Exotic Atoms

Paolo Crivelli

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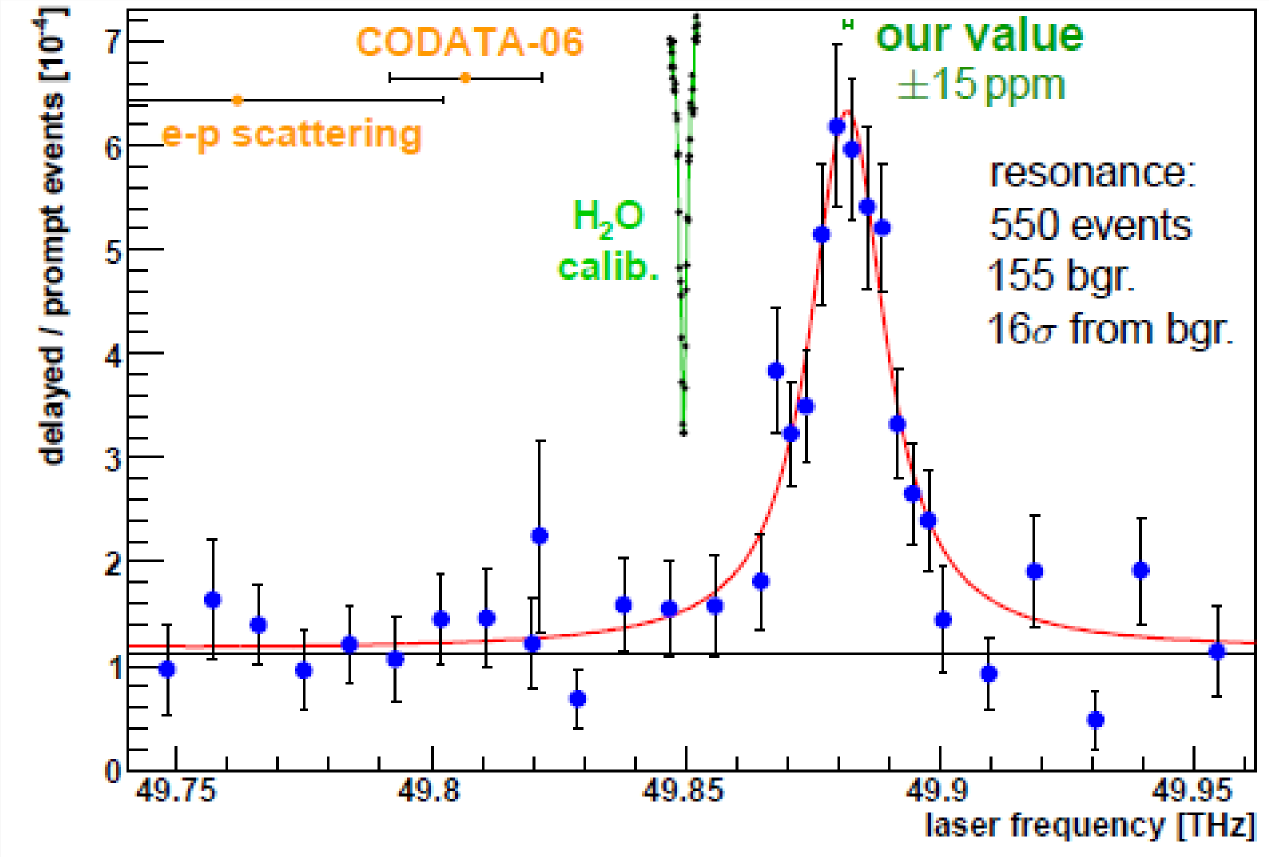
CHIPP plenary meeting, Kartause-Ittingen, 13.09.2012

My work is supported by the Swiss National Science Foundation
(Ambizione grant PZ00P2_132059) and by the ETH Research Grant ETH-47 12-1

Muonic Hydrogen- Results (2010)

F. Kottmann, CHIPP, Gersau 24.08.2010



Reference:
R. Pohl, A. Antognini, F. Nez, D. Taqqu, et al., Nature **466**, 213 (2010)

Collaboration:
- MPQ Garching
- LKB Paris
- Coimbra and Aveiro
- Stuttgart
- Fribourg
- Yale
- PSI - ETHZ - ...

Statistics: ± 0.70 GHz
Systematics: ± 0.30 GHz (laser calibration)

Discrepancy (to CODATA-06):
$\sim 75\ \mathrm{GHz} \leftrightarrow 5.0\,\sigma \leftrightarrow \delta\nu/\nu = 1.5 \times 10^{-3}$

The proton radius puzzle (2012)

7σ discrepancy between r_p from muonic hydrogen and CODATA-10

- Re-analysis and new e-p scattering data consistent with previous results
- Muonic hydrogen QED theory confirmed (Antognini et al., arXiv:1208.2637)
- Second transition in muonic-H (measured also in 2009) confirms previous results (see next slide)

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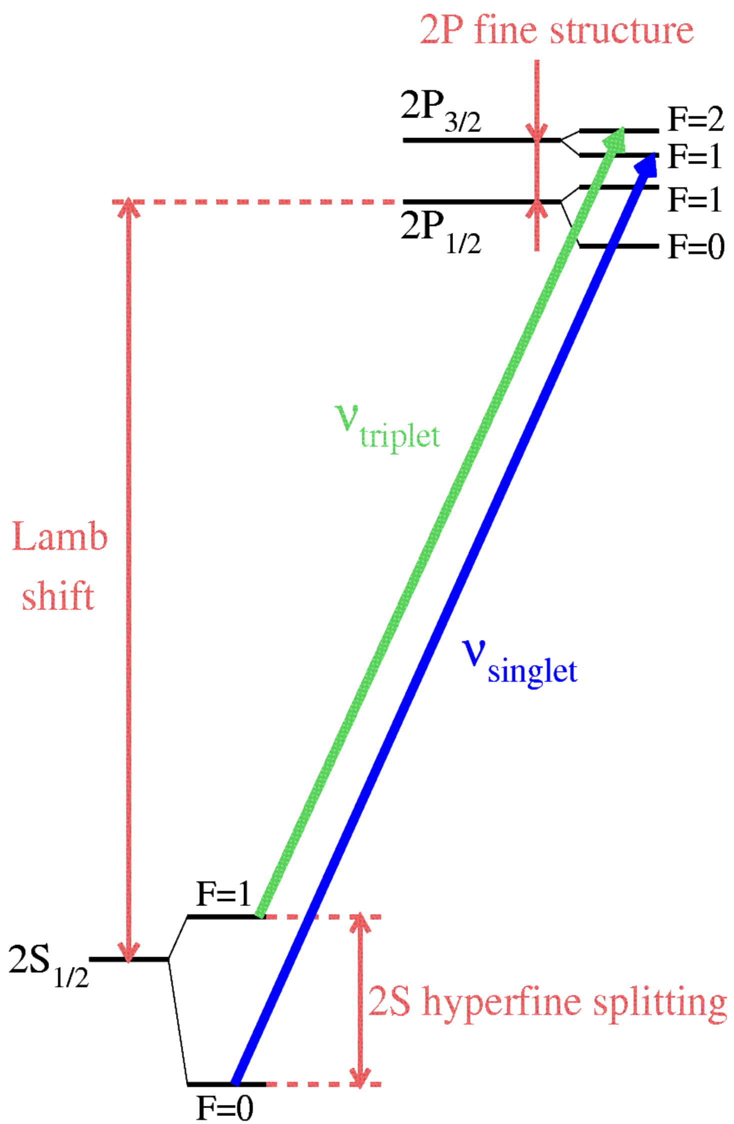
What is the origin?

- Alternative analysis of scattering data consistent results with muonic hydrogen
- New physics?
- Value of the Rydberg constant? Several experiments are ongoing in H to check it.

New results from muonic hydrogen

Antognini et al., submitted (2012)



Second transition confirms previous muonic-H results

- Combining the two transitions:
    - pure 2S-2P Lamb shift
    - 2S HFS

- Improved r_p value to $u_r = 5\times10^{-4}$
    - Deuteron radius to $u_r = 1\times10^{-4}$
    - Rydberg constant to $u_r = 1\times10^{-12}$

- From HFS
    - Zemach and magnetic radius of the proton (in agreement with other results)

Muonic Helium

CREMA (Charged Radius Experiment with Muonic Atoms) collaboration

- Goal: measure several 2S-2P transitions in muonic helium ions μHe^+
  → Determine alpha and helion charge radius to $u_r=10^{-4}$ (0.0004 fm)

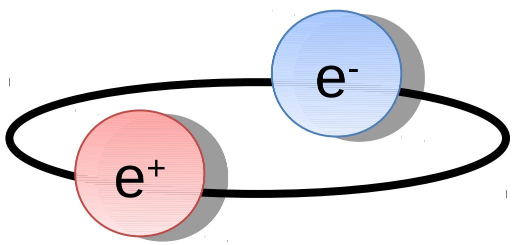
- Aims
  → help to solve the proton radius puzzle
  → absolute nuclear charge radii ^3He, ^4He, ^6He
  → low energy effective nuclear theories
  → "improved" bound-state QED test when combined with He^+ spectroscopy

- Proposal approved at PSI in 2010

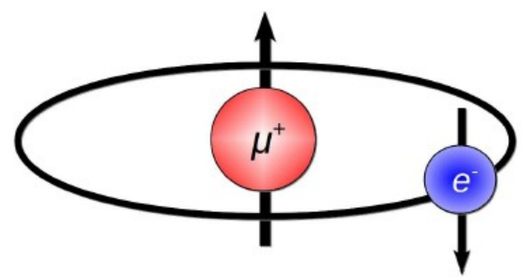
1^{st} BEAM TIME EXPECTED IN 2013

Leptonic atoms

Positronium (Ps)



Muonium (Mu)



Leptonic atoms

Precise test of
bound state QED
free from finite size effects

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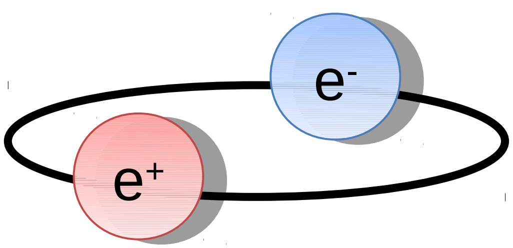

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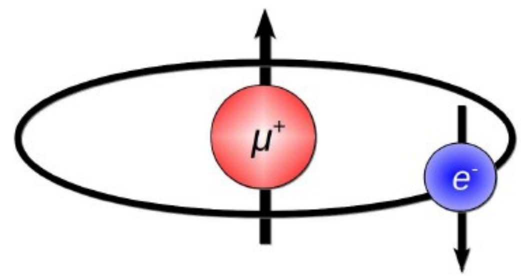

Leptonic atoms

Precise test of bound state QED free from finite size effects

Fundamental constants (m_{e+}/m_{e-}, m_{μ}, $q_{e-}/q_{\mu+}$ ..)

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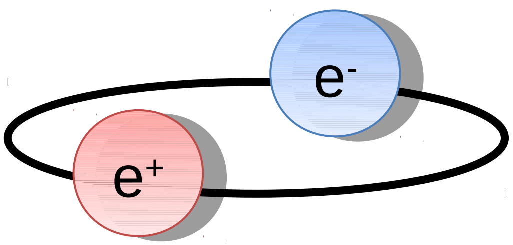

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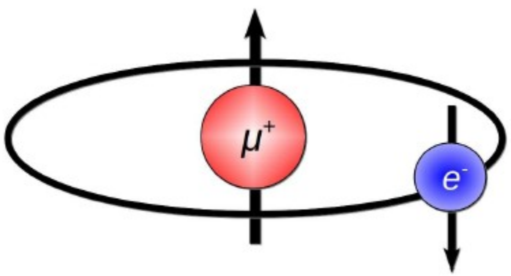

Leptonic atoms

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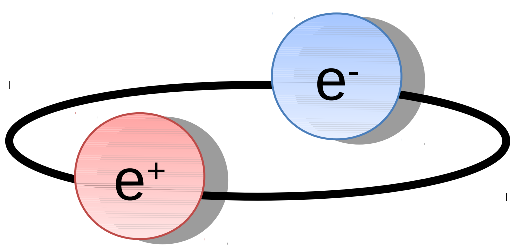

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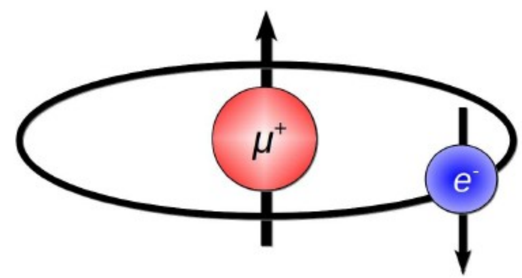

Test of the fundamental
symmetries

Leptonic atoms

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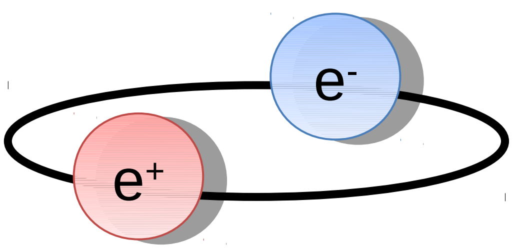

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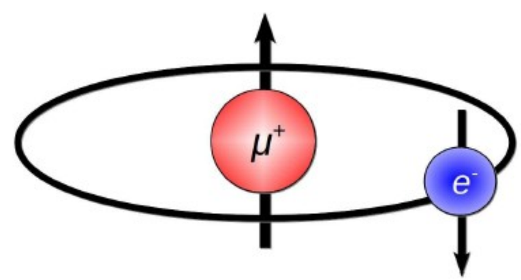

Test of the fundamental
symmetries

Search for new physics

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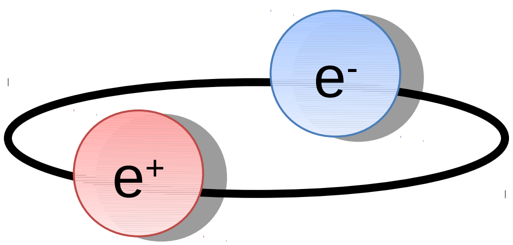

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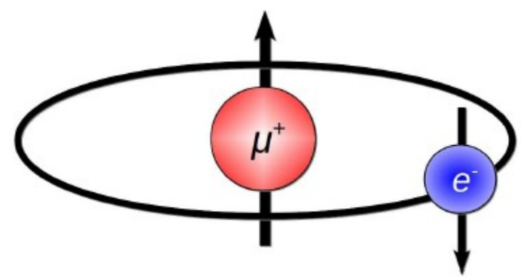

Test of the fundamental
symmetries

Test the effect of gravity
on
anti-matter

Search for new physics

Ps and Mu sources

Quality of the Ps and Mu sources: main limitation to improve the current experiments.

