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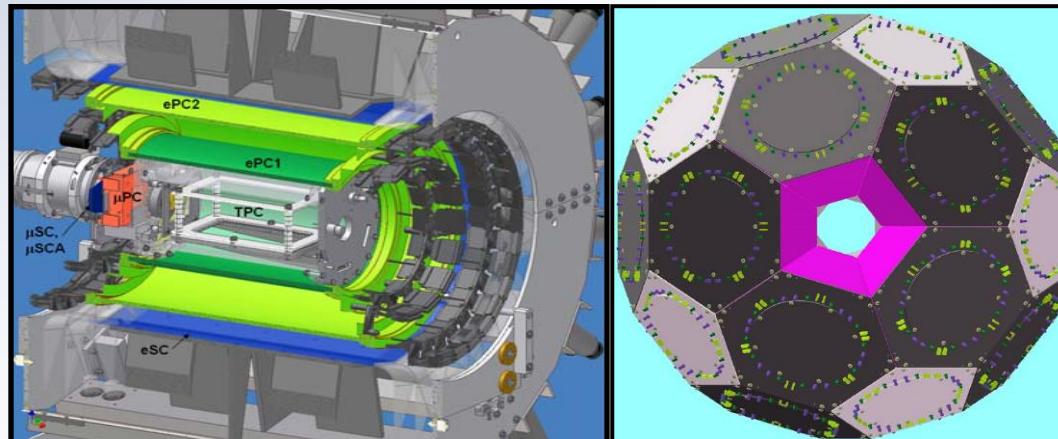
Nuclear Muon Capture in Hydrogen and its Interplay with Muon Atomic Physics

Peter Kammel



g_P

MuCap

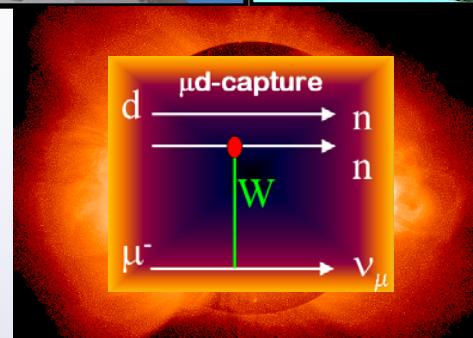


G_F

MuLan

L_{1A}

“MuSun”
project

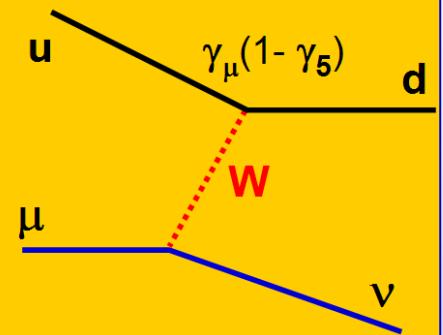


➤ Historical: V-A and μ -e Universality

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

charged current

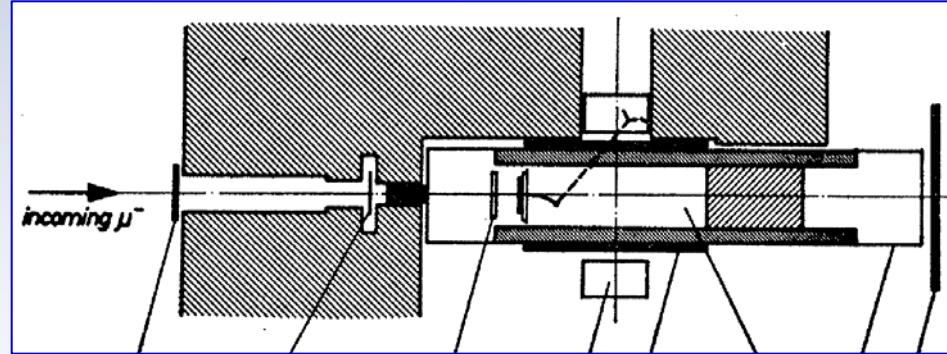
quark level



My Talk is Dedicated to the Pioneers



Emilio Zavattini 1927-2007



1969 Bologna-Pisa-CERN



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

1973 Dubna group

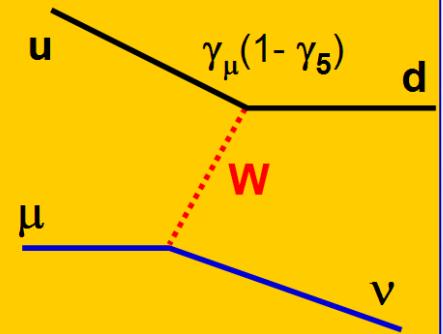


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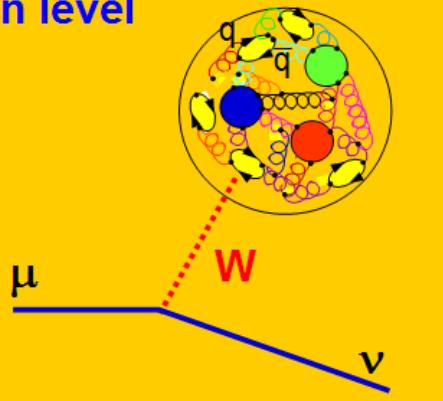
quark level



➤ Today: EW current key probe for

- Understanding hadrons from fundamental QCD
- Symmetries of Standard Model
- Basic astrophysics reactions

nucleon level



QCD

$$\mathcal{L}_{\text{QCD}} = \bar{\psi} (i\gamma_\mu \mathcal{D}^\mu - \mathbf{m}) \psi - \frac{1}{4} \mathbf{G}_{\mu\nu} \mathbf{G}^{\mu\nu}$$



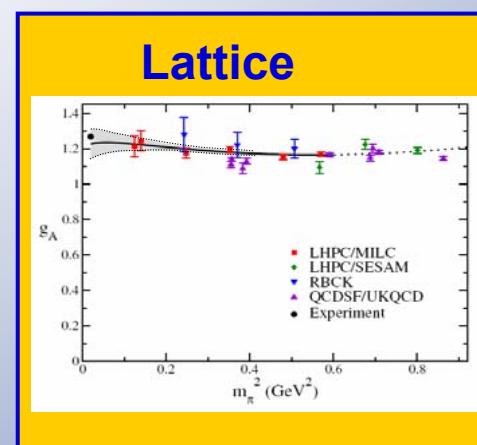
- high q^2 ($q > \text{some GeV}$) short distance $< 0.1 \text{ fm}$

Weakly interacting quarks and gluons
asymptotic freedom

- low q^2 ($q \ll 1 \text{ GeV}$) long distance $> 1 \text{ fm}$

QCD has chiral symmetry
spontaneously broken
 π is Nambu-Goldstone boson, weakly interacting
chiral effective theory \leftrightarrow Nuclear Physics

- Lattice QCD: ab initio calculations
issues: continuum transition, etc.
physical quark masses not reached



Edwards et al. LHPC
Coll (2006)



Formfactors and g_P



➤ Muon Capture

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

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

➤ Formfactors

Lorentz, T invariance

$$V_\alpha = g_V(q^2) \gamma_\alpha + \frac{i g_M(q^2)}{2 M_N} \sigma_{\alpha\beta} q^\beta$$

$$A_\alpha = g_A(q^2) \gamma_\alpha \gamma_5 + \frac{\mathbf{g}_P(q^2)}{m_\mu} q_\alpha \gamma_5$$

+ second class currents suppressed by isospin symm.

