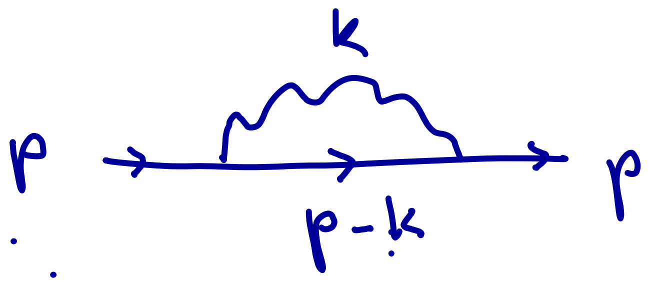
TESTOVI ELEKTROSLABE TEORIJE

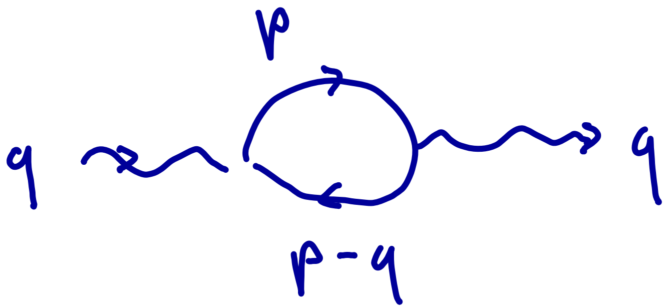
EW PRECIZNOST PRIJE I NAKON POTVRDE HIGGSA

- POOPĆENJE QED NA EW
- PRECIZNO MJERENE OPSERVABLE
- SPECIFIČNE I UNIVERZALNE KVANTNE POPRAVKE

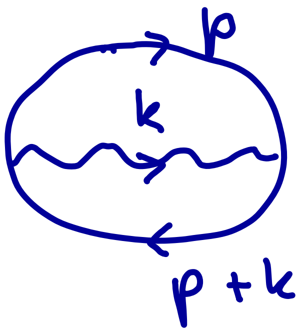
KVANTNE PETLJE u 2. redu QED – upoznate na diplomskom studiju



vlastita energija



vakuumska polarizacija



vakuumska petlja

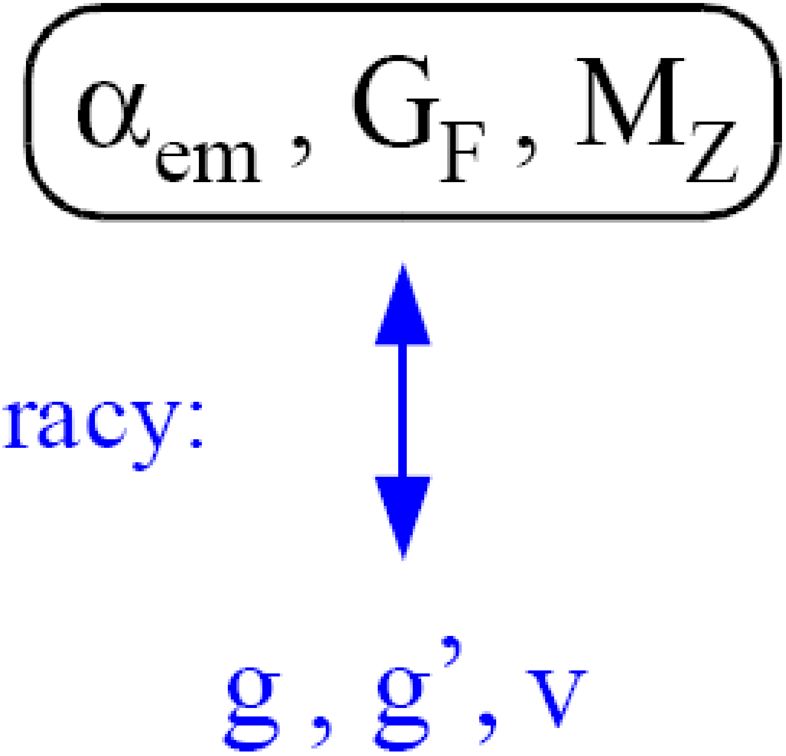
ELEKTROSLABE KOREKCIJE

HIGGSOVA FIZIKA – NOVA ERA FIZIKE EW PRECIZNOSTI

- A) PRECIZNO MJERENE OPSERVABLE
- B) PRECIZNE PREDIKCIJE VISOKO-ENERGIJSKIH OPSERVABLI
- C) UNIVERZALNE RADIJACIJSKE POPRAVKE 4-FERMIONSKIM PROCESIMA
- D) NOVA EW PRECIZNOST

A) PRECIZNO MJERENE OPSERVABLE

Basic set:



$\boxed{\alpha_{em}\,,\, G_F\,,\, M_Z}$

$\updownarrow$

$g\,,\, g'\,,\, v$

fantastic exp. accuracy:

- $(g-2)_e$
- τ_μ
- Z line shape

MJERENE NA VELIKU TOČNOST:

$$\begin{aligned} M_Z &= (91.1875 \pm 0.0021)\ \mathrm{GeV} \\ G_F &= (1.166\,371 \pm 0.000\,006) \cdot 10^{-5}\ \mathrm{GeV}^{-2} \\ \alpha^{-1} &= 137.035\,999\,710 \pm 0.000\,000\,096 \end{aligned}$$

$$\begin{aligned} M_Z &= 91.150(30)\ \mathrm{GeV}\ \text{(from LEP, SLC)}, \\ G_F &= 1.16637(2) \times 10^{-5}\ (\mathrm{GeV})^{-2}\ (\text{from } \mu \to e\nu_\mu\bar{\nu}_e), \\ \alpha &= 137.0359895(61)^{-1}\ (\text{from } g-2 \text{ of electron}), \end{aligned}$$

Pitanje kuta slabog miješanja

- NIJE FUNDAMENTALNI PARAMETAR TEORIJE
- DVIJE DEFINICIJE – konzistentne na granastoj razini:

$$\underbrace{1-\frac{M_W^2}{M_Z^2}=\sin^2\Theta_W}_{\text{odabir}}=\frac{e^2}{g^2}$$

odabir – prije i nakon

(Veltman, Sirlin) radijacijskih popravki

REZULTAT RAČUNA

$$\Delta\rho^{t,b,H} = \frac{\alpha N_c}{16\pi\sin^2\theta_W}\,\frac{1}{M_W^2}\left(m_t^2+m_b^2-\frac{2m_t^2m_b^2}{m_t^2-m_b^2}\ln\frac{m_t^2}{m_b^2}\right.$$

$$\left.-\frac{3M_W^2\sin^2\theta_W}{\cos^2\theta_W}\ln\frac{M_H^2}{M_W^2}\right)$$

$$\Delta\rho^{t,b} = \frac{\Sigma_Z^{t,b}(0)}{M_Z^2}-\frac{\Sigma_W^{t,b}(0)}{M_W^2}.$$

$$\simeq \frac{\alpha N_c}{16\pi s_W^2c_W^2}\,\frac{m_t^2}{M_Z^2}$$

"NON-DECOUPLING":

$\rightarrow \infty$ ($m_t^2 \rightarrow \infty$, dakle sa samim b-om)

RAZLOG LOGARITAMSKOG PONAŠANJA DOPRINOSA HIGGSA (Veltmannov “screening theorem”)

