Muonium Production in Porous Silica Thin Film

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Outline

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  Muonium, Motivation and Mu Production

- **Experimental Setup**

  μE4 beam and LEμSR spectrometer

- **Principles of the Experiment**

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- **Analysis and Preliminary Results**

  μSR Spectra, Fraction of μ and Mu, Forward-Backward Asymmetry

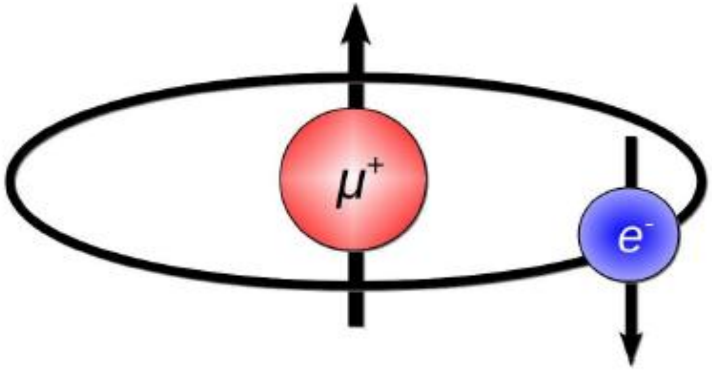
- **Conclusions and Outlook**

Muonium

INTRODUCTION

Muonium **(Mu)**

- Hydrogen-like atom consisting of μ^+ and e^-.
- 1/9 of Hydrogen mass, lifetime = 2.2 μs.
- Main decay channel : $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- Pure leptonic system governed by QED.



Motivation

Development of new sources for the next generation Mu experiments, with the following requirements:

- **High vacuum yield** ← This talk
- Small emission velocities (down to cryogenic temperature)
- Long term stability

An improved Mu source leads to:

- Better result for lepton flavor violation experiment
- More precise test of bound state QED (proton radius puzzle)
- More precise extraction of fundamental constants (m_μ, α)

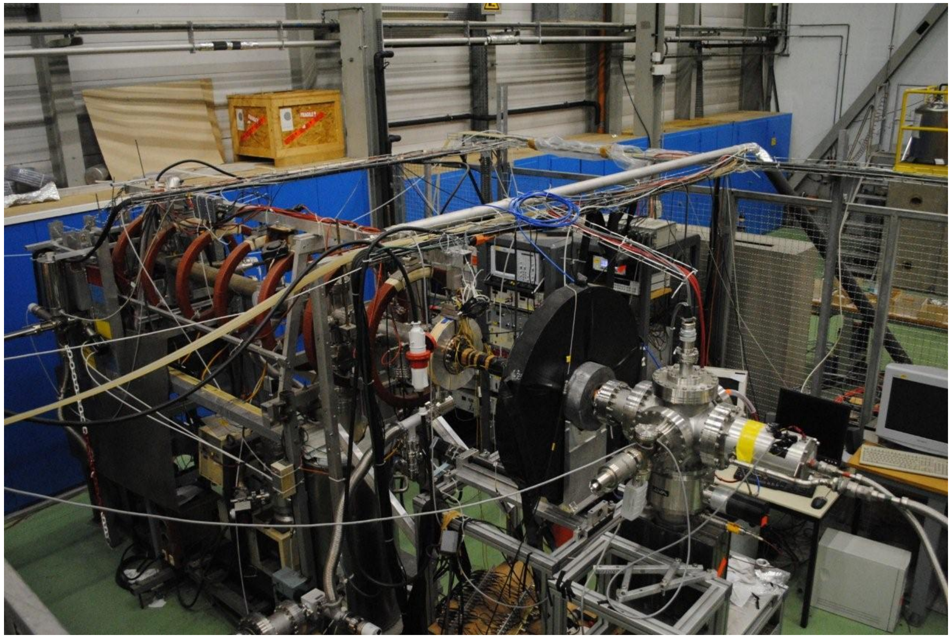
Silica Porous Material

Mu and Positronium (Ps) have similar formation mechanisms and yields in vacuum:

Source	Ps (e^+e^-)	Mu (μ^+e^-)
Silica Powder	**10%**	**10%**
Silica Porous Material	**30-40%**	**30-40% (?)**

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

Based on this analogy, we thought that Silica Porous material could produce Mu more efficiently. (preselected using the ETHZ slow positron beam)



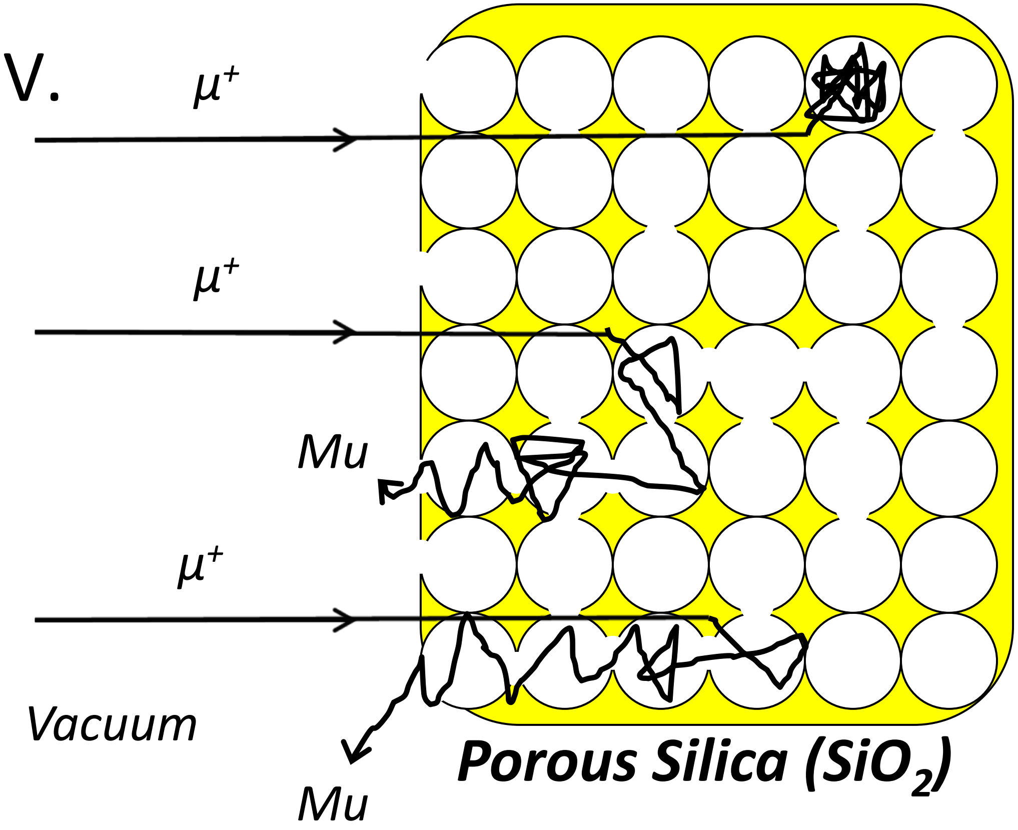
ETHZ Slow Positron Beam
(Will be moved from CERN to ETHZ)

Muonium Production

- μ^+ with 2-30 keV of energy is implanted into the sample.
- μ^+ slows down and stops in the porous bulk material.
- Mu is formed in the porous bulk material.
- Mu drifts to the pore's wall and is ejected into the pore with energy of a few eV.
- Mu diffuses and is thermalized in the pores.
- Mu can reach the surface and exit into vacuum.