All form factors precisely known from SM symmetries and data.

CVC, n beta decay

$$\frac{\delta \Lambda_S}{\Lambda_S} = 0.46\%$$

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

$$\frac{\delta \Lambda_S}{\Lambda_S} = 0.184 \frac{\delta g_P}{g_P} \approx 9\%$$





g_P determined by chiral symmetry of QCD:

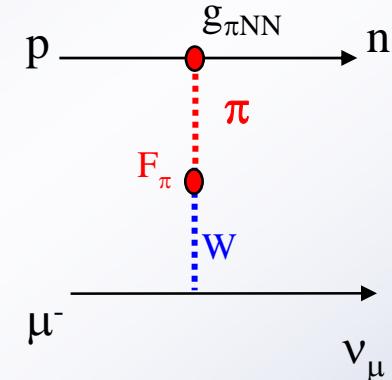
$$g_p(q^2) = \frac{2m_\mu g_{\pi NN}(q^2)F_\pi}{m_\pi^2 - q^2} - \frac{1}{3}g_a(0)m_\mu m_N r_A^2$$

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

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

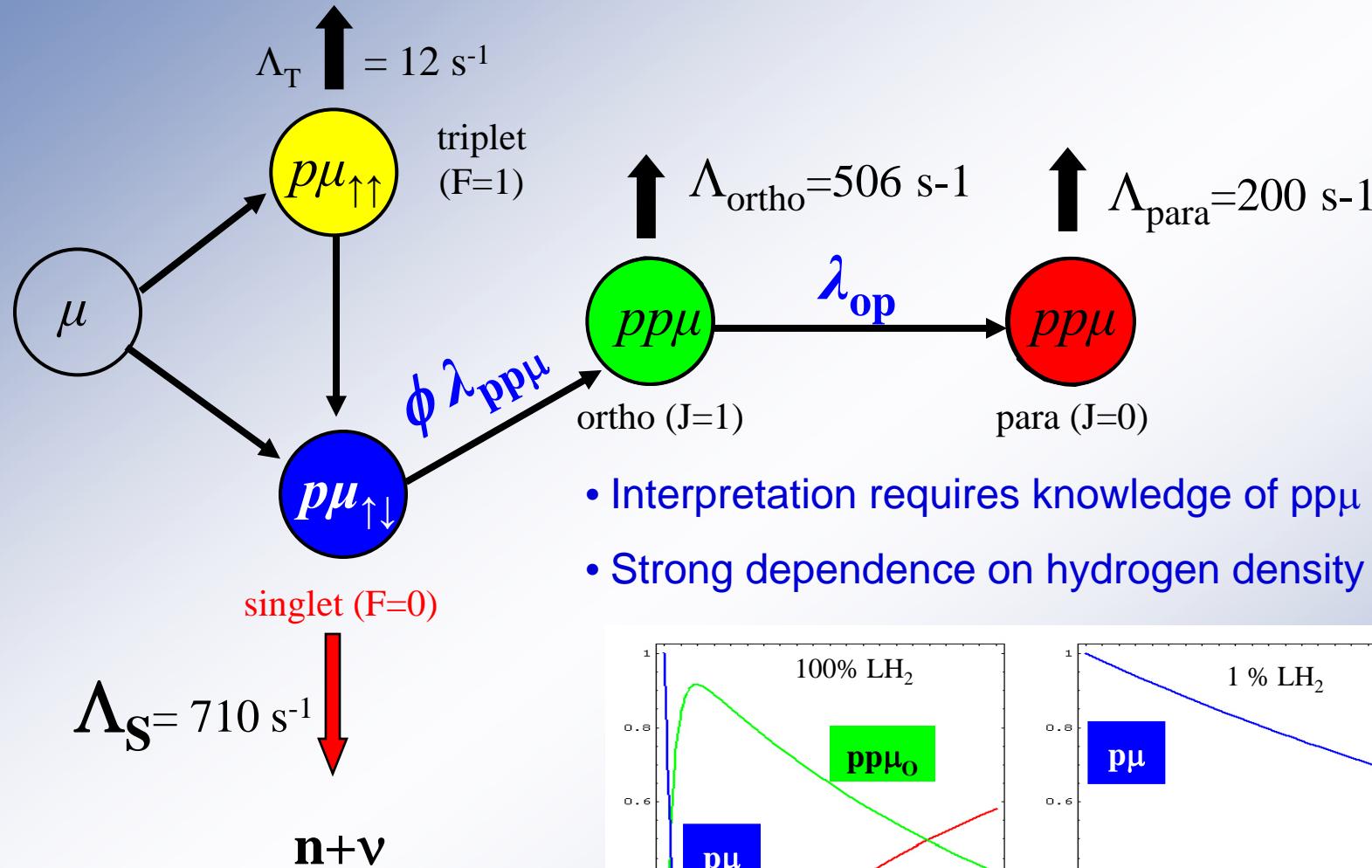
Recent reviews:

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

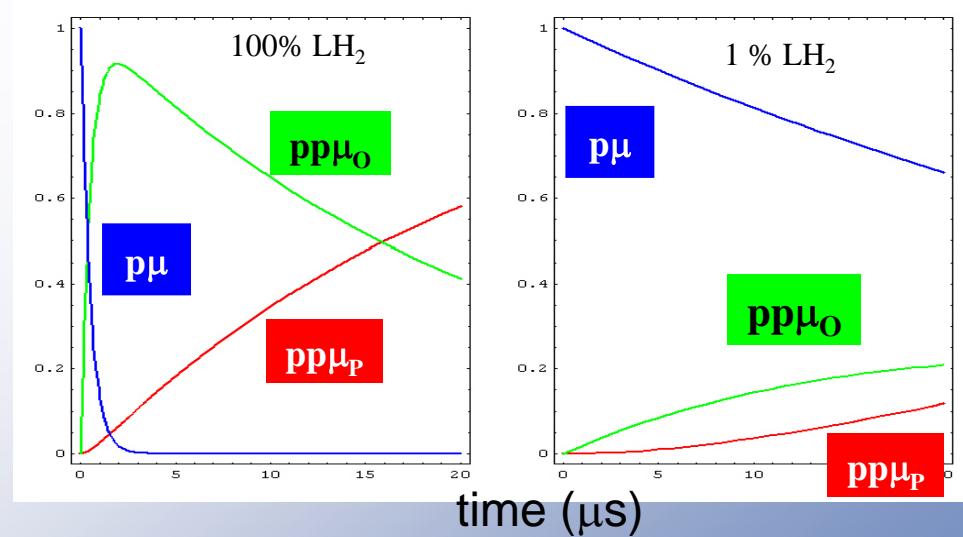
V. Bernard et al., Nucl. Part. Phys. 28 (2002), R1



