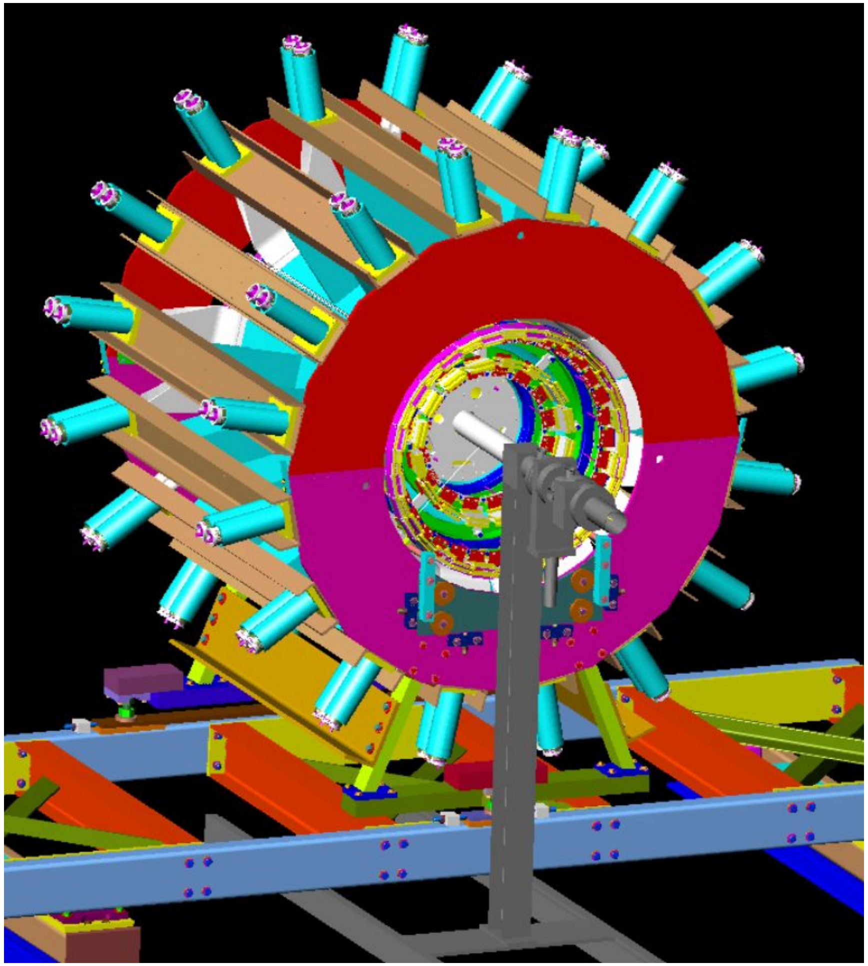
Analysis of Systematic Errors in the MuCap Experiment



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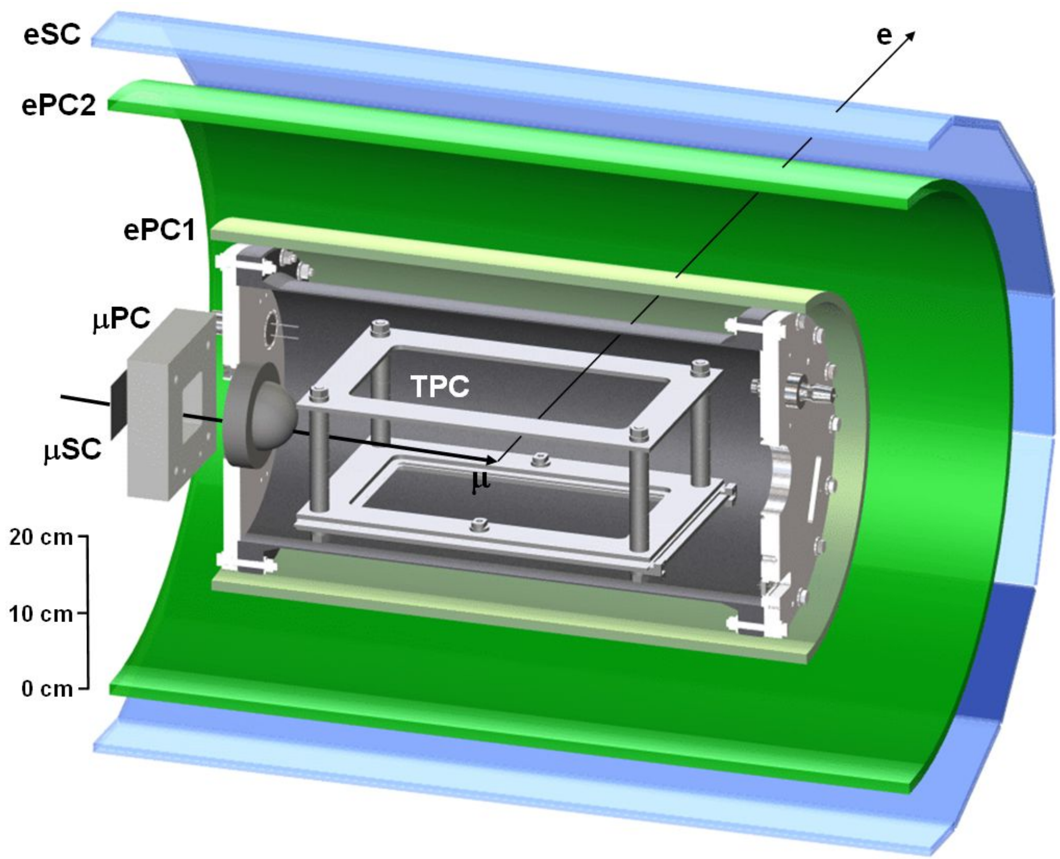
Experiment basics

