Positronium and Muonium 1S-2S laser spectroscopy

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Collaboration of Rubbia and Kirch groups
and PSI muon and LEM groups

SWICH 2018- 5th of April 2018 – Murten (Switzerland)

Leptonic atoms

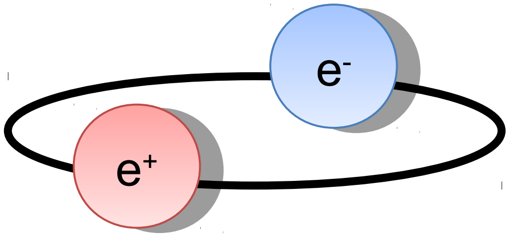
Precise test of
bound state QED
free from finite size effects

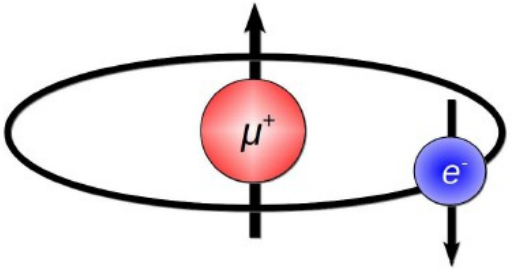
See Also's talk

Fundamental
constants

Positronium (Ps)

Muonium (Mu)





Test of the fundamental
symmetries and search
for new physics

New results on massless dark
photon: arXiv:1803.05744

Applications in material
science

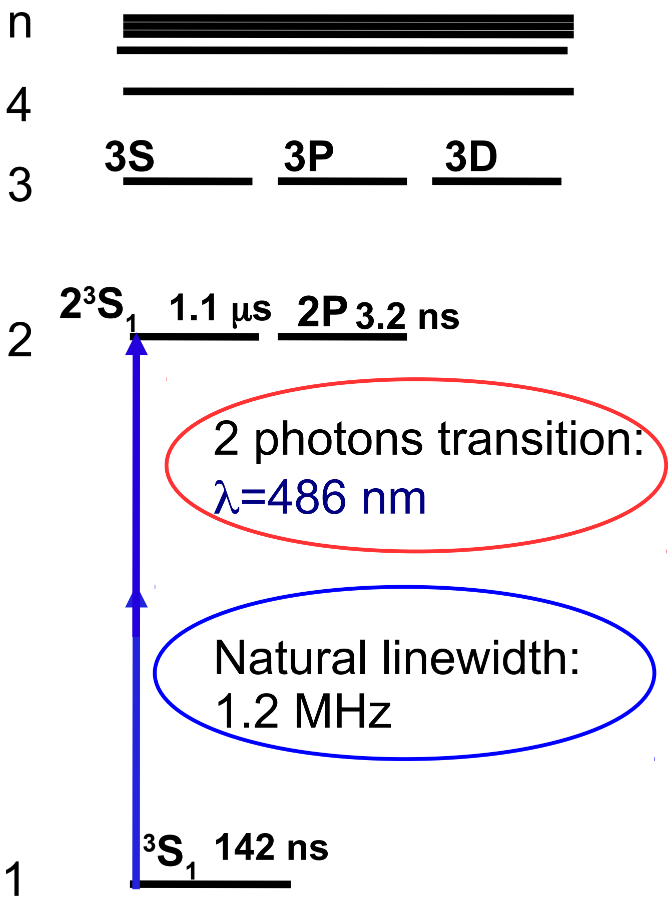
Nat. Comm. 6, 8633 (2015) and Ang.
Chemie Int. Ed. 54, 1591-1594 (2015).

Test the effect of gravity
on
anti-matter

See Ciro's talk

Ps/Mu energy levels

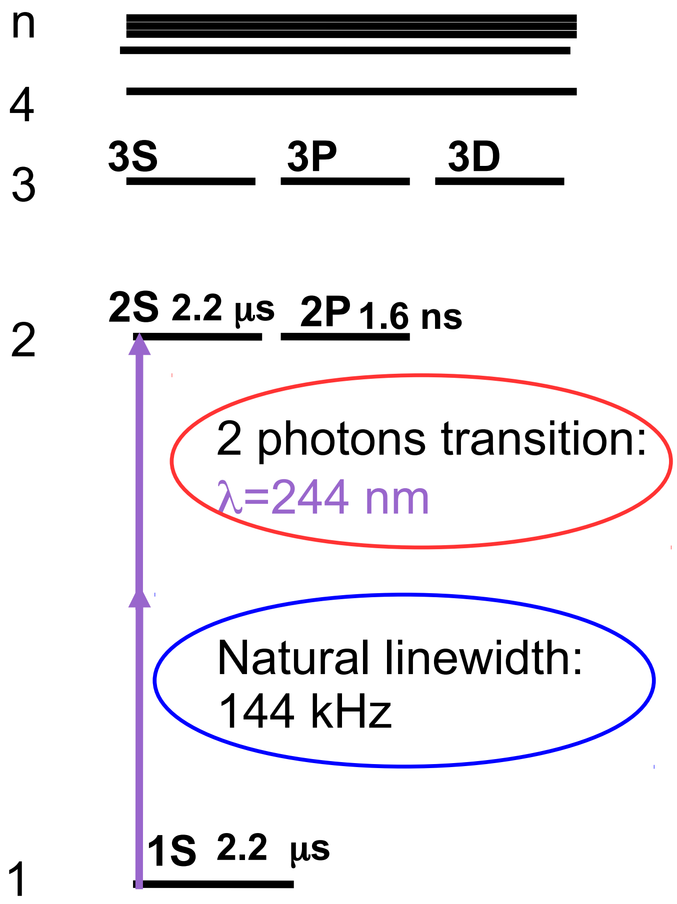
Ps Energy levels



2 photons transition:
λ=486 nm

Natural linewidth:
1.2 MHz

Mu Energy levels

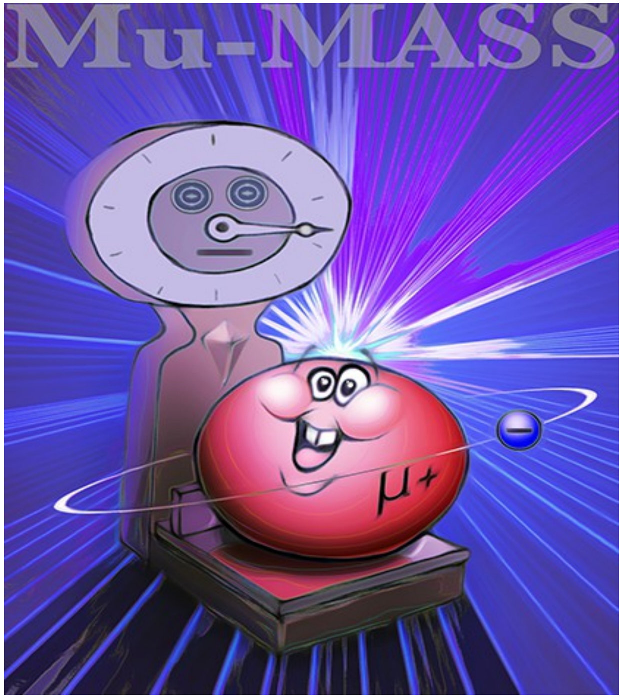


2 photons transition:
λ=244 nm

Natural linewidth:
144 kHz

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

Muonium 1S-2S spectroscopy



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)

