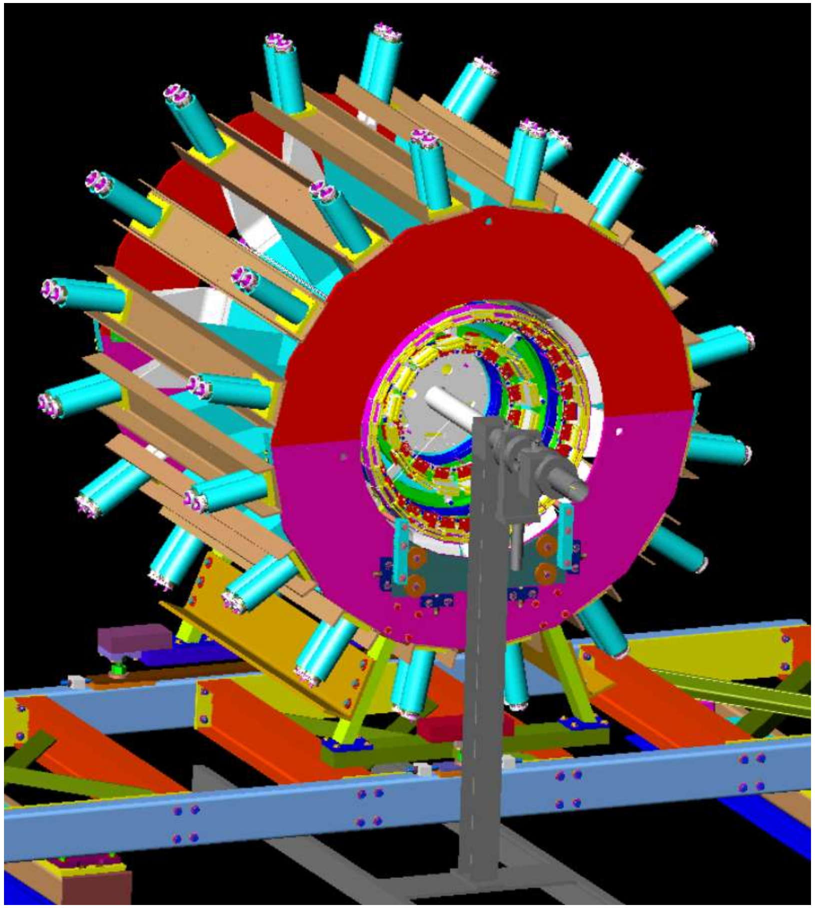
The MuCap experiment: A measurement of the muon capture rate in hydrogen gas



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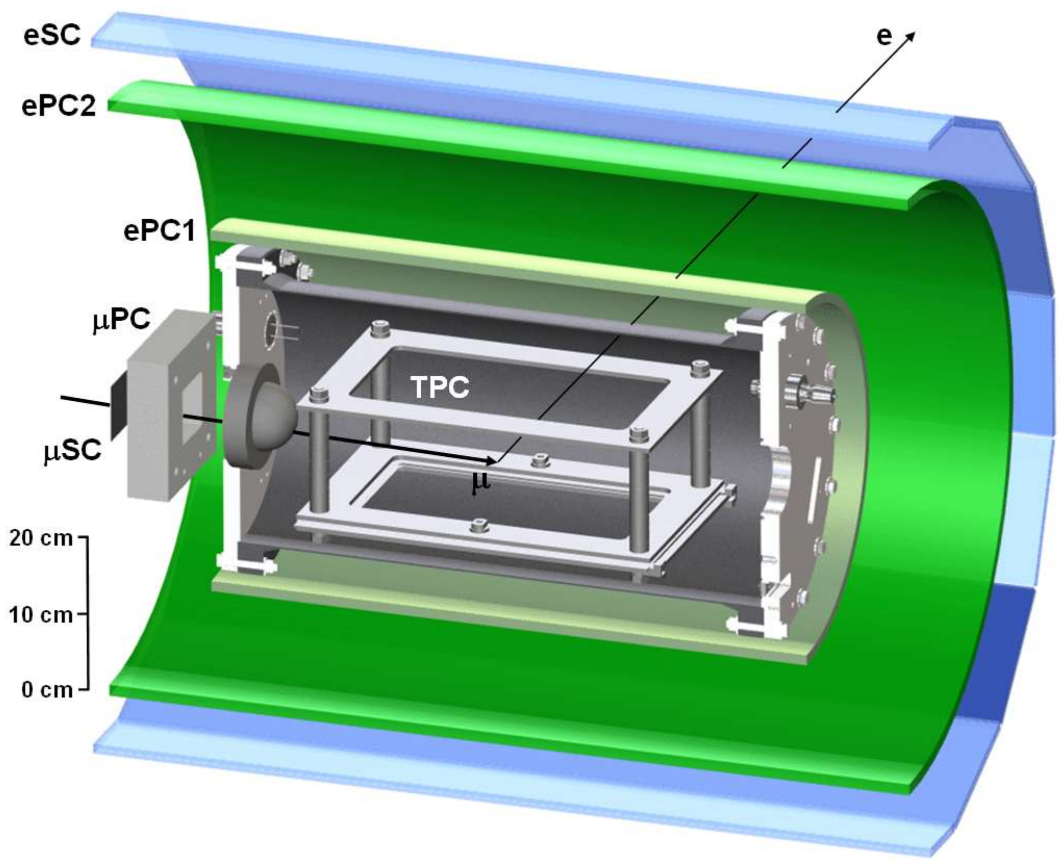
Experiment basics

We seek to measure the rate of the (semileptonic, weak) process of ordinary muon capture by the proton,

