Precise theory predictions in neutron decay

Nordita Workshop

Particle Physics with Neutrons at the ESS

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December 13, 2018

Outline

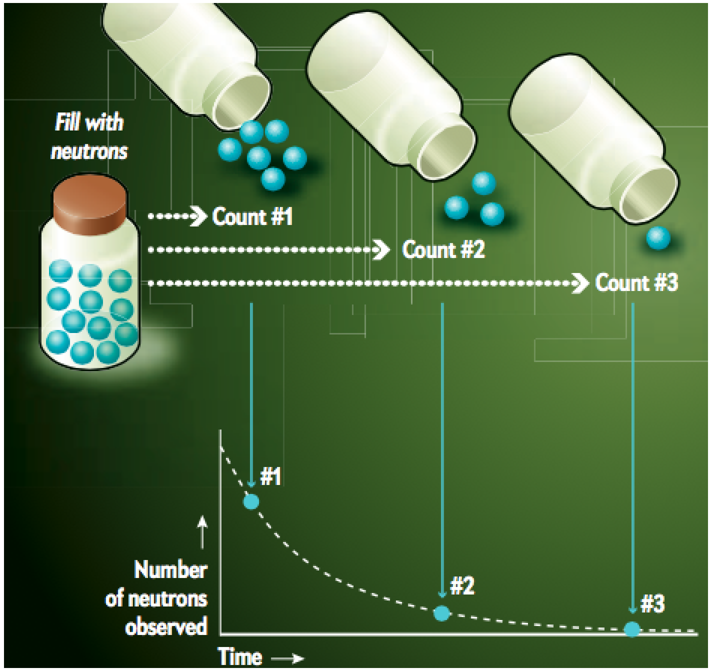
Neutron decay puzzles: lifetime and g_A

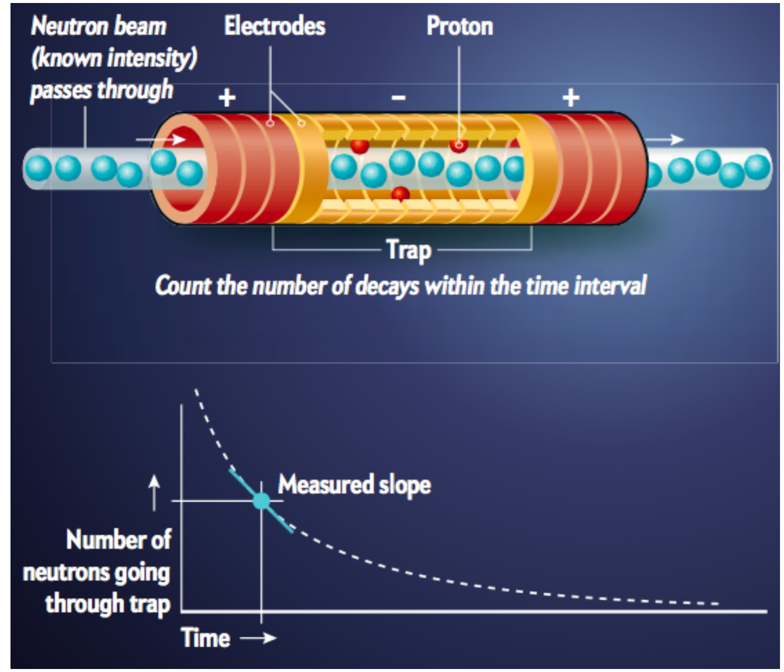
Standard Model prediction:

master formula: connection between the lifetime and the g_A

Structure of radiative corrections.

Neutron lifetime measurement: two approaches

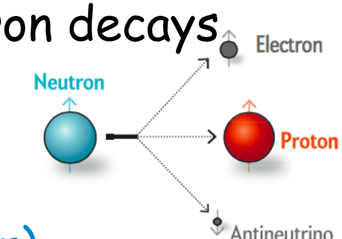




Greene and Geltenbort 2016

Trap 880(1) s:
- count surviving neutrons
- traditional: material traps
- recently also magnetic traps
- inclusive: sensitive to all n decays!

Beam 888(2) s:
- protons collected, counted
- exclusive: sensitive only to n -> p decays
- future: all n -> electron decays



Tempting to speculate about exotic decays (inclusive lifetime shorter)

Dark matter solution?

