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Title: The MuCap Experiment

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Form 836 (7/06)

Title: The MuCap Experiment

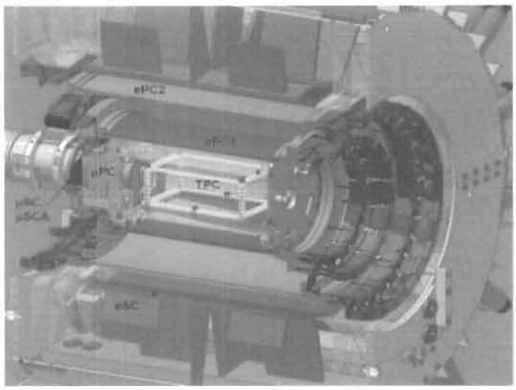
Speaker: Steven Clayton

Venue: 11th International Workshop on Neutrino Factories, Superbeams and Beta Beams (NuFact09), July 20-25, 2009.

Abstract: Muon capture on the proton is sensitive to the weak pseudoscalar form factor, g_P, one of the basic parameters characterizing the nucleon electroweak charged-current interaction. There is a precise theoretical prediction for g_P based on chiral symmetry of QCD, yet the results of past experiments are controversial: they are dependent on a poorly-known, mu-molecular kinetic parameter, and there is no point of mutual agreement between theory and all experiments. The goal of the MuCap experiment is to clarify the situation by measuring the rate of muon capture on the free proton to 1%, which determines g_P to 7%, higher precision than achieved in previous experiments and without ambiguities in the interpretation. This talk will cover the motivation for and design of the MuCap experiment, first physics results from the new measurement, and improvements toward the final precision goal.

The MuCap Experiment

Steven Clayton*
University of Illinois



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

Outline:
1) Nucleon form factors
2) Mu-molecular kinetics
3) Experimental challenges
4) MuCap strategy
5) First physics results
6) Improvements since first physics results

*Present address: LANL

MuCap Collaboration

V.A. Andreev, T.I. Banks, B. Besymjannykh, L. Bonnet, R.M. Carey, T.A. Case, D. Chitwood, S.M. Clayton, K.M. Crowe, P. Debevec, J. Deutsch, P.U. Dick, A. Dijksman, J. Egger, D. Fahrni, O. Fedorchenko, A.A. Fetisov, S.J. Freedman, V.A. Ganzha, T. Gorringe, J. Govaerts, F.E. Gray, F.J. Hartmann, D.W. Hertzog, M. Hildebrandt, A. Hofer, V.I. Jatsoura, P. Kammel, B. Kiburg, S. Knaak, P. Kravtsov, A.G. Krivshich, B. Lauss, M. Levchenko, E.M. Maev, O.E. Maev, R. McNabb, L. Meier, D. Michotte, F. Mulhauser, C.J.G. Onderwater, C.S. Özben, C. Petitjean, G.E. Petrov, R. Prieels, S. Sadetsky, G.N. Schapkin, R. Schmidt, G.G. Semenchuk, M. Soroka, V. Tichenko, V. Trofimov, A. Vasilyev, A.A. Vorobyov, M. Vznuzdaev, D. Webber, P. Winter, P. Zolnierzcuk

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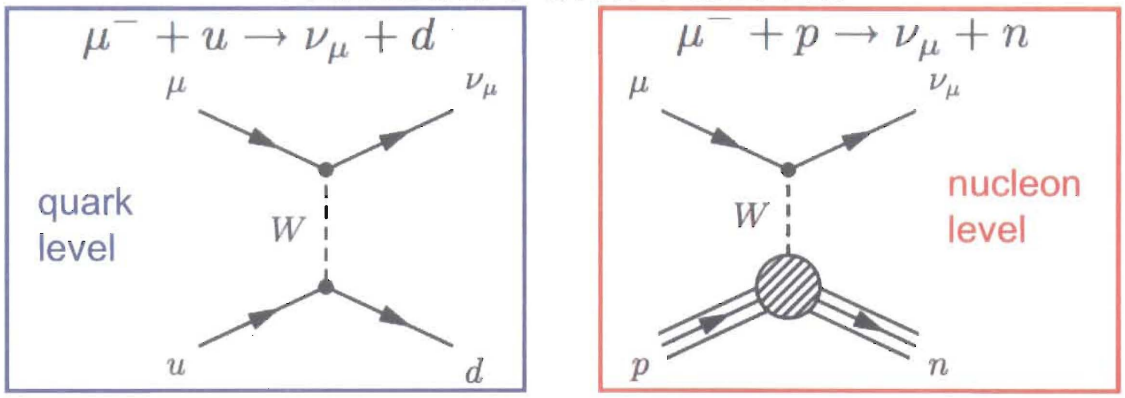
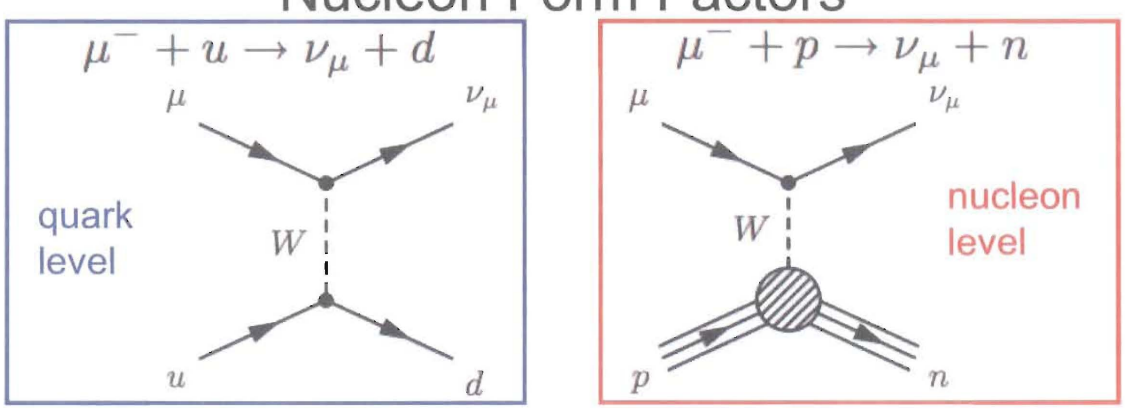
University of California, Berkeley (UCB and LBNL), USA
University of Illinois at Urbana-Champaign (UIUC), USA
Université Catholique de Louvain, Belgium
TU München, Garching, Germany
University of Kentucky, Lexington, USA
Boston University, USA

Nucleon Form Factors



$$\mathcal{M} = \frac{G_F}{\sqrt{2}} V_{ud} \langle \nu_\mu | \gamma^\alpha (1-\gamma_5) | \mu \rangle \; \langle d | \gamma^\alpha (1-\gamma_5) | u \rangle$$

Nucleon Form Factors



$$\mathcal{M} = \frac{G_F}{\sqrt{2}} V_{ud} \langle \nu_\mu | \gamma^\alpha (1-\gamma_5) | \mu \rangle \, \langle n | V^\alpha - A^\alpha | p \rangle$$

$$V^\alpha = \underline{g_v(q^2)}\gamma^\alpha + i\underline{g_m(q^2)}\sigma^{\alpha\beta}\frac{q_\beta}{2M_N} + \underbrace{\cancel{g_s(q^2)}}_{=0}\frac{q^\alpha}{m_\mu}$$

CVC — EM FF's

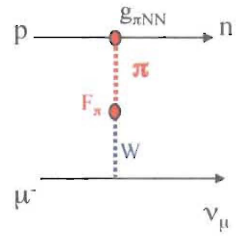
$$A^\alpha = g_a(q^2)\gamma^\alpha\gamma_5 + \cancel{ig_t(q^2)}\sigma^{\alpha\beta}\frac{q_\beta}{2M_N}\gamma_5 + g_p(q^2)\frac{q^\alpha}{m_\mu}\gamma_5$$

n-decay

G-parity

Pseudoscalar Form Factor g_p

g_P determined by chiral symmetry of QCD:



$$g_p(q^2) = \frac{2m_\mu g_{\pi NN}(q^2) F_\pi}{m_\pi^2 - q^2} - \frac{1}{3} g_a(0) m_\mu m_N r_A^2$$

g_P=	(8.74 ± 0.23)	– (0.48 ± 0.02)	= **8.26 ± 0.23**	
PCAC	pole term	Adler, Dothan, Wolfenstein		
ChPT	leading order	one loop	two-loop <1%	

N. Kaiser Phys. Rev. C67 (2003) 027002

- **solid QCD prediction via ChPT (2-3% level)**
- **basic test of QCD symmetries**

Recent reviews:
T. Gorringe, H. Fearing, Rev. Mod. Physics 76 (2004) 31
V. Bernard et al., Nucl. Part. Phys. 28 (2002), R1

Sensitivity of Λ_S to Form Factors

$$\frac{\delta\Lambda_S}{\Lambda_S} = \boxed{2\frac{\delta V_{ud}}{V_{ud}} + 0.466\frac{\delta g_v}{g_v} + 0.151\frac{\delta g_m}{g_m} + 1.567\frac{\delta g_a}{g_a}} - 0.179\frac{\delta g_p}{g_p}$$

Contributes 0.4% uncertainty to Λ_S(theory)

Uncertainty of extraction of g_p from Λ_S is dominated by uncertainty in g_a.