High vacuum yield

Small emission velocities

Long term stability

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- Positrons: Rare gas moderators and positrons accumulators.

C. M. Surko and R. G. Greaves, Phys. Plasmas 11, 2333 (2004)

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- Muons: efforts undertaken at PSI and J-PARC.

D. Taqqu, Phys. Rev. Lett. 97, 194801 (2006) and e.g. A. Toyoda et al., arXiv:1110.1125.

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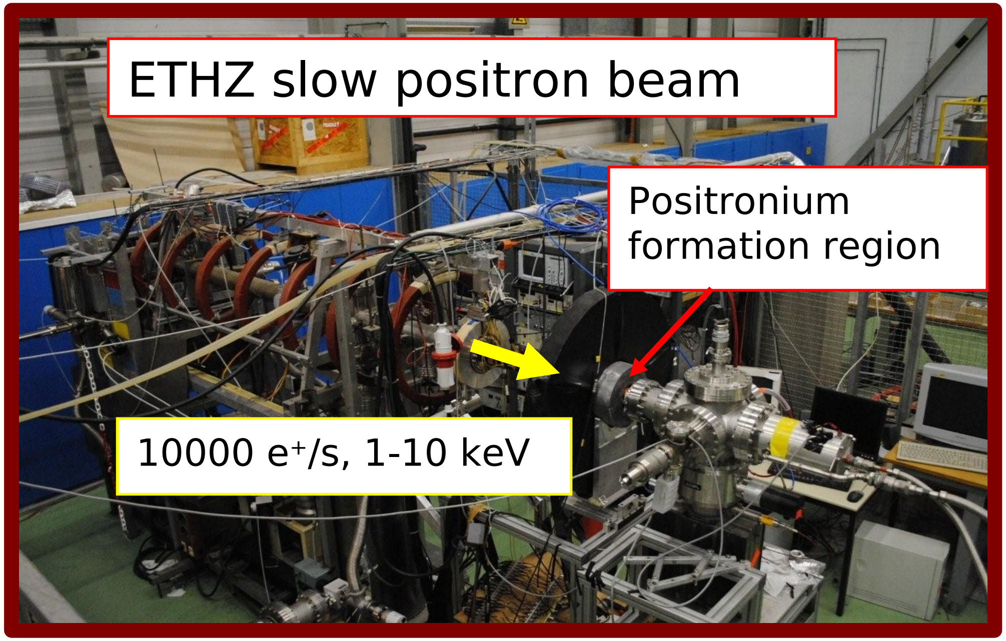
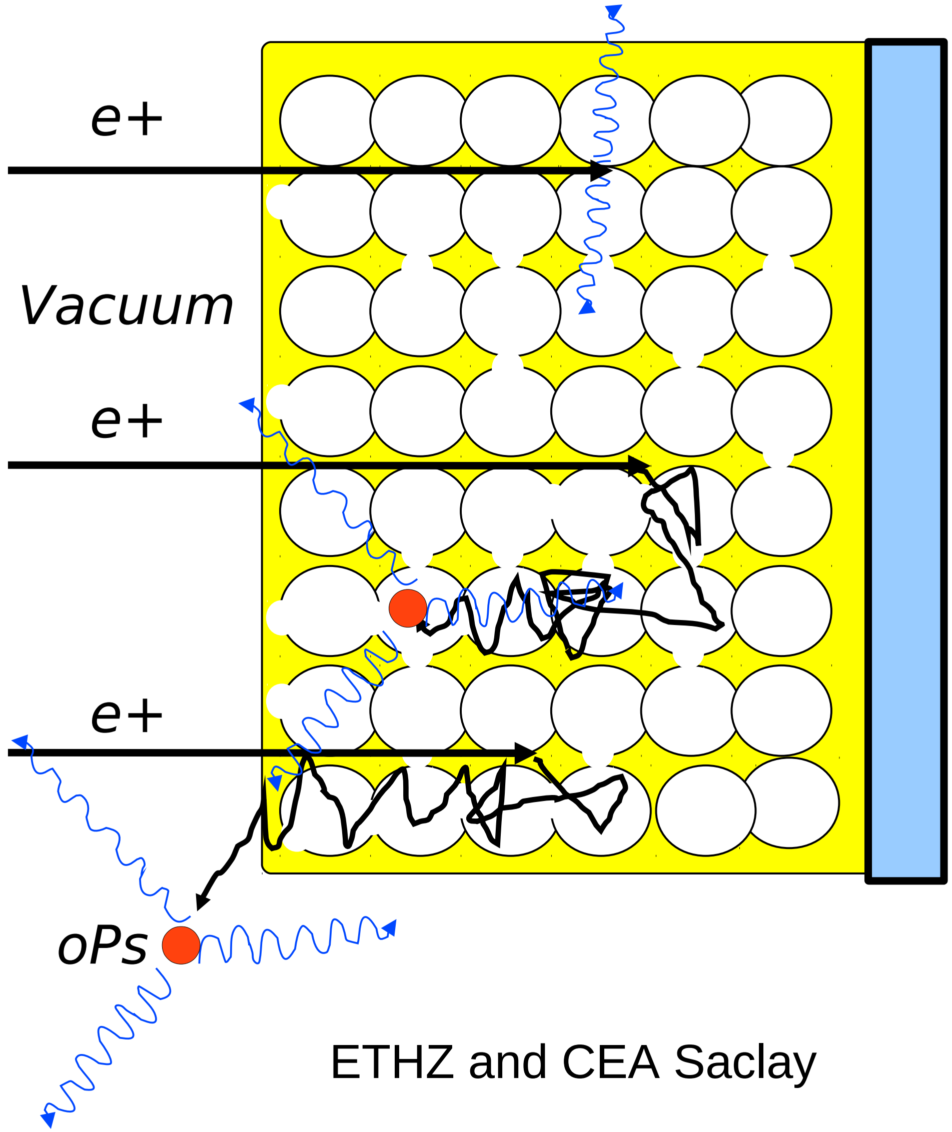
2) Improve the $e+ \rightarrow$ Ps and $\mu+ \rightarrow$ Mu conversion targets (this talk).

Ps production in porous SiO_2 thin films



- e^+ implanted with few keV
(range of 300 nm for 5 keV energy)
- e^+ slow down and stop in the bulk material
- Ps formation in the bulk material
  (~60% in SiO_2)
- Ps ejection in the pores (work energy ~1 eV)
- Thermalization and diffusion in the pores
- A fraction of Ps 30-40 % exits into vacuum

Porous Silica thin film
~500 -1000nm and 3-5 nm pore size

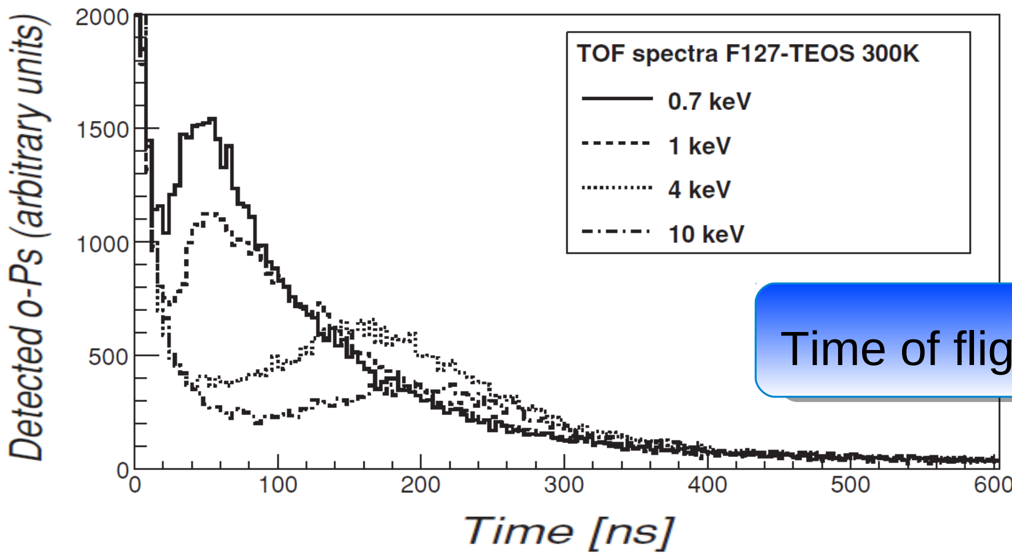


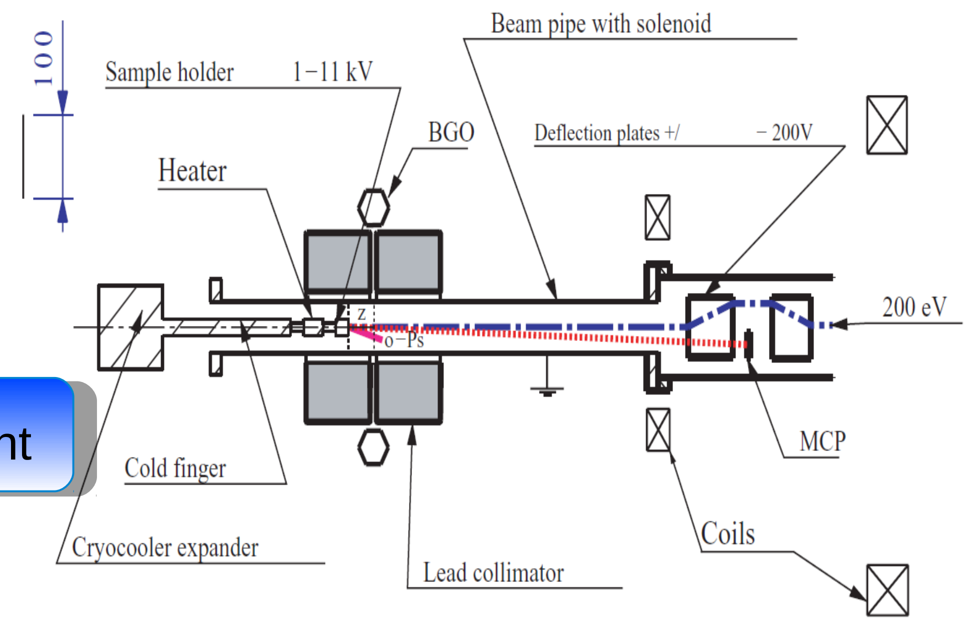
ETHZ and CEA Saclay

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

Measurement of Ps energy

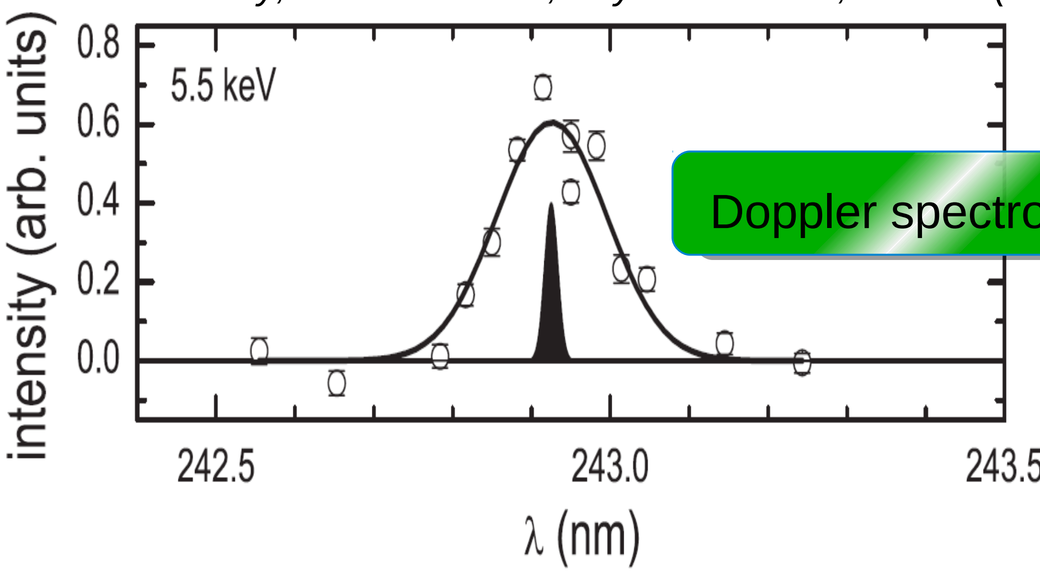
P. Crivelli et al. , Phys. Rev. A81, 052703 (2010)

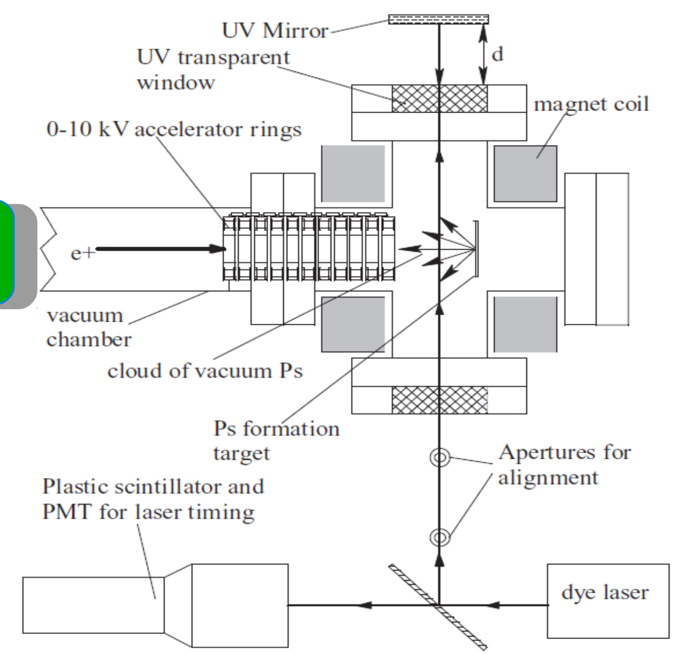




Time of flight

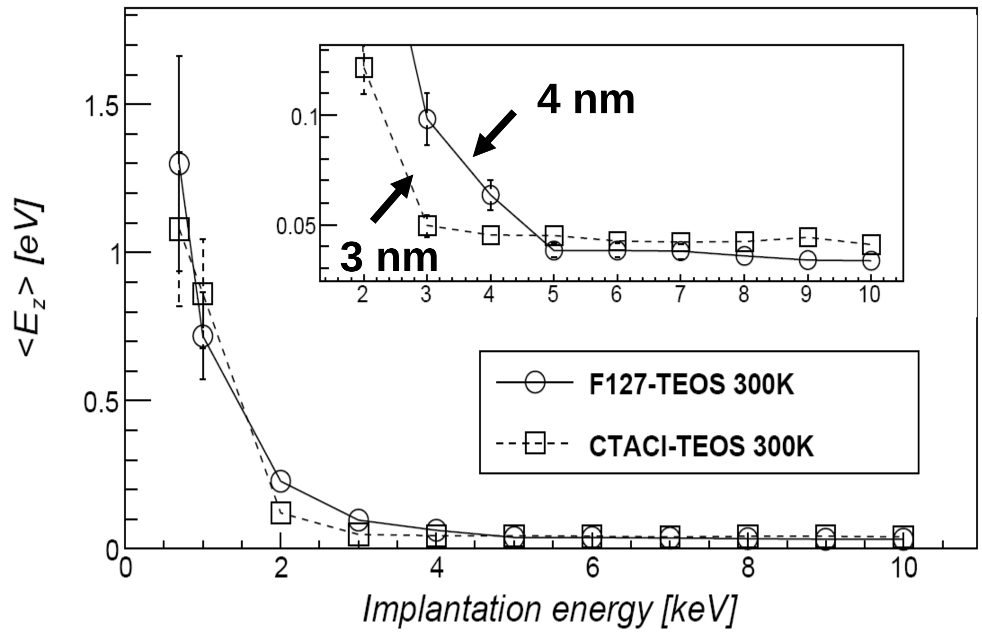
D. Cassidy, P. Crivelli et al., Phys. Rev. A 81, 012715 (2010)