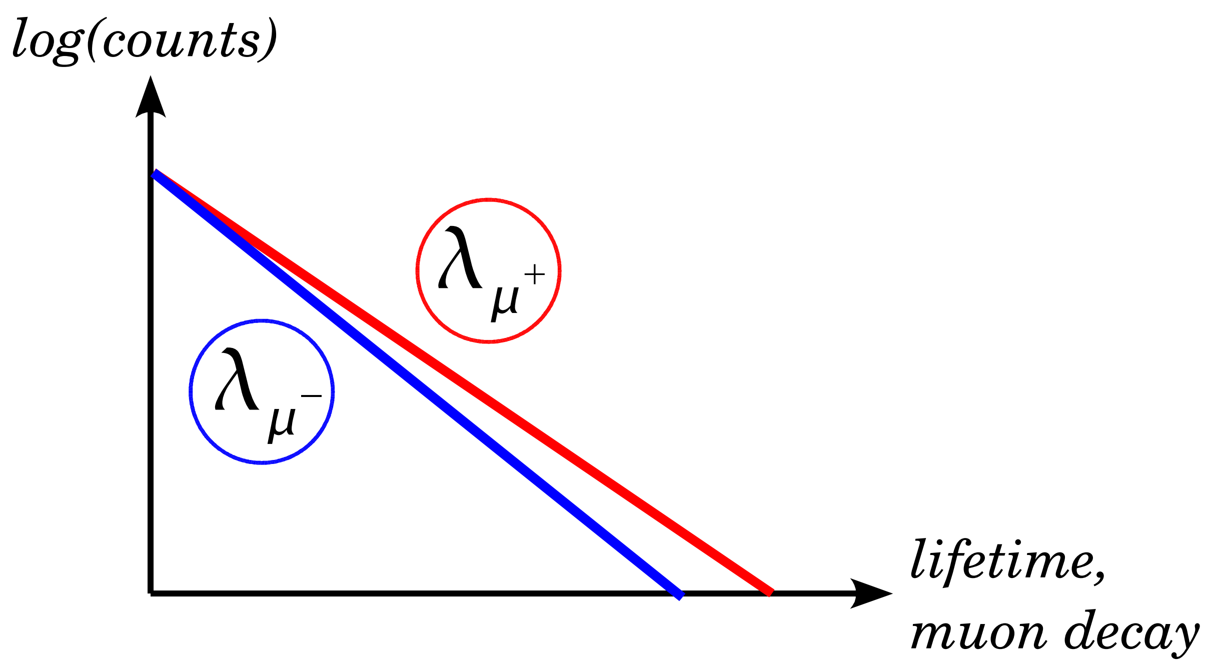
$$\mu^- + p \rightarrow n + \nu ,$$

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, which can only decay:

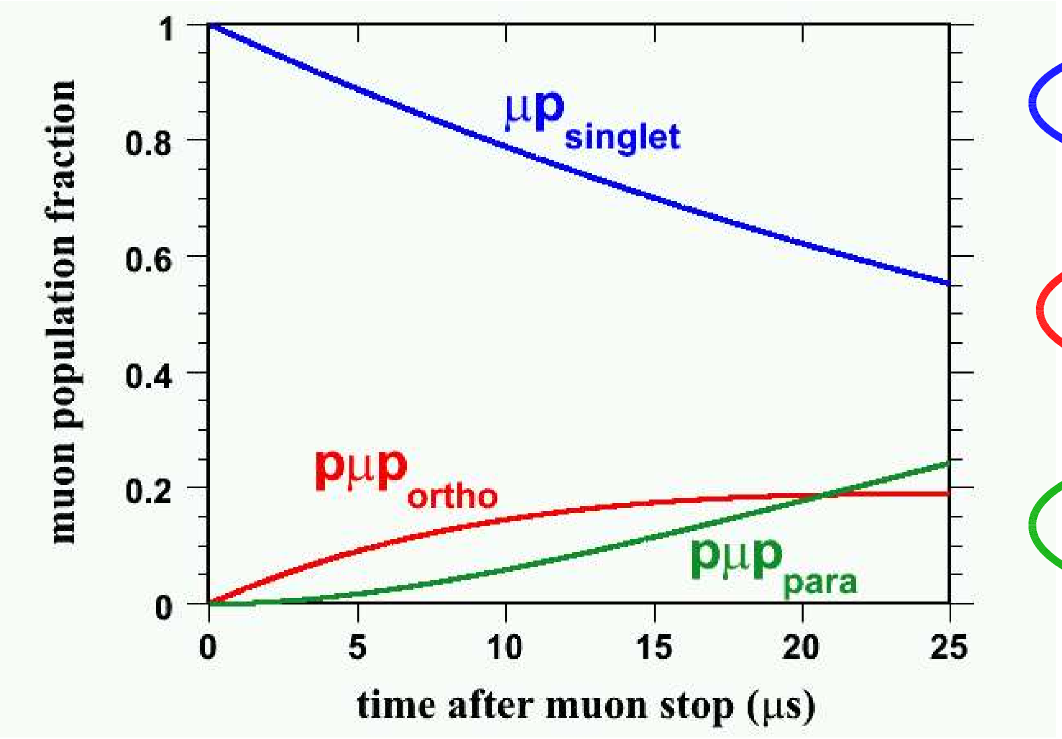


The muon capture rate can be obtained from the small (0.15%) difference between the two disappearance rates,

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

Motivation

In our hydrogen gas target of density 1% relative to LH_2, most muons reside in the hyperfine singlet ground state of the μp atom,



$$\Lambda_S \approx 710\ s^{-1}$$

$$\Lambda_{om} \approx 506\ s^{-1}$$

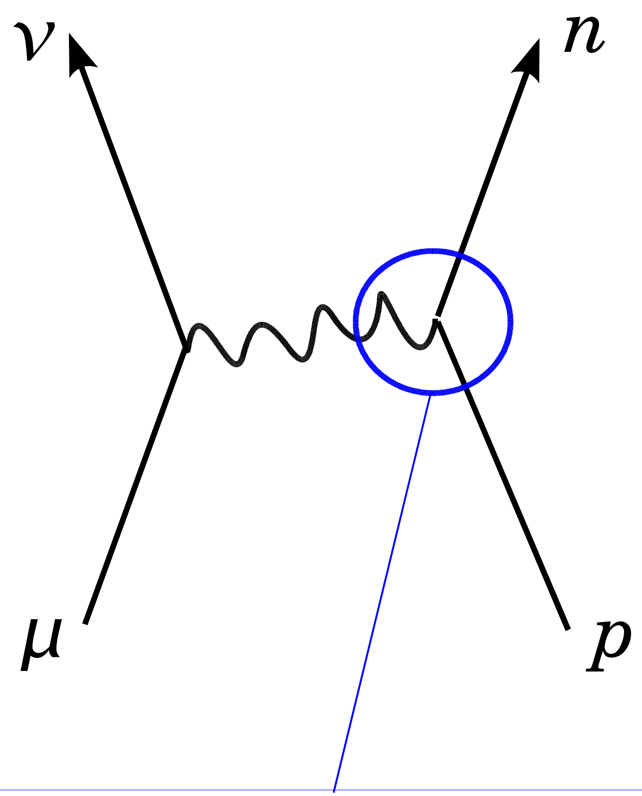
$$\Lambda_{pm} \approx 208\ s^{-1}$$

which means that most muon captures (96%) proceed from the singlet state:

