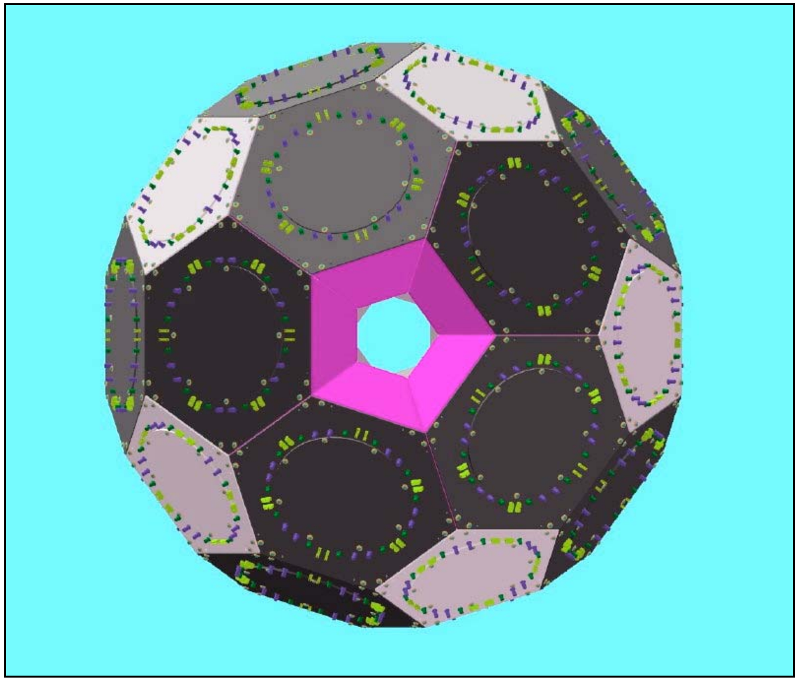
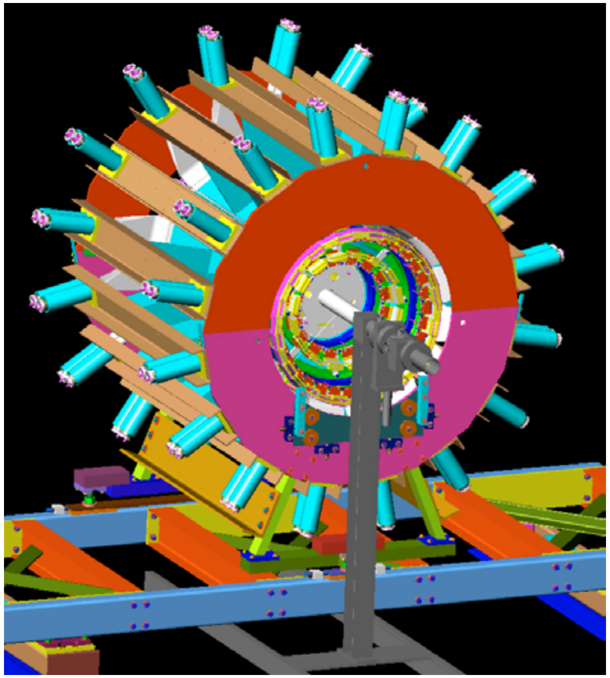
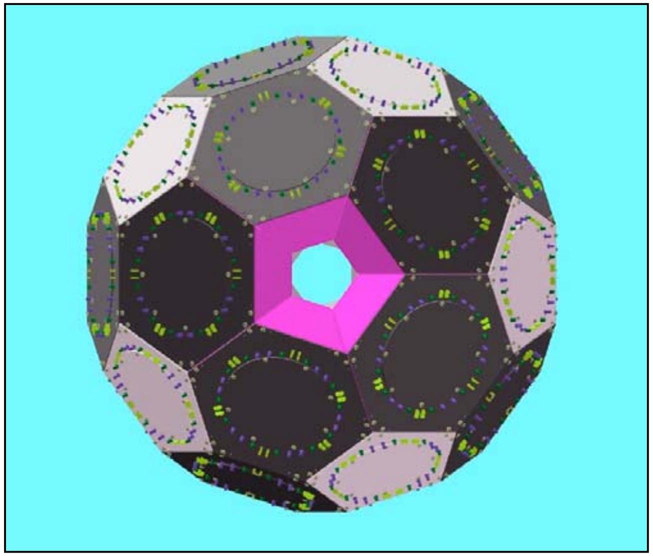
First results from the MuLan and MuCap experiments





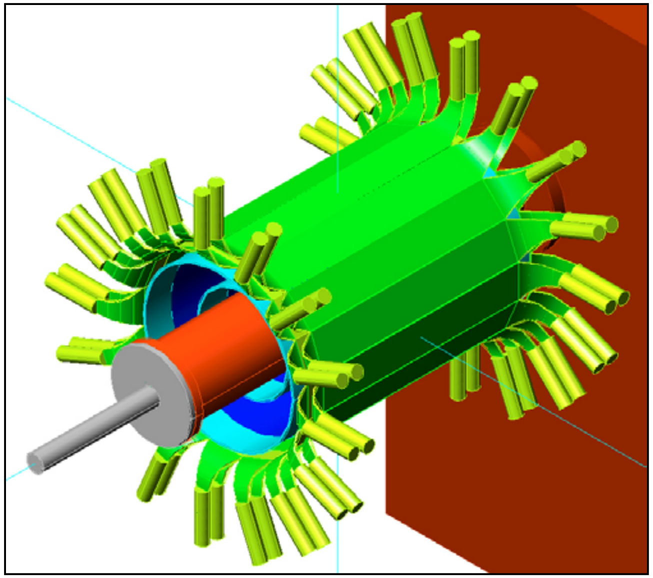
Tom Banks, University of California, Berkeley
NuFact07, Okayama, Japan
August 8, 2007

Sister experiments



MuLan

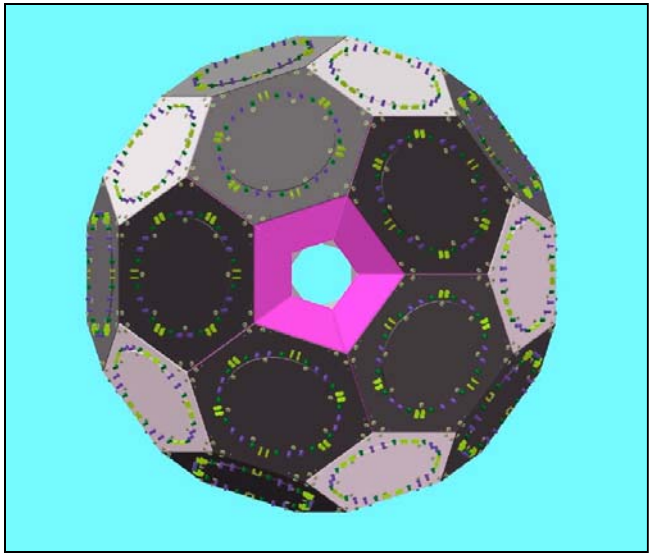
Precision measurement of the positive muon's lifetime, to determine the Fermi constant, G_F .

