Schwache Wechselwirkung

4-Fermion Wechselwirkung

geladene Ströme

allgemeinste Matrixelemente

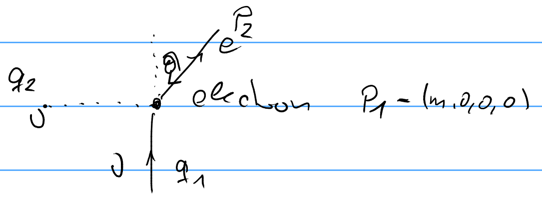
$$\mathcal{M} = \sum_i C_i \, \underbrace{\bar{\nu}\, O_i\, e}\; \underbrace{\bar{e}\, O_i (1-\gamma_5)\, \nu}$$

$O_i = \{$	S	1	skalar
	P	γ_5	pseudo-skalar
	T	$\sigma_{\mu\nu}$	tensor
	V	γ_μ	vektor
	A	$\gamma_\mu \gamma_5$	axial vektor

V ± A anstelle von V und A getrennt

Prozesse der Form $\overset{q_1}{\nu}\overset{p_1}{e} \to \overset{q_2}{\nu}\overset{p_2}{e}$, $\bar{\nu} e \to \bar{\nu} e$

Lab-System



$q_1 = (E, 0, 0, E)$ $\qquad$ $p_1 = (m, 0, 0, 0)$

$q_2 = (E' + m - E, \; -p' \sin\theta_2, 0, -p' \cos\theta_2)$ $\qquad$ $p_2 = (E', p' \sin\theta_2, 0, p' \cos\theta_2)$

$$E'^2 - p'^2 = m^2 \Rightarrow E' = \sqrt{p'^2 + m^2} = yE$$

↳ Bruchteil der einl. Neutrino Energie

Skalarprodukte, invariant unter Lorentztrafos

$$p_1 q_1 = p_2 q_2 = mE \qquad m \ll E$$

$$p_1 q_2 = p_2 q_1 = m(E + m - E') \approx mE(1-y)$$

$$p_1 p_2 = mE' = mEy \qquad q_1 q_2 = m(E' - m) \approx mEy$$

CMS - System

s = CMS Schwerpunktsenergie^2

$S = (p_1 + q_1)^2$

$q_1 = (p^*, 0, 0, p^*)$ $\qquad p_1 = (\omega^*, 0, 0, -p^*)$

$s = (p^* + \omega^*)^2$ $\qquad \omega^{*2} - p^{*2} = m^2$

$p^* = \frac{s - m^2}{2\sqrt{s}}$ $\qquad \omega^* = \frac{s + m^2}{2\sqrt{s}}$

$q_2 = (p^*, -\sin\theta p^*, 0, -\cos\theta p^*)$ $\qquad p_2 = (\omega^*, \sin\theta p^*, 0, \cos\theta p^*)$

$$p_1 q_1 = p_2 q_2 = p^*(p^* + \omega^*) \approx 2 p^{*2} \qquad m \ll E, \; p^* \approx \omega^*$$

$$p_1 q_2 = p_2 q_1 = p^*(\omega^* - p^* \cos\theta) \approx p^{*2}(1 - \cos\theta)$$

$$p_1 p_2 = \omega^{*2} + p^{*2}\cos\theta \approx p^{*2}(1 + \cos\theta)$$

$$q_1 q_2 = p^*(1 + \cos\theta)$$

Einfachste Möglichkeit: Streuung $\nu e \to \nu e$ Skalare WW

$$\mathcal{M} = \bar{u}(\nu, q_2)\, u(e, p_1)\, \bar{u}(e, p_2)\,(1-\gamma_5)\, u(\nu, q_1)$$

$$|\mathcal{M}|^2 = \sum_{\text{spin}} \underbrace{\bar{u}(\nu, q_2)\, u(e, p_1)}_{1}\, \underbrace{\bar{u}(e, p_2)\,(1-\gamma_5)\, u(\nu, q_1)}_{2}\, \underbrace{\bar{u}(\nu, q_1)\,(1+\gamma_5)\, u(e, p_2)}_{2}\, \underbrace{\bar{u}(e, p_1)\, u(\nu, q_2)}_{1}$$

