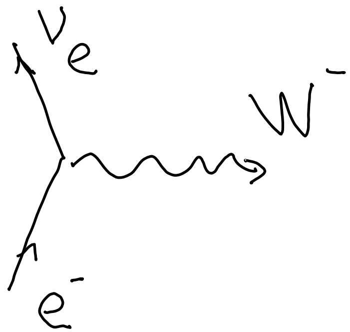
XI. Elektroslaba sila

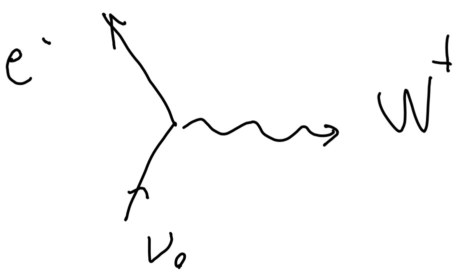
OD ELEKTROSLABOG MIJEŠANJA DO ELEKTROSLABOG UJEDINJENJA

- SPONTANO NARUŠENJE SIMETRIJE I HIGGSOV MEHANIZAM

IZOSPINSKA STRUKTURA NABIJENE SLABE STRUJE



$$j^+_\mu = \bar{\nu}_e \gamma_\mu \frac{1-\gamma_5}{2} e = \bar{\nu}_{eL} \gamma_\mu e_L$$

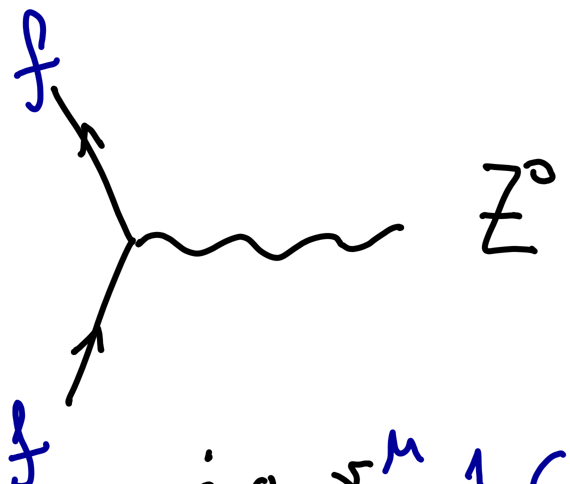


$$j^-_\mu = \bar{e} \gamma_\mu \frac{1-\gamma}{2} \nu_e$$

ili kompaktno

$$j^\pm_\mu = \bar{\chi}_L \gamma_\mu \tau^\pm \chi_L \quad ; \chi_L = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$$

NEUTRALNA SLABA STRUJA



$$-i g_Z \gamma^\mu \frac{1}{2}\left(c_V^f - c_A^f \gamma_5\right)$$

RAZOTKRIVA STRUKTURU DODATNOG SLABOG NABOJA – izospinska veže samo L-projekcije:

$$j^3_\mu = \bar{\chi}_L \gamma^\mu \frac{\tau^3}{2} \chi_L = \frac{1}{2} \bar{\nu}_L \gamma_\mu \nu_L - \frac{1}{2} \bar{e}_L \gamma_\mu e_L$$

STRUJA SLABOG HIPERNABOJA

Uz e.m. struju

$$j_\mu^{e.m.} = -\bar{e}\gamma_\mu e = -\bar{e}_R\gamma_\mu e_R - \bar{e}_L\gamma_\mu e_L$$

uvodimo struju generiranu hipernabojem Y : $j_\mu^Y = \bar{\Psi}\gamma_\mu Y \Psi$

$$Q = T^3 + \frac{Y}{2} \quad \Rightarrow$$

$$j_\mu^{em} = j_\mu^3 + \frac{1}{2} j_\mu^Y$$

koju "vidi" hipernabojni bozon

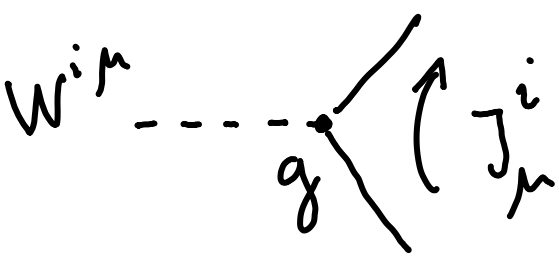
ELEKTROSLABI "GWS" MODEL

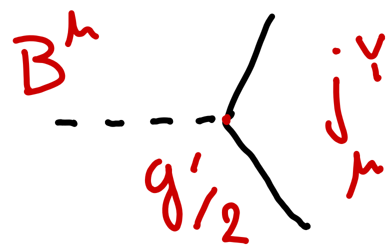
QED MEĐUDJELOVANJE

$$-iej^{em}_{\mu} A^{\mu}$$

SADRŽANO U "ELEKTROSLABOM"