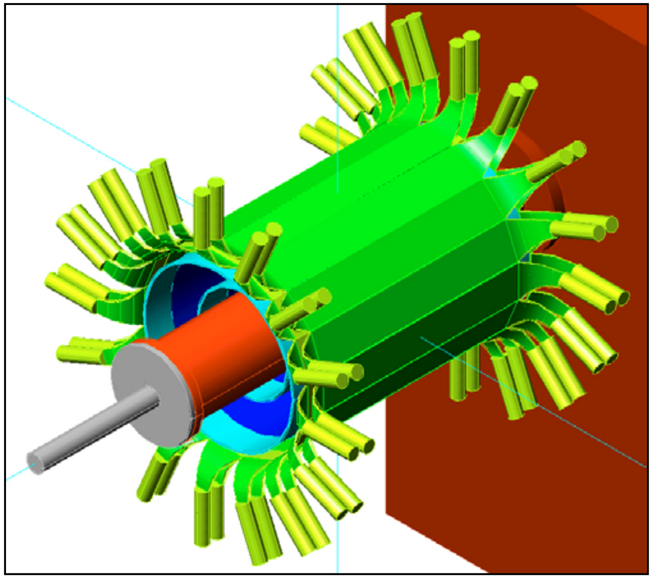


MuCap

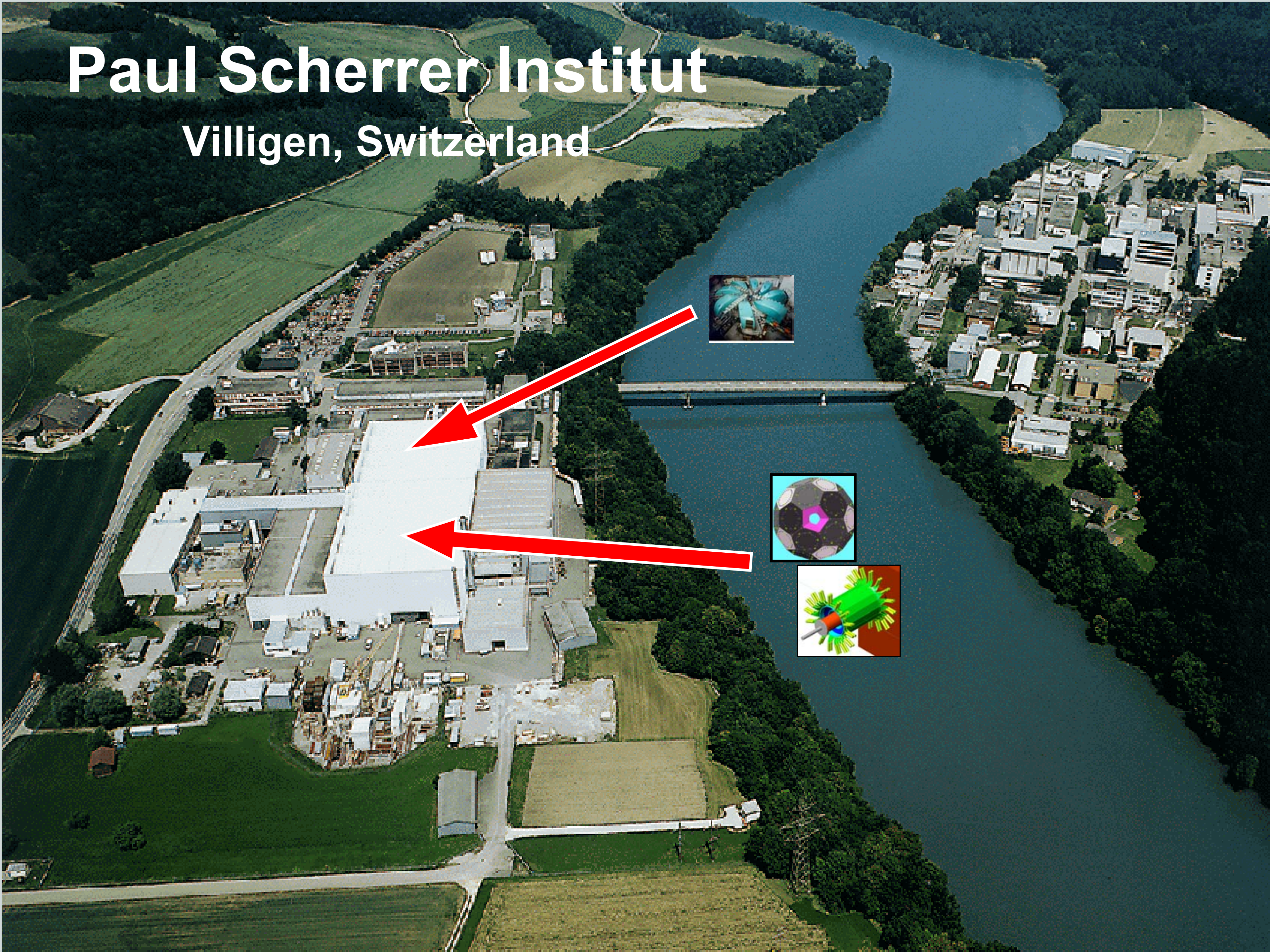
Precision measurement of the negative muon's lifetime in hydrogen gas, to determine the nuclear muon capture rate, which in turn determines the nucleon's pseudoscalar coupling, g_P.

Similarities

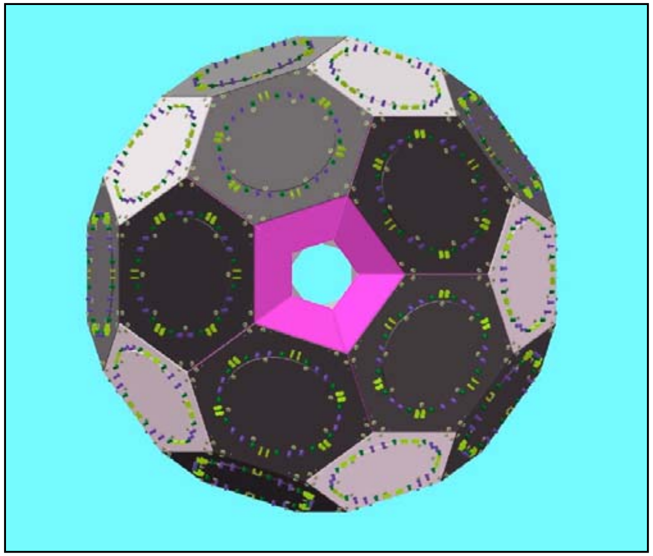


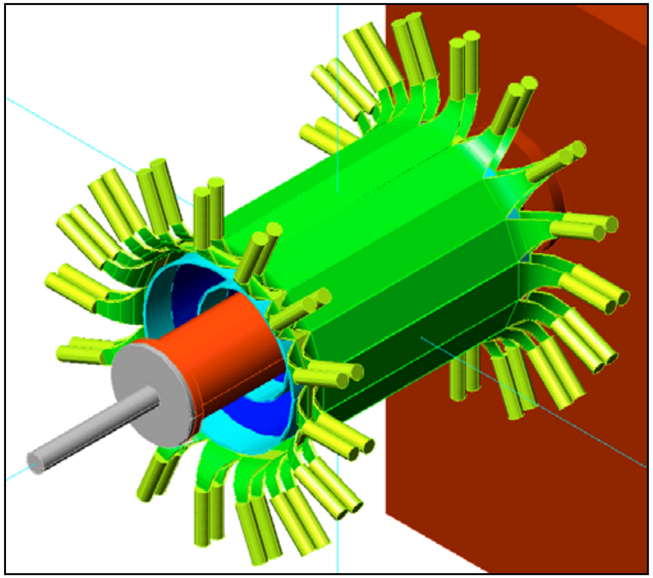


- Both are ongoing experiments conducted at the Paul Scherrer Institut near Zurich, Switzerland.


Paul Scherrer Institut
Villigen, Switzerland

Similarities





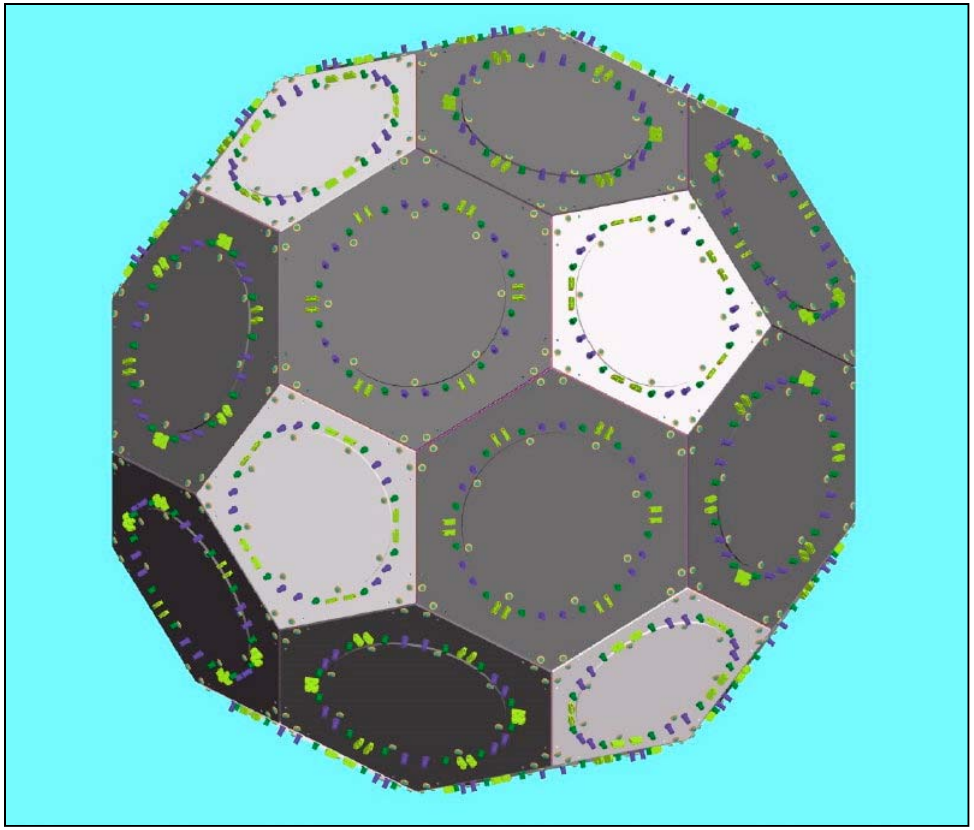
- Both are ongoing experiments conducted at the Paul Scherrer Institut near Zurich, Switzerland.

- Both use a similar experimental technique (i.e., the muon lifetime) to measure fundamental weak interaction parameters.