We seek to measure the rate of ordinary muon capture by the proton,

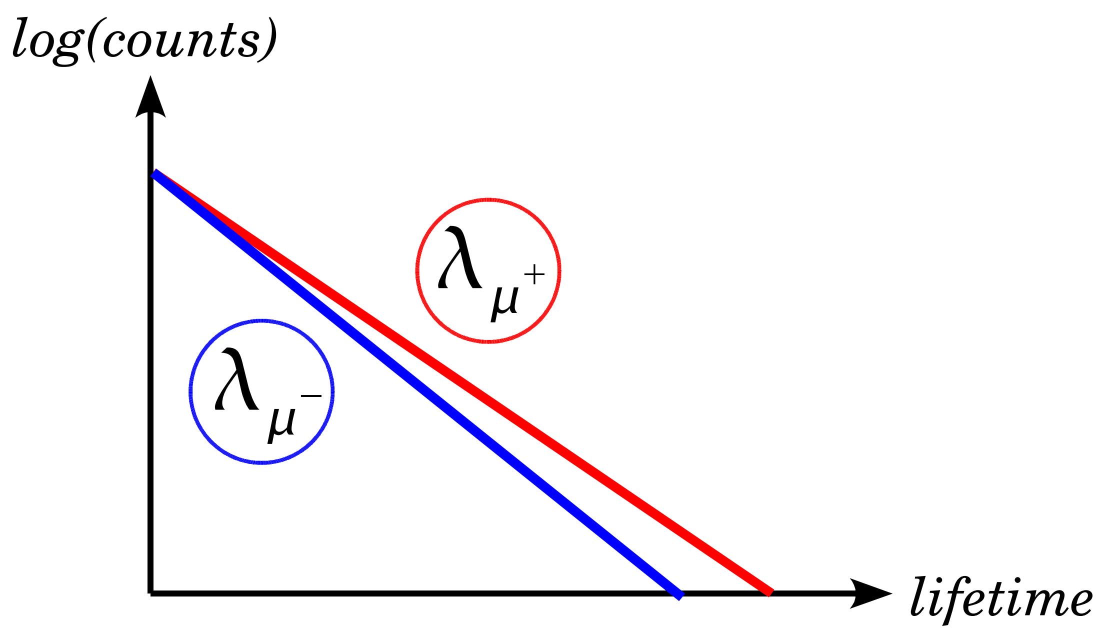
$$\mu^- + p \rightarrow n + \nu ,$$

by stopping negative muons in hydrogen gas and observing the time spectrum of decay electrons.



Experimental method

Negative muons can disappear via decay or capture, so they disappear at a faster rate than positive muons:



The capture rate can be obtained from the small (0.15%) difference between the two disappearance rates,

$$\Lambda_{capture} = \lambda_{\mu^-} - \lambda_{\mu^+} \ .$$

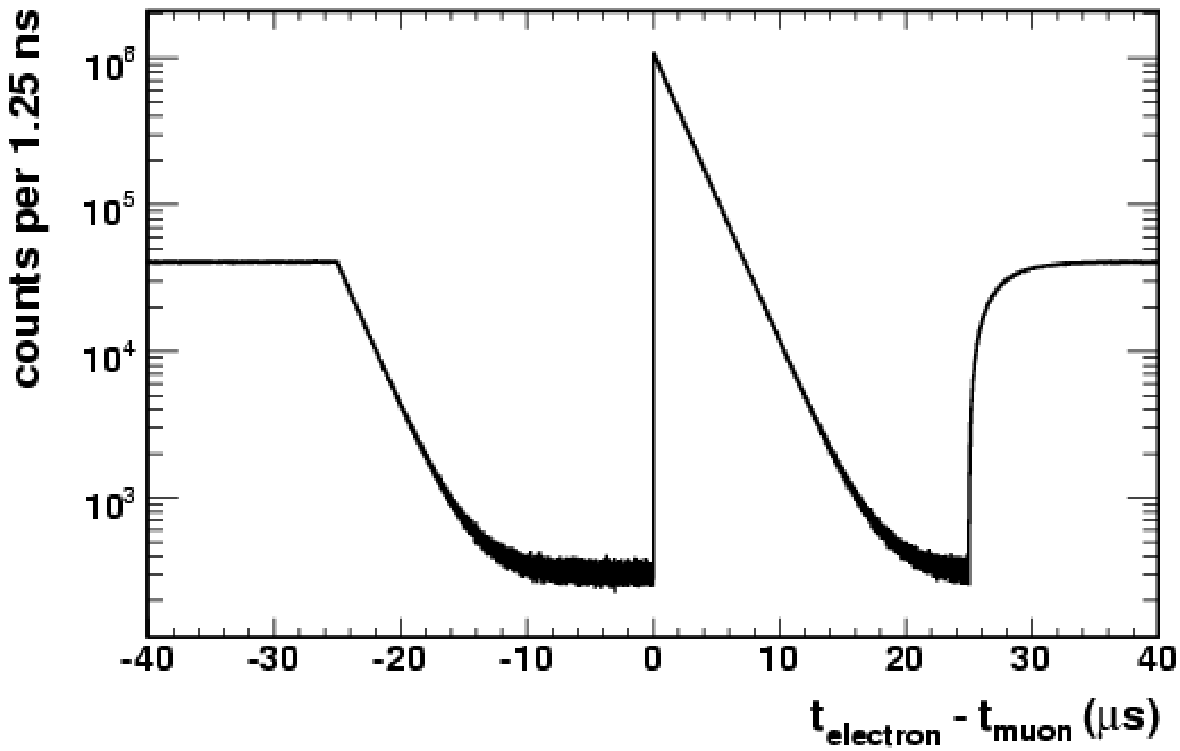
Motivation

In our hydrogen gas target of density 1% compared to LH_2, most muon captures proceed from the hyperfine singlet ground state of the μp atom:

$$\Lambda_{capture} \approx \Lambda_S \, .$$

A 1% measurement of Λ_S would determine the nucleon's weak induced pseudoscalar coupling, g_P, to 7%. The pseudoscalar coupling has long been the least well known of the nucleon's form factors.