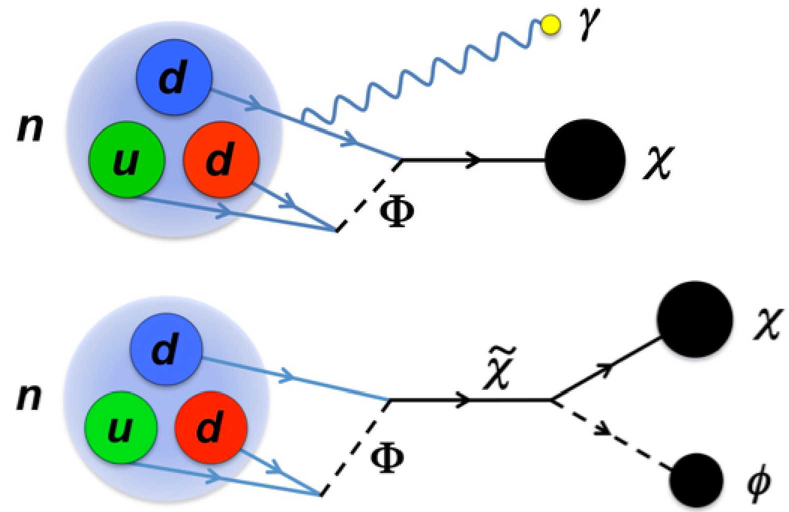
PHYSICAL REVIEW LETTERS **120,** 191801 (2018)

Featured in Physics

Dark Matter Interpretation of the Neutron Decay Anomaly

Bartosz Fornal and Benjamín Grinstein

$$\mathrm{BR}(n \to \chi + X) \simeq 1\%$$



Mass range for χ, roughly:

$$m_p - m_e < m_\chi < m_p + m_e$$

Mass range, refined:

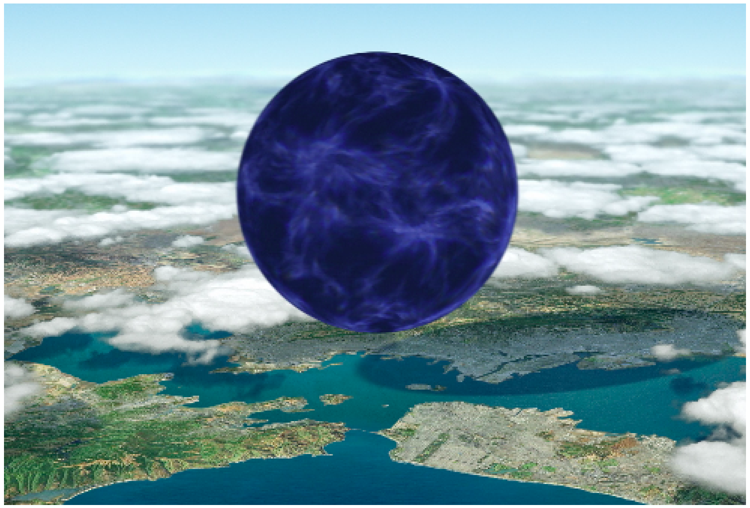
$$937.9 \text{ MeV} < m_\chi < 938.8 \text{ MeV}$$

Stability of beryllium-9

No χ-decay into proton+electron

Objections to the dark-matter decay

Objection 1: existence of heavy neutron stars



Radius stabilized by Pauli exclusion

If neutrons decay into dark matter, radius decreases -> density increases -> collapse; maximum mass

$$\sim 0.7 - 0.8 M_\odot$$

But larger masses have been observed,

$$\sim 2 M_\odot$$

1802.08244 D. McKeen, Ann E. Nelson, S. Reddy, D. Zhou
1802.08282 G. Baym, D.H. Beck, P. Geltenbort, J. Shelton
1802.08427 T.F. Motta, P.A.M. Guichon, A.W. Thomas

Strong repulsive self-interactions: a way around this bound; but then not a good DM candidate.

1803.04961 Cline & Cornell
1805.03656 Karananas & Kassiteridis

Very recent idea: neutron-DM repulsion suppresses n decays into DM in a neutron star.

