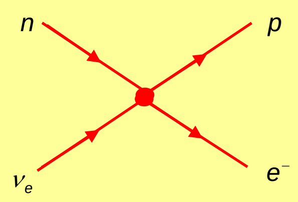
4. V-A Theory for charged current weak interactions

Fermi's original ansatz for $n \to p\, e^- \, \bar{\nu}_e$



4-fermion interaction with fermion vector currents:

$$M = \frac{G_F}{\sqrt{2}} \cdot J_{N,\mu} \cdot J_e^{\mu^+} = \frac{G_F}{\sqrt{2}} \cdot \left(\bar{u}_p \gamma_\mu u_n\right) \cdot \left(\bar{u}_e \gamma_\mu v_\nu\right)$$

↳ Fermi coupling constant

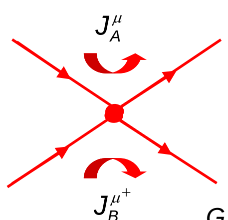
<u>Problem:</u> ansatz cannot explain parity violation

Most general ansatz:
Lorentz invariant form of fermion currents

$$M = \frac{G_F}{\sqrt{2}} \cdot \sum_i \left(\bar{u}_p \Gamma_i u_n\right) \cdot \left(\bar{u}_e \Gamma_i v_\nu\right)$$

↳ Most possibilities ruled out, left over with V-A ansatz

4.1 V-A ansatz for fundamental fermions



$$M = \frac{G_F}{\sqrt{2}} \cdot J_{A,\mu} \cdot J_B^{\mu^+}$$

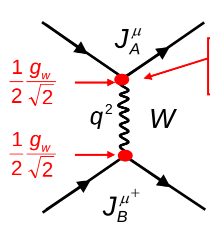
J_A and J_B are lepton and quark currents

$$J_\ell^\mu = \bar{u}_\ell \gamma^\mu (1-\gamma^5) u_\nu$$
$$J_q^\mu = \bar{u}_d \gamma^\mu (1-\gamma^5) u_u$$

Reminder

$$u_L = \frac{1}{2}(1-\gamma^5) u$$
$$u_R = \frac{1}{2}(1+\gamma^5) u$$

According today's understanding the 4-fermion coupling is the $q^2 \to 0$ limit of W propagator:



g_w = coupling for weak interaction

$$M = \frac{1}{2}\frac{g_w}{\sqrt{2}} \cdot J_{A,\mu} \frac{\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{M_W^2}\right)}{q^2 - M_W^2} \cdot \frac{1}{2}\frac{g_w}{\sqrt{2}} \cdot J_B^{\mu^+}$$

for $q^2 \to 0$: $= \frac{1}{M_W^2}$

$$\frac{G_F}{\sqrt{2}} = \frac{g_w^2}{8M_W^2}$$

With $G_F \approx 1.16 \times 10^{-5}\,\mathrm{GeV}^{-2}$ follows w $M_W \approx 80\,\mathrm{GeV}$: $g_w \approx 0.65$

V-A coupling of leptons and quarks

Reminder

$$\bar{u}_\ell \gamma^\mu (1-\gamma^5) u_\nu = \bar{u}_\ell \gamma^\mu u_\nu^L = (\bar{u}_\ell^L + \bar{u}_\ell^R)\gamma^\mu u_\nu^L = \bar{u}_\ell^L \gamma^\mu u_\nu^L$$

In V-A theory the weak interaction couples left-handed lepton/quark currents (right-handed anti-lepton/quark currents) with an universal coupling strength:

$$\frac{G_F}{\sqrt{2}} = \frac{g_w^2}{8M_W^2}$$

Corresponding to the weakly interacting particles ordered in left-handed doublets one finds the following left-handed fermion currents:

Lepton currents:

1. $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$ $\quad j_{e\nu}^\mu = \bar{u}_e \gamma^\mu (1-\gamma^5) u_\nu$
2. $\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}$ $\quad j_{\mu\nu}^\mu = \bar{u}_\mu \gamma^\mu (1-\gamma^5) u_\nu$
3. $\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$ $\quad j_{\tau\nu}^\mu = \bar{u}_\tau \gamma^\mu (1-\gamma^5) u_\nu$

Quark currents:

1. $\begin{pmatrix} u \\ d' \end{pmatrix}$ $\quad j_{du}^\mu = \bar{u}_d \gamma^\mu (1-\gamma^5) u_u$
2. $\begin{pmatrix} c \\ s' \end{pmatrix}$ $\quad j_{sc}^\mu = \bar{u}_s \gamma^\mu (1-\gamma^5) u_c$
3. $\begin{pmatrix} t \\ b' \end{pmatrix}$ $\quad j_{bt}^\mu = \bar{u}_b \gamma^\mu (1-\gamma^5) u_t$

CKM matrix to describe the quark mixing

One finds that the weak eigenstates of the down type quarks are not equal to the their mass/flavor eigenstates:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Cabibbo-**K**obayashi-**M**askawa mixing matrix

The quark mixing is the origin of the flavor number violation of the weak interaction.