Doppler spectroscopy

Ps as a particle in a box



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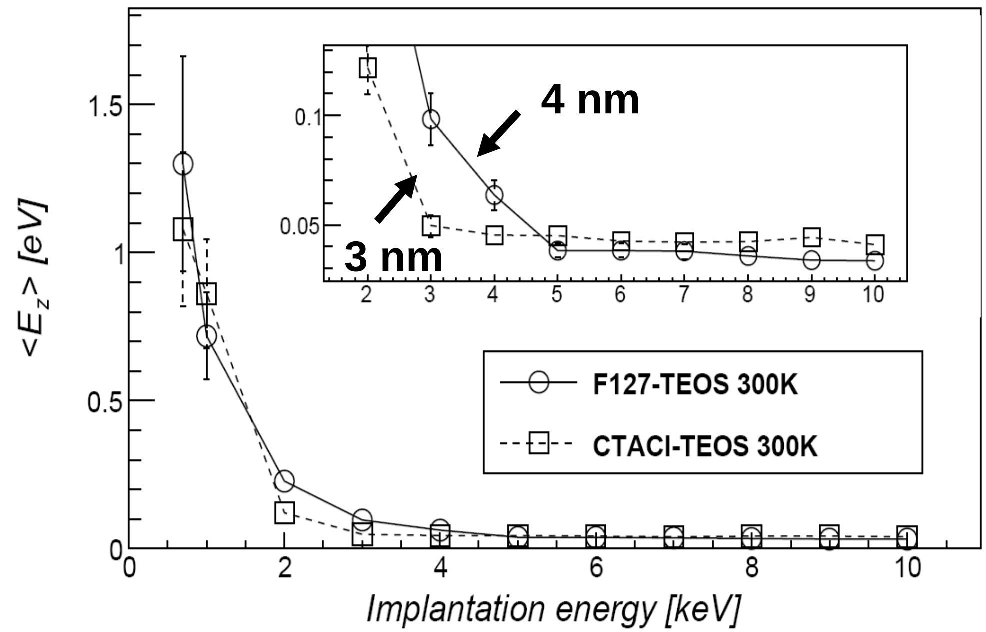
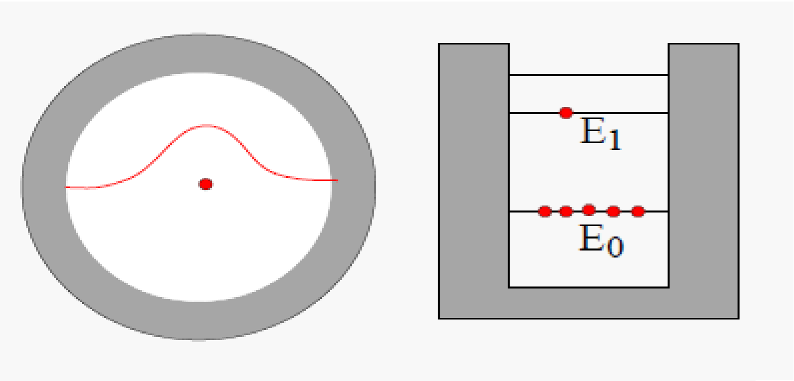
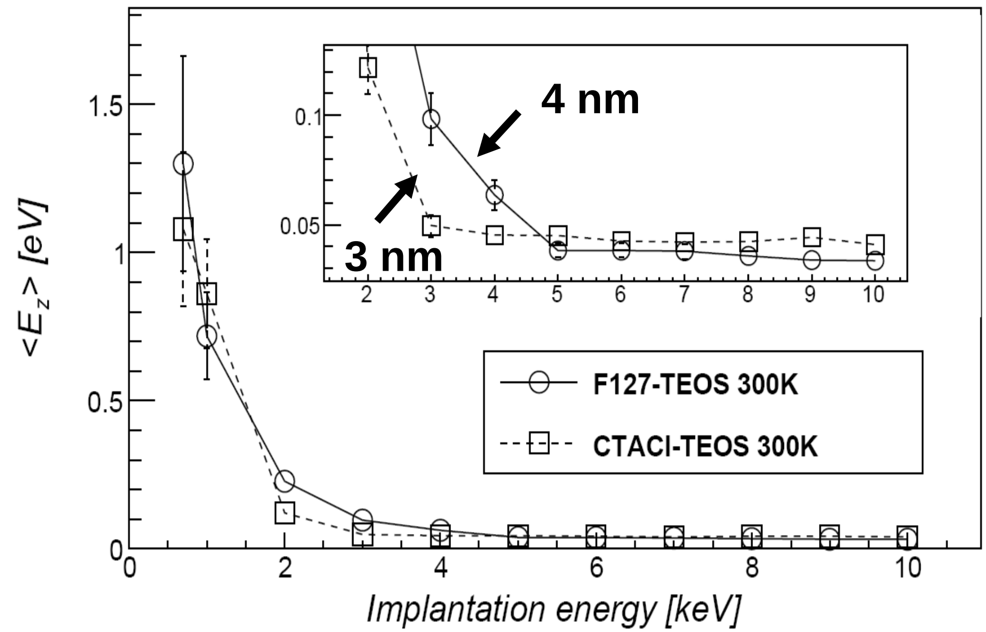
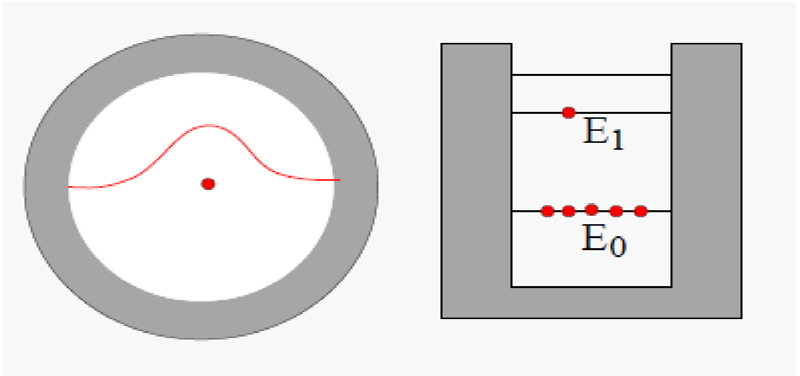




$$E_{\rm Ps} = \frac{h^2}{2m\,d^2} \approx 0.8\,{\rm eV}\,(1\,{\rm nm}/d)^2$$

Ps as a particle in a box





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

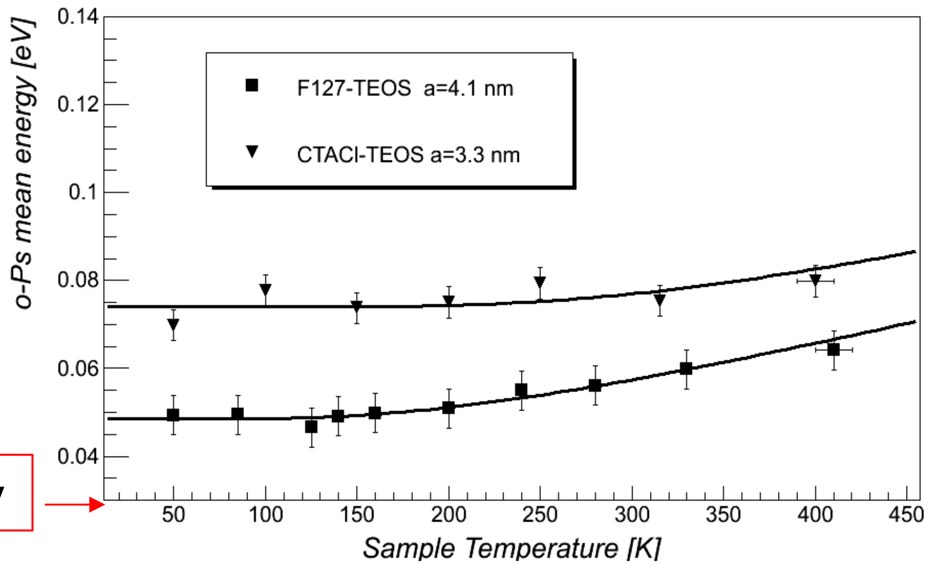
Model Ps as a particle in a box

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

Z is the partition function defined as

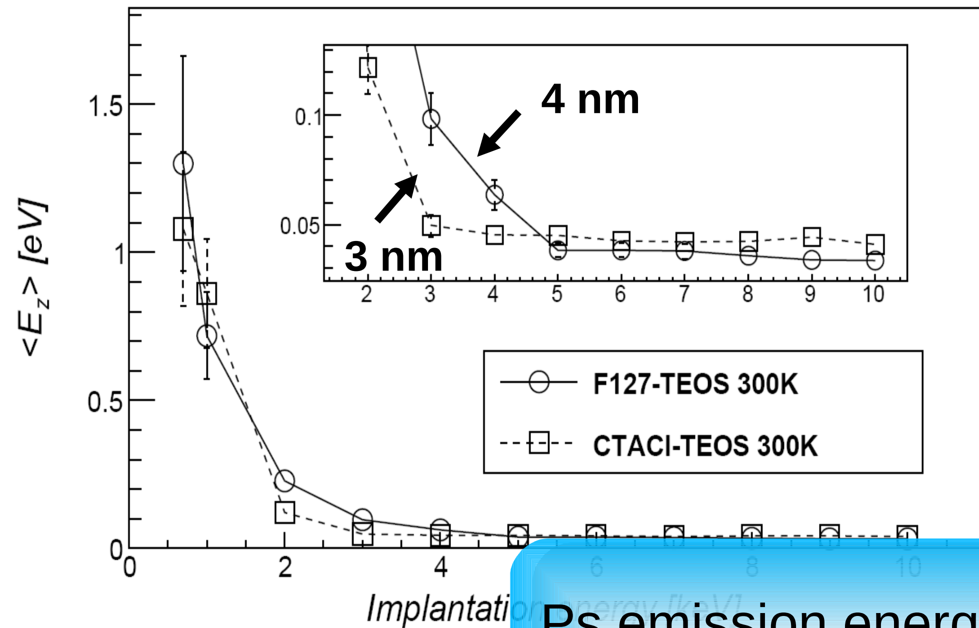
$$Z(a) = \sum_{n=1}^{\infty} e^{-\frac{h^2 n^2}{8ma^2}/kT},$$

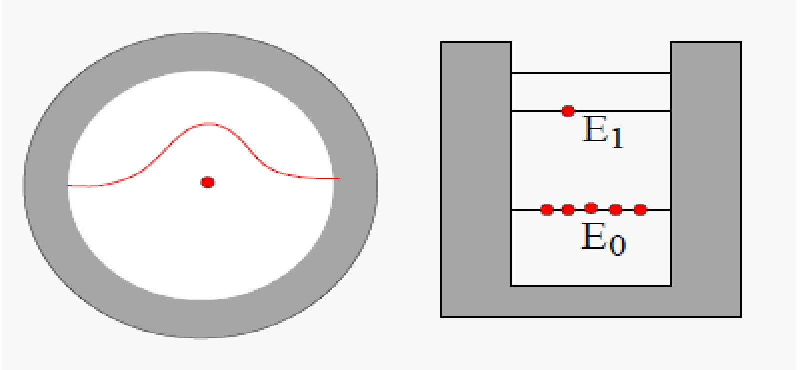
Thermal energy



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

Ps as a particle in a box





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

Ps emission energy into vacuum defined by ground state energy in the pores

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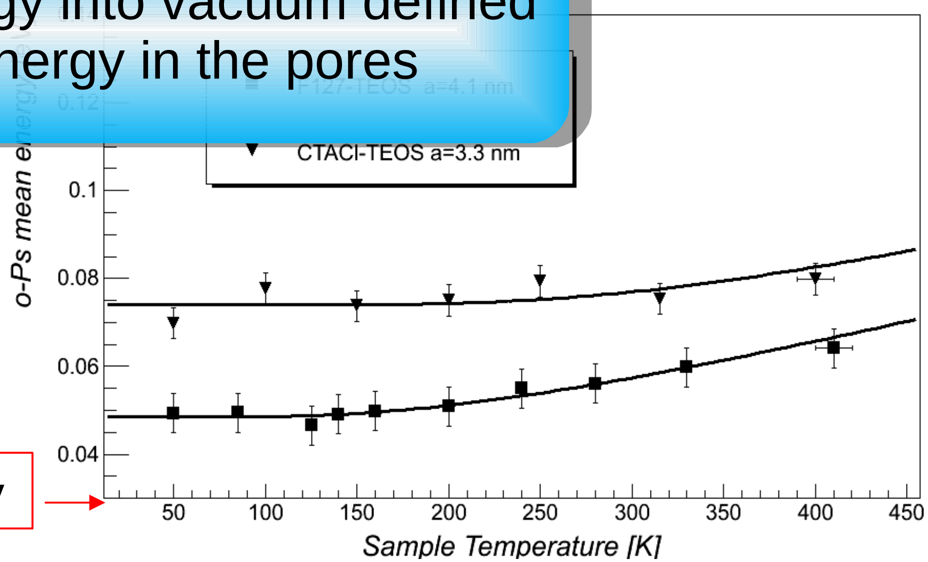

P. Crivelli et al. , Phys. Rev. A81, 052703 (2010)

Mu production in SiO2 thin films

Ps and Mu have similar formation mechanisms and yields in vacuum in silica powders (used for Mu production in previous experiments).
→ Test the targets developed for Ps at the low energy muon beam line at PSI

We were confident that those would be promising candidate for:
1) Higher Mu vacuum yield
2) Low Mu emission velocity ($\lambda_{Mu} \sim 1/10\ \lambda_{Ps}$)
3) Stable source (Ps vacuum yield constant in a time scale of months while powders degradation in few hours).

