Fundamental Symmetries and Precision Physics*

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CENPA: Center for Experimental Nuclear Physics and Astrophysics

- **Lecture 1**
  - **Motivations**
  - **Symmetries, Parity, and the Weak Interaction**
  - **The Fermi Constant**
  - **Muon Decay as a test of V-A theory**
- **Lecture 2**
  - **Neutron beta decay**
  - **Parity as a tool to probe matter: PVES**
  - **Highly sensitive low-energy probes of New Physics**
- **Lecture 3 (transition here at some point …)**
  - **CPV and Electric Dipole Moments**
  - **Charged Lepton Flavor Violation**
  - **Muon g-2**

***With some random experimental details and a modern perspective**

Much of the motivation of this field is about looking for New Physics … using low-energy experimental techniques

translation: not colliders

Contents lists available at SciVerse ScienceDirect

Progress in Particle and Nuclear Physics

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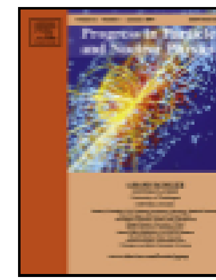

Review

Low energy probes of physics beyond the standard model

Vincenzo Cirigliano [a], Michael J. Ramsey-Musolf [b,c,*]

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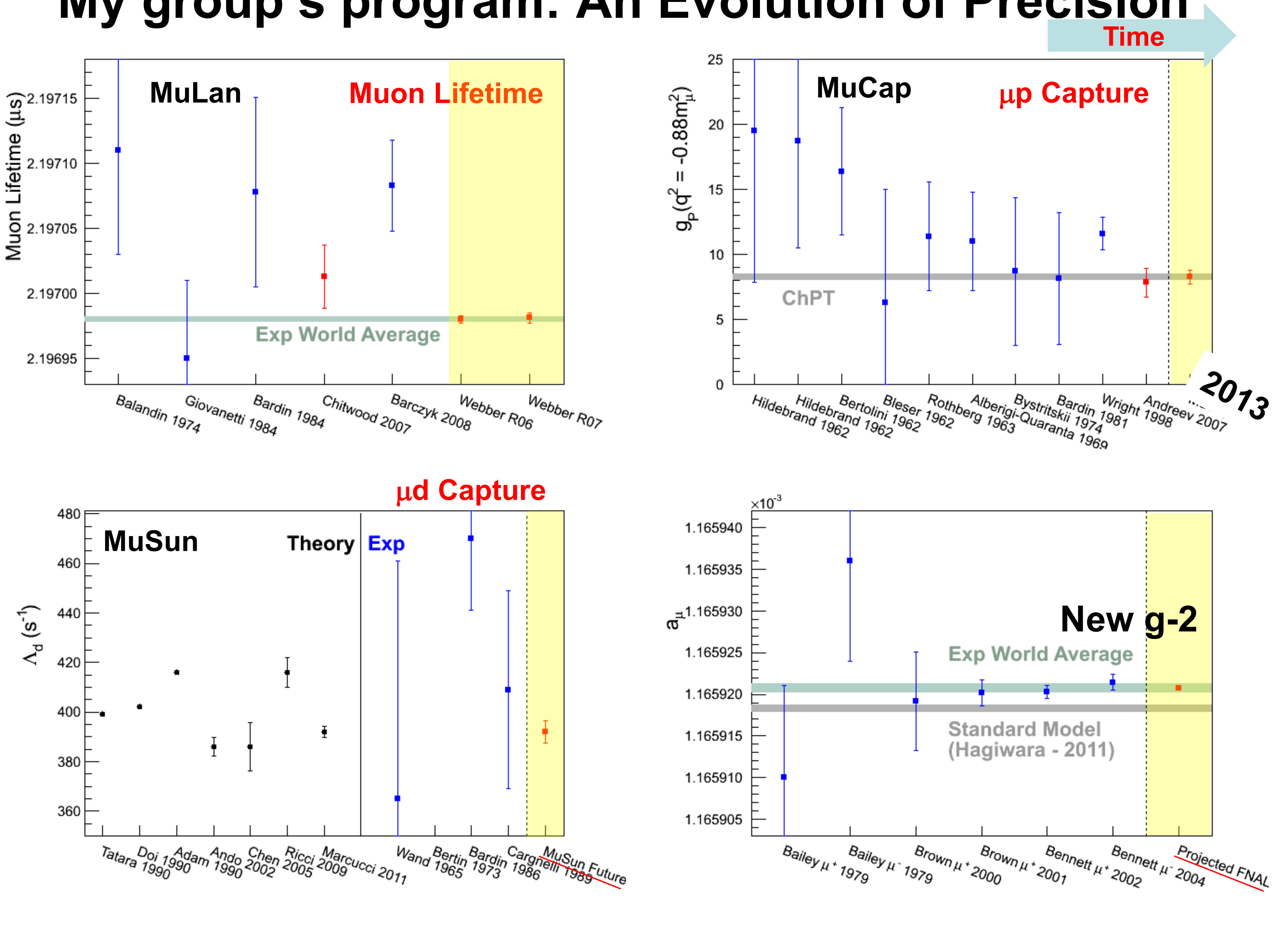
My group's program: An Evolution of Precision

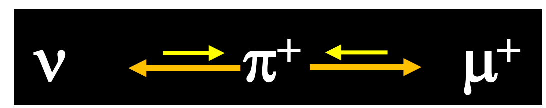


Muon Primer

- **Mass ~ 207 m_e** (50 ppb)
  - $(m_\mu/m_e)^2 \approx$ 43,000 times more sensitive to "new physics" through quantum loops compared to electrons (taus would be better!)

- **Lifetime ~2.2 μs** (1 ppm)
  - High-intensity beams; can stop and study; can possibly collide

- **Primary production: $\pi^+ \rightarrow \mu^+ \nu_\mu$** (99.98%)
  - Polarized naturally:



- **Primary decay $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$** (~99%)
  - Purely weak; distribution in θ and *E* reveals weak parameters

- **Lepton number is conserved**

(BRs 4 < 10^{-13})

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

Neutron Primer

- **Mass ~ 939.5 MeV** **(6 ppb)**
- **Free *n* Lifetime ~880 s** **(we will return to this)**
- **Magnetic moment: -1.91 μ_N** **(all "anomalous")**
- **Electric Dipole moment: < 0.3 x 10^{-25} e cm** **(we will discuss)**
- **Primary decay n → $p e^- \bar{\nu}_e$** **(we will also discuss)**
- **Baryon number is conserved**

Electron Primer

- **Seriously ?**

- **It’s light, charged, stable, and we know lots about it**

The Motivation for Tests of Fundamental Symmetries and the Role of Precision Measurement (the conventional)

- Establish the Standard Model parameters and laws. Examples include:
  – Masses M_Z, M_W, M_H, m_b, m_t, m_e, m_u, m_ν, … "NP Role"
  – Couplings: α_{QED}, α_{Strong}, G_F, G_{grav}
  – Structure of interactions $SU(3)_C \times SU(2)_L \times U(1)_Y$
  – Broad issues
    - Numbers of generations
    - Mixing angles, quarks and neutrinos
    - Lepton number and flavor
      – Majorana or Dirac neutrinos [See lectures by Kumar]
      – Charged Lepton Flavor Violation
    - CP violation parameters in K and B sector
- The Standard Model as we know it has been built on an enormous experimental foundation involving ***Precision*** and ***Energy*** frontier efforts
- And, some exquisite ***Theory*** !

The Motivation for Tests of Fundamental Symmetries and the Role of Precision Measurement (the exotic)

- **Can we sensitively test the SM limitations to help answer key questions:**
  - Baryon Asymmetry of the Universe
  - EW symmetry breaking
- **Are the Standard Model predictions complete?**
  - What is missing?
  - What extensions are needed?
- **The community has also begun to worry ...**

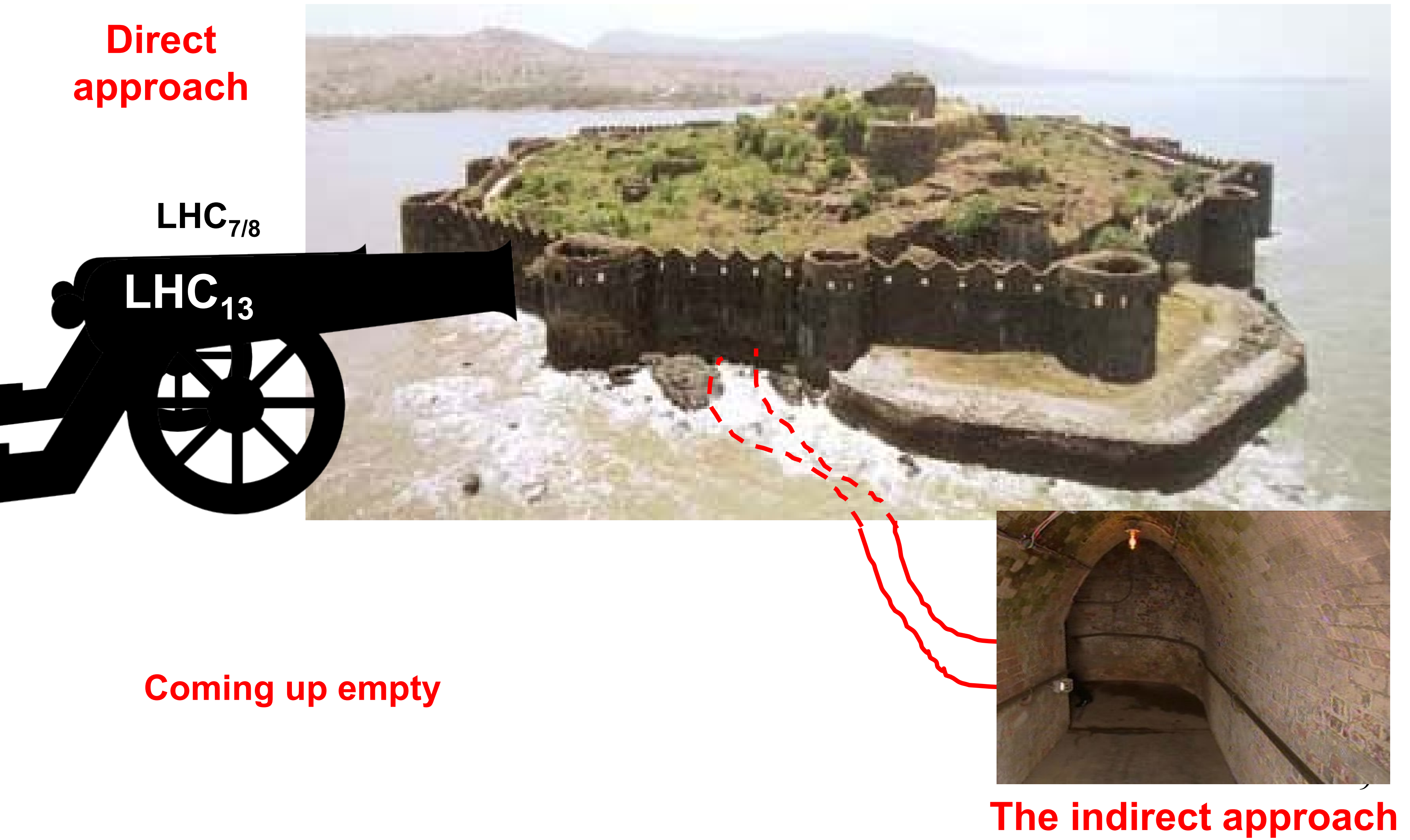
So far: No direct evidence for Supersymmetry, Extra Dimensions, 4th Generation, New Dynamics…

At The LHC!

The Higgs – Last Particle Ever Discovered?

Marciano

The unconquered Standard Model



Discrete Fundamental Symmetries

- **Parity**
  - Does experiment distinguish between left and right?

- **Time Reversal**
  - **Are physics processes the same in both time directions ?**

- **Charge Conjugation**
  - **Do particles and antiparticles behave the same**

Combined Symmetries

- **CP**
  - E.g, Do particles and their antiparticles decay with the same patterns?

- **CPT**
  - Combination felt to be very solid for any local QM gauge theory. No violations at all sensed. Implications include
    - If CP is violated, T must be violated (a bit of a shock)
    - CPT and Lorentz violation are tested as one
    - Many tests of particle and antiparticle properties, such as magnetic moments of proton – antiproton, electron – positron, muon – antimuon; Lifetimes of particle – antiparticle, and others
  - Very unlikely to have time for much here, but ongoing efforts exist

Topic 1

A Radical Thought

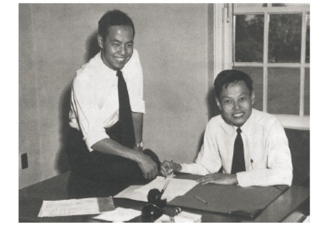
Question of Parity Conservation in Weak Interactions*

T. D. Lee, *Columbia University, New York, New York*

AND

C. N. Yang,† *Brookhaven National Laboratory, Upton, New York*
(Received June 22, 1956)

Lee and Yang



1956

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

- A troubling problem was the $\tau^+ - \theta^+$ puzzle, … well really K^+ decay:

	$K^+ \rightarrow \pi^+ \pi^0$	&	$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	
named	θ^+		τ^+	**Same particle?**
parity	+1		-1	

- Conjecture: two different decay modes of the same particle, with same mass and same lifetime
  - Can happen if parity is not strictly conserved
- This begged the question, "*Has parity been checked in the Weak Interaction?*" $\rightarrow$ *answer*: Not very well

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*
(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

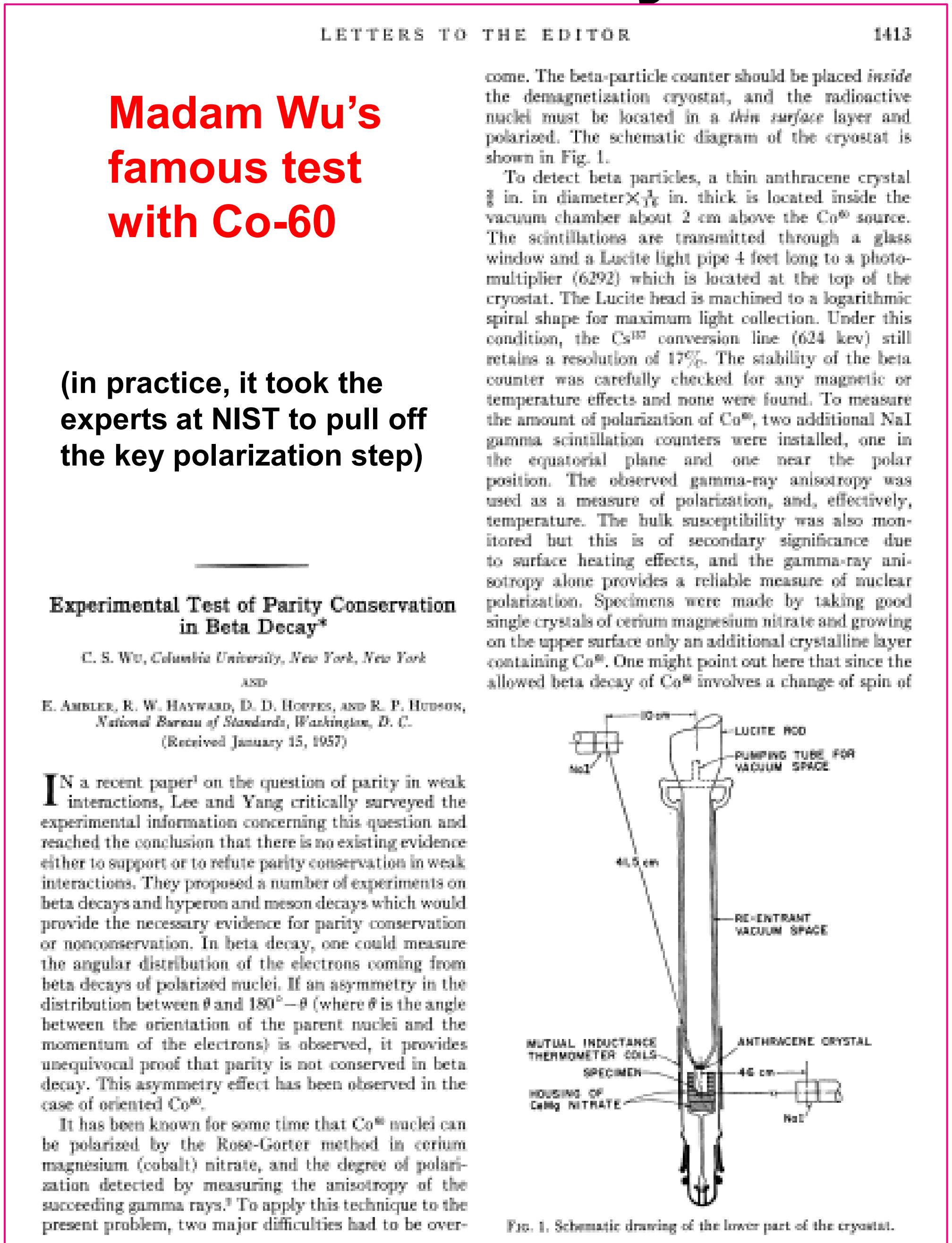
- **Then, what would constitute a weak-interaction parity test?**
  - **Are muons polarized with respect to their momentum in pion decay?**
  - **Is the decay pattern of electrons from muon decay non-symmetric with respect to the muon's spin?**
  - **Are the decay products from a polarized hyperon non-symmetrically emitted?**
  - **Is the beta decay of a polarized Co-60 nucleus non-symmetric?**

  - **… these are common …**
    - **You need "an axis" to define a direction**
    - **You need something that is not symmetric with respect to that axis**

A flurry of tests begins …

Madam Wu's famous test with Co-60

(in practice, it took the experts at NIST to pull off the key polarization step)



LETTERS TO THE EDITOR 1413

Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

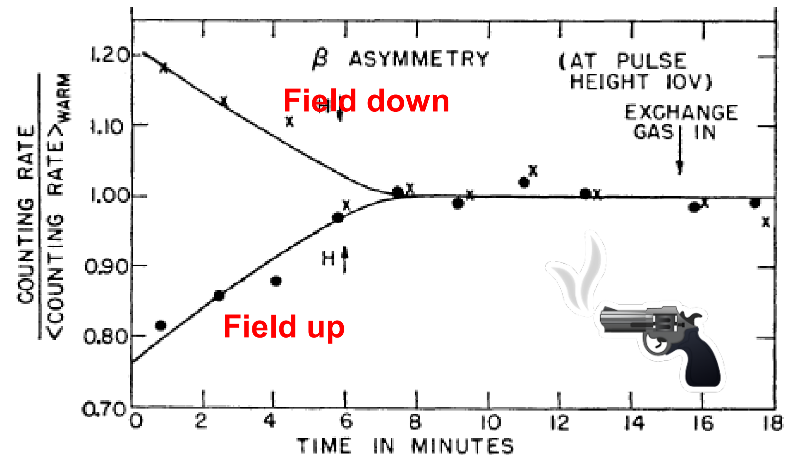
(Received January 15, 1957)

In a recent paper[1] on the question of parity in weak interactions, Lee and Yang critically surveyed the experimental information concerning this question and reached the conclusion that there is no existing evidence either to support or to refute parity conservation in weak interactions. They proposed a number of experiments on beta decays and hyperon and meson decays which would provide the necessary evidence for parity conservation or nonconservation. In beta decay, one could measure the angular distribution of the electrons coming from beta decays of polarized nuclei. If an asymmetry in the distribution between θ and $180°-\theta$ (where θ is the angle between the orientation of the parent nuclei and the momentum of the electrons) is observed, it provides unequivocal proof that parity is not conserved in beta decay. This asymmetry effect has been observed in the case of oriented Co^{60}.