$\frac{\partial\Lambda_S}{\partial g_X}\frac{g_X}{\Lambda_S}$ from Govaerts, Lucio-Martinez, Nucl. Phys. A 678 (2000) 110-146

μ^- Stopping in Hydrogen

μ^- is a heavy electron:

- Quickly forms a μp atom, transitions to ground state, transitions to singlet hyperfine state.

  Bohr radius $a \approx a_0\, m_e/m_\mu \approx a_0/200$

- Most of the time, the μ decays:

  $\mu^- \rightarrow \nu_\mu + e^- + \nu_e$ **rate $\lambda_0 \approx 1/\tau_{\mu+}$** BR≈0.999

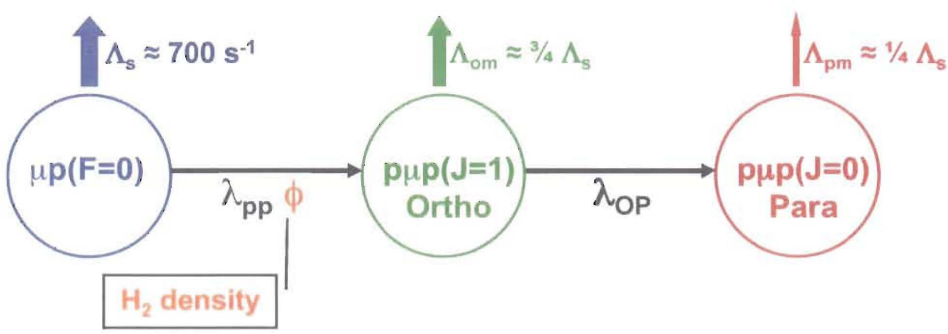
- Occasionally, it *nuclear* captures on the proton:

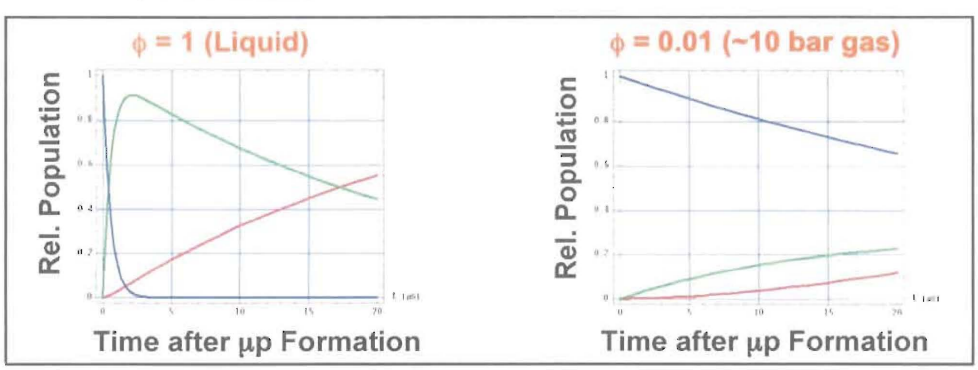
  $\mu^- + p \rightarrow \nu_\mu + n$ **rate Λ_S** BR~10^{-3}

  $\mu^- + p \rightarrow \nu_\mu + n + \gamma$ BR~10^{-8}, E>60 MeV

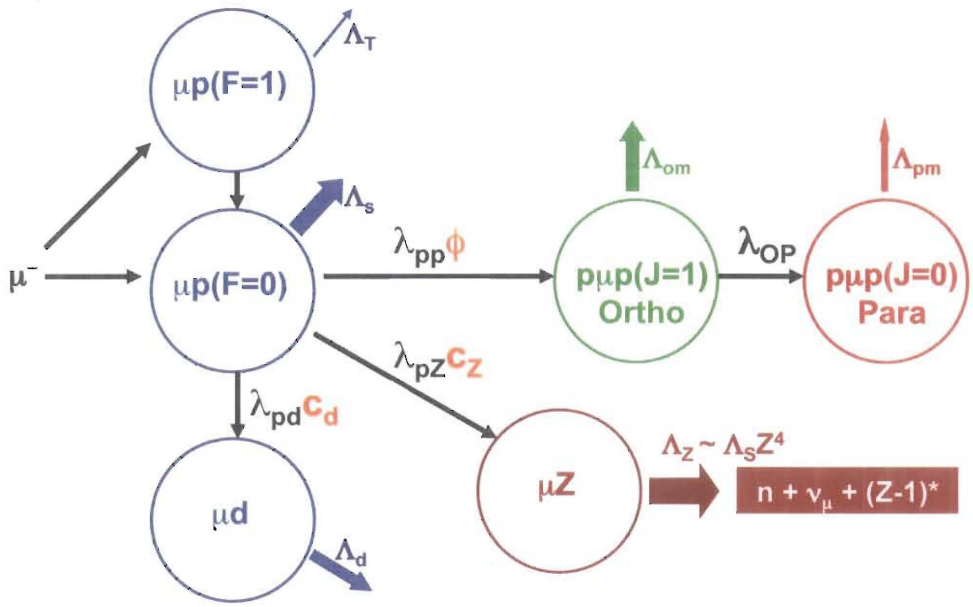
Complications: molecular formation/transitions, transfer to impurity atoms, …

Muon Atomic/Molecular State in Experiment must be known to connect with theory.





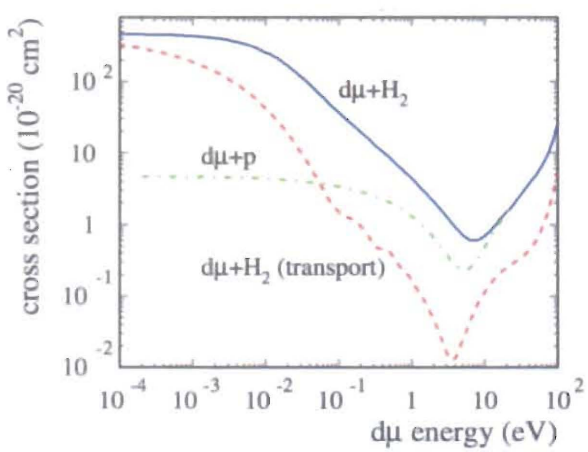
Muon atomic transitions set stringent purity requirements.



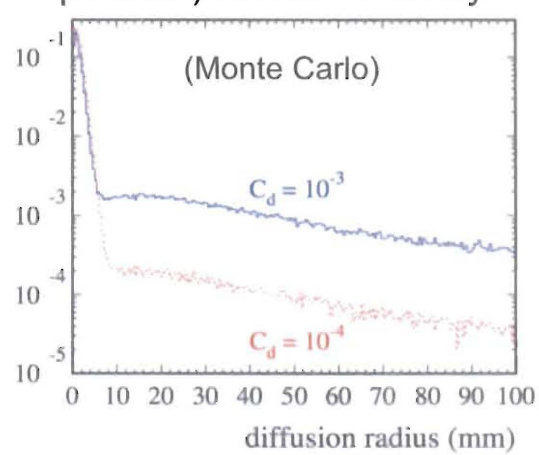
H_2 must be pure isotopically and chemically: c_d < 1 ppm, c_Z < 10 ppb

μd Diffusion into Z > 1 Materials

μd scattering in H_2



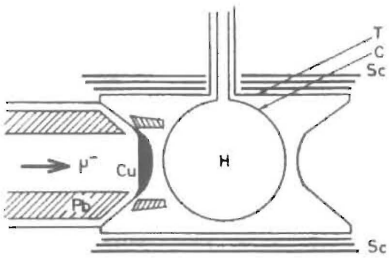
displacement (from μ^- stop position) at time of decay



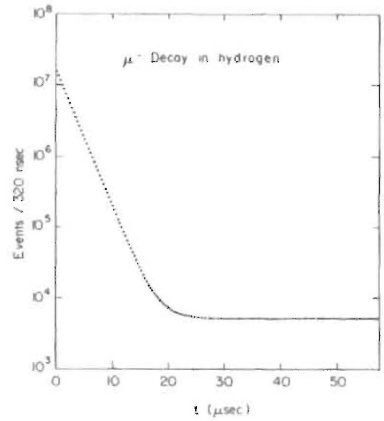
- Ramsauer-Townsend minimum in the scattering cross section
  - μd can diffuse ~10 cm before muon decay

Prev. expt: Ordinary muon capture in H_2

Bardin et al., Nuclear Physics A352 (1981) 365-378



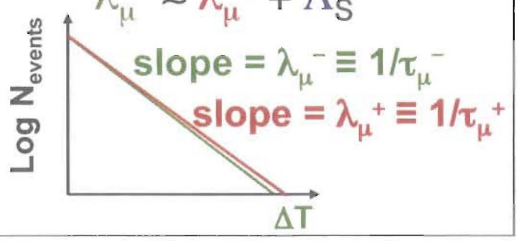
Purified, liquid protium target



Typical time distribution of the events from negative muons stopped in liquid protium.

