Positronium and Muonium 1S-2S Spectroscopy

Paolo Crivelli

Institute for Particle Physics, ETH Zurich

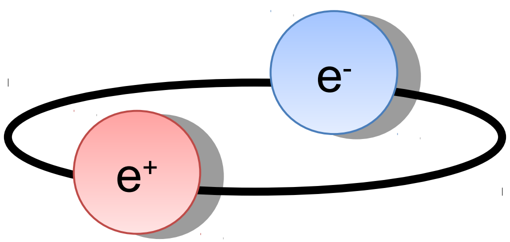
PSI2016 -17th of October – Paul Scherrer Institute, Switzerland

Leptonic atoms

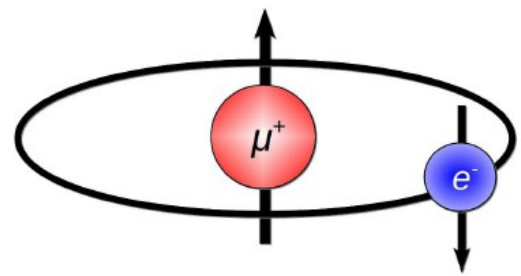
Precise test of
bound state QED
free from finite size effects

Fundamental
constants

Positronium (Ps)



Muonium (Mu)



Test of the fundamental
symmetries and search
for new physics

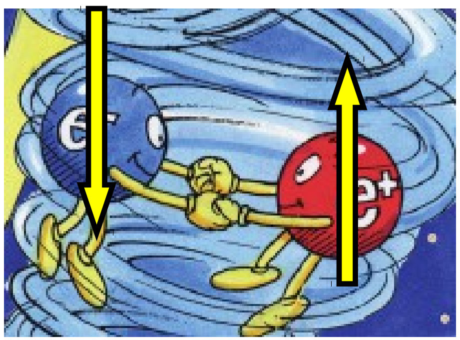
Test the effect of gravity
on
anti-matter

Applications in material
science

Positronium (Ps)

<u>Two ground states:</u>

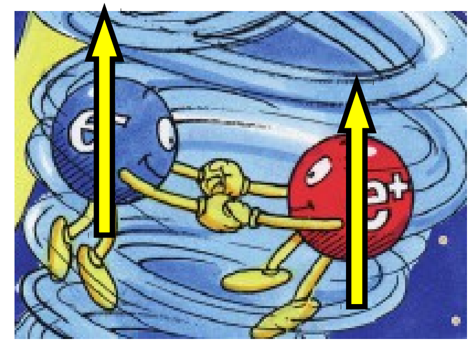
Parapositronium (p-Ps) singlet spin state $^1S_0$



.

$$|0,0\rangle = (\uparrow\downarrow - \downarrow\uparrow)/\sqrt{2} \Big\} \quad s=0 \quad \text{(singlet)}$$

Orthopositronium (o-Ps) triplet spin state $^3S_1$

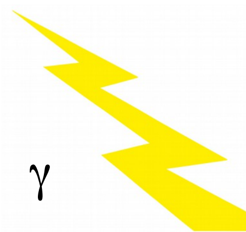


$$\left.\begin{array}{l} |1,1\rangle = \uparrow\uparrow \\ |1,0\rangle = (\uparrow\downarrow + \downarrow\uparrow)/\sqrt{2} \\ |1,-1\rangle = \downarrow\downarrow \end{array}\right\} \quad s=1 \quad \text{(triplet)}$$

Positronium (Ps)

Two ground states:

Parapositronium (p-Ps) singlet spin state $^1S_0$



γ

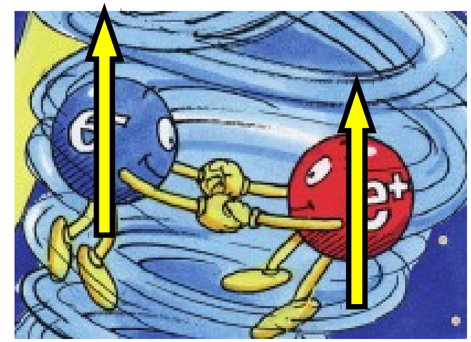
$E = m\,c^2$

γ

$$|k_1| = |k_2| = 511\,keV$$

$$\Gamma^{-1} = \tau \approx 125 \text{ ps}$$

Orthopositronium (o-Ps) triplet spin state $^3S_1$



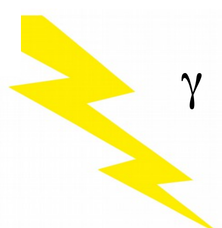
$$\left.\begin{array}{r}|1,1\rangle = \uparrow\uparrow \\ |1,0\rangle = (\uparrow\downarrow + \downarrow\uparrow)/\sqrt{2} \\ |1,-1\rangle = \downarrow\downarrow\end{array}\right\} \quad s = 1 \quad \text{(triplet)}$$

Positronium (Ps)

<u>Two ground states:</u>

Parapositronium (p-Ps) singlet spin state $^1S_0$

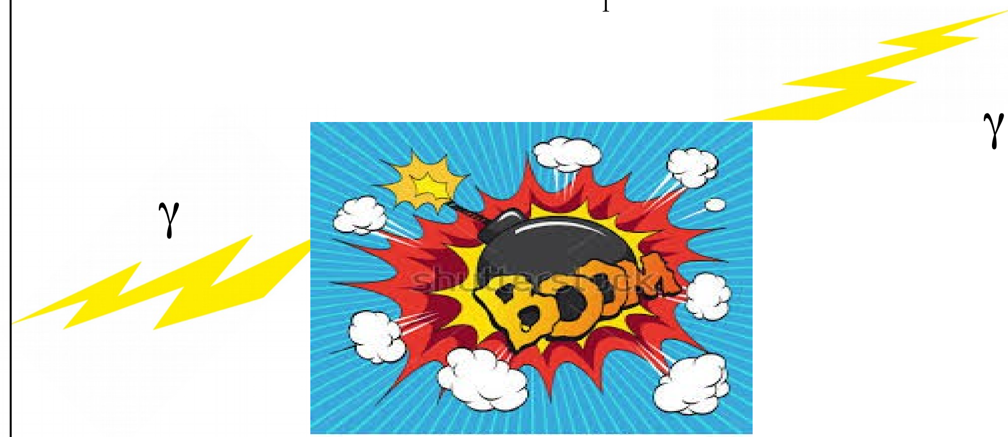
$E = m c^2$



$$|k_1| = |k_2| = 511\, keV$$

$$\Gamma^{-1} = \tau \approx 125 \text{ ps}$$

Orthopositronium (o-Ps) triplet spin state $^3S_1$



$$0 \le |k_i| \le 511\, keV$$

$$\Gamma^{-1} = \tau \approx 142 \text{ ns}$$

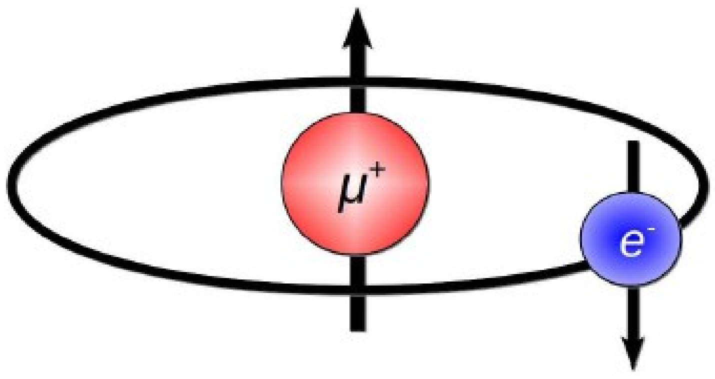
Muonium (Mu)

Mu (positive muon-electron bound state)

Predicted in 1957 (Friedmann, Telegdi, Hughes)

Unstable with lifetime of 2.2 μs.

Main decay channel: $\mu^+ \to e^+ + \nu_\mu + \nu_e$



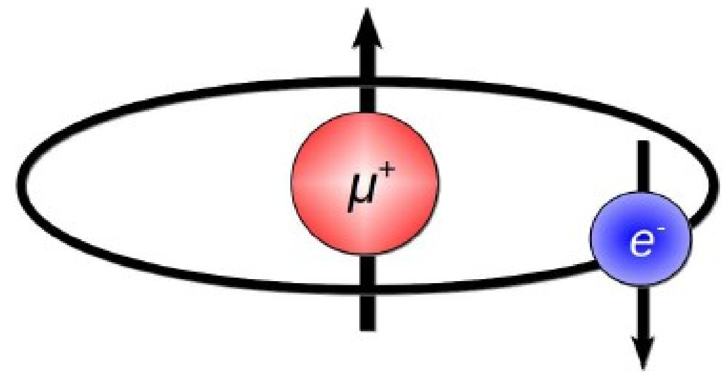
Muonium (Mu)

Mu (positive muon-electron bound state)

Predicted in 1957 (Friedmann, Telegdi, Hughes)

Unstable with lifetime of 2.2 μs.

Main decay channel: $\mu^+ \rightarrow e^+ + \nu_\mu + \nu_e$



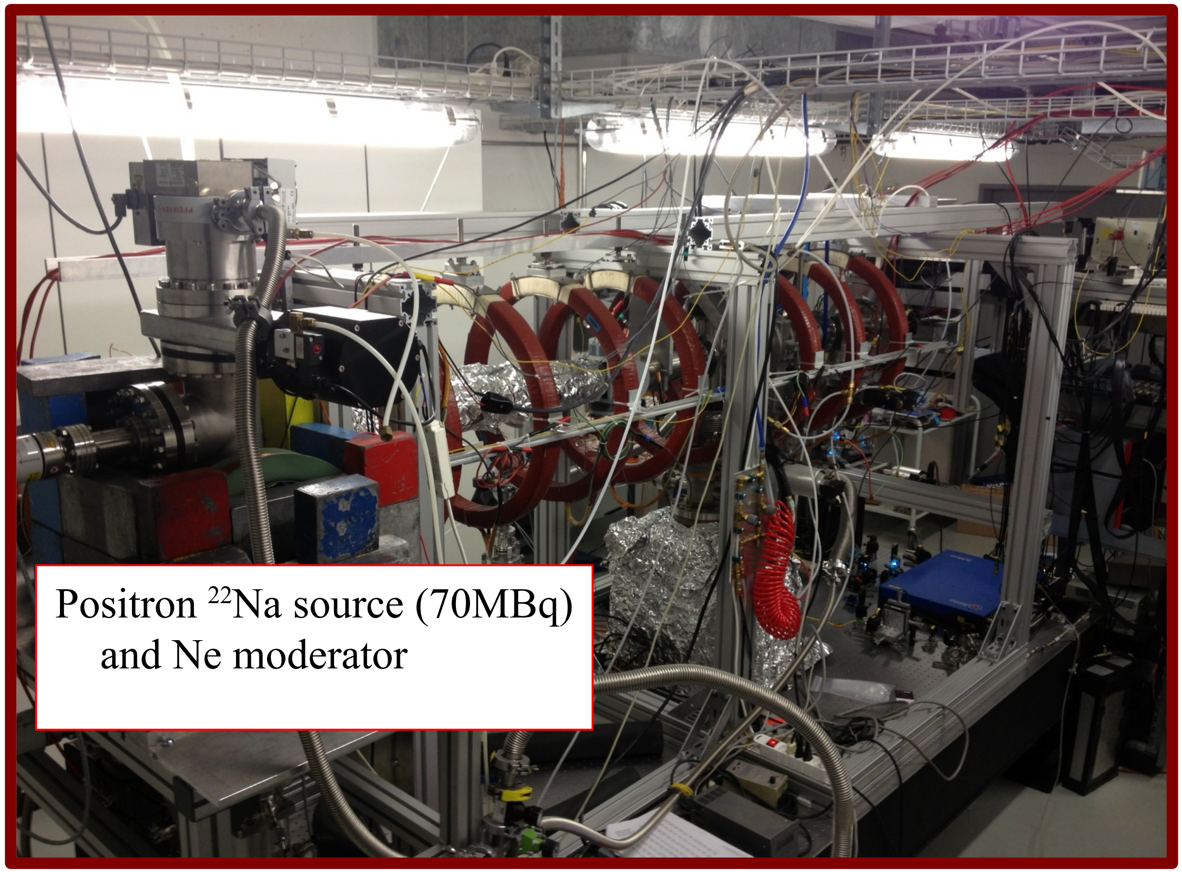
Discovered in 1960 (Hughes) by detecting muonium spin (Larmor) precession in an external magnetic field perpendicular to the spin direction ($\tau = \mu \times B$).

$\omega = \gamma B$, γ is gyromagnetic ratio, γ_μ = 13.6 kHz/G and γMu = 1.4 MHz/G

$$\omega_{\mathrm{Mu}} \approx 103\,\omega_{\mu^+}$$ ⇒ Possible to distinguish between a free muon and one that bound to form Mu

ETH slow positron beam (2012)

Efficient production of positronium in vacuum requires slow positrons



Positron ^{22}Na source (70MBq) and Ne moderator

Produced in beta decay: $p \rightarrow n + e^+ + \nu$

Three body decay -> Positron energy is a continuum (for ^{22}Na from 0 to 543 keV)

Positrons (muons) moderation with rare gases

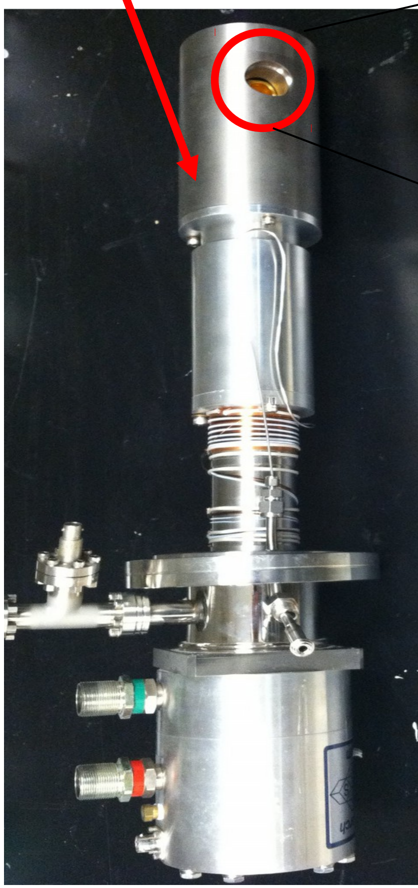
Tungsten alloy shield

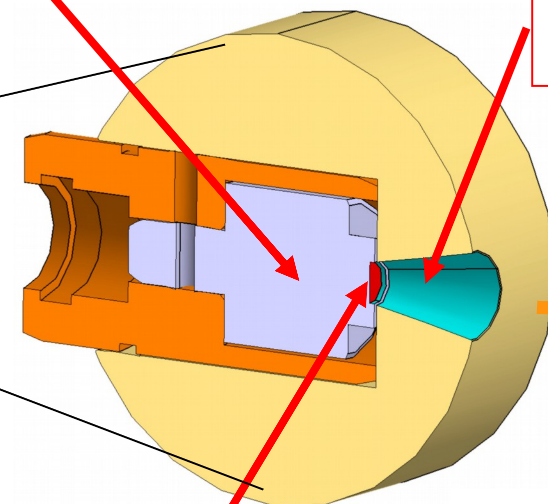
70 MBq ^{22}Na e+ source

Neon film ~ 500 nm grown @ 7K

below band gap (~ 20 eV) energy loss very inefficient (only phonon scattering)

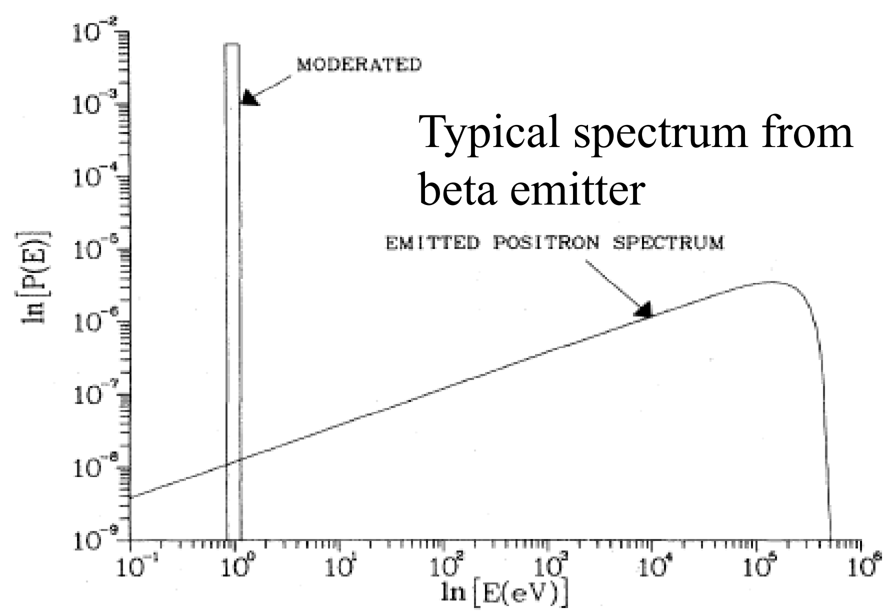
-> large fraction of positrons reach the surface and are emitted as epithermal e+