Muonic Processes Complicate Interpretation



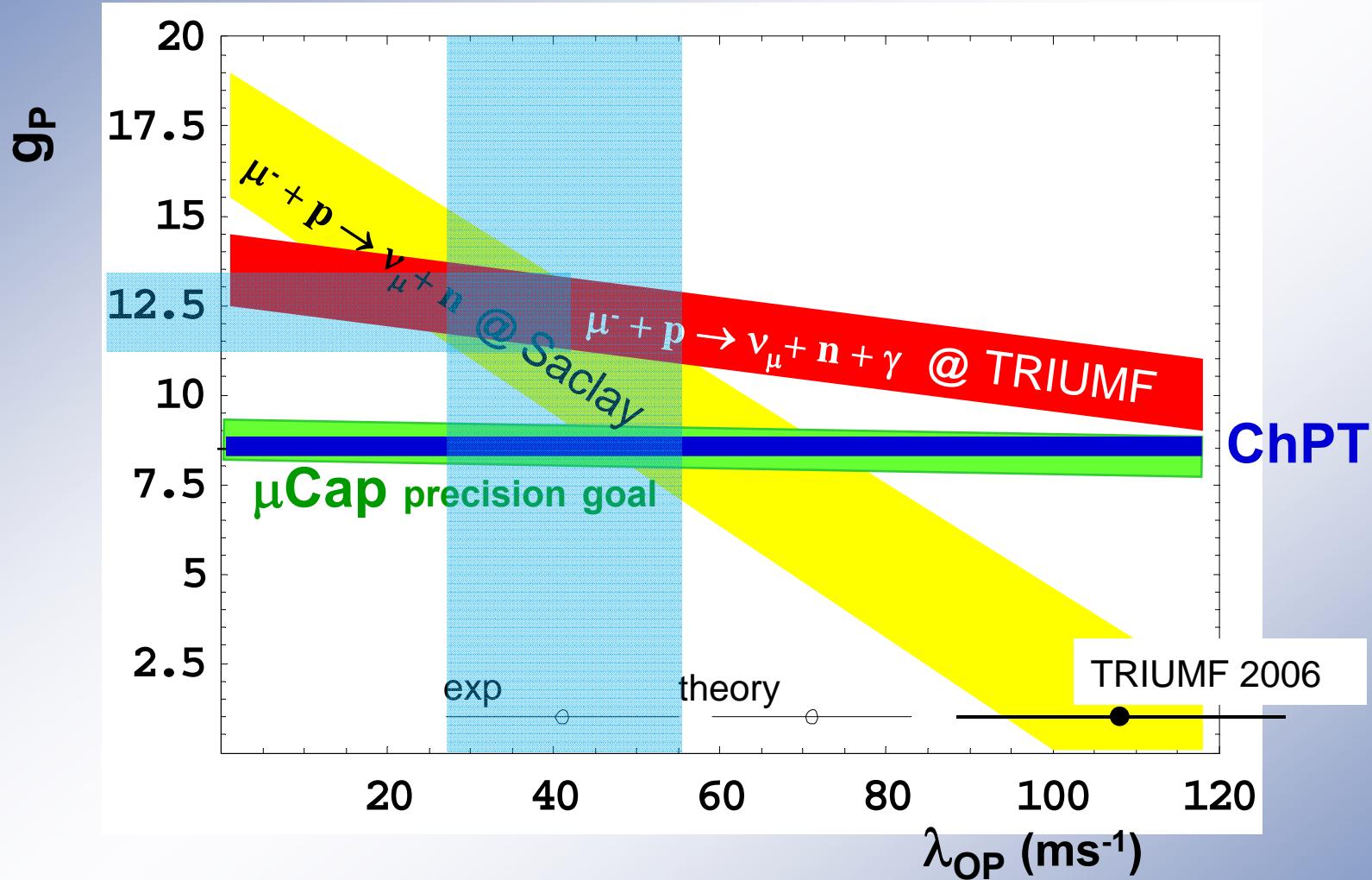
- Interpretation requires knowledge of $pp\mu$ population
- Strong dependence on hydrogen density ϕ



MuCap



Precise Theory vs. 45 Years of Exp. Efforts

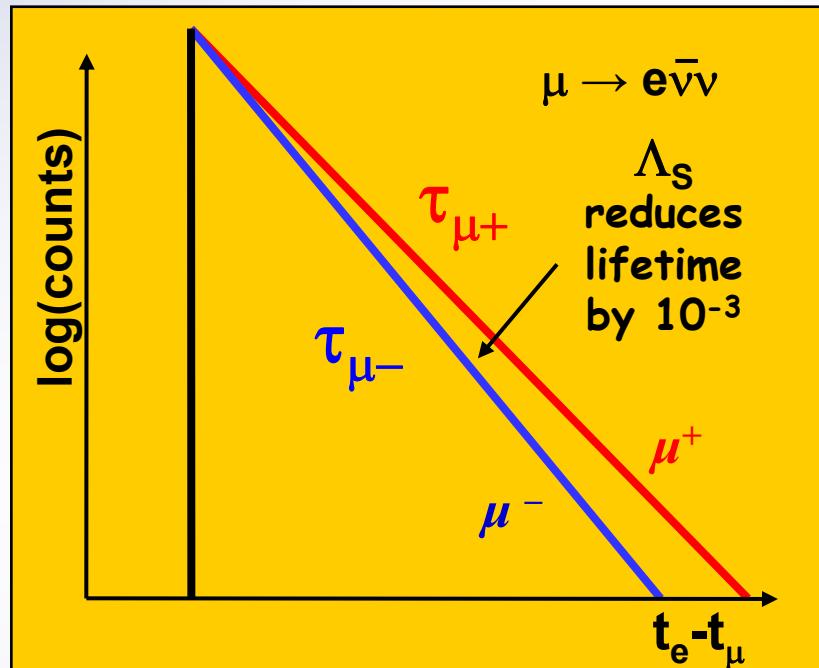


- no overlap theory & OMC & RMC
- large uncertainty in $\lambda_{OP} \rightarrow g_P \pm 50\% ?$

MuCap



- Lifetime method
 $10^{10} \mu \rightarrow e\bar{\nu}\bar{\nu}$ 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”

