Nuclear Muon Capture in Hydrogen

and its Interplay with Muon Atomic Physics

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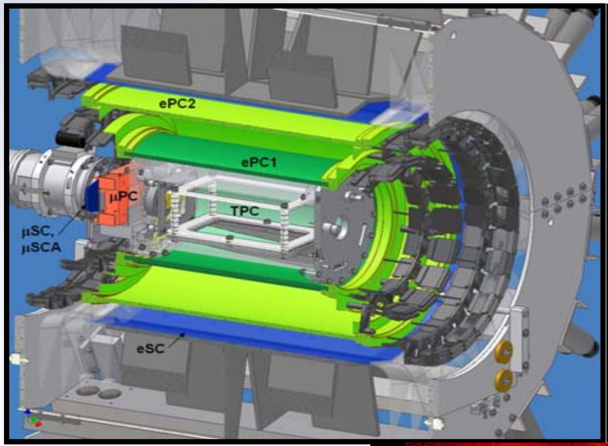
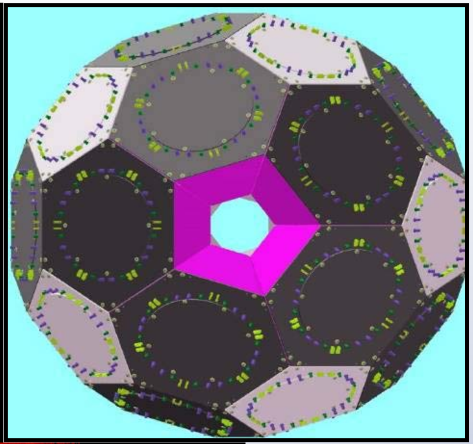
g_P

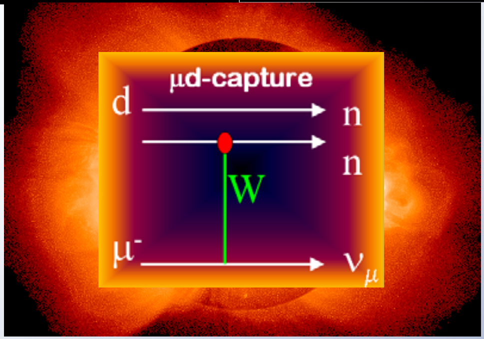
MuCap





G_F

MuLan



L_{1A}

"MuSun" project

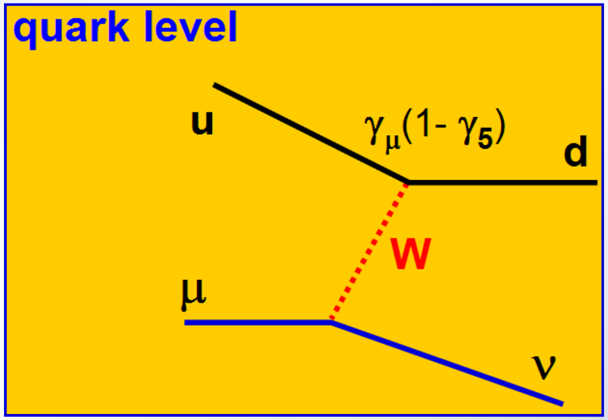
MuCap

Physics Context

- **Historical: V-A and μ-e Universality**

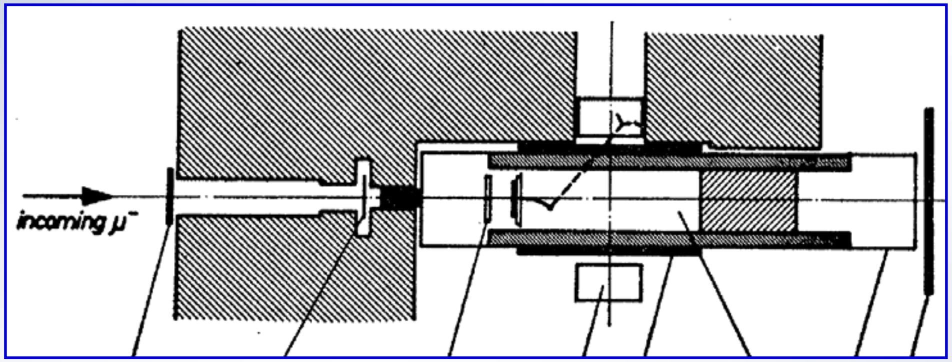
$\mu^- + p \rightarrow \nu_\mu + n$

charged current



My Talk is Dedicated to the Pioneers

Emilio Zavattini 1927-2007



1969 Bologna-Pisa-CERN

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

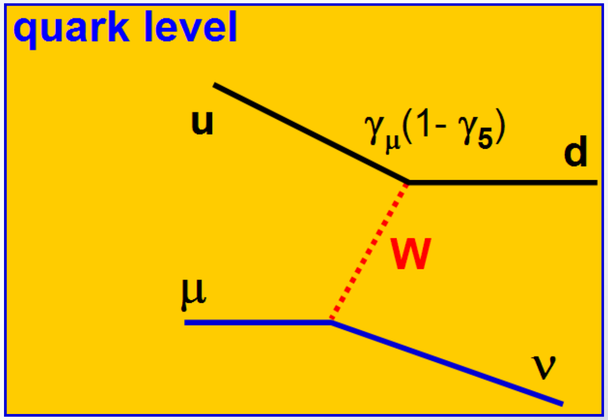
1973 Dubna group

Physics Context

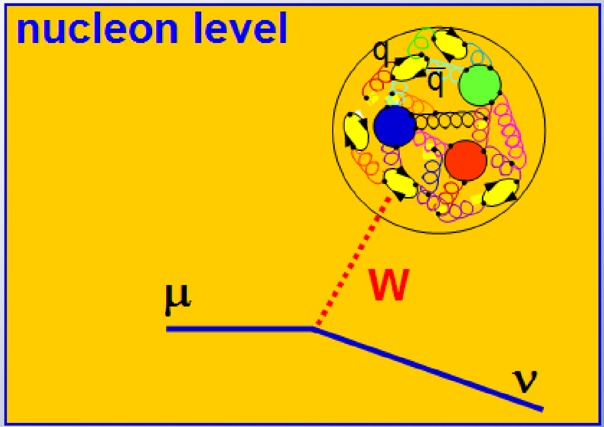
- **Historical: V-A and μ-e Universality**

$$\boxed{\mu^- + p \rightarrow \nu_\mu + n}$$

charged current



- **Today: EW current key probe for**
  - Understanding hadrons from fundamental QCD
  - Symmetries of Standard Model
  - Basic astrophysics reactions



QCD

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

- **high q^2 (q > some GeV)** **short distance <0.1 fm**

  Weakly interacting quarks and gluons
  asymptotic freedom

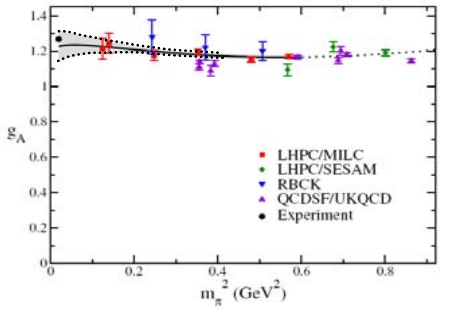
- **low q^2 (q << 1GeV)** **long distance > 1 fm**

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

- **Lattice QCD: ab initio calculations**

  issues: continuum transition, etc.
  physical quark masses not reached

Lattice



Edwards et al. LHPC Coll (2006)

MuCap

Formfactors and g_P

- **Muon Capture**

$\mu^- + p \rightarrow \nu_\mu + n$ rate Λ_S at $q^2 = -0.88\ m_\mu^2$

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

- **Formfactors**

Lorentz, T invariance

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

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

+ second class currents
suppressed by isospin symm.

All form factors precisely known from SM symmetries and data.

CVC, n beta decay

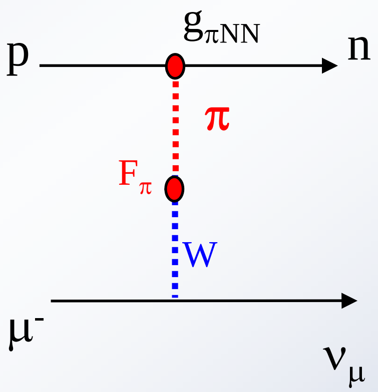
$$\frac{\delta\Lambda_S}{\Lambda_S} = 0.46\%$$

apart from g_P = 8.3 ± 50%

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

MuCap

Pseudoscalar Form Factor g_P



g_P determined by chiral symmetry of QCD:

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

g_P = (8.74 ± 0.23) – (0.48 ± 0.02) = **8.26 ± 0.23**

PCAC pole term Adler, Dothan, Wolfenstein

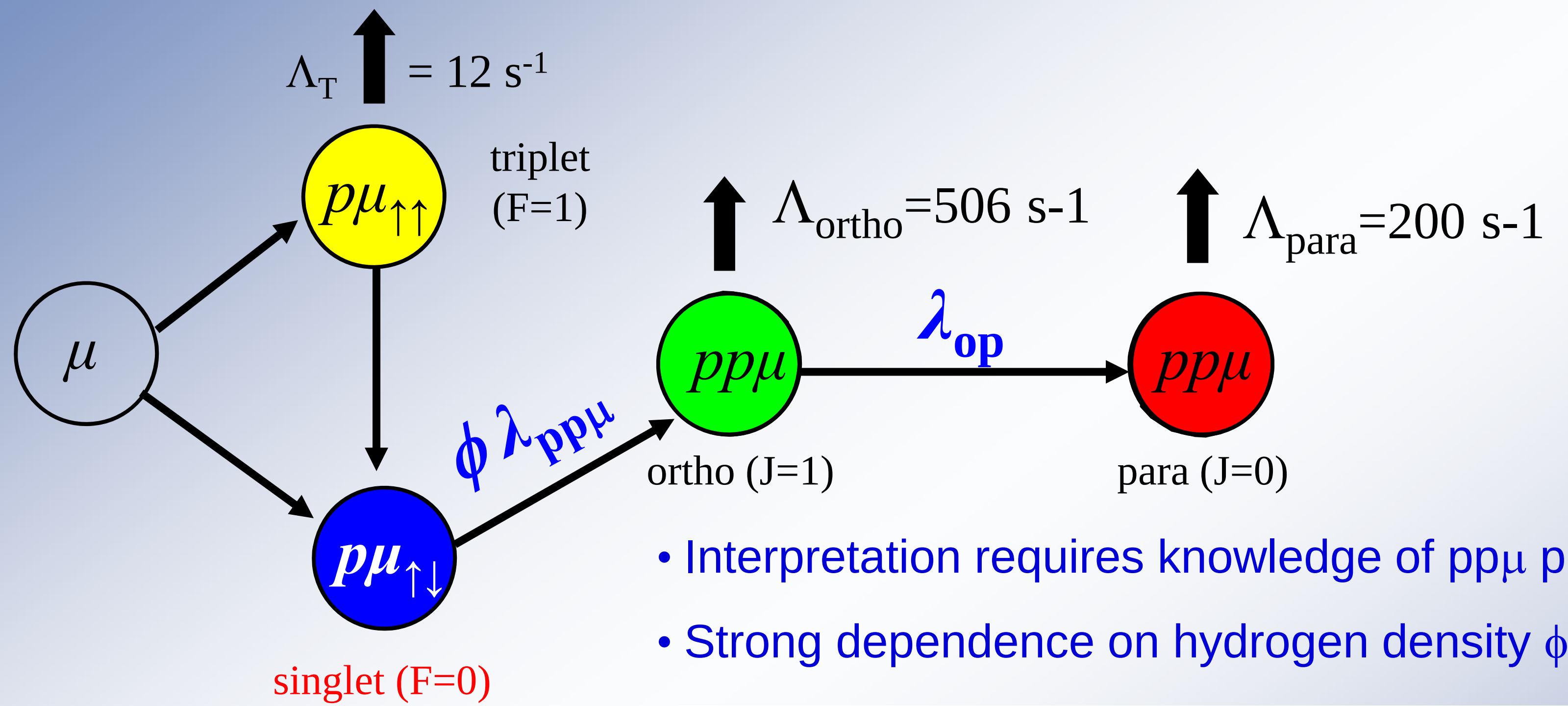
ChPT leading order one loop two-loop <1%

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

- **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



Λ_T = 12 s^{-1}

$p\mu_{\uparrow\uparrow}$

triplet (F=1)

μ

$\phi\,\lambda_{pp\mu}$

$p\mu_{\uparrow\downarrow}$

singlet (F=0)

$pp\mu$

Λ_{ortho}=506 s-1

ortho (J=1)

λ_{op}

$pp\mu$

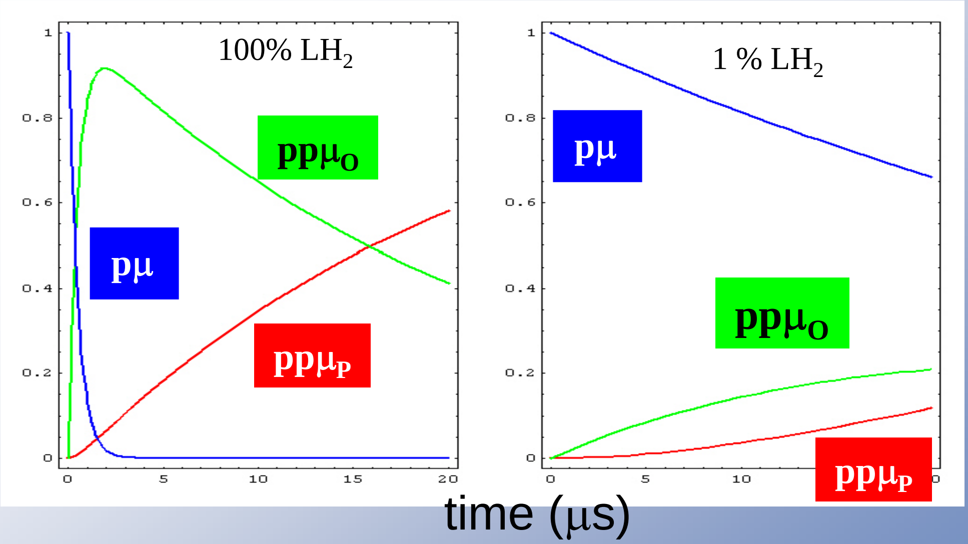
Λ_{para}=200 s-1

para (J=0)

Λ_S= 710 s^{-1}

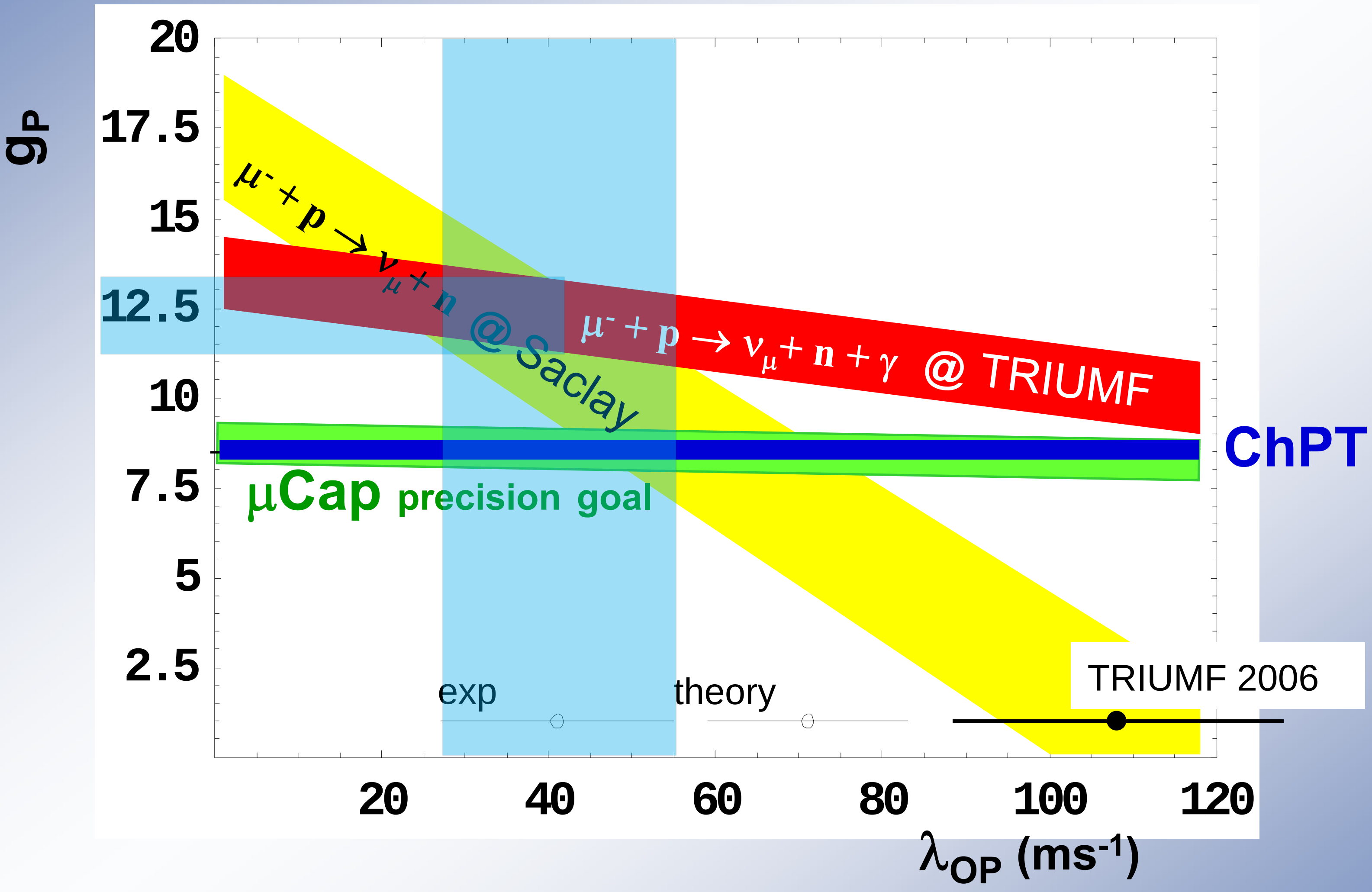
n+ν

- Interpretation requires knowledge of ppμ 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

