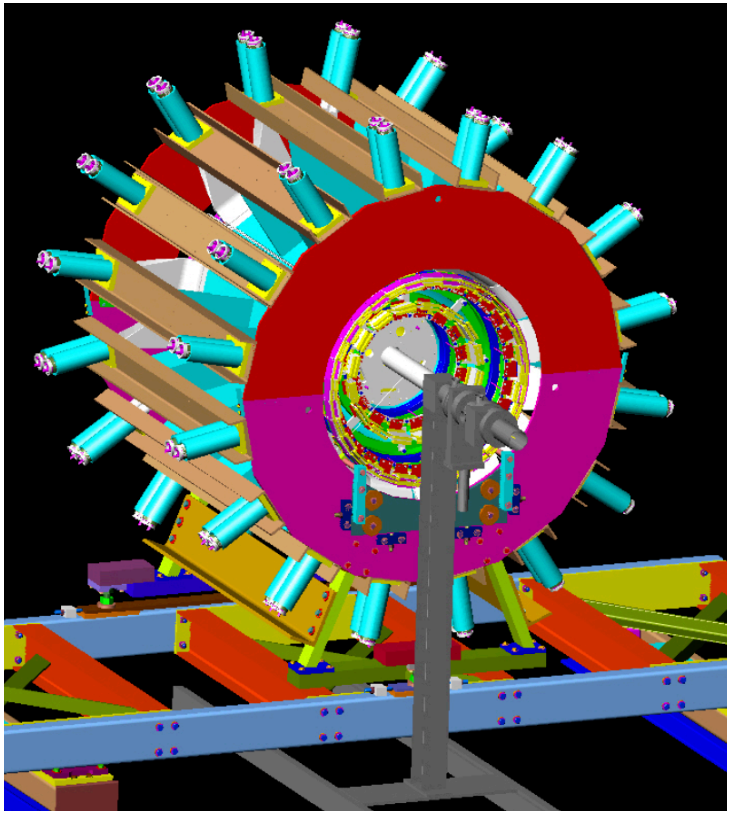
An Introduction to the MuCap Experiment



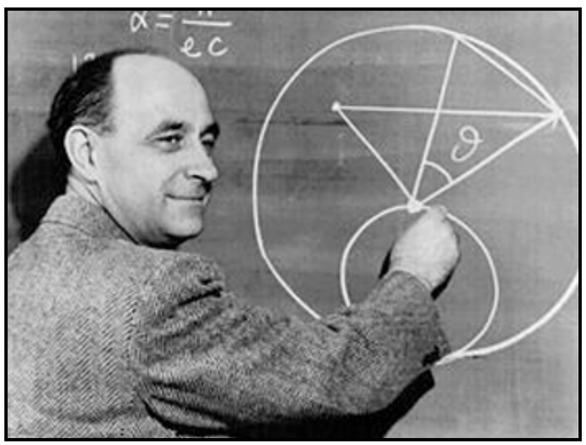
Tom Banks, UC Berkeley
APS April Meeting
May 4, 2009

Muon capture

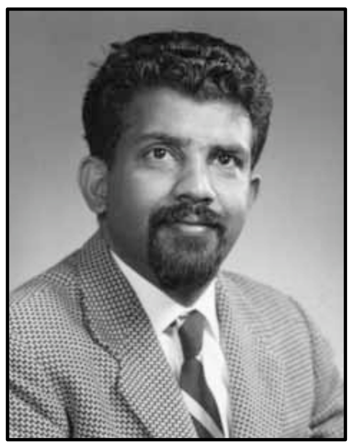
MuCap studies the process of nuclear muon capture:

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

In the 1950s and 1960s, muon capture attracted attention — alongside beta decay and muon decay — for its potential to shine light on the fundamental character of the weak interaction, such as its μ-e universality and *V*−*A* structure.



Fermi



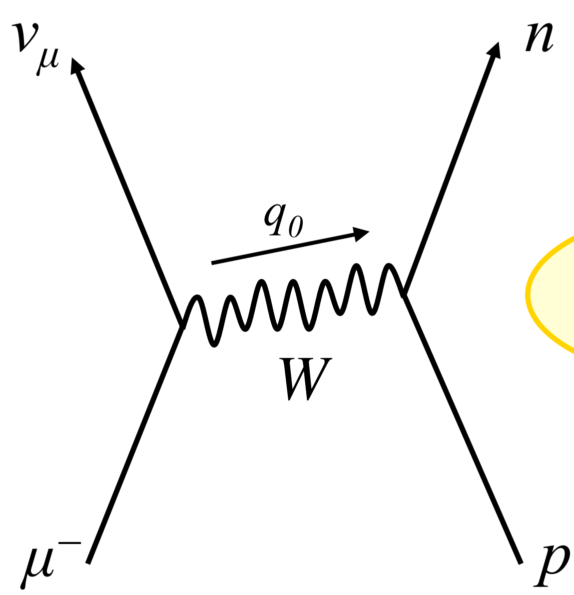
Sudarshan

Marshak

Gell-Mann & Feynman

Muon capture

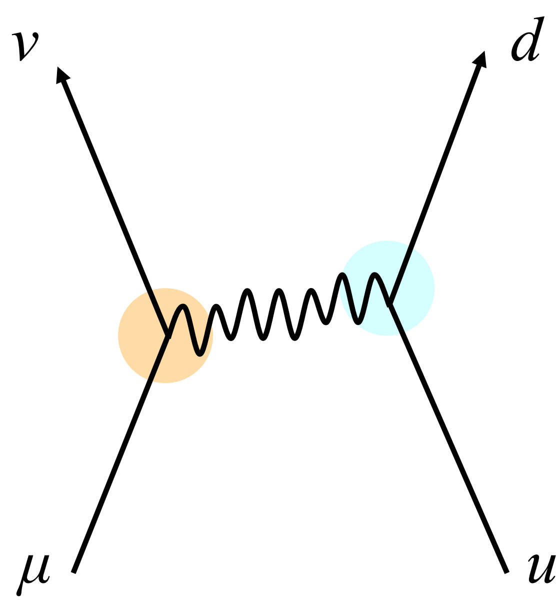
- Semileptonic, charged-current weak interaction process
- Relatively large, fixed momentum transfer



$$q_0^2 = -0.88 m_\mu^2$$

Muon capture

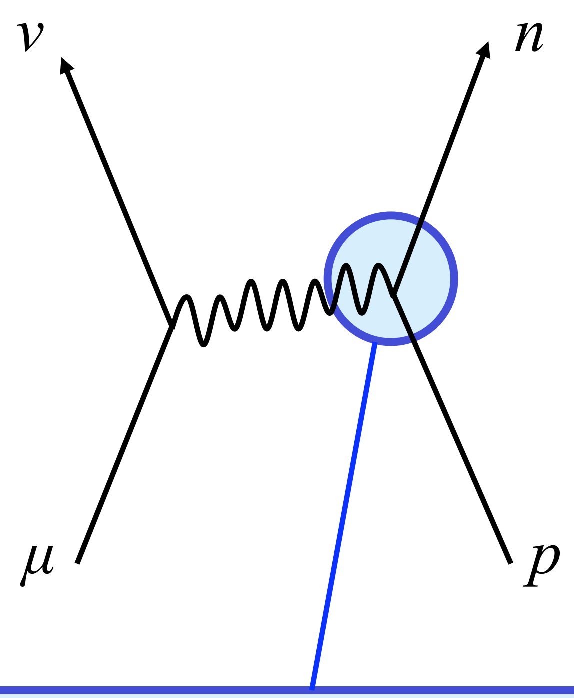
At a fundamental level, the leptonic and quark currents possess the simple *V*−*A* structure characteristic of the weak interaction.



$$L = \frac{G_F V_{ud}}{\sqrt{2}} \left[\nu \gamma_\alpha (1 - \gamma_5) \mu \right] \left[d \gamma_\alpha (1 - \gamma_5) u \right]$$

Muon capture

In reality, the QCD substructure of the nucleon complicates the weak interaction physics. These effects are encapsulated in the nucleonic charged current's four "induced form factors":



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

The pseudoscalar coupling g_P

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

- The pseudoscalar g_P is by far the least well known of the form factors:

$g_V = 0.976(1)$

$g_M = 3.583(3)$

$g_A = 1.247(4)$

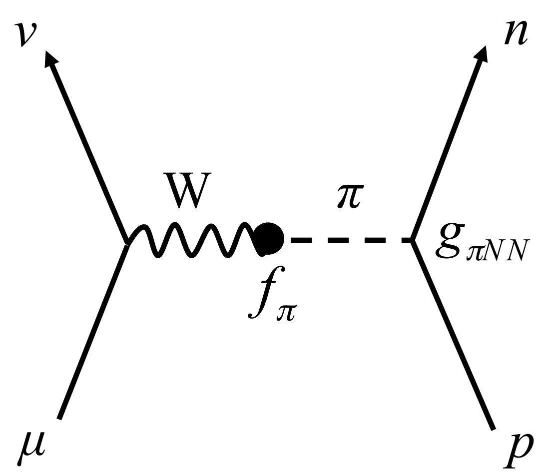
$g_P = 8.26, 8.7, 10.6, 12.2, \ldots ?$

values and q^2-dependence known from EM form factors via CVC (g_V, g_M)

value known from β–decay; q^2-dependence known from neutrino scattering (g_A)

- Modern theories make relatively precise (3%) predictions for g_P, but existing experimental results are inconsistent