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

Motivation

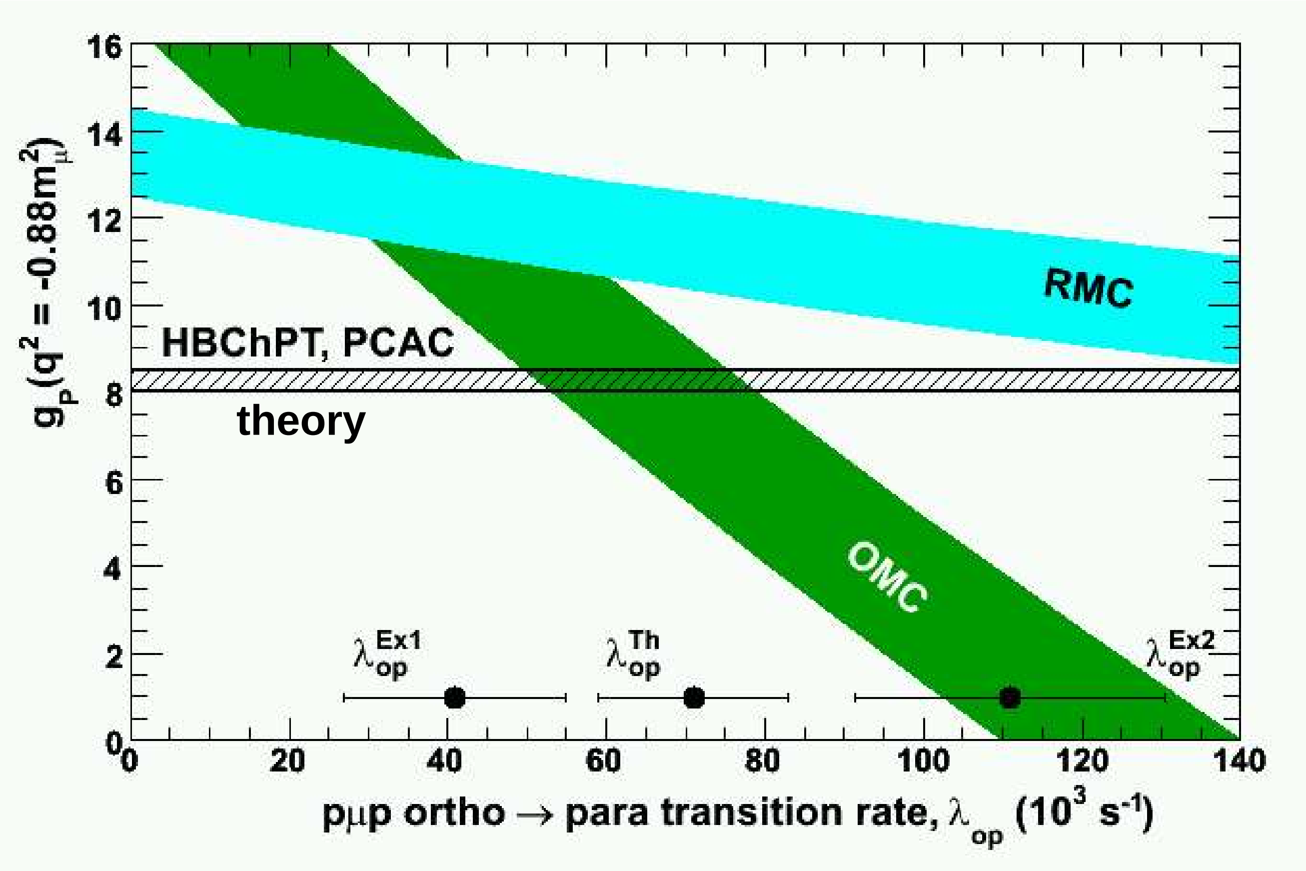
A 1% measurement of Λ_S would determine the nucleon's weak induced pseudoscalar coupling, g_P, to 7%.



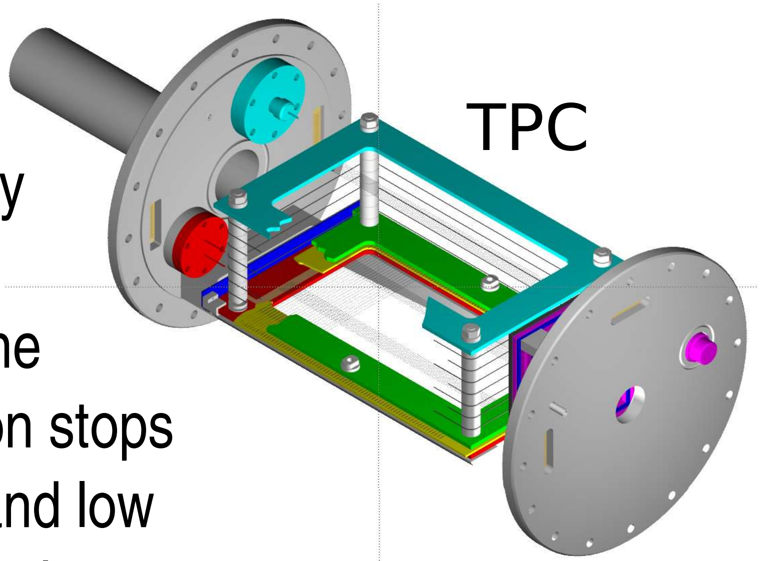
$$< n | (\gamma_\alpha) g_V + (i \sigma_{\alpha\beta} q^\beta) g_M + (\gamma_\alpha \gamma_5) g_A + (q_\alpha \gamma_5) g_P | p >$$

Motivation

The pseudoscalar coupling has long been the least well known of the nucleon's form factors. Prior to the advent of MuCap, the situation regarding g_P was inconclusive – existing theoretical and experimental values were mutually inconsistent:



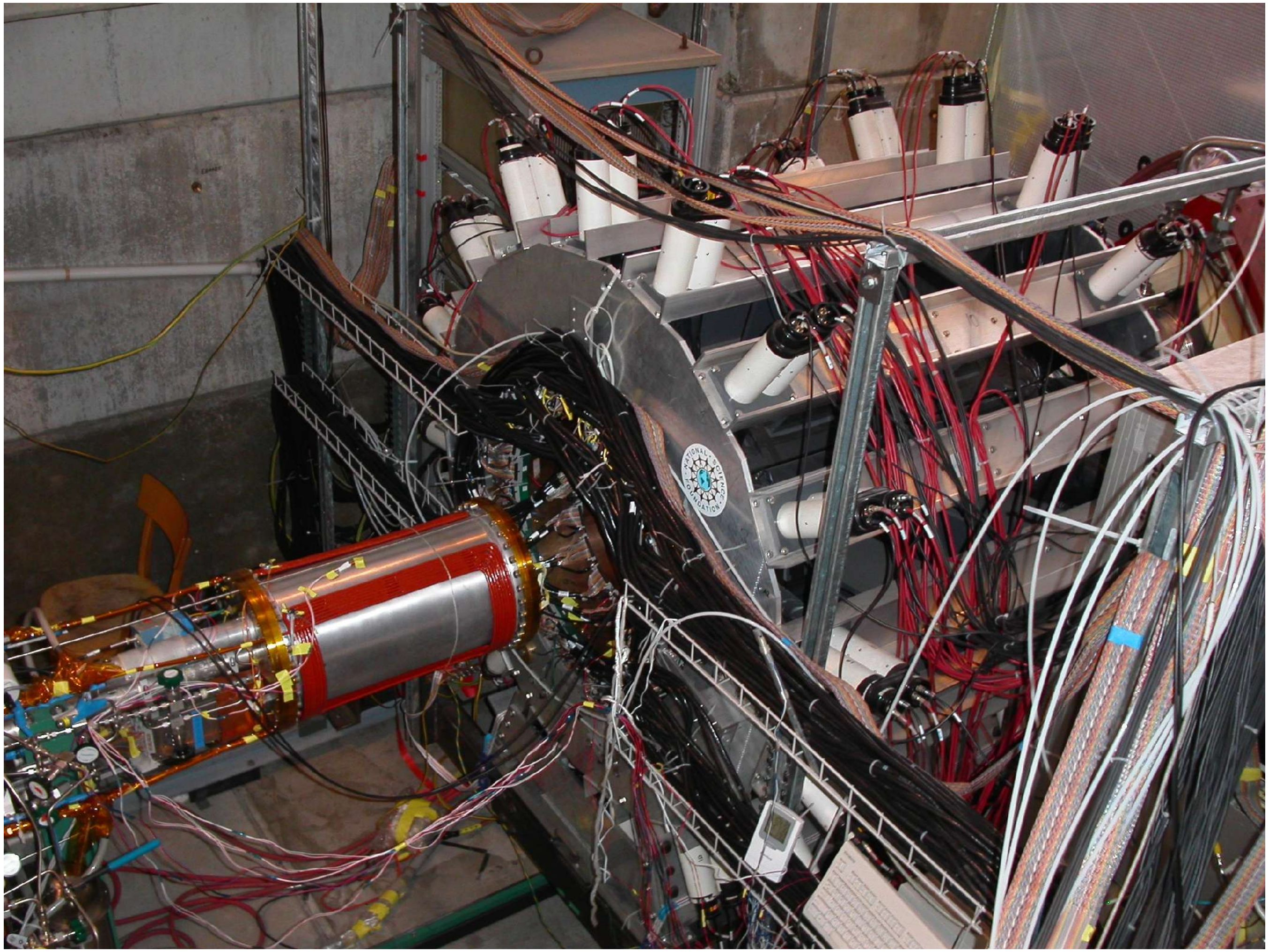
How is MuCap better?



- **Target**: We use a time projection chamber (TPC) operating in ultra-pure, low-density hydrogen gas (Z>1 impurities are at 5×10^{-8} level, deuterium is ~ 1 ppm), which has never been done before. The TPC enables us to identify good muon stops in the hydrogen target, while the gas' high purity and low density minimize capture contributions from molecules, deuterium, and Z>1 elements.

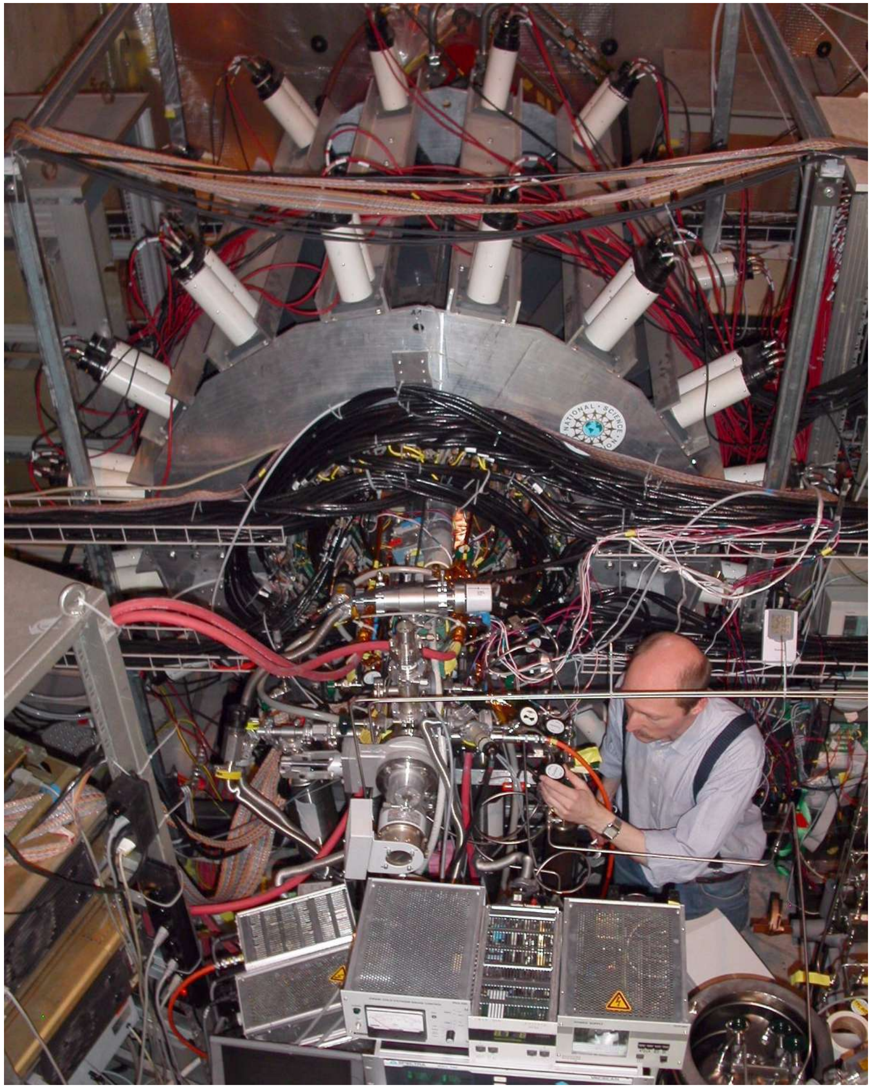
- **High statistics**: In order to measure the capture rate to 1% precision, we must measure the μ^- lifetime to 10 ppm, which requires recording 10^{10} μ^- decay events. This is possible through our unique combination of detectors and our analysis capabilities.