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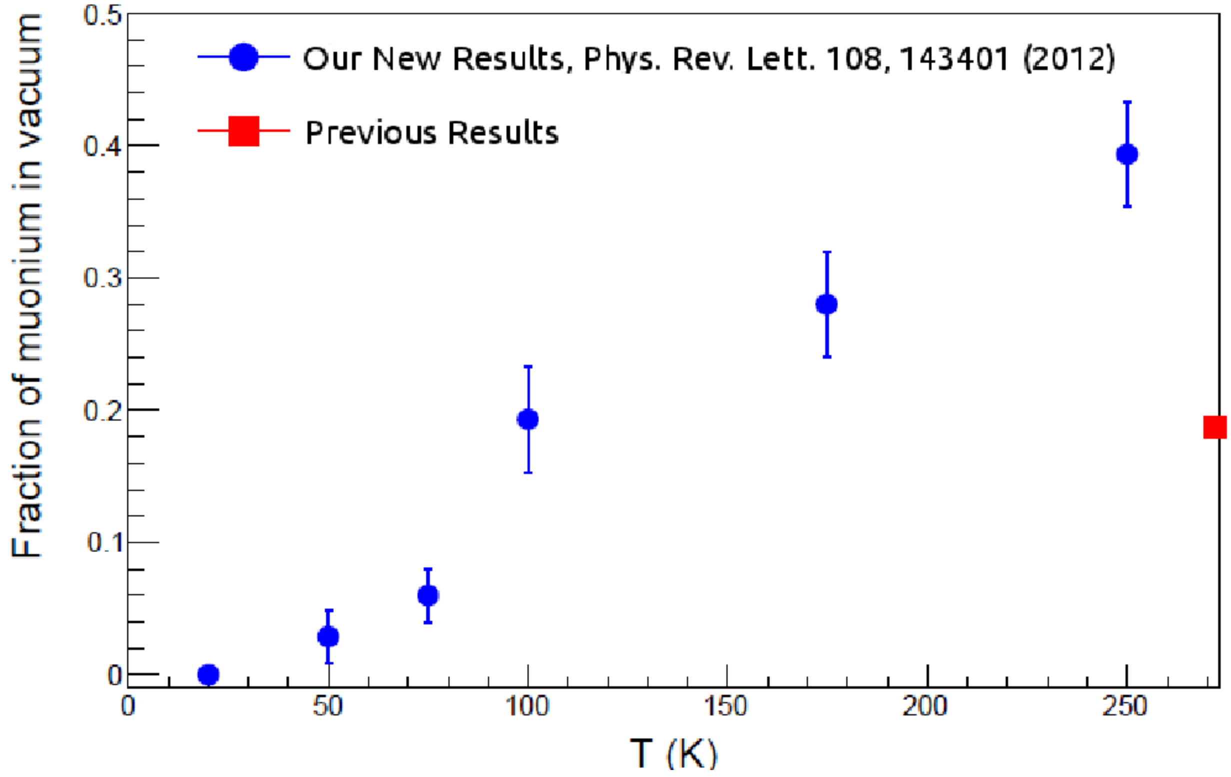
PRL **108,** 143401 (2012) PHYSICAL REVIEW LETTERS week ending 6 APRIL 2012

Muonium Emission into Vacuum from Mesoporous Thin Films at Cryogenic Temperatures

A. Antognini,[1,*] P. Crivelli,[1,†] T. Prokscha,[2,‡] K. S. Khaw,[1] B. Barbiellini,[3] L. Liszkay,[4] K. Kirch,[1,2] K. Kwuida,[1] E. Morenzoni,[2] F. M. Piegsa,[1] Z. Salman,[2] and A. Suter[2]
[1]*Institute for Particle Physics, ETH Zurich, Switzerland*
[2]*Paul Scherrer Institute, Villigen, Switzerland*
[3]*Department of Physics, Northeastern University, Boston, Massachusetts 02115, USA*
[4]*CEA, Irfu, Sédi, Centre de Saclay, F-91191 Gif-sur-Yvette, France*
(Received 23 December 2011; published 3 April 2012)

Results of Mu production into vacuum

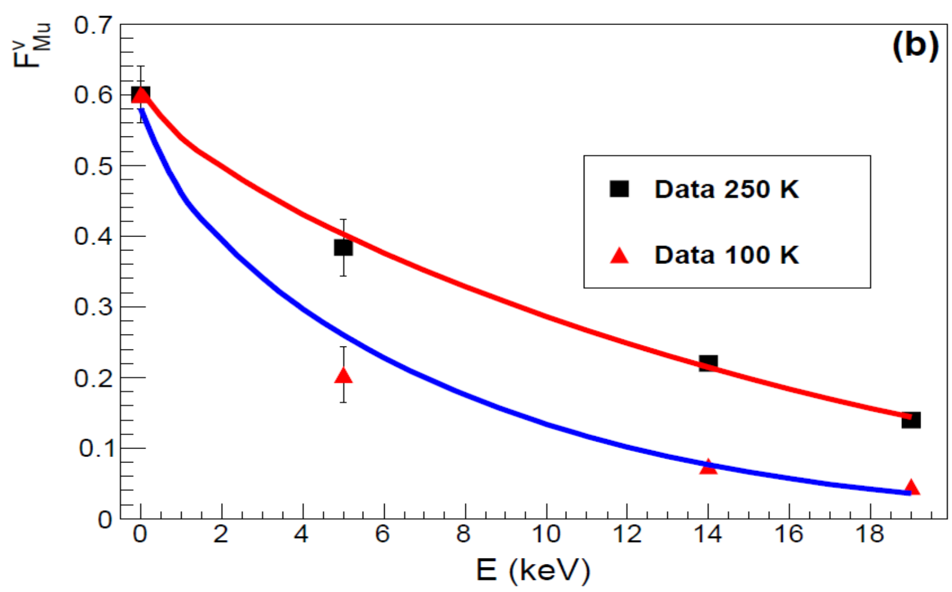


Sizeable fraction of thermalized muonium emitted into vacuum from SiO_2 thin film at 5 keV implantation energy:

- At 250 K, the yield (38%) is more than a factor of two higher than previously found in SiO_2 powders at room temperature (RT).
- At 100 K, the yield (20%) is still as large as previously found at RT.

Mu diffusion

$$\boxed{F_{\rm Mu}^{v}(E) = F_{\rm Mu}^{0}(E)J(E)}$$



Solution of 1D diffusion model

$$\boxed{J(E) = \int_0^l e^{-\beta x} P(x,E)dx}$$

$$\mu^+ \text{ implantation profile } P(x,E)$$

Inverse of diffusion lenght

$$\boxed{\beta = 1/\sqrt{D_{Mu}\tau}}$$

Model developed for Ps:
A. Mills and C. Murray, Appl. Phys. 21, 323 (1980)
K. Lynn and H. Lutz, Phys. Rev. B22, 4143 (1980)

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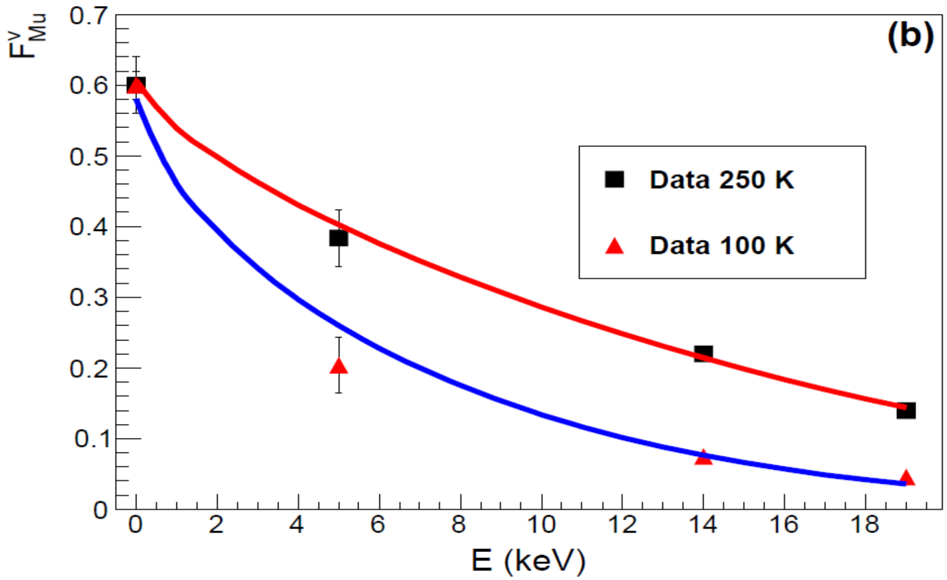

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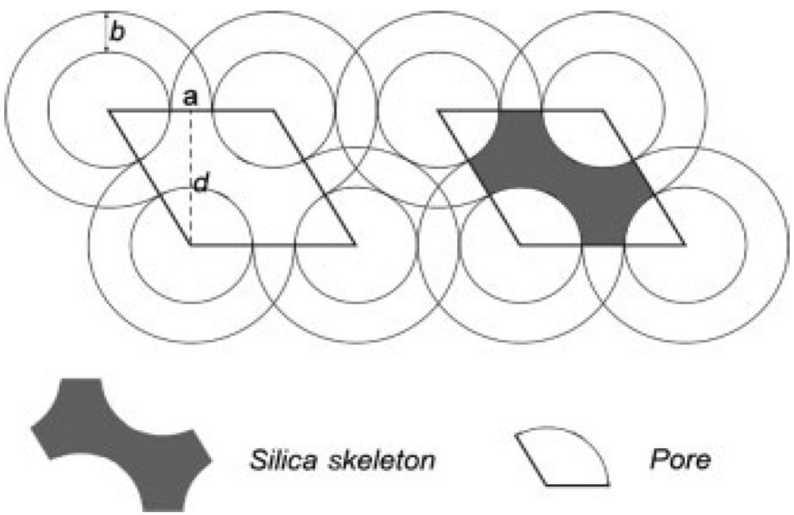
$$\boxed{D^{250\mathrm{K}}_{\mathrm{Mu}} = (1.6 \pm 0.1) \times 10^{-4} \ \mathrm{cm}^2/\mathrm{s}}$$

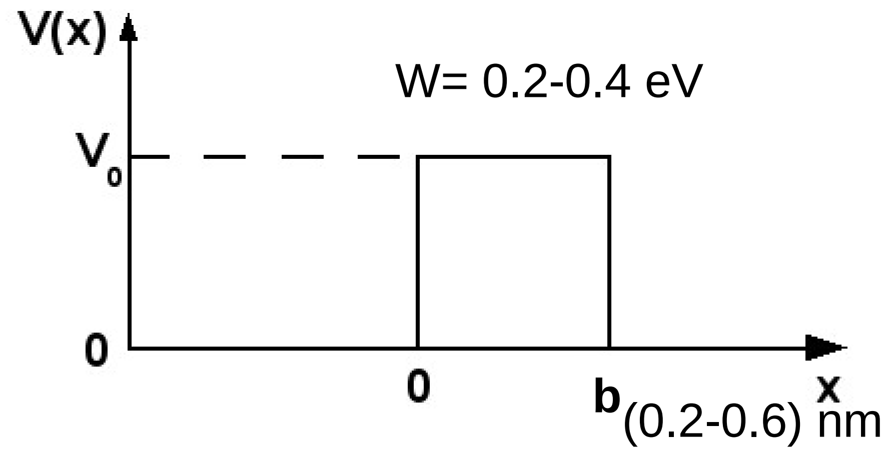
$$\boxed{D^{100\mathrm{K}}_{\mathrm{Mu}} = (4.2 \pm 0.5) \times 10^{-5} \ \mathrm{cm}^2/\mathrm{s}}$$

3 orders of magnitude smaller than expected from a classical diffusion model as used to for SiO2 powders (Dmu~meanfreepath*vMu)!

G. Marshall et al. Phys. Rev. D25 1174 (1982)

Pore-to-pore QM tunneling





Our model: diffusion of Mu as quantum mechanical tunneling from pore-to-pore.
Tunneling probability at a potential barrier for $E < V_0$:

$$P_t = \frac{1}{1 + \frac{V_0^2 \sinh^2(b\sqrt{2m_{\mathrm{Mu}}/h^2(V_0 - E)})}{4E(V_0 - E)}}$$

Since in our regime the tunneling probability scales approximately linearly with T:

$$D_{\mathrm{Mu}}(T) \propto P_t \sqrt{E_{\mathrm{Mu}}} \propto T\sqrt{T} \propto T^{3/2}$$

Measured ratio $D_{\mathrm{Mu}}^{250\mathrm{K}} / D_{\mathrm{Mu}}^{100\mathrm{K}} \approx 3.8 \pm 0.5$.
Expected value from the $T^{3/2}$ dependence of $(250\mathrm{K}/100\mathrm{K})^{3/2} \approx 4$

1S-2S spectroscopy of Ps and Mu

Our results on Ps and Mu formation open the way to improve the accuracy of the 1S-2S frequency interval measurements of leptonic atoms.