The pseudoscalar coupling g_P



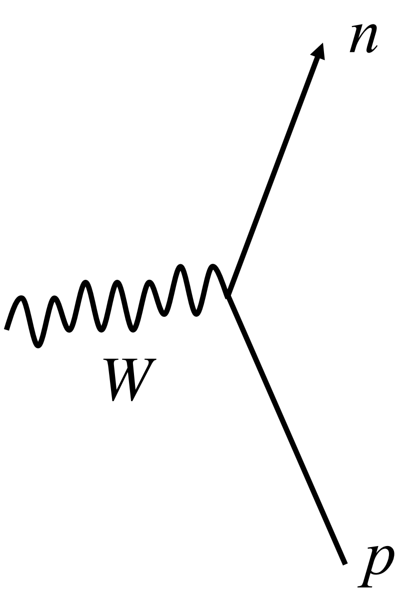
- Pion pole is dominant contributor to the pseudoscalar form factor
- PCAC yielded an expression for the pseudoscalar more than 30 years ago:

$$g_P(q^2) = \frac{2m_\mu f_\pi g_{\pi NN}(q^2)}{m_\pi^2 - q^2} - \frac{1}{3} g_A(0) m_\mu m_N \langle r_A^2 \rangle$$

- Modern chiral perturbation theories (ChPT), which are low-E effective QCD, reproduce the PCAC result in systematic expansions: $g_P(q_0^2) = 8.26 \pm 0.23$
- Very recent progress in numerical lattice QCD calculations of form factors

Measuring g_P

- The pseudoscalar form factor participates in any process involving the nucleon's charged current, including:
  - beta decay
  - neutrino scattering
  - pion electroproduction
  - muon capture



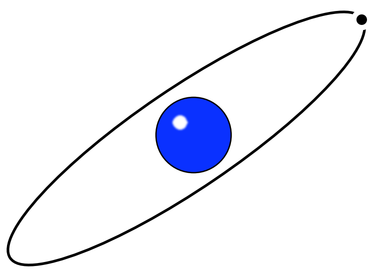
- Muon capture is the most attractive because of its
  - large momentum transfer
  - comparative ease of measurement
  - model-independent connection to g_P

- Muon capture offers a unique probe of the nucleon's electroweak axial structure

Measuring g_P via muon capture

Muon capture can take place in any nucleus, but there are trade-offs involved…

Hydrogen

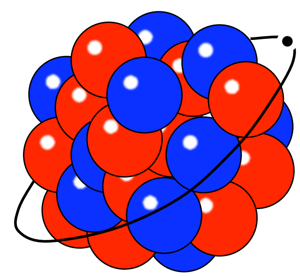


$$a_\mu \approx a_e\left(\frac{m_e}{m_\mu}\right)$$

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

- 👍 No nuclear environment
- 👎 Low capture rate: 10^{-3} of decay rate $\lambda_0 \approx 455$ kHz
- 👎 Complications from muon kinetics
- 👎 All-neutral final state

Z > 1 nuclei



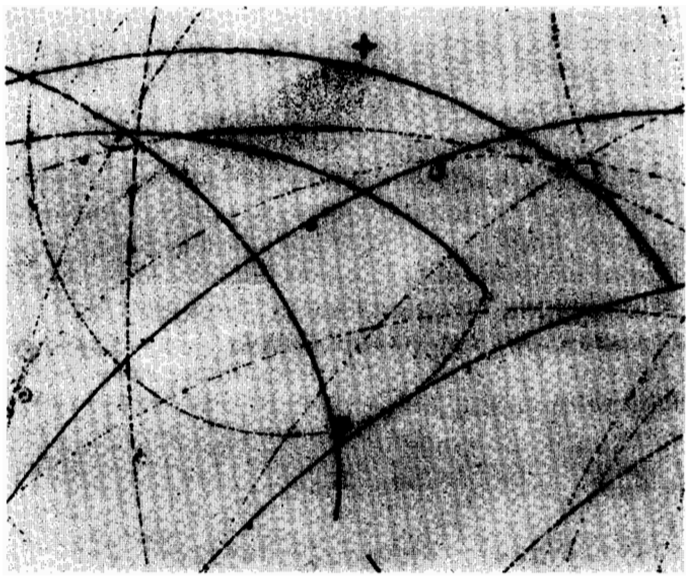
$$a_\mu \approx \frac{a_e}{Z}\left(\frac{m_e}{m_\mu}\right)$$

$$\mu^- + {}^{A}_{Z}N \rightarrow {}^{A}_{Z-1}N^* + \nu_\mu$$

- 👍 High capture rate: $\Lambda_c \propto Z^4$
- 👎 Complications from nuclear environment

Capture experiments in H_2: 1960—1980

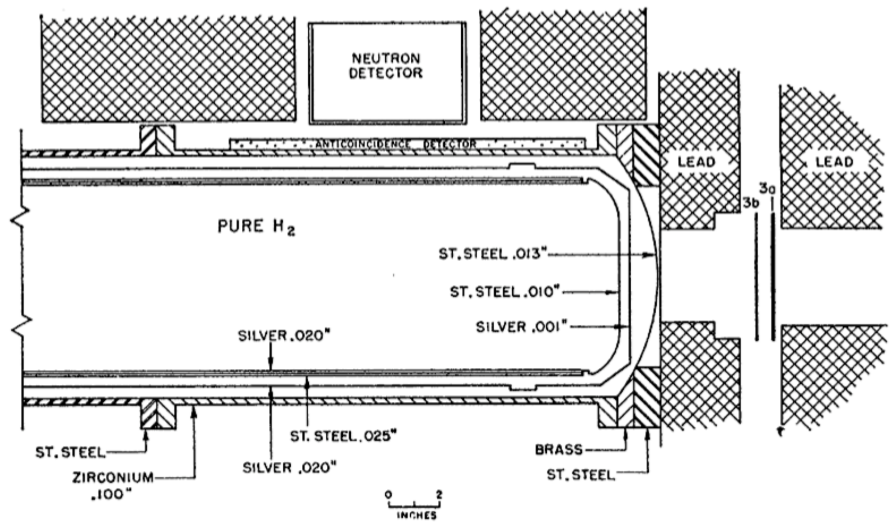
Bubble chambers



- Observed 5.2 MeV final-state neutrons, absence of decay electrons
- Measured time-integrated capture rate
- Statistics limited

• R.H. Hildebrand, Phys. Rev. Lett. 8, 34–37 (1962)
• Bertolini et al. (1962)

Neutron counters

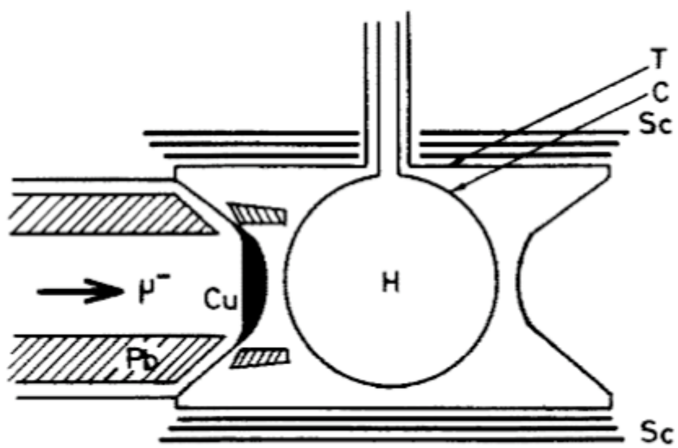


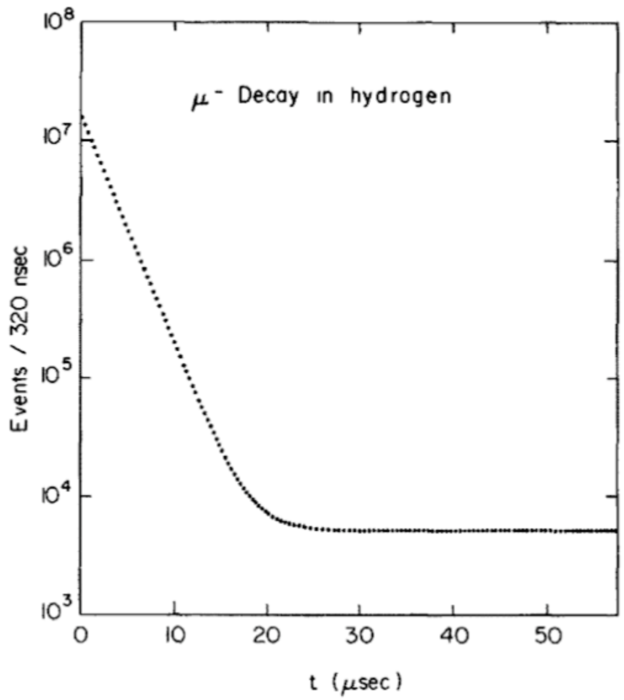
- Observed 5.2 MeV final-state neutrons, absence of decay electrons
- Measured capture time distribution
- Limited by calibration efficiency of scintillating neutron detectors

• E. Bleser et al., Phys. Rev. Lett. 8, 288 (1962)
• J.E. Rothberg et al., Phys. Rev. 132, 2664 (1963)
• A.A. Quaranta et al., Phys. Rev. 177, 2118 (1969)
• V.M. Bystritsky et al. Sov. Phys. JETP 39, 19 (1974)

Capture experiments in H_2: 1980s

"Lifetime technique"





The 1981 Saclay experiment used a novel approach: instead of directly observing capture events by detecting final-state neutrons, they measured the time spectrum of μ^- decay electrons in liquid hydrogen and compared it to the μ^+ time spectrum.