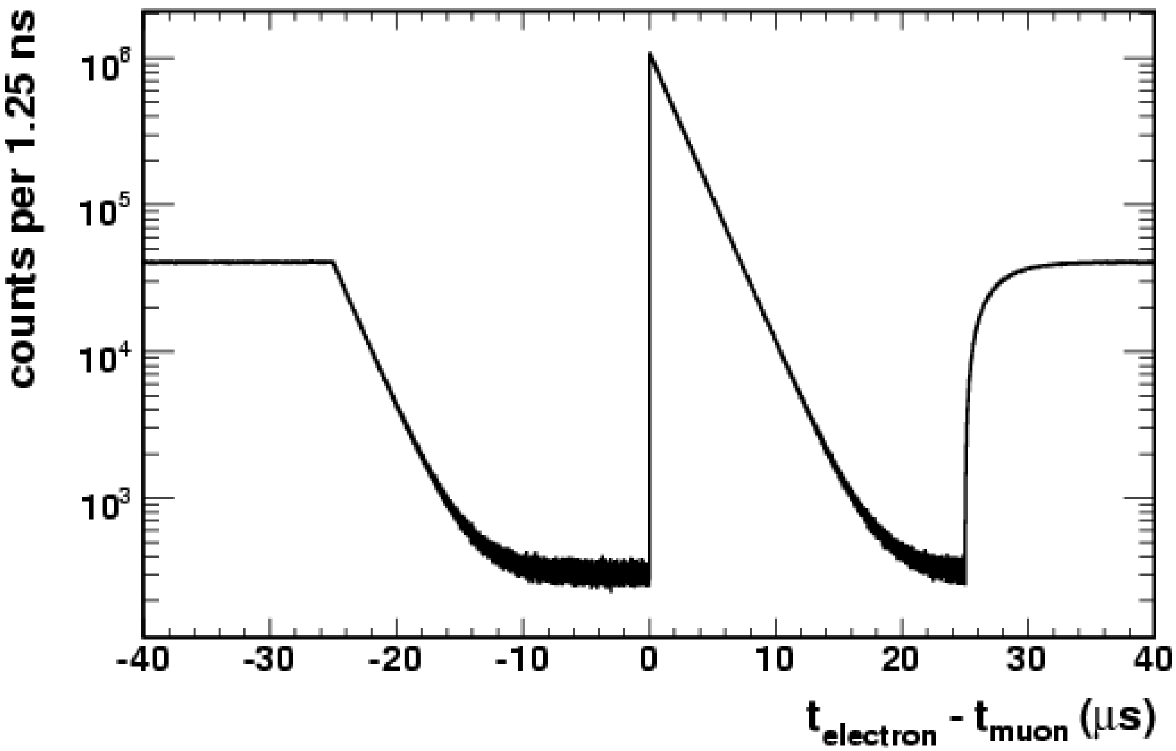
2004 data set



We recorded $\approx 1.6 \times 10^9$ μ^- decay events during our first physics run in 2004. The muon disappearance rate is obtained by fitting the measured decay time spectrum with a simple exponential function of the form

$$f(t) = Ne^{-\lambda t} + B.$$

2004 data set

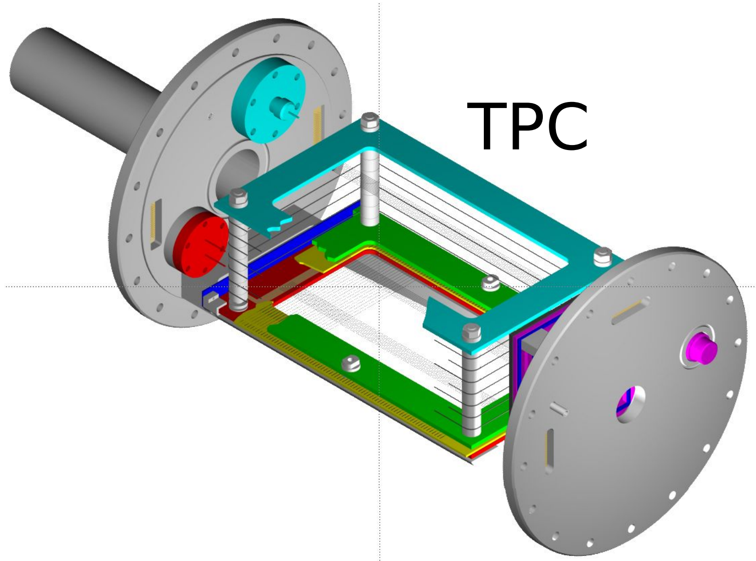


$$\lambda = 455\ 886.6 \pm 12.6\ s^{-1}$$

However, in reality the lifetime spectrum is not a pure exponential, and the fitted muon disappearance rate $\lambda \neq \left(\lambda_{\mu^+} + \Lambda_S \right)$!

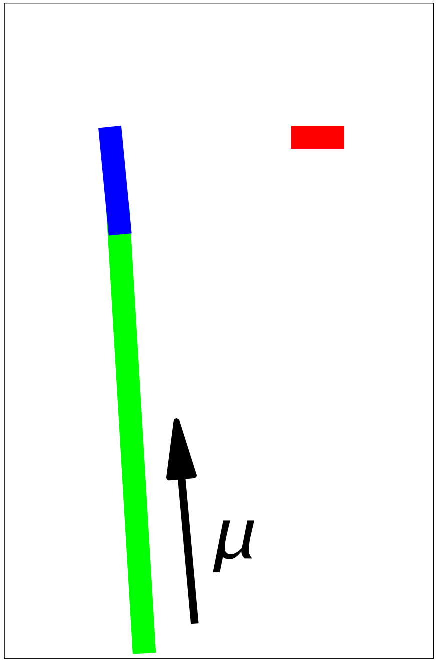
Captures in elements $Z > 1$: gas impurities

Muons will transfer to elemental impurities in the hydrogen gas, and the capture rate scales as Z^4.



The TPC provides a means to monitor captures by these gas impurities.

