XI. Porijeklo masa čestica standardnog modela

HIGGSOV MEHANIZAM i MASE BOZONA STANDARDNOG MODELA

- HIGGSOV MEHANIZAM U SM-u
- MASE BAŽDARNIH BOZONA
- MASA HIGGSA

ABELOVSKI HIGGSOV MEHANIZAM Originalni U(1)-simetrični Lagrangian s kompleksnim skalarnim poljem

$$\mathcal{L}_\Phi = \mathcal{L}_{\Phi,\mathrm{kin}} + \mathcal{L}_{\Phi,\mathrm{pot}}$$

two real scalar fields ϕ and η,

$$\Phi(x) = \frac{1}{\sqrt{2}}\phi(x)e^{i\eta(x)}$$

odrotiramo

$$\mathcal{L}_{\Phi,\mathrm{kin}} = (D_\mu\Phi)^*\,(D^\mu\Phi)\ ,$$

$$-\mathcal{L}_{\Phi,\mathrm{pot}} = V(\Phi) = \mu^2|\Phi|^2 + \lambda|\Phi|^4$$

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

$$(D_\mu\Phi)^*\,(D^\mu\Phi) \to \frac{1}{2}(\partial_\mu\phi)^2 + \frac{1}{2}e^2q^2\phi^2 A_\mu A^\mu\ ,$$

$$\phi(x) = v + H(x)$$

Higgs'64: Goldstoneov teorem ne vrijedi za slomljenu lokalnu simetriju

$$-\mathcal{L}_{\text{Higgs}} = \frac{1}{2} m_H^2 H^2 + \frac{\kappa}{3!} H^3 + \frac{\xi}{4!} H^4 \; ,$$

$$m_H^2 = 2\lambda v^2, \quad \kappa = 3\frac{m_H^2}{v}, \quad \xi = 3\frac{m_H^2}{v^2} \; .$$

- **Skalarna čestica dobije masu**

Englert & Brout'64: i vektorsko polje pribavlja masu

$$\mathcal{L}_{\text{Higgs}-\text{photon}} = \frac{1}{2} m_A^2 A_\mu A^\mu + e^2 q^2 v H A_\mu A^\mu + \frac{1}{2} e^2 q^2 H^2 A_\mu A^\mu$$

$$m_A^2 = e^2 q^2 v^2 \ .$$

- **Weinberg'67: Generiranje mase kiralnih fermiona lomljenjem baždarne simetrije**

$$\psi = (\psi_L, \psi_R)^T,$$

$$\mathcal{L}_{\text{fermion mass}} = y_\psi \psi_L^\dagger \Phi \psi_R + \text{c.c.} \ ,$$

$$\mathcal{L}_{\text{fermion mass}} = m_\psi \psi_L^\dagger \psi_R + \frac{m_\psi}{v} H \psi_L^\dagger \psi_R + \text{c.c.} \ ,$$

$$m_\psi = y_\psi \frac{v}{\sqrt{2}} \ .$$

London-Anderson-Englert-Brout Higgs-Guralnik-Hagen-Kibble-Weinberg

- Englert-Brout: prvi realistični modeli s elementarnim skalarom, Lorentzovom simetrijom i neabelovskim baždarnim poljima
- Higgs: uz jedno kompleksno skalarno polje predviđa opservabilni bozon po analogiji sa supravodljivošću
- Weinberg: uz dublet kompleksnih skalara demonstrira "čaroliju" jednog SM-higgsa

SPONTANO NARUŠENJE NEABELOVE SIMETRIJE SM-a

$$SU(2)_W \otimes U(1)_Y \longrightarrow U(1)_{e.m.}$$

Bezmaseni baždarni bozoni — simetrične faze

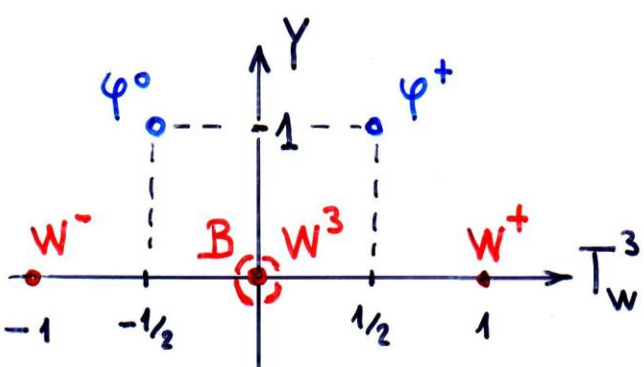
W^i $(i=1,2,3)$, B

Higgsovo polje nosi kvantne brojeve "W" & Y

$$\Phi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$ dublet kompleksnih skalarnih polja

$$\varphi^+ = \frac{1}{\sqrt{2}}(\varphi_1 + i\varphi_2)$$

$$\varphi^0 = \frac{1}{\sqrt{2}}(\varphi_3 + i\varphi_4)$$



SKALARNI POTENCIJAL

$$\mathcal{L}_\Phi = (\mathcal{D}_\mu \Phi)^\dagger (\mathcal{D}^\mu \Phi) - V(\Phi) + \mathcal{L}_{\text{Yukawa}}$$

$$\mathcal{L} \supset \tfrac{1}{2}\partial_\mu \phi_i \partial^\mu \phi_i$$

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

$$\Phi^\dagger \Phi = \frac{1}{2}(\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2)$$

Minimum potencijala za $\Phi^\dagger \Phi = \dfrac{\mu^2}{2\lambda}$

IZBOR

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)$$

Potencijal izražen tim poljima ima minimum za

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

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

dakle za

$$\Phi^\dagger \Phi = |\phi^+|^2 + |\phi^0|^2 = \frac{\mu^2}{2\lambda} = \frac{v^2}{2}.$$

Budući da se za $(-\mu^2) < 0$ minimum potencijala postiže za:

$$|\langle 0\,|\Phi|\,0\rangle| = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}, \qquad v \equiv \sqrt{\frac{\mu^2}{\lambda}}$$

možemo pisati

$$V(\Phi) = -\frac{\lambda}{4}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2 .$$