Lifetime technique

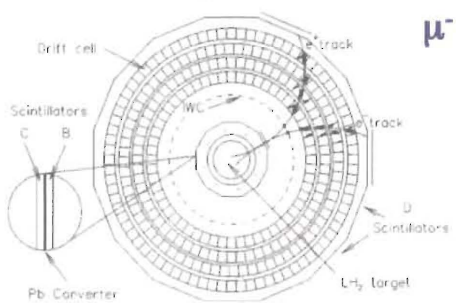
$\lambda_{\mu}^{-} \approx \lambda_{\mu}^{+} + \Lambda_S$

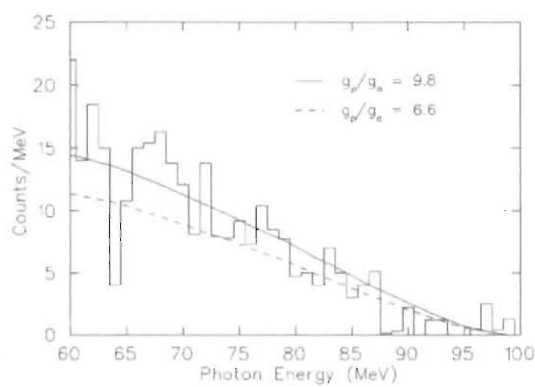


Prev. expt.: Radiative muon capture in H_2

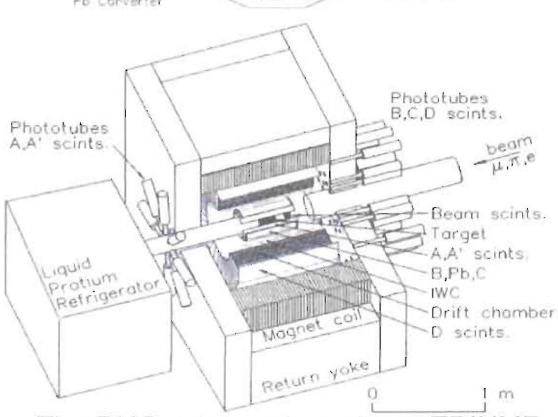
$\mu^- + p \rightarrow \nu_\mu + n + \gamma$ (BR~10^{-8}, E>60 MeV)

Only one measurement of RMC:
Wright et al., PRC v57 (Jan. 1998), p373.



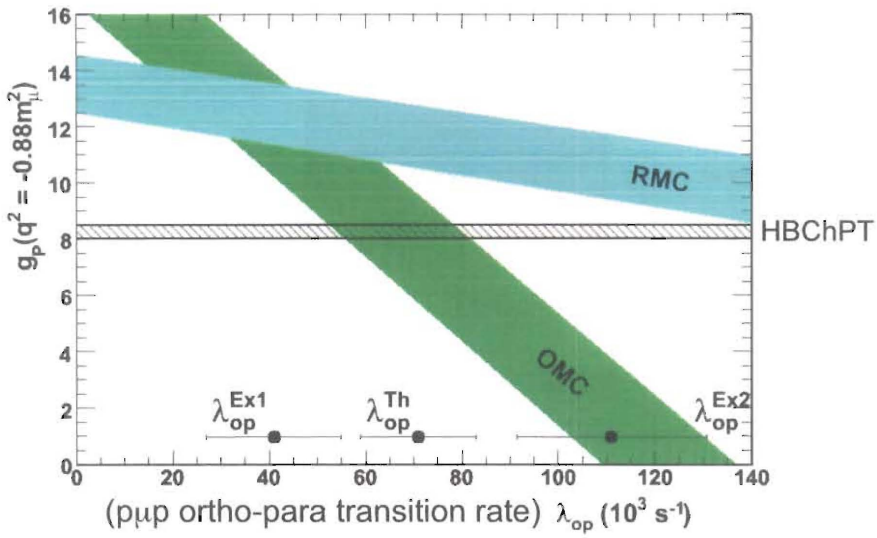


Photon spectrum after all cuts and background subtraction, shown with theoretical fit.



The RMC pair spectrometer at TRIUMF

Previous Data on g_p



No common region of overlap between both expts. and theory

g_P basic and experimentally least known weak nucleon form factor

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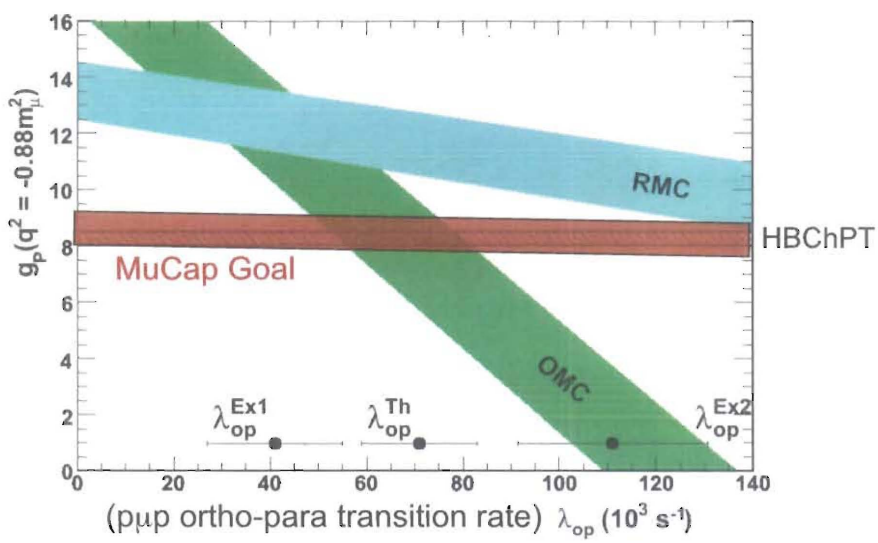

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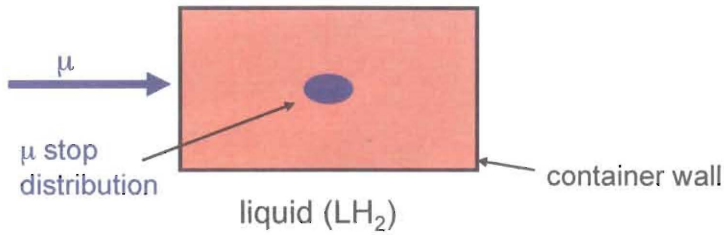
g_P basic and experimentally least known weak nucleon form factor

Experimental Challenges

1) Unambiguous interpretation requires low-density hydrogen target to reduce μ-molecular formation.



2) H2 must be pure chemically (c_O,c_N < 10 ppb) and isotopically (c_d < 1 ppm).

3) All neutral final state of muon capture is difficult to detect (would require absolute calibration of neutron detectors, accurate subtraction of backgrounds).