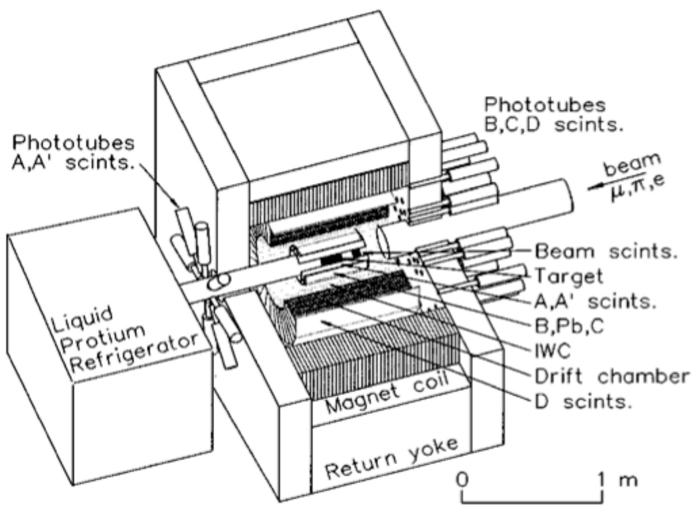
G. Bardin et al., Nucl. Phys. A352, 365–378 (1981)

Capture experiments in H_2: RMC

Radiative muon capture (RMC) in hydrogen provides yet another avenue:

$$\mu^- + p \rightarrow n + \nu_\mu + \gamma$$

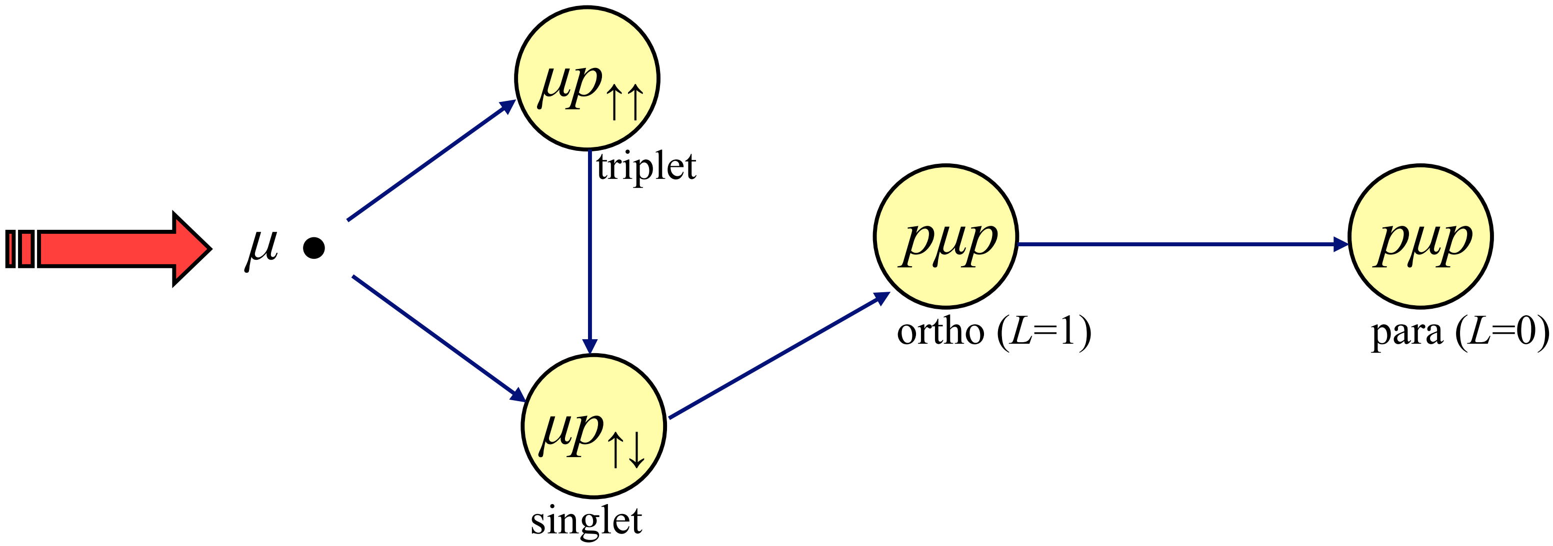
- 👍 Variable momentum transfer → more sensitive to pion pole than ordinary muon capture (OMC)
- 👍 Less sensitive to molecular effects than OMC experiments
- 👎 Branching ratio ~ 10^{-8} (compared to OMC ~ 10^{-3})



Only 1 RMC measurement to date: 1996 TRIUMF experiment counted photons with E > 60 MeV

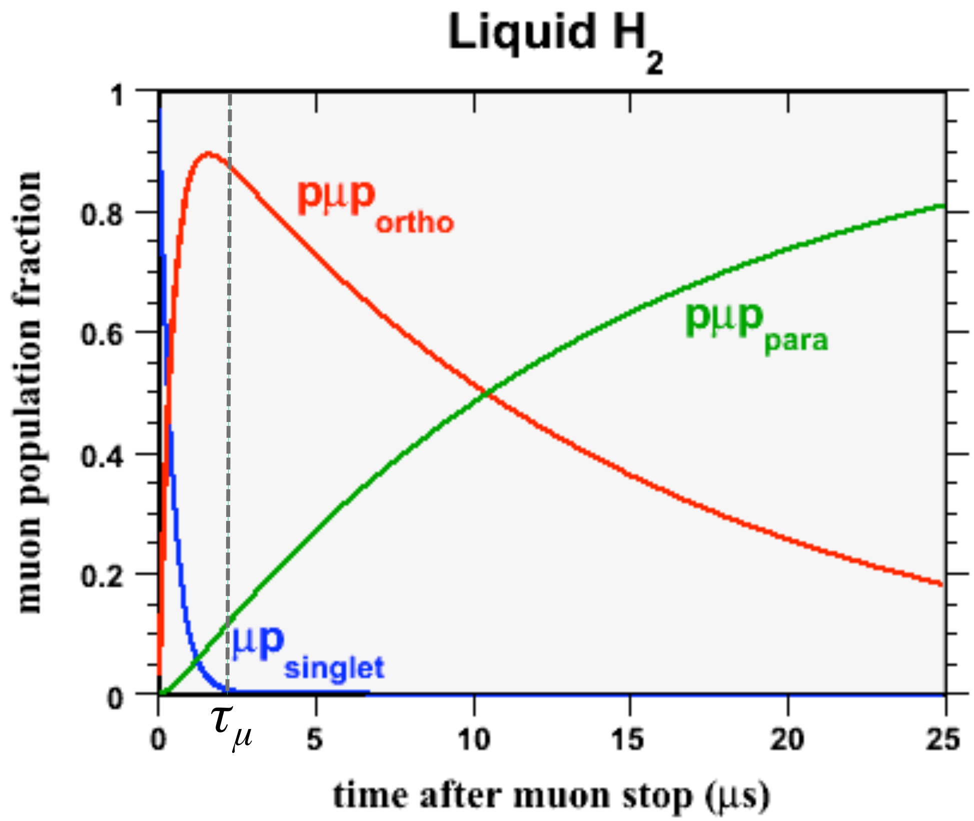
D. H. Wright et al., Phys. Rev. C 57, 373–390 (1998)

Muon kinetics in H_2: $p\mu p$ formation



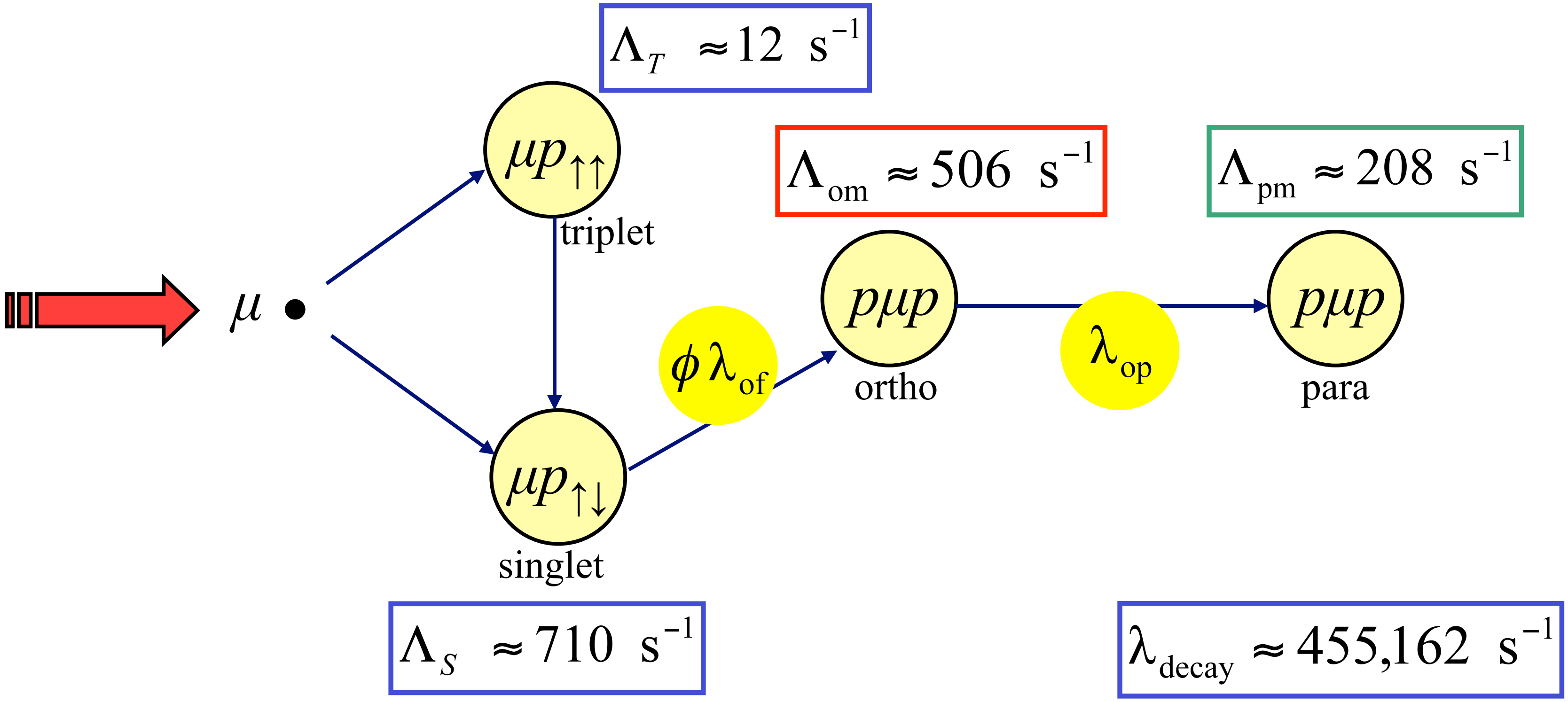
- Even in pure hydrogen gas, negative muons form a variety of atomic and molecular states
- Stopped muons immediately form μp singlet atoms
- As time goes on, the muons tend to form $p\mu p$ molecules, at a rate proportional to the hydrogen density ϕ

