

First Results from the New Muon Lifetime Experiments at PSI

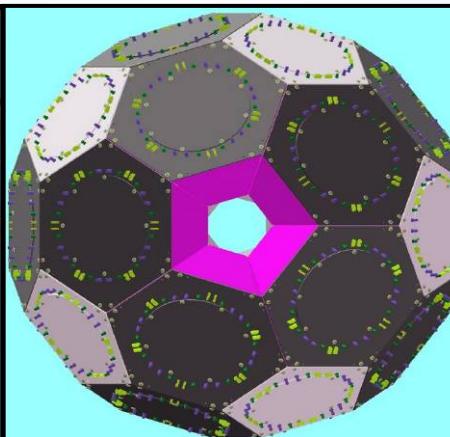
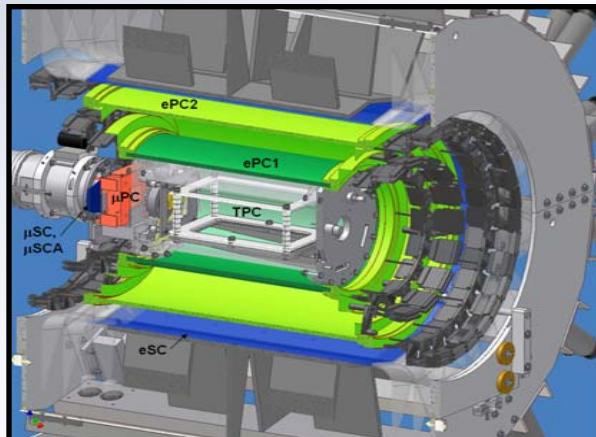


Peter Kammel



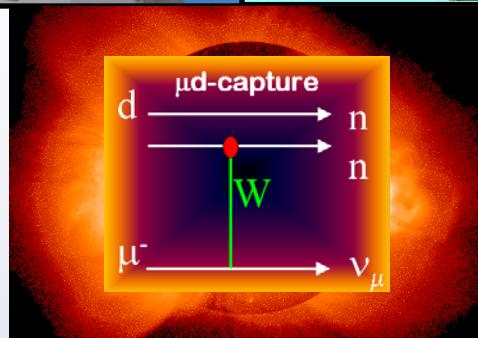
g_P

MuCap



G_F

MuLan



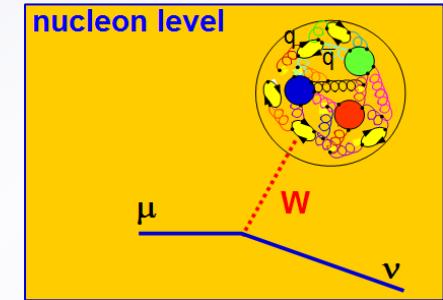
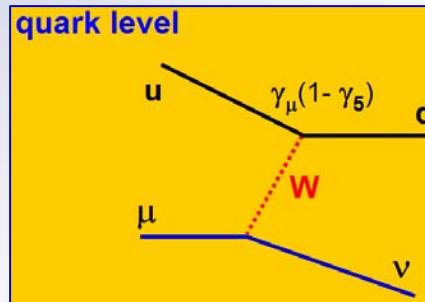
L_{1A}

“MuSun”
project



➤ EW current key probe

- Understanding hadrons from QCD
- Symmetries of Standard Model



➤ Muon Capture

$$\mu^- + p \rightarrow \nu_\mu + n \quad \text{rate } \Lambda_S \quad \text{at } q^2 = -0.88 m_\mu^2$$

$$\mathcal{M} = \frac{-iG_F V_{ud}}{\sqrt{2}} \bar{u}(p_\nu) \gamma_\alpha (1 - \gamma_5) u(p_\mu) \bar{u}(p_f) \tau_- [V^\alpha - A^\alpha] u(p_i)$$

➤ Formfactors

Lorentz, T invariance

$$V_\alpha = g_V(q^2) \gamma_\alpha$$

$$A_\alpha = g_A(q^2) \gamma_\alpha \gamma_5$$

The Black Sheep of Form Factors
T. Hemmert



All form factors precisely known from
SM symmetries and data

apart from $g_P = 8.3 \pm 50\%$

ass currents
ppressed by
ospin symm.

g_p determined by chiral symmetry of QCD:

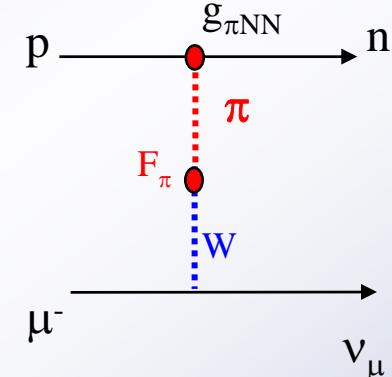
$$g_p(q^2) = \frac{2m_\mu g_{\pi NN}(q^2)F_\pi}{m_\pi^2 - q^2} - \frac{1}{3}g_a(0)m_\mu m_N r_A^2$$

