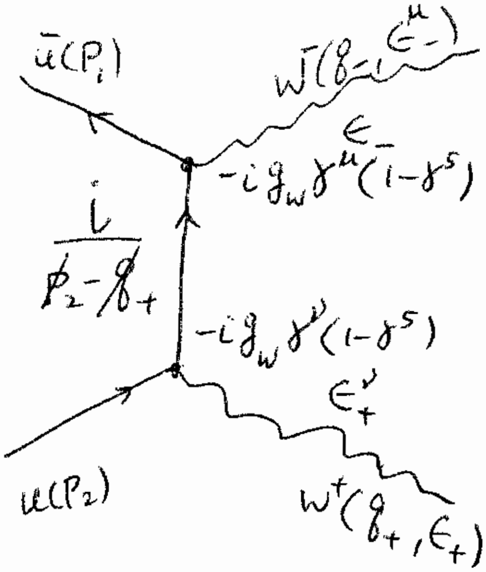
$$\bar{u}(P_1) + u(P_2) \rightarrow W^+(q_+, \epsilon_+) + W^-(q_-, \epsilon_-)$$

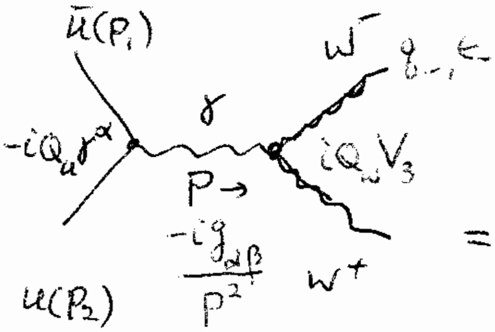


$$M_1 = -ig_W^2 \bar{v}(P_1)(1+\gamma^5) \not{\epsilon}_- \frac{\not{P}_2 - \not{q}_+}{(P_2 - q_+)^2} \not{\epsilon}_+ (1-\gamma^5)$$

$$= -2ig_W^2 \bar{v}(P_1)(1+\gamma^5) \not{\epsilon}_- \frac{\not{P}_2 - \not{q}_+}{(P_2 - q_+)^2} \not{\epsilon}_+ u(P_2)$$

$$\because (1+\gamma^5)(1+\gamma^5) = 1 + 2\gamma^5 + 1 = 2(1+\gamma^5)$$

$$\frac{\not{P}_2 - \not{q}_+}{(P_2 - q_+)^2} \frac{q_+^{\mu}}{m_W} u_2 = \frac{\not{P}_2 \not{q}_+}{-2P_2 \cdot q_+} \frac{u_2}{m_W} = \frac{2q_+ \cdot P_2 - \not{q}_+ \not{P}_2}{-2P_2 \cdot q_+} u_2 =$$



$$P = q_+ + q_-$$

$$M_2 = iQ_u Q_W \bar{v}(P_1) \gamma^{\alpha} u(P_2) \frac{1}{s} V(q_+, \epsilon_+, q_-, \epsilon_-, -P)$$

$$= iQ_u Q_W \bar{v}(P_1) \gamma^{\alpha} u(P_2) \frac{1}{s} \Big[(q_+ - q_-)_{\alpha} \, \epsilon_+ \cdot \epsilon_-$$

$$+ (2q_- + q_+) \cdot \epsilon_+ \ \epsilon_{-\alpha}$$

$$+ (-2q_+ - q_-) \cdot \epsilon_- \ \epsilon_{+\alpha} \Big]$$

The 1st & the 3rd terms cancel.