150000 e^+/s

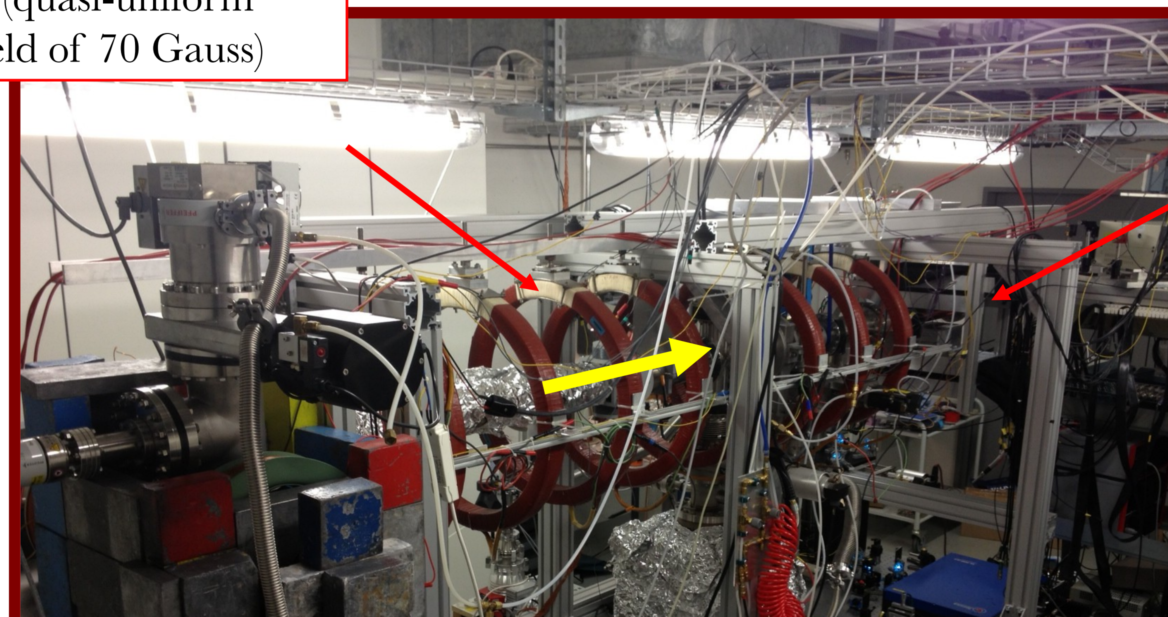
Titanium window 5 μm



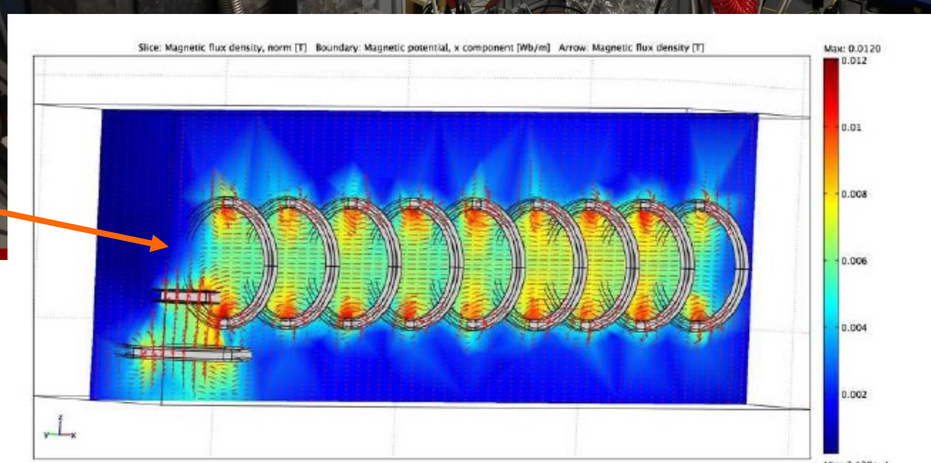
Positron transportation

Magnetic coils for positron transportation (quasi-uniform longitudinal field of 70 Gauss)

Positronium formation region acceleration up to 20 kV

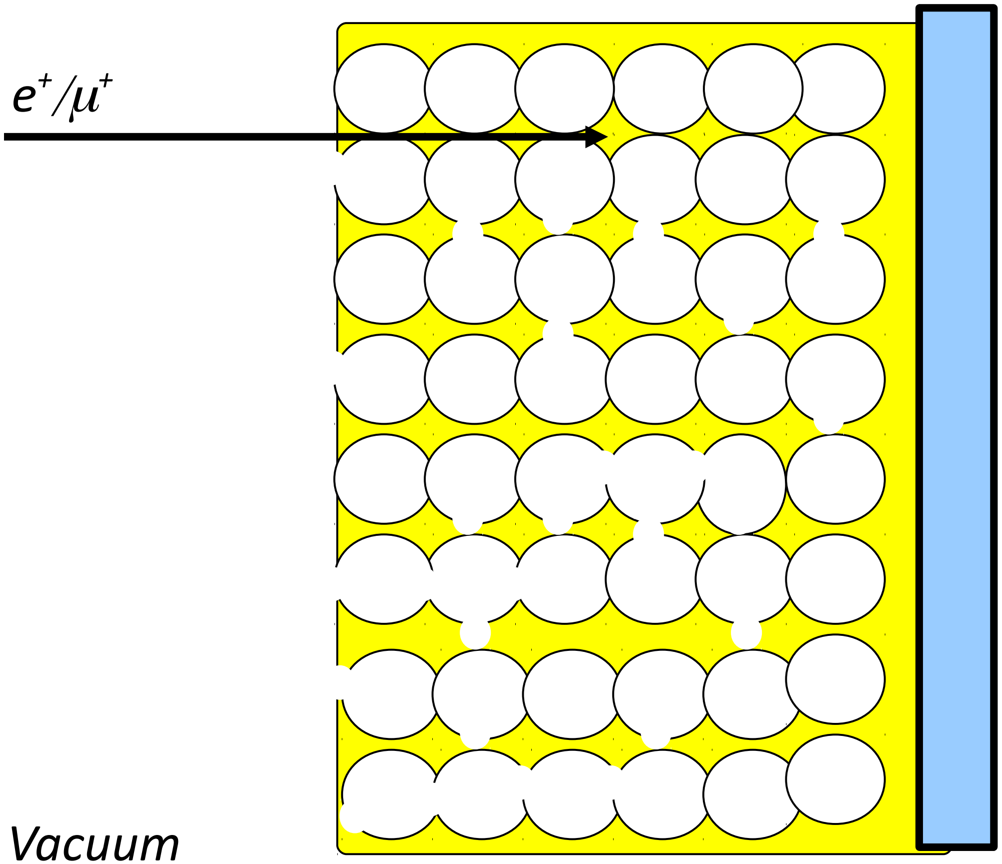


Separation of Slow and fast e^+



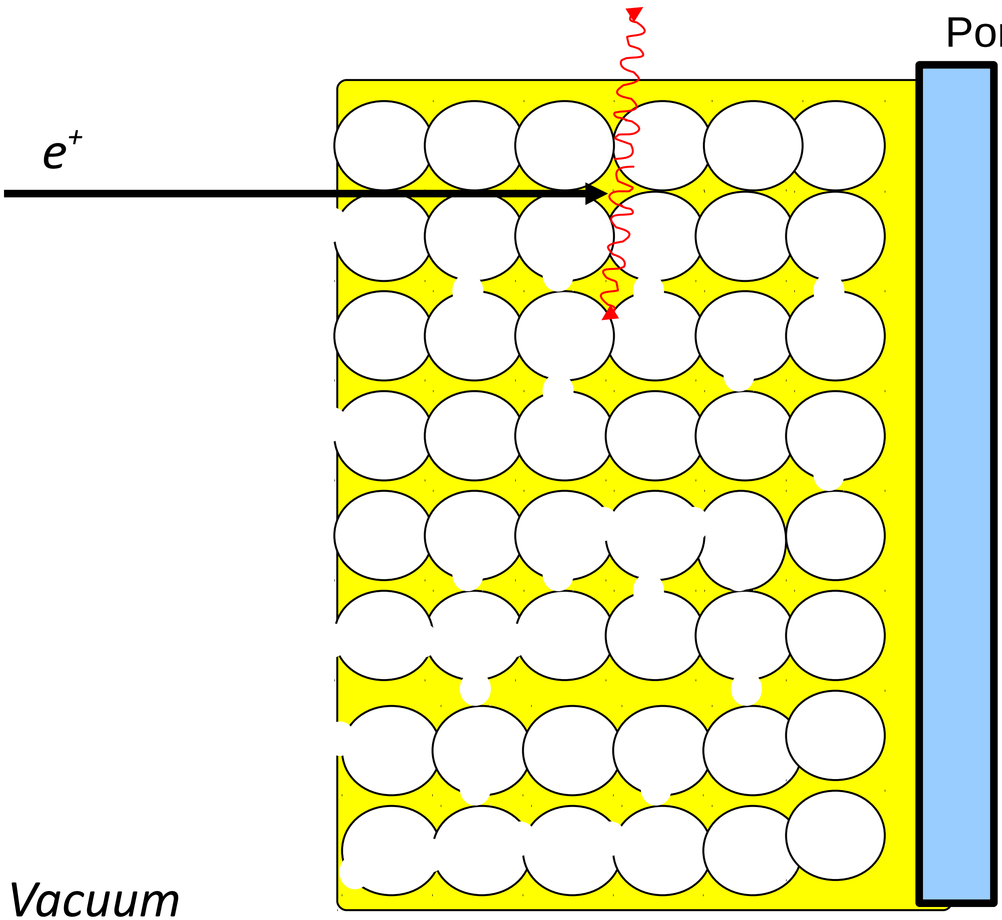
Positronium/Muonium formation

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



- Positron implanted with keV energies
- Rapidly thermalizes in the bulk (~ps)

Positronium formation

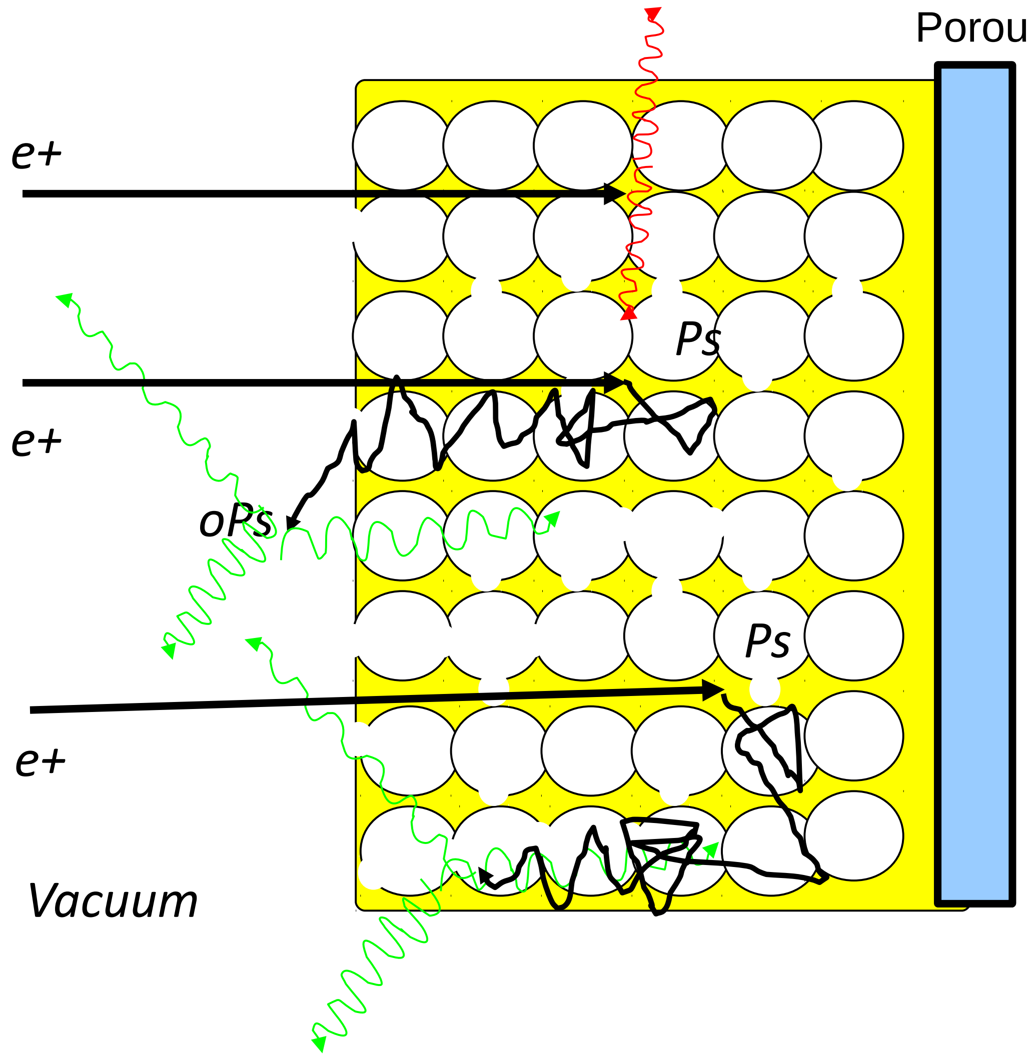


Porous Silica thin film ~1000nm 3-4 nm pore size

- Positron implanted with keV energies
- Rapidly thermalizes in the bulk (~ps)

- Positron diffusion and annihilation

Positronium formation



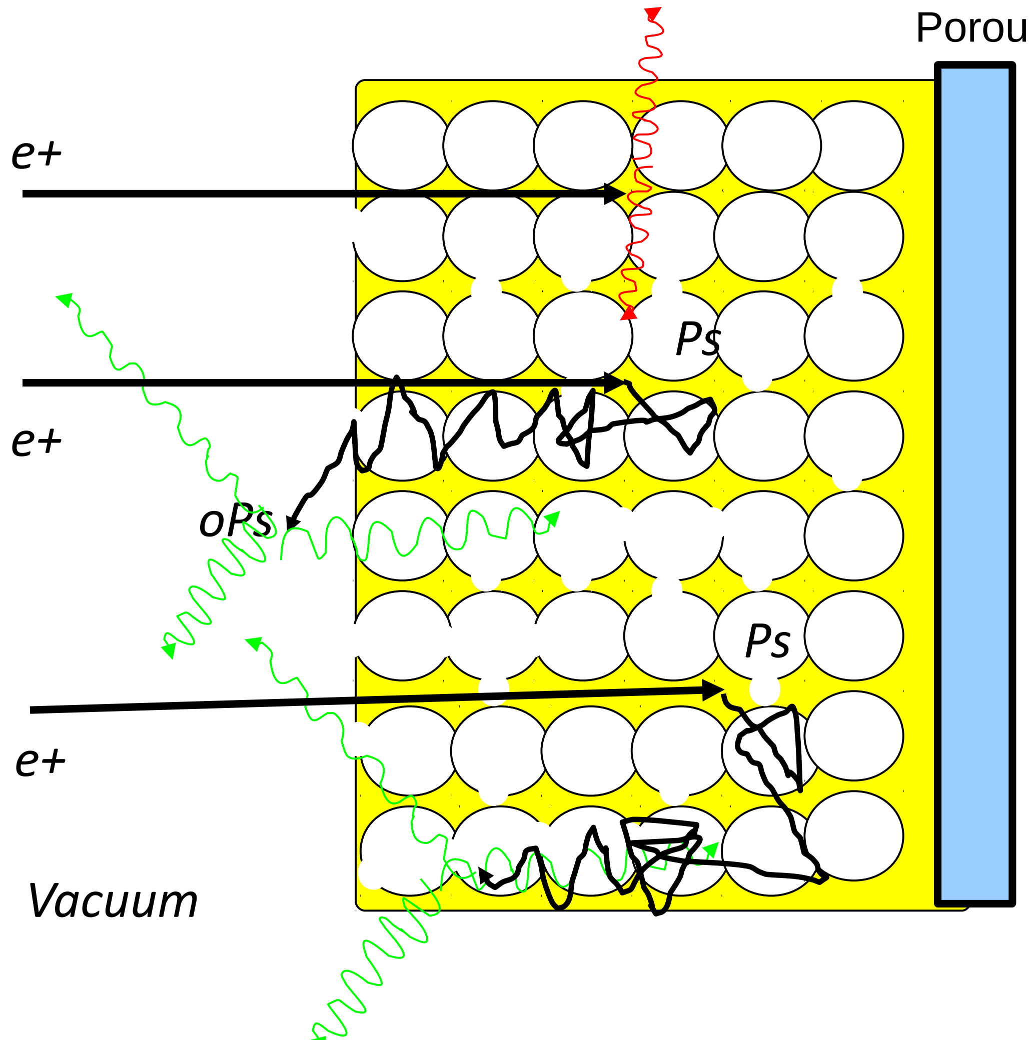
Positron implanted with keV energies
Rapidly thermalizes in the bulk (~ps)

Positron diffusion and annihilation

Positronium formation (1/4 pPs, 3/4 oPs) in SiO_2 by capturing 1 ionized electron
Diffusion to the pore surface and emission in the pores:
$W_{Ps}=\mu_{Ps} + E_B - 6.8\ eV=-1\ eV$
Thermalization via collisions and diffusion in interconnected pore network

Positronium formation

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



Positron implanted with keV energies
Rapidly thermalizes in the bulk (~ps)

Positron diffusion and annihilation

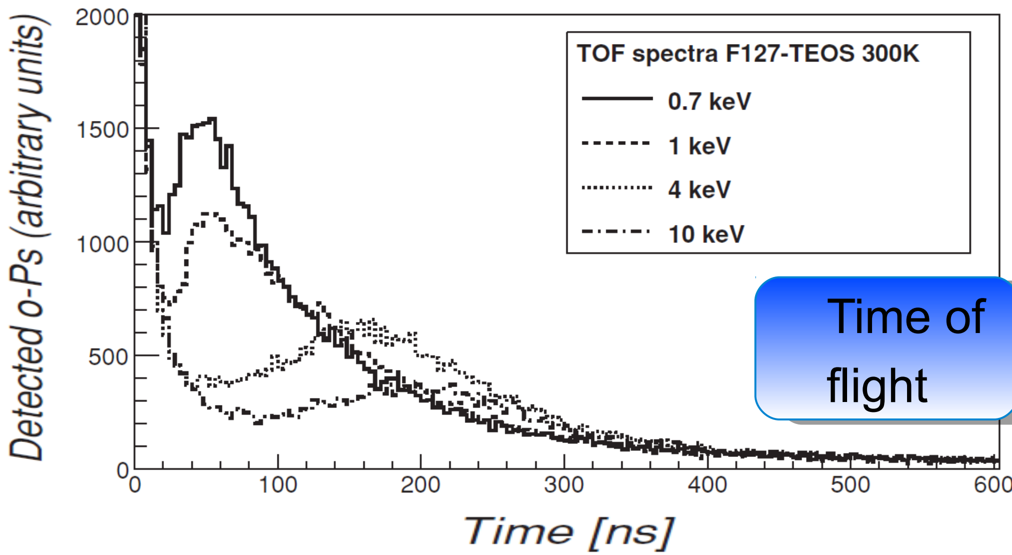
Positronium formation (1/4 pPs, 3/4 oPs) in SiO_2 by capturing 1 ionized electron
Diffusion to the pore surface and emission in the pores:
$W_{Ps} = \mu_{Ps} + E_B - 6.8\ \text{eV} = -1\ \text{eV}$
Thermalization via collisions and diffusion in interconnected pore network