1811.06546 Grinstein, Kouvaris, Nielsen

Objection 2: connection between g_A and τ_n

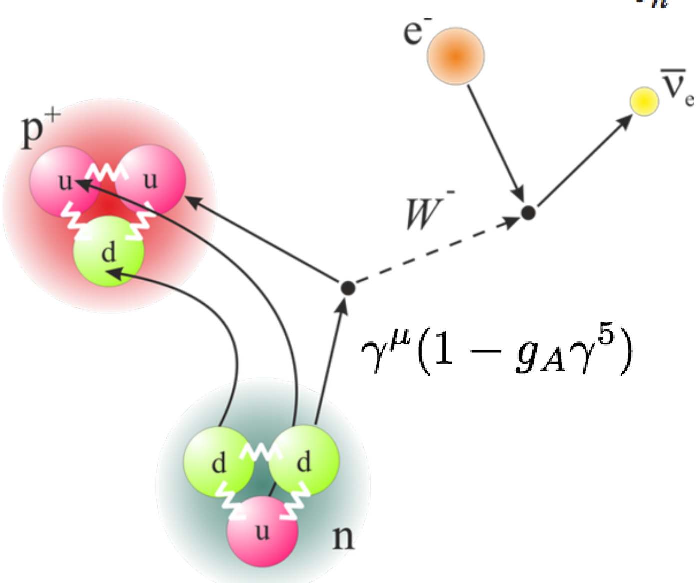
PHYSICAL REVIEW LETTERS **120**, 202002 (2018)

Neutron Lifetime and Axial Coupling Connection

A. Czarnecki, W. J. Marciano, and A. Sirlin

Two neutron puzzles:

$$\left.\begin{aligned}\tau_n^{\text{beam}} &= 888.0(2.0)\ \text{s}\\ \tau_n^{\text{trap}} &= 879.4(6)\ \text{s}\end{aligned}\right\}\ 8.6(2.1)\,\text{s} \simeq 4\sigma$$



$$\left.\begin{aligned}g_A^{\text{pre2002}} &= 1.2637(21)\\ g_A^{\text{post2002}} &= 1.2755(11)\end{aligned}\right\}\ 0.0118(24) \simeq 5\sigma$$