Take W^+ longitudinal : $\epsilon_+^{\mu} \longrightarrow \frac{q_+^{\mu}}{m}$ use $2q_- \cdot q_+ \ \not{\epsilon}_- = 2(E_+^2 + P_+^2)\not{\epsilon}_-$

$\therefore 2q_- \cdot q_+ \not{\epsilon}_- + q_+^2 = (4E_+^2 - m_W^2)\not{\epsilon}_- = (s - m_W^2)$;

$$M_1 \rightarrow 2ig_W^2 \frac{1}{m_W} \bar{v}(P_1)(1+\gamma^5) \not{\epsilon}_- u(P_2) \qquad (V-A)$$

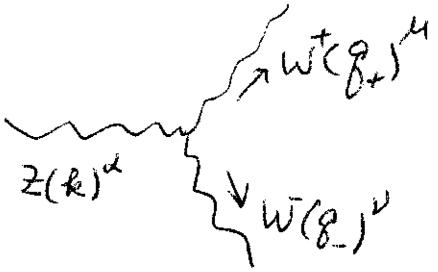
$$M_2 \rightarrow iQ_u Q_W \frac{1}{m_W} \frac{s - m_W^2}{s} \bar{v}(P_1) \not{\epsilon}_- u(P_2) \qquad \text{pure } V$$

No cancellation possible !

$\Rightarrow$ Need another particle with V & A couplings to $f\bar{f}$.

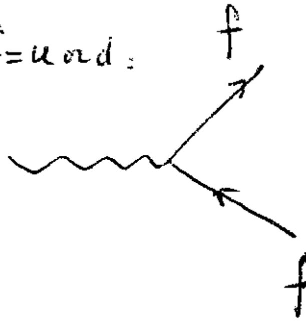
Z^0 (!)

Introduce the Z^0, a photon like particle with both $V+A$!



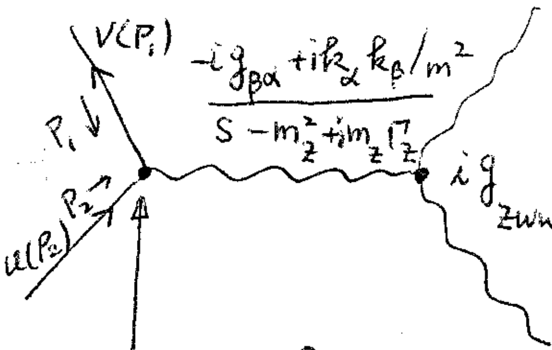
$$i\, g_{ZWW}\, V(q_+, \mu, q_-, \nu, k, \alpha)$$

f = u or d:



$$i\,(V_f + a_f \gamma^5)\,\gamma^\mu$$

The extra diagram is



$$k = +q_+ + q_-$$

$$i\, g_{ZWW}\, V(q_+, \mu, q_-, \nu, -k, \alpha)$$

$$i(V_u + a_u \gamma^5)\gamma^\beta$$

$$\because \begin{cases} \bar{v}(P_1)\,\not{P}_1 = 0 \\ k\cdot\epsilon = 0 \text{ etc.} \\ \not{P}_2\, u(P_2) = 0 \end{cases}$$

$$M_3 = i g_{ZWW}\, \bar{v}(P_1)(V_u + a_u\gamma^5)\,\gamma^\beta u(P_2)\, \frac{(-g_{\beta\alpha} + \overbrace{\cancel{k_\alpha k_\beta / m^2}}^{0})}{s - m_Z^2 + i m_Z \Gamma_Z}\, V(q_+, \mu, q_-, \nu, -q_+ - q_-, \alpha)$$

$$M_3 = i g_{ZWW} \frac{\bar{v}(P_1)(V_u + a_u \gamma^5)\gamma^\beta u(P_2)}{s - m_Z^2 + i m_Z \Gamma_Z} \Big[(q_+ - q_-)_\beta (\epsilon_+ \cdot \epsilon_-)$$

$$+ (2q_- + q_+)_\mu \cdot \epsilon_+^\mu \, \epsilon_{-\beta}$$

$$+ (-q_- - 2q_+)_\mu \cdot \epsilon_-^\mu \, \epsilon_{+\beta} \Big]$$

$$\underset{\lim \epsilon_+ \to \frac{q_+}{m_W}}{M_3 \longrightarrow} i g_{ZWW} \frac{\bar{v}(P_1)(V_u + a_u \gamma^5)\gamma^\beta u(P_2)}{s - m_Z^2 + i m_Z \Gamma_Z} \Big[(q_+ - q_-)(q_+ \cdot \epsilon_-)$$

$$+ (2q_- + q_+) \cdot q_+ \, \epsilon_{-\beta}$$

$$+ (- \quad 2q_+) \cdot \epsilon_- \, q_+ \Big] / m_W$$

$$q_+^2 + 2q_- \cdot q_+ = 2(E_W^2 + P_W^2) = 4E^2 - m^2 = s - m_W^2$$

$$\therefore M_3 \Rightarrow i g_{ZWW} \frac{s - m_W^2}{s - m_Z^2} \bar{v}(P_1)(V_u + a_u \gamma^5) \not{\epsilon}_- u(P_2)$$

