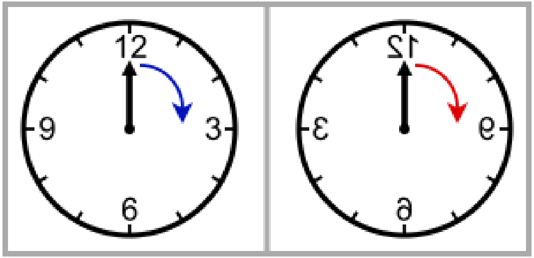
Particle Physics II
Lecture 2: The weak interaction

Lesya Shchutska

March 7, 2024

Fundamental symmetries and SM interactions

- reminder: parity transformation
- QED, QCD and parity conservation
- experimental observation of parity violation: Wu experiment
- structure of weak interaction



Parity

- the parity operator performs spatial inversion:

$$\psi'(\vec{x},t) = \hat{P}\psi(\vec{x},t) = \psi(-\vec{x},t) \tag{1}$$

- applying $\hat{P}$ twice:

$$\hat{P}\hat{P}\psi(\vec{x},t) = \hat{P}\psi(-\vec{x},t) = \psi(\vec{x},t) \tag{2}$$

- so $\hat{P}\hat{P} = I \implies \hat{P}^{-1} = \hat{P}$
- to preserve the normalization of the wave-function:

$$\langle\psi|\psi\rangle = \left\langle\psi'\middle|\psi'\right\rangle = \langle\psi|\hat{P}^{\dagger}\hat{P}|\psi\rangle \tag{3}$$

$$\hat{P}^{\dagger}\hat{P} = I \implies \hat{P}\text{ unitary} \tag{4}$$

- but since $\hat{P}\hat{P} = I$ then also $\hat{P} = \hat{P}^{\dagger} \implies \hat{P}$ hermitian

This implies parity is an observable quantity. If the interaction Hamiltonian commutes with $\hat{P}$, parity is an observable conserved quantity.

Parity

- if $\psi(\vec{x},t)$ is an eigenfunction of the parity operator with eigenvalue P:

$$\hat{P}\psi(\vec{x},t) = P\psi(\vec{x},t) \implies \hat{P}\hat{P}\psi(\vec{x},t) = P\hat{P}\psi(\vec{x},t) = P^2\psi(\vec{x},t) \tag{5}$$

  since $\hat{P}\hat{P} = I$ then $P^2 = 1$

- $\implies$ Parity has eigenvalues $P = \pm 1$
- QED and QCD are invariant under parity
- experimentally observe that Weak interactions do not conserve parity

Intrinsic Parities of fundamental particles

Spin-1 Bosons:

- from gauge field theory get that gauge bosons have $P = -1$:

$$P_\gamma = P_g = P_{W^+} = P_{W^-} = P_Z = -1 \tag{6}$$

Spin-$\frac{1}{2}$ Fermions:

- from Dirac equation: spin-$\frac{1}{2}$ particles have opposite parity to spin-$\frac{1}{2}$ antiparticles
- convention: spin-$\frac{1}{2}$ particles have $P = +1$:

$$P_{e^-} = P_{\mu^-} = P_{\tau^-} = P_\nu = P_q = +1 \tag{7}$$

and antiparticles have opposite parity, i.e.:

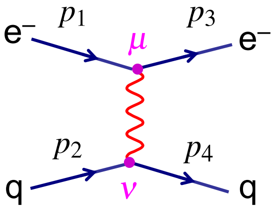
$$P_{e^+} = P_{\mu^+} = P_{\tau^+} = P_{\bar{\nu}} = P_{\bar{q}} = -1 \tag{8}$$

- for Dirac spinors the parity operator is

$$\hat{P} = \gamma^0 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \tag{9}$$