Muon kinetics in H_2: $p\mu p$ formation



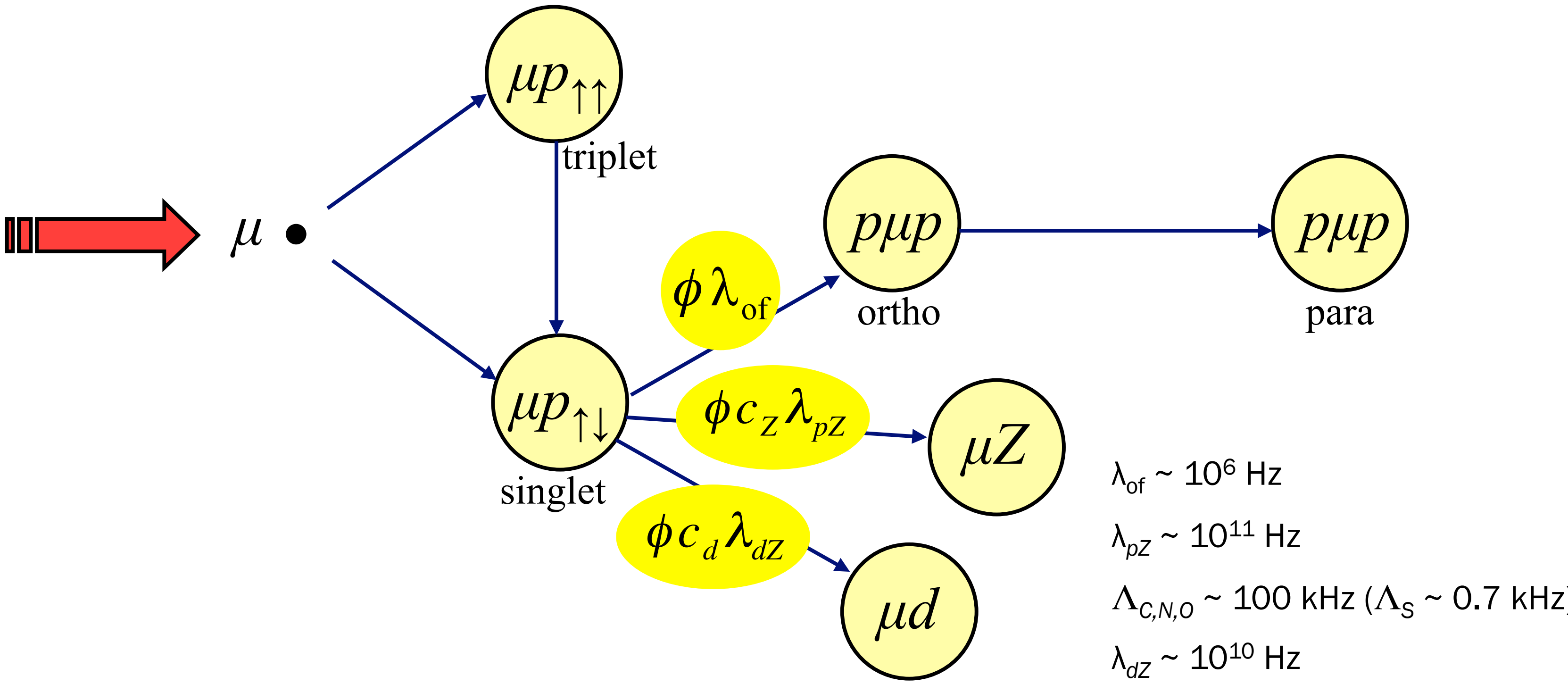
Muons stopped in liquid hydrogen spend most of their time in $p\mu p$ molecules.

Muon kinetics in H_2: $p\mu p$ formation



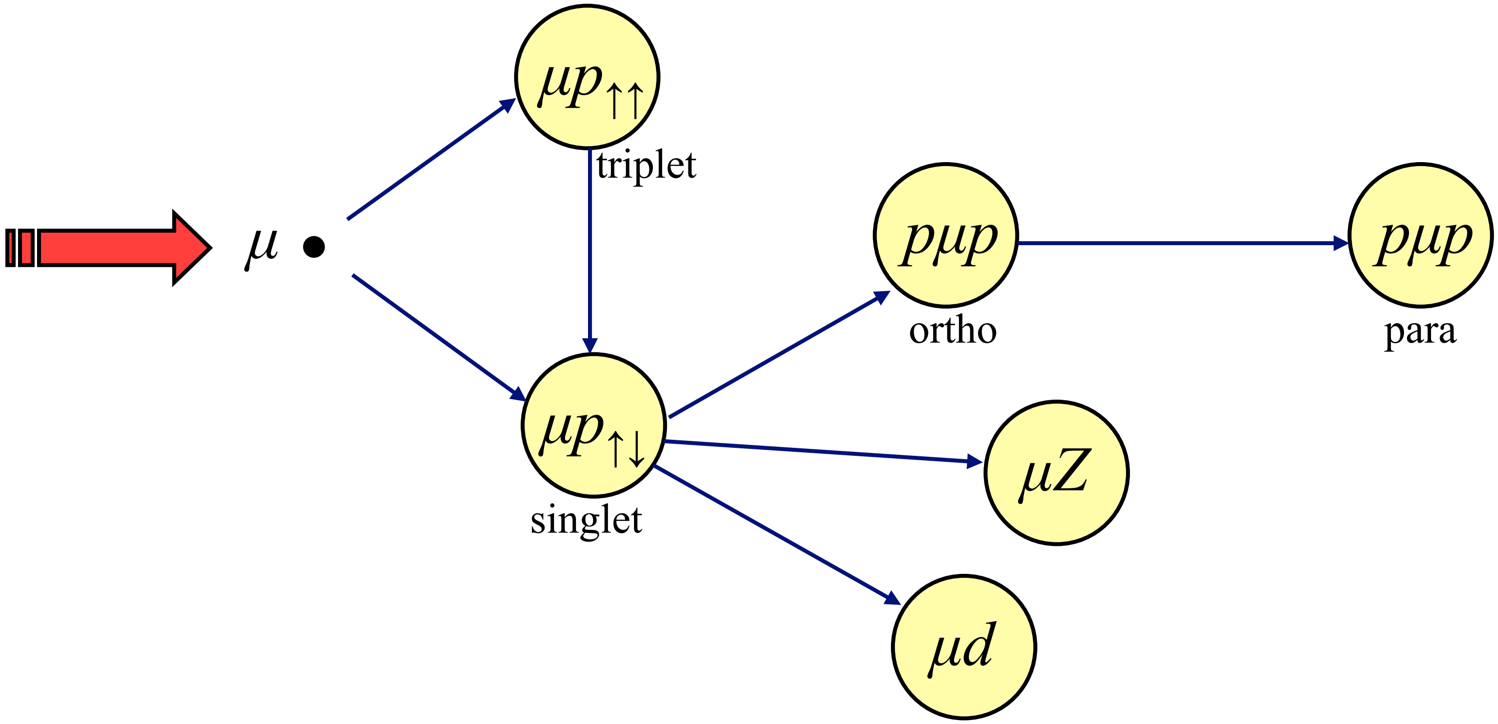
- Due to V-A, the capture rates are strongly dependent on the spin state → each muonic state has a unique nuclear capture rate
- Overall capture rate is a time-dependent combination of contributing rates
- The important transition rate λ_{op} is poorly known

Muon kinetics in H_2: Impurities



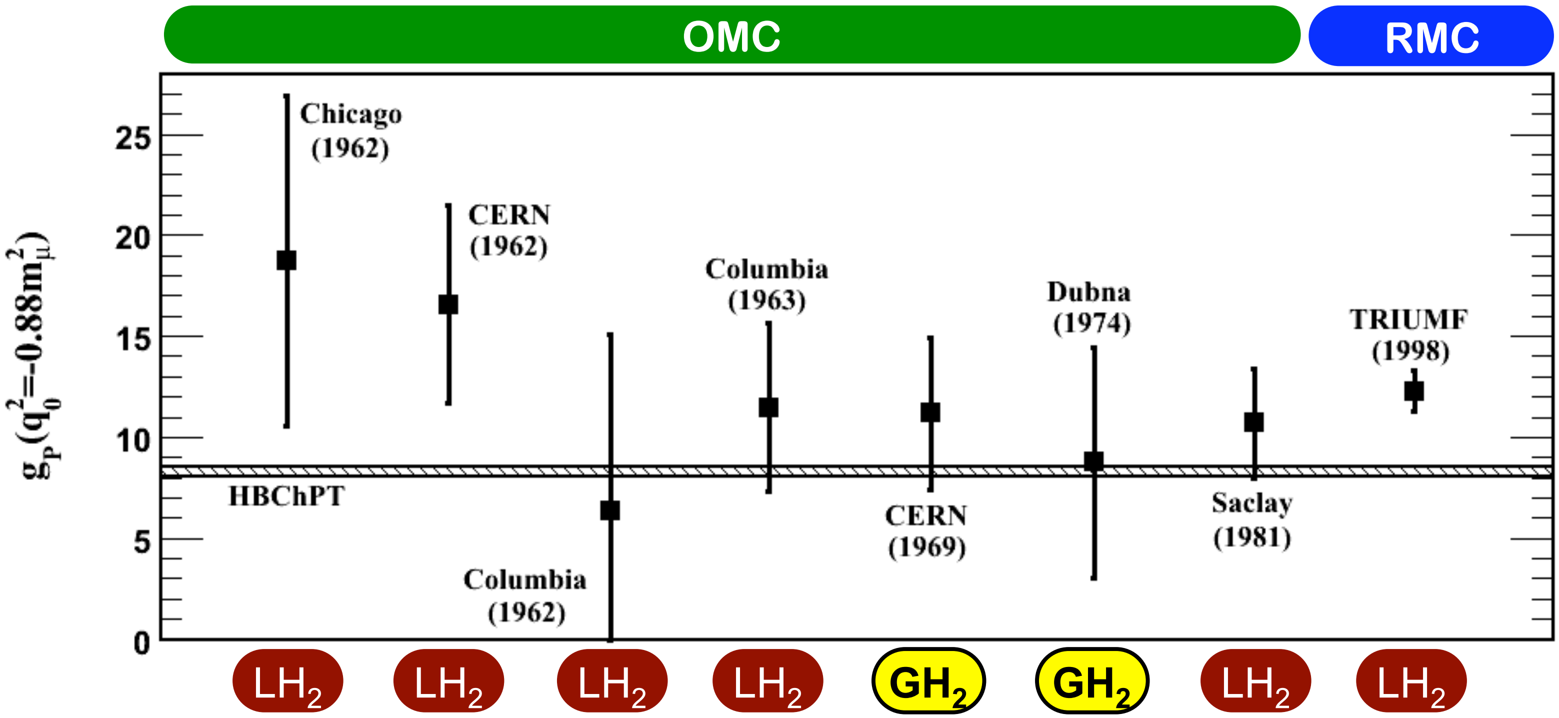
- Muons preferentially & irreversibly transfer to Z>1 and isotopic impurities, which provide more capture pathways with unique rates
- Small amounts of impurities can severely distort the observed capture rate
- μd atoms can (i) rapidly diffuse away from stopping point, (ii) participate in $p\mu d$ fusion