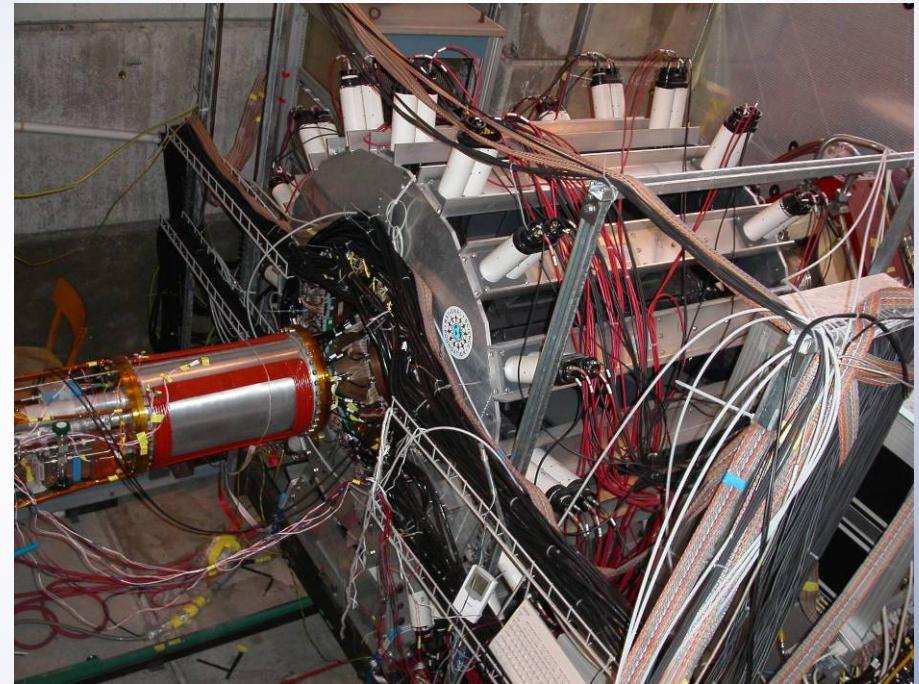
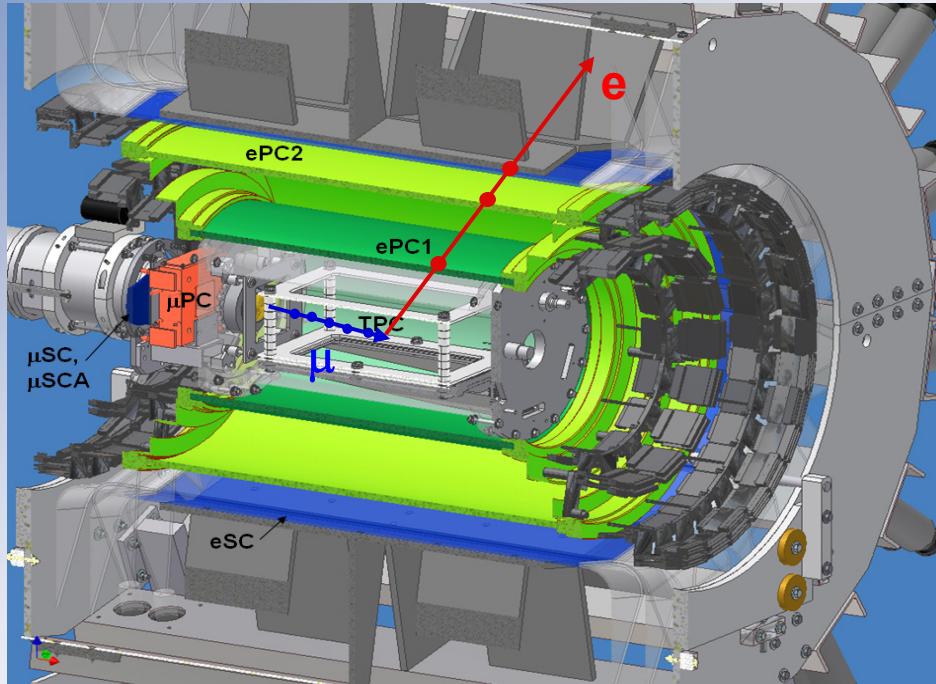