Until the early 70s, only 3 quark flavor were known. The weak transition between quarks was described by a quark doublet:

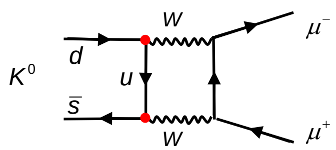
$$\begin{pmatrix} u \\ d' \end{pmatrix} = \begin{pmatrix} u \\ \cos\theta_c \cdot d + \sin\theta_c \cdot s \end{pmatrix}$$

Mixing angle θ_c = Cabibbo-Angle

The mixing described automatically the suppression of $\Delta S=1$ transitions ($\sim\sin^2\theta_c$)

Missing FCNC and GIM mechanism

FCNC in the 3 quark model: $K^0 \to \mu^+\mu^-$



$M \sim \sin\theta_c \cos\theta_c$

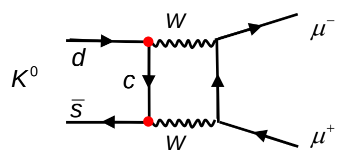
Theoretically one predicts large BR, in contradiction with experimental limits for this decay:

$$\frac{BR(K_L \to \mu^+\mu^-)}{BR(K_L \to all)} = (7.2 \pm 0.5)\cdot 10^{-9}$$

Proposal by Glashow, Iliopoulos, Maiani, 1970:

There exists a fourth quark which builds together with the s quark a second doublet:

$$\begin{pmatrix} c \\ s' \end{pmatrix} = \begin{pmatrix} c \\ -\sin\theta_c \cdot d + \cos\theta_c \cdot s \end{pmatrix}$$



$M \sim -\sin\theta_c \cos\theta_c$

Additional Feynman-Graph for $K^0 \to \mu\mu$ which compensates the first one:

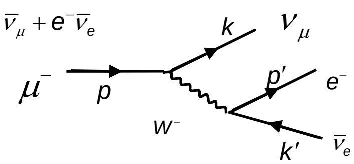
Prediction of a fourth quark

4.2 Test of V-A structure in particle decays

4.2.1 Muon decay

a) Muon lifetime

$\mu^- \to \bar{\nu}_\mu + e^- \bar{\nu}_e$



$$M = \frac{G_F}{\sqrt{2}}\left[\bar{u}_\nu(k)\gamma_\alpha(1-\gamma^5)u_\mu(p)\right]\left[\bar{u}_e(p')\gamma^\alpha(1-\gamma^5)v_\nu(k')\right]$$

Analogous to the QED calculations of chapter III one finds after a lengthy calculation:

$$M = \frac{1}{2}\sum_{Spins}|M|^2 = 64G_F^2(k\cdot p')(k'\cdot p)$$

Using $d\Gamma = \frac{1}{2E}|M|^2 dL$ one obtains the electron spectrum in the muon rest frame:

$$\frac{d\Gamma}{dE'} = \frac{G_F^2}{12\pi^3}m_\mu^2 E'^2(3 - \frac{4E'}{m_\mu})$$

with E' = electron energy

$$\frac{1}{\tau} = \Gamma = \int_0^{m_\mu/2}\frac{d\Gamma}{dE'}dE' = \frac{G_F^2 m_\mu^5}{192\pi^3}$$