Muon kinetics in H_2: Impurities



Knowledge of the states' occupation numbers is essential for a correct interpretation of experimental results!

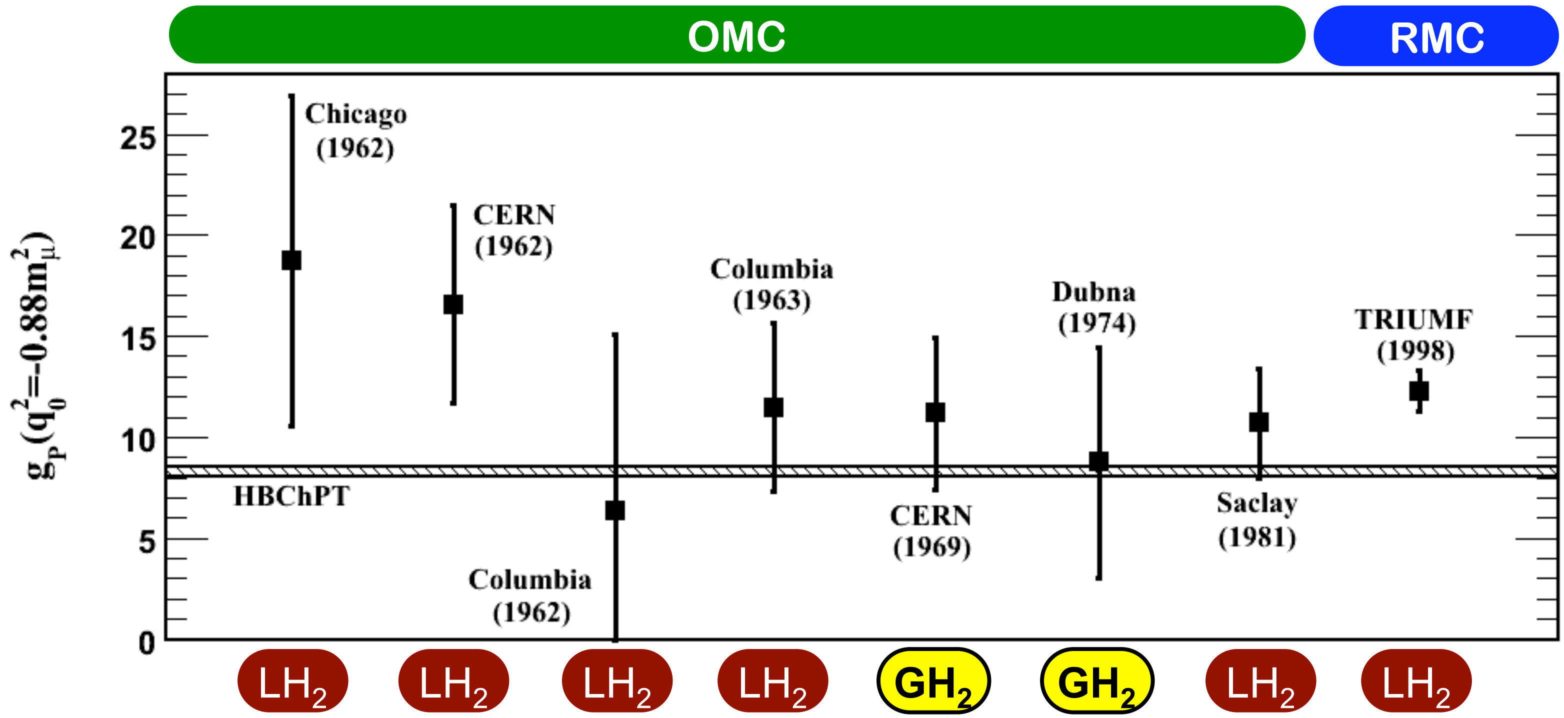
Experimental results



" Radiative muon capture in hydrogen was carried out only recently with the result that the derived g_P was almost 50% too high. If this result is correct, it would be a sign of new physics... "

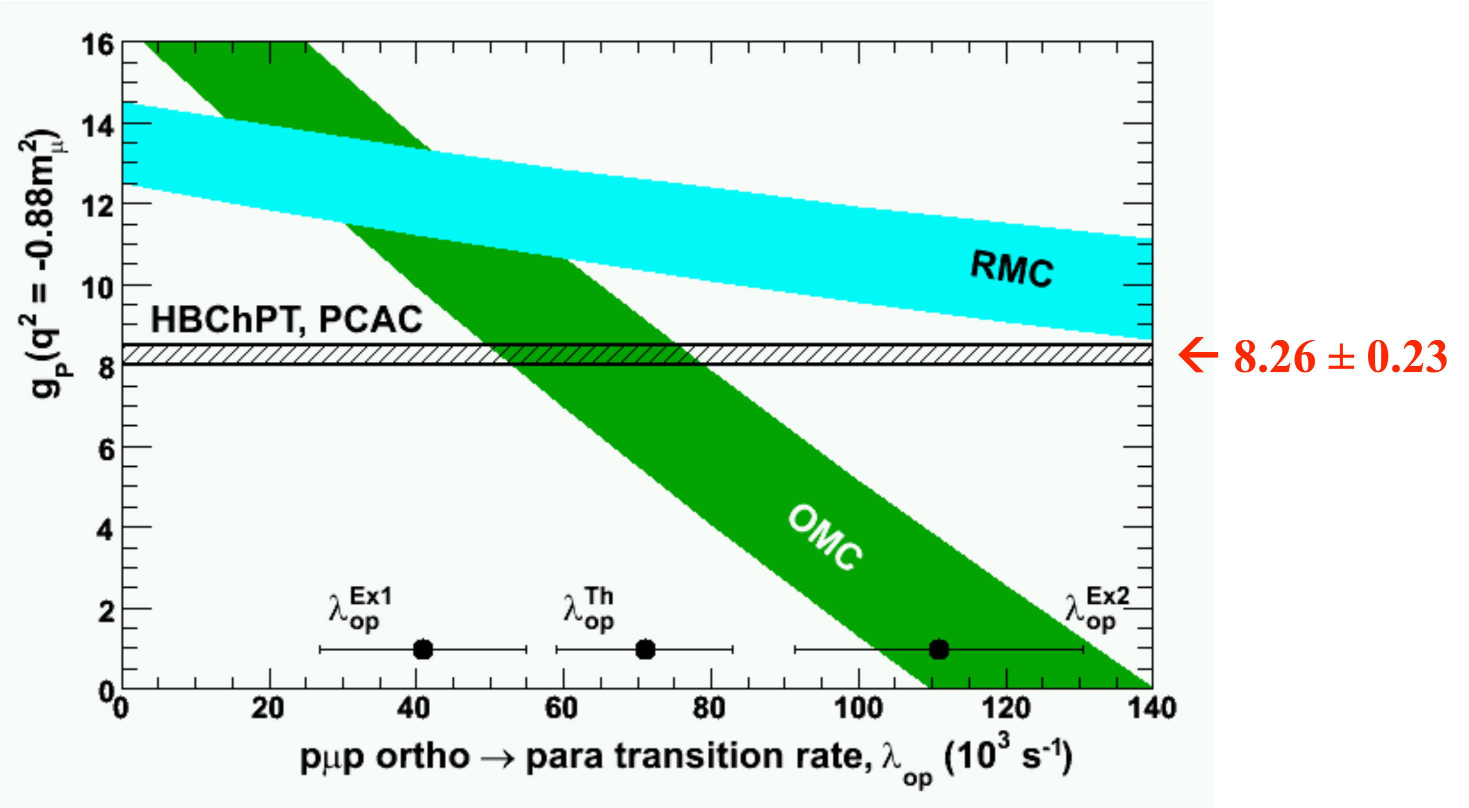
— Lincoln Wolfenstein (Ann. Rev. Nucl. Part. Sci. 2003)