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

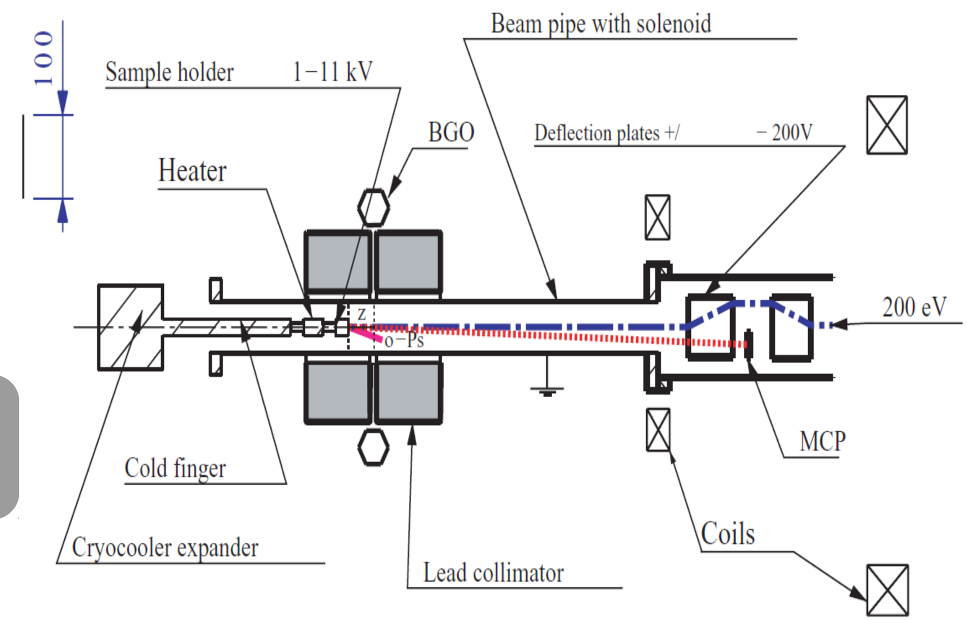
P. Crivelli et al., Phys. Rev. A. 81, 052703 (2010)

Measurement of Ps energy

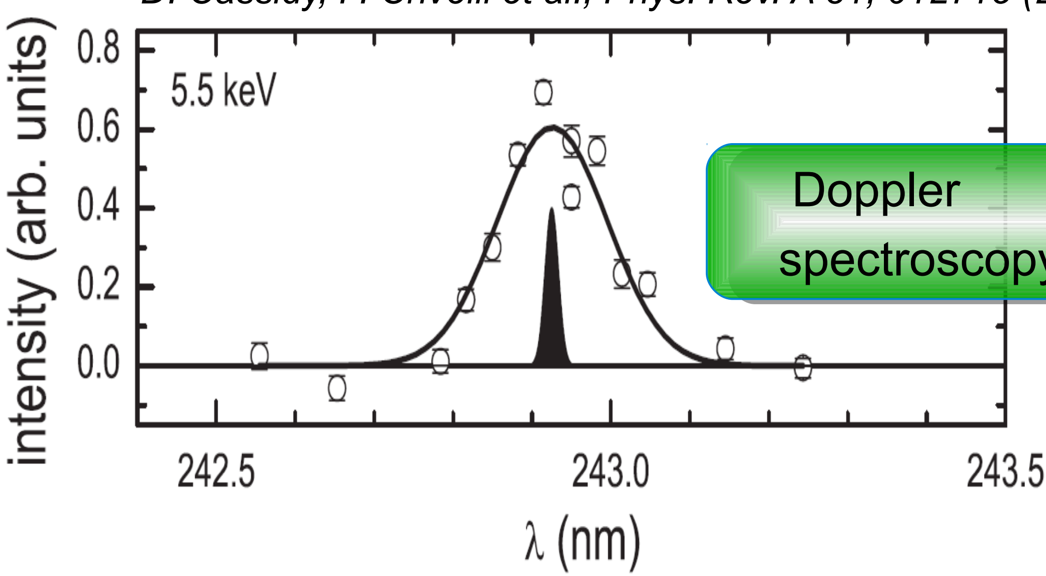
P. Crivelli et al. , Phys. Rev. A81, 052703 (2010)



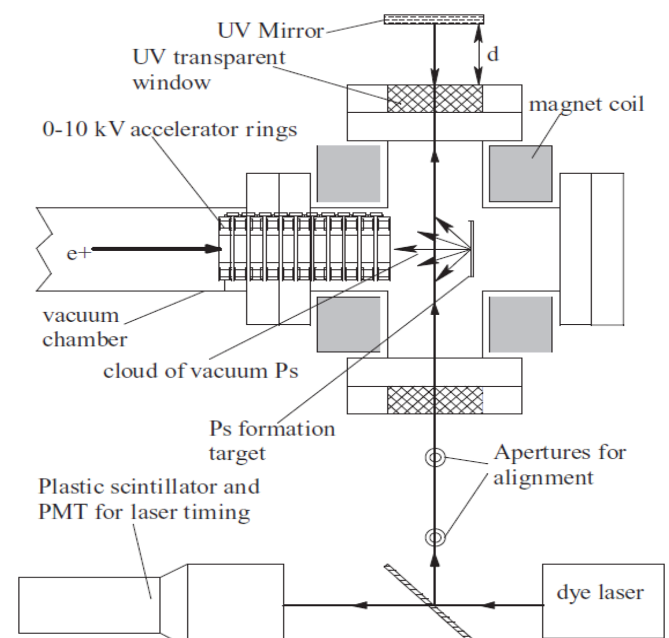
Time of flight



D. Cassidy, P. Crivelli et al., Phys. Rev. A 81, 012715 (2010)



Doppler spectroscopy



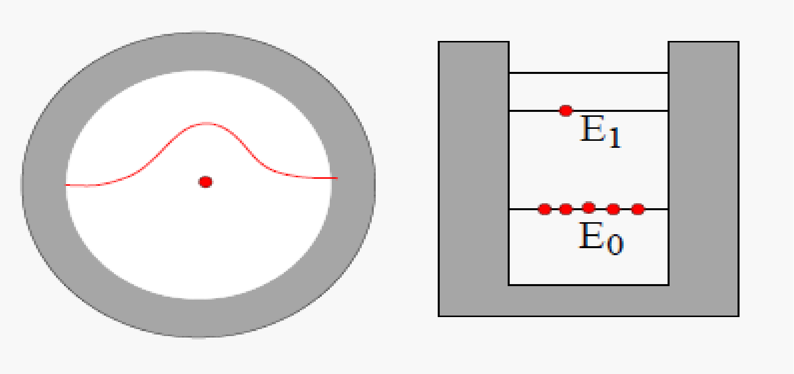
Ps as a particle in a box

Ps de Broglie wavelength at kinetic energy E_{Ps},

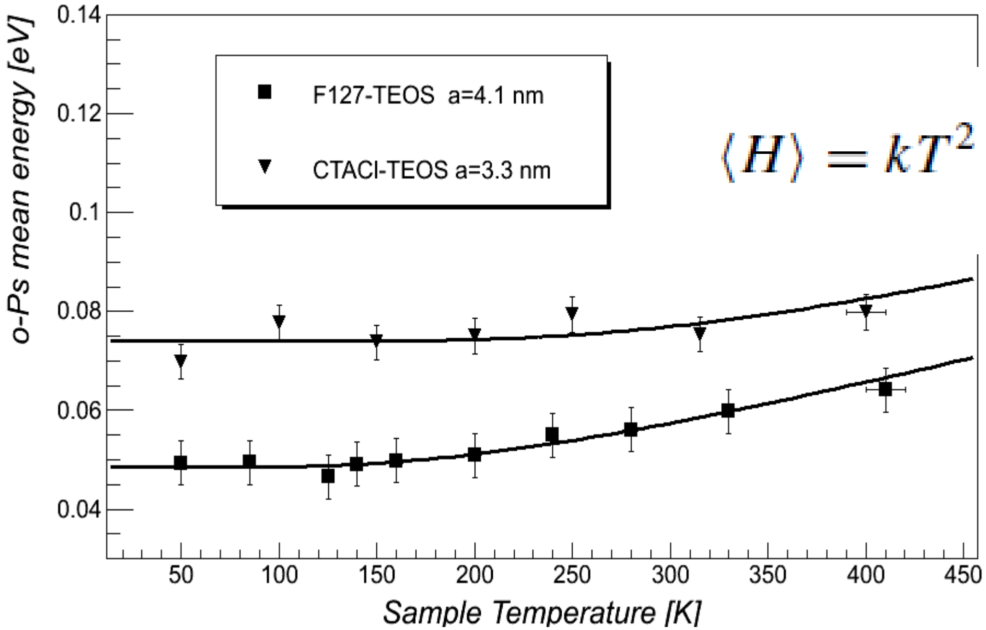
$$\lambda_{Ps} = h(2m_{Ps}E_{Ps})^{-1/2} \sim 0.9\,\mathrm{nm}(1\,\mathrm{eV}/E_{Ps})^{1/2},$$

For Ps with 100 meV, λ_{Ps} is comparable with the pore size.

⇒ QM effects!



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



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

Z is the partition function defined as

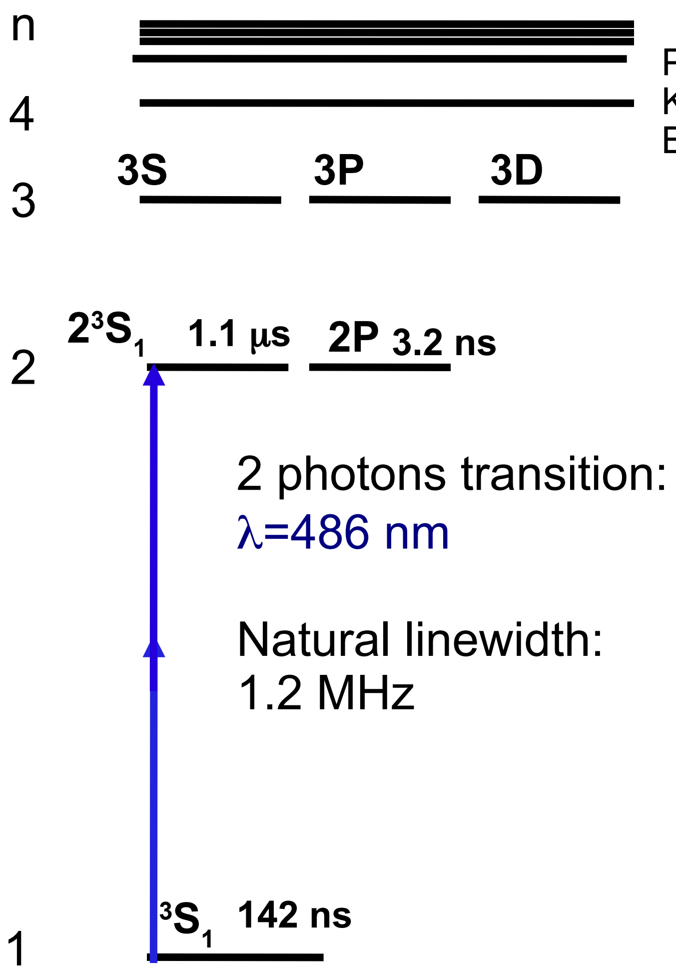
$$Z(a) = \sum_{n=1}^{\infty} e^{-\frac{h^2 n^2}{8ma^2}/kT},$$

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

Positronium 1S-2S transition

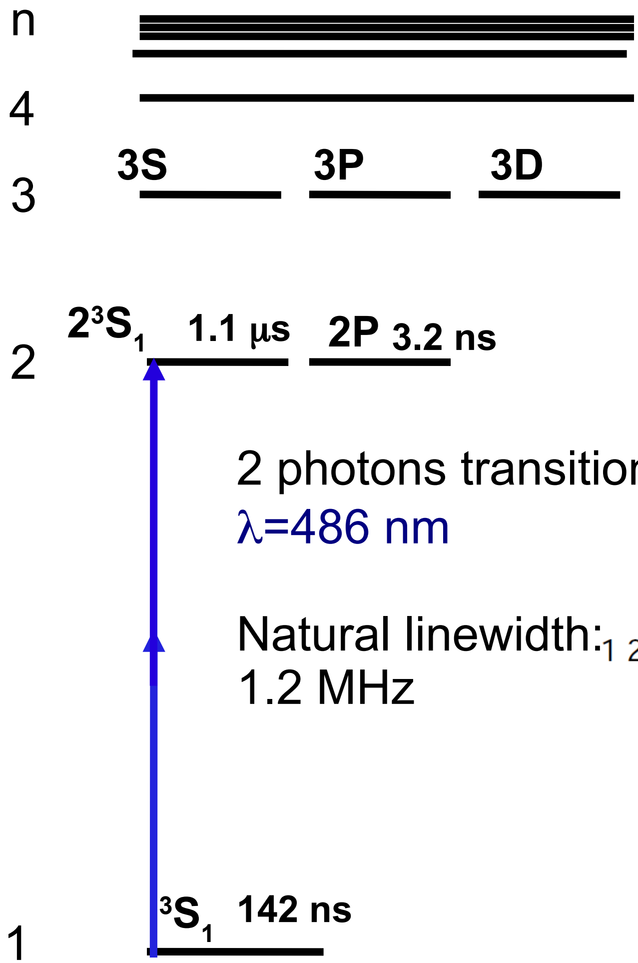
P. Crivelli (ETHZ), D. Cooke (ETHZ), A. Rubbia (ETHZ), A. Antognini (ETHZ/PSI), K. Kirch (ETHZ/PSI), G. Wichmann (ETHZ), J. Alnis (MPQ), T. W. Haensch (MPQ), B. Brown (Marquette)

Ps Energy levels



Positronium 1S-2S transition

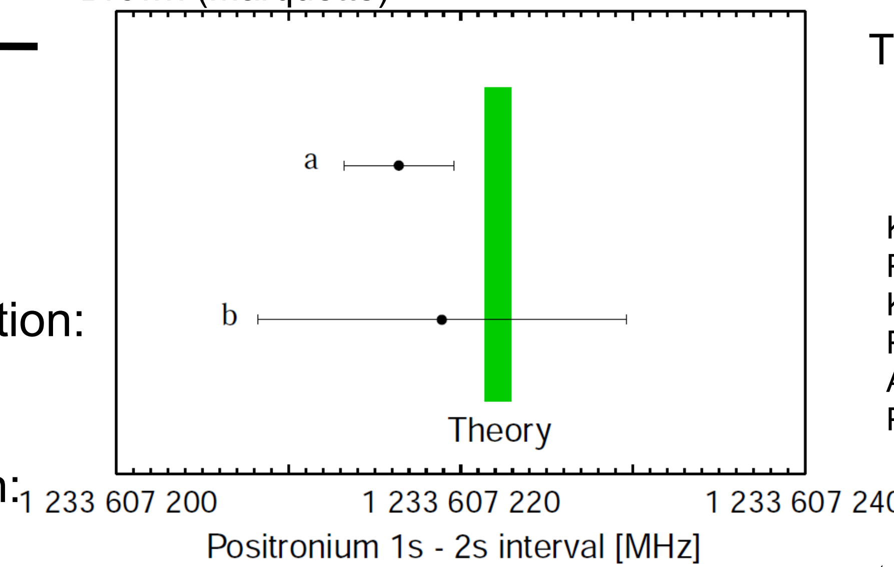
Ps Energy levels



2 photons transition:
λ=486 nm

Natural linewidth:
1.2 MHz

P. Crivelli (ETHZ), D. Cooke (ETHZ), A. Rubbia (ETHZ), A. Antognini (ETHZ/PSI), K. Kirch (ETHZ/PSI), G. Wichmann (ETHZ), J. Alnis (MPQ), T. W. Haensch (MPQ), B. Brown (Marquette)



Theory:

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

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:

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

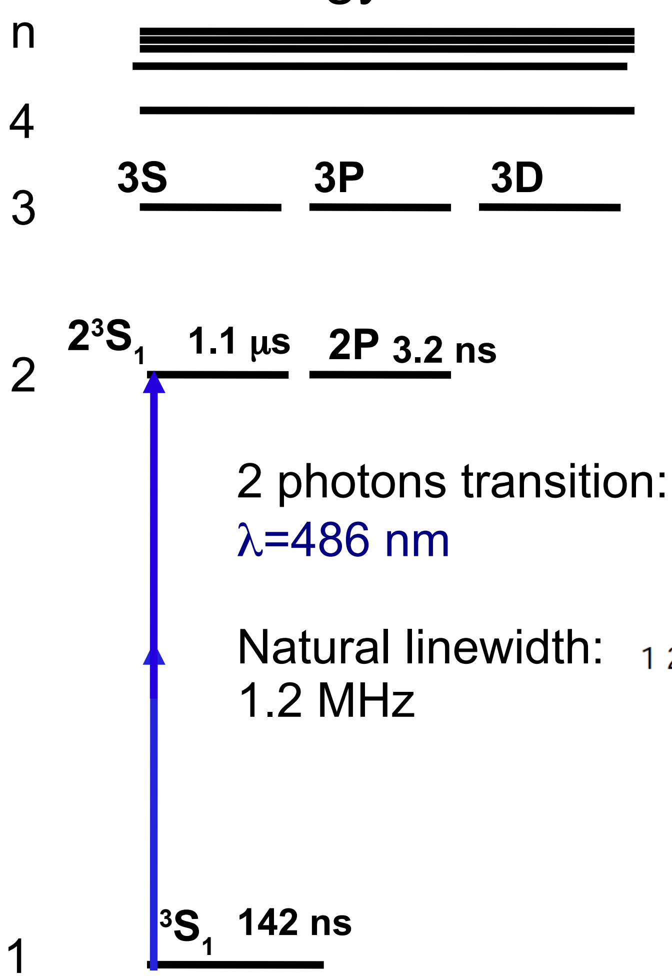
M. S. Fee et al., Phys. Rev. Lett. 70, 1397 (1993)

$$\nu^{b} = 1233607218.9(10.7) \text{ MHz}$$

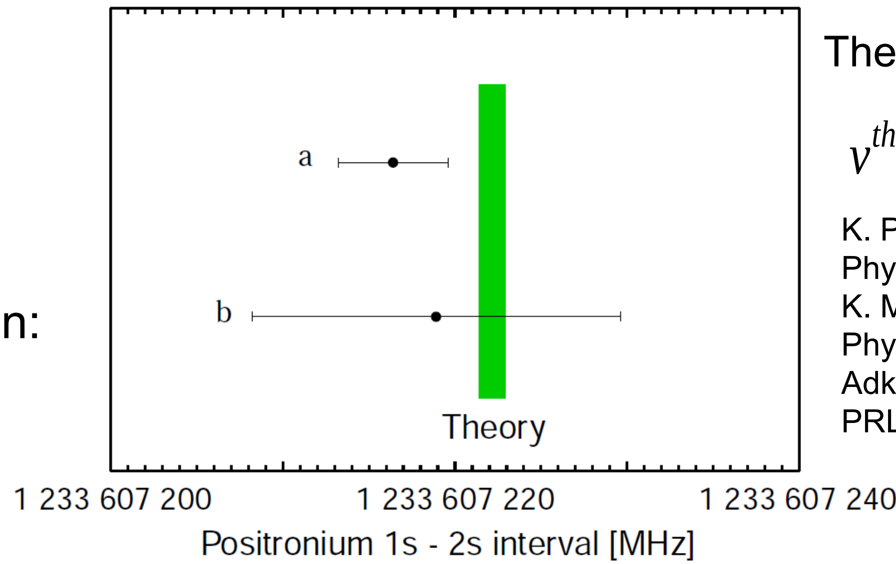
S. Chu, A. P. Mills, Jr. and J. Hall, Phys. Rev. Lett. 52, 1689 (1984)