2004 data collection



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

2004 data collection – first physics run



MuCap detectors assembled at the Paul Scherrer Institut, Switzerland,
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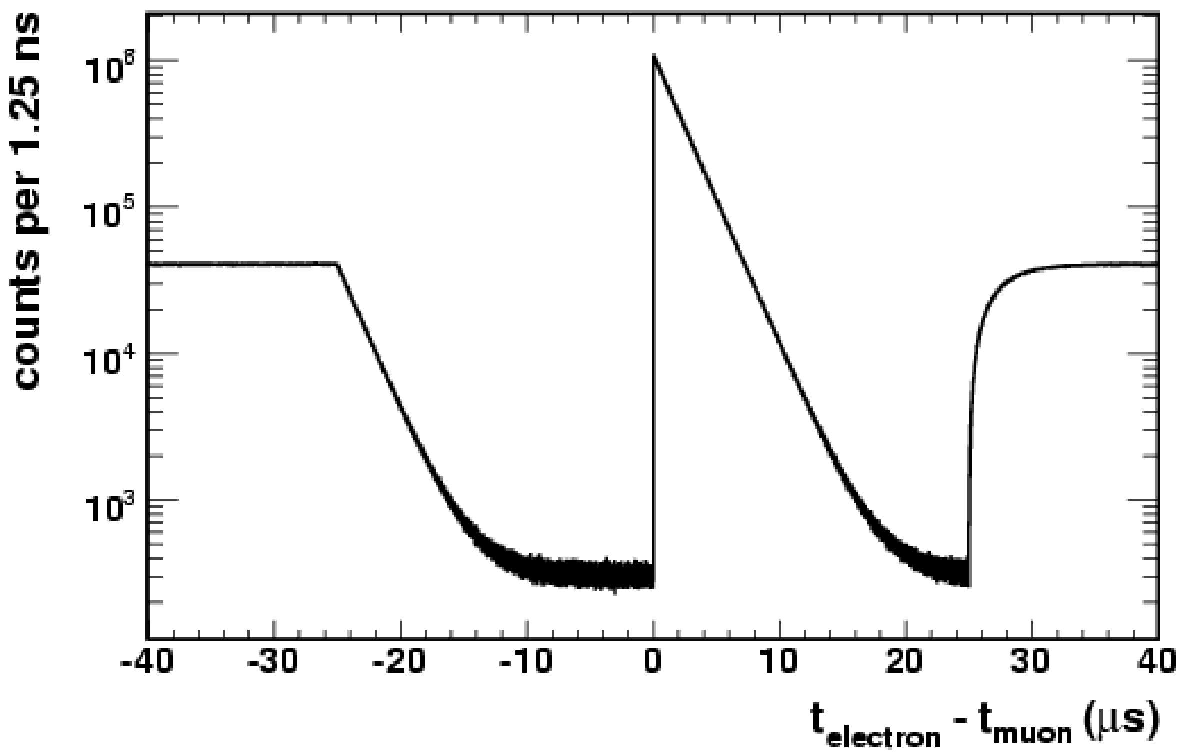
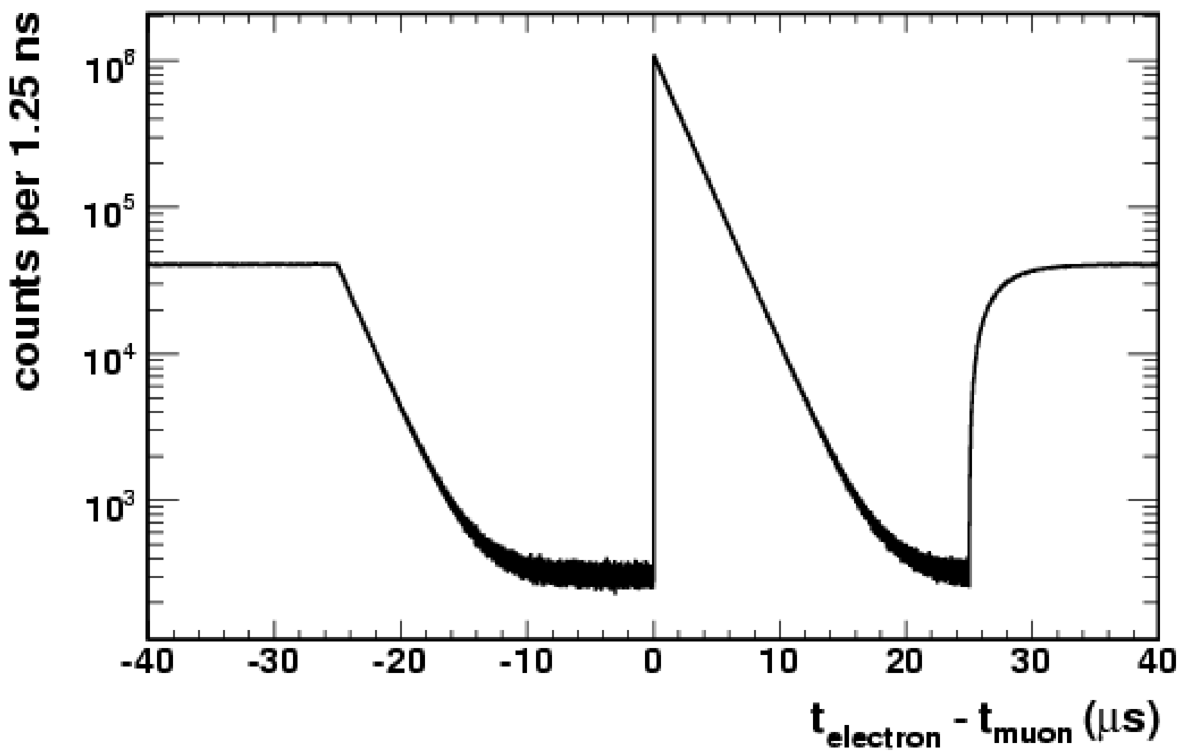
2004 data analysis



We recorded $\approx 1.6\times10^9$ 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 analysis

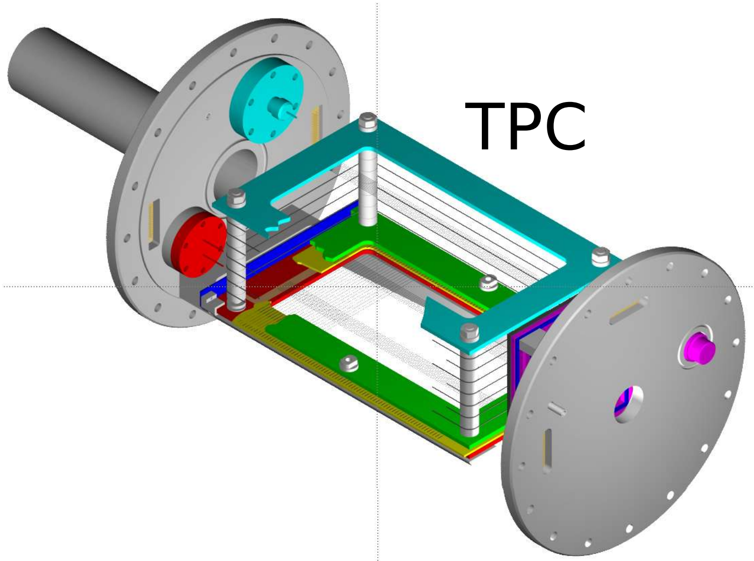


$$\lambda = 455\ 886.6 \pm 12.6\ s^{-1}$$

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

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.