It has been known for some time that Co^{60} nuclei can be polarized by the Rose-Gorter method in cerium magnesium (cobalt) nitrate, and the degree of polarization detected by measuring the anisotropy of the succeeding gamma rays.[2] To apply this technique to the present problem, two major difficulties had to be overcome. The beta-particle counter should be placed *inside* the demagnetization cryostat, and the radioactive nuclei must be located in a *thin surface* layer and polarized. The schematic diagram of the cryostat is shown in Fig. 1.

To detect beta particles, a thin anthracene crystal $\frac{3}{8}$ in. in diameter $\times \frac{1}{16}$ in. thick is located inside the vacuum chamber about 2 cm above the Co^{60} source. The scintillations are transmitted through a glass window and a Lucite light pipe 4 feet long to a photomultiplier (6292) which is located at the top of the cryostat. The Lucite head is machined to a logarithmic spiral shape for maximum light collection. Under this condition, the Cs^{137} conversion line (624 kev) still retains a resolution of 17%. The stability of the beta counter was carefully checked for any magnetic or temperature effects and none were found. To measure the amount of polarization of Co^{60}, two additional NaI gamma scintillation counters were installed, one in the equatorial plane and one near the polar position. The observed gamma-ray anisotropy was used as a measure of polarization, and, effectively, temperature. The bulk susceptibility was also monitored but this is of secondary significance due to surface heating effects, and the gamma-ray anisotropy alone provides a reliable measure of nuclear polarization. Specimens were made by taking good single crystals of cerium magnesium nitrate and growing on the upper surface only an additional crystalline layer containing Co^{60}. One might point out here that since the allowed beta decay of Co^{60} involves a change of spin of

Fig. 1. Schematic drawing of the lower part of the cryostat.



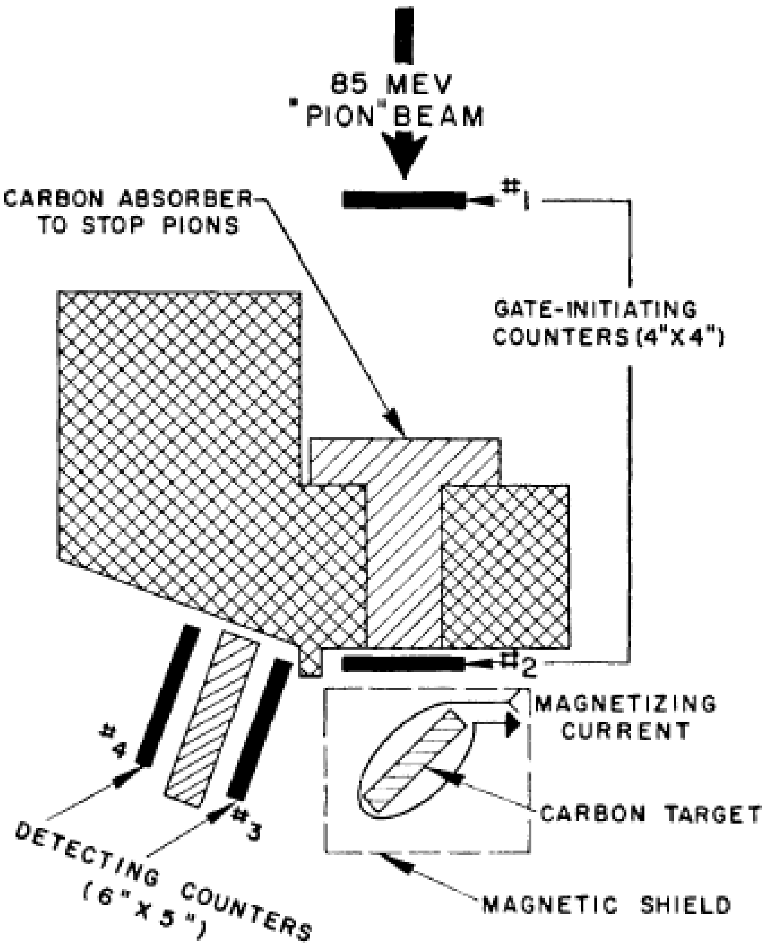
When field is up, betas go more "down"; when field is down, betas go more "up"

A flurry of tests begins …

Garwin, Lederman, Weinrich follow with muon decay experiment

$$\pi^+ \to \mu^+ + \nu,$$

$$\mu^+ \to e^+ + 2\nu.$$



Solid curve is 1 – 1/3 cos θ

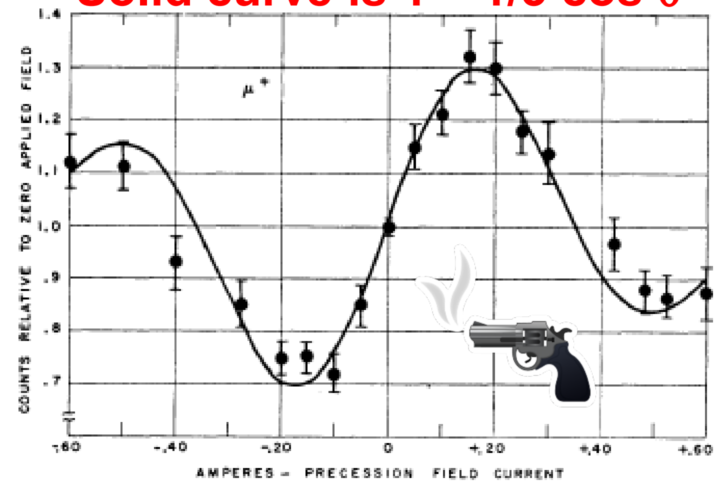


FIG. 2. Variation of gated 3–4 counting rate with magnetizing current. The solid curve is computed from an assumed electron angular distribution $1-\frac{1}{3}\cos\theta$, with counter and gate-width resolution folded in.

Counts vs. Magnetic Field compared to B = 0

Lee and Yang also suggest that, if PV were so, it offers a natural way to determine the muon's magnetic moment !

And, later, we will return to this subject with a modern focus

$$\pi^+ \to \mu^+ + \nu, \tag{1}$$

$$\mu^+ \to e^+ + 2\nu. \tag{2}$$

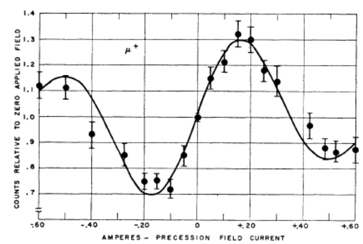
They have pointed out that parity nonconservation implies a polarization of the spin of the muon emitted from stopped pions in (1) along the direction of motion and that furthermore, the angular distribution of electrons in (2) should serve as an analyzer for the muon polarization. They also point out that the longitudinal polarization of the muons offers a natural way of determining the magnetic moment.[5] Confirmation of

Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

RICHARD L. GARWIN,† LEON M. LEDERMAN, AND MARCEL WEINRICH

Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York

(Received January 15, 1957)



$g_\mu = 2.0 \pm 0.1$

→ Spin of μ is ½ (Dirac, point-like object)

Remarks on Possible Noninvariance under Time Reversal and Charge Conjugation*

T. D. LEE, *Columbia University, New York, New York*

AND

REINHARD OEHME AND C. N. YANG, *Institute for Advanced Study, Princeton, New Jersey*

(Received January 7, 1957)

Using this theorem, one concludes that if any left-right asymmetry of the form $\boldsymbol{\sigma}\cdot\mathbf{p}$ is found, the part of this asymmetry that is independent of the distortion of the final-state wave functions can arise only if charge conjugation symmetry breaks down for the weak interactions. In particular, in decays where there is no strong final-state interactions, as, e.g., in $\pi \to \mu + \nu$ and $\mu \to e + \nu + \nu$ decays, the detection[1] of parity nonconservation through the observation of $\boldsymbol{\sigma}\cdot\mathbf{p}$ becomes impossible if C is strictly conserved.

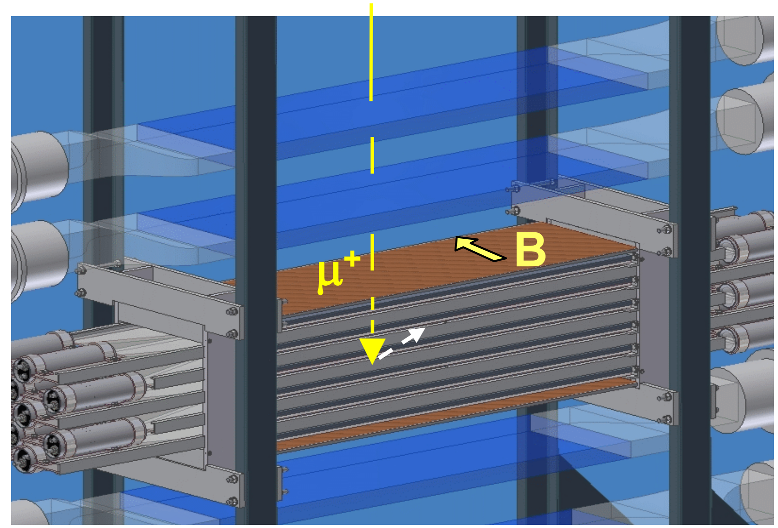
And angular distribution proves by theorem here that charge conjugation is also not conserved in WI

Parity violation "at home"

At rest, the muon precesses in a magnetic field, giving *g*,

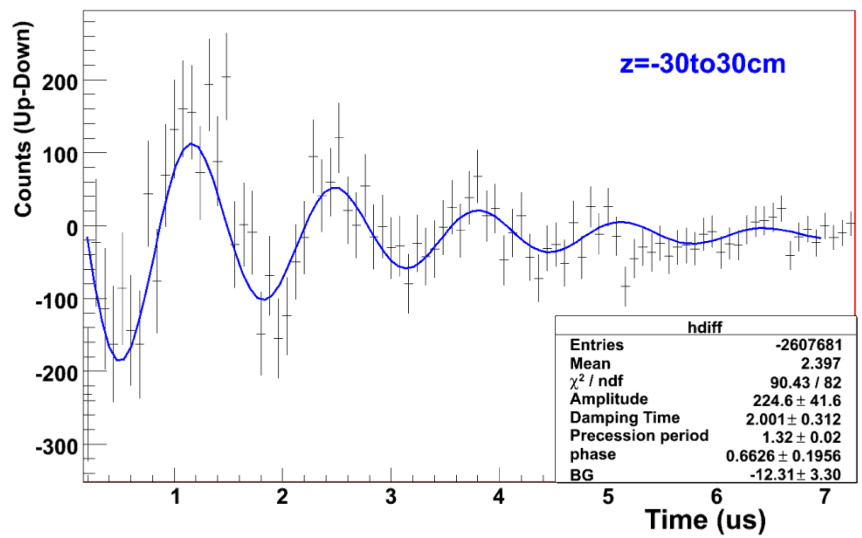
(or the magnetic moment)

$$\omega = \frac{geB}{2m_\mu}$$



g = 2.1 ± 0.1

Fitting Error ~ 1.5 %
Magnetic field error ~ 5.5 %



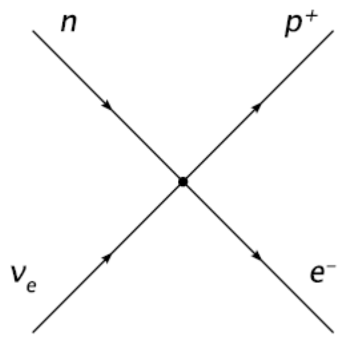
Univ. Illinois cosmic ray setup for undergraduate modern experimental physics course

Parity Violation appears on all Weak Decays

- Leptonic
  - Muon, tau decays
- Hadrons
  - Kaon, B-meson
  - Neutron
  - Nuclei

Weak Interaction Primer*

- Fermi's idea for neutron beta decay
  - 4-point interaction $M = \frac{G_F}{\sqrt{2}}[\overline{u_P}\gamma^\mu u_N][\overline{u_e}\gamma^\nu u_\nu]$
  - A charge-changing interaction
    - (hadronic → leptonic current)
  - No propagator (was wrong)
  - Purely Vector (also wrong)



- Actually: 3 massive gauge bosons mediate WI
  - $W^\pm$, Z^0 → propagator form: $\frac{1}{M_{W,Z}^2 - q^2}$.
  - At low energy → $\frac{1}{M_W^2}$
  - The "coupling" or "strength" is $G_F/\sqrt{2}$
  - The "real" weak coupling is g_w. We will see relation soon
    - Fun fact:

$$\text{EM coupling}:\ \alpha_{EM} = \frac{1}{137} \quad \text{Weak coupling}:\ \alpha_W = \frac{g_w^2}{4\pi} = \frac{1}{30}$$

*I'd love to cite the source I used, but the lovely posted lecture has no name…

Parity & V-A*

- **Parity transform:** $\hat{P}\psi(t,x,y,z) = \psi(t,-x,-y,-z) = \psi'(t',x',y',z')$
  $= \pm\gamma^0\psi(t,x,y,z)$
- **Under P, transform of Dirac equation unchanged** $\psi \to \hat{P}\psi = \pm\gamma^0\psi$
  - **Eigenvalues of P operator are ±1**
- **The V-A Interaction (took a while to establish)**
  - **Most general matrix element** $M \propto [\overline{u_{\psi,f}}\,\hat{O}\,u_{\psi,i}]\frac{1}{M^2-q^2}[\overline{u_{\phi,f}}\,\hat{O}\,u_{\phi,i}]$
  - **Ô is combination of γ matrices**
  - **Need combination where charged WI only couples to Left-Handed chiral particles**

$$P_L = \tfrac{1}{2}(1-\gamma^5)$$

  - **Only the vector (V) and axial vector (A) currents are responsible for PV nature of WI**

Name	Symbol	Current	Number of components	Effect under Parity
Scalar	S	$\bar{\psi}\psi$	1	+
Vector	V	$\bar{\psi}\gamma^\mu\psi$	4	(+,-,-,-)
Tensor	T	$\bar{\psi}\sigma^{\mu\nu}\psi$	6	
Axial Vector	A	$\bar{\psi}\gamma^\mu\gamma^5\psi$	4	(+,+,+,+)
Pseudo-Scalar	P	$\bar{\psi}\gamma^5\psi$	1	-

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Parity & V-A*

- **What we observe is always a square of an amplitude:**

$$\begin{aligned} |M|^2 &\sim (V-A)(V-A) \\ &= VV - 2AV + AA \end{aligned}$$

- **Apply a parity transformation (V flips, A does not)**

$$\begin{aligned} \hat{P}\{|M|^2\} &\sim \hat{P}\{(V-A)(V-A)\} \\ &= \hat{P}\{VV - 2AV + AA\} \\ &= (-V)(-V) + AA - 2A(-V) \\ &= VV + AA + 2AV \end{aligned}$$

- **Compare $|M|^2$ to $\hat{P}\{|M|^2\}$ A big difference; the interference term 2AV**

- **V-A "violates parity maximally" since both currents have same strength**

$$\frac{1}{2}\overline{\psi}\gamma^\mu(c_V - c_A\gamma^5)\phi$$

  - **c_V =1 and c_A = 1**

$$j^{CC}_{weak} = \frac{g_w}{\sqrt{2}}\overline{u}\gamma^\mu\frac{1}{2}(1-\gamma^5)u$$ **Weak Charged Current**