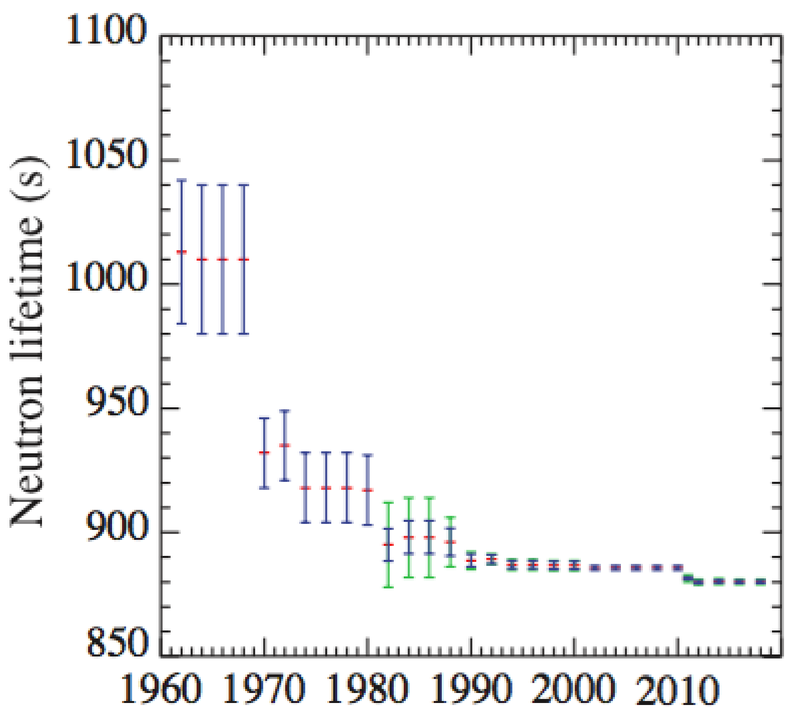
Connection: lifetime and g_A

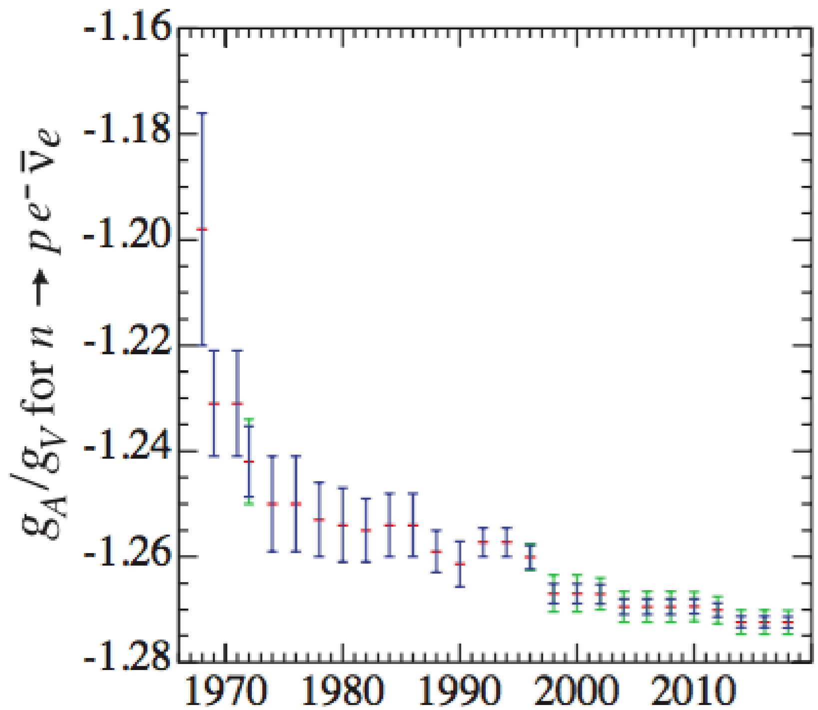
$$\frac{1}{\tau_n} = \frac{G_\mu^2 |V_{\mathrm{ud}}|^2}{2\pi^3} m_e^5 (1 + 3g_A^2)(1 + \mathrm{RC}) f \longrightarrow \tau_n \left(1 + 3g_A^2\right) = \text{SM-predictable}$$

Connection: lifetime and g_A

$$\frac{1}{\tau_n} = \frac{G_\mu^2 |V_{\rm ud}|^2}{2\pi^3} m_e^5 (1+3g_A^2)(1+\mathrm{RC}) f \longrightarrow \tau_n\,(1+3g_A^2) = \text{SM-predictable}$$

Lifetime and g_A measured separately but (usually) move together,





Neutron lifetime uncertainty: experimental

Summary of the 2012 Santa Fe workshop:

(Dubbers, Kumar, Pendlebury)

"error being divided by 2 or 3 every ten years (...) at all times the lifetime error was underestimated by a factor of three"

Lifetime and g_A : favored values

Master formula:

$$|V_{\rm ud}|^2 \tau_n (1 + 3g_A^2) = 4908.6(1.9)\ \mathrm{s},$$

Anti-correlation of RC in V_{ud} and the n-lifetime: more precise connection,

$$\tau_n (1 + 3g_A^2) = 5172.0(1.1)\ \mathrm{s},$$

Examples:

$$\tau_n^{\rm trap} = 879.4(6)\ \mathrm{s} \to g_A = 1.2756(5),$$

$$\tau_n^{\rm beam} = 888.0(2.0)\ \mathrm{s} \to g_A = 1.2681(17),$$

$$g_A^{\rm post2002} = 1.2755(11) \to \tau_n = 879.5(1.3)\ \mathrm{s},$$

$$g_A^{\rm pre2002} = 1.2637(21) \to \tau_n = 893.1(2.4)\ \mathrm{s}.$$

Our recommended values:

$$\tau_n^{\rm favored} = 879.4(6)\ \mathrm{s},$$

$$g_A^{\rm favored} = 1.2755(11).$$

AC, W. J. Marciano, A. Sirlin, PRL 2018

Lifetime and g_A : favored values

Master formula:

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Anti-correlation of RC in V_{ud} and the n-lifetime:
more precise connection

$$\tau_n(1+3g_A^2) = 5172.0(1.1)\ \mathrm{s}$$

Not much room
for dark decays:

Total exotic neutron decay branching ratio < 0.27% for g_A = 1.2755(11)