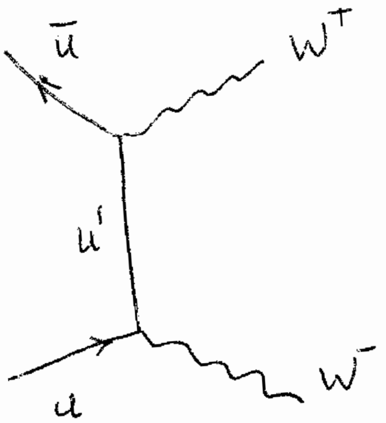
$$M = M_1 + M_2 + M_3$$

$$V: \quad 2g_W^2 + Q_u Q_W + g_{ZWW} V_u = 0$$

$$A: \quad 2g_W^2 \quad + g_{ZWW} a_u = 0$$

One could propose a u quark with charge

$$Q_{u'} = \frac{5}{3}e \qquad \text{instead of the } Z^0$$



$$M_3' = -i\,\bar{v}(P_1)(V+A\gamma^5)\not{\epsilon}_+ \frac{\not{q}_+ - \not{P}_1}{(q_+ - P_1)^2}(V+A\gamma^5)\not{\epsilon}_- u$$

Let $\epsilon_+^\mu \to q_+^\mu / m_W$

$$M_3' \longrightarrow -i\,\bar{v}(P_1)(V^2 + A^2 + 2VA\gamma^5)\not{\epsilon}_- u(P_2)$$

So

$$V^2 + A^2 = 2g_W^2 + Q_u Q_W$$

$$2VA = 2g_W^2$$

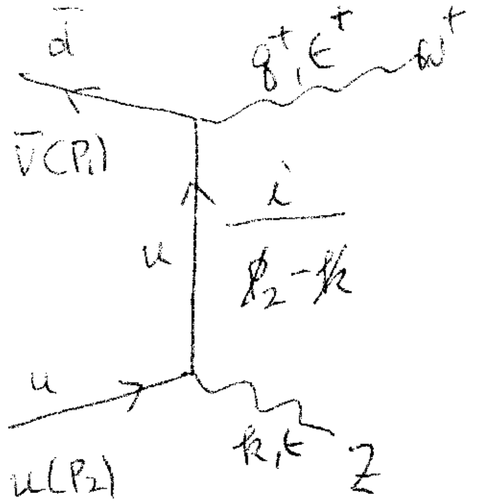
But 1) $(V-A)^2 = Q_u Q_W < 0$ complex coupling

2) $\sigma(u'\bar{u'})$ would be divergent, unless a u'' with

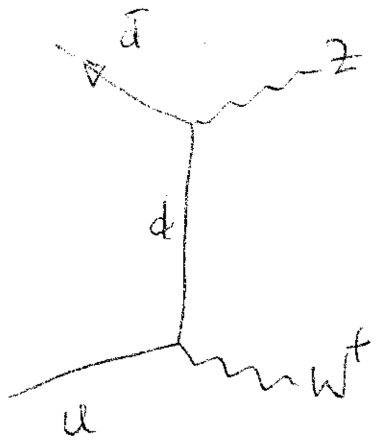
$$Q \text{ of } u'' = \frac{8}{3}e = Q_{u'} - Q_W$$