MuCap Experimental Strategy

- **Lifetime method**

  10^{10} $\mu \rightarrow e\nu\bar{\nu}$ decays

  measure $\tau_{\mu-}$ to 10ppm,

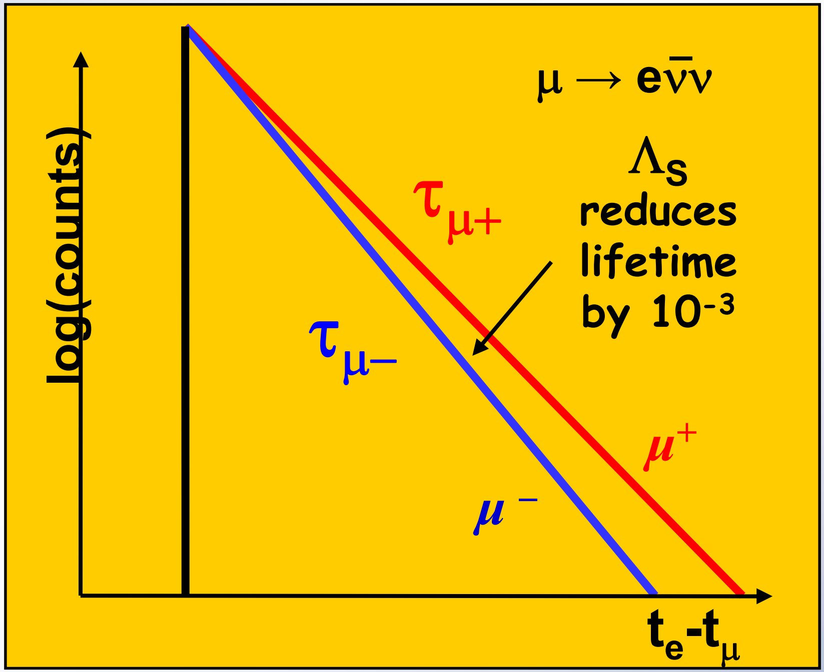
  $\rightarrow \Lambda_S = 1/\tau_{\mu-} - 1/\tau_{\mu+}$ to 1%

- **Unambiguous interpretation at 1% LH_2 density**

- **Clean μ stop definition in active target (TPC) to avoid wall stops**

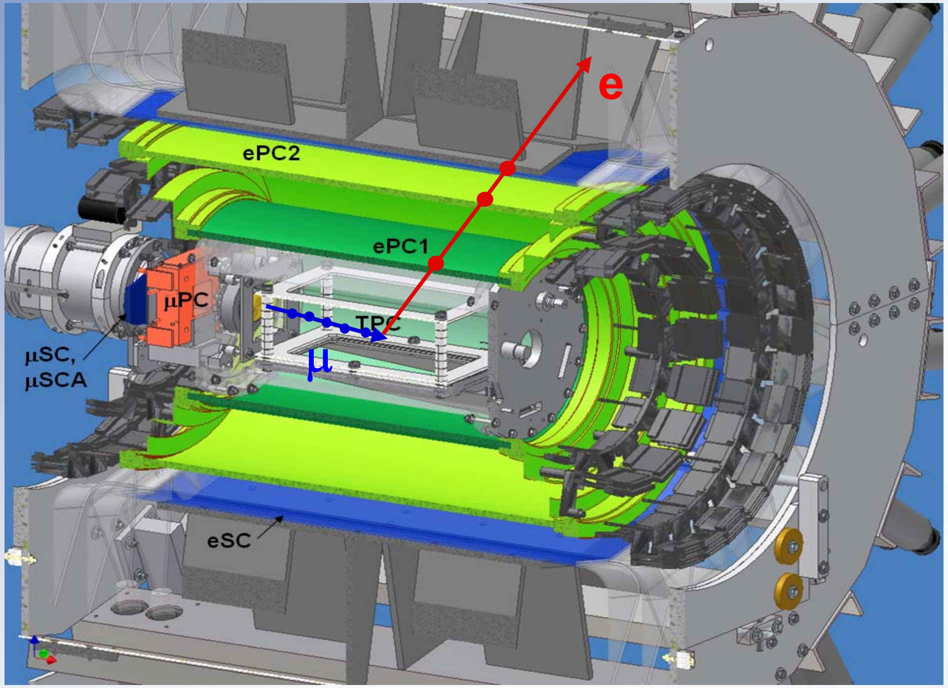
- **Ultra-pure gas system and purity monitoring at 10 ppb level**

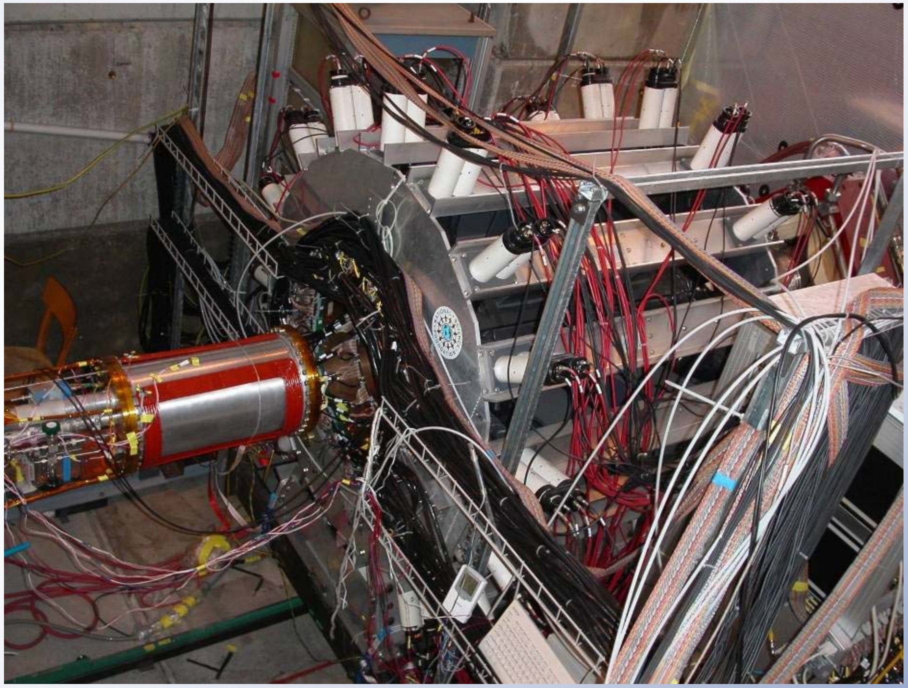
- **Isotopically pure "protium"**



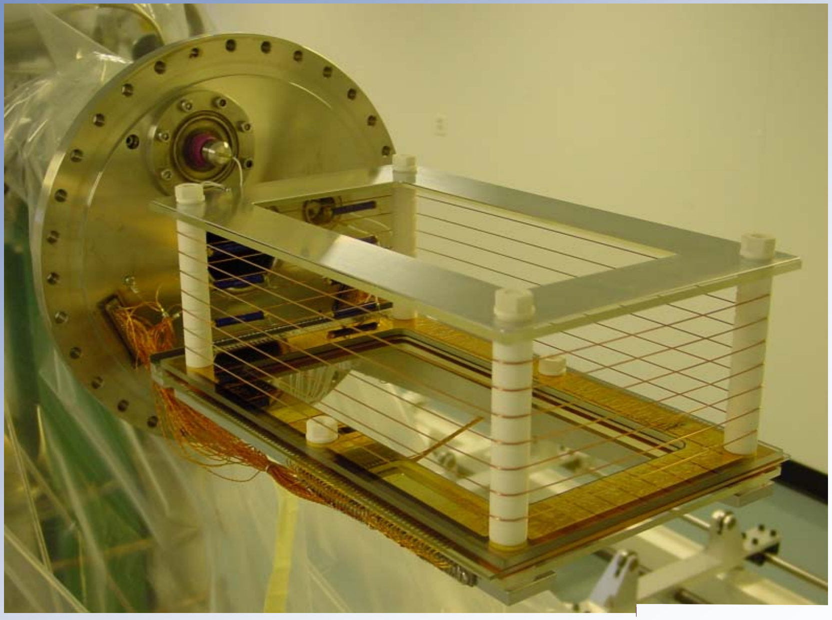
fulfill all requirements simultaneously
unique MuCap capabilities

MuCap Detector



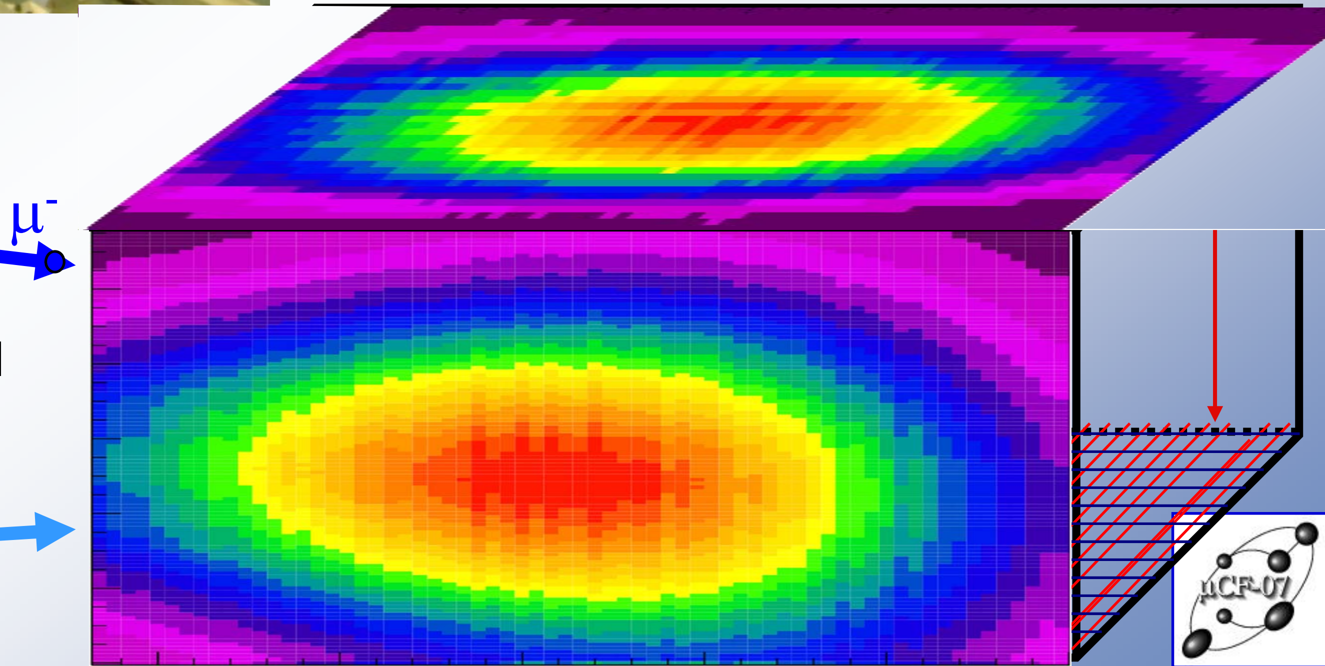


MuCap Muons stop in active TPC target



10 bar ultra-pure hydrogen, 1.16% LH_2
2.0 kV/cm drift field
~5.4 kV on 3.5 mm anode half gap
bakeable glass/ceramic materials