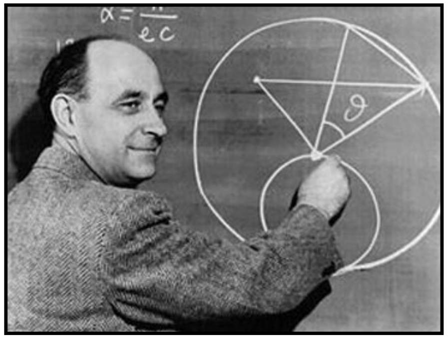
***I'd love to cite the source I used, but the lovely posted narrative has no author listed …**

Topic 2

Aspects of the Weak Interaction

$$\alpha = \frac{e^2}{\hbar c}$$

Muon Lifetime

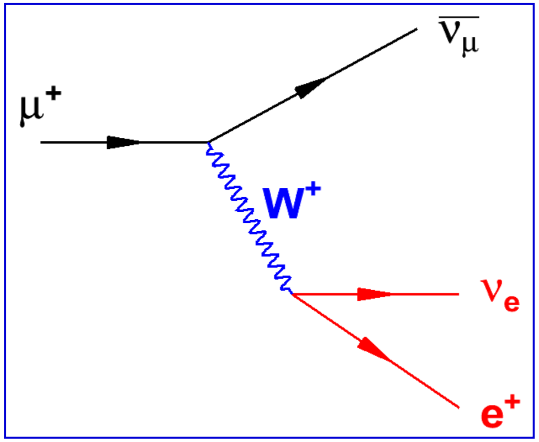


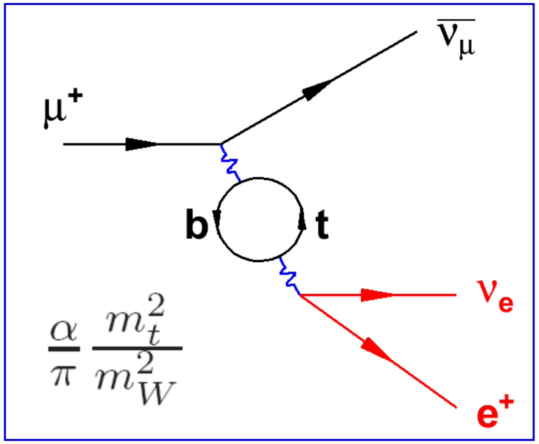
Fundamental electro-weak couplings

G_F	α	M_Z
15 ppm $\rightarrow$ 0.5 ppm	0.37 ppb	23 ppm

Implicit to all EW precision physics

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

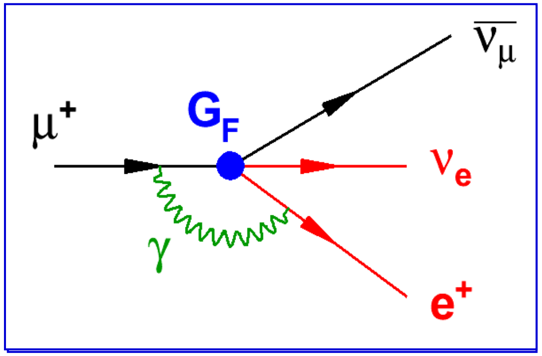




Uniquely defined by muon decay

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

QED



Extraction of G_F from τ_μ :
reduced error from
15 to ~0.5 ppm

From τ_μ to $\sin^2 \theta_W$

- Momentum transfer $q^2 = (p_\mu - p_{\nu\mu})^2 = (p_e + p_{\nu e})^2 < m_\mu^2$ much smaller than M_W^2
- Thus, W propagator shrinks to a point and can be well approximated through a local four-fermion interaction, (Fermi's original conjecture)

$$\frac{g^2}{M_W^2 - q^2} \approx \frac{g^2}{M_W^2} = \frac{4\pi\alpha}{\sin^2\theta_W \, M_W^2} \equiv 4\sqrt{2}G_F$$

$G_F = (1.166\,378\,8 \pm 0.000\,000\,7) \cdot 10^{-5}\ \mathrm{GeV}^{-2}$

$$\Rightarrow \quad \sin^2\theta_W = 0.215$$

(there are further quantum corrections here not included)

Let’s be careful
G_μ or G_F ?

- Lepton Universality is assumed
  - The bare gauge couplings assumed the same regardless of the lepton involved

$$g_{2_0}^{e} = g_{2_0}^{\mu} = g_{2_0}^{\tau}$$

  - And the bare natural relations

$$\sin^2\theta_W^0 = \frac{e_0^2}{g_{2_0}^2} = 1 - (m_W^0/m_Z^0)^2,$$

  - Is this really true? And how well do we know it?

Fermi Constants and "New Physics" – W. Marciano

$$\Gamma(\tau \to \ell\nu\bar{\nu}(\gamma)) = \frac{G_{\tau\ell}^2 m_\tau^5}{192\pi^3} f\left(\frac{m_\ell^2}{m_\tau^2}\right)\left(1+\frac{3}{5}\frac{m_\tau^2}{m_W^2}\right)\left(1+\frac{\alpha}{2\pi}\left(\frac{25}{4}-\pi^2\right)\right)$$

$$\left\{\begin{array}{l}\Gamma(\tau \to e\nu\bar{\nu}(\gamma)) = 4.035(19)\times 10^{-13}\ \mathrm{GeV} \\ \Gamma(\tau \to \mu\nu\bar{\nu}(\gamma)) = 3.933(19)\times 10^{-13}\ \mathrm{GeV}\end{array}\right.$$

$$\left\{\begin{array}{l}G_{\tau e} = 1.1666(28)\times 10^{-5}\ \mathrm{GeV}^{-2} \\ G_{\tau\mu} = 1.1679(28)\times 10^{-5}\ \mathrm{GeV}^{-2}\end{array}\right.$$

Tests Lepton Universality to 0.2%

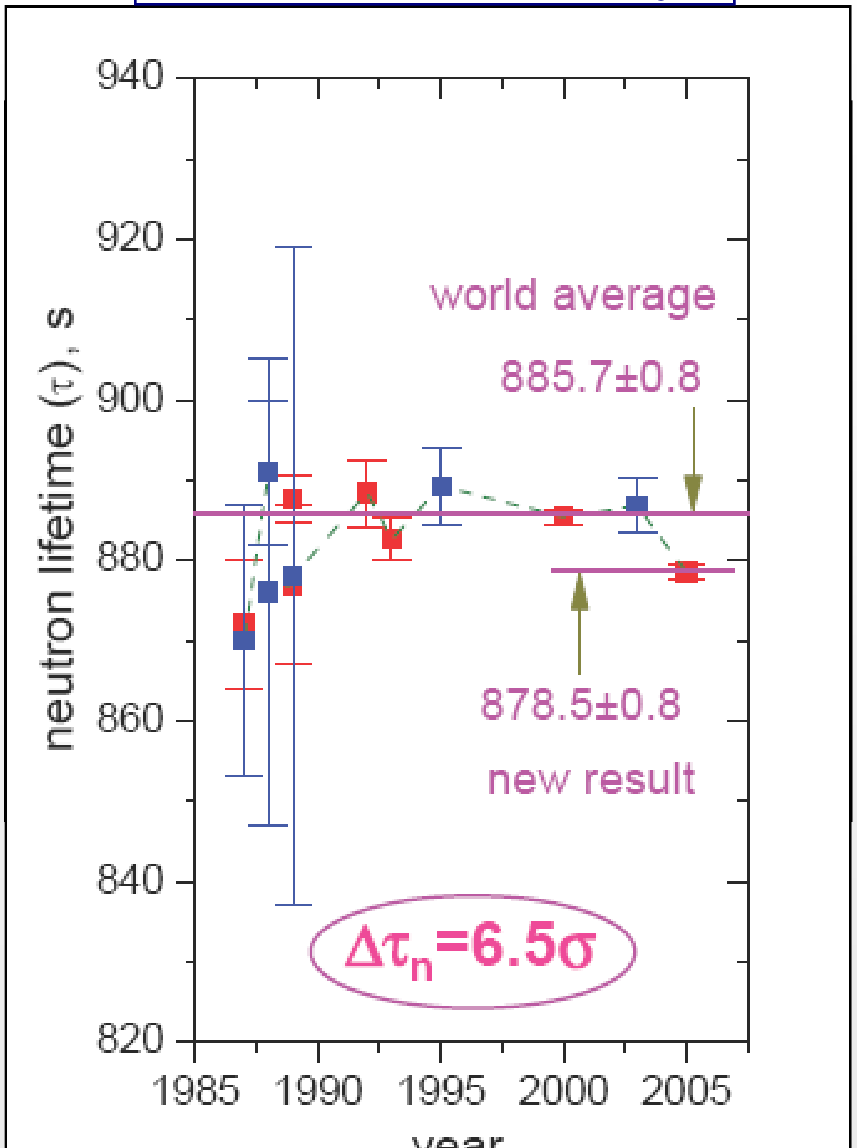
(much more to this study)

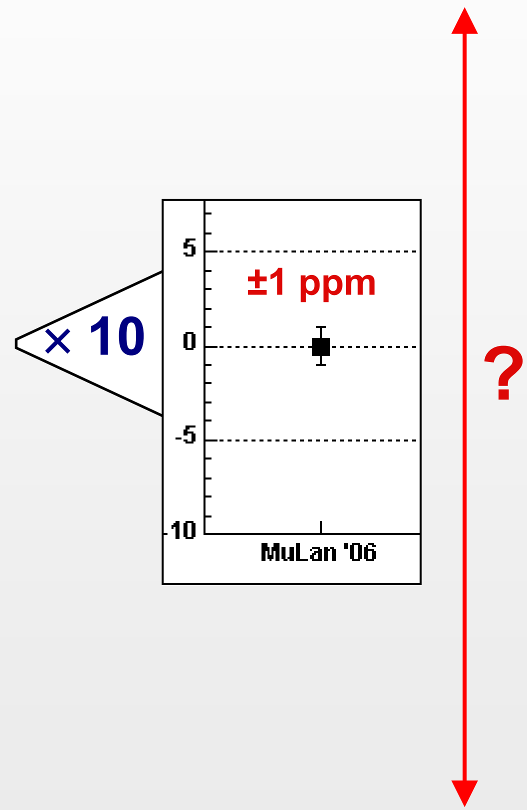
There are even more precise limits at ~10^{-4}

World avg $\delta\tau_\mu/\tau_\mu$ is 18 ppm, but is it right?

Precision
vs
Accuracy

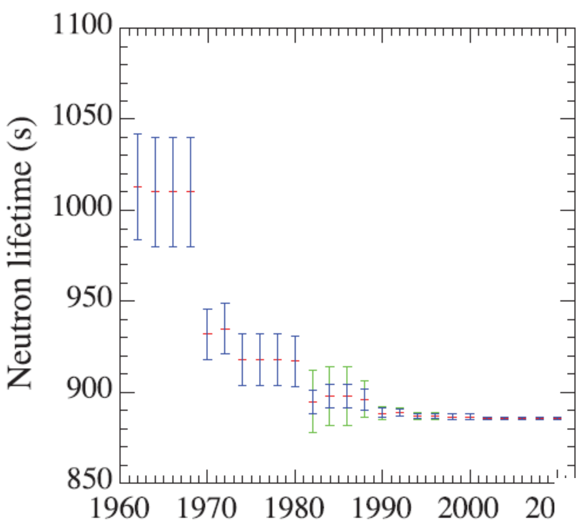
Lessons from History

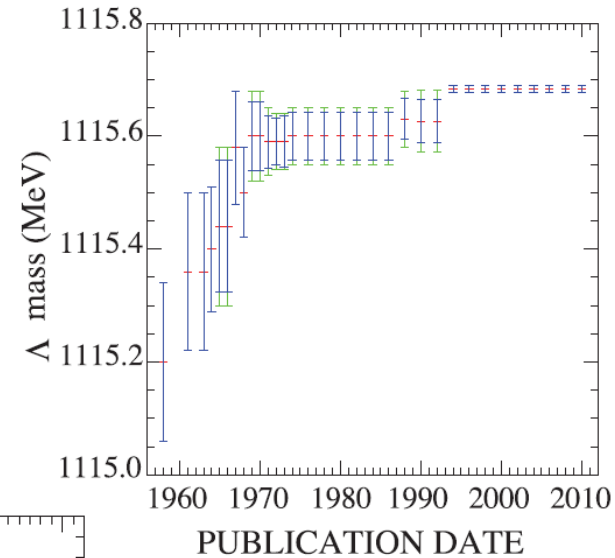


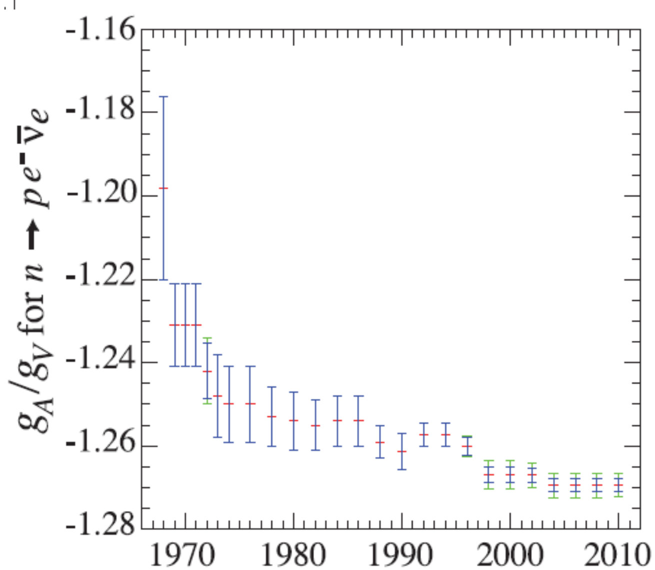


Goal of MuLan is 1 ppm.

ASIDE: Precision measurements have a checkered history. Before common practice was to 'blind*' results tended to have a trend toward an asymptotic value.







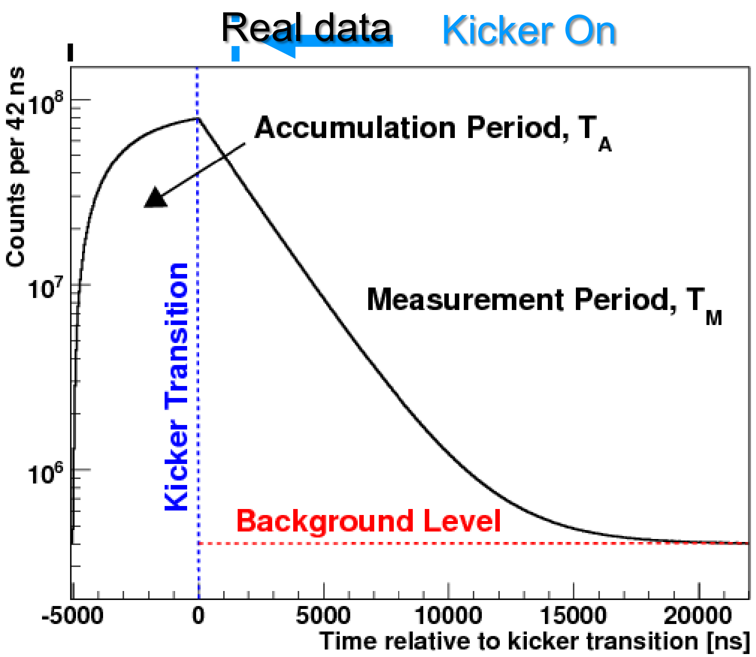
*If you want me to talk about how to blind experiments, just ask …

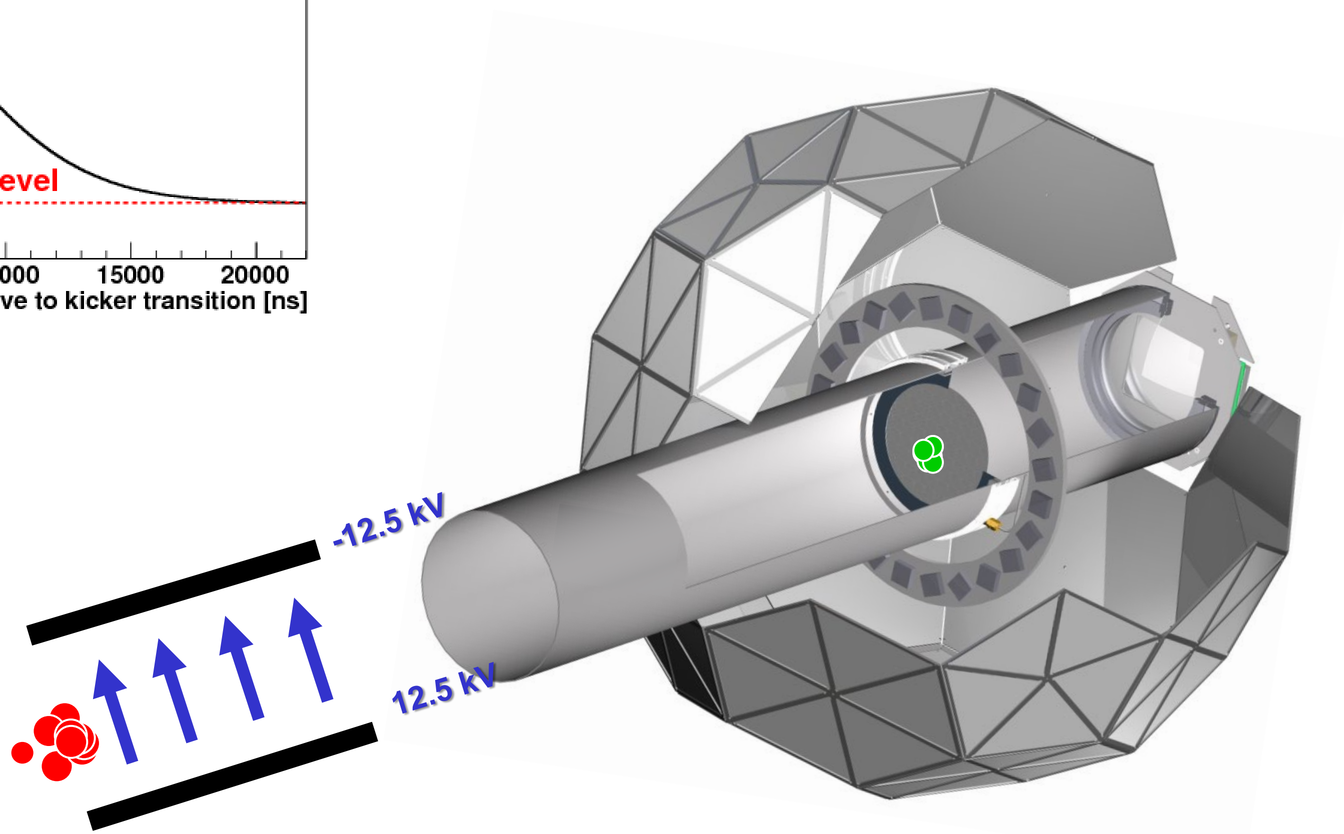
Spoiler Alert

$\tau_{(\mathrm{MuLan})}$ = 2 196 980.3 ± 2.2 ps (1 ppm)

