Physics Beyond SM and precision tests of the Neutron β-decay

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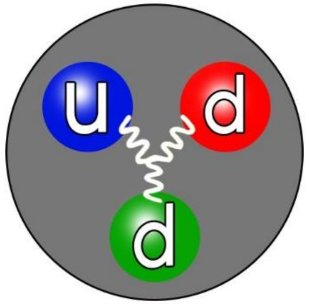
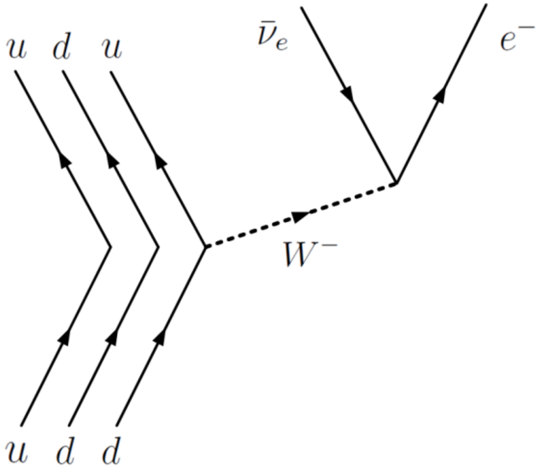
Neutron Decay

- Neutron is a baryon, consisting of one up quark and two down quarks;
- Quarks carry color charge and interact via the Strong force, exchanging the gluons;
- Free neutron is unstable: β^- -decay in about 15 minutes, but in some nuclei it can be stable.





$n \rightarrow p + e^- + \bar{\nu}_e$ or in terms of the quarks $d \rightarrow u + e^- + \bar{\nu}_e$

Process conserves Baryon number, Lepton number and electric charge;

Current has (V – A) type, so at vertex: $-\frac{ig}{2\sqrt{2}}\gamma^\mu(g_V - g_A\gamma^5)$

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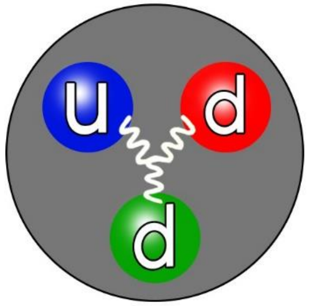

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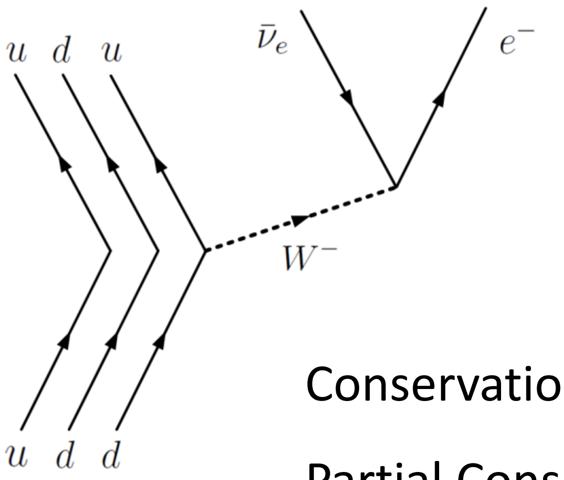

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Conservation of Vector Current *(CVC)* => $g_V = 1$

