FISICA DE LAS INTERACCIONES FUNDAMENTALES

1ER CUATRIMESTRE 2026

CLASE 15

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CLASE 15: Interacciones débiles

Temas: fenomenología, teoría efectiva de Fermi, violación de paridad, mixing, SU(2)

fenomenología: *si hay neutrinos, es débil…*

decaimientos de piones cargados

$$\pi^+ \ (u\bar{d}) \longrightarrow \mu^+ \nu_\mu$$
$$\pi^- \ (d\bar{u}) \longrightarrow \mu^- \bar{\nu}_\mu$$

(99.98%) $\quad 2.6 \ 10^{-8} s$

e.m. ~ $10^{-16} s$

fuertes. ~ $10^{-23} s$

ejemplo e.m. $\quad \pi^0 \ (u\bar{u} - d\bar{d}) \longrightarrow \gamma\gamma \quad (99.79\%) \quad 8.4 \ 10^{-17} s$

ejemplo fuerte $\quad \phi^0 \ (s\bar{s}) \longrightarrow K^+ K^- (u\bar{s}, s\bar{u})$

$$\mu^- \longrightarrow e^- \bar{\nu}_e \nu_\mu \qquad 2.2 \ 10^{-6} s$$

$$n \longrightarrow p \, e^- \bar{\nu}_e \qquad (d \longrightarrow u \, e^- \bar{\nu}_e)$$
$$p \longrightarrow n \, e^+ \nu_e \qquad (u \longrightarrow d \, e^+ \nu_e)$$

$$\begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}$$

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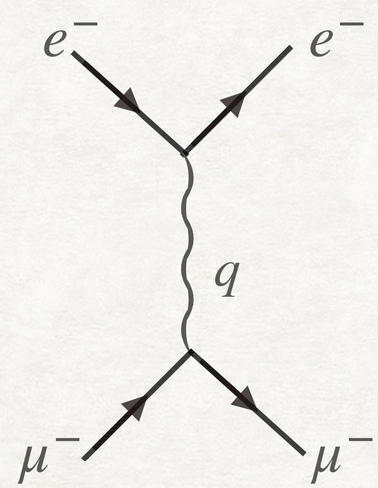
teoría de Fermi: *calcar QED*

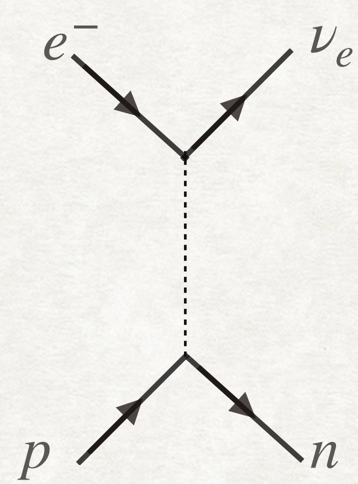
$e^-\mu^- \longrightarrow e^-\mu^-$



$$\mathscr{M} \sim \frac{1}{-q^2} J_\rho^{(e^-)} \, J^\rho_{(\mu^-)}$$

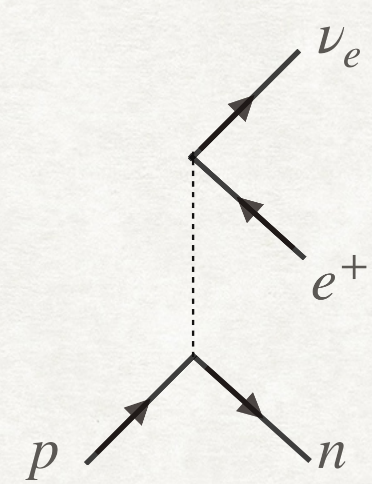
$$\sim \frac{e^2}{-q^2} \, \overline{u}_e \gamma_\rho u_e \; \overline{u}_\mu \gamma^\rho u_\mu$$