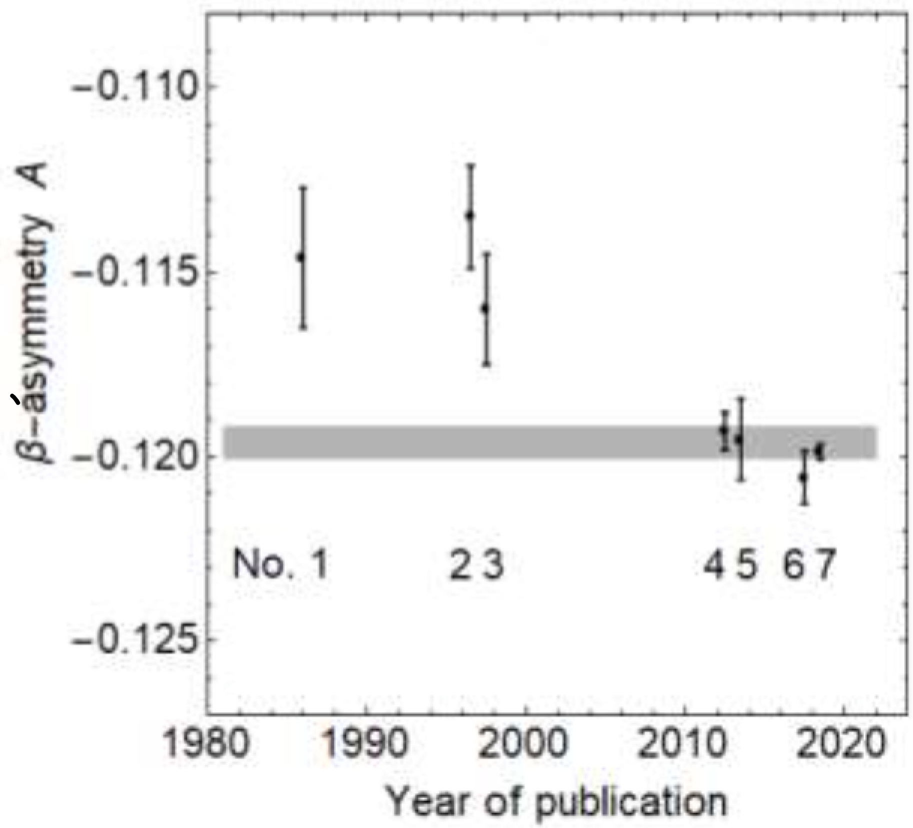
AC, W. J. Marciano, A. Sirlin, PRL 2018

New asymmetry measurement: PerkeoIII

(talk by Bastian Märkisch)

$$A_0 = \frac{2g_A(1-g_A)}{1+3g_A^2}$$

$$A_0 \simeq -0.1199 - 0.37(g_A - 1.2766)$$



arXiv:1812.00626

The new PerkeoIII asymmetry increases g_A and tightens the bound on exotic decays (see Bastian's talk for the number).

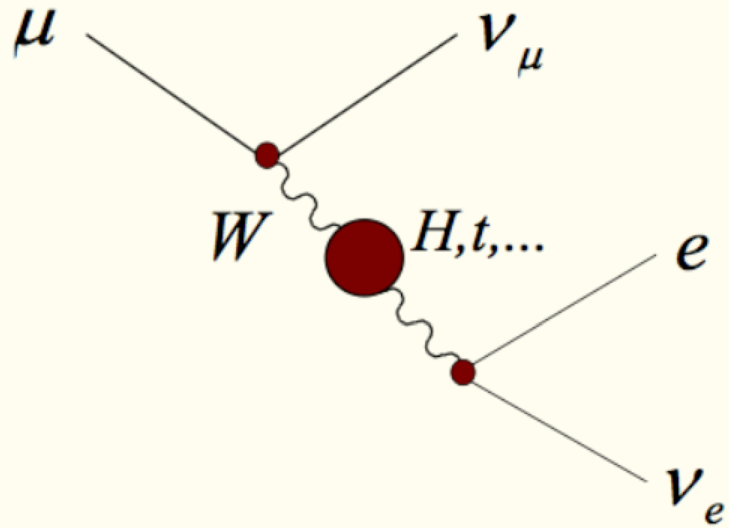
Lifetime (trap) and asymmetry measurements of τ_n and g_A^2 at 10^{-4} can push that bound to about 0.03%: an important goal. (Also a unitarity test via V_{ud})