Potencijal $V(\Phi)$ je invarijantan na lokalne (baždarne) transformacije

$$\Phi(x) \rightarrow \Phi'(x) = e^{i\vec{\alpha}(x)\cdot\vec{\tau}/2}\Phi(x),$$

a isto će se postići i za kinetički član kad u njemu zamijenimo obične derivacije kovarijantnim

$$\begin{aligned} \mathcal{L}_S &= (D_\mu\Phi)^\dagger(D^\mu\Phi) - V(\Phi)\,, \\ D_\mu\Phi &= \left(\partial_\mu - \frac{1}{2}ig\vec{\tau}\cdot\vec{W}_\mu - \frac{1}{2}ig'B_\mu\right)\Phi\,. \end{aligned} \qquad (6.40)$$

Četiri realna skalarna polja
s odgovarajućom normalizacijom

- **Kinetički član** $\mathcal{L} \supset \frac{1}{2}\partial_\mu \phi_i \partial^\mu \phi_i$
- **Maseni član** $V \supset \frac{1}{2} m^2 \phi^2$

$$V = -\frac{\mu^2}{2}\left(\phi_1^2 + \phi_2^2 + (h+v)^2 + \phi_4^2\right) + \frac{\lambda}{4}\left(\phi_1^2 + \phi_2^2 + (h+v)^2 + \phi_4^2\right)^2$$

Odabir (VEV) **orijentacije za** $\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1 + i\phi_2 \\ v + h + i\phi_4 \end{pmatrix}$

$$\langle\phi_3\rangle \equiv v = \sqrt{\frac{\mu^2}{\lambda}}, \qquad \langle\phi_1\rangle = \langle\phi_2\rangle = \langle\phi_4\rangle = 0$$

Realno polje iščezavajuće VEV $\langle h \rangle = 0$ **pribavlja masu** $m_h = \sqrt{2\lambda v^2}$

Izbor unitarnog baždarenja:

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

- Na drugi način, SU(2) rotacijom

$$\Phi = \frac{1}{\sqrt{2}} \exp\left(\frac{i\xi^a\sigma^a}{v}\right) \begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

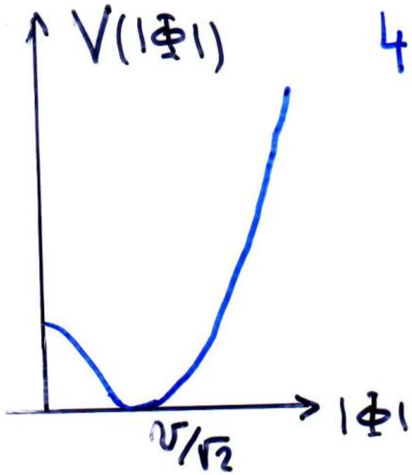
To linear order, $\xi^1 = \phi_2$, $\xi^2 = \phi_1$, and $\xi^3 = -\phi_3$

- odn. baždarnim transformacijama

$$\Phi \to \exp\left(i\lambda_L^a(x)\frac{\sigma^a}{2}\right)\Phi$$ **uz** $$\lambda_L^a(x) = -2\xi^a/v$$

Mase bozona izborom unitarnog baždarenja

Spontano lomljenje: $\begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \xrightarrow{e^{i\vec{\tau}\vec{\vartheta}(x)}} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$



4 skalarnih polja

1 realno skalarno polje

3 polja odlaze u longitudinalne komp. W^+, W^- i Z bozona

$$W_\mu^\pm = \frac{1}{\sqrt{2}}\left(W_\mu^1 \mp i W_\mu^2\right)$$

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

$$A_\mu = B_\mu \cos\theta_W + W_\mu^3 \sin\theta_W$$ ostaje bezmasen

Predikcija masa baždarnih bozona:

Uvrštavanjem kovarijantne derivacije

$$D_\mu \Phi = \left(\partial_\mu - \frac{i}{2} g \vec{\tau} \cdot \vec{W}_\mu - \frac{i}{2} g' B_\mu\right) \Phi \qquad \text{i} \quad \Phi = \frac{1}{\sqrt{2}} \binom{0}{v+H}$$

u kinetički član Higgsovog polja $(D_\mu \Phi)^\dagger (D^\mu \Phi)$

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

$$M_Z^2 = \frac{1}{4} (g^2 + g'^2) v^2$$

Mase baždarnih bozona iscrpnije

- Iz kovarijantnog kinetičkog člana

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

sa skalarom u unitarnom baždarenju:

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

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

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

nabijeni →

neutralni →

Identifikacija nabijenih bozona

$$W^1_\mu \sigma^1 + W^2_\mu \sigma^2 = \frac{1}{2}(W^1_\mu - iW^2_\mu)(\sigma^1 + i\sigma^2) + \frac{1}{2}(W^1_\mu + iW^2_\mu)(\sigma^1 - i\sigma^2)$$

$$= \sqrt{2}\frac{W^1_\mu - iW^2_\mu}{\sqrt{2}}\sigma^+ + \sqrt{2}\frac{W^1_\mu + iW^2_\mu}{\sqrt{2}}\sigma^-$$

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

- Iz očuvanja električnog naboja pri djelovanju na lijeve fermionske dublete

$$\frac{W^1_\mu - iW^2_\mu}{\sqrt{2}} (\bar{u}\ \bar{d})\, \sigma^+ \gamma^\mu P_L \begin{pmatrix} u \\ d \end{pmatrix} = \frac{W^1_\mu - iW^2_\mu}{\sqrt{2}} \bar{u}\gamma^\mu P_L d \quad \Rightarrow \quad \frac{W^1_\mu - iW^2_\mu}{\sqrt{2}} = W^+_\mu$$

$$\frac{W^1_\mu + iW^2_\mu}{\sqrt{2}} (\bar{u}\ \bar{d})\, \sigma^- \gamma^\mu P_L \begin{pmatrix} u \\ d \end{pmatrix} = \frac{W^1_\mu + iW^2_\mu}{\sqrt{2}} \bar{d}\gamma^\mu P_L u \quad \Rightarrow \quad \frac{W^1_\mu + iW^2_\mu}{\sqrt{2}} = W^-_\mu$$

