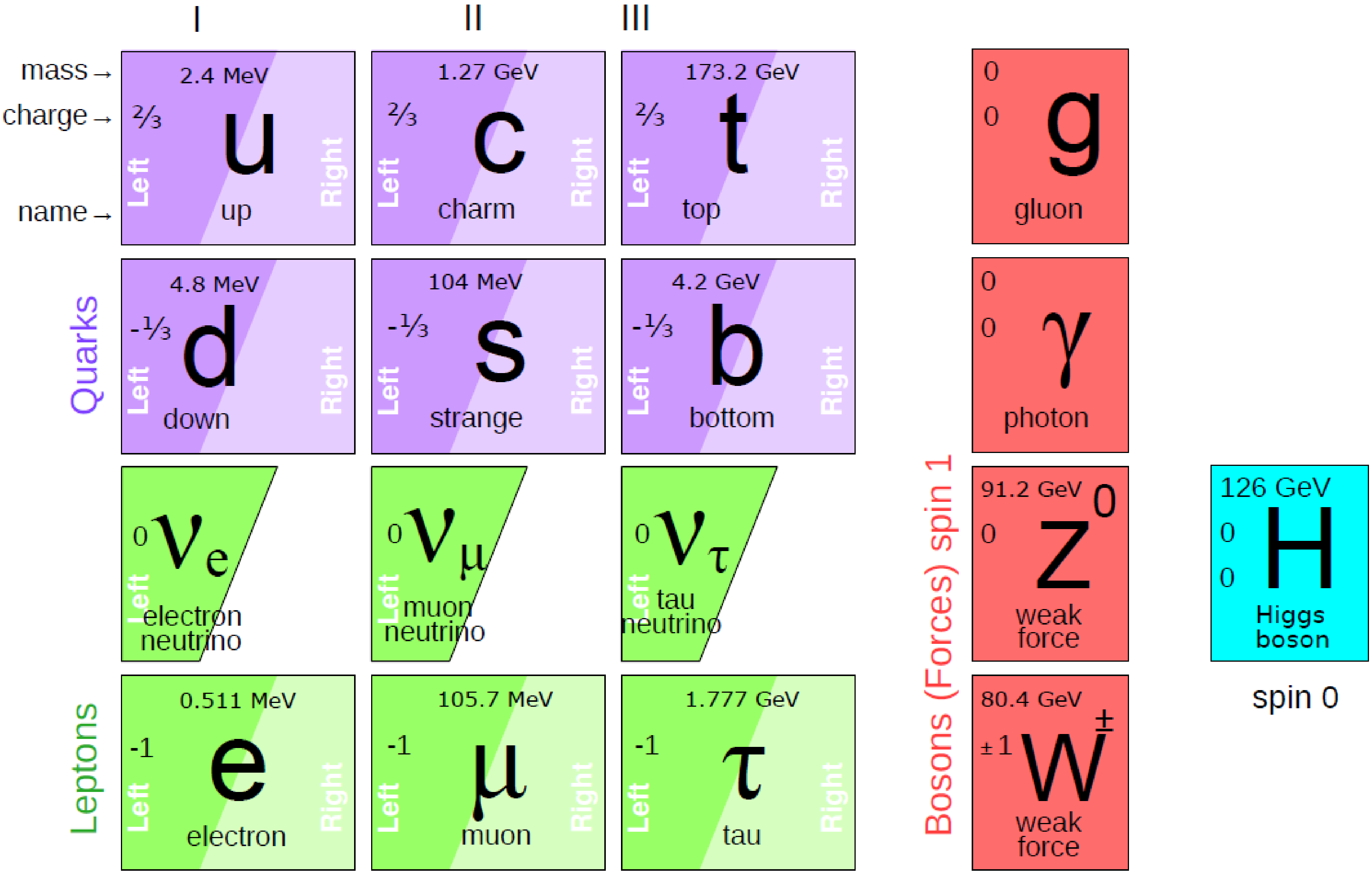
DODATNI HIGGSOVI i MASE BOZONA u SM i BSM

- MASE BAŽDARNIH BOZONA u SM-u
- MASE S DODATNIM HIGGSOM
- REALNI I KOMPLEKSNI TRIPLET
- 2 HIGGSOVA DUBLETA (2HDM)