Fraction of Mu that comes out per implanted μ^+ = F_{Mu}^{vac}

Pore size = 4 nm

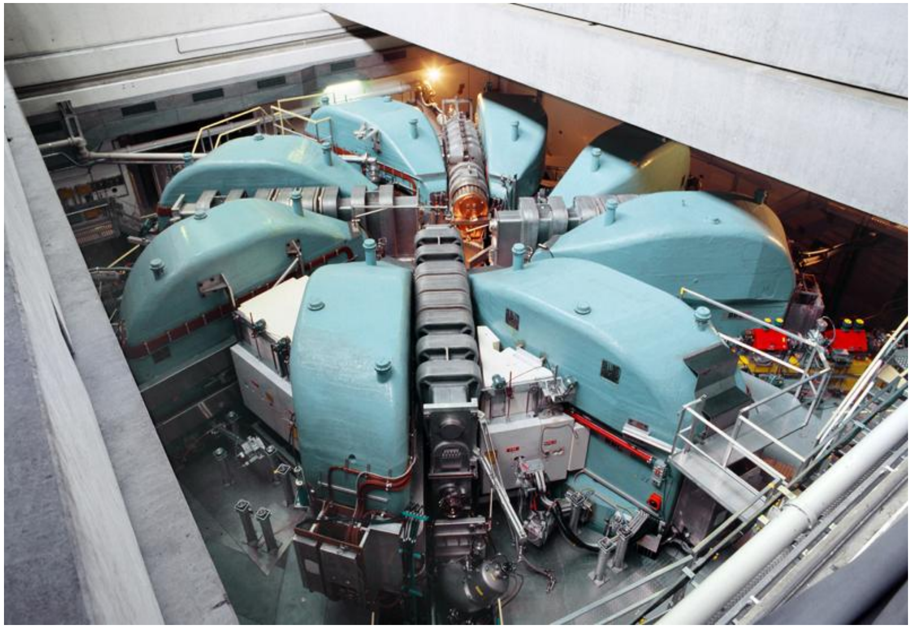


Porous Silica (SiO_2)