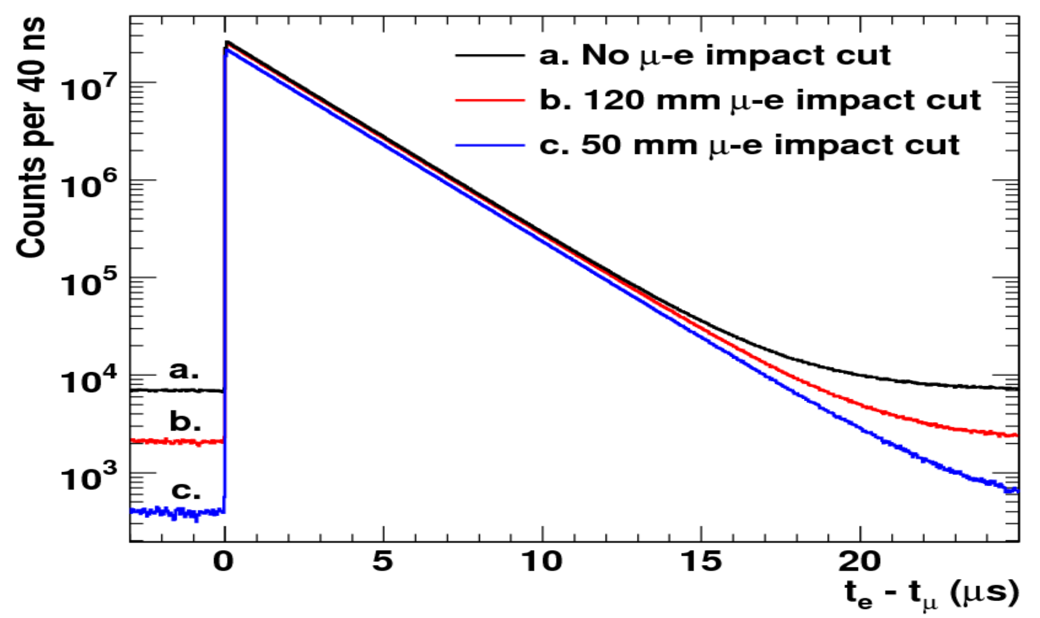
Observed muon stopping distribution



3D tracking w/o material in fiducial volume

MuCap

Time Spectra



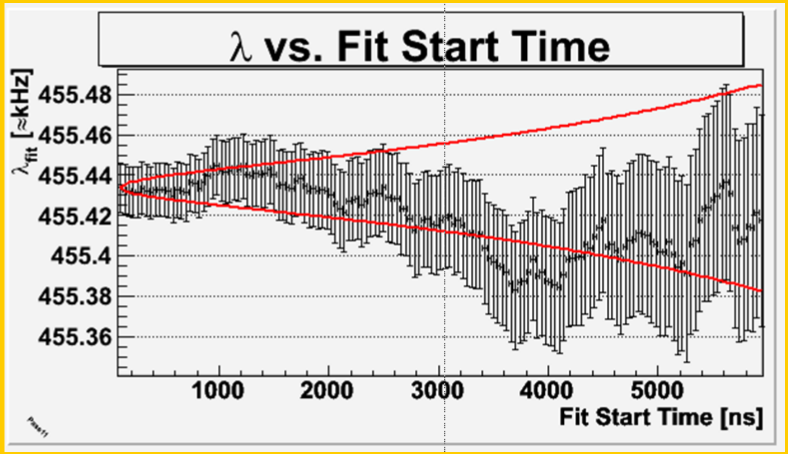
μ-e impact parameter cut

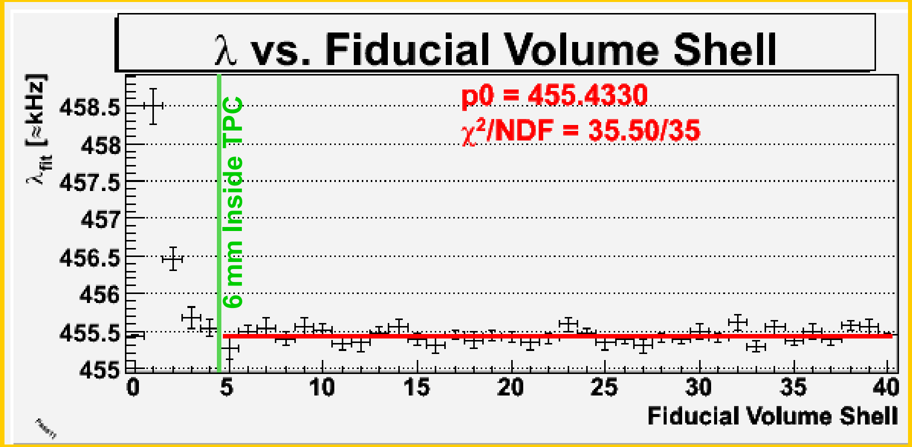
huge background suppression

diffusion (deuterium) monitoring

blinded master clock frequency

variety of consistency checks





MuCap Unique Capabilities: Impurities

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

Λ_Z (C, N, O) ~ (40-100) x Λ_S

~10 ppb purity required

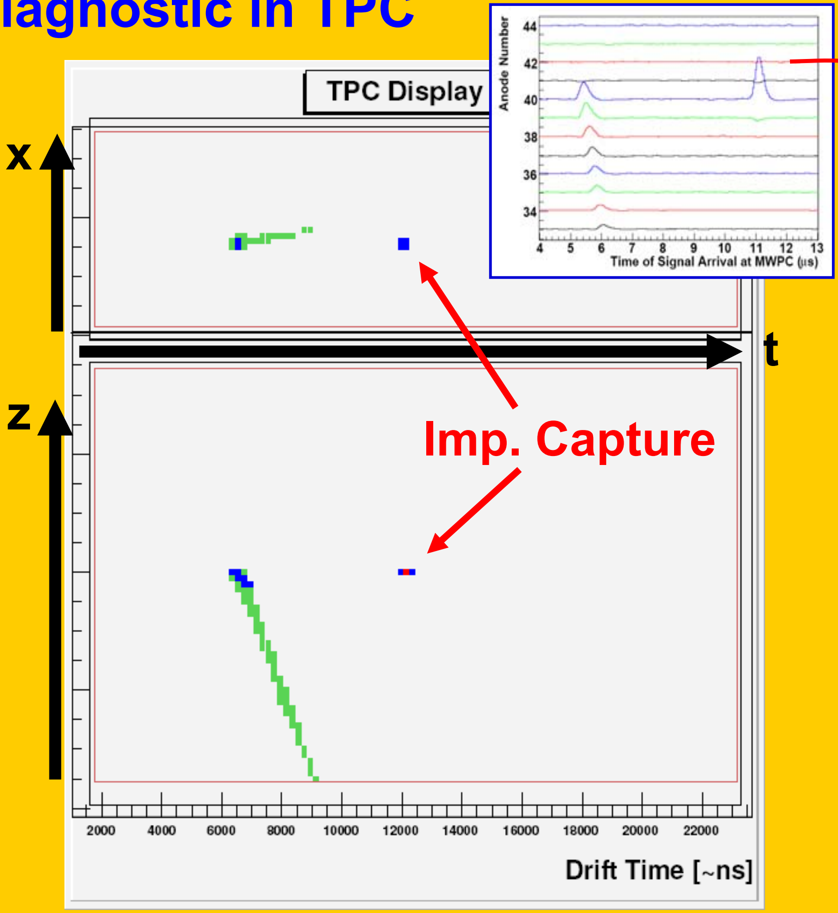
Hardware

Circulating **H**ydrogen **U**ltrahigh **P**urification **S**ystem

Gas chromatography

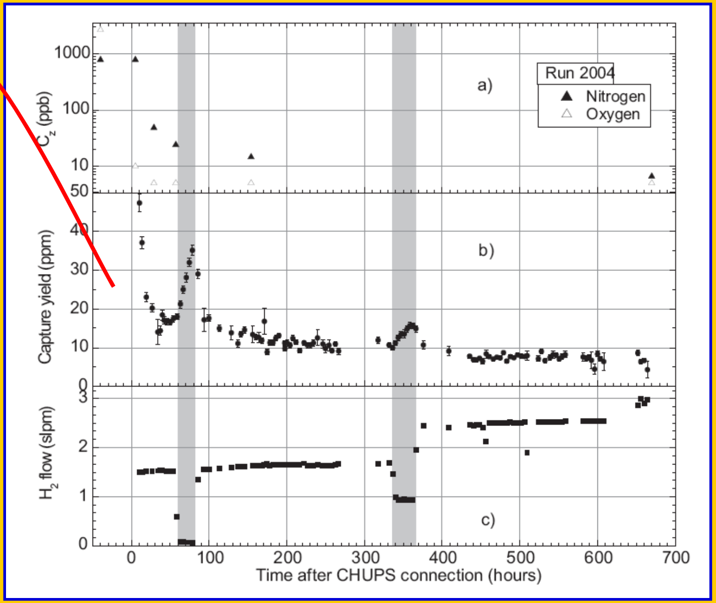
CRDF 2002, 2005

Diagnostic in TPC



Imp. Capture

Results



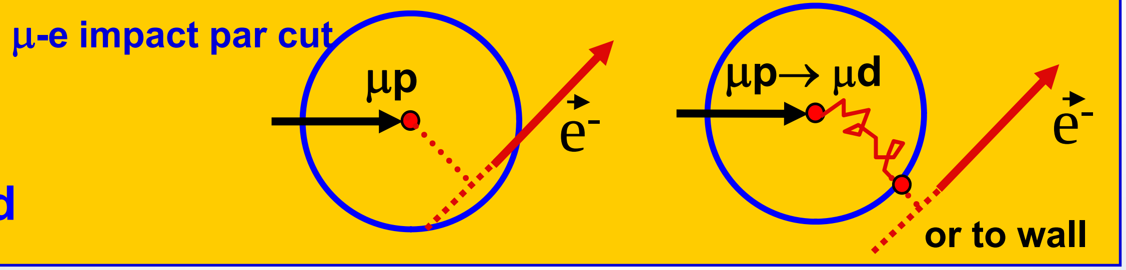
- c_N, c_O < 7 ppb, c_{H2O}~18-30 ppb
- correction based on observed capture yield

MuCap Unique Capabilities: μp, μd diffusion

$\mu p + d \to \mu d + p$ (134 eV)

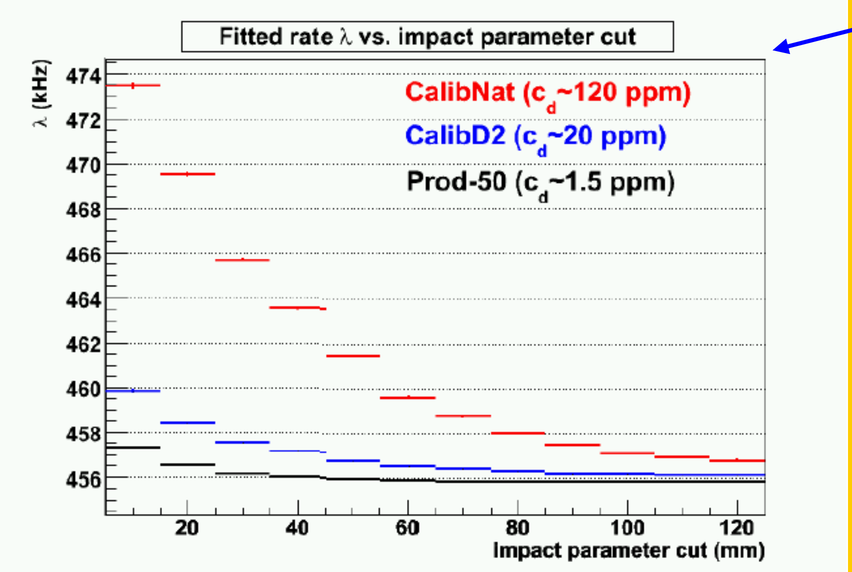
large diffusion range of μd

< 1 ppm isotopic purity required



Diagnostic:

- λ vs. μ-e vertex cut



- AMS, ETH Zurich

Results

- Directly from data

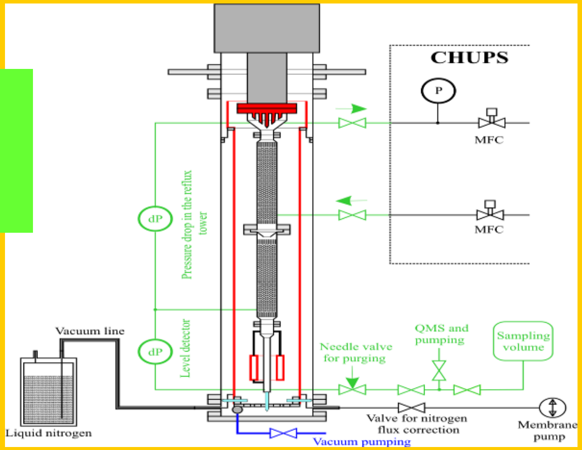
  c_d= 1.49 ± 0.12 ppm
- AMS (2006)

  c_d= 1.44 ± 0.15 ppm

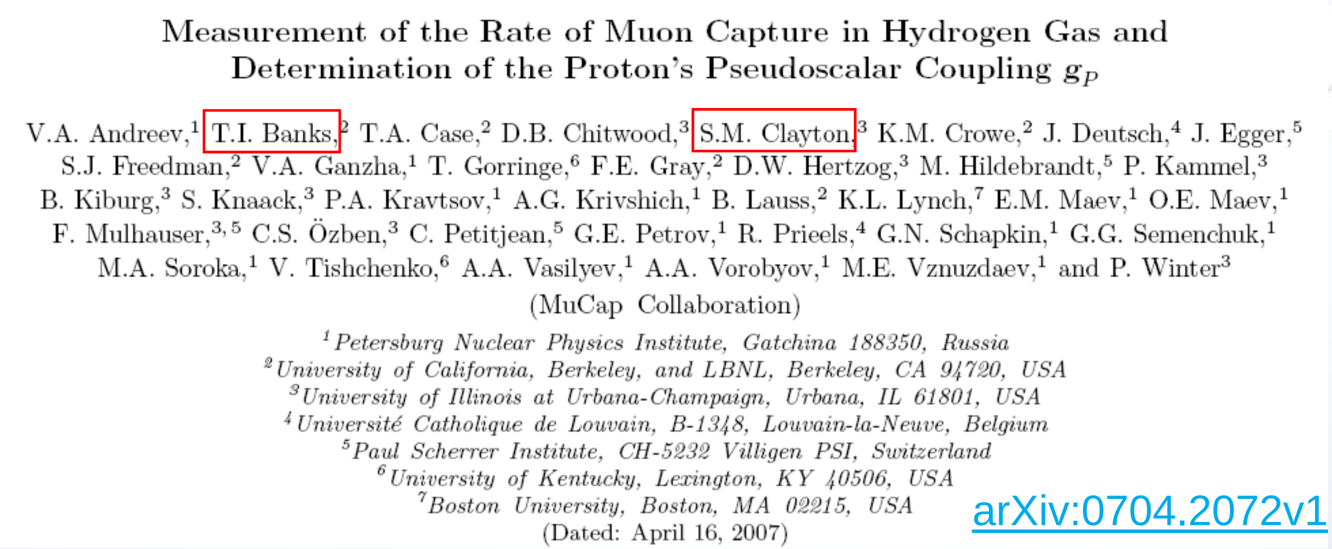
On-site isotopic purifier 2006 (PNPI, CRDF)

World Record

c_d < 0.1 ppm



MuCap



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. Winter[3]

(MuCap Collaboration)

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[4] *Université Catholique de Louvain, B-1348, Louvain-la-Neuve, Belgium*
[5] *Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland*
[6] *University of Kentucky, Lexington, KY 40506, USA*
[7] *Boston University, Boston, MA 02215, USA*

(Dated: April 16, 2007)

arXiv:0704.2072v1 [nucl-ex]

accepted PRL

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

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%):

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

→

further sub percent theory required

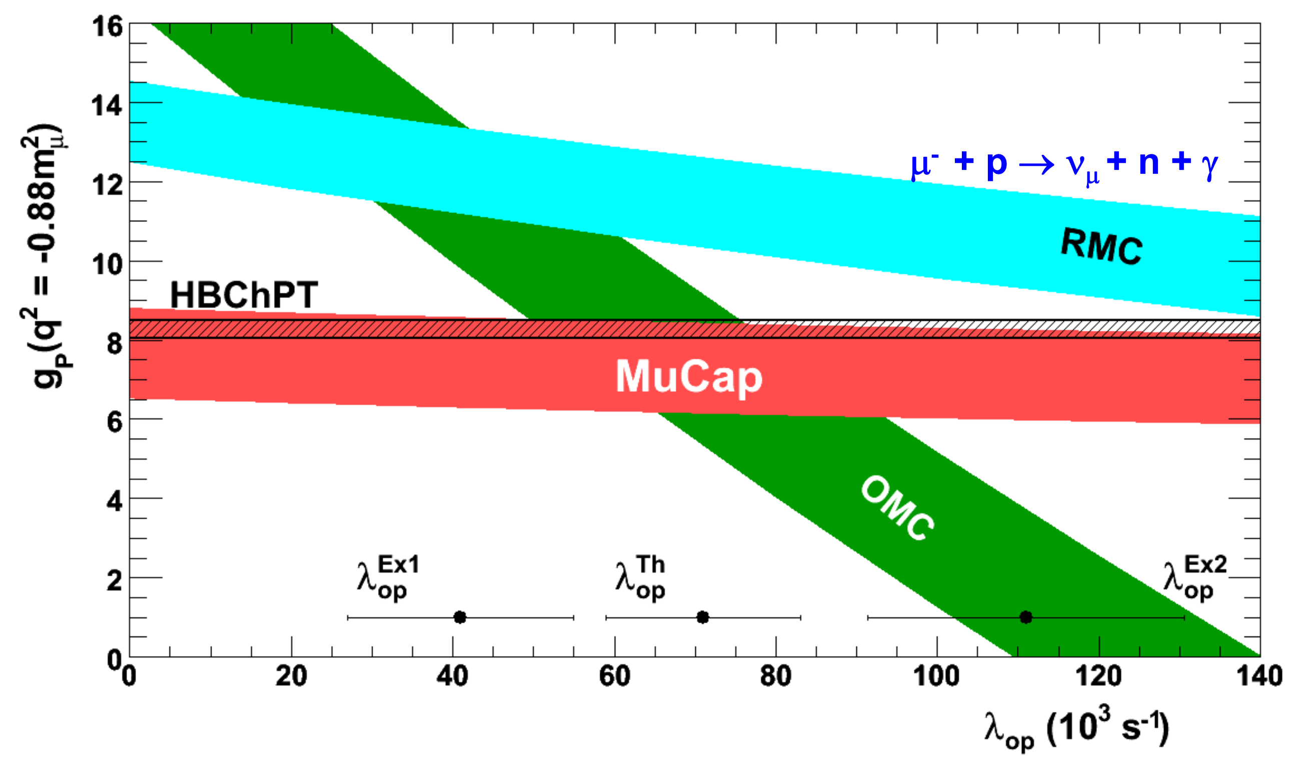
$$\Lambda_S^{theory} = 710.6\ s^{-1}$$

arXiv: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

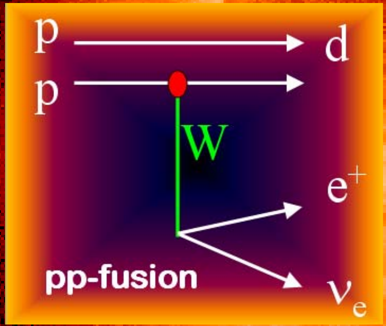
MuCap

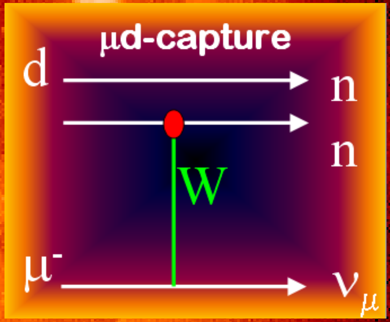
- **MuCap result nearly model independent**
  First precise and unambiguous result
- **Consistent with chiral prediction**
  Does not confirm radiative muon capture (RMC) discrepancy
- **Final result ('06 and '07 data) will reduce error twofold**

“Calibrating the Sun” via Muon Capture on the Deuteron

“MuSun”

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

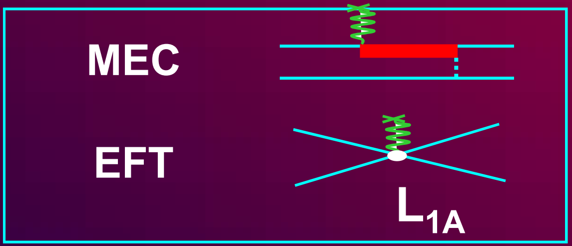




model-independent connection via EFT & L_{1A}

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 μCap technique and careful optimization**

MuSun

Proposal planned 2007

measurement of absolute rate to <1%

μSun I: μCap technique, 1% LD_2, 300 K,

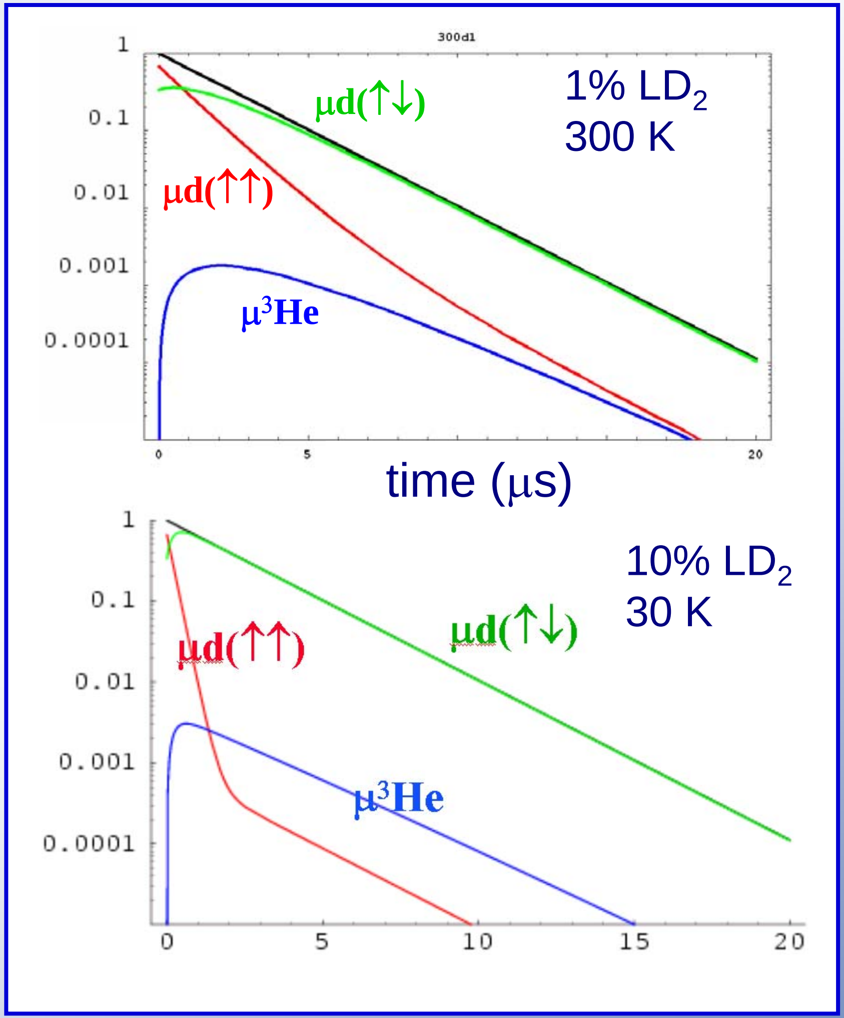
measure time spectra of capture neutrons

monitor populations with fusion and capture reactions

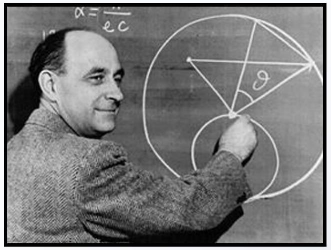
First measurement of polarization observables in μ+d capture?