Three Generations of Matter (Fermions) spin ½



	I	II	III			
mass → charge → name →	2.4 MeV ⅔ u up Left Right	1.27 GeV ⅔ c charm Left Right	173.2 GeV ⅔ t top Left Right		0 0 g gluon	
Quarks	4.8 MeV -⅓ d down Left Right	104 MeV -⅓ s strange Left Right	4.2 GeV -⅓ b bottom Left Right		0 0 γ photon	
	0 ν_e Left electron neutrino	0 ν_μ Left muon neutrino	0 ν_τ Left tau neutrino	Bosons (Forces) spin 1	91.2 GeV 0 Z^0 weak force	126 GeV 0 0 H Higgs boson
Leptons	0.511 MeV -1 e electron Left Right	105.7 MeV -1 μ muon Left Right	1.777 GeV -1 τ tau Left Right		80.4 GeV ±1 $W^\pm$ weak force	spin 0

Bozoni u SM prije i nakon EWSB

$$\begin{array}{ccc} W^1, W^2, H^+, H^- & \longrightarrow & W^+, W^- \\ W^3, B, \mathrm{Im}(H^0) & \longrightarrow & \gamma, Z \\ g \times 8 & & \\ \mathrm{Re}H^0 & \longrightarrow & H \end{array}$$

- Kompleksni skalarni dublet – razvija se oko VEV

$$V(\phi^\dagger \phi) = -\frac{m_H^2}{2} \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

$$v = \sqrt{m_H^2/(2\lambda)} = (\sqrt{2} G_F)^{-1/2} \simeq 246 \text{ GeV}$$

$$\phi \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(v + \mathrm{Re}(H^0) + i\mathrm{Im}(H^0)) \end{pmatrix}$$

Mase baždarnih bozona u SM

- Iz kovarijantnog kinetičkog člana

$$\mathcal{L} \supset (\mathcal{D}_\mu \Phi)^\dagger (\mathcal{D}^\mu \Phi) \qquad \mathcal{D}_\mu = \partial_\mu - i\frac{g'}{2}B_\mu - i\frac{g}{2}W^a_\mu \sigma^a$$

sa skalarom u unitarnom baždarenju:

$$\mathcal{D}_\mu \Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} -\frac{i}{2}g(W^1_\mu - iW^2_\mu)(v+h) \\ \partial_\mu h + \frac{i}{2}(gW^3_\mu - g'B_\mu)(v+h) \end{pmatrix}$$

$$(\mathcal{D}_\mu \Phi)^\dagger (\mathcal{D}^\mu \Phi) = \frac{1}{2}(\partial_\mu h)(\partial^\mu h) + \frac{1}{8}g^2(v+h)^2(W^1_\mu - iW^2_\mu)(W^{1\mu} + iW^{2\mu})$$

$$+\frac{1}{8}(v+h)^2\left(-g'B_\mu + gW^3_\mu\right)^2$$

nabijeni

neutralni

Identifikacija nabijenih bozona

$$W_\mu^1\sigma^1 + W_\mu^2\sigma^2 = \frac{1}{2}(W_\mu^1 - iW_\mu^2)(\sigma^1 + i\sigma^2) + \frac{1}{2}(W_\mu^1 + iW_\mu^2)(\sigma^1 - i\sigma^2)$$

$$= \sqrt{2}\frac{W_\mu^1 - iW_\mu^2}{\sqrt{2}}\sigma^+ + \sqrt{2}\frac{W_\mu^1 + iW_\mu^2}{\sqrt{2}}\sigma^-$$

$$(\sigma^1 + i\sigma^2) = 2\sigma^+ = 2\left(\begin{array}{cc} 0 & 1 \\ 0 & 0 \end{array}\right), \qquad (\sigma^1 - i\sigma^2) = 2\sigma^- = 2\left(\begin{array}{cc} 0 & 0 \\ 1 & 0 \end{array}\right)$$

- **Iz očuvanja električnog naboja pri djelovanju na lijeve fermionske dublete**

$$\boxed{\begin{array}{lcll} \frac{W_\mu^1 - iW_\mu^2}{\sqrt{2}}(\bar{u}\ \bar{d})\,\sigma^+\gamma^\mu P_L\left(\begin{array}{c} u \\ d \end{array}\right) & = & \frac{W_\mu^1 - iW_\mu^2}{\sqrt{2}}\bar{u}\gamma^\mu P_L d & \Rightarrow \quad \frac{W_\mu^1 - iW_\mu^2}{\sqrt{2}} = W_\mu^+ \\ \frac{W_\mu^1 + iW_\mu^2}{\sqrt{2}}(\bar{u}\ \bar{d})\,\sigma^-\gamma^\mu P_L\left(\begin{array}{c} u \\ d \end{array}\right) & = & \frac{W_\mu^1 + iW_\mu^2}{\sqrt{2}}\bar{d}\gamma^\mu P_L u & \Rightarrow \quad \frac{W_\mu^1 + iW_\mu^2}{\sqrt{2}} = W_\mu^- \end{array}}$$