$$g_p = (8.74 \pm 0.23) - (0.48 \pm 0.02) = 8.26 \pm 0.23$$

PCAC pole term Adler, Dothan, Wolfenstein

ChPT leading order one loop two-loop <1%

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

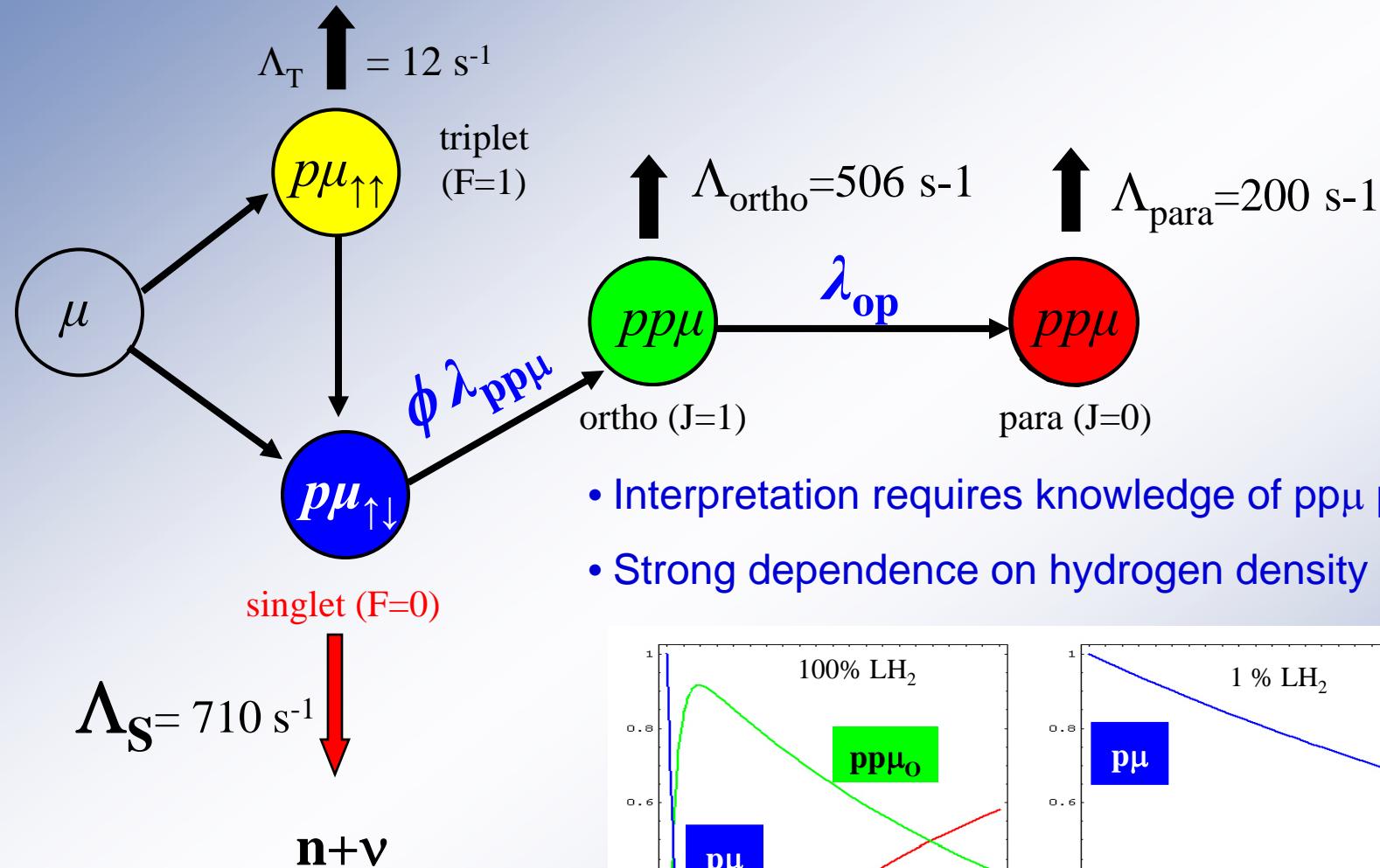


- g_p basic and experimentally least known EW nucleon form factor
- solid QCD prediction via HBChPT (2-3% level)
- basic test of QCD symmetries

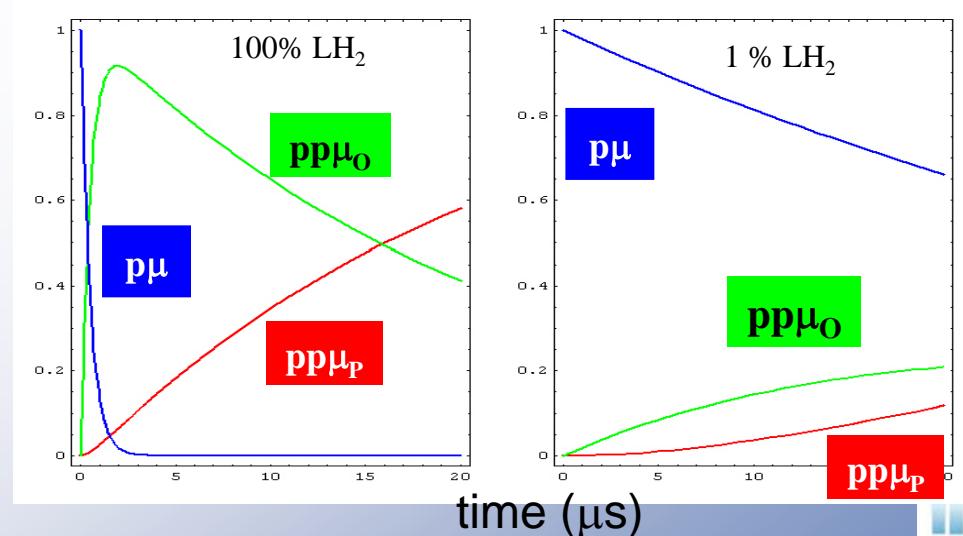
Recent reviews:

T. Gorrige, H. Fearing, Rev. Mod. Physics 76 (2004) 31

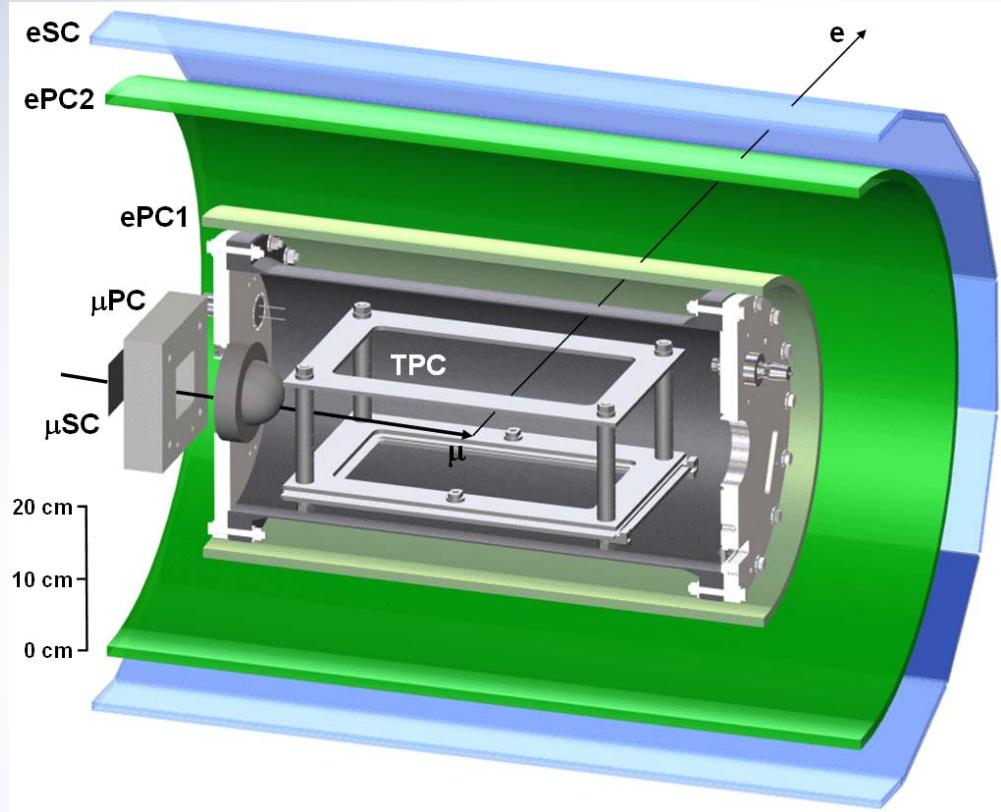
V. Bernard et al., Nucl. Part. Phys. 28 (2002), R1



- Interpretation requires knowledge of $pp\mu$ population
- Strong dependence on hydrogen density ϕ

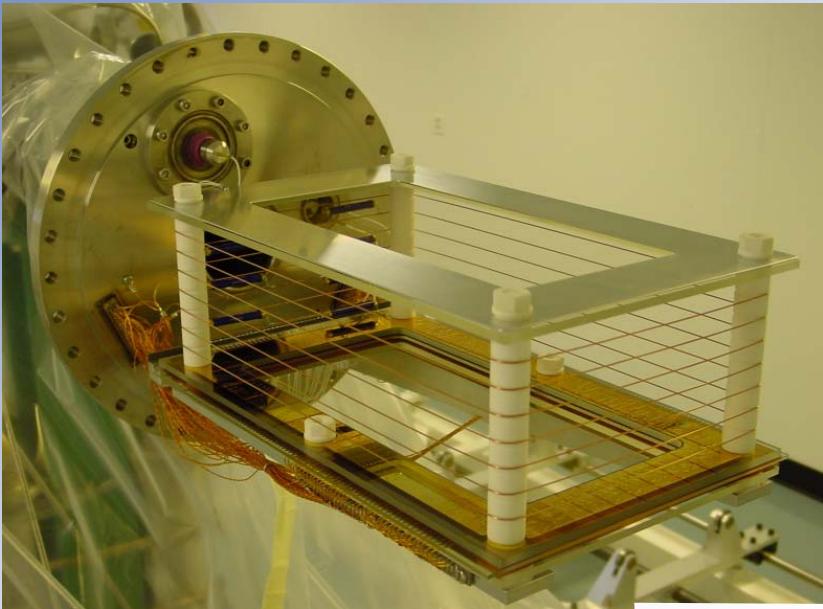


- Lifetime method
 $10^{10} \mu \rightarrow e\nu\bar{\nu}$ decays
measure τ_{μ^-} to 10ppm,
 $\rightarrow \Lambda_s = 1/\tau_{\mu^-} - 1/\tau_{\mu^+}$ to 1%
- Unambiguous interpretation at 1% LH_2 density
- Clean μ stop definition in active target (TPC) to avoid wall stops
- Ultra-pure gas system and purity monitoring at 10 ppb level
- Isotopically pure “protium”