TPC capture signature



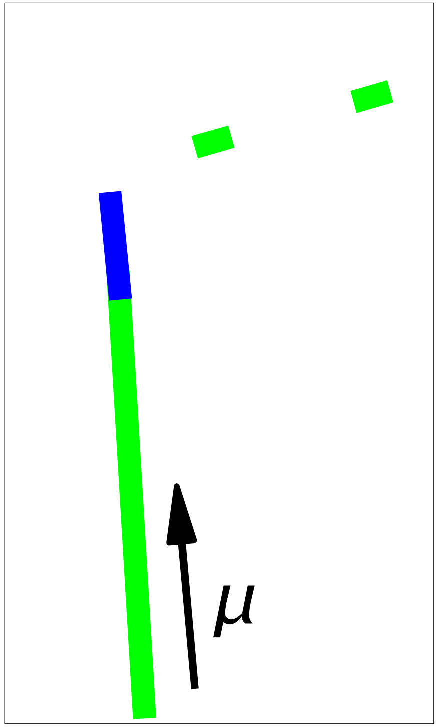
The observable is the capture yield Y, the number of captures per good muon stop. The effect on the muon lifetime is proportional to Y, and the exact proportionality for contaminants N,O is established by calibration measurements. The correction is:

$$\Delta\lambda_Z = -19.2 \pm 5.0\ s^{-1}$$

Captures in elements $Z > 1$: muon scatter events

Sometimes a muon will appear to have stopped in the TPC, but actually scattered out of the fiducial volume. Such events are dangerous, because the scattered muon can stop in surrounding detector materials.

TPC scatter signature



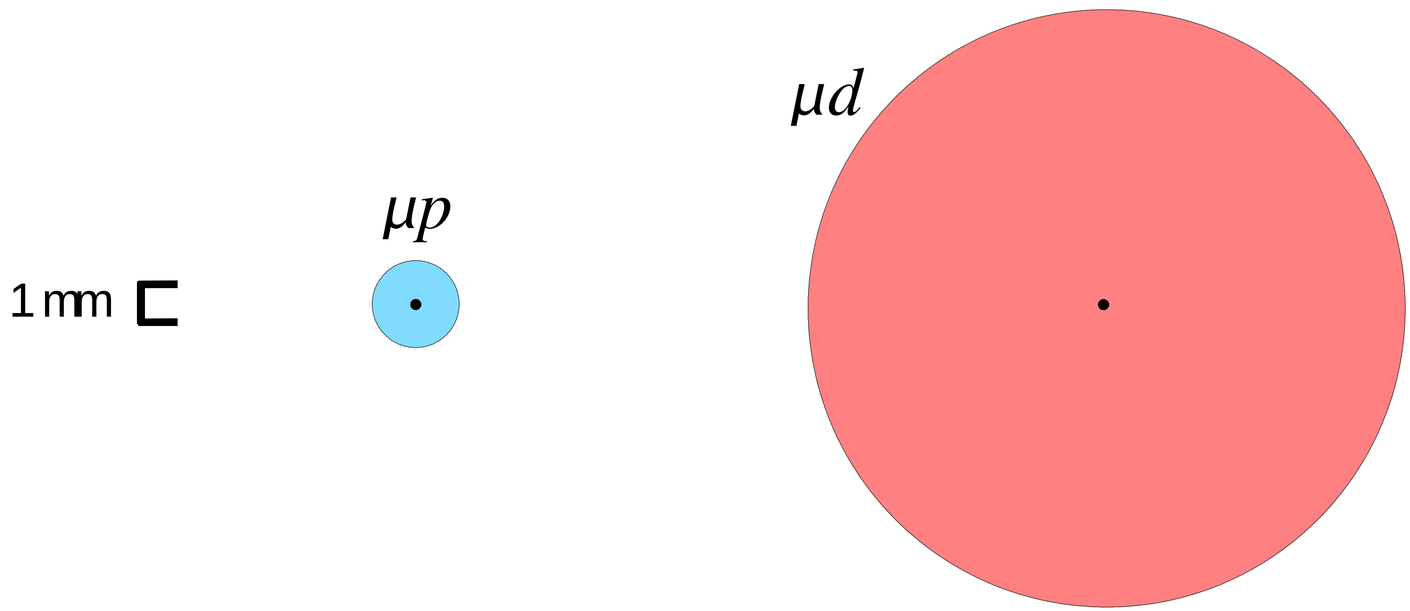
We can catch some of these events, but the signature is not always robust.