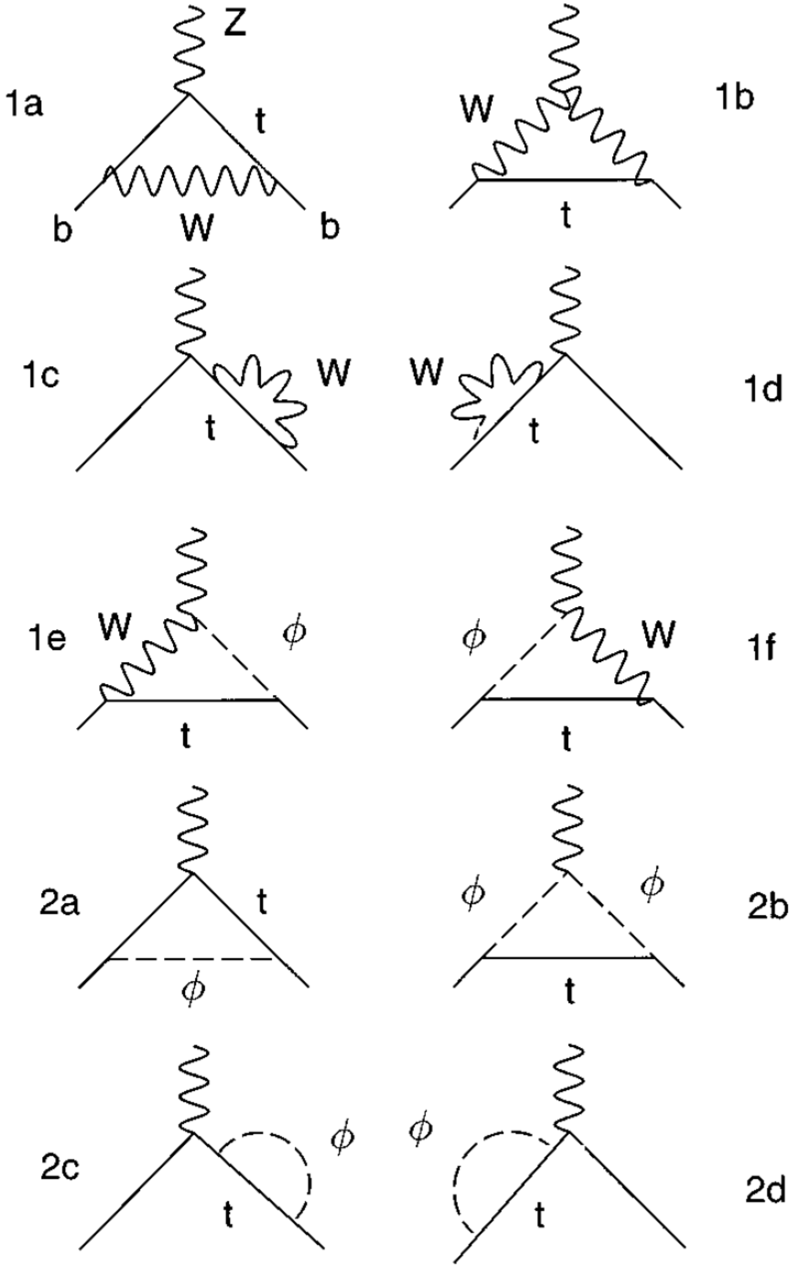
- **Odsutnost vezanja W i Z na higgs, koje bi u unitarnom baždarenju bilo proporcionano higgsovom kvartičnom vezanju**

B) PRECIZNE PREDIKCIJE ZA SPECIFIČNE VISOKO-ENERGIJSKE OPSERVABLE

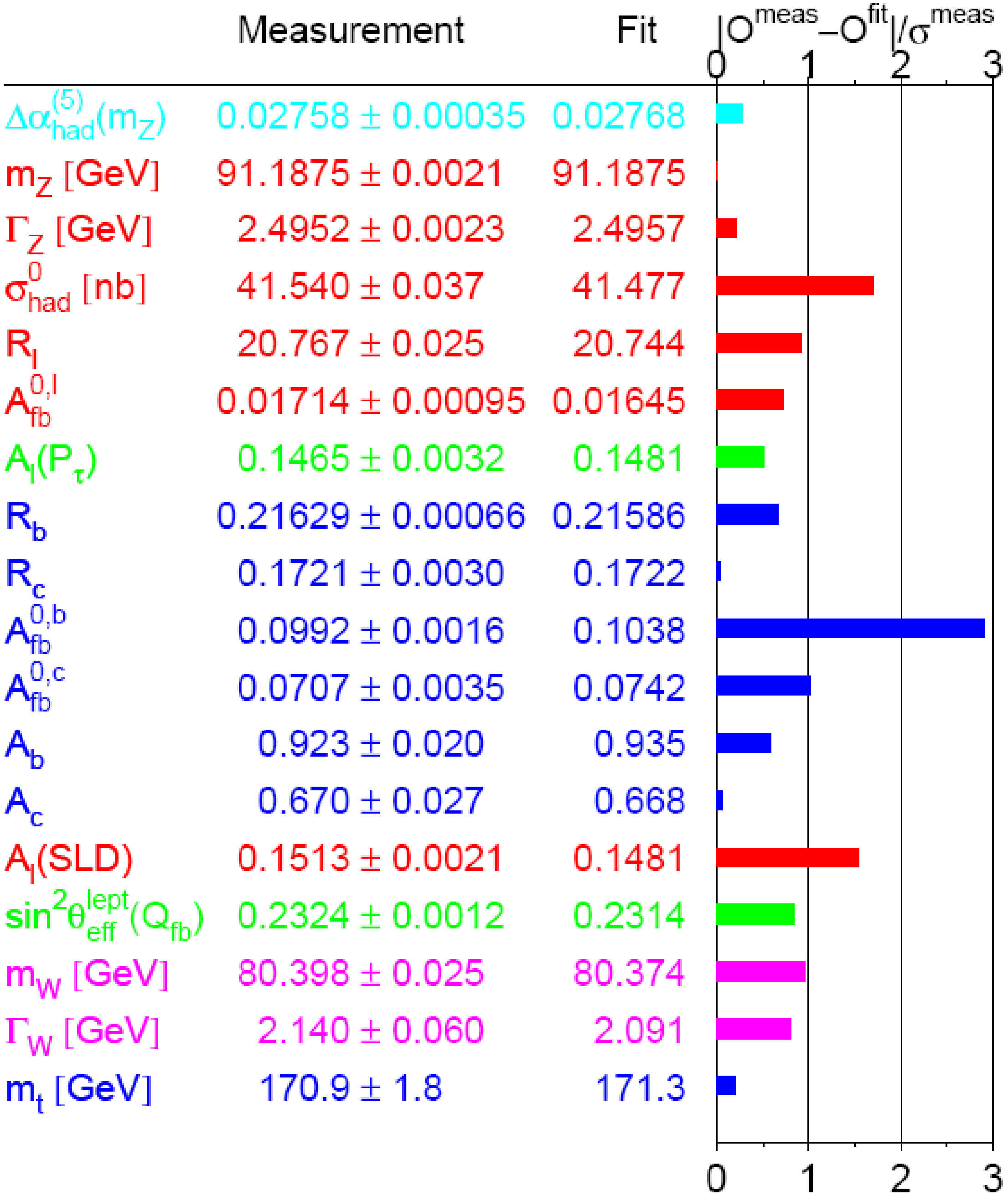
$$\Gamma_Z , M_W , \sigma_h , R_h , R_b , A^l_{FB} , A^b_{FB} , A^\tau_{pol} , \ldots$$

OPSERVABLE NA Z-REZONANCI

- UKUPNA ŠIRINA
- Z-ASIMETRIJE
- Parametar Rb

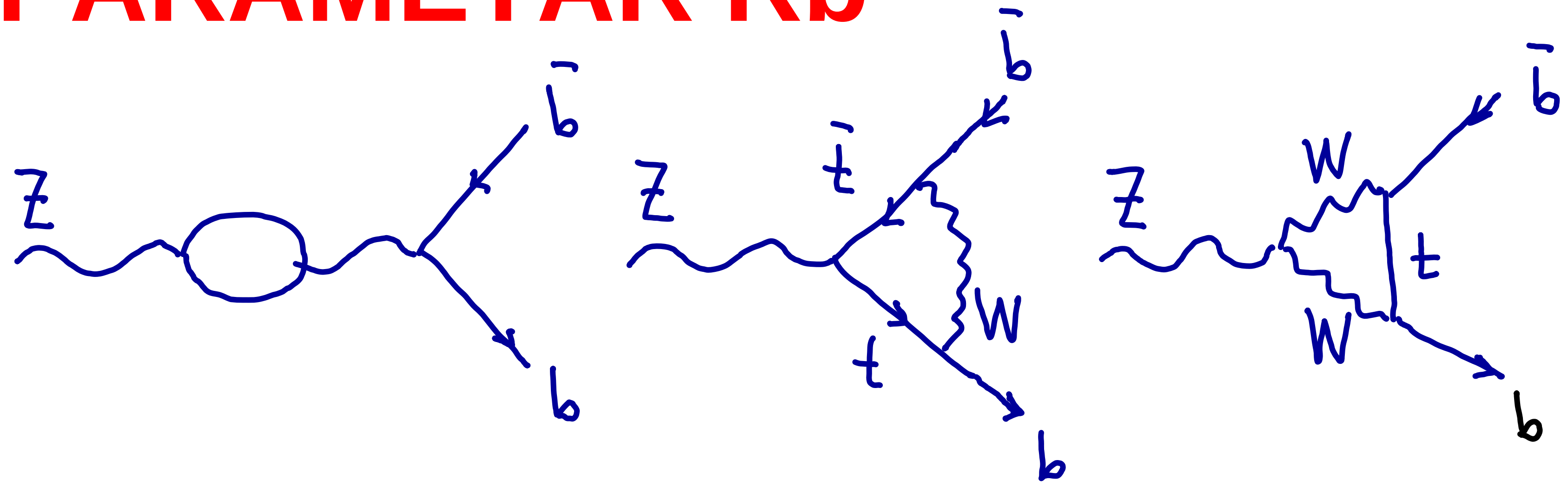


Usporedba mjerenja i analize SM s globalnom EW-prilagodbom



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^{0} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3