$e^-p \longrightarrow \nu_e n$

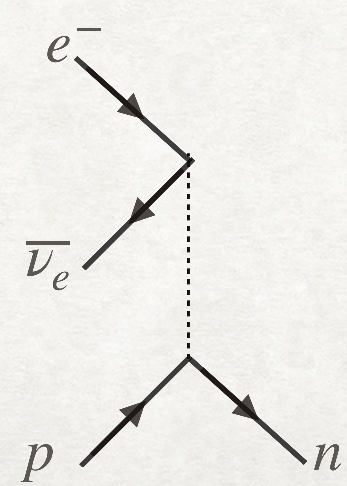


$$\mathscr{M} \sim \quad G_F \quad J_\rho^{(e^-\nu_e)} \, J^\rho_{(pn)}$$

$$\sim G_F \, \overline{u}_{\nu_e} \gamma_\rho u_e \; \overline{u}_n \gamma^\rho u_p$$

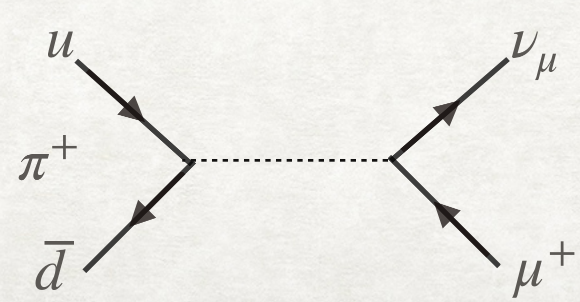


$p \longrightarrow e^+\nu_e n$



$n \longrightarrow e^-\overline{\nu}_e p$

$\binom{p}{n} \longrightarrow \binom{u}{d} \qquad \binom{\nu_e}{e^-} \longrightarrow \binom{\nu_\mu}{\mu^-}$



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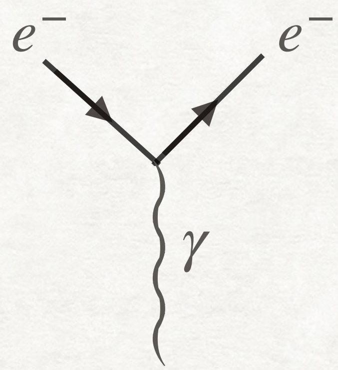
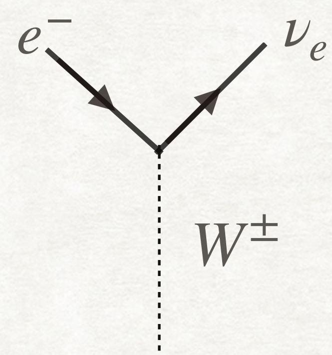
teoría de Fermi: *calcar QED*





$$\frac{e^2}{-q^2}$$

$$G_F \sim \frac{g^2}{M_W^2 - q^2}$$

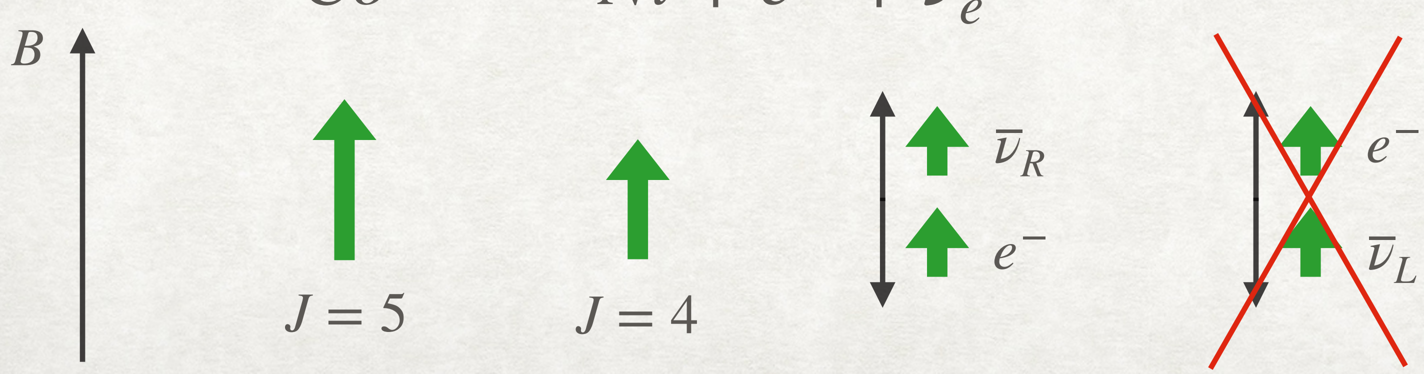
si $M_W \gg q$ $\quad G_F \simeq \dfrac{g^2}{M_W^2}$