The 1S-2S signal rate is proportional to

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

Ps/Mu source with high yield and low energy

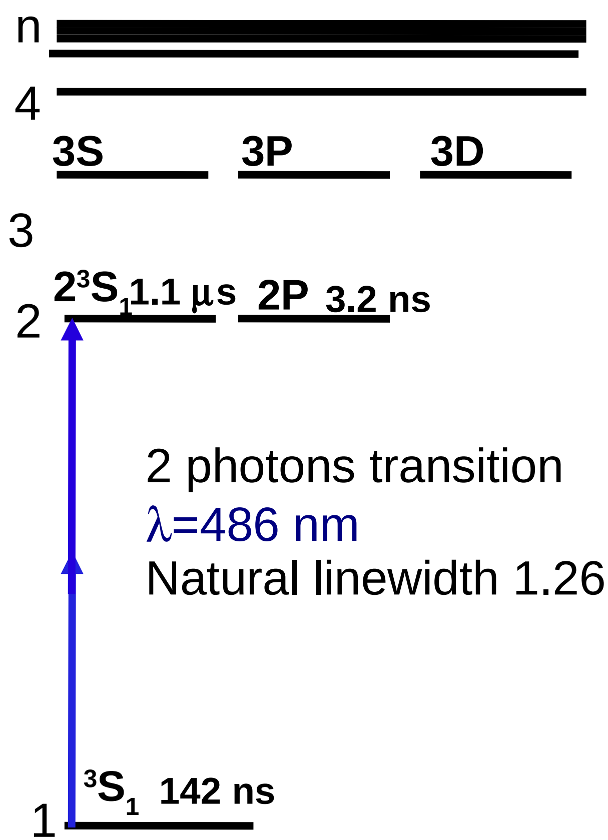
→ Decrease requirements of laser intensity

→ Decrease systematical effects

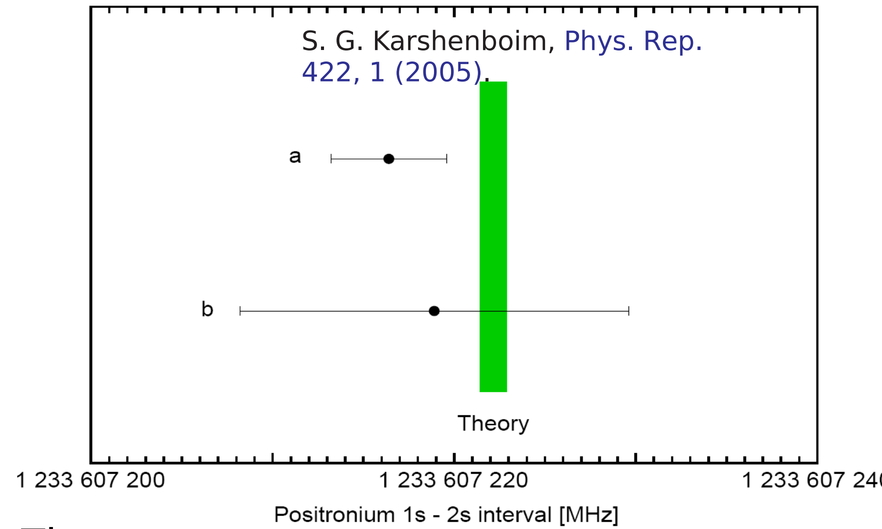
→ Increase statistical significance

Positronium 1S-2S transition

Ps Energy levels



2 photons transition
λ=486 nm
Natural linewidth 1.26 MHz



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).

Experiment

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

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

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

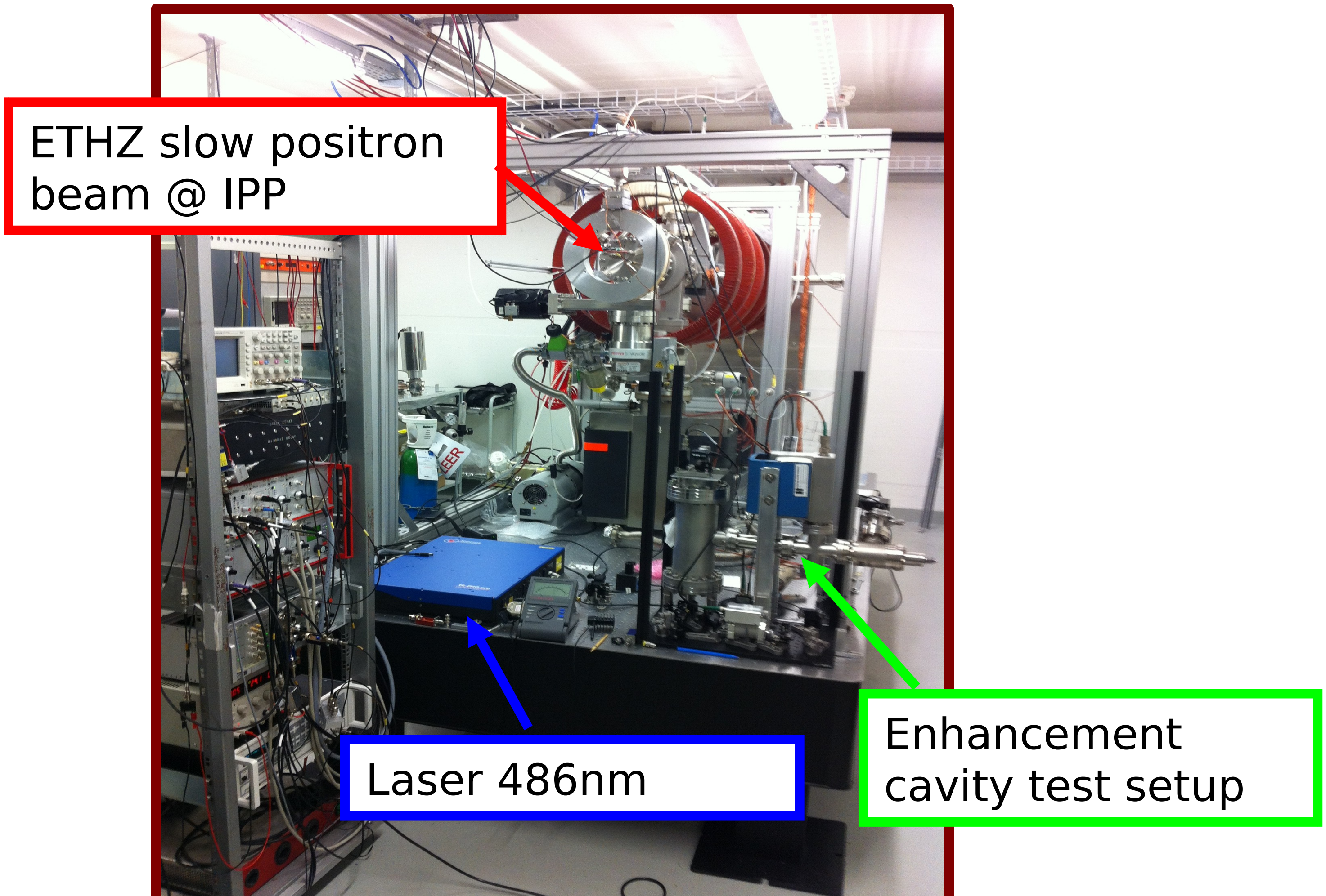
S. Chu, A. P. Mills, Jr. and J. Hall, Phys. Rev. Lett. 52, 1689 (1984)

Measurement of 1S-2S of Ps at a level about 5×10^{-10} => check QED calculations at the order $\alpha^7 m$ and provide the best determination of m_{e+}/m_{e-}.

New measurement @ ETH

P. Crivelli (ETHZ), D. Cooke (ETHZ), A. Antognini (ETHZ), K. Kirch (ETHZ/PSI),
J. Alnis (MPQ), T. Haensch (MPQ), B. Brown (MU, USA)

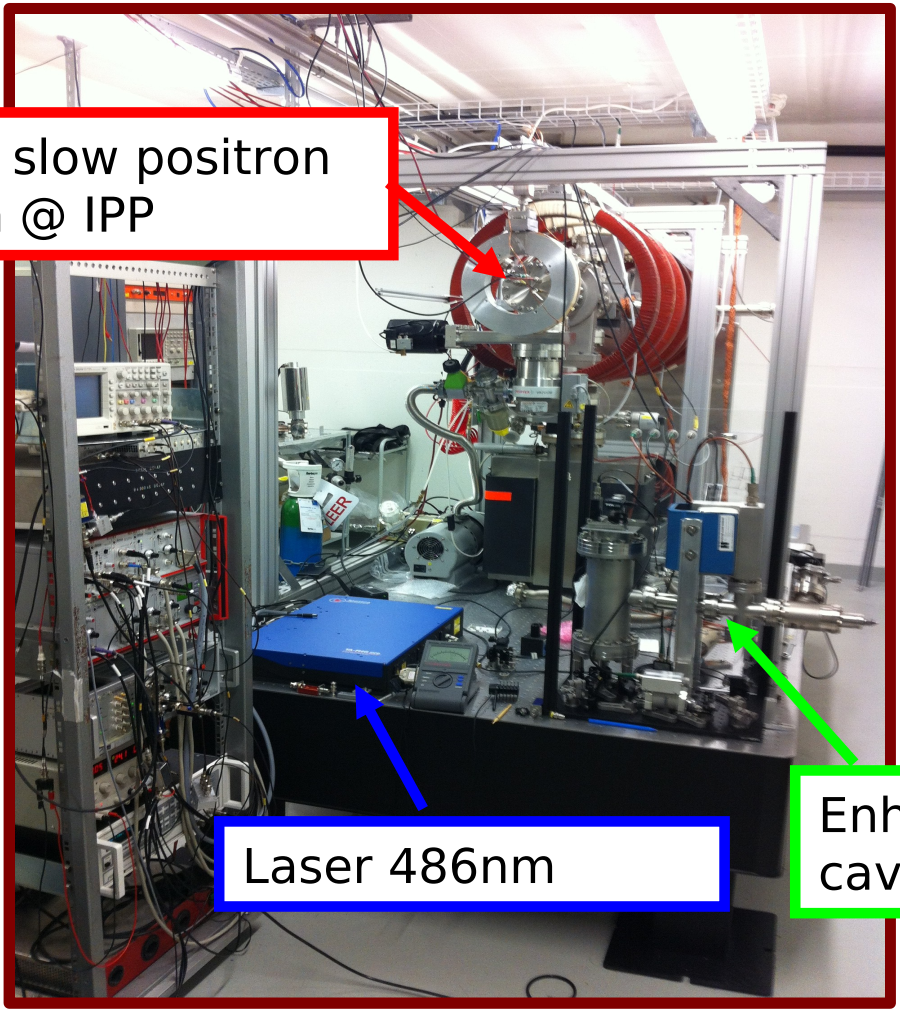
Project supported by the SNSF and ETH started in April 2011.



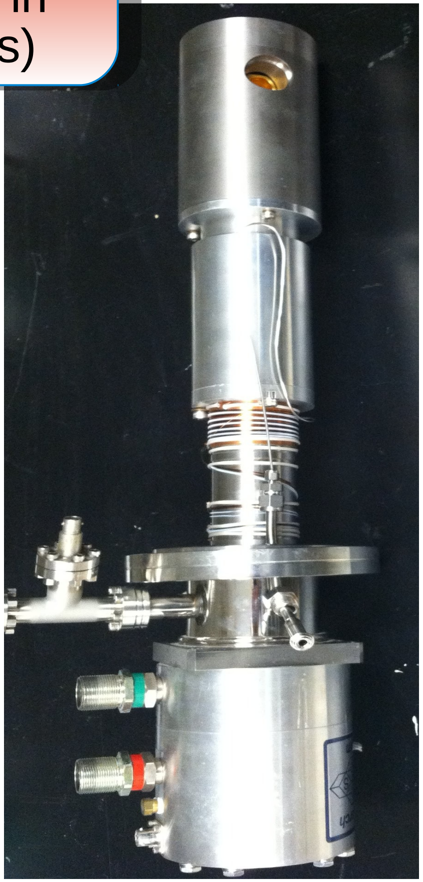
New measurement @ ETH

P. Crivelli (ETHZ), D. Cooke (ETHZ), A. Antognini (ETHZ), K. Kirch (ETHZ/PSI),
J. Alnis (MPQ), T. Haensch (MPQ), B. Brown (MU, USA)

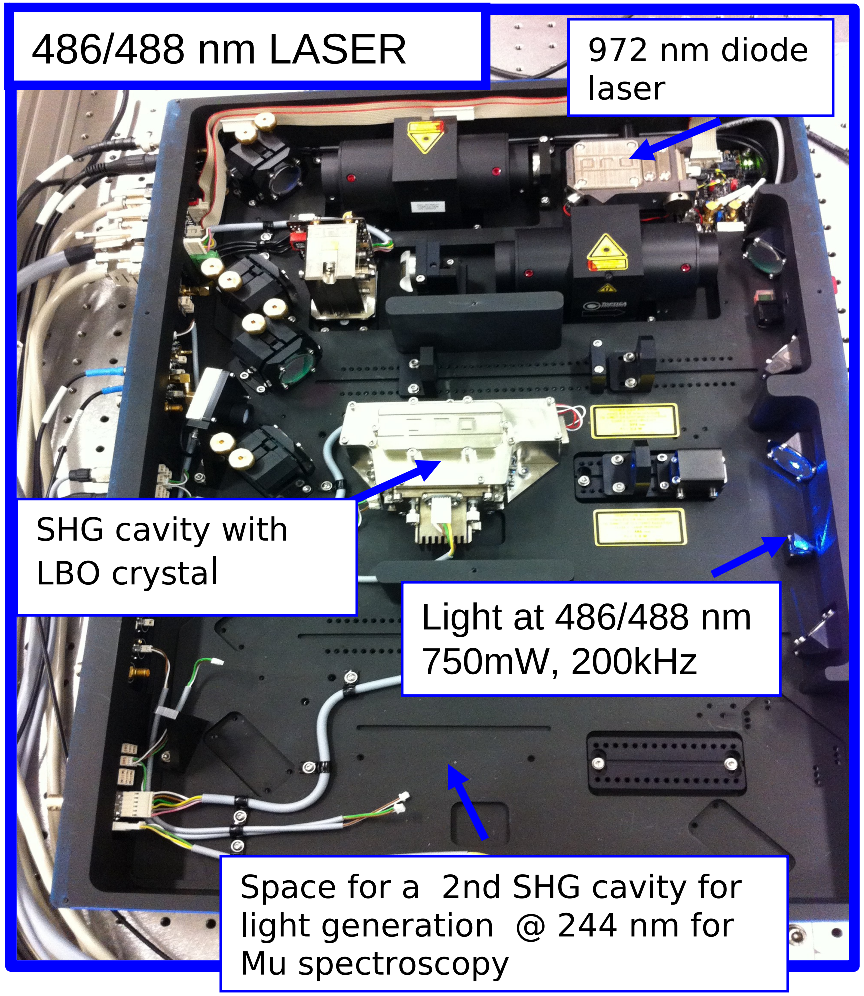
Project supported by the SNSF and ETH started in April 2011.