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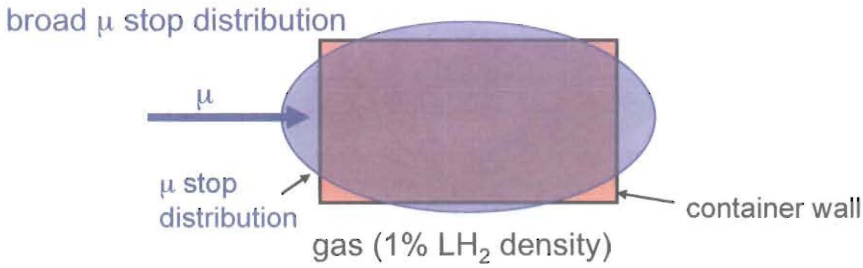

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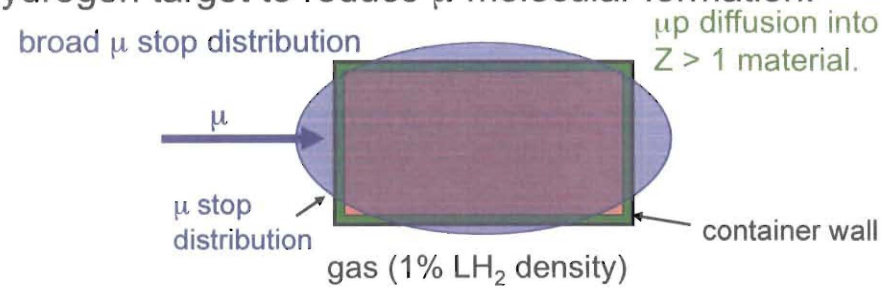

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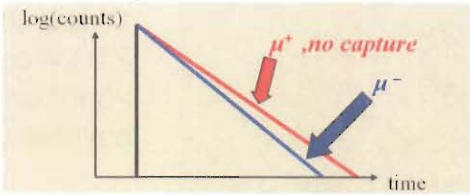
μCap Experimental Strategy

- Unambiguous interpretation
  - capture mostly from F=0 μp state at 1% LH_2 density
- Lifetime method
  - 10^{10} $\mu^- \rightarrow e\nu\nu$ decays
  - measure τ_{μ^-} to 10ppm
  - $\rightarrow \Lambda_S = 1/\tau_{\mu^-} - 1/\tau_{\mu^+}$ to 1%



- Clean μ stop definition in active target (TPC) to avoid μZ capture, 10 ppm level
- Ultra-pure gas system and purity monitoring to avoid: μp + Z → μZ + p, ~10 ppb impurities
- Isotopically pure "protium" to avoid μp + d → μd + p, ~1 ppm deuterium

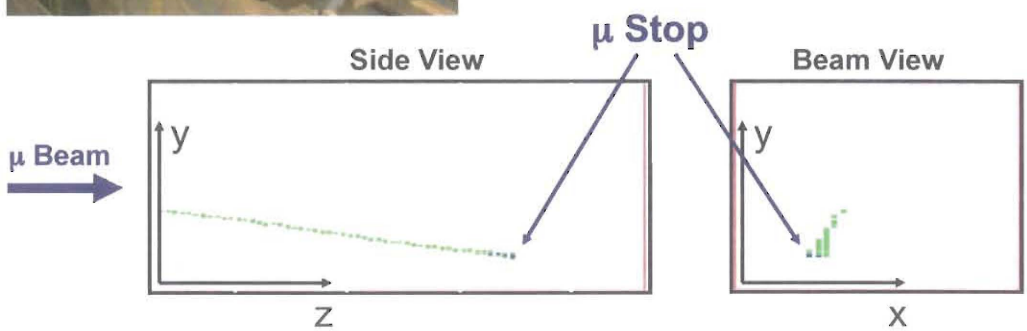
diffusion range ~cm

fulfill all requirements simultaneously
unique μCap capabilities

3D tracking w/o material in fiducial volume

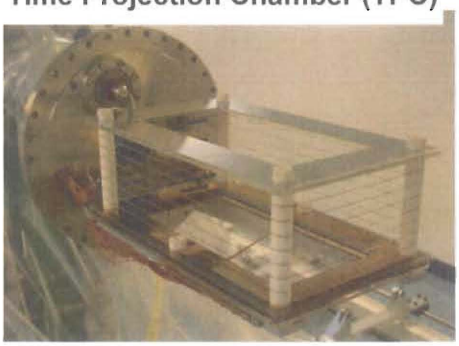
Time Projection Chamber (TPC)

10 bar ultra-pure hydrogen, 1% LH_2
2.0 kV/cm drift field
>5 kV on 3.5 mm anode half gap
bakable glass/ceramic materials



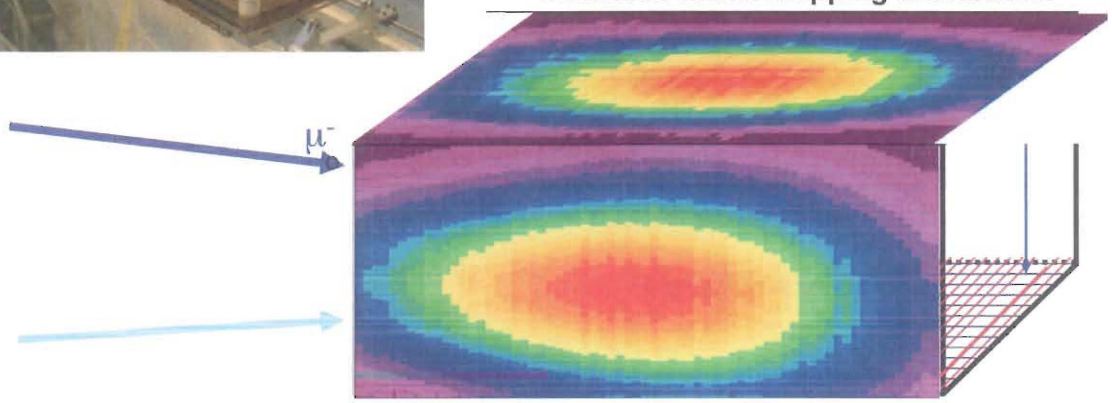
3D tracking w/o material in fiducial volume

Time Projection Chamber (TPC)



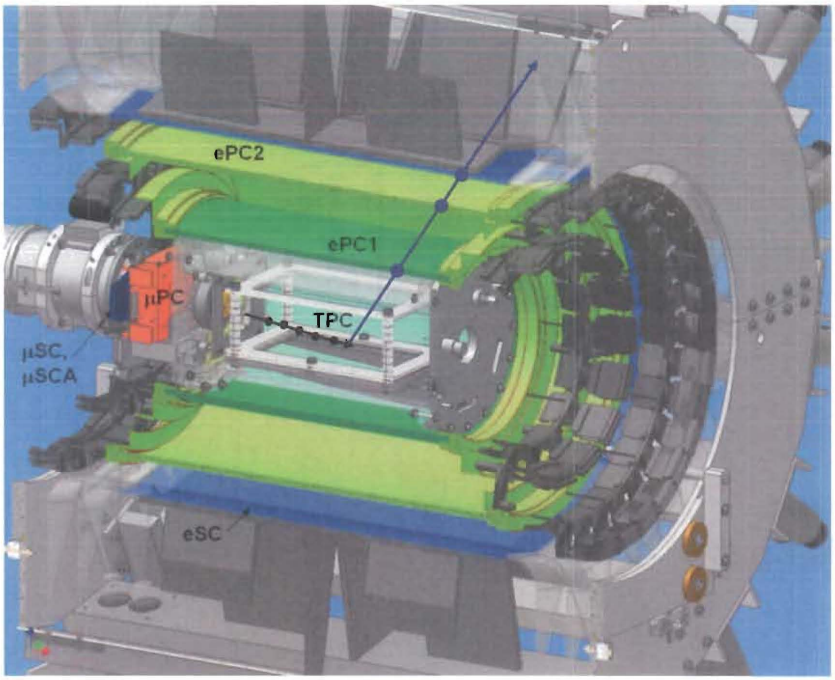
10 bar ultra-pure hydrogen, 1% LH_2
2.0 kV/cm drift field
>5 kV on 3.5 mm anode half gap
bakable glass/ceramic materials