Masa W bozona

$$\boxed{M_W^2 = \frac{g^2 v^2}{4}}$$

$$\begin{aligned}\mathcal{L} \supset\ & \frac{1}{8} g^2 (v+h)^2 (W^1_\mu - iW^2_\mu)(W^{1\mu} + iW^{2\mu}) \leftarrow \text{nabij.} \\ =\ & \frac{1}{4} g^2 (v+h)^2 W^+_\mu W^{-\mu} \\ =\ & \boxed{\frac{g^2v^2}{4}} W^+_\mu W^{-\mu} + \underbrace{\frac{g^2 v}{2} h W^+_\mu W^{-\mu} + \frac{g^2}{4} hh W^+_\mu W^{-\mu}}\end{aligned}$$

- **Jednoznačno predviđene interakcije s higgsom daju Feynmanova pravila:**

$$hW^+_\mu W^-_\nu : \qquad i\frac{g^2 v}{2} g_{\mu\nu} = igM_W g_{\mu\nu} = 2i\frac{M_W^2}{v} g_{\mu\nu},$$

$$hhW^+_\mu W^-_\nu : \qquad i\frac{g^2}{4} \times 2!\, g_{\mu\nu} = 2i\frac{M_W^2}{v^2} g_{\mu\nu},$$

Masa Z bozona

-prepoznavanjem

$$\boxed{M_Z^2 = \frac{(g^2 + g'^2)v^2}{4}}$$

$$\begin{aligned}(gW_\mu^3 - g'B_\mu) &= \sqrt{g^2+g'^2}\left(\frac{g}{\sqrt{g^2+g'^2}}W_\mu^3 - \frac{g}{\sqrt{g^2+g'^2}}B_\mu\right)\\ &\equiv \sqrt{g^2+g'^2}\,(c_W W_\mu^3 - s_W B_\mu)\\ &\equiv \sqrt{g^2+g'^2}\,Z_\mu,\end{aligned}$$

$$\begin{aligned}\mathcal{L} &\supset \frac{1}{8}(v+h)^2\left(-g'B_\mu + gW_\mu^3\right)^2\\ &= \frac{1}{8}(g^2+g'^2)(v+h)^2 Z_\mu Z^\mu\\ &= \boxed{\frac{(g^2+g'^2)v^2}{8 = 4\cdot 2}} Z_\mu Z^\mu + \frac{(g^2+g'^2)v}{4} h Z_\mu Z^\mu + \frac{(g^2+g'^2)}{8} hh Z_\mu Z^\mu\end{aligned}$$

- **Feynmanova pravila interakcija s higgsom:**

$$hZ_\mu Z_\nu: \qquad i\frac{(g^2+g'^2)v}{4}\times 2!\,g_{\mu\nu} = i\sqrt{g^2+g'^2}M_Z g_{\mu\nu} = 2i\frac{M_Z^2}{v}g_{\mu\nu}$$

$$hhZ_\mu Z_\nu: \qquad i\frac{(g^2+g'^2)}{8}\times 2!\times 2!\,g_{\mu\nu} = 2i\frac{M_Z^2}{v^2}g_{\mu\nu},$$

Dodatni kompleksni skalarni multiplet X

gauge-kinetic Lagrangian

$$\mathcal{L} \supset (\mathcal{D}_\mu \Phi)^\dagger (\mathcal{D}^\mu \Phi) + (\mathcal{D}_\mu X)^\dagger (\mathcal{D}^\mu X)$$

$$\mathcal{D}_\mu = \partial_\mu - ig' B_\mu Y - ig W^a_\mu T^a = \partial_\mu - ig' B_\mu Y - ig \left[\frac{1}{2} (W^+_\mu T^+ + W^-_\mu T^-) + W^3_\mu T^3 \right]$$