Consequently, we must rely on simulations to estimate our identification efficiency. We remove the scatters we find, and conservatively assume ~50% inefficiency. The correction is:

$$\Delta\lambda_{scatter} = -3.1 \pm 3.0\ s^{-1}$$

Diffusion effects: deuterium impurities

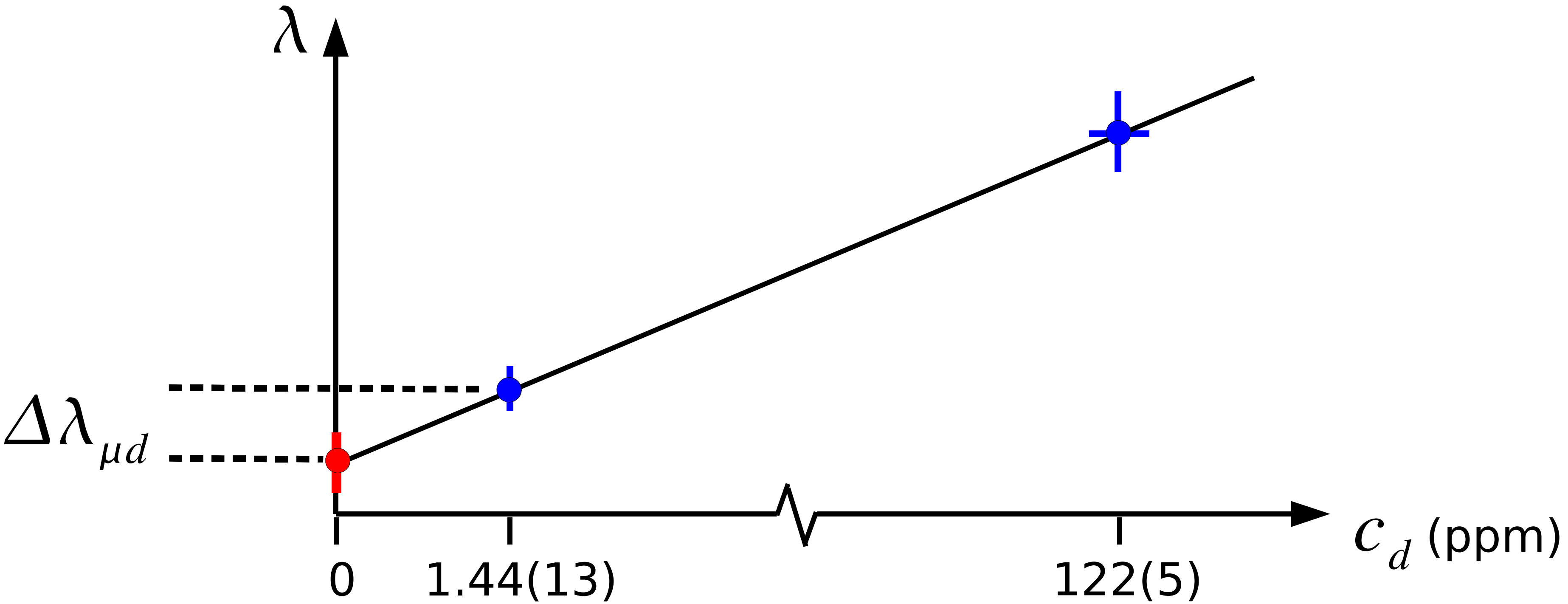
Muons preferentially transfer from $\mu p \rightarrow \mu d$, and the hydrogen gas is more "transparent" to μd atoms, so they diffuse more rapidly:



As a result, muons can (1) diffuse out of the decay vertex reconstruction radius, or (2) diffuse into surrounding detector materials. Both processes increase the effective muon disappearance rate.

Diffusion effects: deuterium impurities

To correct for the effects of μd diffusion, we perform a zero-extrapolation:



$$\Delta\lambda_{\mu d} = -10.2 \pm 1.6\ s^{-1}$$

Diffusion effects: protons

Although μp diffusion distances are small (~ 1mm), the scattering of decay electrons by the pressure vessel magnifies the behavior. By combining the electron scattering distribution with a simple isotropic diffusion model, we calculate:

$$\Delta \lambda_{\mu p} = -2.7 \pm 0.5 \ s^{-1}$$

Molecular formation

Even in completely pure hydrogen gas, muons will tend to form $p\mu p$ molecules as time passes. The nuclear capture rates in such molecules are lower than in the μp atom.