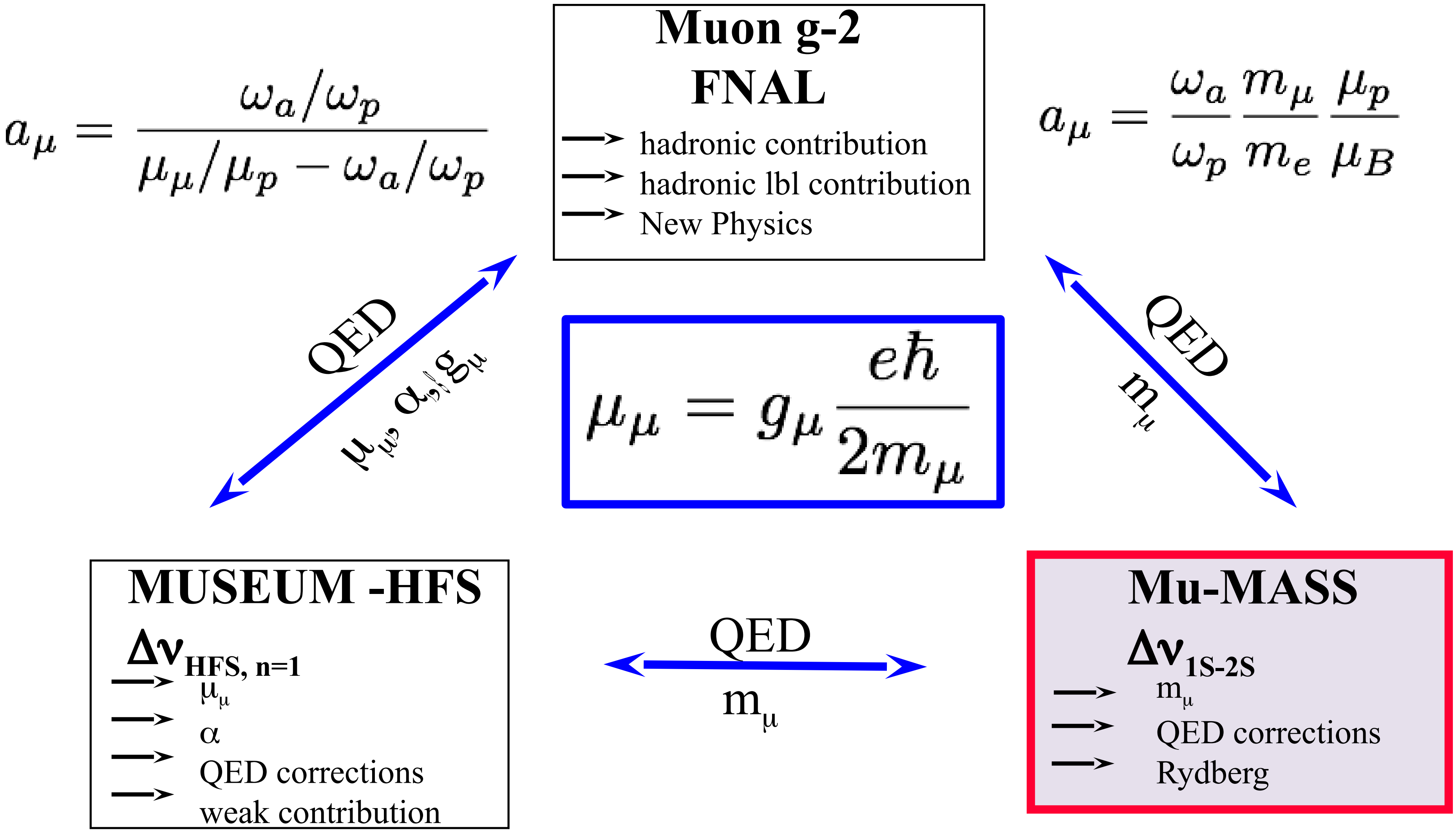
Reduced mass contribution:
1.187 THz (4800 ppm)

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

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

Improvement by 3 orders of magnitude seems possible!

Muonium 1S-2S spectroscopy



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

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

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

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

QED

m_μ

Mu-MASS

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

- → m_μ
- → QED corrections
- → Rydberg

Adapted from K. Jungmann
DPG 2017 (Mainz)

Positronium/Muonium Sources

Experiments statistically limited:
1) Improve primary beams (in progress at PSI, muCool)
2) Improve conversion e+/μ+->Ps/Mu into vacuum

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1) Improve primary beams (in progress at PSI, muCool)
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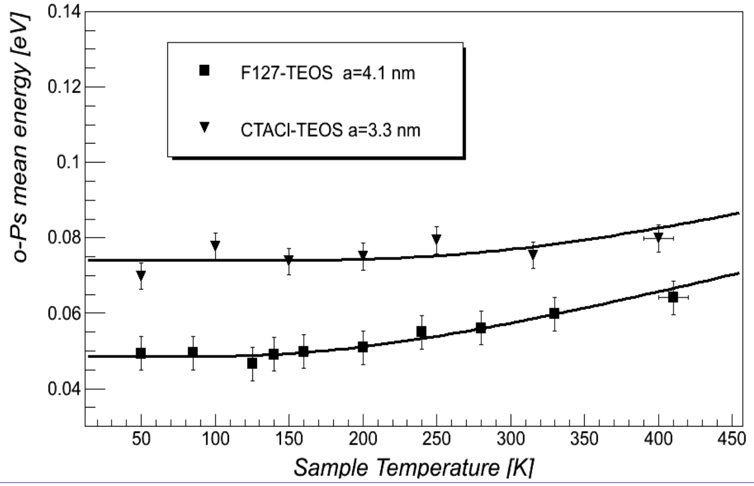
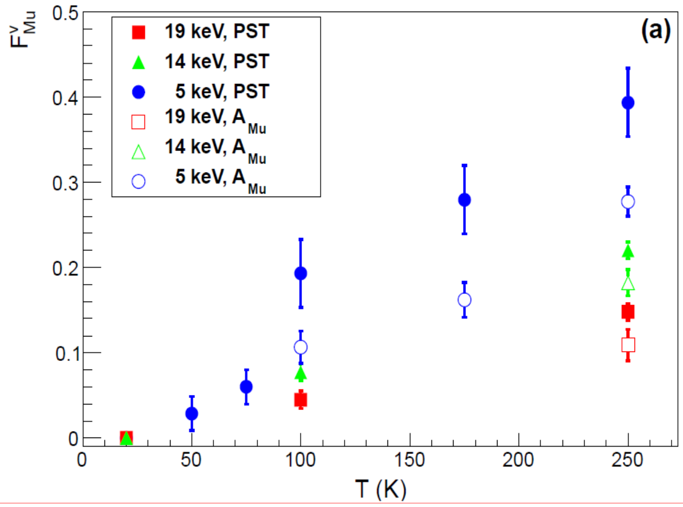
ETHZ: 30% e+->Ps into vacuum with 40 meV (almost 10^5 m/s).

P. Crivelli et al, PRA 81, 052703 (2010), PRB 89, 241103(R) (2014)



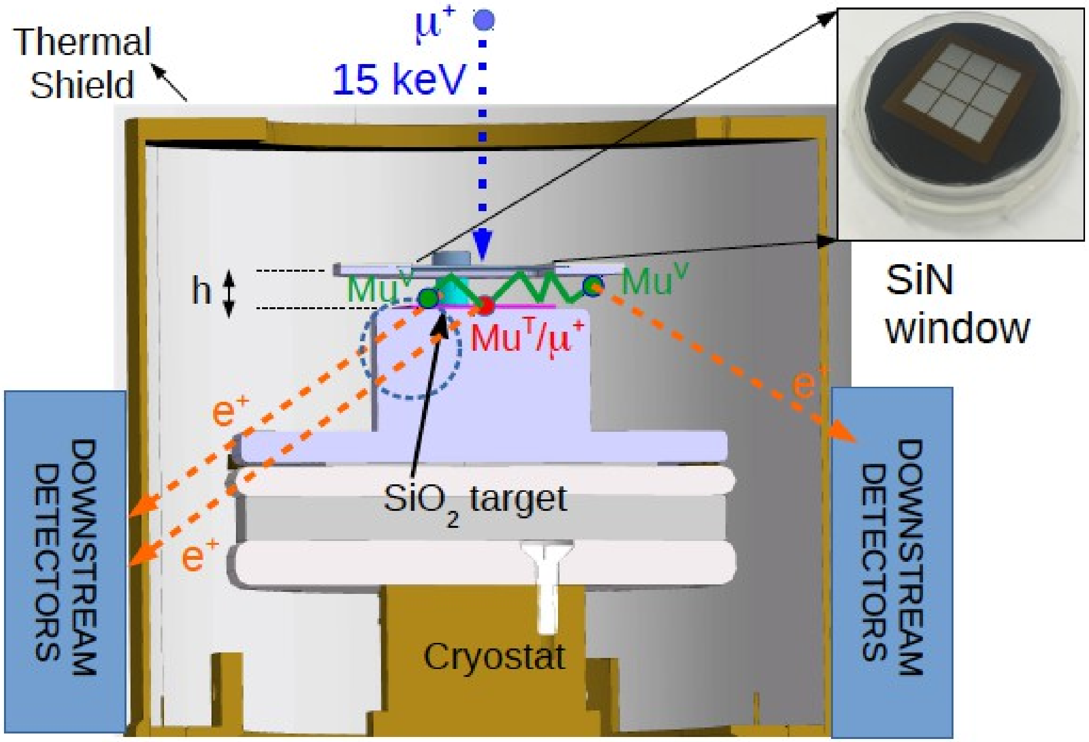
A. Antognini, P.C et al., PRL 108, 143401 (2012)