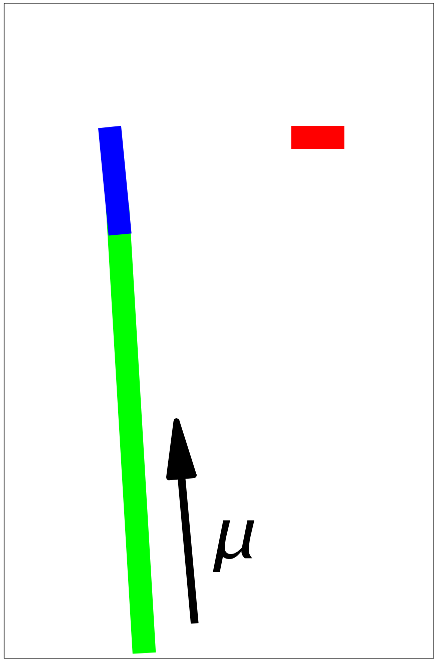


The TPC provides a means to monitor captures by these gas impurities.

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:

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

TPC capture signature



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

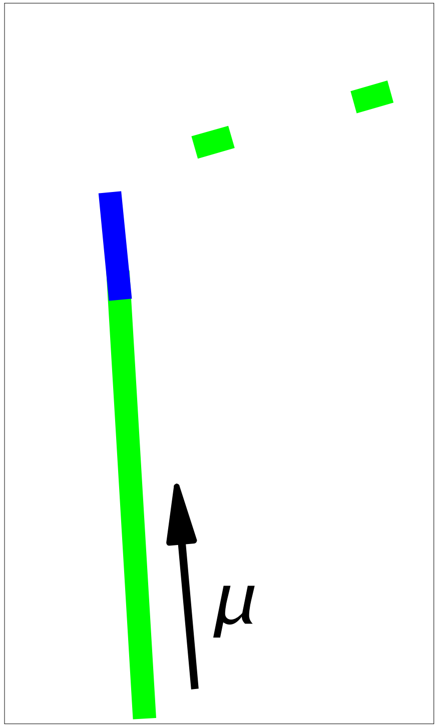
Sometimes a muon will appear to have stopped in the TPC, but actually scattered out of the fiducial volume. Such events are dangerous, because the scattered muon can stop in surrounding detector materials.

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:

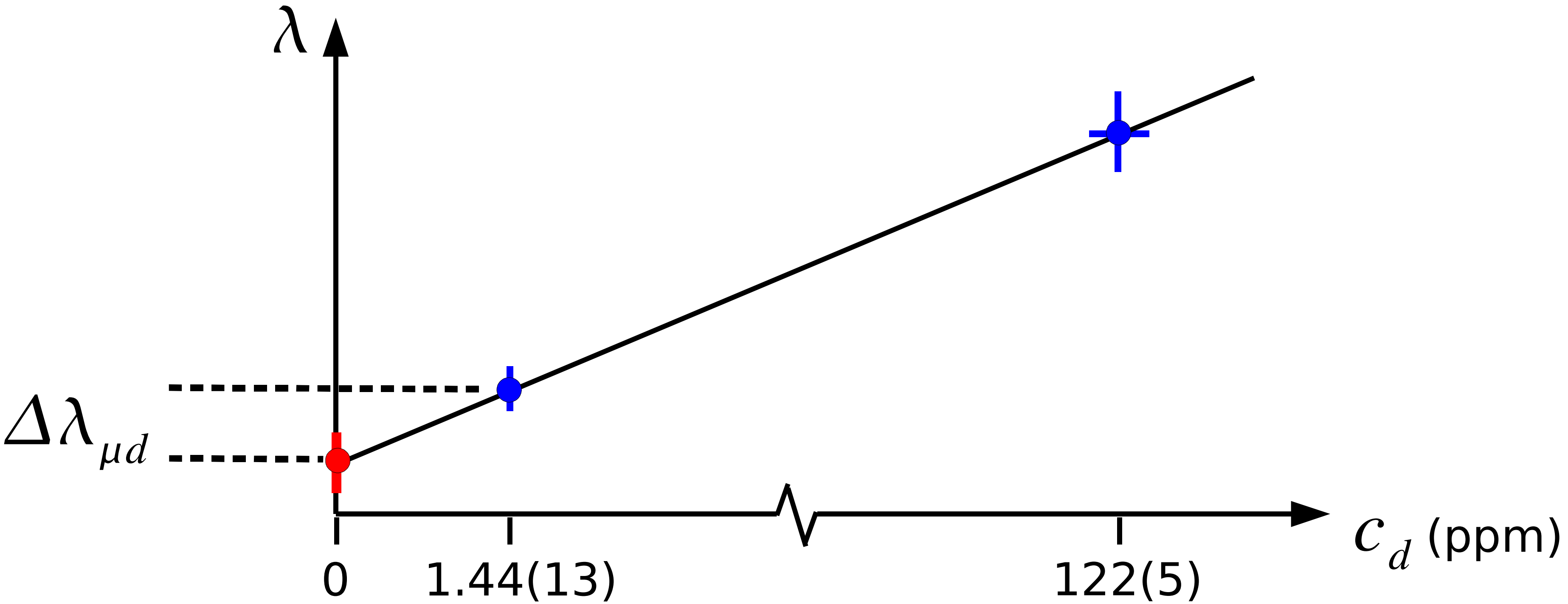
$$\Delta \lambda_{scatter} = -3.1 \pm 3.0\ s^{-1}$$