PARAMETAR Rb



ne-univerzalne korekcije

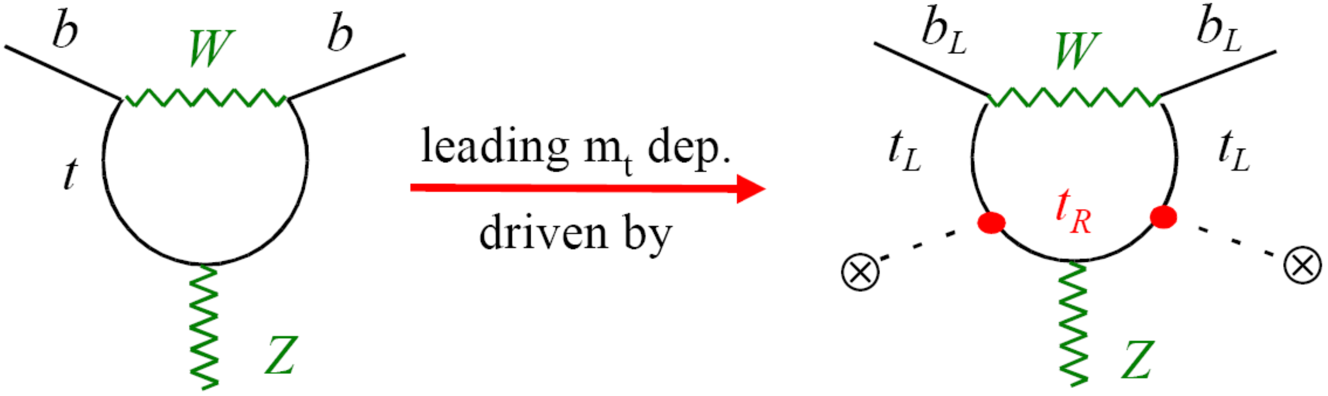
daju korekciju naboju $b_L Z$-vezanja

$$Q_{Z_L} = -\left(\frac{1}{2} - \frac{1}{3}s_w^2 - \frac{\alpha}{16\pi s_w^2}\frac{m_t^2}{M_w^2}\right)$$

OKUSNO-SPECIFIČNE, NEUNIVERZALNE KOREKCIJE

E.g.:

$$R_b = \frac{\Gamma(Z \to bb)}{\Gamma(Z \to \text{had})}$$



leading m_t dep.

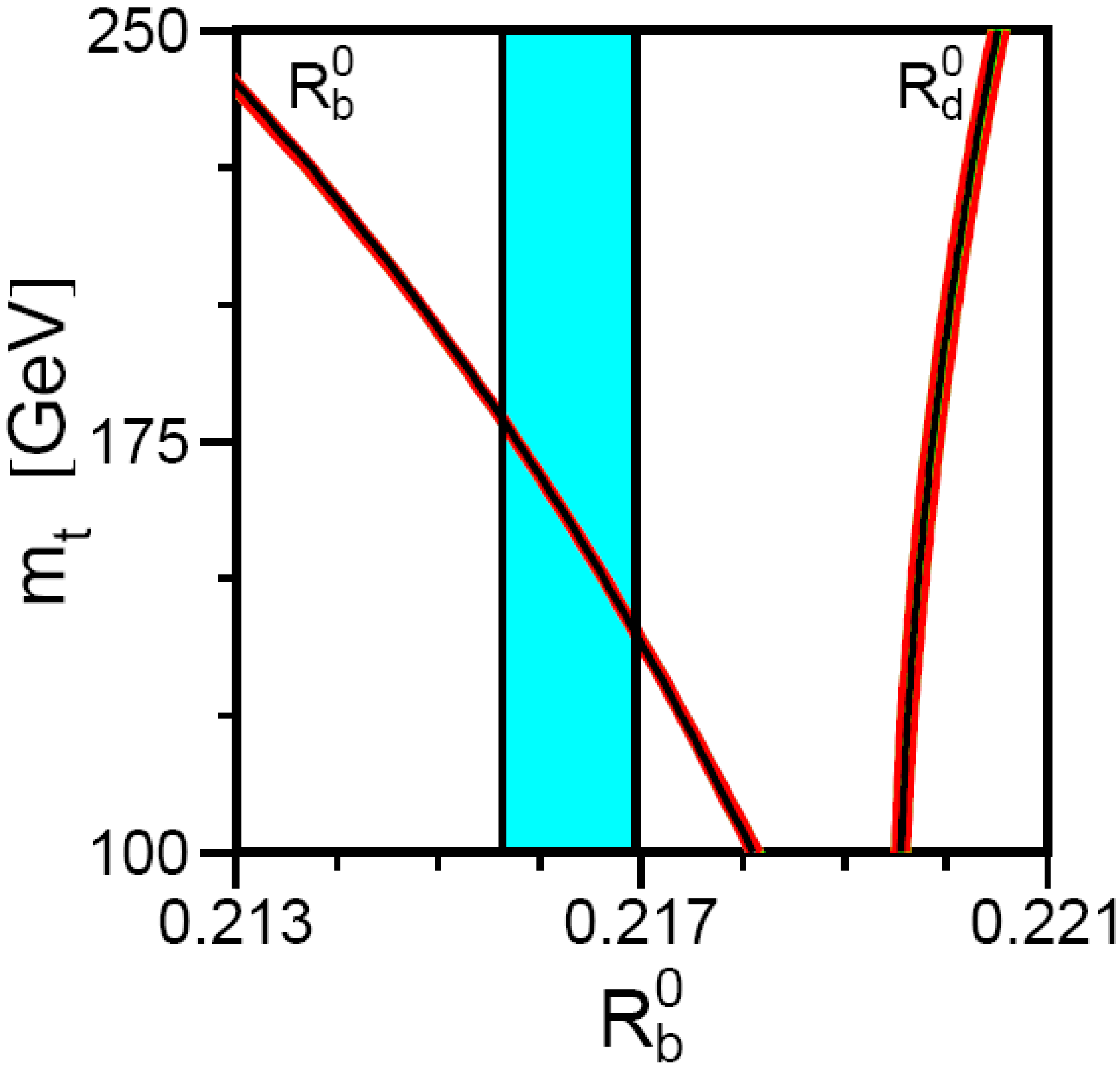
driven by

$$R_b = R_0 [\ 1 - G_F m_t^2/2\pi^2\sqrt{2}\ + \dots\ ] \approx 0.2182 - \boxed{0.0024}$$

$$\sim \frac{g^2 y_t^2 \langle \phi^+ \phi \rangle Z_\mu b_L \gamma^\mu b_L}{M^2_W}$$

<u>tree−level</u>
+ flavour−universal corrections

Mjerenje Rb (LEP,SLD) određuje masu t-kvarka



RAČUN U SLUČAJU LORENTZOVE SIMETRIJE

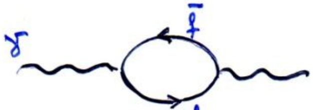
nastavak dodiplomske razine [JP FEČ '97]

GRANASTI DIJAGRAMI / UNITARNO BAŽDARENJE

na poslijediplomsku :

DIJAGRAMI S PETLJAMA gdje struktura ∞-sti ovisi o obliku propagatora / prednost RENORMALIZABILNIH 't Hooftovih R_ξ BAŽDARENJA

Od QED na razini jedne petlje

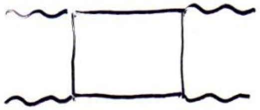


VAKUUMSKA POLARIZACIJA

VLASTITA ENERGIJA FERMIONA

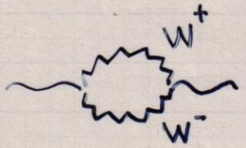
KOREKCIJA VRHA

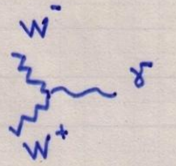
DVOSTRUKA IZMJENA BOZONA

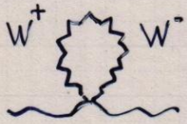


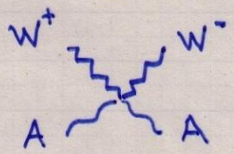
RASPRŠENJE SVJETLOSTI NA SVJETLOSTI

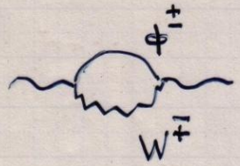
preko QED ugrađene u EW teoriju
— primjerice