Masa W bozona

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

$$\mathcal{L} \supset \frac{1}{8} g^2 (v+h)^2 (W_\mu^1 - i W_\mu^2)(W^{1\mu} + i W^{2\mu})$$ ← nabij.

$$= \frac{1}{4} g^2 (v+h)^2 W_\mu^+ W^{-\mu}$$

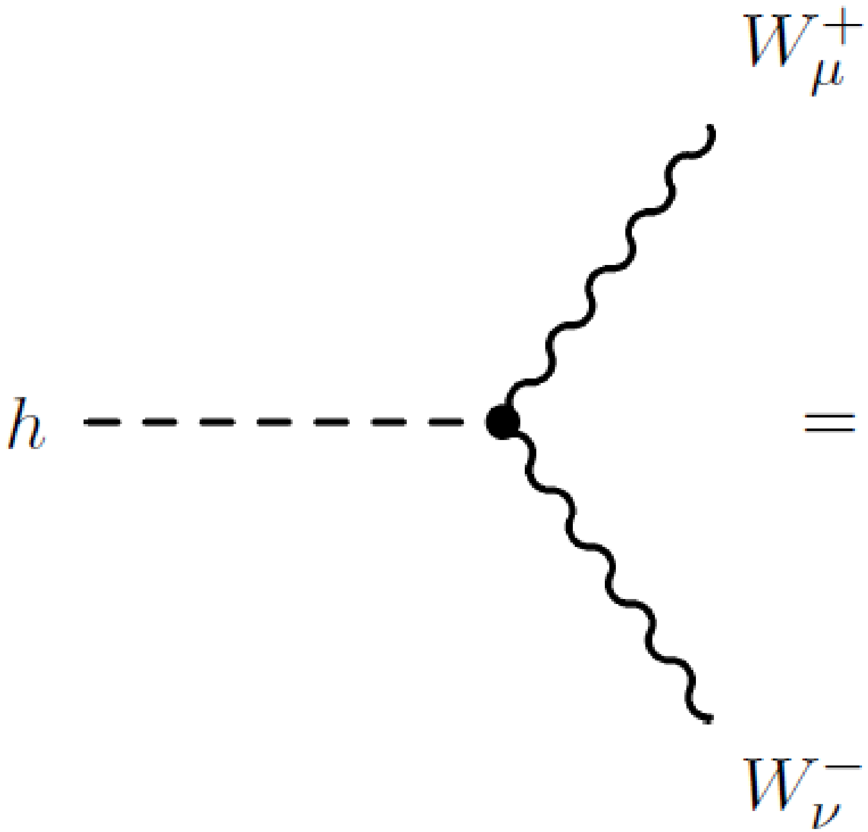
$$= \frac{g^2 v^2}{4} W_\mu^+ W^{-\mu} + \frac{g^2 v}{2} h W_\mu^+ W^{-\mu} + \frac{g^2}{4} hh W_\mu^+ W^{-\mu}$$

- Jednoznačno predviđene interakcije s higgsom daju Feynmanova pravila:

$$hW_\mu^+ W_\nu^- : \qquad i\frac{g^2 v}{2} g_{\mu\nu} = i g M_W g_{\mu\nu} = 2i \frac{M_W^2}{v} g_{\mu\nu},$$

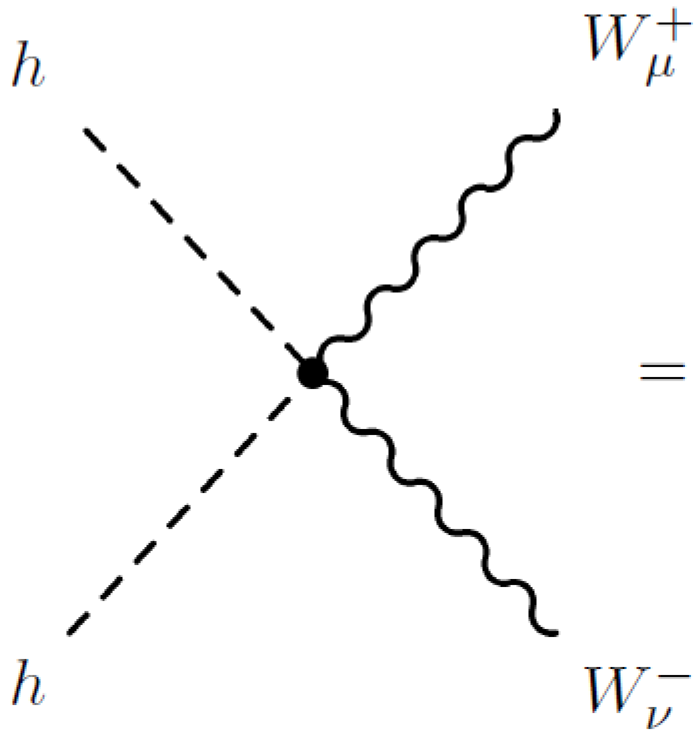
$$hhW_\mu^+ W_\nu^- : \qquad i\frac{g^2}{4} \times 2! \, g_{\mu\nu} = 2i \frac{M_W^2}{v^2} g_{\mu\nu},$$

Feynmanovo pravilo za vrh hWW



$$= i\frac{g^2 v}{2} g_{\mu\nu} = 2i\frac{M_W^2}{v} g_{\mu\nu}$$

Feynmanovo pravilo za vrh hhWW (s kombinatorijskih 2!)