Partial Conservation of Axial Current *(PCAC)* => $g_A \approx 1.27$

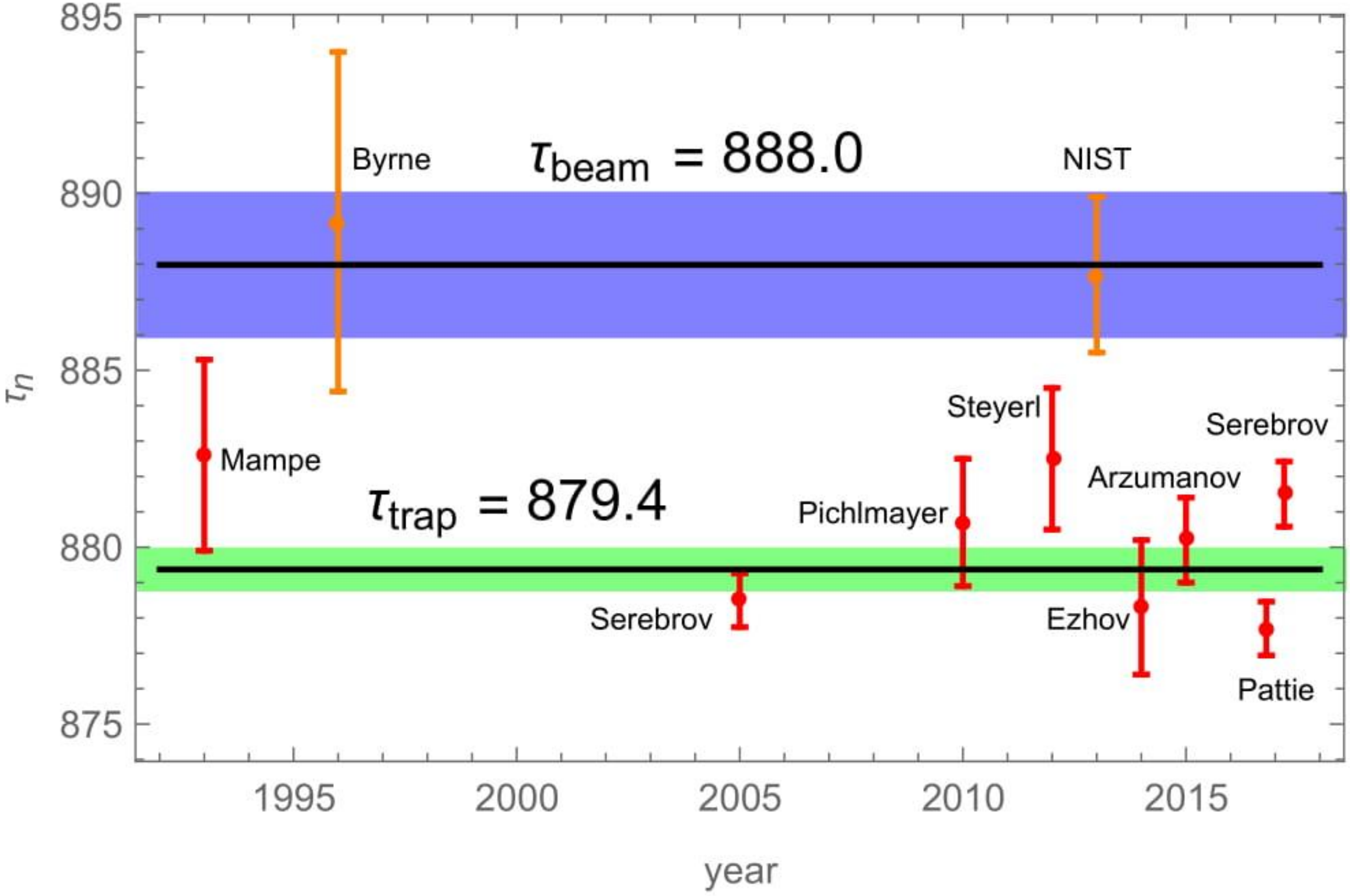
$\lambda \equiv \frac{g_A}{g_V}$ effect of *Strong interaction* (non-perturbative)

$$\Gamma = \frac{1}{\tau} = \frac{f_n m_e^5}{(2\pi)^3} G_F^2 |V_{ud}|^2 g_V^2 (1 + 3g_A^2)(1 + RC)$$

$$\left\{\begin{array}{l} V_{ud} \text{ from CKM matrix} \\ f_n(M_n, M_P, m_e) \; - \; \text{phase space term} \\ RC \; - \; \text{Radiative Corrections} \end{array}\right.$$

$$G_F = G_\mu \Longrightarrow \tau_n = \frac{4908.6 \pm 1.9}{|V_{ud}|^2(1 + 3g_A^2)} \xrightarrow[\text{From superallowed transitions}]{V_{ud} = 0.97420(22)} \tau_n(1 + 3g_A^2) = (5172.0 \pm 1.1)\ \text{s}$$

Neutron Lifetime Problem



- Beam experiments count produced protons and measure β-decay rate

$$\Gamma_\beta = \tau_\beta^{-1} = \tau_{\text{beam}}^{-1}$$

- Trap experiments measure neutron disappearance rate;

$$\Gamma_n = \tau_n^{-1} = \tau_{\text{trap}}^{-1}$$

- If neutron has new (BSM) decay channel

$$\Gamma_n = \Gamma_\beta + \Gamma_{\text{new}} > \Gamma_\beta$$

or $\tau_{\text{beam}} > \tau_{\text{trap}}$

$$\Delta\tau = \tau_{beam} - \tau_{trap} = (8.6 \pm 2.0)\text{s}$$

Axial Coupling

Axial coupling g_A is extracted from measurements of asymmetry parameters of decay.