Infinite series

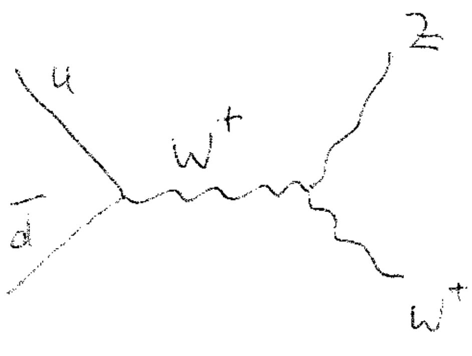
$\bar{d}\, u \to W\, Z$



$$M_1 = -i g_w \bar{v}(P_1) \gamma_\mu (1-\gamma_5) \epsilon_+^\mu \frac{i}{\not p_2 - \not k} \gamma_\nu i(V_u - A_u \gamma_5) \epsilon^\nu u(P_2)$$



$$M_2 : M_1 \begin{array}{l} (\epsilon_+ \leftrightarrow \epsilon) \\ (q^+ \leftrightarrow k) \\ (V_d - A_d \gamma_5) \end{array}$$



$$M_3 = -i g_w \bar{v}(P_1) \gamma_\mu (1-\gamma_5) u(P_2)\; i g_{ZWW} \frac{1}{s - m_W^2} V(q_+, \epsilon_+, k, \epsilon, (-q_+ - k))$$

$$M_1 + M_2 + M_3 \xrightarrow[\epsilon_+ \to q_+/m_W]{} 0$$

$$g_{ZWW} = V_d + A_d - V_u - A_u$$

Constraints on the couplings from unitarity

from $M(u\bar{d} \to W^+\gamma)\Big|_{\epsilon^\mu \to k^\mu} = 0$

(1) $Q_W = Q_d - Q_u$

6 eqs. 7 parameters

$\therefore$ 1 left

$\sin^2\theta_W \sim 0.23$

---

from $M(u\bar{d} \to W^+Z)$: $\epsilon_+^\mu \to q_+^\mu/m_W$, $\epsilon_{Z^0}^\mu \to q_0^\mu/m_Z$

$$\overset{(7)}{g_{WWZ}} = \overset{(3)}{v_d} + \overset{(4)}{a_d} - \overset{(5)}{v_u} - \overset{(6)}{a_u}$$

---

from $M(u\bar{u} \to W^+W^-)\Big|_{\epsilon_+^\mu \to q_+^\mu/m_W} = 0$

$$\overset{(2)}{2g_W^2} + Q_u Q_W + v_u g_{WWZ} = 0 \qquad V$$

$$2g_W^2 + a_u g_{WWZ} = 0 \qquad A$$

---

from $d\bar{d} \to W^+W^-$:

$$-2g_W^2 + Q_d Q_W + v_d g_{WWZ} = 0 \qquad V$$

$$-2g_W^2 + a_d g_{WWZ} = 0 \qquad A$$

$f\bar{f} \to ZZ, \gamma\gamma$ do not lead to constraints, since the amplitudes are automatically o.k.

unitary $\leftrightarrow$ $\qquad g_W = \frac{e}{S_W\sqrt{8}}$

Now $\quad g_{WWZ} = -e\,\frac{c_W}{S_W} \qquad m_W = \sqrt{\frac{\pi\alpha}{G\sqrt{2}}}\,/S_W = \frac{37.28}{S_W}$ GeV

$$a_u = -a_d = \frac{e}{4 S_W c_W}$$

$$V_u = \quad '' \quad \{1 - 4 S_W^2 Q_u\}$$

$$V_d = \quad '' \quad \{1 + 4 S_W^2 Q_d\}$$

---

next $\quad g_{HWW} = -e\,\frac{m_W}{S_W}$

$$g_{HZZ} = -e\,\frac{m_Z}{S_W c_W}$$

$$c_W = \frac{m_W}{m_Z}$$

$$m_W = \sqrt{\frac{\pi\alpha}{G\sqrt{2}}}\;\frac{1}{S_W} \quad \sim 78$$

$$m_Z = m_W/c_W \quad \sim 88$$

$$g_{Hff} = \frac{e}{2S_W}\,\frac{m_f}{m_W}$$

$$g_{ZZHH} = \frac{e^2}{2S_W^2 c_W^2}$$

$$g_{WWHH} = \frac{e^2}{2S_W^2}$$

g_{3H}

g_{4H}