Parity conservation in QED and QCD

From QED Feynman rules for the QED process $e^- q \to e^- q$:



$$-iM = [\bar{u}_e(p_3) ie\gamma^\mu u_e(p_1)] \frac{-ig_{\mu\nu}}{q^2} [\bar{u}_q(p_4) ie\gamma^\nu u_q(p_2)] \quad (10)$$

which can be expressed in terms of the electron and quark 4-vector currents:

$$M = -\frac{e^2}{q^2} g_{\mu\nu} j_e^\mu j_q^\nu = -\frac{e^2}{q^2} j_e \cdot j_q \quad (11)$$

with $j_e = \bar{u}_e(p_3)\gamma^\mu u_e(p_1)$ and $j_q = \bar{u}_e(p_4)\gamma^\mu u_e(p_2)$

Parity conservation in QED and QCD

Under parity transformation:

- spinors transform as $u \xrightarrow{\hat{P}} \hat{P}u = \gamma^0 u$
- adjoint spinors transform as

$$\bar{u} = u^\dagger \gamma^0 \xrightarrow{\hat{P}} \left(\hat{P}u\right)^\dagger \gamma^0 = u^\dagger \gamma^{0\dagger} \gamma^0 = u^\dagger \gamma^0 \gamma^0 = \bar{u}\gamma^0 \quad (12)$$

$$\implies \bar{u} \xrightarrow{\hat{P}} \bar{u}\gamma^0 \quad (13)$$

- hence $j_e = \bar{u}_e(p_3)\gamma^\mu u_e(p_1) \xrightarrow{\hat{P}} \bar{u}_e(p_3)\gamma^0\gamma^\mu\gamma^0 u_e(p_1)$
- its components:

$$0 : j_e^0 \xrightarrow{\hat{P}} \bar{u}\gamma^0\gamma^0\gamma^0 u = \bar{u}\gamma^0 u = j_e^0, \text{ since } \gamma^0\gamma^0 = 1 \quad (14)$$

$$k = 1,2,3 : j_e^k \xrightarrow{\hat{P}} \bar{u}\gamma^0\gamma^k\gamma^0 u = -\bar{u}\gamma^k\gamma^0\gamma^0 u = -\bar{u}\gamma^k u = -j_e^k, \quad (15)$$

$$\text{since } \gamma^0\gamma^k = -\gamma^k\gamma^0 \quad (16)$$

- the time-like component remains unchanged and the space-like components change

Parity conservation in QED and QCD

- similarly for the quark vector current: $j_q^0 \xrightarrow{\hat{P}} j_q^0$, $j_q^k \xrightarrow{\hat{P}} -j_q^k$, $k = 1, 2, 3$
- consequently for the four-vector scalar product:

  $j_e \cdot j_q = j_e^0 j_q^0 - j_e^k j_q^k \xrightarrow{\hat{P}} j_e^0 j_q^0 - (-j_e^k)(-j_q^k) = j_e \cdot j_q$

QED Matrix elements are parity invariant
$\Longrightarrow$ **Parity is conserved in QED**

The QCD vertex has the same form and thus:

$\Longrightarrow$ **Parity is conserved in QCD**

Vectors and axial vectors

- the parity operator $\hat{P}$ corresponds to a discrete transformation $x \to -x$, etc
- under the parity transformation:
  1. vectors change sign:

$$\vec{r} \xrightarrow{\hat{P}} -\vec{r} \tag{17}$$

$$\vec{p} \xrightarrow{\hat{P}} -\vec{p} \quad (p_x = \frac{\partial}{\partial x}) \tag{18}$$

  2. axial vectors remain unchanged

$$\vec{L} \xrightarrow{\hat{P}} \vec{L} \quad (\vec{L} = \vec{r} \times \vec{p}) \tag{19}$$

$$\vec{\mu} \xrightarrow{\hat{P}} \vec{\mu} \quad (\vec{\mu} \propto \vec{L}) \tag{20}$$

Note that $\vec{B}$ is an axial vector too: $\mathrm{d}\vec{B} \propto \vec{J} \times \vec{r}\, \mathrm{d}^3\vec{r}$