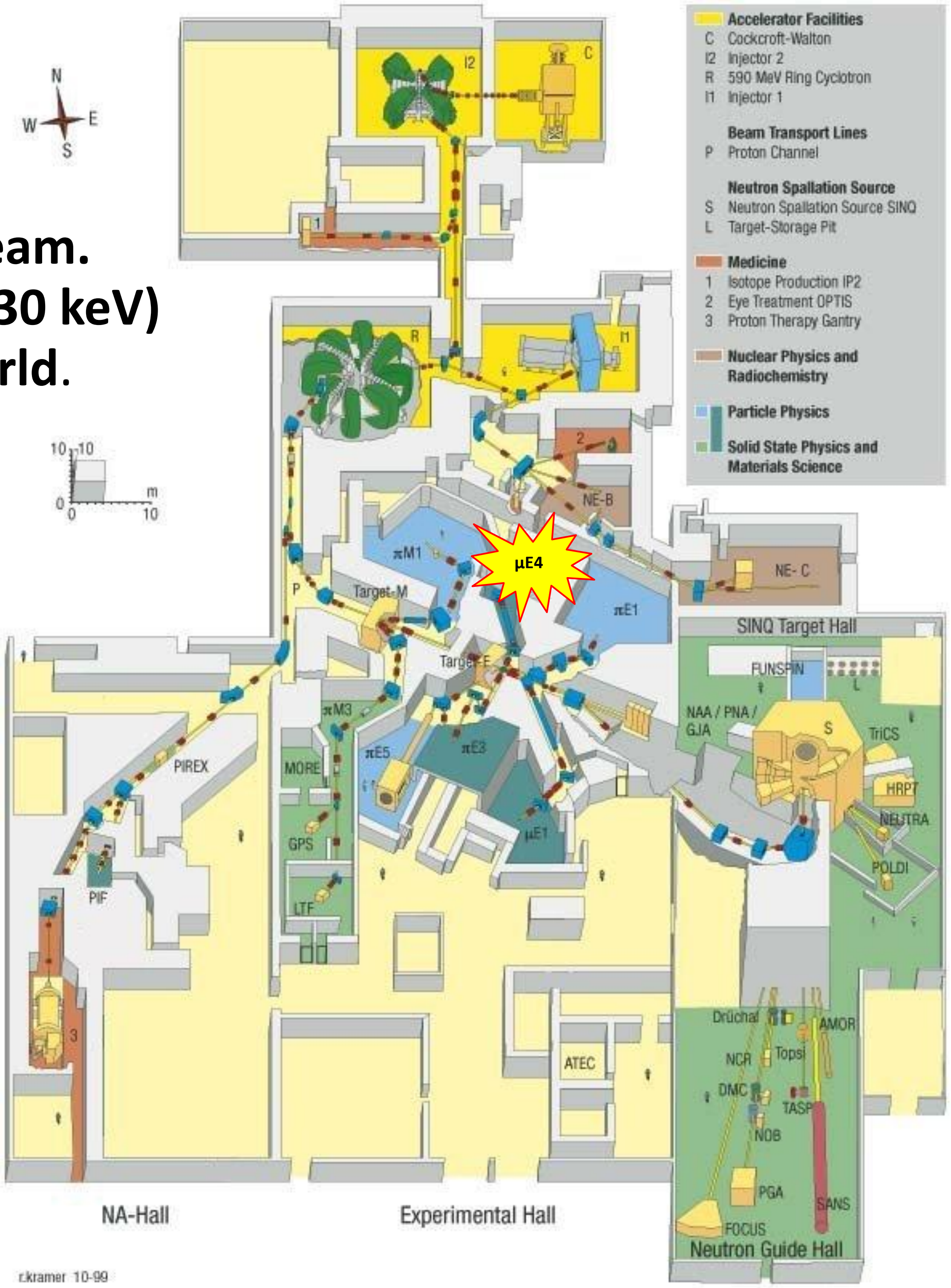
μE4 beam and LEμSR spectrometer

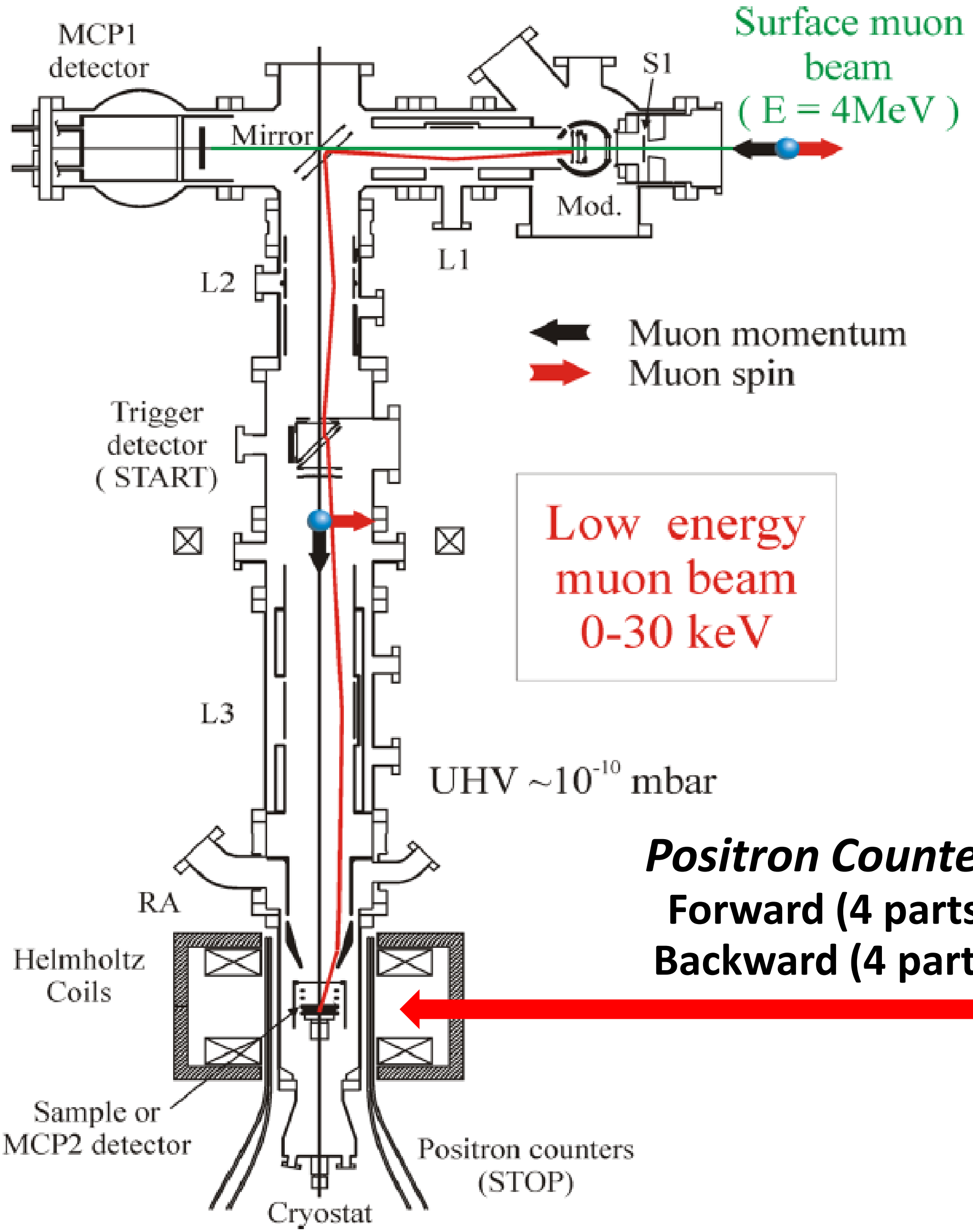
EXPERIMENTAL SETUP

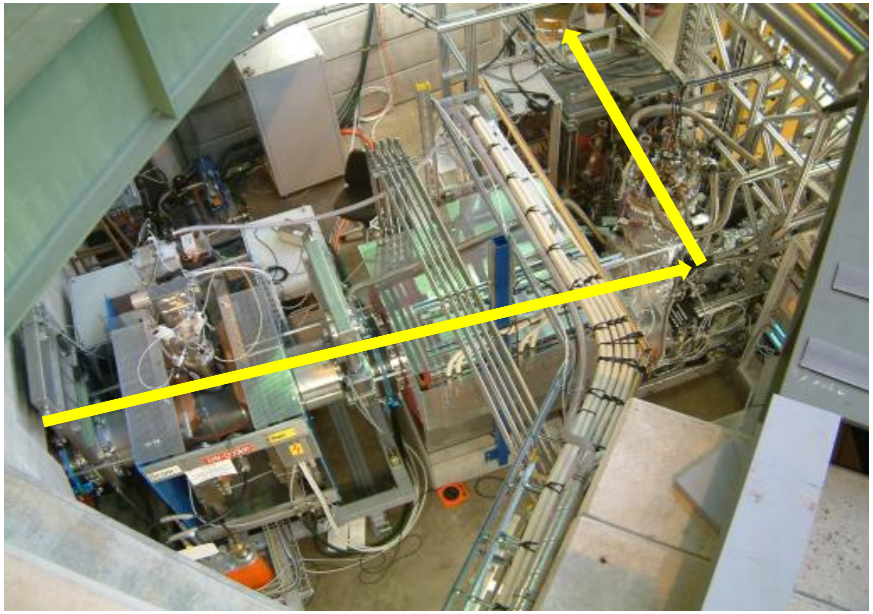
- Experiment was done at **Paul Scherrer Institute (PSI)** using **μE4 beam.**
- It is the **low energy muon beam (0-30 keV)** with the **highest intensity in the world**. (3000 s^{-1} on the sample)



PSI Proton Accelerator



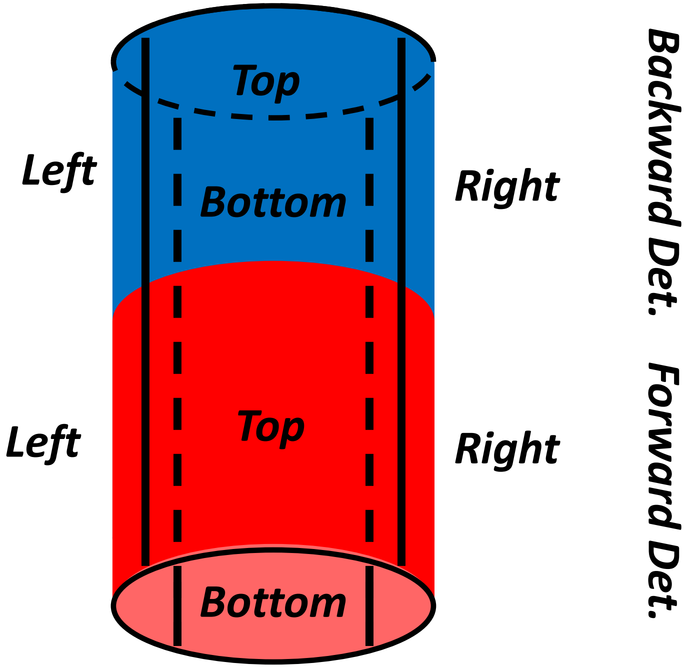




Positron Counters

Forward (4 parts)

Backward (4 parts)