μSun II: **new cryo TPC**

Kinetics requires optimized target conditions: T<50 K, >5% LD_2 density



MuLan Scientific Case



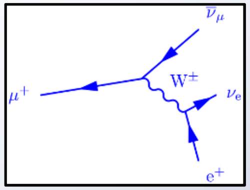
- **Fundamental electroweak parameters**

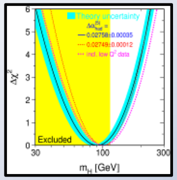
G_F	α	M_Z
9 ppm	0.0007 ppm	23 ppm

- **G_F**

Implicit to all EW precision physics

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

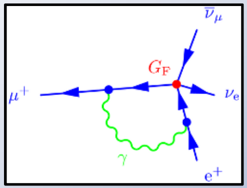




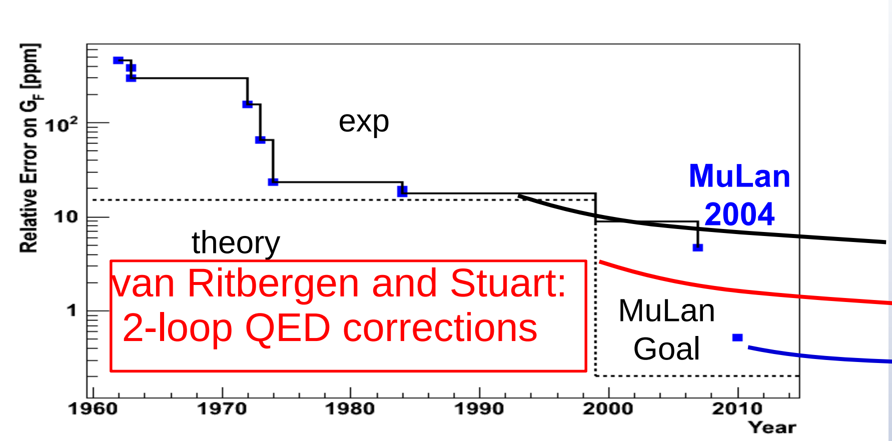
Uniquely related to muon decay

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

QED



Precision G_F ↔ τ relation no longer theory limited



van Ritbergen and Stuart:
2-loop QED corrections

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

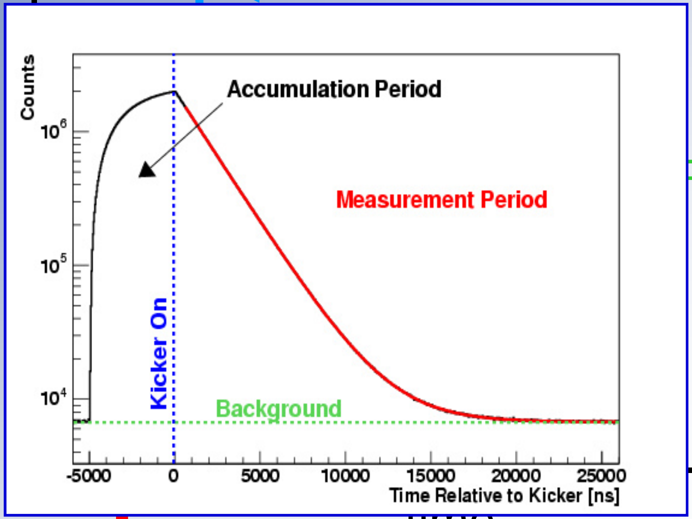
17 ppm 18 ppm 90 ppb 30 ppm

MuLan Experiment

Real data

Kicker On

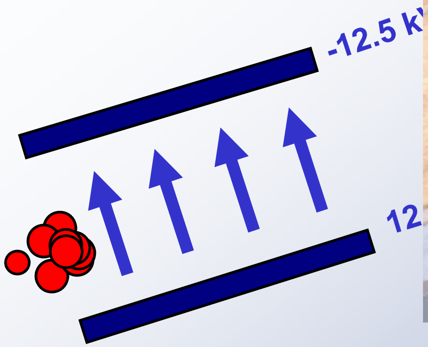
Number (log scale)



Period

time

Fill Period



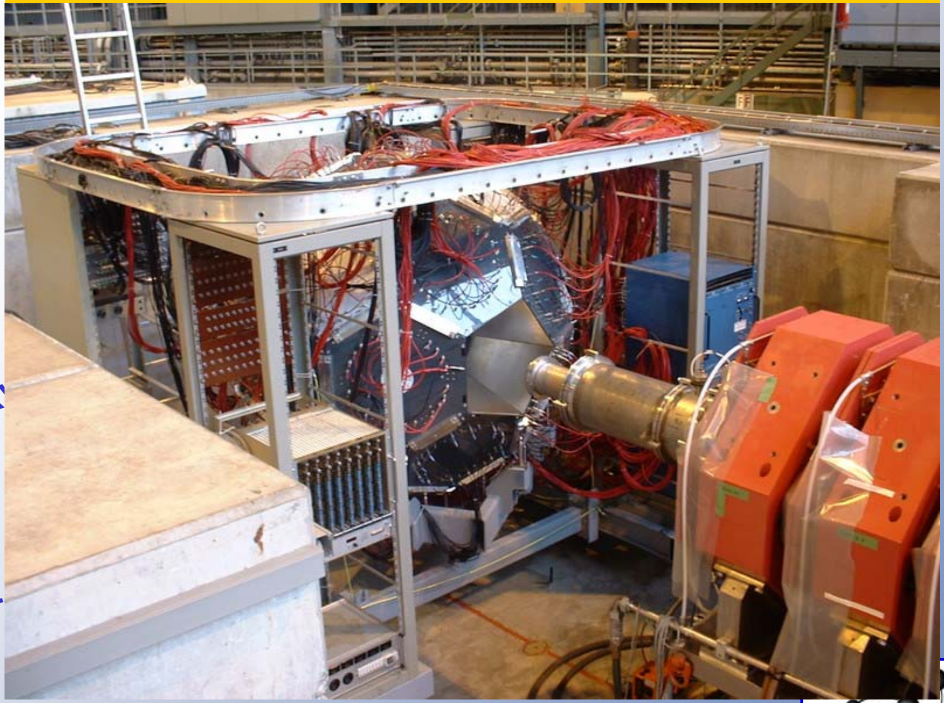
"Early-to-late" changes

- **Instrumental shifts**
  - Gain or threshold
  - Time response
- **Effective acceptance**
  - Residual polarization or precession

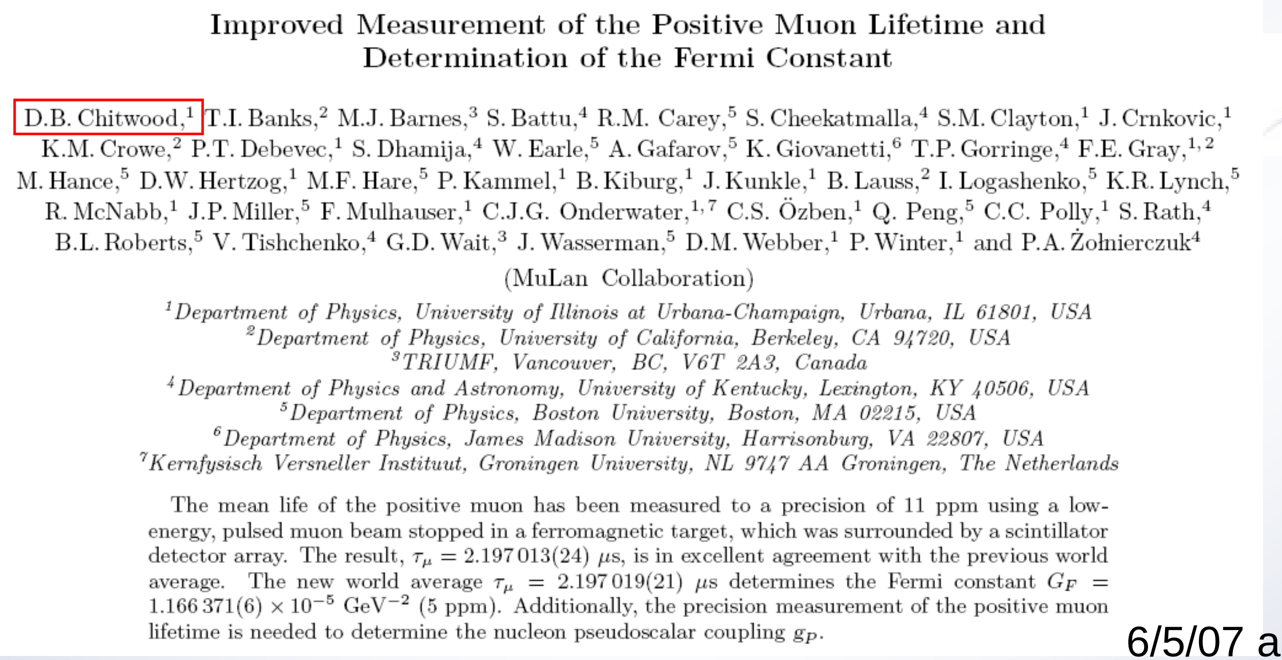
Pileup

- **Missing events**

Systematics



MuLan



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. Kammel,[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. Żołnierczuk[4]

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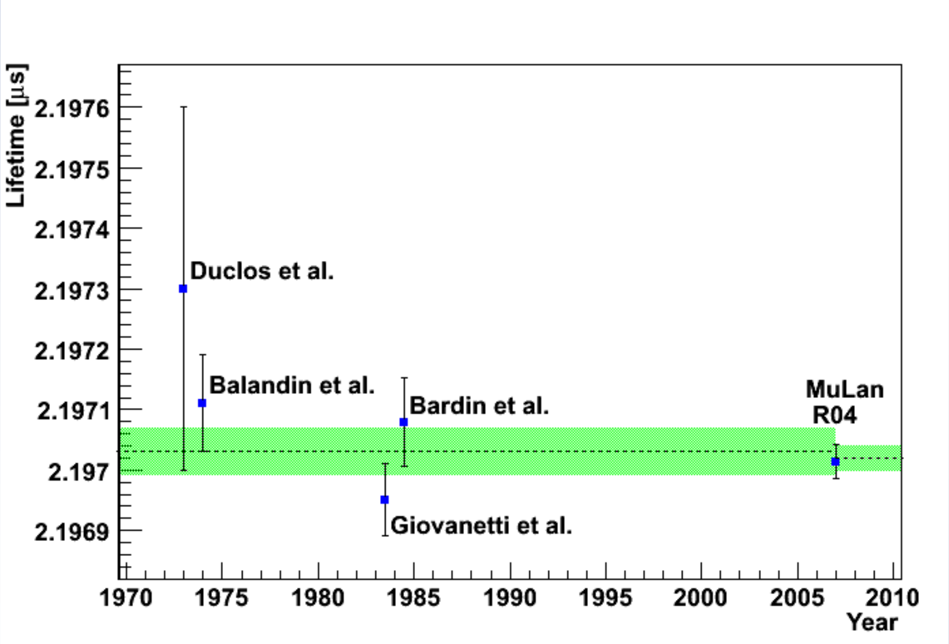
[7] *Kernfysisch Versneller Instituut, Groningen University, NL 9747 AA Groningen, The Netherlands*

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, $\tau_\mu = 2.197\,013(24)$ μs, is in excellent agreement with the previous world average. The new world average $\tau_\mu = 2.197\,019(21)$ μs determines the Fermi constant $G_F = 1.166\,371(6) \times 10^{-5}$ GeV^{-2} (5 ppm). Additionally, the precision measurement of the positive muon lifetime is needed to determine the nucleon pseudoscalar coupling g_P.

6/5/07 accepted PRL

arXiv:0704.1981v1 [hep-ex]



τ_μ(MuLan) = 2.197 013(21)(11) μs (11ppm)

τ_μ(World) = 2.197 019(21) μs (9.6 ppm)

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

Summary I: Relevant MCF issues

MuCap:

- **Th/Exp:** ortho-para rate $\lambda_{OP}(\phi)$
- **Exp:** Precision measurement of formation rate ppμ–ortho planned
- **Th:** ppμ–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:** dμ hyperfine transition at 300K
- **Th/Exp:** time evolution of dμ polarization
- **Exp:** dμ polarization observables in muon decay and capture
- **Th/Exp:** precision measurement dd $\rightarrow$ ^{4}He + γ ?

Summary II: Weak Interactions

MuLan:

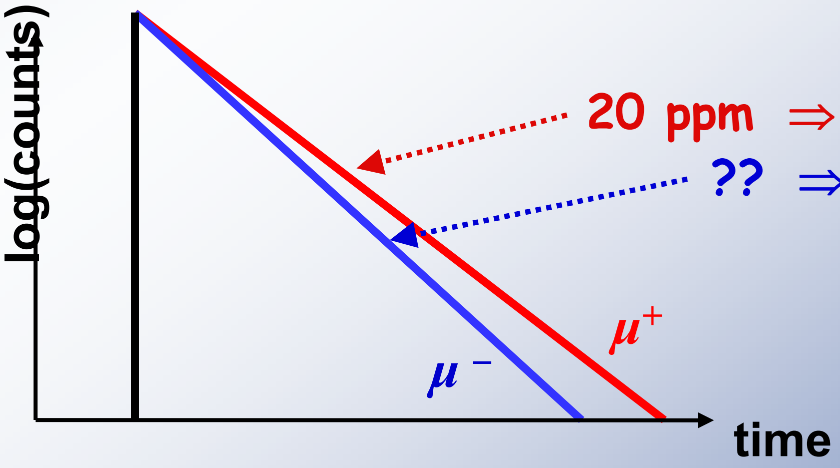
- First G_F update in 23 years – 2.5x improvement, no surprise in result
- Factor 10 additional improvement on the way

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

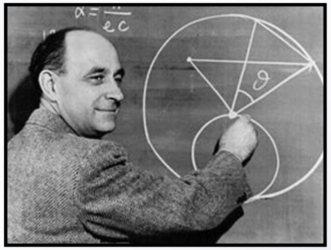


	2006	2008 projected
20 ppm ⇒	10 ppm ⇒	1 ppm
?? ⇒	30 ppm ⇒	10 ppm

MuLan

MuLan

MuLan Scientific Case



- **Fundamental electroweak parameters**

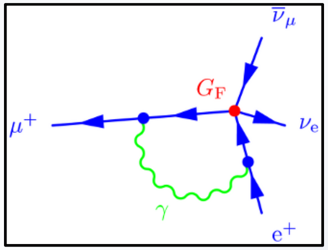
G_F	α	M_Z
9 ppm	0.0007 ppm	23 ppm

- **G_F**

Uniquely defined by muon decay

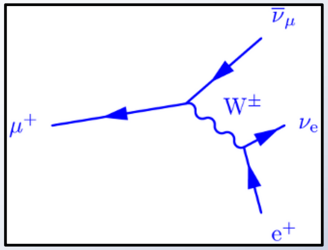
$$\frac{1}{\tau_{\mu^+}} = \frac{G_F{}^2 m_\mu^5}{192\pi^3}(1+q)$$

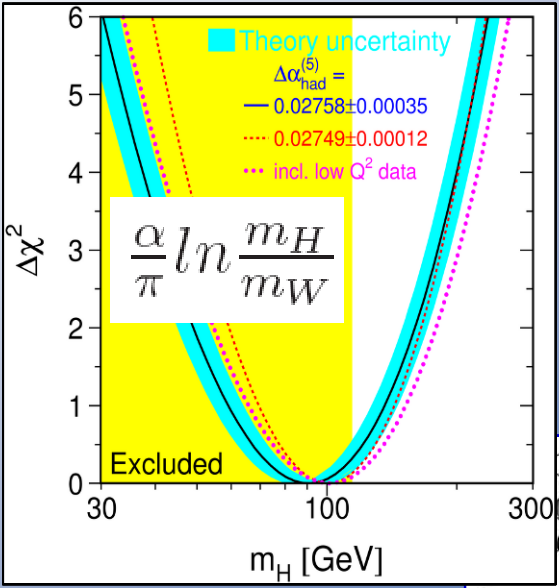
QED



Implicit to all EW precision physics

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

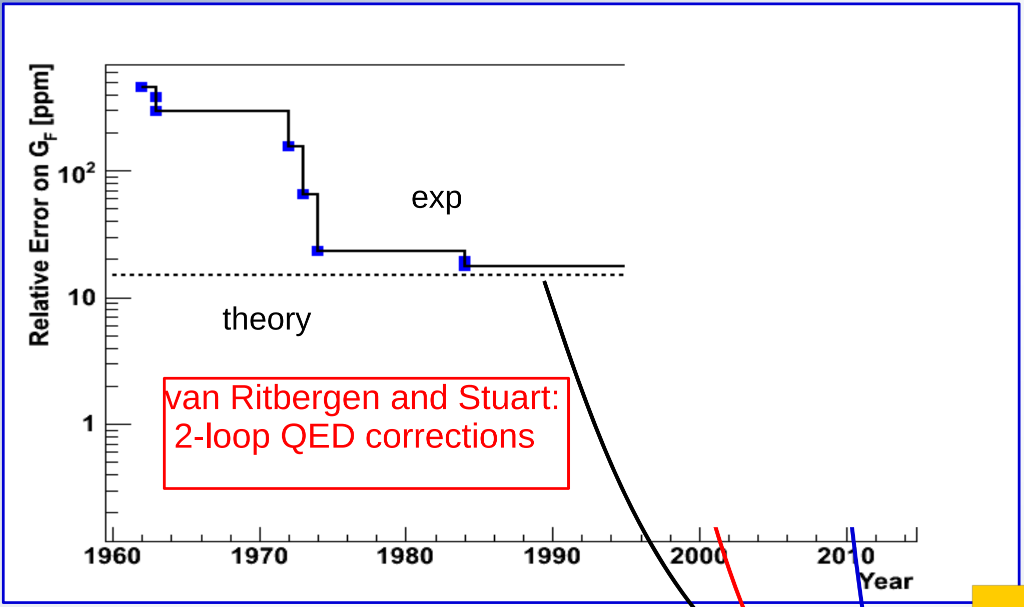




MuLan

Dramatic Progress in QED Calc.