G_F = 1.166 378 7(6) x 10^{-5} GeV^{-2} (0.5 ppm

MuLan measured ~ 2 x 10^{12} decays



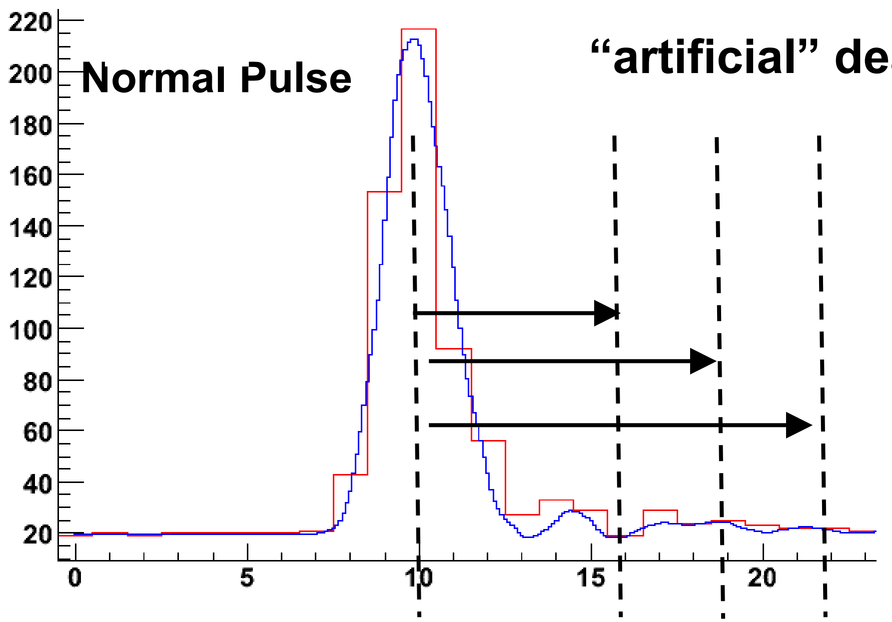


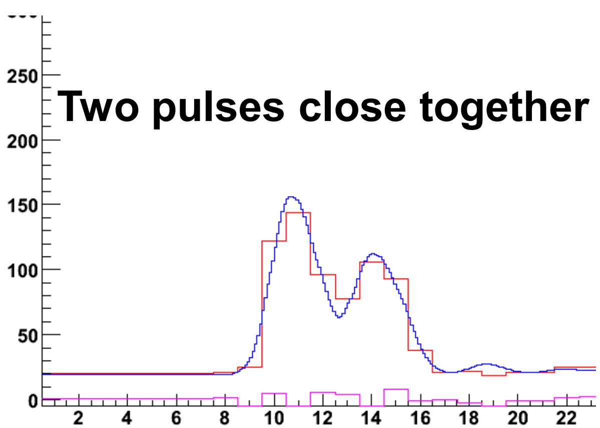
at PSI

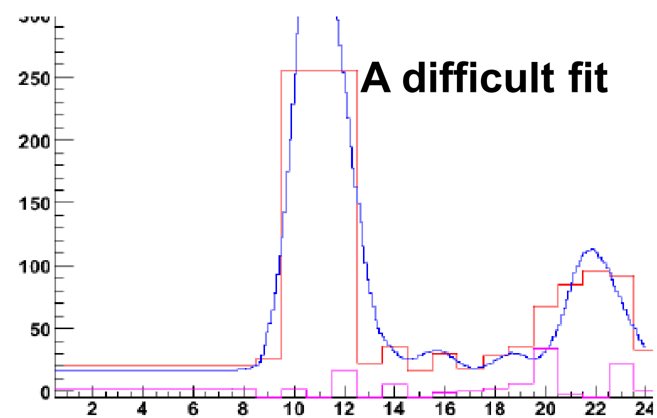
Detector has symmetric design around stops

Modern experiments record the complete waveforms using digitizers. Here, 500 MSPS, 8 bit
“Now” 800 MSPS,12-bit

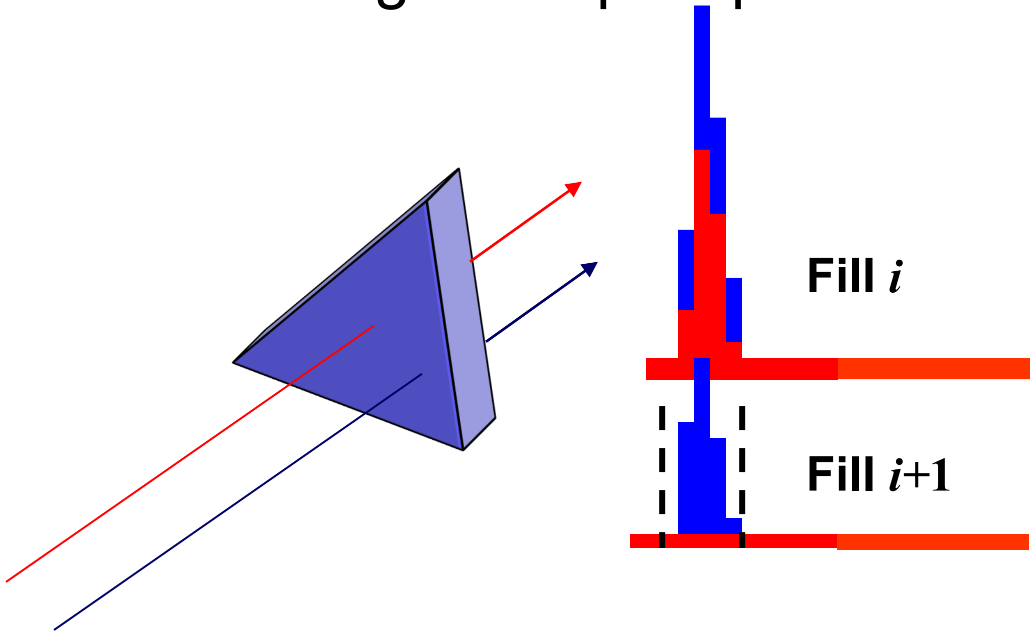
>2 x 10^{12} decays



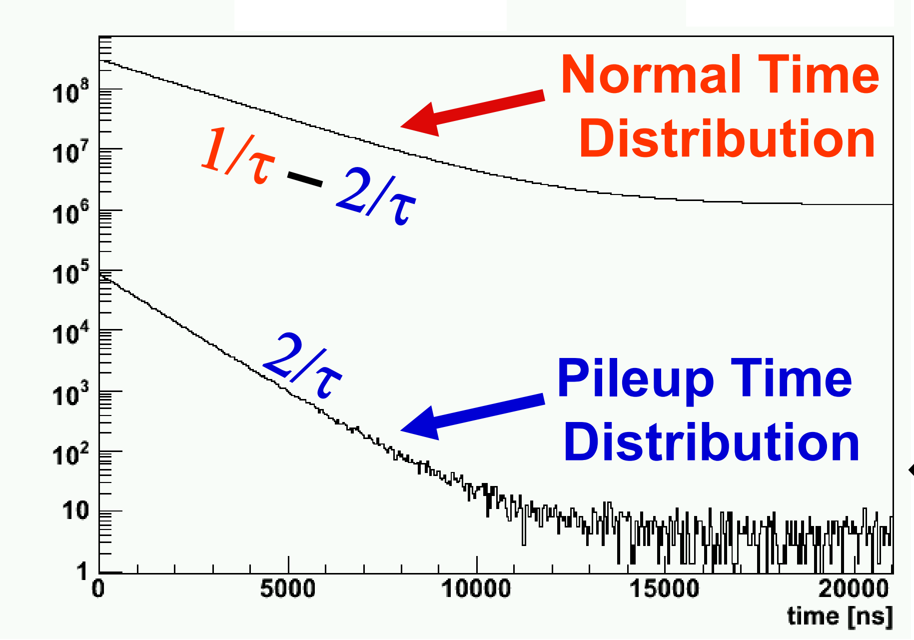




If you count 1 when 2 went through, it's called Pileup
Leading order pileup is a ~5x10^{-4} effect, yet …

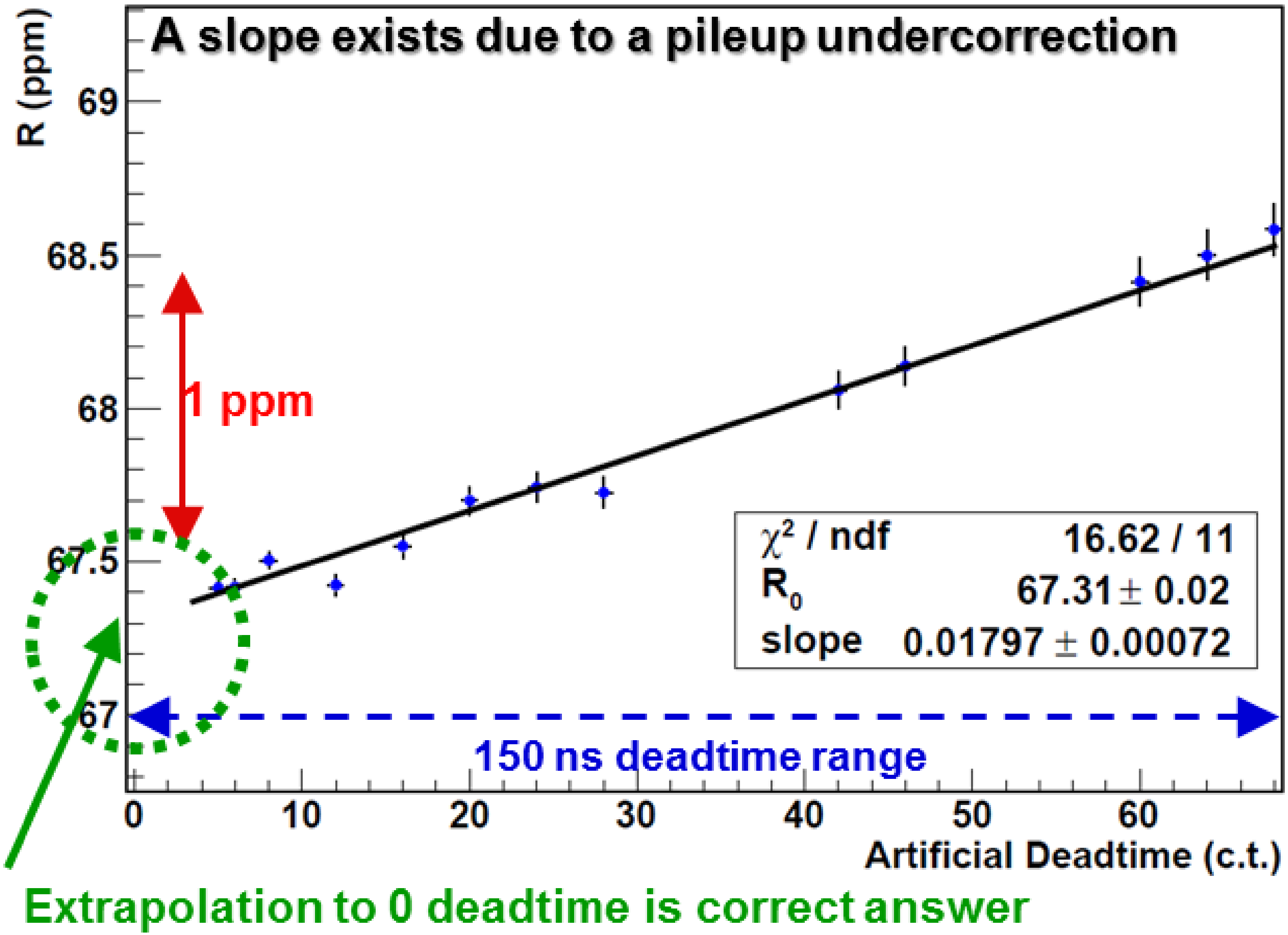


- Statistically reconstruct pileup time distribution
- Fit corrected distribution