$$= \sum_{\text{spins}} \mathrm{tr}\{u(e, p_1)\bar{u}(e, p_1) u(\nu, q_2) \bar{u}(\nu, q_2)\}$$
$$\cdot \mathrm{tr}\{(1-\gamma_5) u(\nu, q_1) \bar{u}(\nu, q_1)(1+\gamma_5) u(e, p_2) \bar{u}(e, p_2)\}$$

$$= \underbrace{\mathrm{tr}\{(m + \not{p}_1)\not{q}_2\}}_{4 p_1 \cdot q_2} \; \underbrace{\mathrm{tr}\{(1-\gamma_5)\not{q}_1(1+\gamma_5)(m + \not{p}_2)\}}$$

$$\mathrm{tr}\{(1-\gamma_5)(1-\gamma_5)\not{q}_1(m + \not{p}_2)\}$$

$$2\,\mathrm{tr}\{(1-\gamma_5)\not{q}_1(m + \not{p}_2)\}$$

$$8\, q_1 \cdot p_2$$

$$\sum_{\sigma \in \text{spin}} u(p, m, \sigma)\bar{u}(p, m, \sigma) = \not{p} + m$$

$$\sum v(p, m, \sigma)\bar{v}(p, m, \sigma) = \not{p} - m$$

$$|M|^2 = 32 (p_1 \cdot q_2)(q_1 \cdot p_2)$$

mitteln über Elektronspins

$$\overline{|M|}^2 = \frac{1}{2} |M|^2 = 16 (p_1 \cdot q_2)(q_1 \cdot p_2) = p^{*4} (1-\cos\theta)^2$$

$$\frac{d\sigma}{d\Omega} = \frac{\overline{|M|}^2}{64\pi^2 s} \Rightarrow \boxed{\frac{d\sigma}{d\Omega} = \frac{mE(1-\cos\theta)^2}{32\pi^2}}$$

$$\sigma = \int d\Omega \frac{d\sigma}{d\Omega} = \frac{mE}{16\pi} \int_{-1}^{1} dz (1-z)^2 = \boxed{\frac{mE}{6\pi} \cdot \sigma}$$

$$\int d\Omega = \underbrace{\int_0^{2\pi} d\phi}_{2\pi} \int_{-1}^{1} d\cos\theta$$

- $\bar{\nu} e \to \bar{\nu} e$: vertausche $q_1 \leftrightarrow q_2$

$$|M|^2 = 16 (p_1 q_1)(p_2 q_2) \Rightarrow \boxed{\frac{d\sigma}{d\Omega} = \frac{mE}{2\pi} \qquad \sigma = \frac{mE}{2\pi}}$$

$\bar{\nu} e \to \bar{\nu} e$ Faktor 3 größer als $\nu e \to \nu e$

- V-A WW $\qquad \nu e \to \nu e$

$$M = \bar{u}(\nu, q_2) \gamma^\mu (1-\gamma_5) u(e, p_1) \bar{u}(e, p_2) \gamma_\mu (1-\gamma_5) u(\nu, q_1)$$

$$|M|^2 = \bar{u}(\nu, q_2) \gamma^\mu (1-\gamma_5) u(e, p_1) \bar{u}(e, p_2) \gamma_\mu (1-\gamma_5) u(\nu, q_1)$$
$$\bar{u}(\nu, q_1) (1+\gamma_5) \gamma^\nu u(e, p_2) \bar{u}(e, p_1) (1+\gamma_5) \gamma_\nu \bar{u}(\nu, q_2)$$

$$= tr\{ \gamma^\mu (1-\gamma_5)(\not{p}_1 + m)(1+\gamma_5) \gamma^\nu \not{q}_2 \}$$
$$tr\{ \gamma_\mu (1-\gamma_5) \not{q}_1 (1+\gamma_5) \gamma_\nu (\not{p}_2 + m) \}$$
$$= A^{\mu\nu} \cdot B_{\mu\nu}$$

$$A^{\mu\nu} = tr\{ \gamma^\mu (1-\gamma_5)(\not{q}_1 + m)(1+\gamma_5)\gamma^\nu \not{q}_2 \}$$