TPC scatter signature



Diffusion effects: deuterium impurities

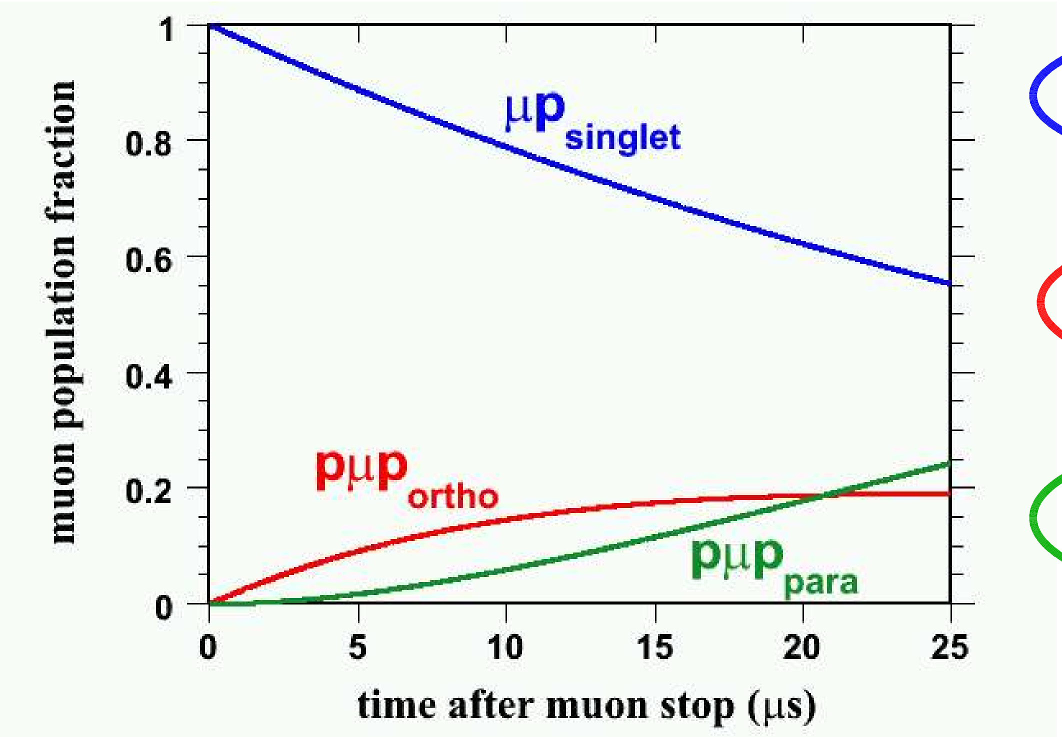
To correct for the effects of μd diffusion, we perform a zero-extrapolation:



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

Molecular formation

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



$$\Lambda_S \approx 710 \ s^{-1}$$

$$\Lambda_{om} \approx 506 \ s^{-1}$$

$$\Lambda_{pm} \approx 208 \ s^{-1}$$

We must correct for the effects of captures in molecules:

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

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:

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

Summary of corrections

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 for the muon capture rate

Finally, subtracting the μ^+ decay rate gives:

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

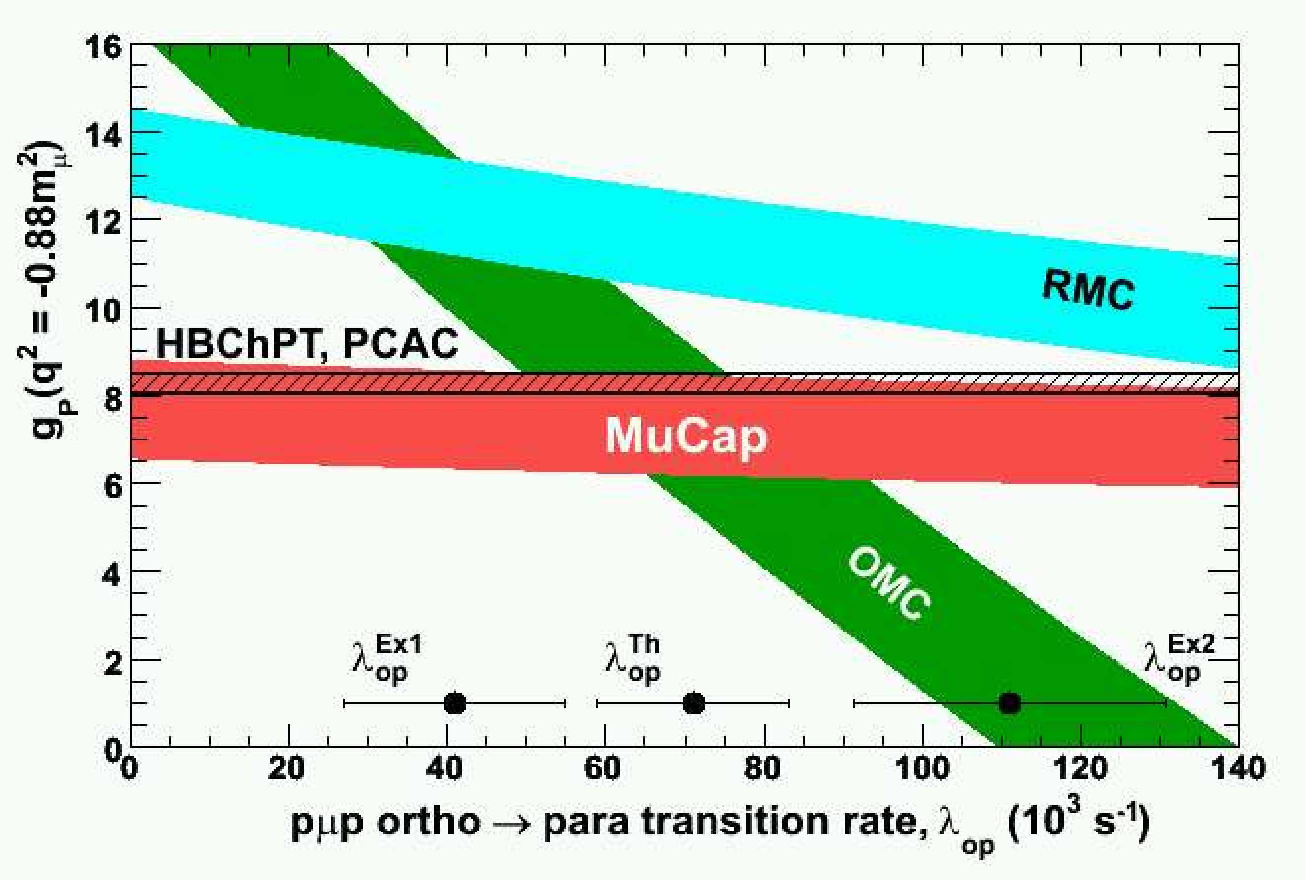
Roughly 13.7 Hz of the uncertainty is statistical, and 10.7 Hz is systematic. This result is consistent within 1σ with the latest theoretical calculations which predict $\approx$ (711.5 ± 4.6) Hz, and was recently accepted for publication in Physical Review Letters (see arXiv:0704.3968).

Implications for g_P

From Λ_S we can extract the following value for g_P,

$$g_P = 7.3 \pm 1.1$$

which is consistent with the ChPT prediction 8.26 ± 0.23, and therefore corroborates the modern understanding of the role of chiral symmetries in QCD.



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, which will in turn reduce the error on g_P from 15% to 7%.