Positronium 1S-2S transition

Ps Energy levels



P. Crivelli (ETHZ), D. Cooke (ETHZ), A. Rubbia (ETHZ), A. Antognini (ETHZ/PSI), K. Kirch (ETHZ/PSI), G. Wichmann (ETHZ), J. Alnis (MPQ), T. W. Haensch (MPQ), B. Brown (Marquette)



Theory:

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

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:

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

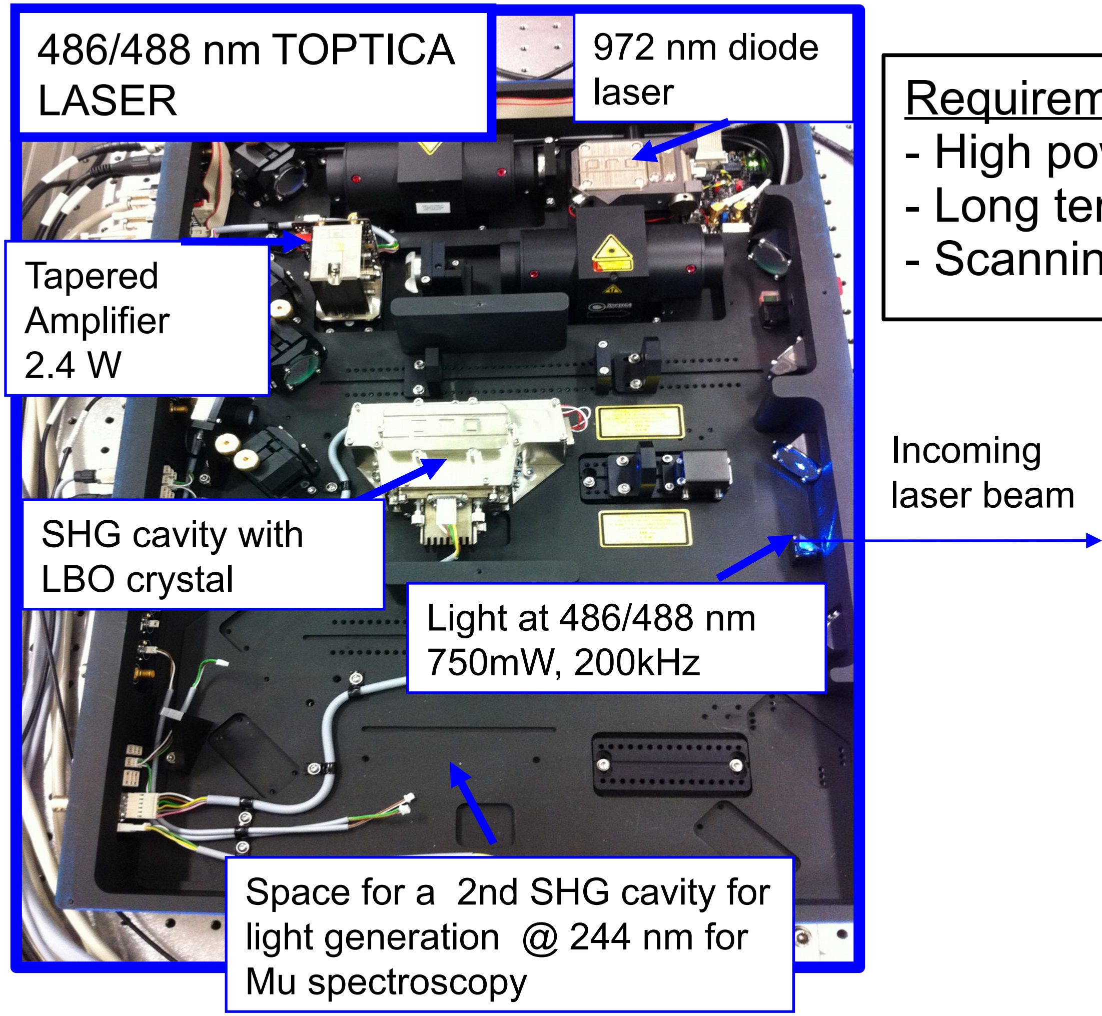
M. S. Fee et al., Phys. Rev. Lett. 70, 1397 (1993)

$$\nu^{b} = 1233607218.9(10.7) \text{ MHz}$$

S. Chu, A. P. Mills, Jr. and J. Hall, Phys. Rev. Lett. 52, 1689 (1984)

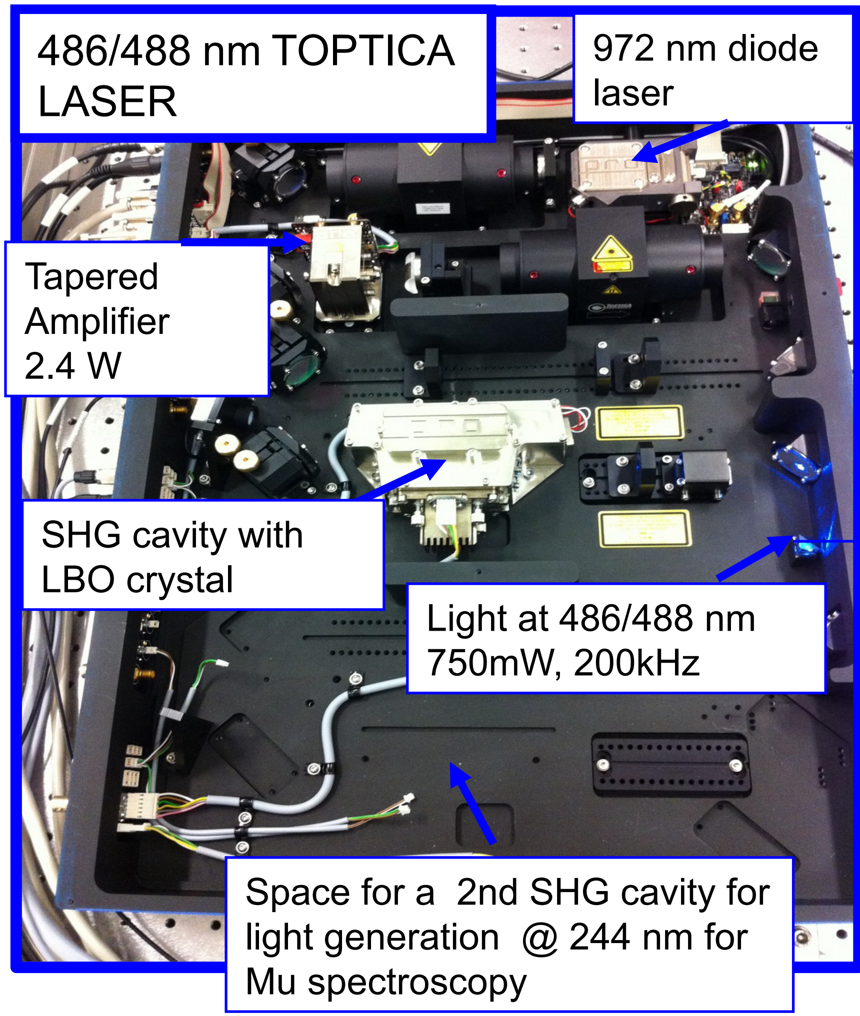
Measurement of 1S-2S of Ps at a level about 5×10^{-10} =>
check QED calculations at the order $\alpha^7 m$
Stringent test of the Standard Model Extension (SME)
Kostelecky and Vargas, Phys. Rev. D 92, 056002 (2015)

The laser system

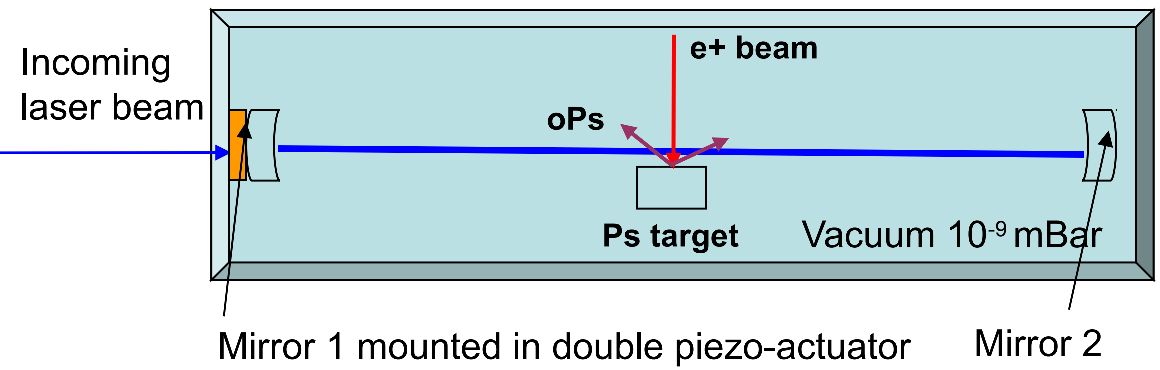


<u>Requirements</u>:
- High power (~kW) at 486 nm -> detectable signal
- Long term stability (continuous data taking ~days)
- Scanning of the laser ± 100 MHz

The laser system

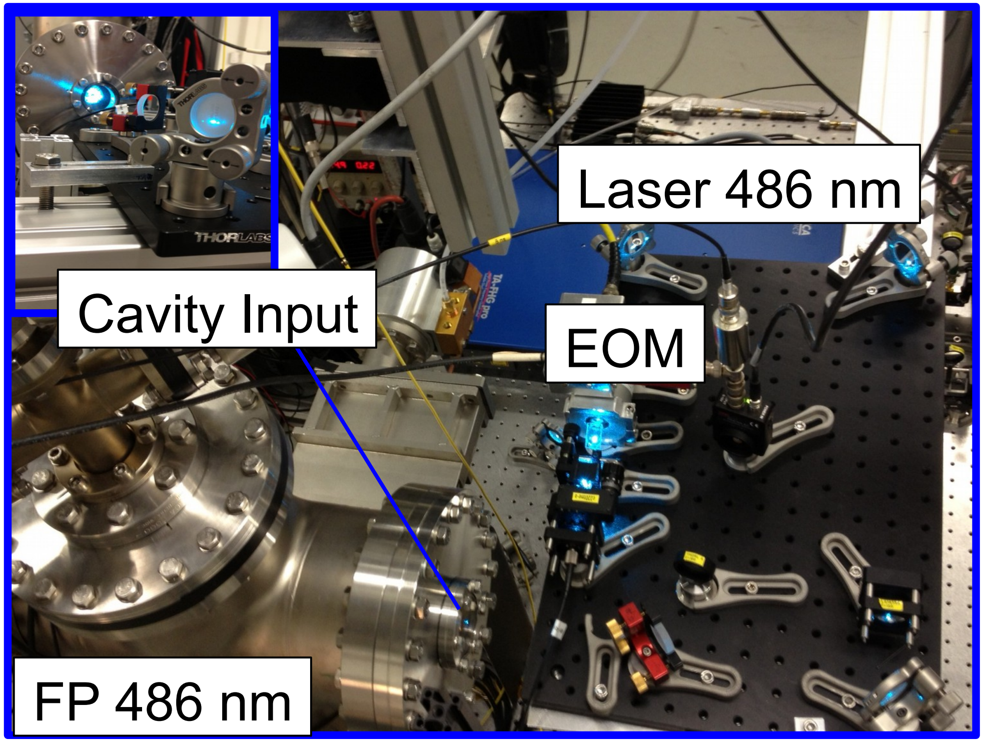


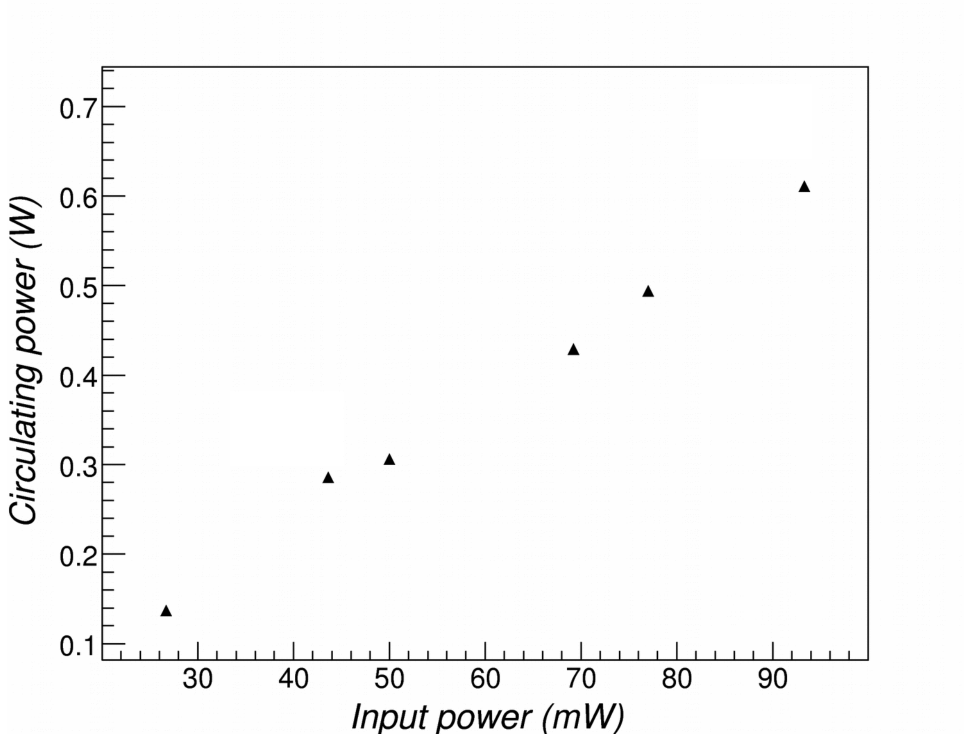
<u>Requirements</u>:
- High power (~kW) at 486 nm -> detectable signal
- Long term stability (continuous data taking ~days)
- Scanning of the laser ± 100 MHz

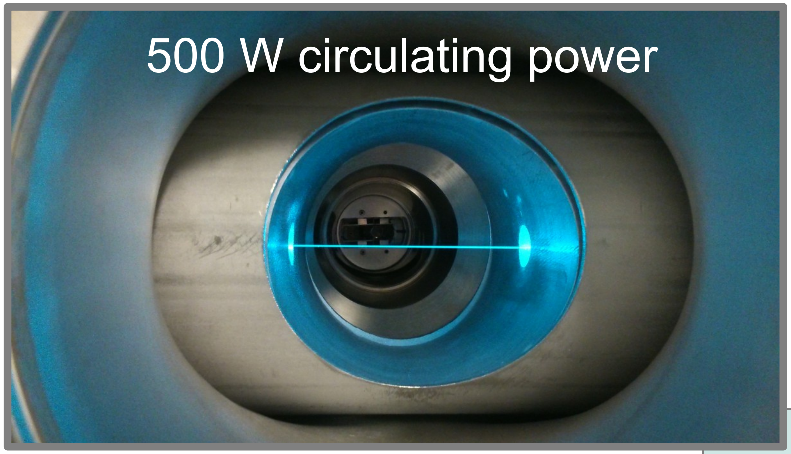


High finesse resonator for power build up
500 mW ⇨ 1 kW

The enhancement cavity @ 486 nm







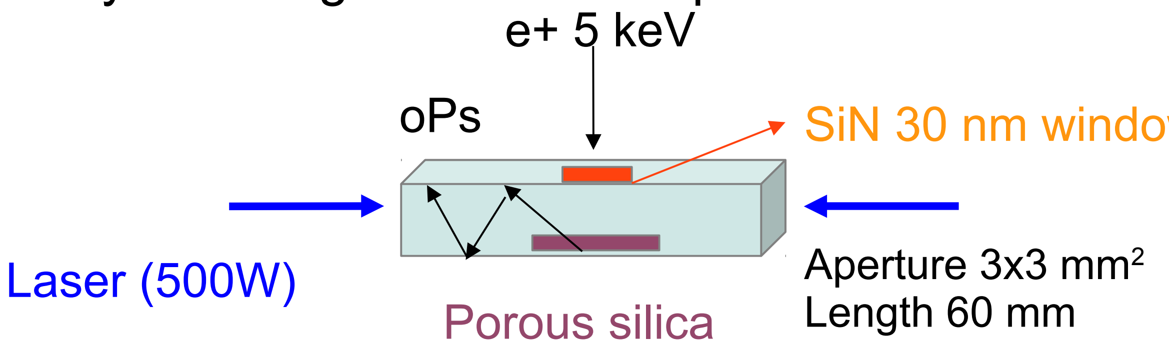
At 0.4 MW/cm^2 (0.7 kW circulating power) mirror degradation observed.