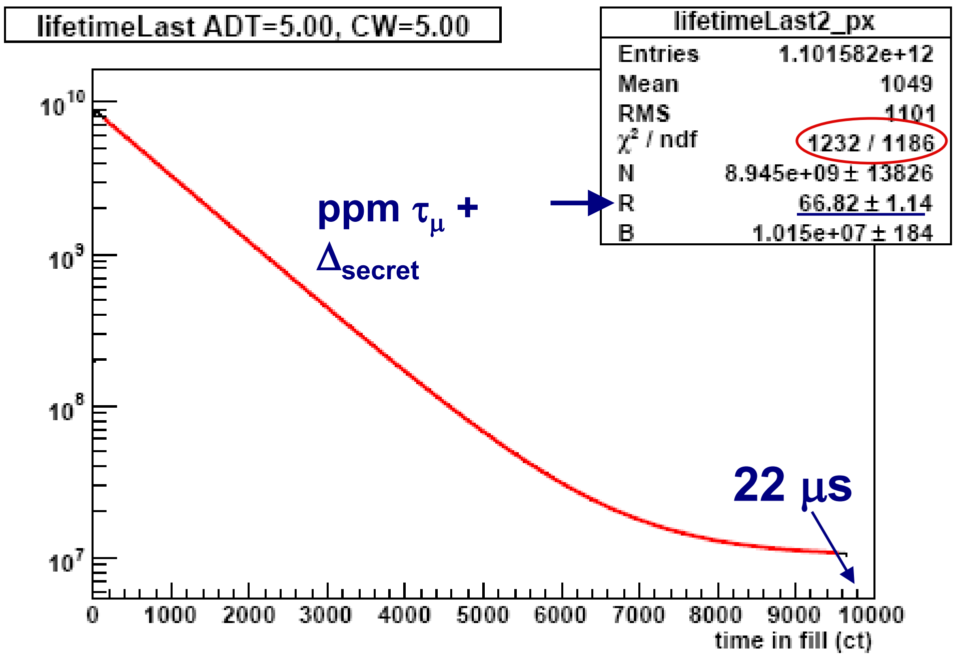


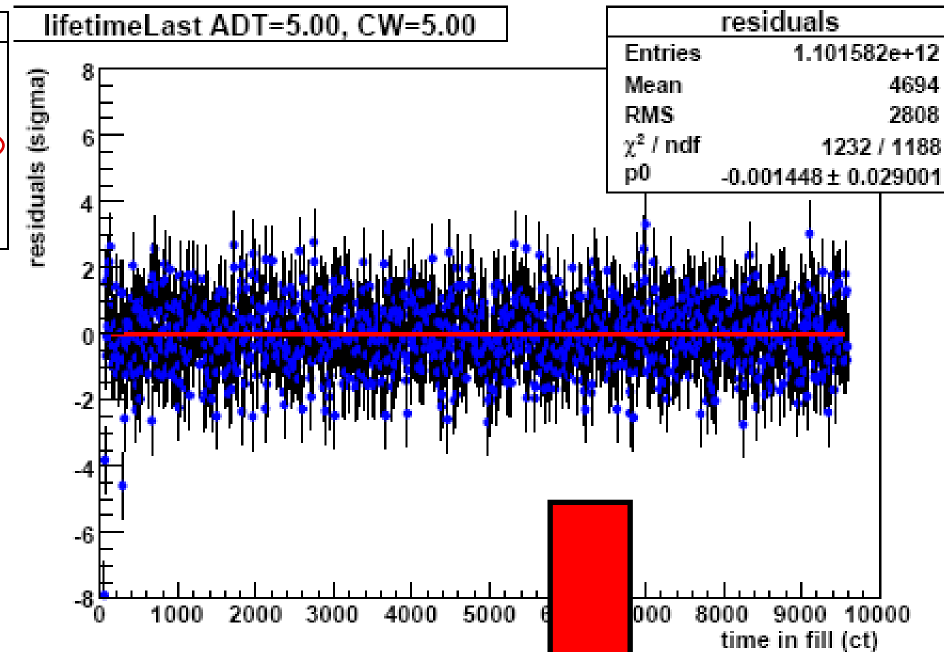
This is only the 1st order effect

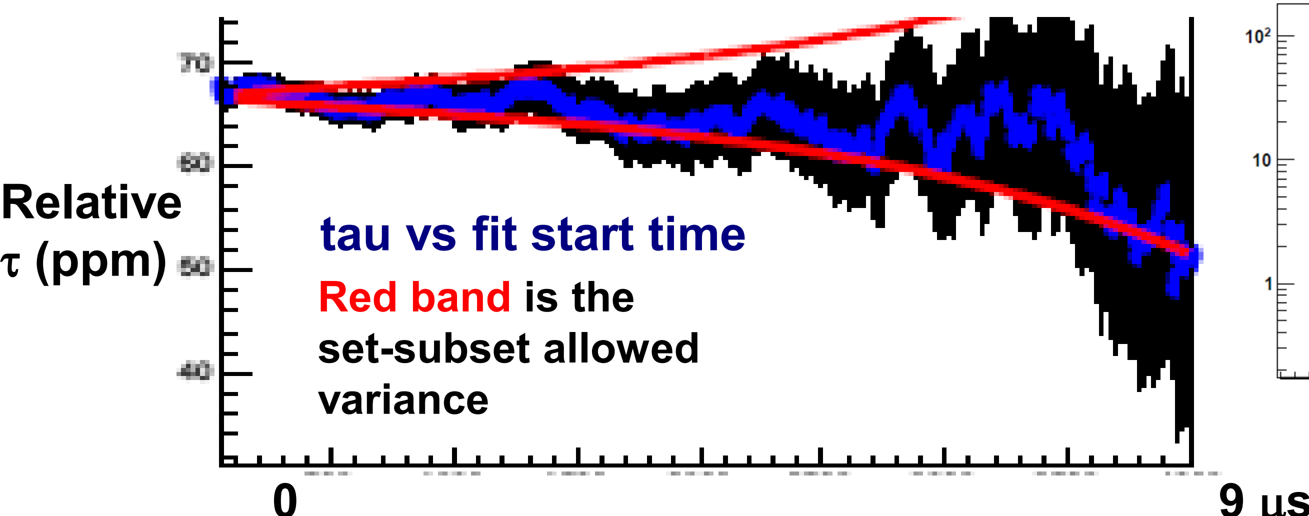
Final deadtime corrected lifetime

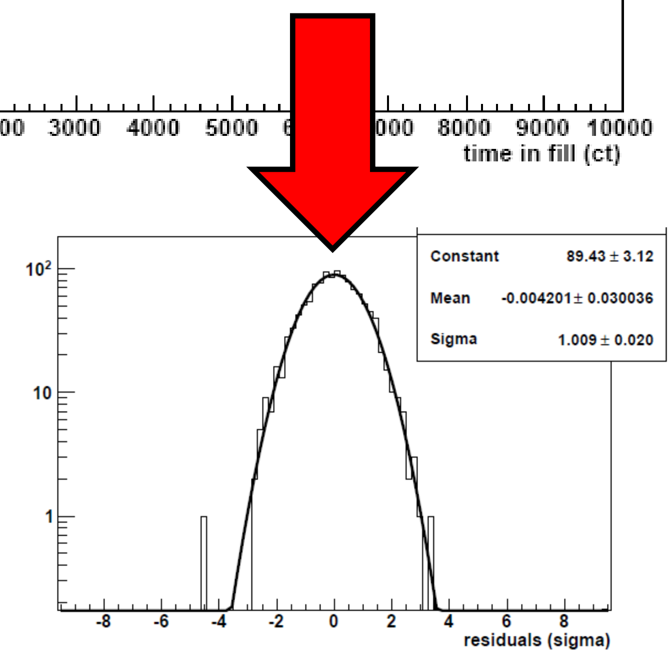


SYSTEMATICs, SYSEMATICs, and many tests



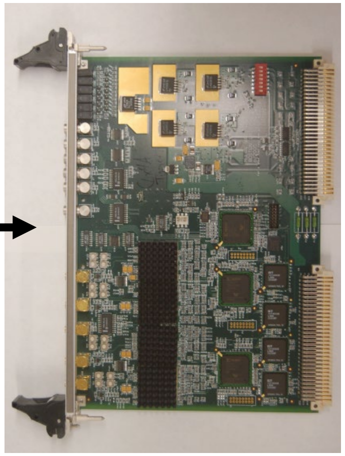






The analysis is double blinded to avoid biasing the results.

Agilent E4400 Function Generator

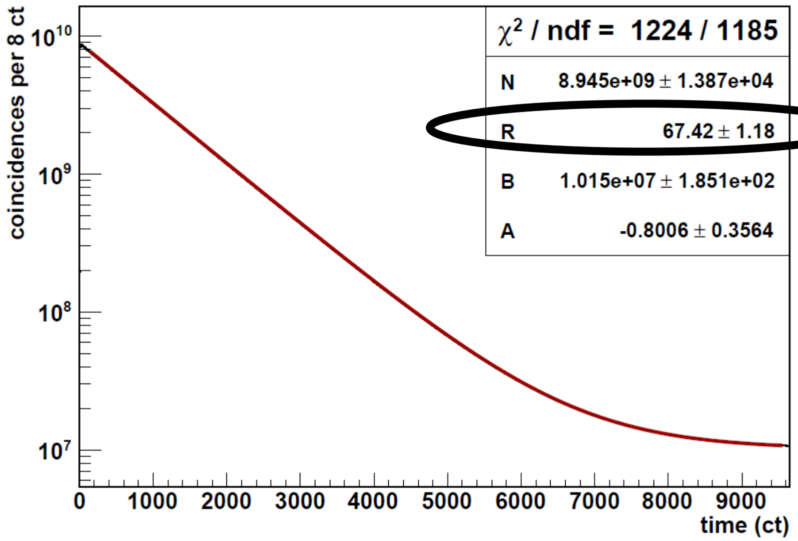


1 ct = 2.217XXX ns

f = 451.0 +/- 0.2 MHz

Input frequency only known to 200 kHz [~ +/- 443 ppm]

Fit results reported in terms of a relative secret reference value

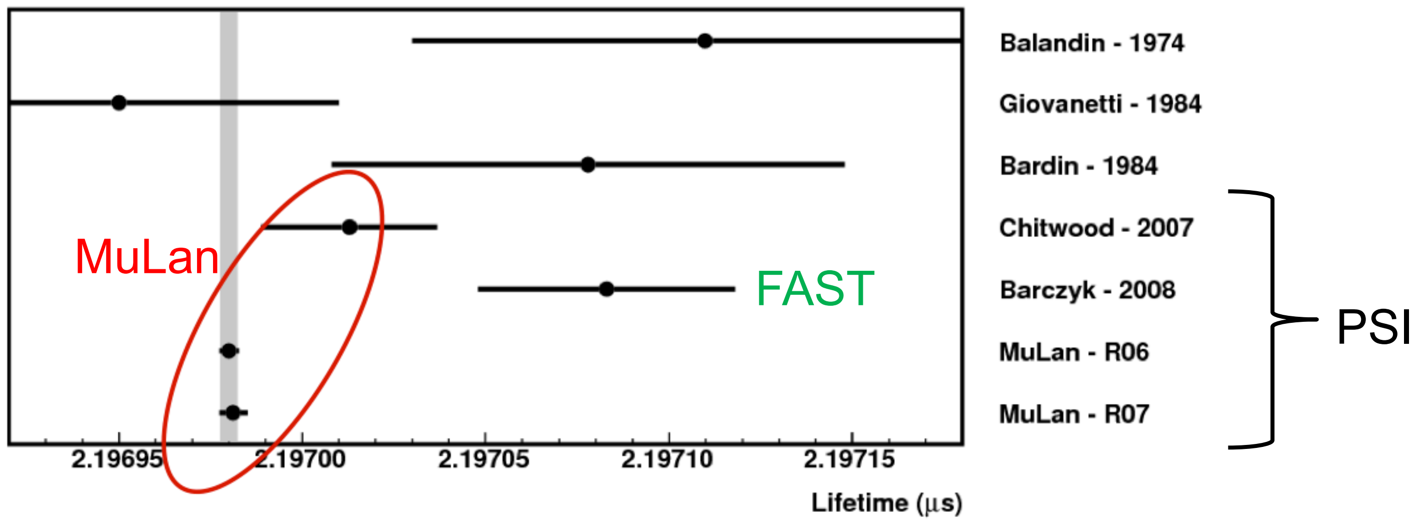


$$R = \frac{\tau - \tau_0}{\tau_0} \times 10^6$$

$\tau_0 =$ XXXX.XXXX ns

ΔR=1 is 1 ppm shift of lifetime

Okay, enough. Unblind it



The most precise particle or nuclear or atomic lifetime ever measured

τ(R06) = 2 196 979.9 ± 2.5 ± 0.9 ps
τ(R07) = 2 196 981.2 ± 3.7 ± 0.9 ps

τ(Combined) = 2 196 980.3 ± 2.2 ps (1.0 ppm)
$\Delta\tau$(R07 – R06) = 1.3 ps

PRL 106, 041803 (2011)
Phys. Rev. D 87, 052003 (**2013**)

From τ_μ to G_F …

$$G_F = \sqrt{\frac{192\pi^3}{\tau_\mu m_\mu^5} \frac{1}{1 + \Delta q^{(0)} + \Delta q^{(1)} + \Delta q^{(2)}}},$$

The determination of G_F in units of GeV^{-2} from the measurement of τ_μ in units of ps requires a unit conversion via Planck's constant, $\hbar$. For Planck's constant, the value recommended by the 2010 CODATA committee [9] of $\hbar = [6.58211928(15) \times 10^{-25}]$ GeV · s is used.

For the muon mass, the recommended value of $m_\mu = [105.6583715(35)]$ MeV [9] is used. This value is derived from the combination of the measurements of the electron mass and the electron-to-muon mass ratio.

Computing the theoretical corrections requires both the electron-to-muon mass ratio m_e/m_μ and the fine structure constant $\alpha(m_\mu)$ at the momentum transfer $q = m_\mu$ of the μ-decay process. The recommended value of $m_e/m_\mu = 4.83633166(12) \times 10^{-3}$ [9] is used. For the fine structure constant $\alpha(m_\mu)$ the value $\alpha(m_\mu) = 1.0/135.902660087(44)$ is used. The value is obtained from Eq. (4.13) of van Ritbergen and Stuart [2] using the CODATA value of the fine structure constant $\alpha(0) = 1.0/137.035999074(44)$ [9] at zero momentum transfer.

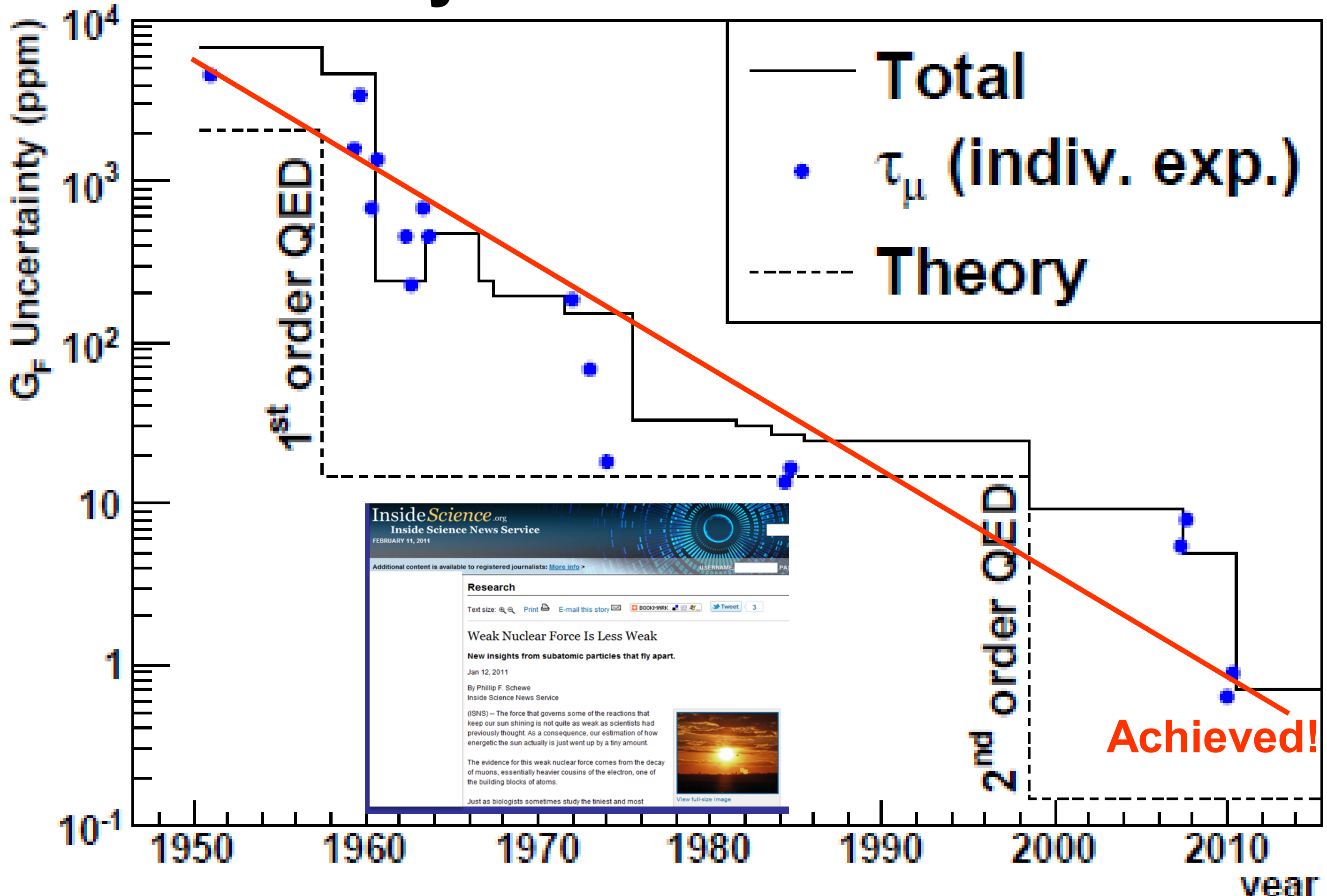
The value for the phase space term $\Delta q^{(0)} = -187.1$ ppm is obtained from Eq. (2.7) in Ref. [2] and the value for the one-loop QED correction $\Delta q^{(1)} = -4233.7$ ppm is obtained from Eq. (2.8) in Ref. [2]. Note that Eq. (2.8) of Ref. [2] incorporates the effects of the nonzero electron mass on the one-loop QED correction.[21]

The value for the two-loop QED correction $\Delta q^{(2)} = +36.3$ ppm is obtained by summing the individual contributions from purely-photonic loops [Eq. (9) in Ref. [3]], electron loops [Eq. (10) in Ref. [3]], muon loops [Eq. (19) in Ref. [4]], tau loops [Eq. (20) in Ref. [4]], and hadronic loops [Eq. (16) in Ref. [4]]. Additionally, a correction of -0.4 ppm, first evaluated by Pak and Czarnecki [8], is included to account for the effects of the nonzero electron mass on the two-loop QED correction.

Using Eq. (23) and the aforementioned values for the τ_μ, m_μ, and the theoretical corrections $\Delta q^{(0)}$, $\Delta q^{(1)}$, and $\Delta q^{(2)}$, we obtain

$$G_F(\mathrm{MuLan}) = [1.1663787(6) \times 10^{-5}]\ \mathrm{GeV}^{-2}\ (0.5\ \mathrm{ppm}).$$

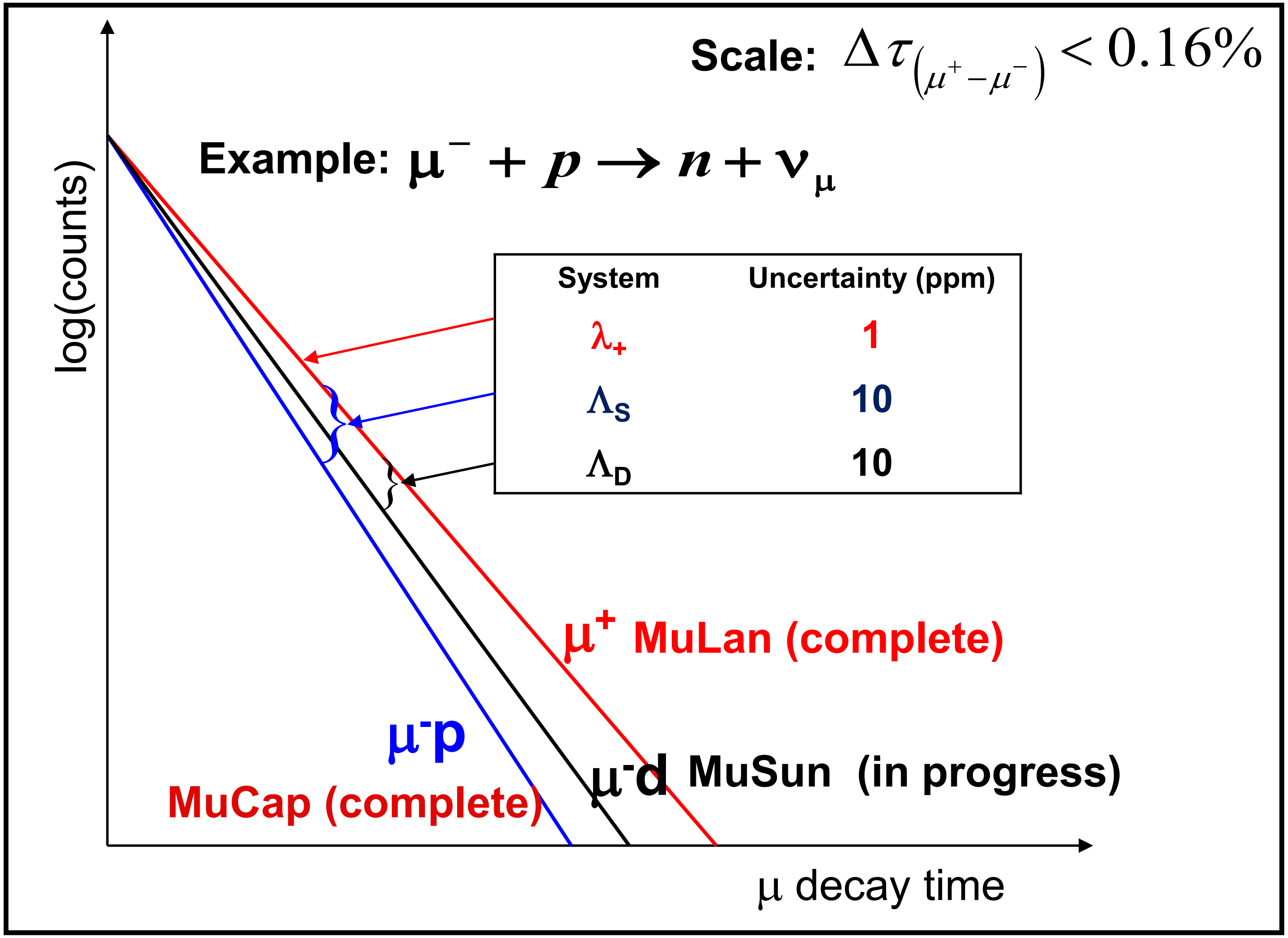
G_F & τ_μ precision has improved by ~4 orders of magnitude over 60 years.