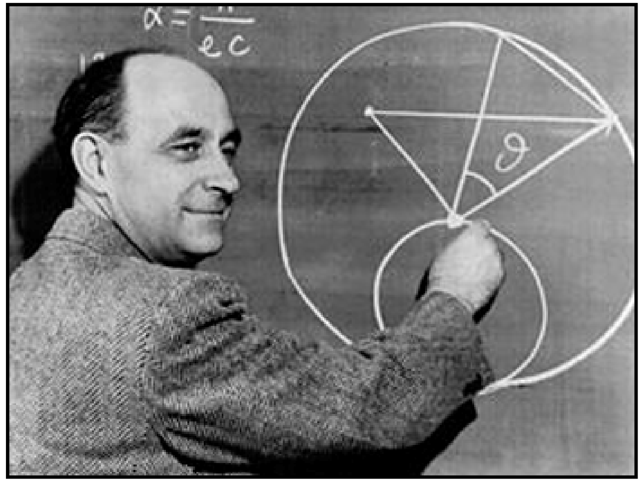
- Overlap in personnel, materials

- Both recorded first physics data in fall 2004, and both recently published their results from that data in the same issue of PRL (July 20, 2007)

The MuLan experiment: Muon Lifetime Analysis



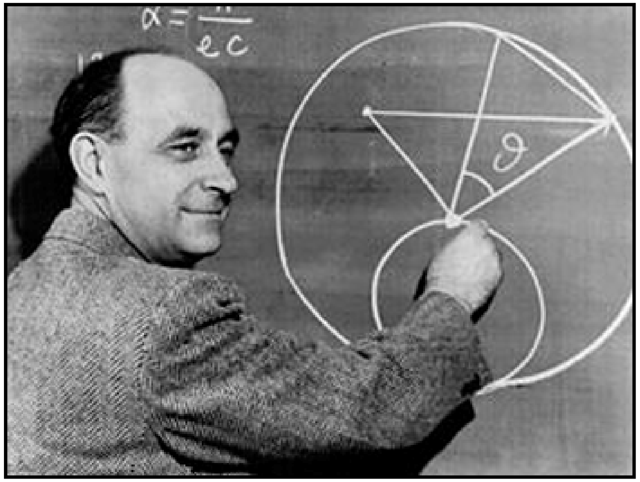
Motivation



The most precise way of determining the Fermi constant is from the mean life of the positive muon:

$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3}(1+\Delta q)$$

Motivation



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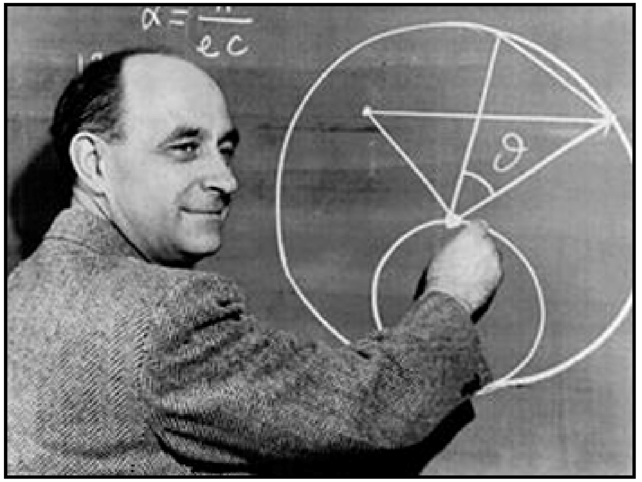
$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3}(1 + \Delta q)$$

For a long time, the uncertainty in G_F was dominated by the higher-order QED corrections in Δq.

Motivation



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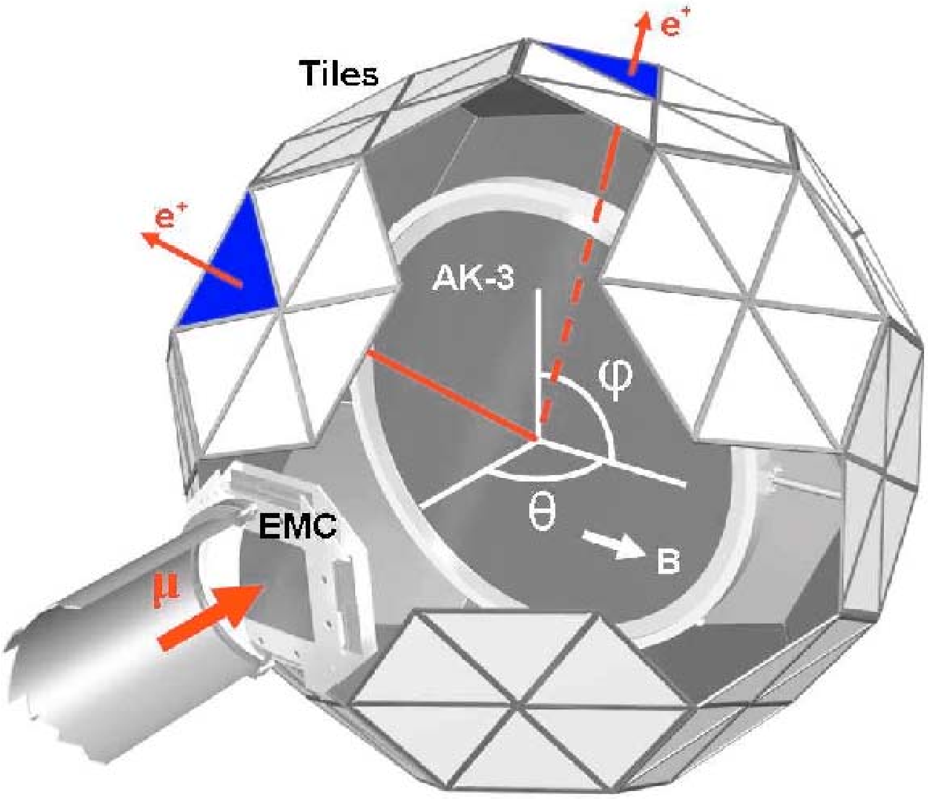
In 1999, the theoretical uncertainty was reduced to less than 0.3 ppm, shifting the focus to the muon lifetime, which has not been measured in over 20 years.

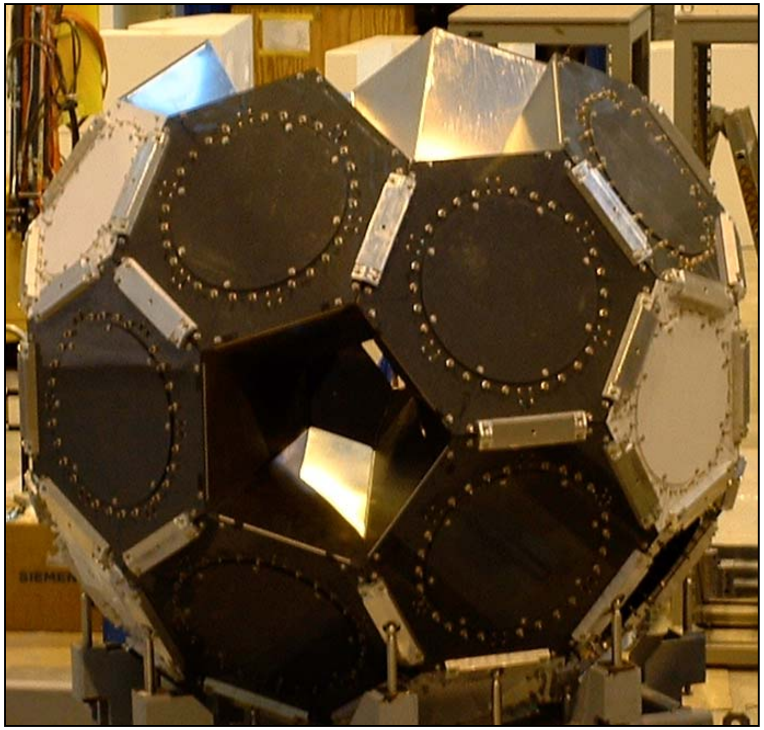
Experimental design

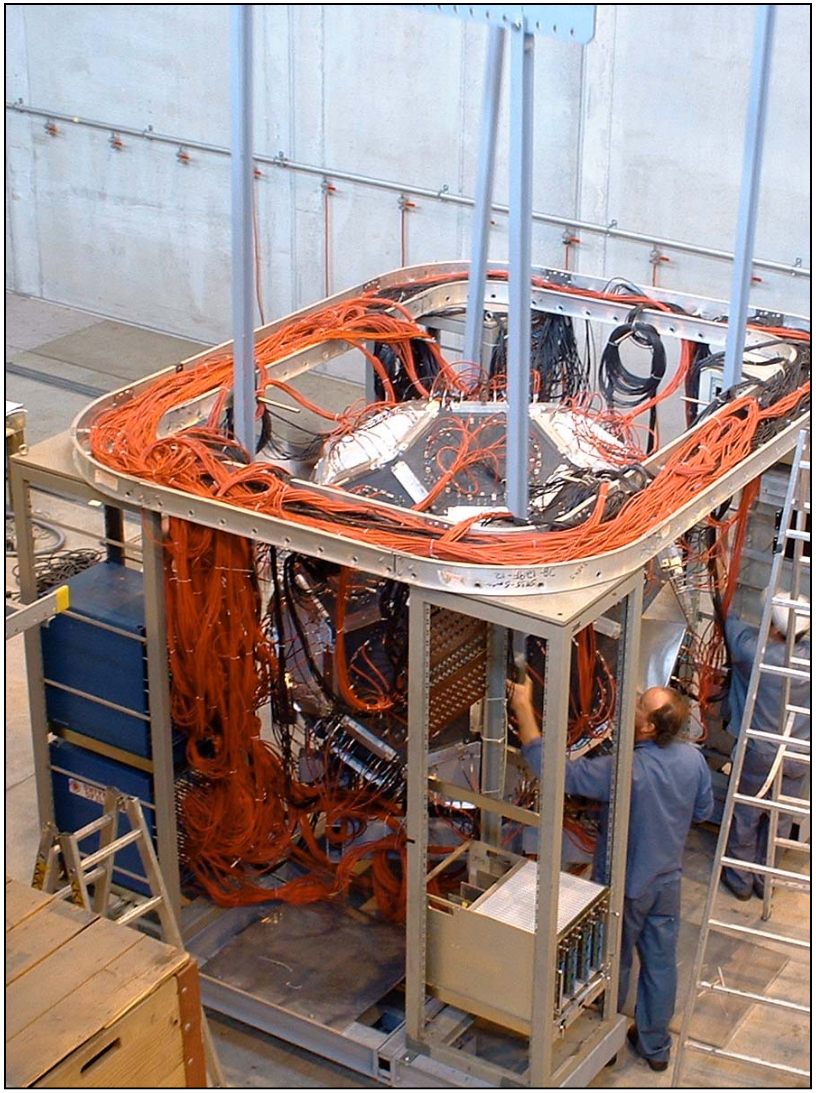
Positive muons are stopped in a ferromagnetic target disk, and decay positrons are detected by a surrounding soccer-ball-shaped scintillator array:



The goal is to ultimately record 10^{12} decay events in this fashion and make a 1 ppm lifetime measurement.