*fulfill all requirements simultaneously
unique MuCap capabilities*

Muons stop in active TPC target

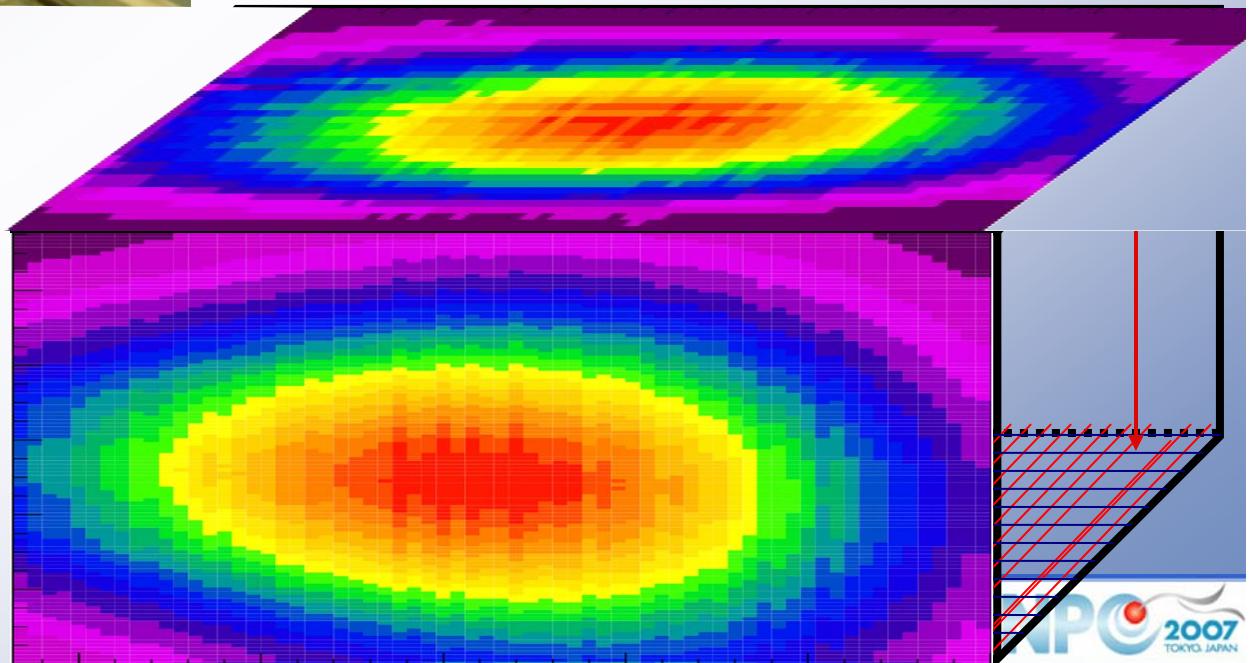


10 bar ultra-pure hydrogen, 1.16% LH₂
2.0 kV/cm drift field
~5.4 kV on 3.5 mm anode half gap
bakeable glass/ceramic materials