Parity violation in β-decay

- P-conservation was widely accepted by physicists in 1920-50s, and was experimentally verified in QED and QCD
- however, in mid-1950s some kaons decays could not be explained by a P-conserving theory:
  - there seemed to be 2 types of K: decaying either to 2π or to 3π
  - known as $\tau - \theta$ puzzle (τ and θ referred to types of kaons)
- theorists Tsung-Dao Lee and Chen-Ning Yang after a literature review concluded that there was no experimental evidence about parity conservation in weak decays
- they approached Chien-Shiung Wu, who was an expert on beta decay spectroscopy, with ideas on an experiment
- and finally decided to use ^{60}Co nuclei and carry out an experiment in a low-temperature laboratory of the National Bureau of Standards

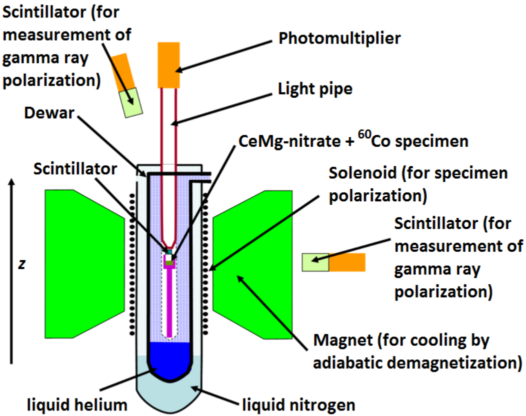
Parity violation in β-decay

- in **1956** Chien-Shiung Wu et al studied β-decay of polarized ^{60}Co nuclei:

$$^{60}\text{Co} \rightarrow ^{60}\text{Ni}^* + e^- + \bar{\nu}_e \qquad (21)$$

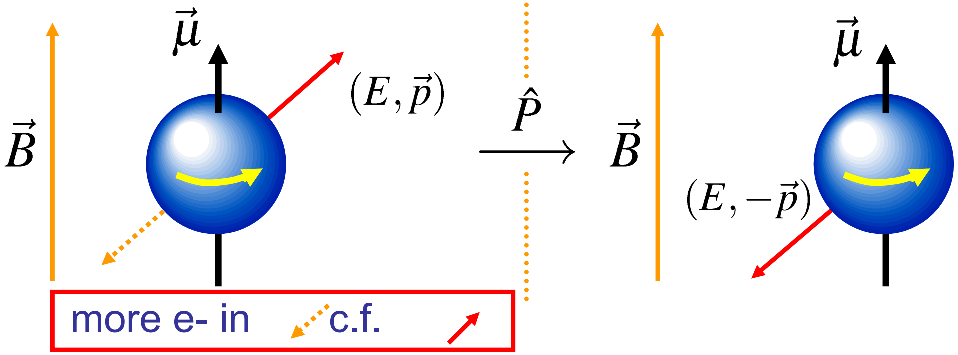
$$^{60}\text{Ni}^* \rightarrow ^{60}\text{Ni} + 2\gamma \qquad (22)$$

- atoms that were aligned by a uniform magnetic field and cooled to near absolute zero so that thermal motions did not ruin the alignment
- photons are emitted due to QED $\Longrightarrow$ conserve parity and can be used as a control!



Parity violation in β-decay

- anisotropy in photons was measured as roughly 40:60
- and observed electrons emitted preferentially in direction opposite to applied magnetic field:



Parity violation in β-decay

- if parity were conserved: expect equal rate for producing e^- in directions along and opposite to the nuclear spin
- conclude parity is violated in weak interaction
- the results shocked the physics community
- Wolfgang Pauli: “That’s total nonsense!”, and then “Then it must be repeated!”
- the experiment was repeated by other teams, and results were confirmed
- $\implies$ weak interaction vertex is not of the form $\bar{u}_e \gamma^\mu u_\nu$

- the requirement of Lorentz invariance of the matrix element severely restricts the form of the interaction vertex
- QED and QCD are **vector** interactions:

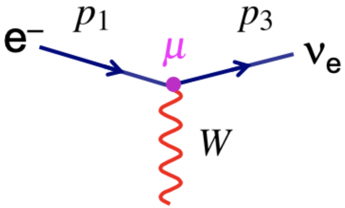
$$j^\mu = \bar{\psi}\gamma^\mu\phi \tag{23}$$

  This combination transforms as a 4-vector
- in general, there are only 5 possible combinations of two spinors and γ-matrices that form Lorentz-invariant currents, called **"bilinear covariants"**:

Type	Form	Components	"Boson Spin"
♦ SCALAR	$\overline{\psi}\phi$	1	0
♦ PSEUDOSCALAR	$\overline{\psi}\gamma^5\phi$	1	0
♦ VECTOR	$\overline{\psi}\gamma^\mu\phi$	4	1
♦ AXIAL VECTOR	$\overline{\psi}\gamma^\mu\gamma^5\phi$	4	1
♦ TENSOR	$\overline{\psi}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)\phi$	6	2

V–A structure of the weak interaction

- the most general form for the interaction between a fermion and a boson is a linear combination of bilinear covariants
- for an interaction corresponding to the **exchange of a spin-1** particle the most general form is a linear combination of vector and axial-vector
- the form for weak interaction is **determined from experiment** to be **vector – axial-vector** or **V–A** (V minus A)



$$j^\mu \propto \bar{u}_{\nu_e}(\gamma^\mu - \gamma^\mu \gamma^5) u_e$$

V – A

Can this account for parity violation?

- parity transformation of a pure axial-vector current $j_A = \bar{\psi}\gamma^\mu\gamma^5\phi$:

$$j_A^\mu \xrightarrow{\hat{P}} -j_{A\mu} \tag{24}$$

- the space-like components remain unchanged and the time-like components change sign
- this is opposite to the parity properties of a vector current

$j_A^0 \xrightarrow{\hat{P}} -j_A^0; \quad j_A^k \xrightarrow{\hat{P}} +j_A^k;$	$j_V^0 \xrightarrow{\hat{P}} +j_V^0; \quad j_V^k \xrightarrow{\hat{P}} -j_V^k$

V–A structure of the weak interaction

- to describe an interaction, one needs to look at the matrix element
- consider matrix elements for two currents:

$$\mathcal{M} \propto g_{\mu\nu} j_1^\mu j_2^\nu = j_1^0 j_2^0 - \sum_{k=1}^{3} j_1^k j_2^k \tag{25}$$

- for the combination of a two axial-vector currents:

$$j_{A1} \cdot j_{A2} \xrightarrow{\hat{P}} \left(-j_1^0\right)\left(-j_2^0\right) - \sum_{k=1}^{3} \left(j_1^k\right)\left(j_2^k\right) = j_{A1} \cdot j_{A2} \tag{26}$$

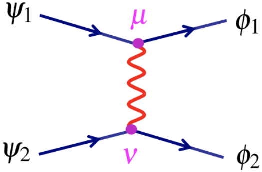
- hence parity is conserved for both pure vector and pure axial-vector interactions
- but the combination of a vector and an axial-vector currents

$$j_{V1} \cdot j_{A2} \xrightarrow{\hat{P}} \left(j_1^0\right)\left(-j_2^0\right) - \sum_{k=1}^{3} \left(-j_1^k\right)\left(j_2^k\right) = -j_{V1} \cdot j_{A2} \tag{27}$$

changes sign under parity $\implies$ can give parity violation!

V–A structure of the weak interaction

- now consider a general linear combination of vector and axial-vector (relevant for the Z boson vertex)



$$
\left\{
\begin{array}{c}
j_1 = \overline{\phi}_1 (g_V \gamma^\mu + g_A \gamma^\mu \gamma^5) \psi_1 = g_V j_1^V + g_A j_1^A \\
\dfrac{g_{\mu\nu}}{q^2 - m^2} \\
j_2 = \overline{\phi}_2 (g_V \gamma^\mu + g_A \gamma^\mu \gamma^5) \psi_2 = g_V j_2^V + g_A j_2^A
\end{array}
\right.
$$

$$M_{fi} \propto j_1 . j_2 = g_V^2 j_1^V . j_2^V + g_A^2 j_1^A . j_2^A + g_V g_A (j_1^V . j_2^A + j_1^A . j_2^V)$$