$$= 2 tr\{ (1-\gamma_5) \gamma^\nu \not{q}_2 \gamma^\mu (\not{p}_1 + m) \}$$

$$= 8(q_2^\mu p_1^\nu - g_{\mu\nu} q_2 p_1 + q_2^\nu p_1^\mu)$$
$$- 8i \, \varepsilon_{\mu\nu\rho\sigma} q_2^\rho p_1^\sigma$$

$$B^{\mu\nu} = 8(q_1^\mu p_2^\nu - g_{\mu\nu} q_1 p_2 + q_1^\nu p_2^\mu)$$
$$+ 8i \, \varepsilon_{\mu\nu\rho\sigma} q_1^\rho p_2^\sigma$$

$$\bar{u} \gamma^\mu \cdots \gamma^\nu u = \mathbb{R}/\mathbb{C}$$

$$\bar{u} \gamma^\mu \cdots \gamma^\nu u = tr(\bar{u} \gamma^\mu \cdots \gamma^\nu u)$$

Spur zyklisch $= tr(u\bar{u} \gamma^\mu \cdots \gamma^\nu)$

$u\bar{u} \to \not{p} + m$

$\to$ Problem: Spuren von γ' .. auszurechnen

$$|M|^2 = A^{\mu\nu} B_{\mu\nu}$$
$$= 128 \left((q_1 - q_2)(p_1 p_2) + (q_1 p_1)(q_2 p_2) \right)$$
$$- 64 i \, \varepsilon_{\mu\nu\rho\sigma} q_2^\rho p_1^\sigma (q_1^\mu p_2^\nu + q_1^\nu p_2^\mu) \; * = 0 \text{ nur 3 unabh. Impulse}$$
$$+ 64 i \, \varepsilon_{\mu\nu\rho\sigma} q_1^\rho p_2^\sigma (q_2^\mu p_1^\nu + q_2^\nu p_1^\mu) \; *$$
$$+ 64 \, \varepsilon_{\mu\nu\rho\sigma} \varepsilon^{\mu\nu\rho'\sigma'} q_2^\rho p_1^\sigma q_1^{\rho'} p_2^{\sigma'} \leftarrow 128(q_1 p_1 \, q_2 p_2 - q_1 q_2 \, p_1 p_2)$$

$$|M|^2 = 256 (q_1 p_1)(q_2 p_2) = 256 (mE)^2$$

$$\frac{d\sigma}{dy} = \frac{4mE}{\pi} \qquad \sigma = \frac{4mE}{\pi}$$

- $\bar{\nu}_e \to \bar{\nu}_e \qquad q_1 \leftrightarrow q_2$

$$\frac{d\sigma}{dy} = \frac{4mE}{\pi}(1-y)^2 \qquad \sigma = \frac{4mE}{3\pi}$$

$$\mathcal{L}_{eff} = -\frac{G_F}{\sqrt{2}}\, \bar{\nu} \gamma^\mu (1-\gamma_5)\, e\, \bar{e}\, \gamma_\mu (1-\gamma_5)\, \nu$$

$\Rightarrow$ geladene Ströme universell, alles was bisher passiert lässt sich auch auf

$$\nu_\mu e \rightarrow \nu_e \mu$$

identische Kinematik im Lab System

$$E' = \sqrt{p'^2 - \mu^2} \qquad \mu = \text{Muonmasse}$$

$$\frac{d\sigma}{d\Omega} = \frac{|M|^2}{64\pi^2 s} \frac{p'_{cm}}{p_{cm}} = \frac{|M|^2}{64\pi^2 s} \left(1 - \frac{(\mu^2 - m^2)}{2mE}\right)^2$$

$$\rightsquigarrow \quad \sigma(\nu_\mu e \rightarrow \nu_e \mu) = \frac{2G_F^2}{\pi} mE \left(1 - \frac{(\mu^2 - m^2)}{2mE}\right)^2$$

Entwickle Streuamplitude $f(\theta)$ $\quad \left(|f(\theta)|^2 = \frac{d\sigma}{d\Omega} \right)$

$$f(\theta) = \left(2 \frac{d\sigma}{d\Omega}\right)^{1/2} = \frac{1}{\sqrt{s}} \sum_{J=0}^{\infty} (2J+1)\, P_J(\cos\theta)\, M_J$$

M_J: Partialwellen Amplitude

$|M_J| < 1$ $\hat{=}$ Unitaritätserhaltung

$$M_0 = \frac{G_F s}{\pi\sqrt{2}} \left(1 - \frac{(\mu^2 - m^2)}{s}\right) \xrightarrow{s\to\infty} \frac{G_F s}{\pi\sqrt{2}} \leq 1$$

d.h. $\quad s \leq \frac{\pi\sqrt{2}}{G_F} \qquad s \leq 600\ \text{GeV}$

Strahlenergie $\quad p_{CM} \leq 300\ \text{GeV}$

4-Fermi Theorie kann nicht für hohe Energien korrekt sein!