$$= i\frac{g^2}{4}\cdot 2g_{\mu\nu} = 2i\frac{M_W^2}{v^2}g_{\mu\nu}$$

Masa Z bozona

-prepoznavanjem

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

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

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

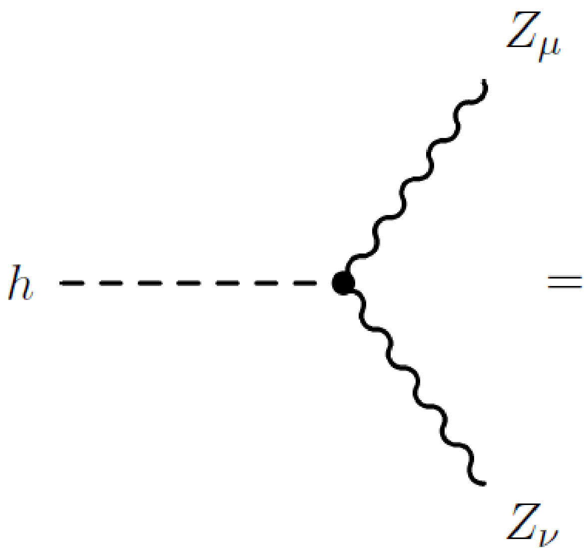
$8 = 4\cdot 2$

- **Feynmanova pravila interakcija s higgsom:**

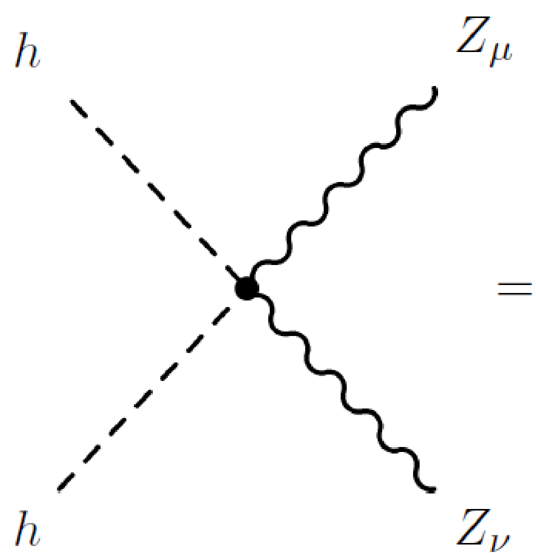
$$hZ_\mu Z_\nu: \qquad i\frac{(g^2+g'^2)v}{4}\times 2!\,g_{\mu\nu} = i\sqrt{g^2+g'^2}M_Z g_{\mu\nu} = 2i\frac{M_Z^2}{v}g_{\mu\nu}$$

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

Feynmanova pravila za hZZ i hhZZ

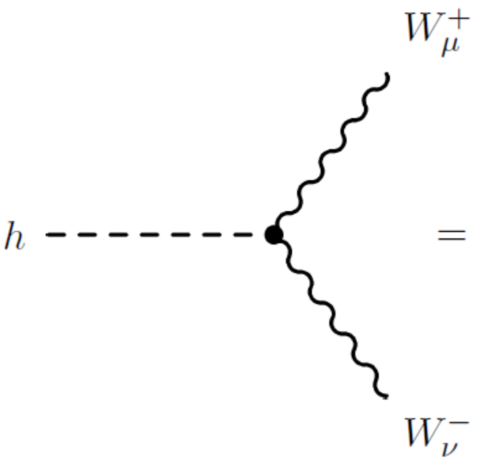


$$= i\frac{(g^2 + g'^2)v}{4} \cdot 2g_{\mu\nu} = 2i\frac{M_Z^2}{v} g_{\mu\nu}$$

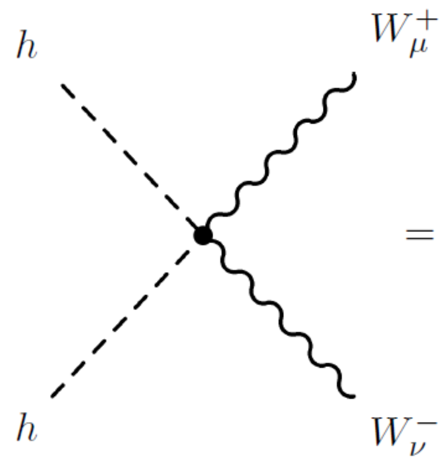


$$= i\frac{(g^2 + g'^2)}{8} \cdot 2 \cdot 2g_{\mu\nu} = 2i\frac{M_Z^2}{v^2} g_{\mu\nu}$$

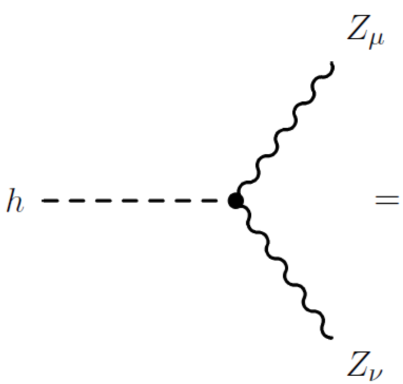
Feynmanova pravila (s dodatnim faktorima 2 za 2 identična h/Z)



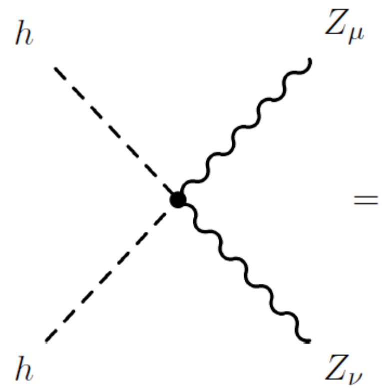
$$= i\frac{g^2 v}{2} g_{\mu\nu} = 2i\frac{M_W^2}{v} g_{\mu\nu}$$



$$= i\frac{g^2}{4} \cdot 2g_{\mu\nu} = 2i\frac{M_W^2}{v^2} g_{\mu\nu}$$



$$= i\frac{(g^2 + g'^2)v}{4} \cdot 2g_{\mu\nu} = 2i\frac{M_Z^2}{v} g_{\mu\nu}$$



$$= i\frac{(g^2 + g'^2)}{8} \cdot 2 \cdot 2g_{\mu\nu} = 2i\frac{M_Z^2}{v^2} g_{\mu\nu}$$

Kovarijantna derivacija SM-a izražena fizikalnim bozonima

$$\mathcal{D}_\mu = \partial_\mu - i g_s G^a_\mu t^a - i\frac{g}{2}\left(W^+_\mu T^+ + W^-_\mu T^-\right)$$

$$- iZ_\mu \left(g c_W T^3 - g' s_W Y\right) - iA_\mu \left(g s_W T^3 + g' c_W Y\right)$$