V–A structure of the weak interaction

- consider the parity transformation of this scalar product:

$$j_1 \cdot j_2 \xrightarrow{\hat{P}} g_V^2 j_1^V \cdot j_2^V + g_A^2 j_1^A \cdot j_2^A - g_V g_A \left(j_1^V \cdot j_2^A + j_1^A \cdot j_2^A \right) \qquad (28)$$

- if either g_A or g_V is zero, **parity is conserved**, i.e. parity is conserved in **pure vector** or **pure axial-vector** interaction

- relative strength of parity violating part $\propto \dfrac{g_V g_A}{g_V^2 + g_A^2}$

Maximal parity violation for V–A or for V+A

Chiral structure of QED

- chiral projection operators:

$$P_R = \frac{1}{2}\left(1+\gamma^5\right); \quad P_L = \frac{1}{2}\left(1-\gamma^5\right) \tag{29}$$

project out chiral right- and left-handed states

- in the ultrarelativistic limit, chiral states correspond to helicity states
- any spinor can be expressed as:

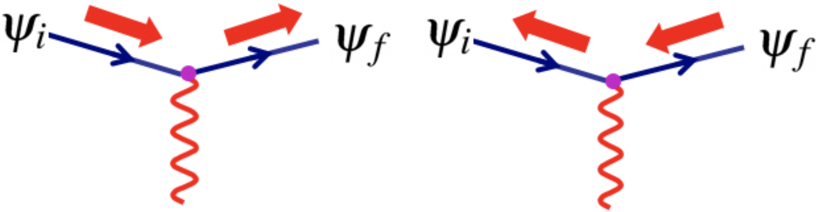
$$\psi = \frac{1}{2}\left(1+\gamma^5\right)\psi + \frac{1}{2}\left(1-\gamma^5\right)\psi = P_R\psi + P_L\psi = \psi_R + \psi_L \tag{30}$$

- the QED vertex $\bar{\psi}\gamma^\mu\phi$ in terms of chiral states:

$$\bar{\psi}\gamma^\mu\phi = \bar{\psi}_R\gamma^\mu\phi_R + \bar{\psi}_R\gamma^\mu\phi_L + \bar{\psi}_L\gamma^\mu\phi_R + \bar{\psi}_L\gamma^\mu\phi_L \tag{31}$$

conserves chirality, as $\bar{\psi}_R\gamma^\mu\phi_L = \bar{\psi}_L\gamma^\mu\phi_R = 0$

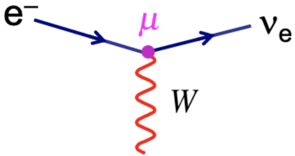
- in the ultra-relativistic limit only two helicity combinations are non-zero



Helicity structure of the weak interaction

- the charged current ($W^{\pm}$) weak vertex is:

$$\frac{-ig_W}{\sqrt{2}}\frac{1}{2}\gamma^{\mu}\left(1-\gamma^{5}\right) \tag{32}$$



Helicity structure of the weak interaction

- since $\frac{1}{2}(1-\gamma^5)$ projects out left-handed chiral particle states:

$$\bar{\psi}\frac{1}{2}\gamma^\mu(1-\gamma^5)\phi = \bar{\psi}\gamma^\mu\phi_L \tag{33}$$

- writing $\bar{\psi} = \bar{\psi}_R + \bar{\psi}_L$ and from discussion of QED, $\bar{\psi}_R\gamma^\mu\phi_L = 0$ gives

$$\bar{\psi}\frac{1}{2}\gamma^\mu(1-\gamma^5)\phi = \bar{\psi}_L\gamma^\mu\phi_L \tag{34}$$