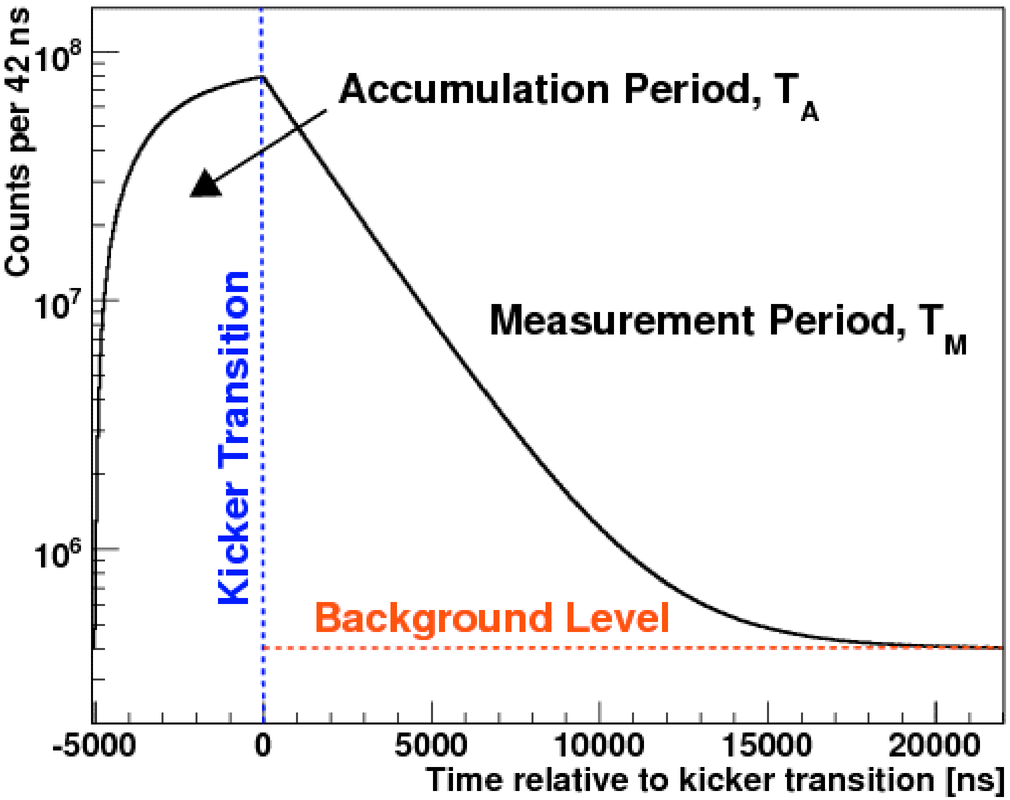
Experimental design





Lifetime spectrum

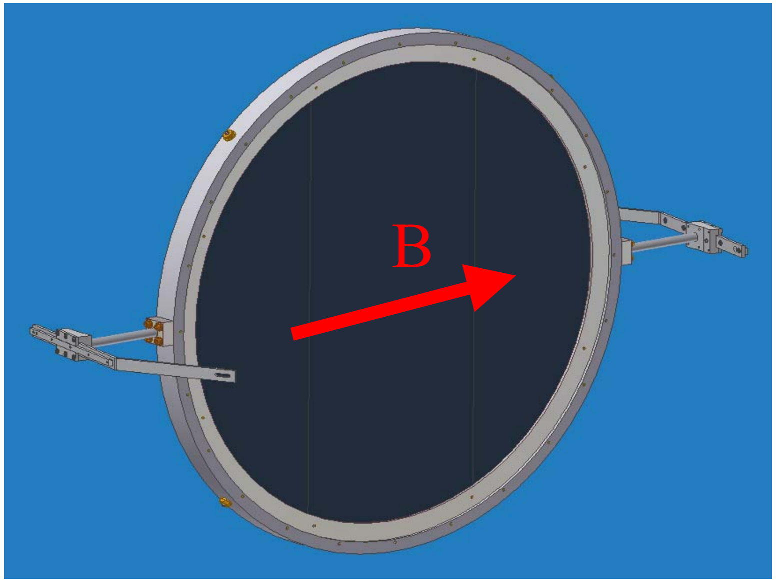
A pulsed DC muon beam generates the lifetime spectrum shown.



2004 targets

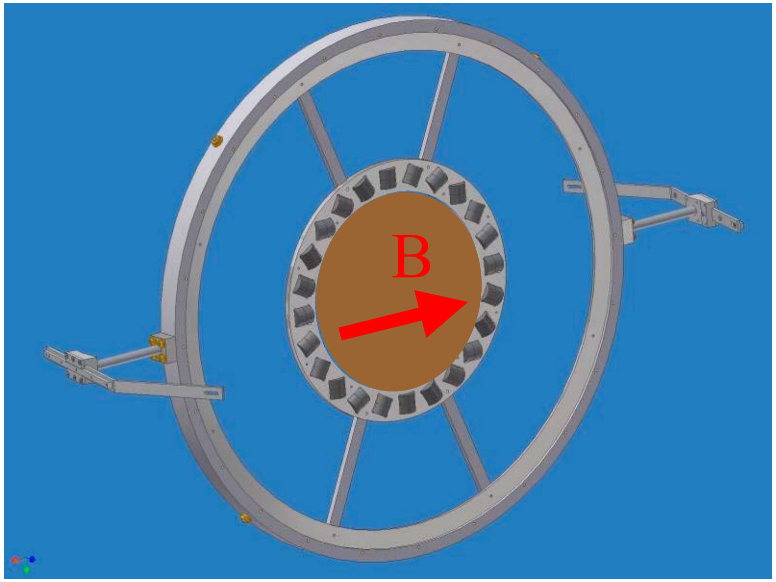
Arnokrome III (AK-3)

- 30% Cr, 10% Co, 60% Fe
- High internal B field (~ 4000 G)



Pressed sulfur

- Held in Kapton wrapping
- 130 G field from Halbach magnet



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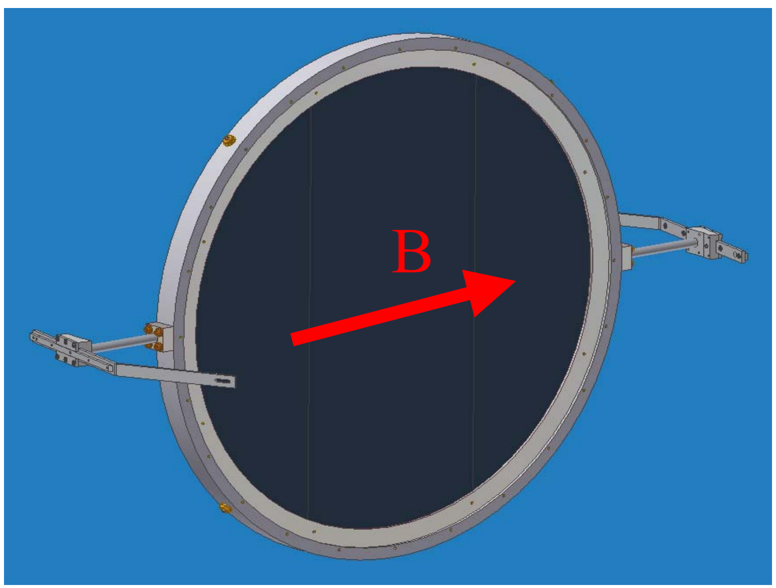