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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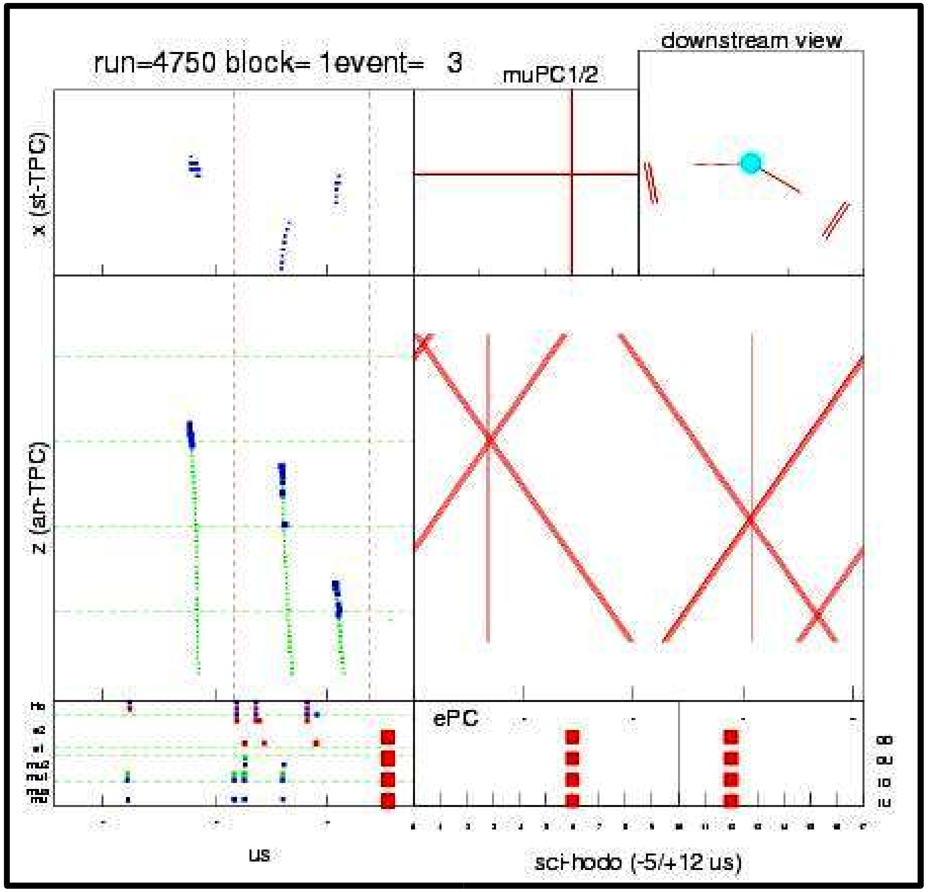
www.npl.uiuc.edu/exp/mucapture

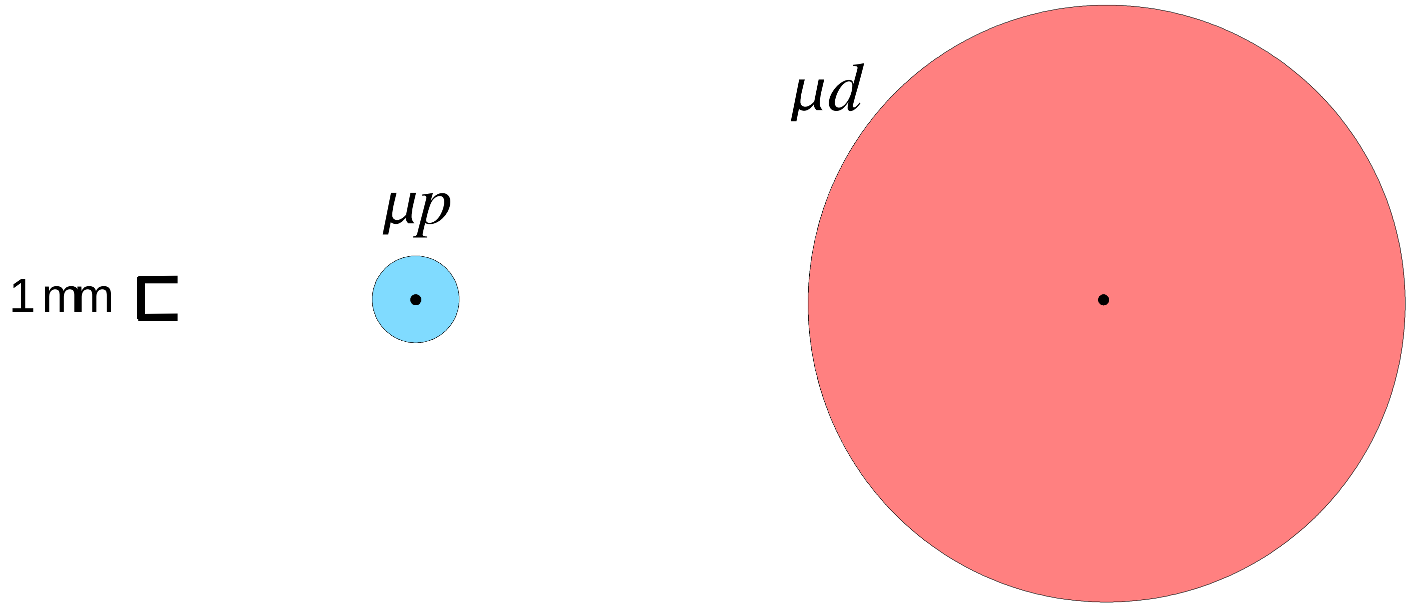
2004 Data Collection



Sample event display

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.

$$g_p^{MuCap} = g_p^{theory} + \frac{\partial g_p}{\partial \Lambda_S}(\Lambda_S^{MuCap} - \Lambda_S^{theory})$$

Average HBChPT calculations of Λ_S:

$$(687.4\ \mathrm{s}^{-1} + 695\ \mathrm{s}^{-1})/2 = 691.2\ \mathrm{s}^{-1}$$

Apply new rad. correction (2.8%):

$$(1 + 0.028)691.2\ \mathrm{s}^{-1} = 710.6\ \mathrm{s}^{-1}$$

$$\rightarrow \Lambda_S^{theory} = 710.6\ \mathrm{s}^{-1}$$

$$g_p^{MuCap} = 8.26 + (-0.065\ \mathrm{s})\left((725.0 \pm 17.4\ \mathrm{s}^{-1}) - (710.6\ \mathrm{s}^{-1})\right)$$

$$= 7.3 \pm 1.1$$ (MuCap 2007, Final)

Note: uncertainty in theory (~0.5%) not propagated.
For next MuCap result (Λ_S to 1%) further theory input would be appreciated!