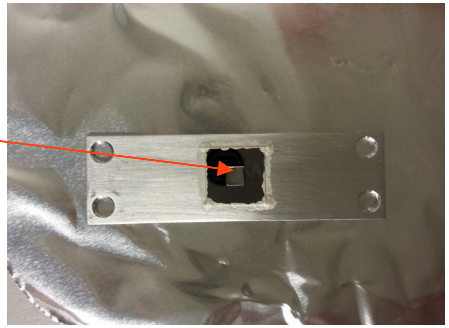
Run @ 0.4-0.5 kW:
-> Excitation prob ~ 1x10^{-4}
-> Resonant 3γ PI ~ 1x10^{-5}

Generation of 500 W, no degradation over hours of continuous operation.

Detection of Ps 1S-2S

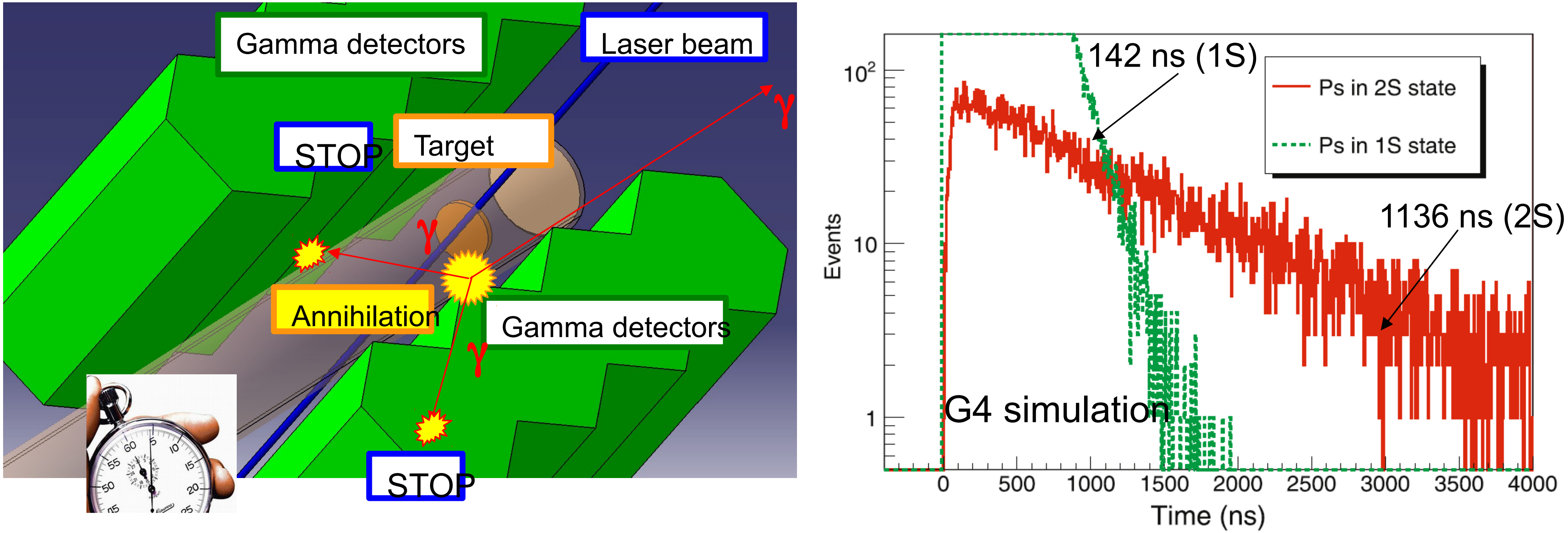
To enhance Ps interaction time with laser we developed a new target in a "tube" geometry-> During its lifetime Ps passes about 10 times in the laser beam



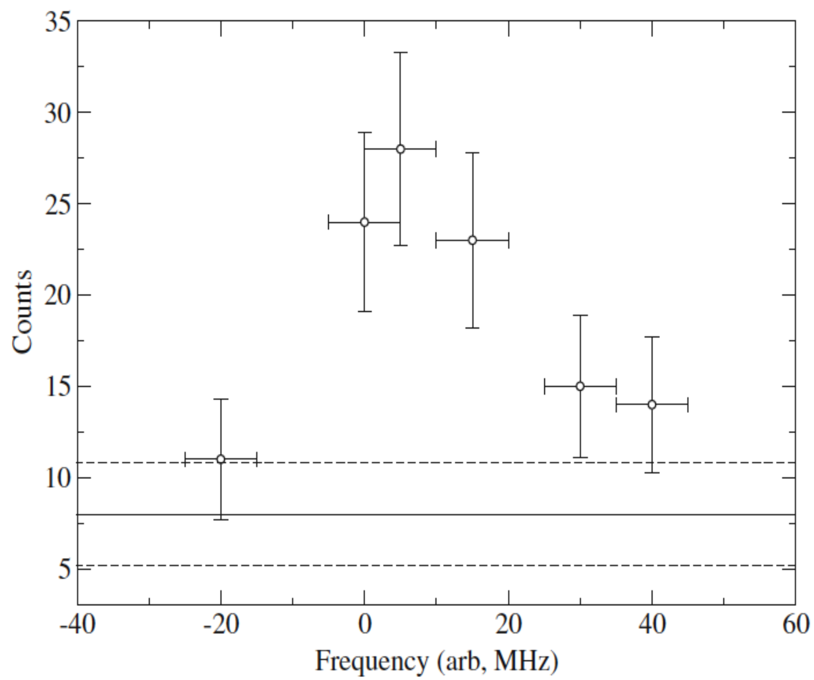


Detection of annihilation photons. Lifetime of excited S states ~ n^3

$\tau_{2S}/\tau_{1S} = 8$



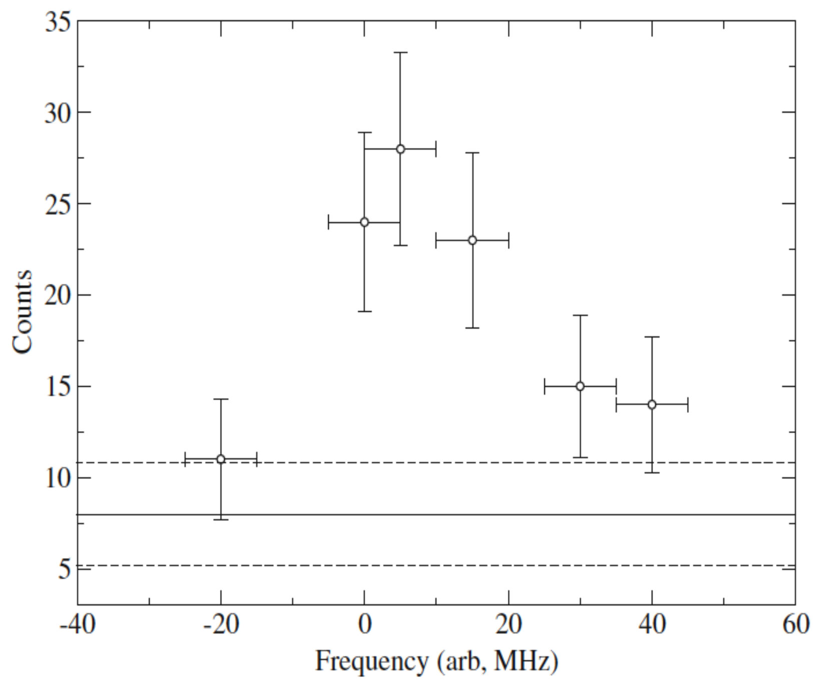
Preliminary results (2014)



D.Cooke et al, Hyperfine Interact. 233 (2015) 1-3, 67
[arXiv:1503.05755 [physics.atom-ph]]

First successful scans
(about 3 hours data taking,
~ 10^6 positronium atoms/point)

Preliminary results (2014)

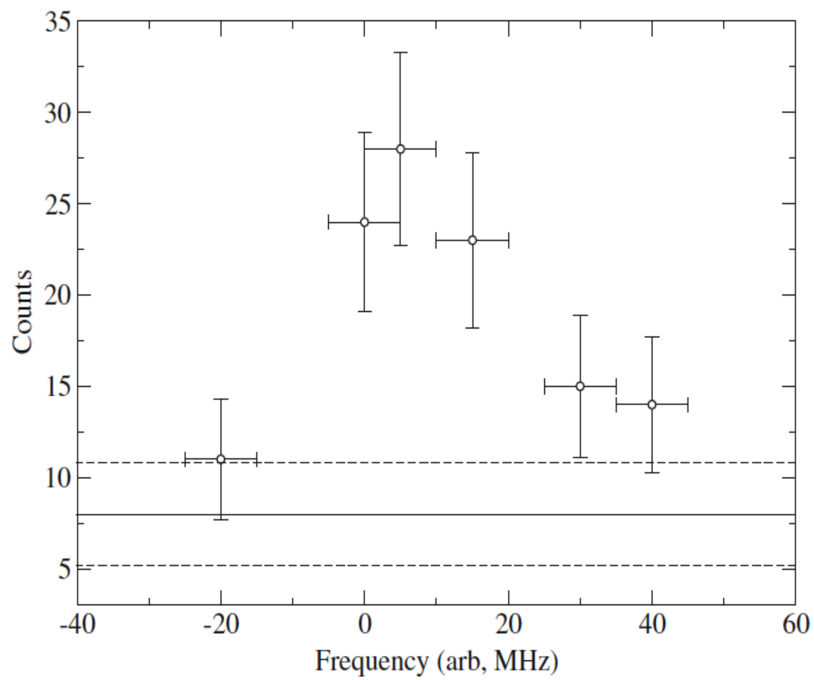


D.Cooke et al, Hyperfine Interact. 233 (2015) 1-3, 67
[arXiv:1503.05755 [physics.atom-ph]]

First successful scans
(about 3 hours data taking,
~ 10^6 positronium atoms/point)

→ S/N ratio should be improved.

Preliminary results (2014)



D.Cooke et al, Hyperfine Interact. 233 (2015) 1-3, 67
[arXiv:1503.05755 [physics.atom-ph]]

First successful scans
(about 3 hours data taking,
~ 10^6 positronium atoms/point)

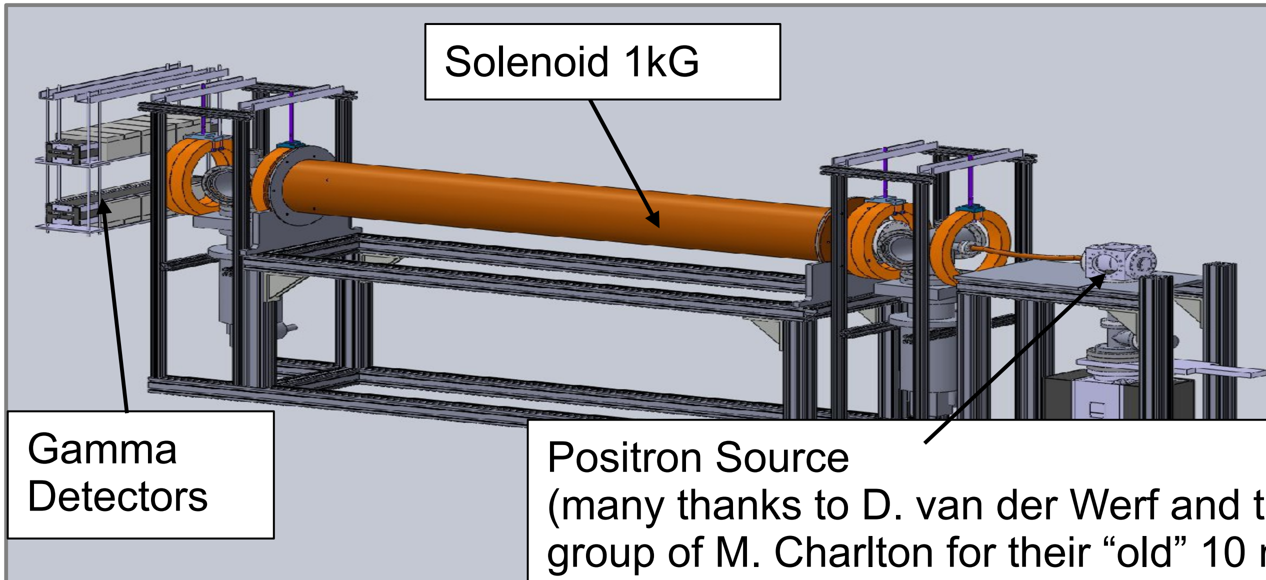
S/N ratio should be improved.

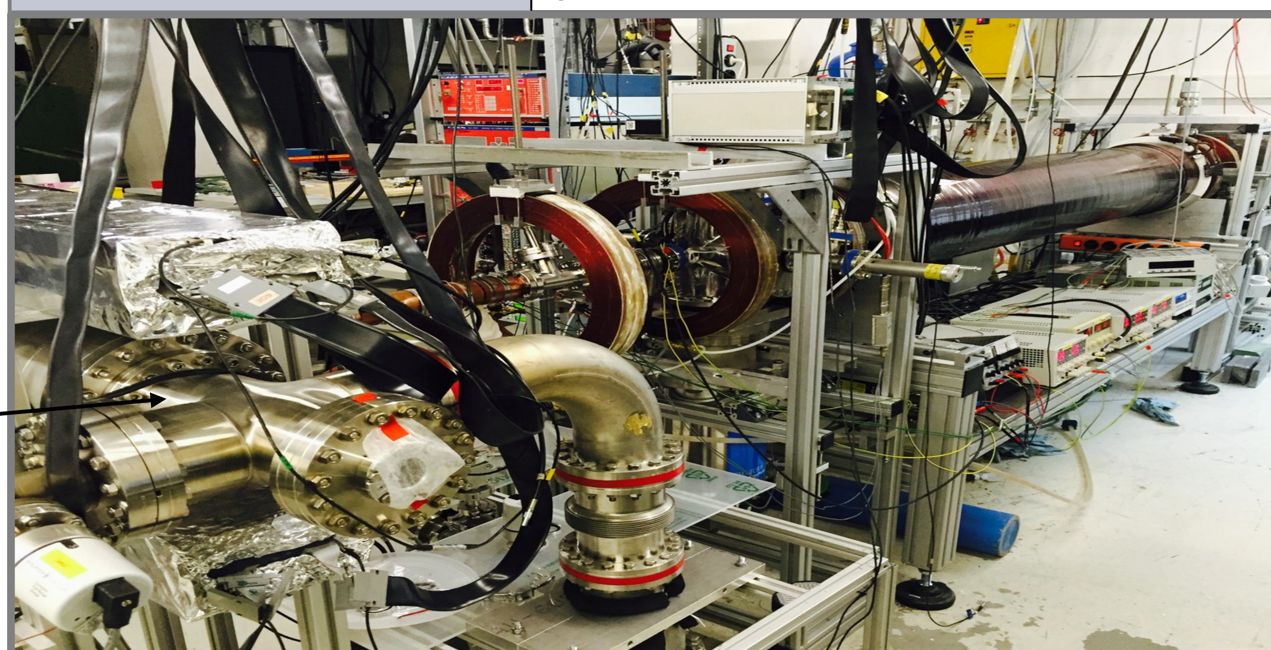
Need for a bunched beam → use buffer gas trap

→ noise from accidentals reduced by 2 orders of magnitude

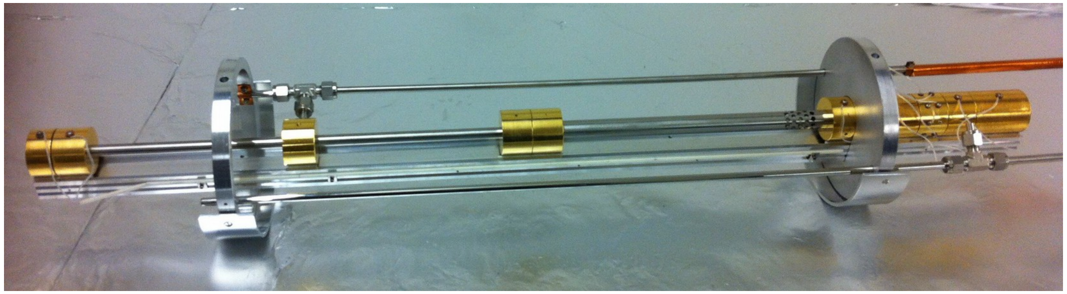
→ In addition to lifetime method possibility to use pulsed lasers to photo-ionize Ps (systematic studies and increase in the signal rate)