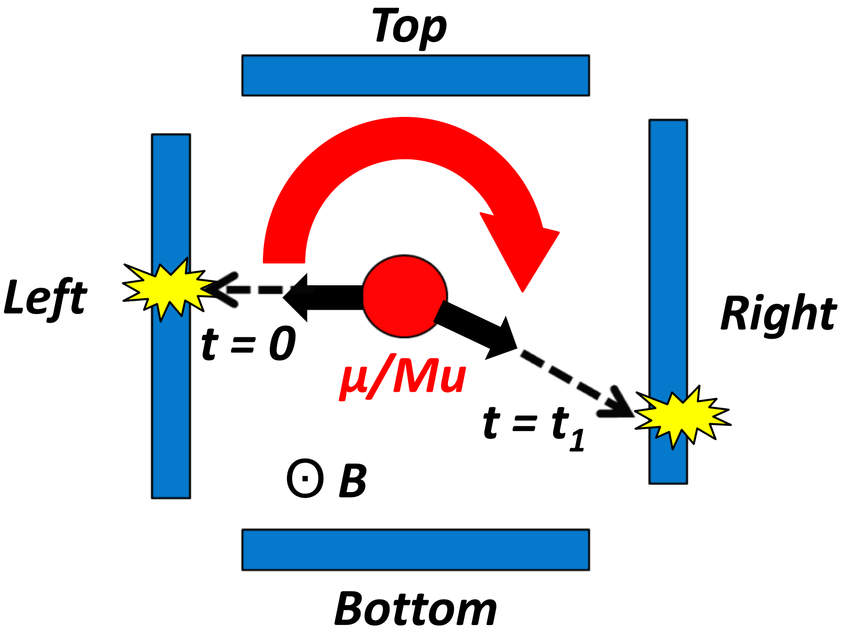
LEμSR spectrometer

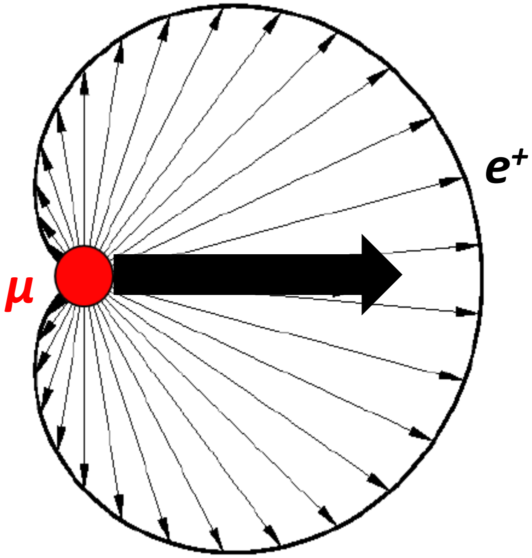
μSR Technique

PRINCIPLES OF THE EXPERIMENT

μSR = *Muon Spin Rotation*

- Monitor the evolution of **μ** spin after implantation, under external magnetic field. (Larmor precession frequency, $\omega = \gamma B$, γ is gyromagnetic ratio, **γ_μ = 13.6 kHz/G** and **γ_{Mu} = 1.40 MHz/G →** $\omega_{\mathrm{Mu}} = 103\ \omega_\mu$ for same B)
- Decay positron emitted preferentially in the direction of muon spin, due to the parity violation of weak interaction.

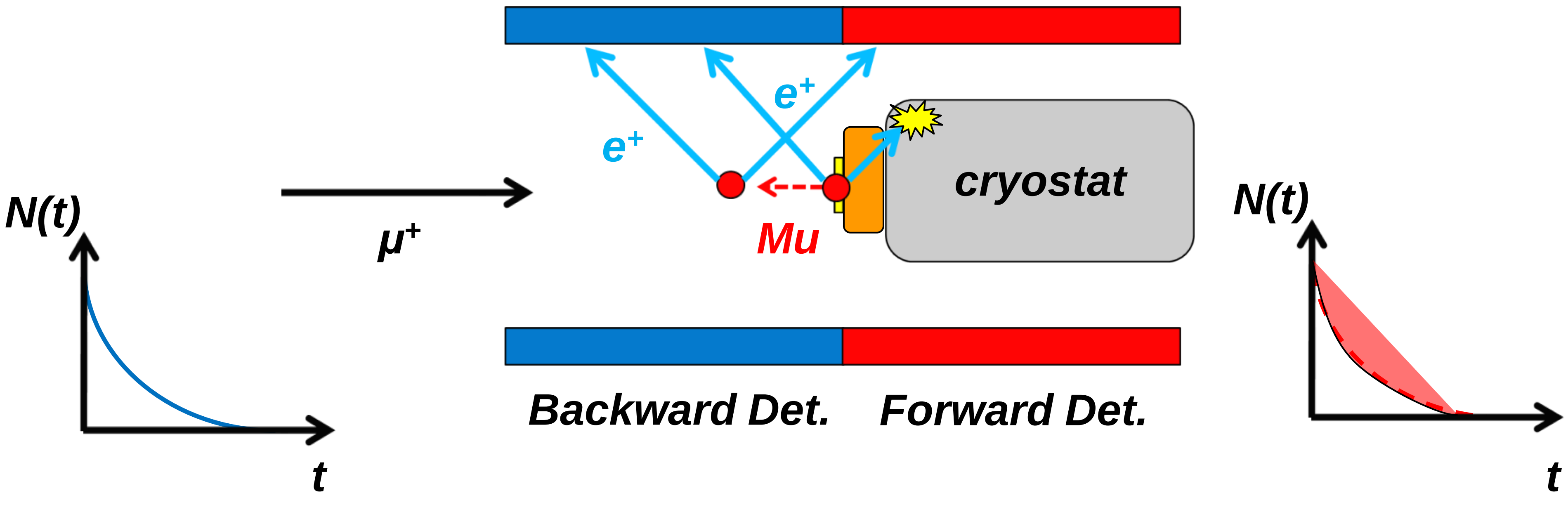




Angular distribution of decay positron

Positron Shielding Technique (PST)

- μ/Mu that decays inside the Porous Silica will have its positron shielded by the material behind the sample.
- In case of zero emission into vacuum, exponential time distributions are expected for both detectors.
- In case of emission into vacuum, there is a deviation from exponential distribution for forward detector. (Position dependent of detection efficiency)



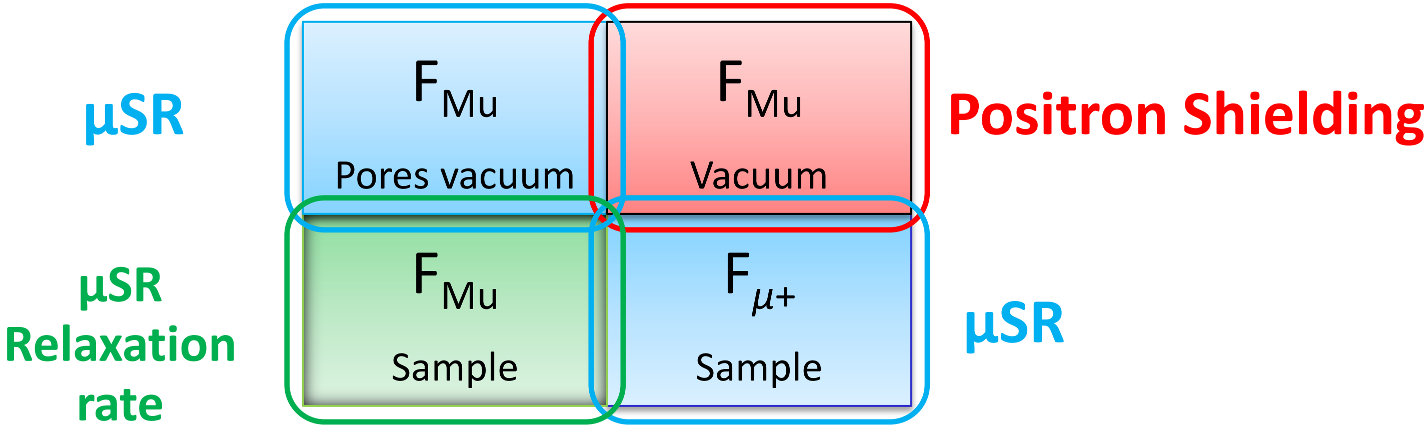
Summary of the techniques

From µSR Technique, we can extract

- the residual fraction of µ that do not convert to Mu.
- the fraction of Mu which do not depolarize.
- the depolarization rates of µ and Mu in the samples.