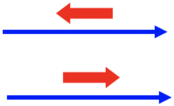
- $\Longrightarrow$ **Only the left-handed chiral components of particle spinors and right-handed chiral components of antiparticle spinors participate in charged current weak interactions**

Helicity structure of the weak interaction

- at very high energy ($E \gg m$), the left-handed chiral components are helicity eigenstates:

$\frac{1}{2}(1-\gamma^5)u \Rightarrow$

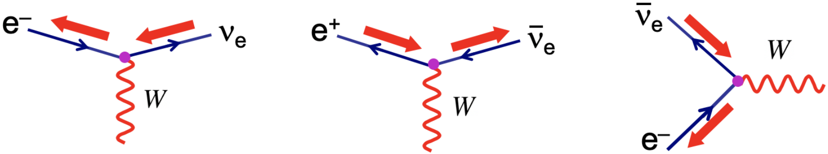
$\frac{1}{2}(1-\gamma^5)v \Rightarrow$



LEFT-HANDED PARTICLES
Helicity = -1

RIGHT-HANDED ANTI-PARTICLES
Helicity = +1

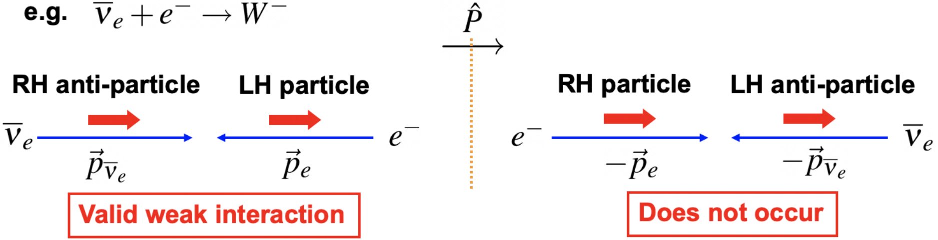
- $\Longrightarrow$ **In the ultra-relativistic limit only left-handed particles and right-handed antiparticles participate in charged current weak interactions**
- e.g. in the relativistic limit, the only possible electron - neutrino interactions are:



Helicity structure of the weak interaction

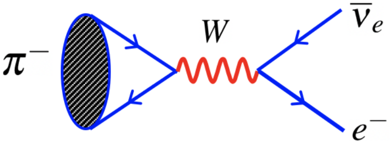
- the helicity dependence of the weak interaction $\leftrightarrow$ parity violation

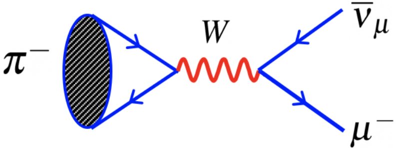
e.g. $\overline{\nu}_e + e^- \rightarrow W^-$



Helicity in pion decay

- the decays of charged pions provide a good demonstration of the role of helicity in the weak interaction





EXPERIMENTALLY:

$$\frac{\Gamma(\pi^- \to e^- \overline{\nu}_e)}{\Gamma(\pi^- \to \mu^- \overline{\nu}_\mu)} = 1.23 \times 10^{-4}$$

- while might've expected the decay to electrons to dominate - due to increased phase space...
- the opposite happens, the electron decay is helicity suppressed

Helicity in pion decay

Consider decay in pion rest frame:

- pion is spin 0: so the spins of the $\bar{\nu}$ and μ are opposite
- weak interaction only couples to RH chiral antiparticle states
- since neutrinos are (almost) massless, they must be in RH helicity state
- therefore, to conserve angular momentum, muon is emitted in a RH helicity state:

- but only left-handed chiral particle states participate in weak interaction

Helicity in pion decay

- using explicit form of the RH helicity to the Dirac equation, can split it in two parts: left-handed chiral and right-handed chiral

$$u_\uparrow = P_R u_\uparrow + P_L u_\uparrow = \frac{1}{2}\left(1 + \frac{|\vec{p}|}{E+m}\right) u_R + \frac{1}{2}\left(1 - \frac{|\vec{p}|}{E+m}\right) u_L$$

RH Helicity ($u_\uparrow$) **RH Chiral** (u_R) **LH Chiral** (u_L)

- in the limit $E \gg m$, RH helicty = RH chiral
- although only LH chiral particles participate in the weak interaction the contribution from RH helicity states is not necessarily zero!