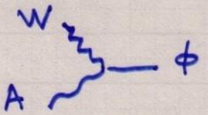


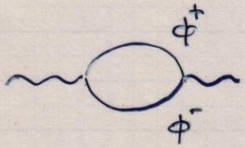


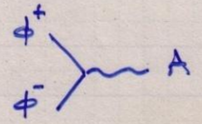


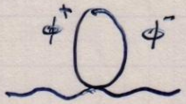


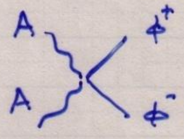








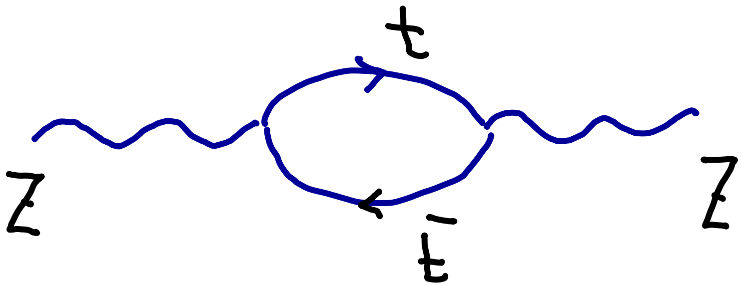


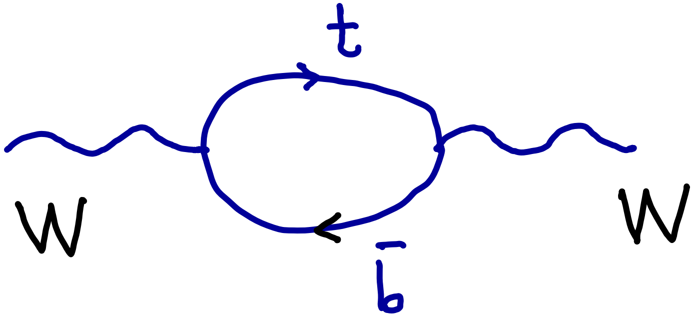


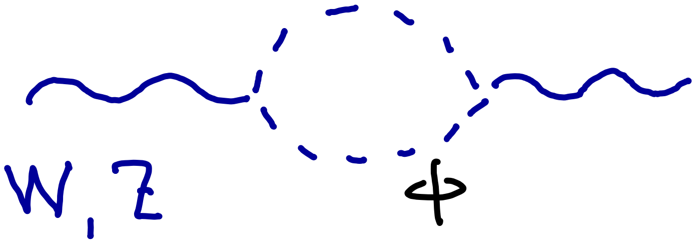
C) UNIVERZALNE RADIJACIJSKE POPRAVKE 4-FERMIONSKIM PROCESIMA

- NEIZRAVNE-UNIVERZALNE ("oblique") (vakuumska polarizacija)
- IZRAVNE ("direct") korekcije vrhu i pravokutnom dijagramu

EFEKT VLASTITIH ENERGIJA W & Z BOZONA







$$\left.\begin{aligned} M_Z^2 &\to M_Z^2 + \delta M_Z^2 \\ M_W^2 &\to M_W^2 + \delta M_W^2 \end{aligned}\right\} \Rightarrow$$

$$\sin^2\theta_W \to 1 - \frac{M_W^2 + \delta M_W^2}{M_Z^2 + \delta M_Z^2}$$

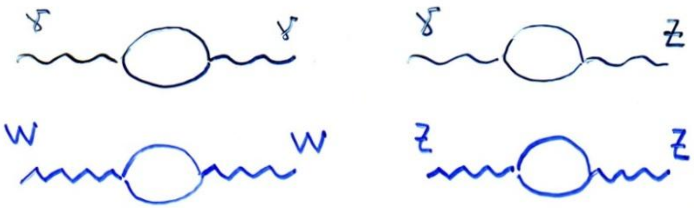
$$= 1 - \frac{M_W^2}{M_Z^2} + \frac{M_W^2}{M_Z^2}\left(\underbrace{\frac{\delta M_Z^2}{M_Z^2} - \frac{\delta M_W^2}{M_W^2}}_{\equiv \Delta\rho}\right)$$

kao dio neizravnih (engl. "oblique") korekcija
(u usporedbi s izravnim korekcijama vrha i pravokutnih dijagrama / dvostruke izmjene bozona)

- studij učinka novih/teških čestica u niskoenergijskom režimu putem vlastitih energija baždarnih bozona :

$$\Pi^{\mu\nu}_{AB}(q^2) \sim g^{\mu\nu}\Pi_{AB}(q^2) + C_{AB}(q^2)\, q^\mu q^\nu$$

$$A, B = \gamma, Z, W$$



EM baždarna invarijantnost zahtijeva

$$\Pi_{\gamma\gamma}(0) = \Pi_{\gamma Z}(0) = 0 \quad ,$$

pa za konačni q^2 učinci γ-γ & γ-Z vakuumske polarizacije idu kao q^2/Λ^2 (zanemarivi za skalu nove fizike $\Lambda \gg v$).

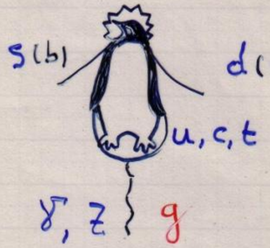
Učinci putem W-W & Z-Z polarizacije :

$$\frac{1}{M_W^2}\left[\Pi^{new}_{WW}(M_W^2) - \Pi^{new}_{WW}(0)\right]_{\overline{MS}} \equiv \frac{\alpha(M_Z)}{4s^2}\bigg|_{\overline{MS}} S_{\underset{Z}{W}}$$ očuvan slabi izospin

W → Z

$$\frac{1}{M_W^2}\Pi^{new}_{WW}(0) - \frac{1}{M_Z^2}\Pi^{new}_{ZZ}(0) \equiv \alpha(M_Z)\big|_{\overline{MS}}\, T$$ narušen slabi izospin

do elektroslabih (γ, Z) i jakih (gluonskih) pingvina [usp. FEČ, str. 372]



s kratkodosežnim (SD od engl. "short distance") korekcijama u elektroslabo-jakoj teoriji !

bojni singlet

$$\eta_1(q^2) = 2\,C_+(q^2) - C_-(q^2)$$

osjetljiv na izbor Λ_{QCD} i mijenja predznak na $q^2 \sim$ par GeV^2 . . . .

bojni oktet → stabilni koeficijent

$$\eta_8(q^2) = \frac{1}{2}\left(C_+(q^2) + C_-(q^2)\right)$$

Wilsonovi koeficijenti 4-kvarkovskih operatora $O_\pm\,(\Delta S = 1)$:

$$\boxed{C_\pm(q^2) = \left[\frac{\alpha_s(q^2)}{\alpha_s(M_W^2)}\right]^{a_\pm/b}}$$

$\downarrow$

$$\overbrace{a_+ = -2\ ;\ a_- = 4}^{\text{anomalne dim.}} \quad ;\quad b = 11 - \frac{2}{3}N_f \leftarrow \text{broj aktivnih okusa}$$