Experimental results



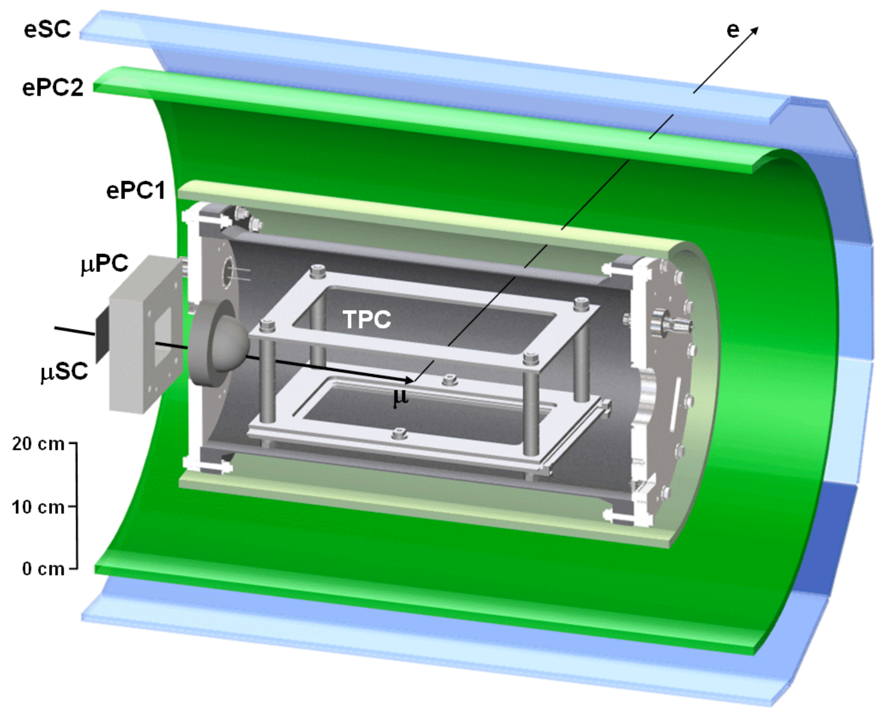
Plotting the g_P values in this way does not tell the entire story, however…

Experimental results



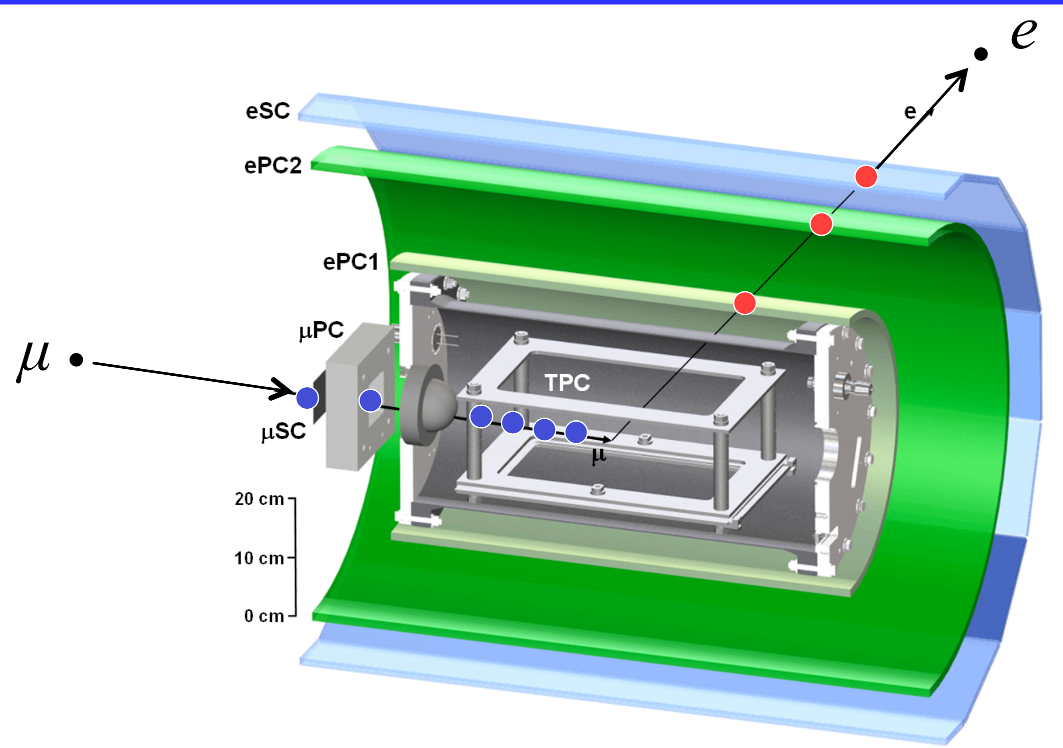
Prior to MuCap, the situation surrounding g_P was inconclusive, in large part due to uncertainties in the kinematics of muonic molecules.

MuCap experimental concept



MuCap measures the rate of nuclear muon capture by the proton by stopping negative muons in hydrogen gas and observing the time spectrum of decay electrons.

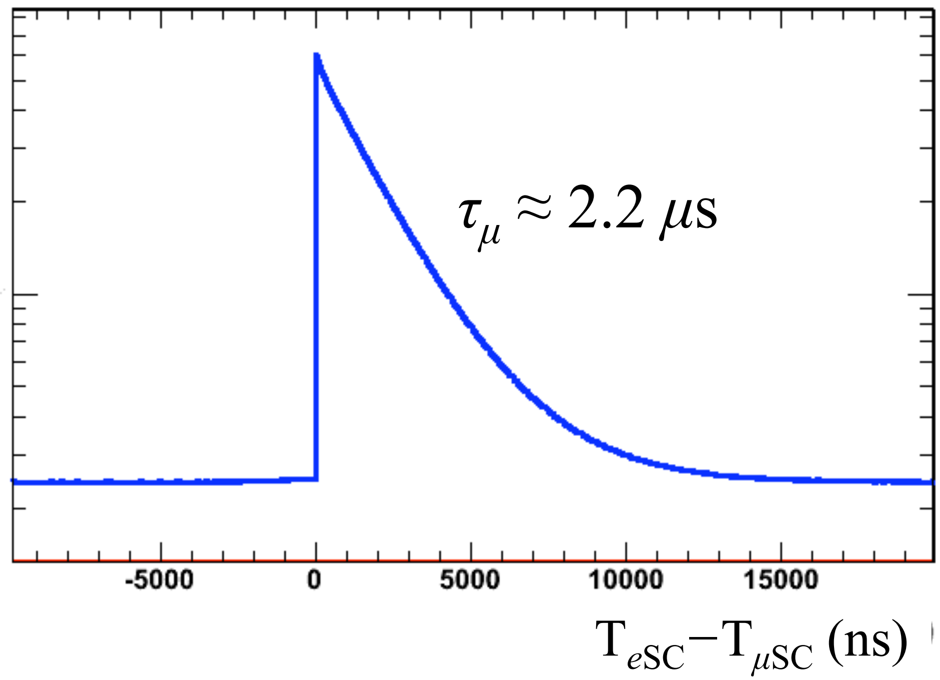
MuCap experimental concept



- **Muon detectors**
  - **μSC:** fast timing of muon arrivals
  - **μPC1, TPC:** 3D tracking of incoming muon trajectories
- **Electron detectors**
  - **ePC1, ePC2:** 3D tracking of outgoing electron trajectories
  - **eSC:** fast timing of outgoing decay electrons

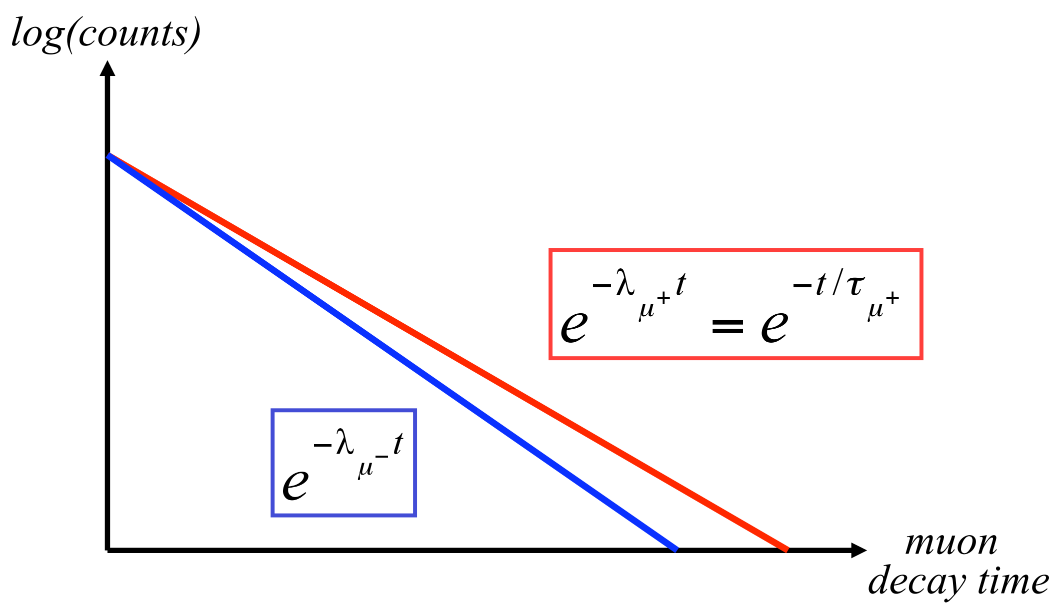
MuCap experimental concept

To obtain the muon lifetime, the muon decay times are histogrammed and fit with an exponential:



To achieve a 10 ppm lifetime measurement, it is necessary to collect 10^{10} decay events.