Measurement of the Positive Muon Lifetime and Determination of the Fermi Constant to Part-per-Million Precision

D.M. Webber,[1] V. Tishchenko,[2] Q. Peng,[3] S. Battu,[2] R.M. Carey,[3] D.B. Chitwood,[1] J. Crnkovic,[1] P.T. Debevec,[1] S. Dhamija,[2] W. Earle,[3] A. Gafarov,[3] K. Giovanetti,[4] T.P. Gorringe,[2] F.E. Gray,[5] Z. Hartwig,[3] D.W. Hertzog,[1] B. Johnson,[6] P. Kammel,[1] B. Kiburg,[1] S. Kizilgul,[1] J. Kunkle,[1] B. Lauss,[7] I. Logashenko,[3] K.R. Lynch,[3] R. McNabb,[1] J.P. Miller,[3] F. Mulhauser,[1,7] C.J.G. Onderwater,[1,8] J. Phillips,[3] S. Rath,[2] B.L. Roberts,[3] P. Winter,[1] and B. Wolfe[1]
(MuLan Collaboration)

The 1 ppm μ^+ lifetime is compared to the μ^- lifetime in gaseous p or d targets to determine the capture rate



System	Uncertainty (ppm)
λ_+	1
Λ_S	10
Λ_D	10

$$\frac{1}{\tau} = \Lambda_{total} = \Lambda_{decay} + \Lambda_{capture}$$

Extract physics here

The singlet muon capture Λ_S on the proton is sensitive to axial nucleon structure

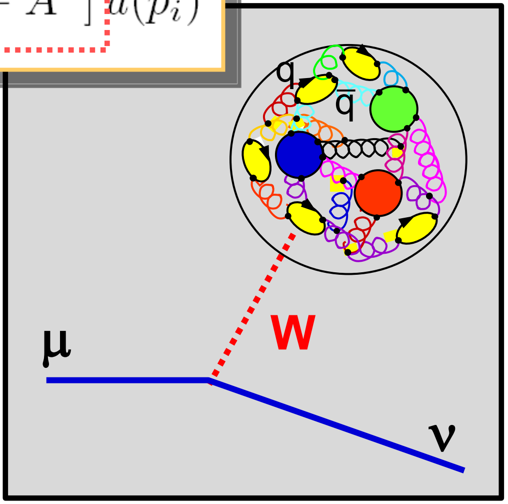
Λ_S

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

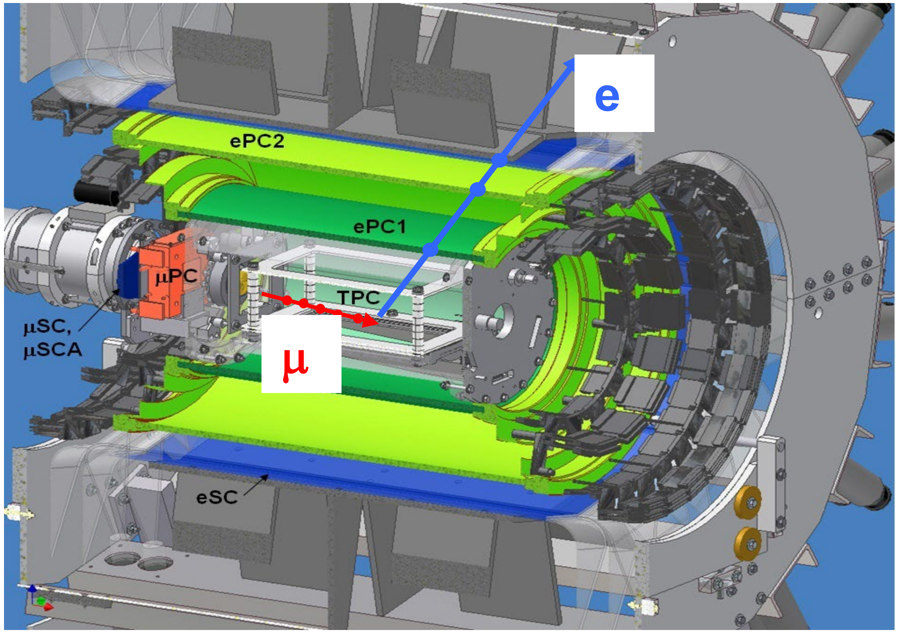
$$V_\alpha = g_V(q^2)\,\gamma_\alpha + \frac{i\,g_M(q^2)}{2\,M_N}\,\sigma_{\alpha\beta}\,q^\beta$$

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

$$\frac{\Delta\Lambda_S}{\Lambda_S} = 1\% \quad \Rightarrow \quad \frac{\Delta g_P}{g_P} \approx 6.1\%$$



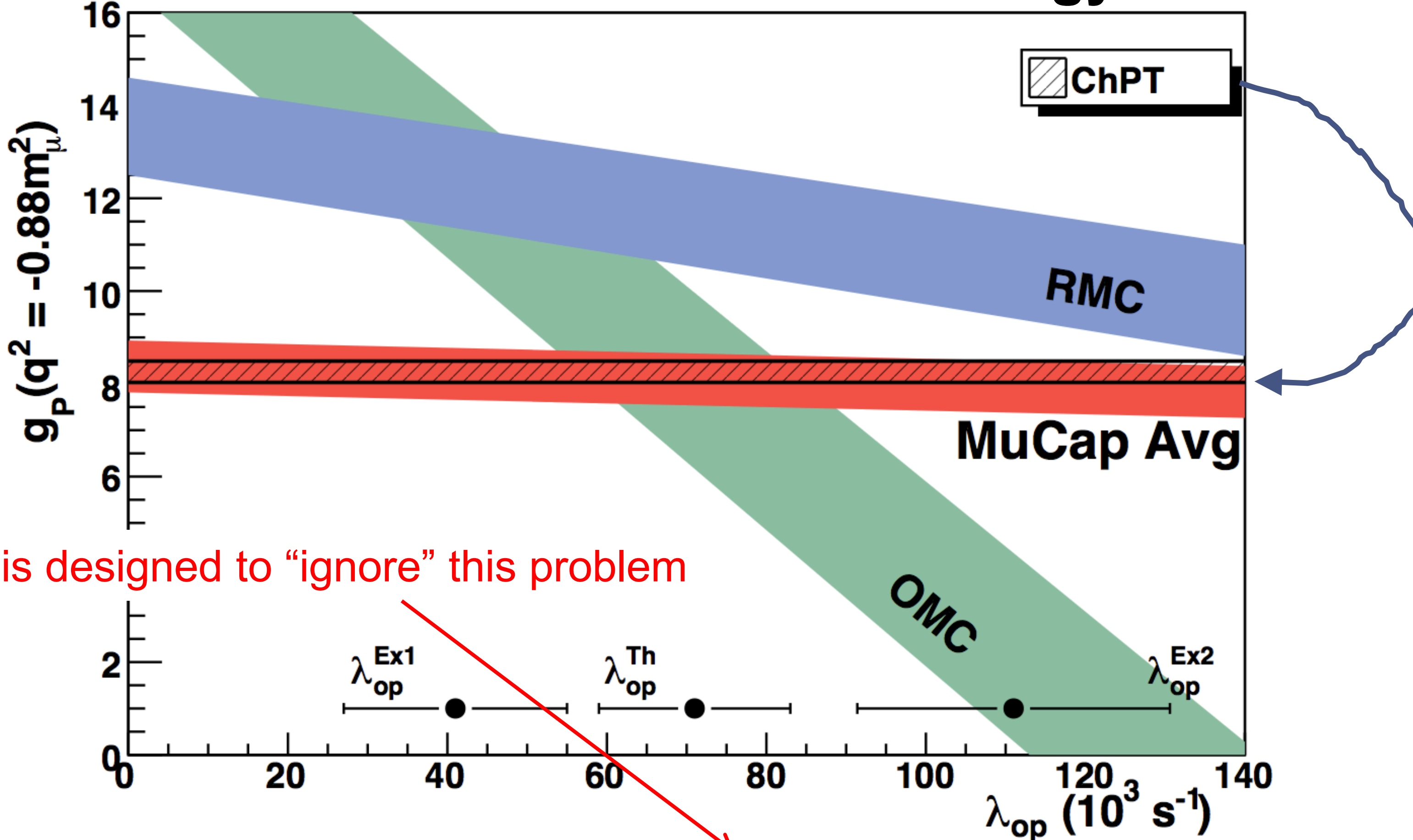
Technique: Precision lifetime measurement in an ultra-pure hydrogen time projection chamber



1st Precise and Unambiguous Result

Verifies Basic Prediction of Low-Energy QCD

Physics Axis



MuCap is designed to “ignore” this problem

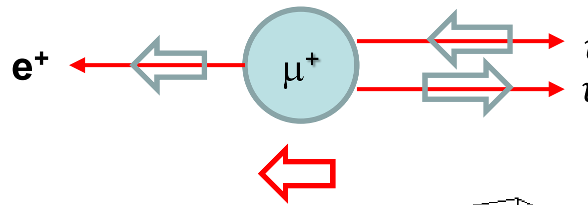
Horizontal axis represents some not-well-known Mu-Molecular physics

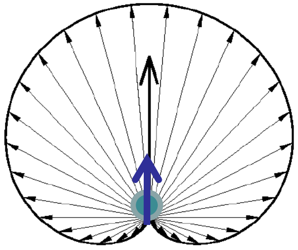
Why do we say the result is Unambiguous ?

Phys.Rev.Lett. 110 (2013) 012504

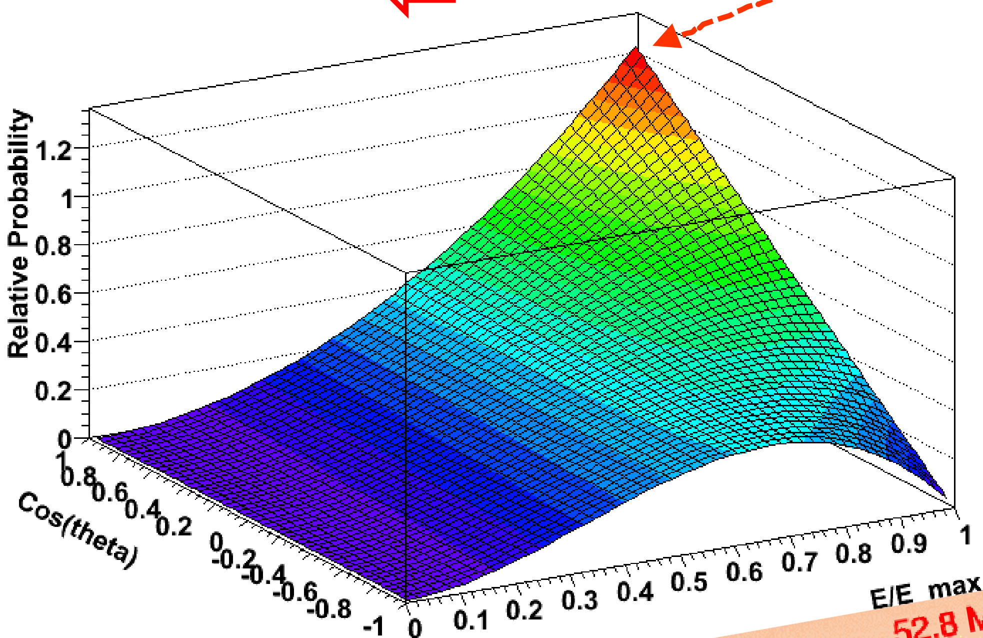
The Structure of the Weak Interaction
Is it *really* only V-A ? (no tensor, scaler terms …)

Primary decay $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

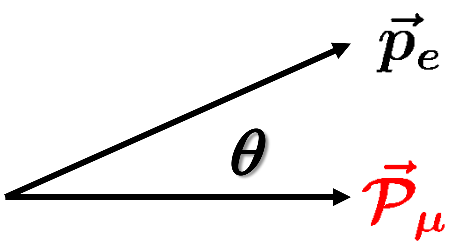


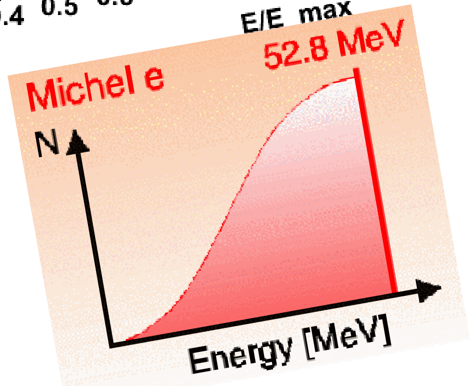


$$1 + a\cos\theta$$



Angle with respect to (positive) muon spin





Final results from *TWIST* measurement of muon decay parameters

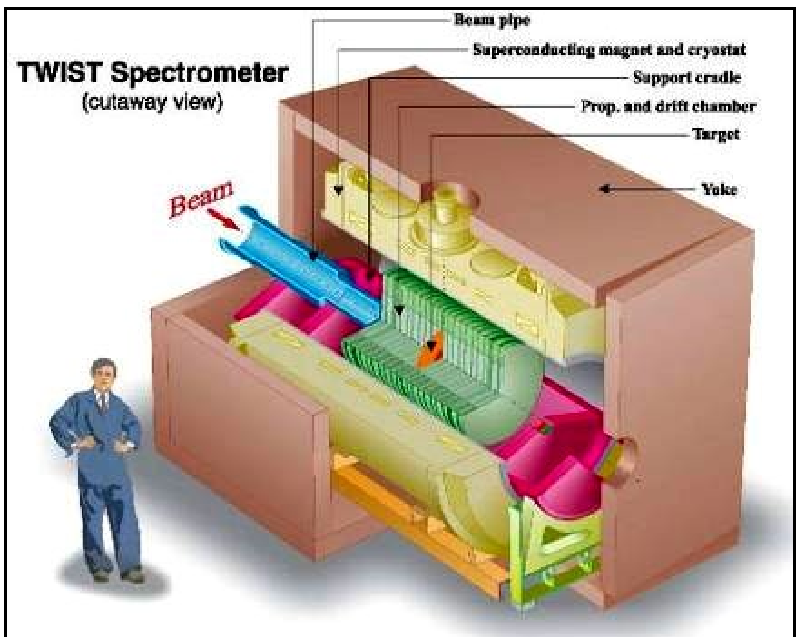
Is muon decay purely V-A?