Using the kinetic equations describing muon processes in pure hydrogen, we use conservative averages of published molecular formation rates to calculate:

$$\Delta\lambda_{p\mu p} = 23.5 \pm 7.3\ s^{-1}$$

Summary

Source	λ (s^{-1})		σ (s^{-1})
Uncorrected rate	455 886.6	±	12.6
$Z > 1$ gas impurities	–19.2	±	5.0
Muon scatter events	–3.1	±	3.0
μd diffusion	–10.2	±	1.6
μp diffusion	–2.7	±	0.5
$p\mu p$ molecule formation	23.5	±	7.3
Muon detector inefficiencies		±	3.0
Analysis consistency		±	5.0
μp bound state decay rate effect	12.3		
Adjusted disappearance rate	455 887.2	±	16.8

Result

Finally, subtracting the μ^+ decay rate gives:

$$\Lambda_S = 725.0 \pm 17.4\ s^{-1}$$

Roughly 13.7 Hz of the uncertainty is statistical, and 10.7 Hz is systematic.
The result is consistent within 1σ with the latest theoretical calculations, which predict $\approx$ 710 Hz.

The implications for g_P will be addressed in the following talk.

Future

During 2005 and 2006, we collected additional data of superior quality.

- Higher statistics: ~ 10^{10} decay events
- Cleaner hydrogen gas:
  - The Z >1 impurity content was reduced by a factor of 2
  - The deuterium content was reduced by a factor of 10
- The TPC operated at higher voltage, with increased sensitivity

As a result, the statistical and systematic errors are each expected to be reduced by a factor of 2. Analysis is of the latest data is in progress, and we hope to reduce the total error on Λ_S from 2.5% to less than 1%, below the design goal.

Collaborating Institutions

Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia
Paul Scherrer Institute (PSI), Villigen, Switzerland
University of California, Berkeley (UCB and LBNL), USA
University of Illinois, Urbana-Champaign (UIUC), USA
Universite Catholique de Louvain, Belgium
TU Munich, Garching, Germany
University of Kentucky, USA
Boston University, USA