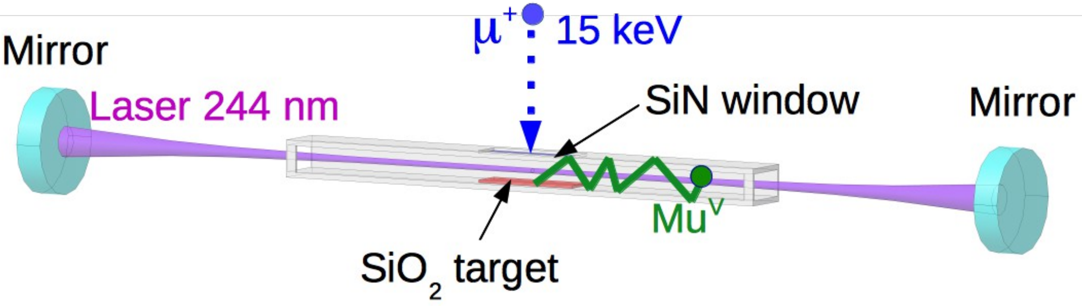


ETHZ/PSI: 20/40% μ+->Mu into vacuum at 100/250K

Muonium spatial confinement

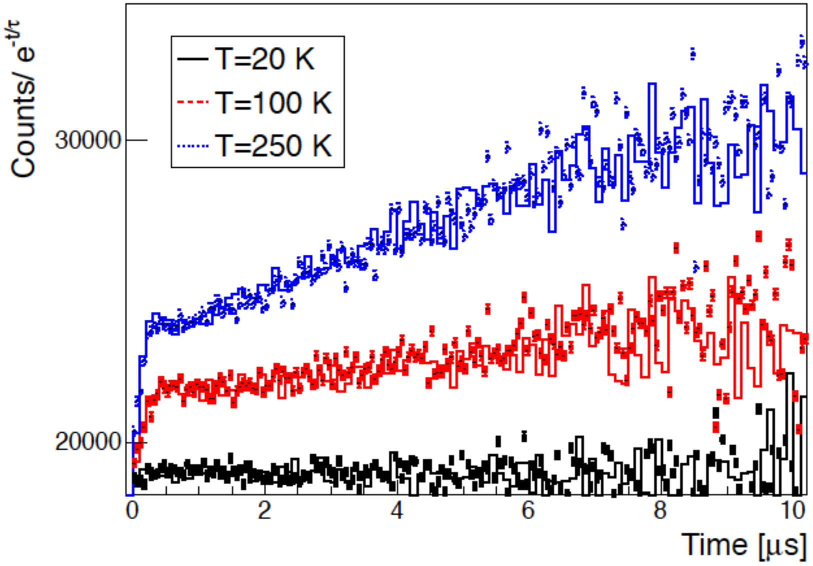
K. S. Khaw, A. Antognini, T. Prokscha, K. Kirch, L. Liszkay, Z., Salman, P. Crivelli, PRA 94, 022716 (2016)

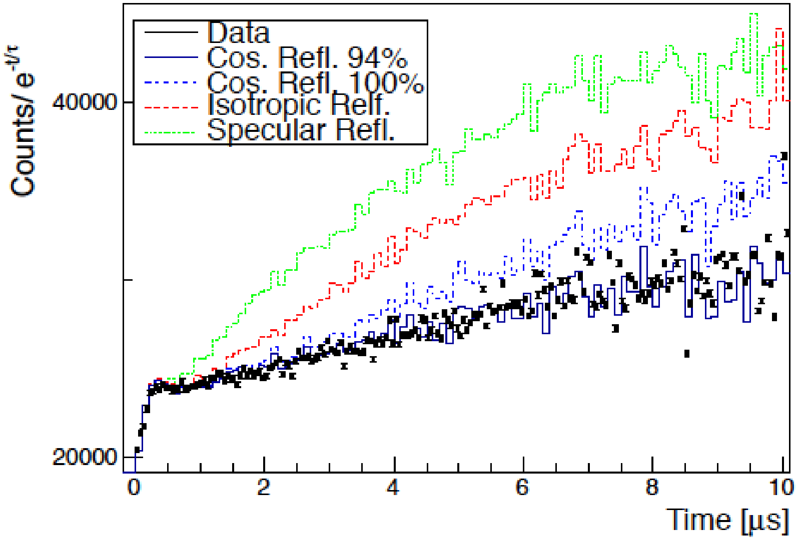




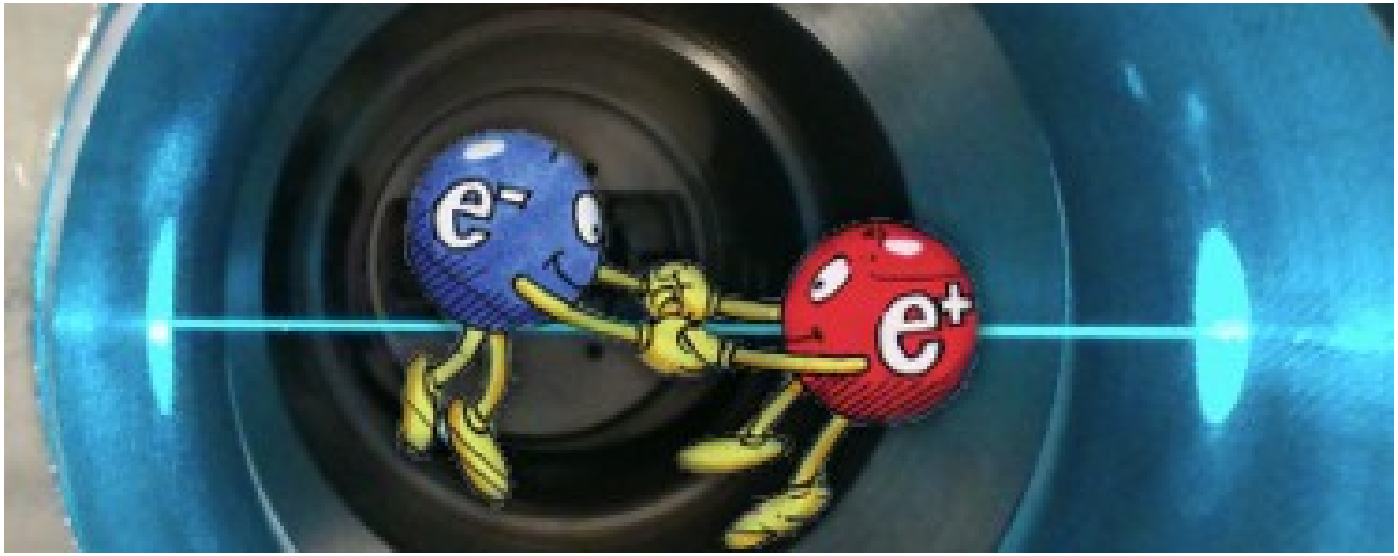
Factor 5 enhancement in exc. probability