si $e^2 \sim g^2$ $\quad M_W \sim 100\,GeV$

violación de paridad: *los neutrinos o la interacción?*

$$\sigma(\pi^+ \longrightarrow \mu^+ \nu_{\mu L}) \neq 0 \qquad \sigma(\pi^+ \longrightarrow \mu^+ \nu_{\mu R}) = 0$$

$$^{60}Co \longrightarrow {}^{60}Ni + e^- + \overline{\nu}_e$$



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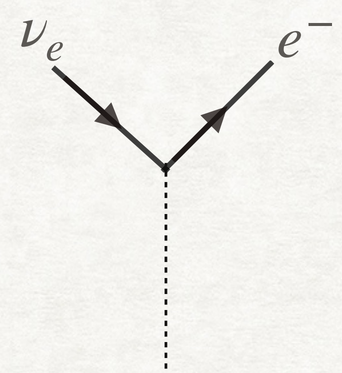
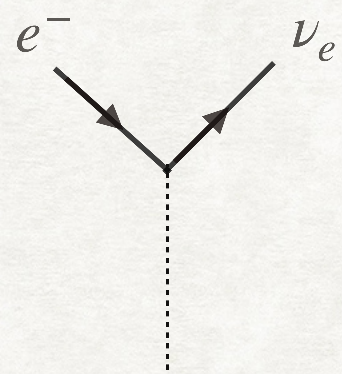
violación de paridad:



$$J^\mu = \overline{u}_e \gamma^\mu \frac{1}{2}(1-\gamma^5)\, u_{\nu_e}$$



$$J^\mu = \overline{u}_{\nu_e} \gamma^\mu \frac{1}{2}(1-\gamma^5)\, u_e$$
$$= \overline{u}_{\nu_e} \frac{1}{2}(1+\gamma^5)\gamma^\mu \; u_e$$

$$J^\mu \;\equiv\; \overline{u}_{\nu_e} \gamma^\mu \frac{1}{2}(1-\gamma^5)\, u_e$$ *"aumenta" la carga*

$$J^\dagger_\mu \;\equiv\; \overline{u}_e \gamma_\mu \frac{1}{2}(1-\gamma^5)\, u_{\nu_e}$$ *"disminuye" la carga*