$m_\nu \approx 0$: RH Helicity $\equiv$ RH Chiral

$m_\mu \neq 0$: RH Helicity has LH Chiral Component

Helicity in pion decay

- expect matrix element to be proportional to LH chiral component of RH helicity electron/muon spinor:

$$M_{fi} \propto \frac{1}{2}\left(1 - \frac{|\vec{p}|}{E+m}\right) = \boxed{\frac{m_\mu}{m_\pi + m_\mu}}$$

from the kinematics of pion decay at rest

- hence because the electron mass is much smaller than the pion mass the decay $\pi^- \to e^- \bar{\nu}_e$ is heavily suppressed

Evidence for V–A

The V–A nature of the charged current weak interaction vertex fits with experiment:

1. Example: charged pion decay
   - experimentally measure

$$\frac{\Gamma(\pi^- \to e^-\bar{\nu}_e)}{\Gamma(\pi^- \to \mu^-\bar{\nu}_\mu)} = (1.230 \pm 0.004) \times 10^{-4} \tag{35}$$

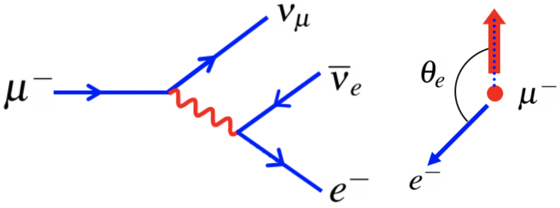
   - theoretical predictions depend on Lorentz structure of the interaction:

V-A $(\overline{\psi}\gamma^\mu(1-\gamma^5)\phi)$ **or** **V+A** $(\overline{\psi}\gamma^\mu(1+\gamma^5)\phi)$ ➡ $\frac{\Gamma(\pi^- \to e^-\overline{\nu}_e)}{\Gamma(\pi^- \to \mu^-\overline{\nu}_\mu)} \approx 1.3 \times 10^{-4}$

Scalar $(\overline{\psi}\phi)$ **or** **Pseudo-Scalar** $(\overline{\psi}\gamma^5\phi)$ ➡ $\frac{\Gamma(\pi^- \to e^-\overline{\nu}_e)}{\Gamma(\pi^- \to \mu^-\overline{\nu}_\mu)} = 5.5$

Evidence for V–A

2. Example: muon decay
   - measure electron energy and angular distributions relative to muon spin direction



   - results expressed in terms of general S+P+V+A+T form in "Michel Parameters"
   - e.g. TWIST expt: 6×10^{10} μ decays Phys. Rev. D 85 (2012) 092013
   - measurement: $\rho = 0.74977 \pm 0.00012(stat.) \pm 0.00023(syst.)$;
   - V–A prediction: $\rho = 0.75$

Weak charged current propagator

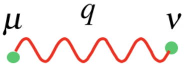
- the charged-current weak interaction is different from QED and QCD since it's mediated by massive W-bosons (80.3 GeV)
- this leads to a more complicated form for the propagator:
  - for the exchange of a massive particle:

$$\frac{1}{q^2} \text{ (massless) } \rightarrow \frac{1}{q^2 - m^2} \text{ (massive)} \tag{36}$$

  - in addition, the sum over W boson polarizations modifies the numerator

- **W boson propagator**:

$$\frac{-i\left[g_{\mu\nu} - q_\mu q_\nu / m_W^2\right]}{q^2 - m_W^2}$$



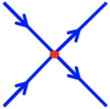
- in the limit where q^2 is small compared to $m_W = 80.3$ GeV, the interaction takes a simpler form:

$$\frac{i g_{\mu\nu}}{m_W^2}$$

- the interaction appears point-like (i.e. no q^2 dependence)