From Positron Shielding Technique, we can extract

- the fraction of Mu emitted into vacuum.



µSR

F_{Mu} Pores vacuum

F_{Mu} Vacuum

Positron Shielding

µSR Relaxation rate

F_{Mu} Sample

$F_{\mu+}$ Sample

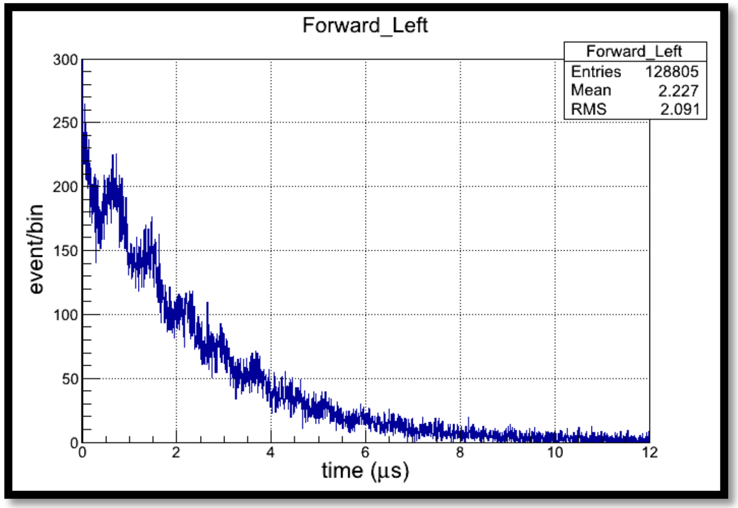
µSR

We can then cross check the consistency of the data.

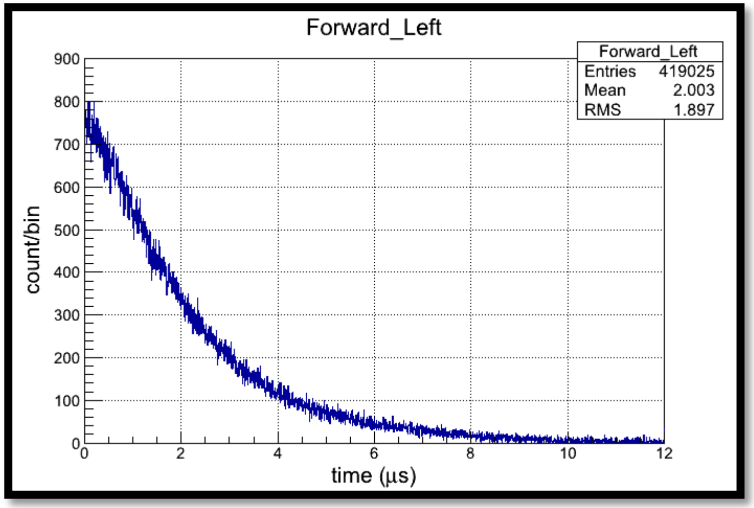
μSR Spectra
ANALYSIS

T = 250 K, B = 100 G

T = 250 K, B = 6 G



← Time Spectra →



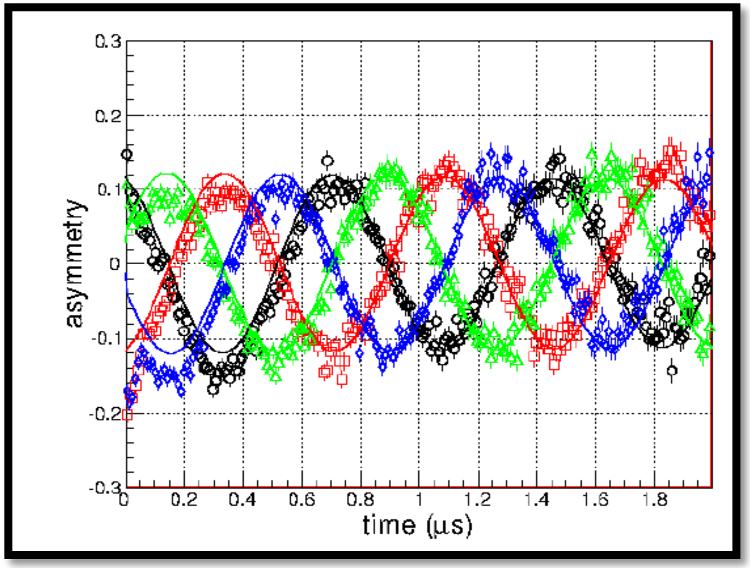
↘ Fit with ↙

$$N(t) = N_0 e^{-t/\tau_\mu}\{1 + A_\mu(t) + A_{Mu}(t)\}$$

$$A_\mu(t) = A_\mu e^{-\lambda_\mu t}\cos(\omega_\mu t - \varphi_\mu)$$

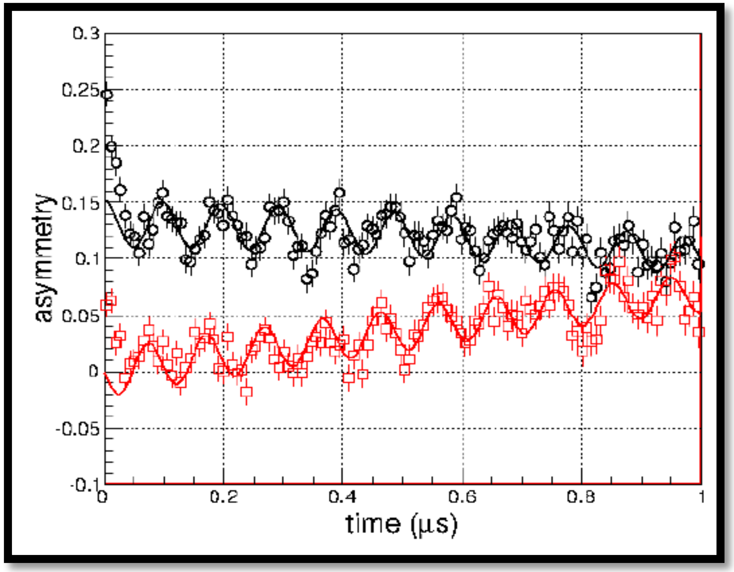
$$A_{Mu}(t) = A_{Mu} e^{-\lambda_{Mu} t}\cos(\omega_{Mu} t - \varphi_{Mu})$$