Measurement of the muon lifetime thus provides a determination of the fundamental coupling $\mathbf{G_F}$

$$\tau_\mu = (2.19703 \pm 0.00004)\cdot 10^{-6}s$$

$$G_\mu = (1.16639 \pm 0.00001)\cdot 10^{-5}\text{GeV}^{-2}$$

Fermi constant measured in muon decays is often called $\mathbf{G_\mu}$

b) Test of V-A structure in the muon decay

Most general form of the matrix element for

$$M = \frac{G_F}{\sqrt{2}} \cdot \sum_{\substack{i=S,V,T \\ \lambda=L,R \\ \lambda'=\begin{cases}\pm\lambda \text{ for S,V} \\ -\lambda \text{ for T}\end{cases}}} g^i_{\lambda'\lambda} \underbrace{\left(\bar{u}_{\lambda'}(e)\Gamma^i v_{\lambda'_i}(\nu_e)\right)\left(\bar{u}_{\lambda_i}(\nu_\mu)\Gamma^i u_\lambda(\nu_e)\right)}$$

Chirality λ_i, λ'_i determined by Γ_i

$$\lambda'_i = \begin{cases} \lambda' & i = S,T \\ -\lambda' & i = V \end{cases}$$

$$\lambda_i = \begin{cases} \lambda & i = V \\ -\lambda & i = S,T \end{cases}$$

Possible current-current couplings:

i \ λ'λ	RR	RL	LR	LL
S	x	x	x	x
V	x	x	x	x
T		x	x	

There are in general 10 complex amplitudes $g^i_{\lambda'\lambda}$

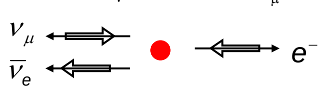
Pure V-A coupling: $g^V_{LL} = 1$

all other $g^i_{\lambda'\lambda} = 0$

Experimental determination of $g^i_{\lambda'\lambda}$ from energy spectra and spin correlation of the decay electrons from the polarized muons

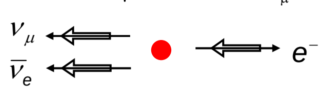
<u>Idea:</u>

V-A at μ vertex ⇒ LH ν_μ



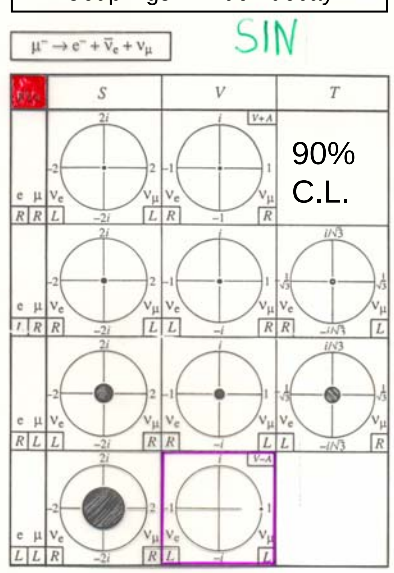
Configuration w/ max e- momentum possible

V+A at μ vertex ⇒ RH ν_μ



Due to angular momentum conservation not possible

Couplings in muon decay

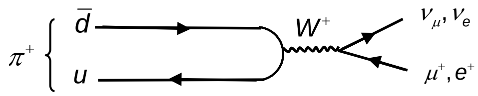


V-A theory is confirmed

4.2.2 Pion decay

$\pi^+ \rightarrow \mu^+ \nu_\mu$

$\pi^+ \rightarrow e^+ \nu_e$



Naïve expectation:

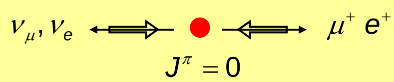
Assuming the same decay dynamics the decay rate to e^+ should be much larger than to μ^+ as the phase space is much bigger.

Measurement: (PDG)

$$\frac{\Gamma(\pi^+ \rightarrow e^+ \nu_e)}{\Gamma(\pi^+ \rightarrow \mu^+ \nu_\mu)} = (1.230 \pm 0.004) \cdot 10^{-4}$$

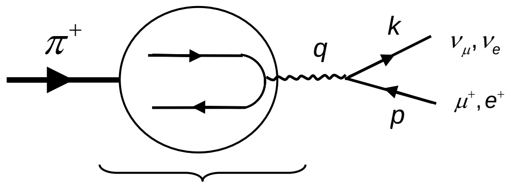
Large suppression due to a dynamic effect.

Qualitative explanation within V-A theory:



Angular momentum conservation forces the lepton into the "wrong" helicity state: suppressed ~ β=v/c i.e. for vanishing lepton masses the pion could not decay into leptons.