$$-igJ^{i}_{\mu} W^{i\mu} - i\frac{g'}{2} j^{Y}_{\mu} B^{\mu}$$





$W^{3\mu}$ & B^{μ} daju neutralni dio

ELEKTROSLABO MIJEŠANJE

$$A_\mu = B_\mu \cos\Theta_W + W_\mu^3 \sin\Theta_W$$

$$Z_\mu = -B_\mu \sin\Theta_W + W_\mu^3 \cos\Theta_W$$

vodi na fizikalne interakcije

$$-ie\, j_\mu^{em} A^\mu$$

$$-i \frac{g}{\cos\Theta_W} \left(J_\mu^3 - \sin^2\Theta_W\, j_\mu^{em} \right) Z^\mu$$

uz $\quad g \sin\Theta_W = g' \cos\Theta_W = e$

$$\left\{ \begin{array}{l} e = gg'/\sqrt{g^2+g'^2} \\ \frac{1}{e} = \frac{1}{g} + \frac{1}{g'} \end{array} \right.$$

INTERAKCIJA NEUTRALNE SLABE STRUJE

$$\mathcal{L}_{NC} = -4\rho \frac{G_F}{\sqrt{2}} \Big(\underbrace{J_\mu^3 - \sin^2\Theta_W \, j_\mu^{em}}_{} \Big)^2$$

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\Theta_W}$$

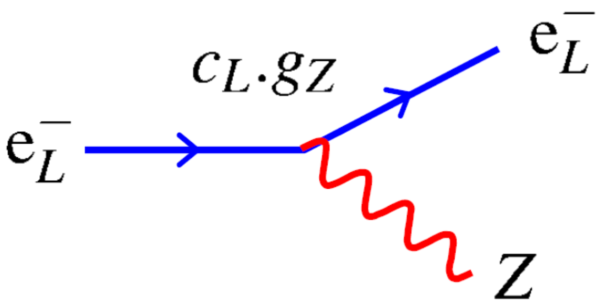
$$J_{NC}^\mu = J_3^\mu - \sin^2\Theta_W \, j_{em}^\mu = \bar{\Psi} \gamma^\mu \left[\frac{1}{2}(1-\gamma_5) T^3 - \sin^2\Theta_W Q \right] \psi$$

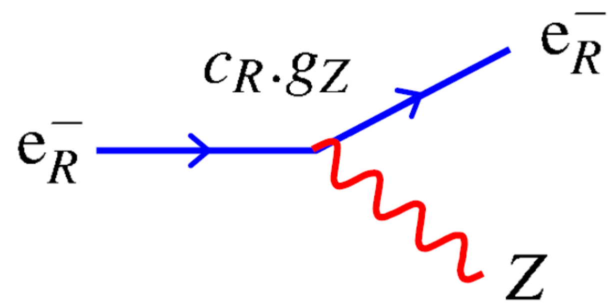
$$= \bar{\Psi} \gamma^\mu \frac{1}{2} \left(C_V^f - C_A^f \gamma_5 \right) \psi$$

$$C_V^f = T_3^f - 2 Q_f \sin^2\Theta_W \,, \quad C_A^f = T_3^f$$

Unlike for the Charged Current Weak interaction (W) the Z Boson couples to both LH and RH chiral components, but not equally…

$$
\begin{aligned}
j_\mu^Z &= g_Z(I_W^3 - Q\sin^2\theta_W)[\bar{e}_L\gamma_\mu e_L] - g_Z Q\sin\theta_W^2[e_R\gamma_\mu e_R] \\
&= g_Z c_L[\bar{e}_L\gamma_\mu e_L] + g_Z c_R[e_R\gamma_\mu e_R]
\end{aligned}
$$





$$\boxed{c_L = I_W^3 - Q\sin^2\theta_W}$$

$$\boxed{c_R = -Q\sin^2\theta_W}$$

W^3 part of Z couples only to LH components (like $W^\pm$)