A: Amplitude
τ : Lifetime
λ: Relaxation Rate
ω: Precession Frequency
φ: Phase



← $A_\mu(t)$

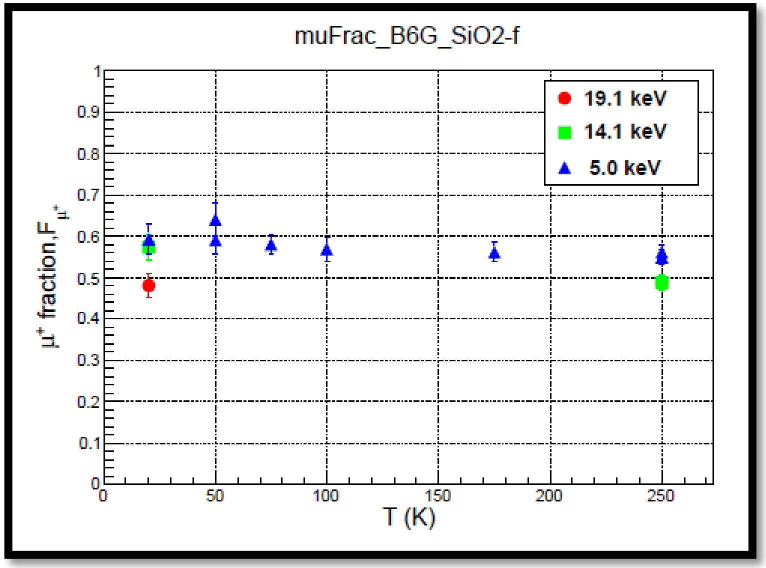
$A_{Mu}(t)$ →

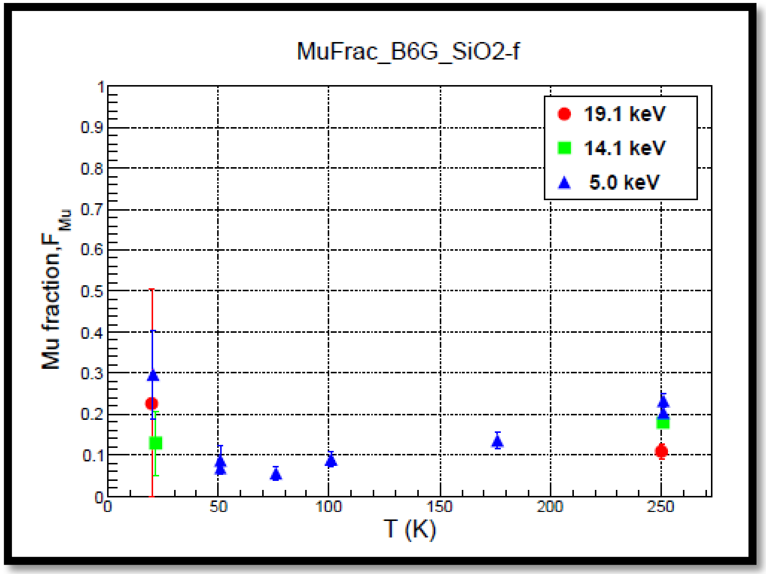


Fraction of μ and Mu

Fraction of μ and Mu ($F_{\mu+}$, F_{Mu}) are given by the fitted amplitudes. The total amplitude, A_{tot} = 0.27 was measured from the reference sample of Silica Suprasil. $A_{tot} = A_{\mu^+} + 2A_{Mu}$ (singlet and M_s=0 triplet do not contribute)

$$F_{\mu^+} = \frac{A_{\mu^+}}{A_{tot}} \qquad F_{Mu} = \frac{2A_{Mu}}{A_{tot}}$$

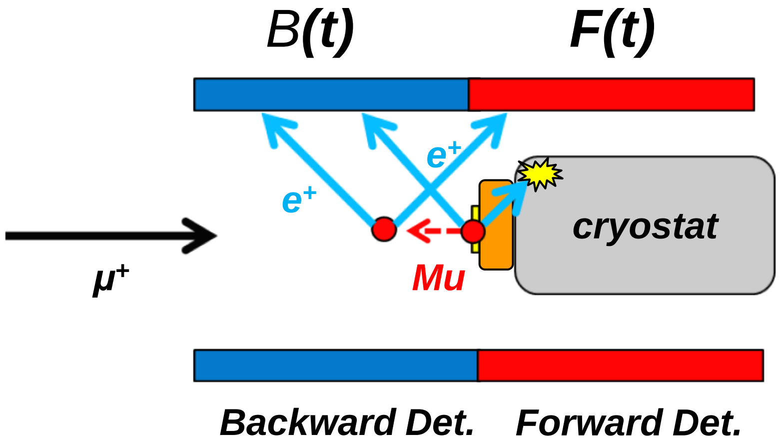




Mu formation fraction = 1 - $F_{\mu+}$ = 45% and temperature independent.

(Notice that $F_{\mu+}+F_{Mu}\neq 1$! This is due to the fast depolarization of Mu due to spin exchange collisions.)

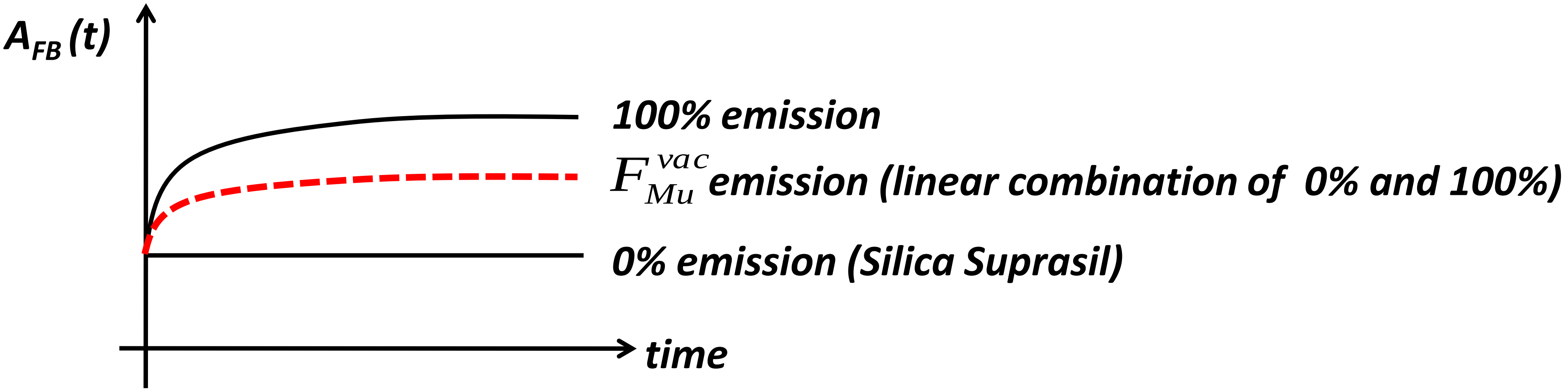
Forward-Backward Asymmetry (A_{FB})



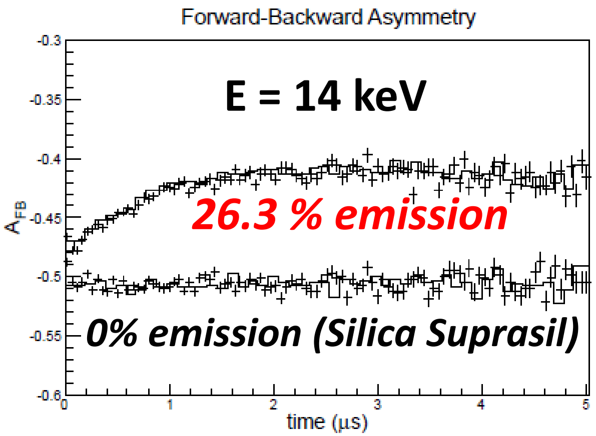
$$A_{FB}(t) = \frac{F(t) - B(t)}{F(t) + B(t)}$$