Observed muon stopping distribution

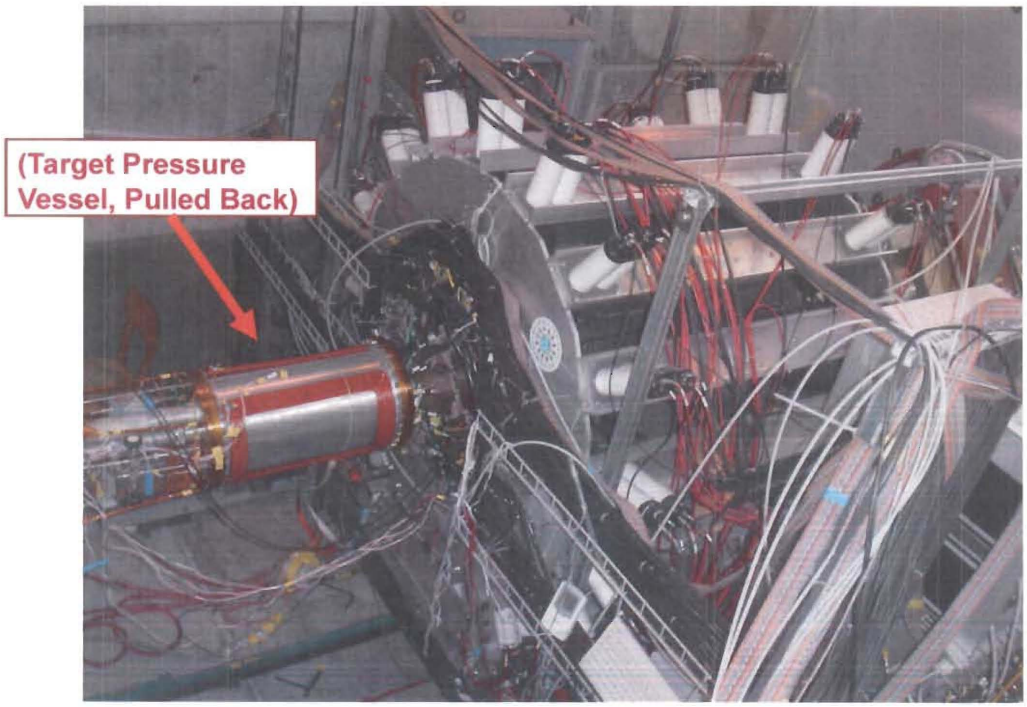


μCap Detailed Diagram

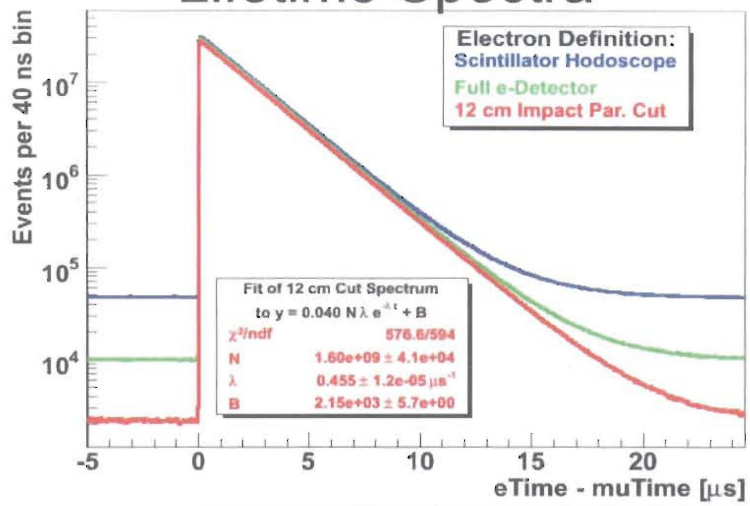
- Tracking of Muon to Stop Position in Ultrapure H_2 Gas
- Tracking of Decay Electron



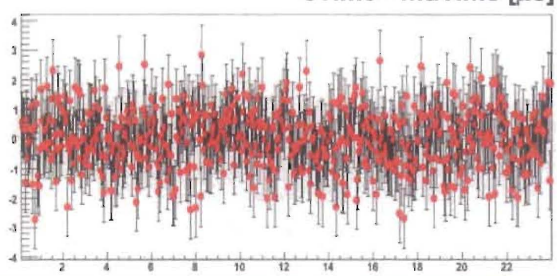
Commissioning and First Physics Data in 2004



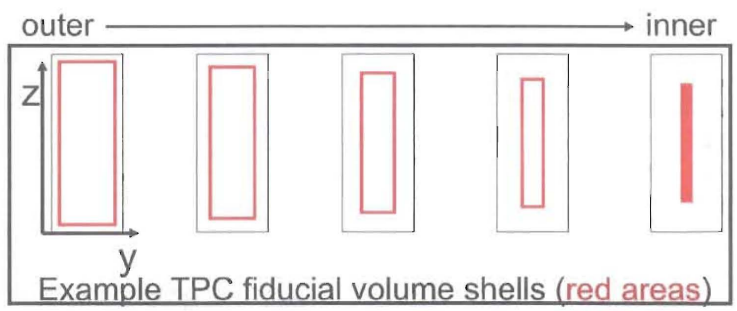
Lifetime Spectra

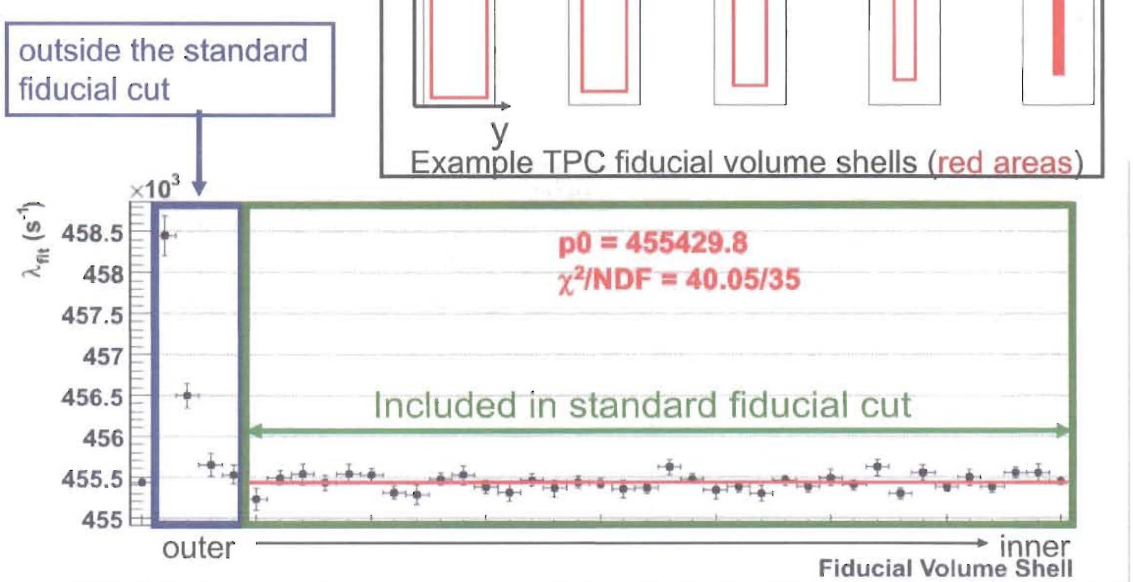


Normalized residuals ("pull")



Lifetime vs. Non-Overlapping Fiducial Volume Shell



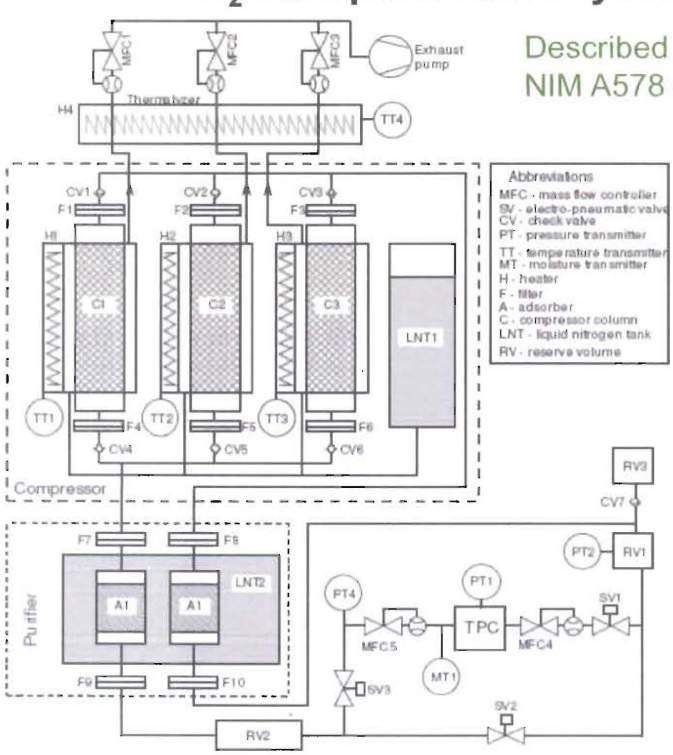


Internal corrections to λ_{μ^-}

Source	Correction (s^{-1})	Uncertainty (s^{-1})
$Z > 1$ impurities ($\Delta\lambda_Z$)	-17.4	4.6
Deuterium ($\Delta\lambda_d$)	-12.1	1.8
μp Diffusion ($\Delta\lambda_k$)	-3.1	0.1
Unseen $\mu + p$ scatters ($\Delta\lambda_{\rm sc}$)	0.0	3.0
μ stop definition ($\Delta\lambda_{\rm tr}$)	0.0	2.0
μ pileup veto inefficiency ($\Delta\lambda_\kappa$)	0.0	3.0
Analysis methods ($\Delta\lambda_{\rm Ana}$)	0.0	5.0
Total	-32.6	± 8.4

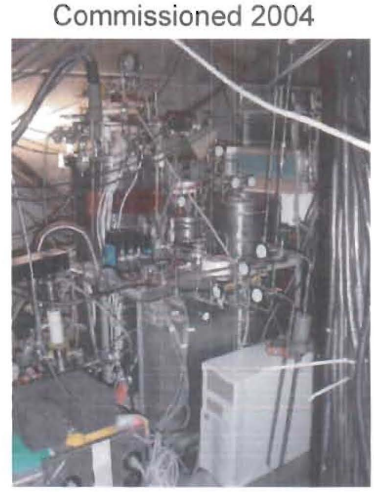
(statistical uncertainty of λ_{μ^-}: 12 s^{-1})

Gas impurities (Z > 1) are removed by a continuous H_2 ultra-purification system (CHUPS).