Observed muon stopping distribution

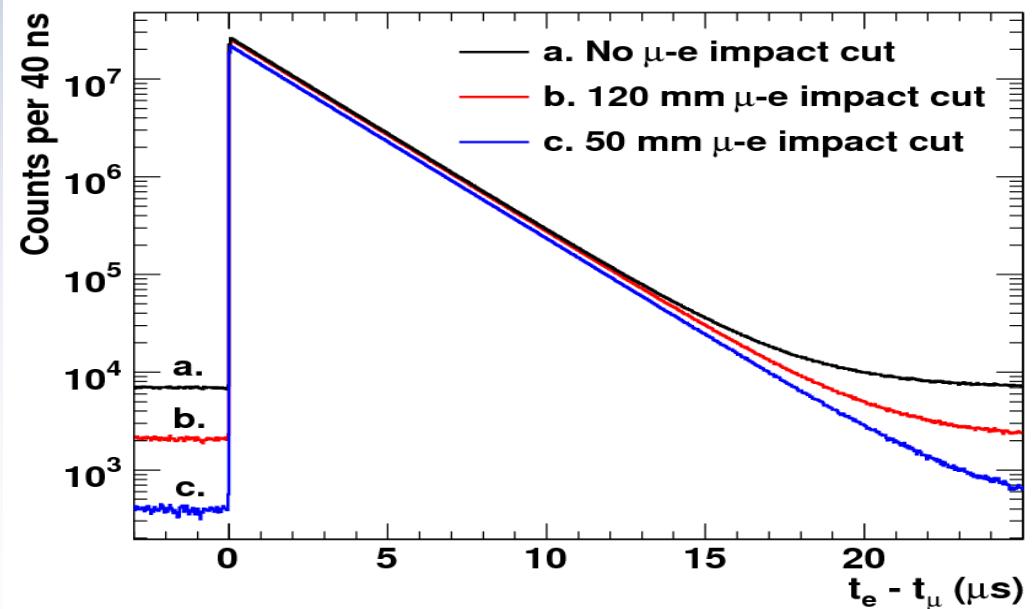
μ^-

3D tracking w/o material
in fiducial volume

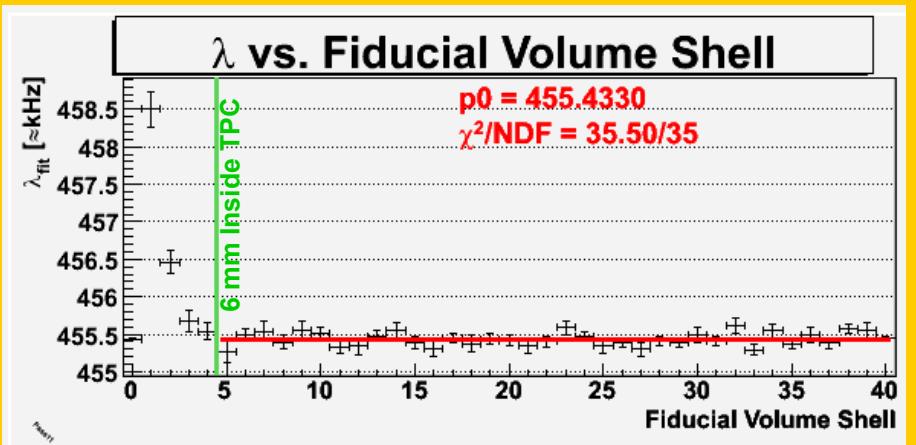
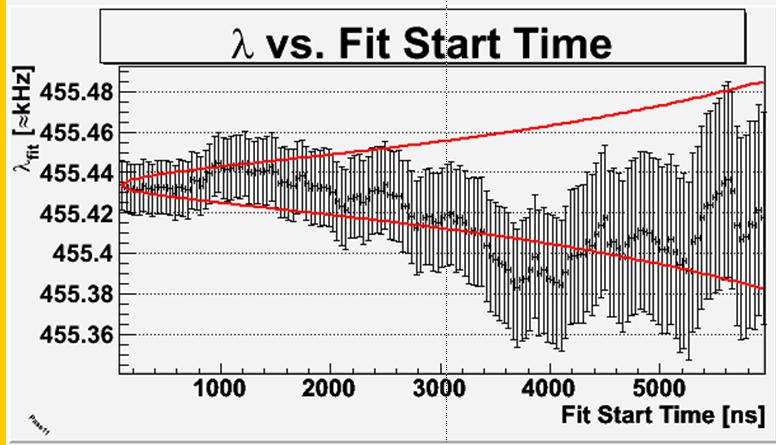


μ -e impact parameter cut
huge background suppression
diffusion (deuterium) monitoring

*blinded master
clock frequency*



variety of consistency checks



Measurement of the Rate of Muon Capture in Hydrogen Gas and Determination of the Proton's Pseudoscalar Coupling g_P



V.A. Andreev,¹ T.I. Banks,² T.A. Case,² D.B. Chitwood,³ S.M. Clayton,³ K.M. Crowe,² J. Deutsch,⁴ J. Egger,⁵ S.J. Freedman,² V.A. Ganzha,¹ T. Gorringe,⁶ F.E. Gray,² D.W. Hertzog,³ M. Hildebrandt,⁵ P. Kammel,³ B. Kiburg,³ S. Knaack,³ P.A. Kravtsov,¹ A.G. Krivshich,¹ B. Lauss,² K.L. Lynch,⁷ E.M. Maev,¹ O.E. Maev,¹ F. Mulhauser,^{3,5} C.S. Özben,³ C. Petitjean,⁵ G.E. Petrov,¹ R. Prieels,⁴ G.N. Schapkin,¹ G.G. Semenchuk,¹ M.A. Soroka,¹ V. Tishchenko,⁶ A.A. Vasilyev,¹ A.A. Vorobyov,¹ M.E. Vznuzdaev,¹ and P. Winter³
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(Dated: April 16, 2007)

[arXiv:0704.2072v1](https://arxiv.org/abs/0704.2072v1) [nucl-ex]

accepted PRL

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

Average of HBChPT calculations of Λ_S :

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

Apply new rad. correction (2.8%):

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

further sub percent theory required

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

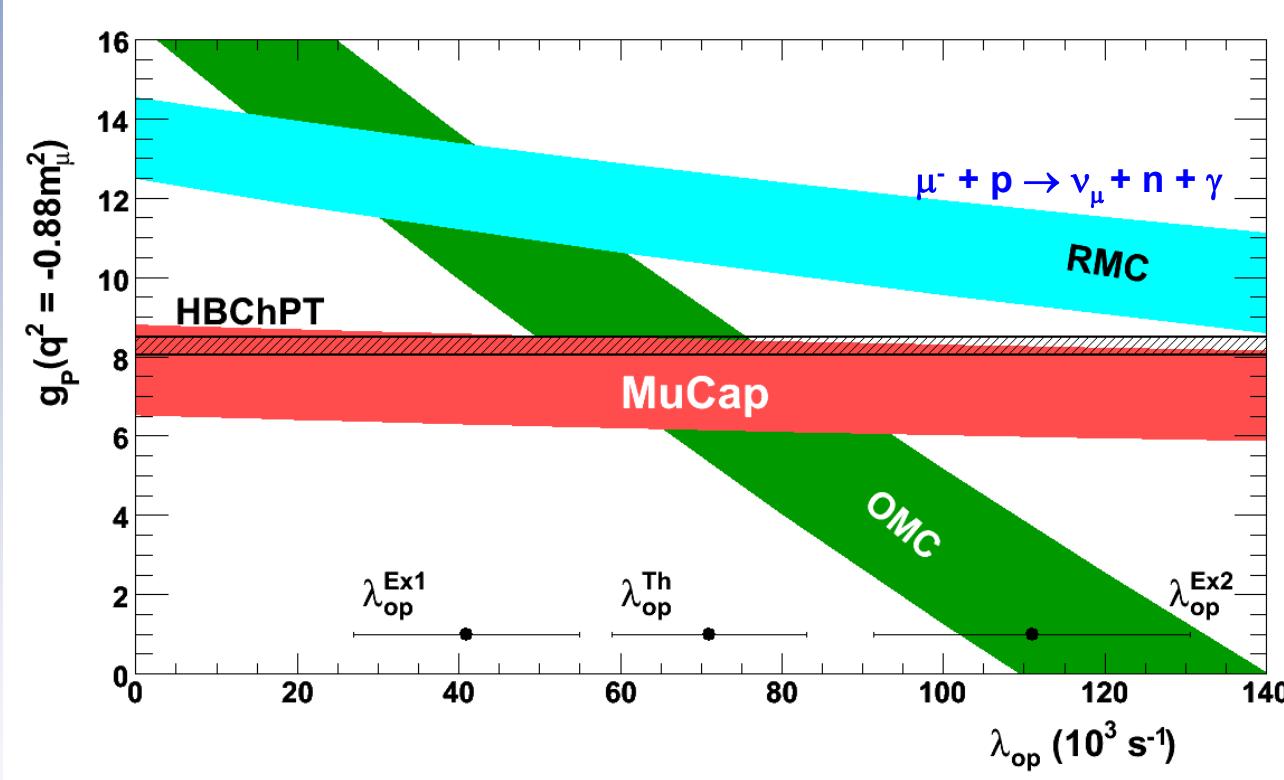
[arXiv:0704.3968v1](https://arxiv.org/abs/0704.3968v1) [hep-ph]