- Uz definicije $s_W = g'/\sqrt{g^2+g'^2},\ c_W = g/\sqrt{g^2+g'^2},$

$$\left(g s_W T^3 + g' c_W Y\right) = \frac{g g'}{\sqrt{g^2+g'^2}}\left(T^3 + Y\right) \equiv eQ, \qquad e = \frac{g g'}{\sqrt{g^2+g'^2}} = g s_W = g' c_W,$$

$$\left(g c_W T^3 - g' s_W Y\right) = \frac{g^2+g'^2}{\sqrt{g^2+g'^2}} T^3 - \frac{g'^2}{\sqrt{g^2+g'^2}} Q = \sqrt{g^2+g'^2}\left(T^3 - s_W^2 Q\right)$$

$$- i\frac{e}{s_W c_W} Z_\mu \left(T^3 - s_W^2 Q\right) - ieA_\mu Q$$

Određivanje skale elektroslabog faznog prijelaza:

Skalu lomljenja simetrije moglo se utvrditi i prije mjerenja $M_{W,Z}$ masa

- (V-A) teorija slabih međudjelovanja predviđa na niskim energijama

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} = \frac{1}{2v^2} \quad \Bigg\} \Rightarrow \boxed{v = \left(\sqrt{2}\,G_F\right)^{-1/2} = 246\ \text{GeV}}$$

& mjeren $G_F \simeq 1.17 \cdot 10^{-5}\ \text{GeV}^{-2}$

ŠTO JE S MASOM HIGGSA?

Bila je neodređena sve do otkrića Higgsolike rezonancije na 126 GeV na LHC-u (4.7.2013.): $\lambda = 0.13$ ← *1

$$V(\Phi) = -\frac{\lambda}{4}\left(\Phi^\dagger\phi - \frac{v^2}{2}\right)^2$$

Masa Higgsove čestice ostaje neodređena:

$$V(\Phi) = \frac{1}{2}(2\mu^2)\,H^2_{(x)} + \cdots \Rightarrow \boxed{M_H = \sqrt{2}\mu = \sqrt{2\lambda}\,v}$$

ovisnost o jakosti samointerakcije λ

*1 slabo vezanje

SAMOINTERAKCIJE HIGGSA

-minimizacijom potencijala i unitarno bažd.

$$\mu^2 = \lambda v^2 \qquad \Phi^\dagger\Phi = \frac{1}{2}(h+v)^2$$

$$\mathcal{L}_V = -V(\Phi) = \mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2$$

$$= -\lambda v^2 h^2 - \lambda v h^3 - \frac{\lambda}{4}h^4 + \text{const.}$$

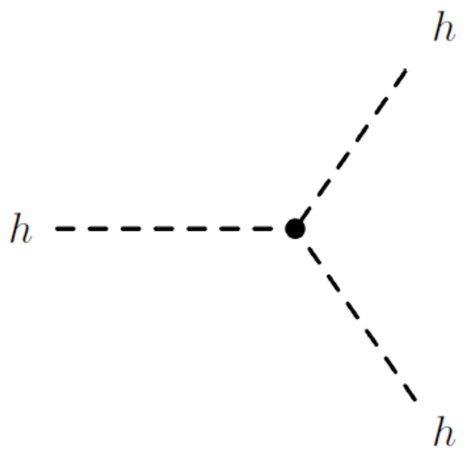
- Član mase i Feynmanova pravila interakcija

$$-\lambda v^2 = -m_h^2/2$$

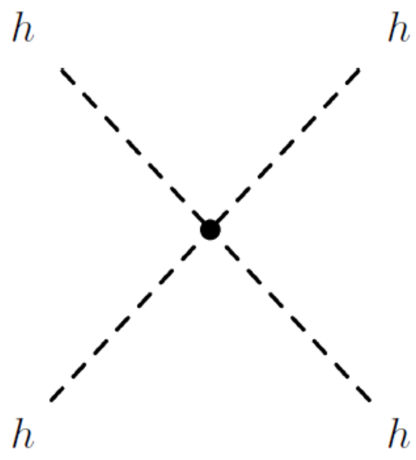
$$hhh: \quad -i\lambda v \times 3! = -6i\lambda v = -3i\frac{m_h^2}{v}$$

$$hhhh: \quad -i\frac{\lambda}{4} \times 4! = -6i\lambda = -3i\frac{m_h^2}{v^2}$$