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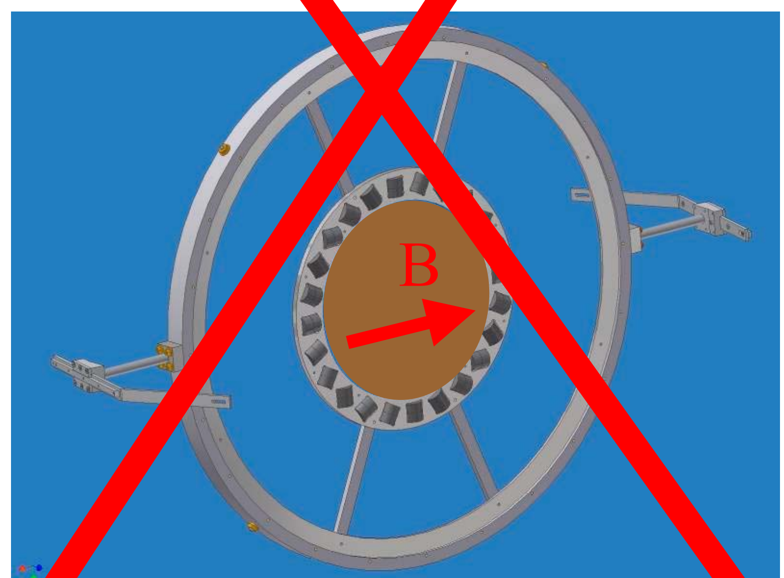
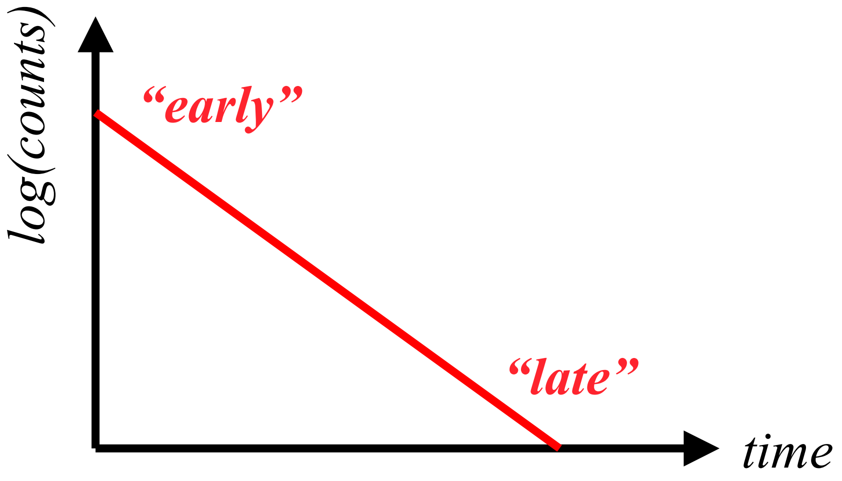


Systematics

When dealing with a precision experiment involving large statistics, it's all about the systematics... Since we are measuring the lifetime, the primary challenge is avoiding "early-to-late" changes:



Such distortions can arise from:

- muon pileup and deadtime effects, resulting in missed events
- instrumental shifts in gain, threshold, or time response
- spatial acceptance (muon polarization and spin rotation)

Systematics

The final table:

Source	Size (ppm)
Extinction stability	3.5
Errant muon stops	2.0
Dead time correction	2.0
Gain stability	1.8
MTDC response	1.0
Repeated events (+1 ppm shift)	1.0
Multiple hit timing shifts	0.8
Queuing loss	0.7
Total	5.2

Results

The 1.8 x 10^{10} decay events in the 2004 MuLan AK-3 data yielded the result (D. Chitwood et al., PRL **99**, 032001 (2007)):

	$\tau_\mu (\mu \text{s})$	$G_F (\times 10^{-5} \text{GeV}^{-2})$
Previous world average	2.197 030(40)	1.166 370(10)
MuLan (2007)	2.197 013(24)	
Updated world average	2.197 019(21)	1.166 371(6)

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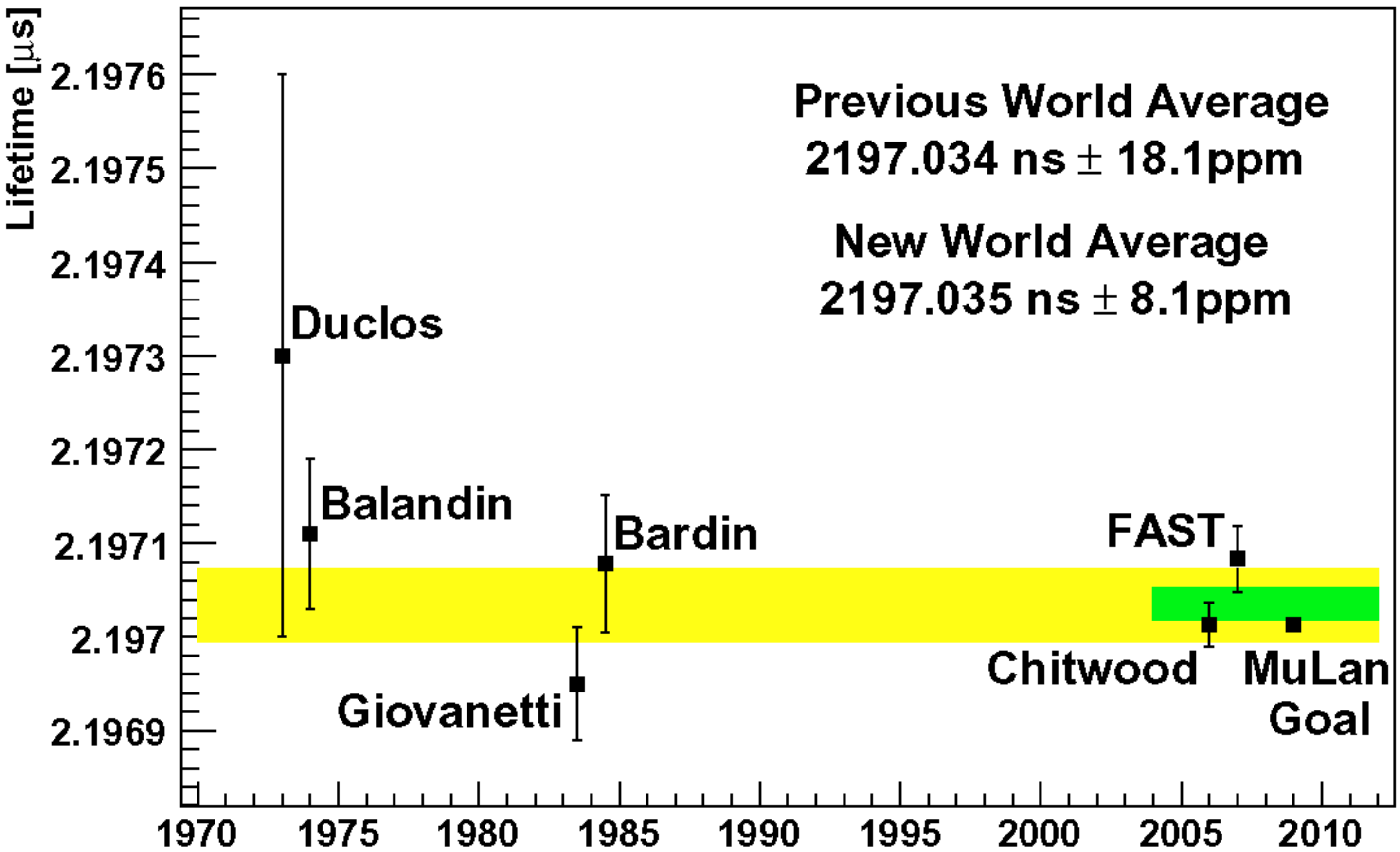
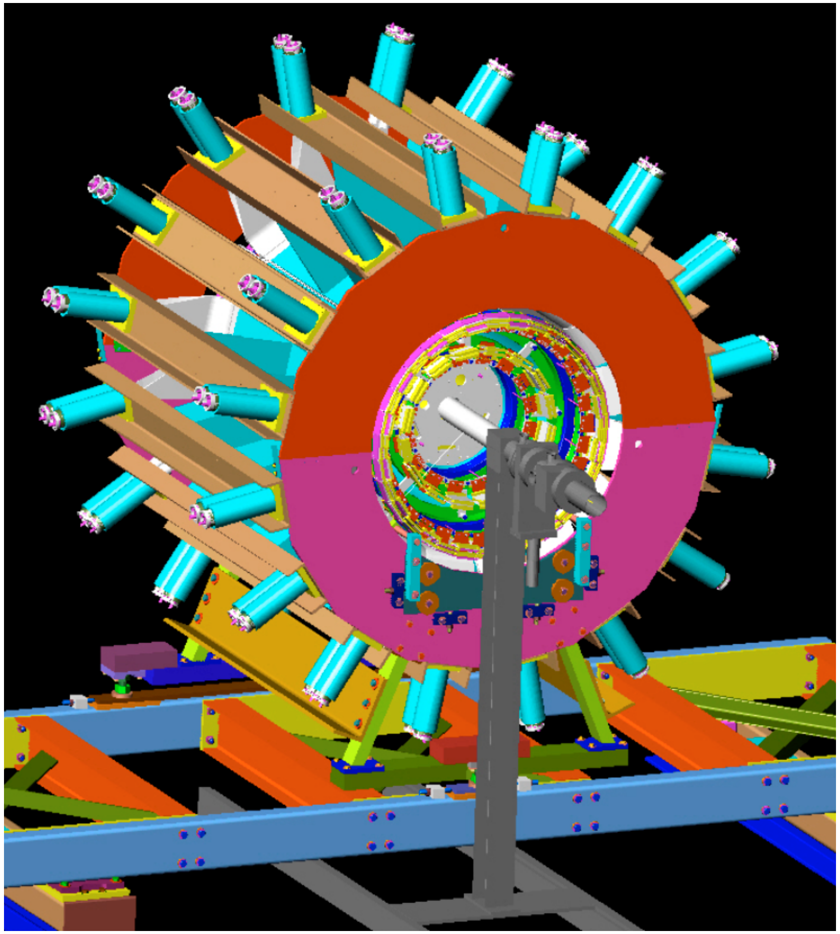
FAST	2.197 083(35)	