Radiative corrections: neutron and muon

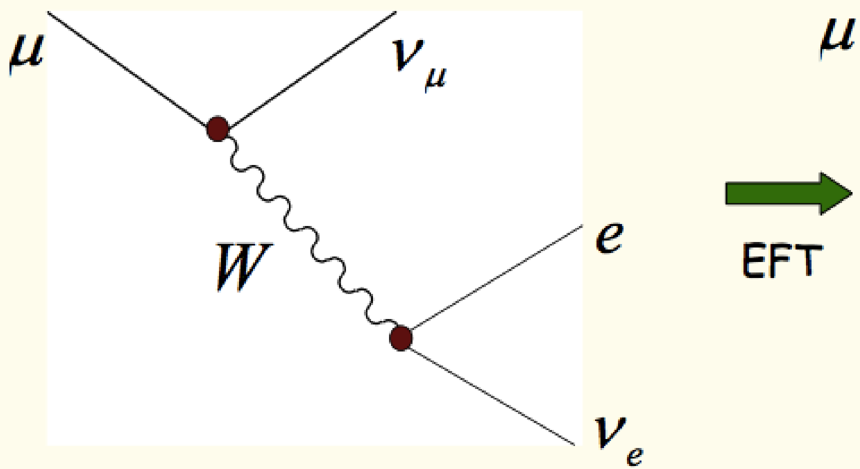
Definition of the Fermi constant via muon decay: absorbs part of radiative corrections

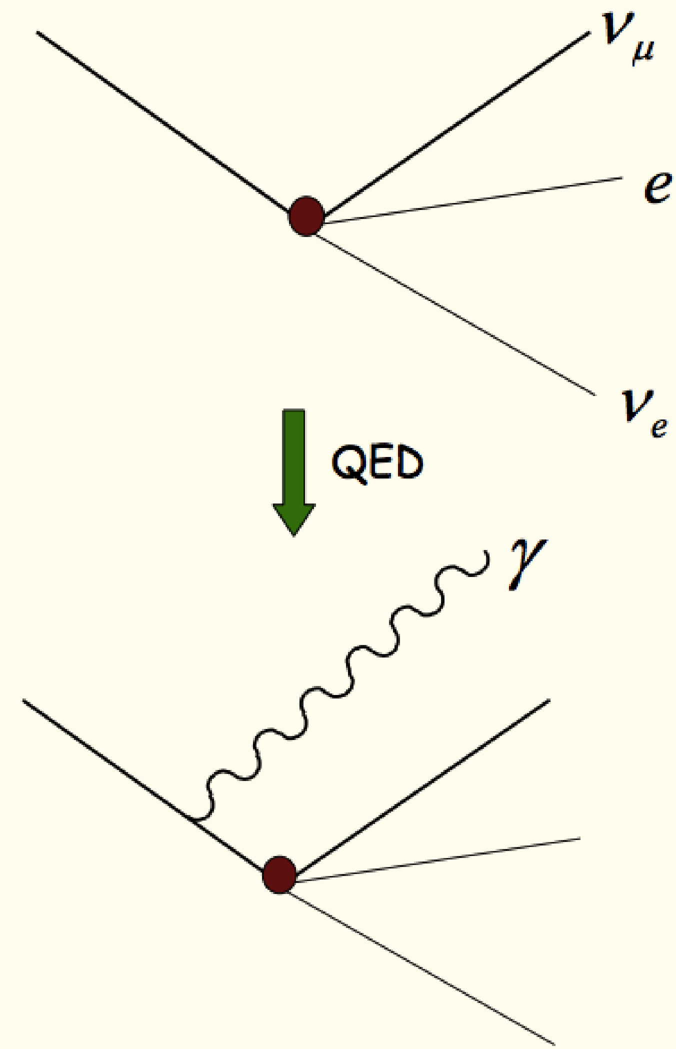
$$G_\mu \sim \frac{\alpha}{M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)}\left(1+\Delta r\right)$$

$$\Delta\alpha^5_{\text{had}} - c\,m_t^2 + c'\ln M_H^2 + \ldots$$



Determination of the Fermi constant





$$\frac{1}{\tau_\mu} = \frac{G_\mu^2 m_\mu^5}{192\pi^3}\left[1 + \Delta q\right]$$

Finite m_e and QED corrections
in the four-fermion EFT

QED radiative corrections in Fermi theory

1956: one-photon, with m_e — Behrends, Finkelstein, Sirlin

1999: two-photon, $m_e=0$ — van Ritbergen and Stuart

2008: two-photon, with m_e — Pak, AC

Related work:
Numerical tests of the $O(\alpha^2)$ result (not able to determine the m_e effect):
Chetyrkin, Harlander, Seidensticker, Steinhauser (1999);
Blokland, AC, Ślusarczyk, Tkachov (2004)