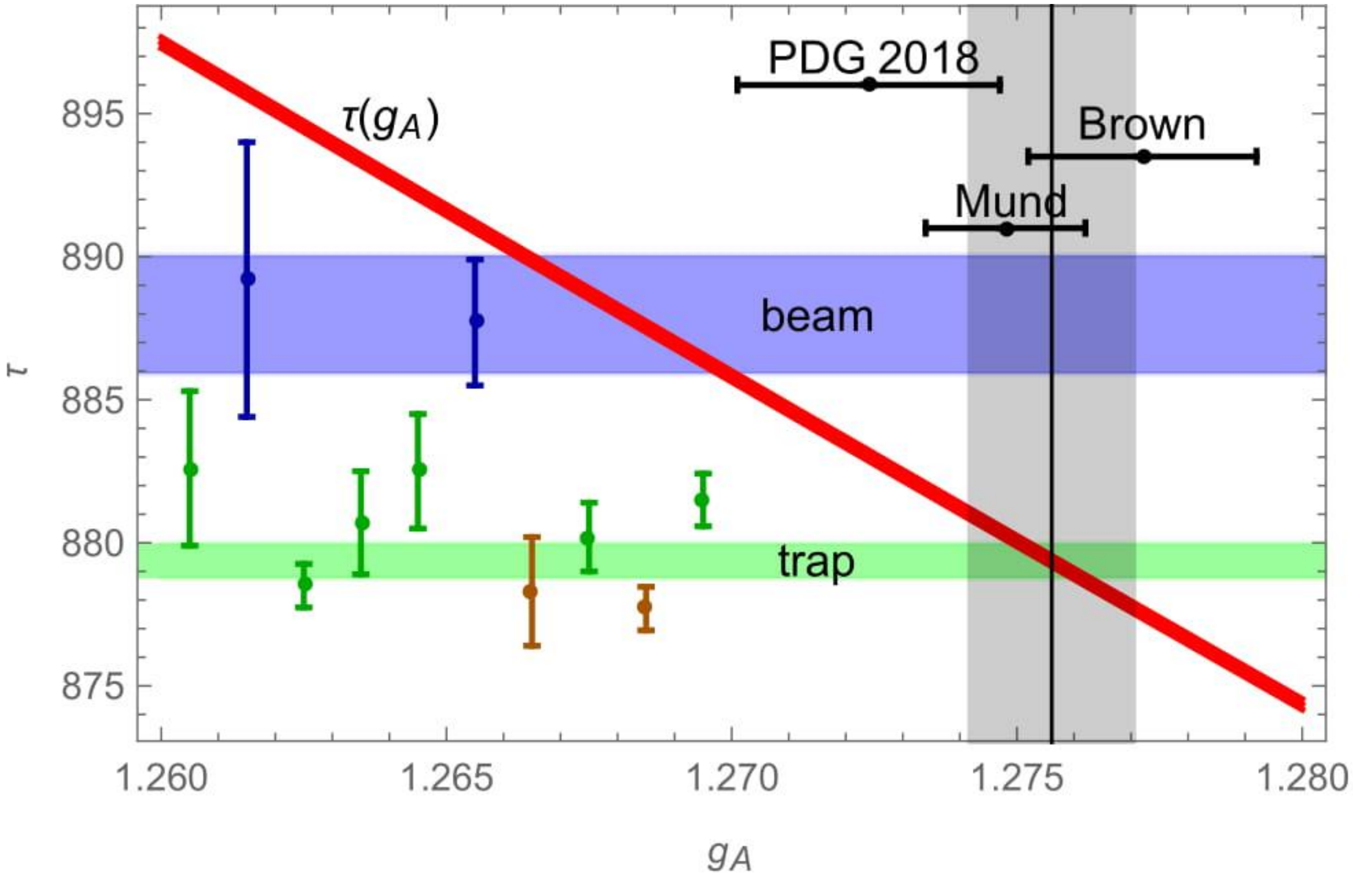
From relation:

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

$$\tau_{\mathrm{trap}} = 879.4(0.6) \quad \rightarrow \quad g_A = 1.2756(5)$$

$$\tau_{\mathrm{beam}} = 888.0(2.0) \quad \rightarrow \quad g_A = 1.2681(18)$$

$$g_A^{\mathrm{new}} = 1.2755(11) \quad \rightarrow \quad \tau_\beta^{SM} = 879.5(1.3)$$



$\tau_n = \tau_{\mathrm{trap}} = \tau_\beta^{SM} < \tau_{\mathrm{beam}}$ against dark decay prediction $\tau_n = \tau_{\mathrm{trap}} < \tau_\beta = \tau_{\mathrm{beam}}$

Only possibility is $\tau_\beta \neq \tau_\beta^{SM}$ due to BSM contributions in β-decay

BSM: adding possible non-standard four-fermion operators

Involving all possible current structures

$$J_i = \sum_i C_i \bar{\psi} \mathcal{O}_i \psi$$

$$i = S, P, V, A, T$$

where i is running through all possible bilinear covariants, that satisfy Lorentz invariance

$\bar{\psi}\psi$	scalar
$\bar{\psi}\gamma^5\psi$	pseudoscalar
$\bar{\psi}\gamma^\mu\psi$	vector
$\bar{\psi}\gamma^\mu\gamma^5\psi$	axial vector
$\bar{\psi}\sigma^{\mu\nu}\psi$	tensor

$$\begin{aligned}
\mathcal{H}^{\text{eff}}_{ude\nu} = \frac{G_F V_{ud}}{\sqrt{2}} [\ & (1+\epsilon_L)\ \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
& + \tilde{\epsilon}_L\, \bar{e}\gamma_\mu(1+\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
& + \epsilon_R\, \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \\
& + \tilde{\epsilon}_R\, \bar{e}\gamma_\mu(1+\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \\
& + \epsilon_T\ \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_e \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \\
& +\ \tilde{\epsilon}_T\ \bar{e}\sigma_{\mu\nu}(1+\gamma_5)\nu_e \cdot \bar{u}\sigma^{\mu\nu}(1+\gamma_5)d \\
& + \epsilon_S\, \bar{e}(1-\gamma_5)\nu_e \cdot \bar{u}d\ +\ \tilde{\epsilon}_S\, \bar{e}(1+\gamma_5)\nu_e \cdot \bar{u}d \\
& - \epsilon_P\, \bar{e}(1-\gamma_5)\nu_e \cdot \bar{u}\gamma_5 d\ -\ \tilde{\epsilon}_P\, \bar{e}(1+\gamma_5)\nu_e \cdot \bar{u}\gamma_5 d] \\
& + \text{h.c.}
\end{aligned}$$

$$\begin{aligned}
\mathcal{H} \quad = \quad & \bar{p}\ n\ \ (C_S \bar{e}\nu_e - C'_S \bar{e}\gamma_5\nu_e) \\
& + \bar{p}\gamma^\mu n\, (C_V \bar{e}\gamma_\mu\nu_e - C'_V \bar{e}\gamma_\mu\gamma_5\nu_e) \\
& + \frac{1}{2}\bar{p}\sigma^{\mu\nu} n\, (C_T \bar{e}\sigma_{\mu\nu}\nu_e - C'_T \bar{e}\sigma_{\mu\nu}\gamma_5\nu_e) \\
& - \bar{p}\gamma^\mu\gamma_5 n\, (C_A \bar{e}\gamma_\mu\gamma_5\nu_e - C'_A \bar{e}\gamma_\mu\nu_e) \\
& + \bar{p}\gamma_5 n\ \ (C_P \bar{e}\gamma_5\nu_e - C'_P \bar{e}\nu_e) + \text{h.c.}
\end{aligned}$$

In SM $\quad C_{S,P,T} = C'_{S,P,T} = 0$

$$C_V, C'_V = G_F V_{ud}/\sqrt{2}, \quad C_A, C'_A = \lambda C_V$$

Decay Rate Distribution Function and Asymmetry Parameters

The distribution in the electron and neutrino directions and in the electron energy from oriented nuclei is given by

$$\omega(\langle\mathbf{J}\rangle|E_e,\Omega_e,\Omega_\nu)dE_e d\Omega_e d\Omega_\nu =$$

$$\frac{F(\pm Z,E_e)}{(2\pi)^5} p_e E_e (E_0 - E_e)^2 dE_e d\Omega_e d\Omega_\nu \times$$

$$\frac{1}{2}\xi\left\{1 + a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e}\right.$$