Determination of decay rates:



Quarks in pion are bound

$$M = \frac{G_F}{\sqrt{2}} \cdot (\pi)_\mu \cdot \left[\bar{u}_\nu \gamma^\mu (1-\gamma^5) v_\mu\right] \Rightarrow M = \frac{G_F}{\sqrt{2}} \cdot \left(p_\mu + k_\mu\right) \cdot f_\pi \cdot \left[\bar{u}_\nu \gamma^\mu (1-\gamma^5) v_\mu\right]$$

As the pion spin s_π=0, q is the only relevant 4-vector:

$$q^\mu = p^\mu + k^\mu$$

$$(\pi)_\mu = q_\mu \underbrace{f_\pi(q^2)}$$

Pion form factor:

$$q^2 = m_\pi^2 : \quad f_\pi(q^2) = f_\pi(m_\pi^2) = f_\pi$$

$$\Gamma(\pi^+ \to \mu^+ \nu_\mu) = \frac{G_F^2}{8\pi} \cdot f_\pi^2 \cdot m_\pi m_\mu^2 (1 - \frac{m_\mu^2}{m_\pi^2})$$

$$\Gamma(\pi^+ \to e^+ \nu_\mu) = \frac{G_F^2}{8\pi} \cdot f_\pi^2 \cdot m_\pi m_e^2 (1 - \frac{m_e^2}{m_\pi^2})$$

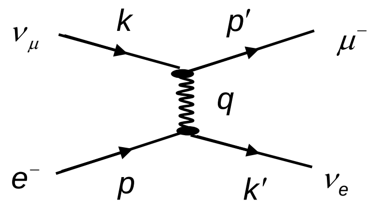
$$\frac{\Gamma(\pi^+ \to e^+ \nu_\mu)}{\Gamma(\pi^+ \to \mu^+ \nu_\mu)} = \left(\frac{m_e^2}{m_\mu^2}\right)\left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right) = 1.275 \cdot 10^{-4}$$

The prediction of the V-A theory is confirmed by the experimental observation.

4.3 Neutrino scattering

a) Neutrino-electron scattering

$$\nu_\mu e^- \to \mu^- \nu_e$$



$$M = \frac{G_F}{\sqrt{2}} \left[\bar{u}_\nu(k')\gamma_\alpha(1-\gamma^5)u_e(p)\right]\left[\bar{u}_\mu(p')\gamma^\alpha(1-\gamma^5)u_\nu(k)\right]$$

$$\overline{|M|^2} = \frac{1}{2}\sum_{Spins}|M|^2 = \ldots = 64 G_F^2 (k \cdot p)(k' \cdot p') = 16 G_F^2 \cdot s^2$$

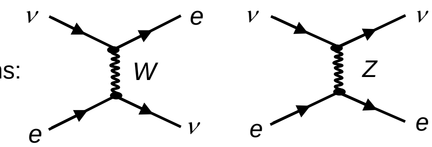
Limit $m_e \approx m_\mu \approx 0$ $\quad$ $s = (k+p)^2 = 2kp = 2k'p'$

Using the phase space factor of chapter II:

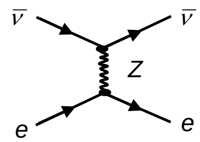
$$\frac{d\sigma}{d\Omega}(\nu_\mu e^-) = \frac{1}{64\pi^2 s}\overline{|M|^2} = \frac{G_F^2 s}{4\pi^2}$$

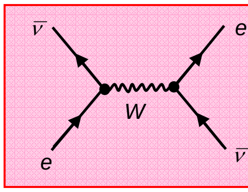
$$\sigma(\nu_\mu e^-) = \frac{G_F^2 s}{\pi}$$

For $\nu_e e^- \to \nu_e e^-$ there are 2 contributions:

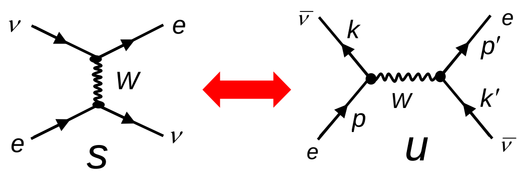


Similar for $\bar{\nu}_e e^- \to \bar{\nu}_e e^-$





Contribution of the charged current:



$$\frac{d\sigma}{d\Omega}(\bar{\nu}e^-) = \frac{G_F^2 s}{16\pi^2}(1-\cos\theta)^2$$

$$\sigma(\bar{\nu}e^-) = \frac{G_F^2 s}{3\pi}$$

$$\overline{|M|^2}(\bar{\nu}e) = 16 G_F^2 u^2 = 4 G_F^2 s^2 (1-\cos\theta)^2$$

θ Angle between ingoing ν and outgoing e.

