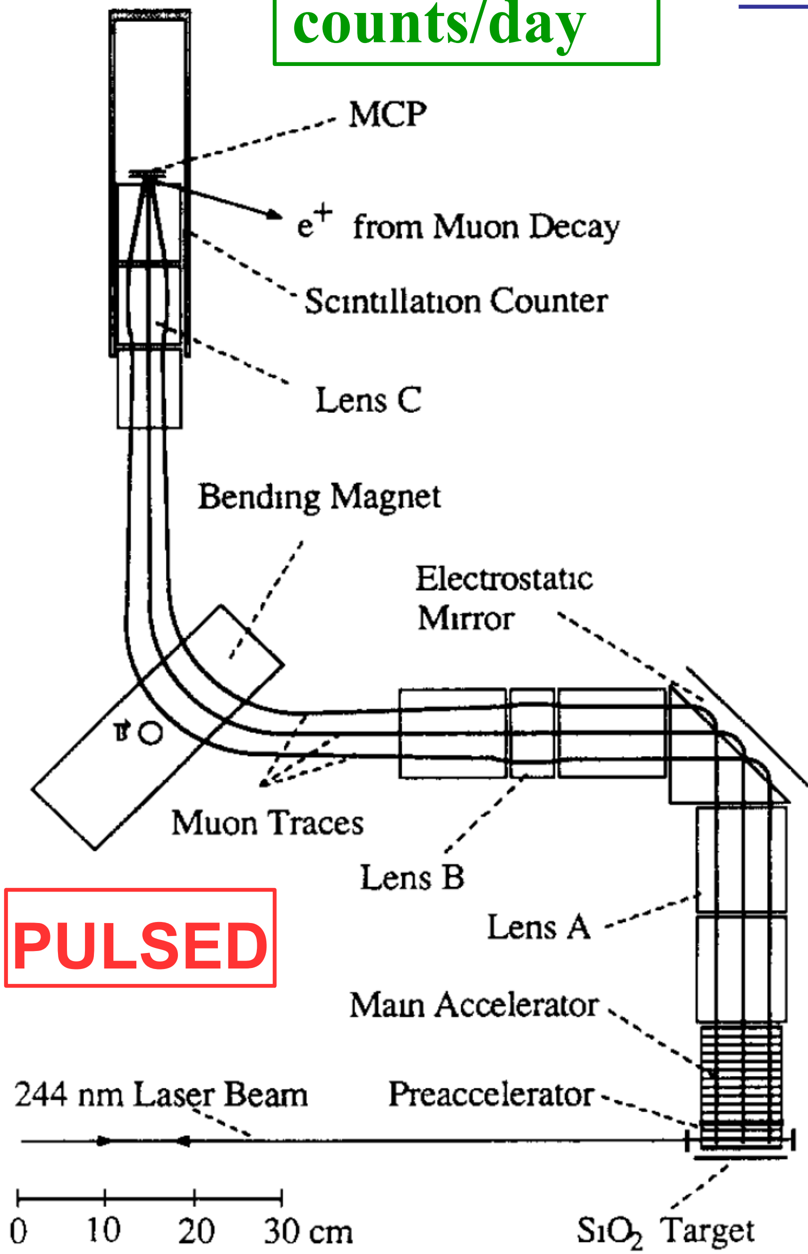
POTENTIAL IMPROVEMENTS
→ GBAR LINAC
→ Colder Ps source?

MuoniuM lAser SpectroScopy

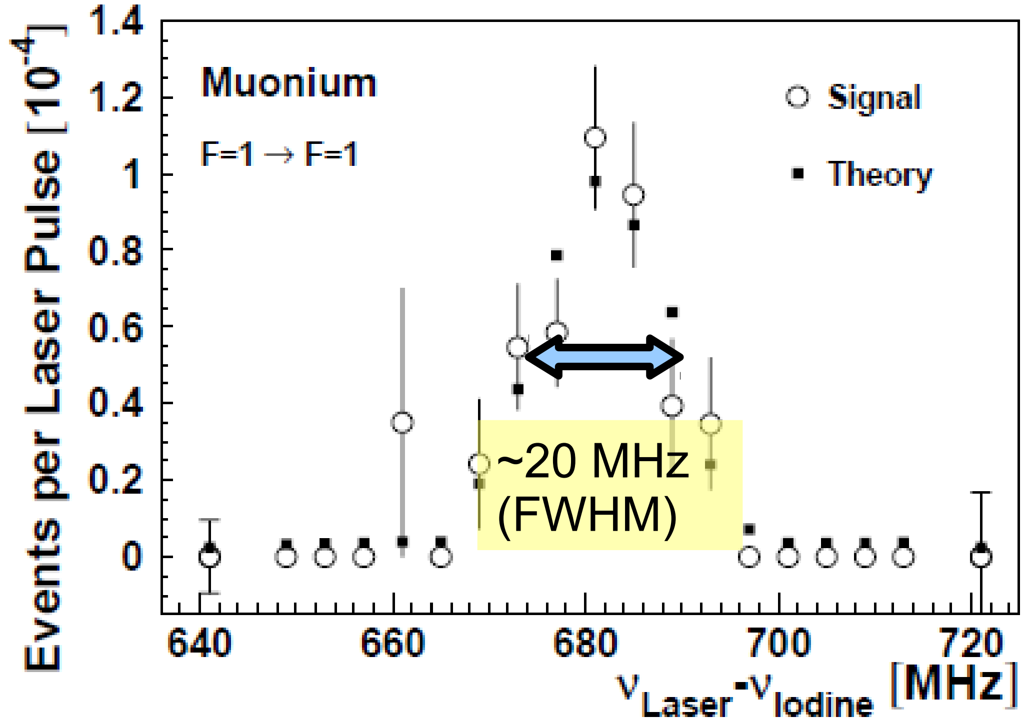


Current (1999) 1S-2S results

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 Mu CW 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

(Z. Burkley et al., Appl. Phys. B 123, 5 (2016) and arXiv:1801.08536)

First CW spectroscopy

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!

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)

Systematic related to pulsed excitation eliminated

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)

→ Improvement in reach using the LEM beamline at PSI

Outlook -Mu 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 (see talk A. Soter)

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), a (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.

Thank you to the organizers for the very kind invitation and your attention ☺