Graphical summary of τ_{μ^+} experiments



The MuCap experiment: A measurement of the Muon Capture rate in hydrogen gas

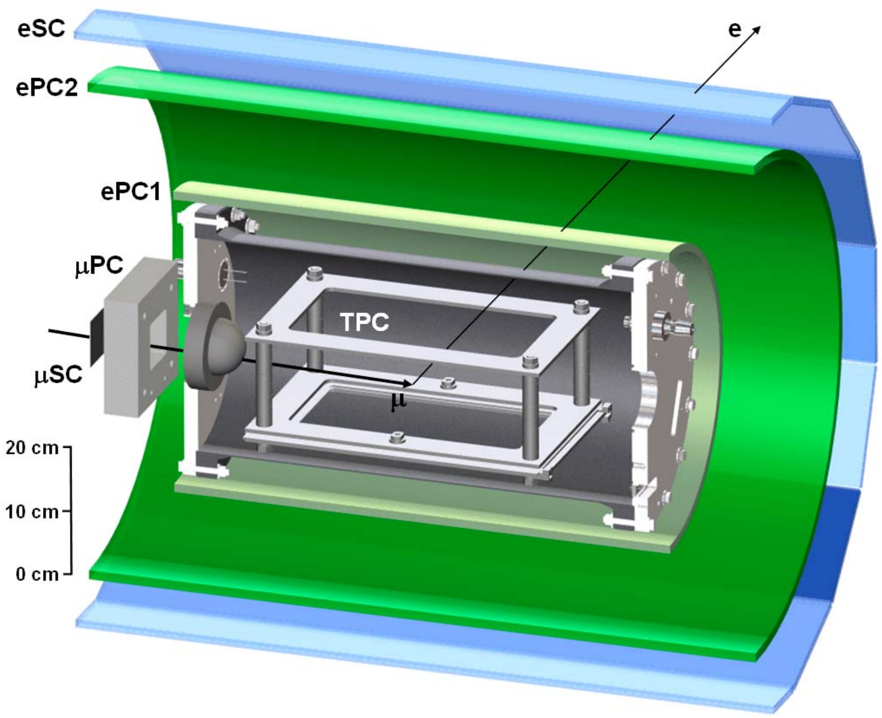


Experimental basics

We measure the rate of the (semileptonic, weak) process of nuclear muon capture by the proton,

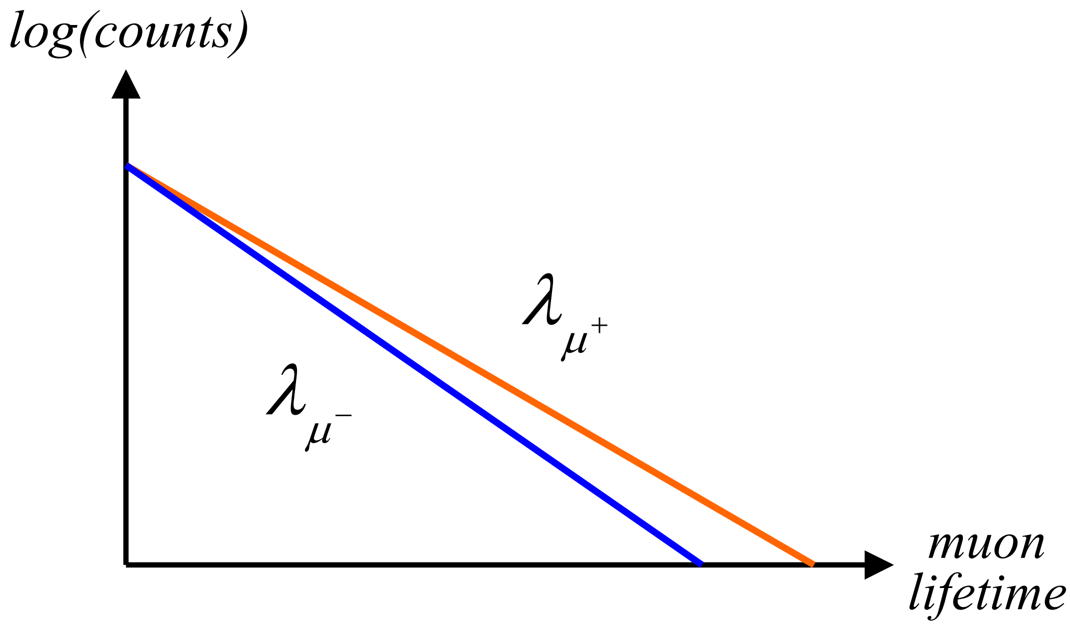
$$\mu^- + p \to n + \nu_\mu$$

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



Experimental basics

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

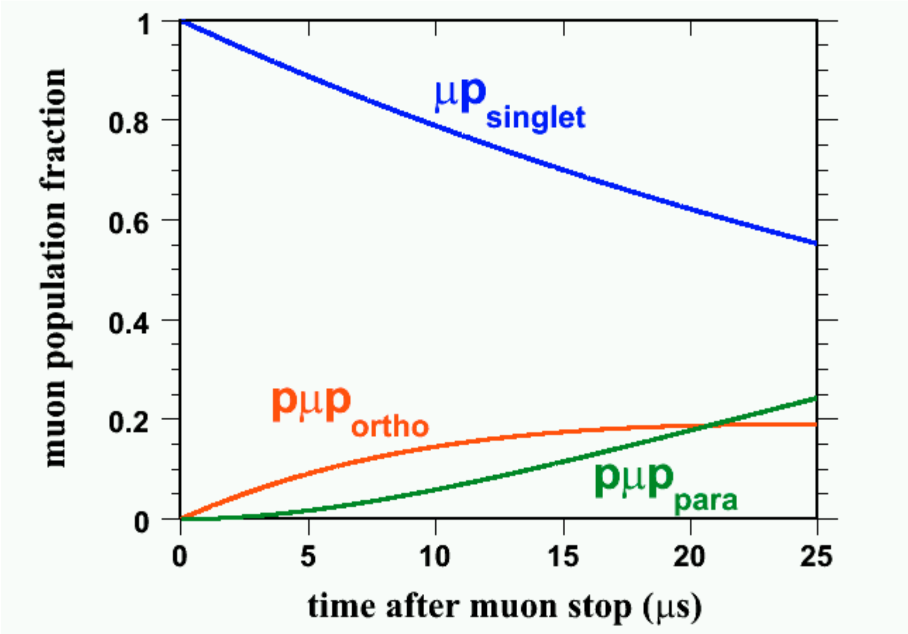


The muon capture rate can therefore be obtained from the small (0.16%) difference between the two disappearance rates:

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

Motivation

In our gaseous hydrogen target, most muons reside in the hyperfine singlet ground state of the μp atom:



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

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

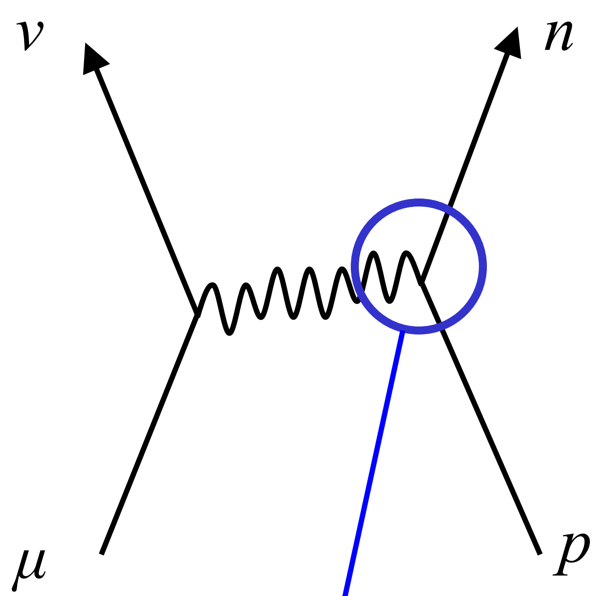
$$\Lambda_{\mathrm{pm}} \approx 208 \ \mathrm{s}^{-1}$$

Consequently, most captures (96%) proceed from the singlet state:

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

Motivation

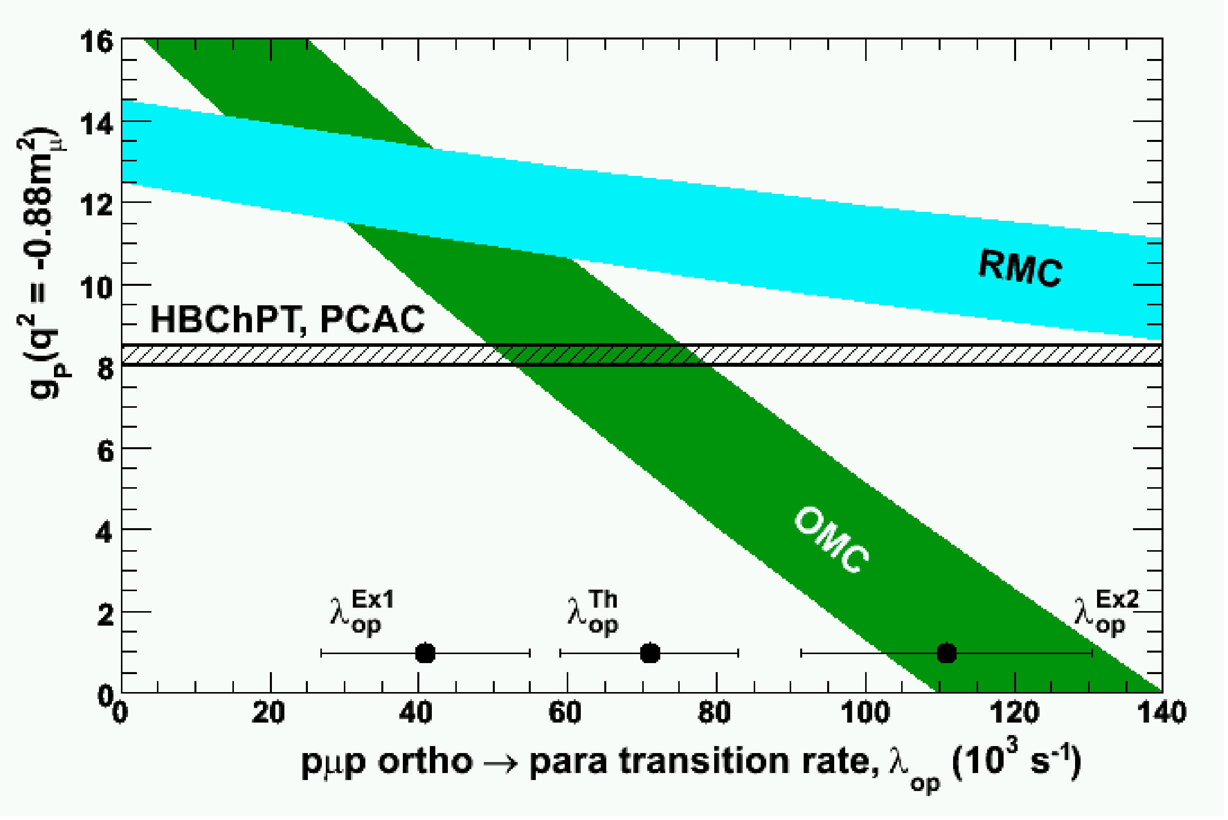
A 1% measurement of Λ_S would determine the nucleon's weak induced pseudoscalar coupling, g_P, to 7%.



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

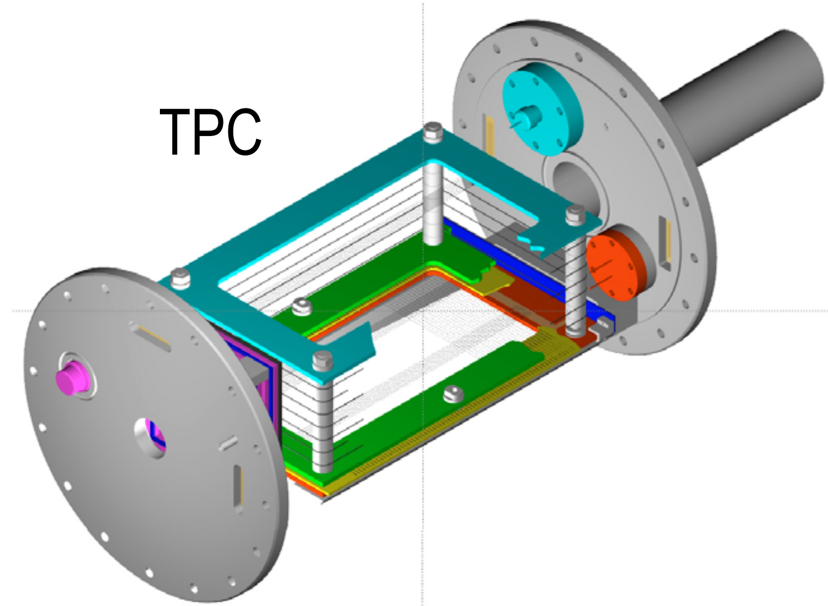
Motivation

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



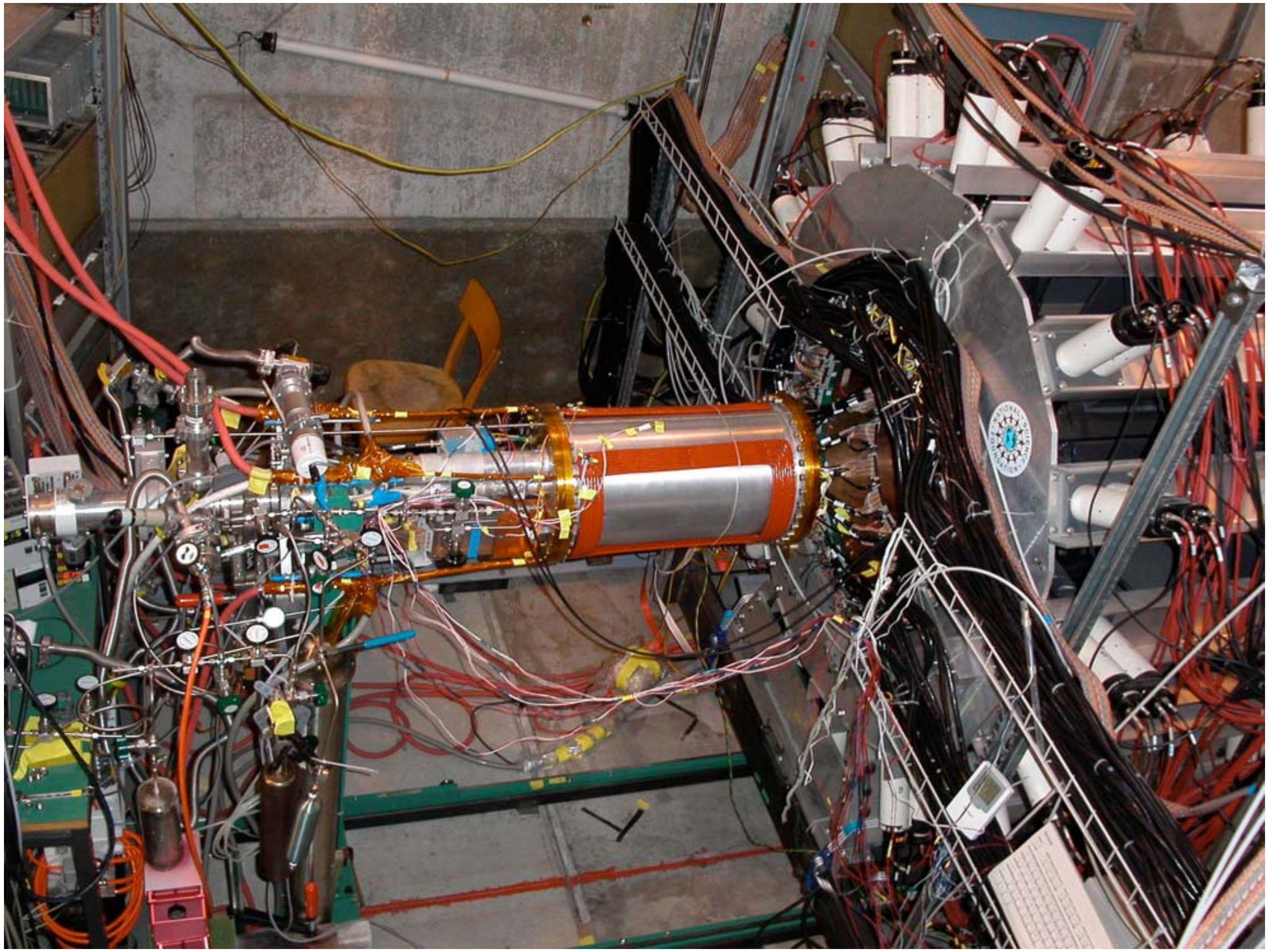
How is MuCap better?

1. **Target**: Our target is a time projection chamber (TPC) operating in ultraclean, low-density hydrogen gas. This has never been done before.



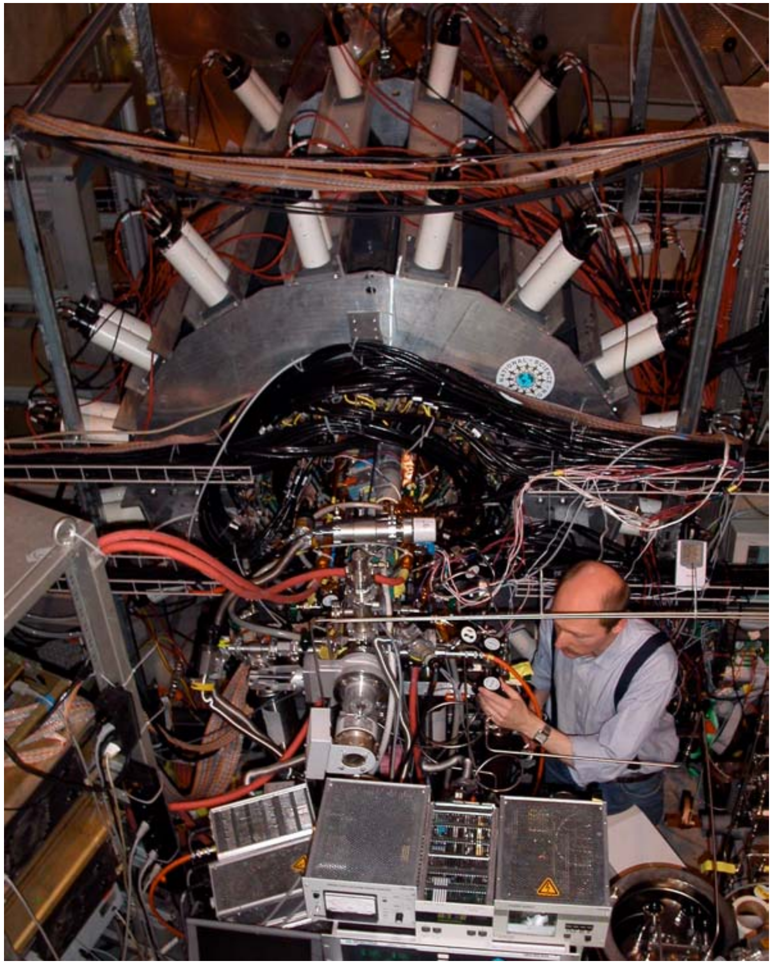
2. **Statistics**: To measure the capture rate to 1%, we must collect 1010 decay events. This is possible through our unique combination of detectors and analysis capabilities.