$$+c\left[\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{3E_e E_\nu} - \frac{(\mathbf{p}_e\cdot\mathbf{j})(\mathbf{p}_\nu\cdot\mathbf{j})}{E_e E_\nu}\right]\left[\frac{J(J+1) - 3\langle\mathbf{J}\cdot\mathbf{j}\rangle^2}{J(2J-1)}\right]$$

$$\left.+\frac{\mathbf{J}}{J}\cdot\left[A\frac{\mathbf{p}_e}{E_e} + B\frac{\mathbf{p}_\nu}{E_\nu} + D\frac{\mathbf{p}_e\times\mathbf{p}_\nu}{E_e E_\nu}\right]\right\}$$

$\mathbf{J}$ polarization of nuclei, $\mathbf{j} = \mathbf{J}/|\mathbf{J}|$

$E_e,\ p_e,\ \Omega_e,\ E_\nu,\ p_\nu,\ \Omega_\nu$
Energy, momentum and angular coordinates of electron and neutrino

$F(\pm Z, E_e)$ Fermi function

$a,\ b,\ c,\ A,\ B,\ D$
Asymmetry parameters, are functions of $C_i,\ C_i'$

Fierz term $b\xi = \pm 2\gamma Re\left[|M_F|^2(C_S C_V^* + C_S' C_V'^*) + |M_{GT}|^2(C_T C_A^* + C_T' C_A'^*)\right]$

M_F $0^+ \to 0^+$ Superallowed Fermi transition $\Delta J = 0$

M_{GT} Gamow-Teller transition $\Delta J = 0, \pm 1$

A - correlation between electron momentum and nuclei polarization

In general

$$\begin{aligned} A\xi \;=\; & |M_{GT}|^2\lambda_{J'J}\Big[\pm 2Re\,(C_T C_T'^{*} - C_A C_A'^{*}) + 2\frac{\alpha Z m}{p_e} Im\,(C_T C_A'^{*} + C_T' C_A^{*})\Big] \\ & + \delta_{J'J} M_F M_{GT}\sqrt{\frac{J}{J+1}} \times \Big[2Re\,(C_S C_T'^{*} + C_S' C_T^{*} - C_V C_A'^{*} - C_V' C_A^{*}) \\ & \pm 2\frac{\alpha Z m}{p_e} Im\,(C_S C_A'^{*} + C_S' C_A^{*} - C_V C_T'^{*} - C_V' C_T^{*})\Big] \end{aligned}$$

In SM

$$A = -2\frac{\lambda^2 + \lambda}{1 + 3\lambda^2}$$

For any asymmetry parameter

$$\tilde{X} = \frac{X}{1 + b\langle \frac{m}{E_e} \rangle}$$

Integrating distribution function gives so called *ft* values

$$ft_i = \frac{K}{\xi}\frac{1}{1 + b\,\langle m_e/E_e \rangle}$$

$$\xi = |M_F|^2\Big(|C_S|^2 + |C_V|^2 + |C_S'|^2 + |C_V'|^2\Big) + |M_{GT}|^2\Big(|C_T|^2 + |C_A|^2 + |C_T'|^2 + |C_A'|^2\Big)$$

Taking the ratio of superallowed transition and neutron decay

$$\frac{\mathcal{F}t^{0^+\rightarrow 0^+}}{f_n \tau_n ln2(1 + \delta_R')} = \frac{\xi^n\,\Big(1 + b_n\langle \frac{m_e}{E_e} \rangle\Big)}{\xi^{0^+\rightarrow 0^+}\,\Big(1 + b_F\langle \frac{m_e}{E_e} \rangle\Big)}$$