$\nu e \to \mu \nu$ Verletzt Unitarität ab $s = 600$ GeV

Erweiterung: Mediator für den geladenen Strom

W-Boson:
- Ladung ± 1
- massiv → kleine Energieüberträge reproduziert Niederenergie Pheno

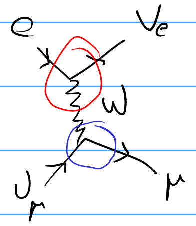
Kopplung $\quad -i\left(\frac{G_F M_W^2}{\sqrt{2}}\right)^{1/2} \gamma_\mu (1-\gamma_5)$

↳ gefittet, daß Niederenergie Pheno stimmt

Propagator $\quad \frac{-i\left(g^{\mu\nu} - \frac{k^\mu k^\nu}{M_W^2}\right)}{k^2 - M_W^2}$

3 physikalische Polarisationen (2 Transversal + Longitudinal)

$\nu e \to \nu \mu$:



$k = p_2 - q_1 = p_1 - q_2$

↓

$$\mathcal{M}_W = \frac{i G_F M_W^2}{\sqrt{2}} \bar{u}(\nu_e, q_2)\, \gamma^\mu (1-\gamma_5)\, u(e, p_1) \quad \frac{g_{\mu\nu} - k_\mu k_\nu / M_W^2}{k^2 - M_W^2}$$

$$\otimes\ \bar{u}(\mu, p_2)\, \gamma^\nu (1-\gamma_5)\, u(\nu, q_1)$$

Hochenergielimes, $k_\mu k_\nu$ → Dirac → Massen $\frac{m}{M_W} \ll 1$ vernachlässigen

$$\frac{M_W^2}{k^2 - M_W^2} \mathcal{M}_{4\text{-Fermi}} = \mathcal{M}_W$$

$$\frac{d\sigma}{d\Omega} = \frac{G_F^2 mE \left(1 - (\mu^2 - m^2)/2mE\right)^2}{2\pi^2 \left(1 + mE(1-\cos\theta)/M_W^2\right)^2}$$

tot WQ $\quad \sigma = \frac{2 G_F^2 m E}{\pi} \frac{\left(1 - (\mu^2 - m^2)/2mE\right)^2}{\left(1 + 2mE/M_W^2\right)}$

$$\lim_{E \to \infty} \sigma = \frac{G_F^2 M_W^2}{\pi} \quad \text{vernachlässigt } (m_e, m_\mu)$$

WQ explodiert nicht mehr für $E \to \infty$

S-Wellen Unitarität ist noch wie vor verletzt

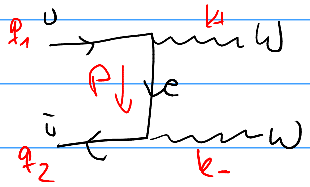
$$\mathcal{M}_0 = \frac{\sqrt{s}}{2} \int_{-1}^{1} d(\cos\theta)\, f(\theta) = \frac{G_F M_W^2}{\pi\sqrt{2}} \log\left(1 + \frac{s}{M_W^2}\right)$$

im Limes $M_W \to \infty$ reproduziert das das vorherige Ergebnis

$$\mathcal{M}_0 < 1 \Rightarrow s < M_W^2 \left(\exp\left(\frac{\pi\sqrt{2}}{G_F M_W^2} \right) - 1 \right)$$

$$\rightsquigarrow E \approx 3{,}5 \; 10^{35} \text{ GeV}$$

neuer Prozess: $\nu\bar{\nu} \to W_0^+ W_0^-$ long. pol. W-Bosons



$$p = q_1 - k_+ = k_- - q_2$$

$\gamma^\mu \varepsilon^*_\mu$

$$\mathcal{M} = -\frac{i G_F M_W^2}{\sqrt{2}} \bar{v}(\nu, q_2)\, \not{\varepsilon}^*_- (1-\gamma_5) \frac{\not{p} + m}{p^2 - m^2}\, \not{\varepsilon}^*_+ (1-\gamma_5)\, u(\nu, q_1)$$