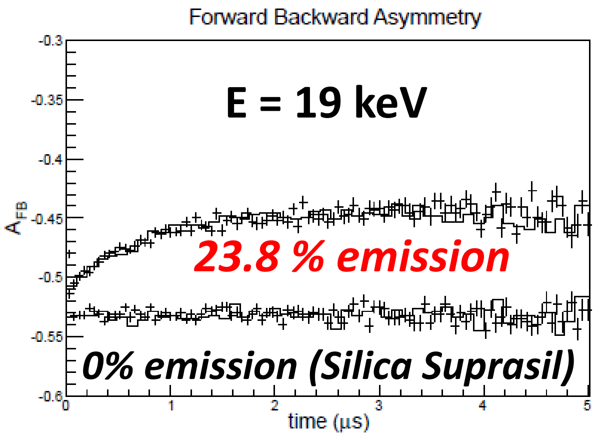
In case of 0% Mu emission,
A_{FB} (t) = constant
For non-zero Mu emission,
A_{FB} (t) ≠ constant

- With the help of GEANT4, we simulated the cases of 0% and 100% Mu vacuum emission at different temperatures. 0% is corresponding to Silica Suprasil sample where no emission into vacuum is expected.
- By introducing a free parameter which is the fraction of Mu emitted into vacuum, we fitted the data according to the temperatures.



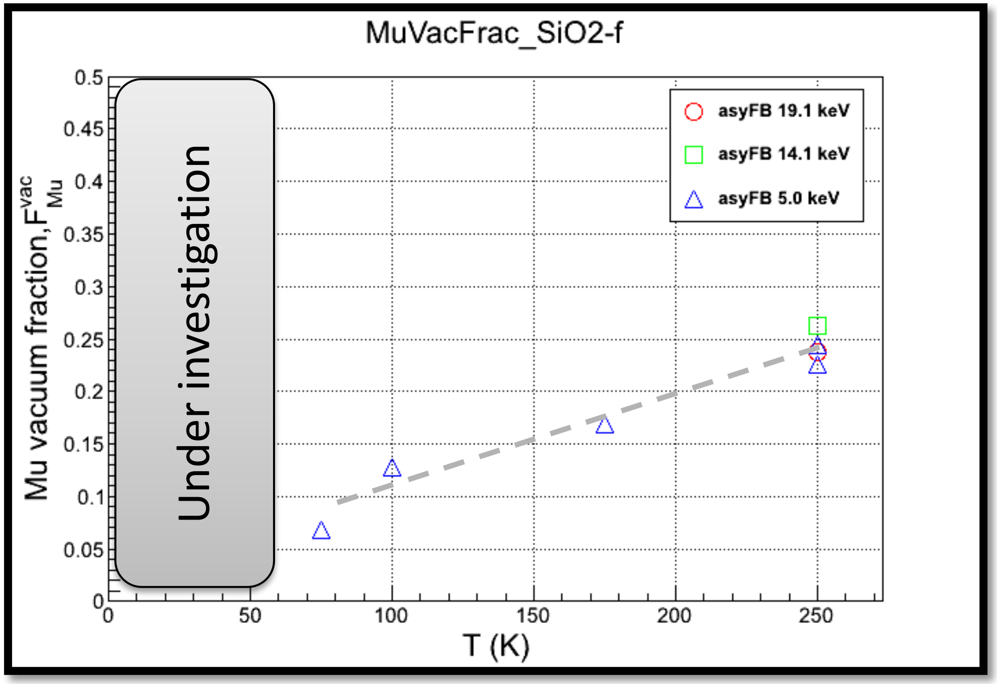
Extraction of Mu Vacuum Emission





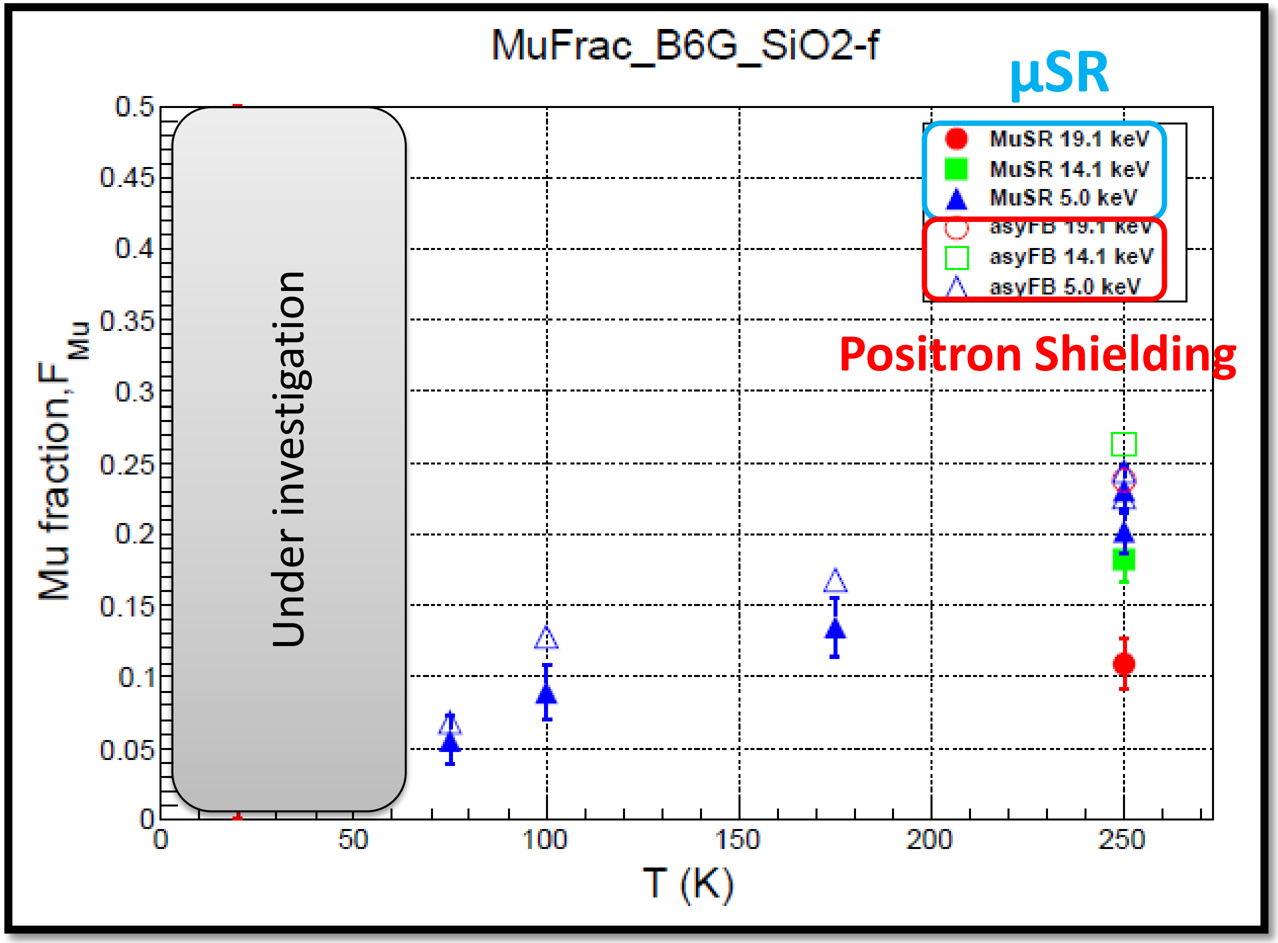
+ Data (T = 250 K)
-- Simulation (T = 250 K)

The shapes are well reproduced by the simulations.