DATA-SIM 1mm

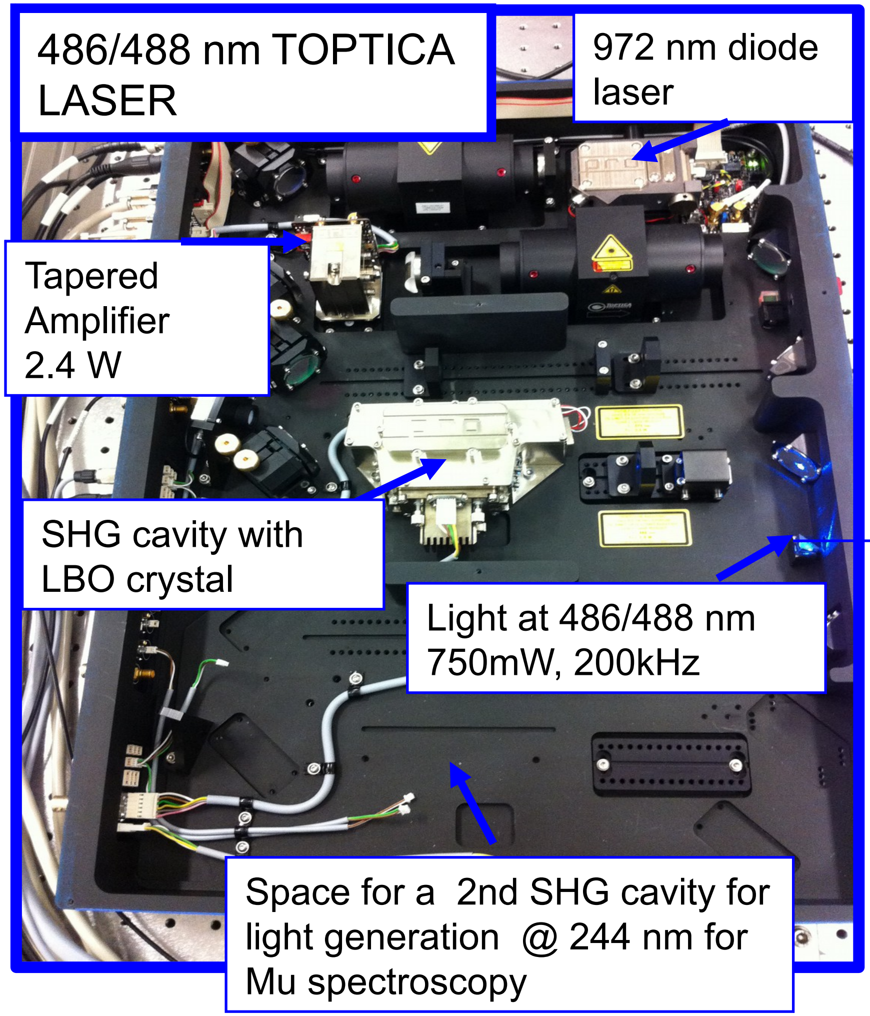




Laser spectroscopy



The Ps/Mu laser system



486/488 nm TOPTICA LASER

972 nm diode laser

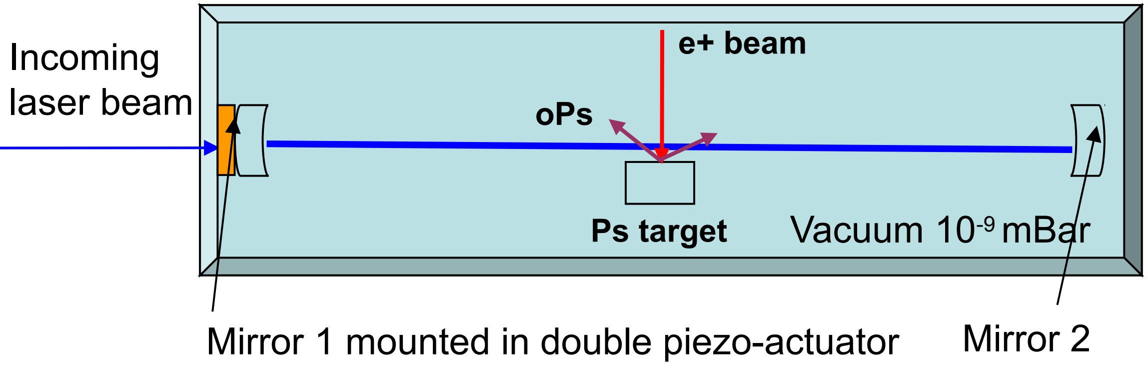
Tapered Amplifier 2.4 W

SHG cavity with LBO crystal

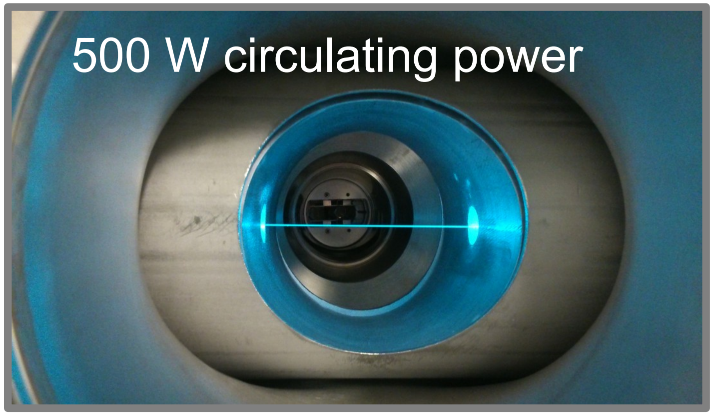
Light at 486/488 nm 750mW, 200kHz

Space for a 2nd SHG cavity for light generation @ 244 nm for Mu spectroscopy

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



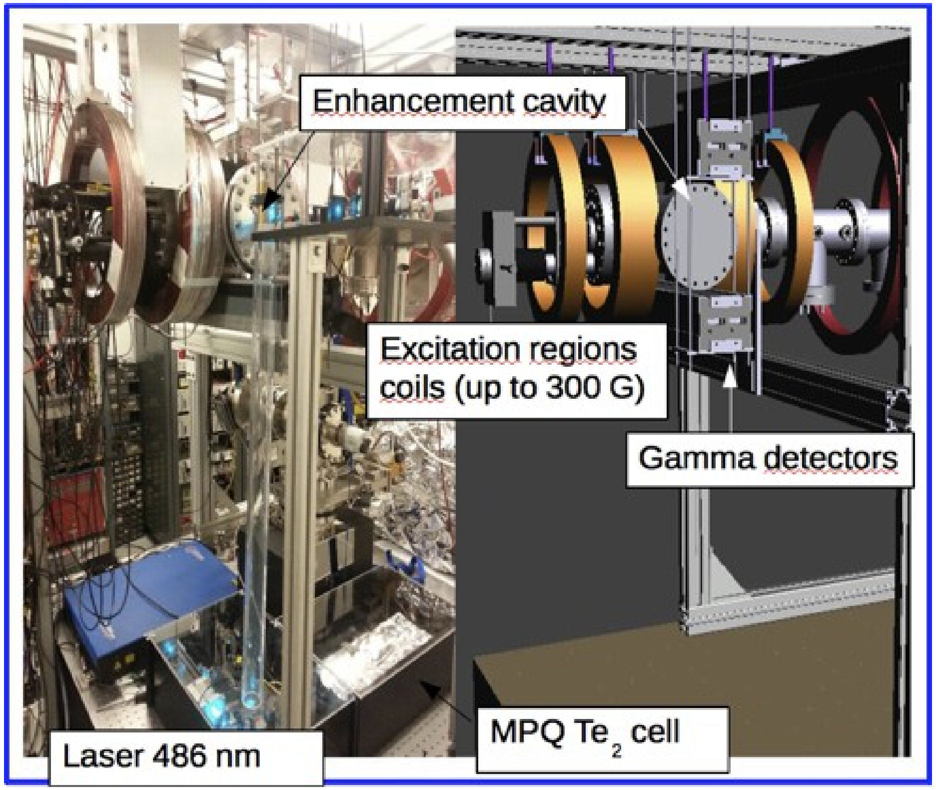
High finesse resonator for power build up
500 mW ⇨ 1 kW