B_μ part of Z couples equally to LH and RH components

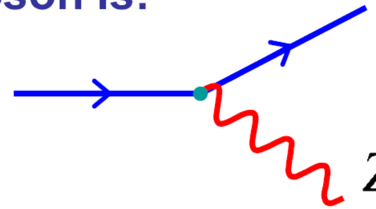
$$j_\mu^Z = \frac{g_Z}{2}\bar{u}\gamma_\mu\left[(c_L + c_R) + (c_R - c_L)\gamma_5)\right]u$$

Which in terms of V and A components gives: $$j_\mu^Z = \frac{g_Z}{2}\bar{u}\gamma_\mu\left[c_V - c_A\gamma_5\right]u$$

with $\boxed{c_V = c_L + c_R = I_W^3 - 2Q\sin^2\theta_W}$ $\boxed{c_A = c_L - c_R = I_W^3}$

Hence the vertex factor for the Z boson is:

$$\boxed{-ig_Z\tfrac{1}{2}\gamma_\mu\left[c_V - c_A\gamma_5\right]}$$



Fermion	Q	I_W^3	c_L	c_R	c_V	c_A
ν_e, ν_μ, ν_τ	0	$+\frac{1}{2}$	$+\frac{1}{2}$	0	$+\frac{1}{2}$	$+\frac{1}{2}$
e^-, μ^-, τ^-	-1	$-\frac{1}{2}$	-0.27	0.23	-0.04	$-\frac{1}{2}$
u, c, t	$+\frac{2}{3}$	$+\frac{1}{2}$	0.35	-0.15	$+0.19$	$+\frac{1}{2}$
d, s, b	$-\frac{1}{3}$	$-\frac{1}{2}$	-0.42	0.08	-0.35	$-\frac{1}{2}$

PROBLEM POMIRENJA MASIVNIH BOZONA I BAŽDARNE SIMETRIJE

- INTERAKCIJE ŽELIMO SVESTI POD BAŽDARNI PRINCIP
- IZVEDIVO U PRISTUPU SPONTANO SLOMLJENE SIMETRIJE

PRIMJERI SLOMLJENIH SIMETRIJA

NARUŠENE DISKRETNE SIMETRIJE

KLJUČ OPAŽANJA
"SLABIJEG KROZ JAČE"

$\cancel{P}$ 1957. g-da Wu
ustanovila da se β-raspadi u zrcaljenom svijetu odvijaju različito od originalnih :

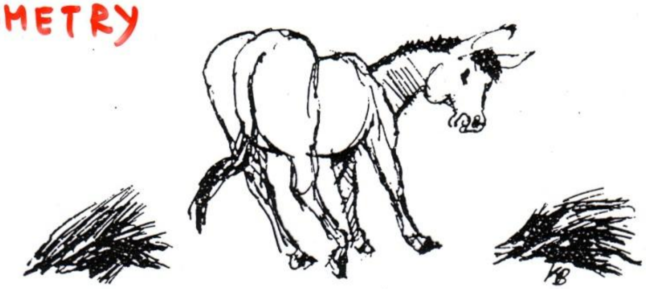
$\cancel{CP}$ 1964. Cronin & Fitch
na raspadima dugoživućih neutralnih kaona

- $K_L \not\to 2\pi$ ako je CP očuvano
  u pokusu se pojavljuje s grananjem $2 \cdot 10^{-3}$
- $K_L \to \pi^- \underbrace{e^+}\nu_e$ češći od CP-konjugiranog $K_L \to \pi^+ e^- \bar{\nu}_e$
  omogućuje apsolutnu definiciju pozitivnog naboja
  – razlikovanje materije i antimaterije !

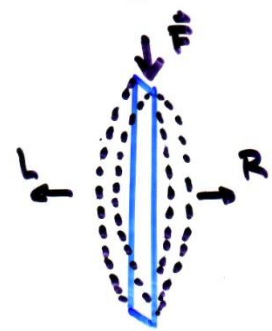
$CPT = I$ teorem potvrđen na točnost

$$\frac{m_{\bar{K}^0} - m_{K^0}}{m_{K^0}} \quad \begin{matrix} < 3.5 \cdot 10^{-18} \\ < 9 \cdot 10^{-19} \end{matrix}$$