2005, Anastasiou, Melnikov, Petriello: $O(\alpha^2)$ electron spectrum

Neutron decay rate in terms of G_μ

$$\frac{1}{\tau_n} = \frac{G_\mu^2 |V_{\rm ud}|^2}{2\pi^3} m_e^5 (1+3g_A^2)(1+\mathrm{RC}) f$$

$$\mathrm{RC} = 0.03886(38)$$

Marciano and Sirlin, PRL 96, 032002 (2006)

$$f = 1.6887\,(1)$$

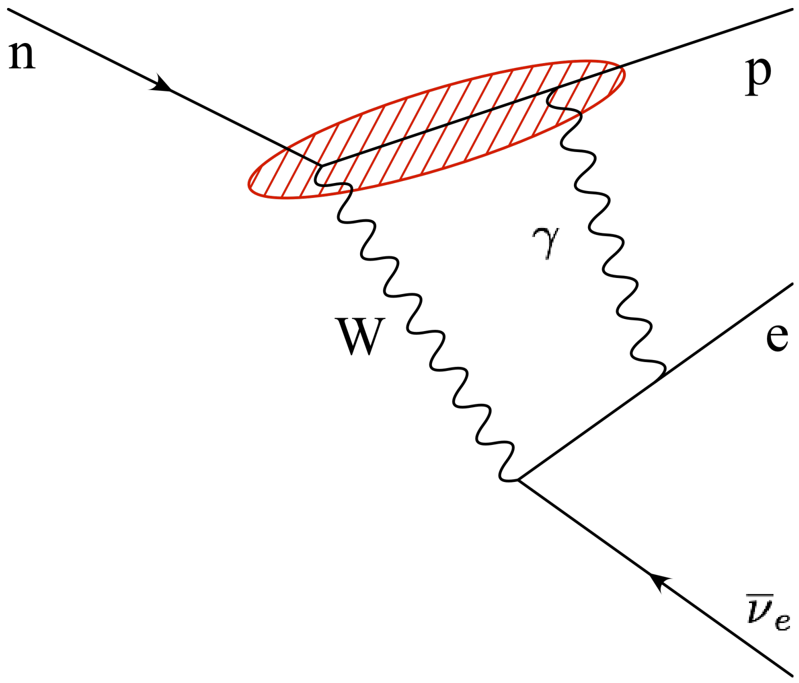
phase space factor

Wilkinson, Nucl. Phys. A377, 474 (1982).

Note: RC the same for V and A parts; this defines g_A,
results in ~1% corrections in the extraction of g_A from the A-asymmetry

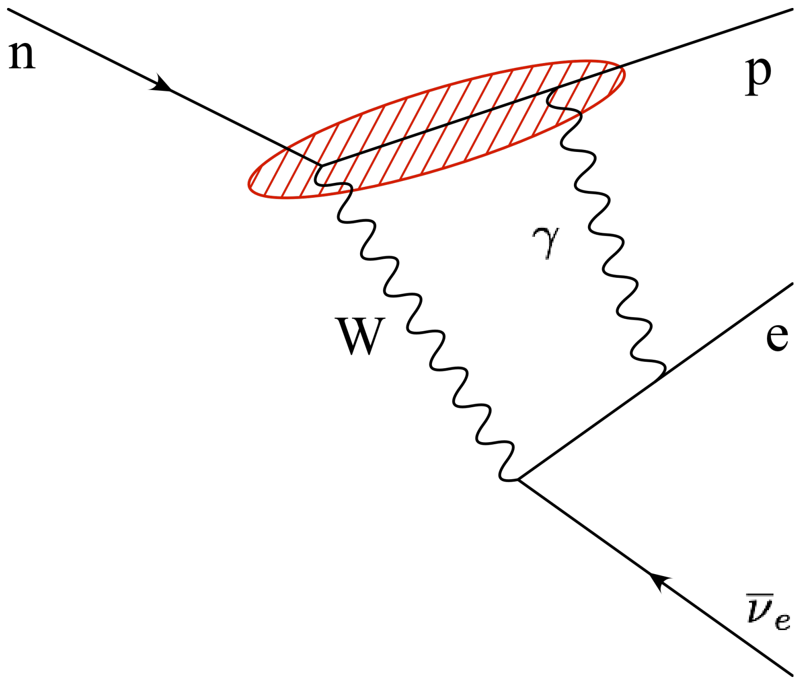
Uncertainty in RC mainly from the gamma-W box.
Important: that uncertainty (anti)correlated with V_{ud}

The gamma-W box and strong interactions



$$\mathrm{RC}_{EW} = \frac{\alpha}{2\pi}\left\{\overline{g}(E_m) + 3\ln\frac{m_Z}{m_p} + \ln\frac{m_Z}{m_A} + A_g + 2C_{\mathrm{Born}}\right\}.$$