Feynmanova pravila u unitarnom baždarenju za samointerakcije



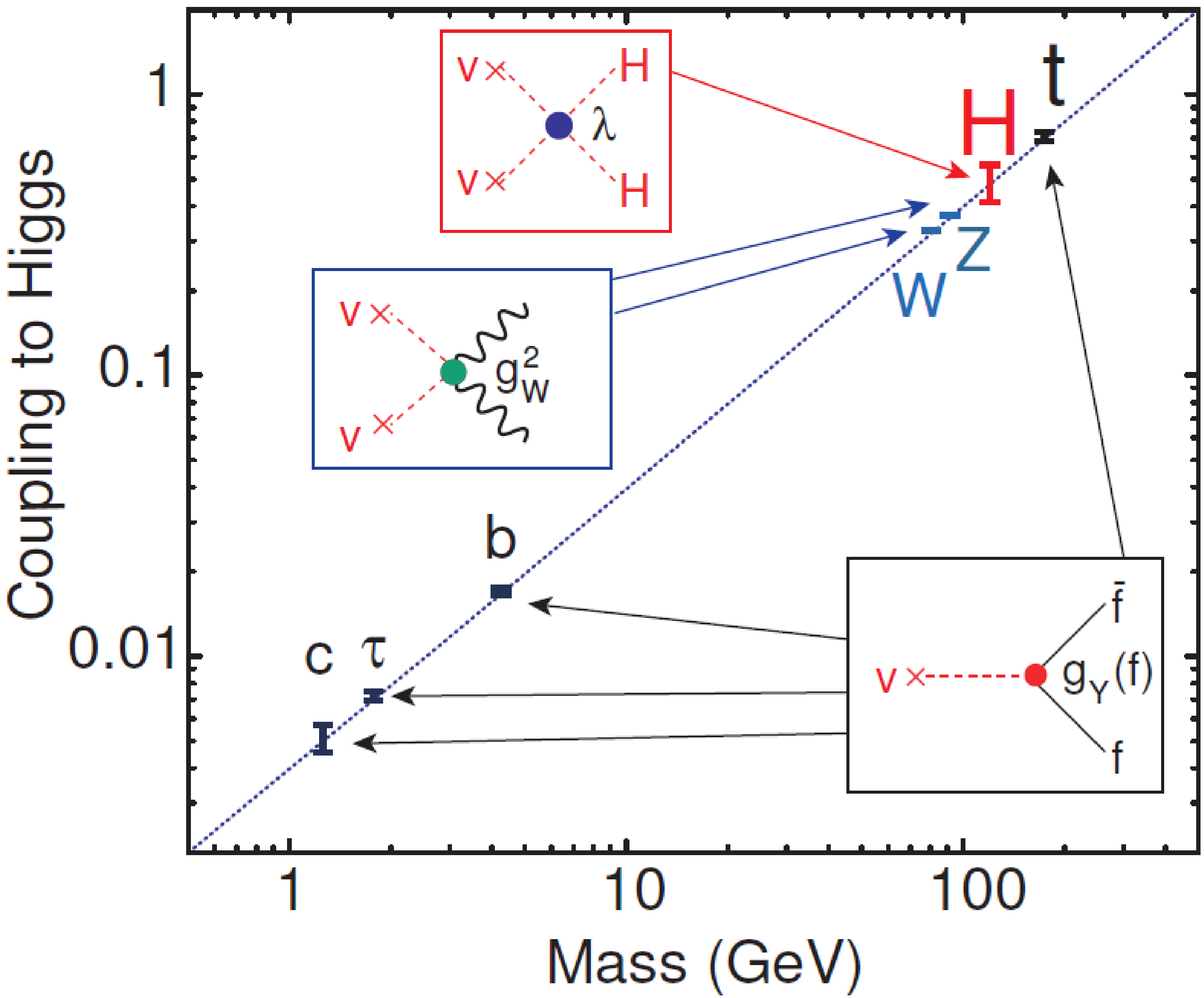
$$= -i\lambda v \cdot 3! = -6i\lambda v = -3i\frac{m}{v}$$



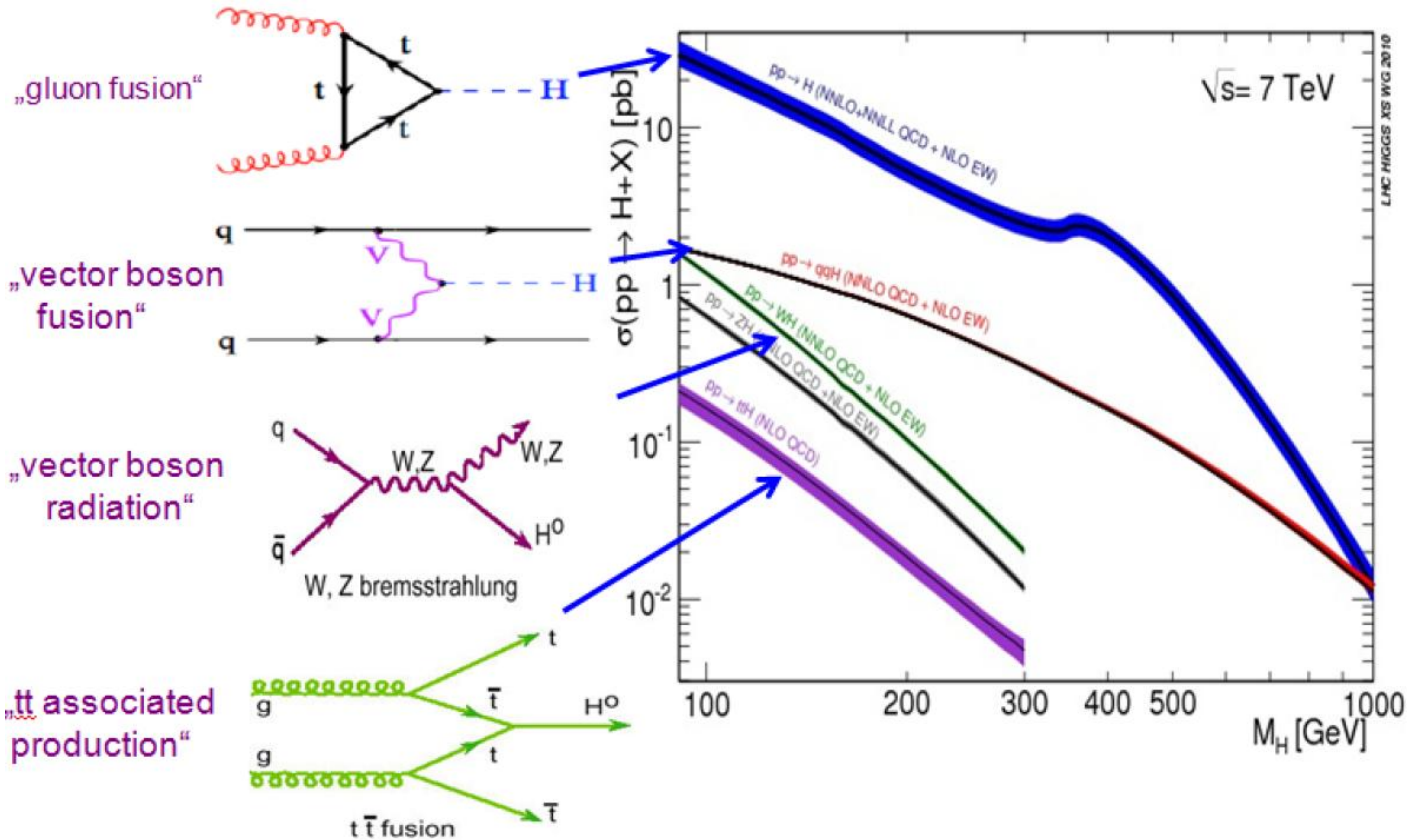
$$= -i\frac{\lambda}{4} \cdot 4! = -6i\lambda = -3i\frac{m_h^2}{v^2}$$