Extraction of G_F from τ_μ not theory limited



van Ritbergen and Stuart:
2-loop QED corrections

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

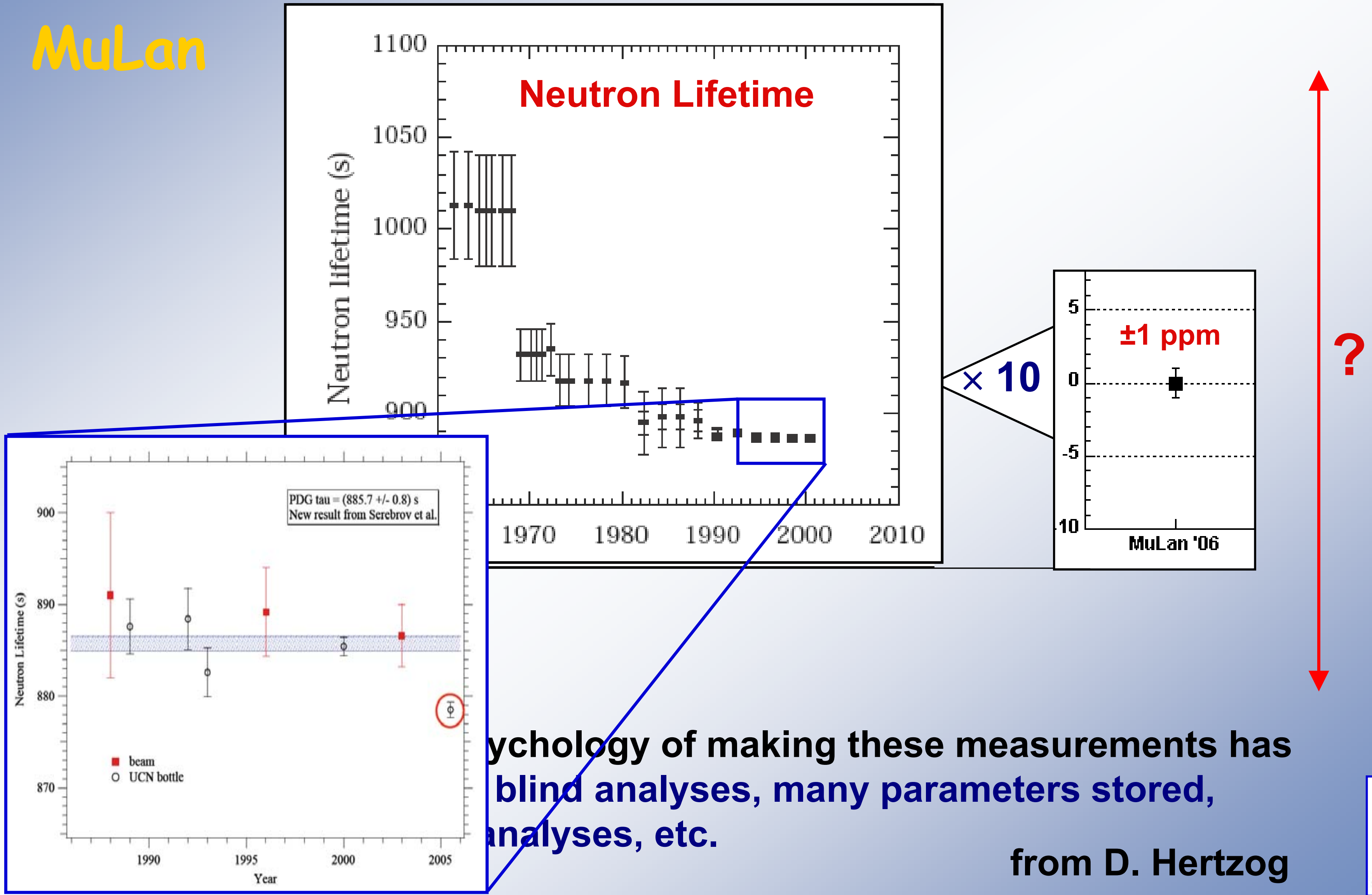
$\delta\nu_\mu$ **from** δm^2

17 ppm 18 ppm 90 ppb 30 ppm

Present $\delta\tau_\mu/\tau_\mu$ is 18 ppm and best single measurement is 27 ppm

Lessons from History

MuLan

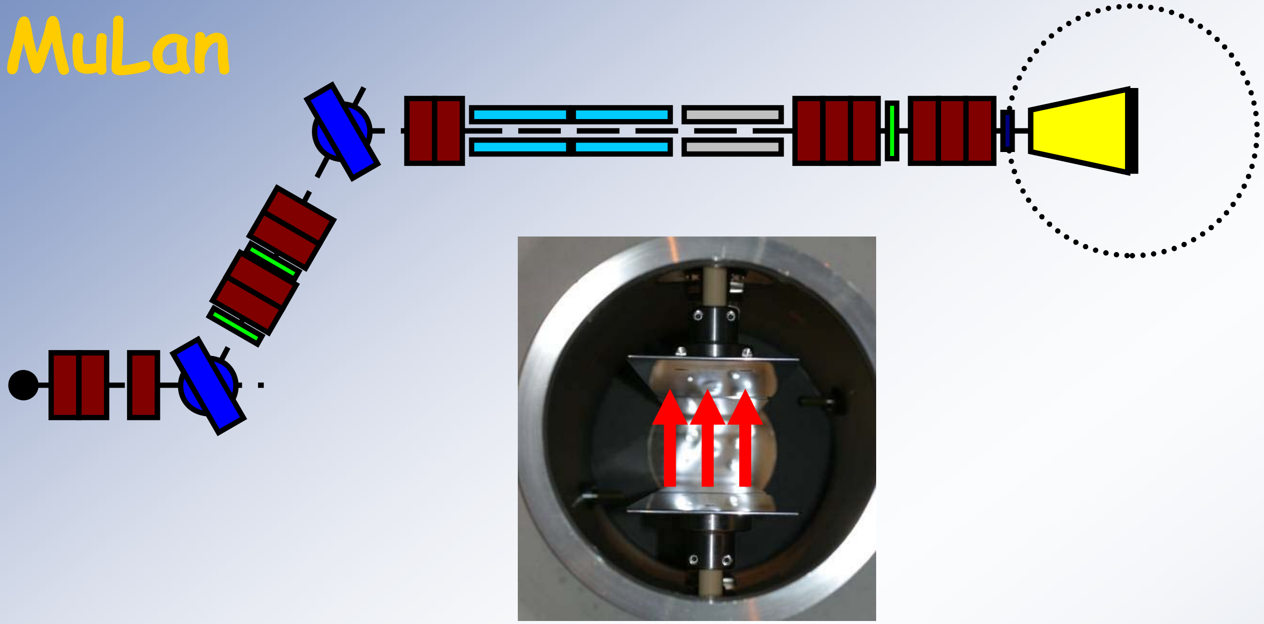


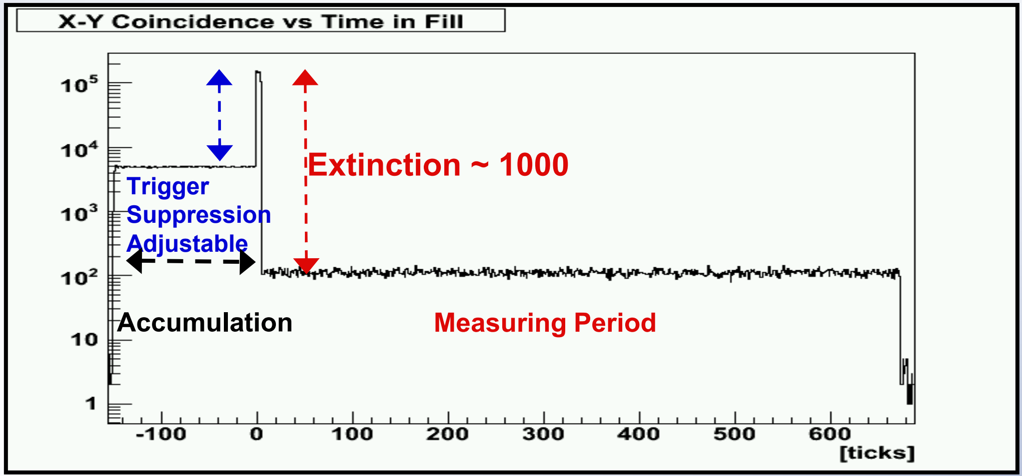
ychology of making these measurements has
blind analyses, many parameters stored,
analyses, etc.

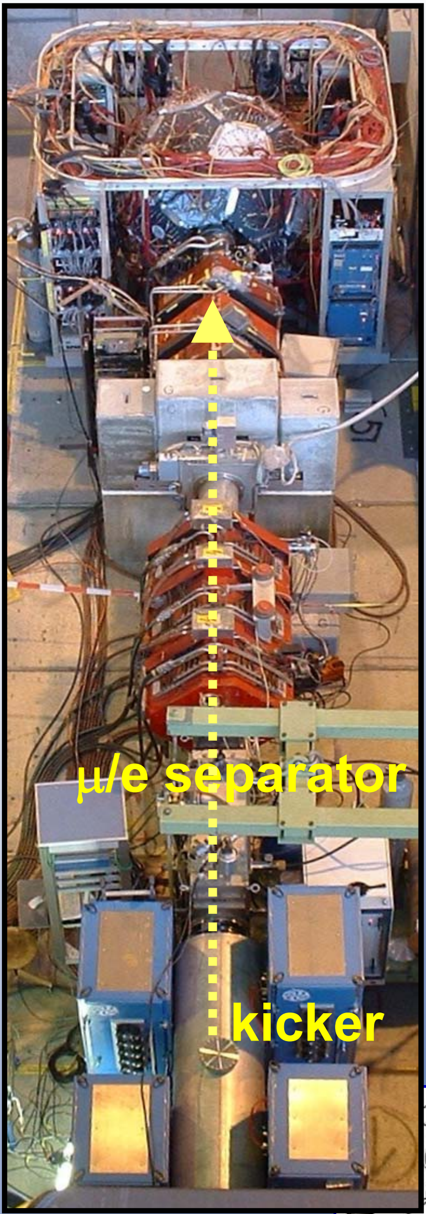
from D. Hertzog

Create a time-structured “surface” muon beam with flux of roughly 10^7 μ^+ Hz @ 28 MeV/c, (~ 4 MeV)

MuLan

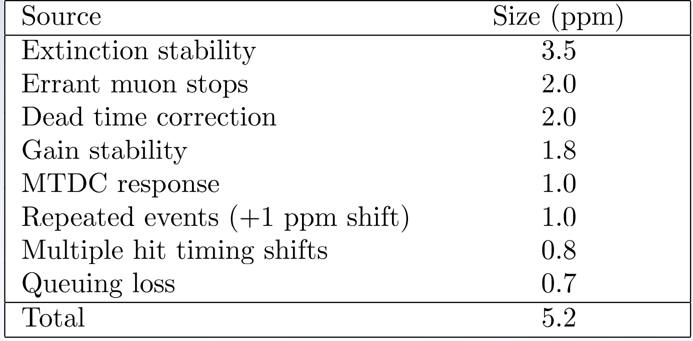






MuLan

Systematics



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

“Early-to-late” changes

- **Instrumental shifts**
  - Gain or threshold
  - Time response
  - Kicker and accidentals

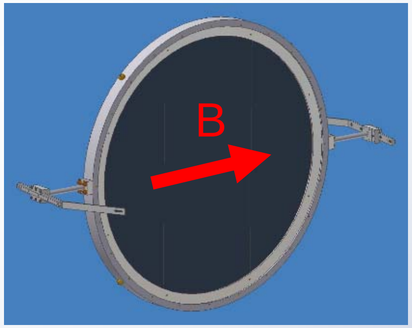
500 MHz WFD in 2005

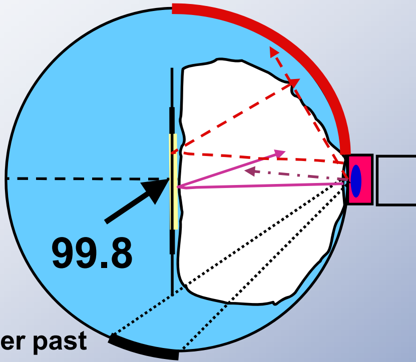
- **Effective acceptance**
  - Residual polarization or precession

target: Arnokrome III (AK-3) internal ~4000 G

symmetric detector

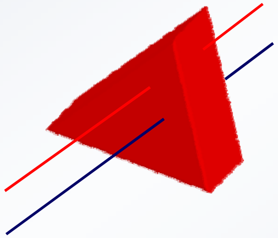
stray muons studied

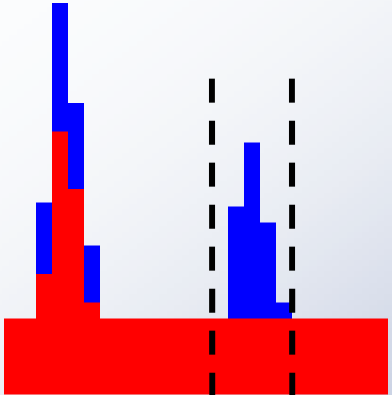


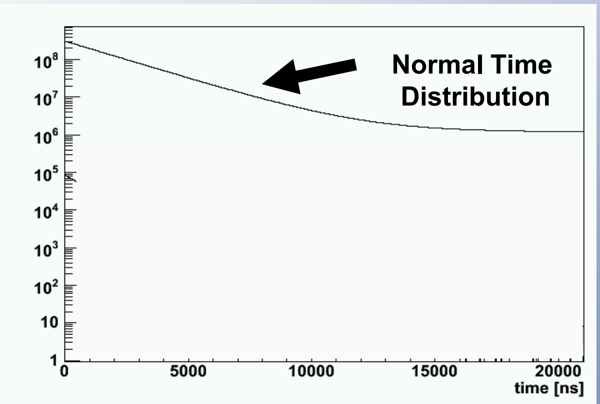


Scatter past AK3

- **Pileup leads to missed events**







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  - Residual polarization or precession
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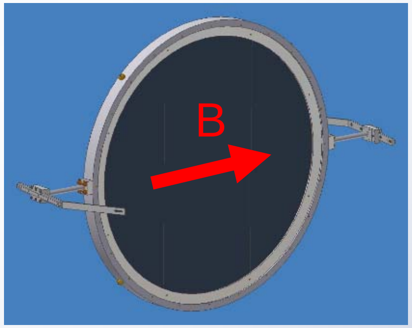
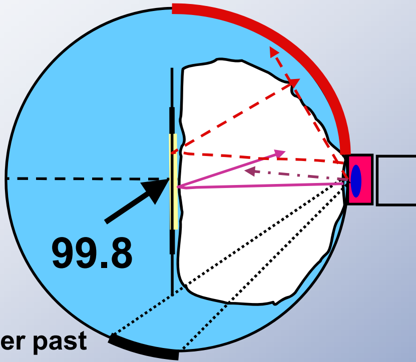
  - symmetric detector
  - stray muons studied





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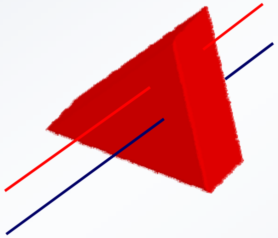
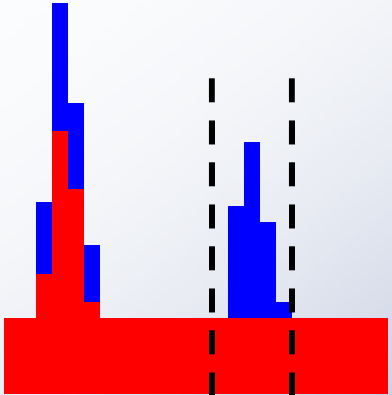
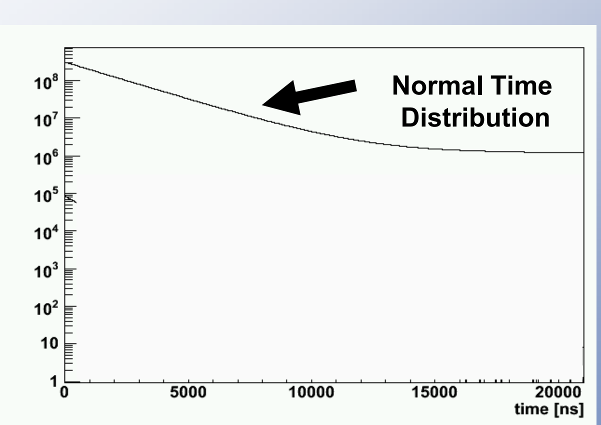






G_F and new physics

W. Marciano 1999

- RC $O(\alpha^2)$

$$\mathrm{R.C.} = \frac{\alpha}{2\pi}\left(\frac{25}{4}-\pi^2\right)\left[1+\frac{\alpha}{\pi}\left(\frac{2}{3}\ln\frac{m_\mu}{m_e}-3.7\right) + \left(\frac{\alpha}{\pi}\right)^2\left(\frac{4}{9}\ln^2\frac{m_\mu}{m_e}-2.0\ln\frac{m_\mu}{m_e}+C\right)+\cdots\right]$$

- Input

$\alpha(0)$	= 1/137.035999710(96)	0.7 ppb
$\alpha(M_Z)$	= 1/127.918(18)	140 ppm
G_F	= 1.166 37(1) x 10^{-5} GeV^{-2}	9 ppm
M_Z	= 91.1876(21) GeV	23 ppm
m_t	= 172.7(2.9) (0.6) GeV	
M_W	= 80.392(39) GeV	
$\sin^2\theta_W$	= 0.23100(22) GeV	