*fulfill all requirements simultaneously
unique MuCap capabilities*

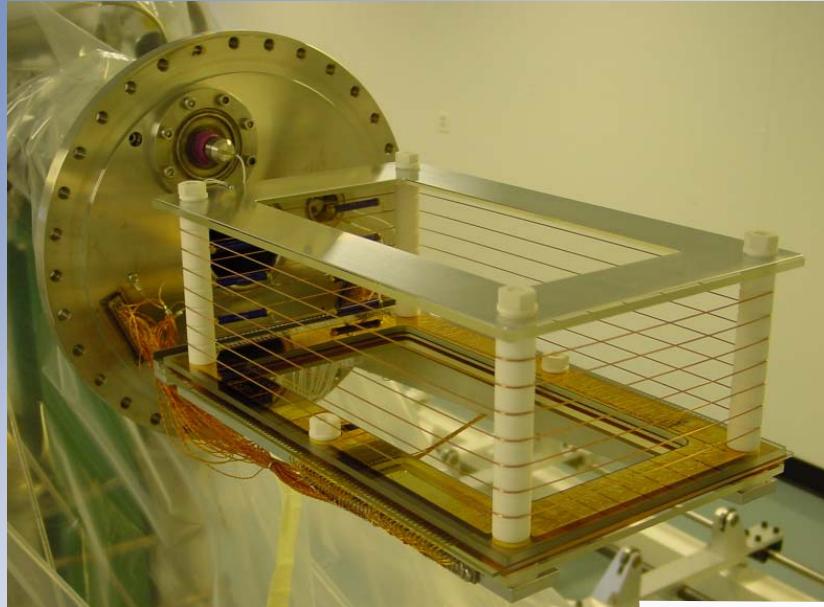


MuCap

MuCap Detector

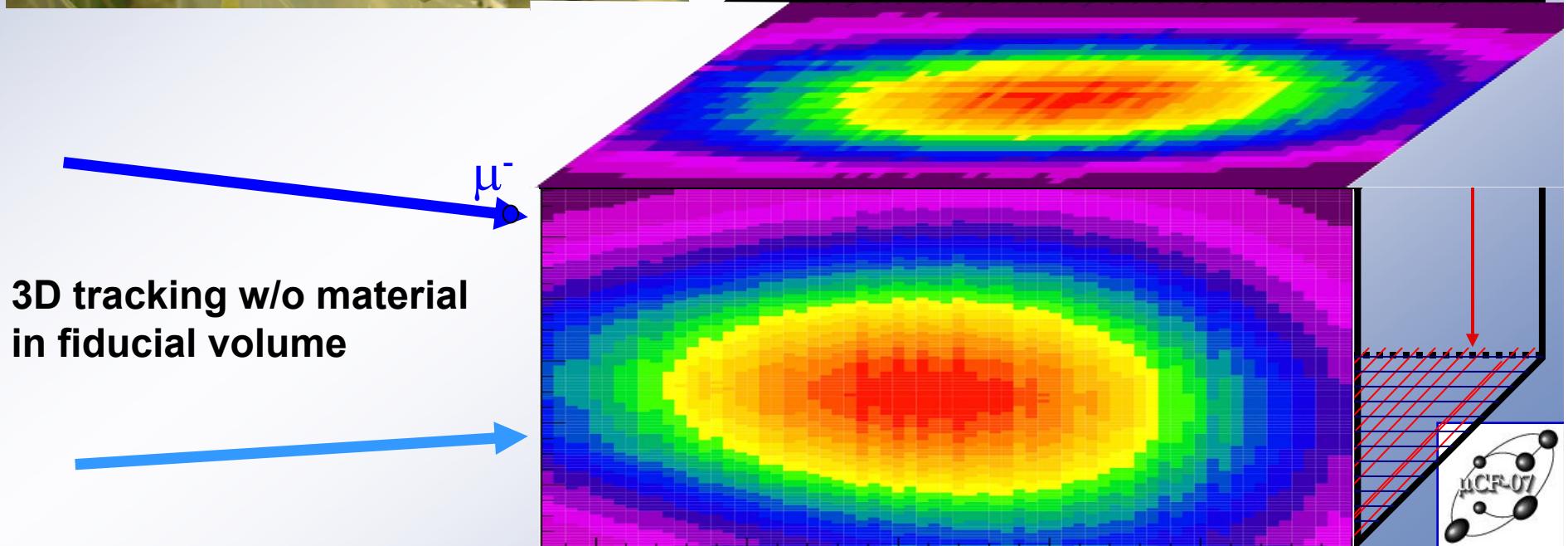


MuCap Muons stop in active TPC target



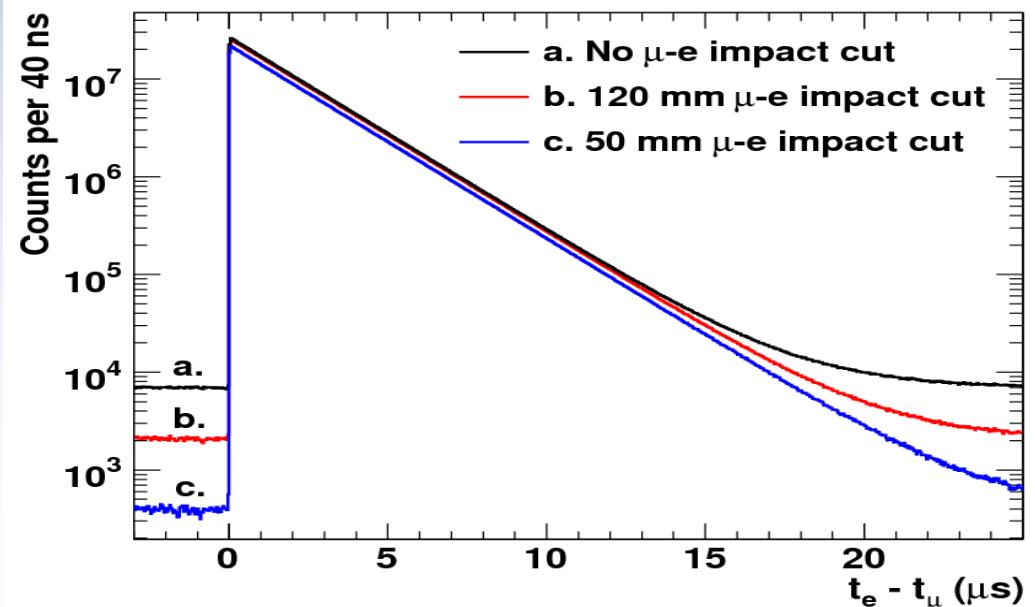
10 bar ultra-pure hydrogen, 1.16% LH₂
2.0 kV/cm drift field
~5.4 kV on 3.5 mm anode half gap
bakeable glass/ceramic materials

Observed muon stopping distribution

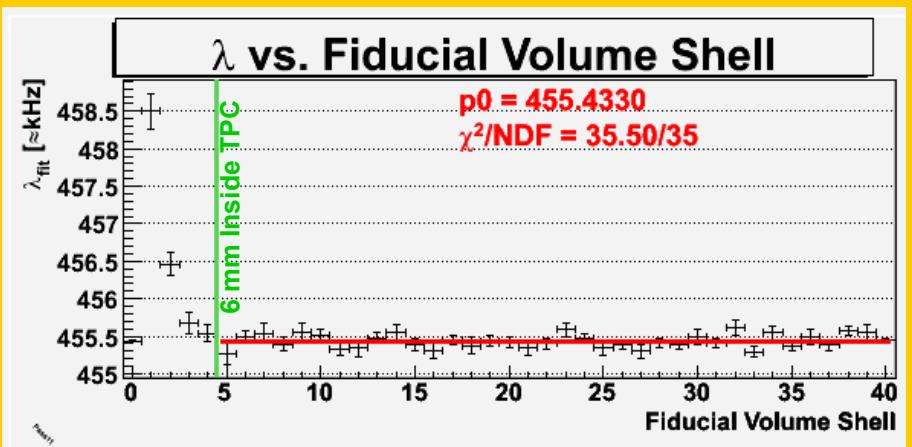
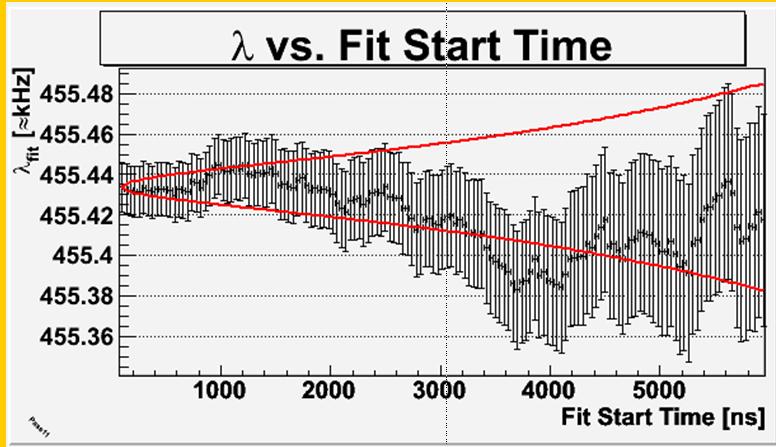


μ -e impact parameter cut
huge background suppression
diffusion (deuterium) monitoring

*blinded master
clock frequency*



variety of consistency checks



MuCap Unique Capabilities: Impurities

rare impurity capture $\mu Z \rightarrow (Z-1) + n + \nu$

$$\Lambda_Z (C, N, O) \sim (40-100) \times \Lambda_s$$

~10 ppb purity required

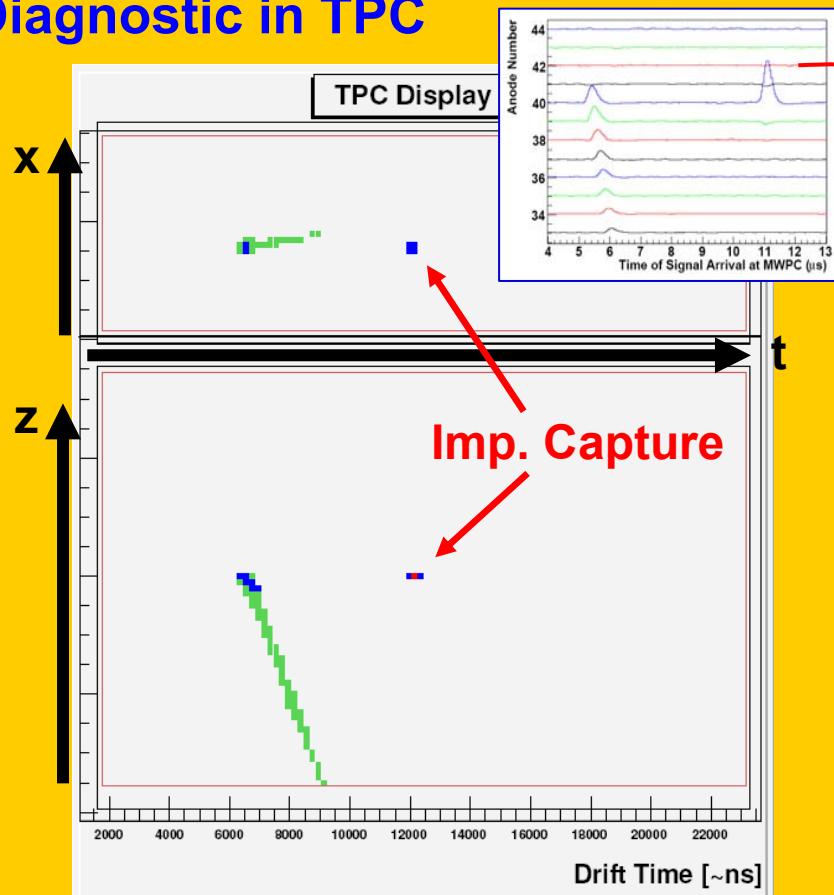
Hardware

Circulating Hydrogen Ultrahigh Purification System

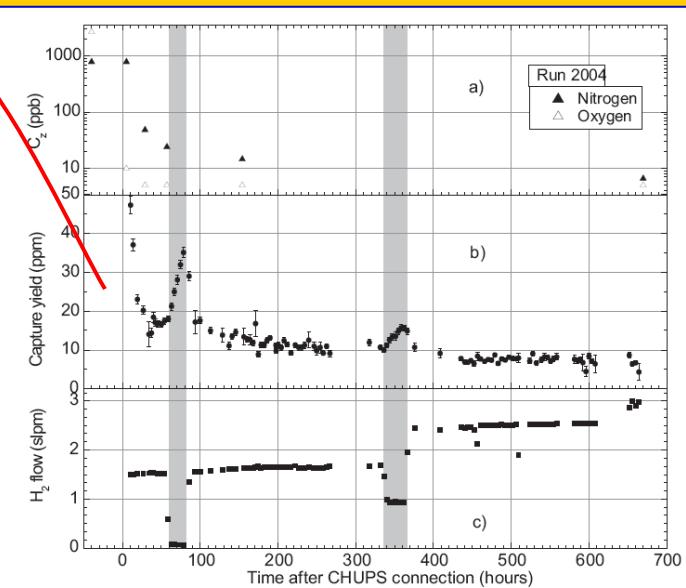
Gas chromatography

CRDF 2002, 2005

Diagnostic in TPC



Results



- $c_N, c_O < 7$ ppb, $c_{H_2O} \sim 18-30$ ppb
- correction based on observed capture yield