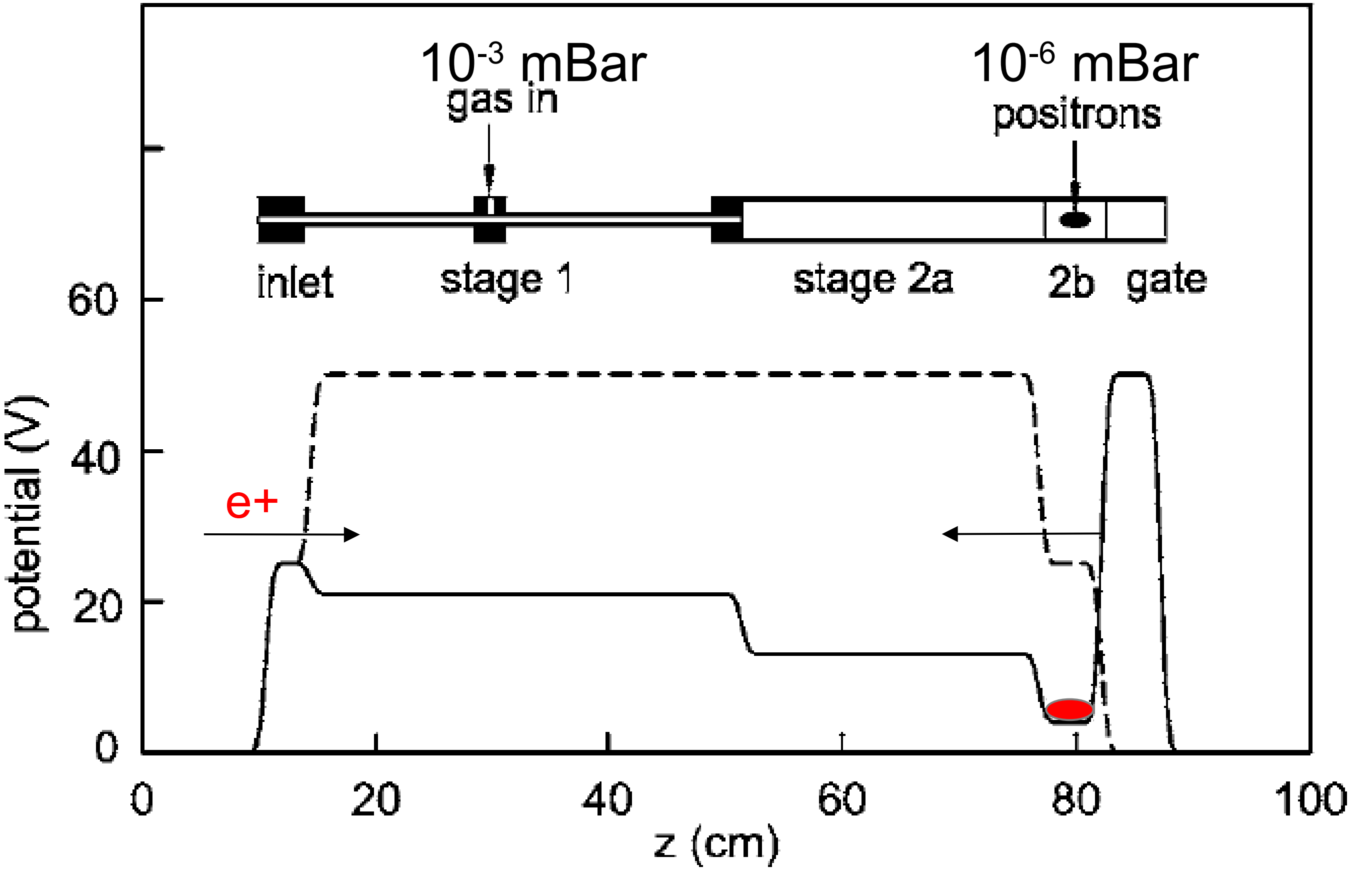
New beam line based on positron buffer gas trap (2015)





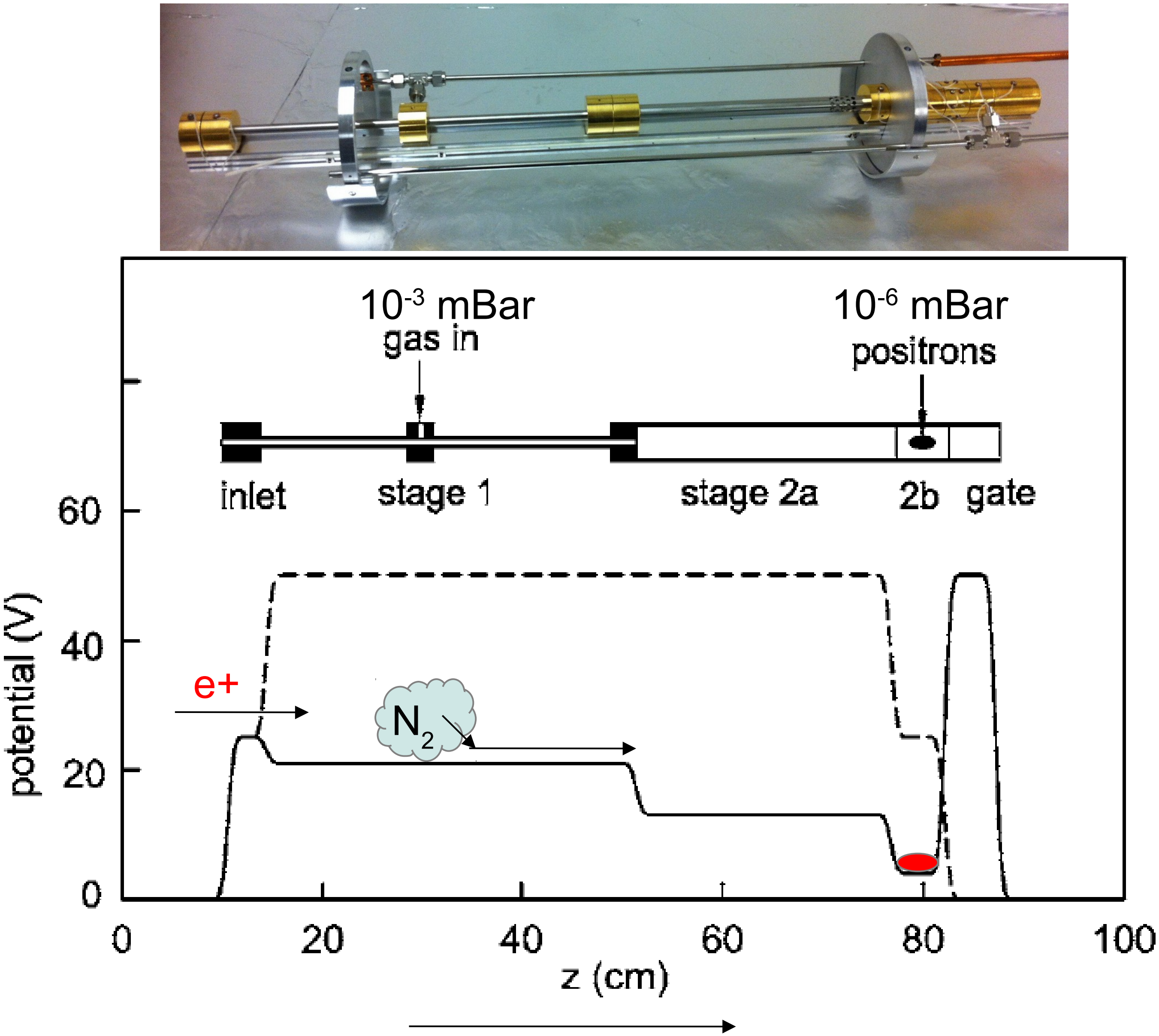
Positron Trap principle





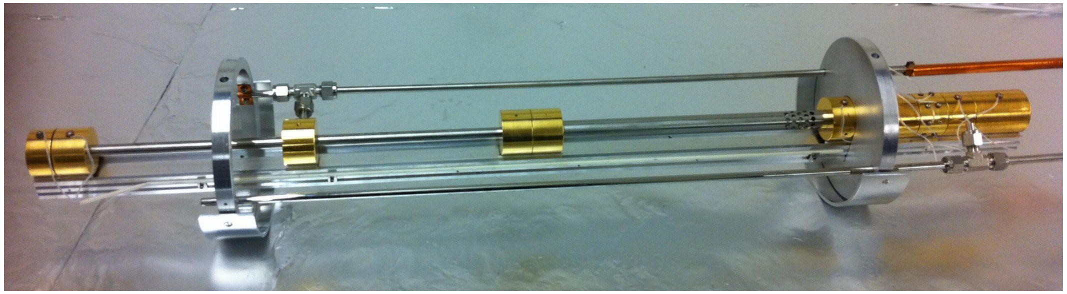
B-field up to 1 kG

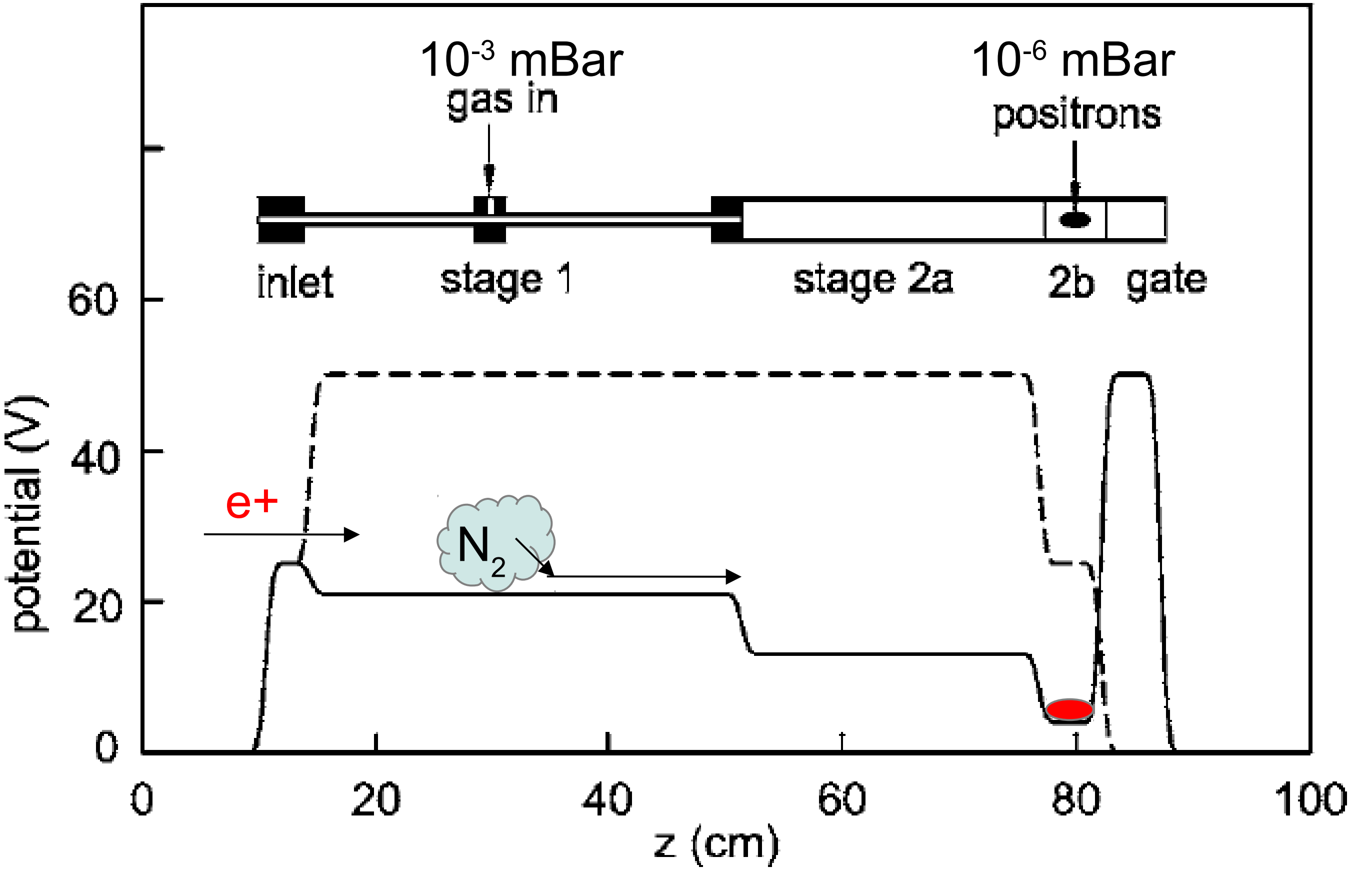
Positron Trap principle



B-field up to 1 kG

Positron Trap principle





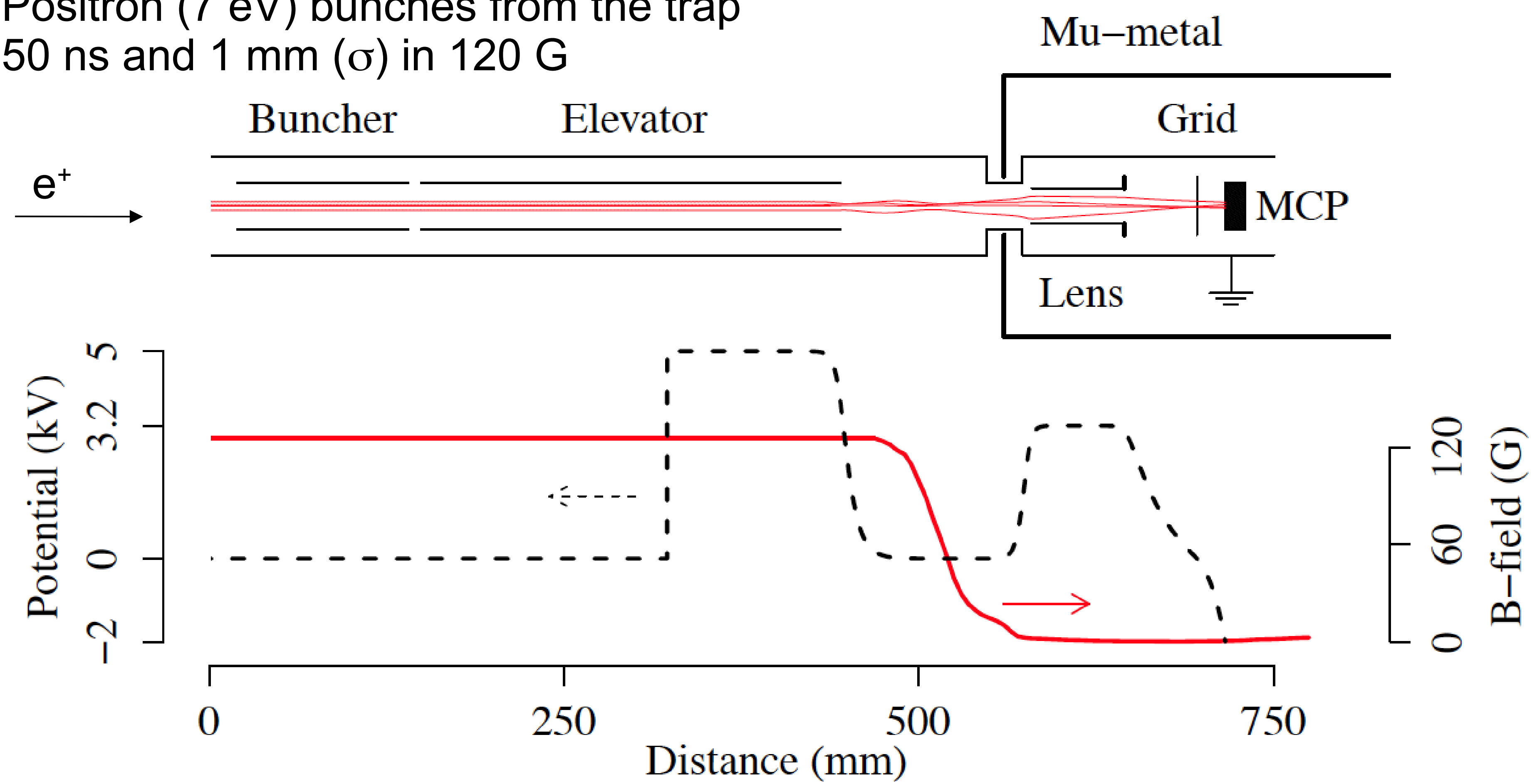
Positrons in few eVs bunches (50 ns)
At 10 Hz rep rate

B-field up to 1 kG

Bunching and extraction to a field free e-m region

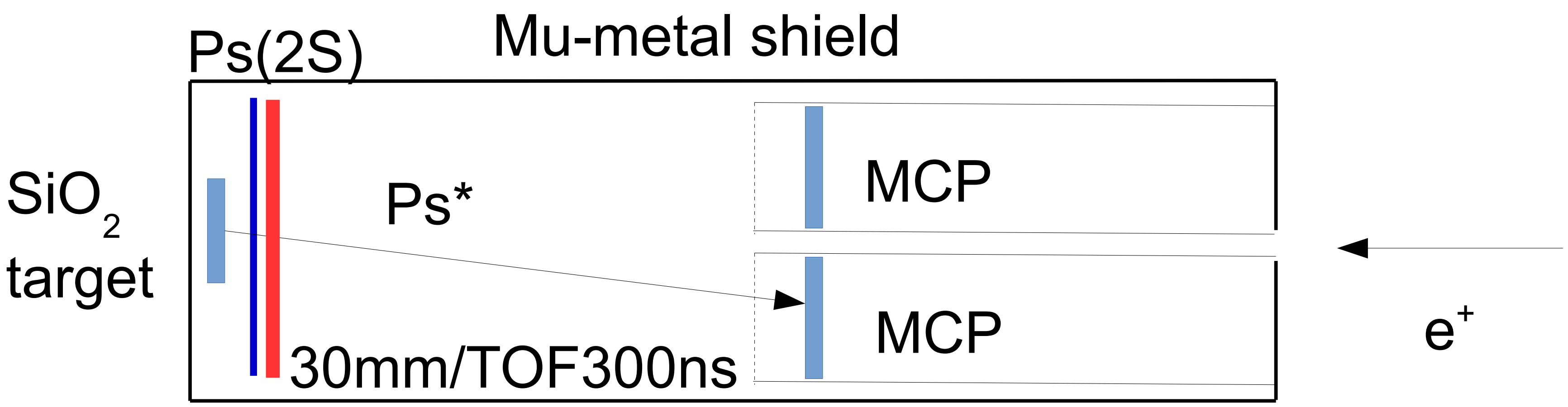
D. A. Cooke G., Barandun, S Vergani,, B Brown, A Rubbia and P Crivelli, J. Phys. B: At. Mol. Opt. Phys. 49 014001 (2016), arXiv:1508.06213 [physics.ins-det].

Positron (7 eV) bunches from the trap
50 ns and 1 mm (σ) in 120 G



On target (kept at ground): positron bunches of 1 ns with a beam spot of 1 mm extracted to the field free e-m region with 90 % efficiency.

New detection scheme



→ Excitation 2S atoms to Rydberg states (n=20) → time-of-flight measurement of 2S atoms using position sensitive MCP detector to correct for 2nd order Doppler shift.

→ Increase in the S/N ratio by two orders of magnitude.

→ Extraction to a field free e-m region → removal of systematic due to DC Stark and Zeeman (affecting m=0 triplet states) and motional Stark shift.

Status and outlook of 1S -2S experiment

Enhancement cavity has been installed, new detection scheme being tested with seeded pulsed dye amplifier (currently 365 nm direct two photon doppler free Ps* excitation and later with 486 nm + 730 nm).

Status and outlook of 1S -2S experiment

Enhancement cavity has been installed, new detection scheme being tested with seeded pulsed dye amplifier (currently 365 nm direct two photon doppler free Ps* excitation and later with 486 nm + 730 nm).