- Interesting physics reach

But

- other GF determinations 100x poorer

$$g^{e}_{2_0} = g^{\mu}_{2_0} = g^{\tau}_{2_0}$$

$$\sin^2\theta^0_W = \frac{e_0^2}{g^2_{2_0}} = 1-(m^0_W/m^0_Z)^2$$

Note: Experimental limits on η (non SM) are largest uncertainty of Fermi constant

G_F depends on η

$$G_F \approx G_F^{V-A}\left(1 - 2\eta\frac{m_e}{m_\mu}\right), \qquad (7)$$

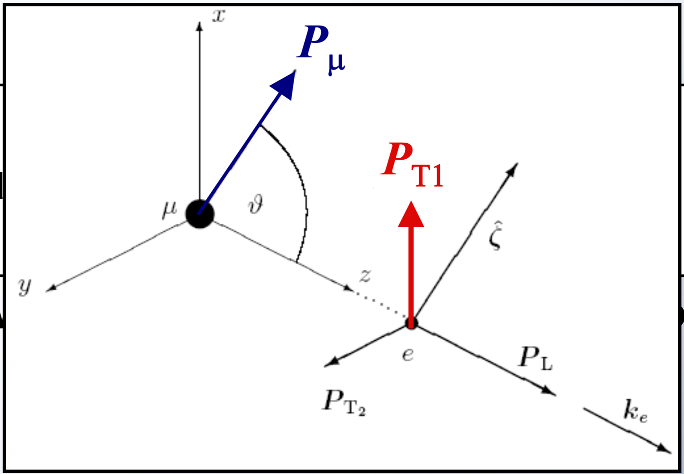
where m_e/m_μ is the mass ratio of electron and muon.

$$\eta = (-2.1 \pm 7.0 \pm 1.0) \times 10^{-3},$$

Danneberg et al,
PRL 94 021802 (2005)

→ 70 ppm uncertainty on G_F

Access to η through transverse polarization measurement of outgoing positron

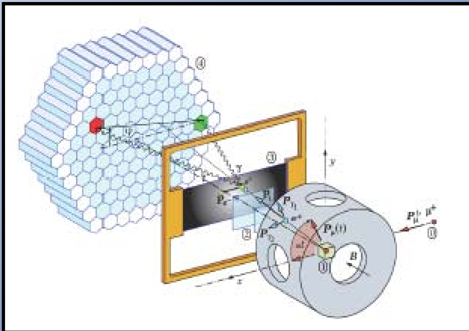


Gl

Nev

r η

Fetscher expt. PSI



MuSun

MuSun

Axial Currents in 2N System

- **Reactions**

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

basic solar fusion reaction

$p + p \rightarrow d + e^+ + \nu$

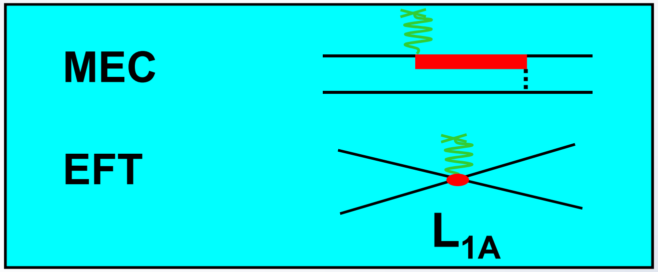
key reactions for SNO

$\nu + d \rightarrow p + p + e^-$ (CC)

$\nu + d \rightarrow p + n + \nu$ (NC)

…

- **Theory SNPA – EFT** **(HBChPT, $\not\pi$EFT, hybrid)**
  - 1B NN description accurate
  - 2B not well constrained by theory

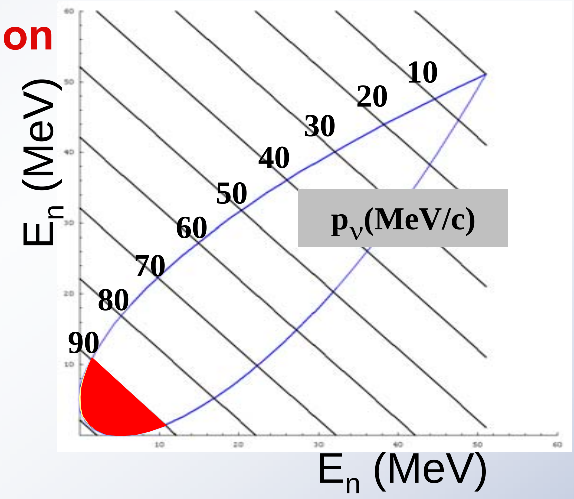


EFT: Class of axial current reactions related by single parameter L_{1A}

➡ Quest for L_{1A}

- **Precision μ+d experiment (PK, Chen)**

best determination of L_{1A} from 2N system



theory: ✓

precise enough?

reaction soft enough for L_{1A}?

Ando, Park, Kubodera, Myhrer (2002)
Chen, Inoue, Ji, Li (2005)

experiment: ✓

1% precision possible ?

MuCap technique

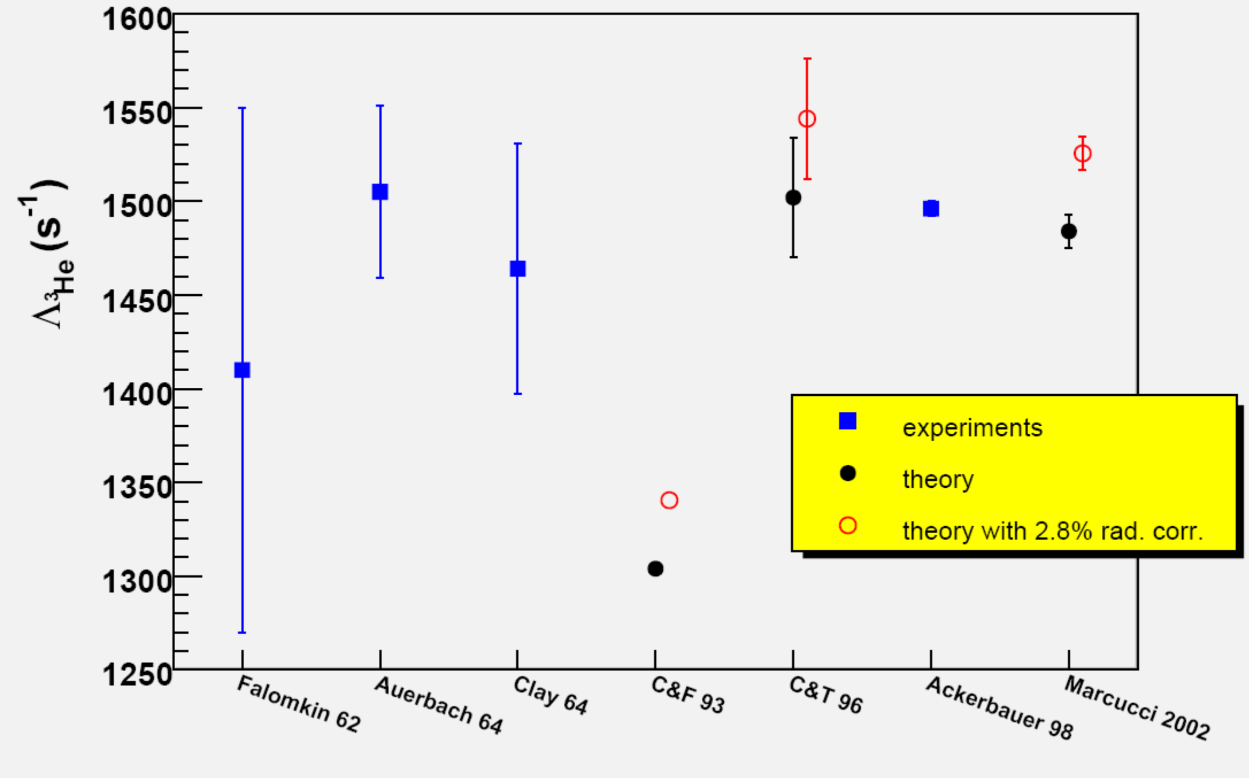
$\mu + {}^3\mathrm{He} \rightarrow {}^3\mathrm{H} + \nu$

$$\boxed{\mu^- + {}^3He \quad \rightarrow \quad t + \nu_\mu}$$

$$\mu^- + {}^3He \quad \rightarrow \quad d + n + \nu_\mu$$

$$\mu^- + {}^3He \quad \rightarrow \quad p + n + n + \nu_\mu$$

authors	Λ_{stat} (s^{-1})	comment
Congleton & Fearing	1304	IA
Congleton & Truhlik	1502 ± 32	IA + MEC
Ackerbauer et al	1496.0 ± 4.0	^{3}He TPC
Marcucci et al.	1484 ± 8	IA+MEC, T beta constraint



PCAC	**g_P= 8.12**
Exp & CT	**8.53±1.54**
Exp & M	**7.55±0.42**
Exp & M, rad	**9.48±0.42**

needs check

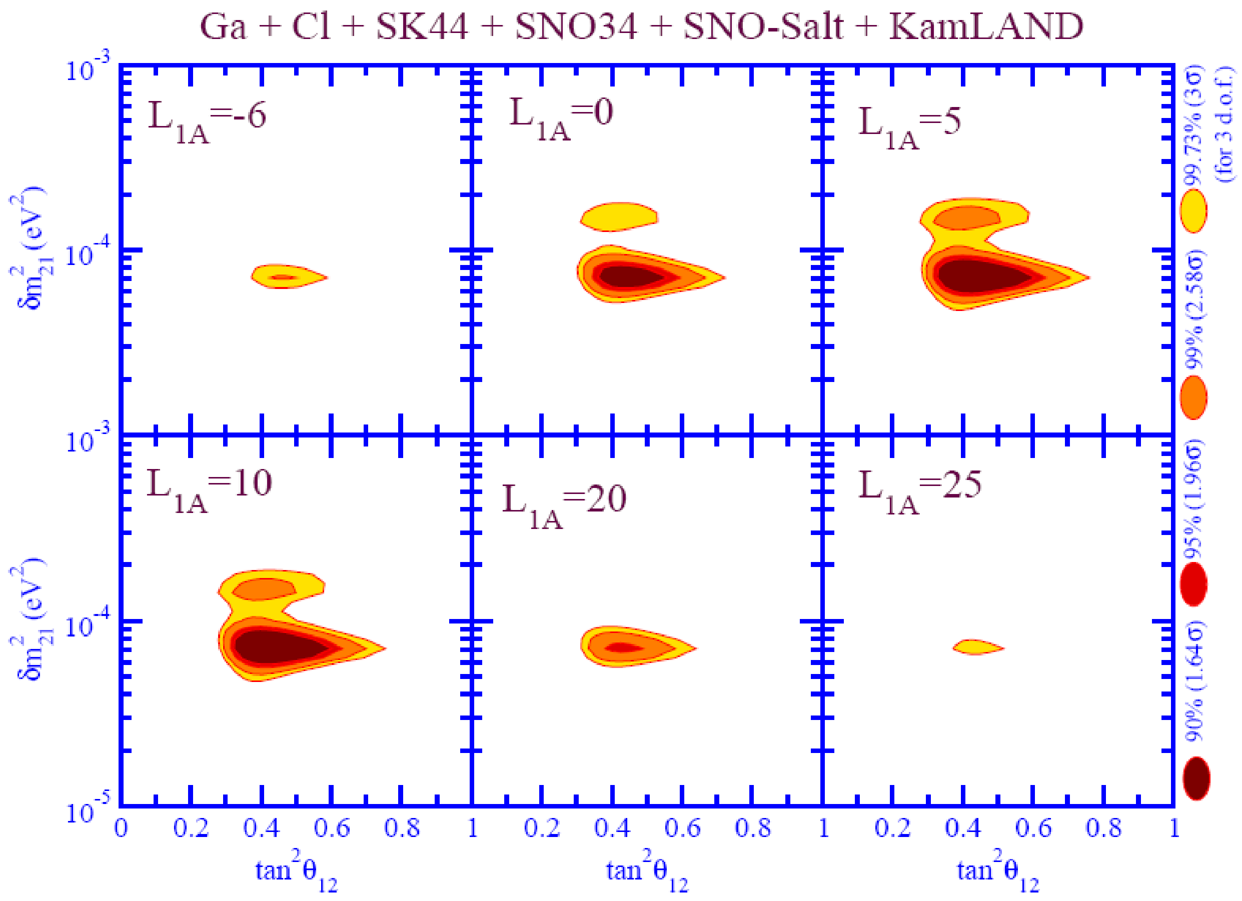
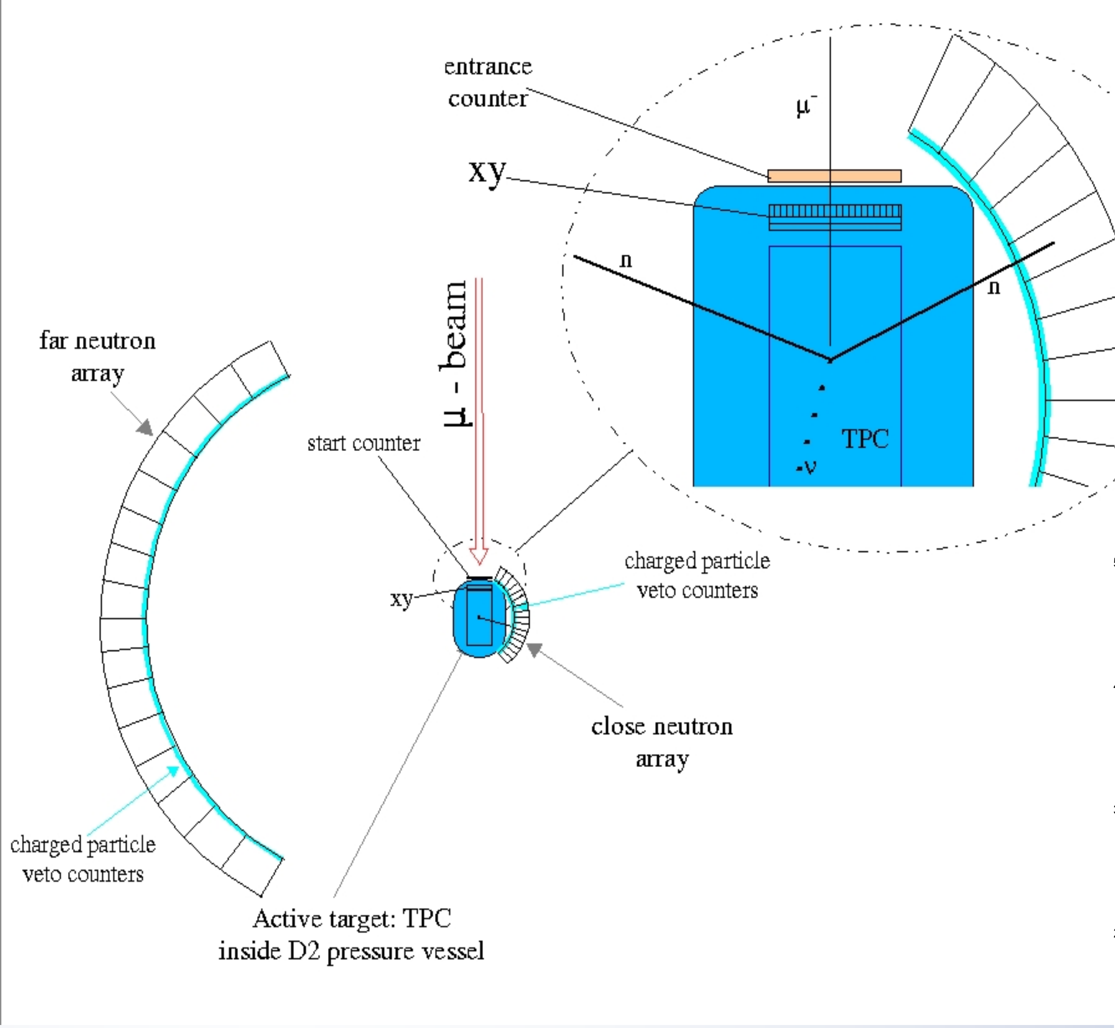
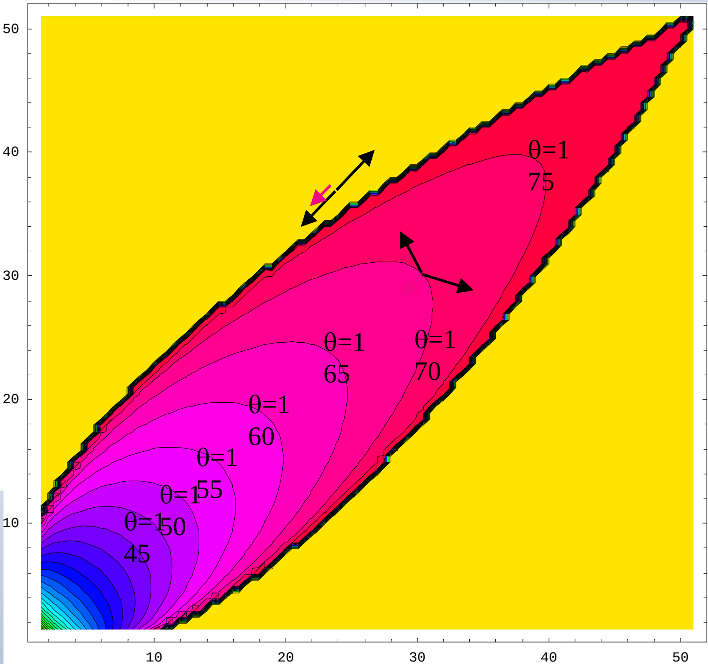


Fig. 3. The change in the allowed region of the mixing parameter space using combined solar neutrino data and KamLAND as a function of L_{1A}. In the calculations leading to this figure the neutrino mixing angle θ_{13} is taken to be zero. The shaded areas corresponds to 90 % , 95 % , 99 % , and 99.73 % confidence levels.