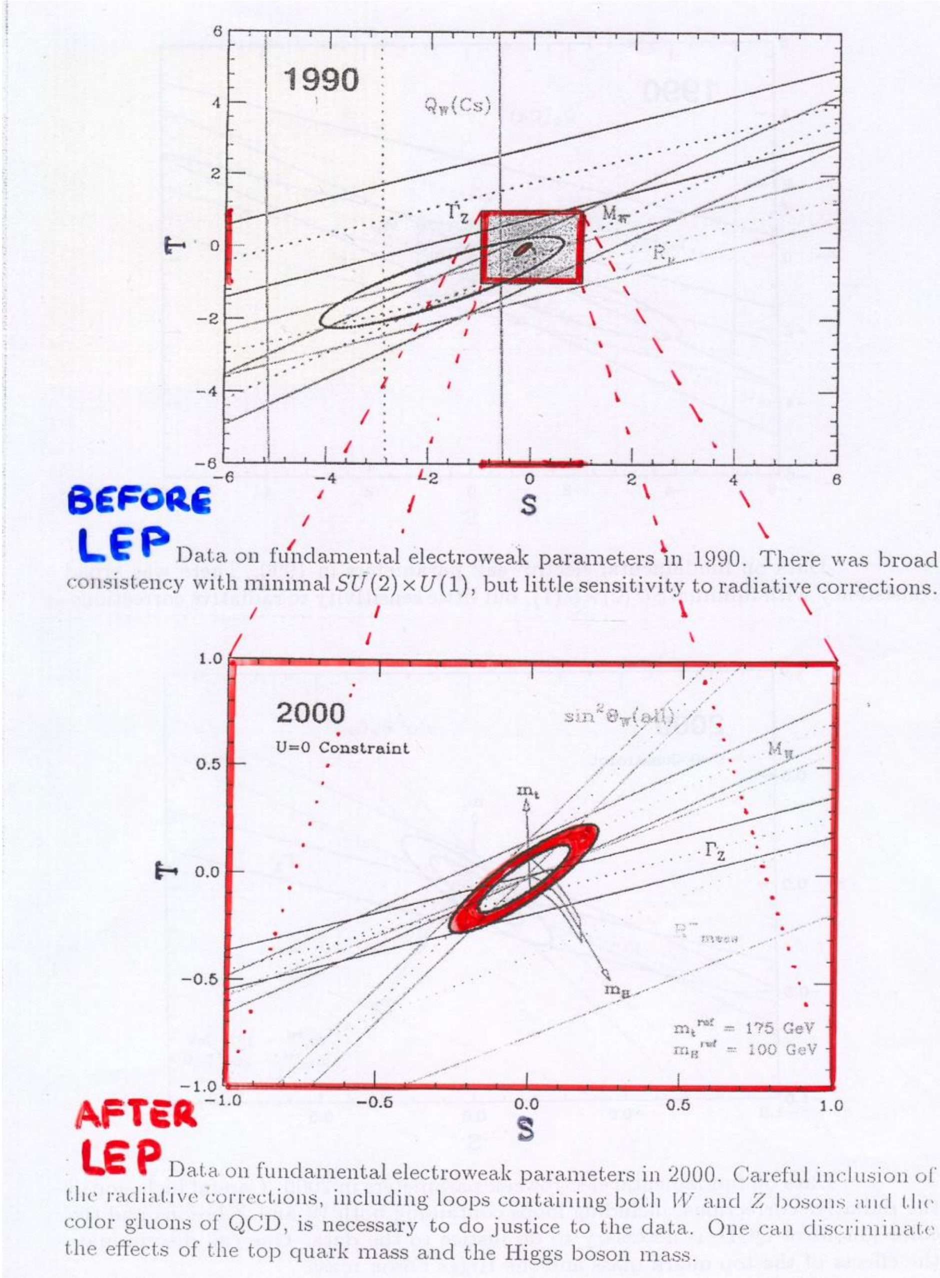
S, T, U EW-PARAMETRI PESKIN-TAKEUCHIJA za fiziku BSM, uz pretp.:

- U igri samo EW baždarni bozoni (ali mogući novi fermioni ili skalari BSM)
- Vezanja NP na lake fermione su potisnuta
- Skala NP velika prema masama W i Z

REVIJE “up to the Higgs discovery”

- Hewett, Takeuchi, Thomas:hep-ph/9603391
- G. Isidori/0911.3219
- R. Barbieri:1503.08153

Usp. PDG
Fig. 10.3



BEFORE LEP

Data on fundamental electroweak parameters in 1990. There was broad consistency with minimal $SU(2)\times U(1)$, but little sensitivity to radiative corrections.

AFTER LEP

Data on fundamental electroweak parameters in 2000. Careful inclusion of the radiative corrections, including loops containing both W and Z bosons and the color gluons of QCD, is necessary to do justice to the data. One can discriminate the effects of the top quark mass and the Higgs boson mass.

PRISTUP EFEKTIVNIH TEORIJA

$$S = \frac{16\pi}{gg'} \frac{\partial}{\partial q^2} \mathscr{A}(W_3 \to B)\Big|_{q^2=0} \qquad \text{and} \qquad T = \frac{1}{\alpha}\left(\frac{m_W^2}{m_Z^2 \cos^2\theta_W} - 1\right)$$

- odgovaraju korekcijama operatora S i T koji su dim 6

the dimension-six part of the Lagrangian, $\mathscr{L}_{d=6} = (c_T/\Lambda^2)Q_T + (c_S/\Lambda^2)Q_S$

$$\Delta S = -c_S \frac{16\pi v^2}{\Lambda^2}, \qquad \Delta T = c_T \frac{8\pi v^2}{\Lambda^2}.$$

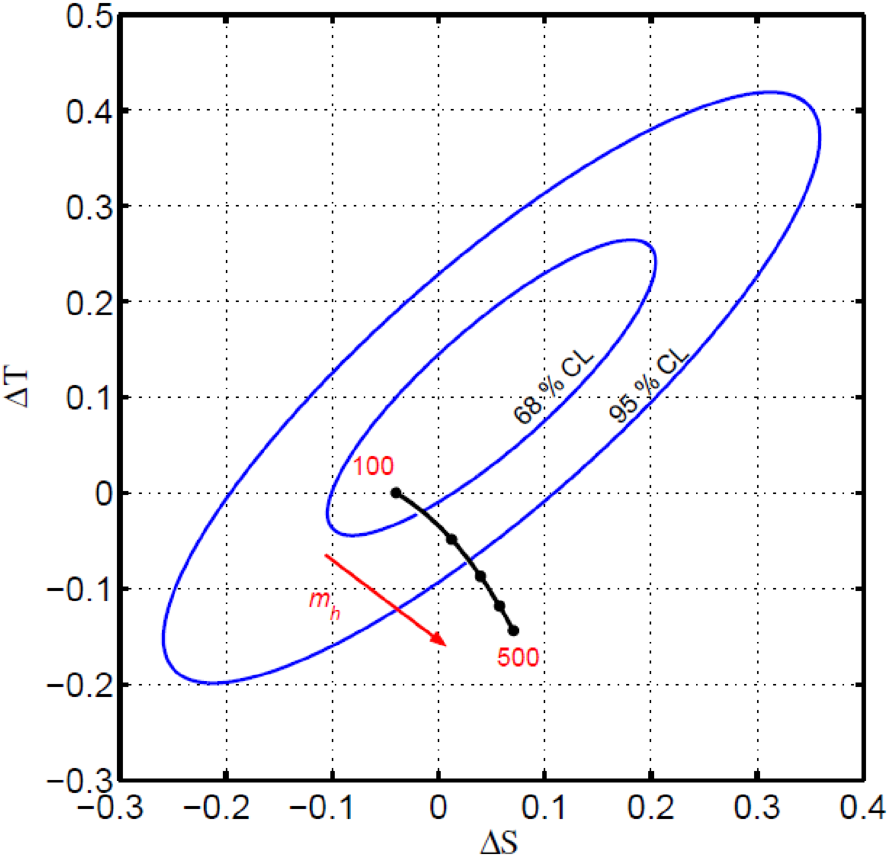


Figure 1: Experimentally allowed range for the S and T parameters (blue ellipses), from Ref. [1]. The $\Delta S = \Delta T = 0$ point corresponds to the SM prediction for $m_t = 175$ GeV and $m_h = 100$ GeV. The black curve is the SM prediction for $m_t = 171.4$ GeV and different values of m_h (in GeV).

D) NOVA EW PRECIZNOST

We are in the era of precision Higgs physics
- Calculations + experiment
- Theory may be limiting factor in precision coupling extraction

Higgs production is a window to high scale physics
- Need to look at big picture—new physics in the Higgs sector is typically associated with new particles (more Higgs particles, SUSY particles, top partners…)
- 2 Higgs production can discriminate between models

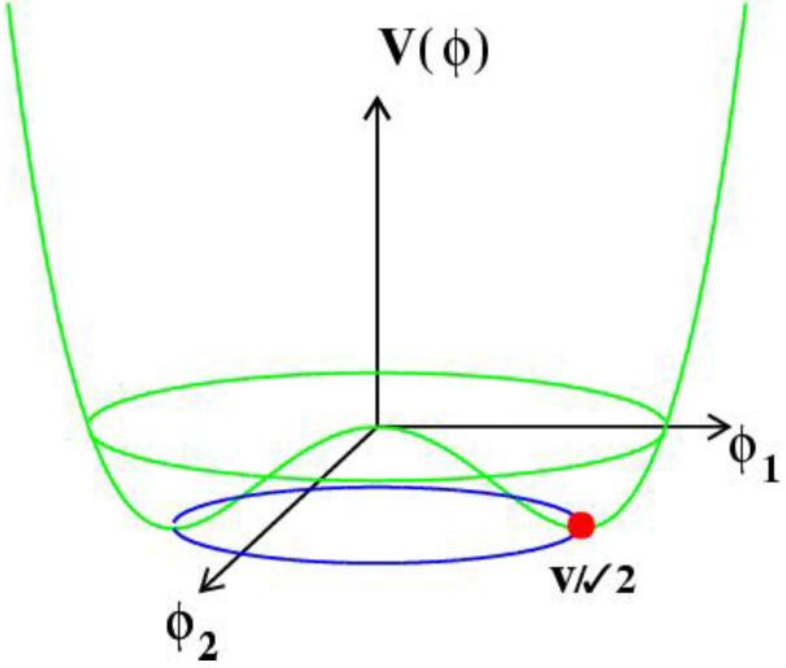
The SM is an extremely good effective theory

HIGGSOV SEKTOR JE PERTURBATIVAN

$$V = \frac{m_h^2}{2} h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4$$

$$\boxed{SM: \quad \lambda_3 = \lambda_4 = \frac{m_h^2}{2v^2}}$$

- Fundamental test of model
- $\lambda_3 \sim .13$ is perturbative



Many possibilities:

- Supersymmetry (squarks in loop)
- Color octet scalars [Kribs]
- More scalars (neutral or charged) [Thomas]
- New operators involving Higgs particle
- New fermions (top partners)
- Higgs produced in NP particle decays[Haas, Kribs, Thomas]

How far can Higgs production get from the SM prediction?