Result of V-A structure

For the charged current (CC) contribution to the (anti) neutrino electron scattering one finds

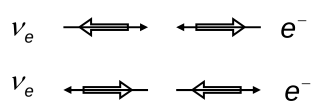
$$\frac{\sigma_{\nu e}^{cc}}{\sigma_{\bar{\nu} e}^{cc}} = 3$$

Different angular distribution of (anti) neutrino scattering can be understood from a helicity discussion

$$\frac{d\sigma}{d\Omega}(\nu_\mu e^-) = \frac{G_F^2 s}{4\pi^2}$$

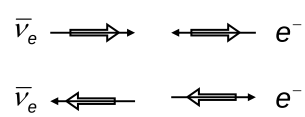
$$\frac{d\sigma}{d\Omega}(\bar{\nu}e^-) = \frac{G_F^2 s}{16\pi^2}(1-\cos\theta)^2$$

$\nu_e e^- \to \nu_e e^-$ | | $\bar{\nu}_e e^- \to \bar{\nu}_e e^-$



initial

final state

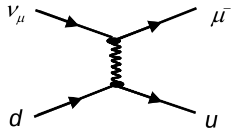


Allowed → isotropic

Forbidden (angular mom.) → (1-cosθ)

b) Neutrino-quark scattering

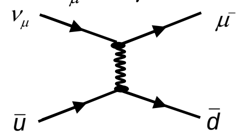
$\nu_\mu d \to \mu^- u$



$$\frac{d\sigma}{d\Omega}(\nu_\mu d) = \frac{G_F^2 s}{4\pi^2}$$

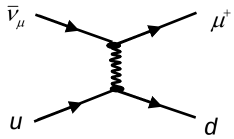
$$\sigma(\nu_\mu d) = \frac{G_F^2 s}{\pi}$$

$\nu_\mu \bar{u} \to \mu^- \bar{d}$



$$\frac{d\sigma}{d\Omega}(\nu_\mu \bar{u}) = \frac{d\sigma}{d\Omega}(\bar{\nu}_\mu u)$$

$\bar{\nu}_\mu u \to \mu^+ d$



$$\frac{d\sigma}{d\Omega}(\bar{\nu}_\mu u) = \frac{G_F^2 s}{16\pi^2}(1+\cos\theta)^2$$

$$\sigma(\bar{\nu}_\mu u) = \frac{G_F^2 s}{3\pi}$$

θ Scattering angle of μ

$\bar{\nu}_\mu \bar{d} \to \mu^+ \bar{u}$

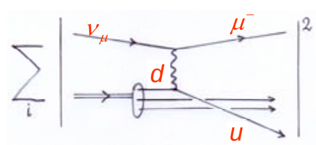
$$\frac{d\sigma}{d\Omega}(\bar{\nu}_\mu \bar{d}) = \frac{d\sigma}{d\Omega}(\nu_\mu d)$$

Neutrinos only interact w/ d and anti-u quarks
Anti-neutrinos only interact w/ u and anti-d quarks

c) Neutrino-nucleon (iso-scalar) scattering

QPM: $x = \frac{Q^2}{2M\nu}$ $y = \frac{\nu}{E}$ $\nu = E - E'$

$$\frac{d\sigma(\nu_\mu N \to \mu^- X)}{dy} =$$

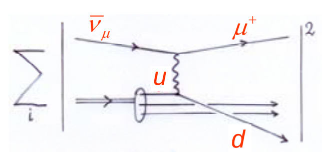


$$\frac{d^2\sigma(\nu N)}{dxdy} = \sum_i f_i(x)\left(\frac{d\sigma_i(\nu q_i)}{dy}\right)_{\hat{s}=xs}$$

$$\frac{d^2\sigma(\nu N)}{dxdy} = \frac{G_F^2}{2\pi}\cdot\left[Q(x) + \overline{Q}(x)(1-y)^2\right]$$

$$1 - y \equiv \frac{p\cdot k'}{p\cdot k} \approx \frac{1}{2}(1+\cos\theta)$$

$$\frac{d\sigma(\bar{\nu}_\mu N \to \mu^+ X)}{dy} =$$



$$\frac{d^2\sigma(\bar{\nu} N)}{dxdy} = \frac{G_F^2}{2\pi}\cdot\left[\overline{Q}(x) + Q(x)(1-y)^2\right]$$