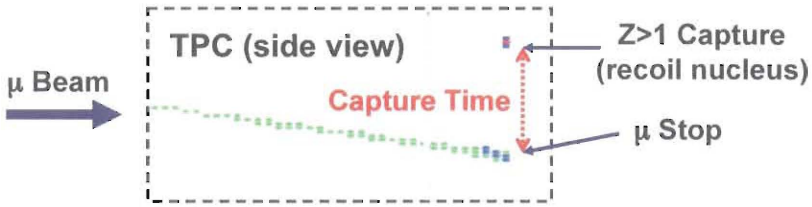
Described in NIM A578 (2007) 485-497.

Commissioned 2004



c_{N2}, c_{O2} < 0.01 ppm

In situ detection of Z > 1 captures



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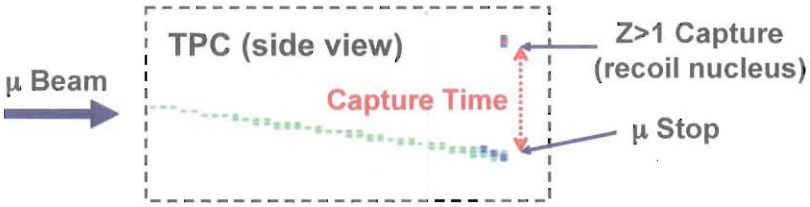
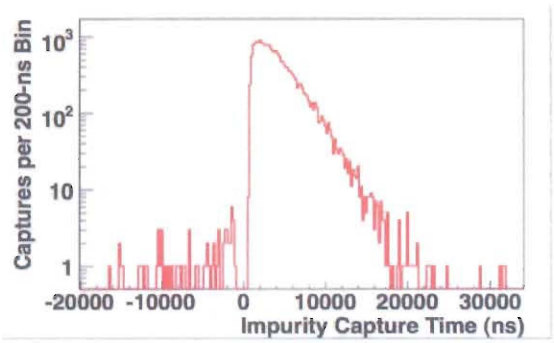
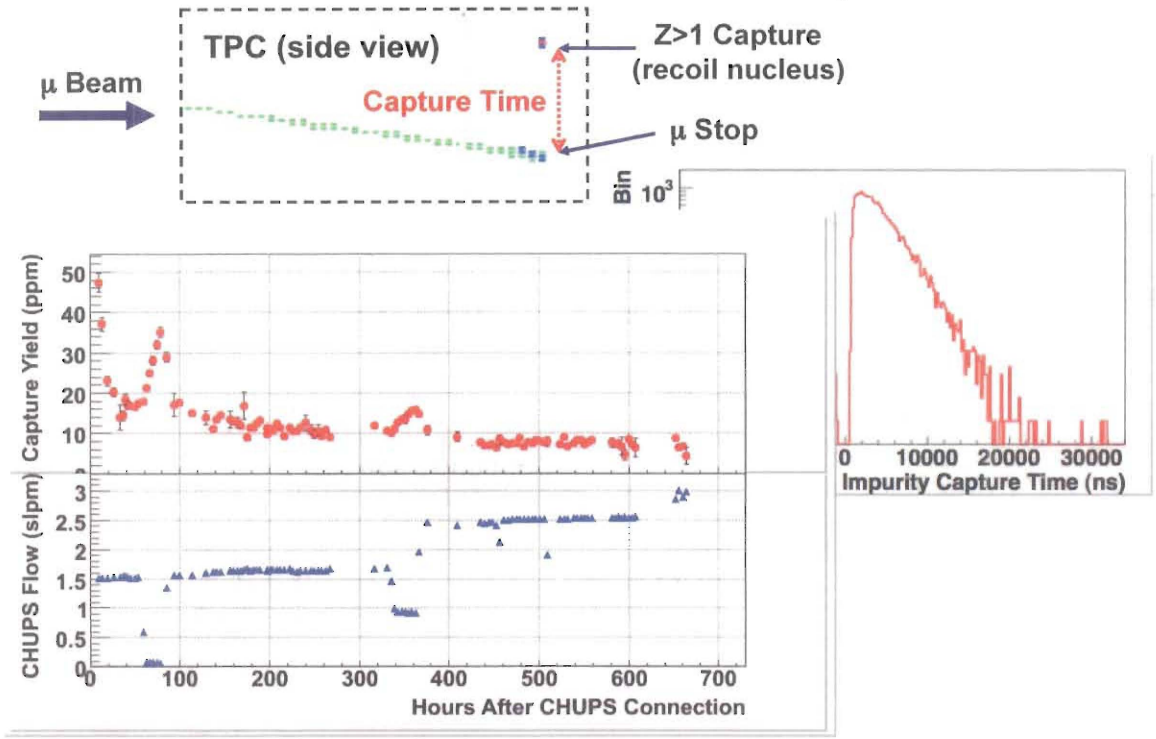
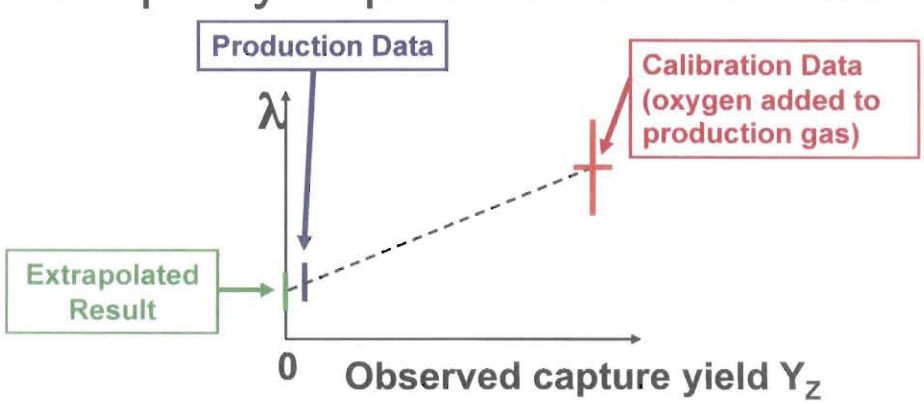




In situ detection of Z > 1 captures



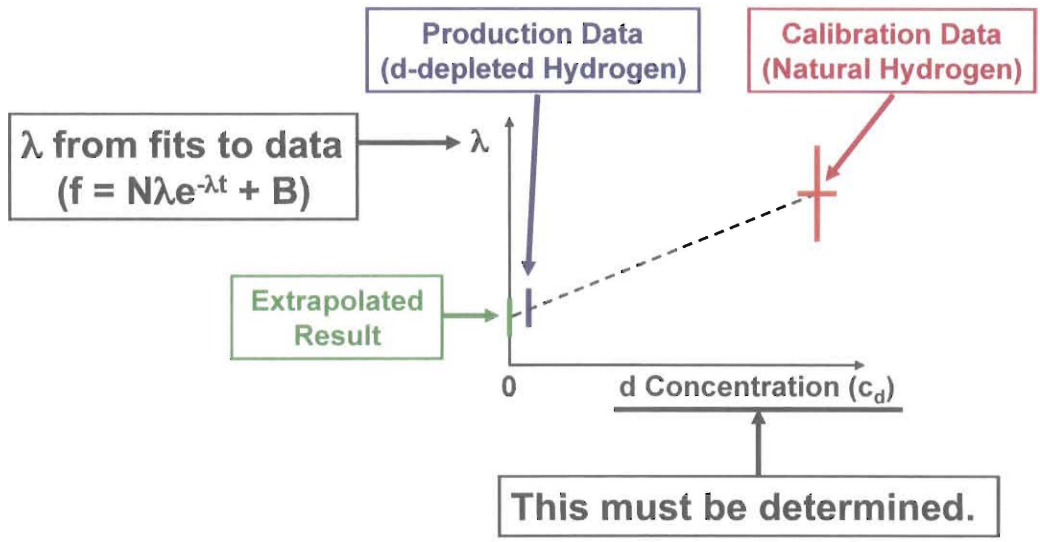
The final Z > 1 correction $\Delta\lambda_Z$ is based on impurity-doped calibration data.