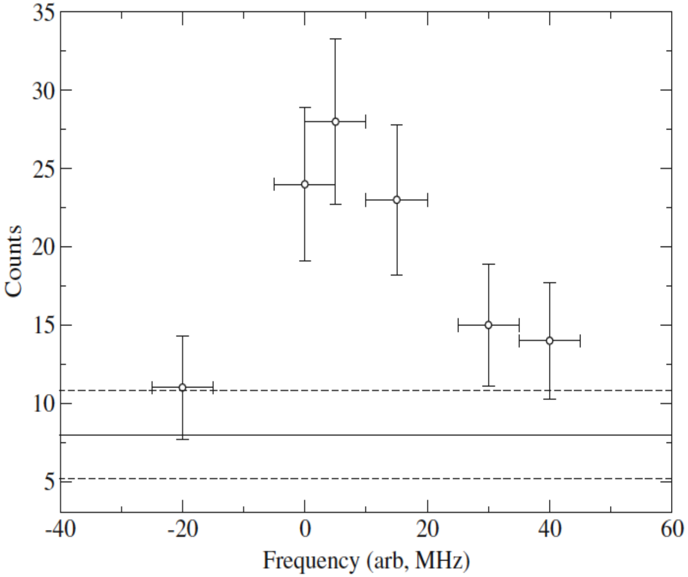

500 W circulating power

Detection of Ps annihilations in the 2S state

D.Cooke, PC, J. Alnis, A. Antognini, B. Brown, S. Friedreich, A. Gabard, T. W. Haensch, K. Kirch, A. Rubbia and V. Vrankovic,l, Hyp. Interact. 233 (2015) 1-3, 67

CW slow positron beam setup



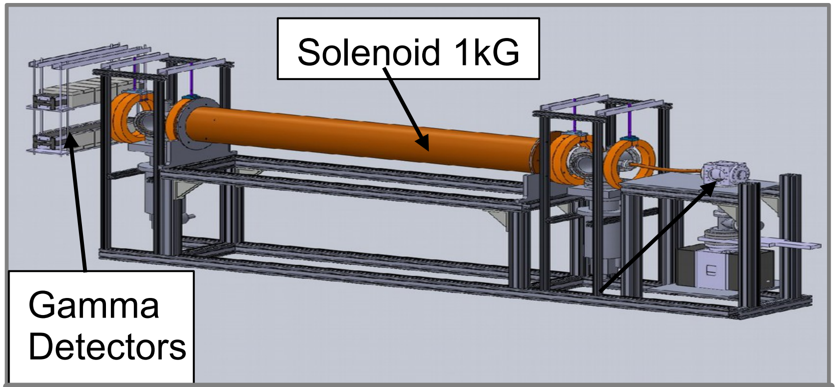


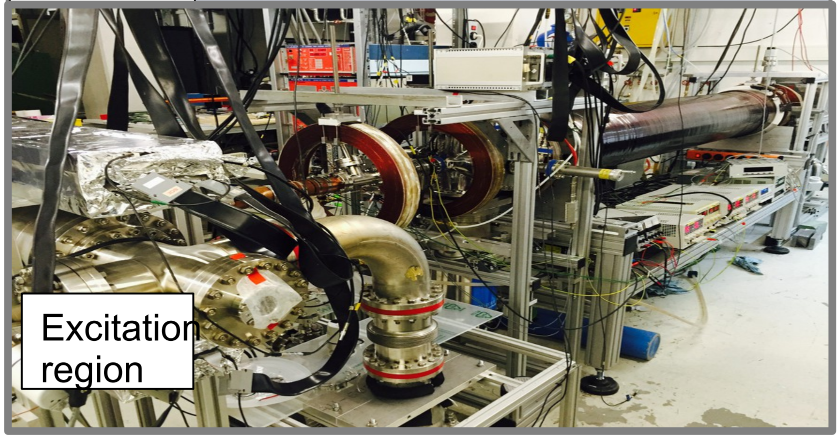
S/N ratio should be improved.

Use bunched beam (buffer gas trap)
→ Noise from **accidentals** reduced by 2 orders of magnitude
→ Reduction and correction of **systematic** effects

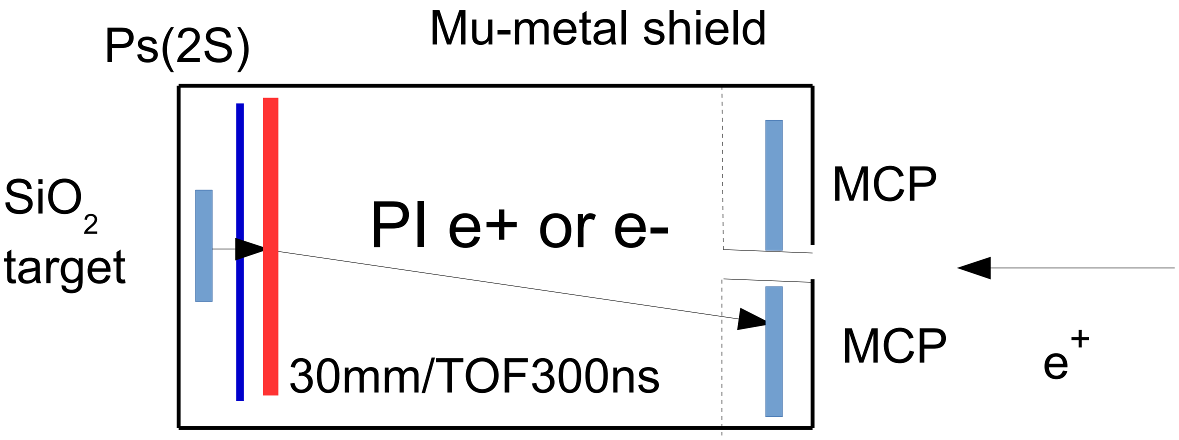
New beam line based on positron buffer gas trap

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



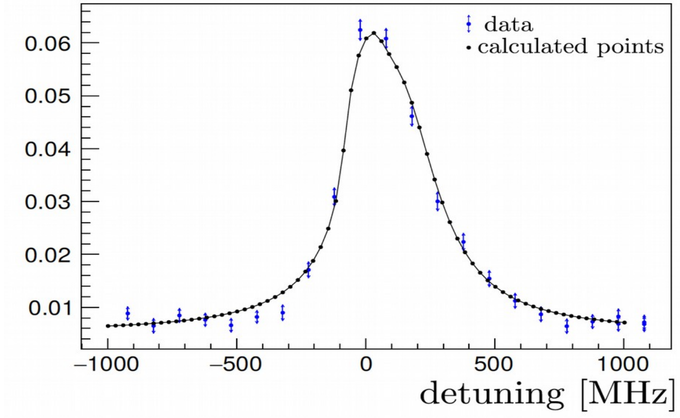


Different detection methods:



→ Improved S/N ratio
→ Field free region (no related systematic)
→ correction for the 2nd order Doppler shift

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



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 of 5×10^{-10}

→ check QED calculation *Adkins, Kim, Parsons and Fell, PRL 115 233401 (2015)*

→ Lorentz/CPT test (sidereal variations)

V.A. Kostelecky and A.J. Vargas, Phys. Rev. D 92, 056002 (2015);