$$\mathscr{M} \sim G_F\, J^\mu J^\dagger_\mu$$

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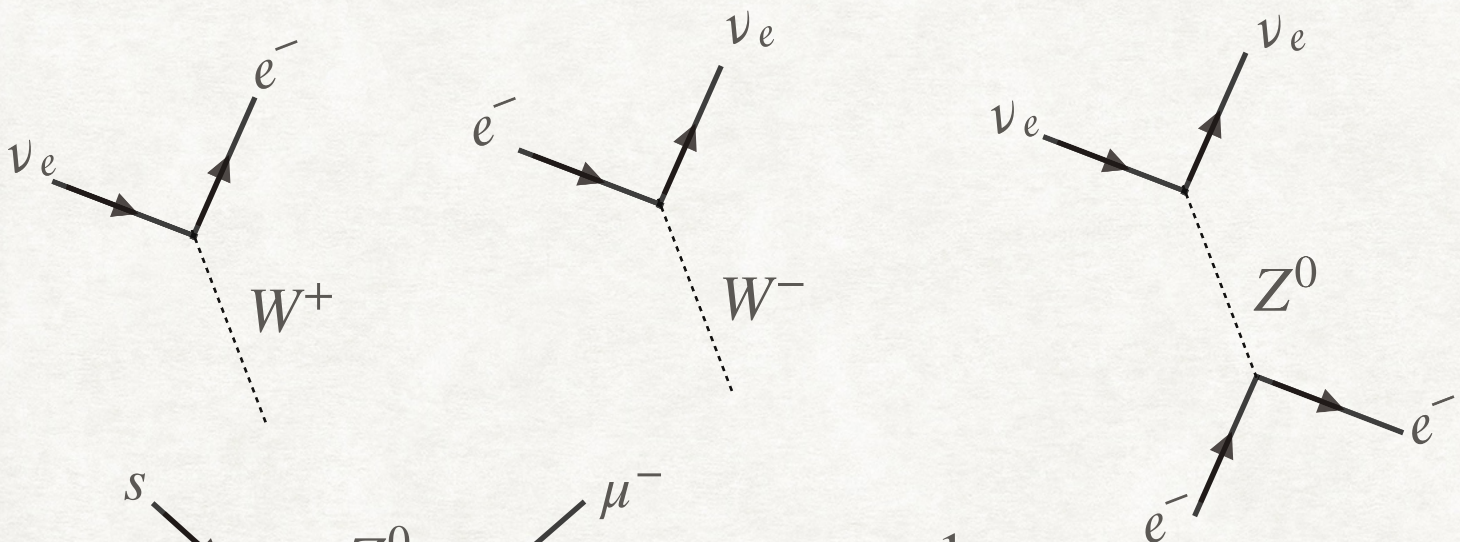
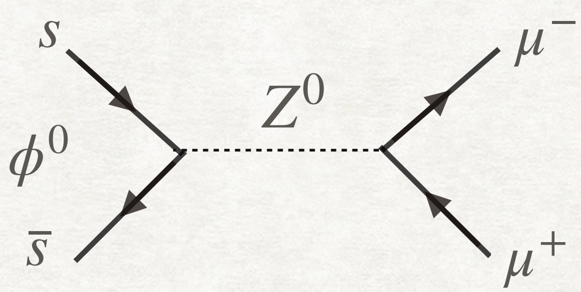
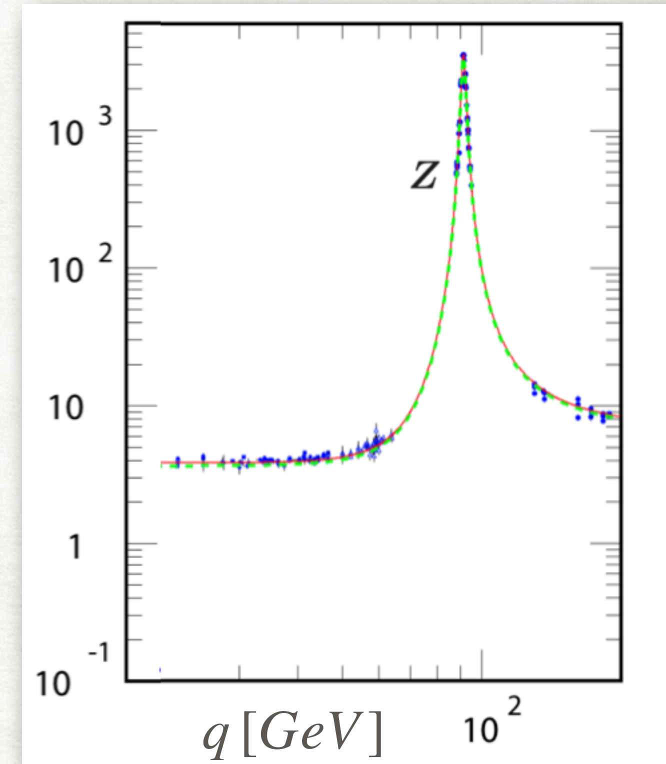
mediadores neutros:





$$\sim \frac{1}{M_Z^2 - q^2}$$

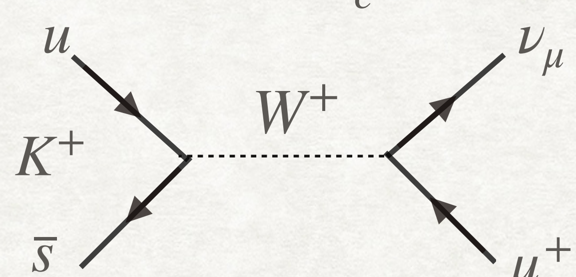
$$M_Z \simeq 91\, GeV$$



mixing:

$$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix} \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix} \begin{pmatrix}u\\ d\end{pmatrix} \begin{pmatrix}c\\ s\end{pmatrix}$$