Total cross section after integration over x and y (0…1):

$$\sigma(\nu N) = \frac{G_F^2 M E_\nu}{2\pi} \cdot \left[Q_I + \frac{1}{3} \overline{Q}_I \right]$$

$$\sigma(\overline{\nu} N) = \frac{G_F^2 M E_\nu}{2\pi} \cdot \left[\overline{Q}_I + \frac{1}{3} Q_I \right]$$

with $Q_I = \int xQ(x)dx$

$$R = \frac{\sigma_{\overline{\nu}N}}{\sigma_{\nu N}} = \frac{1 + 3\overline{Q}/Q}{3 + \overline{Q}/Q}$$

If nucleon consists only of valence quarks ($\overline{Q}$=0): R=1/3 , because of V-A structure

Measurement: $R = \frac{0.34}{0.67} \Rightarrow \overline{Q}/Q \approx 0.15$

$\Rightarrow$ There are sea quarks !

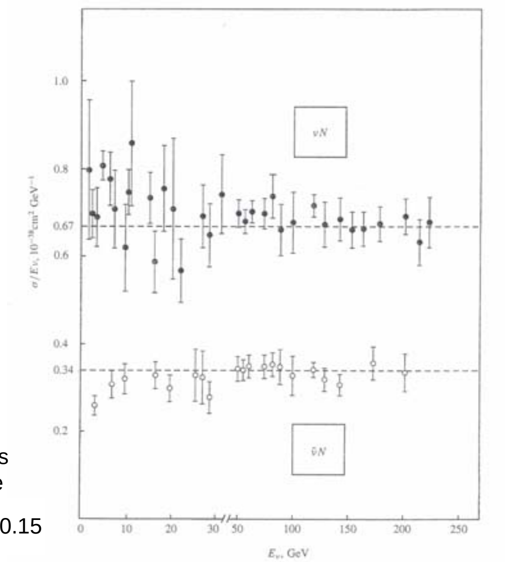


Fig. 5.13. Neutrino and antineutrino cross-sections on nucleons. The ratio σ/E_ν is plotted as a function of energy and is indeed a constant, as predicted in (5.45) and (5.46).

4.4 Problems with V-A theory

- Cross section for $\nu e^- \to e^- \nu_e$ in 4-fermion ansatz: i.e. cross section goes to infinity if s→∞: violates unitarity

$$\sigma(\nu e^-) = \frac{G_F^2 s}{\pi}$$

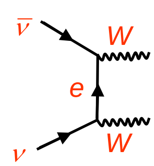
- Lee and Wu (1965) introduced a massive exchange boson. Effect of propagator:

$$\frac{G_F}{\sqrt{2}} \mapsto \frac{G_F}{\sqrt{2}} \frac{1}{1 - q^2/M_W^2} \qquad \sigma(\nu e^-) \mapsto \frac{G_F^2 M_W^2}{\pi}$$

Energy behavior of cross section becomes better but still violates unitarity at very high s.

- In addition there are boson production processes of the kind:

In the V-A theory they also violate unitarity !!

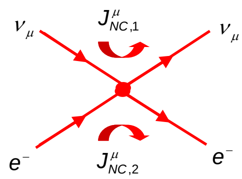


Violates unitarity

We need a new theory: Standard Model

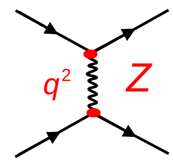
5. Structure of neutral currents

Ansatz: Four-fermion interaction



$$M = 2\frac{4G_{NC}}{\sqrt{2}} \cdot J_{NC,1,\mu} \cdot J^\mu_{NC,2}$$

as $q^2 \to 0$ approximation of:



Experimental determination of the structure of the weak neutral currents:

$$J^\mu_{NC} = \bar{u}\,\gamma^\mu \frac{1}{2}(g_V - g_A\gamma^5)u$$

➡ Neutral weak interaction couples to left- and right-handed fermion current contributions differently:

$$g_L = \frac{1}{2}(g_V + g_A) \qquad g_R = \frac{1}{2}(g_V - g_A)$$

5.1 Vector and axial-vector couplings

In the Standard Model prediction for g_v and g_A:

	g_V	g_A
ν	$1/2$	$1/2$
ℓ^-	$-1/2 + 2\sin^2\theta_W$	$-1/2$
$u-quark$	$+1/2 - 4/3\sin^2\theta_W$	$1/2$
$d-quark$	$-1/2 + 2/3\sin^2\theta_W$	$-1/2$