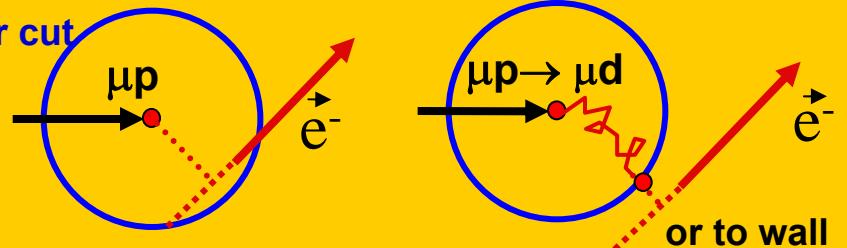
MuCap Unique Capabilities: μp , μd diffusion



large diffusion range of μd

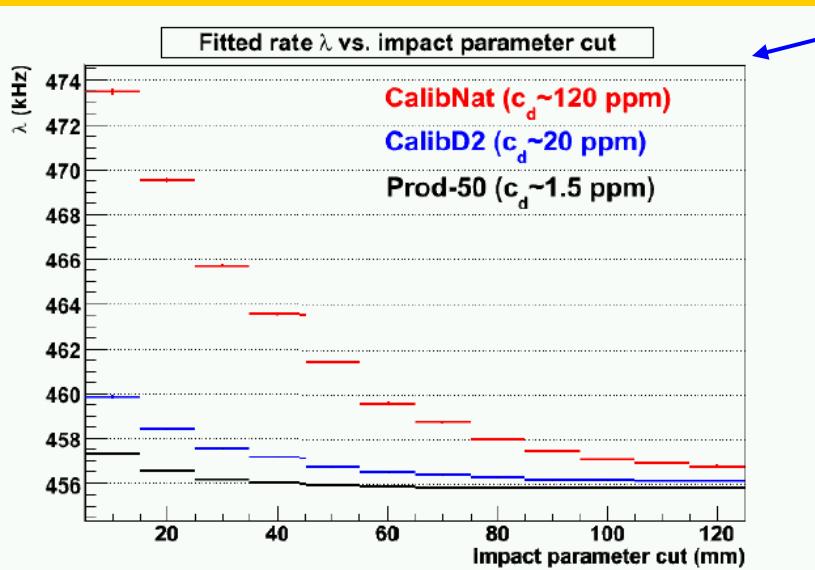
< 1 ppm isotopic purity required

μ -e impact par cut



Diagnostic:

- λ vs. μ -e vertex cut



- AMS, ETH Zurich

Results

- Directly from data

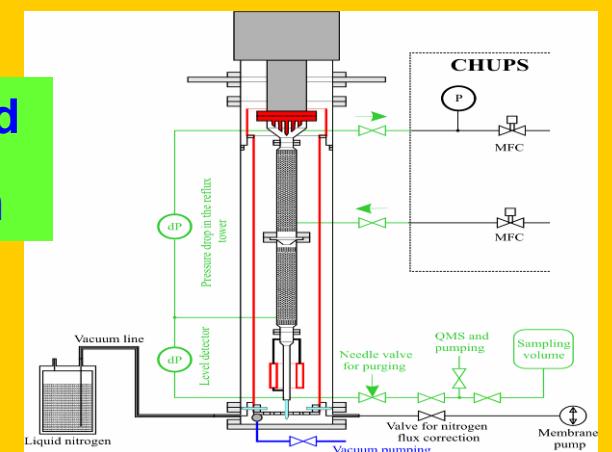
$$c_d = 1.49 \pm 0.12 \text{ ppm}$$

- AMS (2006)

$$c_d = 1.44 \pm 0.15 \text{ ppm}$$

On-site isotopic purifier 2006 (PNPI, CRDF)

World Record
 $c_d < 0.1$ ppm



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
(MuCap Collaboration)

¹Petersburg Nuclear Physics Institute, Gatchina 188350, Russia

²University of California, Berkeley, and LBNL, Berkeley, CA 94720, USA

³University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

⁴Université Catholique de Louvain, B-1348, Louvain-la-Neuve, Belgium

⁵Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland

⁶University of Kentucky, Lexington, KY 40506, USA

⁷Boston University, Boston, MA 02215, USA

(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]

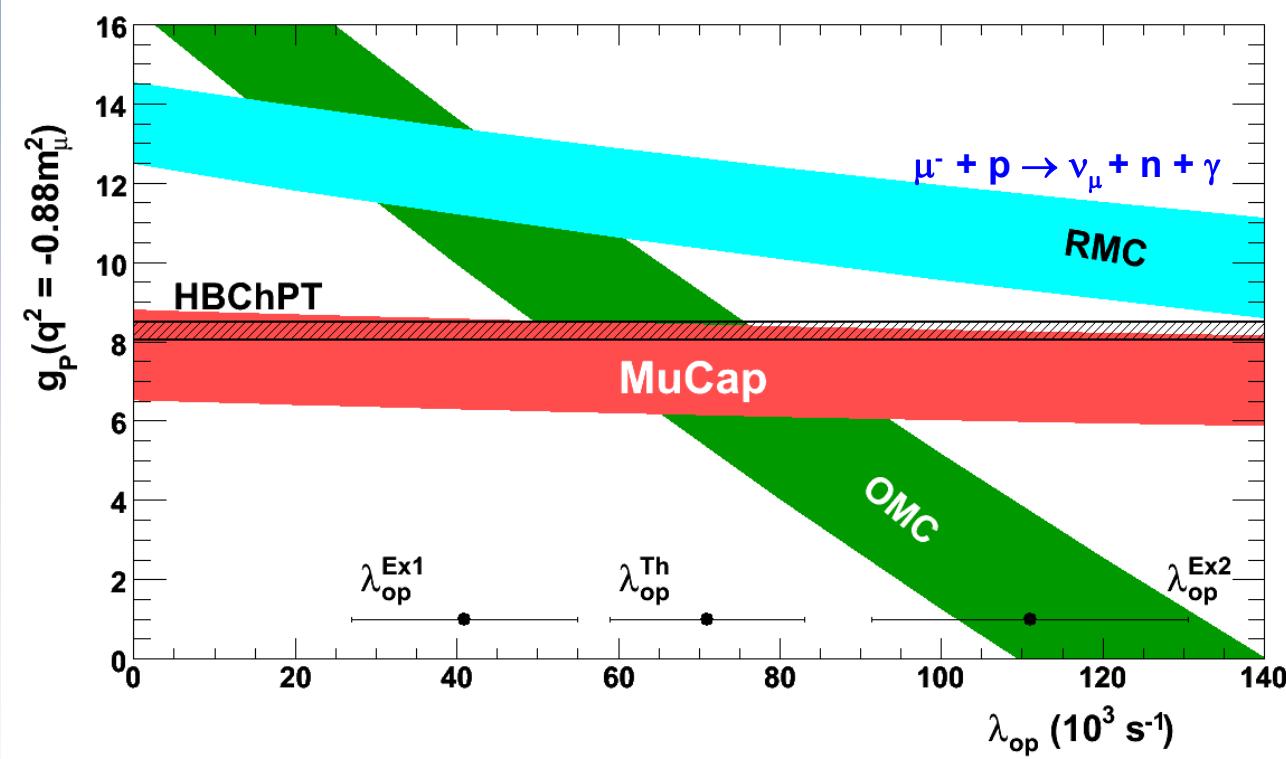
Czarnecki, Marciano, Sirlin

$$g_P = 7.3 \pm 1.1$$

(MuCap 2007)