SPONTANEOUSLY BROKEN SYMMETRY

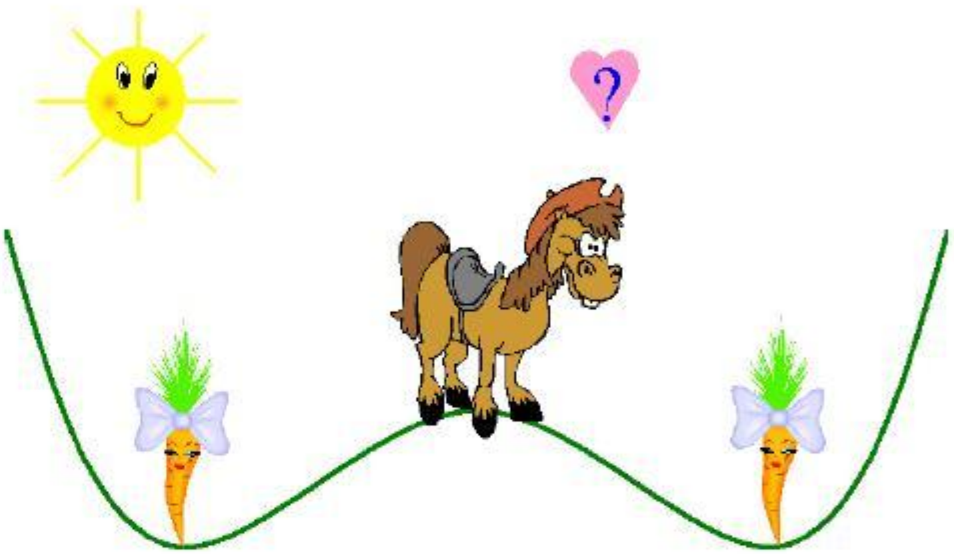


◊ DISCRETE



◊ CONTINUOUS

SPONTANO NARUŠENJE DISKRETNE SIMETRIJE



- Spas za Buridanovog magarca

(Jean Buridan – franc. skolastički filozof iz 14. st.)

magarac koji se našao pred dva jednaka kupa sijena uginuo je od gladi, jer se nije mogao odlučiti za kojim će kupom posegnuti.

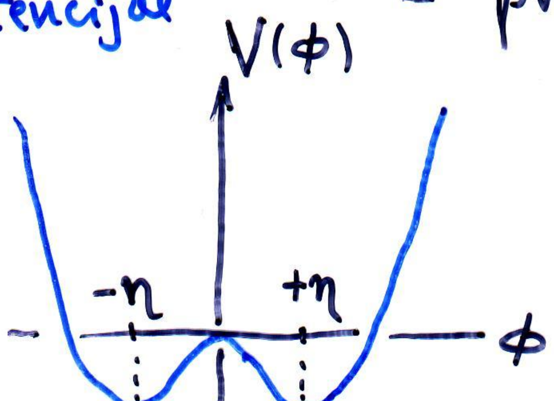
- Izbor lijevog ili desnog VAKUUMA (stanja najniže energije)

– pri oslanjanju na ravnalo

– pri hlađenju feromagnetika (ϕ = magnetizacija)