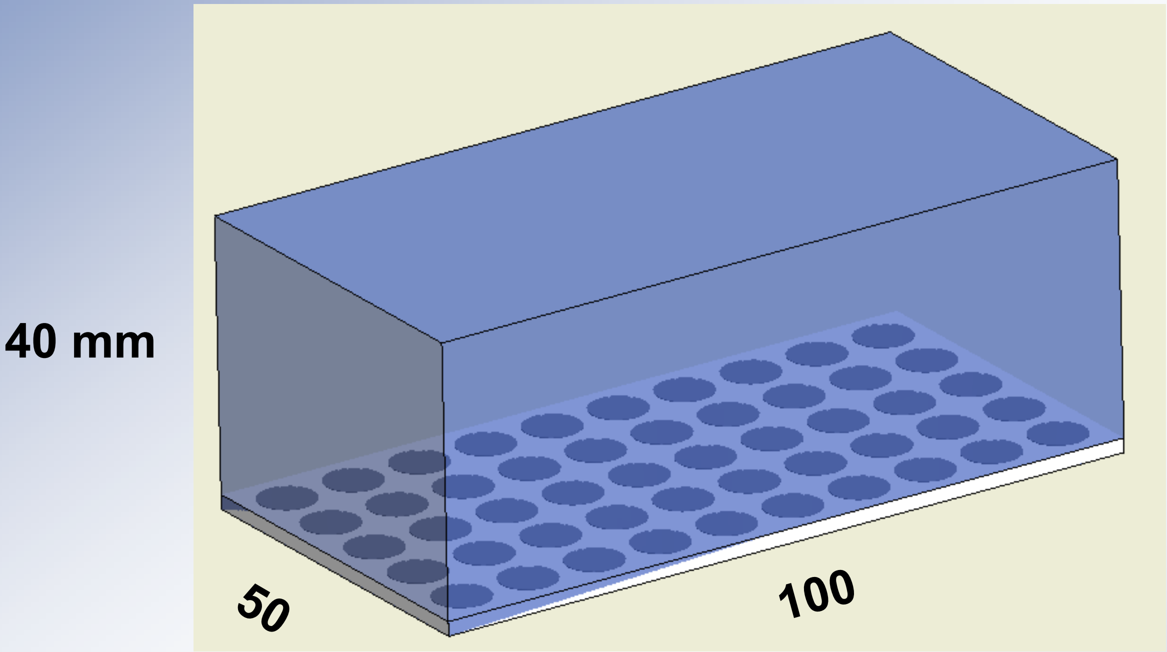
Balantekin et al.

Concept stage II





TPC details



GEM Microstructure ?

	grid cath			grid an			gas	cath
	mm	kV	kV/mm	mm	kV	kV/mm		mm
He TPC	14.3	40	2.80	0.8	3.5	4.38	120bar He	8
D TPC	40	100	2.50	0.8	4	5.00	50-100bar D	10

Recombination ?

Signal (Gain?)

Summary physics motivation

precision measurement of total μd capture rate to 1% provides

- first precise measurement of charged-current reaction in 2N system
- first precise 2N experimental information relevant for *absolute* solar neutrino cross sections and flux.
- comparison of EFT/SNPA approach for space-like axial two-body current and 2N vs 3N constraints.
- a_{nn} information ? *(needs study)*

systematic measurement of μd capture Dalitz Plot provides

- information on time-like axial two-body currents
- reduced rate Λ', accessible to $\not{\pi}$EFT
- complementary g_P sensitivity, if MECs sufficiently under control *(needs study)*

first measurement of μd capture asymmetry and hfs effects provides

- complementary g_p info *(needs study)*

MuCap

$$
\begin{aligned}
L_{\mathrm{QCD}} &= -\frac{1}{4} F^{(a)}_{\mu\nu}\ F^{(a)\mu\nu} + i \sum_q \overline{\psi}^i_q\ \gamma^\mu\ (D_\mu)_{ij}\ \psi^j_q \\
&\quad - \sum_q m_q\ \overline{\psi}^i_q\ \psi_{qi}\ , \\
F^{(a)}_{\mu\nu} &= \partial_\mu\ A^a_\nu - \partial_\nu\ A^a_\mu - g_s\ f_{abc}\ A^b_\mu\ A^c_\nu\ , \\
(D_\mu)_{ij} &= \delta_{ij}\ \partial_\mu + i g_s\ \sum_a \frac{\lambda^a_{i,j}}{2} A^a_\mu\ ,
\end{aligned}
$$

Additional slides start here

Λ_S sensitivity to g

$$\frac{\Delta\Lambda_S}{\Lambda_S} = 0.466\,\frac{\Delta g_V}{g_V} + 0.151\,\frac{\Delta g_M}{g_M} + 1.567\,\frac{\Delta g_A}{g_A} - 0.184\,\frac{\Delta g_P}{g_P}$$

$\delta\Lambda_S$ with present δg

$$\frac{\Delta\Lambda_S}{\Lambda_S}(\%) = \sqrt{0.0239^2 + 0.0104^2 + \underline{0.504^2} + \underline{9.2^2}}$$

$$\frac{\delta\Lambda}{\Lambda} = 0.466\,\frac{\delta g_V}{g_V} + 0.151\,\frac{\delta g_M}{g_M} + 1.567\,\frac{\delta g_A}{g_A} - 0.184\,\frac{\delta g_P}{g_P} + 0.0238\,\delta g_{S,T}$$

$$\frac{\delta\Lambda}{\Lambda}[\%] = \quad 0.024 \qquad 0.01 \qquad 0.38 \qquad 3.7 \qquad 0.24$$

error from V_{ud} = 0.16 %

assuming optimistic
20% g_P error

assuming g_T<0.1

45 Years of Experiments to Determine g_P

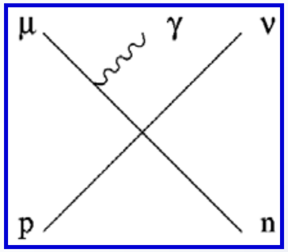
- $\mu^- + p \rightarrow \nu_\mu + n$ **OMC** BR~10^{-3}

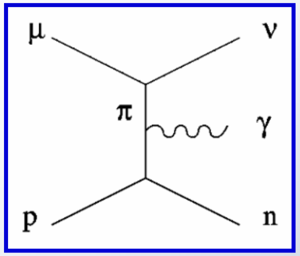
8 experiments, typical precision 10-15%, Saclay 4%

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

279±25 events
$BR_\gamma(k>60MeV)=(2.10\pm0.21)x10^{-8}$

Wright et al. (1998)





…

- $\mu^- + {}^3He \rightarrow \nu_\mu + {}^3H$

	authors	**Λ_{stat} (s^{-1})**	**comment**
theory 1993	***Congleton & Fearing***	**1304**	**1B**
theory 1996	***Congleton & Truhlik***	**1502±32**	**1B + 2B**
exp 1998	***Ackerbauer et al***	**1496.0±4.0**	**^{3}He TPC**
theory 2002	***Marcucci et al.***	**1484±8**	**1B+2B, T beta constraint**

$$g_P(-0.954m_\mu^2) = 8.53 \pm 1.54$$

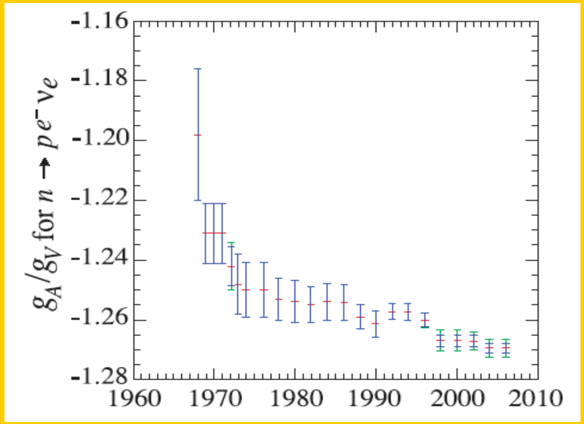
rad. corrections?

- **Beta Decay Correlations**

MuCap

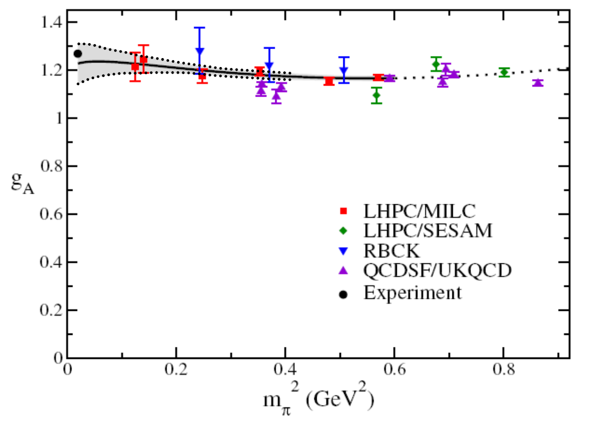
Axialvector Form Factor g_A

Exp. History



PDG 2006

Lattice QCD



Edwards et al. LHPC Coll (2006)

$$g_A(q^2) = g_A(0)(1 + \tfrac{1}{6} < r_A^2 > q^2)$$

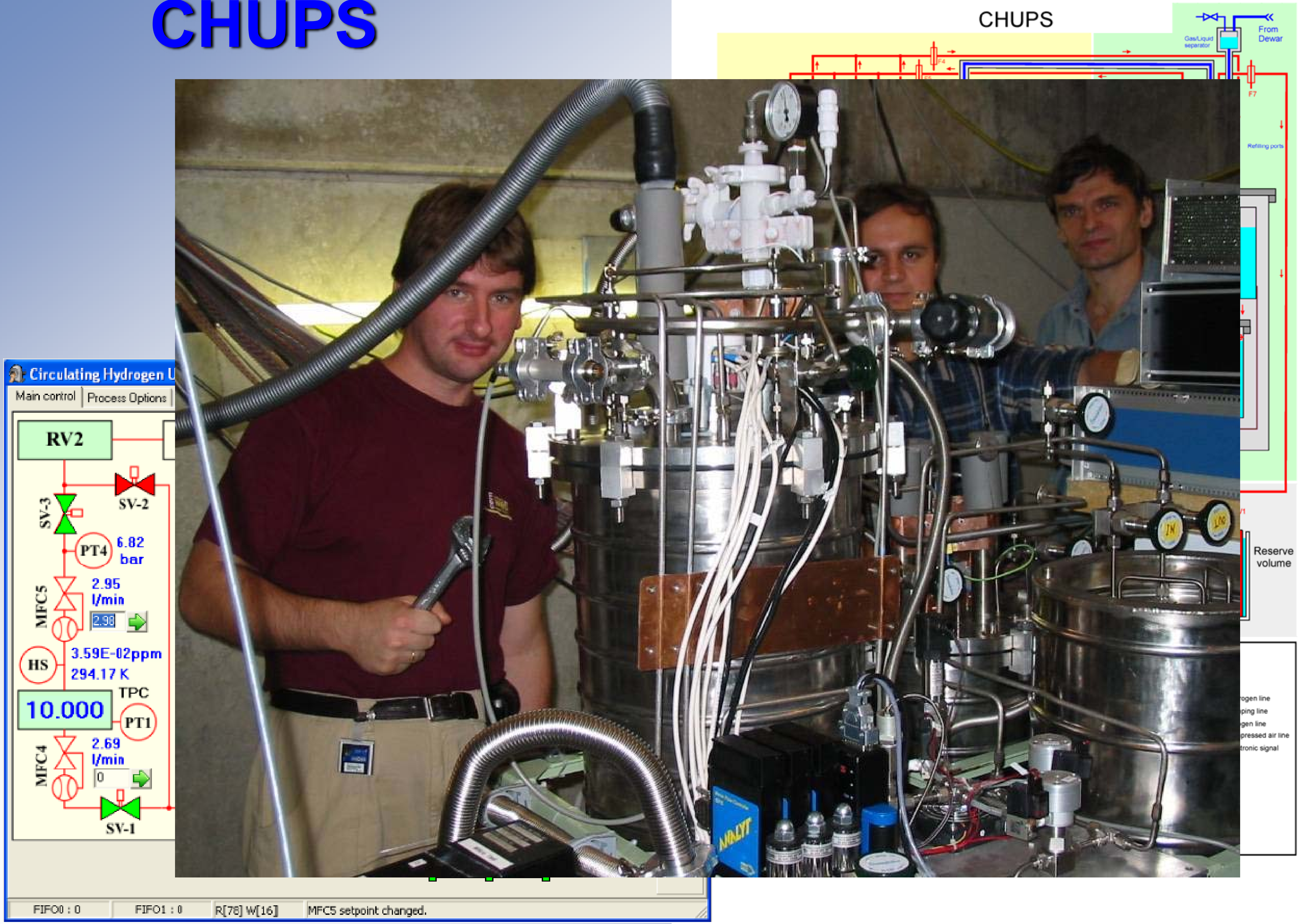
$$g_A(0) = 1.2695 \pm 0.0029$$

$$g_A(-0.88 m_\mu^2) = 1.245 \pm 0.004$$

introduces 0.46% uncertainty to Λ_S (theory)

μCF-07

CHUPS



6.82 bar

2.95 l/min

2.98

3.59E-02ppm

294.17 K

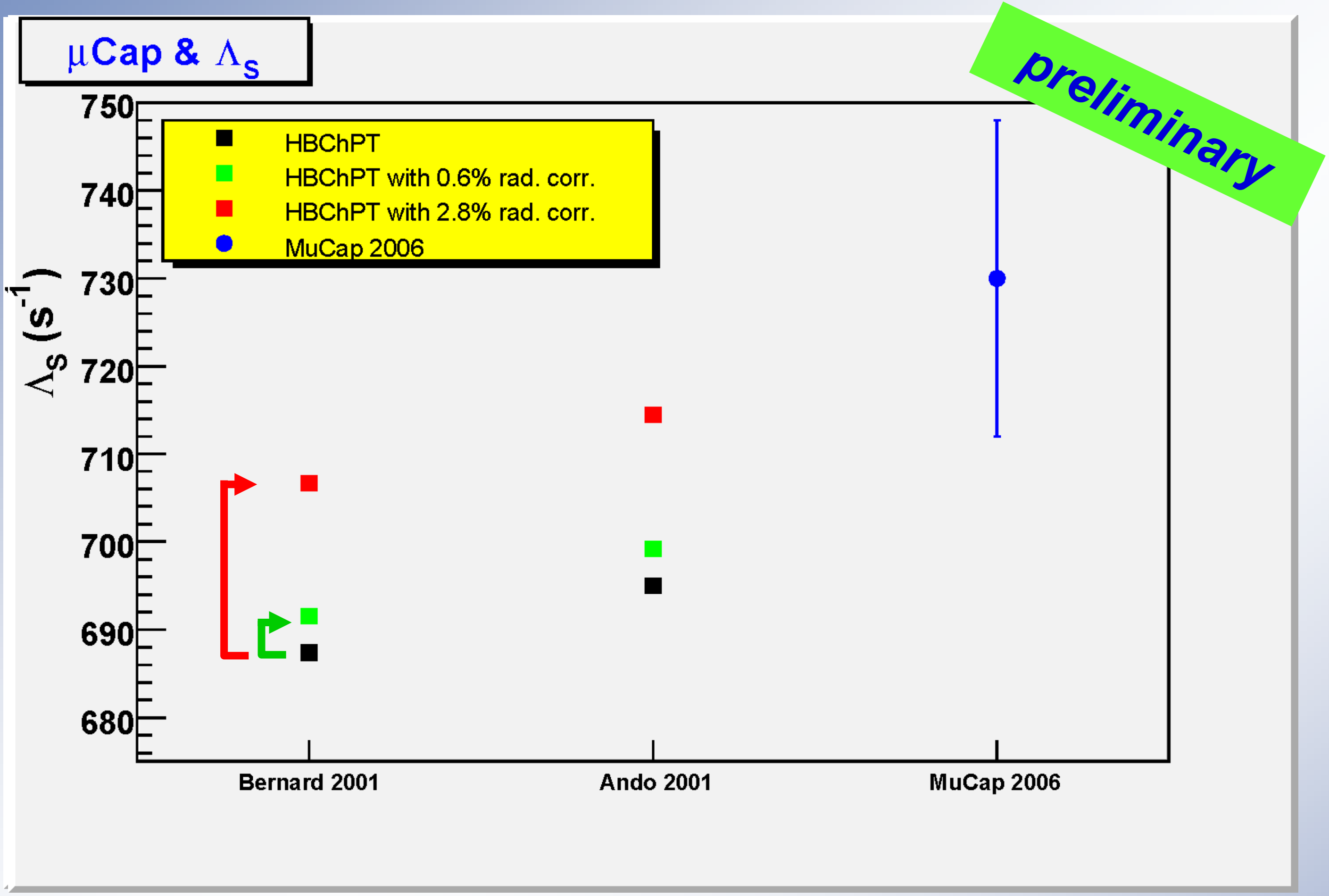
10.000

2.69 l/min

0

FIFO0 : 0 | FIFO1 : 0 | R[78] W[16] | MFC5 setpoint changed.

μCap and Λ_S calculations



rad. corrections

- *Goldman (1972)*
- *Czarnecki Marciano Sirlin (2006) private comm. preliminary*

MuCap agrees within ~1σ with Λ_S theory

Thorough theory studies needed for next MuCap 1% stage !