With available source of Ps: 30% @ 40 meV

Measurement of 1S-2S of Ps at a level about 5×10^{-10} seems feasible
=> check QED calculations

Status and outlook of 1S -2S experiment

Enhancement cavity has been installed, new detection scheme being tested with seeded pulsed dye amplifier (currently 365 nm direct two photon doppler free Ps* excitation and later with 486 nm + 730 nm).

With available source of Ps: 30% @ 40 meV

Measurement of 1S-2S of Ps at a level about 5×10^{-10} seems feasible
=> check QED calculations

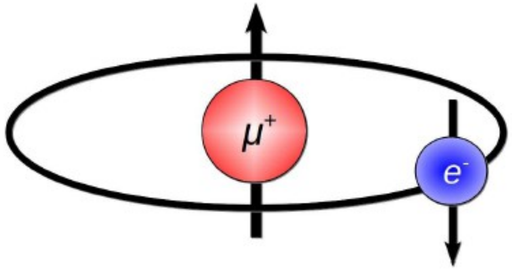
To go beyond a 0.5 ppb precision in the 1S-2S transition, slow (<10000 m/s) Ps is a mandatory ingredient.

→ Main contribution to the line broadening due to the time-of-flight effect will be comparable with the Ps natural linewidth of 1.2 MHz.

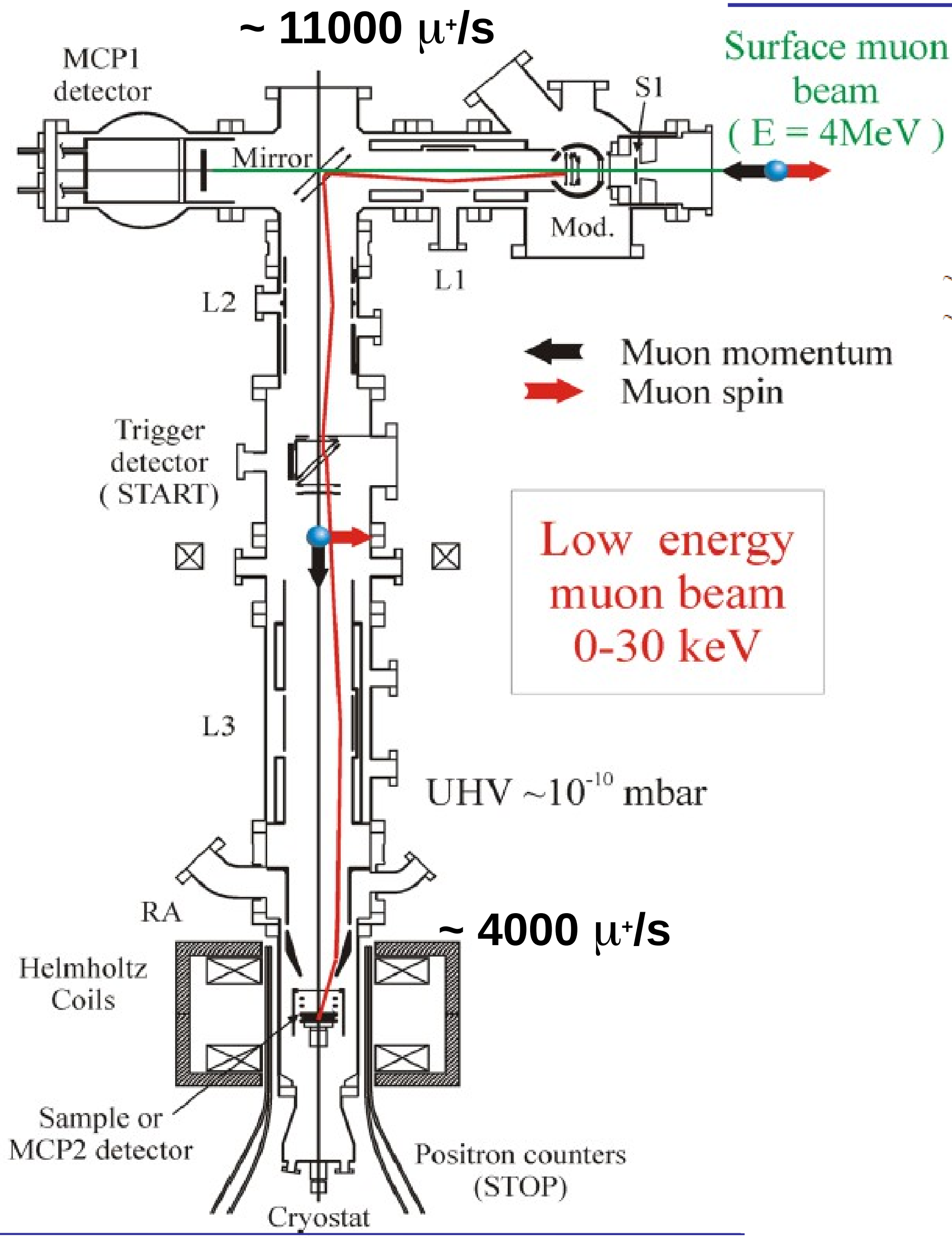
→ Main systematic from 2nd order Doppler will be reduced by two orders of magnitude.

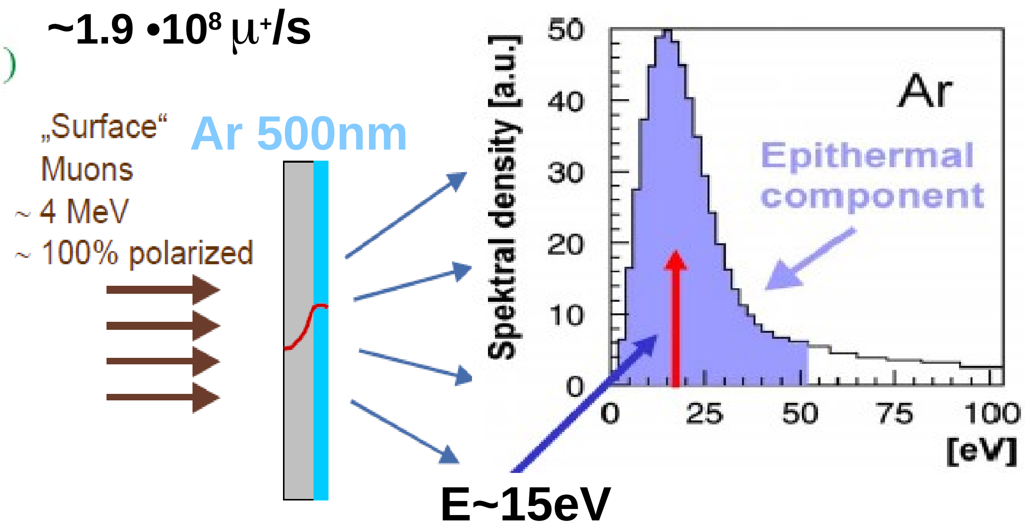
A measurement at a level of few ppt could be in reach → independent determination of the Rydberg constant.

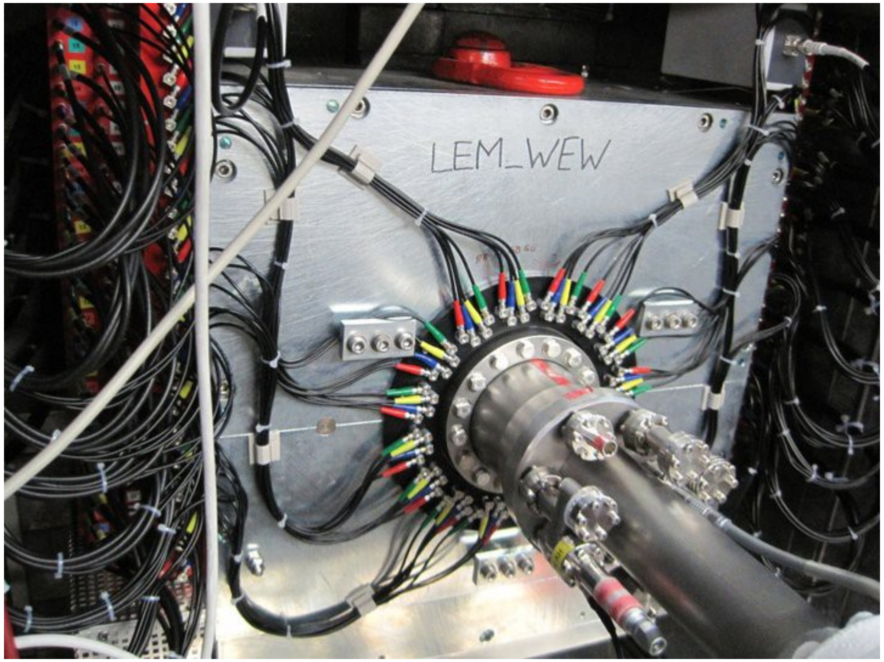
Muonium (Mu)



Low energy muon (LEM) beam @PSI



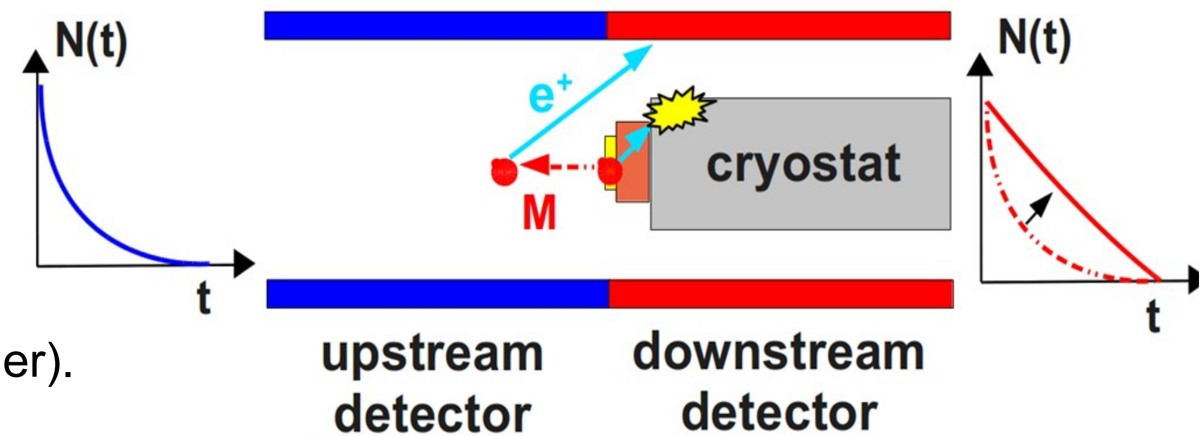


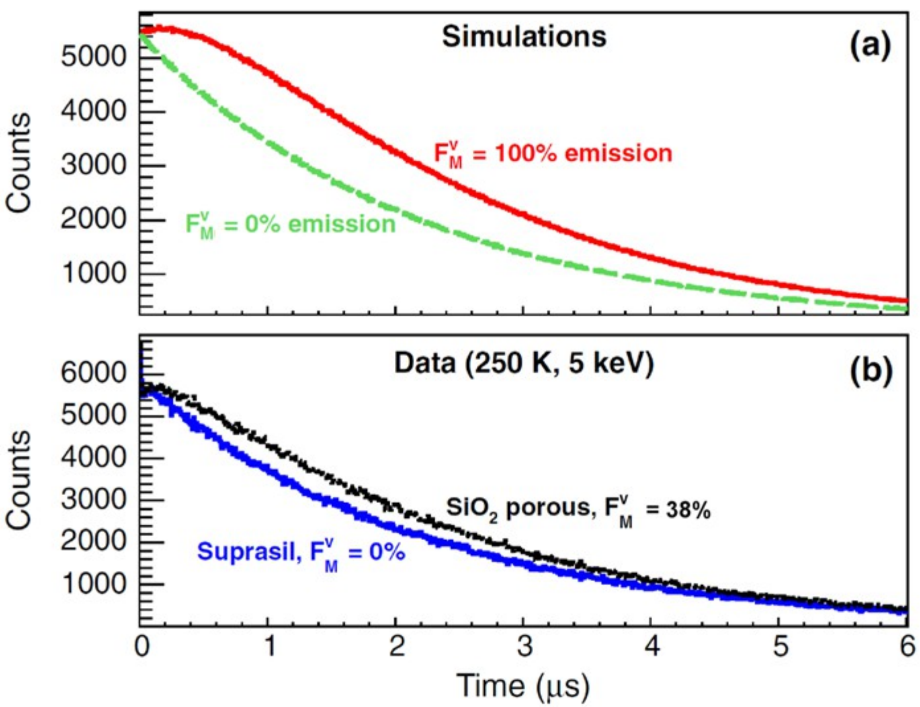


Muonium formation in porous silica

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)

Same targets developed for Ps
(in analogy to Ps/Mu in powders)
-> No limitation as for Ps of
the ground state energy (Mu much heavier).

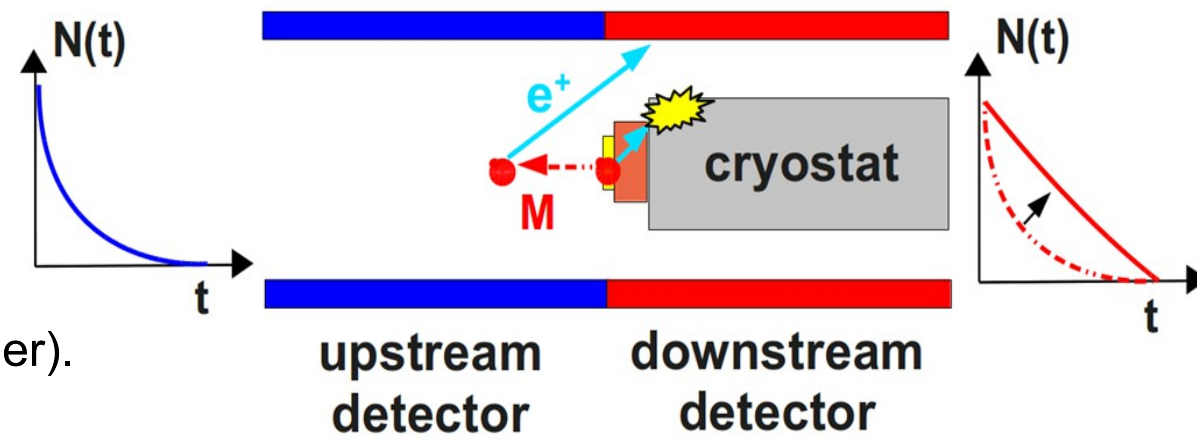


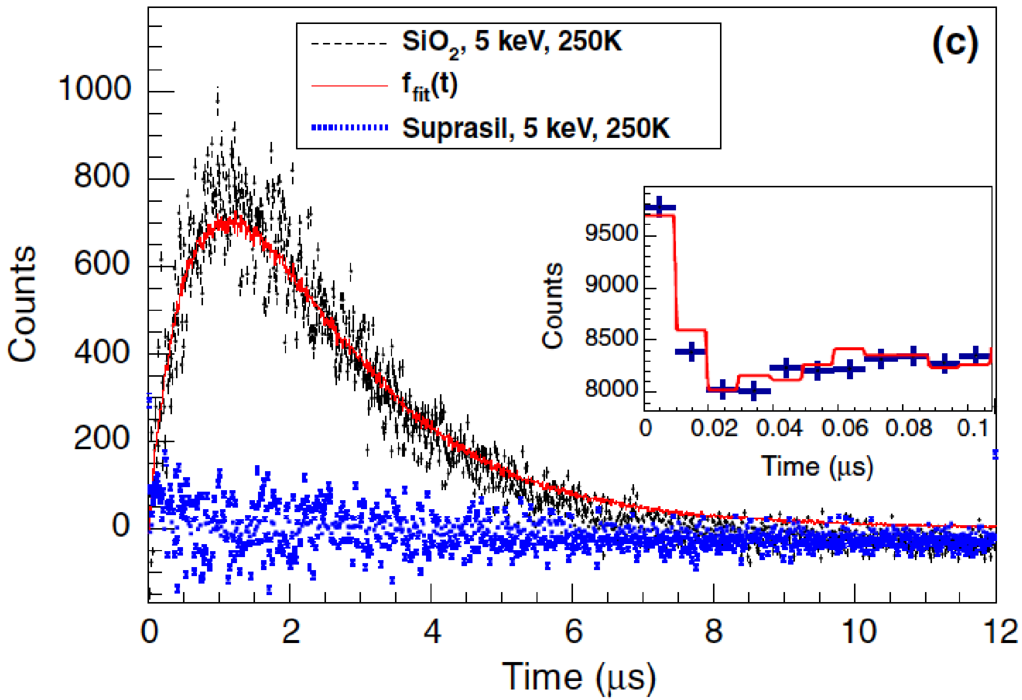


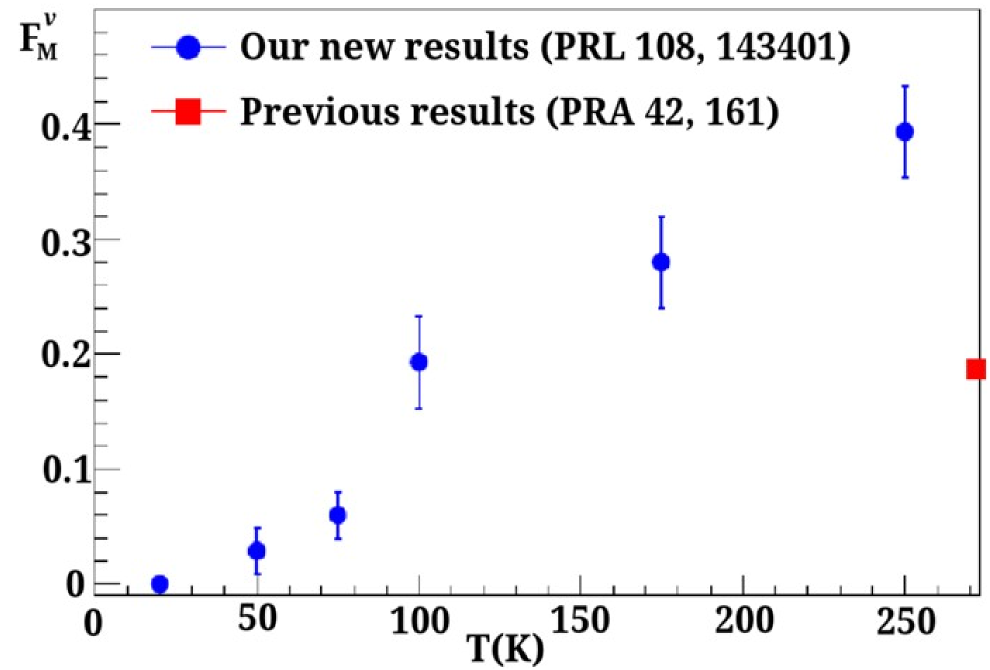
Muonium formation in porous silica

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)

Same targets developed for Ps
(in analogy to Ps/Mu in powders)
-> No limitation as for Ps of
the ground state energy (Mu much heavier).