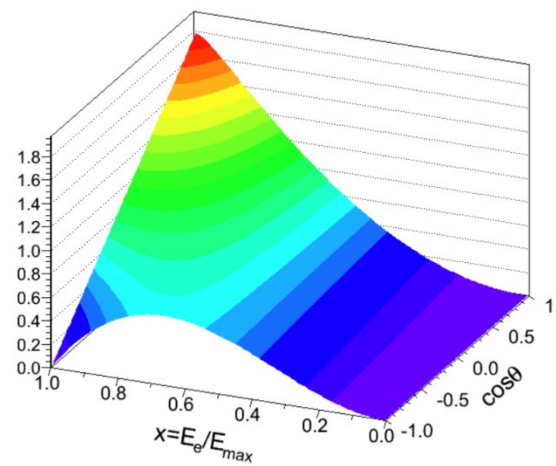
Sensitive to attractive SM extensions:

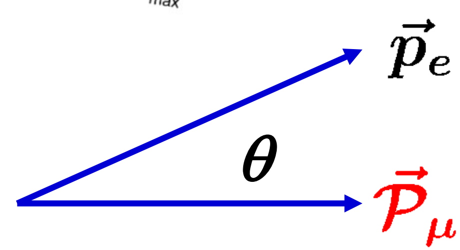
L-R symmetric models, which would permit a W_R

Basic idea:

Measure the energy and angular distribution of e^+ from $\mu^+ \rightarrow e^+ \nu_e \nu_\mu$ and compare to Monte Carlo expectations







Even more generally: Muon decay spectrum in greater detail: TWIST experiment

$$\frac{d^2\Gamma}{x^2 dx d(\cos\theta)} \propto (3-3x) + \frac{2}{3}\rho(4x-3) + 3\eta\frac{x_0}{x}(1-x)$$

$$+ P_\mu \xi \cos\theta \left[(1-x) + \frac{2}{3}\delta(4x-3) \right]$$

where $x = \dfrac{E_e}{E_{e,\max}}$

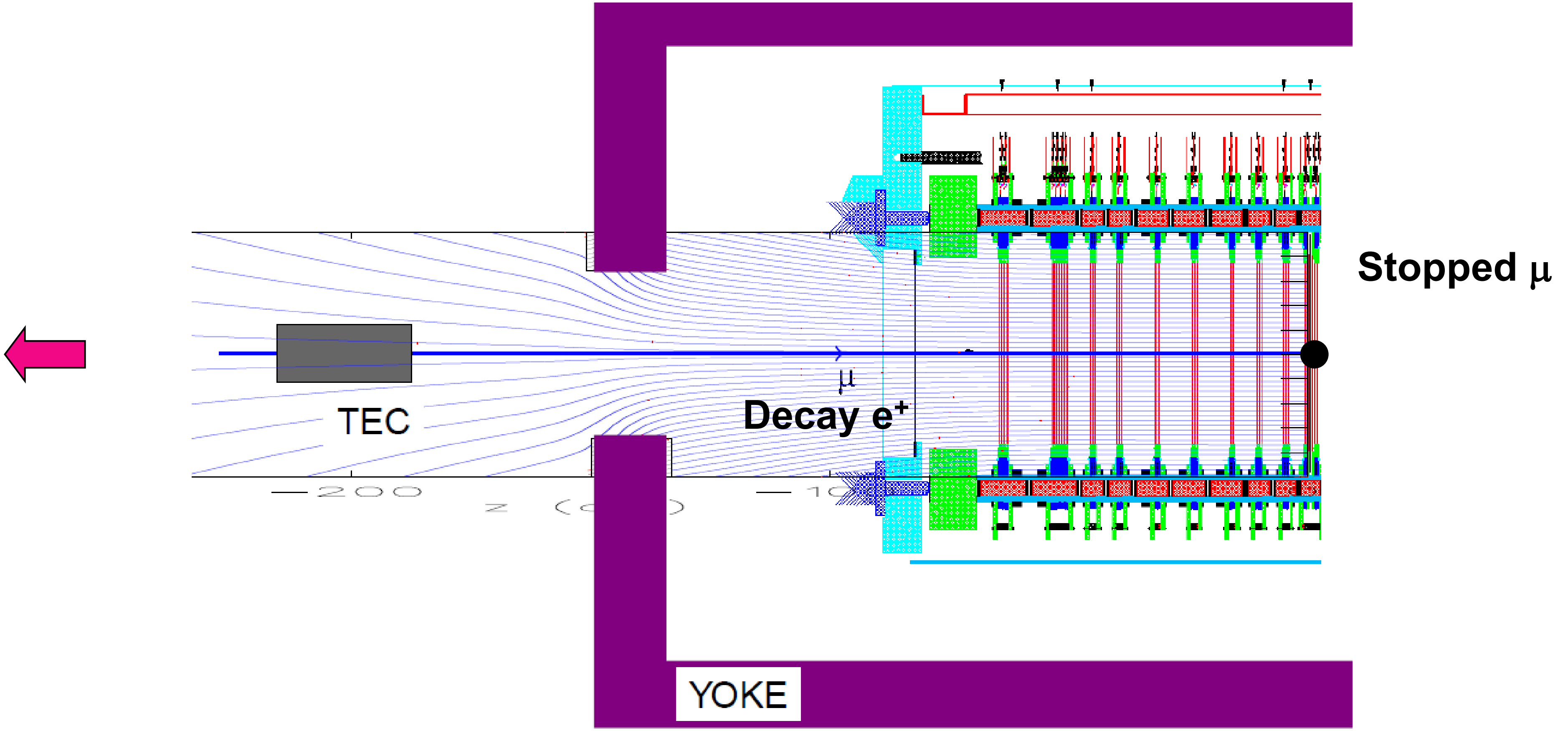
		SM
ρ	= 0.7518 ± 0.0026	3/4
η	= -0.007 ± 0.013	0
$P_\mu\xi$	= 1.0027 ± 0.0079 ± 0.0030	1
δ	= 0.7486 ± 0.0026 ± 0.0028	3/4
$P_\mu(\xi\delta/\rho)$	> 0.99682 (90% c.l.)	1

The formalism, "Michel" parameters

- Muon decay parameters ρ, η, $\mathcal{P}_\mu \xi$, δ
- Differential decay rate *vs.* energy and angle:

$$\frac{d^2\Gamma}{dx\ d\cos\theta} = \frac{1}{4} m_\mu W_{\mu e}^4 G_F^2 \sqrt{x^2 - x_0^2} \cdot$$

$$\{\mathcal{F}_{IS}(x, \rho, \eta) + \mathcal{P}_\mu \cos\theta \cdot \mathcal{F}_{AS}(x, \xi, \delta)\} + R.C.$$

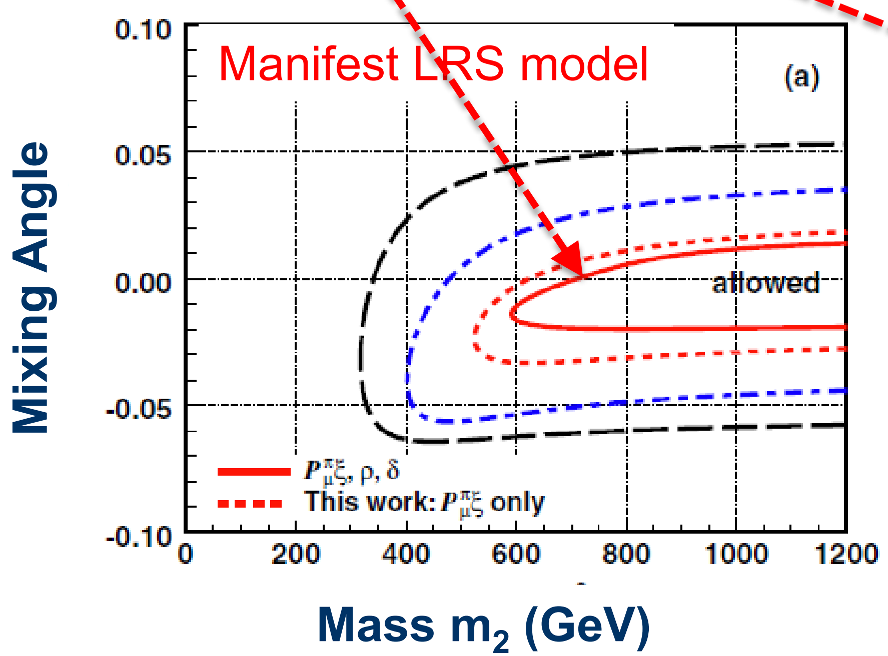


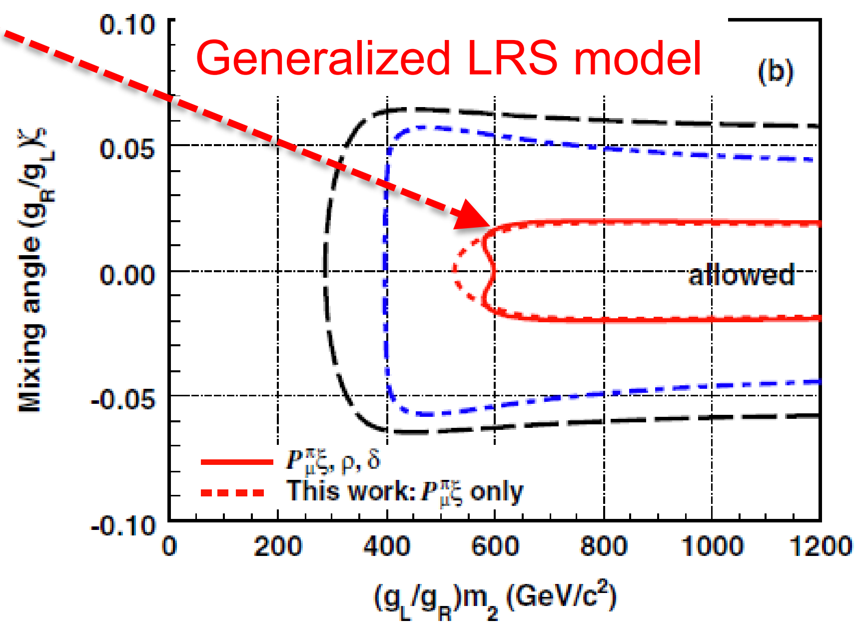
Michel Parameters: TWIST final results

"SM still okay"

SM	
3/4	ρ = 0.74977 ± 0.00012 (stat) ± 0.00023 (syst)
3/4	δ = 0.75049 ± 0.00021 (stat) ± 0.00027 (syst)
1	$\mathcal{P}_\mu^\pi \xi$ = 1.00084 ± 0.00029 (stat) $^{+0.00165}_{-0.00063}$ (syst)

Results mostly constrain right-handed muon terms





PHYSICAL REVIEW D **84**, 032005 (2011)

Phys. Rev. D 85, 092013 (2012)

Topic 3

Parity Violation, the Weak Interaction, & neutrons

Progress in Particle and Nuclear Physics 71 (2013) 93–118

Contents lists available at SciVerse ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

ELSEVIER

Review

Beta decays and non-standard interactions in the LHC era

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[b] Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506-0055, USA

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The Neutron as a Fundamental Laboratory

Neutron beta decay

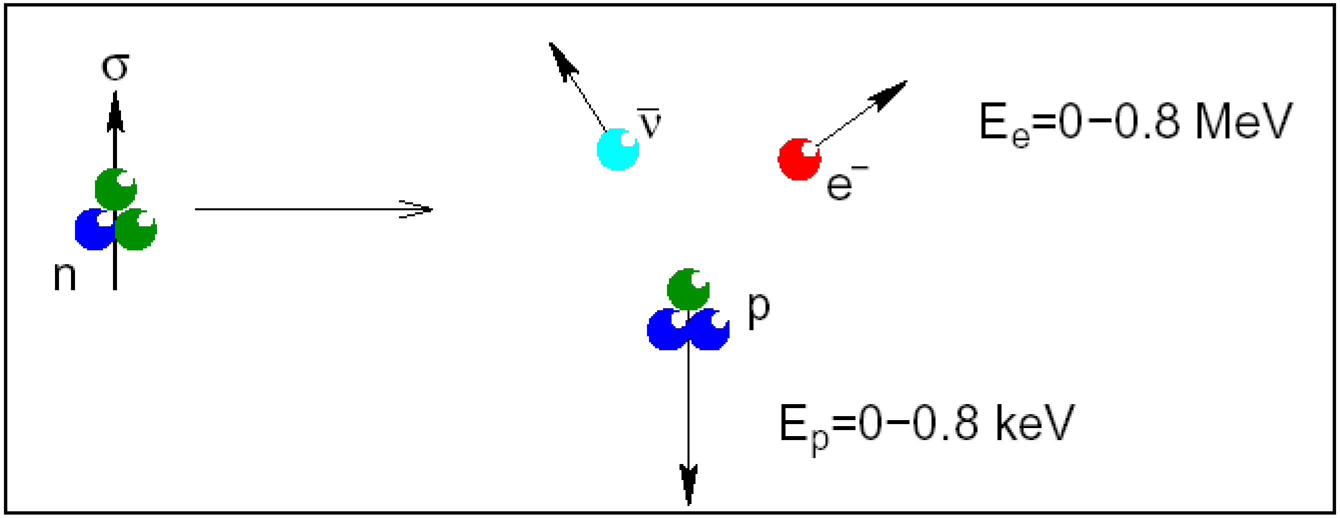
$n \rightarrow p^+ + e^- + \nu'_e$

neutron lifetime $\tau \approx 15$ min

β-endpoint energy: $E_{max} = 782$ keV

Only 3 parameters needed: V_{ud}, λ, ϕ

- CKM matrix element V_{ud},
- ratio of c.c. $\lambda = g_A/g_V = |\lambda| e^{i\varphi}$
- relative phase φ
  (T-symmetry: $\varphi = 180^0$)



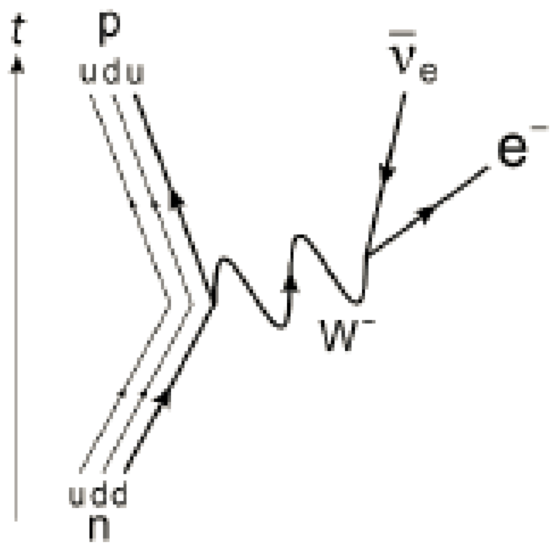
Dynamics and observables

Basic beta decay Lagrangian for a baryon

$$\mathcal{L}_W(x) = -\frac{G_F}{\sqrt{2}} V_{ud} \left[\bar{\psi}_p(x)\gamma_\mu(1+\lambda\gamma^5)\psi_n(x)\right] \left[\bar{\psi}_e(x)\gamma_\mu(1+\gamma^5)\psi_\nu(x)\right]$$

$$= -\frac{1}{\sqrt{2}} \left[\bar{\psi}_p(x)\gamma_\mu(g_V+g_A\gamma^5)\psi_n(x)\right] \left[\bar{\psi}_e(x)\gamma_\mu(1+\gamma^5)\psi_\nu(x)\right]$$

where $\boxed{g_v = G_F V_{ud} = G_F G_V}$ and $\boxed{g_A = G_F V_{ud}\lambda = G_F G_A}$.



$G_F \simeq 1.1664 \times 10^{-11}\,\mathrm{MeV}^{-2}$ (for our purposes, infinitely well determined in μ decay)

$\lambda \simeq -1.272$ (from correlations in n decay)

Rate of neutron decay/lifetime is given by:

$$\Gamma = \frac{1}{\tau_n} = (1+3\lambda^2)\frac{G_F^2 V_{ud}^2}{2\pi^3} f_{\mathrm{Fermi}}^{Z=1}(E_{\max})$$

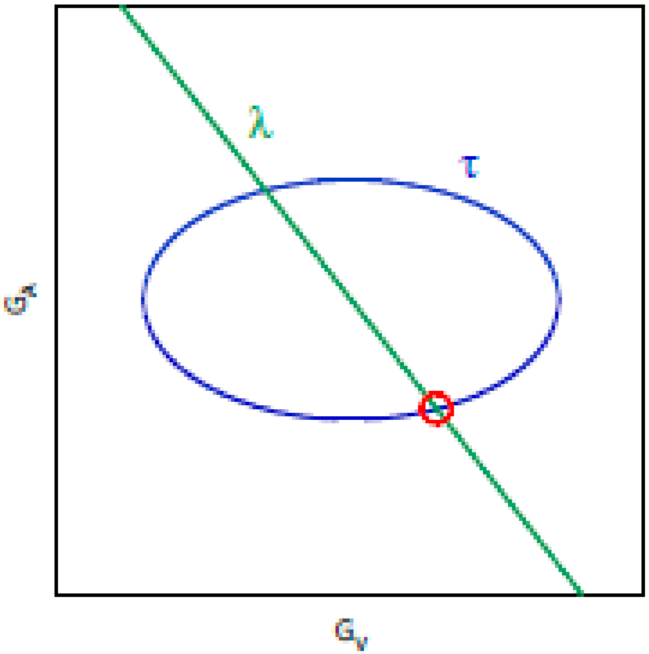
Slides: D. Pocanic

Extracting V_{ud} from *n* decay

Evaluating the preceding relation we get:

$$|V_{ud}|^2 = \frac{4908.7(1.9)\,\mathrm{sec}}{\tau_n(1+3\lambda^2)}, \text{ or}$$

$$\tau_n^{-1} = \mathrm{const.}(G_V^2 + 3G_A^2)$$



We therefore need to measure:

- neutron lifetime τ_n (counting neutrons)
- ratio $\lambda = G_A/G_V$ (decay correlations)

Key questions:

- How thick (uncertain) are the τ_n ellipse and the λ line?
- How reliable and consistent are the results from different methods of τ_n and λ evaluation?