g_P Landscape after MuCap 06



Before MuCap experiments inconclusive and mutually inconsistent

MuCap

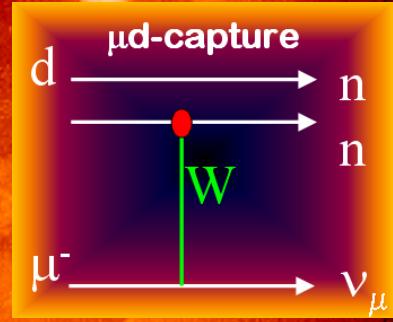
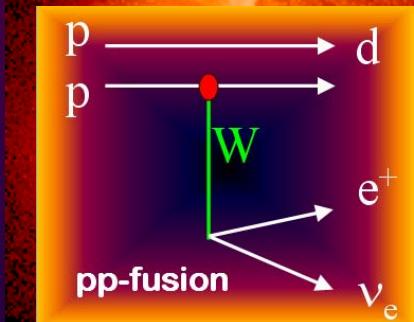
- MuCap result nearly model independent
First precise and unambiguous result
- Consistent with chiral prediction
Does not confirm radiative muon capture (RMC) discrepancy
- Final result ('06 and '07 data) will reduce error twofold



“Calibrating the Sun” via Muon Capture on the Deuteron



“MuSun”



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

Goal

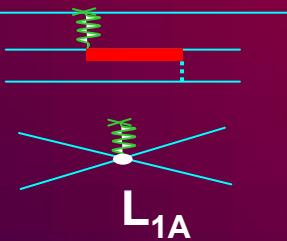
total μd capture rate to 1% precision

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
- high precision feasible by μ Cap technique and careful optimization

MEC

EFT



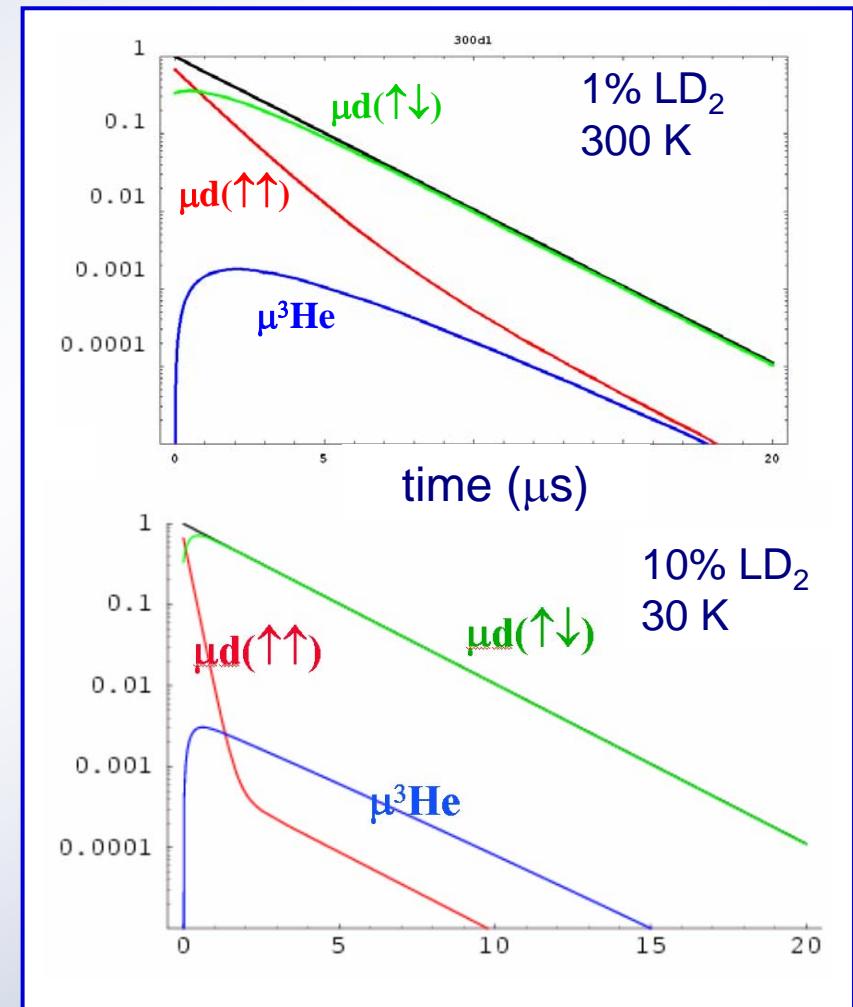
measurement of absolute rate to <1%

μSun I: μCap technique, 1% LD₂, 300 K,
measure time spectra of capture neutrons
monitor populations with fusion and
capture reactions

**First measurement of polarization
observables in μ+d capture?**

μSun II: new cryo TPC

Kinetics requires optimized target
conditions: T<50 K, >5% LD₂ density



MuLan Scientific Case



■ Fundamental electroweak parameters

 G_F

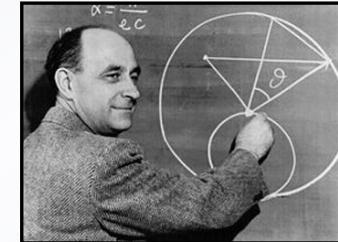
9 ppm

 α

0.0007 ppm

 M_Z

23 ppm



■ G_F

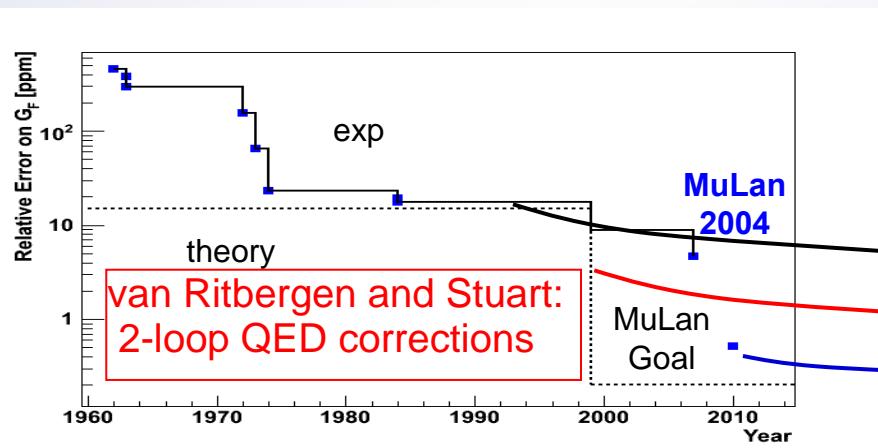
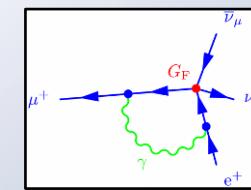
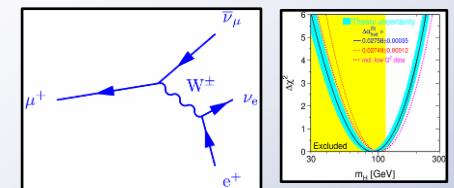
Implicit to all EW precision physics