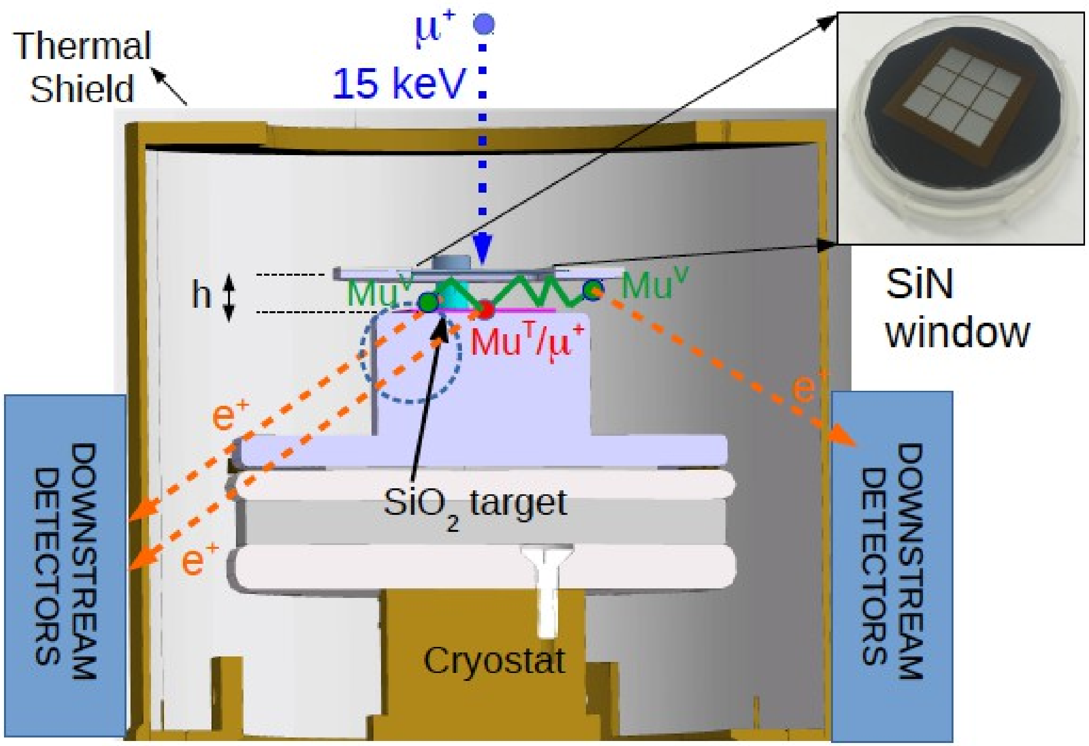


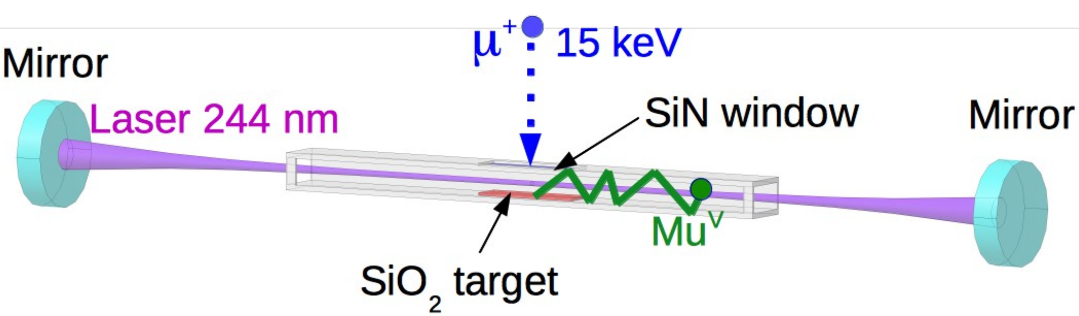




Muonium spatial confinement

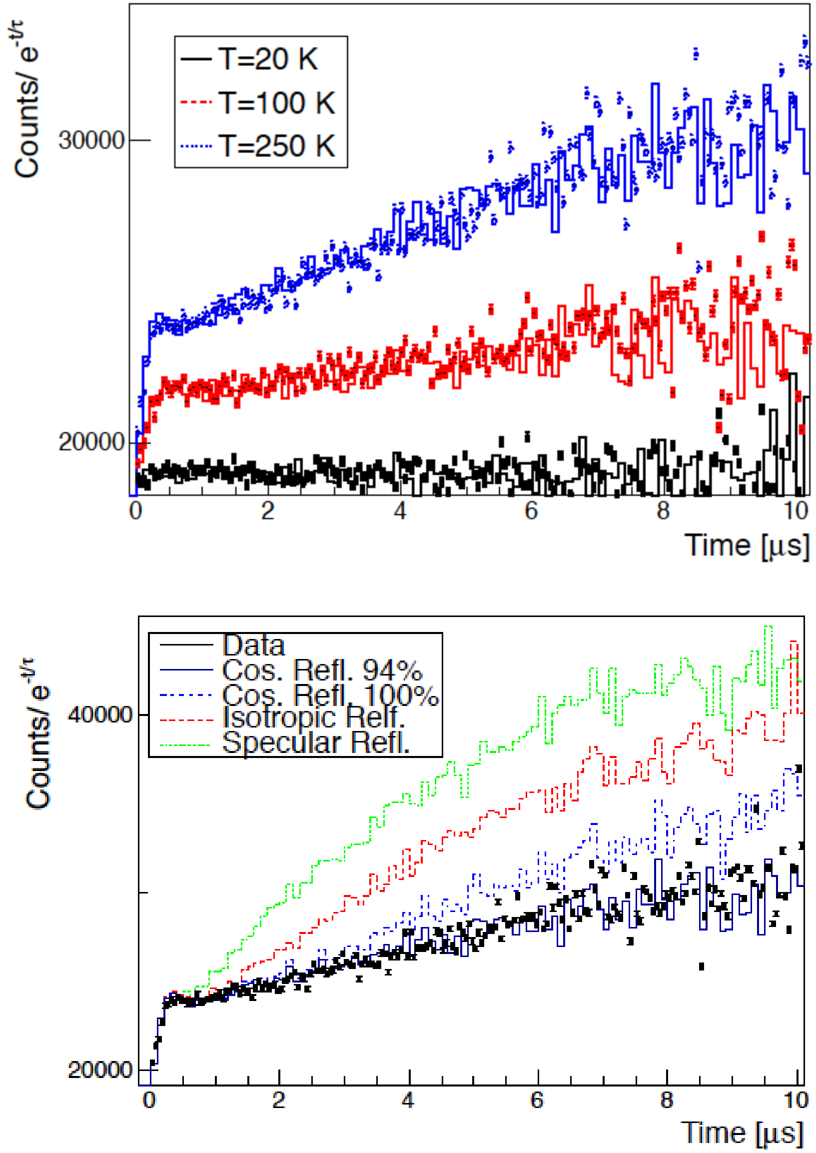
K. S. Khaw, A. Antognini, T. Prokscha, K. Kirch, L. Liszkay, Z., Salman, P. Crivelli, PRA 94, 022716 (2016)





Factor 5 enhancement in exc. probability

DATA-SIM 1mm



1S-2S Mu 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

Our recent results on Mu formation at 100K opens the way for the first CW spectroscopy of the 1S-2S transition in Mu!

More than a factor of 10 improvement is possible (currently @ 4 ppb, W. Meyer et al. PRL84, 1136 (2000)) with existing muon beam line at PSI → improvement of of q_μ/q_e and muon mass

Combined with HFS measurement (see poster of Yasuhiro Ueno on Tuesday) → Stringent test of bound state QED

Czarnecki, Eidelmani, Karshenboim Phys.Rev. D65 (2002) 053004

Outlook -Mu spectroscopy

- Muon tagging via secondary electrons from the SiN window, 2 ns timing achieved and factor of 2 smaller muon beam → larger overlap of Mu with laser beam.

-The same laser system developed for the Ps experiment will be used for Mu by adding a second SHG generation stage and UV enhancement cavity (commercially available).

- Same technique as we are implementing for Ps with excitation from 2S in Rydberg states could be used to enhance the signal and measure the Mu atoms velocity.

- New low energy beam line under development at PSI (Kirch group, ETHZ/PSI, see posters of Ivana Belosevich and Narongrit Ritjoho on Tuesday) and at JPARC (see talk of Glen Marshall on Wednesday)

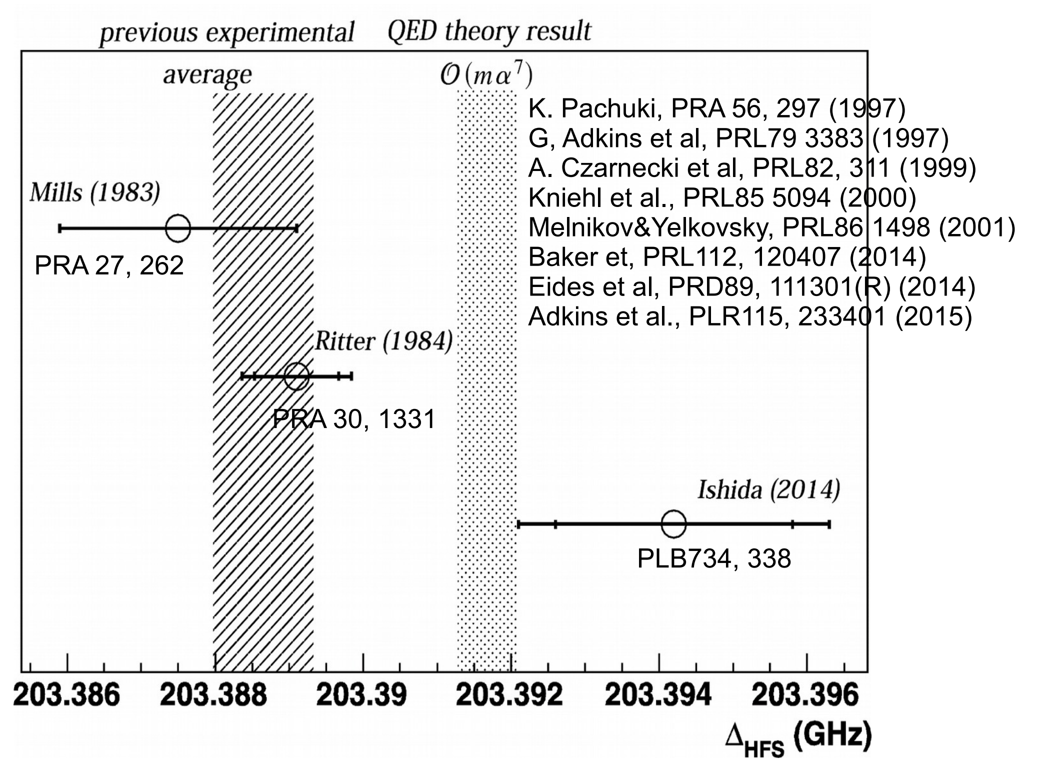
  → 2 orders of magnitude more low energy muons expected.

  → 1S-2S results will be statistically limited → further improvement possible.

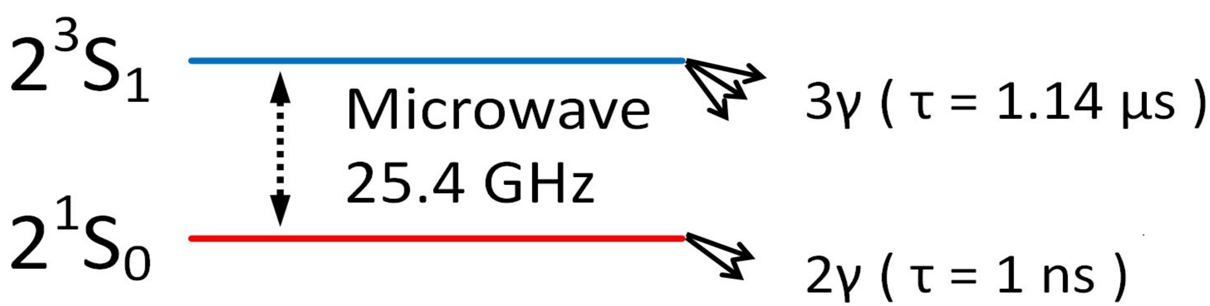
Hyperfine splitting measurement of Ps in 2S state

HFS of Ps in the ground state:
more than 3σ discrepancy between most precise measurements & theory

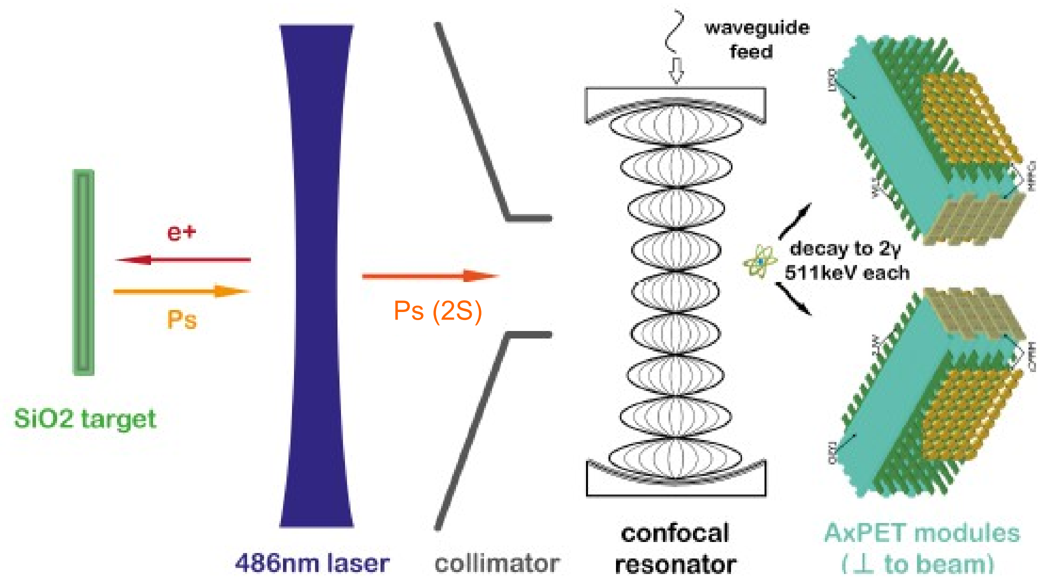
Possible experimental issues:
- measurement in gas → extrapolation to zero density
- measurement in high magnetic field → inhomogeneities

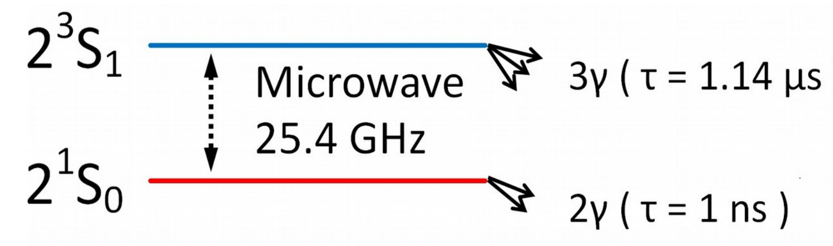


Origin? Our idea: use Ps emitted into vacuum (no extrapolation) and direct transition (no B-field) in 2S state (source commercially available)



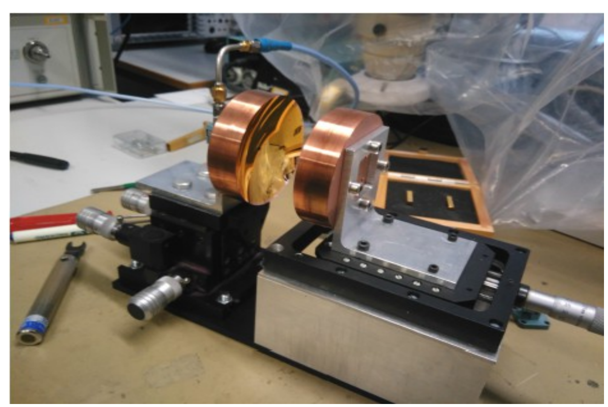
Hyperfine splitting measurement of Ps in 2S state

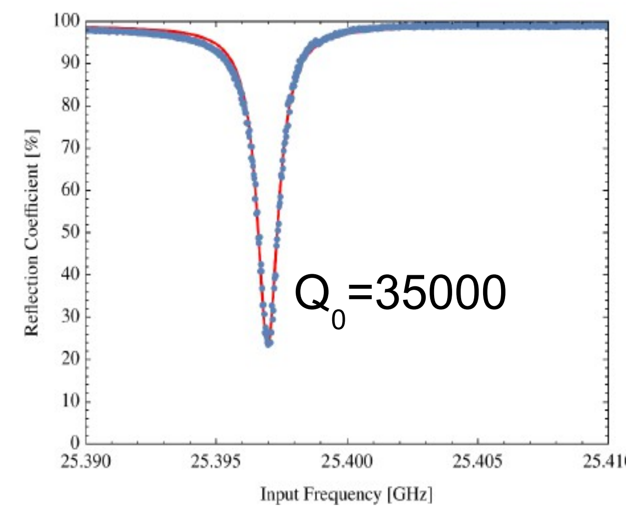




Many thanks to G. Dissertori (ETHZ) and his group for allowing us to use their PET scanner prototype.

Status:
-SNSF funding for PhD student (M. Heiss) received this year
- Experiment in preparation: MW cavity tested, readout of AxPET being refurbished, desing of vacuum chamber in progress.





Goal: Measurement of the 2S HFS at a level of ppm

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