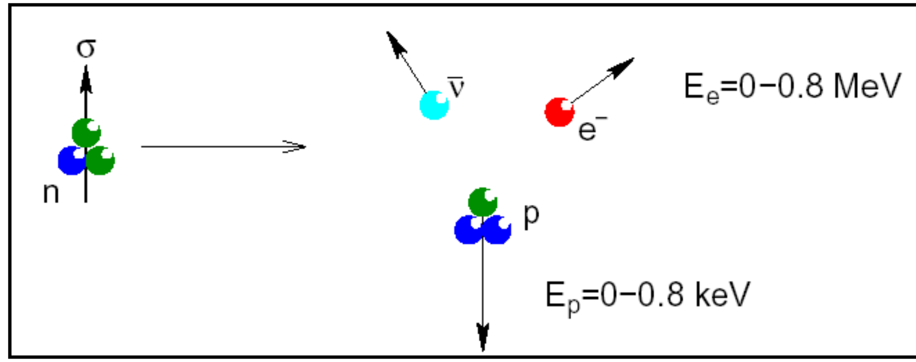
Slides: D. Pocanic

Richness in the Neutron Decay Distribution

$n \rightarrow p^+ + e^- + \nu'_e$

neutron lifetime $\tau \approx 15$ min

β-endpoint energy: $E_{max} = 782$ keV



$$dW \propto \frac{1}{\tau_n} F(E_e)\left[1 + a\frac{\boldsymbol{p}_e \cdot \boldsymbol{p}_\upsilon}{E_e \cdot E_\upsilon} + b\frac{m_e}{E_e} + A\frac{\sigma_n \cdot \boldsymbol{p}_e}{E_e} + B\frac{\sigma_n \cdot \boldsymbol{p}_\upsilon}{E_\upsilon}\right]$$

$$\tau_n \propto 1/(g_A^2 + 3g_V^2)$$

$$a = \frac{1 - \left(\frac{g_A}{g_V}\right)^2}{1 - 3\left(\frac{g_A}{g_V}\right)^2}$$

$$b = 0$$

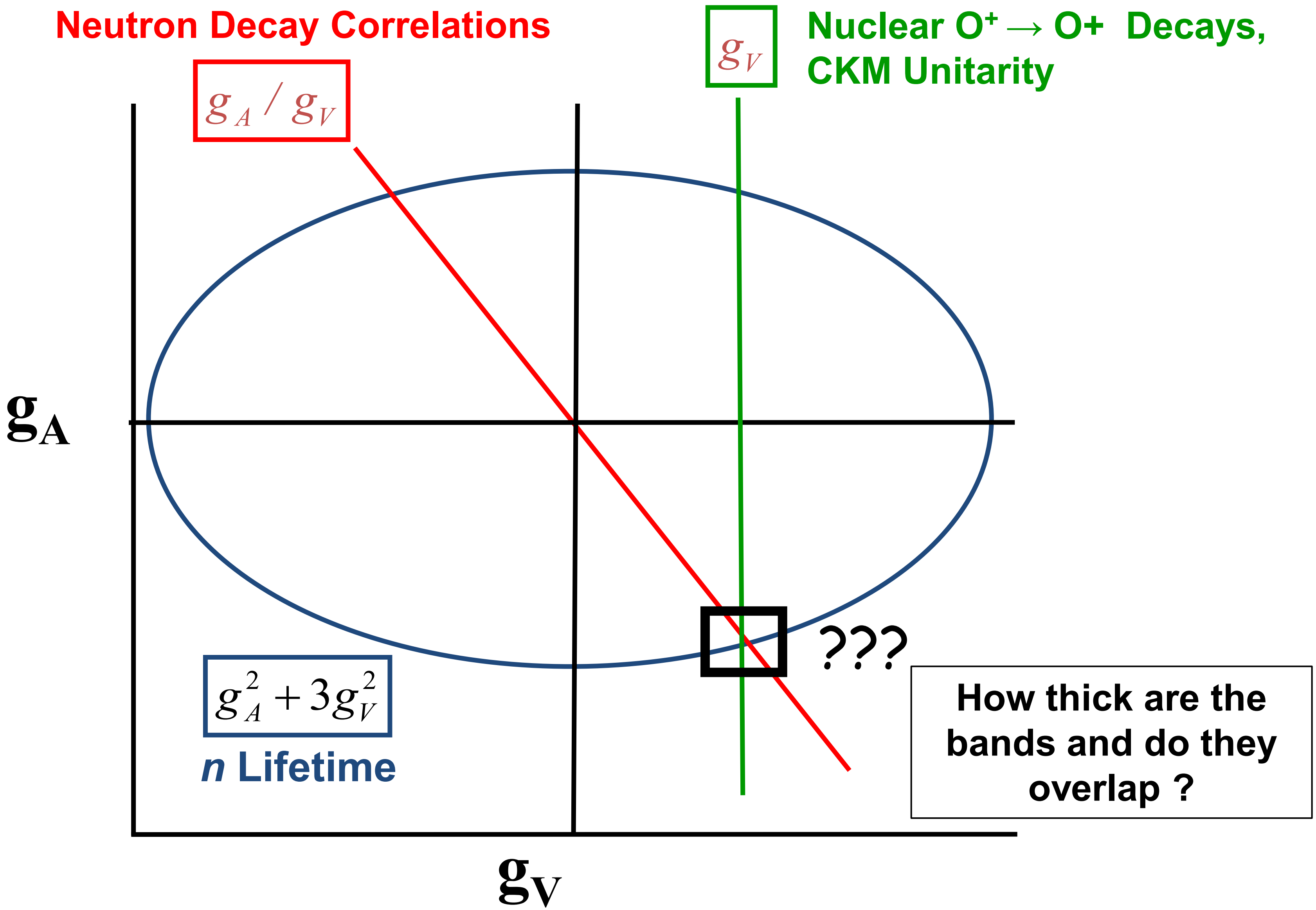
$$A = -2\frac{\left(\frac{g_A}{g_V}\right)^2 + \left(\frac{g_A}{g_V}\right)}{1 - 3\left(\frac{g_A}{g_V}\right)^2}$$

$$B = 2\frac{\left(\frac{g_A}{g_V}\right)^2 - \left(\frac{g_A}{g_V}\right)}{1 + 3\left(\frac{g_A}{g_V}\right)^2}$$

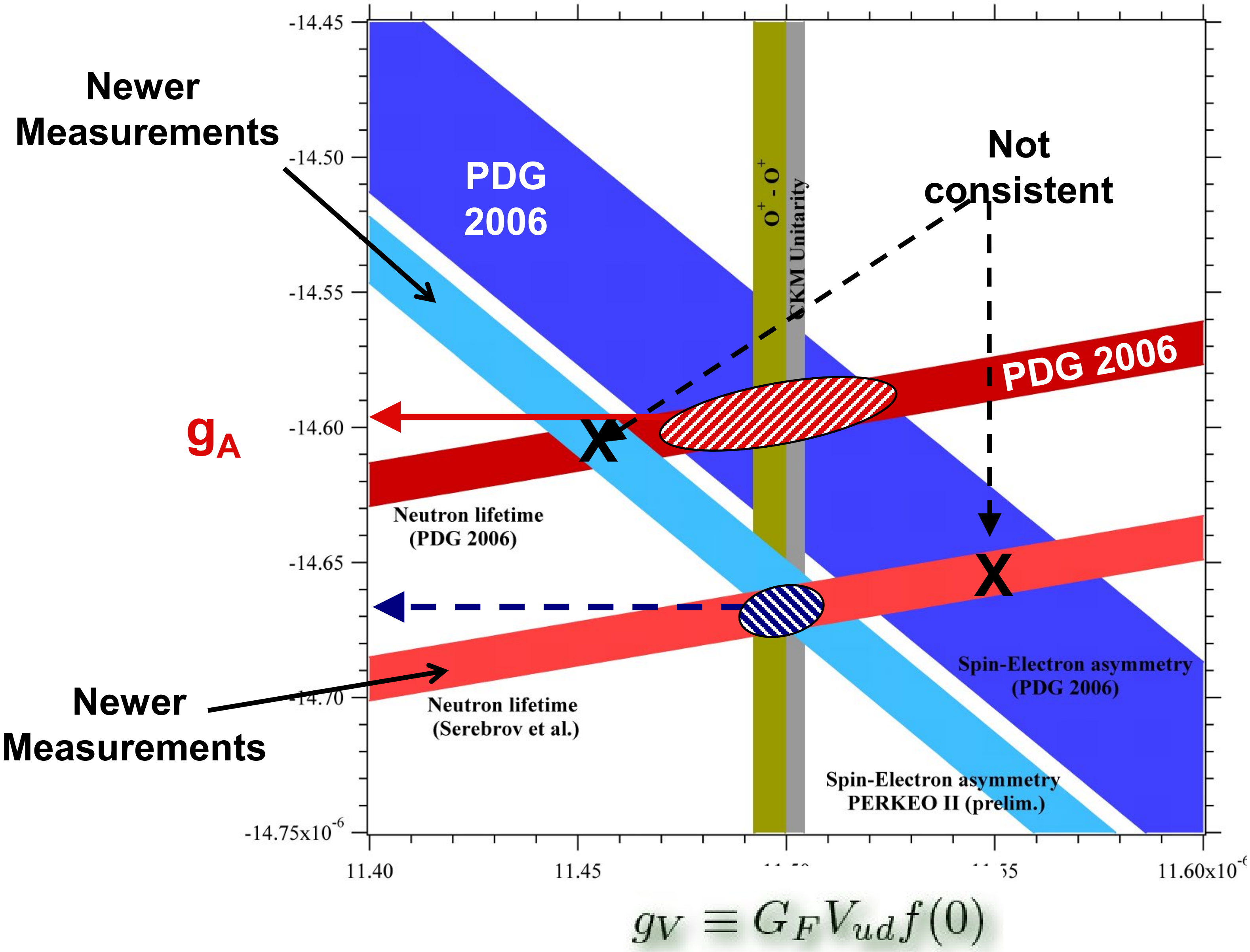
Neutron beta decay measurements give:

$$(g_A^2 + 3g_V^2)$$

$$g_A / g_V$$


Neutron Decay Correlations
g_A / g_V
g_V
Nuclear $O^+ \rightarrow$ O+ Decays,
CKM Unitarity
g_A
???
$g_A^2 + 3g_V^2$
n Lifetime
g_V
How thick are the bands and do they overlap ?

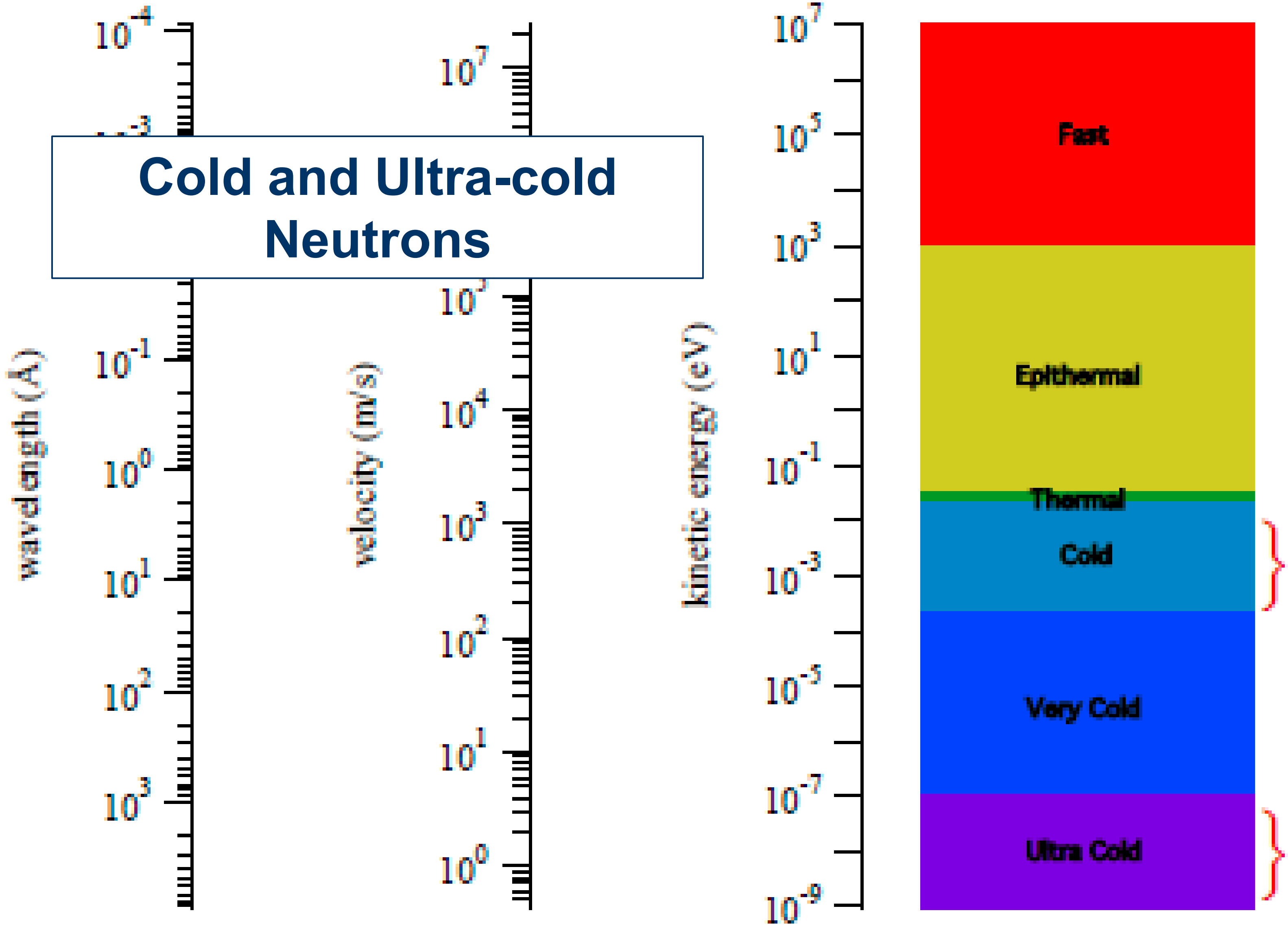
2007 picture: Lifetime and Correlations combine in a confused picture for the physics of g_A or unitarity



J. Nico, 2007

Let's look at more recent versions of these experiments, but define two "kinds" of *n* sources

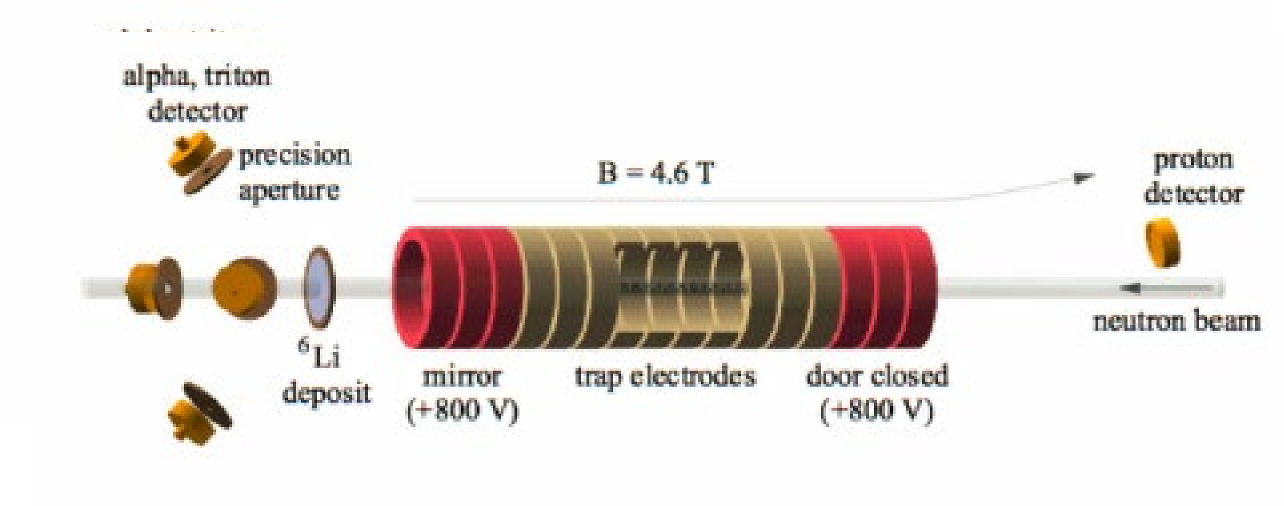
Cold and Ultra-cold Neutrons

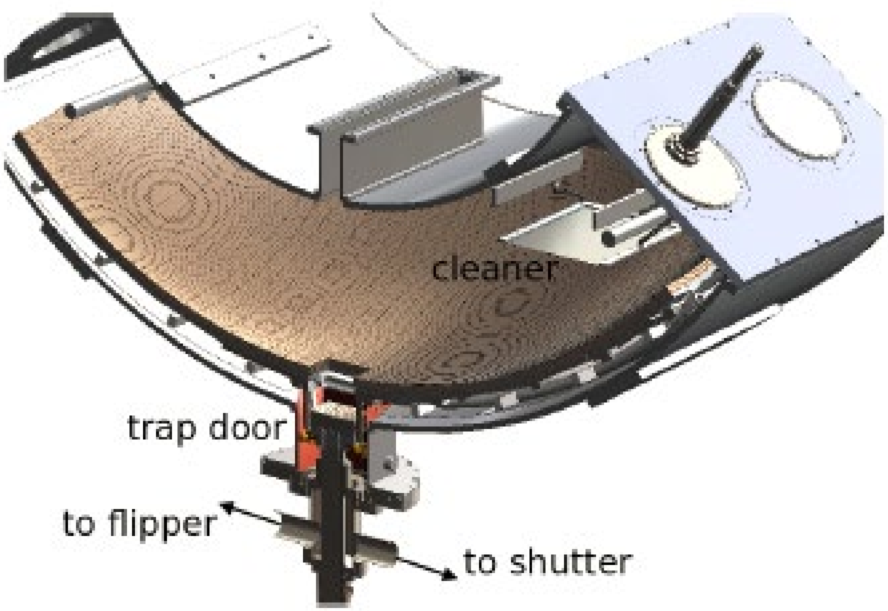


Difficulty is consistency in neutron decay experiments

- **Lifetime experiments**:
  - **Cold** "beam" of neutrons … arrange to trap, store, then count the feeble decay protons
  - Bottled up **Ultra Cold** neutrons … hold them for a while, dump, and count how many are left
- **Asymmetry experiments**
  - **Cold** *polarized* beam passes through a spectrometer and count the left and right going particles vs. the spin orientation (very few decay, but there are many in the beam)
  - **Ultra-cold** *polarized* neutrons and somewhat similar arrangement, but very few in the "beam" but many decay in the fiducial volume

Modern Lifetime Methods





Bottle
Keep *n* away from all walls
1) **Gravity (up)**
2) **Magnetic dipoles (down)**

Stopping Point

for today

PHYSICS AT THE FARM : DISCOVERY OF THE MUON.