W moderator replaced with solid Ne:
-> Factor 20 increase in e+ flux (2 x 10^5 e+/s)



The laser (Ps and Mu)



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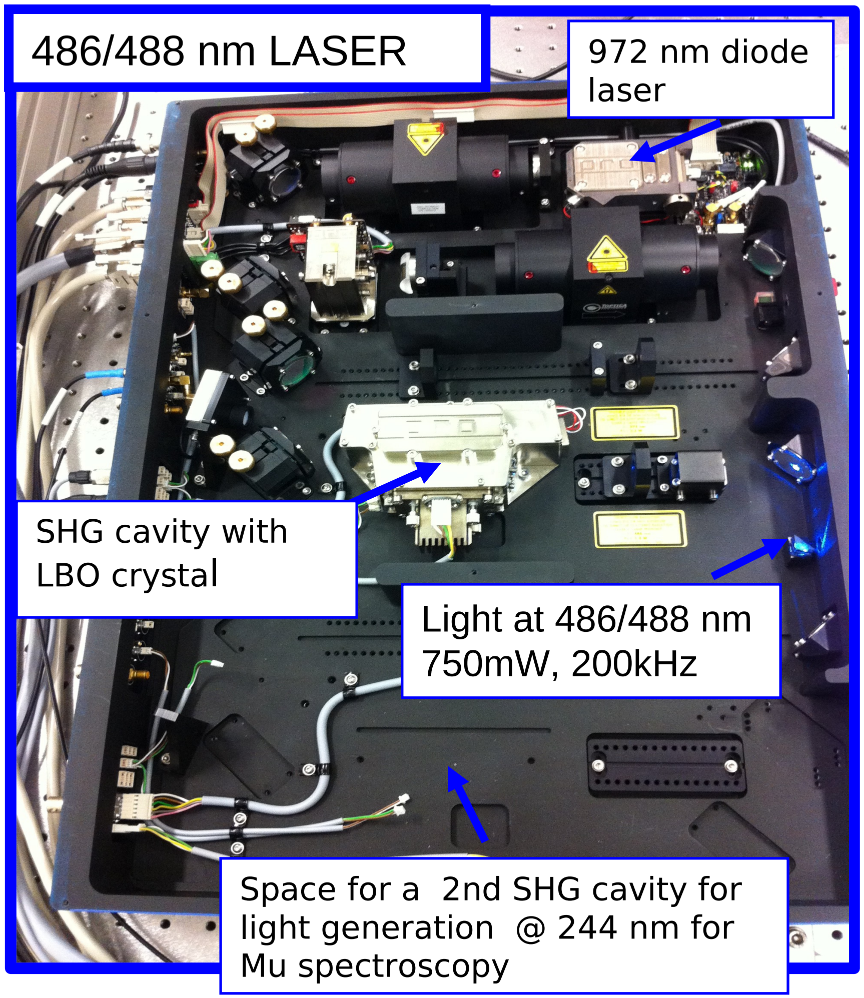
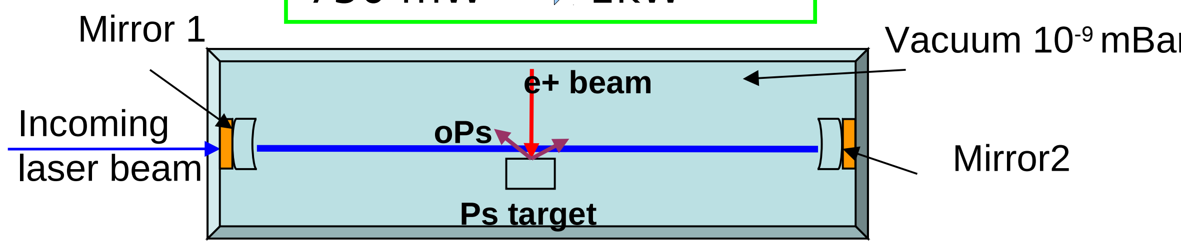


Enhancement cavity:
750 mW → 1kW



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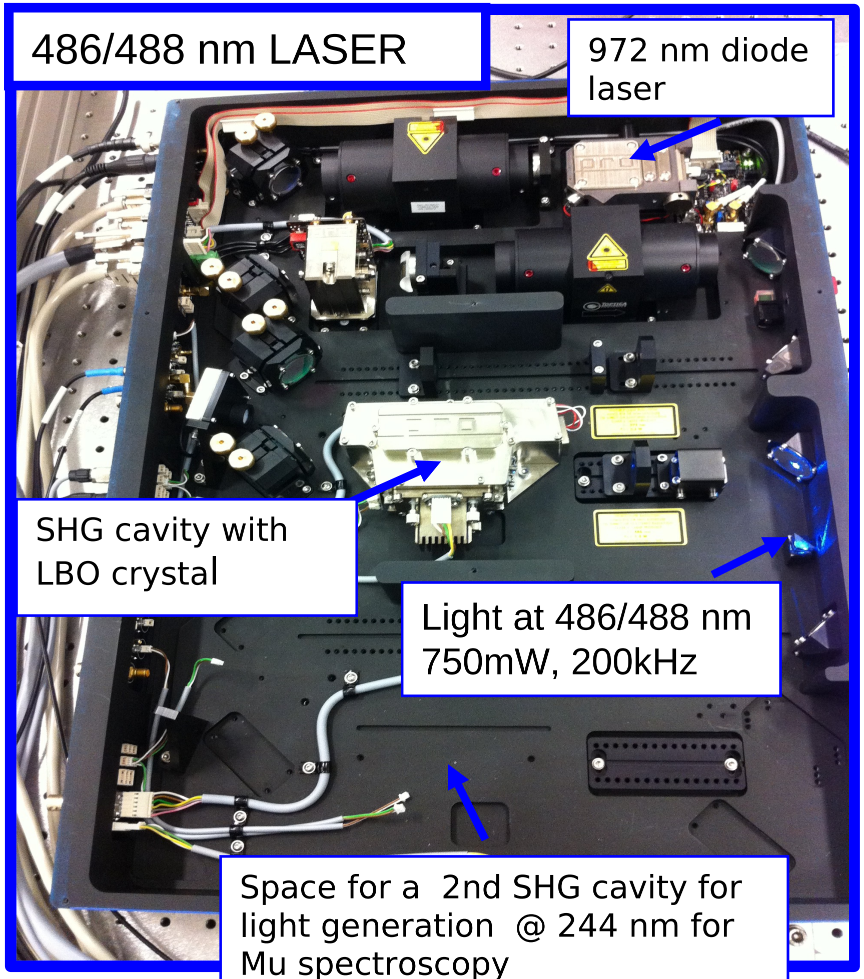

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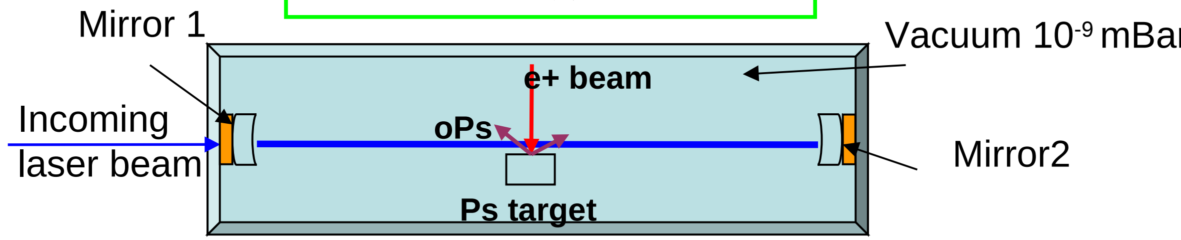
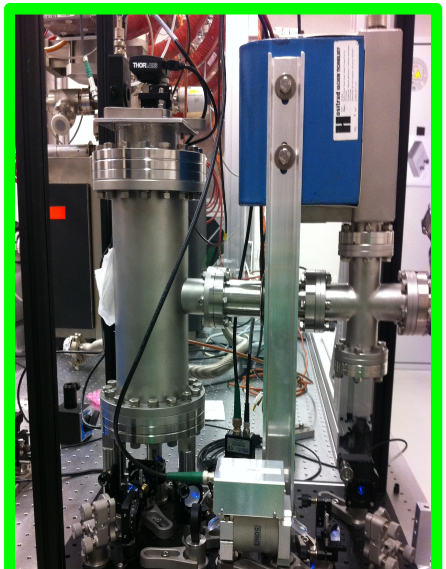
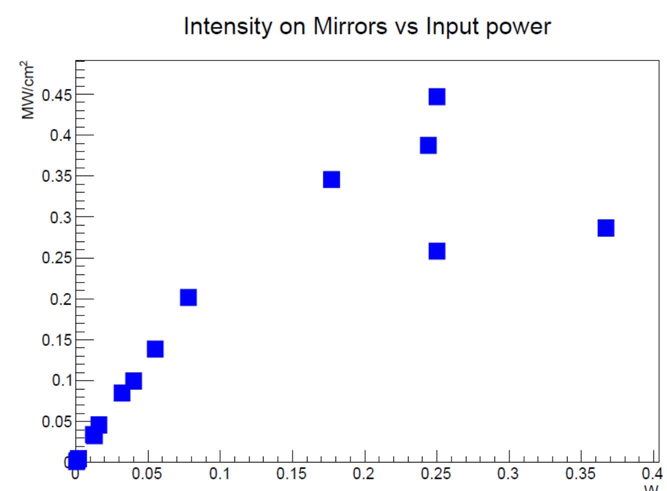




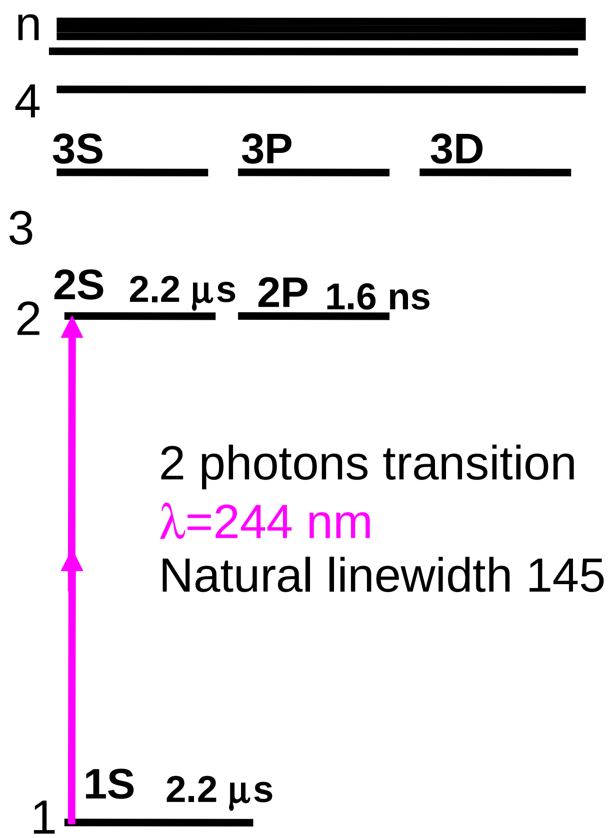
Enhancement cavity test setup



More than 1 kW circulating power before mirror degradation
-> Excitation rate=0.01*(Number of Ps in vacuum)

Status of Muonium 1S-2S

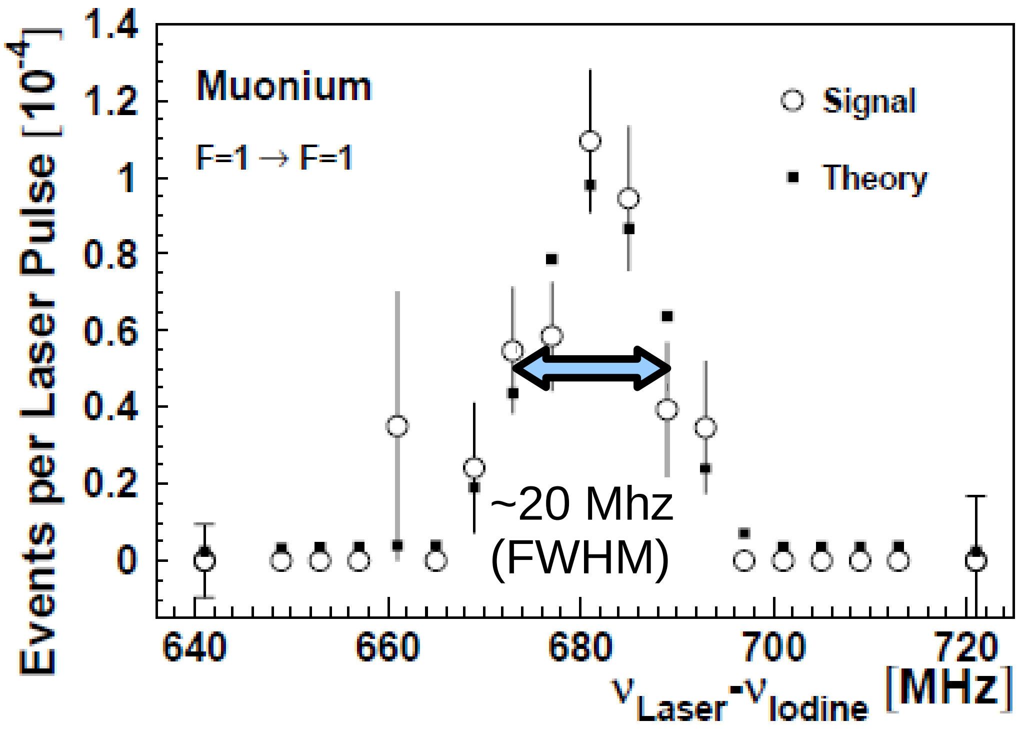
Mu Energy levels



2 photons transition

λ=244 nm

Natural linewidth 145 kHz



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

V. Meyer et al., Phys. Rev. Lett. 84, 1136 (2000).

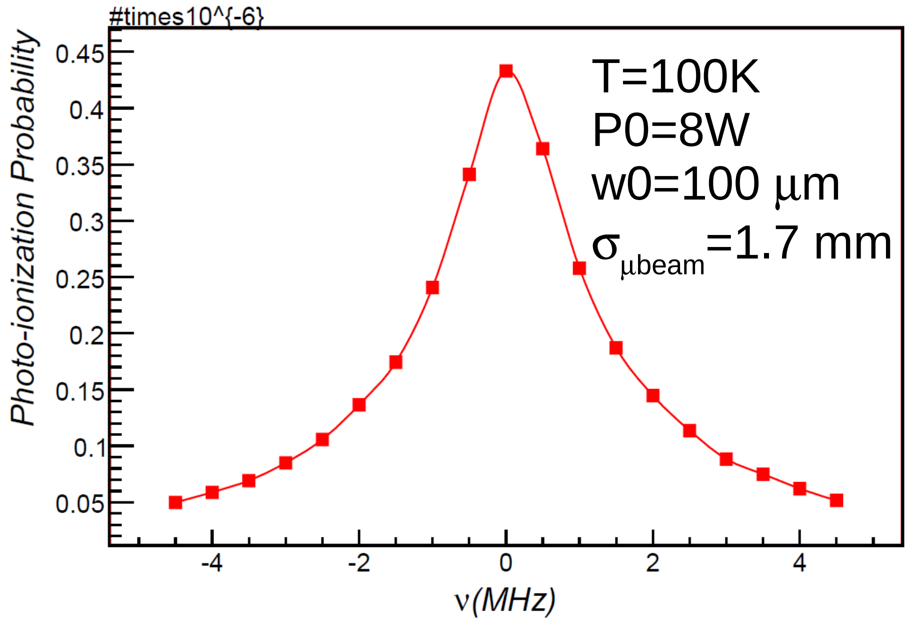
$$\Delta\nu_{1s2s}(\text{theory}) = 2\,455\,528\,935.4(1.4)\ \text{MHz}$$