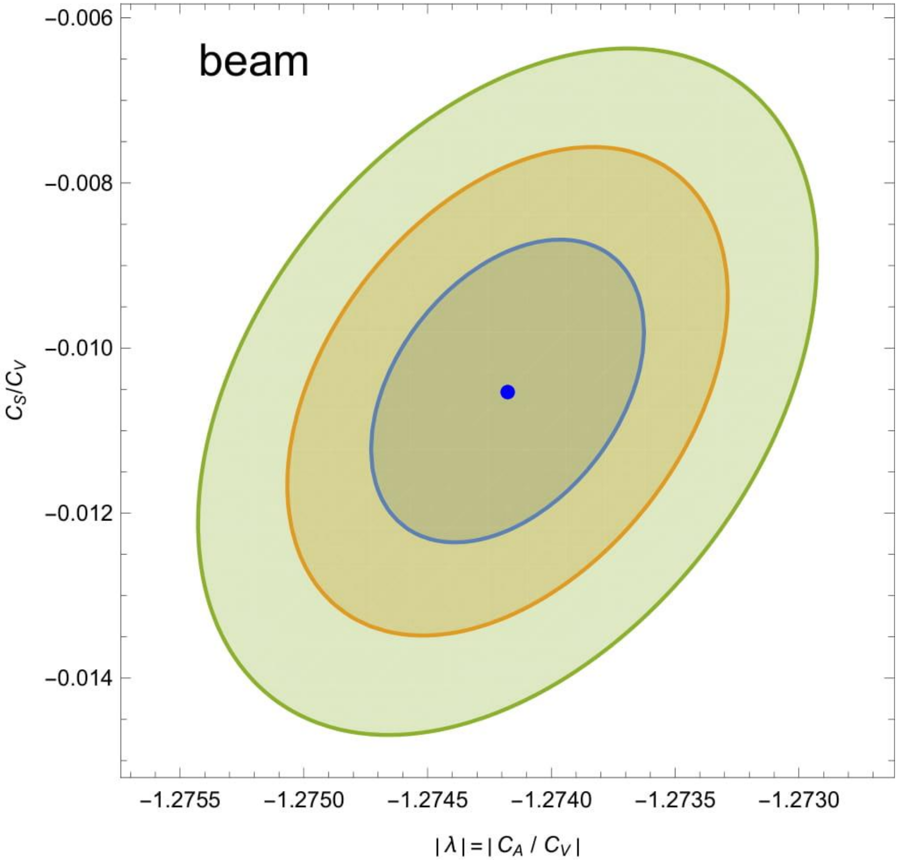
Results of Fits: Adding Scalar coupling

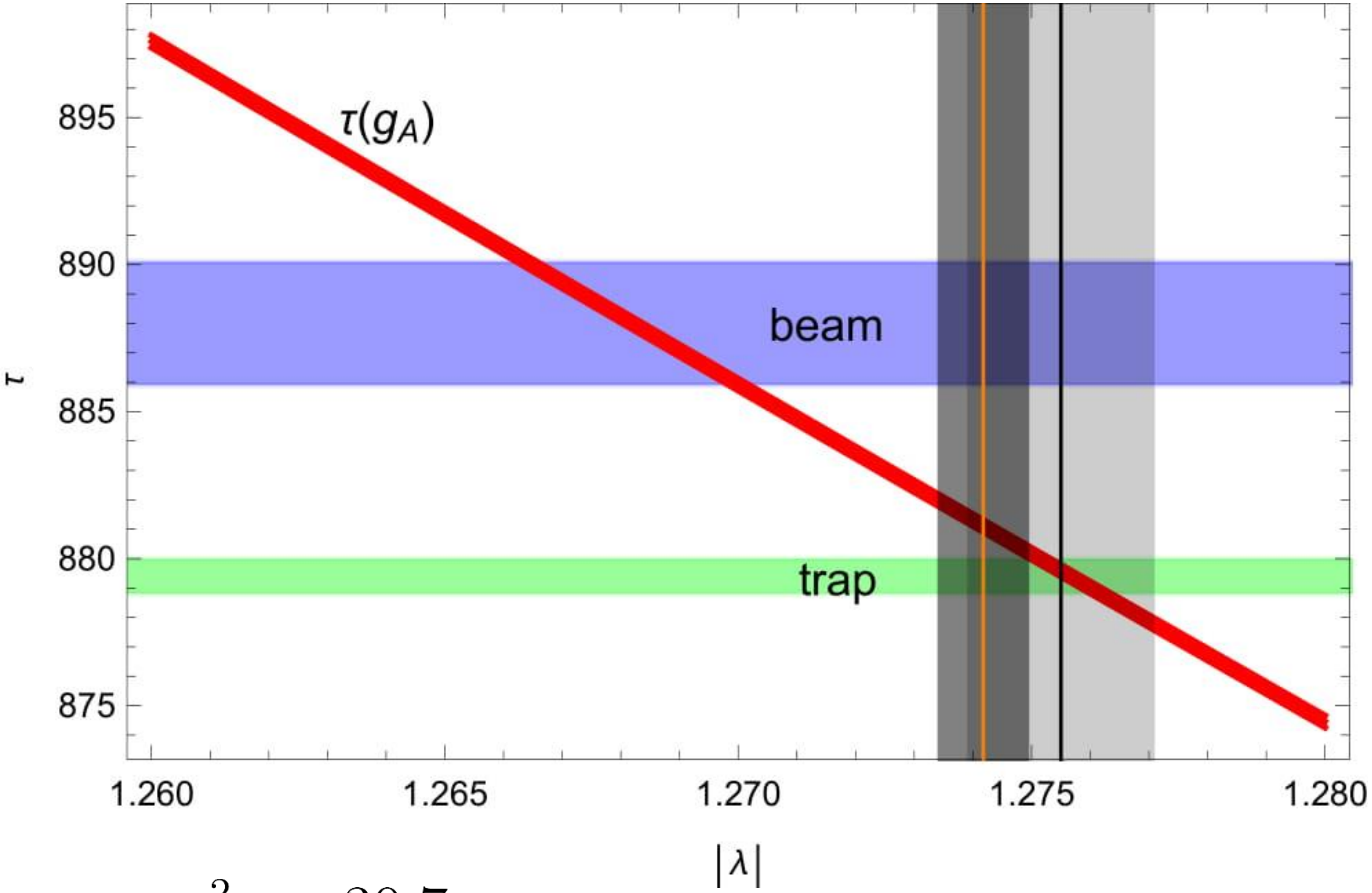
data: $\tau_{\text{beam}}, \quad A, \quad ft$ values