with $\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2} \approx 0.223$

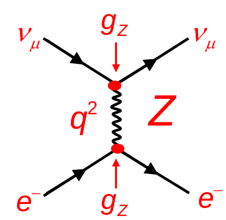
In case of the left-handed neutrinos:

$$J^\mu_\nu = \bar{u}_\nu\gamma^\mu \cdot \frac{1}{2}\cdot\underbrace{\frac{1}{2}(1-\gamma^5)}u_\nu$$

pure V-A structure

5.2 Effective coupling G_{NC}

As 4-fermion interaction is the $q^2 \to 0$ approximation of a massive boson exchange:



$$M = J_{\nu,\mu} \cdot g_Z \cdot \frac{g_{\mu\nu} - q_\mu q_\nu / M_Z^2}{q^2 - M_Z^2} \cdot g_Z \cdot J_\nu^\nu$$

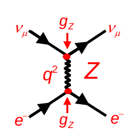
Comparison of the coupling constants in the $q^2 \to 0$ limit:

$$\frac{G_{NC}}{\sqrt{2}} = \frac{g_Z^2}{8M_Z^2} = \frac{g_W^2}{8M_W^2} \cdot \underbrace{\frac{g_Z^2 M_W^2}{g_W^2 M_Z^2}}_{\rho = 1 \quad \text{in the SM}} = \frac{g_W^2}{8M_W^2} \cdot \rho = \frac{G_F}{\sqrt{2}}$$

For the matrix element $M(\nu e \to \nu e)_{NC}$ one than finds:

$$M = \frac{G_F}{\sqrt{2}} \left[\bar{u}_\nu \gamma_\mu \frac{1}{2}(1-\gamma^5) u_\nu(p) \right] \left[\bar{u}_e \gamma^\mu (g_V^e - g_A^e \gamma^5) u_e \right]$$

5.3 Neutrino-electron scattering (NC)



Using the matrix element above one finds:

$\nu_\mu e^- \to \nu_\mu e^-$

$$\frac{d\sigma}{dy} = \frac{G_F^2 s}{\pi} \left[\overbrace{\left(\frac{g_V^e + g_A^e}{2} \right)^2}^{g_L^2} + \overbrace{\left(\frac{g_V^e - g_A^e}{2} \right)^2}^{g_R^2} (1-y)^2 \right]$$

$$\sigma(\nu_\mu e^-) = 2mE_\nu \frac{G_F^2}{\pi} \left[\left(\frac{g_V^e + g_A^e}{2} \right)^2 + \frac{1}{3} \left(\frac{g_V^e - g_A^e}{2} \right)^2 \right]$$

$\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-$

$$\frac{d\sigma}{dy} = \frac{G_F^2 s}{\pi} \left[\overbrace{\left(\frac{g_V^e - g_A^e}{2} \right)^2}^{g_R^2} + \overbrace{\left(\frac{g_V^e + g_A^e}{2} \right)^2}^{g_L^2} (1-y)^2 \right]$$

$$\sigma(\bar{\nu}_\mu e^-) = 2mE_\nu \frac{G_F^2}{\pi} \left[\left(\frac{g_V^e - g_A^e}{2} \right)^2 + \frac{1}{3} \left(\frac{g_V^e + g_A^e}{2} \right)^2 \right]$$

Determination of the vector/axial-vector couplings

$$\sigma(\nu_\mu e^-) = 2mE_\nu \frac{G_F^2}{3\pi}\left[g_V^{e^2} + g_V^e g_A^e + g_A^{e^2}\right]$$

$$\sigma(\bar{\nu}_\mu e^-) = 2mE_\nu \frac{G_F^2}{3\pi}\left[g_V^{e^2} - g_V^e g_A^e + g_A^{e^2}\right]$$

$$\frac{\sigma(\nu_\mu e)}{E_\nu} = [1{,}9 \pm 0{,}4\ (\text{stat.}) \pm 0{,}4\ (\text{syst.})] \cdot 10^{-42}\ \frac{\text{cm}^2}{\text{GeV}},$$

$$\frac{\sigma(\bar{\nu}_\mu e)}{E_{\bar{\nu}}} = [1{,}5 \pm 0{,}3\ (\text{stat.}) \pm 0{,}4\ (\text{syst.})] \cdot 10^{-42}\ \frac{\text{cm}^2}{\text{GeV}}.$$