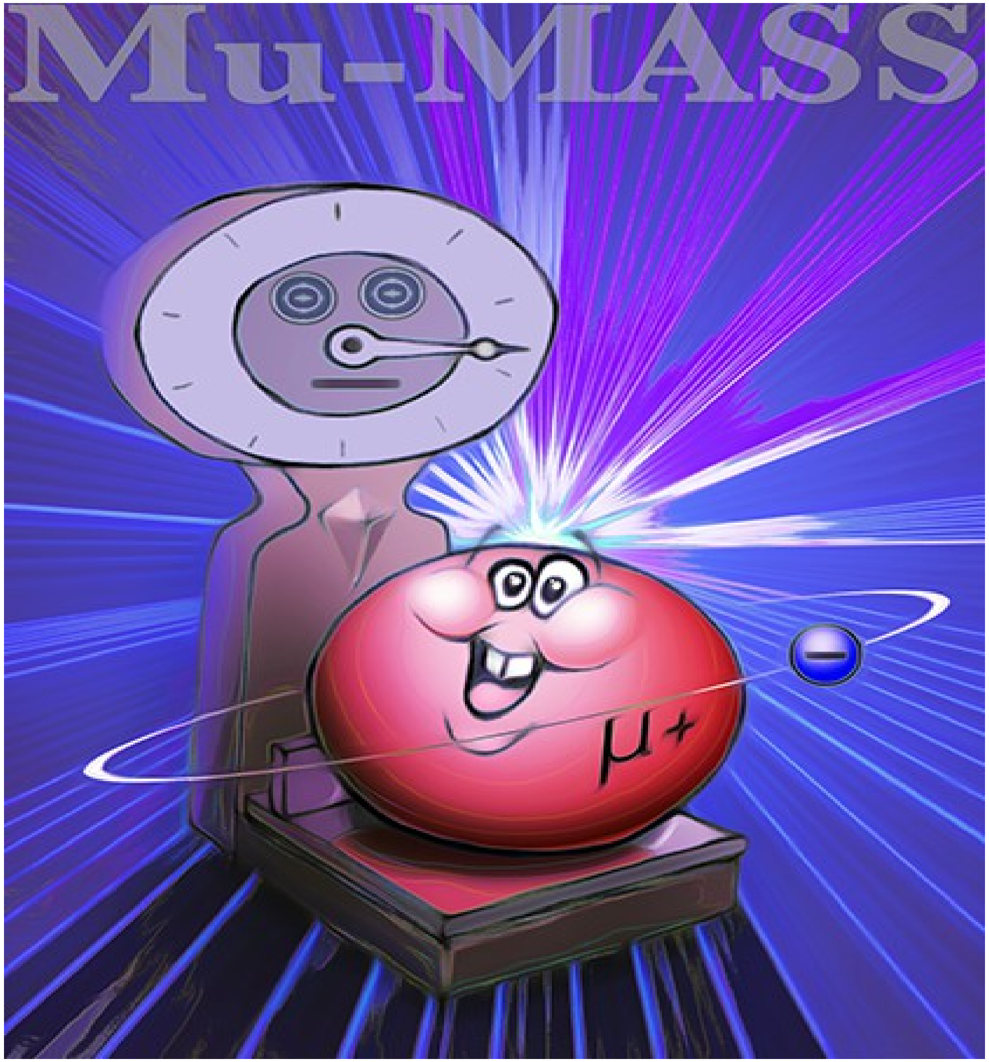
POTENTIAL IMPROVEMENTS

→ GBAR LINAC

→ Colder Ps source? Broadband laser cooling?

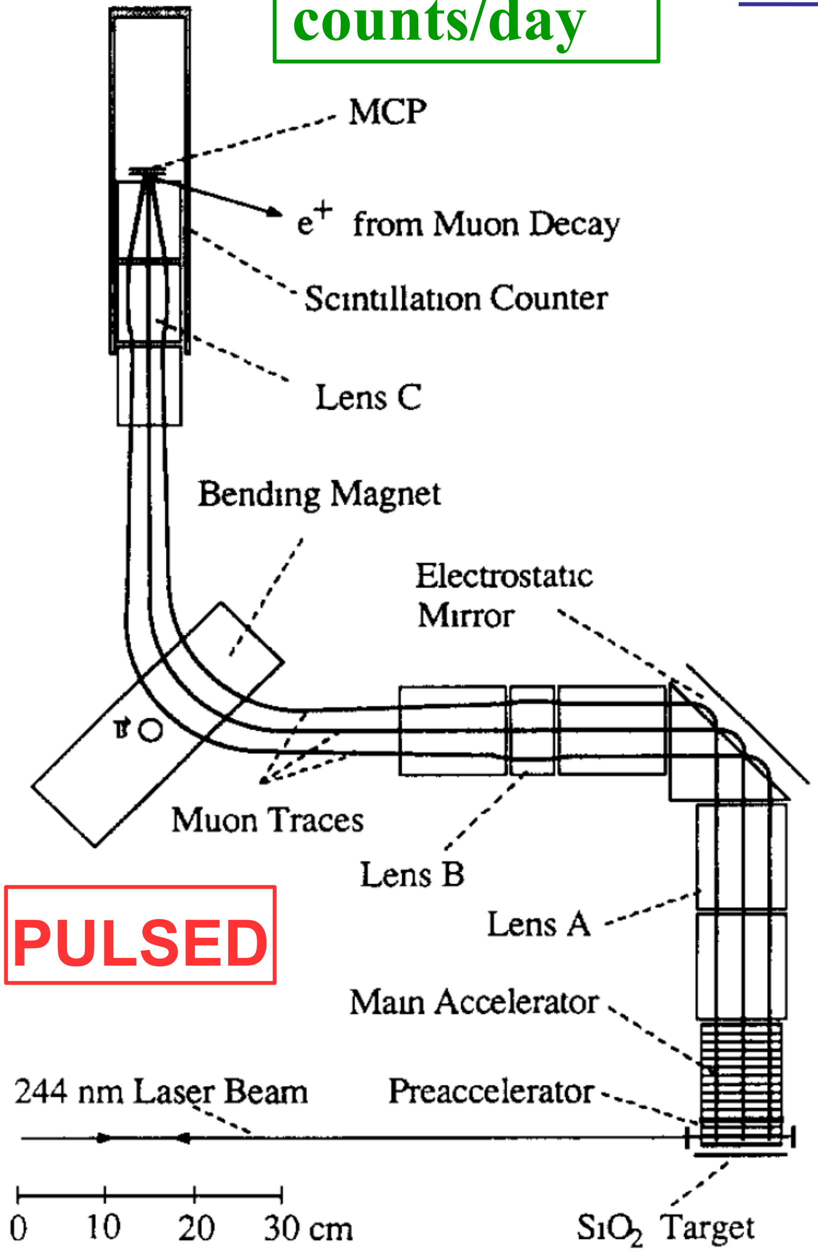
P. Crivelli, D. A. Cooke and S. Friedreich, Int. J. Mod. Phys. Conf. Ser. 30, 1460257 (2014).

MuoniuM lAser SpectroScopy

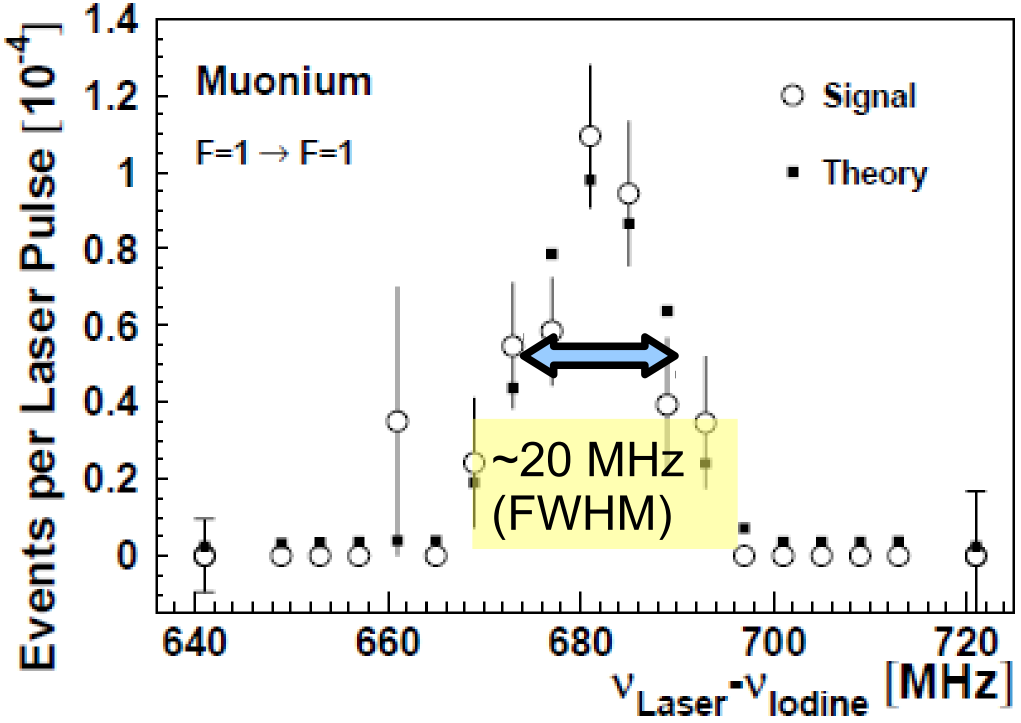


Current (1999) 1S-2S results

BKG: 2.5 counts/day



PULSED



~20 MHz (FWHM)

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

$$R \sim N_{\mathrm{Mu}} \cdot I^2 \cdot t^2 \quad \text{where} \quad \begin{cases} N_{\mathrm{Mu}} : & \text{Muonium production rate} \\ I : & \text{Laser intensity} \\ t \sim v^{-1} : & \text{Interaction time} \end{cases}$$