2004 data collection



MuCap detectors assembled at PSI,
October – November 2004.

2004 data collection



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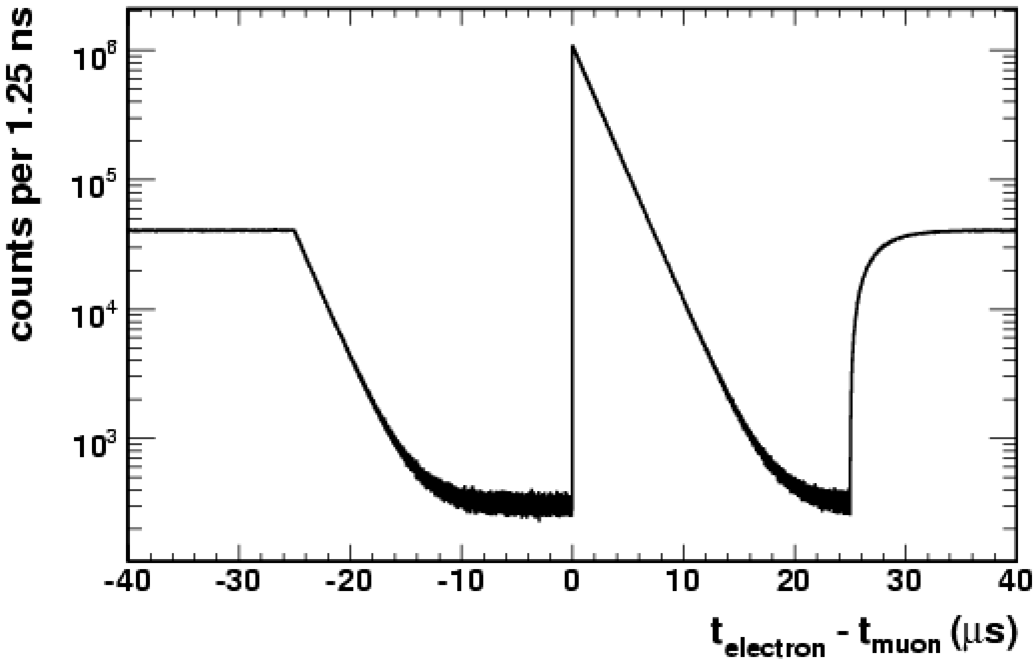
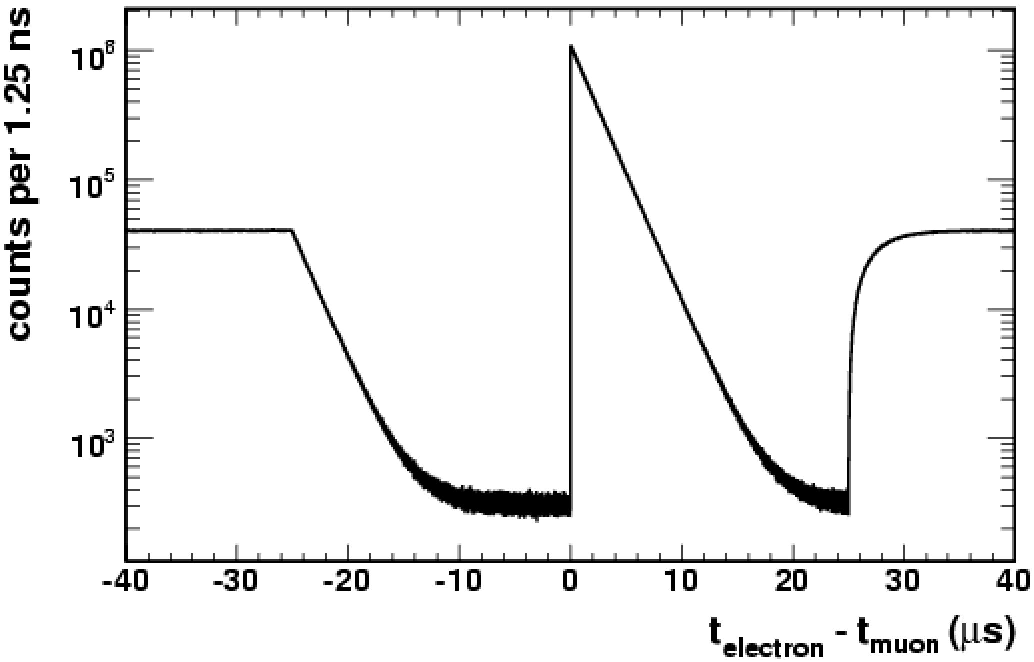
2004 data analysis



We recorded roughly 1.6 x 10^9 negative muon decay events during our first physics run in 2004. The muon disappearance rate is obtained by fitting the measured decay spectrum with an exponential function,

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

2004 data analysis



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

However, in reality the lifetime spectrum is not a pure exponential, and the fitted disappearance rate

$$\lambda \neq \lambda_{\mu^+} + \Lambda_S \ !$$

Summary of corrections

Source	λ (s^{-1})	σ_λ (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
mup bound state decay rate	12.3	
Adjusted disappearance rate	455 887.2	± 16.8

Result for the capture rate

Subtracting the positive muon lifetime measured by MuLan yields

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

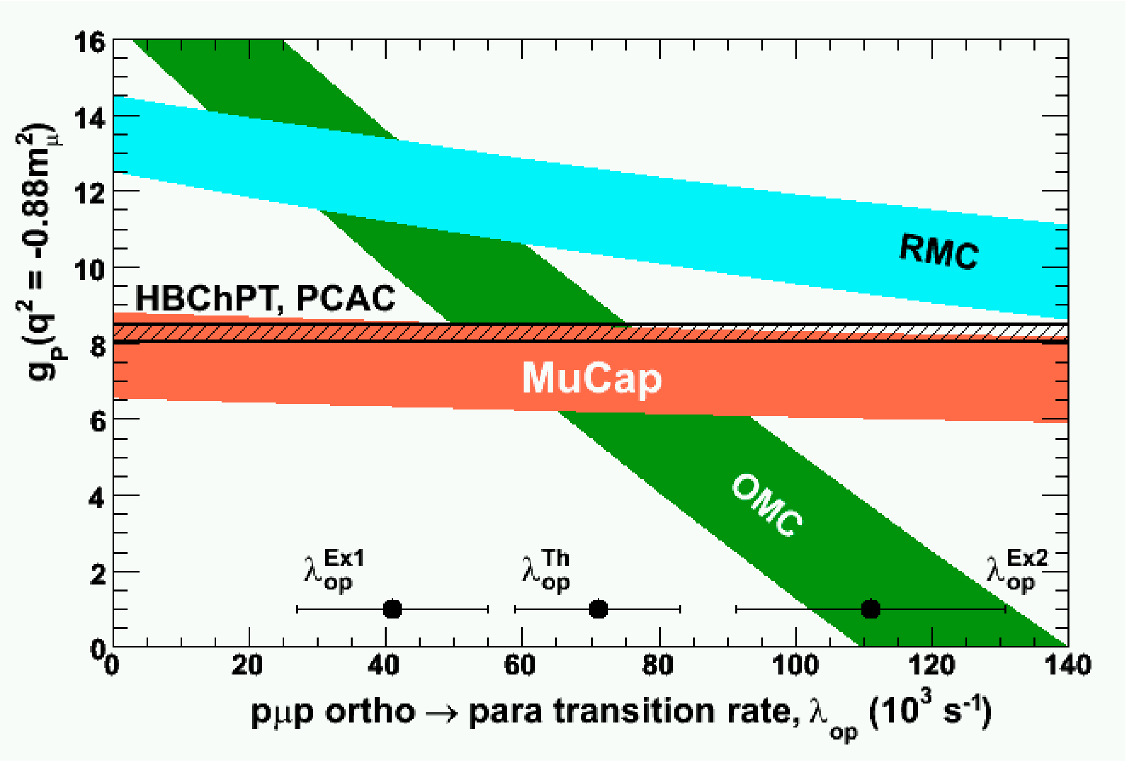
Roughly 13.7 Hz of the uncertainty is statistical, and 10.7 Hz is systematic. This result is consistent within 1σ with the latest theoretical calculations which predict 711.5 ± 4.5 Hz. Both results appeared in the July 20, 2007 issue of Physical Review Letters. (PRL **99**, 032002 and 032003 (2007))

Implications for g_P

From the capture rate we can extract the value

$$g_P = 7.3 \pm 1.1$$

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



Future

During 2005 – 2007 we have continued to collect data of superior quality:

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

As a result, we expect to reduce the statistical and systematic errors by at least a factor of two. Analysis of recent data is in progress, and we hope to reach the design goal of a 1% capture measurement.

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
University of Kentucky, USA
Boston University, USA

The MuCap experiment is supported in part by the United States Department of Energy and the National Science Foundation.

www.npl.uiuc.edu/exp/mucapture