Kinematik

$q_1 = (Q, \dots, Q)$ $\quad k_+ = (Q, k\sin\theta, 0, k\cos\theta)$

$q_2 = (Q, \dots, -Q)$ $\quad k_- = (Q, -k\sin\theta, 0, -k\cos\theta)$

$k = \sqrt{Q^2 - M_W^2}$ $\quad k \approx Q$ für $\frac{M_W^2}{Q^2}$ klein

Polarisationsvektoren $\varepsilon^\mu_\pm = (0, \hat{\varepsilon}_\pm)$ im Ruhesystem

$$\text{Boost} \Rightarrow \varepsilon_\pm = \left(\frac{\vec{k}_\pm \cdot \hat{\varepsilon}_\pm}{M_W}, \; \hat{\varepsilon}_\pm - \frac{\vec{k}_\pm (\vec{k}_\pm \hat{\varepsilon}_\pm)}{M_W (Q + M_W)} \right)$$

$$\text{long Polarisation} \quad \varepsilon_\pm = \left(\frac{k}{M_W}, \; \frac{Q \hat{k}_\pm}{M_W} \right)$$

$$\lim Q \to \infty \Rightarrow \varepsilon_\pm = \frac{k_\pm}{M_W}$$

einsetzen: $M = \frac{-iG_F}{\sqrt{2}} \bar{v}(v,q_2) \not{k}_-(1-\gamma_5) \frac{\not{p}+m}{p^2-m^2} \not{k}_+ (1-\gamma_5) u(v,q_1)$

Dirac Gleichung $\not{q}_1 u(v,q_1) = 0$ $\bar{u}(v,q_2)\not{q}_2 = 0$

$\not{k}_+ = \not{k}_+ - \not{q}_1 = -\not{p}$

$\not{k}_- = \not{k}_- - \not{q}_2 = +\not{p}$ vernachlässige elektronmasse

$M = \frac{iG_F}{\sqrt{2}} \bar{v}(v,q_2) \not{p} (1-\gamma_5) \underbrace{\frac{\not{p}\not{p}}{p^2}}_{1} (1-\gamma_5) u(v,q_1)$

$$M = \sqrt{2}\, i G_F\, \bar{v}(v,q_2) \not{p} (1-\gamma_5)\, u(v,q_1)$$

$|M|^2 = 32\, G_F^2\, Q^2 k^2 \sin^2\theta$

$\sigma(v\bar{v} \to W^+W^-) \xrightarrow{s \gg m_W^2} \frac{G_F^2 s}{3\pi}$ Verletzt Unitarität nicht akzeptabel!

Der echte schwache leptonische Sektor des SM

$SU(2)_L \otimes U(1)_Y$

$Q = I_3 + \frac{1}{2} Y$ Gell-Mann – Nishijima Relation

(Q: elekt. Ladung; I_3: 3-komp schw. Isospins; Y: Hyperladung)

Linkshändige Leptonen L : $Y_L = -1$

rechtshändige " R : $Y_L = -2$

$[I_3, Y] = 0$

Eichfelder $B_\mu^1, B_\mu^2, B_\mu^3$ $SU(2)_L$

A_μ $U(1)_Y$

$\mathcal{L}_{gauge} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} - \frac{1}{2} f_{\mu\nu} f^{\mu\nu}$

($F^a_{\mu\nu}$: $SU(2)$; $f_{\mu\nu}$: $U(1)$)

Strukturkonstanten der SU(2)
↓

$$F^e_{\mu\nu} = \partial_\nu B^e_\mu - \partial_\mu B^e_\nu + g\,\varepsilon_{jke}\,B^j_\mu B^k_\nu$$

$$f_{\mu\nu} = \partial_\nu A_\mu - \partial_\mu A_\nu$$

$$\mathcal{L}_{Lepton} = \bar{R}\, i\gamma^\mu \left(\partial_\mu + \frac{ig'}{2} A_\mu Y\right) R + \bar{L}\, i\gamma^\mu \left(\partial_\mu + \frac{ig'}{2} A_\mu Y + \frac{ig}{2}\tau_i B^i_\mu\right) L$$