- Standardni model zahtijeva uvođenje još neotkrivenog Higgsovog polja
- To je SKALARNO POLJE koje prožima sav prostor
- Mogućnost pobuđenja tog polja (produkcija Higgsove čestice) na LHC-u

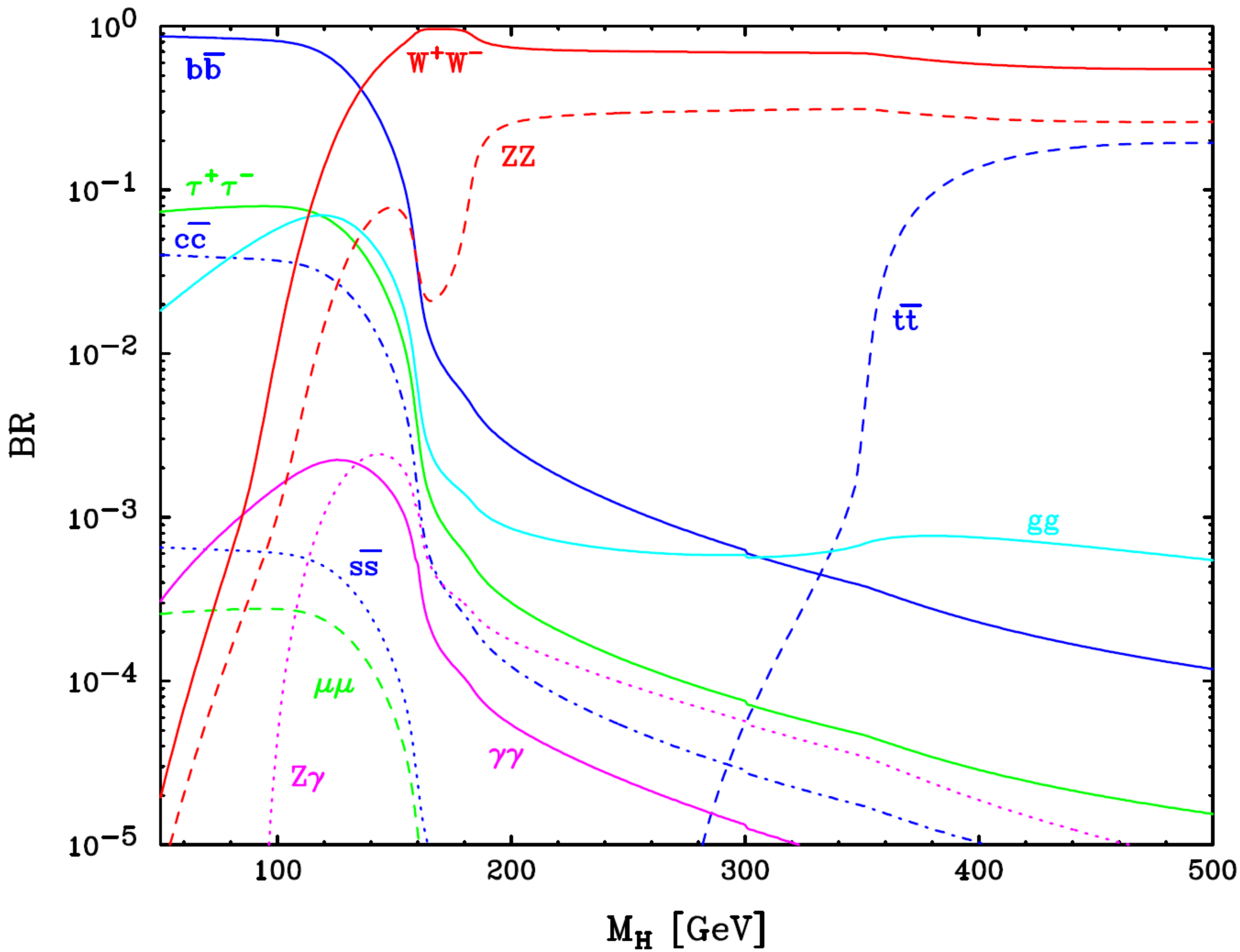
Vezanja Higgsovih bozona u SM



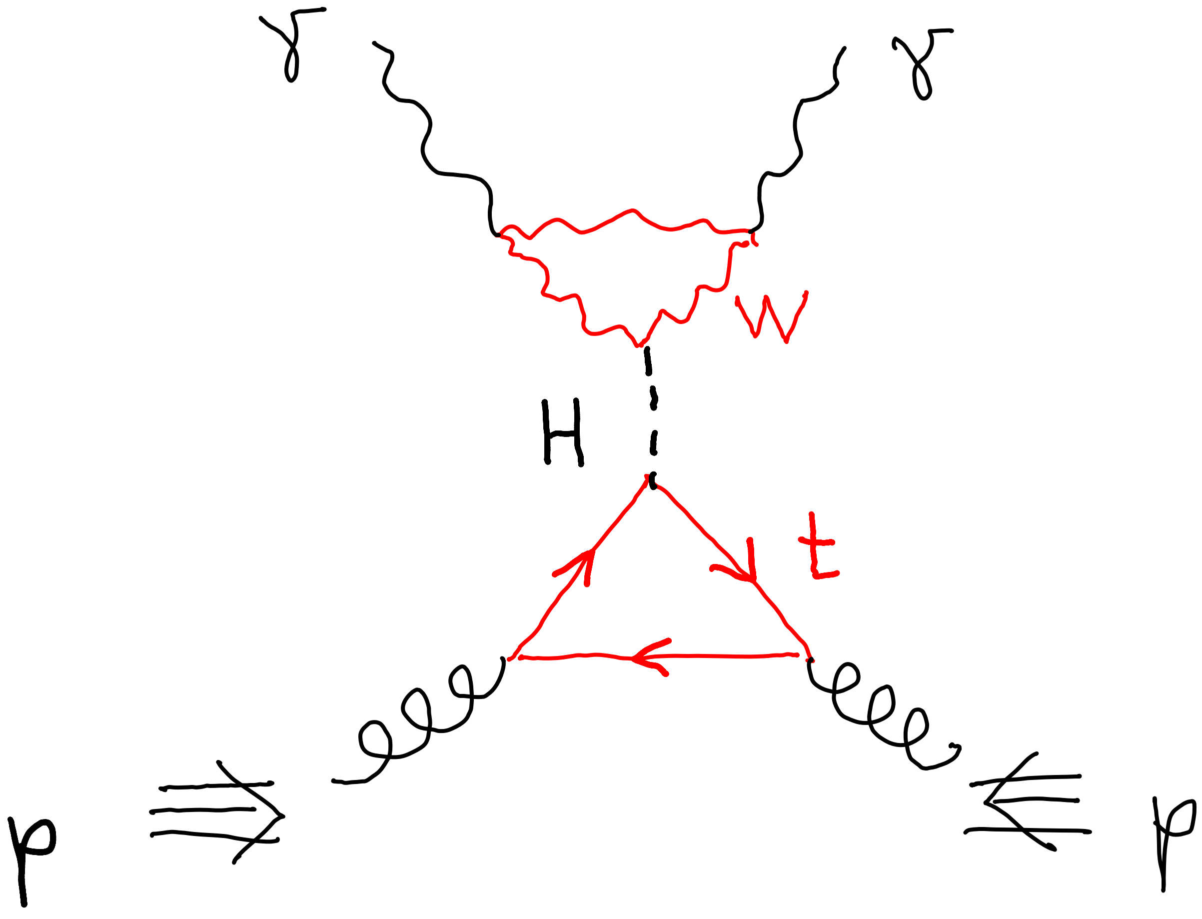
Produkcija Higgsovih bozona



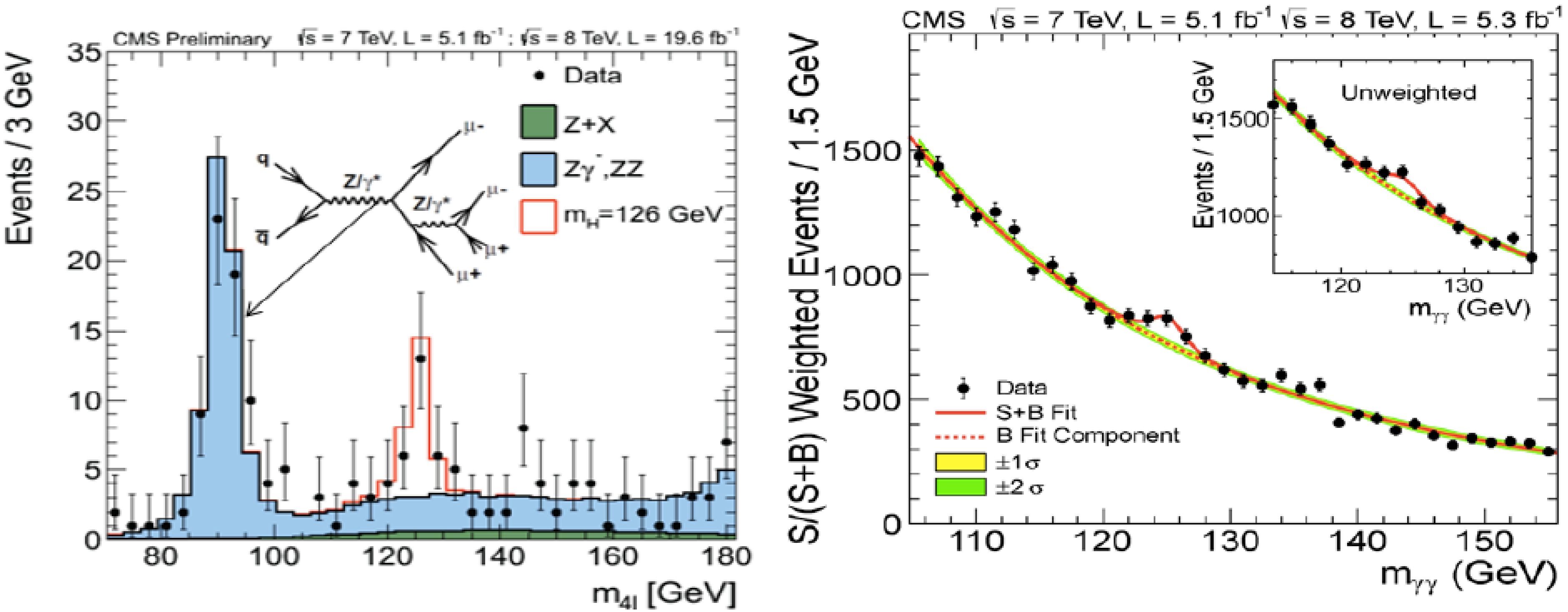
Raspadi Higgsovog bozona



Virtualna fizika u eri LHC-a:
Produkc. i raspad kvantnom petljom



Pojačanje spektra na invarijantnoj masi 126 GeV



Omjeri grananja za Higgsov bozona SM-a mase 126 GeV

Decay mode	BR	Notes (as of early 2014)
$b\bar{b}$	58%	Observed at about 2σ at CMS
WW^*	22%	Observed at 4σ
gg	8.6%	
$\tau\tau$	6.3%	Observed at 1–2 σ
$c\bar{c}$	2.9%	
ZZ^*	2.6%	Discovery mode (in $ZZ^* \to 4\mu$, $2\mu 2e$, $4e$)
$\gamma\gamma$	0.23%	Discovery mode
$Z\gamma$	0.15%	
$\mu\mu$	0.022%	
Γ_{tot}	4.1 MeV	

NAKON OTKRIĆA HIGGSA

Zagonetka finog podešavanja za tri parametra Higgsovog potencijala

$$V = \text{const.} + m_H^2 |H|^2 + \lambda |H|^4$$

- Problem kozmološke konstante
- Problem prirodnosti higgsa
- Problem vakuumske stabilnosti