- in 1934, before the discovery of parity violation, Fermi proposed, in analogy with QED, that the invariant matrix element for β-decay was of the form:

$$M_{fi} = G_{\rm F}\, g_{\mu\nu}[\overline{\psi}\gamma^{\mu}\psi][\overline{\psi}\gamma^{\nu}\psi]$$



where $G_F = 1.166 \times 10^{-5}\ \mathrm{GeV}^{-2}$

Note the absence of a propagator: i.e. this represents an interaction at a point

- after the discovery of parity violation in 1957 this was modified to

$$M_{fi} = \frac{G_F}{\sqrt{2}} g_{\mu\nu} \left[\bar{\psi}\gamma^{\mu}(1-\gamma^5)\psi\right] \left[\bar{\psi}\gamma^{\nu}(1-\gamma^5)\psi\right] \tag{37}$$

the factor $\sqrt{2}$ was included so the numerical value of G_F did not need to be changed

- we can compare this to the prediction for W-boson exchange:

$$M_{fi} = [\tfrac{g_W}{\sqrt{2}}\overline{\Psi}\tfrac{1}{2}\gamma^{\mu}(1-\gamma^5)\psi]\frac{g_{\mu\nu}-q_{\mu}q_{\nu}/m_W^2}{q^2-m_W^2}[\tfrac{g_W}{\sqrt{2}}\overline{\Psi}\tfrac{1}{2}\gamma^{\nu}(1-\gamma^5)\psi]$$

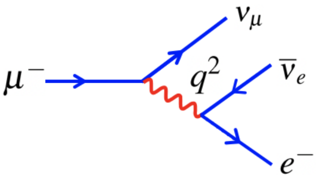
which for $q^2 \ll m_W^2$ becomes:

$$M_{fi} = \frac{g_W^2}{8m_W^2} g_{\mu\nu}\left[\bar{\psi}\gamma^{\mu}(1-\gamma^5)\psi\right]\left[\bar{\psi}\gamma^{\nu}(1-\gamma^5)\psi\right] \tag{38}$$

- $\Longrightarrow \dfrac{G_F}{\sqrt{2}} = \dfrac{g_W^2}{8m_W^2}$

- still usually use G_F to express strength of weak interaction as this is the quantity that is precisely determined in muon decay

- strength of weak interaction most precisely measured in muon decay



- here $q^2 < m_\mu$ (0.106 GeV)
- to a very good approximation the W-boson propagator can be written

$$\frac{-i\left[g_{\mu\nu} - q_\mu q_\nu / m_W^2\right]}{q^2 - m_W^2} \approx \frac{i g_{\mu\nu}}{m_W^2} \qquad (39)$$

- in muon decay measure g_W^2 / m_W^2
- in muon decay $G_F = 1.16639(1) \times 10^{-5}\ \text{GeV}^{-2}$

Strength of weak interaction

- to obtain the intrinsic strength of weak interaction need to know mass of W boson $m_W = 80.403 \pm 0.029$ GeV

$$\Longrightarrow \alpha_W = \frac{g_W^2}{4\pi} = \frac{8m_W^2 G_F}{4\sqrt{2}\pi} = \frac{1}{30} \tag{40}$$

- the intrinsic strength of the weak interaction is similar to, but greater than, the EM interaction!

- it is the massive W-boson in the propagator which makes it appear weak

- for $q^2 \gg m_W^2$ weak interactions are more likely than EM

Summary

- weak interaction is of form Vector – Axial-vector (V–A)

$$\frac{-ig_{\mu\nu}}{\sqrt{2}}\frac{1}{2}\gamma^{\mu}\left(1-\gamma^{5}\right) \tag{41}$$

- consequently only left-handed chiral particle states and right-handed chiral antiparticle states participate in the weak interaction

$$\Longrightarrow \quad \text{maximal parity violation} \tag{42}$$

- weak interaction also violates Charge Conjugation symmetry
- at low q^2 weak interaction is only weak because of the large W-boson mass

$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8m_W^2} \tag{43}$$

- intrinsic strength of weak interaction is similar to that of QED