Theory and Sensitivities

author	year	g_P	Λ_S	Λ_T	comment
Primakoff	1959		664(20)	11.9(7)	smaller g_A
Opat	1964		634	13.3	smaller g_A
Bernard et al	1994	8.44(23)			
Fearing et al	1997	8.21(9)			
Govaerts et al	2000	8.475(76)	688.4(38)	12.01(12)	
Bernard et al	2000/1		687.4 (711*)	12.9	NNLO, small scale
Ando et al	2001		695 (722*)	11.9	NNLO

PCAC:

$q^2=0$ GT relation:

$g_{\pi NN}(0)\ F_\pi = M\ g_A(0)$

$q^2<0$ $g_p(q^2) = 2\ m\ M/(m_\pi^2 - q^2)\ g_A(0)$

$g_P = 8.7$

Sensitivity of capture rate:

$$\frac{\delta\Lambda}{\Lambda} = 0.466\,\frac{\delta g_V}{g_V} + 0.151\,\frac{\delta g_M}{g_M} + 1.567\,\frac{\delta g_A}{g_A} - 0.184\,\frac{\delta g_P}{g_P} + 0.0238\,\delta g_{S,T}$$

$$\frac{\delta\Lambda}{\Lambda}[\%] = \quad 0.024 \qquad 0.01 \qquad 0.38 \qquad 3.7 \qquad 0.24$$

assuming optimistic 20% g_P error

assuming $g_T<0.1$

error from V_{ud} = 0.16 %

Parameters

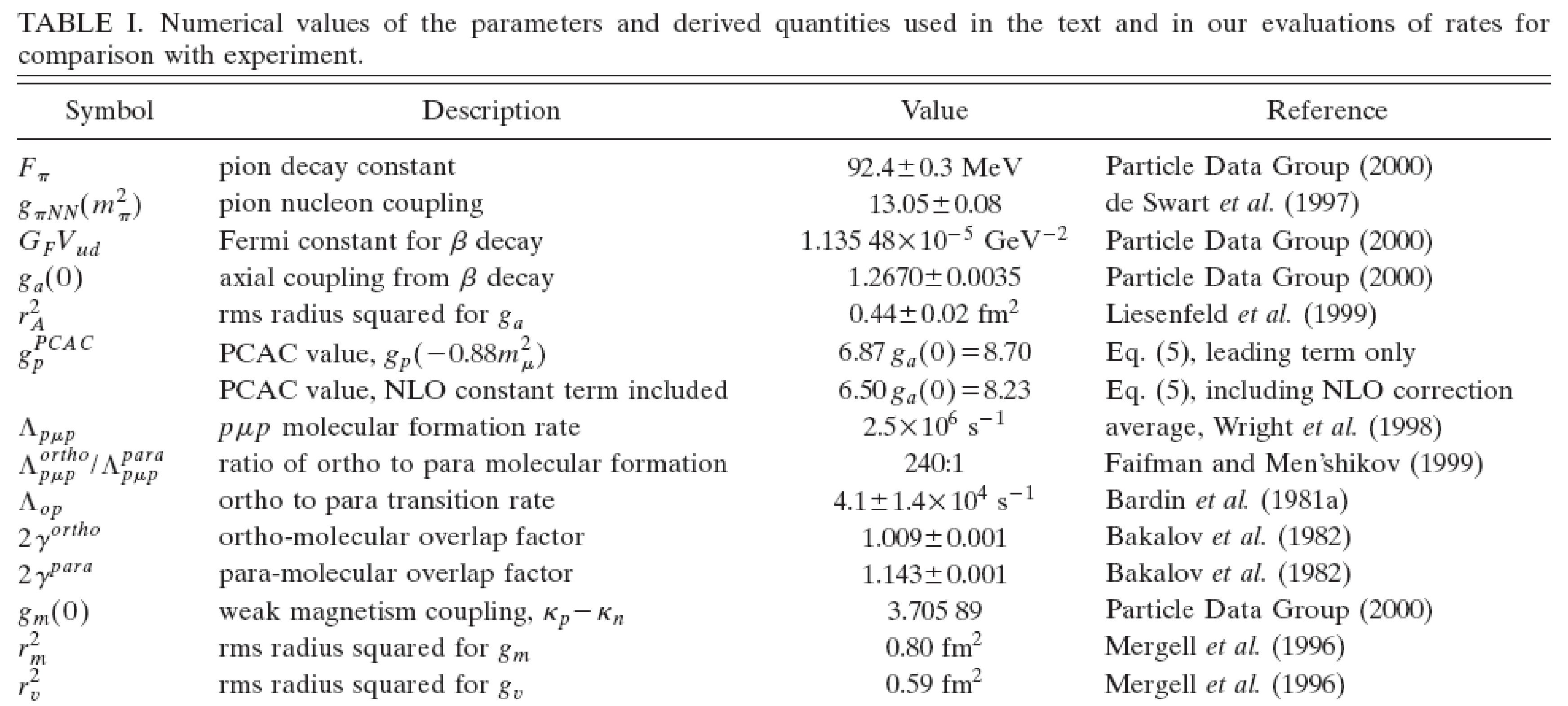


TABLE I. Numerical values of the parameters and derived quantities used in the text and in our evaluations of rates for comparison with experiment.

Symbol	Description	Value	Reference
F_π	pion decay constant	92.4 ± 0.3 MeV	Particle Data Group (2000)
$g_{\pi NN}(m_\pi^2)$	pion nucleon coupling	13.05 ± 0.08	de Swart *et al.* (1997)
$G_F V_{ud}$	Fermi constant for β decay	$1.135\,48 \times 10^{-5}$ GeV^{-2}	Particle Data Group (2000)
$g_a(0)$	axial coupling from β decay	1.2670 ± 0.0035	Particle Data Group (2000)
r_A^2	rms radius squared for g_a	0.44 ± 0.02 fm^2	Liesenfeld *et al.* (1999)
g_p^{PCAC}	PCAC value, $g_p(-0.88 m_\mu^2)$	$6.87\, g_a(0) = 8.70$	Eq. (5), leading term only
	PCAC value, NLO constant term included	$6.50\, g_a(0) = 8.23$	Eq. (5), including NLO correction
$\Lambda_{p\mu p}$	$p\mu p$ molecular formation rate	2.5×10^6 s^{-1}	average, Wright *et al.* (1998)
$\Lambda_{p\mu p}^{ortho}/\Lambda_{p\mu p}^{para}$	ratio of ortho to para molecular formation	240:1	Faifman and Men'shikov (1999)
Λ_{op}	ortho to para transition rate	$4.1 \pm 1.4 \times 10^4$ s^{-1}	Bardin *et al.* (1981a)
$2\gamma^{ortho}$	ortho-molecular overlap factor	1.009 ± 0.001	Bakalov *et al.* (1982)
$2\gamma^{para}$	para-molecular overlap factor	1.143 ± 0.001	Bakalov *et al.* (1982)
$g_m(0)$	weak magnetism coupling, $\kappa_p - \kappa_n$	3.705 89	Particle Data Group (2000)
r_m^2	rms radius squared for g_m	0.80 fm^2	Mergell *et al.* (1996)
r_v^2	rms radius squared for g_v	0.59 fm^2	Mergell *et al.* (1996)

Nucleon charged current at $q^2 = -0.88\ m_\mu^2$

$$J_\alpha = V_\alpha - A_\alpha$$

$$V_\alpha = g_V(q^2)\,\gamma_\alpha \quad + \; i g_M(q^2)/2M\,\sigma_{\alpha\beta}\,q^\beta \; + \; g_S(q^2)/m\; q_\alpha$$

$$A_\alpha = g_A(q^2)\,\gamma_\alpha\,\gamma_5 + \; g_P(q^2)\,q_\alpha/m\,\gamma_5 \quad + i g_T(q^2)/2M\,\sigma_{\alpha\beta}\,q^\beta\,\gamma_5$$

nucleon weak formfactors g_V, g_M, g_A

- determined by SM symmetries and data
- contribute <0.4% uncertainty to Λ_S

$g_V = 0.9755(5)$

$g_M = 3.5821(25)$

$g_A = 1.245(3)$

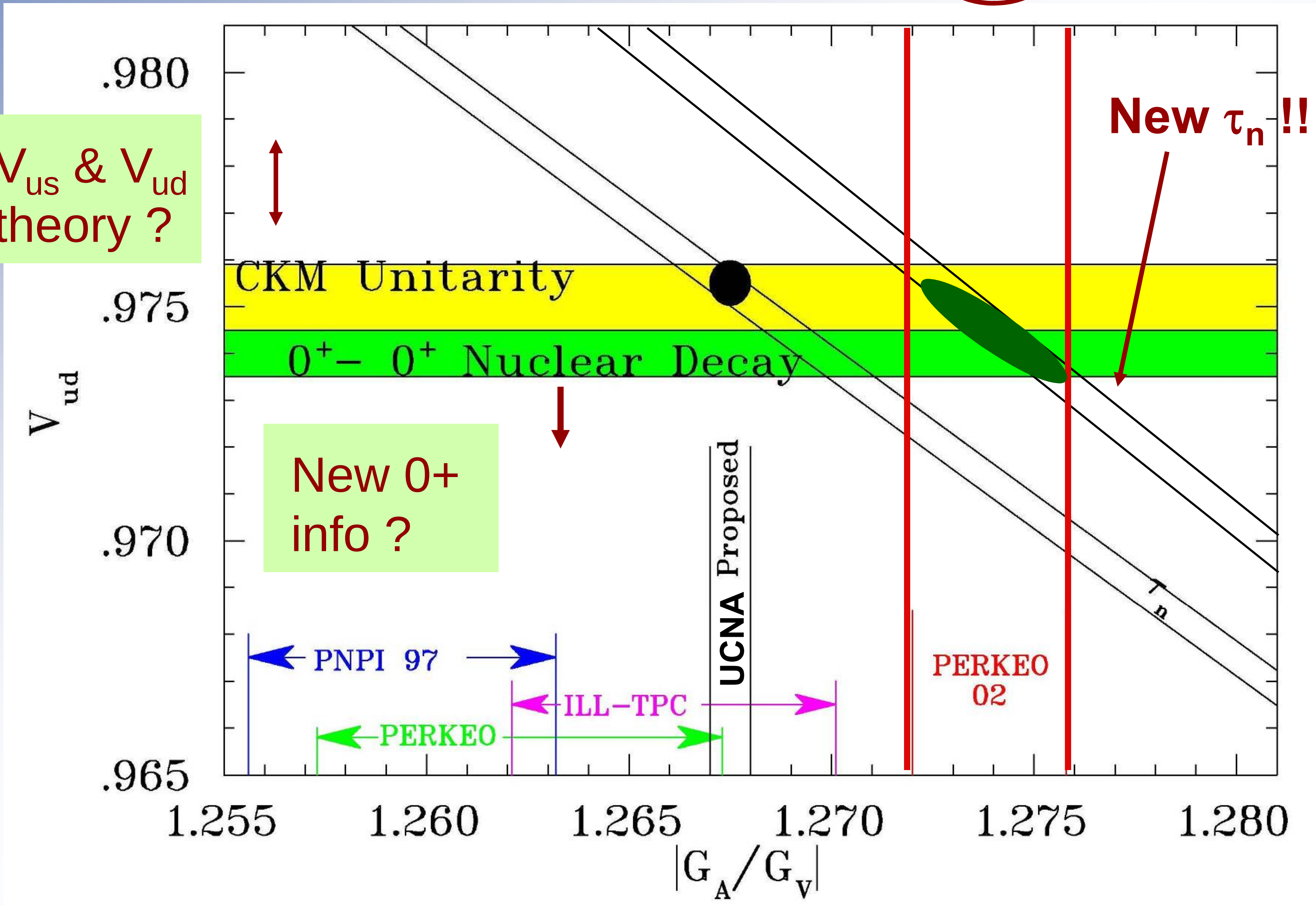
remains

$g_P = ?$

- Vector current in SM determined via CVC
  $g_V(0)=1$, $g(q^2)=1+q^2\,r^2/6$, $r_V^2=0.59\ \mathrm{fm}^2$
  $g_M(0)=\mu_p-\mu_n-1=3.70589$, $r_M^2=0.80\ \mathrm{fm}^2$
  q^2 dependence from e scatt.
- Axial vector FF from experiment
  $g_A(0)=1.2670(35)$, $r_A^2=0.42\pm0.04\ \mathrm{fm}^2$
  q^2 dependence from quasi-elastic ν scattering,
  π e-production
- 2nd class FF g_S, g_T forbidden by G symmetry, e.g.
  $g_T/g_A=-0.15 \pm 0.15$ (exp),
  -0.0152 ± 0.0053(QCD sum rule, up-down mass difference)
- error from V_{ud} = 0.16 %

Neutron

CKM Summary: New V_{us} & τ_n ?



V_{us} & V_{ud} theory ?

New 0+ info ?

New τ_n !!

neutron (J. Nico, CIPANP 06)

$$dW \propto (g_V^2 + 3g_A^2)F(E_e)[1 + a\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_eE_\nu} + \vec{\sigma_n}\cdot(A\frac{\vec{p_e}}{E_e} + B\frac{\vec{p_\nu}}{E_\nu} + D\frac{\vec{p_e}\times\vec{p_\nu}}{E_eE_\nu})]$$

Jackson, Treiman, Wyld, *Nucl. Phys.* **4**, 206 (1957)

Lifetime

$$\tau = \frac{1}{f(1+\delta_R)}\frac{K/ln2}{(1+\Delta_R^V)(g_V^2+3g_A^2)} = (885.7 \pm 0.8)\,\mathrm{s}$$

Coupling ratio

$$\lambda = \frac{|g_A|}{|g_V|}e^{i\phi} = (-1.2695 \pm 0.0029)$$

Electron-antineutrino asymmetry

$$a = \frac{1-|\lambda|^2}{1+3|\lambda|^2} = (-0.103 \pm 0.004)$$

Spin-antineutrino asymmetry

$$B = 2\frac{|\lambda|^2 - |\lambda|cos\phi}{1+3|\lambda|^2} = (0.983 \pm 0.004)$$

Spin-electron asymmetry

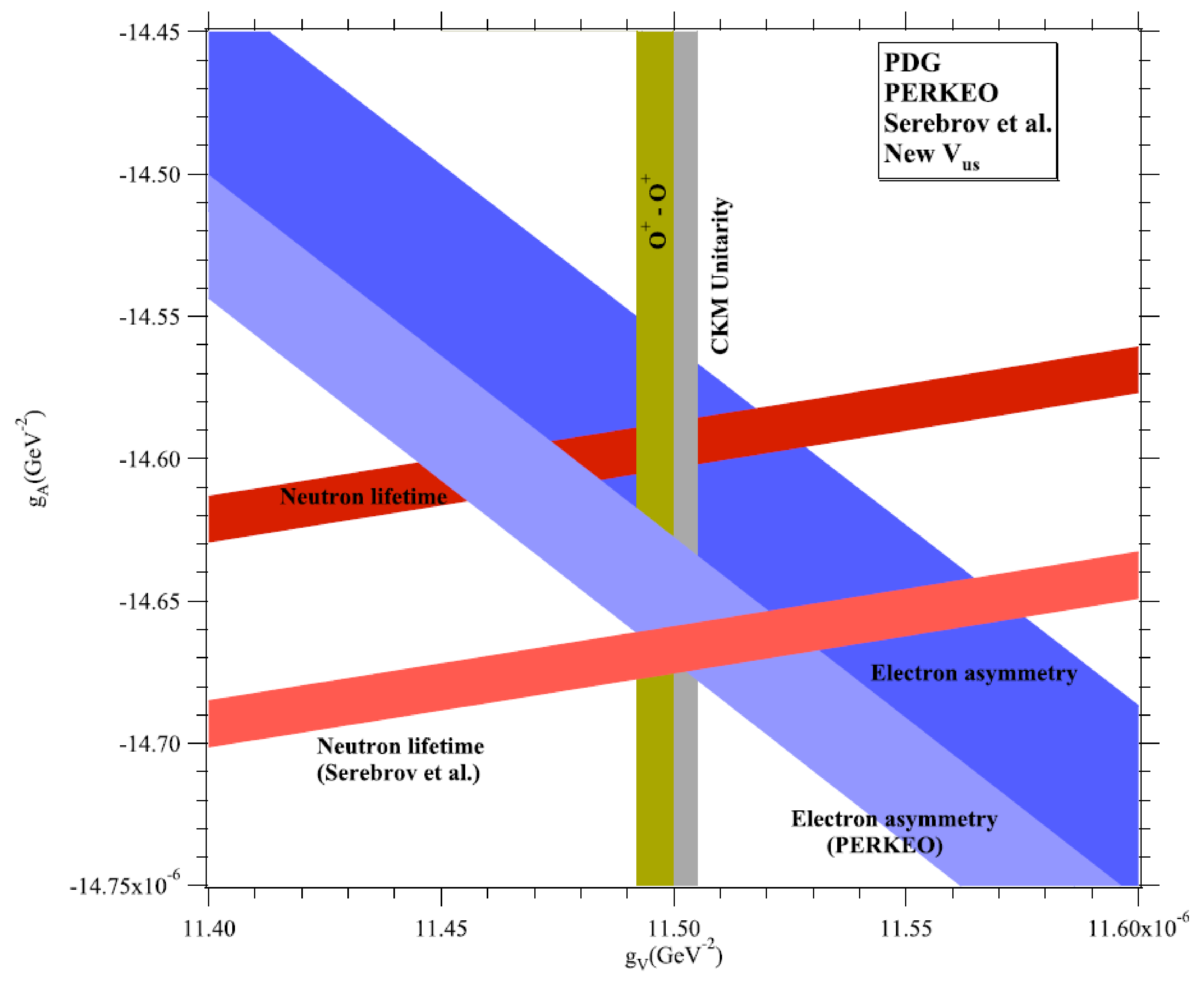
$$A = -2\frac{|\lambda|^2 + |\lambda|cos\phi}{1+3|\lambda|^2} = (-0.1173 \pm 0.0013)$$

Triple correlation

$$D = 2\frac{|\lambda|sin\phi}{1+3|\lambda|^2} = (-4 \pm 6) \times 10^{-4}$$

PDG, 2005 update

neutron


PDG
PERKEO
Serebrov et al.
New V_{us}
$0^+ - 0^+$
CKM Unitarity
Neutron lifetime
Neutron lifetime (Serebrov et al.)
Electron asymmetry
Electron asymmetry (PERKEO)
$g_A(\mathrm{GeV}^{-2})$
$g_V(\mathrm{GeV}^{-2})$
-14.45
-14.50
-14.55
-14.60
-14.65
-14.70
-14.75×10^{-6}
11.40
11.45
11.50
11.55
11.60×10^{-6}