What is the Higgs telling us?

PRIMJER 1: 2HDM

Many models have extended Higgs sectors

- Two Higgs doublet models can be used as effective theories for many of these models
- 5 Higgs bosons: h, H, A, $H^{\pm}$
- 4 types of 2HDM models which avoid tree level FCNCs
- Classified in terms of tan $\beta = v_2/v_1$, α, m_h

$$\sin 2\alpha = -\sin 2\beta \left(\frac{M_H^2 + m_h^2}{M_H^2 - m_h^2} \right)$$

- Predictive models (MSSM is special case)

Couplings to h:

$$L \sim -\Sigma_i g_{hii} \frac{m_i}{v} \overline{f}_i f_i h - \Sigma_{i=W,Z} g_{hVV} \frac{2M_V^2}{v} V_\mu V^\mu h$$

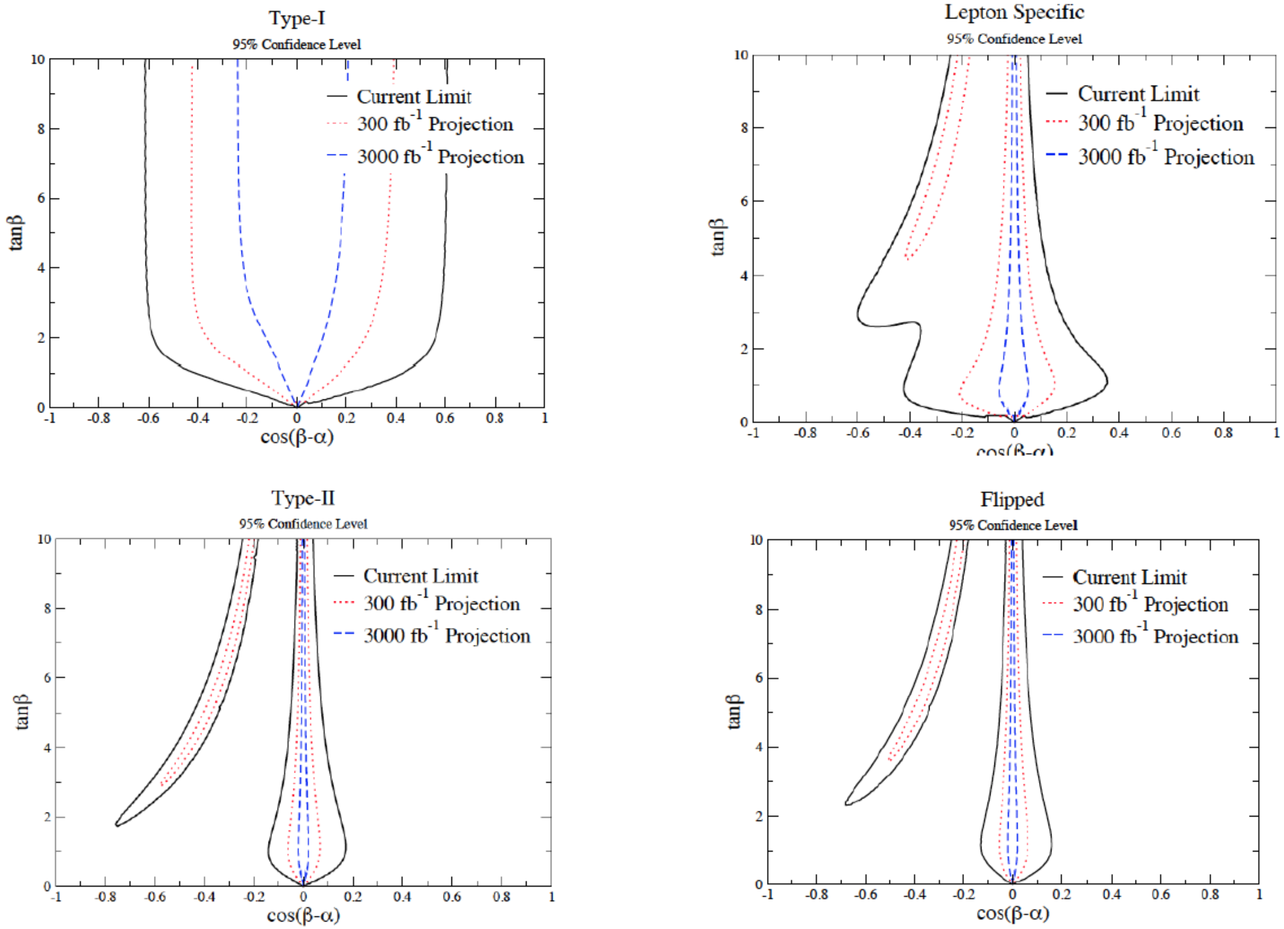
	I	II	Lepton-Specific	Flipped
g_{hVV}	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
$g_{ht\overline{t}}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$
$g_{hb\overline{b}}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
$g_{h\tau^+\tau^-}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$

↑

Type II is MSSM-like

S. Dawson

PRILAGODBE 2HDM-a



SM limit is cos(α−β)=0

We are near SM couplings already!

[Chen, Dawson, 1301.0309; Chen, Dawson, Sher]

S. Dawson

[Thomas]

LIMES ODVEZIVANJA 2HDM-a TIPA-II

Assume M_{H+}, $M_A >> M_Z$

$$\alpha \Delta T \sim \mathcal{O}\left(\frac{M_Z^2}{M_A^2}\right)$$

$$\Delta S \sim \frac{1}{12\pi}\cos^2(\beta-\alpha)\left[\log\left(\frac{M_A^2}{M_h^2}\right)-\frac{5}{6}\right]$$

Coupling shifts are small: $g_{hii} \equiv g_{hii}^{SM}\left(1+\frac{\delta g_{hii}}{g_{hii}^{SM}}\right)$

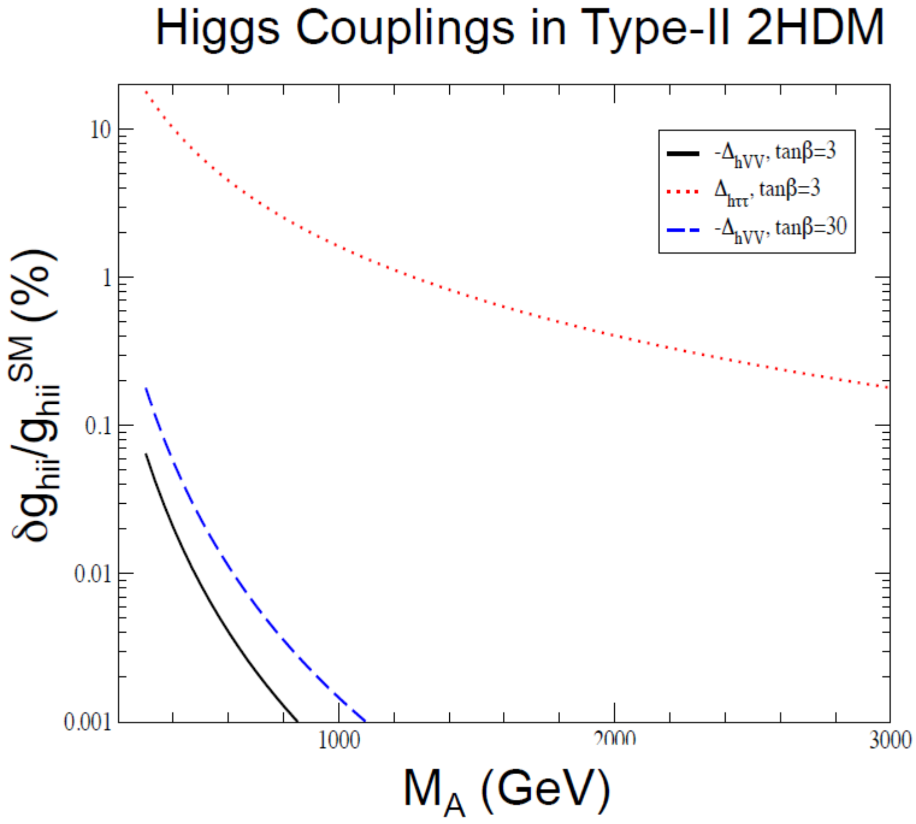
$$\frac{\delta g_{hVV}}{g_{hVV}^{SM}} = -\frac{2M_Z^4\cot^2\beta}{M_A^4}$$

$$\frac{\delta g_{ht\bar{t}}}{g_{ht\bar{t}}^{SM}} = -\frac{2M_Z^2\cot^2\beta}{M_A^2}$$

$$\frac{\delta g_{hb\bar{b}}}{g_{hb\bar{b}}^{SM}} = \frac{2M_Z^2}{M_A^2}$$

Higgs physics is new precision electroweak physics

Budući da je svijet “SM-like”