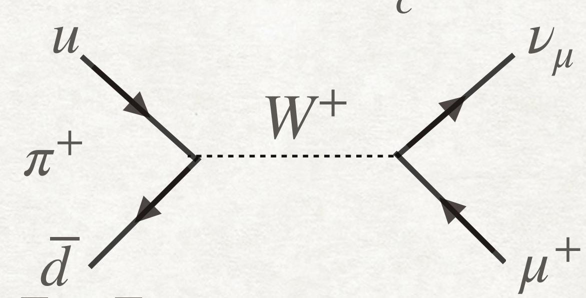
$\sim \sin\theta_c$



$\bar{s} = \bar{d}' \sin\theta_c + \bar{s}' \cos\theta_c$

$\ll$

$\sim \cos\theta_c$



$\bar{d} = \bar{d}' \cos\theta_c - \bar{s}' \sin\theta_c$

Cabibbo Kobayashi Maskawa

$$\begin{pmatrix}u\\ d'\end{pmatrix} \begin{pmatrix}c\\ s'\end{pmatrix}$$

$$\begin{cases} d' \equiv d\cos\theta_c + s\sin\theta_c \\ s' \equiv -\,d\sin\theta_c + s\cos\theta_c \end{cases}$$

$$\begin{cases} d \equiv d'\cos\theta_c - s'\sin\theta_c \\ s \equiv d'\sin\theta_c + s'\cos\theta_c \end{cases}$$

$\theta_c \simeq 13^o$

$\sin^2\theta_c \simeq 0.05$

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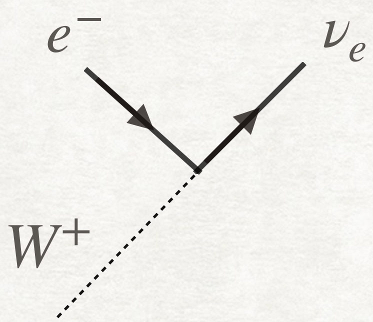
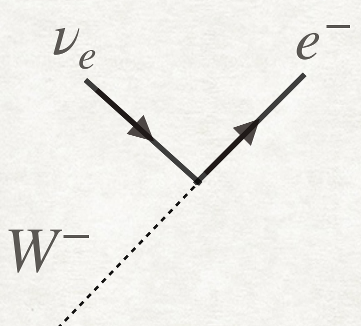
Gauge SU(2)$_L$:

$$\Psi^e_L \equiv \begin{pmatrix} \psi_{\nu_{eL}} \\ \psi_{e_L} \end{pmatrix} \quad \Psi^\mu_L \equiv \begin{pmatrix} \psi_{\nu_{\mu L}} \\ \psi_{\mu_L} \end{pmatrix} \quad \cdots \qquad \overline{\Psi}^e_L \equiv \left(\overline{\psi}_{\nu_{eL}},\ \overline{\psi}_{e_L}\right) \quad \overline{\Psi}^\mu_L \equiv \left(\overline{\psi}_{\nu_{\mu L}},\ \psi_{\mu_L}\right) \quad \cdots$$

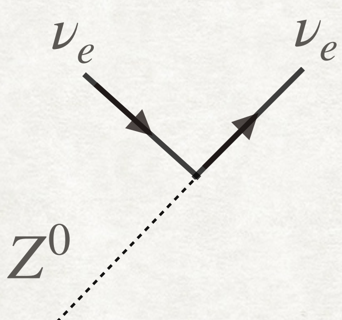


$$J^\mu_+ = \overline{\psi}_{\nu_e}\gamma^\mu \frac{1}{2}(1-\gamma^5)\,\psi_e = \overline{\psi}_{\nu_{eL}}\gamma^\mu\ \psi_{e_L} \ = \overline{\Psi}^e_L\gamma^\mu\,\sigma_+\,\Psi^e_L \qquad \sigma_+ \equiv \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$$

$$\sigma_\pm \equiv \frac{1}{2}(\sigma_1 \pm i\sigma_2)$$



$$J^\mu_- = \overline{\psi}_e\gamma^\mu \frac{1}{2}(1-\gamma^5)\,\psi_{\nu_e} \ = \overline{\psi}_{e_L}\gamma^\mu\ \psi_{\nu_{eL}} \ = \overline{\Psi}^e_L\gamma^\mu\,\sigma_-\,\Psi^e_L \qquad \sigma_- \equiv \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$$