Need a Mu source with high yield and low energy

Decrease requirements of laser intensity

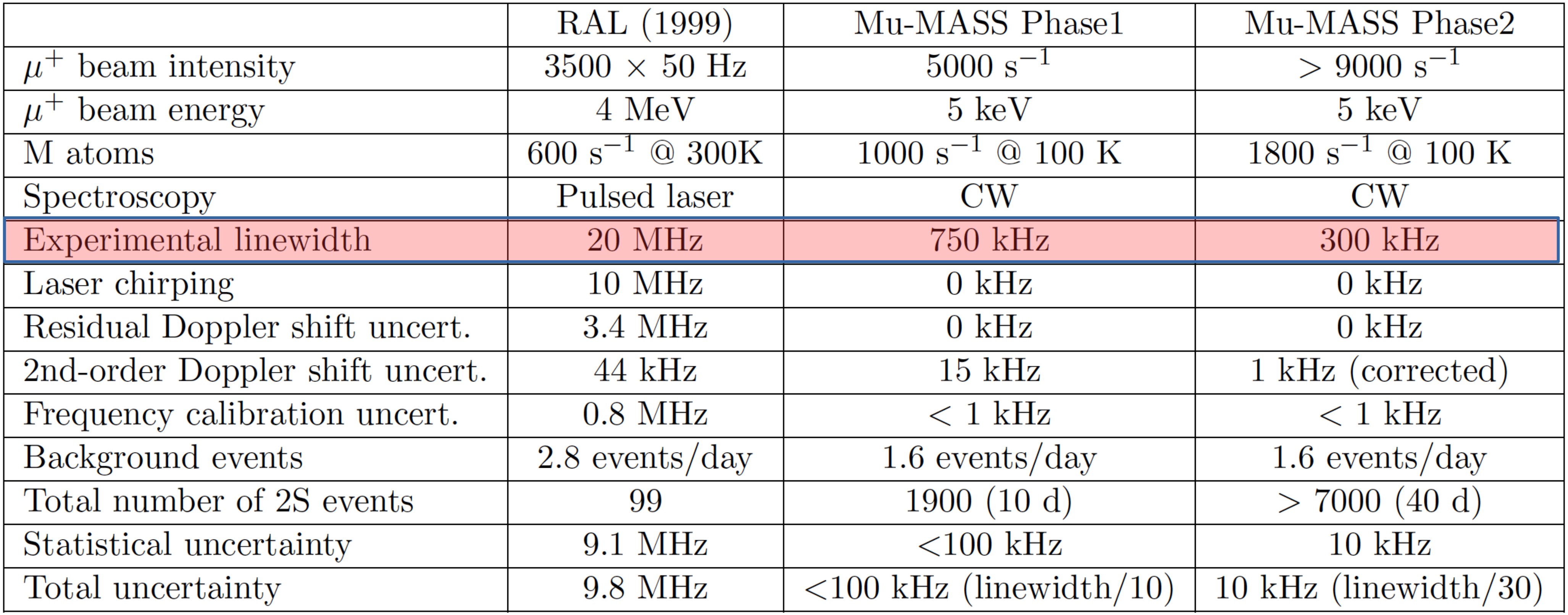
Mu @ 100 K

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

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Systematic related to pulsed excitation eliminated

Pulsed vs CW spectroscopy

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Improvement in reach using exisitng LEM beamline at PSI
→ Improve muon mass (1 ppb) adn q_μ/q_e (1 ppt)
→ stringent test of bound state QED (rel. accuracy 1 ppt)
→ Rydberg costantfree of finite size effects (few ppt) and α at 1 ppb
→ Test of SME

Conclusions

- **Switzerland:** leading role in physics of leptonic atoms and exotic atoms in general.

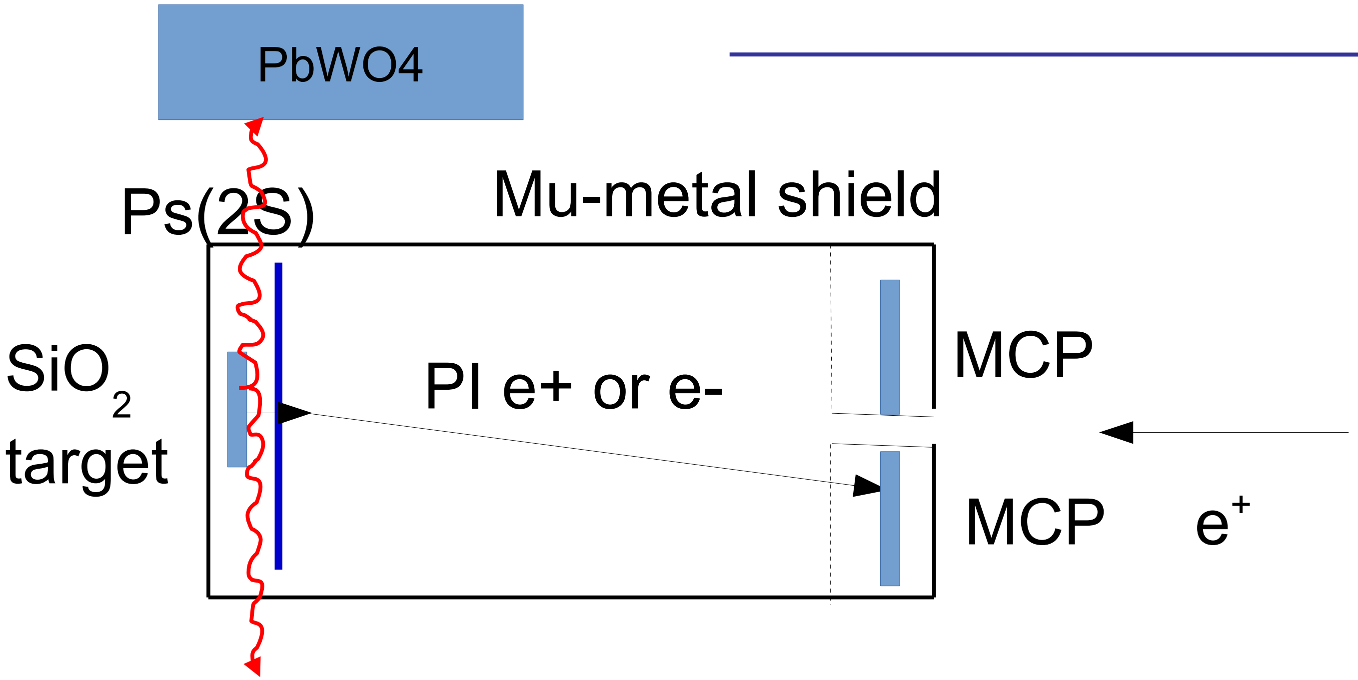
- Unique facilities: ETHZ (positrons beams), PSI (slow/surface muon/pion beam lines, muonic and pionic atoms), CERN (AD → ELENA, GBAR LINAC → intense positron beam)

TIMELINE for spectroscopy of Ps, Mu and HBAR:
- 2018-2021 Ps spectroscopy (1S-2S and HFS-2S)
- 2019-2024 Mu spectroscopy (1S-2S)
- 2022-2027 Spectroscopy of optically trapped HBAR (using ultra cold GBAR atoms)

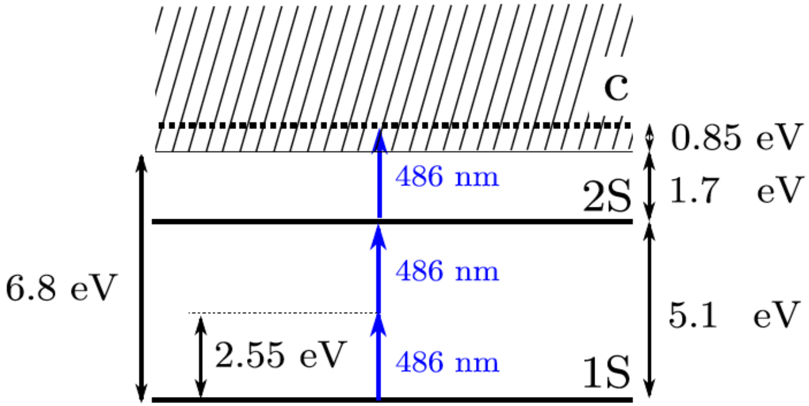
P. Crivelli, N. Kolachevsky, "Optical trapping of anti-hydrogen towards an atomic anti-clock", arXiv:1707.02214 (2017).