tr. 13

Potencijal



$$V(\phi) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda^2}{4}\phi^4$$

$$\frac{\partial V(\phi)}{\partial \phi} = -\mu^2\phi + \lambda^2\phi^3 = 0$$

ENERGIJA VAKUUMA SMANJENA U PRISUTNOSTI SKALARNOG POLJA

$\Rightarrow \quad \boxed{\phi_0 = \pm \frac{\mu}{\lambda} = \pm \eta}$

Početna simetrija

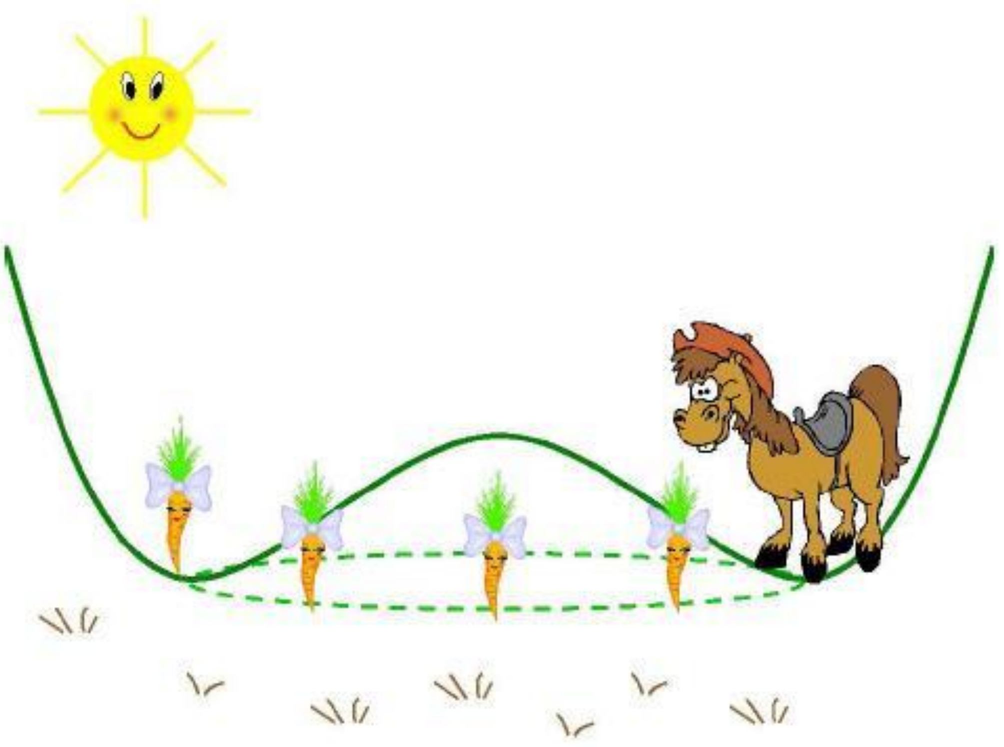
$\phi \rightarrow -\phi$ narušena izborom vakuuma. Primjerice, pobuđenja oko vakuuma $+\eta$, supstitucija $\phi(x) = \eta + \chi(x) \Rightarrow$

kubični član $\lambda^2 \eta \chi^3_{(x)}$ narušava simetriju;

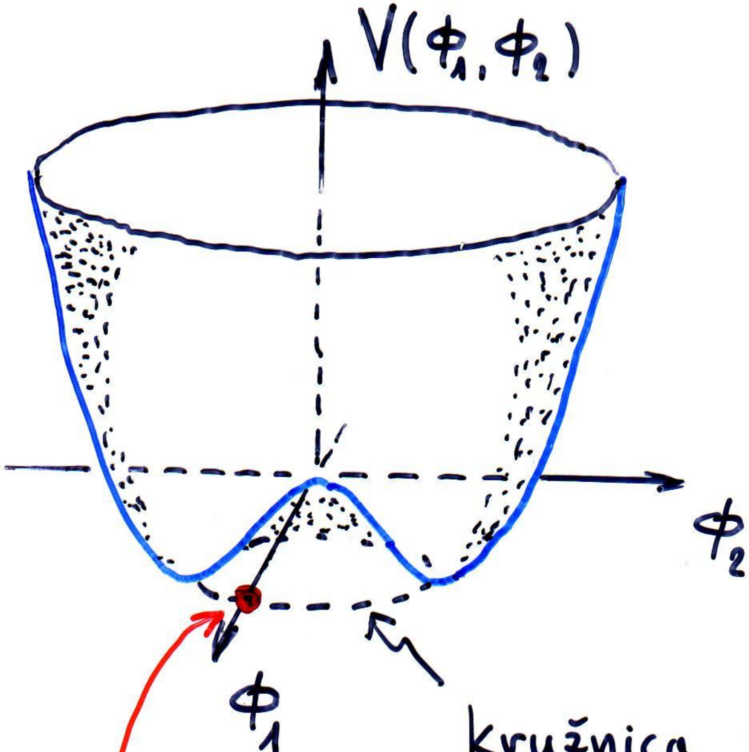
kvadratični član $\frac{1}{2} \underbrace{2\lambda^2\eta^2}_{m^2} \chi^2_{(x)}$ govori o masi pobuđenja.