Czarnecki, Marciano, Sirlin

$$g_P = 7.3 \pm 1.1$$

(MuCap 2007)

MuCap g_P Landscape after MuCap 06



Before MuCap experiments inconclusive and mutually inconsistent

MuCap

- MuCap result nearly model independent
First precise and unambiguous result
- Consistent with chiral prediction
Does not confirm radiative muon capture (RMC) discrepancy
- Final result ('06 and '07 data) will reduce error twofold

MuLan Scientific Case



■ Fundamental electroweak parameters

 G_F

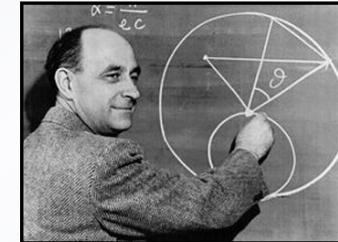
9 ppm

 α

0.0007 ppm

 M_Z

23 ppm



■ G_F

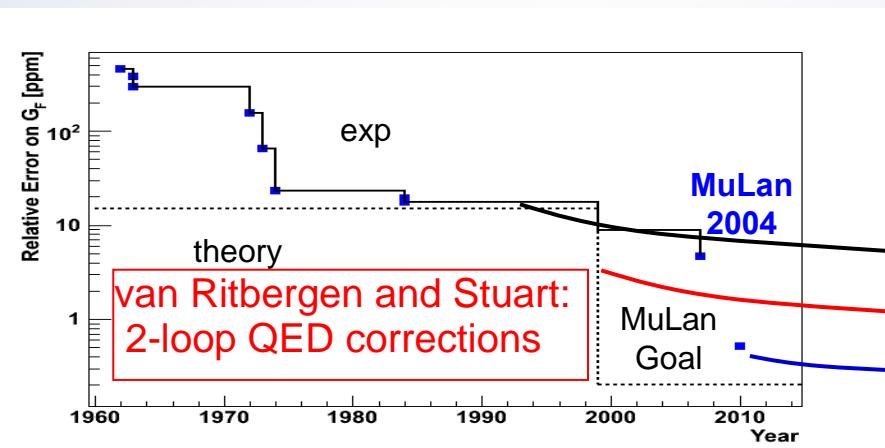
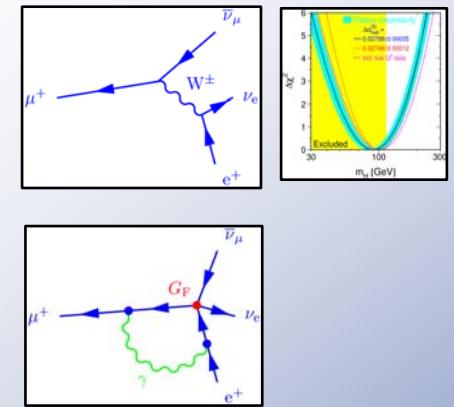
Implicit to all EW precision physics

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} (1 + \Delta r(m_t, m_H, \dots))$$