J. R. Sapirstein and D. R. Yermie, in: QED,
T. Kinoshita (ed.), World Scientific, Singapore, p.560

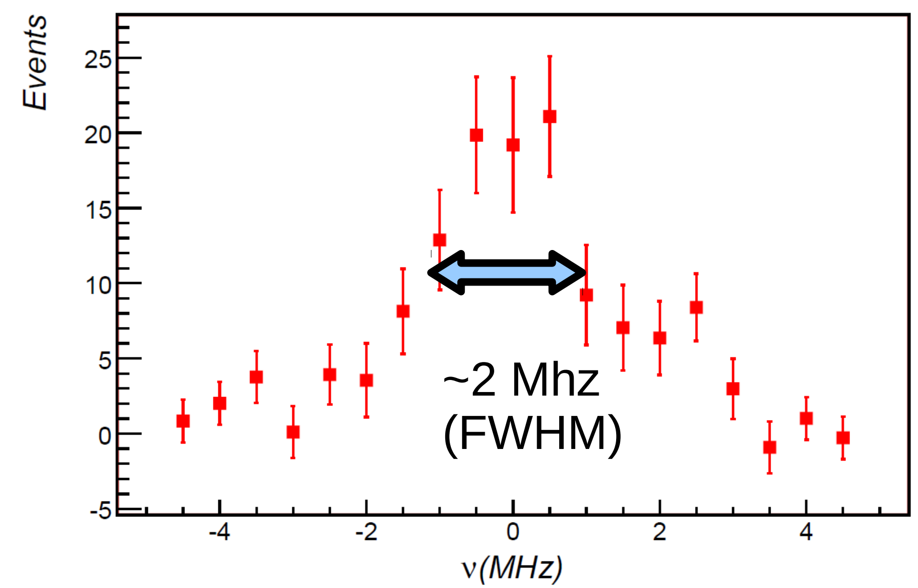
$$m_{\mu^+}/m_{e^-} = 206.768\,38(17)$$
$$q_{\mu^+}/q_{e^-} = -1 - 1.1(2.1)\cdot 10^{-9}$$

Expected signal rate and accuracy

Simulated lineshape



Expected resonance curve



With a similar setup as the existing LEM beam @PSI 4000 μ+ /s
-> On resonance 27 events/day expected and 2.5 background/events per day.
-> Such a measurement would take 2 weeks time

Measurement of 1S-2S of Mu at a level about 1×10^{-9} => check QED calculations and provide best determination of $m_{\mu+}/m_{e-}$ and $q_{\mu+}/q_{e-}$.

Summary & Outlook

Positronium

- The beam intensity has been increased by a factor of 20.
- The laser power necessary for the measurement has been produced.
- The stabilization of the laser to 1 kHz is in progress.
- Promising targets for Ps production at cryogenic temperature have been prepared and will be tested soon.
- Results expected for 2014.

Summary & Outlook

Positronium

- The beam intensity has been increased by a factor of 20.
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Muonium

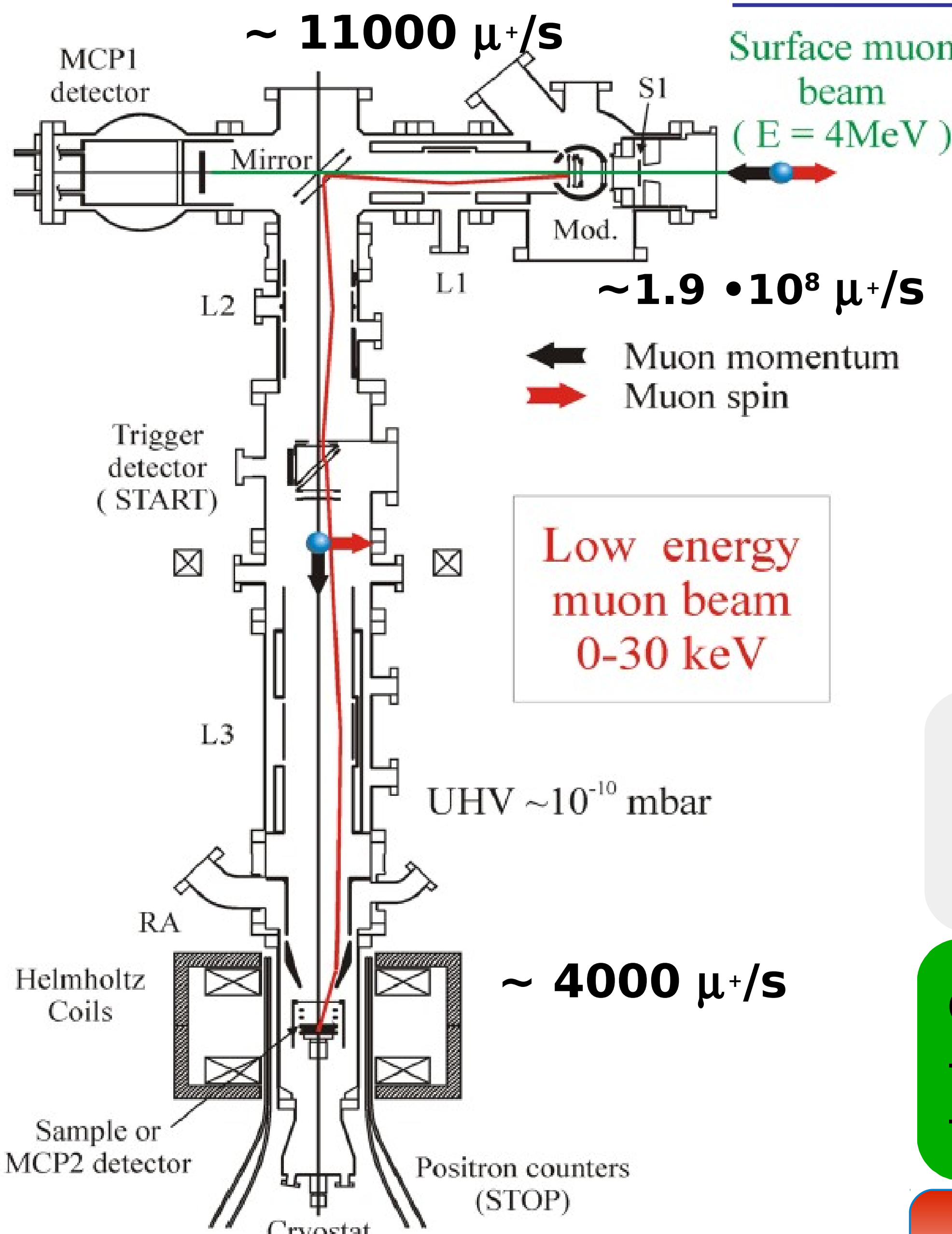
- Our results on Mu formation open the way to the first continous wave spectroscopy of the 1S-2S transition -> an improvement in the accuracy of a factor of 10 is possible (result limited by statistical uncertainty)
- We were granted 5 days beam time at the end of July 2012 at the LEM facility (PSI). Analysis of the data is in progress.
- The laser system is under development for the Ps experiment.

Thank you very much for your attention!

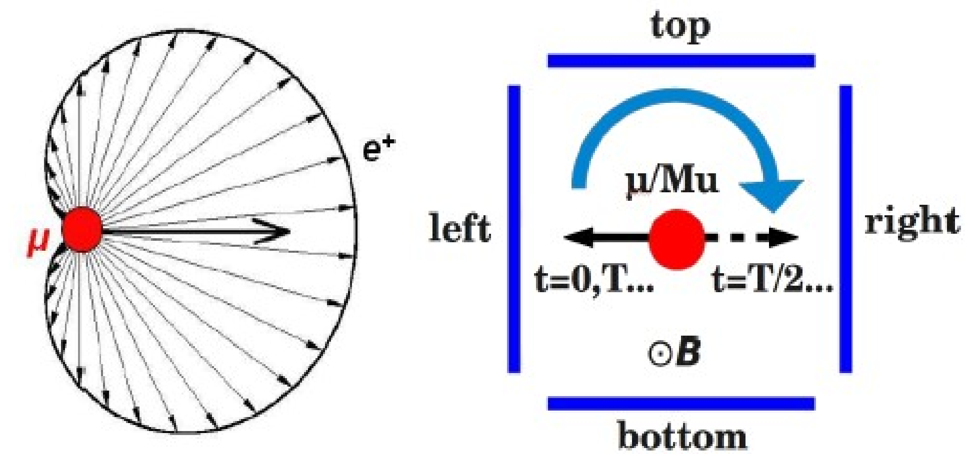
Backup slides

Low energy muon (LEM) beam @PSI

T. Prokscha, et al., NIM. A 595, 317 (2008)



Muon spin rotation technique (muSR)



(a) Angular distribution of decay positron

(b) Larmor precession

Larmor precession: $\omega_{Mu} = 103\ \omega_{\mu+}$

-> possible to distinguish if an implanted μ^+ remains unbound or forms Mu

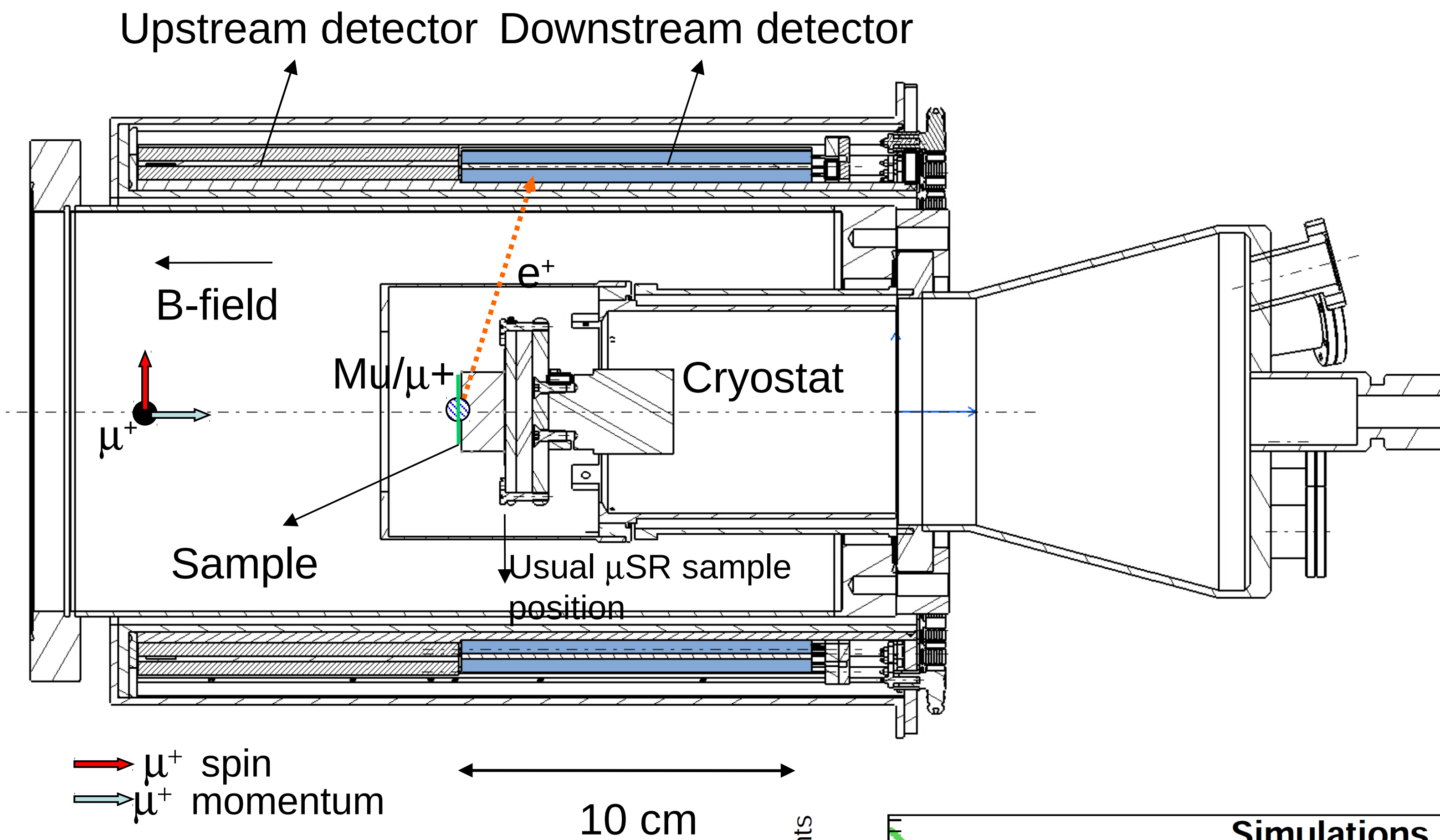
Our muSR results:

-> 60% of μ^+ converts to Mu

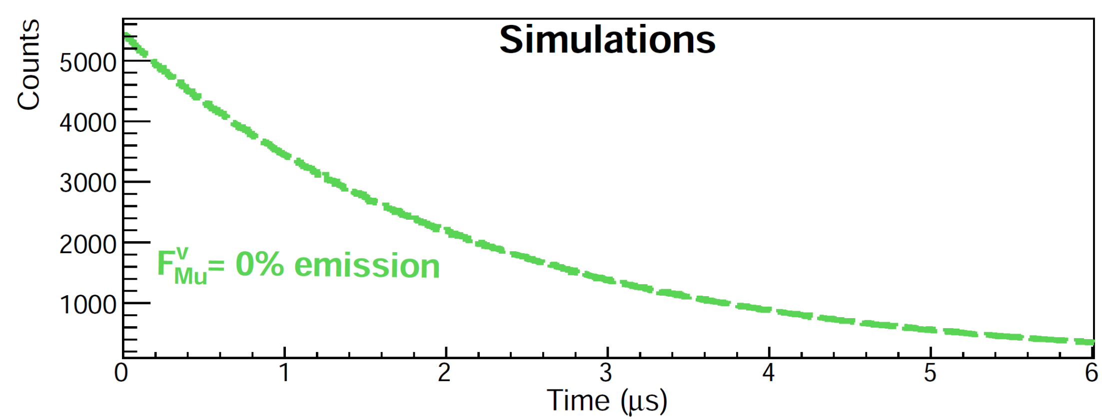
-> 25% of Mu retain their polarization

Fraction of Mu emitted into vacuum ?