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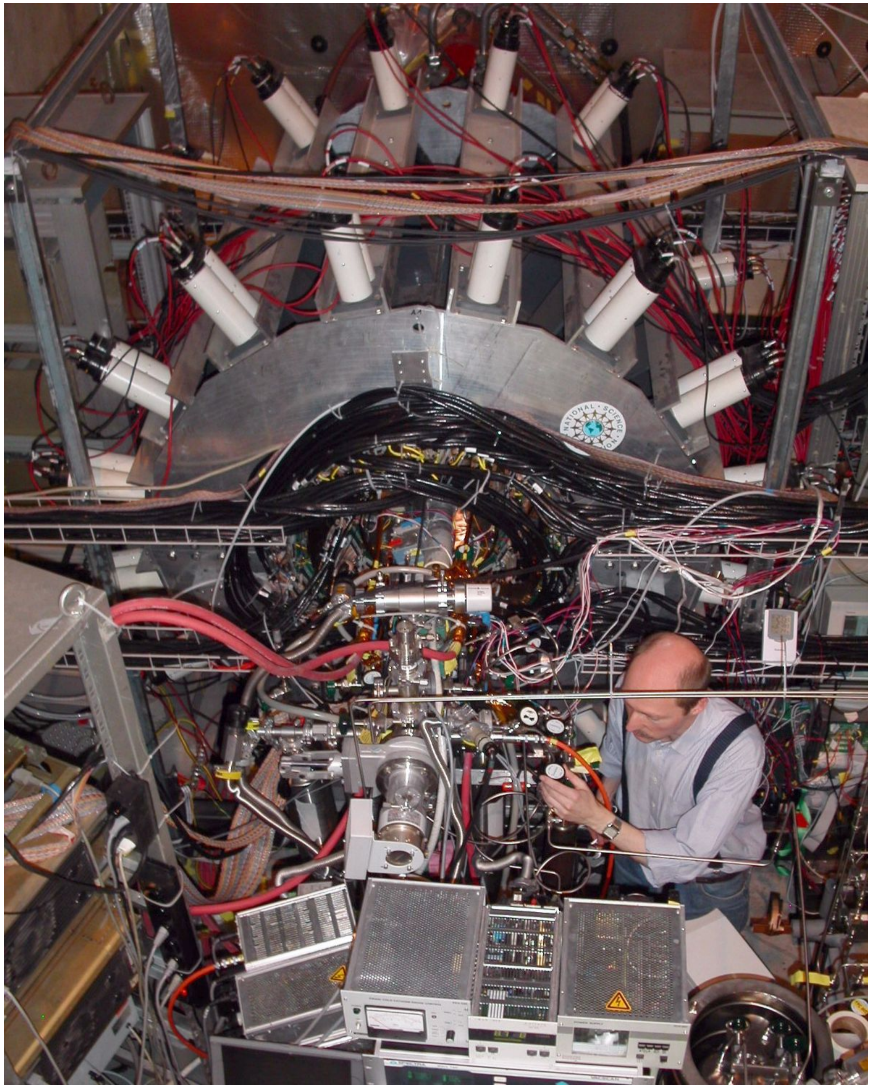
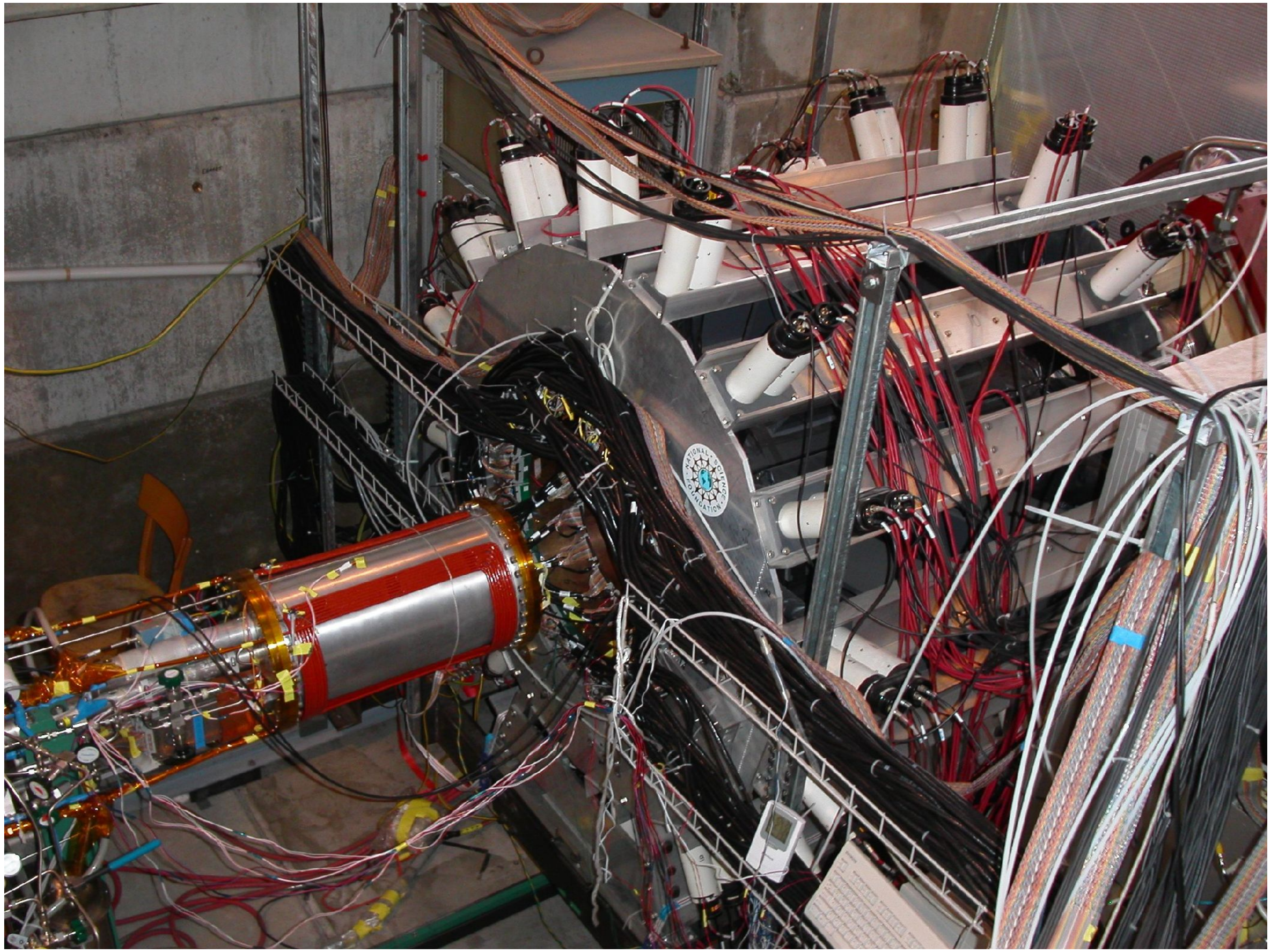
www.npl.uiuc.edu/exp/mucapture

2004 data collection



MuCap detectors assembled at the Paul Scherrer Institut, Switzerland, October – November, 2004.

2004 data collection



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