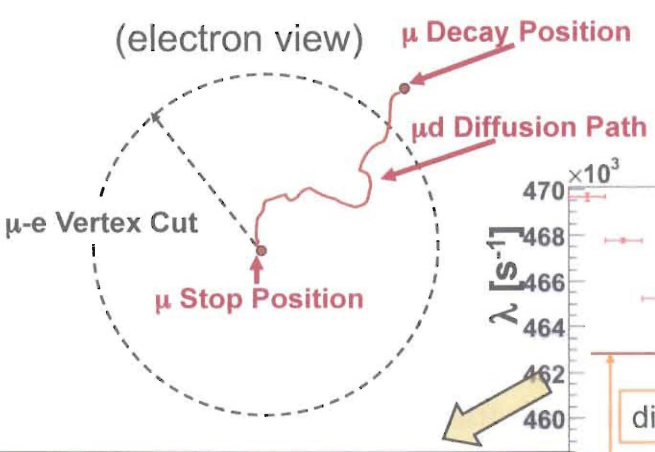
Lifetime deviation is linear with the Z>1 capture yield.

Some adjustments were made because calibration data with the main contaminant, oxygen (H_2O), were taken in a later running period (2006).

Residual deuterium content is accounted for by a zero-extrapolation procedure.

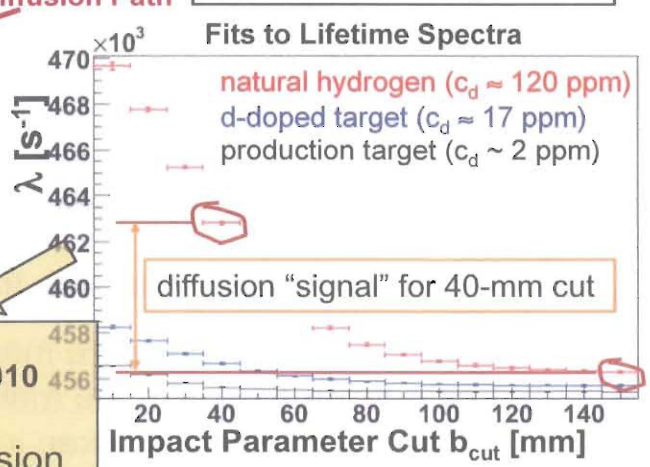


c_d Determination: Data Analysis Approach



μd can diffuse out of acceptance region:

- signal proportional to number of μd, and therefore to c_d.



$$\frac{c_d(\text{Production})}{c_d(\text{Natural H2})} = 0.0125 \pm 0.0010$$

*after accounting for μp diffusion

c_D Monitoring: External Measurement

Measurements with New ETH Zürich Tandem Accelerator:

- **2004 Production Gas,**
  c_D = 1.44 ± 0.13 ppm D
- **2005 Production Gas,**
  c_D = 1.45 ± 0.14 ppm D

The "Data Analysis Approach" gives a consistent result:

- **2004 Production Gas,**
  c_D = (0.0125 ± 0.0010) × (122 ppm D)
  = 1.53 ± 0.12 ppm

MuCap Λ_S from the μ^- lifetime λ_{μ^-}

$$\lambda_\mu^- = \lambda_0 + \Lambda_S + \Delta\lambda_{p\mu p}$$

molecular formation

$$\lambda_\mu^+ + \Delta\lambda_{\mu p}$$

μ^+ decay rate — bound-state effect

	Value (s^{-1})	Uncertainty (s^{-1}) Stat.	Syst.
MuCap λ_μ^-	455849.1	12.4	8.4
Molecular Formation (λ_{OF}) Correction	17.3		4.7
Molecular Transitions (λ_{OP}) Correction	5.7		3.4
Bound State Correction ($\Delta\lambda_{\mu p}$)	12.3		
World Average λ_μ^+	455162.2	4.4	
MuCap Λ_S [a]	722.2	13.6	10.6

Averaged with UCB result gives

$$\Lambda_S^{\text{MuCap}} = 725.0 \pm 13.7_{\text{stat}} \pm 10.7_{\text{syst}}\ \text{s}^{-1}$$

Λ_s and g_P Results 07

- MuCap Result 07 with τ_{μ^+} from PDG and MuLan

PRL 99, 032001 (2007)

$\Lambda_S^{MuCap} = 725.0 \pm 13.7_{stat} \pm 10.7_{sys}\ s^{-1}$

- Theory 07

Average of HBChPT calculations of Λ_S:

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

Apply new rad. correction (2.8%):

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

$\Lambda_S^{Theory} = 710.6\ s^{-1}$

further sub percent theory required

Czarnecki, Marciano, Sirlin , PRL 99 (2007)

- Pseudoscalar coupling from MuCap 07

$g_P = 7.3 \pm 1.1$

Λ_s and g_P Results 07

- MuCap Result 07 with τ_{μ^+} from PDG and MuLan

PRL 99, 032001 (2007)

$\Lambda_S^{MuCap} = 725.0 \pm 13.7_{stat} \pm 10.7_{sys}\ s^{-1}$

- Theory 07

Average of HBChPT c

$(687.4\ s^{-1} + 695\ s^{-}$

Apply new rad. correct

$(1 + 0.028)691.2\ s$

Czarnecki, Marciano, Sirlin

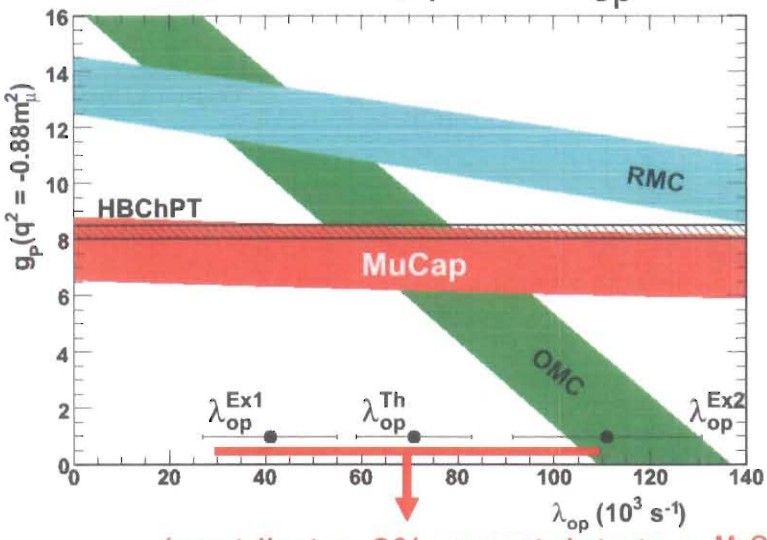
- Pseudosc

☐ **Improved Measurement of the Positive-Muon Lifetime and Determination of the Fermi Constant**
D. B. Chitwood *et al.* (MuLan Collaboration)
Published 16 July 2007
032001 Abstract Full Text: [PDF (241 kB) GZipped PS Buy Article]

☐ **Measurement of the Muon Capture Rate in Hydrogen Gas and Determination of the Proton's Pseudoscalar Coupling *gp***
V. A. Andreev *et al.* (MuCap Collaboration)
Published 16 July 2007
032002 Abstract Full Text: [PDF (270 kB) GZipped PS Buy Article]

☐ **Electroweak Radiative Corrections to Muon Capture**
Andrzej Czarnecki, William J. Marciano, and Alberto Sirlin
Published 16 July 2007
032003 Abstract Full Text: [PDF (101 kB) GZipped PS Buy Article]

Updated g_P vs. λ_{op}

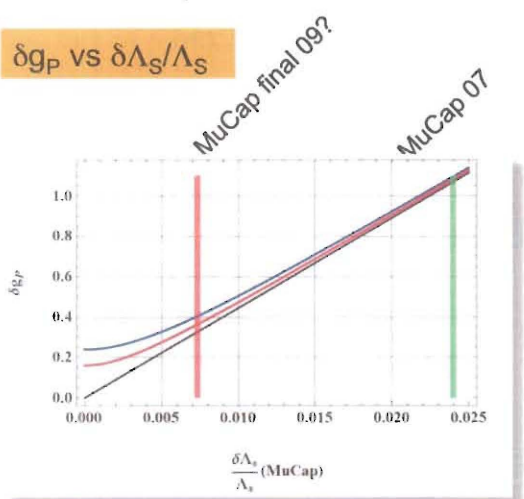


(contributes 3% uncertainty to g_P^{MuCap})

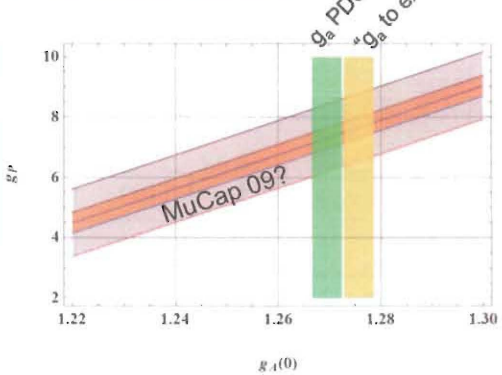
- MuCap 2007 result (with g_P to 15%) is consistent with theory.
- This is the first precise, unambiguous experimental determination of g_P