The "Lifetime Technique"

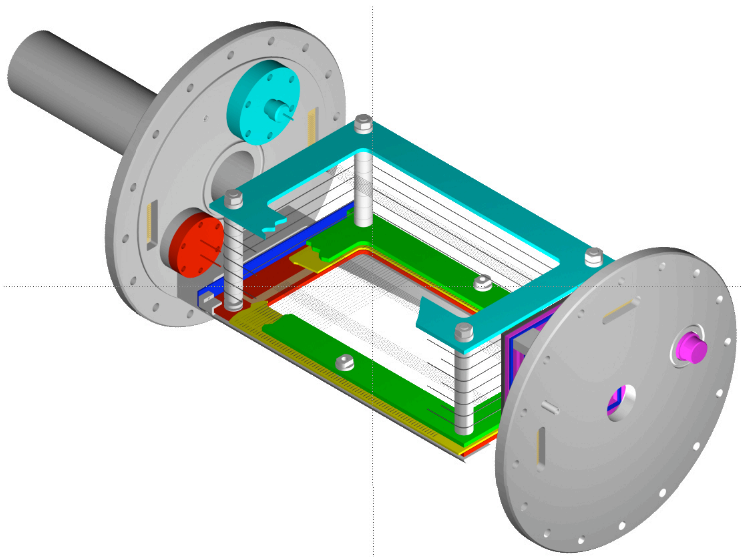


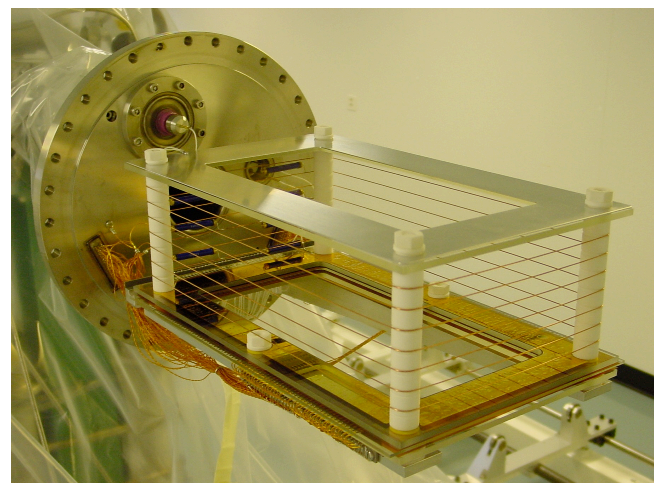
- Negative muons can disappear via decay or nuclear capture
- Positive muons can only decay
- The muon capture rate can be obtained from the small (0.16%) difference between the disappearance rates (i.e. inverse lifetimes) of the two species:

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

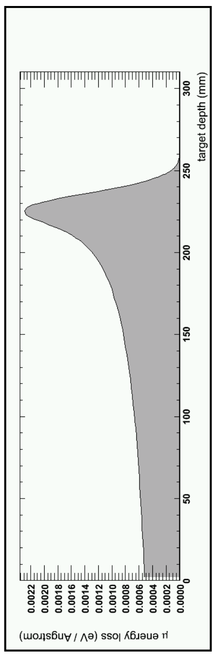
Time Projection Chamber

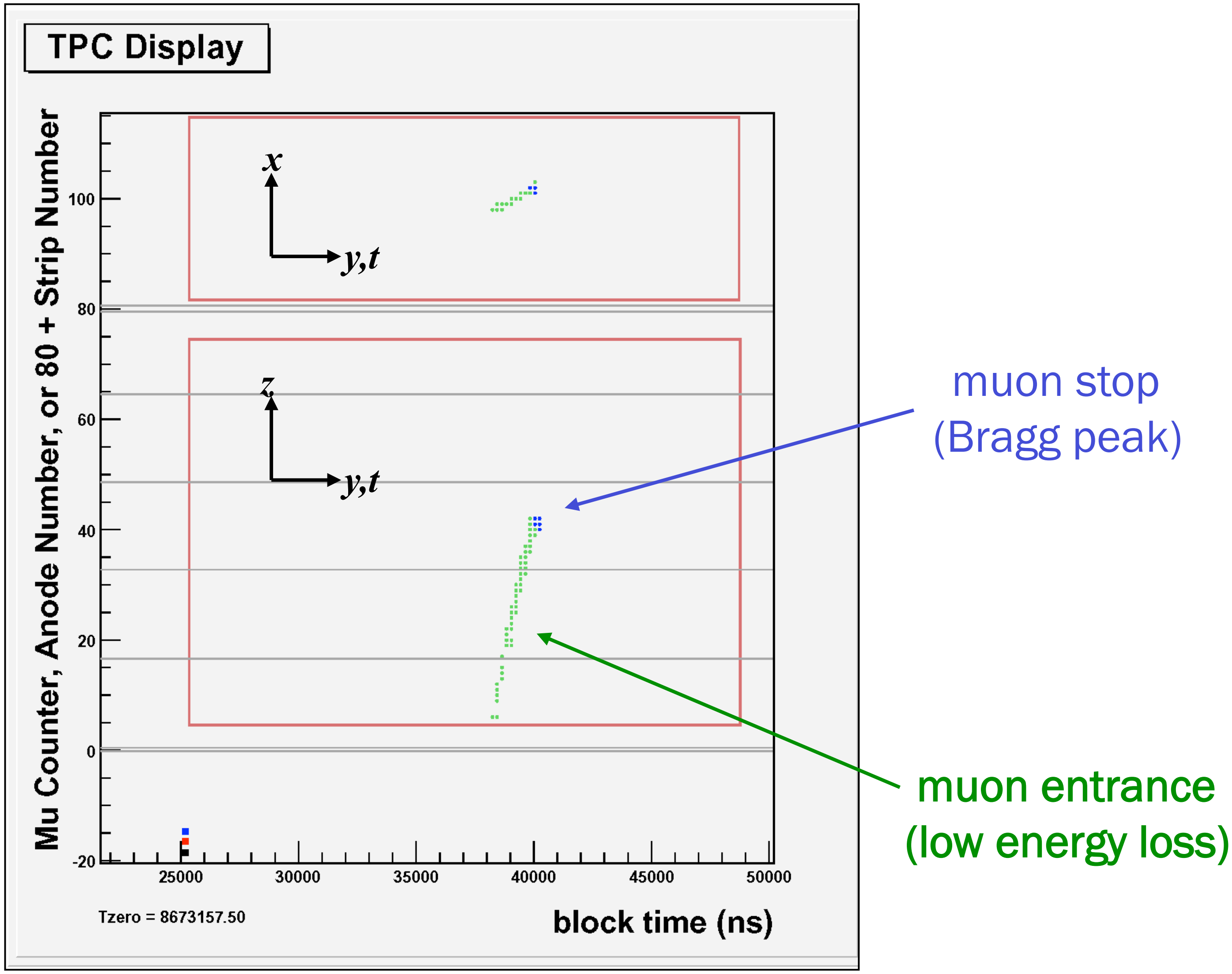
- Active target: H_2 gas is both muon stopping target and chamber gas
- TPC is first of its kind
- Provides three-dimensional tracking of incoming muons, enabling identification of “clean” muon stops
- Constructed of bakeable materials (quartz, ceramic)
- Operates at P=10 bar, room temp, 5 kV drift field (2 kV/cm)