Wie zuvor führe komplexes SU(2) Duplett ein

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad Y_\phi = +1$$

$$\mathcal{L}_{Skalar} = (D^\mu \phi)^+ (D_\mu \phi) - V(\phi^+\phi) \quad \Big| \quad V(\phi^+\phi) = \mu^2 \phi^+\phi + |\lambda| (\phi^+\phi)^2$$

mit $D^\mu = \partial^\mu + \frac{ig'}{2} A^\mu Y + \frac{ig}{2}\tau_i B^{i\mu}$

$$\mathcal{L}_{Yukawa} = -\lambda_e \left(\bar{R}(\phi^+ L) + (\bar{L}\phi) R\right)$$

← koppelt ϕ an links + rechtshändige Felder!

im Moment nur für Elektron (kein rechtshändiges Neutrino)

spontane Symmetriebrechung $\phi_0 = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$ $\qquad v = \sqrt{-\mu^2/|\lambda|}$

$SU(2) \otimes U(1) \rightarrow$??? | Welche Symmetrien gibt es noch

rechne explizit nach, Generator angewendet auf Zustand = 0

$$\tau_1 \phi_0 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix} \neq 0 \qquad \text{gebrochen!}$$

$$\tau_2 \phi_0 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} -iv/\sqrt{2} \\ 0 \end{pmatrix} \neq 0 \qquad \text{gebrochen!}$$

$$\tau_3 \phi_0 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} 0 \\ -v/\sqrt{2} \end{pmatrix} \neq 0 \qquad \text{gebrochen!}$$

$$Y \phi_0 = Y_\phi \phi_0 = +1\,\phi_0 \neq 0 \qquad \text{gebrochen!}$$

allerdings $Q\,\phi_0 = \frac{1}{2}(\tau_3 + Y)\,\phi_0 = \frac{1}{2}\begin{pmatrix} Y_\phi + 1 & 0 \\ 0 & Y_\phi - 1 \end{pmatrix} \phi_0 = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \phi_0$

$$\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = 0$$

also Q verbleibt, d.h.

$$SU(2)_L \otimes U(1)_Y \xrightarrow[\text{Symm. br.}]{\text{spon}} U(1)_Q$$

entwickeln ϕ um Vakuum $\quad \phi = \begin{pmatrix} 0 \\ (v+h)/\sqrt{2} \end{pmatrix}$

h phys Feld

$$\mathcal{L}_{Skalar} = \frac{v^2}{8}\left[g^2 |B_\mu^1 - iB_\mu^2|^2 + (g' A_\mu - g B_\mu^3)^2 \right]$$

$$+ \frac{1}{2}(\partial^\mu h \, \partial_\mu h + 2\mu^2 h^2) + \text{WW-Terme}$$

3 massive Eichbosonen $\quad W_\mu^\pm = \frac{B_\mu^1 \mp B_\mu^2}{\sqrt{2}}$

$$\frac{v^2 g^2}{4}(W_\mu^+ W^{-\mu})$$

W-Masse gegeben durch Eichkopplung und den Higgs vev.

$$M_W = \frac{gv}{2}$$

$$Z_\mu = \frac{-g' A_\mu + g B_\mu^3}{\sqrt{g^2 + g'^2}} \quad \rightarrow \quad M_Z = \sqrt{g^2 + g'^2}\, v/2 = M_W \sqrt{1 + \frac{g'^2}{g^2}}$$

Orthogonal zu Z_μ: $\quad A_\mu = \frac{g A_\mu + g' B_\mu^3}{\sqrt{g^2 + g'^2}} \quad M_A = 0$

Aus Yukawa Sektor erhält man Masse des Elektrons

$$\mathcal{L}_{Yukawa} = -\frac{\lambda_e v}{\sqrt{2}} \bar{e} e - \frac{\lambda_e h}{\sqrt{2}} \bar{e} e$$