- **Doprinosi masama W, Z** the terms proportional to v_X^2

$$(\mathcal{D}_\mu X)^\dagger (\mathcal{D}^\mu X) \supset X^\dagger \left[\frac{g^2}{4} W^+_\mu W^{-\mu} (T^+ T^- + T^- T^+) + g^2 W^3_\mu W^{3\mu} (T^3)^2 \right.$$
$$\left. + g'^2 B_\mu B^\mu (Y)^2 + 2 g g' B_\mu W^{3\mu} (Y T^3) \right] X,$$

use $\boxed{Q = T^3 + Y}$ so that $T^3 = Q - Y = -Y$
for the neutral component of X where the vev lives

Za skalar X ukupnog izospina T

$$\begin{aligned}
T^+T^- + T^-T^+ &= \sqrt{2}(T^1+iT^2)\sqrt{2}(T^1-iT^2)+\sqrt{2}(T^1-iT^2)\sqrt{2}(T^1+iT^2)\\
&= 4\left[(T^1)^2+(T^2)^2\right]\\
&= 4\left[|\vec{T}|^2-(T^3)^2\right]\\
&= 4\left[T(T+1)-(T^3)^2\right],
\end{aligned}$$

- doprinosi masama – u konvenciji Q=T+Y

$$\begin{aligned}
(\mathcal{D}_\mu X)^\dagger(\mathcal{D}^\mu X) \supset\ & X^\dagger\left\{g^2W^+_\mu W^{-\mu}\left[T(T+1)-Y^2\right]+g^2W^3_\mu W^{3\mu}(Y)^2\right.\\
&\left.+g'^2B_\mu B^\mu(Y)^2-2gg'B_\mu W^{3\mu}(Y)^2\right\}X.
\end{aligned}$$

◇	Doublet, $Y=1/2$:	$T(T+1)-Y^2=\frac{1}{2}$,	$Y^2=\frac{1}{4}$.
◇	Triplet, $Y=0$:	$T(T+1)-Y^2=2$,	$Y^2=0$.
◇	Triplet, $Y=1$:	$T(T+1)-Y^2=1$,	$Y^2=1$.

1. Dublet SM-a
T=1/2, Y=1/2(1)

$$\langle\Phi\rangle = \begin{pmatrix} 0 \\ v_\phi/\sqrt{2} \end{pmatrix}$$

$$(\mathcal{D}_\mu\Phi)^\dagger(\mathcal{D}^\mu\Phi) \supset \frac{g^2 v_\phi^2}{4} W_\mu^+ W^{-\mu} + \frac{g^2 v_\phi^2}{8} W_\mu^3 W^{3\mu} + \frac{g'^2 v_\phi^2}{8} B_\mu B^\mu - 2\frac{g g' v_\phi^2}{8} B_\mu W^{3\mu}$$

- Doprinos kvadratima masa W i Z, u bazi (W^1, W^2, W^3, B):

$$M_\Phi^2 = \frac{v_\phi^2}{4}\begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & g^2 & -gg' \\ 0 & 0 & -gg' & g'^2 \end{pmatrix}$$

The lower 2 × 2 block is diagonalized by the weak mixing angle,

$$\sin\theta_W = \frac{g'}{\sqrt{g^2+g'^2}}.$$

2. Realni triplet T=1, Y=0 s VEV:

$$\Xi = \begin{pmatrix} \xi^+ \\ \xi^0 \\ \xi^- \end{pmatrix} \to \begin{pmatrix} \xi^+ \\ \xi^0 + v_\xi \\ \xi^- \end{pmatrix}$$

$$\langle \Xi \rangle = \begin{pmatrix} 0 \\ v_\xi \\ 0 \end{pmatrix}$$

$$\frac{1}{2}(\mathcal{D}_\mu \Xi)^\dagger (\mathcal{D}^\mu \Xi) \supset g^2 v_\xi^2 W_\mu^+ W^{-\mu}$$

- Zbog Y=0 ne doprinosi masama neutralnih bozona

$$M_\Xi^2 = v_\xi^2 \begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

3. Kompleksni triplet

T=1, Y=1(2) s VEV:

$$\langle X \rangle = \begin{pmatrix} 0 \\ 0 \\ v_\chi \end{pmatrix}$$

$$X = \begin{pmatrix} \chi^{++} \\ \chi^{+} \\ \chi^{0} \end{pmatrix} \to \begin{pmatrix} \chi^{++} \\ \chi^{+} \\ v_\chi + (h_\chi + i a_\chi)/\sqrt{2} \end{pmatrix}$$

$$(\mathcal{D}_\mu X)^\dagger (\mathcal{D}^\mu X) \supset g^2 v_\chi^2 W_\mu^+ W^{-\mu} + g^2 v_\chi^2 W_\mu^3 W^{3\mu} + g'^2 v_\chi^2 B_\mu B^\mu - 2 g g' v_\chi^2 B_\mu W^{3\mu}$$