Results from Positron Shielding Technique. No systematic errors are included at the moment. Mu vacuum emission is proportional to the temperature.

Preliminary Results



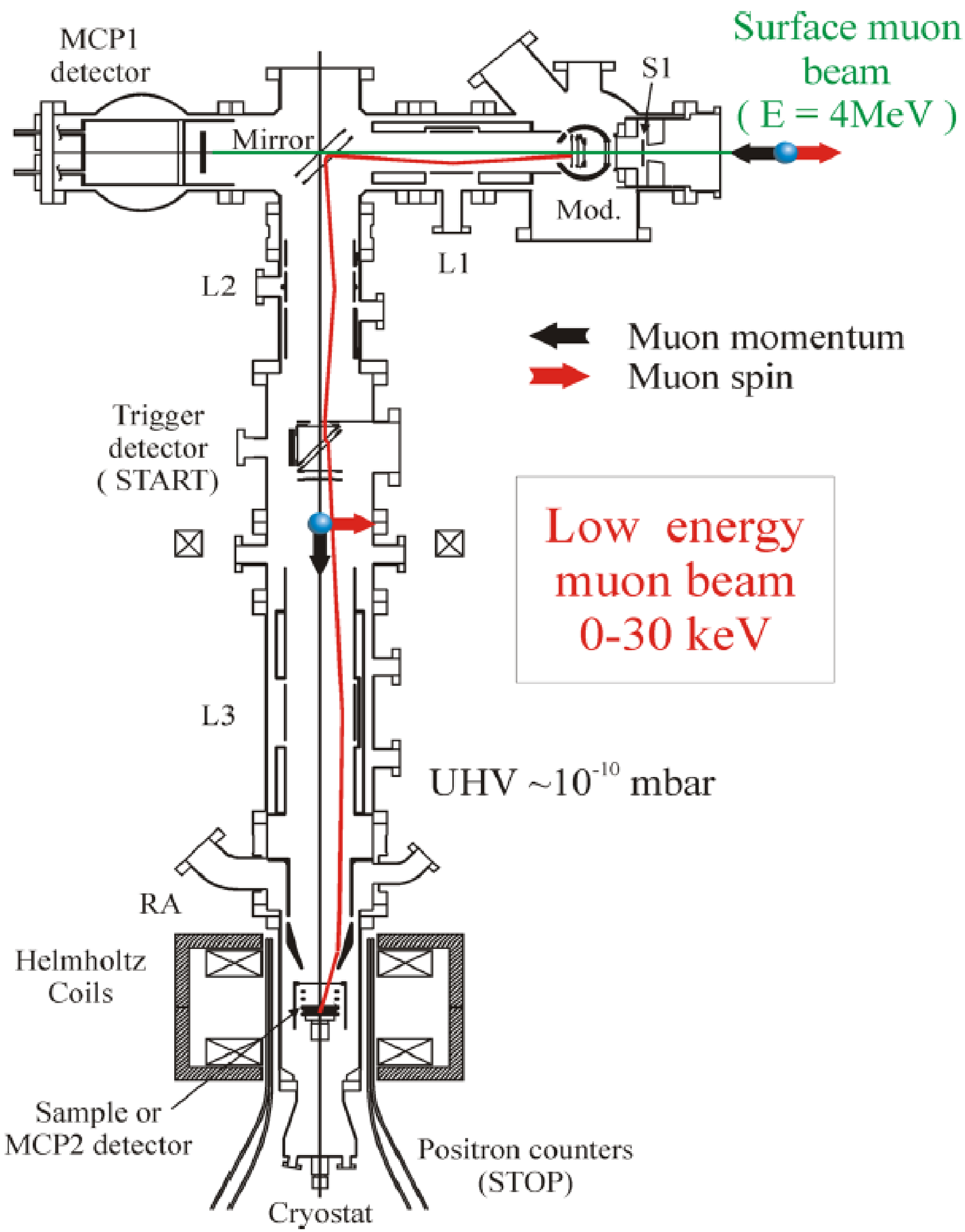
Comparison of results from μSR and positron shielding techniques.

Notice that **values from PST are always higher compared to μSR Technique**. This is due to the emission of depolarized Mu into vacuum that could not be extracted using μSR technique. Also, **higher implantation energy leads to higher fraction of depolarized Mu**.

Conclusions and Outlook

- Mu formation in Silica Porous Material is 45% per implanted μ^+, independent on temperature.
- Mu emission in vacuum is as high as 25% per implanted μ^+, at 250 K. (a factor of 2 better than other sources.)
- First measurement of Mu emission in vacuum at low temperature. (10% even at 100 K)
- Temperature dependent of Mu vacuum emission is under investigation → study of diffusion.

Backup



Transport system

Entrance scintillator (S1)

▼

Moderator (Mod)

▼

Einzel lens (L1, LN2 cooled)

▼

Electrostatic mirror

▼

Einzel lens (L2), Multi Channel Plate detector (MCP1)

▼

Trigger detector (Start)

▼

Einzel lens (L3, LN2 cooled)

▼

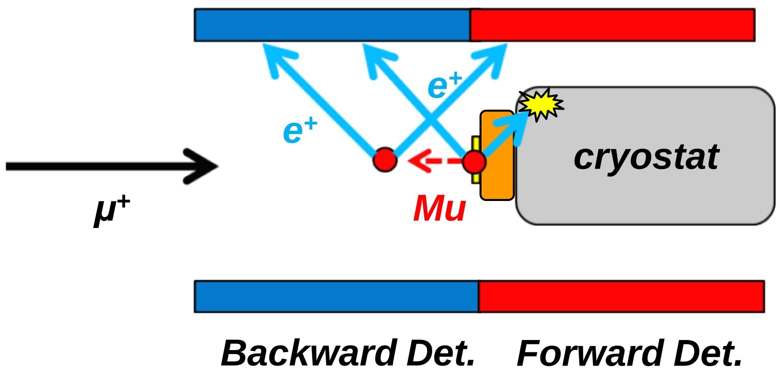
Ring anode (RA)

▼

Sample, Multi Channel Plate detector (MCP2)

▼

Positron counters (Stop)



If both spectra are exponential decay, i.e. in case of 0% Mu emission,

$F(t) = F_0 \exp(-t/\tau_\mu)$, $B(t) = B_0 \exp(-t/\tau_\mu)$

$A_{FB} = (F_0 - B_0)/(F_0 + B_0) = constant$

For non-zero Mu emission,

$F(t) = F_0 \exp(-t/\tau_\mu) + e(t)$,

$A_{FB} \rightarrow A_{FB}(t) \neq constant$