This requires sub-percent level measurements of Higgs couplings to distinguish the 2HDM model from the Standard Model

➔If we don’t see any new particles, this will be very hard!

Mjerenja vezanja higgsa

- Higgs coupling extracted from global fit
  - Measure σ•BR

$$L \sim g_{hii} f_i \overline{f}_i h$$

$$g_{hii} \equiv \left(1 + \frac{\delta g_{hii}}{g_{hii}^{SM}}\right) g_{hii}^{SM}$$

	LHC (300 fb^{-1}/exp)	**LHC (3 ab^{-1}/exp)**	**ILC 250 (250 fb^{-1})**
$\frac{\delta g_{hWW}}{g_{hWW}^{SM}}$	$2.7 - 5.7\%$	$1.0 - 4.5\%$	4.3%
$\frac{\delta g_{h\tau\tau}}{g_{h\tau\tau}^{SM}}$	$5.1 - 8.5\%$	$2.0 - 5.4\%$	3.5%

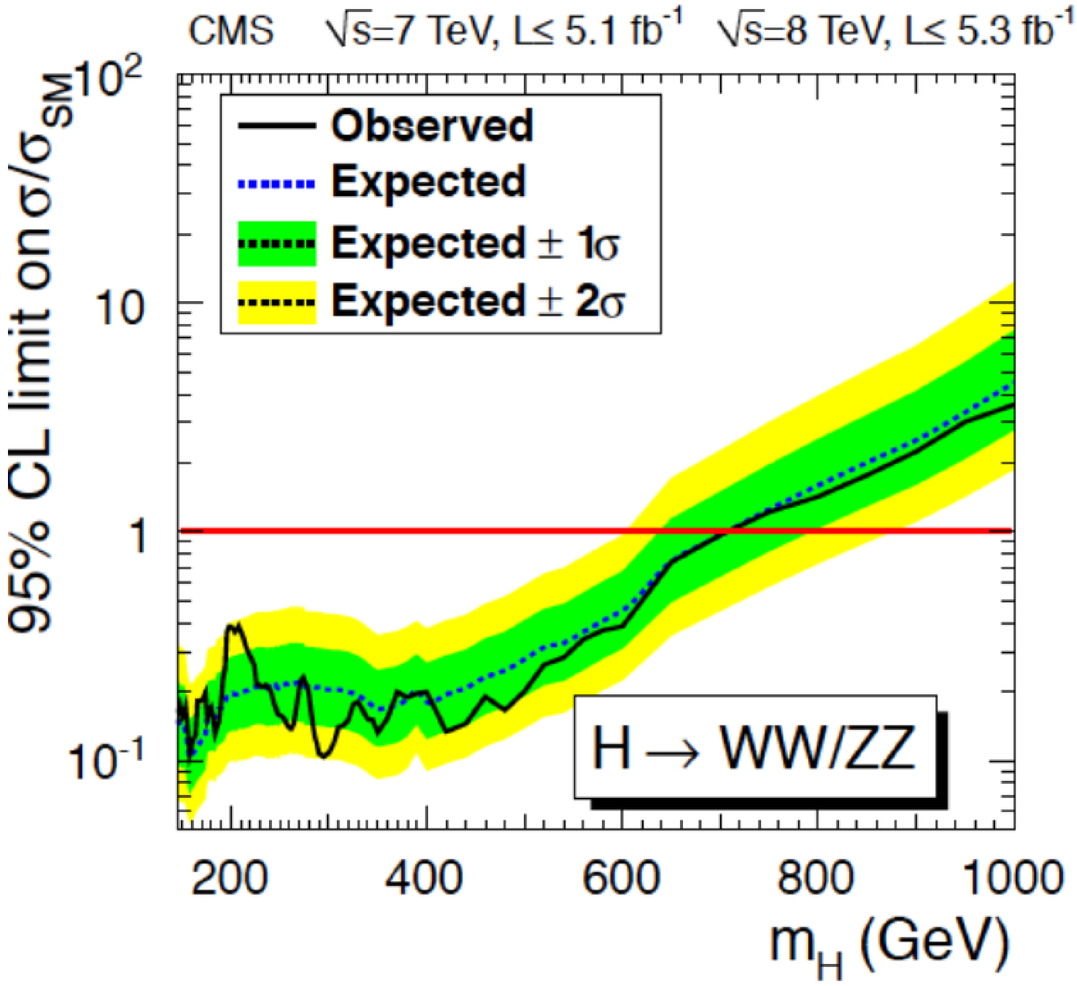
Assume systematics ~1/√L

S. Dawson

[Janot, ICFA Higgs factor workshop,
European Strategy Report]

Komplementarni pristup

Look for new particles of 2HDM (H,A,$H^{\pm}$)



$$g_{HVV} = cos(\beta - \alpha)$$

$$g_{Ht\bar{t}} = \left(\frac{\sin\alpha}{\sin\beta}\right)$$

PRIMJER 2: Top Seesaw, Little Higgs, Composite Higgs…

- Special cases of models with weak singlet vector like charge 2/3 quark, U_L, which mixes with SM-like third generation $q_L \sim (u_L, d_L)$, u_R, d_R
- Generic mass matrix

$$L_M = -a\bar{q}_L \tilde{H} u_R - b\bar{q}_L \tilde{H} U_R - c\bar{U}_L u_R - \boxed{d\bar{U}_L U_R} + hc$$

- Physical top is mixture of (u, U)

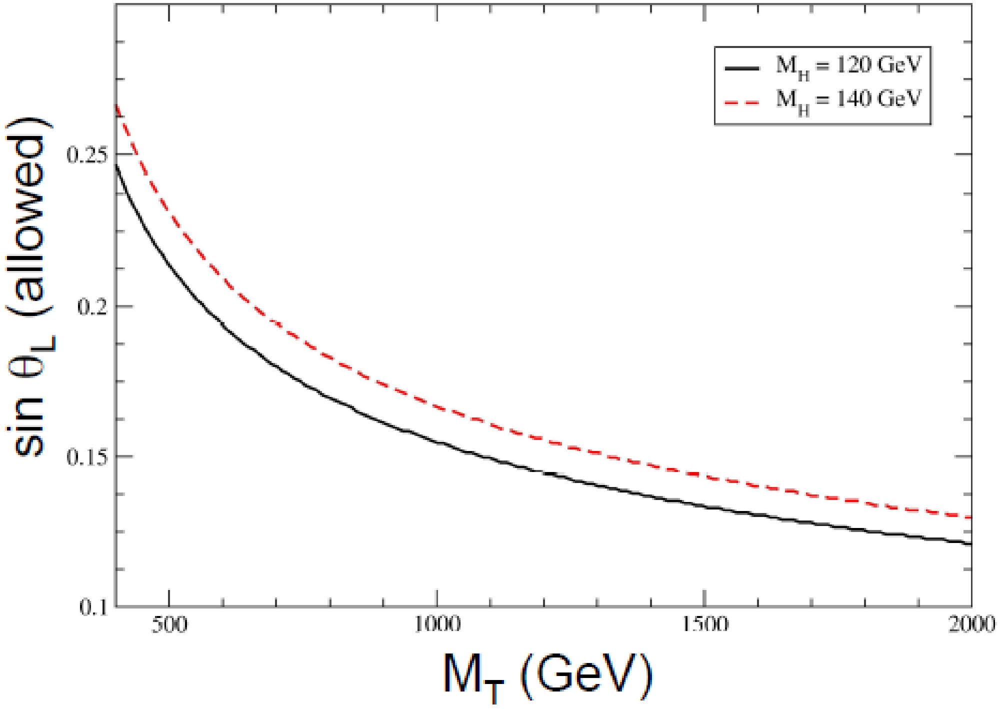
$$\begin{pmatrix} t_L \\ T_L \end{pmatrix} = \begin{pmatrix} c_L & -s_L \\ s_L & c_L \end{pmatrix} \begin{pmatrix} u_L \\ U_L \end{pmatrix}$$