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

Uniquely related to muon decay

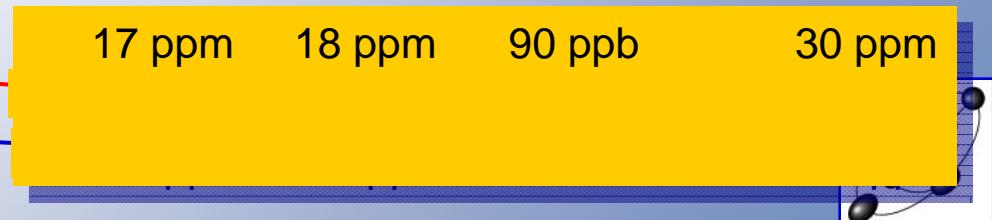
$$\frac{1}{\tau_{\mu^+}} = \frac{G_F^2 m_\mu^5}{192\pi^3} (1 + q)$$

QED

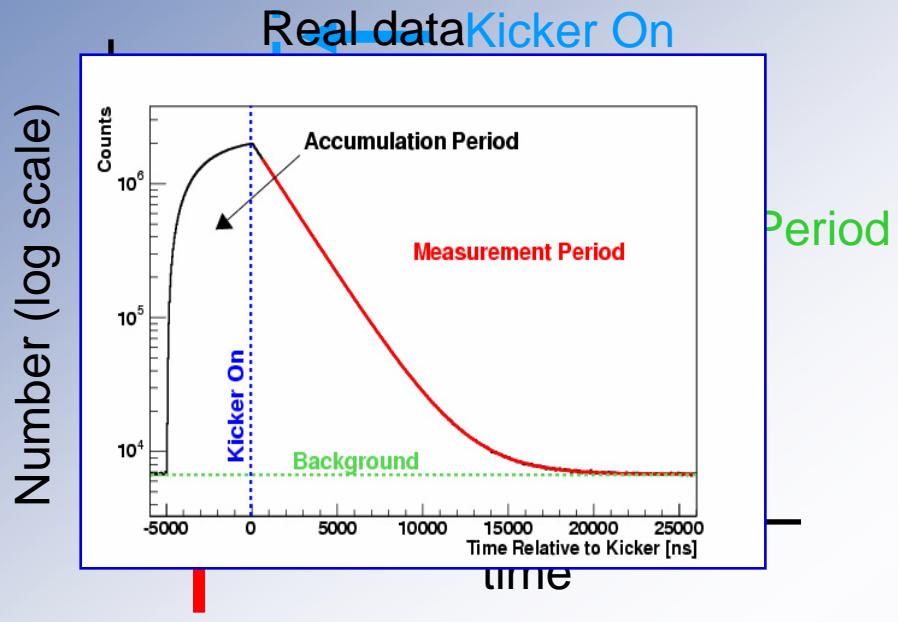
Precision $G_F \rightarrow \tau$ relation no longer theory limited

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

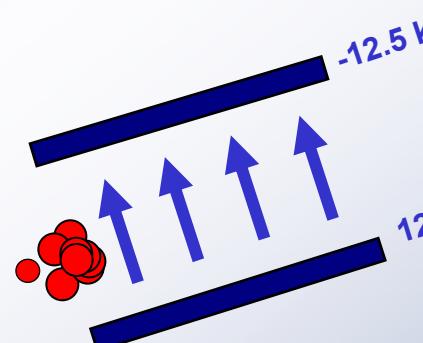
17 ppm 18 ppm 90 ppb 30 ppm



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. Żohmierczuk⁴

(MuLan Collaboration)

¹Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

²Department of Physics, University of California, Berkeley, CA 94720, USA

³TRIUMF, Vancouver, BC, V6T 2A3, Canada

⁴Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506, USA

⁵Department of Physics, Boston University, Boston, MA 02215, USA

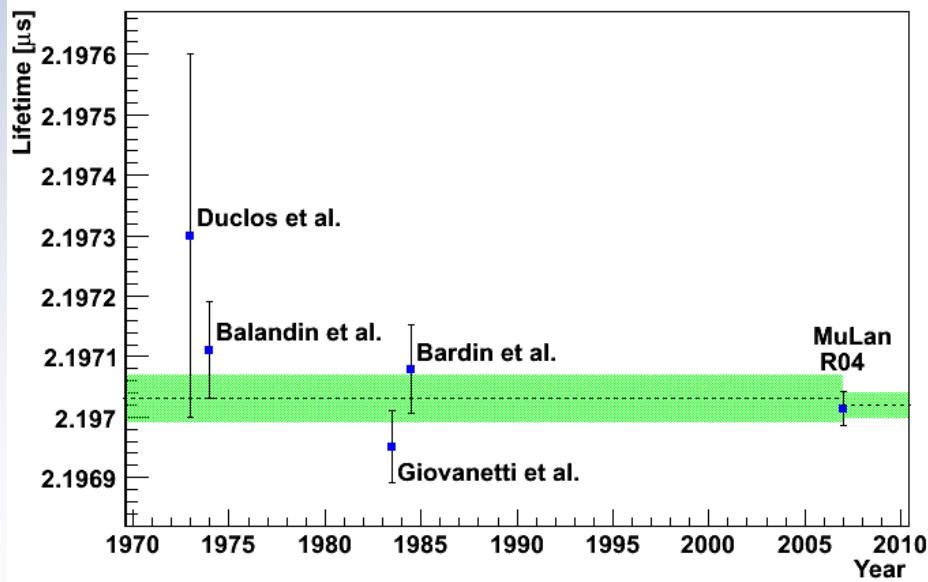
⁶Department of Physics, James Madison University, Harrisonburg, VA 22807, USA

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]



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

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

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



Summary I: Relevant MCF issues



MuCap:

- Th/Exp: ortho-para rate $\lambda_{OP}(\phi)$
- Exp: Precision measurement of formation rate $p\bar{p}\mu$ -ortho planned
- Th: $p\bar{p}\mu$ -para formation suppressed, $S_{tot}=1/2$ assumed
- Th/Exp: new experimental info on μp and μd scattering, theory cross sections and simulations
- Exp: measurements of μZ transfer and Auger effect
- Th: cross section for μ^+ diffusion

MuSun:

- Exp: $d\mu$ hyperfine transition at 300K
- Th/Exp: time evolution of $d\mu$ polarization
- Exp: $d\mu$ polarization observables in muon decay and capture
- Th/Exp: precision measurement $dd \rightarrow {}^4He + \gamma ?$



Summary II: Weak Interactions



MuLan:

- First G_F update in 23 years – 2.5x improvement, no surprise in result
- Factor 10 additional improvement on the way

MuCap:

- First precise g_P measurement with clear interpretation
- Consistent with ChPT expectation, does not support RMC puzzle
- Factor 2-3 additional improvement on the way

MuSun

- muon-deuteron capture, needs g_P as input
- New benchmark in EW reactions in $2N$ system