Expectations for Final MuCap Precision

δg_P vs $\delta\Lambda_S/\Lambda_S$



Allowed g_P vs g_A



	$\frac{\delta\Lambda_S}{\Lambda_S}$
• big exp. improvement	0.7 %
• sub-percent theory needed	?
• PDG g_a contributes	0.36 %
• Rad. corr.	0.4 %

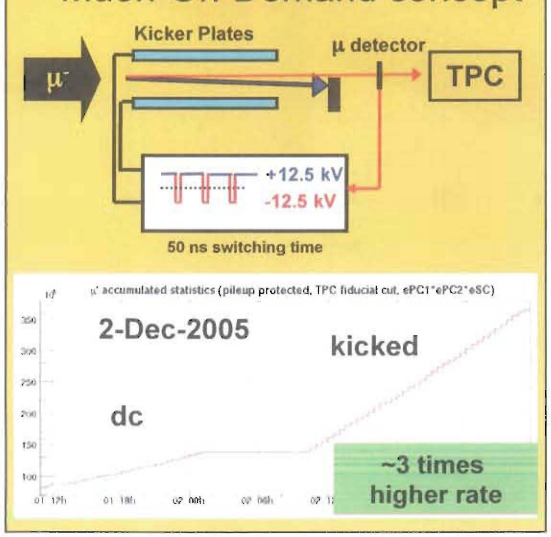
Several upgrades should lead to a 3-fold improved precision in 2006-2007 runs

Source	2007 Uncertainty (s^{-1})	Projected Final Uncertainty (s^{-1})
Statistical	13.7	3.7
Z > 1 impurities	5.0	2
μd diffusion	1.6	0.5
μp diffusion	0.5	0.5
μ + p scattering	3	1
μ pileup veto eff.	3	1
Analysis Methods	5	2
Muon kinetics	5.8	2
Systematic	10.7	3.8
Total	17.4	5.3

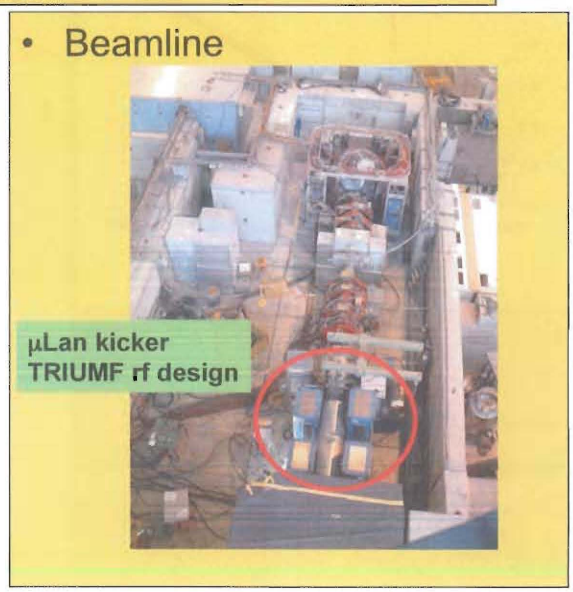
Muon-On-Demand

- Single muon requirement (to prevent systematics from pile-up)
- limits accepted μ rate to ~ 7 kHz,
- while PSI beam can provide ~ 70 kHz

- Muon-On-Demand concept



- Beamline



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Z>1 Impurities Reduced and Measured

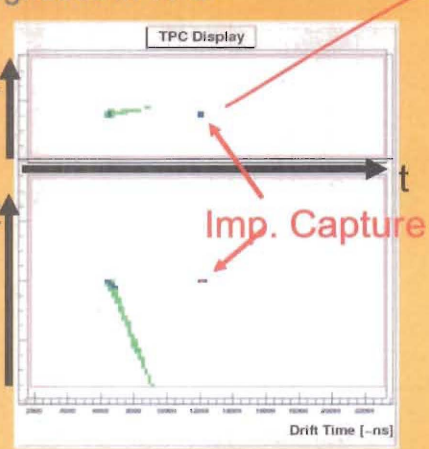
Circulating Hydrogen Ultrahigh Purification System (CHUPS)

Gas chromatography

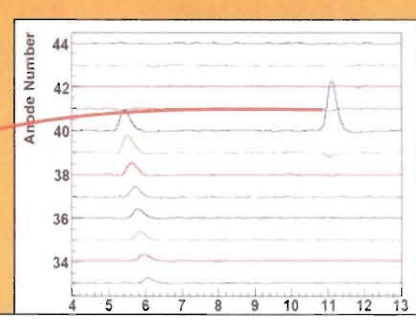
c_N, c_O < 5 ppb, c_{H2O} <10 ppb

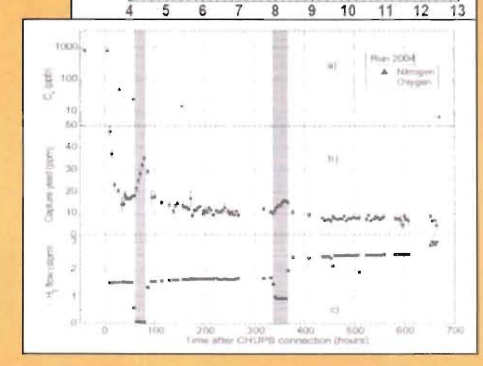
CRDF support

Diagnostic in TPC



•FADC upgrade on all TPC channels





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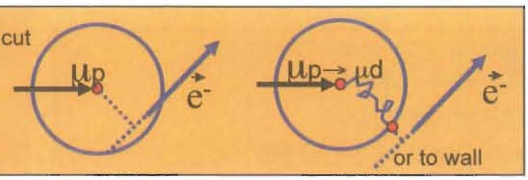
Analysis Methods	5	2
Muon kinetics	5.8	2
Systematic	10.7	3.8

Record Isotopic Purity Achieved

μp + d → μd + p (134 eV)
large diffusion range of μd

< 1 ppm isotopic purity required

μ-e impact par cut



Diagnostic:

2007 Result

Data (λ vs. μ-e vertex cut):

c_d= 1.49 ± 0.12 ppm

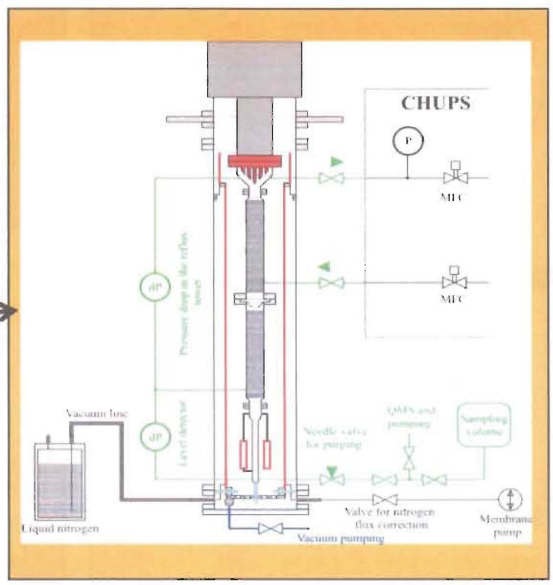
AMS (ETH Zurich):

c_d= 1.44 ± 0.15 ppm

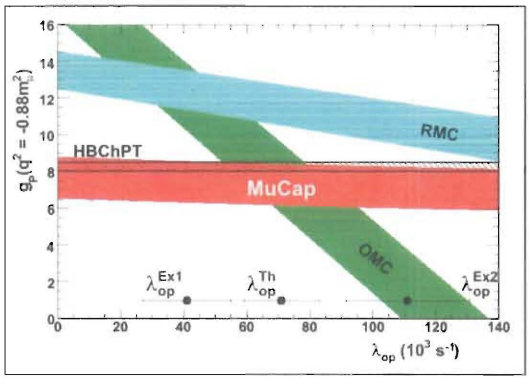
On-site isotopic separator:

c_d < 0.010 ppm !

World record



Summary



- First g_P with non-controversial interpretation
- Agrees with χPT expectation
- Factor 2.5 additional improvement on the way
  - kicker → >10^{10} good events on tape
  - higher purity target + more impurity-doped calibration runs → smaller Z>1 correction
  - deuterium removal → negligible deuterium correction

"Calibrating the Sun" via Muon Capture on the Deuteron

NEW PROJECT

$$\mu^- + d \rightarrow n + n + \nu$$

Motivation for the MuSun Experiment:

- First precise measurement of basic Electroweak reaction in 2N system,
- Impact on fundamental astrophysics reactions (ν's in SNO, pp fusion)
- Comparison to modern high-precision calculations