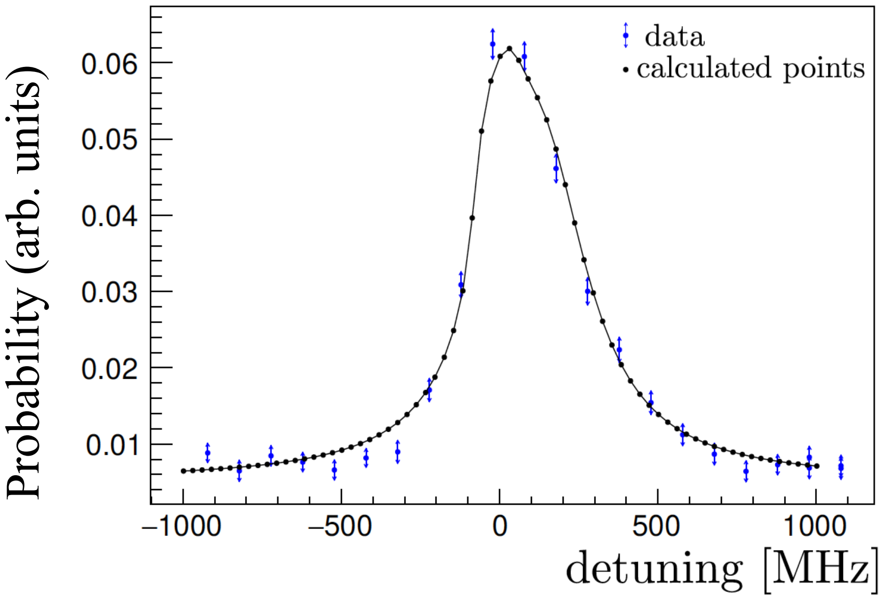
Backup slides

Detection schemes- PI in the 2S exc. Laser

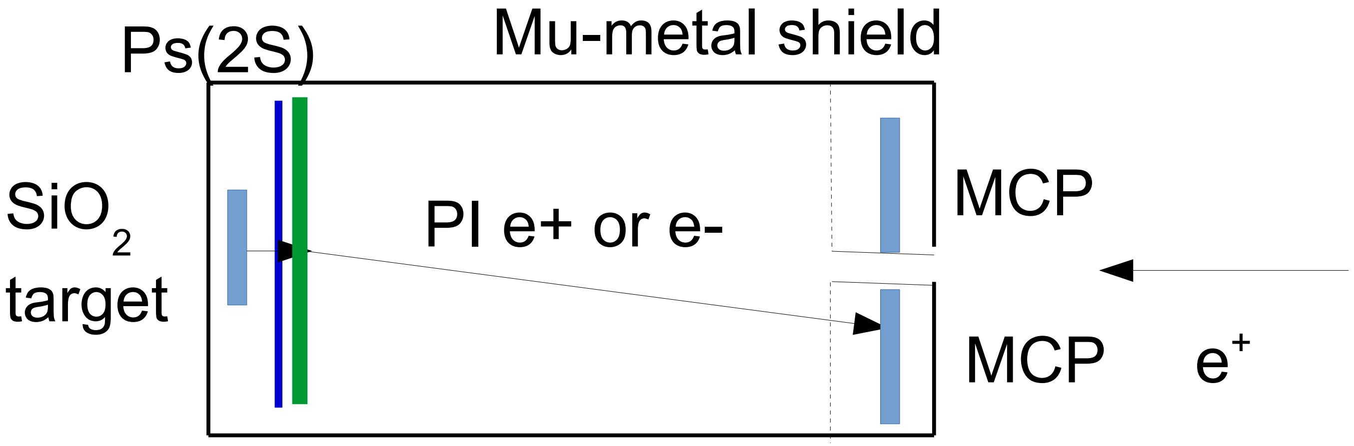


1) Photo-ionized Ps in the 2S excitation laser detected either by SSPALS or e^+ or e^- in an MCP



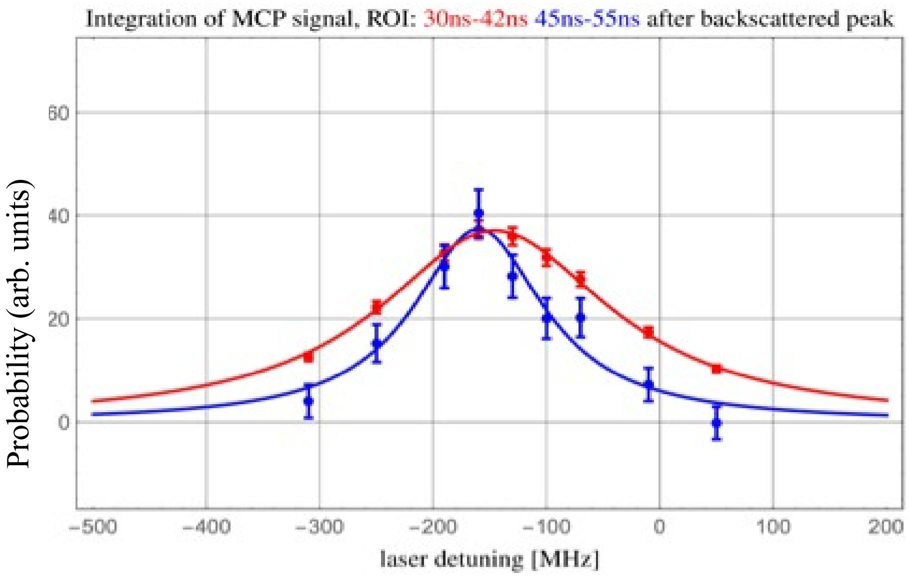


Detection schemes- external PI

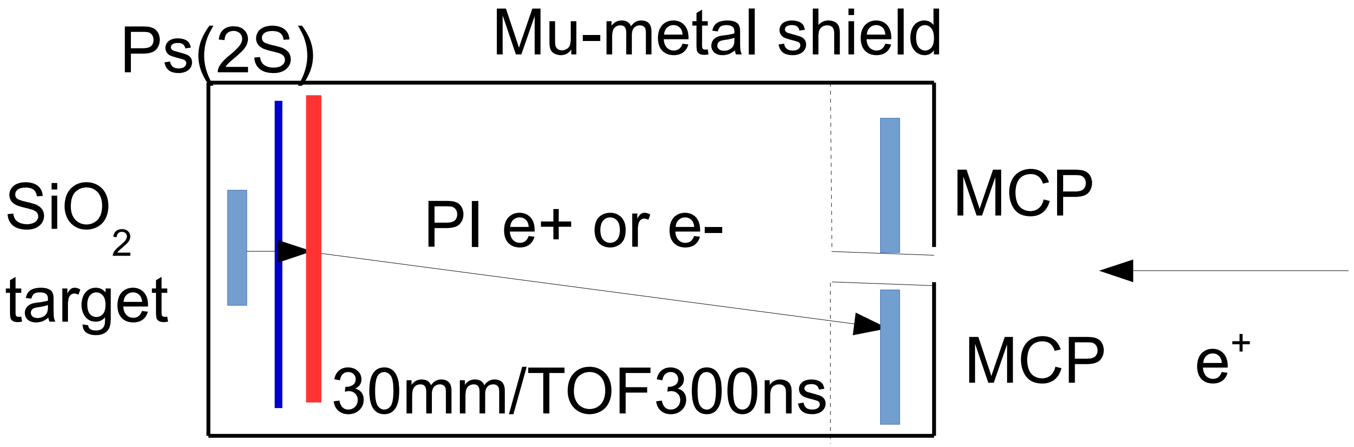


2) Photo-ionization: external laser 532 nm

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



Detection schemes- field ionization of Ps*



Ps(2S)

Mu-metal shield

SiO_2 target

PI e+ or e-

MCP

MCP

e^+

30mm/TOF300ns

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)