The gamma-W box and strong interactions

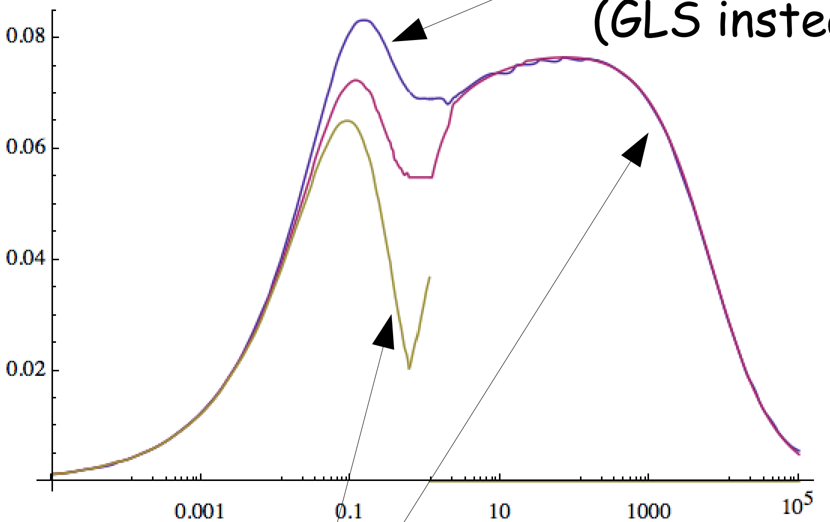


$$\mathrm{RC}_{EW} = \frac{\alpha}{2\pi}\left\{\overline{g}(E_m) + 3\ln\frac{m_Z}{m_p} + \underbrace{\ln\frac{m_Z}{m_A} + A_g + 2C_{\mathrm{Born}}}_{2.82\,\frac{\alpha}{\pi}}\right\}.$$

Relate the axial part to the Bjorken sum rule

Marciano+Sirlin, PRL 96, 032002 (2006)

Integrand of the gamma-W box (axial)



See Misha Gorchtein's talk (GLS instead of Bj SR)

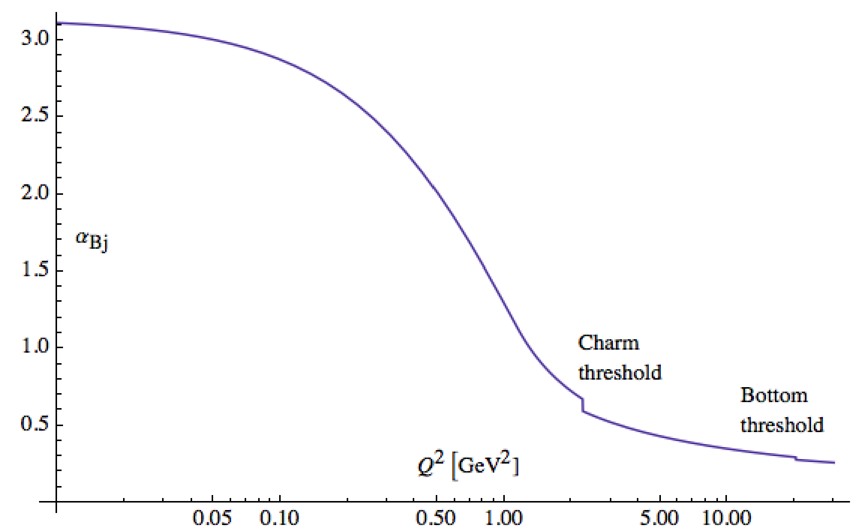
Q^2 [GeV^2]

Marciano+Sirlin, PRL 96, 032002 (2006)

Red line: uses effective strong coupling,
High Q2: 4-loop result

Baikov, Chetyrkin, Kuhn, PRL 104, 132004 (2010)

Low Q2: $\pi\left(1-\exp-\frac{Q^2}{Q_0^2}\right)$ Brodsky



Summary

Neutron decay provides input parameter g_A important for a variety of processes. In the future, may provide V_{ud} with precision competitive to superallowed nuclear Fermi decays.

Goal, common the experimenters and theorists: make neutron error negligible.

Measurements of lifetime and g_A^2 at 10^{-4} relative accuracy level: very important. Will probe exotic decay channels of the neutron at the 0.03% level.