free parameters: $\lambda = \frac{C_A}{C_V}, \quad \frac{C_S}{C_V}, \quad \frac{C_T}{C_A}$

$$\lambda = -1.2742 \pm 0.0008$$

$$\frac{C_S}{C_V} = -0.0105 \pm 0.0026$$





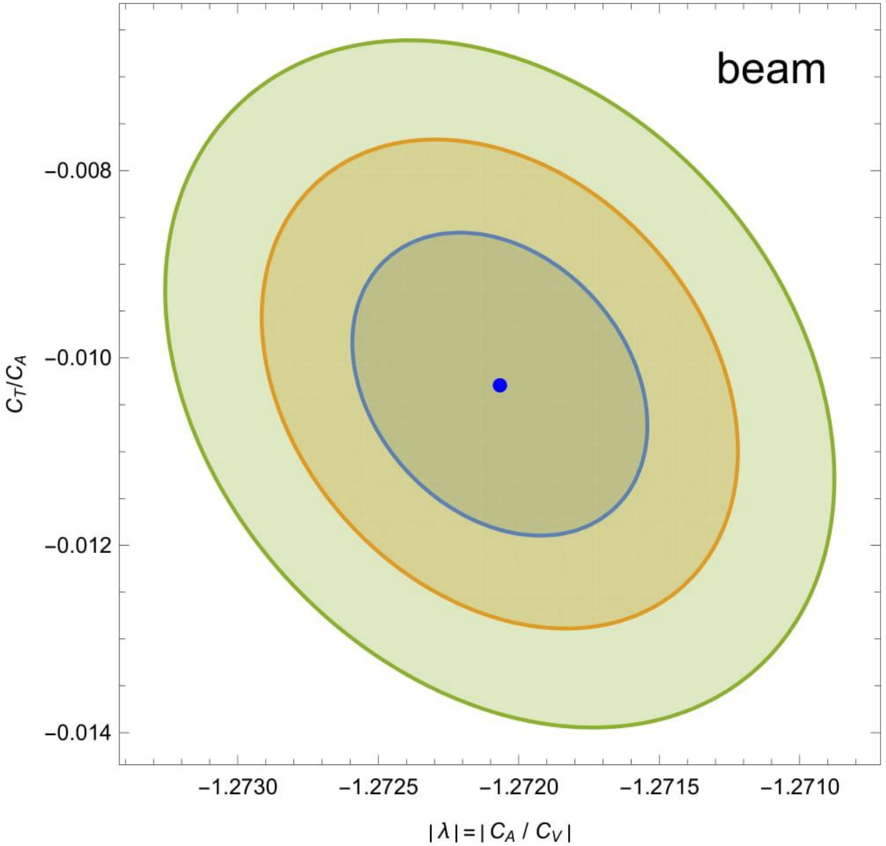
$$\frac{\chi^2}{dof} = \frac{30.7}{13} = 2.4$$