$$J^\mu_3 \ = \frac{1}{2}\overline{\psi}_{\nu_{eL}}\gamma^\mu\ \psi_{\nu_{eL}} - \frac{1}{2}\overline{\psi}_{e_L}\gamma^\mu\ \psi_{e_L} \ = \overline{\Psi}^e_L\gamma^\mu\,\frac{\sigma_3}{2}\,\Psi^e_L$$

$$J^\mu_i = \overline{\Psi}^e_L\gamma^\mu\,\frac{\sigma_i}{2}\,\Psi^e_L$$

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Gauge SU(2)$_L$:

$$\Psi_L^e \equiv \begin{pmatrix} \psi_{\nu_{eL}} \\ \psi_{e_L} \end{pmatrix} \quad \Psi_L^\mu \equiv \begin{pmatrix} \psi_{\nu_{\mu L}} \\ \psi_{\mu_L} \end{pmatrix} \quad \cdots \qquad \overline{\Psi}_L^e \equiv \left(\overline{\psi}_{\nu_{eL}},\ \overline{\psi}_{e_L}\right) \quad \overline{\Psi}_L^\mu \equiv \left(\overline{\psi}_{\nu_{\mu L}},\ \psi_{\mu_L}\right) \quad \cdots$$

$$\mathscr{L} = \overline{\Psi}_L(i\gamma^\mu \partial_\mu - M)\Psi_L \qquad \Psi_L^e \longrightarrow e^{ig\frac{\sigma_i}{2}\alpha_i(x)}\,\Psi_L^e \qquad M \equiv \begin{pmatrix} 0 & 0 \\ 0 & m_e \end{pmatrix} \quad M_W \neq 0 \quad M_{Z^0} \neq 0$$

$$D_\mu \equiv \partial_\mu - ig\frac{\sigma_i}{2}W_\mu^i \qquad 2^2 - 1 = 3$$ *campos compensadores*

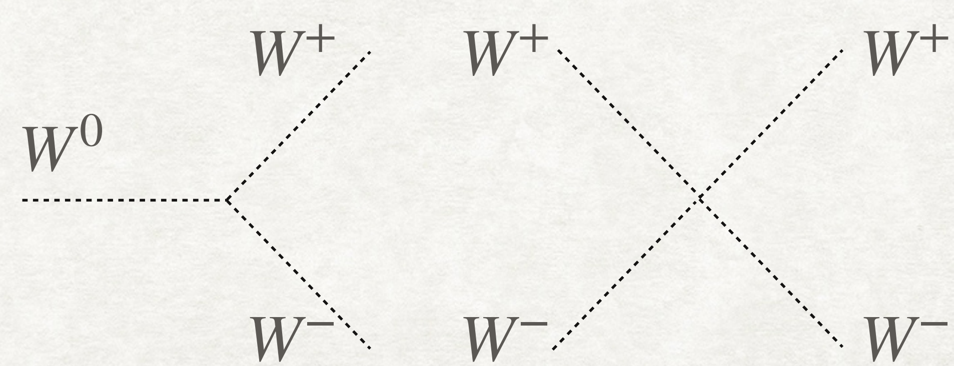
$$W_\mu^\pm \equiv \frac{-1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2)$$

$$W^0 \equiv W_\mu^3$$

$$W_\mu^i \longrightarrow W_\mu^{\prime i} = \partial_\mu \alpha^i + W_\mu^i - g\,\epsilon_{ijk}\alpha^j W_\mu^k$$

$$W_{\mu\nu}^i = (\partial_\mu W_\nu^i - \partial_\nu W_\mu^i) + gW_\mu^j W_\nu^k \epsilon_{ijk}$$

$$W_{\mu\nu}^i W_i^{\mu\nu} \sim$$



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Gauge $SU(2)_L$:

lista de problemas:

$M_W \neq 0 \quad M_{Z^0} \neq 0$ términos de masa explícitos $\sim M_W^2 W_\mu W^\mu$ romperían la invariancia de gauge

$M \equiv \begin{pmatrix} 0 & 0 \\ 0 & m_e \end{pmatrix}$ términos de masa (distintas) para los fermiones romperían la invariancia de gauge

$W^\pm$ tienen carga eléctrica, cómo interactúan con QED?

hay interacciones débiles sin intercambio de carga entre las componentes R de los quarks