$m = \sqrt{2}\lambda\eta = \sqrt{2}\mu$

SPONTANO NARUŠENJE KONTINUIRANE SIMETRIJE



Izbor jednog od vakuuma na kružnici minimuma energije (primjerice, pri oslanjanju na štup).



kružnica minimuma

$$\phi_1^2 + \phi_2^2 = \frac{\mu^2}{\lambda^2} \equiv \eta^2$$

Početna simetrija na rotacije u (ϕ_1, ϕ_2) ravnini

$$V(\phi_1, \phi_2) = -\frac{\mu^2}{2}(\phi_1^2 + \phi_2^2) + \frac{\lambda^2}{4}(\phi_1^2 + \phi_2^2)^2$$

$$\phi_1 \to \phi_1 \cos\vartheta + \phi_2 \sin\vartheta$$

$$\phi_2 \to -\phi_1 \sin\vartheta + \phi_2 \cos\vartheta$$

Odabir vakuuma $\quad \phi_{1\,min} = \frac{\mu}{\lambda} \equiv \eta \quad , \quad \phi_{2\,min} = 0$

te fluktuacija $\chi(x)$, $\xi(x)$
oko vakuuma

$$\phi_1(x) = \eta + \underbrace{\chi(x)}_{} \quad , \quad \phi_2(x) = \underbrace{\xi(x)}_{} \qquad (*)$$

$\Rightarrow$ masivno polje

- radijalnih oscilacija $\quad m_\chi = \sqrt{2}\,\mu$

$$m_\xi = 0$$

- umjesto početne simetrije "vidimo" bezmaseno tangencijalno pobuđenje
(Goldstoneov teorem za spont. slomlj. kontin. globalnu simetriju)

Primjer feromagneta: χ fluktuacije u veličini magnetizacije
ξ fluktuacije u njenom smjeru.
(spinski valovi)

SPONTANO SLOMLJENA LOKALNA SIMETRIJA U(1)

Goldstonove (bezmasene skalarne) čestice moći će se zaobići u baždarnoj teoriji

– kinetički član skalarnog polja sadrži kovarijantnu derivaciju $D_\mu = \partial_\mu + ieA_\mu$

$$\frac{1}{2}(D_\mu \phi_1)(D^\mu \phi_1) + \frac{1}{2}(D_\mu \phi_2)(D^\mu \phi_2) \Rightarrow \text{član } \frac{1}{2}e^2\eta^2 A^\mu A_\mu$$

gdje će supstitucija (*) / odabir vakuuma dati baždarnom polju masu $\underline{\underline{m_A = e\eta}}$

(no ξ je kao i prije bezmaseno)

Uz tu supstituciju dolazimo do izraza

$$\mathcal{L} = \left[\frac{1}{2}(\partial_\mu \chi)^2 - \mu^2 \chi^2\right] + \left[\frac{1}{2}(\partial_\mu \xi)^2\right] + \left[-\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}e^2\eta^2 A^\mu A_\mu\right]$$
$$-2i(e\eta)(\partial_\mu \xi)A^\mu + \text{viši članovi} \; . \tag{6.26}$$

Postojanje člana u $\mathcal{L}$ razmjernog s $A_\mu A^\mu$ znači da je vektorska čestica *dobila masu*

$$m_A = e\eta \; . \tag{6.27}$$

Skalarno polje χ također ima masu, a ξ izgleda kao da je bezmaseno. Pritom su uz bezmaseno polje ξ vezana dva problema:

- u fizikalnoj situaciji ne očekujemo pojavljivanje bezmasenih skalarnih čestica;
- u lagrangianu (6.26) pojavio se član $(\partial_\mu \xi)A^\mu$ s dva različita polja, što omogućuje prijelaz vektorskog bozona u ξ. To znači da polja nismo dobro identificirali.

Obje ove teškoće vezane uz pojavljivanje polja ξ mogu se ukloniti lokalnom baždarnom transformacijom

$$\phi(x) \;\rightarrow\; e^{i\theta(x)}\phi(x) = (\cos\theta + i\sin\theta)(\phi_1 + i\phi_2) \; . \tag{6.28}$$

Ovdje ulazi u igru baždarna simetrija – sloboda odabira baždarenja u kome $\xi = 0$

$$\phi_1 \sin\vartheta + \phi_2 \cos\vartheta = 0$$

Rezultat je Higgsov mehanizam za lokalnu $U(1)$:

2 skalarna polja s masom	$\rightarrow$	1 skalarno polje
1 vektorsko polje bez mase (2 polarizacije)		1 vektorsko (baždarno) polje s masom (3 stanja polarizac.)

br. stupnjeva slobode $\quad 2 + 2 \quad = \quad 1 + 3$

Ovaj se mehanizam prenosi na $SU(2)_W \times U(1)_Y$!