- **Doprinos kvadratima masa W i Z**

$$M_X^2 = v_\chi^2 \begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & 2g^2 & -2gg' \\ 0 & 0 & -2gg' & 2g'^2 \end{pmatrix}$$

the lower 2 × 2 block of this matrix is still diagonalized by the same weak mixing angle θ_W

does not generate the same masses for the W and Z in the limit $g' \to 0$

4. Skrbnička simetrija uz oba tripleta, Y=0 i Y=1(2)

$$M_W^2 = \frac{g^2}{4}(v_\phi^2 + 4v_\xi^2 + 4v_\chi^2)$$

$$\rho \equiv \frac{M_W^2}{c_W^2 M_Z^2} = \frac{v_\phi^2 + 4v_\xi^2 + 4v_\chi^2}{v_\phi^2 + 8v_\chi^2}$$

$$M_Z^2 = \frac{g^2 + g'^2}{4}(v_\phi^2 + 8v_\chi^2) = \frac{g^2}{4c_W^2}(v_\phi^2 + 8v_\chi^2)$$

- "rho parameter" blizu 1 za zasebno male ili fino podešene VEV-ove tripleta $v_\xi = v_\chi \equiv v_3$

$$M_{X+\Xi}^2 = 2v_3^2 \begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & g^2 & -gg' \\ 0 & 0 & -gg' & g'^2 \end{pmatrix}$$

the rotation symmetry

The custodial SU(2) symmetry is restored: $W^1 \leftrightarrow W^2 \leftrightarrow W^3$

in the limit $g' \to 0$, the W and Z masses again become equal

Obnavljanje skrbničke simetrije po analogiji s bidubletom - dva tripleta Y=1 i Y=0 u objektu dim. 3x3

to *engineer* the relationship $v_\xi = v_\chi$

$$\langle \tilde{X} \rangle = \begin{pmatrix} v_\chi & 0 & 0 \\ 0 & v_\chi & 0 \\ 0 & 0 & v_\chi \end{pmatrix}$$

$$\tilde{X} = \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ \chi^{-} & \xi^{0} & \chi^{+} \\ \chi^{--} & \xi^{-} & \chi^{0} \end{pmatrix}$$

where $\chi^- = -\chi^{+*}$ and $\xi^- = -\xi^{+*}$

transforms as a triplet under both the global $\mathrm{SU}(2)_L$ and $\mathrm{SU}(2)_R$

by allowing an alignment among VEVs, we can keep $\rho_{\mathrm{tree}} = 1$

- **Ako je to i simetrija skalarnog potencijala**

the resulting model is called the Georgi-Machacek model

"Doubly Charged Higgs Bosons,"
Nucl. Phys. B **262**, 463 (1985)

Elektroslabi parametar blizak 1

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \qquad \rho_{\mathrm{exp}} = 1.0004^{+0.0003}_{-0.0004}$$

- U proširenim Higgsovim sektorima

$$\rho_{\mathrm{tree}} = \frac{\sum_i [T_i(T_i+1) - Y_i^2] v_i^2}{2\sum_i Y_i^2 v_i^2}$$

ne mijenja SM vrijednost ukoliko

$$T_i(T_i+1) - 3Y_i^2 = 0$$

Tri glavne mogućnosti:

isospin singlets with $Y_i = 0$,
doublets with $Y_i = 1/2$,
and septets with $Y_i = 2$

larger isospin representation fields
isospin 26-plet with $Y_i = 15/2$
cause violation of perturbative unitarity

2 HIGGSOVA DUBLETA (2HDM)

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ (h_1 + v_1 + ia_1)/\sqrt{2} \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ (h_2 + v_2 + ia_2)/\sqrt{2} \end{pmatrix}$$

- oba VEV u neutralnim komp. za neslomljenu bažd. simetrija EM
- realnost oba VEV izjegava narušenje CP u skalarnom sektoru