T is charge 2/3 top partner

2 parameters: M_T, θ_L

Miješanje topa s partnerom

STU 95% CL Allowed Region
(below curves)



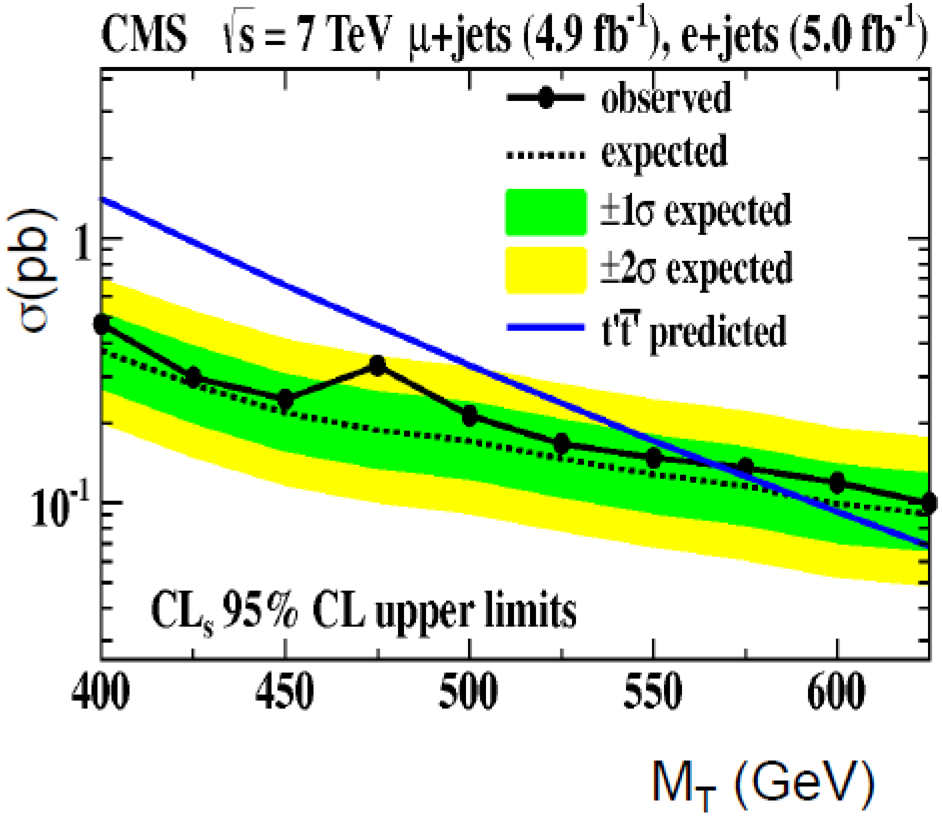
As Higgs mass gets larger, allowed parameter space shrinks

S. Dawson

[Dawson, Furlan, 1205.4733]

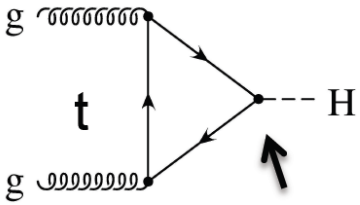
Eksperimentalna granica

- Assumes BR(T→ bW)=1
- Here, additional suppression of $(\sin\theta_L)^4$

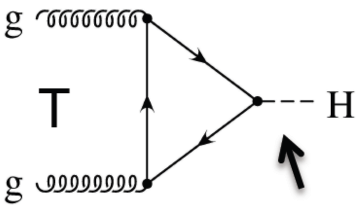


Model s top-partnerom

- Production suppressed (but not observably so)



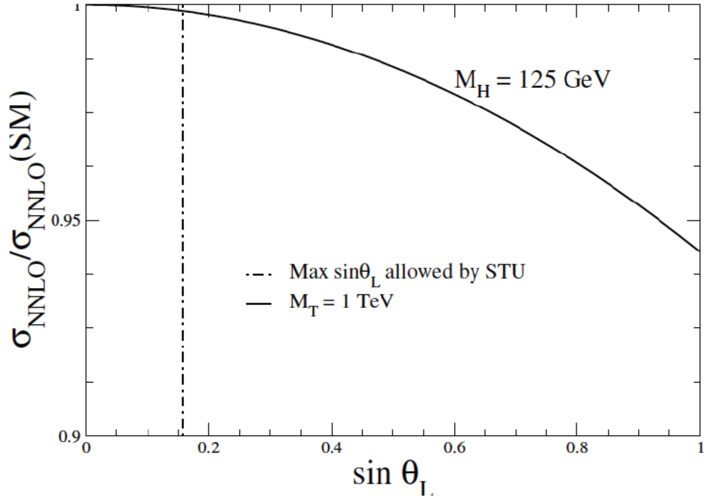
$\cos\theta_L{}^2$



$\sin\theta_L{}^2$

$$\frac{\sigma}{\sigma_{SM}} \sim 1 - \frac{7}{60}\frac{M_H^2}{m_t^2}\left(1 - \frac{m_t^2}{M_T^2}\right.$$

Top partner model, √s=7 TeV

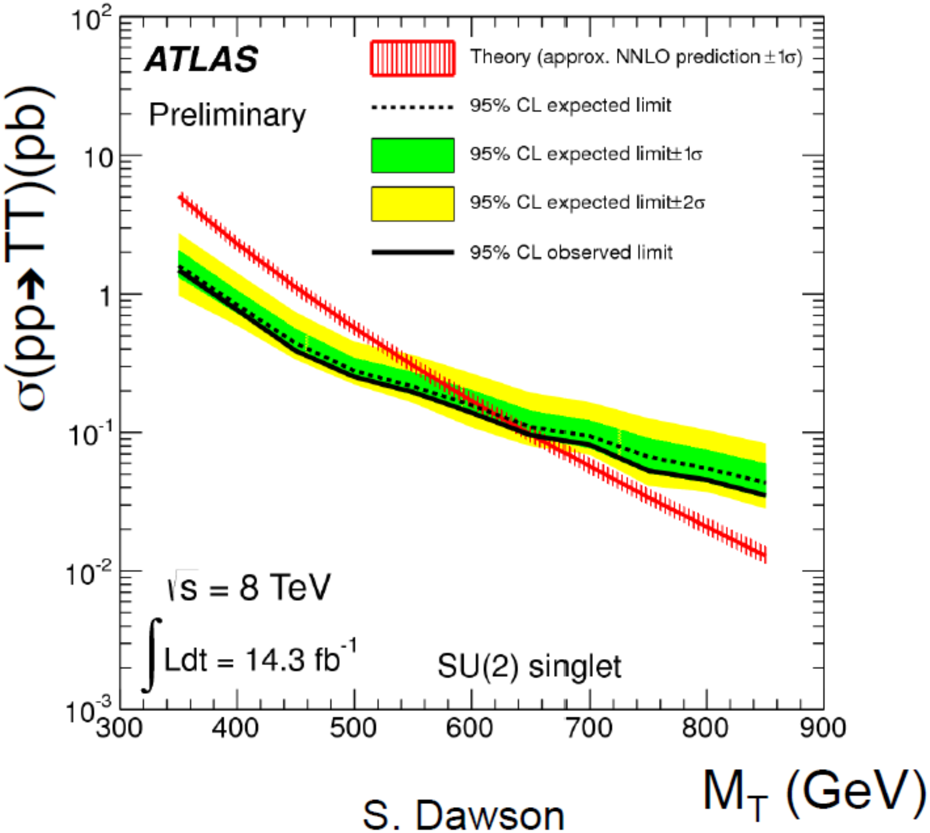


Example of model where new physics will be observed by top partner production, not by measuring Higgs properties

Produkcija higgsa i t-partnera

- T→th
  - – Branching ratio can be O(30%)

$$Tth :\sim \sin(2\theta_L)^2$$



Sažetak 2 modela

- 2HDMs, Top Partner models

These models have parameter spaces restricted by experimental Higgs measurements

Knowledge about NP from coupling constant measurements requires 1-10% percentage accuracy

BUT.....all of these models have new particles not present in the SM

S. Dawson