Positron shielding technique (PST)



No emission in vacuum
Exponential decay distribution
From Mu and μ+ decays



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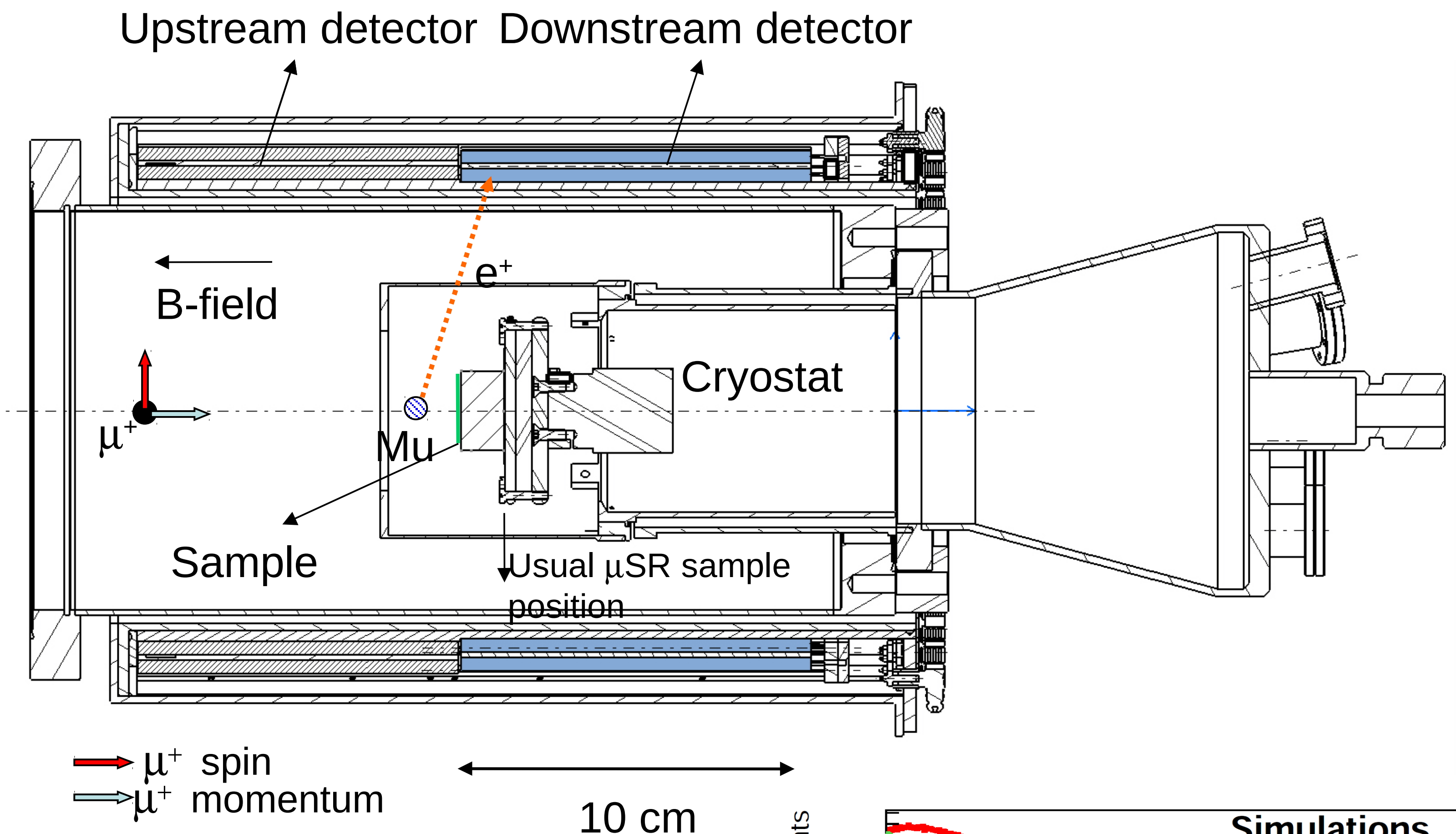
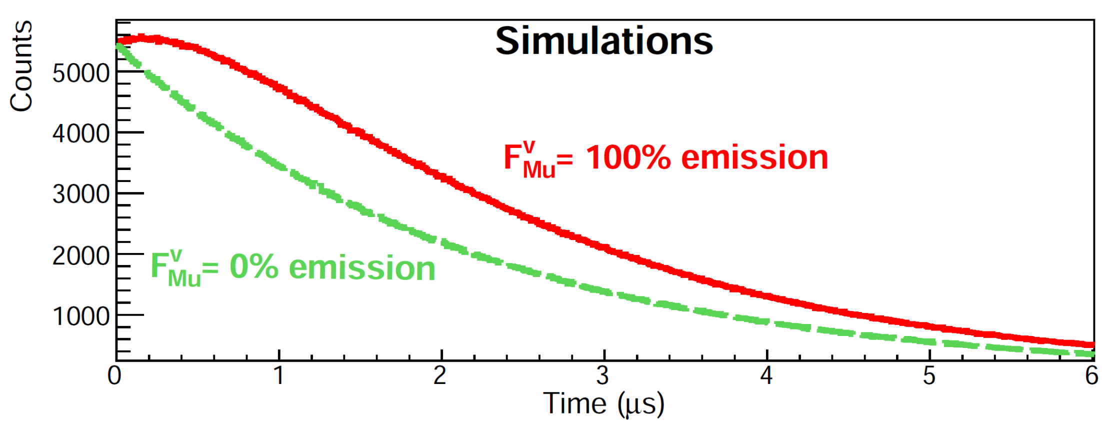
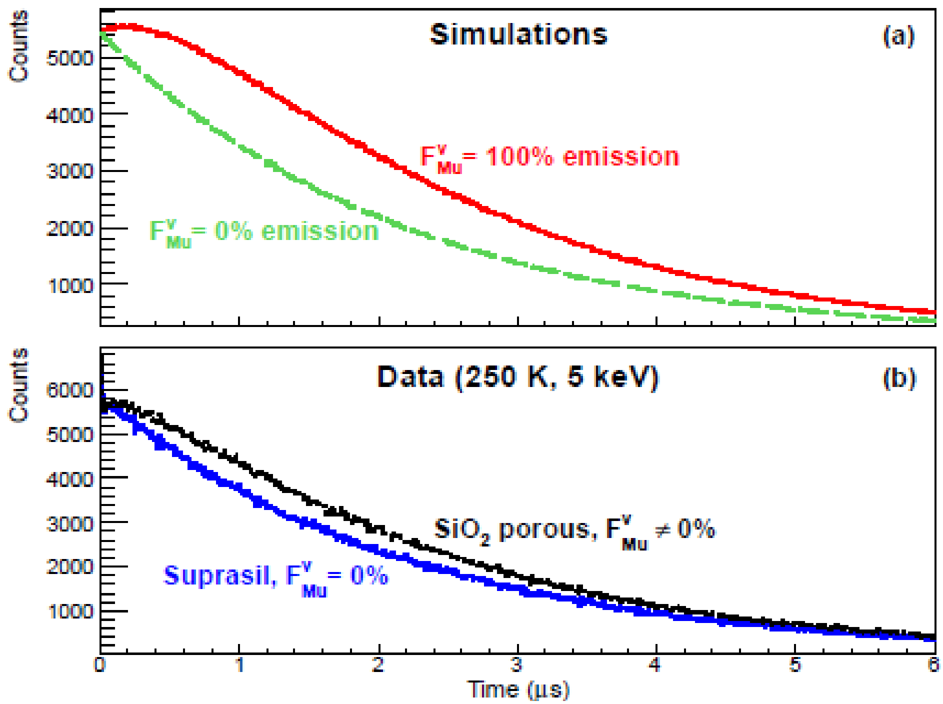
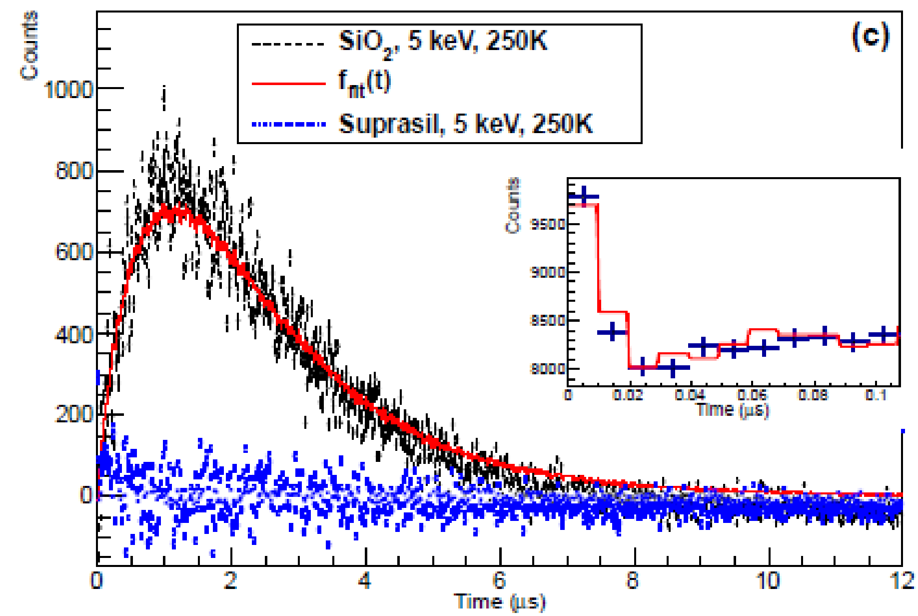


Mu emission in vacuum detection efficiency in downstream detector is time dependent -> deviation from exponential decay



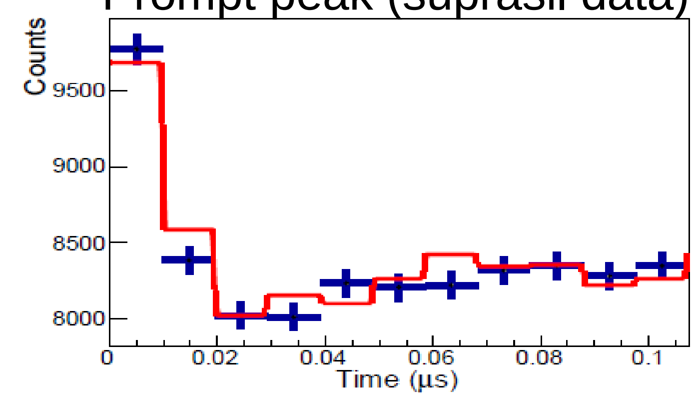
PST results





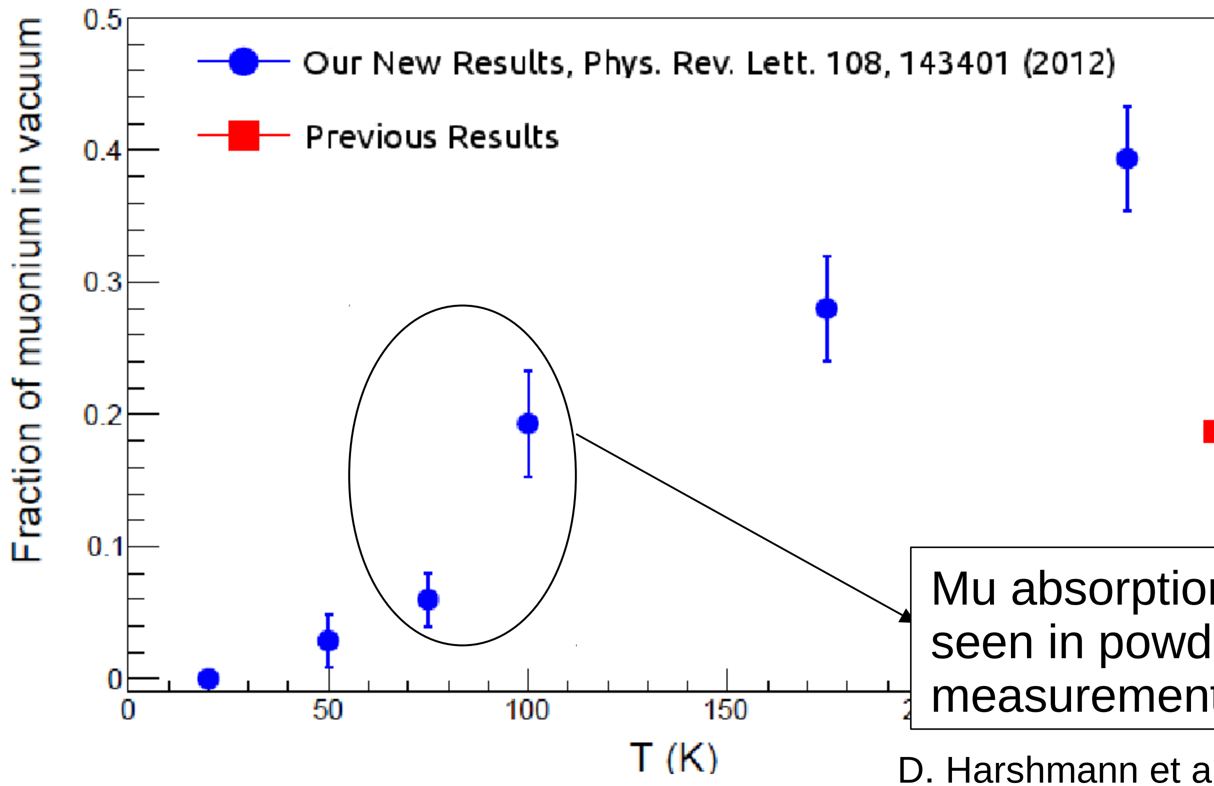
$$f_{\rm fit}(t) = n[(1 - F^{v}_{Mu}) f_0(t) + F^{v}_{Mu} f_{100}(t)] + n_{pp} f_{pp}(t)$$

Prompt peak (suprasil data)



$$\boxed{\text{Vacuum yield } F^{\rm v}_{\rm Mu}}$$

PST results



Mu absorption at the SiO2 walls as seen in powders via HFS measurements.

D. Harshmann et al. Phys. Lett. A104, 482 (1984)

Sizeable fraction of thermalized muonium emitted into vacuum from SiO_2 thin film at 5 keV implantation energy:

- At 250 K, the yield (38%) is more than a factor of two higher than previously found in SiO_2 powders at room temperature (RT).
- At 100 K, the yield (20%) is still as large as previously found at RT.

Expected accuracy

<u>With available source of Ps (30% @ 40 meV)</u>
1) Uncertainty from statistics 1.8 MHz -> 0.3 MHz.
-Better positron beam
-Higher detection efficiency based on the lifetime method
-Long term stability of the laser system
2) Systematic uncertainty 1.9 MHz -> 0.4 MHz.
- Main contribution of 1993 exp. unknown parameters in photoionization laser
→ proposed method free of this systematic.
- Main systematic 2nd order Dopplershift ~0.4 MHz
- No restriction of beam time (careful study the systematics)

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

Colder (100K) Ps → higher precision
(new porous films being prepared, CEA Saclay)

Hydrogen spectroscopy