Uniquely related to muon decay

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

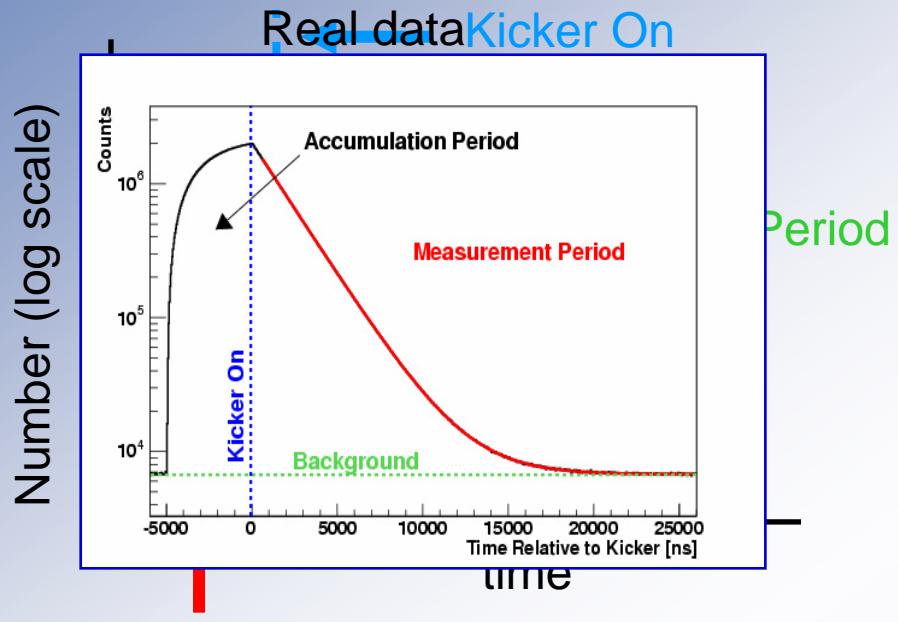
QED

Precision $G_F \rightarrow \tau$ relation no longer theory limited

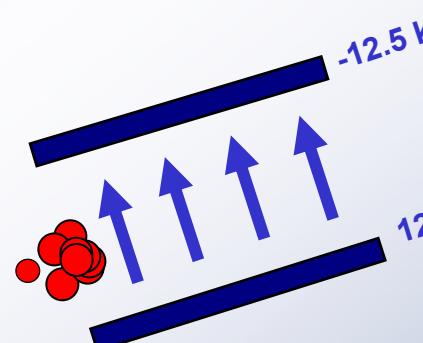
$$\frac{\delta G_F}{G_F} = \frac{1}{2} \sqrt{\left(\frac{\delta \tau_\mu}{\tau_\mu} \right)^2 + \left(5 \frac{\delta m_\mu}{m_\mu} \right)^2 + \left(\frac{\delta \text{theory}}{\text{theory}} \right)^2}$$

17 ppm 18 ppm 90 ppb 30 ppm

MuLan Experiment



Fill Period



Improved Measurement of the Positive Muon Lifetime and Determination of the Fermi Constant

D.B. Chitwood,¹ T.I. Banks,² M.J. Barnes,³ S. Battu,⁴ R.M. Carey,⁵ S. Cheekatmalla,⁴ S.M. Clayton,¹ J. Crnkovic,¹ K.M. Crowe,² P.T. Debevec,¹ S. Dhamija,⁴ W. Earle,⁵ A. Gafarov,⁵ K. Giovanetti,⁶ T.P. Gorringe,⁴ F.E. Gray,^{1,2} M. Hance,⁵ D.W. Hertzog,¹ M.F. Hare,⁵ P. Kammler,¹ B. Kiburg,¹ J. Kunkle,¹ B. Lauss,² I. Logashenko,⁵ K.R. Lynch,⁵ R. McNabb,¹ J.P. Miller,⁵ F. Mulhauser,¹ C.J.G. Onderwater,^{1,7} C.S. Özben,¹ Q. Peng,⁵ C.C. Polly,¹ S. Rath,⁴ B.L. Roberts,⁵ V. Tishchenko,⁴ G.D. Wait,³ J. Wasserman,⁵ D.M. Webber,¹ P. Winter,¹ and P.A. Żohierczuk⁴

(MuLan Collaboration)

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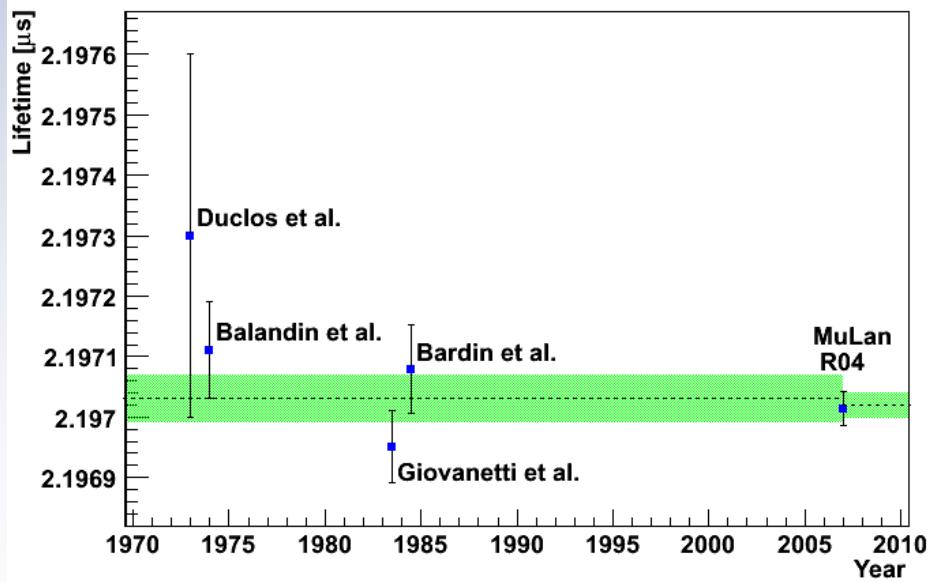
⁶Department of Physics, James Madison University, Harrisonburg, VA 22807, USA

⁷Kernfysisch Versneller Instituut, Groningen University, NL 9747 AA Groningen, The Netherlands

The mean life of the positive muon has been measured to a precision of 11 ppm using a low-energy, pulsed muon beam stopped in a ferromagnetic target, which was surrounded by a scintillator detector array. The result, $\tau_\mu = 2.197\,013(24) \mu\text{s}$, is in excellent agreement with the previous world average. The new world average $\tau_\mu = 2.197\,019(21) \mu\text{s}$ determines the Fermi constant $G_F = 1.166\,371(6) \times 10^{-5} \text{ GeV}^{-2}$ (5 ppm). Additionally, the precision measurement of the positive muon lifetime is needed to determine the nucleon pseudoscalar coupling g_F .