Time Projection Chamber

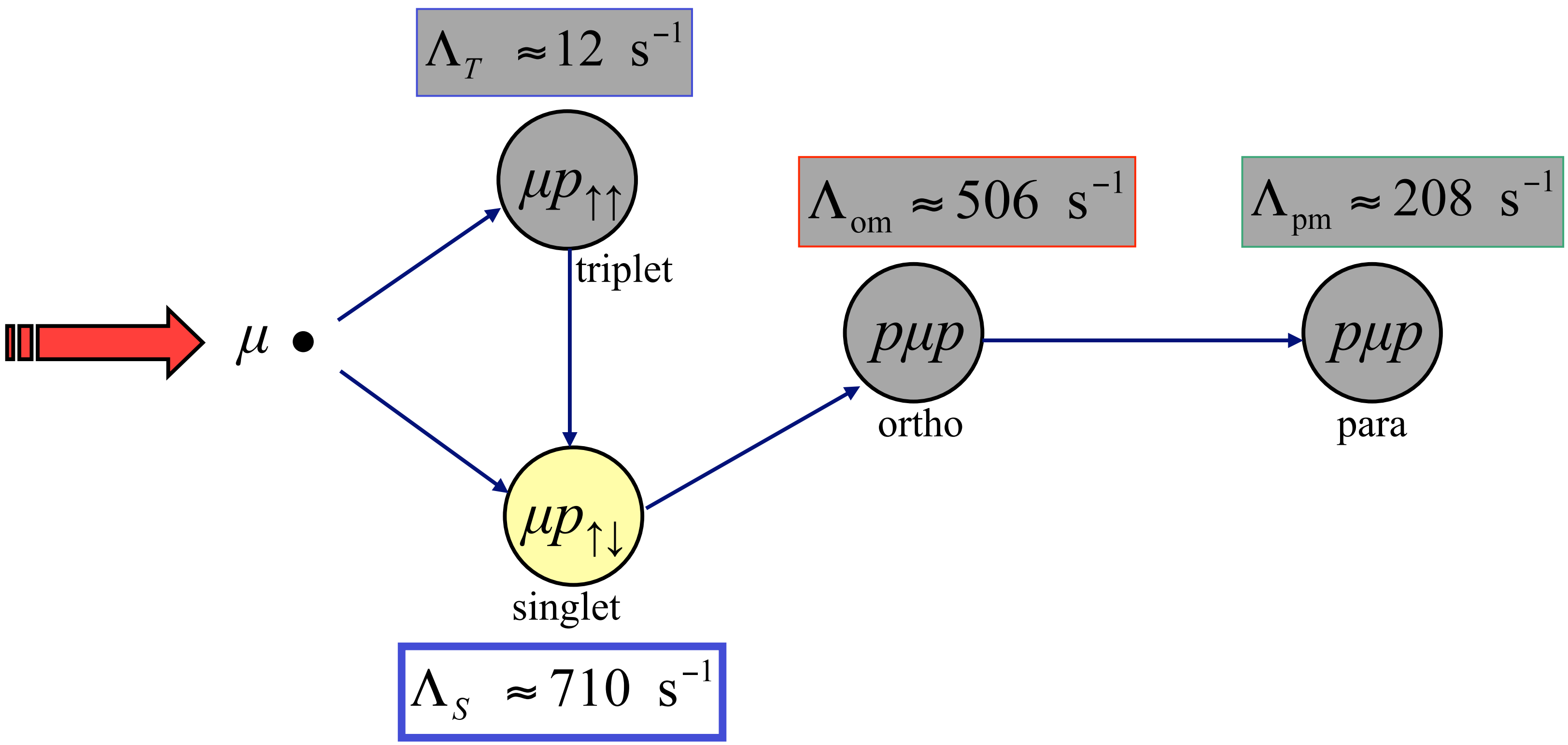




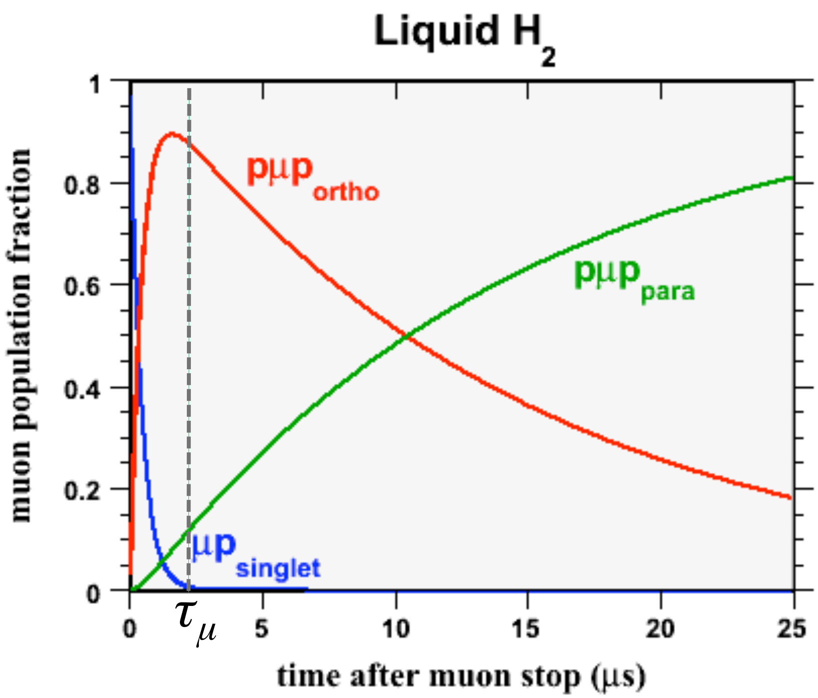
Hydrogen target

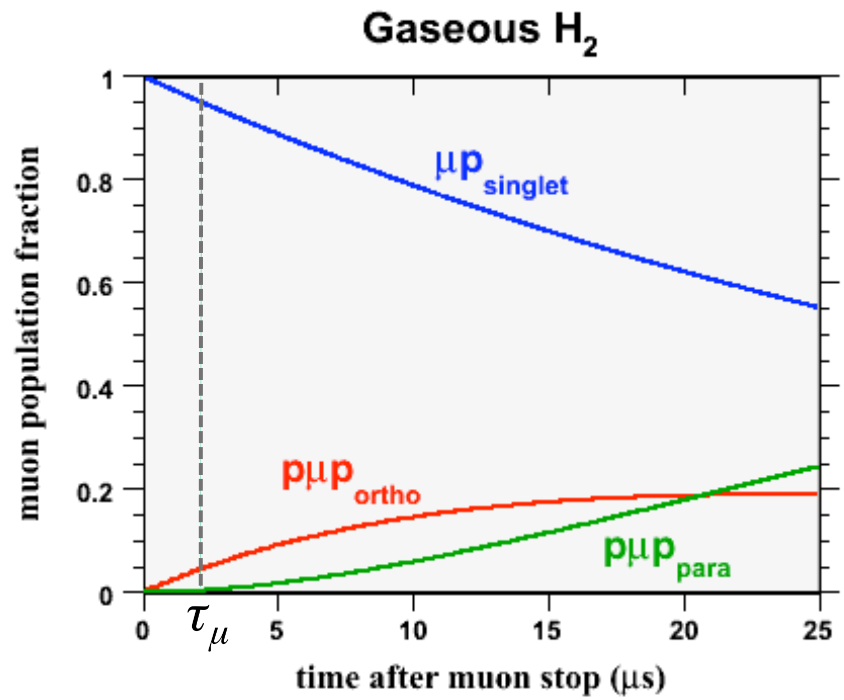
We use a low-density (1% of LH_2) hydrogen gas target, which is an optimal compromise among competing demands:

- preservation of substantial muon stopping power
- minimization of μp diffusion
- suppression of $p\mu p$ molecule formation



Hydrogen target





State	Capture fraction
μp	22%
$p\mu p$	78%

State	Capture fraction
μp	96%
$p\mu p$	4%

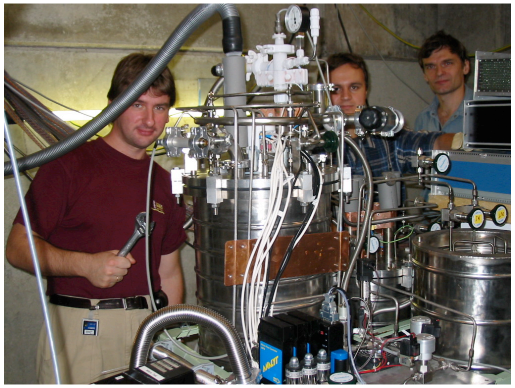
Hydrogen target

Z>1 Impurities

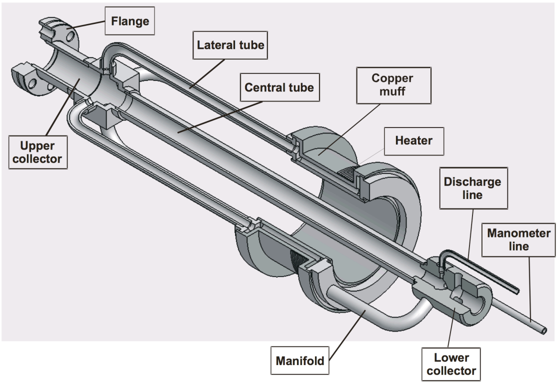
- Use bakeable TPC & pressure vessel
- Pass H_2 through palladium filter
- Use custom-built Circulating Hydrogen Ultra-high Purification System (CHUPS) to continuously clean H_2, maintain impurity levels at ~ 5×10^{-8}

Deuterium

- Use deuterium-depleted H_2 with $c_d \approx 1.5$ ppm (“protium”)
- More recently, a cryogenic system — the Deuterium Removal Unit (DRU) — was built to produce & maintain deuterium levels at < 6 ppb (!)



CHUPS and DRU systems built by PNPI



Strategy

We can’t eliminate gas impurities and molecular effects, but we can minimize and characterize them, and then perform small corrections to the measured lifetime.

Experimental goal

10^{10} μ^- decay events in pure hydrogen gas
(c_Z < 10 ppb, c_d < 1 ppm)

↓

10 ppm measurement of μ^- disappearance rate

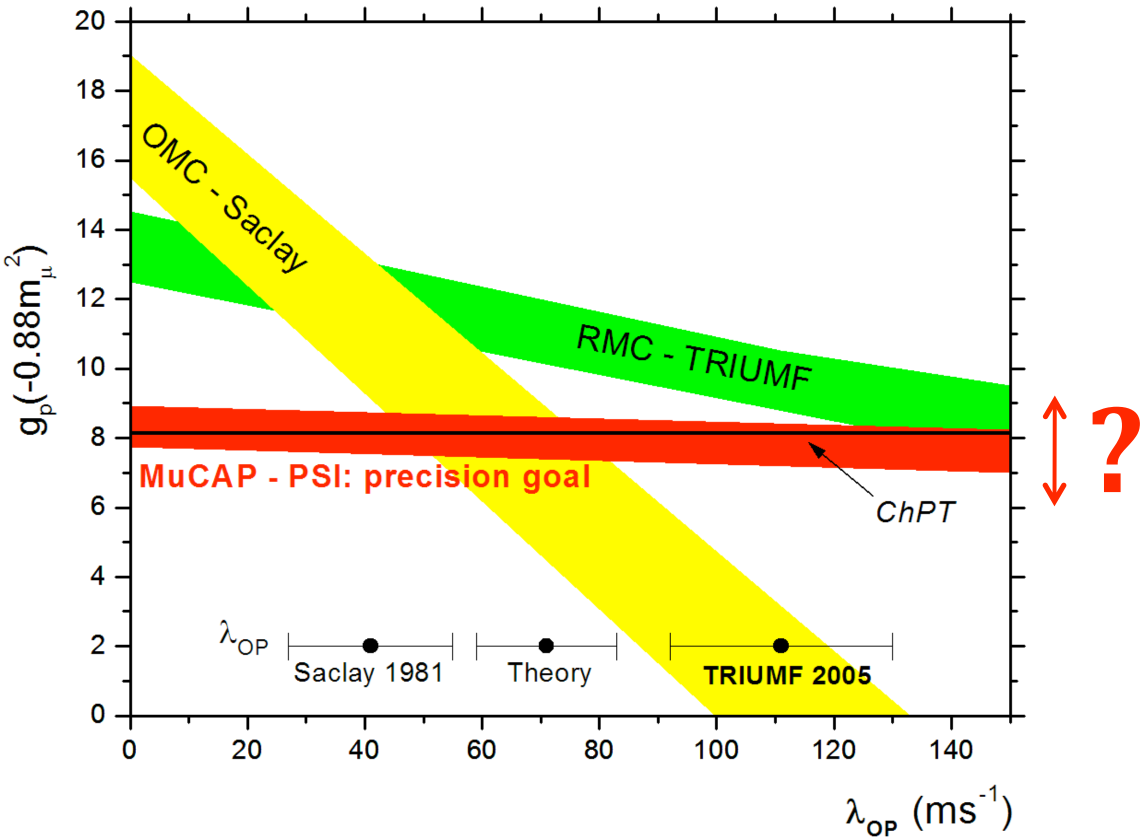
↓

1% determination of μp nuclear capture rate Λ_S

↓

7% determination of g_P

Experimental goal



A precise determination of g_P that is relatively insensitive to molecular ambiguities would test our understanding of chiral symmetry breaking in QCD.

MuCap Collaboration

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

MuCap Collaboration

Thanks to the many hard-working members of the MuCap collaboration!

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