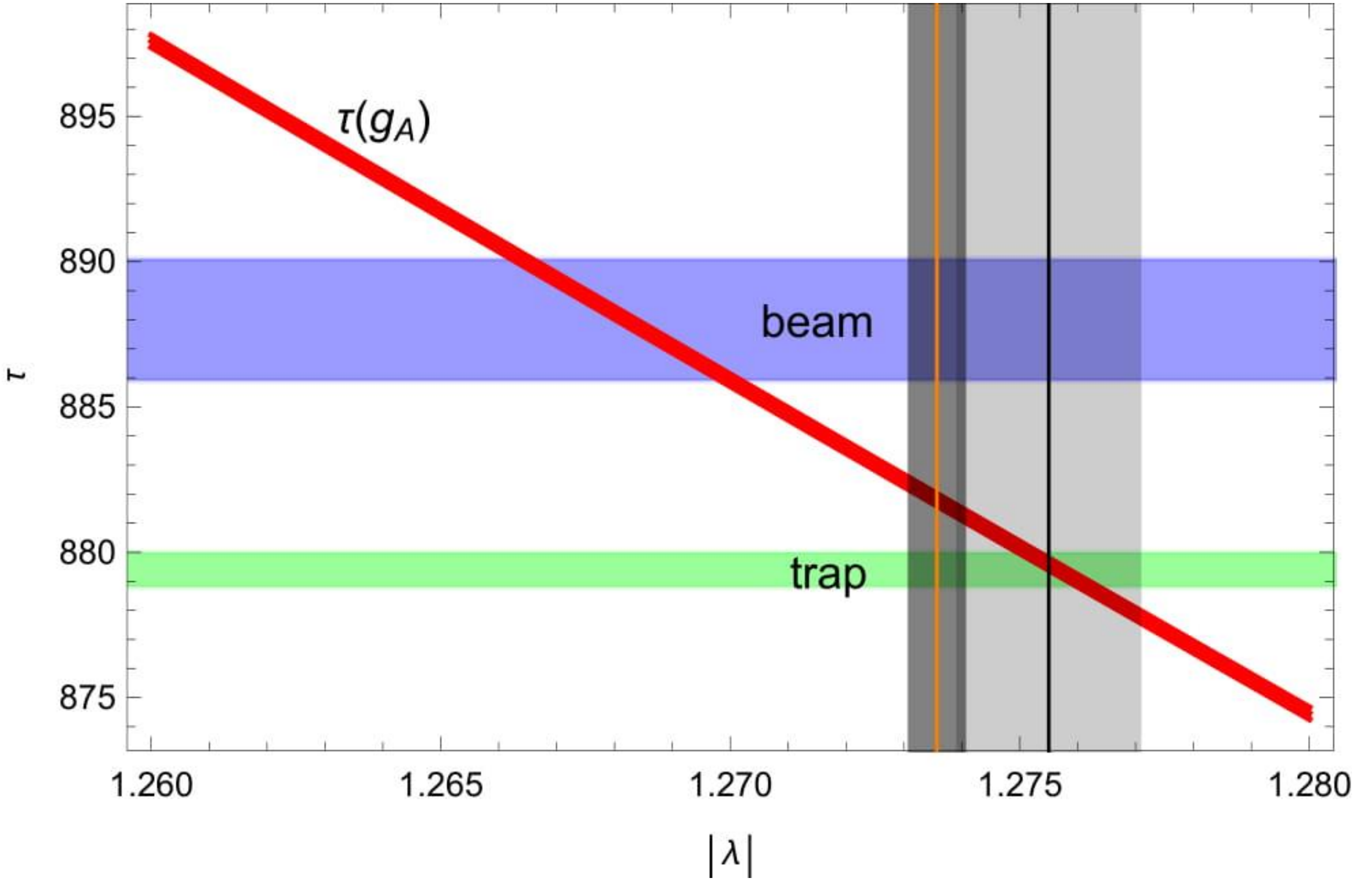
Results of Fits: Adding Tensor Coupling

$$\lambda = -1.2736 \pm 0.0006$$

$$\frac{C_T}{C_A} = -0.0103 \pm 0.0015$$

$$\frac{\chi^2}{dof} = \frac{24.7}{13} = 1.9$$





Summary: Inclusion of scalar and tensor currents in the theory was unable to modify λ parameter in the way, to make it compatible with beam lifetime and V_{ud} .

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