6/5/07 accepted PRL

arXiv:0704.1981v1 [hep-ex]



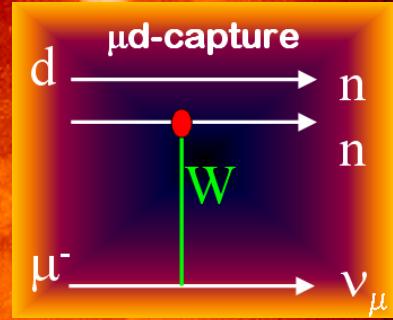
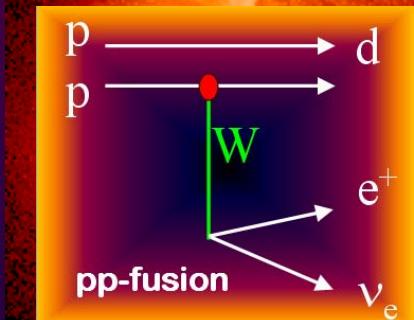
$$\tau_\mu(\text{MuLan}) = 2.197\,013(21)(11) \mu\text{s} \quad (11\text{ ppm})$$

$$\tau_\mu(\text{World}) = 2.197\,019(21) \mu\text{s} \quad (9.6\text{ ppm})$$

$$G_F = 1.166\,371(6) \times 10^{-5} \text{ GeV}^{-2} \quad (5\text{ ppm})$$

“Calibrating the Sun” via Muon Capture on the Deuteron

“MuSun”



model-independent connection via EFT & L_{1A}

Goal

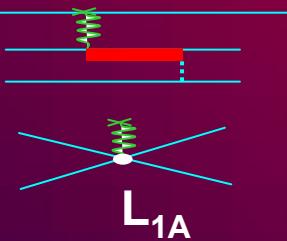
total μd capture rate to 1% precision

Motivation

- first precise measurement of basic EW reaction in 2N system,
benchmark measurement with 10x higher precision
- impact on fundamental astrophysics reactions (SNO, pp)
- comparison of modern high precision calculations (EFT/SNPA)
- high precision feasible by μ Cap technique and careful optimization

MEC

EFT



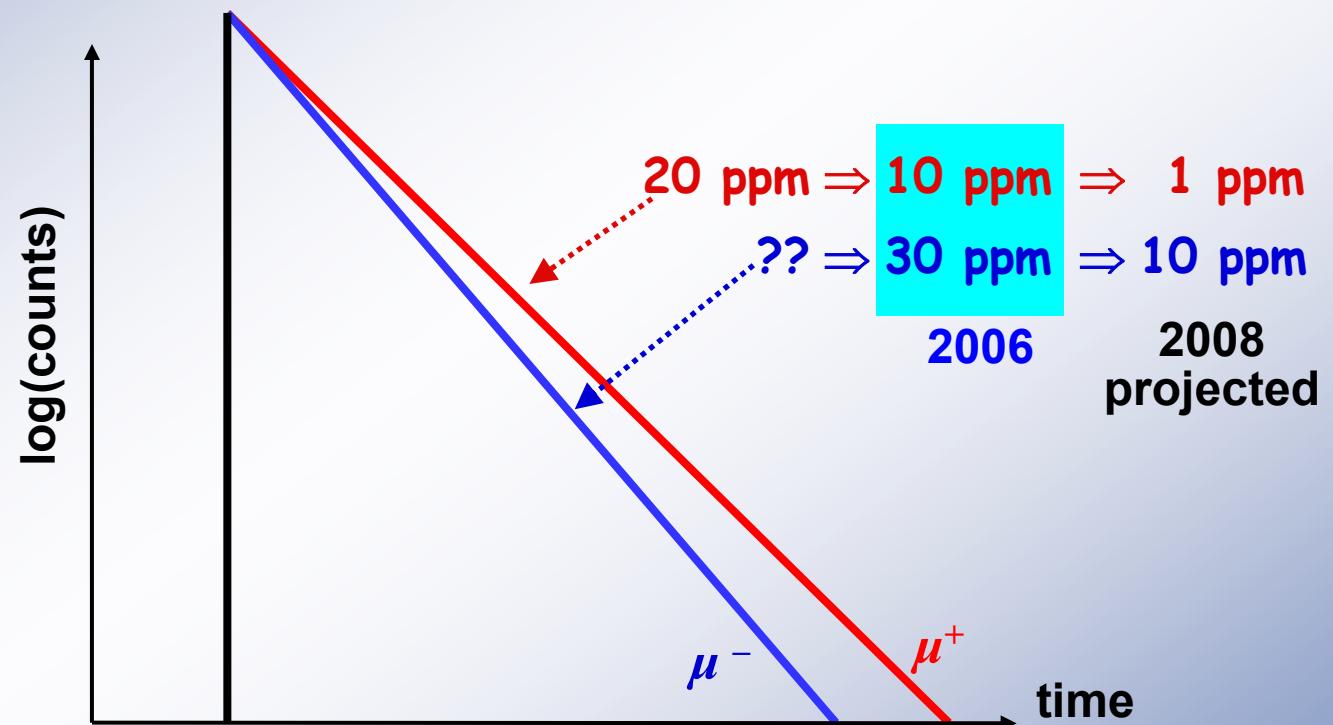
proposal end 2007

Synergy and Outlook



- MuLan

- MuCap



- MuSun needs both, g_P and precision lifetimes