Masse $\uparrow$ $\qquad$ $\uparrow$ Kopplung $\bar{e}eh$ prop. zur Masse

$$\mathcal{L}_{W,e} = -\frac{g}{\sqrt{2}}(\bar{\nu}_L \gamma^\mu e_L W_\mu^+ + \bar{e}_L \gamma^\mu \nu_L W_\mu^-)$$

$$= -\frac{g}{2\sqrt{2}}(\bar{\nu} \gamma^\mu (1-\gamma_5) e W_\mu^+ + \bar{e} \gamma^\mu (1-\gamma_5) \nu W_\mu^-)$$

Vergleich mit Niederenergiepheno

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

$$\mathcal{L}_{0,e} = \frac{g g'}{\sqrt{g^2+g'^2}}\, \bar{e}\gamma^\mu A_\mu e - \frac{\sqrt{g^2+g'^2}}{2}\, \bar{\nu}_L \gamma^\mu \nu_L Z_\mu$$

$$+ \frac{1}{\sqrt{g^2+g'^2}} \left[-g^2 \bar{e}_R \gamma^\mu e_R + \frac{g^2+g'^2}{2} \bar{e}_L \gamma^\mu e_L \right] Z_\mu$$

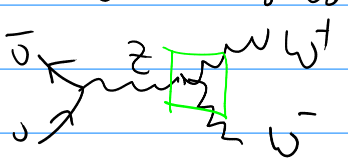
Verbindung mit QED : $\frac{g g'}{\sqrt{g^2+g'^2}} = e$

$g' = g \tan\theta_W$ $\qquad$ $\sqrt{g^2+g'^2} = \frac{g}{\cos\theta_W}$

$$Z_\mu = -A_\mu \sin\theta_W + B^3_\mu \cos\theta_W$$
$$A_\mu = A_\mu \cos\theta_W + B^3_\mu \sin\theta_W$$

Zurück zu $\nu\bar{\nu} \to W_0^+ W_0^-$ $\qquad$ $S^\mu = q_1^\mu + q_2^\mu$

Neu:



$$M_Z = \frac{-ig^2}{4(s-M_Z^2)}\, \bar{v}(\nu, p_2)\gamma_\mu(1-\gamma_5)u(\nu, p_1)\left(g^{\mu\nu} - \frac{S^\mu S^\nu}{M_Z^2}\right)$$

$$\varepsilon_+^{*\alpha} \varepsilon_-^{*\beta} \left[g_{\alpha\beta}(k_- - k_+)_\nu + g_{\alpha\nu}(k_+ + S)_\beta + g_{\beta\nu}(k_- + S)_\alpha \right]$$

$$= \frac{ig^2}{4(s-M_Z^2)}\, \bar{v}\gamma_\mu u \left[\varepsilon_+^* \varepsilon_-^* (k_- - k_+)_\nu + k_+ \varepsilon_-^* \varepsilon_{+\nu}^* - k_- \varepsilon_+^* \varepsilon_{-\nu}^* \right.$$
$$\left. + \varepsilon_-^* S\, \varepsilon_{+\nu}^* - \varepsilon_+^* S\, \varepsilon_{-\nu}^* \right]$$

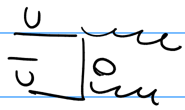
Setze für long Polvektor wieder HE Form ein

$\varepsilon^\mu_\pm = \frac{k^\mu_\pm}{M_W}$ $\qquad k_+ S = k_- S = \frac{S^2}{2}$

$M_Z = \frac{ig}{8M_W^2}\bar v(q_2)(\not k_+ - \not k_-)(1-\gamma_5)u(q_1)$

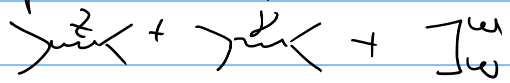
Imp-erh. + Dirac $= \frac{-ig}{4M_W^2}\bar v(q_2)\not{q}(1-\gamma_5)u(q_1)$

$= -iG_F\sqrt{2}\,\bar v(q_2)\not{q}(1-\gamma_5)u(q_1)$

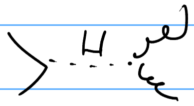
dieser Beitrag hebt genau  weg

und die Streuamplitude wird unitär

• Für Masselose Leptonen ist Unitarität erhalten

Für $e^+e^- \to W^+W^-$ 

Aber! Nur für Masselose Elektronen

Mit Elektron Masse auch 
Higgs-Austausch